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Sticky Price Models of the Business Cycle: Can the Contract Multiplier Solve the Persistence Problem?

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ABSTRACT

We construct a quantitative equilibrium model with price setting and use it to ask whether with staggered price setting monetary shocks can generate business cycle fluctuations. These fluctuations include persistent output fluctuations along with the other defining features of business cycles, like volatile investment and smooth consumption. We assume that prices are exogenously sticky for a short period of time. Persistent output fluctuations require endogenous price stickiness in the sense that firms choose not to change prices very much when they can do so. We find that for a wide range of parameter values the amount of endogenous stickiness is small. As a result, we find that in a standard quantitative business cycle model staggered price setting, by itself, does not generate business cycle fluctuations.

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A long-standing question in macroeconomics is, What fraction of output variability can be attributed to monetary instability? Answering this question requires constructing models in which monetary disturbances generate fluctuations in aggregates similar to those observed over the business cycle. Ever since the early 1970s, macroeconomists have known that it is possible to construct general equilibrium models in which monetary disturbances generate contemporaneous output fluctuations. Examples of such endeavors include Lucas (1972, 1990), Fischer (1977), Phelps and Taylor (1977), and Lucas and Woodford (1993). The difficult problem is to construct models in which monetary disturbances generate persistent movements in output, along with the other defining features of business cycles, like volatile investment and smooth consumption. One way of generating monetary business cycles is to assume prices are exogenously stuck for long periods of time so that monetary shocks induce fluctuations in output which are also persistent. Having prices exogenously stuck for a long period of time seems unappealing.

The literature on staggered price setting provides a promising way of generating long periods of endogenous price stickiness with short periods of exogenous price stickiness. The idea of staggered price setting is that it leads to interactions among price setters that generate longer movements in output than does a similar model with synchronized price setting. With staggered price setting, because other firms' prices are exogenously stuck, firms might *choose* not to change their prices in response to money shocks. In subsequent periods other firms in turn might choose not to change their prices. This mechanism is one way of generating long periods of endogenous price stickiness from short periods of exogenous price stickiness and thus persistent fluctuations. This mechanism is in the spirit of the menu cost literature in which small menu costs of changing prices result in large output fluctuations (Mankiw 1985, Akerlof and Yellen 1985). Taylor (1980), in a reduced-form model of staggered wage contracts, provides an eloquent exposition of this mechanism.

> Because of the staggering, some firms will have established their wage rates prior to the current negotiations, but others will establish their wage rates in future periods. Hence, when considering relative wages, firms and unions must look both forward and

> backward in time to see what other workers will be paid during their own contract period. In effect, each contract is written relative to other contracts, and this causes shocks to be passed on from one contract to another—a sort of "contract multiplier."

Blanchard (1983), in a model of staggered price setting, investigates this mechanism for generating persistent output fluctuations. In both of these papers, the rules for setting wages or prices are exogenously specified.

The purpose of this paper is to construct a quantitative general equilibrium model to ask whether this mechanism can generate a monetary business cycle. In particular, we ask whether staggered price setting with a short period of exogenous price stickiness can generate long periods of endogenous price stickiness, persistent output fluctuations, and the kinds of comovements between output, consumption, investment, and employment seen in the data. In asking this question the perspective we adopt is similar to that of Kydland and Prescott (1982) who assess the ability of a single type of shock to account for the bulk of business cycle fluctuations. We focus on monetary shocks while they focus on technology shocks. Our main finding is that staggered price setting, by itself, does not generate business cycles driven by monetary shocks.

In our analysis we use a variant of a standard sticky price model. In the literature on sticky prices the standard model is a static one in which imperfectly competitive firms set nominal prices and real money balances enter the consumer's utility function. (See, for example, Blanchard and Kiyotaki 1987, Ball and Romer 1989, 1990.) We take this setup and turn it into a business cycle model by adding time, uncertainty, capital accumulation, as well as staggered price setting. (For some recent work embedding sticky prices in business cycle models, see Ohanian and Stockman 1994, Cho and Cooley 1995, King and Watson 1995, Rotemberg 1995, Woodford 1996, and Yun 1996. For a slightly different approach using fixed costs see Caplin and Spulber 1987 and Caplin and Leahy 1991.)

In our model there is a continuum of monopolistically competitive firms that produce differentiated products using capital and labor. These firms set nominal prices for a fixed number of periods and do so in a staggered fashion. In particular, in each period, a fraction $1/N$ of these firms choose new prices which are then fixed for N periods. The consumer side of the model is standard. Consumers are infinitely lived and have preferences over consumption, leisure, and real money balances. The nominal money supply follows an exogenous stochastic process.

Our measure of persistence is the *contract multiplier*. In the model we define this multiplier as the ratio of the half life of output following a monetary shock to the expected length of time before a representative firm can change its price. The size of this multiplier provides one way of assessing the contribution of staggered price setting to persistence in output fluctuations. We show that with synchronized price setting this multiplier is 1, so that the multiplier also measures the half life of output with staggering relative to the half life with synchronized price setting. In order to calculate the contract multiplier needed for the model to produce the persistence seen in the data we need an estimate of the half life of output in the data. Since business cycles typically last around 4 to 5 years, under our perspective that monetary shocks account for the bulk of business cycle fluctuations, we argue that this half life is roughly 2 to $2\frac{1}{2}$ years.

In our models the expected length of time before the representative firm can change its price is one-half the length of exogenous price stickiness. If one finds plausible that the period of exogenous price stickiness is one quarter, then the contract multiplier needed to give a half life of $2\frac{1}{2}$ years is 20. With one month of exogenous price stickiness, the needed contract multiplier is 60, while with one year of exogenous price stickiness the needed multiplier is 5. An attractive feature of the contract multiplier is that in our quantitative models it turns out to be approximately invariant to the length of exogenous price stickiness.

Our benchmark specification is the standard one in the business cycle literature. The utility function has unit elasticity of substitution between consumption and leisure and is thus consistent with balanced growth. Our specification of demand for intermediate goods has constant elasticity following Dixit and Stiglitz (1977). Our technology has constant returns to scale. When we calibrate the model, we find that the multiplier is roughly 1. Thus, for our benchmark specification the staggered price setting mechanism does not generate persistence.

In order to gain some intuition for these results we eliminate capital and impose a static money demand equation. The linearized version of this model consists of two equations: a static money demand equation and a price-setting equation. Prices are set as a function of both past and future prices and of the sum of future outputs. These equations are essentially identical to those used by Taylor (1980). The only difference, besides relabeling his wages as our prices, is that in Taylor's formulation the magnitude of the coefficient on the sum of future outputs is set as a free parameter while in ours it is a function of the parameters of the underlying economy. For this model to generate persistence this coefficient must be small. When this coefficient is small, the output effects of monetary shocks do not induce price-setting monopolists to raise their prices so that monetary shocks can have persistent effects. In our model this coefficient is the product of two parameters, namely the sensitivity of prices to costs (wages) and on the sensitivity of costs to output. With unit elasticity of substitution preferences costs are extremely sensitive to output so that this coefficient is large and monetary shocks do not have persistent effects on output.

This finding suggests exploring preferences in which costs are insensitive to output. If preferences are of the zero income effect variety with high labor supply elasticity so that the utility is essentially linear in both consumption and labor it turns out that costs are insensitive to output. We show that in a version of this model without capital and with a static money demand, the contract multiplier is 20. Once we add intertemporal links, namely capital accumulation and interest sensitive money demand the contract multiplier falls to a value less than 1. With such intertemporal links money shocks lead to an investment boom in the impact period which raises the demand for labor and therefore wage rates. Since utility is close to linear in both consumption and labor, the rise in wage rates leads to a large increase in both consumption and labor in the impact period relative to future periods. Thus the half life of output and the multiplier are both small. It turns out that in the model with intertemporal links prices change hardly at all after a monetary shock, but output is not persistent. This finding shows that endogenous price stickiness, by itself, does not necessarily imply persistent output fluctuations. The results for this model also show that while eliminating the intertemporal links of capital accumulation and interest sensitive money demand makes it easy to develop analytical expressions, this procedure can be quite misleading.

Next we explore an avenue, suggested by Kimball (1995), designed to make prices less sensitive to cost changes. If intermediate goods producers face an elasticity of demand which rises as their relative prices rise, so that demand is convex, they may optimally choose not to raise their prices very much following a monetary shock that raises output and costs. We consider economies with such features and show that generating persistence requires extraordinarily convex demand functions for intermediate goods. To appreciate just how convex demand is we show that with Kimball's parameterization for very small ε, an $\varepsilon\%$ change in prices leads to an $11\varepsilon\%$ drop in demand, while a 2.3% change in prices leads demand to drop to zero. Even with such extraordinary convexity the contract multiplier drops off sharply from 5.62 in the model without capital or interest-sensitive money demand to 1.87 in the model with such intertemporal links.

Rotemberg (1995) suggests that persistence can be increased if firms face upward-sloping marginal cost curves. One way of incorporating this feature is to assume that firms use specific factors which are inelastically supplied. With decreasing returns to scale costs are less sensitive to wage changes so that prices are less sensitive to wage changes. With factor specificities the elasticity of demand plays an important role, and it is possible to obtain large contract multipliers in the model without capital when demand is extremely elastic. In this case also it turns out that adding intertemporal links reduces the contract multiplier significantly.

We analyze the sensitivity of the contract multiplier in our economies with intertemporal links to variations of the parameters within broad ranges. In our benchmark economy the contract multiplier ranges from below 1 to 3.5. The key parameter affecting the multiplier is the elasticity of demand. With an elasticity of demand of 300, which is 30 times higher than in our baseline setting, we show that the multiplier can be as high as 3.5. In the zero income effects economy the contract multiplier is never above 1. In the convex demand economy the multiplier ranges from below 1 to 5.3. Here the key parameter is again the elasticity of demand but it turns out that extremely low elasticities are needed to generate a large multiplier. In the specific factors economy, the multiplier ranges from below 1 to about 5.3. In this economy, as in the benchmark economy, the multiplier is increasing in the demand elasticity and can be as high as 5.3 for an elasticity of 300.

We consider a model with combinations of all variations. Any version with zero income effects gives a tiny multiplier. When we consider a model which incorporates both convex demand and specific factors together we do not get a larger multiplier than when we consider both separately. Thus, there is no sense in which the multiplier for the model with all three variations is the sum of the multipliers for each one separately. Taken as a whole, our results suggest that in order to get the kind of persistence seen in the data the length of exogenous price stickiness needs to be roughly $2\frac{1}{2}$ years.

1. A benchmark monetary economy

Consider a monetary economy populated by a large number of identical, infinitely lived consumers. In each period t, the economy experiences one of finitely many events $s_{t.}$ We denote by $s^t = (s_0, \ldots, s_t)$ the history of events up through and including period t. The probability, as of period zero, of any particular history s^t is $\pi(s^t)$. The initial realization s_0 is given.

In each period t the commodities in this economy are labor, a consumption-capital good, money, and a continuum of intermediate goods indexed by $i \in [0, 1]$. The technology for producing final goods from intermediate goods at history s^t is

$$(1) \qquad y(s^t) = \left[\int y(i, s^t)^\theta \, di \right]^{\frac{1}{\theta}},$$

where $y(s^t)$ is the final good and $y(i, s^t)$ is an intermediate good of type i. The technology for producing each intermediate good i is a standard constant returns to scale production function

$$(2) \qquad y(i, s^t) = F(k(i, s^t), l(i, s^t)),$$

where $k(i, s^t)$ and $l(i, s^t)$ are the inputs of capital and labor.

Final goods producers behave competitively. In each period t they choose inputs $y(i, s^t)$, for all $i \in [0, 1]$, and output $y(s^t)$ to maximize profits given by

$$(3) \qquad \max \ \bar{P}(s^t)y(s^t) - \int P(i, s^{t-1})y(i, s^t)\, di$$

subject to (1), where $\bar{P}(s^t)$ is the price of the final good in period t and $P(i, s^{t-1})$ is the price of intermediate good i in period t. The intermediate goods prices do not depend on s_t because date t prices in our economy are set before the realization of the date t shocks. Solving the problem in (3) gives the input demand functions

$$(4) \qquad y^d(i, s^t) = \left[\frac{\bar{P}(s^t)}{P(i, s^{t-1})}\right]^{\frac{1}{1-\theta}} y(s^t).$$

The zero profit condition implies that

$$(5) \qquad \bar{P}(s^t) = \left[\int P(i, s^{t-1})^{\frac{\theta}{\theta-1}}\, di\right]^{\frac{\theta-1}{\theta}}.$$

Notice that in equilibrium the output price at date t only depends on s^{t-1}.

Intermediate goods producers behave as imperfect competitors. They set prices for N periods and do so in a staggered fashion. In particular, in each period t fraction $1/N$ of these producers choose new prices $P(i, s^{t-1})$ before the realization of the event s_t. These prices are set for N periods, so for this group of intermediate goods producers,

$$P(i, s^{t+\tau-1}) = P(i, s^{t-1})$$

for $\tau = 0, \ldots, N-1$. The intermediate goods producers are indexed so that producers indexed $i \in [0, 1/N]$ set new prices in 0, N, $2N$, etc., while producers indexed $i \in [1/N, 2/N]$ set new prices in 1, $N+1$, $2N+1$, etc., for the N cohorts of intermediate goods producers. At time t each producer in a cohort chooses prices $P(i, s^{t-1})$ to maximize discounted profits from periods t to $t+N-1$. That is, each solves

$$(6) \qquad \max_{P(i,s^{t-1})} \sum_{\tau=t}^{t+N-1} \sum_{s^\tau} Q(s^\tau|s^{t-1}) \left[P(i, s^{t-1}) - v(s^\tau)\bar{P}(s^\tau)\right] y^d(i, s^\tau),$$

where $Q(s^\tau|s^{t-1})$ is the price of one dollar in s^τ in units of dollars at s^{t-1}, $v(s^t)$ is the unit cost of production at s^t, and $y^d(i, s^t)$ is given in (4). The unit cost of production is given by

$$(7) \qquad v(s^t) = \min_{k,l} \ r(s^t)k + w(s^t)l$$

subject to $F(k, l) \geq 1$, where $r(s^t)$ is the rental rate on capital and $w(s^t)$ is the real wage rate. The solution to the problem stated in (6) is

$$(8) \qquad P(i, s^{t-1}) = \frac{\sum_{\tau=t}^{t+N-1} \sum_{s^\tau} Q(s^\tau|s^{t-1})\bar{P}(s^\tau)^{\frac{2-\theta}{1-\theta}} v(s^\tau)y(s^\tau)}{\theta \sum_{\tau=t}^{t+N-1} \sum_{s^\tau} Q(s^\tau|s^{t-1})\bar{P}(s^\tau)^{\frac{1}{1-\theta}} y(s^\tau)}.$$

Implicit in this problem are the demands for capital and labor by the intermediate goods producers. (Note that these factor demands are the unit factor demands, which solve (7), multiplied by the level of output of the intermediate goods producer.) These factor demands, $k(i, s^t)$ and $l(i, s^t)$, of producer i in period t are made after the realization of the event s_t and thus depend on s^t. Cost minimization implies that

$$(9) \qquad \frac{F_l(k(i, s^t), l(i, s^t))}{F_k(k(i, s^t), l(i, s^t))} = \frac{w(s^t)}{r(s^t)}.$$

Given constant returns to scale this implies that capital-labor ratios are equated across the intermediate goods firms, so for all $i \in [0, 1]$,

$$(10) \qquad \frac{k(i, s^t)}{l(i, s^t)} = \frac{k(0, s^t)}{l(0, s^t)}.$$

In what follows, each intermediate goods firm has the Cobb-Douglas production function

$$F(k(i, s^t), l(i, s^t)) = k(i, s^t)^\alpha l(i, s^t)^{1-\alpha}$$

and thus (9) can be written as

$$(11) \qquad \left(\frac{1-\alpha}{\alpha}\right) \frac{k(i, s^t)}{l(i, s^t)} = \frac{w(s^t)}{r(s^t)}.$$

Consumer preferences are given by

$$\sum_{t=0}^{\infty}\sum_{s^t} \beta^t \pi(s^t)\, U(c(s^t), l(s^t), M(s^t)/\bar{P}(s^t)), \tag{12}$$

where $c(s^t)$, $l(s^t)$, and $M(s^t)$ are consumption, labor, and nominal money balances, respectively. In each period $t = 0, 1, \ldots$, consumers choose their time t allocations after the realization of the event s_t. The problem of consumers is to choose rules for consumption $c(s^t)$, labor $l(s^t)$, capital stocks $k(s^t)$, nominal money balances $M(s^t)$, and one-period nominal bonds $B(s^{t+1})$ to maximize (12) subject to the sequence of budget constraints

$$\begin{aligned}
\bar{P}(s^t)(c(s^t) + k(s^t)) + M(s^t) + \sum_{s_{t+1}} Q(s^{t+1}|s^t)B(s^{t+1}) \\
\leq \bar{P}(s^t)\left(w(s^t)l(s^t) + [r(s^t) + 1 - \delta]k(s^{t-1})\right) \\
+ M(s^{t-1}) + B(s^t) + \Pi(s^t) + T(s^t), \quad t = 0, 1, \ldots.
\end{aligned}$$

and borrowing constraints, $B(s^{t+1}) \geq \bar{B}$ for some large negative number $\bar{B}$. Here $\Pi(s^t)$ is the nominal profits of the intermediate goods producers, $T(s^t)$ is nominal transfers, and δ is the depreciation rate of capital. The initial conditions $k(s^{-1})$, $M(s^{-1})$, and $B(s^0)$ are also given. Each of the nominal bonds $B(s^{t+1})$ is a claim to one dollar in state s^{t+1} and costs $Q(s^{t+1}|s^t)$ dollars in state s^t. In terms of relating the prices in the intermediate goods producer's problem to these prices, note that

$$Q(s^\tau|s^t) = Q(s^{t+1}|s^t)Q(s^{t+2}|s^{t+1})\cdots Q(s^\tau|s^{\tau-1}) \quad \text{for all } \tau > t.$$

The first order conditions for the consumer can be written as

$$-\frac{U_l(s^t)}{U_c(s^t)} = w(s^t) \tag{13}$$

$$\frac{U_c(s^t)}{\bar{P}(s^t)} - \frac{U_m(s^t)}{\bar{P}(s^t)} = \beta \sum_{s_{t+1}} \pi(s^{t+1}|s^t)\frac{U_c(s^{t+1})}{\bar{P}(s^{t+1})} \tag{14}$$

$$U_c(s^t) = \beta \sum_{s_{t+1}} \pi(s^{t+1}|s^t)U_c(s^{t+1})[r(s^{t+1}) + 1 - \delta] \tag{15}$$

$$Q(s^\tau|s^t) = \beta^{\tau-t}\pi(s^\tau|s^t)\frac{U_c(s^\tau)}{U_c(s^t)}\frac{\bar{P}(s^t)}{\bar{P}(s^\tau)} \quad \text{for all } \tau > t, \tag{16}$$

where $U_c(s^t)$, $U_l(s^t)$, and $U_m(s^t)$ denote the derivatives of the utility function with respect to its arguments and $\pi(s^\tau|s^t) = \pi(s^\tau)/\pi(s^t)$ is the conditional probability of s^τ given s^t.

The nominal money supply process is given by

$$(17) \quad M(s^t) = \mu(s^t)M(s^{t-1}),$$

where $\mu(s^t)$ is a stochastic process. New money balances are distributed to consumers in a lump-sum fashion by having transfers satisfy

$$(18) \quad T(s^t) = M(s^t) - M(s^{t-1}).$$

In terms of market clearing conditions, consider first the factor markets. Notice that the capital stock chosen by consumers in period $t-1$ for rental in period t is $k(s^{t-1})$ while the labor supply in period t is $l(s^t)$. In turn, each intermediate goods producer i chooses his factor demands after the realization of uncertainty s_t in period t, so the demands for capital and labor are $k(i, s^t)$ and $l(i, s^t)$. Factor market clearing thus requires that

$$(19) \quad k(s^{t-1}) = \int k(i, s^t)\, di$$

$$(20) \quad l(s^t) = \int l(i, s^t)\, di.$$

Bond market clearing requires $B(s^{t+1}) = 0$. The resource constraint for this economy is

$$(21) \quad c(s^t) + k(s^t) = y(s^t) + (1-\delta)k(s^{t-1}).$$

An *equilibrium* for this economy is a collection of allocations for consumers $c(s^t)$, $l(s^t)$, $k(s^{t-1})$, $M(s^t)$, $B(s^{t+1})$; allocations for intermediate goods producers $k(i, s^t)$, $l(i, s^t)$ for $i \in [0, 1]$; allocations for final goods producers $y(s^t)$ and $y(i, s^t)$ for $i \in [0, 1]$ together with prices $w(s^t)$, $r(s^t)$, $Q(s^\tau|s^t)$ for $\tau = t, \ldots, t+N-1$, $\bar{P}(s^t)$, and $P(i, s^{t-1})$ for $i \in [0, 1]$ that satisfy the following conditions: (i) taking prices as given, consumer allocations solve the consumer's problem; (ii) taking all prices but his own as given, each intermediate goods producer's price solves (6); (iii) taking the prices as given, the final goods producer's allocations solve the final goods producer's problem; (iv) the factor market conditions (19) and (20), and the resource constraint (21) hold and the bond market clears; and (v) the money supply process and transfers satisfy (17) and (18).

2. Computation of equilibrium

In this section we briefly describe how we compute an equilibrium. We begin by substituting out a number of variables and reducing the equilibrium to four equations: the resource constraint, a pricing equation, an Euler equation for money, and an Euler equation for capital. Once we have these four equations we compute Markov equilibria in which allocations are functions of the state of the economy. These state variables are lagged prices, the capital stock and money shocks. The decision variables are current prices, consumption, labor, and investment. In what follows we will focus on the symmetric equilibrium in which all the intermediate goods producers of the same cohort make identical decisions. Thus $P(i,s^t) = P(j,s^t)$, $k(i,s^t) = k(j,s^t)$, $l(i,s^t) = l(j,s^t)$, $y(i,s^t) = y(j,s^t)$ for all $i,j \in [0,1/N]$ and so on for the N cohorts.

We begin with the resource constraint. Equating demands and supplies for each intermediate good using (2) and (4) and integrating gives

$$\bar{P}(s^t)^{\frac{1}{1-\theta}} \left(\int P(i,s^{t-1})^{\frac{1}{\theta-1}} di \right) y(s^t) = F(k(s^{t-1})/l(s^t),1) \left(\int l(i,s^t) di \right)$$

where we have exploited the fact the F is CRS and that capital-labor ratios are equated across producers from (10). Simplifying, using (20) gives

$$y(s^t) = F(k(s^{t-1}), l(s^t)) \left(\frac{\bar{P}(s^t)^{\frac{1}{\theta-1}}}{\int P(i,s^{t-1})^{\frac{1}{\theta-1}} di} \right). \tag{22}$$

Substituting (22) into (21) gives the resource constraint that we use in our computations.

We can now develop the pricing equation. We first express unit cost in terms of the aggregate allocations. To do so we solve the maximization problem in (7) and use (10) and (13) to get

$$v(s^t) = -\frac{1}{(1-\alpha)} \frac{U_l\,(s^t)}{U_c(s^t)} \left(\frac{l(s^t)}{k(s^{t-1})} \right)^{\alpha}. \tag{23}$$

Since all prices are equal within each cohort of producers we need only record one price per cohort and not the index identifying the producers. Thus from now on we drop the dependence on i, and we let $P(s^{t-1})$ denote the prices set at the beginning of period t, $P(s^{t-2})$ denote the prices set at the beginning of period $t-1$, and so on. Using (5), we can write the aggregate price level as

$$(24) \quad \bar{P}(s^t) = \left[\frac{1}{N}P(s^{t-1})^{\frac{\theta}{\theta-1}} + \cdots + \frac{1}{N}P(s^{t-N})^{\frac{\theta}{\theta-1}}\right]^{\frac{\theta-1}{\theta}}.$$

Using (16), (22), (23), and (24) in (8), we obtain the pricing equation we use in our computations. Finally, we rewrite the Euler equations for money and capital, (14) and (15), using (24) to substitute for $\bar{P}(s^t)$ and using (10), (11) and (13) to substitute for $r(s^t)$.

We are interested in a stationary equilibrium and thus restrict the stochastic processes for the growth of the money supply to be Markov. A stationary equilibrium for this economy consists of stationary decision rules which are functions of the state of the economy. Because producers choose their prices before the current money shock is realized, while other allocations are chosen after the money shock is realized, at each date we need to record two states for the economy. The state for producers at t must record the $N-1$ intermediate goods prices in addition to the capital stock and lagged money growth rates. The state for other allocations at t, such as consumer allocations and input allocations for producers, must record the state for producers plus the current money growth rates. At any date t there are $N-1$ prices prevailing for intermediate goods, namely, those set at the beginning of period $t-1$, $P(s^{t-2})$, those set at the beginning of period $t-2$, $P(s^{t-3})$ and so on up through those set in period $t-(N-1)$, $P(s^{t-N})$. We normalize prices by dividing them by the money stock. Thus the state for producers is

$$\left[\frac{P(s^{t-2})}{M(s^{t-1})}, \ldots, \frac{P(s^{t-N})}{M(s^{t-1})}, k(s^{t-1}), \mu(s^{t-1})\right].$$

The state for other allocations also includes $\mu(s^t)$. The decision variables for period t are aggregate consumption in t, $c(s^t)$; aggregate labor supply in t, $l(s^t)$; and the normalized price of the cohort of intermediate goods producers that are setting their prices at the beginning of period t, $P(s^{t-1})/M(s^{t-1})$.

Recall that our objective in this paper is to examine whether monetary disturbances can generate persistent movements in output and the kind of fluctuations in consumption and investment we see in the data. In some of the models that we consider it turns out that investment is extremely volatile. In order to reduce the volatility of investment in these models we introduce adjustment costs in changing the capital stock employed by each intermediate goods producer. Specifically, the law of motion for capital used in producing good i is given by

$$(25) \qquad k(i,s^t) = (1-\delta)k(i,s^{t-1}) - \phi\left(\frac{x(i,s^t)}{k(i,s^{t-1})}\right)k(i,s^{t-1}) + x(i,s^t),$$

where ϕ is the adjustment cost function. The problem of monopolist i is to choose $P(i,s^{t-1})$ and $l(i,s^\tau)$, $x(i,s^\tau)$, and $k(i,s^\tau)$ for $\tau = t,...,t+N-1$ to maximize

$$\sum_{\tau=t}^{t+N-1}\sum_{s^\tau} Q(s^\tau|s^{t-1})\left[P(i,s^{t-1})y^d(i,s^\tau) - w(s^\tau)\bar{P}(s^\tau)l(i,s^\tau) - \bar{P}(s^\tau)x(i,s^\tau)\right]$$

subject to (25), where $y^d(i,s^\tau)$ is given by (4). Clearly, in computing an equilibrium for this economy we need to record the capital stock employed by the representative producer in each cohort and we expand the state and decision variables accordingly. We linearize the resulting equations around the steady state and use standard methods to obtain linear decision rules. For cases with $N=1$ and 2 we checked the accuracy of the linear decision rules against nonlinear decision rules obtained by the finite element method. (See McGrattan 1996.)

3. Calibration of the benchmark economy

In this section we describe how we choose parameter values for the benchmark economy which are summarized in Table 1. In a later section we conduct a wide range of sensitivity analyses so we view this calibration as only setting the midpoint of the ranges for each of the parameters. These ranges are set wide enough to encompass most estimates of the various parameters in the literature.

We consider a utility function of the form

$$(26) \qquad U(c,l,m) = \left[\left(\omega\, c^{\frac{\eta-1}{\eta}} + (1-\omega)\, m^{\frac{\eta-1}{\eta}}\right)^{\frac{\eta}{\eta-1}}(1-l)^{\psi}\right]^{1-\sigma} \Big/ (1-\sigma).$$

Utility functions of this form are attractive because they are consistent with balanced growth (see Cooley and Prescott 1995).

We chose parameter values as follows. To obtain ω and η we drew on the money demand literature. Our model can be used to price a variety of assets including a nominal bond which costs one dollar at s^t and pays $R(s^t)$ dollars in all states s^{t+1}. The first order condition for this asset can be written as

$$U_m(s^t) = U_c(s^t)\left(\frac{R(s^t)-1}{R(s^t)}\right).$$

Using our specification of utility the first order condition can be rewritten as

$$\log \frac{M(s^t)}{\bar{P}(s^t)} = -\eta \log \frac{\omega}{1-\omega} + \log c(s^t) - \eta \log \left(\frac{R(s^t)-1}{R(s^t)}\right). \tag{27}$$

We regressed the log of consumption velocity on the interest rate variable in (27) using M1, the GDP deflator, the consumption of services, nondurables, and durables and the three month Treasury bill rate from 1960:1-1995:4 with data from Citibase. The implied value of ω from our regression is 0.94. Our estimate of the interest elasticity is $\eta = 0.39$ and has a standard error of 0.033. This elasticity is similar to that estimated by Lucas (1988) and Mankiw and Summers (1986) and smaller than that of Stock and Watson (1993).

Based on Basu (1993), Basu and Fernald (1994a,b), and Basu and Kimball (1995), we chose $\theta = 0.9$ which implies a markup of 11 percent and an elasticity of demand ε of 10.

We set the parameters β, δ, ψ, and α using balanced growth path relationships in our model and various statistics in the data. The parameter values are given in Table 1. With these parameters, our model predicts an annualized capital-output ratio of 2.65, an investment-output ratio of 0.23, a share of time allocated to the market of 1/3. The capital-output ratio and the investment-output ratio are those calculated for the United States by Christiano (1988) and the time allocated to market is similar to that in Cooley and Prescott (1995). In using the national income accounts to determine the capital share in our model we assume that monopoly profits are allocated proportionately to capital and labor. With this assumption the capital share of income in our model is 1/3 which is similar to the capital share estimated in Christiano (1988).

We chose an adjustment cost function of the form

$$\phi\left(\frac{x}{k}\right) = \frac{b}{2}\left(\frac{x}{k} - \delta\right)^2$$

where $b \geq 0$. We adjust b so that the Hodrick-Prescott filtered data from the model produces a standard deviation of investment relative to that of output similar to the corresponding statistic for the U.S. economy (3.23). We set $b = 0$ when the economy with no adjustment costs generates too small of a relative volatility of investment.

The stochastic process for the growth rate of the money stock is given by

$$\log \mu_t = \rho \log \mu_{t-1} + \epsilon_t,$$

where ϵ is a normally distributed i.i.d. mean zero shock. The serial correlation for money growth was calculated using quarterly data on M1 from 1959:3 through 1995:2 obtained from Citibase. We obtained $\rho = 0.57$.

In our experiments we vary the amount of staggering N as well as the length of time of exogenous price stickiness which we denote by T. When we do so we adjust the discount factor, the depreciation rate, and the serial correlation of money growth rates so as to keep the capital-output and investment-output ratio and the quarterly serial correlation the same. Specifically, we set $\beta = 0.97^{\frac{T}{N}}$, $\delta = 1 - 0.92^{\frac{T}{N}}$, and $\rho = 0.57^{\frac{4T}{N}}$ where T is measured in years. For most of the experiments we set T equal to one quarter of one year and $N = 13$ so that prices are stuck for one-quarter at a time, a cohort of producers chooses prices every week and consumers make their decisions weekly.

4. The contract multiplier

The idea of the contract multiplier is that a small length of exogenous price stickiness can generate prolonged output movements. One measure of the persistence of output movements is the half life of output defined as the length of time before output returns to half of its impact value following a shock starting from the steady state. The *contract multiplier* is defined as the ratio of the half life of output to the expected length of time before a representative firm can change its price. If we randomly sample firms at a point in time in our staggered price setting model the average length of time until firms can adjust their prices is one-half the length of exogenous stickiness. Thus, the contract multiplier is the half life of output divided by one half the length of exogenous stickiness.

One rationale for this measure is that it is the ratio of the half life of output in an economy with staggered price setting to that in an otherwise identical economy with synchronized price setting. In this sense a multiplier of, say, 5 means that staggered price setting generates output movements that last 5 times longer than they would with synchronized price setting. To establish this we conducted some experiments with synchronized price setting and found that movements in output last only as long as the time the price setters have a chance to set new prices. To see this consider, for example, our benchmark economy with the parameters of Table 1 and synchronized price setting. Suppose that prices are set on the first week of each quarter. Figure 1 shows the impulse response associated with a money shock that occurs just after prices are set. Clearly, the half life of output is one quarter. If the money shock occurs on the last week of the quarter it turns out that the half life of output is one week. More generally, if money shocks occur randomly throughout the quarter then on average the half life of output is one-half of one quarter.

In terms of the data, measuring the half life of output following a monetary shock is a difficult task. One perspective, and the one that we adopt, is that monetary shocks account for the bulk of business cycle fluctuations. This perspective dates back to at least Friedman and Schwartz (1963). (See Eckstein and Sinai 1986 and Romer and Romer 1989 for recent expositions of this view). An alternative perspective, see Sims (1980), is that any one shock in the economy accounts for a relatively small fraction of business cycle fluctuations. Under this view an alternative methodology than the one pursued here is appropriate. We do not pursue this line because this is not our perspective.

With our perspective we ask whether an economy subject to only monetary shocks can produce business cycle fluctuations of the kind seen in the data. This focus on a single-shock theory of business cycles is similar to that in Kydland and Prescott (1982), except that we focus on monetary shocks while they focus on technology shocks. Our view suggests that the half life of output is about 2 to $2\frac{1}{2}$ years since the average length of business cycles is about 4-5 years (see, for example, Burns and Mitchell 1946).

An alternative and decidedly secondary way to measure the half life of output is as follows. We fit an ARMA process to the logarithm of real GDP, after removing a quadratic trend. The fitted equation is

$$\log y_t = \underset{(.066)}{1.30} \log y_{t-1} - \underset{(.066)}{.38} \log y_{t-2} + \epsilon_t$$

where the numbers in parentheses are standard errors. The Ljung-Box Q test indicates little evidence for serial correlation of the residuals (Q =13.8 with significance level 0.46). From this we calculate the length of time before output returns to half of its impact value, following a one time shock, starting at its mean value of 0. The half life of output in the data is 10 quarters or $2\frac{1}{2}$ years.

If one finds plausible that the period of exogenous price stickiness is one quarter then the contract multiplier needed to match this measure of persistence is 20. With one month of exogenous price stickiness, the needed contract multiplier is 60, while with one year of exogenous price stickiness the needed multiplier is 5. For the bulk of our analysis we will consider economies in which the period of exogenous price stickiness is one-quarter. An attractive feature of the contract multiplier is that in our quantitative models it turns out to be approximately invariant to the length of exogenous price stickiness.

5. Findings for the benchmark economy

The main question addressed in this section is whether staggered price setting can lead to persistent movements in output. We begin by considering a stripped down version of the model that we can solve analytically for the equilibrium. In this version we abstract from capital and impose a static money demand equation. We show that in order to get persistence the equilibrium wage rate must change very little when consumption changes. We show that for the class of preferences in our benchmark model the equilibrium wage changes by so much that we cannot get persistence.

Consider a version of our model without capital and with two cohorts of monopolists staggering their price setting ($N = 2$). Suppose that the utility function is given by (26), as in the benchmark economy. We log-linearize our pricing equation around the deterministic steady state. We let x_{it}, x_t, p_t, w_t, y_t and m_t represent the logarithmic deviations from a steady state for $P(i, s^{t-1})$, $P(s^{t-1})$, $\bar{P}(s^t)$, $w(s^t)$, $c(s^t)$, and $M(s^t)$ respectively. Consider the pricing equation (8). If we set $\beta = 1$ in this equation and linearize it around the deterministic steady state, we get

$$(28) \quad x_{it} = \frac{1}{2}E_{t-1}p_t + \frac{1}{2}E_{t-1}p_{t+1} + \frac{1}{2}E_{t-1}(w_t + w_{t+1}).$$

The price level p_t is a weighted average of the individual prices,

$$(29) \quad p_t = \frac{x_t}{2} + \frac{x_{t-1}}{2}.$$

Substituting (29) into (28) and imposing equilibrium gives

$$(30) \quad x_t = \frac{1}{2}x_{t-1} + \frac{1}{2}E_{t-1}x_{t+1} + E_{t-1}(w_t + w_{t+1}).$$

Log-linearizing the labor supply equation (13) around the deterministic steady state gives

$$(31) \quad w_t = \gamma y_t,$$

where γ is derived by evaluating $-U_l/U_c$ at a steady state with $c = l = m$ to get

$$(32) \quad -\frac{U_l}{U_c}\bigg|_{c=l=m} = \frac{\psi}{\omega}\frac{c}{(1-c)} \quad (= w = \theta)$$

and then taking derivatives and using (32) to substitute for w and $c/(1-c)$ in the resulting expressions. We get

$$(33) \qquad \gamma = \frac{\partial \log \left(-\frac{U_l}{U_c}|_{c=l=m} \right)}{\partial \log c} = 1 + \frac{\theta \omega}{\psi}.$$

We simply impose a static money demand equation given by

$$(34) \qquad y_t + p_t = m_t,$$

where m_t is an exogenously given stochastic process. Substituting (31) into (30) gives

$$(35) \qquad x_t = \frac{1}{2} x_{t-1} + \frac{1}{2} E_{t-1} x_{t+1} + \gamma E_{t-1} (y_t + y_{t+1}).$$

The system of equations (29), (34), and (35) is the same as that in Taylor (1980). (In his original article, Taylor focused on real shocks. The subsequent literature, including West 1988 and Blanchard 1990, focuses on monetary shocks.) The only difference between our price-setting equation and Taylor's wage-setting equation is that our value of γ depends on the underlying preferences and technology while for Taylor γ is a structural parameter.

The system of equations (29), (34) and (35) can be solved to determine how money shocks are divided into movements in prices and movements in output. From (34) it follows that large movements in output require small movements in the price level. But from (35) it follows that large movements in output have small effects on the price level only if γ is small. To see how γ influences the division of money shocks into price and output movements, we solve the model for x_t, p_t, and y_t. Substituting for y_t in (35) using (29) and (34) we obtain

$$E_{t-1} x_{t+1} - 2 \frac{1+\gamma}{1-\gamma} x_t + x_{t-1} = - \frac{2\gamma}{(1-\gamma)} E_{t-1} \left(m_t + m_{t+1} \right).$$

We can use standard methods to write x_t as

$$(36) \qquad x_t = a x_{t-1} + \frac{2a\gamma}{1-\gamma} E_{t-1} \sum_{i=0}^{\infty} a^i (m_{t+i} + m_{t+1+i}),$$

where a is the root with absolute value less than 1 which solves $a^2 - \lambda a + 1 = 0$ where $\lambda = 2(1+\gamma)/(1-\gamma)$. This root is equal to

$$a = \frac{1-\sqrt{\gamma}}{1+\sqrt{\gamma}}. \tag{37}$$

Now suppose that m_t is a random walk. After simplifying (36) we can write

$$x_t = a x_{t-1} + (1-a) m_{t-1}.$$

Substituting for x_t in (29) we obtain

$$p_t = a p_{t-1} + \frac{1}{2}(1-a)(m_{t-1} + m_{t-2}).$$

Finally, substituting for p_t in (34) we obtain

$$y_t = a y_{t-1} + (m_t - m_{t-1}) + \frac{1}{2}(1-a)(m_{t-1} - m_{t-2}).$$

As should be clear, the persistence properties of output with respect to money shocks depend critically on the value of a and, therefore, on the value of γ.

For an arbitrary a, with $0 \leq a \leq 1$ we compute the half life of output as follows. A shock to m of Δ at $t-1$ starting from a steady state of 0 leads to an increase in output of $y_0 = \Delta$, and for $t \geq 1$,

$$y_t = \frac{1}{2} a^{t-1}(1+a)\Delta.$$

If $a > 0$ the half life t solves $1 = a^{t-1}(1+a)$, so that

$$t = 1 - \frac{\log(1+a)}{\log a}.$$

If $a < 0$ then output is clearly not persistent. In this case we simply find the half life by interpolating between $t = 0$ and $t = 1$ and the resulting half life is $1/(1-a)$.

When $N = 2$, one-half the length of exogenous price stickiness is 1. Thus, in order to get a multiplier of 20 we need a half life of 20 and hence a must solve $1 = a^{19}(1+a)$. The resulting $a = 0.965$ and the implied value of $\gamma = 0.00031$. Recall that in our model

$$\gamma = 1 + \frac{\theta\omega}{\psi}.$$

Because γ is necessarily greater than 1, from (37) a is negative and the contract multiplier is less than 1. For example, using the parameters in Table 1, the multiplier is calculated to be 0.9.

This multiplier is calculated under the assumption that the discount factor is 1. In Table 2 we report values of the multiplier for a variety of economies which, except where noted, use our calibrated parameters. The 'no links' column refers to economies without capital and interest insensitive money demand, while the next three columns refer to economies with only interest sensitive money demand, with only capital and with both interest sensitive money demand and capital, respectively. In all experiments in Table 2 the length of price stickiness T is set at one quarter. We report multipliers with $N = 2$ and i.i.d. money growth. These multipliers mimic our analytical results (and differ only because of the discount factor). We also report multipliers with $N = 13$ and serially correlated money growth. We think of these latter multipliers as more relevant for comparing with data.

In our benchmark model with $N = 2$, no persistence in money growth ($\rho = 0$), and no links the multiplier is 0.9. From Table 2 we see that raising the amount of staggering to $N = 13$ and adding persistent money growth raises the multiplier to only 1.03. We go on to investigate whether adding intertemporal links raises the contract multiplier. We do so by computing the contract multiplier for our benchmark economy with capital and interest sensitive money demand. Table 2 shows that with both links for $N = 2$ and no persistence in money growth ($\rho = 0$) the contract multiplier is 1.03, while for $N = 13$ and persistent money growth ($\rho = .57$ at a quarterly frequency) the contract multiplier is 1.06. For completeness, in Table 2 we also report the contract multiplier for versions of the benchmark economy when we shut down one intertemporal link at a time. Clearly adding intertemporal links leaves the contract multiplier roughly unchanged. Recall that if the multiplier is close to one then staggered price setting is not giving any more persistence in output than would synchronized price setting. With this contract multiplier in order to generate the half life of output seen in the data the exogenous length of price stickiness would have to be 5 years.

Taylor (1980) and Blanchard (1983) conjectured that, holding constant the length of time that prices are fixed, increasing the amount of staggering increases the persistence of output fluctuations. We investigate this conjecture by considering versions of our benchmark economies with $N = 2$, 13 and 26. The resulting multipliers are 1.03, 1.06, and 1.06. These results show that increasing the amount of staggering has little effect on the persistence of output responses. Thus the Taylor-Blanchard conjecture does not hold in a business cycle model modified in the obvious way to include sticky prices.

We also examined whether the contract multiplier varied with the length of exogenous price stickiness and found that it did not. For example, for our benchmark economy changing the length of price stickiness from one quarter to one year changed the contract multiplier from 1.06 to 1.0.

In our benchmark economies our contract multiplier is extremely small because prices are extremely sensitive to movements in marginal costs. One way of seeing this is to note that in versions without capital, γ is too large and hence a is too small. These results suggest that in order to generate a large contract multiplier we must find some mechanism that makes prices insensitive to movements in marginal costs.

6. Zero income effects

In this section we consider a particular specification of preferences in which marginal rates of substitution between leisure and consumption change very little even when consumption and leisure change a lot. With this specification of preferences γ is small so that prices are insensitive to movements in marginal costs. Intuitively, these preferences should generate a large contract multiplier. We find that without the intertemporal links of capital accumulation and interest sensitive money demand they do. Once we add intertemporal links, however, money shocks lead to an investment boom in the impact period which raises the demand for labor and therefore wage rates. Since utility is close to linear in both consumption and labor the rise in wage rates leads to a large increase in both consumption and labor in the impact period relative to future periods. This makes both the half life of output and the multiplier small.

We investigate implications for γ of utility functions of the form

$$(38) \quad U(c,l,m) = \left[\frac{c^{1-\kappa}}{1-\kappa} - \omega_1 \frac{l^{1+\xi}}{1+\xi} + \omega_2 \frac{m^{1-\nu}}{1-\nu}\right]^{1-\sigma} /(1-\sigma).$$

Log-linearizing the labor supply equation (13) as in (32) and (33), we obtain

$$\gamma = \kappa + \xi,$$

where $1/\xi$ is the labor supply elasticity evaluated at the steady state. With these preferences it is possible to obtain a large contract multiplier as long as κ and ξ are small enough. For example, $\kappa = 0.0002$ and a labor supply elasticity of $9,091$ yield $\gamma = 0.00031$ and a contract multiplier of 20. These calculations suggest that preferences with zero income effects and high labor supply elasticities offer one route to persistence. (Blanchard and Fischer 1989 and Blanchard 1990 point to the importance of high labor supply elasticities in generating persistence. These calculations make clear that near quasi-linearity in consumption is also crucial.)

To set the parameter ν we use the following money demand equation for this economy

$$(39) \quad \log m = \text{constant} + \frac{\kappa}{\nu} \log c - \frac{1}{\nu} \log \frac{R-1}{R},$$

where m is real balances and R is the gross nominal interest rate. This money demand equation makes clear that once κ is given we cannot vary the interest elasticity of money demand without also varying the consumption elasticity. Because of this when we eliminate the intertemporal link of interest sensitive money demand, we replace the money demand equation by a static money demand equation of the form (34). When we allow intertemporal links we set $\kappa = \nu$ so that the consumption elasticity of money demand is 1 (as balanced growth dictates).

Eliminating the intertemporal links of capital accumulation and interest sensitive money demand makes it easy to develop analytical expressions for the equilibrium of the model. While the results are often useful they can also be misleading. The economy with zero income effects provides one dramatic illustration of the extent to which eliminating intertemporal links can lead one to substantially overestimate the contract multiplier. Table 2 shows with $N = 2$, no persistence in money growth and no intertemporal links the multiplier is 21.28. The same economy with intertemporal links has a multiplier of only 0.50. This table also shows that the key intertemporal link that affects the multiplier is capital accumulation. For the economy with $N = 13$ and persistent money growth, the reduction in the multiplier is even more dramatic.

Obviously it is possible to make the contract multiplier in the model with capital equal to that in the model without capital by adding adjustment costs that are so large that the capital stock never changes. In the model with $N = 13$, persistent money growth, and both intertemporal links, it turns out that the volatility of investment relative to output is 0.45 which is substantially less than the corresponding statistic in the data. Thus, adding adjustment costs to investment will only decrease this relative volatility even further. Since a key feature of business cycle fluctuations is the volatility of investment, adding adjustment costs only makes this a poorer business cycle model along this dimension. In any case, we experimented with adding adjustment costs to this model and found that for a very large range of adjustment costs the multiplier did not change very much. The reason is that adding adjustment costs reduces the size of the output response in the impact period but also reduces the size of the output response in subsequent periods.

We now develop some intuition for why the contract multiplier is so small in the model with capital. In Figures 2A and 2B we illustrate how adding intertemporal links changes the contract multiplier. In Figure 2A we plot the impulse responses of output, consumption, and employment associated with a one-time money shock of 1 percent for our benchmark model with $N = 2$ and the preferences as in (38). In Figure 2B, we plot the analogous impulse responses for capital and the price level. For this economy, there is a large response of output, consumption, and employment in the impact period, and these variables rise by approximately 1 percent in subsequent periods. As is clear from Figure 2A, the large initial response of output makes the contract multiplier less than 1. The impulse response for the price level is barely different from zero over the four quarters shown, and the impulse response for the capital stock shows a rise of 1 percent in all periods after the impact period. Thus, the results suggest that a rough approximation to the behavior of the system is that the price level is constant at its old steady state level. Output, consumption, and employment respond a very large amount in the impact period, and output, consumption, employment, and the capital stock are higher by 1 percent in all periods after the impact period.

In order to understand the mechanics behind the large output response in the impact period, we assume that prices are constant and that, after the impact period, all real variables are constant and higher by the same percentage amount. Under these assumptions we first show that after the impact period, labeled period 0, the real variables rise by the same percentage amount as the money supply, namely 1 percent. To see this note that with preferences given by (38) the money demand equation is given by (39). Since the price level and allocations are constant, the nominal interest rate between periods t and $t+1$ for $t \geq 1$ is at its steady state level. (See equation 16.) Since the money supply rises by 1% and prices are constant real balances rise by 1 percent and so from (39) consumption rises by 1 percent. Under our assumption that all real variables are higher by the same amount it follows that output, labor, and the capital stock all rise by 1 percent. By similar logic, from (15), we see that the return to capital is constant and equal to its old steady state value in all periods after the impact period. One can show that each intermediate goods firm finds it optimal not to change its price. To see this, recall that $r = vF_k$. Since r is constant and the marginal product of capital F_k is constant, the unit cost of production v must be constant, so that producers optimally choose not to change their prices.

One way of gaining intuition for why the consumption and employment responses in the impact period are so large is to note that smoothing the marginal utility of consumption essentially requires smoothing $c - \omega_1 l$ assuming κ and ξ are close to zero. It is clear that there are many ways to smooth the marginal utility of consumption while at the same time allowing consumption and labor to vary dramatically.

The consumption and labor allocations in the impact period are determined by the resource constraint and the size of the investment response. Next we show how these variables are determined. Consider the first order condition for capital accumulation at date 0 given by

$$U_{c0} = \beta E_0[U_{c1}(r_1 + 1 - \delta)]. \tag{40}$$

Next we log-linearize (40), the resource constraint, and the capital accumulation equation to solve for the output response in the impact period. Using the form of the utility function with κ, ξ, and ν close to 0 in (40) gives

$$c_0 - \omega_1 l_0 + \omega_2 m_0 = A(c_1 - \omega_1 l_1 + \omega_2 m_1),$$

where A is a constant. Since c_1, l_1, m_1 and m_0 all rise by 1 percent then so does $(c_0 - \omega_1 l_0)$ which implies, after log-linearizing and rearranging, that

$$c\hat{c} - \omega_1 l\hat{l} = 0.01(c - \omega_1 l),$$

where variables without carets, like c and l, denote steady state values and variables with carets, like $\hat{c}$ and $\hat{l}$, are percentage deviations in period 0 from the steady state. In a steady state the first order condition for labor implies $\omega_1 l^{\xi}/c^{-\kappa} = \theta(1-\alpha)y/l$. Since ξ and κ are close to 0 this implies $\omega_1 l = \theta(1-\alpha)y$. Substituting for $\omega_1 l$ and rearranging gives

$$\frac{c}{y}\hat{c} - \theta(1-\alpha)\hat{l} = 0.01\frac{c - \theta(1-\alpha)y}{y}. \tag{41}$$

Log-linearizing the resource constraint gives

$$\frac{c}{y}\hat{c} - (1-\alpha)\hat{l} = -\frac{i}{y}\hat{\imath}. \tag{42}$$

Inspecting (41) and (42) it is clear that when θ is close to 1, this system of equations is nearly singular. Log-linearizing the capital accumulation equation gives $\hat{\imath} = \hat{k}_1/\delta = 0.01/\delta$ where $\hat{k}_1$ is the percentage deviation in the capital stock in period 1. Since δ is small the right side of (42) is a large negative number while the right side of (41) is a small positive number. Together with the near-singularity of the two equations it is clear that consumption and labor must respond by large amounts. Using the facts that $\hat{y} = (1-\alpha)\hat{l}$ and $c/y = 1 - \alpha\theta$ gives

$$(43) \quad \hat{y} = 0.01 \left(1 + \frac{\alpha}{(\frac{1}{\theta} - 1)\delta}\right).$$

Recall that the term $1/\theta - 1$ is the net markup which is typically a small fraction. The depreciation rate is also typically a small fraction. Thus, the expression in (43) shows that the output response is likely to be very large unless $\alpha = 0$. If we use the parameters reported in Table 1 (with $N = 2$ and $T = 1/4$), the calculations above imply that output rises by 290 percent on impact, which is close to what we found in our numerical results.

In general, as we drive κ and ξ to zero, the solution for output, capital, and the price level (in log deviations) is well approximated by:

$$(44) \quad y_t = k_t + B\mu_t$$

$$(45) \quad k_{t+1} = k_t + D\mu_t$$

$$(46) \quad x_t = x_{t-1}$$

where B and D are constants with B typically much larger than D. (Details are provided in an appendix available upon request.) Impulse responses displayed in Figures 2A and 2B exhibit a pattern similar to that for the system in (44)-(46). On impact, output rises significantly and then falls dramatically one period later. Prices barely move and the capital stock jumps once and only gradually returns to its steady state. Thus, the multiplier in the zero income effects model with capital is less than 1.

The results for this model emphasize the central role of intertemporal links in business cycle models with staggered price setting. In models with a static money demand equation of the form $m - p = y$, it is clear that the contract multiplier is large if and only if the price level responds slowly over time. In our zero income effects model the price level responds only slowly but the contract multiplier is tiny.

We should mention that one problem with preferences of this kind is that they are inconsistent with a balanced growth path. To see just how inconsistent they are with balanced growth suppose wage rates and consumption grow at 2 percent per year. Then, with our parameter values it is easy to show that labor input rises by 57 percent each day.

7. Convex demand

In this section we explore an avenue, suggested by Kimball (1995) designed to make prices less sensitive to marginal costs which should tend to increase the size of the multiplier. To motivate Kimball's idea note that the log-linearized pricing equation given in (30) implies that a 1 percent increase in marginal costs (which are simply wage rates in our model without capital) results in a 1 percent increase in prices set by the current cohort of intermediate goods producers. This feature of the model arises because the intermediate goods producers face a demand function with constant elasticity. The intuition for this feature is as follows. In static models a monopolist's markup of price over marginal cost is a simple function of the elasticity of demand. With constant elasticity of demand the markup is constant, so that when costs rise by 1 percent so do prices.

Kimball (1995) suggests an alternative formulation of the final goods production technology that gives rise to demand functions with the following feature: as prices rise the elasticity of demand increases so that the demand curve is convex. Demand functions of this kind can lead the markup to decline as prices rise, thus implying that a 1 percent increase in marginal costs results in less than a 1 percent increase in prices. Thus, after a monetary shock each cohort of firms does not raise their prices very much so that output deviates from its steady state for a long time. Mechanically, this type of demand function leads to a log-linearized pricing equation of the form (30) with a coefficient less than one on wages. The analysis above suggests that with this kind of pricing behavior, monetary shocks can have persistent effects on output.

We begin by analyzing this alternative formulation in a version of our model without capital and with $N = 2$. This alternative formulation closely follows Kimball (1995). Let the technology for producing final goods be implicitly defined by

$$\int g(y_i/y)di = 1,$$

where y_i is the use of the intermediate good i and y is the output of the final good. Profit maximization by final goods producers, together with zero profits implies

$$\frac{P_i}{P} = \frac{g'(y_i/y)}{\int g'(y_i/y)(y_i/y)di}.$$

This condition can be inverted to yield the demand function confronting each intermediate goods producer

$$\frac{y_i^d}{y} = d\left(\frac{P_i}{P}\int g'(y_i/y)(y_i/y)di\right),$$

where $d \equiv g'^{-1}$. Substituting this demand function into problem (6) we can solve for the optimal price for intermediate goods producer i. Log-linearizing the resulting optimal pricing equation yields

$$(47) \quad x_{it} = \frac{1}{2}E_{t-1}p_t + \frac{1}{2}E_{t-1}p_{t+1} + \frac{\varphi}{2}E_{t-1}(w_t + w_{t+1}),$$

where x_{it} is the log of the intermediate goods price set by producer i at date t, w_t is the log of the wage rate, and φ is given by

$$(48) \quad \varphi = \frac{1 - 1/\varepsilon}{2 - \chi/\varepsilon},$$

where ε is the elasticity of demand evaluated at the steady state (i.e., $\varepsilon = -d'(g'(1))g'(1)$) and χ is the parameter governing the curvature of the demand function (i.e., $\chi = -d''(g'(1))g'(1)/d'(g'(1))$). Substituting $w_t = (1 + \theta\omega/\psi)y_t$ into (47) we obtain

$$x_t = \frac{1}{2}x_{t-1} + \frac{1}{2}E_{t-1}x_{t+1} + \gamma E_{t-1}(y_t + y_{t+1}),$$

where $\gamma = \varphi(1+\theta\omega/\psi)$ and y_t is the log of output. The analysis above makes clear that lower values of γ lead to more persistent output movements. The parameter φ is determined by the values of ε and χ. From equation (48) it is clear that if the demand function is sufficiently convex so that χ is sufficiently negative, then φ, and hence γ, can be made arbitrarily small and output can be made arbitrarily persistent. Note also that increases in ε, holding χ fixed, reduce φ. We show later that this relation is important.

The intuition connecting the value of the curvature parameter χ to the persistence of output is that when the demand curve is very convex firms choose to lower their markups as their costs rise and raise their markups as their costs fall. The resulting insensitivity of prices to monetary shocks implies potential output persistence.

The key question is what values of χ imply substantial persistence. Kimball (1995) chooses a parameterization in which a 1 percent increase in market share, y_i/y, leads to a decline in the elasticity of demand from 11 to 8. In our model the elasticity of demand in the steady state is 10, so we choose a parameterization in which a 1 percent increase in market share, y_i/y, leads to a decline in the elasticity of demand from 10 to 7. We use a Taylor series expansion of the elasticity of demand around the steady state to calculate the value of the curvature parameter associated with Kimball's parameterization. The elasticity of demand is given by $\varepsilon\left(\frac{y_i}{y}\right) = -d'\left(g'\left(\frac{y_i}{y}\right)\right) g'\left(\frac{y_i}{y}\right)/(\frac{y_i}{y})$. Using the fact that $g'' = 1/d'$, the Taylor series expansion of $\varepsilon(y_i/y)$ around $y_i/y = 1$ is given by

$$\varepsilon\left(\frac{y_i}{y}\right) \cong \varepsilon(1) - [1 + \varepsilon(1) - \chi]\left(\frac{y_i}{y} - 1\right).$$

Using Kimball's parameterization we obtain a value of $\chi = -289$. This value implies that $\varphi = 0.029$ and with our other parameters the resulting value of γ is 0.045. This value implies a contract multiplier of 2.2. Unfortunately, however, this parameterization implies that the demand function must be extraordinarily convex. To appreciate how convex this demand function must be, consider a second-order Taylor series expansion of the demand function at the steady state, given by

$$(49) \quad d\left(\frac{P_i}{\bar{P}} g'(1)\right) \cong 1 - \varepsilon(1)\left(\frac{P_i}{\bar{P}} - 1\right) + \frac{\varepsilon(1)\chi}{2}\left(\frac{P_i}{\bar{P}} - 1\right)^2.$$

Using the parameterization that gives a multiplier of 2.2, this demand function implies that a 2 percent increase in relative prices results in an 78 percent reduction in demand and a 2.3 percent increase in relative prices results in zero demand. We think that a demand function with this extreme level of convexity is clearly inconsistent both with casual empiricism and a wide variety of demand studies for a whole range of products.

Introducing persistent money growth into this model raises the multiplier. Consider the multipliers reported in Table 2 for the convex demand model with no intertemporal links. For the case with $N = 2$ and no persistence in money growth, the multiplier is 2.17, which is similar to what we found above. For the case with $N = 13$ and persistent money growth, the multiplier is 5.62. In this case once we introduce capital and interest-sensitive money demand the multiplier falls to 1.87, which is not much larger than the multiplier of our benchmark economy. The intuition for these results is similar to that in the zero income effects model.

The basic idea behind the propagation mechanism discussed in this section is that individual firms confront essentially kinked demand curves so that their relative prices do not change much in response to changes in costs. We find this basic idea intriguing, but we think that the most promising way of exploring this idea is to investigate models in which firms perceive kinks in their demand because of strategic considerations such as trigger strategies which specify price wars when firms lower prices too much. Importantly, with the strategic considerations we can generate forces that give the price-setters incentives not to raise prices following shocks without doing violence to the results from microeconomic studies on demands for individual products. Moreover, if models like these are going to generate persistence it seems likely that they will do so without staggered price-setting. While we see this strategic approach as a promising avenue for generating persistence, we see no obvious connection between it and the idea that staggered price-setting increases persistence.

8. Specific factors

In this section we assume that each intermediate good is produced using a specific factor in addition to labor and capital. Each of these specific factors is inelastically supplied. The motivation for including these specificities is that they can potentially lead to greater persistence in output. As the discussion of the benchmark model makes clear, a key factor determining persistence in models without intertemporal links is the sensitivity of the monopolist's price to changes in economy-wide output. With specific factors there are two forces, which we label the *output effect* and the *wage effect* respectively, that affect this sensitivity. Increases in economy-wide output induce increases in the monopolist's output and raise the monopolist's costs because of decreasing returns to scale. This increase in costs induces the monopolist to raise his price. By itself, this output effect makes prices more sensitive to changes in output. Increases in wage rates induce a smaller increase in the monopolist's price with decreasing returns to scale. By itself, this wage effect makes prices less sensitive to changes in output. The wage effect is stronger the more elastic is demand. When demand is sufficiently elastic the wage effect dominates and the monopolist's price is relatively insensitive to aggregate output and monetary shocks have more persistent effects.

We begin by analyzing a version of this model without intertemporal links. The production function for producing intermediate goods is given by

$$y(i, s^t) = l(i, s^t)^{1-\alpha}.$$

One interpretation of this production function is that it is a constant returns to scale production function in labor and a specific factor such as land. The price-setting equation for the monopolist is given by the analogue of (28)

$$x_{it} = \frac{1}{2}E_{t-1}p_t + \frac{1}{2}E_{t-1}p_{t+1} + \frac{1}{2}\frac{E_{t-1}(w_t + w_{t+1})}{1 + A\varepsilon} + \frac{A}{2}\frac{E_{t-1}(y_t + y_{t+1})}{1 + A\varepsilon}, \tag{50}$$

where $A = \alpha/(1-\alpha)$ and $\varepsilon = 1/(1-\theta)$ is the elasticity of demand. Comparing (50) to (28) we see that with decreasing returns to scale there are two changes. Relative to (28), (50) has an extra term. This extra term, the last one in (50), is the output effect discussed above and reflects the increase in marginal costs associated with an increase in output. The response of the price to the wage rate is reduced by $1/(1 + A\varepsilon)$ and is the wage effect discussed above. With constant returns to scale ($A = 0$), this price-setting equation does not depend on the elasticity of demand or directly upon aggregate output. With decreasing returns to scale, the larger is the demand elasticity the less sensitive is the best response to wage rates and economy-wide output. Using (29) and (31) in (50) and imposing equilibrium gives an equation of the form in (35) with

$$\gamma = \frac{1 + \theta\omega/\psi + A}{1 + A\varepsilon}.$$

For the parameters given in Table 1, namely $\theta = 0.9$, $\varepsilon = 10$, $\psi = 1.5$, $\omega = 0.94$, and $A = 3/2$, we get $\gamma = 0.19$. This value of γ yields a contract multiplier of only 1.35. If, however, the elasticity of demand is large enough, then γ can be made arbitrarily close to 0 and the contract multiplier can be made arbitrarily large. For example, we can generate a contract multiplier of 20 with an elasticity of demand of $\varepsilon = 6500$ ($\theta = 0.9998$).

While high enough demand elasticities can lead to substantial persistence they also lead to extremely counterfactual implications regarding the distribution of output across firms in our economy. To see this, note that relative outputs of monopolists i and j are given by $y(i, s^t)/y(j, s^t) = [P(j, s^t)/P(i, s^t)]^{\varepsilon}$. For example, with $\varepsilon = 6500$ a 1 percent difference in relative prices implies a difference in relative outputs equal to 1.2×10^{30} percent (1.01^{6500}).

Introducing intertemporal links into this model also reduces the size of the contract multiplier. Assume that the technology for producing each intermediate good i is given by

$$F(k(i, s^t), l(i, s^t)) = k(i, s^t)^{\alpha_1} l(i, s^t)^{\alpha_2},$$

where $\alpha_1 + \alpha_2 < 1$. In Table 2, we report results that show how the multiplier changes once we include capital and interest-sensitive money demand. For the specific factors case, we assume that with $\alpha_1 = 2/9$ and $\alpha_2 = 4/9$. when capital is included. We also assume that adjustment costs to capital are set so that the relative volatility of investment to output is similar to that in the data. In the 'no links' case without capital or interest-sensitive money demand, the multiplier is 1.84 with $N = 13$ and $\rho = 0.57^{\frac{1}{13}}$. Introducing capital and interest-sensitive money demand reduces this multiplier to 1.37 which is not much higher than its value in our benchmark case.

9. Sensitivity analysis and the model with all effects combined

In this section we examine how the contract multiplier changes in the various models as we vary parameters, both one at a time and simultaneously. We also consider how combining the various models we have explored changes the multipliers. Here we focus on a number of key parameters and, in an appendix, available upon request, we report on how the multiplier varies with all of the parameters.

We begin with the benchmark economy. In Figure 3 we show how the multiplier varies as we vary one parameter at a time for the benchmark economy, holding fixed the relative volatility of investment to output. The other parameters for this economy, with the exception of the adjustment cost parameter, are set at their calibrated values given in Table 1. Panels A and B illustrate the roles of the intertemporal links. Panel A shows that the multiplier is very nonlinear in the interest elasticity of money demand and that the multiplier rises sharply only when the interest elasticity is less than 0.05. Panel B shows that the multiplier does not change very much as we vary the capital share.

Panel C shows that making the utility function more concave than log (increasing σ above 1) reduces the multiplier. The contract multiplier varies with the risk aversion parameter because in all of our experiments we choose the adjustment cost parameter to produce the volatility of investment relative to output seen in the data. As the utility function gets more concave the volatility of investment falls without adjustment costs. In order to keep the volatility of investment constant we need to reduce adjustment costs as we raise risk aversion. Lowering adjustment costs reduces the contract multiplier. When the risk aversion parameter is above 2.2 the adjustment cost parameter is zero and the contract multiplier is constant and small.

Panel D illustrates that the contract multiplier increases as the demand elasticity ε $(= 1/(1-\theta))$ increases. The intuition for this finding is similar to that in the specific factors economy. Since capital does not move very much, it acts like a factor in fixed supply.

We also conducted experiments in which we varied a number of the parameters simultaneously within the ranges reported in Table 3. We set the discount factor β, the depreciation rate δ, and the share parameter in utility ω at their calibrated values. (See Table 1.) Our ranges for the interest elasticity η, the capital share α, the risk aversion σ, and the weight on leisure ψ were chosen to include most of the estimates provided in the literature. We chose ρ so that money growth ranges from i.i.d. to very persistent. We chose the elasticity of demand to range from fairly inelastic to an upper bound that was dictated by computational feasibility. Within these parameter ranges the largest value of the multiplier we found is 3.46. This occurs with an interest elasticity of 0.2, a demand elasticity of 300, a capital share of 0.22, risk aversion of 1 (i.e., log utility), a weight of 0.11 on leisure in utility, and a serial correlation of 0.57 on money growth.

In Figure 4 we show how the multiplier varies as we vary one parameter at a time for the convex demand economy, holding fixed the relative volatility of investment. The other parameters for this economy, with the exception of the adjustment cost parameter, are set at their calibrated values and the curvature parameter governing convexity of demand is set at Kimball's posited value. Panel A shows that the multiplier is very nonlinear in the interest elasticity of money demand and that the multiplier rises sharply only when the interest elasticity is less than 0.05. Panel B shows that the multiplier decreases as the capital share increases. Panel C is very similar to the corresponding panel in Figure 3.

Panel D illustrates how the contract multiplier varies as the demand curvature parameter χ varies. It shows that in order to get a contract multiplier of 20 we need a curvature parameter of $\chi=$ 46,240. With this curvature parameter, (49) implies that a 1/2 percent increase in relative prices results in zero demand. Even with such an extremely convex demand function when we raise σ from 1 to 2.2 the contract multiplier falls from 20 to 0.08. Again this fall in the contract multiplier is due to the decrease in the adjustment cost parameter when we raise σ. The empirical asset pricing literature suggests a risk aversion parameter significantly above 1 so that even this level of convexity of demand may not be enough to generate the requisite persistence. When we vary a number of the parameters simultaneously within the ranges reported in Table 3 the largest value of the multiplier we found is 5.34. The parameter values associated with this value of the multiplier are reported in Table 3.

In Figure 5 we show how the multiplier varies as we vary one parameter at a time for the specific factors economy, holding fixed the relative volatility of investment. The results reported in Panels A, B, and C are very similar to the analogs in Figure 4. In Panel D we examine the effect of varying the extent of decreasing returns to scale on the contract multiplier by varying α_1 and α_2 while keeping α_2/α_1 equal to 2. The decreasing returns to scale parameter is the share of total income going to capital and labor with the residual going to the fixed factor. We see that the contract multiplier does not change very much as we vary these parameters. We varied a number of the parameters simultaneously in the range reported in Table 3 and found that the largest value of the multiplier we found is 5.28. The parameter values associated with this value of the multiplier are reported in the table.

Finally, we considered a model in which we incorporated zero income effects, convex demand and specific factors to investigate whether there are any significant interaction effects. In Table 2 we report the results for this 'mega' model at our calibrated values. The last column of Table 2 shows that introducing both features raises the multiplier very modestly to 2.06 from 1.87 (convex demand only) and 1.37 (specific factors only). We simultaneously varied the parameters in the ranges reported in Table 3. The maximum value of the contract multiplier is 5.34 and occurs with the same extreme parameter settings as the maximum of the convex demand economy.

One way to understand this is to first note that any version with zero income effects gives a tiny multiplier. Thus, the only possible interesting interactions are between the convex demand and the specific factor specifications. Figure 6 shows that the convex demand specification gives a large multiplier when the demand elasticity is small, while the specific factor specification gives a large multiplier when this demand elasticity is large. Thus, when we combine both features we can either choose the elasticity small and get essentially the same multiplier as with convex demand alone or we choose this elasticity large and get essentially the same multiplier as with specific factors alone. Thus, there is no sense in which these three variations tend to reinforce each other, and there is no sense in which the multiplier for the model with all three variations is the sum of the multipliers for each one separately.

10. Conclusion

The task we undertake in this paper is to develop a model in which prices are exogenously sticky for a short period of time, but through the staggered-price mechanism, endogenously sticky for a long period of time with output therefore persistent. Prices would be endogenously sticky if firms choose not to change prices very much when they can do so. We found it convenient to use the contract multiplier as a measure of persistence. One interpretation of our findings is that if 5 years of exogenous price stickiness is plausible then conventional models used in the business cycle literature can generate persistent output fluctuations. With the amount of convexity in demand posited by Kimball (1995), or with extremely elastic demand and sizable departures from constant returns to scale, generating persistence requires exogenous price stickiness of $2\frac{1}{2}$ years. If one quarter of exogenous price stickiness is plausible then generating persistence requires extraordinarily convex demand or extremely elastic demand.

The central challenge to a theory of monetary business cycles is to find a solution to the persistence problem and our findings suggest we should look elsewhere for mechanisms to generate persistence following monetary shocks.

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