

Sticky Housing and the Real Effects of Monetary Policy¹

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Abstract

This paper asks why monetary contractions have strong effects on the housing market. The paper presents a model with staggered housing adjustment in which monetary policy has real effects in the absence of any rigidity in producer pricing or wages. Limited participation in financial markets leads to a rise in the real mortgage rate following an increase in the nominal short rate. Since households must take on a mortgage to consume housing, the rise in the real interest rate reduces the share of residential investment in output.

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1 Introduction

Why does monetary policy have real effects on the economy? Increasingly, policy makers and academics realize that one of the primary channels for the transmission of monetary policy is the housing market. Residential investment responds more quickly and strongly to monetary policy shocks than other sectors of the economy. Perhaps most obviously, the majority of housing is purchased using long-term financial contracts. Most monetary general equilibrium models feature only one-period financial contracts. By contrast, mortgages are not typically refinanced every quarter. Even when households do choose to incur the transactions costs associated with refinancing, it is much more costly to change the *level* of housing consumption.

I build a monetary general equilibrium model that incorporates two features of housing consumption not well-modeled by existing literature on the monetary transmission mechanism: 1) households move infrequently and 2) housing must be purchased using a mortgage. The model involves no rigidities in producer pricing: instead, a change in the money supply affects the real interest rate because only lenders have access to the government bond market such that changes in the money supply are not distributed equally.

This specific limited participation mechanism follows the work of Alvarez, Atkeson, and Kehoe (2002) and Occhino (2004). See also the survey by Edmond and Weill (2008) which provides an excellent overview of newer limited participation models including the mechanism at work in Alvarez, Atkeson, and Kehoe (2002) and Occhino (2004). Alvarez, Atkeson, and Kehoe (2002) and Occhino (2004) focus on the liquidity affect alone that limited participation in government bond markets produces. The key feature of these models is that the marginal utility of agents that interact in the bond market determines the interest rate. Alvarez, Atkeson, and Kehoe (2002) and Occhino (2004) work with endowment economies such that there is no change in the composition of real output following monetary policy shocks. In contrast to these papers, the present paper segments markets according to the role of agents in the economy. Here, only lenders receive the monetary injection. Because the burden of a monetary contraction falls entirely upon lenders, their consumption initially falls. As a result, they value a dollar received in the present much more highly and, because the shock is transitory, expect their consumption to increase over time. They therefore require a higher return on their loans since these loans will be repaid at a time when their marginal utility is higher.

As a result of the rise in both the short rate and the mortgage rate, which is linked to the

short rate through a variant of the expectations hypothesis, households shift their consumption into nondurables and away from residential investment following a rise in the nominal short rate. This fits with the intuition people have regarding why residential investment falls so much more than nondurable consumption and yet, to date, the literature has lacked a micro-founded model with this simple mechanism to explain the change in residential investment following a monetary policy shock.

I also find only a modest change in the decline in residential investment when the time between adjustments decreases. While the incentive to decrease housing consumption following a rise in the mortgage rate increases with the duration of the contract, the rise in the mortgage rate decreases with longer contracts because of the expectations hypothesis of interest rates: since the fall in the real short rate is relatively short-lived and the mortgage rate is a weighted average of this rate, the longer the contract is, the smaller the rise in the short rate. However, for a given increase in the real mortgage rate, lengthening the time between adjustments has a substantial effect on the magnitude of the decline in residential investment.

The model can match the comovement of residential investment and nondurable consumption, as well as the relative timing of the response of the two goods, when the two goods are intratemporal complements. In this case, most types of home buyers in the model do not immediately adjust their nondurable consumption in response to a monetary shock. Instead, they wait to reduce their nondurable consumption until such time as they have had a chance to reduce their housing consumption.

Insofar as households must borrow to consume housing in my model, I also draw on work by Christiano and Eichenbaum (1992, 1995) and Christiano, Eichenbaum, and Evans (1997, 2005). In the CEE framework, firms must borrow their wage bill in advance of production making marginal cost more sensitive to changes in the real interest rate. The difference here is that borrowing is for residential rather business investment and contracts are long-term.

Despite the importance of housing and durable goods in the monetary transmission mechanism, most monetary general equilibrium models ignore the role of housing altogether and none to my knowledge have incorporated the linkage between mortgages and housing consumption. Iacoviello (2005), Carlstrom and Fuerst (2006), Erceg and Levin (2006), and Barsky, House, and Kimball (2007) do look at housing in general equilibrium monetary models. Iacoviello's (2005) paper is a sticky price model that uses housing to propagate and amplify the monetary shock

through a financial accelerator mechanism. He abstracts from nonconvex adjustment costs and financial contracts last only one period in his model. Furthermore, his focus is on the behavior of house prices such that he holds the housing stock fixed leaving no role for changes in residential investment.

Erceg and Levin (2006) build a two sector sticky price and sticky wage model that incorporates convex adjustment costs of adjusting durables/residential investment. The Erceg and Levin (2006) model is able to explain the magnitude of the response in durables/residential investment with nominal rigidities and large convex adjustment contrasts. Barsky, House, and Kimball (2007) look at the relative importance of producer price rigidities in durable and nondurable goods. They find that, if prices in the durable goods sector are flexible, there are essentially no real effects of sticky prices in the nondurable goods sector. Carlstrom and Fuerst (2006) similarly look at a model with flexible prices in the durable goods sector but sticky prices in the nondurable goods sector, sticky wages, and convex adjustment costs. Their model is able to generate a decline in the durable goods sector following a shock.

In contrast to these papers, there are no nominal rigidities in my model, households must take on a mortgage to consume housing, nonconvex adjustment costs are captured using staggered adjustment, and the decline in residential investment happens because the real mortgage rate rises. The model thus provides an avenue through which monetary policy can affect real activity in a flexible price world.

Another stream of literature (e.g., Lessard and Modigliani 1975 and Kearl 1979), has emphasized the tilt effect of inflation on nominally indexed mortgage contracts. When the mortgage contract consists of nominal, constant payments, as is the case in standard fixed-rate mortgages, an inflationary environment will shift the burden of mortgage payments to the earlier years of the mortgage as rational lenders incorporate higher expectations for future inflation into the contract. When households are credit constrained, this leads to a decline in housing demand when inflation expectations rise. In this view, monetary policy that leads to higher long-term expectations of inflation reduces housing demand. However, I confine my attention to the effect of unanticipated monetary policy shocks in this paper.

The finding that residential investment responds more strongly than other components of GDP is not new and the results here are broadly similar to those found using slightly different data or methodology: Bernanke and Gertler (1995), Fratantoni and Schuh (2003), Barsky,

House, and Kimball (2003), and Hamilton (2008) all provide empirical evidence that housing consumption falls sharply following a contractionary monetary policy shock. Bernanke and Gertler (1995) for example find that the decline in residential investment is larger than the decline in nondurable consumption despite making a much smaller contribution to overall economic activity. Furthermore, residential investment responds to monetary policy shocks before business investment.

This paper also builds on recent papers that have shown the importance of housing and durable good consumption for asset pricing. Flavin and Yamashita (2002) find that the inclusion of the portfolio constraint resulting from the consumption demand for owner-occupied housing can explain why younger households hold proportionately less equity in their portfolio than predicted by the mean-variance portfolio selection approach. Flavin and Nakagawa (2008) and Piazzesi, Schneider, and Tuzel (2007) demonstrate that the failure of the consumption CAPM owes to its omission of housing. Yogo (2006) shows that a pricing kernel that includes durable and nondurable goods nonseparably can, under certain conditions, replicate the cyclical pattern in the equity premium as well as some cross-sectional features of stock returns.

The remainder of the paper proceeds as follows: Section 2 presents empirical impulse response functions to illustrate the reaction of residential investment to monetary policy shocks. Section 3 outlines the benchmark model and provides some motivating evidence for the assumptions in the model. Section 4 presents the results. Section 5 concludes. An appendix contains additional details on the model solution.

2 Empirical Evidence on Residential Investment and Monetary Policy Shocks

In this section, I measure the response of the components of real GDP to a monetary policy shock. I follow the standard approach (e.g., Barth and Ramey 2001, Christiano, Eichenbaum, and Evans 2005, Erceg and Levin 2006) of identifying the monetary policy shock using a Choleski decomposition of a VAR with four lags.

The empirical model is

$$X_t = A_0 + A_1X_{t-1} + A_2X_{t-2} + A_3X_{t-3} + A_4X_{t-4} + C\eta_t \tag{1}$$

where

$$X_t = [\ln GDPEx_t, \ln Nondurables_t, \ln Durables_t, \ln ResidentialInvestment_t, \\ \ln GDPDeflator_t, \ln PPI_t, FF_t, \ln M2_t],$$

η_t is a vector of zero mean i.i.d. shocks, and C is lower triangular. GDPEx consists of all components of GDP other than nondurable consumption, durable consumption, and residential investment. This identification scheme is similar to that of Christiano, Eichenbaum, and Evans (2005): The identifying assumptions are that 1) all variables except the Fed Funds rate and M2 cannot instantaneously react to a change in monetary policy, and 2) the Federal Reserve's information set includes contemporaneous and lagged values of all the real and nominal variables but only the lagged value of the growth rate of the money supply.

The sample period is 1965Q3 – 2007Q4, the period over which the Federal Reserve has followed an interest rate policy for setting monetary policy with the arguable exception of the monetarist period of the early 1980s. This the same sample period as Christiano, Eichenbaum, and Evans use. All variables are seasonally adjusted. I construct real chain-weighted values for all other components of GDP using the Divisia chain-weighted approach outlined in Whelan (2002) on nominal GDP data in BEA table 1.1.5 and the price deflators in BEA table 1.1.4. As no deflator data is available for the change in inventories, I use the GDP deflator for that component. Producer prices, the Fed Funds rate, and M2 are taken from the International Monetary Funds International Financial Database.

Figure 1 shows the impulse responses of the real variables in the system to a 100 basis point unanticipated increase in the Federal Funds rate. The responses are expressed as percentages of the variables and the error bands are constructed using the bootstrap method with 500 repetitions. Residential investment responds by far the most strongly and the most quickly of the four real variables. In the first quarter after the shock, the decline in residential investment is more than nineteen times that of nondurable consumption and more than twice times the decline in durable consumption while the remainder of GDP has yet to decline. The trough for residential investment comes a mere five quarters after the shock at which point its decline exceeds that of the remainder of GDP, nondurables, and durables by factors of 17, nearly 8, and almost 2. The trough in durables also comes after five quarters while the nondurables and the remainder

of GDP reach their lowest points seven and ten quarters after the shock.

The results are similar to those of Erceg and Levin (2006), who measure the combined response of durables and residential investment, and Barsky, House, and Kimball (2003), who use Romer dates to identify monetary policy shocks. Consistent with Barsky, House and Kimball's (2003), the response of residential investment is much sharper than that of durables. The results are also similar to those of Bernanke and Gertler (1995) although here the response in nondurables is slower than the response in residential investment rather than the similar timing in the declines Bernanke and Gertler find.

3 The Model

To explain the strong and rapid response of housing to a monetary policy shock, this paper uses two features of housing consumption not well-modeled by existing literature: first, households infrequently adjust their housing consumption, and second, households usually take on a mortgage to purchase a house. While households can and do increase their housing consumption slightly through home renovations, the primary way households change their housing consumption is by moving. Using the moving estimate from Quigley (2002), the realtor fee costs of Weicher (2006), and Woodward's (2003) closing costs estimates enables a crude estimate of the total direct transactions costs of altering housing consumption. Assuming that the value of the home is \$162,500 to be consistent with a loan of \$130,000, a first-time home buyer incurs direct transactions costs equal to approximately 8% of the value of the home while a homeowner who moves from a house she already owns must also pay the realtor's fees for the sale of the previous home bringing her total direct transactions costs to 13.1%.³

Another key feature of housing that distinguishes it from other consumption goods is that it is usually financed using a long-term contract. As of 2001, approximately three quarters of outstanding U.S. mortgages were traditional fixed rate mortgages with 87% of houses purchased using a mortgage (U.S. Census Bureau 2005, tables 1 and 2 – 1). While the share of mortgage issuance that is fixed rate varies over time (see Koijen, Van Hemert, and Van Nieuwerburgh, 2008), most adjustable rate mortgages feature some period of time in which the rate is fixed (often two years). In practice households can sometimes renegotiate their mortgage when the

³I choose a loan value of \$130,000 to be consistent with the results Woodward reports. The estimate above does not include the search costs or psychic costs of moving. See Venti and Wise (1984) and Bartik, Butler, and Liu (1992) for evidence on these costs.

interest rate falls or change the length of their mortgage in response to unexpected changes in income: As of 2001, about 17% of first mortgages on single family homes were refinanced mortgages (U.S. Census Bureau 2005, table 2-3). Even with refinancing, however, the household cannot change the *amount* of housing it is consuming.

The model is deliberately stylized to focus on the implications of the two main rigidities this model implies. Thus, there are many aspects of housing consumption that are certainly important to understanding the linkage between the monetary transmission mechanism and housing such as the choice of mortgage contract and down payment constraints that the model does not capture.

The main assumptions in the model are 1) there are lumpy adjustment costs in housing consumption that are proxied by fixed J -period investments that home buyers make in a staggered fashion, 2) housing must be purchased using a real mortgage that lasts for J periods and cannot be renegotiated, and 3) the monetary authority changes the money supply by interacting with lenders in the government bond market. Housing adjustment is thus time-dependent rather than state-dependent. This assumption is made primarily for computational convenience and is a reduced form for the actual process governing housing adjustment which results from a combination of the nonconvex adjustment costs as well as stochastic life events such as marriage, job changes, the arrival of children, and death. In the benchmark version of the model, the house depreciates completely at the end of J periods; I consider a special case of the model with partial depreciation in the next section of the paper. Monetary shocks are the only source of uncertainty in the model.

Mortgages are modeled as real financial contracts to focus on the implications of the asymmetric financial market participation for the economy rather than the redistribution between lenders and borrowers that happens as inflation changes the real value of nominally contracted financial payments. The assumption that only lenders can participate in the government bond market is akin to the limited participation models pioneered by Grossman and Weiss (1983) and Rotemberg (1984). The mechanism follows the more recent incarnations of limited participation by Alvarez, Atkeson, and Kehoe (2002) and Occhino (2004) where only a subset of agents can transact in the bond market. I depart from Alvarez, Atkeson, and Kehoe (2002) and Occhino (2004) by having consumers hold money through inserting it in the utility function rather than through imposing a CIA constraint. This simplifies the analysis here, since, unlike in the Alvarez, Atkeson, and Kehoe (2002) and Occhino (2004) endowment economies, the CIA constraints will

not necessarily bind for home buyers. However, the intuition for the liquidity effect remains the same as in Occhino (2004): in response to an increase in the nominal interest rate, lenders purchase more bonds and hold less cash. Because lenders absorb all of the increase in the money supply via changes in their bond holdings, their consumption changes and hence the real interest rate changes.

3.1 Firms

There is a continuum of perfectly competitive firms of measure one that produce undifferentiated goods, Y_t , using only labor, L_t , as an input with the technology

$$Y_t = L_t.$$

They maximize profits by choosing labor, and taking the house price, P_t^H , and the price of nondurables, P_t , and real wages, W_t , as given leading to the equilibrium conditions

$$P_t^H = P_t$$

and

$$W_t = 1.$$

3.2 Households

There are two types of households in the economy: households that consume housing and nondurables and households that consume only nondurable goods. The first type of household, the home buyer, holds cash balances and borrows to buy housing, while households that consume only nondurable goods, lenders, hold cash balances and make loans. Only lenders have access to the government bond market and thus receive the monetary injection. This division of households captures the idea that most households require a mortgage to purchase a home. The set of home buyers is of measure $\epsilon \in (0, 1)$ and the set of lenders is of measure $1 - \epsilon$.

3.2.1 Home Buyers

Home buyers are further subdivided into J types of households that are heterogeneous in the period in which they can change their housing consumption.⁴ Only households that are currently of type 0 can immediately adjust their housing. This captures the infrequent adjustment of housing. That is, slow adjustment is imposed through a staggering structure similar to the mechanism Taylor (1980) uses to model wages. The J types of home buyers are each of measure ϵ/J .

Each period, the household chooses how much to consume of the nondurable good, how much cash to take into the next period, how much to work out of its normalized time endowment of 1, and how much housing to consume if it is a type 0 household. To purchase a home, a type 0 requires a mortgage that it must repay within J periods. To impose this requirement, I assume that the choice of how much housing to consume and how much to borrow is one and the same. I also assume repayment within J periods for computational convenience; none of the intuition of the model relies on this assumption. All mortgages are fixed rate. The household borrows $H_{t,0}$ at time t and repays the mortgage in installments of $H_{t,0} \left(\frac{(R_t-1)R_t^{J-1}}{R_t^J-1} \right)$ for each of the next J periods where R_t is the period t gross real interest rate for $R_t > 1$. This payment schedule comes from the formula for the present value of an annuity where the present value of the annuity is $H_{t,0}$ and the payments start in period 0 rather than the more customary period 1. It can be derived by subtracting the value of a consol that begins in period $t+J$ from the value of a consol that begins in period t . Since the value of the consol is ∞ when $R_t = 1$, the payment schedule is simply $H_{t,0}/J$ in this case.

Housing is subject to One-Hoss Shay depreciation. That is, at the end of J periods, the housing stock of each household depreciates completely. Letting $F_t = \frac{(R_t-1)R_t^{J-1}}{R_t^J-1}$ denote the interest rate factor on mortgage payments, the representative household of type 0's period t value function is thus

$$V_0(M_{t-1,J-1}) = \max_{\{C_{t,0}, H_{t,0}, L_{t,0}, M_{t,0}\}} \left\{ \begin{array}{l} u(C_{t,0}, H_{t,0}) + \omega_1^h \ln \frac{M_{t,0}}{P_t} + \\ \omega_2 \frac{1}{1-\eta} (1 - L_{t,0})^{1-\eta} + \beta E_t V_1(M_{t,0}, H_{t,0}) \end{array} \right\}$$

⁴A Calvo-style probabilistic mechanism to convexify the economy is not appropriate in this framework. This is because home buyers will not in general be homogeneous in their choice of money holdings. That is, optimal real balances are not independent of when the household last changed its housing stock.

subject to

$$C_{t,0} + \frac{M_{t,0}}{P_t} + F_t H_{t,0} = L_{t,0} + \frac{M_{t-1,J-1}}{P_t}$$

where $V_1(\cdot)$ is the value function of a household of type 1 since the household will be a type 1 household next period, $C_{t,j}$ is nondurables' consumption, $H_{t,j}$ is the housing stock, $L_{t,j}$ is labor supply, and $M_{t,j}$ is nominal balances.

A household that is currently of type $j \neq 0, J-1$ cannot change its housing stock in period t but must make mortgage payments on its house. Its value function is thus

$$\begin{aligned} & V_j(M_{t-1,j-1}, H_{t-j,0}) \\ &= \max_{\{C_{t,j}, L_{t,j}, M_{t,j}\}} \left\{ \begin{array}{l} u(C_{t,j}, H_{t-j,0}) + \omega_1^h \ln \frac{M_{t,j}}{P_t} + \\ \omega_2 \frac{1}{1-\eta} (1 - L_{t,j})^{1-\eta} + \beta E_t V_{j+1}(M_{t,j}, H_{t-j,0}) \end{array} \right\} \end{aligned} \quad (2)$$

subject to

$$C_{t,j} + \frac{M_{t,j}}{P_t} + F_{t-j} H_{t-j,0} = L_{t,j} + \frac{M_{t-1,j-1}}{P_t} \quad (3)$$

while a household of type $J-1$ has the value function

$$\begin{aligned} & V_{J-1}(M_{t-1,J-2}, H_{t-(J-1),0}) \\ &= \max_{\{C_{t,J-1}, L_{t,J-1}, M_{t,J-1}\}} \left\{ \begin{array}{l} u(C_{t,J-1}, H_{t-(J-1),0}) + \omega_1^h \ln \frac{M_{t,J-1}}{P_t} + \\ \omega_2 \frac{1}{1-\eta} (1 - L_{t,j})^{1-\eta} + \beta E_t V_0(M_{t,J-1}) \end{array} \right\} \end{aligned} \quad (4)$$

subject to (3) evaluated at $j = J-1$. The difference between equations (2) and (4) is that a household of type $J-1$ will be a household of type 0 next period and housing does not enter the value function of a type 0 agent since the housing stock completely depreciates at the end of J periods.

Optimizing behavior is determined recursively using the first order conditions of each of the different J types of households. The single period utility from housing and nondurable goods is

$$\begin{aligned} u(C_{t,j}, H_{t,j}) &= \frac{1}{\theta} \ln(\gamma H_{t,j}^\theta + C_t^\theta), \\ H_{t,j} &= H_{t-j,0}. \end{aligned}$$

$\theta \leq 1$, $\theta \neq 0$, $\gamma > 0$, such that consumption services from housing are proportional to the housing

stock. I allow for the possibility that the goods are nonseparable based on the empirical evidence Flavin and Nakagawa (2008) and Piazzesi, Schneider, and Tuzel (2007) provide. When $\theta > 0$, $u_{12}(\cdot) < 0$ such that housing and nondurables are Edgeworth substitutes with $\theta = 1$ representing the case of perfect substitutes. When $\theta < 0$, the two goods are Edgeworth complements with $\theta = -\infty$ representing the extreme case of Leontief preferences. The case of separability is given by

$$u(C_{t,j}, H_{t,j}) = \ln(\gamma H_{t,j}) + \ln(C_{t,j}).$$

Letting $u_i(\cdot)$ denote the first derivative of the felicity function with respect to its i th argument, the first order condition for housing at an interior solution is

$$E_t \sum_{j=0}^{J-1} \beta^j u_2(C_{t+j,j}, H_{t,0}) = E_t \sum_{j=0}^{J-1} \beta^j u_1(C_{t+j,j}, H_{t,0}) F_t. \quad (5)$$

The left hand side is the discounted marginal utility of the housing services one unit of housing provides in the periods in which the unit will be held. This must be equal to the decrease in expected utility from mortgage payments in periods t through $t + J - 1$.

3.2.2 Lenders

Lenders in the economy consume only the nondurable good. It is necessary to introduce some heterogeneity between lenders and borrowers to generate positive borrowing in general equilibrium. Bernanke and Gertler (1989) accomplish this by assuming that entrepreneurs do not consume when they are young while Carlstrom and Fuerst (1997) assume entrepreneurs discount the future more heavily than households. I instead assume lenders do not consume housing and do not work. Clearly, all of these assumptions are imperfect and are made for computational purposes only.

Each period, the representative lender chooses how much to consume, how much cash to hold, how much to lend to the type 0 home buyers, and its holdings of government bonds. Lenders do not work. The motivation for this assumption is that the primary suppliers of labor are prime-aged workers who are also net borrowers when they work or from high net worth individuals who are not well represented by the standard labor-leisure decision. However, it remains an empirical question which types of households do in fact transact frequently in the bond market that no work I know of has addressed.

Letting $C_{t,l}$, $b_{t,l}$, $b_{t,GOV,l}$ and $M_{t,l}$ denote the consumption of nondurables, real loans to borrowers, one-period nominal loans to the government, and nominal balances, the representative lender's problem is

$$\max_{\{C_{t,l}, M_{t,l}\}_{t=0}^{\infty}} E_0 \left\{ \sum_{t=0}^{\infty} \beta^t \left(u(C_{t,l}) + \omega_1^l \ln \frac{M_{t,l}}{P_t} \right) \right\}$$

subject to

$$C_{t,l} + b_{t,l} + \frac{b_{t,GOV,l}}{P_t} + \frac{M_{t,l}}{P_t} = \frac{M_{t-1,l}}{P_t} + \sum_{j=0}^{J-1} b_{t-j,l} F_{t-j} + R_{t-1,SHORT} \frac{b_{t-1,GOV,l}}{P_t}$$

and

$$u(C_{t,l}) = \ln C_{t,l}.$$

The Euler equations for cash balances, loans to home buyers, and loans to the government are

$$\begin{aligned} u'(C_{t,l}) &= \omega_1^l \frac{P_t}{M_{t,l}} + \beta E_t \left\{ u'(C_{t+1,l}) \frac{P_t}{P_{t+1}} \right\} \\ u'(C_{t,l}) &= E_t \left\{ \sum_{j=0}^{J-1} \beta^j u'(C_{t+j,l}) F_t \right\} \\ 1 &= E_t \left\{ \beta \frac{u'(C_{t+1,l}) R_{t,SHORT} P_t}{u'(C_{t,l}) P_{t+1}} \right\}. \end{aligned}$$

ω_1^h and ω_1^l will not in general be identical since lenders consume only nondurables while home buyers consume both housing and nondurables. Since the money-in-the-utility function is a reduced form for the benefit consumers get from saving on transactions costs or shopping time, lenders value cash more highly if cash is only required to purchase nondurables. In solving for the steady state, I calibrate ω_1^h and ω_1^l such that real cash balances are proportional to each household type's nondurable consumption.

3.3 The Consolidated Government and Monetary Authority

The monetary authority adjusts the money supply to follow the interest rate targeting rule

$$\frac{R_{t,SHORT}}{R_{SHORT}} = \left(\frac{R_{t-1,SHORT}}{R_{SHORT}} \right)^{\rho_R} \exp(\varepsilon_t)$$

and the period t money supply equals the money supply in the previous period less government sales of bonds plus government repayment of bonds issued in the previous period, i.e.,

$$M_t = M_{t-1} - b_{t,GOV} + R_{t-1,SHORT} b_{t-1,GOV}.$$

3.4 Equilibrium

In equilibrium, the nondurable goods market, housing market, loan markets, and the money market all clear such that in addition to the first order conditions, the interest rate rule, and the government budget constraint, the equilibrium conditions are

$$\begin{aligned} L &= C_t + \frac{\epsilon}{J} H_{t,0} \\ L_t &= \frac{\epsilon}{J} \sum_{j=0}^{J-1} L_{t,j} \\ C_t &= \frac{\epsilon}{J} \sum_{j=0}^{J-1} C_{t,j} + (1 - \epsilon) C_{t,l} \\ b_{t,GOV} &= (1 - \epsilon) b_{t,GOV,l} \\ (1 - \epsilon) b_{t,l} &= \frac{\epsilon}{J} H_{t,0} \\ M_t &= \frac{\epsilon}{J} \sum_{j=0}^{J-1} M_{t,j} + (1 - \epsilon) M_{t,l} \end{aligned}$$

Equilibrium also requires the inclusion of all but one type of household's budget constraints as equilibrium conditions. The omitted agent's budget constraint is then automatically satisfied by the aggregate resource constraint.

To solve for the steady state, I calibrate ω_2 by assuming that all home buyers spend the same fraction of their time allotment working in the steady state. This implies the following result:

Proposition 1 *If all home buyers are identical in their labor supply in the steady state, they are also identical in their nondurables consumption. Further, all home buyers hold identical cash balances in the steady state under these conditions.*

The appendix contains the proof and additional details of the model solution.

4 Housing and Monetary Policy Shocks

This section quantifies the implications of the model for the effects of monetary policy. I first present the benchmark parameterization of the model and then study the effects of an expansionary monetary policy shock in the benchmark model. I then look at how the results depend on the adjustment length. I next consider the case where the monetary authority follows a money supply rule and changes the money supply by a helicopter drop to lenders instead of through conducting open market operations. Finally, I consider a version of the model in which the housing stock only depreciates by a fraction δ over J periods.

4.1 Parameterization

Table 1 contains the benchmark parameter values where a period is to be interpreted as one quarter. In 2005, the median US household last moved five years earlier while the median US home owner last moved nine years earlier (U.S. Census Bureau 2006, Table 2-9). I therefore set $J = 20$. Because housing adjustment is time-dependent rather than state-dependent in my model, using a larger value of J may overstate the true degree of rigidity. Furthermore, in reality households can refinance, an option that might reduce the sensitivity of the model to monetary policy shocks.

I set β , the household's discount factor, to 0.99 and η to 8. The steady state aggregate labor supply is 20% of the time allotment consistent with the parameterization of other general equilibrium models (e.g., King and Rebelo 1999). However, since only a fraction ϵ of households work, $L_j = 0.2/\epsilon$. I fix the share of households that are home buyers to 0.7. These assumptions imply a Frisch labor supply elasticity of $\frac{1}{\eta} \frac{1-L_j}{L_j} = 0.3125$ in line with the estimates of MaCurdy (1981) and Ziliak and Kniesner (1999, 2005). The results are not, however, very sensitive to the values of η or nearby values of ϵ .

Flavin and Nakagawa (2008) estimate θ , the parameter governing the degree of complementarity between housing and nondurables' consumption to be strongly negative implying a large complementarity between the two goods. Their measure of nondurables consumption is food consumption and there may be a particularly high degree of complementarity between these two items. Furthermore, Piazzesi, Schneider, and Tuzel (2007) report several estimates of this parameter, many of which imply the two goods are Edgeworth substitutes. However, theoretical work increasingly assumes the two goods are complements (see, for example, Cocco 2004,

Yao and Zhang 2005, and Kiyotaki, Michaelides, and Nikolov 2007) based on the observation that households that relocate to more expensive cities spend a larger fraction of their income on housing rather than a smaller fraction as the two goods being substitutes would imply. As the literature has not reached a consensus on the value of this parameter, I consider the results for the model under several cases.

To solve for the steady-state of the model, I assume that households spend one third of their income on mortgage payments. I set the persistence of the monetary policy shock to 0.8 and the standard deviation of the shock to 0.01 per quarter such that the impulse responses represent the percent deviations from steady state of the variables in response to an exogenous, persistent increase in the nominal interest rate of 100 basis points. After assuming a value for the share of home buyers' net income spent on consumption, $Cshare$, evaluating (5) at the steady state of the model implies the value of γ . I calibrate ω_1^h and ω_1^s by making steady state real balances of each type of household proportional to their consumption and set steady state velocity to 10.

4.2 The Reaction to Monetary Policy Shocks

Figures 2 and 3 show the aggregate responses of the economy to a contractionary monetary policy shock in the economy when housing and nondurables are separable in home buyers utility function, when the two goods are intratemporal complements, and when the two goods are intratemporal substitutes. Because of the limited participation in government bond markets, it is the marginal utility of consumption of agents that participate in the bond market, lenders, that determines real interest rates. Lenders' consumption initially declines such that the real short rate rises. As in standard asset pricing models, lenders require a higher return to lend a dollar that will be returned to them when their consumption is higher and hence their marginal utility is lower.

The real mortgage rate also rises but by a much smaller amount since it is, to a first order approximation, a weighted average of future short rates. This is simply the expectations hypothesis of the term structure at play. Residential investment thus falls by more than 1% in response to the 100 basis point increase in the nominal short rate. This is not as strong as the fall in residential investment in the data largely because of the full depreciation assumption: the fall in residential investment is much sharper in the version of the model with partial depreciation.

The decline in aggregate output results from home buyers increasing their consumption of

leisure. As the marginal utility from nondurables declines, the marginal utility of leisure also must decline such that the contraction in output is sharpest when the two goods are substitutes. When the two goods are complements, there is a smaller initial decline in the marginal utility of nondurables (since both housing and the consumption of nondurables fall for home owners that have a chance to adjust) such that the aggregate effects are smallest in this case.

When housing and nondurables are separable or substitutes, there is a rise in nondurables on the part of home buyers such that this version of the model does not replicate comovement between residential investment and housing observed in the data. Not surprisingly, there is the greatest substitution towards housing when the two goods are substitutes and the (eventually) a fall in housing consumption when the two goods are complements.

When the two goods are complements, home buyers choose to reduce their nondurable consumption only after they have a chance to reduce to reduce their housing consumption. After each home buyer type has a chance to decrease their housing consumption, they start decreasing their nondurable consumption since they now get lower marginal utility from consuming a unit of nondurables. This corresponds with the delayed response of nondurable consumption observed in the data. Recall that in the data, the trough in nondurable consumption comes about two quarters after the trough in housing consumption consistent with the behavior implied by the infrequent adjustment captured by the model.

A limitation of the model is in its prediction of a rise in the price level following a rise in the short rate. This happens because the consolidated government / monetary authority raises the stock of government debt outstanding to reduce the money supply. Eventually, the government needs to retire the debt. As its only source of revenue in this model is the inflation tax, it eventually must increase the money supply to bring the debt back down to the steady state level. As a result, the nominal money supply increases in the long run. In response to the anticipated long run increase in the money supply, the price level increases immediately. In most industrialized countries, in actual practice fiscal and monetary policy are clearly separate and the monetary authority merely changes the ownership of government bonds from itself to the private sector to change the money supply. Without introducing a more complete description of the monetary authority's operating procedures or allowing the government some other way to raise tax revenue, however, the government's only option to reduce its debt is to monetize it. This mechanism is reminiscent of Cagan's (1956) explanation of hyperinflations.

Without additional frictions, the timing of the impulse responses in the model is inconsistent with the empirical evidence. As is well-known, the effects of monetary policy shocks are only slowly felt throughout the economy. Barth and Ramey (2001), Romer and Romer (2004), and Christiano, Eichenbaum, and Evans (2005) are typical results in the literature: the effect of a monetary policy shock on real and nominal variables peaks at six to eight quarters and continues to have effects for several quarters thereafter. However, sticky price models also suffer from this problem when they are not augmented with additional rigidities as Chari, Kehoe, and McGrattan (2000) emphasize.

4.3 Shorter Contracts

One of the driving forces in the model is that mortgages are long term contracts such that, when the real interest rate rises, households are forced to lock in housing consumption at a higher rate for several periods to come. As a result, we would expect the real effects to be less pronounced if households adjust their housing consumption more frequently. To verify this prediction, figure 4 illustrates the results for the case of separable utility when $J = 4$ and $J = 8$ rather than the benchmark case of $J = 20$ such that households adjust their housing consumption every year or every two years.

As compared with the benchmark case, the aggregate response is smaller as the time between adjustment falls. However, the decline is not as dramatic as might be suspected because the real mortgage rate rises by more with shorter contract lengths. This is simply an effect of the expectations hypothesis of the term structure: when mortgage contracts correspond to $J = 20$, the mortgage rate is a weighted average of the real short rate over the next 20 periods. During many of these periods the real short rate is back at its steady state value such that there is a much smaller change in the mortgage rate than in the cases of $J = 4$ and $J = 8$: the rise in the real mortgage rate when $J = 4$ is more than three times the rise in the real mortgage rate as in the benchmark case.

To explore the effect of the length between adjustment periods alone, figure 5 shows the change in residential investment for the three different contract lengths when the mortgage rate rises by 10 basis points. This is a similar rise in the mortgage rate to that in the benchmark model. To achieve this rise in all three models, I change the size of the shock to the short interest rate for each J . Here, we see that the length of the contract plays a major role in the magnitude

of the decline of residential investment with the fall in the case of $J = 20$ more than five times the fall when $J = 4$.

4.4 A Money Supply Rule

The idea that only lenders can transact in the bond market provides credible microfoundations for limited participation models; older limited participation mechanisms relied on implausibly high transactions costs of going to the bank. Unfortunately, the full limited participation model leads to counterfactual implications for the price level following a contractionary shock. In this subsection, I therefore consider a simpler version of the model without government bonds in which the monetary authority conducts monetary policy by simply reducing the size of its helicopter drop. Analogously to the benchmark model, only lenders receive helicopter drops of money.

Whether one prefers the model with a full mechanism for limited participation or a more reduced form model that leads to more realistic predictions for the price level is ultimately a matter of taste. However, figure 6 shows the results of a 1% negative shock to the growth rate of the money supply in this environment for the case in which the two goods are separable. As before, the real mortgage rate rises leading to a decline in housing in aggregate output and, because of the separability assumption, consumption of nondurables increases. However, the price level jumps immediately to a lower level as expected after a contractionary shock.

4.5 Partial Depreciation

Among the simplifying assumptions in the model that are perhaps least attractive is the full depreciation assumption. This section considers a version of the model that allows for partial depreciation by allowing borrowers to retain their housing stock at the end of J periods less some depreciation. Instead of One-Hoss Shay depreciation, the house now depreciates by a fraction δ at the end of J periods. A type 0 household now has the value function

$$V_0(M_{t-1,J-1}, H_{t-J,0}) = \max_{\{C_{t,0}, H_{t,0}, M_{t,0}, L_{t,0}\}} \left\{ \begin{array}{l} u(C_{t,0}, H_{t,0}) + \omega_1^h \ln \frac{M_{t,0}}{P_t} \\ + \omega_2 \frac{1}{1-\eta_L} (1 - L_{t,0})^{1-\eta_L} + \beta E_t V_1(M_{t,0}, H_{t,0}) \end{array} \right\} \quad (6)$$

subject to

$$C_{t,0} + \frac{M_{t,0}}{P_t} + F_t(H_{t,0} - (1 - \delta)H_{t-J,0}) = L_{t,0} + \frac{M_{t-1,J-1}}{P_t}. \quad (7)$$

That is, the household must now only finance the change in its housing consumption net of depreciation.

The budget constraints for agents of type $j = 1, \dots, J - 1$ become

$$C_{t,j} + \frac{M_{t,j}}{P_t} + F_{t-j} (H_{t-j,0} - (1 - \delta) H_{t-j-J,0}) = L_{t,j} + \frac{M_{t-1,j-1}}{P_t} \quad (8)$$

Finally, the goods market and loan market clearing conditions become

$$Y_t = C_t + \frac{\epsilon}{J} (H_{t,0} - (1 - \delta) H_{t-J,0}) \quad (9)$$

and

$$(1 - \epsilon) b_{t,l} = \frac{\epsilon}{J} (H_{t,0} - (1 - \delta) H_{t-J,0}). \quad (10)$$

The first order condition for housing at an interior solution becomes

$$\begin{aligned} & E_t \sum_{j=0}^{J-1} \beta^j u_2 (C_{t+j,j}, H_{t,0}) + E_t \beta^J F_{t+J} (1 - \delta) u_1 (C_{t+J,0}, H_{t+J,0}) \\ & = E_t \sum_{j=0}^{J-1} \beta^j u_1 (C_{t+j,j}, H_{t,0}) F_t. \end{aligned} \quad (11)$$

The additional term on the left hand side compared to (5) reflects the increase in utility the household now gets from being able to consume more in the future as a result of higher asset holdings.

Figure 7 compares the benchmark model and the model with partial depreciation with $\delta = 0.05$ for the case in which the two goods are separable for the household. Recall that the depreciation rate is the depreciation over five years, rather than the more customary per period depreciation rate such that this calibration corresponds to a 1% annual depreciation rate. The depreciation rate for residential structures is substantially smaller than for nonresidential structures. The BEA (2003) estimates new single family homes depreciate at an annual rate of 1.1%. Harding, Rosenthal, and Sirmans (2007) similarly estimate a 1% annual depreciation rate.

The results are qualitatively similar to those in the two sector model although the changes in residential investment and output are quantitatively more important in the partial depreciation case. Intuitively, with partial depreciation households stand to benefit from changes in

their housing consumption for periods far beyond the present such that all of the mechanisms generating real effects in the model get magnified.

5 Conclusions

Empirically, residential investment plays a central, if not the central, role in the monetary transmission mechanism. Nevertheless, most monetary models omit housing from the model altogether. While there are important exceptions to this general tendency, there has been little work done on modeling the most important, and perhaps obvious, characteristics of housing for the monetary transmission mechanism: households usually consume housing by taking on a mortgage and only infrequently adjust their housing consumption. This paper takes a step towards filling this gap. By imposing the requirement that households must borrow to consume housing, a rise in the real interest rate leads home buyers to consume substantially less housing and more nondurables.

The findings point to several useful directions for future research. First, while bond markets are segmented by lenders and borrowers in the model, heterogeneity in financial market participation could exist for other reasons and have similar effects on the real interest rate and hence on housing consumption if households must borrow to consume housing. Furthermore, the frequency with which households change their housing consumption is exogenous in this paper and there is no option to refinance. As is well-known in the sticky price literature, the real effects of monetary shocks are often quite different in time-dependent models than in state-dependent models.⁵ The same reasoning applies to rigidities in housing. In future research, it would be useful to model staggered housing adjustment in an environment where the household optimally chooses whether to incur the adjustment costs associated both with moving and refinancing. Finally, all mortgages in the model are fixed-rate. How mortgage choice affects the reaction of the housing market and the macroeconomy to monetary shocks under alternative mortgage arrangements remain important unanswered questions that both theoretical and empirical work need to address.

⁵See, for example, Caplin and Spulber (1987), Ball and Romer (1990), Caplin and Leahy (1991), Caballero and Engel (1993), Dotsey, King, and Wolman (1999), and Golosov and Lucas (2007).

Table 1: Benchmark Parameterization (quarterly)

Parameter	Description	Benchmark
J	Number of periods between housing changes	20
β	Discount factor	0.99
ρ_R	AR(1) Coefficient in Interest Rate Rule	0.8
σ_R	Std. dev. of monetary shock	0.01
ϵ	Share of home buyers	0.7
$Cshare$	Steady state fraction of home buyer's income spent on nondurables	2/3
π	Steady state gross inflation rate	1.01
ν	Steady state velocity	10
η	Labor supply elasticity parameter	8

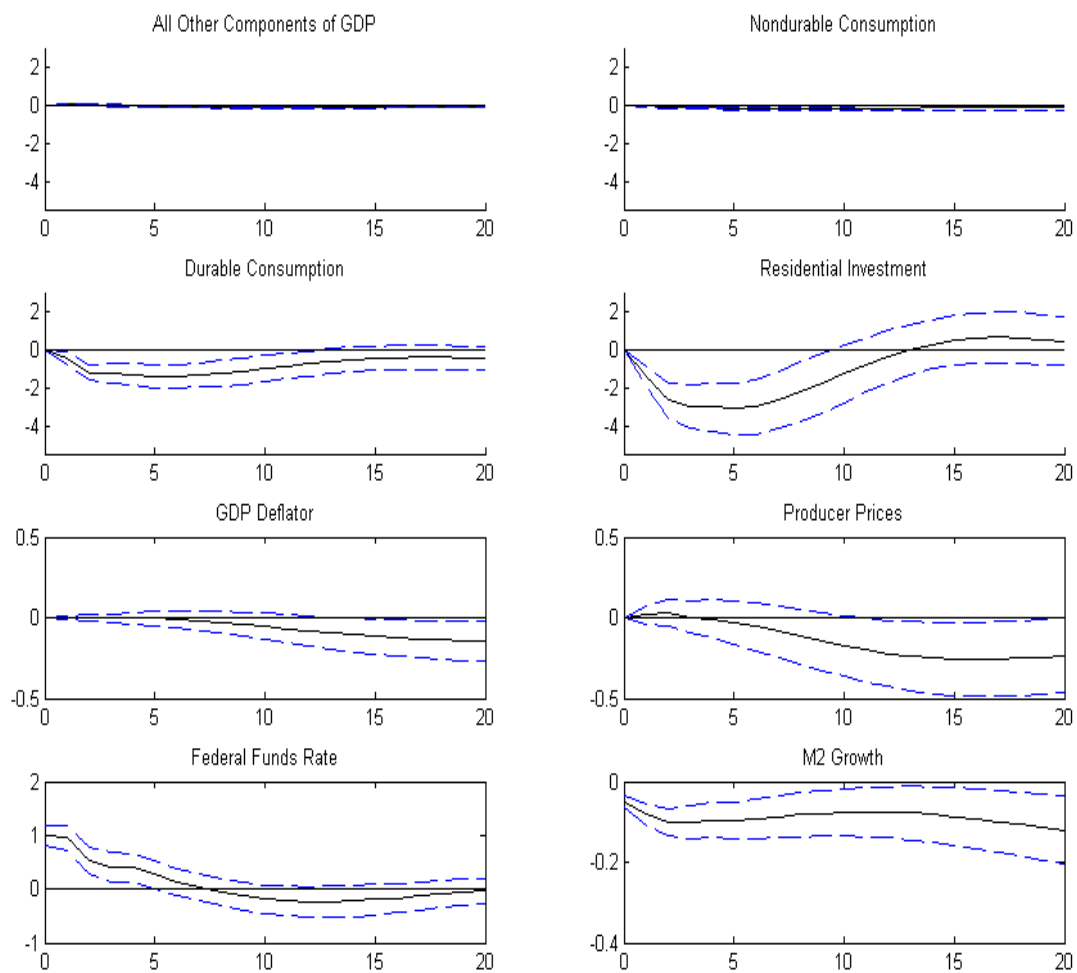


Figure 1: Empirical Impulse Responses to a 100 bp Increase in the Federal Funds Rate
 Impulse responses are expressed in percentages. Dashed lines denote 95% error bands constructed by bootstrapping with 500 repetitions. The sample period is 1965q3 - 2007q4.

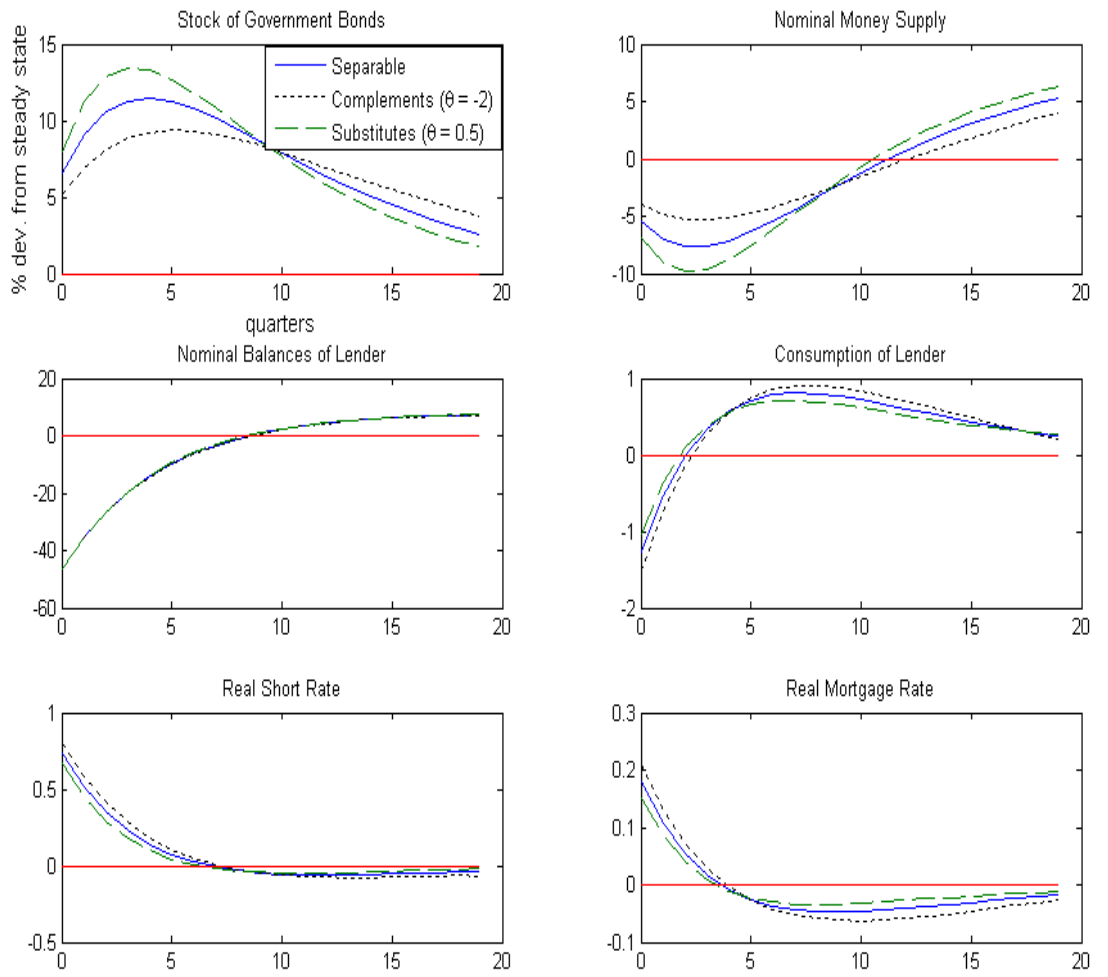


Figure 2: Impulse Responses to a 100 Basis Point Shock to Short Rate

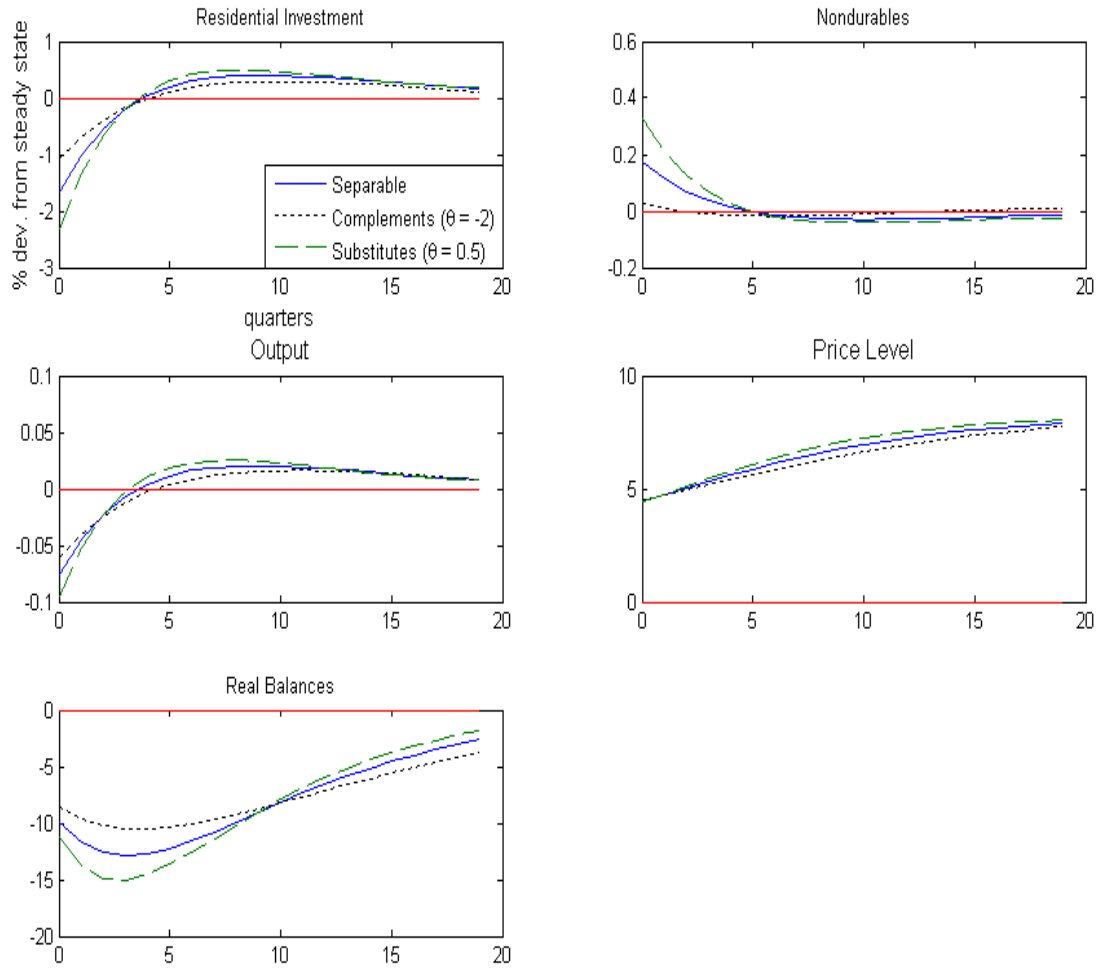


Figure 3: Impulse Responses to a 100 Basis Point Shock to Short Rate

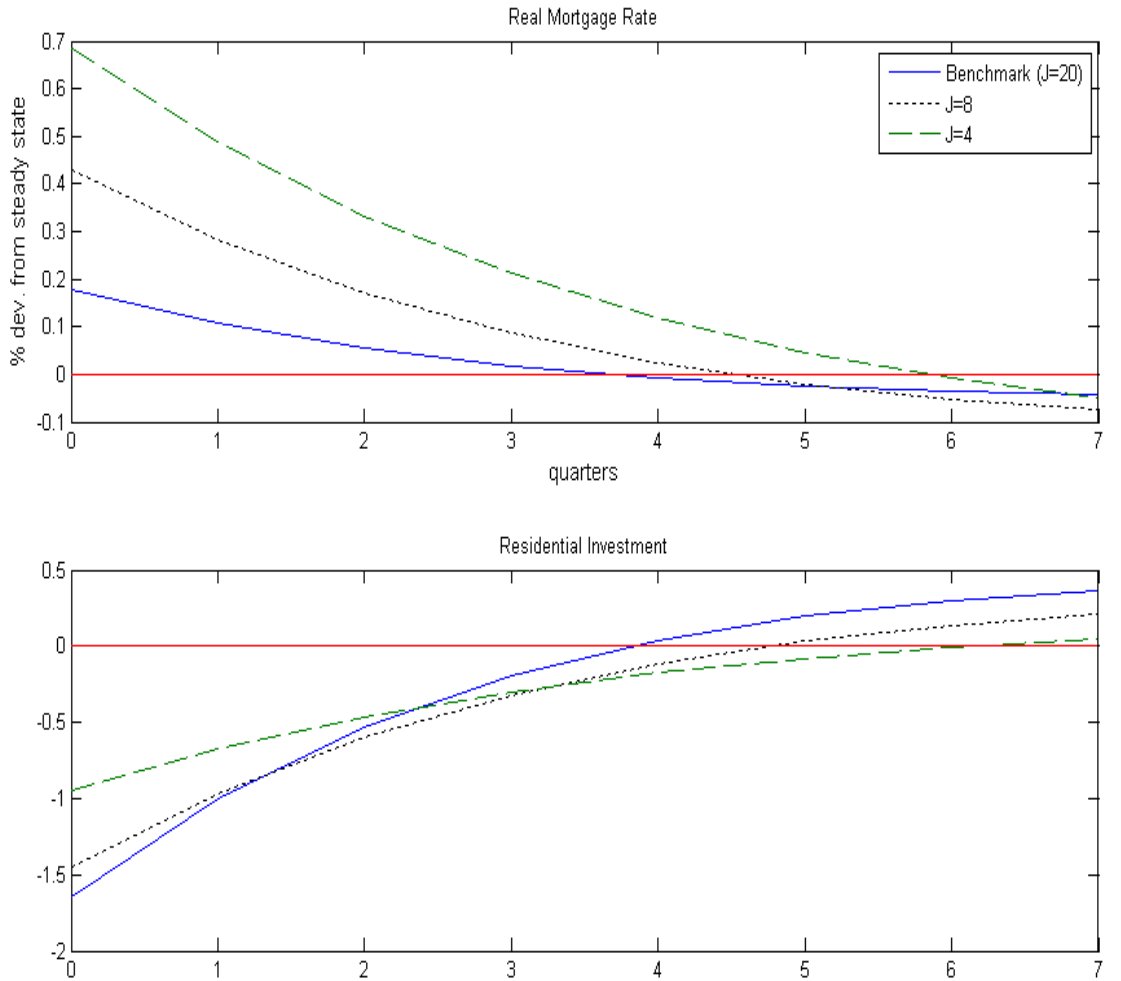


Figure 4: Change in Residential Investment with More Frequent Adjustment, Separable Utility

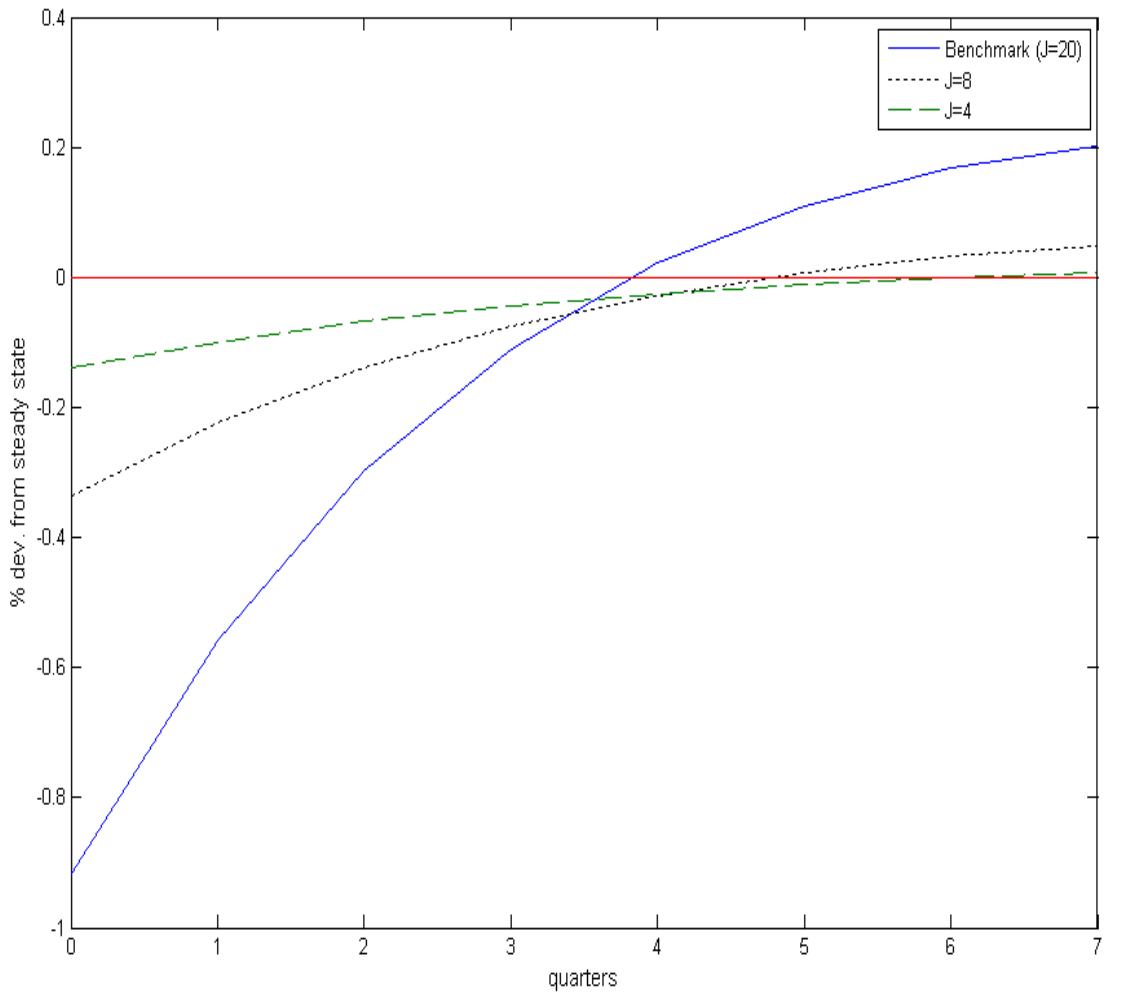


Figure 5: Response of Residential Investment to 10 bp Increase in Mortgage Rate for Different Adjustment Frequencies

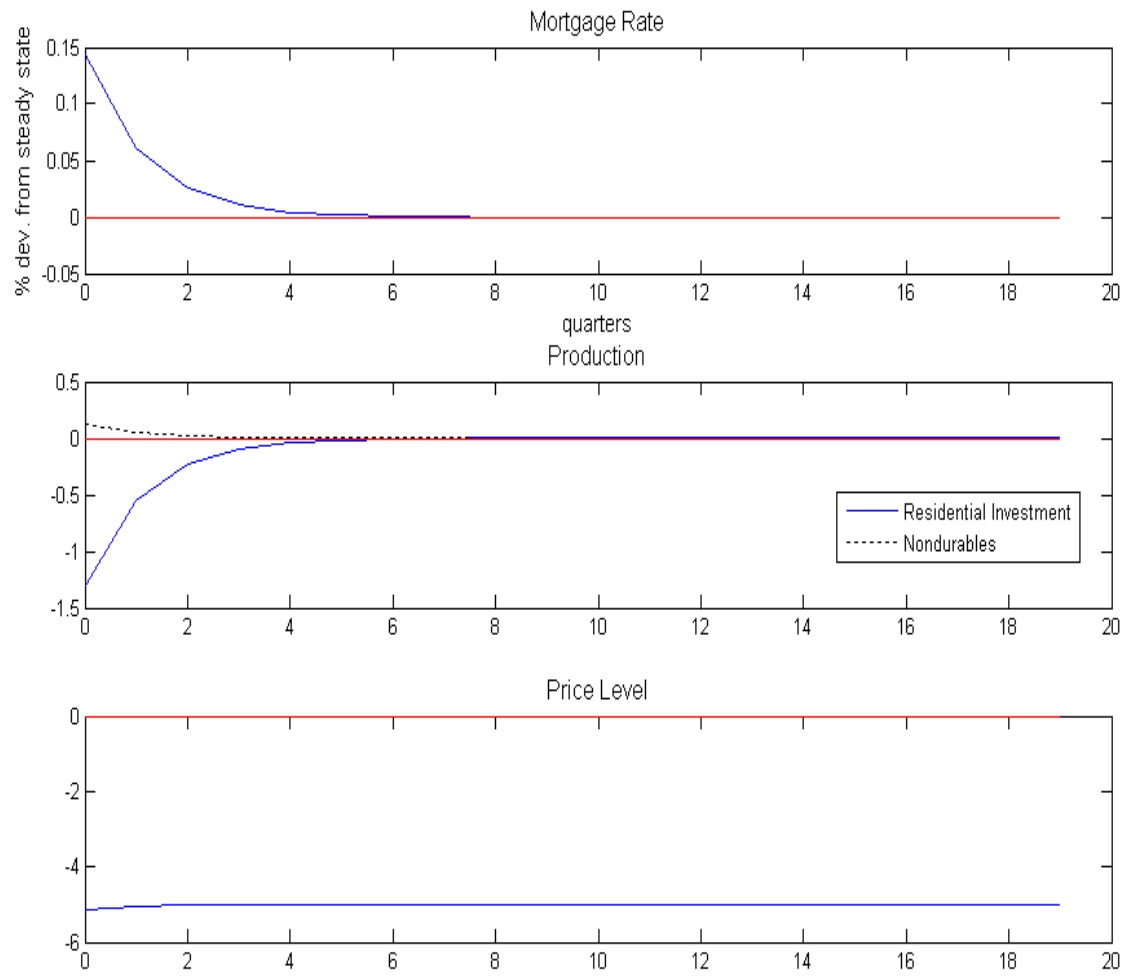


Figure 6: Impulse Responses for a 1% Decline in the Money Supply Growth Rate

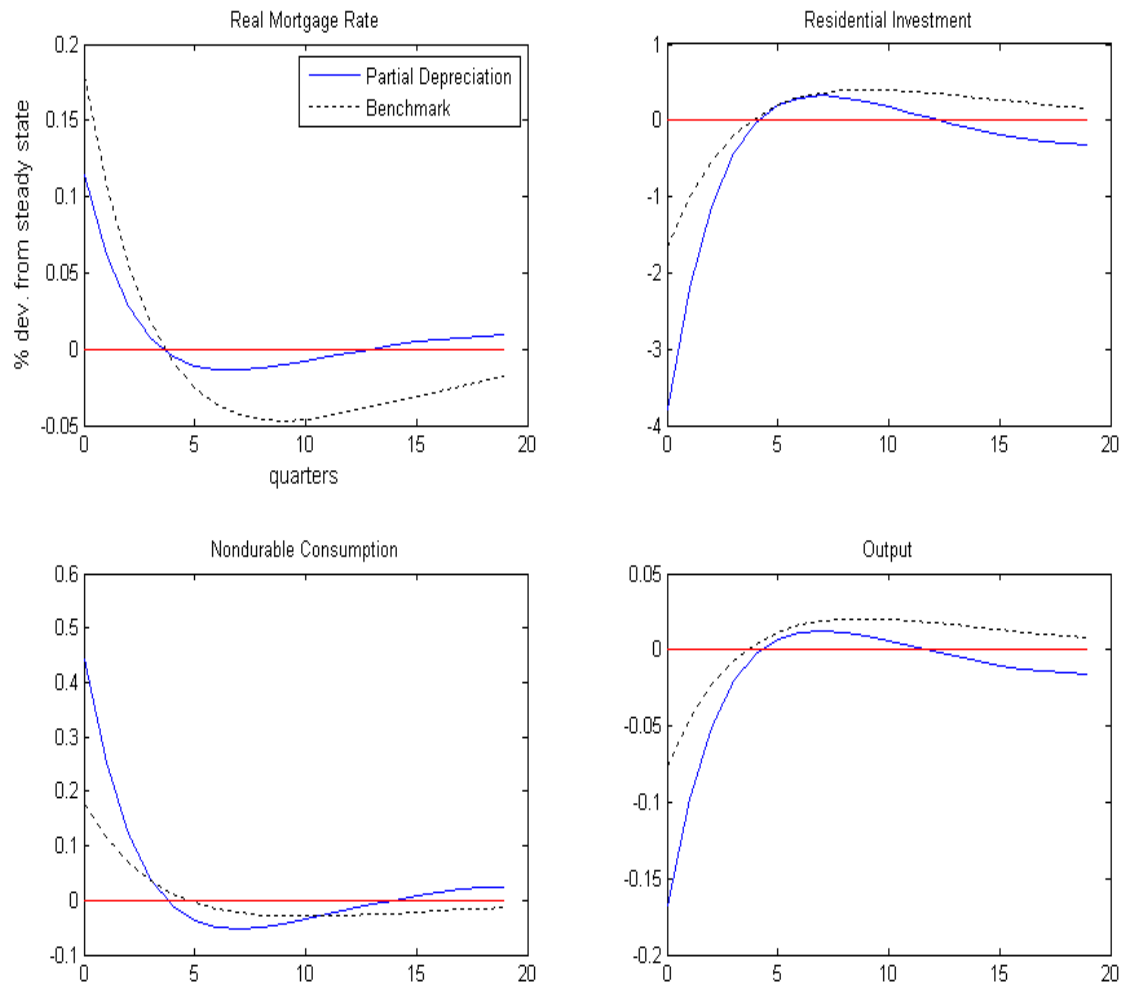


Figure 7: Partial Depreciation of Housing Stock (5% Over Five Years)

Appendix: Solving the Model

The budget constraint and FOCs for housing, cash, and labor supply for a type 0 household are

$$C_{t,0} = L_{t,0} + \frac{M_{t-1,J-1}}{P_t} - \frac{M_{t,0}}{P_t} - H_{t,0}F_t \quad (12)$$

$$E_t \sum_{j=0}^{J-1} \beta^j u_2(C_{t+j,j}, H_{t,0}) = E_t \sum_{j=0}^{J-1} \beta^j u_1(C_{t+j,j}, H_{t,0}) F_t. \quad (13)$$

$$u_1(C_{t,0}, H_{t,0}) = \omega_1^h \frac{P_t}{M_{t,0}} + \beta E_t \left[u_1(C_{t+1,1}, H_{t,0}) \frac{P_t}{P_{t+1}} \right] \quad (14)$$

$$u_1(C_{t,0}, H_{t,0}) = \omega_2 (1 - L_{t,0})^{-\eta_L}. \quad (15)$$

The budget constraint and FOCs for cash and labor supply for a type $j \neq 0, J-1$ are

$$C_{t,j} = L_{t,j} + \frac{M_{t-1,j-1}}{P_t} - \frac{M_{t,j}}{P_t} - H_{t-j,0}F_{t-j} \quad (16)$$

$$u_1(C_{t,j}, H_{t-j,0}) = \omega_1^h \frac{P_t}{M_{t,j}} + \beta E_t \left[u_1(C_{t+1,j+1}, H_{t-j,0}) \frac{P_t}{P_{t+1}} \right] \quad (17)$$

$$u_1(C_{t,j}, H_{t-j,0}) = \omega_2 (1 - L_{t,j})^{-\eta_L}. \quad (18)$$

and for a type $j = J-1$ household they are

$$C_{t,J-1} = L_{t,J-1} + \frac{M_{t-1,J-2}}{P_t} - \frac{M_{t,J-1}}{P_t} - H_{t-(J-1),0}F_{t-(J-1)} \quad (19)$$

$$u_1(C_{t,J-1}, H_{t-(J-1),0}) = \omega_1^h \frac{P_t}{M_{t,J-1}} + \beta E_t \left[u_1(C_{t+1,0}, H_{t+1,0}) \frac{P_t}{P_{t+1}} \right] \quad (20)$$

$$u_1(C_{t,J-1}, H_{t-(J-1),0}) = \omega_2 (1 - L_{t,J-1})^{-\eta_L}. \quad (21)$$

The first order conditions for a lender are

$$u'(C_{t,l}) = \omega_1^l \frac{P_t}{M_{t,l}} + \beta E_t \left\{ u'(C_{t+1,l}) \frac{P_t}{P_{t+1}} \right\} \quad (22)$$

$$u'(C_{t,l}) = E_t \left\{ \sum_{j=0}^{J-1} \beta^j u'(C_{t+j,l}) F_t \right\} \quad (23)$$

$$u'(C_{t,l}) = E_t \left\{ u'(C_{t+1,l}) R_{t,SHORT} \frac{P_t}{P_{t+1}} \right\} \quad (24)$$

We also have the first-order accurate market-clearing conditions

$$L_t = \frac{\epsilon}{J} \sum_{j=0}^{J-1} L_{t,j} \quad (25)$$

$$C_t = \frac{\epsilon}{J} \sum_{j=0}^{J-1} C_{t,j} + (1 - \epsilon) C_{t,l} \quad (26)$$

$$M_t = \frac{\epsilon}{J} \sum_{j=0}^{J-1} M_{t,j} + (1 - \epsilon) M_{t,l} \quad (27)$$

$$L_t = C_t + \frac{\epsilon}{J} H_{t,0} \quad (28)$$

The monetary authority follows

$$\frac{R_{t,SHORT}}{R_{SHORT}} = \left(\frac{R_{t-1,SHORT}}{R_{SHORT}} \right)^{\rho_M} \exp(\varepsilon_t^M) \quad (29)$$

by adjusting the money supply according to

$$M_t = M_{t-1} + R_{t-1,SHORT} b_{t-1,GOV} - b_{t,GOV}. \quad (30)$$

This constitutes a system of $J*3 + 10$ difference equations in the $J*3 + 10$ unknowns $\{C_j, m_j, L_j, j = 0, \dots, J - 1\}$, $C_l, M_l, C, H_0, Y, P, F, R_{SHORT}, b_{GOV}$, and M .

The Steady State

Proof of Proposition 1: The Euler equations for labor supply for all home buyers at an interior solution evaluated at the steady state imply

$$u_1(C_j, H_0) = \omega_2 (1 - L_j)^{-\eta_L}, \quad j = 0, \dots, J - 1$$

where C_j , H_0 , and L_j , are the steady state values of consumption, housing, and hours worked. This implies that their marginal utility of nondurables is the same conditional on the housing stock. Since only the type 0 household chooses housing, nondurables must be identical for all j . The Euler equations for real balances for all households j ,

$$u_1(C_j, H_0) (1 - \beta) = \omega_1^h m_j^{-1}, \quad j = 0, \dots, J - 1$$

then imply m_j is the same for all home buyers.■

To calibrate steady state real balances, I assume that $m_j = \frac{M_j}{P} = \frac{C_j}{\nu}$ and $m_l = \frac{M_l}{P} = \frac{C_l}{\nu}$ where ν is velocity. We can then solve for the steady state values of C_j , C_s , H and the parameter γ by evaluating (5), the budget constraints for a lender and a home buyer, and the resource constraint at the steady state. We have

$$\begin{aligned}
C_j &= Cshare \left(L_j - \frac{C_j}{\nu_j} \left(1 - \frac{1}{\pi} \right) \right) \\
&= Cshare L_j \left(1 + \frac{Cshare}{\nu_j} \left(1 - \frac{1}{\pi} \right) \right)^{-1} \\
H &= \left(L_j - C_j \left(1 + \frac{1}{\nu} \left(1 - \frac{1}{\pi} \right) \right) \right) / F \\
F &= \left(\sum_{j=0}^{J-1} \beta^j \right)^{-1} \\
C_s &= \left(L - \epsilon C_j - \frac{\epsilon}{J} H \right) / (1 - \epsilon) \\
\gamma &= \left(\frac{C_j}{H} \right)^{\theta-1} F
\end{aligned}$$

The steady short rate, real money supply, and real stock of government bonds are then

$$\begin{aligned}
R_{SHORT} &= \frac{\pi}{\beta} \\
m &= \epsilon m_j + (1 - \epsilon) m_s \\
\frac{b_{GOV}}{P} &= -m \frac{\left(1 - \frac{1}{\pi} \right)}{\left(1 - \frac{1}{\beta} \right)}
\end{aligned}$$

I use the DYNARE software suite to solve a first-order log linearization of the model. DYNARE uses a generalized Schur decomposition to solve the model: see Klein (2000) and Sims (2001) for additional details on this general approach to solving systems of linear difference equations.

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