Partial Adjustment and Staggered Price Setting

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Abstract

This paper compares staggered price setting to partial adjustment of prices in a small optimizing IS/LM model. In contrast to the overwhelming perception in the literature, the models are not similar for most parameterizations. These results clarify some confusion in recent work regarding the persistence of output responses to monetary shocks, reveal important quantitative differences between the stabilizing properties of different monetary policies across sticky price specifications, and highlight the role for more research on new-Keynesian "real rigidities" in DGE models.

JEL Codes: E32, E10, E31

1. Introduction

A rapidly growing literature embeds nominal price rigidity into otherwise standard dynamic general equilibrium (or "real business cycle" type) models. This paper compares two popular nominal price rigidity specifications, the partial adjustment model (Rotemberg (1982,1983) and Calvo (1983)) and staggered price setting (Taylor (1980) and Blanchard and Fischer (1989)), in a simple dynamic general equilibrium model. In the partial adjustment model, firms adjust prices according to some constant hazard rate (Calvo (1983)), implying some average frequency of price adjustment and a distribution of periods since last price adjustment about this average; since the distribution includes some prices set considerably longer ago than the average period between price adjustment, this model generates persistent output responses to monetary policy shocks. Under staggered price setting, all firms adjust prices after some fixed period of price rigidity, but the adjustments occur in different periods for different price setters (i.e., are staggered). Taylor (1980) illustrates that such staggering can also generate persistent output responses in a rational expectations model which lacks some of the microeconomic structure typical of dynamic general equilibrium models. Previous research suggests that partial adjustment and staggering imply similar dynamics, at least in reduced form models, and hence a large literature has adopted the simpler partial adjustment model as the sticky price specification in DGE models.[1]

The comparison of partial adjustment and staggering herein addresses two questions:

- Do both models of price rigidity imply similar dynamic responses of output to monetary and real shocks in a standard dynamic general equilibrium (DGE) economy?

The answer is a clear no; the dynamics are both quantitatively and *qualitatively* quite different across the two pricing specifications. This conclusion differs from earlier work and clarifies some of the confusion regarding the dynamics of output following monetary shocks surrounding results in Chari, Kehoe, and McGrattan (1996) and Rotemberg and Woodford (1997).

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[1] Much of this research is cited in Goodfriend and King (1997). Dynamic general equilibrium models with sticky prices have recently emphasized the partial adjustment model of sticky prices, as in Hairault and Portier (1993), Ireland (1996), Kimball (1995), Kim (1998), King and Watson (1996), King and Wolman (1996), Rotemberg and Woodford (1997,1998), Sbordone (1998), and Yun (1996). Examples of staggering include Chari, Kehoe, and McGrattan (1996), Dotsey, King and Wolman (1997), Erceg (1997), and Gust (1997).

- Why is there an overwhelming perception in the literature that the partial adjustment model of Calvo (1983) implies similar dynamics to staggered price setting (see Roberts (1995), Woodford (1995), Jeanne (1998), Gali and Gertler (1998), and Taylor (1998))?

It turns out this presumption arises because for certain parameter values *partial adjustment does imply similar dynamics to staggered price setting.* These parameter values are simply well outside the range implied by typical parameterizations of DGE models. However, model features emphasized in the new-Keynesian literature on "real rigidities" (Ball and Romer (1990)), such as increasing returns (perhaps of a short run nature due to variable capital utilization or effort fluctuations), fluctuations in the degree of imperfect competition, nominal or real wage rigidities, or factor immobilities, all bring the dynamics implied by partial adjustment and staggered price setting specifications closer together--by enhancing persistence under staggered price setting.

To see the importance of the dissimilarities between the partial adjustment model and staggered price setting, consider the analyses of Ireland (1996), Rotemberg and Woodford (1997), or Kim (1998). These authors attempt to estimate (some of) the parameters of a typical dynamic general equilibrium economy in which price rigidity is introduced through partial adjustment.[2] As will be seen below, the behavior of output or marginal cost induced by monetary policy shocks in the partial adjustment model are very insensitive to the parameters of the model which determine the slope of the marginal cost schedule (a key determinant of pricing), revealing that these parameters are poorly identified in a model with partial adjustment. In contrast, the behavior of output changes substantially with the parameters governing the slope of the marginal cost schedule in a model with staggered price setting. This contrast suggests that the choice of nominal price rigidity model can be quite important for estimation of important parameters in DGE models, such as returns to scale, the parameters governing fluctuations in capital or labor utilization, or the cyclical behavior of desired markups. Of course, the insensitivity of the output dynamics to changes in the parameters governing the curvature of

[2] The authors use different estimation/calibration strategies. Ireland and Kim use maximum likelihood, while Rotemberg and Woodford attempt to match the impulse responses of output and inflation to monetary policy shocks. Sbordone (1998) and Gali and Gertler (1998) also estimate/calibrate partial adjustment models.

marginal cost under the partial adjustment model also affects the results from calibration/ simulation exercises--suggesting that the robustness of results reported in the literature of footnote 1 to parameter variations may be quite different in simulations where price rigidity is introduced through staggered price setting.

Section 2 provides an introduction to staggered price setting and partial adjustment in an optimizing model where the supply of money follows a random walk. Section 3 shows that the differing persistence implications of the two models of price adjustment in section 2 hold for the propagation of real shocks under a simple nominal interest rate rule for monetary policy. Section 4 relates the results to previous work and suggests directions for future research.

2. Staggered Price Setting and Partial Adjustment in an Optimizing IS/LM Model[3]

A simple optimizing IS/LM model (as denoted by McCallum and Nelson (1997)) with an exogenous money supply illustrates the model features important for the different dynamic implications of partial adjustment and staggered price setting.

Consumers

A representative consumer has preferences over consumption of the final good (C), labor hours (N), and the utilization/effort (E) with which the labor hours are used. These preferences are given by

$$U = \sum_{I \geq 0} \beta^i \{\log(C_{t+I}) - N_{t+i}{}^{1+s}/(1+s) - E_{t+i}{}^{1+e}/(1+e)\}.$$

Variation in utilization/effort is incorporated to reflect both variation in capital accumulation as well as labor effort; these variations are an important explanation for the empirical finding of *short-run increasing returns to labor* (Bernanke and Parkinson (1991), Burnside, Eichenbaum, and Rebelo (1995)).

Consumers receive labor income (in compensation for both hours and effort), own the firms (and receive any profits), and invest in real bonds, so their budget constraint is given by

[3] The real side of the DGE model used herein is a simple example of the type used in the literature in footnote 1 in order to emphasize the importance of the differences between partial adjustment and staggering for the conclusions reached in that work.

$$C_t + B_{t+1} = W_tN_t + V_tE_t + (1+r_t)B_t + \Pi_t \ ,$$

where W is the real wage for hours, V is the real wage for effort, Π is profits, B is bond holdings, and r is the real interest rate. Utility maximization then implies the familiar equilibrium conditions:

$$1/C_t = \beta E_t \ \{1/C_{t+1}[1+r_{t+1}]\} \ ,$$

$$C_tN_t^s = W_t \ ,$$

$$C_tE_t^e = V_t \ .$$

These conditions simply equate the marginal utility of consumption today with the discounted marginal utility from postponing consumption until next period, the marginal rate of substitution between leisure and consumption to the real wage for hours, and the marginal rate of substitution between effort and consumption to the real wage for effort.

Note that all output of the final good is consumed (Y=C), so log-linearization of the above first order conditions (with lower case denoting the log deviation of the corresponding variable from its steady state value) yields

$$y_t = E_t \ \{y_{t+1} - r_{t+1}\} \ , \tag{2.1}$$

$$y_t = -sn_t + w_t \ . \tag{2.2}$$

$$y_t = -ee_t + v_t \ . \tag{2.3}$$

Final Goods

The final goods sector is competitive (i.e., firms are price takers and adjust nominal prices in each period). The production function for final goods output (Y) takes intermediate goods (distributed over (0,1)) as inputs (Y_i):

$$Y = [\textstyle\int_0^1 Y_i^{\theta} di]^{1/\theta} \ , \ 0<\theta<1.$$

Cost minimization by final goods firms yields the demand functions for intermediate goods

$$Y_i = Y(X_i/P)^{-1/(1-\theta)},$$

where X_i is the price of good I, and P is the aggregate price index (= $[\int_0^1 X_i^{\theta/(\theta-1)} di]^{(\theta-1)/\theta}$). These demand functions for intermediate goods are of the constant elasticity type.

Intermediate Goods

Intermediate goods firms will set nominal prices according to rules discussed below, and meet demand (from the previous subsection) at the posted price. Firms produce output according to the production function

$$Y_{it} = A_t N_{it}^{\alpha} E_{it}^{1-\alpha} = Y_t^{1-1/\beta} N_{it}^{\alpha} E_{it}^{1-\alpha} .$$

The term A ($=Y^{1-1/\beta}$) is an aggregate production externality, reflecting any increasing returns to production during periods when aggregate activity is high. While empirical support for such externalities has weakened substantially in recent years (Basu and Fernald (1997)), these types of externalities played an important role in the new-Keynesian literature on coordination failures and price rigidities, and they play a similarly important role in the comparison of Calvo (1983) and Taylor (1980) pricing specifications in this paper.

Cost minimization yields

$$W_t = \alpha MC_{it} Y_{it}/N_{it} ,$$

$$V_t = (1-\alpha) MC_{it} Y_{it}/E_{it} ,$$

where real marginal cost MC (or the inverse of the price-marginal cost markup) is the lagrange multiplier on the production function in the minimization. Taking logs of the production function and the cost minimization conditions (and eliminating constants) yields[4]

$$w_t = mc_t + y_t - n_t , \tag{2.4}$$

$$y_t = \beta a n_t . \tag{2.5}$$

Note that in (2.5) the equilibrium relationship between effort and labor hours ($e_t = (1+s)n_t/(1+e)$) has been used and $a = \alpha + (1-\alpha)(1+s)/(1+e)$. This value of "a" implies--even in the absence of externalities (β=1)--that labor hours appear to have short-run increasing returns so long as the disutility of effort relative to the disutility of labor hours is sufficiently small (e<s). These short-run increasing returns arise because--with small disutility of effort--effort moves more than hours and hence hours appear to display increasing returns (if effort/utilization is not considered as well). This explanation for the appearance of increasing returns has considerable support (Burnside, Eichenbaum, and Rebelo (1995)).

Solving (2.2), (2.3) and (2.4) for employment, wages, and marginal cost as functions of output yields

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[4] Note also that individual firm subscripts (I) have been removed; this is appropriate so long as the approximation is around a symmetric steady state in which all firms charge the same prices and produce the same output (as occurs under staggered price setting with a zero rate of inflation).

$$n_t = y_t/\beta a \,, \tag{2.6}$$

$$w_t = (s+\beta a)y_t/\beta a \,, \tag{2.7}$$

$$mc_t = [1+s]y_t/\beta a = by_t \,. \tag{2.8}$$

Equation (2.7) reveals the unsurprising conclusion that the elasticity of marginal cost with respect to output (b) is determined by the degree of externalities in production and the elasticities of labor supply of hours and effort ($b = (1+s)/\beta a$).

Price Adjustment Rules 1: Staggered Price Setting

The staggered price setting model is a two period specification, inspired by Taylor (1980) and following the treatment of Blanchard and Fischer (1989). Firms have market power and set prices (X) for two periods at the start of period t; in particular, firms choose the nominal price X_{it} that maximizes

$$\sum_{j=0}^{1} E_t\{\beta^j \Lambda_{t+j}(X_{it} Y_{it+j} - P_{t+j}\Gamma(Y_{it+j}))\},$$

where $\Gamma(Y_{it+j})$ is the cost function of firm I (determined from the minimization problem above), and the firm's discount factor $\beta^j \Lambda_{t+j}$ incorporates both the subjective discount factor of consumers (who own the firms), and the marginal utility of income in period t+j ($\Lambda_{t+j} = 1/C_{t+j}$). The first order condition (given the demand function Y_t^i above) yields

$$X_{it} = [\textstyle\sum_{j=0}^{1} E_t\{\beta^j \Lambda_{t+j} MC_{it+j} Y_{it+j} P_{t+j}\}]/\theta[\textstyle\sum_{j=0}^{1} E_t\{\beta^j \Lambda_{t+j} Y_{it+j}\}],$$

which shows that nominal prices chosen by a firm at time t are a markup ($1/\theta$) over nominal marginal cost over the period for which the price will hold. Log-linearizing for $\beta \approx 1$ yields the equation for the log of nominal prices set in period t used in Blanchard and Fischer (1989) and Chari, Kehoe, and McGrattan (1996),

$$x_t = \tfrac{1}{2} E_t [p_t + mc_t + p_{t+1} + mc_{t+1}] \,. \tag{2.9}$$

The equation for the price level (p) is given by the average of outstanding prices,

$$p_t = \tfrac{1}{2}(x_t + x_{t-1}) \,. \tag{2.10}$$

Price Adjustment Rules 2: Partial Adjustment

The partial adjustment model follows Calvo (1983) and Rotemberg (1987,1996) in assuming that individual firms adjust prices infrequently, with a constant probability in each period (given by π). Firms choose the nominal price X_{it} that maximizes

$$\sum_{j=0}^{\infty} E_t\{((1-\pi)\beta)^j \Lambda_{t+j}(X_{it} Y_{it+j} - P_{t+j}\Gamma(Y_{it+j}))\},$$

where the firm's horizon now consists of the entire future, and the firm weighs that future by the additional factor $(1-\pi)^j$, which is the probability the firm does not adjust between periods t and t+j. The first order condition is

$$X_{it} = [\sum_{j=0}^{\infty} E_t\{((1-\pi)\beta)^j \Lambda_{t+j} MC_{it+j} Y_{it+j} P_{t+j}\}]/\theta[\sum_{j=0}^{\infty} E_t\{((1-\pi)\beta)^j \Lambda_{t+j} Y_{it+j}\}],$$

which shows that nominal prices chosen by a firm at time t are a markup ($1/\theta$) over nominal marginal cost over the period for which the price is expected to hold. Log-linearizing for $\beta \approx 1$ yields the equation for the log of nominal prices set in period t used in Rotemberg (1987,1996),

$$x_t = \pi E_t \sum_{I \geq 0} (1-\pi)^I [p_{t+I} + mc_{t+I}] = \pi E_t [p_t + mc_t] + (1-\pi) E_t x_{t+1} , \tag{2.11}$$

The equation for the price level (p) is given by the average of outstanding prices,

$$p_t = (1-\pi)p_{t-1} + \pi x_t , \tag{2.12}$$

Note that $1/\pi$ is the average frequency of price adjustment in the partial adjustment model, so that a typical use in the literature would set $\pi=0.5$ to approximate two period staggered price setting. Equations (2.10) and (2.12) are quite different expressions (staggering is a moving average of nominal prices chosen (x), whereas partial adjustment is an AR1), suggesting that the conditions under which the two models behave similarly in response to monetary shocks may be quite stringent.

Money

To close the model and examine the behavior of prices and output in response to monetary shocks requires specification of how monetary shocks enter the model. For the purpose of this section, money demand is given by the quantity equation,

$$m_t = y_t + p_t . \tag{2.13}$$

The nominal money supply (m) is a random walk (without drift).

Solution

The model considered above implies that real marginal cost is related to output by (2.8), which implies (in conjunction with (2.9), (2.10), and (2.13)) that output and the price level under staggered price setting are given by

$$p_t^{stag} = kp_{t-1}^{stag} + ½(1-k)(m_t + m_{t-1}), \quad (2.14)$$

$$y_t^{stag} = ky_{t-1}^{stag} + ½(1+k)(m_t - m_{t-1}), \quad (2.15)$$

where $k = (1-b^{1/2})/(1+b^{1/2})$.[5]

In the staggered price setting model, the parameter k indexes *endogenous price stickiness*. For k near 1, prices adjust very slowly and the output effects of nominal aggregate demand shocks are long-lived. For k near zero, prices basically adjust completely to their long run level after the exogenously imposed periods of price stickiness have expired. In order for endogenous price stickiness to arise, marginal cost must be relatively acyclical (as b near zero implies k near 1). This simply illustrates the straightforward notion that rising costs dampen output fluctuations. However, note that under short-run constant returns to labor (i.e., no externalities and movements in labor effort/utilization identical to labor hours), the elasticity of marginal cost with respect to output (b) is always greater than one, implying $k<0$; staggering in this optimizing IS/LM model cannot deliver persistent output responses because marginal costs are strongly procyclical, implying rapid price adjustment. This is true even when labor supply is very elastic ($s \approx 0$). Chari, Kehoe, and McGrattan (1996) and Ellison and Scott (1998) conclude that staggering is incapable of generating persistence based on models similar to that of this section.

The partial adjustment model looks quite different. Solving (2.8) and (2.11)-(2.13) by the method of undetermined coefficients yields the following for price and output behavior under partial adjustment:

$$p_t^{part} = \lambda p_{t-1}^{part} + (1-\lambda)m_t , \quad (2.16)$$

$$y_t^{part} = \lambda y_{t-1}^{part} + \lambda(m_t - m_{t-1}) , \quad (2.17)$$

where λ is the stable solution to $\lambda = (1-\pi) + \pi^2(1-b)\lambda/[1-(1-\pi)\lambda]$. Note that λ is decreasing in b, so a small elasticity of marginal cost with respect to output slows the adjustment of prices and output to their long-run levels, as in the staggered price model. Again, rising costs dampen output fluctuations.

Comparing the Price Adjustment Specifications

[5] Blanchard and Fischer (1989), chapter 8, and Chari, Kehoe, and McGrattan (1996).

Examining the formulas for k and λ reveals that $k=\lambda$ when $b=0$, and $k<\lambda$ for $b>0$, with the difference between k and λ increasing in b. In fact, λ is greater than zero for all values of b (>0), whereas k is less than zero when b is greater than one. Since b is always greater than one under constant returns in the baseline optimizing IS/LM model, staggering implies negative autocorrelation in output while partial adjustment implies positive autocorrelation for "typical" parameterizations of this kind of optimizing model. Therefore, the partial adjustment model used in much previous research gives a very misleading picture of the implications of price rigidity in typical dynamic general equilibrium economies (unless one views the Calvo constant hazard model as more realistic than the traditional staggered price setting model).

Figure 1 makes these results more clear by plotting the autoregressive roots implied by Calvo's partial adjustment model (λ) (with an average period of price stickiness of 2) and Taylor-style staggered price setting (k) for different values of the elasticity of marginal cost with respect to output (b). As is clear, the two models imply very different dynamics for most parameterizations of the model. The partial adjustment model only approximates the dynamics of staggered price setting for low values of b; in fact, this effect is highly nonlinear in b, so that the partial adjustment approximation is only good for $b<0.05$.

Two types of intuition provide some guidance in thinking about *why* the partial adjustment model imparts so much more persistence than the staggered price setting model. In the Calvo interpretation of partial adjustment with $\pi = ½$, firms attach a 25% probability to not adjusting in the next two periods--imparting *by assumption* much more sluggishness to price adjustment after two periods than a staggering model (which implies all firms adjust by the second period). Staggered price setting assumes nothing about price behavior beyond the period of sticky prices. An alternative intuition comes from the equivalence between the constant hazard model of Calvo and quadratic costs of price adjustment (Rotemberg (1987)). Under quadratic costs of price adjustment, the level of prices will adjust smoothly--so that λ is always greater than zero. By contrast, staggered price setting does not impose the smoothness imposed by quadratic costs of price adjustment; such smoothness can be an equilibrium outcome, but only for low values of the elasticity of marginal cost with respect to output (b).

3. Output Persistence In Response to Real Shocks Under Nominal Interest Rate Rules

The previous results reveal that partial adjustment and Taylor-staggering imply very different output dynamics in response to monetary shocks in typical DGE models; the salience of these results for recent confusion in the literature will be picked up in section 4 below. First, this section examines the implications of our two models of price adjustment for output dynamics in response to technology shocks when monetary policy follows a simple nominal interest rate rule. This analysis will expand consideration of the persistence properties of different sticky price specifications to real-side shocks. The results will indicate that staggering generates less persistence in output in response to real shocks than partial adjustment for most parameterizations of the model.

The Basic Setup

The model is largely identical to that of the previous section. The first equation is the “optimizing IS” curve from the consumption euler equation (where the innocuous (for our purposes) assumption of log utility in consumption has been used)

$$y_t = E_t\,\{y_{t+1} - r_{t+1}\}\ , \tag{3.1}$$

The production side of the model is largely the same; the only alteration is the addition of a multiplicative productivity shock to the production function of intermediate goods producers. This alteration simply amends the relationship between marginal cost and output to

$$mc_t = b(y_t - z_t), \tag{3.2}$$

where z is the log of the productivity shock.[6] Equation (3.2) simply states that marginal cost is increasing in the deviation of output from potential output. For illustrative purposes the productivity shock is assumed to be i.i.d. A final element is the nominal interest rate (i_t) rule followed by the monetary authority; for simplicity, the rule is assumed to be an increasing function of the inflation rate:

$$i_t = \phi(p_t - p_{t-1}),\ \phi>1. \tag{3.3}$$

[6] The productivity shock in the production function may need to be scaled by parameters of the supply side (such as returns to scale); hence z represents the normalized productivity disturbance that corresponds to potential output (or output under price flexibility). Similar specifications arise in Rotemberg and Woodford (1997,1998) or Erceg, Henderson, and Levin (1998).

Of course, the real rate equals the nominal rate minus expected inflation ($E_t\, r_{t+1} = E_t\, \{i_t - (p_{t+1} - p_t)\}$.

Solution Under Partial Adjustment

The pricing equations remain the same as in section 2. Solving (3.1)-(3.3) with (2.11)-(2.12) for output and inflation as a function of the productivity disturbance (z) yields

$$y_t = [\phi kb/(1+\phi kb)]z_t \text{ , } k = \pi^2/(1-\pi), \tag{3.4}$$

$$\Delta p_t = [-kb/(1+\phi kb)]z_t \text{ .} \tag{3.5}$$

These solutions are familiar (for example, similar expressions appear in Bernanke and Woodford (1998)). Equation (3.5) indicates that more aggressive policy responses to inflation (large ϕ) dampen inflation fluctuations, and accentuate output fluctuations.[7] One important finding is that output fluctuations are purely transitory (as z is assumed to be i.i.d.). This implication would be changed if productivity shocks were persistent (as typically assumed), in which case output would be as persistent as the productivity disturbance. Such complications do not alter the comparison between partial adjustment and staggering, and hence are ignored.[8]

Solution Under Staggered Price Setting

The solutions under staggered price setting are slightly more complicated; in particular, the solutions for inflation and output both depend on the lagged relative price--which is itself an autoregressive process:

$$y_t = a_1 z_t + a_2(x_{t-1} - p_{t-1}), \tag{3.6}$$

$$\Delta p_t = b_1 z_t + b_2(x_{t-1} - p_{t-1}), \tag{3.7}$$

$$x_t - p_t = c_1 z_t + c_2(x_{t-1} - p_{t-1}) \text{ .} \tag{3.8}$$

The coefficients in this solution can be found by the method of undetermined coefficients; however, closed-form solutions were not easily found. The persistence implications of staggered

[7] Note that while output fluctuations are exacerbated by aggressive policy responses to inflation, these output fluctuations may be welfare improving (if fluctuations in z reflect fluctuations in the productive capacity of the economy). This result is discussed extensively in Rotemberg and Woodford (1998). Note that z could also reflect supply shocks that represent changes in distortions in the economy (taxes, price-marginal cost markups), and then exacerbating fluctuations would not be welfare improving.

[8] West (1988), for example, shows how the persistence of fluctuations in output is driven by the persistence of the exogenous shocks when the monetary authority follows a nominal interest rate rule.

price setting in response to real shocks are clear from (3.6)-(3.8). In particular, output and inflation are ARMA(1,1) processes, with the autoregressive root given by c_2. Therefore, the dynamics will be dominated by this autoregressive root, which is negative. Figure 2 plots the AR root for different values of b assuming ϕ=1.5. As shown, the AR root is close to zero for very small values of b, and becomes increasingly negative quickly as b moves away from 0. This result reveals that staggered price setting implies much less persistence than partial adjustment even in response to real shocks--especially for values of the elasticity of marginal cost with respect to output implied by typical parameterizations of this kind of optimizing IS-LM model.

This result expands the finding of Chari, Kehoe, and McGrattan (1996) regarding monetary shocks by showing that staggered price setting actually lowers the persistence of output fluctuations in response to real shocks, especially for typical parameterizations (where b>1). Of course, for very small values of the elasticity of marginal cost with respect to output, staggered price setting does not have a major impact on the persistence of the output effects of real shocks; finding plausible mechanisms for very small values of b may therefore be crucial to the success of sticky price models. The next section considers this point, and examines how the results comparing staggered price setting and partial adjustment relate to previous work.

4. Implications

Sections 2 and 3 concluded that partial adjustment and Taylor-style staggering do not deliver similar output and inflation dynamics following both real and monetary shocks for most parameterizations. Three implications follow:

- The overwhelming perception in the literature that the two models are nearly identical is incorrect;
- Models that use partial adjustment as a replacement for staggering merely for analytical convenience (rather than theoretical preference) may reach incorrect quantitative conclusions; for example, the stabilizing properties of different nominal interest rate rules differs across specifications;
- For a small set of possible values of the elasticity of marginal cost with respect to output,

partial adjustment and staggering deliver similar implications (because for these parameterizations sluggish price responses arise endogenously under staggering, and hence match the exogenously-imposed stickiness imparted by partial adjustment); finding plausible mechanisms to deliver such a low elasticity of marginal cost with respect to output should be a priority for future work.

I will briefly consider each of these points.

Partial Adjustment and Staggering Are Not Similar

Figures 1 and 2 make this point clear; staggering imparts much less persistence than does partial adjustment for nearly all parameterizations--especially typical ones (without externalities or utilization variations) where $b>1$. This conclusion runs against a strong perception in the literature. Two reasons for the difference arise. First, Jeanne (1998), in an analysis primarily concerned with the impact of real wage cyclicality in the partial adjustment model of sticky prices, briefly considers the staggered price-setting model--but finds that staggering and partial adjustment are very similar. This result seems to occur because Jeanne (1998) computes the solution incorrectly for the staggering model.[9]

Roberts (1995) is another paper purporting to find similarity between the partial adjustment and staggering model. In fact, Roberts argues that staggering and partial adjustment are similar if output is persistent, and then concludes that the models must be similar because in fact output is persistent in the data. This reasoning essentially confines Roberts (1995) analysis to very small values of b--although Roberts does not acknowledge the difficulties of generating small values of b in DGE models because his analysis starts with a reduced form model. If one wishes to parameterize a DGE model based on values typical in the literature, b is not small--and hence partial adjustment and staggering are very different. Therefore, the contrast between partial adjustment and staggering really comes down to whether one wishes to exogenously impose sluggish prices (partial adjustment), or whether one wishes to develop a model where

[9] The difference from Jeanne appears to stem from an error in the computation of the root k for the staggered price setting model in Jeanne (1998); the root λ in the text corresponds to that in Jeanne, but the staggered price setting root is different (although the root k in the text corresponds to that found by previous authors such as Chari, Kehoe, and McGrattan (1996)).

sluggish prices arise endogenously (as can occur with staggering for certain parameterizations.)

Quantitative Lessons

Much of the literature uses either partial adjustment or staggering in calibrated DGE models to answer some quantitative question (see footnote 1). One example is whether sticky prices generate persistent output responses. Chari, Kehoe, and McGrattan (1996) find that it is difficult to generate persistent output responses to monetary shocks in a typically-calibrated DGE model--a result replicated here (i.e., the b>1 case). Rotemberg and Woodford (1997) argue that their model has no problem generating persistence; however, Rotemberg and Woodford (1997) uses partial adjustment rather than staggering, and this choice assumes much greater persistence than the Taylor-style staggering model used in Chari, Kehoe, and McGrattan (1996).[10] Taylor (1998) apparently misses this key point in his summary of the recent literature--where he freely mixes the persistence implications of partial adjustment and staggering when discussing the persistence of output responses to monetary shocks in sticky price models. Quantitative comparisons across models using staggering and models using partial adjustment are inappropriate to address the question of whether alterations to the real sides of such models alter the persistence implications of monetary shocks because the two models start with very different baseline levels of exogenous price stickiness (even when the partial adjustment model is parameterized to deliver an average frequency of price adjustment equivalent to staggering; see figure 1).

Another example is the question of the stabilizing properties of different nominal interest rate rules. The differences in the two models documented herein can affect the answer to that question considerably. Figures 3 and 4 present the variance of inflation for different values of the parameter ϕ in the nominal interest rate rule in the model of section 3 for b=0.05 and b=1. In both figures, the variance of the productivity disturbance is normalized so that inflation has a unit

[10] Rotemberg and Woodford (1997) are also very aware of the need for low values of b; however, as is clear from figure 1, simply choosing partial adjustment automatically goes a long way towards eliminating the problem identified by Chari, Kehoe, and McGrattan (1996)--and the elimnation of the problem occurs because partial adjustment corresponds to quadratic costs of price adjustment and hence assumes smooth price responses. This is not the type of response for which Chari, Kehoe, and McGrattan (1996) are searching.

variance at ϕ=1.5. As shown, the improvement in inflation performance for more aggressive monetary rules (larger ϕ) is much more dramatic under staggering (Taylor) than under partial adjustment (Calvo). This result arises because an aggressive monetary policy has two benefits (in terms of inflation performance) under staggering; it reduces the impact effect of a shock on inflation, and this reduced impact also implies a smaller effect from lagged shocks. Note also that the differences in the two models are stark even for b=0.05--a very small value at which staggering and partial adjustment are relatively similar.

Future Modeling Considerations

In terms of implications for future work, this paper provides two lessons. First, the decision to use staggering or partial adjustment is important--both qualitatively and quantitatively. I prefer to use staggering when quantitative questions are being addressed because it meets the two criteria of Taylor (1998):

1. Staggering assumes that price changes are infrequent;
2. Staggering implies that price changes are not synchronized.

While the Calvo interpretation of partial adjustment appears to fit these criteria, partial adjustment is equivalent to assuming quadratic costs of price adjustment, which implies that prices adjust smoothly and in small increments.

The second lesson is that factors that lower the elasticity of marginal costs with respect to output are key to generating persistent effects of both monetary and real shocks under staggered price setting. This paper considered popular candidates from the new-Keynesian literature on real rigidities in static models (Ball and Romer (1990)) such as increasing returns, a low labor supply elasticity, and variable factor utilization (effort). Other work has pursued similar lines (Dotsey, King, and Wolman (1997)), as well as nominal wage rigidities (Erceg (1997)), real wage rigidity (Jeanne (1998)), and factor immobilities (Gust (1998)). More work on both the microeconomic and macroeconomic implications of these mechanisms--and others--is very important for the development of quantitative DGE models suitable for policy analysis.

References

Ball, L. and D. Romer. (1990) Real Rigidities and the Non-neutrality of Money. *Review of Economic Studies* 57:183-203.

Basu, S. and J. Fernald (1997) Returns to Scale in U.S. Manufacturing: Estimates and Implications. *Journal of Political Economy* 105:249-83.

Bernanke, B. and M. Parkinson (1991) Procylical Productivity and Competing Theories of The Business Cycle: Evidence from Interwar U.S. Manufacturing Industries. *Journal of Political Economy* 99:439-59.

Bernanke, B. and M. Woodford (1997) Inflation Forecasts and Monetary Policy. NBER Working Paper 6157.

Blanchard, O.J. and S. Fischer. (1989) *Lectures on Macroeconomics* (MIT Press, Cambridge).

Burnside, C., M. Eichenbaum, and Rebelo,-Sergio (1995) Capital Utilization and Returns to Scale. *NBER Macroeconomics Annual 1995.*

Calvo, G.A. (1983) Staggered Prices in a Utility Maximizing Framework. *Journal of Monetary Economics* 12:383-398.

Chari, V.V., P.J. Kehoe, and E.R. McGrattan. (1996) Sticky Price Models of the Business Cycle: Can the Contract Multiplier Solve the Persistence Problem. NBER Working Paper 5809.

Cooper, R. and A. John (1988) Coordinating Coordination Failures in Keynesian Models. *Quarterly Journal of Economics* 103:441-463.

Dotsey, M., R.G. King, and A. Wolman (1996) State Dependent Pricing and the Dynamics of Business Cycles. Mimeo.

Dotsey, M., R.G. King, and A. Wolman (1997) Menu Costs, Staggered Price Setting and Elastic Factor Supply. Mimeo.

Ellison, M. and A. Scott (1998) Sticky Prices and Volatile Output: Or When is a Phillips Curve Not a Phillips Curve. CEPR Discussion Paper Series No. 1849.

Erceg, C. (1997) Nominal Wage Rigidities and the Propagation of Aggregate Demand Disturbances. Mimeo.

Erceg, C., D. Henderson, and A. Levin (1998) Tradeoffs Between Inflation and Output-Gap Variances in an Optimizing Agent Model. Federal Reserve Board *International Finance*

Discussion Paper 627.

Gali, J. and M. Gertler (1998) Inflation Dynamics: A Structural Econometric Analysis. Mimeo.

Goodfriend, M. and R.G. King (1997) The New Neoclassical Synthesis and the Role of Monetary Policy. *NBER Macroeconomics Annual 1997* 493-530.

Gust, C. (1997) Staggered Price Contracts and Factor Immobilities: The Persistence Problem Revisited. Mimeo.

Hairault, J.O. and F. Portier. (1993) Money, New Keynesian Macroeconomics and the Business Cycle. *European Economic Review* 37:1533-68.

Ireland, P.N. (1996) A Small, Structural, Quarterly Model for Monetary Policy Evaluation. *Carnegie Rochester Conference on Public Policy* 47:83-108.

Jeanne, Olivier (1998) Generating Real Persistent Effects of Monetary Shocks: How Much Nominal Rigidity Do We Really Need? *European Economic Review* 1009-1032..

Kim, J. (1998) Monetary Policy in a Stochastic Equilibrium Model with Real and Nominal Rigidities. Federal Reserve Board *FEDS Working Paper* 1998-2.

Kimball, M. (1995) The Quantitative Analytics of the Basic Neomonetarist Model. *Journal of Money, Credit, and Banking* 27:1241-1277.

King, R.G. and M. Watson. (1996) Money, Output, Prices, and Interest Rates. *Review of Economics and Statistics* 78:35-53.

King, R.G. and A. Wolman. (1996) Inflation Targeting in a St. Louis Model of the 21st Century. NBER Working Paper 5507.

McCallum, B.T. and E. Nelson (1997) An Optimizing IS/LM Specification for Monetary Policy and Business Cycle Analysis. NBER Working Paper 5875.

Roberts, J. (1995) New-Keynesian Economics and the Phillips Curve. *Journal of Money, Credit, and Banking* 27:975-84.

Romer, D. (1996) *Advanced Macroeconomics* (McGraw Hill, New York).

Rotemberg, J.J. (1987) The New Keynesian Microfoundations. *NBER Macroeconomics Annual 1987*. 69-104.

Rotemberg, J.J. (1996) Prices, Output, and Hours: An Empirical Analysis Based on a Sticky Price Model. *Journal of Monetary Economics* 37:505-533.

Rotemberg, J.J. and M. Woodford (1995) Dynamic General Equilibrium Models with Imperfectly Competitive Product Markets. In T.F. Cooley, ed. *Frontiers of Business Cycle Research* (Princeton University Press, Princeton) 243-293.

Rotemberg, J.J. and M. Woodford (1997) An Optimization Based Econometric Framework for the Evaluation of Monetary Policy. *NBER Macroeconomics Annual 1997*.

Rotemberg, J.J. and M. Woodford (1998) Interest Rate Rules in an Estimated Sticky Price Model. NBER Working Paper 6618.

Sbordone, A. (1998) Prices and Unit Labor Costs: Testing Models of Pricing. Mimeo.

Taylor, J.B. (1980) Aggregate Dynamics and Staggered Contracts. *Journal of Political Economy* 88:1-23.

Taylor, J.B. (1998) Staggered Price and Wage Setting in Macroeconomics. NBER Working Paper 6754.

West, K. (1988) On the Interpretation of Near Random Walk Behavior in GNP. *American Economic Review* 78:202-209.

Woodford, M. (1995) Comment on the Quantitative Analysis of the Basic Neomonetarist Model. *Journal of Money, Credit, and Banking* 27:1277-1284.

Yun, T. (1994) Nominal Price Rigidity, Money Supply Endogeneity, and Business Cycles. *Journal of Monetary Economics* 37:345-370.

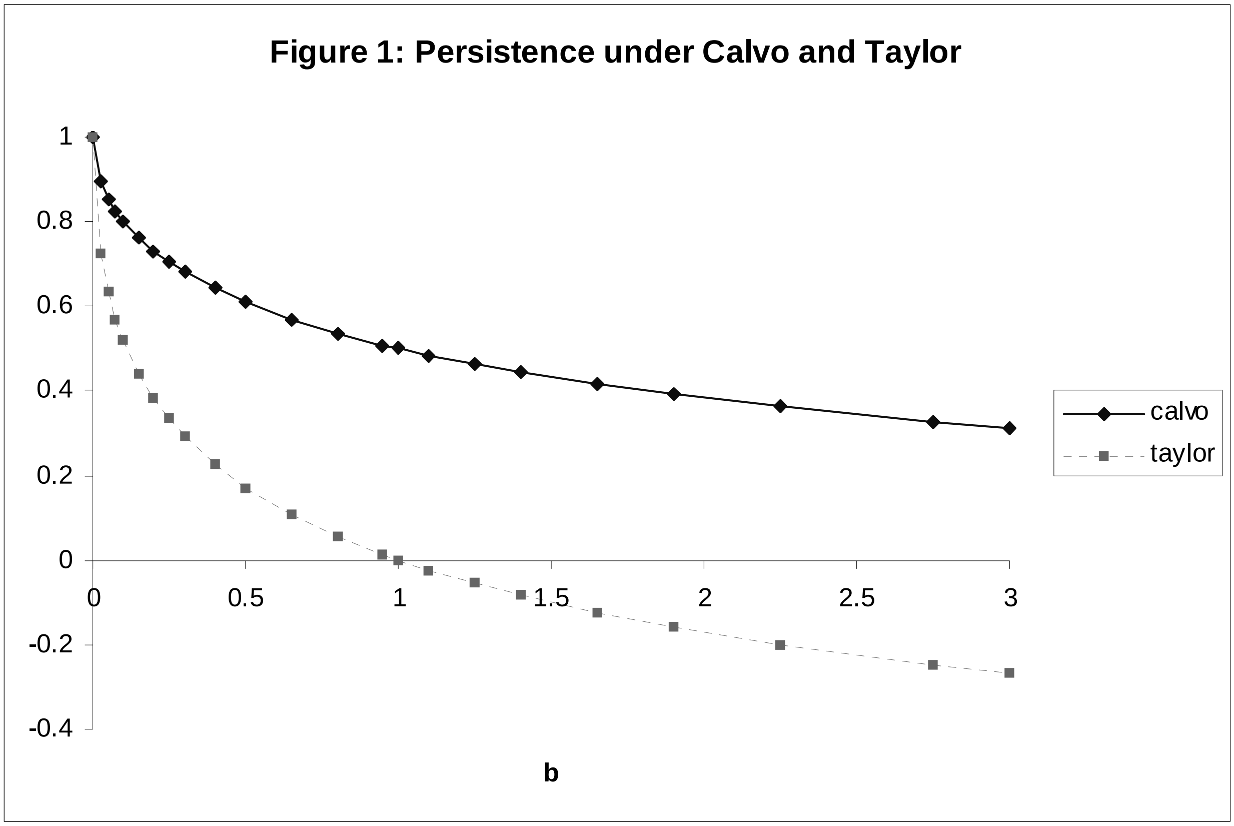
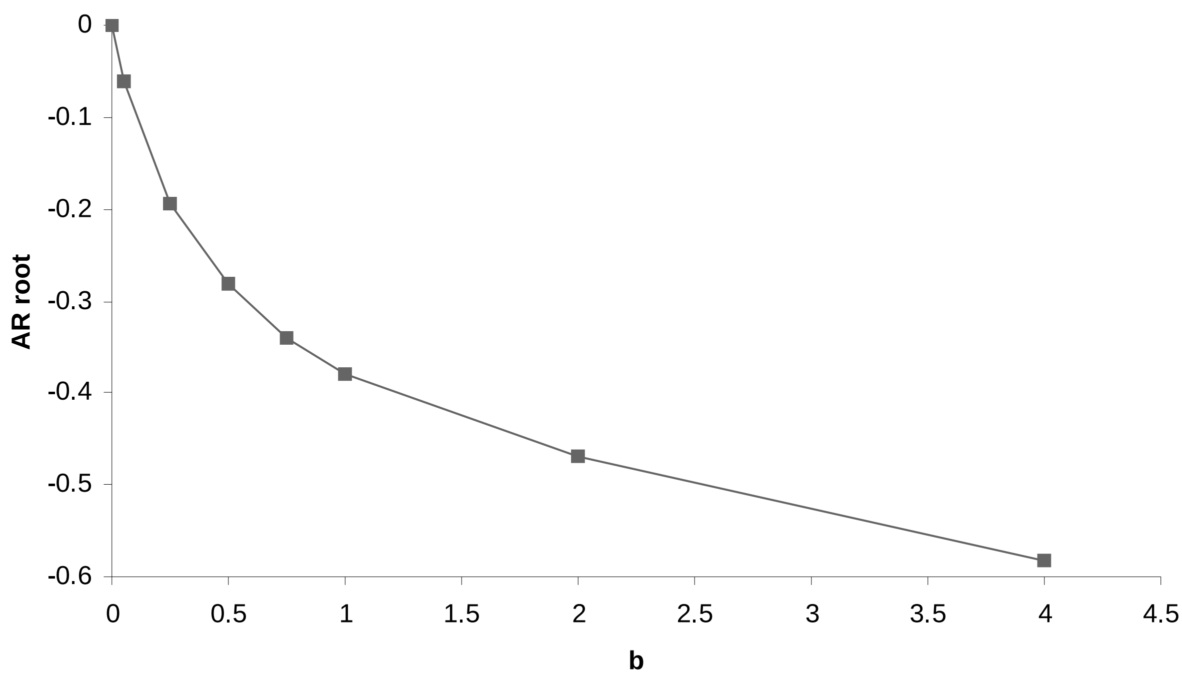


Figure 1: Persistence under Calvo and Taylor
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
0
0.5
1
1.5
2
2.5
3
b
calvo
taylor

Figure 2: Taylor Model AR Root with Interest Rate Rule



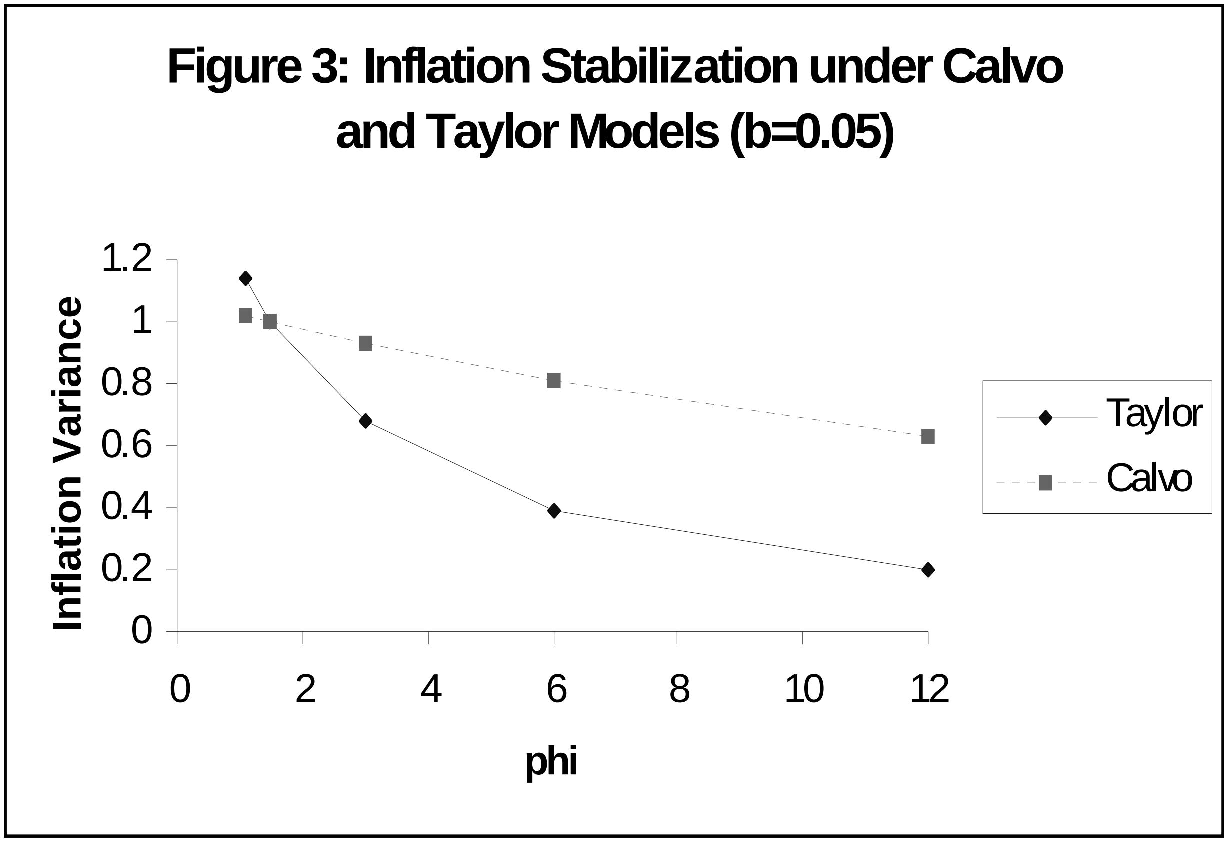


Figure 3: Inflation Stabilization under Calvo and Taylor Models (b=0.05)
Inflation Variance
1.2
1
0.8
0.6
0.4
0.2
0
0
2
4
6
8
10
12
phi
Taylor
Calvo

Figure 4: Inflation Stabilization under Calvo and Taylor Models (b=1)