Technology Shocks in the New Keynesian Model

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Abstract

In a New Keynesian model, technology and cost-push shocks compete as terms that stochastically shift the Phillips curve. A version of this model, estimated via maximum likelihood, points to the cost-push shock as far more important than the technology shock in explaining the behavior of output, inflation, and interest rates in the postwar United States data. These results weaken the links between the current generation of New Keynesian models and the real business cycle models from which they were originally derived; they also suggest that Federal Reserve officials have often faced difficult trade-offs in conducting monetary policy.

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1. Introduction

The development of the forward-looking, microfounded, New Keynesian model stands, in the eyes of many observers, as one of the past decade's most exciting and significant achievements in macroeconomics. To cite just two especially prominent examples: Clarida, Gali, and Gertler (1999) place the New Keynesian model at center stage in their widely-cited review of recent research on monetary policy, while Woodford (2002) builds his comprehensive book manuscript around the same analytic foundations.

In its simplest form, the New Keynesian model consists of just three equations. The first, which Kerr and King (1996) and McCallum and Nelson (1999) call the expectational IS curve, corresponds to the log-linearization of an optimizing household's Euler equation, linking consumption and output growth to the inflation-adjusted return on nominal bonds, that is, to the real interest rate. The second, a forward-looking version of the Phillips curve, describes the optimizing behavior of monopolistically competitive firms that either set prices in a randomly staggered fashion, as suggested by Calvo (1983), or face explicit costs of nominal price adjustment, as suggested by Rotemberg (1982). The third and final equation, a monetary policy rule of the kind proposed by Taylor (1993), dictates that the central bank should adjust the short-term nominal interest rate in response to changes in output and, especially, inflation. The New Keynesian model brings these three equations together to characterize the dynamic behavior of three key macroeconomic variables: output, inflation, and the nominal interest rate.

Thus, the New Keynesian model places heavy emphasis on the behavior of nominal variables, calls special attention to the workings of monetary policy rules, and contains frequent allusions back to the traditional IS-LM framework. All this makes it easy to forget that the New Keynesian models of today share many basic features with, and indeed were originally derived as extensions to, a previous generation of dynamic, stochastic, general equilibrium models: the real business cycle models of Kydland and Prescott (1982), Prescott (1986), Cooley and Prescott (1995), and many others. In real business cycle models, technology shocks play the dominant role in driving macroeconomic fluctuations. Monetary policy either remains absent altogether, as in the three papers just cited, or has minimal effects on the cyclical behavior of the economy, as in Cooley and Hansen (1989).

Yet technology shocks also play a role in the New Keynesian model where, for instance, an increase in productivity lowers each firm's marginal costs and thereby feeds into its optimal pricing decisions. Consequently, in the aggregate, technology shocks act as disturbances to the model's Phillips curve relationship.

The New Keynesian model therefore retains the idea that technology shocks can be quite important in shaping the dynamic behavior of key macroeconomic variables. It merely refines and extends this idea by suggesting, first, that other shocks might be important as well and, second, that in any case the presence of nominal price rigidities helps to determine exactly how shocks of all kinds impact on and propagate through the economy.

This paper re-exposes and explores this link between the current generation of New Keynesian models and the previous generation of real business cycle models. More specifically, it examines, quantitatively and econometrically, the importance of technology shocks within the New Keynesian framework.

Towards that end, section 2 of this paper extends the basic New Keynesian model, following Clarida, Gali, and Gertler (1999), by adding a second, cost-push shock to the Phillips curve specification. Here, as in Smets and Wouters (2002) and Steinsson (2002), this additional shock originates as an exogenous disturbance to firms' desired markups of price over marginal cost. As another term that stochastically shifts the Phillips curve, the cost-push shock competes directly with the technology shock in accounting for fluctuations in output and inflation. This extended model nests, as a special case, the simpler one in which the technology shock alone plays the dominant role. It therefore provides a useful framework in which the basic technology-driven specification can be compared, statistically, to a slightly but obviously more general alternative.

Section 3 of the paper then uses maximum likelihood, together with quarterly data from the postwar United States, to estimate the key parameters of this more general New Keynesian model. There, hypothesis tests and variance decompositions conducted with the estimated model lead directly to the paper's main results, concerning the role of technology shocks in the New Keynesian model. Section 4 concludes by summarizing these results and highlighting their implications.

2. Technology and Cost-Push Shocks in the New Keynesian Model

As explained above, this section modifies the basic New Keynesian model so as to allow, later, for an econometric analysis of the relative importance of technology and cost-push shocks in generating variability in the postwar United States data. The model economy consists of a representative household, a representative finished goods-producing firm, a continuum of intermediate goods-producing firms indexed by $i \in [0, 1]$, and a central bank. During each period $t = 0, 1, 2, ...$, each intermediate goods-producing firm produces a distinct, perishable intermediate good. Hence, intermediate goods may also be indexed by $i \in [0,1]$, so that firm i produces good i. The model features enough symmetry, however, to allow the analysis to focus on the activities of a representative intermediate goods-producing firm, identified by the generic index i.

The representative household enters each period $t = 0, 1, 2, ...$ with money M_{t-1} and bonds B_{t-1}. At the beginning of the period, the household receives a lump-sum monetary transfer T_t from the central bank. Next, the household's bonds mature, providing B_{t-1} additional units of money. The household uses some of this money to purchase new bonds of value B_t/r_t, where r_t denotes the gross nominal interest rate between t and $t+1$. During period t, the household supplies a total of h_t units of labor to the various intermediate goods-producing firms, earning $W_t h_t$ in labor income, where W_t denotes the nominal wage. The household also consumes c_t units of the finished good, purchased at the nominal price P_t from the representative finished goods-producing firm. Finally, at the end of period t, the household receives nominal profits D_t from the intermediate goods-producing firms. It then carries M_t units of money into period $t+1$.

Thus, the household chooses sequences for c_t, h_t, B_t, and M_t to maximize the expected utility function

$$E\sum_{t=0}^{\infty}\beta^t a_t[u(c_t)+v(M_t/P_t)-h_t]$$

subject to the budget constraints

$$M_{t-1}+T_t+B_{t-1}+W_th_t+D_t\geq P_tc_t+B_t/r_t+M_t$$

for all $t=0,1,2,...$. In the household's utility function, the discount factor satisfies $1>\beta>0$, while the single-period utility functions u and v for consumption and real money balances are strictly increasing and concave. As shown below, the preference shock a_t translates, in equilibrium, into a shock to the model's expectational IS curve; it follows the autoregressive process

$$\ln(a_t)=\rho_a\ln(a_{t-1})+\varepsilon_{at}, \tag{1}$$

with $1>\rho_a>-1$, where the zero-mean, serially uncorrelated innovation ε_{at} is normally distributed with standard deviation σ_a.

The representative finished goods-producing firm uses $y_t(i)$ units of each intermediate good $i\in[0,1]$ during each period $t=0,1,2,...$ to manufacture y_t units of the finished good according to the constant-returns-to scale technology described by

$$\left[\int_0^1 y_t(i)^{(\theta_t-1)/\theta_t} di\right]^{\theta_t/(\theta_t-1)} \geq y_t.$$

As shown below and in Smets and Wouters (2002) and Steinsson (2002), θ_t measures the time-varying elasticity of demand for each intermediate good; hence, it appears as a markup, or cost-push, shock in the model's Phillips curve relationship. Here, this cost-push shock follows the autoregressive process

$$\ln(\theta_t) = (1-\rho_\theta)\ln(\theta) + \rho_\theta \ln(\theta_{t-1}) + \varepsilon_{\theta t}, \tag{2}$$

with $1 > \rho_\theta > -1$ and $\theta > 1$, where the zero-mean, serially uncorrelated innovation $\varepsilon_{\theta t}$ is normally distributed with standard deviation σ_θ.

The finished goods-producing firm maximizes its profits by choosing

$$y_t(i) = [P_t(i)/P_t]^{-\theta_t} y_t$$

for all $i \in [0, 1]$ and $t = 0, 1, 2, ...$, which confirms that θ_t measures the time-varying elasticity of demand for each intermediate good. Competition drives the finished goods-producing firm's profits to zero in equilibrium, determining P_t as

$$P_t = \left[\int_0^1 P_t(i)^{1-\theta_t} di \right]^{1/(1-\theta_t)}$$

for all $t = 0, 1, 2, ...$

The representative intermediate goods-producing firm hires $h_t(i)$ units of labor from the representative household during each period $t = 0, 1, 2, ...$ to manufacture $y_t(i)$ units of intermediate good i according to the constant-returns-to-scale technology described by

$$z_t h_t(i) \geq y_t(i).$$

Here, as in the real business cycle model, the aggregate technology shock z_t follows the autoregressive process

$$\ln(z_t) = (1 - \rho_z) \ln(z) + \rho_z \ln(z_{t-1}) + \varepsilon_{zt}, \tag{3}$$

with $1 > \rho_z > -1$ and $z > 0$, where the zero-mean, serially uncorrelated innovation ε_{zt} is normally distributed with standard deviation σ_z.

Since the intermediate goods substitute imperfectly for one another in producing the finished good, the representative intermediate goods-producing firm sells its output in a monopolistically competitive market: during each period $t = 0, 1, 2, ...$, the intermediate goods-producing firm sets the price $P_t(i)$ for its output, subject to the requirement that it satisfy the representative finished goods-producing firm's demand at its chosen price. In addition, the intermediate goods-producing firm faces an explicit cost of nominal price adjustment, measured in units of the finished good and given by

$$\frac{\phi}{2}\left[\frac{P_t(i)}{\pi P_{t-1}(i)} - 1\right]^2 y_t,$$

where $\phi > 0$ governs the magnitude of the price adjustment cost and where $\pi \geq 1$ measures the gross steady-state rate of inflation. This quadratic cost of nominal price adjustment, first proposed by Rotemberg (1982), makes the intermediate goods-producing firm's problem dynamic: it chooses a sequence for $P_t(i)$ to maximize its total market value, as described below in the appendix. At the end of each period $t = 0, 1, 2, ...$, the firm distributes its profits as dividend payment $D_t(i)$ to the representative household.

In a symmetric equilibrium, all intermediate goods-producing firms make identical decisions, so that $y_t(i) = y_t$, $h_t(i) = h_t$, $P_t(i) = P_t$, and $D_t(i) = D_t$ for all $i \in [0, 1]$ and $t = 0, 1, 2, ...$ In addition, the market-clearing conditions

$M_t = M_{t-1} + T_t$ and $B_t = B_{t-1} = 0$ must hold for all $t = 0, 1, 2, ...$ The appendix shows that in any such equilibrium, the first-order conditions describing the optimizing behavior of the representative household and intermediate goods-producing firm can be reduced to

$$\hat{y}_t = E_t\hat{y}_{t+1} - (1/\sigma)(\hat{r}_t - E_t\hat{\pi}_{t+1}) + (1/\sigma)(1-\rho_a)\hat{a}_t \tag{4}$$

and

$$\hat{\pi}_t = \beta E_t\hat{\pi}_{t+1} + (1/\phi)(\theta-1)\sigma\hat{y}_t - (1/\phi)(\theta-1)\hat{z}_t - (1/\phi)\hat{\theta}_t \tag{5}$$

for all $t = 0, 1, 2, ...$ In these two equations, $\hat{y}_t$, $\hat{\pi}_t$, and $\hat{r}_t$ denote the percentage, or logarithmic, deviations of output y_t, inflation $\pi_t = P_t/P_{t-1}$, and the nominal interest rate r_t from their steady-state, or average, levels y, π, and r. Similarly, $\hat{a}_t$, $\hat{z}_t$, and $\hat{\theta}_t$ denote the percentage deviations of the shocks a_t, z_t, and θ_t from their steady-state values $a = 1$, z, and θ. Finally, the new parameter σ corresponds to the steady-state value of the representative household's coefficient of relative risk aversion: $\sigma = -yu''(y)/u'(y) > 0$.

Equation (4) takes the form of an expectational IS curve, linking the expected rate of output growth to the real interest rate with an elasticity that is inversely related to the risk aversion coefficient σ. This equation also confirms that, as suggested earlier, the preference shock $\hat{a}_t$ enters as a disturbance to the model's IS curve. Equation (5), meanwhile, constitutes a version of the forward-looking, New Keynesian Phillips curve. Here, again as suggested earlier, this Phillips curve relationship gets buffeted by two exogenous disturbances: the technology shock $\hat{z}_t$ and the markup, or cost-push, shock $\hat{\theta}_t$. All else equal, the equation associates a higher level of productivity, as measured by a larger value of $\hat{z}_t$, or a more highly elastic demand and correspondingly lower desired markup, as measured by a larger value of $\hat{\theta}_t$, with an easing of inflationary pressures. Naturally, the equation also associates a larger value of the price adjustment cost parameter ϕ with a dampened and more gradual response of inflation to the shocks that hit the economy.

Equations (1)-(3) govern the evolution of the model's exogenous shocks, while (4) and (5) summarize the implications of private agents' optimizing behavior. To complete the specification, therefore, it only remains to describe the central bank's behavior. Here, the central bank conducts monetary policy using a modified Taylor (1993) rule,

$$\hat{r}_t = \rho_r \hat{r}_{t-1} + \rho_y \hat{y}_{t-1} + \rho_\pi \hat{\pi}_{t-1} + \varepsilon_{rt}, \tag{6}$$

according to which it gradually adjusts the short-term nominal interest rate in response to movements in output and inflation. The central bank chooses values for the coefficients ρ_r, ρ_y, and ρ_π in (6); the earlier analyses of Parkin (1978), McCallum (1981), Kerr and King (1996), and Clarida, Gali, and Gertler (2000) suggest that a sufficiently vigorous long-run response of the interest rate to changes in inflation, as measured by $\rho_\pi/(1-\rho_r)$, will insure that this interest rate rule for monetary policy is consistent with the existence of a unique rational expectations equilibrium. Finally, in (6), the zero-mean, serially uncorrelated innovation ε_{rt} is normally distributed with standard deviation σ_r.

3. Econometric Strategy and Results

Equations (1)-(6) now form a system of six equations in three observable variables—output, inflation, and the short-term nominal interest rate—and the three unobservable shocks. The solution to this system, derived using the methods of Blanchard and Kahn (1980), takes the form of a state-space econometric model. Hence, the Kalman filtering techniques described by Hamilton (1994, Ch.13) can be applied to estimate the model's key parameters via maximum likelihood.

Here, this econometric exercise employs quarterly United States data running from 1948:1 through 2002:1. In these data, seasonally-adjusted figures for real

GDP, converted to per-capita terms by dividing by the civilian noninstitutional population, age 16 and over, and log-linearly detrended, serve to measure output. Quarterly changes in the seasonally-adjusted GDP deflator yield the measure of inflation, and quarterly averages of daily readings on the three-month Treasury bill rate provide the measure of the nominal interest rate.

To make the maximum likelihood procedure simpler and more transparent, as well as to insure that the results are easily comparable to those found in previous studies that eschew formal econometrics and work with calibrated versions of the New Keynesian model instead, the empirical strategy used here begins by fixing values for a subset of the model's parameters in advance. Since, for example, the parameter π measures the steady-state inflation rate in the model, its value is chosen to match the average inflation rate in the data. Likewise, the appendix shows that the model's steady-state nominal interest rate r equals π/β; hence, a value for β is chosen so that r matches the average nominal interest rate in the data. The appendix also shows that the parameter z serves only to pin down the steady-state level of output y; hence, its value is chosen so that y equals the average level of detrended, per-capita output in the data. Finally, for σ, θ, and ϕ, the values chosen here coincide with those used previously in Ireland (2000, 2002): a setting of $\sigma = 1$ implies the same level of risk aversion captured by a utility function that is logarithmic in consumption, a setting of $\theta = 6$ yields a steady-state markup of 20 percent, and a setting of $\phi = 50$ generates a significant but not unreasonably large degree of rigidity in nominal prices.

This initial calibration step allows the subsequent estimation procedure to focus exclusively on the remaining parameters, which are of special interest here. These parameters include ρ_a, ρ_z, ρ_θ, σ_a, σ_z, and σ_θ, describing the three shock processes, and ρ_r, ρ_y, ρ_π, and σ_r, which summarize how monetary policy allows these shocks to propagate through the economy. Even with this shortened list of parameters, however, an identification problem arises. Since the technology shock $\hat{z}_t$ and the cost-push shock $\hat{\theta}_t$ both enter into the Phillips curve (5), and since the model permits both of these shocks to follow first-order autoregressive processes, these disturbances cannot be individually distinguished using data on output, inflation, and the interest rate alone.

One possible solution to this identification problem involves expanding the dataset to include a measure of hours worked. With h_t added to the list of observables, the Kalman filter works to construct a realized history of technology shocks, using the aggregate production function, as $z_t = y_t/h_t$. The alternative solution used here avoids relying too heavily on the model's highly simplified production structure. This solution adds ρ_z and σ_z to the list of parameters that are calibrated rather than estimated. With these parameters fixed at the values $\rho_z = 0.95$ and $\sigma_z = 0.007$ chosen by Cooley and Prescott (1995), the technology shock in this New Keynesian model must have the same basic time-series properties as it does in the standard real business cycle model. Given these weaker identifying restrictions, the Kalman filter remains free to construct the most likely path for $\hat{z}_t$ based on data for output, inflation, and the interest rate alone, and the parameters ρ_θ and σ_θ can be freely estimated as well.

Thus, table 1 displays maximum likelihood estimates of ρ_r, ρ_y, ρ_π, ρ_a, ρ_θ, σ_a, σ_θ, and σ_r, together with their standard errors, computed by taking the square roots of the diagonal elements of minus one times the inverted matrix of second derivatives of the maximized log-likelihood function. In the monetary policy rule (6), inflation and the lagged interest rate enter significantly as determinants of the current period's interest rate, while output plays a less important role. Together with the calibrated value $\rho_z = 0.95$, the estimates of $\rho_a = 0.9590$ and $\rho_\theta = 0.9672$ imply that all of the model's exogenous shocks are highly persistent. The large estimate of ρ_θ indicates, more specifically, that the data prefer a version of the model in which the cost-push shock is even more persistent than the technology shock; Smets and Wouters (2002) and Steinsson (2002), by contrast, both assume that cost-push shocks are serially uncorrelated. The large estimate of $\sigma_\theta = 0.0729$, meanwhile, strongly suggests that the addition of the cost-push shock helps the New Keynesian model fit the data. In fact, when the model is reestimated with ρ_θ and σ_θ constrained to equal zero, so that the technology shock is forced to be the only disturbance to the Phillips curve (5), the model's maximized log-likelihood function falls from 2484.7 to 2379.5; a likelihood ratio test easily rejects the null hypothesis that $\rho_\theta = \sigma_\theta = 0$.

Two additional exercises confirm this finding: that the cost-push shocks play a very important role in the estimated model. First, table 2 decomposes forecast error variances in detrended output, inflation, and the nominal interest rate into components attributable to each of the model's four orthogonal disturbances: ε_{at}, ε_{zt}, $\varepsilon_{\theta t}$, and ε_{rt}. The table indicates that at short forecast horizons, preference, cost-push, and monetary policy shocks all contribute heavily in generating output fluctuations. At longer horizons, however, the cost-push shock dominates: it accounts, for example, for more than 80 percent of the unconditional variance in detrended output. Across all forecast horizons, the preference shock accounts for nearly 60 percent of the variance in inflation. The cost-push shock remains important, however, contributing another 30 percent. Finally, the decompositions for the interest rate closely resemble those for inflation, except that by assumption, the monetary policy shock must account for all of the one-step-ahead forecast error under the rule shown in (6). Unlike the cost-push shock, which makes important contributions in explaining movements in all three observable variables, the technology shock plays a minor role in these variance decompositions.

Second, figure 1 plots the impulse responses of detrended output, inflation, and the nominal interest rate to each of the model's four shocks. Since $\hat{z}_t$ and $\hat{\theta}_t$ both enter into the Phillips curve (5), and since the estimate of $\rho_\theta = 0.9672$ comes quite close to matching the calibrated value of $\rho_z = 0.95$, the impulse responses to the technology and cost-push shocks have very similar shapes. Because the cost-push shock is more volatile, however, it generates impulse responses that are about twice as large as those produced by the technology shock.

The impulse responses in figure 1 also serve to confirm that the sets of calibrated and estimated parameters used here imply reasonable dynamics in each variable following each type of shock. After a one-standard-deviation preference, or IS, shock, output rises by one percent and the annualized inflation rate increases by more than 150 basis points. Under the estimated policy rule (6), these movements in output and inflation lead to a gradual monetary tightening that eventually increases the nominal interest rate by about 80 basis points. As noted above, the impulse responses for the technology and cost-push shocks share similar shapes: a favorable disturbance to productivity or markups increases output, decreases inflation, and is accompanied by an easing of monetary policy. Finally, given the estimate of $\sigma_r = 0.0022$, a one-standard-deviation monetary policy shock translates into an 88 basis-point increase in the annualized nominal interest rate that dies off over a two-year period. This policy shock generates a decline in output of just over three-quarters of one percent and a fall in the annualized inflation rate of nearly 75 basis points.

Uniformly, these results point to one conclusion: in this estimated New Keynesian model, the cost-push shock plays a far more important role than the technology shock in driving movements in output, inflation, and the short-term nominal interest rate. But are these findings robust? Clarida, Gali, and Gertler (2000) formalize the idea that the monetary policies adopted by Federal Reserve Chairmen Volker and Greenspan differ from those pursued by their predecessors by showing that the coefficients of an estimated Taylor (1993) rule shift when the sample is split around 1980. Moreover, Kim and Nelson (1999), McConnell and Perez-Quiros (2000), and Stock and Watson (2002) find that a shift in the time-series properties of real GDP occurs at roughly the same point in the United States data, raising the possibility that different sets of shocks hit the American economy before and after 1980. Table 3, therefore, presents the results of one check for robustness by showing what happens when the model is reestimated with data from two disjoint subsamples: the first running from 1948:1 through 1979:4 and the second running from 1980:1 through 2002:1.

In table 3, the estimated coefficients ρ_r, ρ_y, and ρ_π do shift across subsamples, consistent with Clarida, Gali, and Gertler's (2000) findings. Nevertheless, the other basic results from the full sample carry over even after the sample is split. In particular, the subsample estimates of ρ_θ and σ_θ imply that cost-push shocks are large and persistent, both before and after 1980. Indeed, for both subsamples, a likelihood ratio test rejects the null hypothesis that $\rho_\theta = \sigma_\theta = 0$. Tables 4 and 5 repeat the variance decomposition exercise for the pre-1980 and post-1980 periods. The results for the pre-1980 subsample, shown in table 4, look quite similar to the full-sample results from table 1: the cost-push shock continues to be the dominant source of output fluctuations, the preference and cost-push shocks jointly account for most of the variation in inflation and the interest rate, and the technology shock plays a minor role throughout. The post-1980 results in table 5 display some differences. There, technology shocks play a bigger role in driving output fluctuations, and cost-push shocks no longer enter as important determinants of inflation and interest-rate variability. Despite these differences, however, the cost-push shock remains the most important source of output fluctuations, accounting for more than three-fourths of the unconditional variance of detrended output.

4. Conclusions and Implications

This paper extends the basic New Keynesian model to include a markup, or cost-push, disturbance that competes with the technology shock as a term that randomly shifts the Phillips curve relationship. It then applies maximum likelihood to estimate the key parameters of this extended model, under the identifying assumption that the technology shock follows the same stochastic process as it does in Cooley and Prescott's (1995) real business cycle model.

The empirical results, described in detail above, clearly indicate that the cost-push shock plays an important role in allowing the New Keynesian model to fit the postwar United States data. The estimated model, for instance, implies that cost-push shocks have been large and persistent. Econometric hypothesis tests strongly reject a constrained version of the model, in which cost-push shocks are absent, in favor of the more general alternative that incorporates these shocks. And forecast error variance decompositions point to the cost-push shock as the dominant source of output fluctuations and an important contributor to inflation and interest-rate variability as well. The technology shock, meanwhile, plays a far more modest role throughout. Overall, therefore, these results serve to weaken the links between the New Keynesian models of today and the real business cycle models from which they were originally derived.

Clarida, Gali, and Gertler (1999), Woodford (2001), and Gali (2002) also work with New Keynesian models that feature both technology and cost-push shocks. These studies show that for monetary policymakers, only the cost-push shock generates a painful trade-off between stabilizing the inflation rate and stabilizing a welfare-based measure of the output gap; in the face of technology shocks alone, all tension between these two goals disappears. By emphasizing the role of cost-push shocks over the role of technology shocks in explaining the United States data, therefore, the empirical results obtained here suggest that Federal Reserve policymakers have, in fact, faced difficult trade-offs over the postwar period.

Of course, these results also admit alternative interpretations. One could argue, for instance, that the additional cost-push shock introduced here actually works, within the econometric model, to soak up specification error in the technology-driven, New Keynesian Phillips curve. Even under this alternative interpretation, however, the conclusions remain much the same: presumably, one would still be led towards alternative specifications that go even farther beyond the original, real business cycle model.

5. Appendix

This appendix shows how (4) and (5) summarize the optimizing behavior of the representative household and intermediate goods-producing firm. The representative household chooses sequences for c_t, h_t, B_t, and M_t to maximize its expected utility subject to its budget constraints. The first-order conditions for this problem include

$$1 = u'(c_t)w_t, \tag{A.1}$$

$$a_t u'(c_t) = \beta r_t E_t[a_{t+1}u'(c_{t+1})/\pi_{t+1}], \tag{A.2}$$

and

$$w_t h_t + d_t = c_t \tag{A.3}$$

for all $t = 0, 1, 2, ...$, where $w_t = W_t/P_t$ denotes the real wage, $\pi_t = P_t/P_{t-1}$ denotes the gross inflation rate, and $d_t = D_t/P_t$ denotes the real value of profits received from the intermediate goods-producing firms during period t. Equation (A.1) equates the household's marginal rate of substitution between leisure and consumption to the real wage, while (A.2) is the familiar Euler equation, linking the household's marginal rate of intertemporal substitution to the real interest rate. Equation (A.3) corresponds to the household's budget constraint with the market-clearing conditions $M_t = M_{t-1} + T_t$ and $B_t = B_{t-1} = 0$ imposed.

The household's first order conditions also include

$$r_t v'(M_t/P_t) = (r_t - 1)u'(c_t),$$

which implicitly defines the model's money demand relationship. Under the interest rate rule (6), however, this money demand relationship serves only to determine how much money M_t the central bank needs to supply to clear markets at its target rate of interest r_t. Hence, so long as the dynamic behavior of the money stock is not of independent interest, this equation can be dropped from the system, together with all reference to the variable M_t.

The representative intermediate goods-producing firm, meanwhile, chooses a sequence for $P_t(i)$ to maximize its total market value, proportional to

$$E\sum_{t=0}^{\infty} \beta^t a_t u'(c_t)[D_t(i)/P_t],$$

where $\beta^t a_t u'(c_t)/P_t$ measures the marginal utility value to the representative household of an additional dollar in profits received during period t and where

$$\frac{D_t(i)}{P_t} = \left[\frac{P_t(i)}{P_t}\right]^{1-\theta_t} y_t - \left[\frac{P_t(i)}{P_t}\right]^{-\theta_t} \left(\frac{w_t y_t}{z_t}\right) - \frac{\phi}{2}\left[\frac{P_t(i)}{\pi P_{t-1}(i)} - 1\right]^2 y_t \tag{A.4}$$

for all $t = 0, 1, 2, ...$ Equation (A.4) measures the real value of the firm's profits during period t, incorporating the requirement that the firm supply output on demand at its chosen price $P_t(i)$. The first-order conditions for this problem are

$$\begin{aligned} 0 \;=\; & (1-\theta_t)\left[\frac{P_t(i)}{P_t}\right]^{-\theta_t}\left(\frac{y_t}{P_t}\right) + \theta_t\left[\frac{P_t(i)}{P_t}\right]^{-\theta_t-1}\left(\frac{w_t y_t}{z_t P_t}\right) \qquad \text{(A.5)} \\ & -\phi\left[\frac{P_t(i)}{\pi P_{t-1}(i)} - 1\right]\left[\frac{y_t}{\pi P_{t-1}(i)}\right] \\ & +\beta\phi E_t\left\{\left[\frac{a_{t+1}u'(c_{t+1})}{a_t u'(c_t)}\right]\left[\frac{P_{t+1}(i)}{\pi P_t(i)} - 1\right]\left[\frac{y_{t+1}P_{t+1}(i)}{\pi P_t(i)^2}\right]\right\} \end{aligned}$$

for all $t = 0, 1, 2, ...$

In the special case where $\phi = 0$, (A.5) collapses to

$$P_t(i) = \left(\frac{\theta_t}{\theta_t - 1}\right)\left(\frac{W_t}{z_t}\right),$$

indicating that in the absence of costly price adjustment, the representative intermediate goods-producing firm sets its markup of price $P_t(i)$ over marginal cost

W_t/z_t equal to $\theta_t/(\theta_t - 1)$ where, as noted earlier, θ_t measures the price elasticity of demand for its output. Thus, more generally, the disturbance $\hat{\theta}_t$ can be interpreted as a shock to the firm's desired markup; with costly price adjustment, the firm's actual markup will differ from, but tend to gravitate towards, the desired markup over time.

In a symmetric equilibrium, where $y_t(i) = y_t$, $h_t(i) = h_t$, $P_t(i) = P_t$, $D_t(i) = D_t$, and $y_t = z_t h_t$ for all $i \in [0, 1]$ and $t = 0, 1, 2, ...$, (A.3) and (A.4) can be combined to derive the economy's aggregate resource constraint

$$y_t = c_t + \frac{\phi}{2}\left(\frac{\pi_t}{\pi} - 1\right)^2 y_t, \tag{A.6}$$

while (A.1) and (A.5) can be combined to yield

$$\begin{aligned} \theta_t - 1 \quad = \quad & \frac{\theta_t}{z_t u'(c_t)} - \phi\left(\frac{\pi_t}{\pi} - 1\right)\left(\frac{\pi_t}{\pi}\right) \\ & + \beta\phi E_t\left\{\left[\frac{a_{t+1}u'(c_{t+1})}{a_t u'(c_t)}\right]\left(\frac{\pi_{t+1}}{\pi} - 1\right)\left(\frac{\pi_{t+1}}{\pi}\right)\left(\frac{y_{t+1}}{y_t}\right)\right\}. \end{aligned} \tag{A.7}$$

Together with (A.2), (A.6) and (A.7) imply that in the absence of shocks, the economy has a steady state, in which $y_t = y$, $c_t = c$, $\pi_t = \pi$, and $r_t = r$ for all $t = 0, 1, 2, ...$ The central bank must choose the steady-state inflation rate π.

Equations (A.2) and (A.6) then imply that $r = \pi/\beta$ and $y = c$. Finally, (A.7) determines the steady-state level of output y as the solution to

$$zu'(y) = \theta/(\theta - 1).$$

Now let $\hat{y}_t = \ln(y_t/y)$, $\hat{c}_t = \ln(c_t/c)$, $\hat{\pi}_t = \ln(\pi_t/\pi)$, $\hat{r}_t = \ln(r_t/r)$, $\hat{a}_t = \ln(a_t)$, $\hat{z}_t = \ln(z_t/z)$, and $\hat{\theta}_t = \ln(\theta_t/\theta)$. A log-linear approximation to (A.6) implies that $\hat{c}_t = \hat{y}_t$. Hence, log-linear approximations to (A.2) and (A.7) can be written as (4) and (5) in the text, summarizing the representative household and intermediate goods-producing firm's optimizing behavior.

6. References

Blanchard, Olivier Jean and Charles M. Kahn. "The Solution of Linear Difference Models Under Rational Expectations." *Econometrica* 48 (July 1980): 1305-1311.

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

Clarida, Richard, Jordi Gali, and Mark Gertler. "The Science of Monetary

Policy: A New Keynesian Perspective." *Journal of Economic Literature* 37 (December 1999): 1661-1707.

Clarida, Richard, Jordi Gali, and Mark Gertler. "Monetary Policy Rules and Macroeconomic Stability: Evidence and Some Theory." *Quarterly Journal of Economics* 115 (February 2000): 147-180.

Cooley, Thomas F. and Gary D. Hansen. "The Inflation Tax in a Real Business Cycle Model." *American Economic Review* 79 (September 1989): 733-748.

Cooley, Thomas F. and Edward C. Prescott. "Economic Growth and Business Cycles." In Thomas F. Cooley, ed. *Frontiers of Business Cycle Research.* Princeton: Princeton University Press, 1995.

Gali, Jordi. "New Perspectives on Monetary Policy, Inflation, and the Business Cycle." Working Paper 8767. Cambridge: National Bureau of Economic Research, February 2002.

Hamilton, James D. *Time Series Analysis.* Princeton: Princeton University Press, 1994.

Ireland, Peter N. "Interest Rates, Inflation, and Federal Reserve Policy since 1980." *Journal of Money, Credit, and Banking* 32 (August 2000, Part 1):

417-434.

Ireland, Peter N. "Money's Role in the Monetary Business Cycle." Manuscript. Chestnut Hill: Boston College, May 2002.

Kerr, William and Robert G. King. "Limits on Interest Rate Rules in the IS Model." Federal Reserve Bank of Richmond *Economic Quarterly* 82 (Spring 1996): 47-75.

Kim, Chang-Jin and Charles R. Nelson. "Has the U.S. Economy Become More Stable? A Bayesian Approach Based on a Markov-Switching Model of the Business Cycle." *Review of Economics and Statistics* 81 (November 1999): 608-616.

Kydland, Finn E. and Edward C. Prescott. "Time To Build and Aggregate Fluctuations." *Econometrica* 50 (November 1982): 1345-1370.

McCallum, Bennett T. "Price Level Determinacy with an Interest Rate Policy Rule and Rational Expectations." *Journal of Monetary Economics* 8 (November 1981): 319-329.

McCallum, Bennett T. and Edward Nelson. "An Optimizing IS-LM Specification for Monetary Policy and Business Cycle Analysis." *Journal of Money,* *Credit, and Banking* 31 (August 1999, Part 1): 296-316.

McConnell, Margaret M. and Gabriel Perez-Quiros. "Output Fluctuations in the United States: What Has Changed Since the Early 1980's?" *American Economic Review* 90 (December 2000): 1464-1476.

Parkin, Michael. "A Comparison of Alternative Techniques of Monetary Control Under Rational Expectations." *Manchester School of Economic and Social Studies* 46 (September 1978): 252-287.

Prescott, Edward C. "Theory Ahead of Business-Cycle Measurement." *Carnegie-Rochester Conference Series on Public Policy* 25 (Autumn 1986): 11-44.

Rotemberg, Julio J. "Sticky Prices in the United States." *Journal of Political Economy* 90 (December 1982): 1187-1211.

Smets, Frank and Raf Wouters. "An Estimated Stochastic Dynamic General Equilibrium Model of the Euro Area." Manuscript. Frankfurt: European Central Bank, May 2002.

Steinsson, Jon. "Optimal Monetary Policy in an Economy with Inflation Persistence." Manuscript. Cambridge: Harvard University, May 2002.

Stock, James H. and Mark W. Watson. "Has the Business Cycle Changed and Why?" Manuscript. Cambridge: Harvard University, August 2002.

Taylor, John B. "Discretion Versus Policy Rules in Practice." *Carnegie-Rochester Conference Series on Public Policy* 39 (December 1993): 195-214.

Woodford, Michael. "Inflation Stabilization and Welfare." Working Paper 8071. Cambridge: National Bureau of Economic Research, January 2001.

Woodford, Michael. *Interest and Prices: Foundations of a Theory of Monetary Policy*. Manuscript. Princeton: Princeton University, 2002.

Table 1. Maximum Likelihood Estimates and Standard Errors

Parameter	Estimate	Standard Error
ρ_r	0.7919	0.0209
ρ_y	0.0017	0.0023
ρ_π	0.2503	0.0182
ρ_a	0.9590	0.0172
ρ_θ	0.9672	0.0282
σ_a	0.0249	0.0066
σ_θ	0.0729	0.0063
σ_r	0.0022	0.0001
L^*	2484.7	
L^c	2379.5	

Note: L^* denotes the maximized value of the model's log-likelihood function. L^c denotes the maximized value of the log-likelihood function when the constraints $\rho_\theta = \sigma_\theta = 0$ are imposed.

Table 2. Forecast Error Variance Decompositions

Output

Quarters Ahead	Preference Shock	Technology Shock	Cost-Push Shock	Policy Shock
1	44.3	4.6	26.6	24.5
4	22.2	10.5	55.8	11.6
8	12.7	12.5	68.3	6.5
12	9.5	12.8	72.9	4.8
20	7.1	12.5	76.9	3.6
40	5.6	11.5	80.0	2.8
∞	5.3	11.0	81.0	2.6

Inflation

Quarters Ahead	Preference Shock	Technology Shock	Cost-Push Shock	Policy Shock
1	56.4	6.8	25.4	11.3
4	57.9	7.0	27.2	7.9
8	58.3	6.9	28.4	6.3
12	58.3	6.8	29.2	5.6
20	58.1	6.6	30.3	4.9
40	57.6	6.4	31.7	4.4
∞	57.2	6.2	32.3	4.3

Interest Rate

Quarters Ahead	Preference Shock	Technology Shock	Cost-Push Shock	Policy Shock
1	0	0	0	100
4	39.3	4.4	16.7	39.6
8	53.8	5.8	23.5	16.8
12	57.0	6.0	25.6	11.4
20	58.5	5.9	27.6	8.0
40	58.5	5.5	29.6	6.4
∞	58.0	5.3	30.6	6.0

Note: Entries decompose the forecast error variance in each variable at each forecast horizon into percentages due to each shock.

Table 3. Subsample Estimates and Standard Errors

Parameter	Pre-1980 Estimate	Standard Error	Post-1980 Estimate	Standard Error
ρ_r	0.8618	0.0239	0.5541	0.0507
ρ_y	0.0028	0.0030	-0.0063	0.0066
ρ_π	0.1761	0.0172	0.5751	0.0737
ρ_a	0.9532	0.0245	0.9555	0.0319
ρ_θ	0.9223	0.0575	0.9848	0.0234
σ_a	0.0265	0.0078	0.0196	0.0091
σ_θ	0.1002	0.0143	0.0361	0.0055
σ_r	0.0017	0.0001	0.0025	0.0003
L^*	1463.2		1091.8	
L^c	1400.8		1082.6	

Note: L^* denotes the maximized value of the model's log-likelihood function. L^c denotes the maximized value of the log-likelihood function when the constraints $\rho_\theta = \sigma_\theta = 0$ are imposed.

Table 4. Forecast Error Variance Decompositions: Pre-1980 Subsample

Output

Quarters Ahead	Preference Shock	Technology Shock	Cost-Push Shock	Policy Shock
1	54.6	2.8	17.3	25.3
4	28.7	8.0	50.5	12.9
8	17.2	10.9	64.4	7.6
12	13.7	12.3	68.0	6.0
20	11.6	14.0	69.3	5.1
40	10.9	15.4	69.0	4.8
∞	10.8	15.6	68.8	4.7

Inflation

Quarters Ahead	Preference Shock	Technology Shock	Cost-Push Shock	Policy Shock
1	39.8	5.6	44.3	10.3
4	41.3	6.0	44.1	8.6
8	42.4	6.3	43.6	7.8
12	43.1	6.4	43.0	7.4
20	44.0	6.6	42.3	7.1
40	44.8	6.7	41.5	7.0
∞	44.9	6.8	41.4	6.9

Interest Rate

Quarters Ahead	Preference Shock	Technology Shock	Cost-Push Shock	Policy Shock
1	0	0	0	100
4	32.1	3.9	29.5	34.5
8	44.2	5.3	36.4	14.1
12	48.3	5.7	36.3	9.7
20	52.3	6.1	34.3	7.3
40	55.5	6.3	31.9	6.3
∞	56.1	6.4	31.4	6.2

Note: Entries decompose the forecast error variance in each variable at each forecast horizon into percentages due to each shock.

Table 5. Forecast Error Variance Decompositions: Post-1980 Subsample

Output

Quarters Ahead	Preference Shock	Technology Shock	Cost-Push Shock	Policy Shock
1	24.0	21.7	37.6	16.7
4	10.8	33.0	49.6	6.6
8	6.6	34.5	55.0	3.8
12	5.1	33.5	58.5	2.9
20	3.9	30.5	63.5	2.1
40	2.9	25.0	70.6	1.5
∞	2.2	19.6	77.0	1.2

Inflation

Quarters Ahead	Preference Shock	Technology Shock	Cost-Push Shock	Policy Shock
1	85.9	6.3	0.0	7.8
4	89.9	6.2	0.0	3.9
8	91.2	6.1	0.0	2.6
12	91.8	6.0	0.0	2.2
20	92.3	5.9	0.0	1.8
40	92.7	5.7	0.0	1.6
∞	92.8	5.7	0.0	1.6

Interest Rate

Quarters Ahead	Preference Shock	Technology Shock	Cost-Push Shock	Policy Shock
1	0	0	0	100
4	53.8	4.8	0.1	41.2
8	71.8	6.3	0.2	21.7
12	76.9	6.6	0.3	16.2
20	80.4	6.8	0.3	12.5
40	82.2	6.7	0.4	10.6
∞	82.4	6.6	0.6	10.3

Note: Entries decompose the forecast error variance in each variable at each forecast horizon into percentages due to each shock.

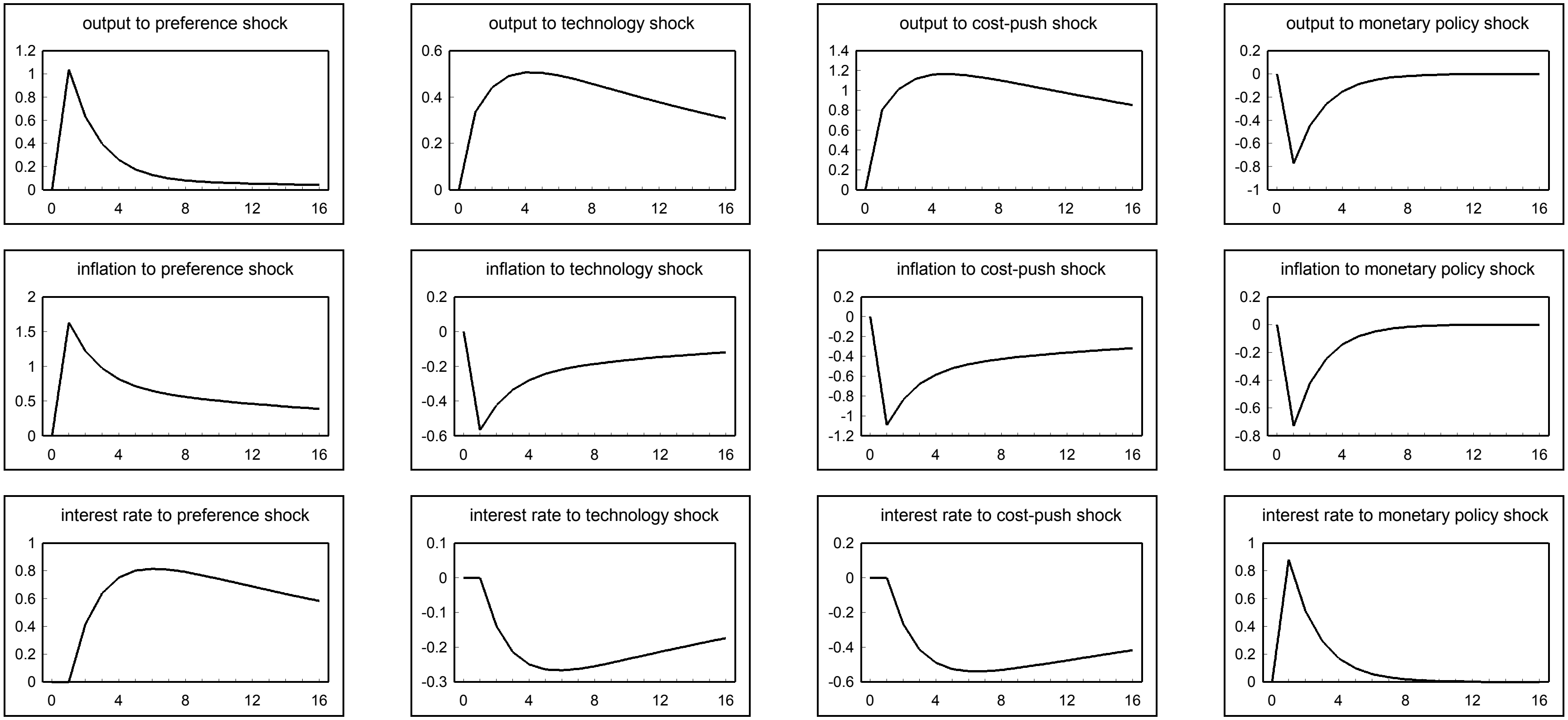

Figure 1. Impulse responses. Each panel shows the percentage-point response of one of the model's variables to a one-standard-deviation shock. The inflation and interest rates are expressed in annualized terms.