# DECONSTRUCTING THE SUCCESS OF REAL BUSINESS CYCLES

EMI NAKAMURA*

*The empirical success of Real Business Cycle (RBC) models is often judged by their ability to explain the behavior of a multitude of real macroeconomic variables using a single exogenous shock process. This paper shows that in a model with the same basic structure as the bare bones RBC model, monetary, cost-push or preference shocks are equally successful at explaining the behavior of macroeconomic variables. Thus, the empirical success of the RBC model with respect to standard RBC evaluation techniques arises from the basic form of the dynamic stochastic general equilibrium model, not from the specific role of the productivity shock.* (*JEL* E32, E37)

## I. INTRODUCTION

A major achievement of Real Business Cycle (RBC) models has been their success at elegantly explaining a remarkably large fraction of business cycle fluctuations in aggregate variables based solely on exogenous variation in productivity. In particular, the RBC literature has emphasized the ability of models driven by productivity shocks to explain the historically observed paths of macroeconomic variables, a method introduced by Plosser (1989). In a recent paper in the Handbook of Macroeconomics, King and Rebelo (1999) remark on the "dramatic" correspondence between simulations of the US economy produced by the RBC model and the actual data when productivity shocks are "remeasured" and the bare-bones model is augmented with the assumptions of indivisible labor and variable capital utilization. RBC models explain the comovement of a multiplicity of macroeconomic variables—consumption, output, labor supply, investment, wages, productivity, etc.—with a *single* exogenous shock series. In other words, they reduce a more than five-dimensional problem to one dimension of unexplained variation.

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*Nakamura:* Columbia Business School and Department of Economics, 3022 Broadway, New York, NY 10027. Phone 212-854-8162, Fax 212-662-8474, E-mail enakamura@columbia.edu

The contribution of the RBC methodology to the business cycle literature can be thought of in two parts. First, RBC models adopt a basic dynamic stochastic general equilibrium framework that has now become standard in the macroeconomics business cycle literature, including New Keynesian models. Second, the RBC literature emphasizes the importance of the productivity shock. This paper investigates the question of how much of the success of RBC, according to standard RBC evaluation techniques, arises from the basic form of the dynamic stochastic general equilibrium model versus the specific role of the productivity shock. The answer to this question says something both about the nature of the dynamic stochastic general equilibrium models used in macroeconomics as well as about the standard RBC tests used to evaluate these models.

The models considered in this paper all have the basic form of the "high-substitution" RBC model developed by King and Rebelo (1999). I consider both the original form of this model, as well as a "Monetary Business Cycle" (MBC) version of the model augmented with a Calvo Phillips curve and a standard Taylor rule specification of monetary policy. I adopt the procedure of "remeasuring" the business cycle shocks to perfectly match the

**ABBREVIATIONS**

DRI: Data Resources Inc.
GDP: Gross Domestic Product
MBC: Monetary Business Cycle
RBC: Real Business Cycle
TFP: Total Factor Productivity



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observed output series by King and Rebelo (1999). I consider the models' success at explaining the behavior of macroeconomic variables given a variety of specifications of shocks: productivity shocks, monetary shocks to the Taylor rule, cost-push shocks, and preference shocks. This exercise shows that any of the models with "remeasured" shocks is able to successfully explain the empirical dynamics of the real variables. The monetary model with remeasured shocks is, if anything, more empirically successful than the RBC model, since it is also able to explain the behavior of inflation and the nominal interest rate in the Volcker-Greenspan era. Thus, this paper adds concreteness to work by Hansen and Heckman (1996) and Fair (1992), suggesting that the RBC standards for evaluating models may be too weak by showing that important classes of business cycle models cannot be distinguished using standard RBC evaluation techniques.

The MBC models considered in this paper have the same basic structure as the model presented in Rotemberg and Woodford (1997). The most closely related paper to the present work is perhaps the innovative paper by Hairault and Portier (1993), which evaluates the performance of a MBC model when presented with various combinations of estimated monetary and productivity shocks. Unlike the present paper, however, the success of the models is evaluated according to their second moment properties.

The paper proceeds as follows. Section II presents the model, which consists of a household sector, a firm sector and a central bank. Aside from the assumptions relating to the price setting behavior of the firm and the behavior of the central bank, the model is exactly the one developed in King and Rebelo (1999), making the results as comparable as possible to the RBC benchmark. In Section IV, I solve for the unique rational expectations equilibrium of the model. Section V presents simulation results. Section VI concludes. There are three appendices. Appendix A describes the construction of the data series, Appendix B describes the calibration of the model, and Appendix C provides a short description of the model of indivisible labor used in the paper.

## II. THE MODEL

I present only a brief description of the model, since its components are standard in the business cycle literature. A more detailed description of the basic RBC framework can be found in King and Rebelo (1999). A detailed discussion of the monopolistic competition and staggered price setting assumptions in the MBC model can be found in Woodford (2003). The RBC model consists of a household sector and a firm sector. The MBC model also incorporates a central bank.

### A. Households

The representative household maximizes the expected discounted sum of a utility function $U(C_t, L_t, \eta_t)$, where $C_t$ denotes consumption of a composite consumption good, $L_t$ denotes leisure and $\eta_t$ denotes a preference shock. Financial markets are complete. All assets may therefore be priced using the stochastic discount factor

$$M_{t,t+1} = \frac{\beta U_c(C_{t+1},\ L_{t+1},\ \eta_{t+1})}{U_c(C_t,\ L_t,\ \eta_t)},$$

where $\beta$ denotes the household's discount factor and $U_c$ denotes the partial derivative of $U$ with respect to $C_t$. This implies that the short-term nominal interest rate, $i_t$, and the real return on capital, $r_{t+1}$, are given by familiar Euler equations

$$(1)\quad U_c(C_t, L_t, \eta_t) = \beta E_t[U_c(C_t+1, L_{t+1}, \eta_{t+1})(1+r_{t+1})],$$

$$(2)\quad U_c(C_t, L_t, \eta_t) = \beta E_t\left[U_c(C_{t+1}, L_{t+1}, \eta_{t+1})\frac{1+i_t}{\Pi_{t+1}}\right],$$

where $\Pi_t$ denotes the rate of inflation. The labor market in the economy is perfectly competitive. The household's optimal labor supply is given by

$$(3)\quad \frac{U_l(C_t,\ L_t,\ \eta_t)}{U_c(C_t,\ L_t,\ \eta_t)} = \frac{W_t}{P_t},$$

where $W_t$ denotes the wage rate.

I follow the RBC literature in assuming that the household's utility function takes a functional form that is consistent with a balanced growth path,

$$(4)\quad u(C_t, L_t, \eta_t) = \eta_t \frac{1}{1-\sigma}\left\{[C_t v(L_t)]^{1-\sigma} - 1\right\}.$$

I follow King and Rebelo (1999) in assuming that the household works a fixed shift with some probability, and otherwise does not work at all. This formulation of "indivisible labor" was originally proposed by Rogerson and Wright (1988). King and Rebelo make use of the indivisible labor assumption to increase the labor supply volatility of the bare-bones RBC model and to increase the overall responsiveness of the RBC model to productivity shocks. See Appendix C for a more detailed discussion of this assumption and the functional form of $v(L_t)$ that it implies.

The composite consumption good, $C_t$, from which the household derives utility, is a constant elasticity of substitution (CES) aggregate of the differentiated goods produced by the firm sector. Optimal household demand for each of these individual goods is therefore given by

$$(5)\qquad c_t(z) = C_t\left[\frac{p_t(z)}{P_t}\right]^{-\theta},$$

where $c_t(z)$ denotes the consumption of individual good $z$, $p_t(z)$ denotes the price of this good, $P_t$ denotes the CES price index that measures the minimum cost of purchasing one unit of $C_t$, and $\theta$ denotes the elasticity of substitution of the goods in $C_t$ as well as the elasticity of demand for each of the goods $c_t(z)$. The RBC version of the model corresponds to the special case of perfect competition, where $\theta \rightarrow \infty$.

### B. Firms

The firm sector consists of a continuum of identical producers selling differentiated goods (Dixit and Stiglitz, 1977). In the MBC version of the model, the individual goods are imperfect substitutes in household consumption. This implies that the firm has some monopoly power and can therefore choose the price of the good it produces. In the RBC version of the model, however, goods markets are perfectly competitive. Firms act to maximize their expected profits. The production function of the representative firm is $A_tF(K_t, N_t, Q_t) = A_t(Q_tK_t)^{1-\alpha}N_t^{\alpha}$, where $K_t$ denotes capital, $N_t$ denotes labor, $A_t$ denotes total factor productivity (TFP) and $Q_t$ denotes capital utilization. I follow King and Rebelo (1999) in assuming that the firm can vary its capital utilization rate and that increased capital utilization leads to increased depreciation of the capital stock. King and Rebelo (1999) make use of this assumption, like indivisible labor, to increase the relative responsiveness of labor supply to exogenous shocks.

Necessary conditions for cost minimization by firms are given by

$$(6)\qquad W_t = A_tF_n(K_t, N_t, Q_t)S_t,$$

$$(7)\qquad \rho_t = A_tF_k(K_t, N_t, Q_t)S_t,$$

$$(8)\qquad P_t\delta(Q_t)K_t = A_tF_Q(K_t, N_t, Q_t)S_t,$$

where $S_t$ denotes the firm's marginal cost, $\rho_t$ denotes the firm's cost of capital and $\delta(Q_t)$ denotes the depreciation rate of capital, which is assumed to be a convex, increasing function of the utilization rate. The first of these equations is the firm's labor demand equation. The second equation is the firm's demand for capital. The third describes optimal utilization of capital. As is standard in the literature, I assume that there is a "gestation lag" of one period between when the household trades off consumption in order to invest and when the firm uses the newly acquired capital in production. Thus, the producer's cost of capital is related to the real rate of return on capital, $r_t$, by the equation,

$$(9)\qquad 1 + r_t = \frac{\rho_t}{P_t} + (1 - \delta(Q_t)),$$

where $1 - \delta$ is the fraction of capital goods left undepreciated at the end of each period.

I assume that the production function is linearly homogeneous. This implies that every firm has the same capital-output ratio (despite having different levels of production in the MBC version of the model), so conditions (6) and (7) hold for the aggregate capital and labor demands as well as for the demands of individual firms.

In the RBC version of the model, prices are flexible and $\theta \rightarrow \infty$. This implies that $p_t(z) = P_t = S_t$. In the MBC version of the model I assume that firms change their prices in a staggered manner as in Calvo (1983). As is well known, this results in the rate of inflation evolving, up to a first-order approximation, according to a New Keynesian Phillips curve,

$$(10) \qquad \pi_t = \beta E_t \pi_{t+1} + \kappa s_t + \varepsilon_t,$$

where $\pi_t$ denotes the log of the inflation rate $\Pi_t$, $s_t$ denotes percentage deviations of real marginal costs $S_t/P_t$ from their steady-state level and $\varepsilon_t$ is a "cost-push" shock.[1]

I also consider a "hybrid" Phillips curve similar to the one proposed by Fuhrer and Moore (1995) in order to improve the fit of the MBC model to nominal variables,

$$(11) \quad \pi_t = 0.5\beta E_t \pi_{t+1} + 0.5\pi_{t-1} + \kappa s_t + \varepsilon_t,$$

This type of Phillips curve can be microfounded by assuming that some fraction of firms set prices according to a "rule of thumb."[2]

Finally, in both the RBC and the MBC specifications of the model, the equation for goods market equilibrium,

$$(12) \quad Y_t = C_t + (K_t + 1 - (1 - \delta(Q_t)K_t)),$$

links the household and firm sectors of the economy. Here $Y_t$ denotes aggregate output.

Let us also define the following standard measure of TFP, the "Solow residual,"

$$(13) \qquad \mathrm{SR}_t = y_t - (1 - \alpha_{\mathrm{sh}})kt - \alpha_{\mathrm{sh}} n_t,$$

where lower case variables denote percentage deviations of the corresponding upper case variable from their steady-state values and $\alpha_{\mathrm{sh}}$ is the labor income share. The Solow Residual is defined here, as in King and Rebelo (1999), as the part of gross domestic product (GDP) left unexplained by the Cobb-Douglas production function. However, in the context of the high-substitution economy described above, the Solow residual mismeasures productivity $A_t$ even for the RBC case, since it does not take into consideration variable capital utilization. The Solow residual further mismeasures TFP in the MBC economy, since the labor share $\alpha_{\mathrm{sh}}$ underestimates the Cobb-Douglas production function parameter $\alpha$.

### *C. The Central Bank*

In the MBC version of the model, the central bank follows a standard "Taylor rule" in setting the nominal interest rate. According to the Taylor rule, the Federal Reserve predictably raises the Federal Funds rate in response to high inflation and output and lowers it when economic conditions reverse. In a seminal paper, Taylor (1993) showed that the behavior of the U.S. Federal Reserve can be well described by a Taylor rule in recent years. I use Taylor's original policy rule, except for a slightly higher value of the constant term, which fits the data better for the sample period I consider in the simulation exercises,

$$(14) \quad i_t = 0.055 + 1.5(\pi_t - 0.02) + 0.5y_t + \nu_t,$$

where $\nu_t$ denotes a monetary policy shock. Notice that in this equation $\pi_t$ refers simply to the inflation rate in the present quarter, not the moving average of the previous year's inflation (the variable used in some of the empirical literature).

## III. REMEASURING THE SHOCKS

King and Rebelo argue that traditional measures of productivity are likely to contain significant measurement errors. They "remeasure" TFP as the sequence of TFP realizations that perfectly matches their model to the data, in terms of the simulated and empirical series for GDP.[3]

How does this approach relate to the more standard procedure of using the Solow residual to estimate productivity? The key identifying assumption in the RBC literature is that productivity shocks are the only source of macroeconomic variation in the economy. Given this premise, the productivity shocks are estimated by minimizing (in some sense) the amount of approximation error. However,

1. I have not been explicit about the microfoundations of this cost-push shock. It has been microfounded in various ways in the literature. For example, it can arise due to a time-varying tax rate on firm sales, or time variation in the elasticity of substitution, $\theta$, as shown by Steinsson (2003).

2. See Steinsson (2003) and Gali and Gertler (1999).

3. In practice, King and Rebelo (1999) target a linear combination of the output and capital series. This procedure yields almost identical results to the simpler procedure described above.

since the model is only an approximation, there is a tradeoff between the model's ability to fit the empirical GDP series and its ability to fit the empirical productivity series. The difference between King and Rebelo's estimation procedure and the more standard method is simply that it minimizes the approximation error of the model in terms of the output series rather than the Solow residual.

A similar type of mismeasurement argument could also be made for a number of other types of shocks to the model: monetary shocks to the Taylor rule, cost-push shocks to the Phillips curve, and preference shocks to the Euler equations. The next section of the paper presents a series of exercises in which each of these types of shocks is "remeasured" according to the King and Rebelo (1999) procedure in order to perfectly match the output series.

King and Rebelo assume that TFP follows a first-order autoregressive process. They estimate the autoregressive parameter by fitting the remeasured productivity series to an AR(1) process,

$$A_t = \rho_A A_t - 1 + e_t, \tag{15}$$

where $A_t$ is TFP, $e_t$ is an independently and identically distributed random variable and $\rho_A$ is the autoregressive parameter.

Similarly, I assume that the monetary shocks evolve according to a first-order autoregressive process,

$$\nu_t = \rho_\nu \nu_{t-1} + e_t, \tag{16}$$

where $e_t$ is an independently and identically distributed random variable; and $\rho_\nu$ is the autoregressive parameter. Identical autoregressive shock processes are also postulated for the cost-push shocks $\varepsilon_t$ and the preference shocks $\eta_t$. However, it is important to remember that each of the simulation exercises that follow considers only *one* of the shocks described above at a time.

As in King and Rebelo (1999) I estimate the persistence parameters in the following way. I first solve the model postulating a given value of the autoregressive parameter. I then calculate the shocks implied by the model solution, and calculate the persistence of this shock series. I use this revised value of the persistence parameter to solve the model, iterating this procedure until the postulated and actual values of the persistence parameter are the same.[4] It is useful to note that given the procedure used to remeasure the shocks, the simulation results for the real variables in the RBC and MBC models are quite robust to changes in the specification of the persistence parameters.

## IV. SOLVING FOR A RATIONAL EXPECTATIONS EQUILIBRIUM

In the simulations that follow, I consider seven different versions of the model presented in Section II. They differ according to the exogenous shock generating the economic fluctuations and the specification of the Phillips curve. I consider two versions of the RBC model: a standard RBC model with a productivity shock (RBC1), and a version of the RBC model with preference shocks (RBC2). In addition, I consider five versions of the MBC model: the MBC model with monetary shocks and a Calvo Phillips curve (MBC1), the MBC model with monetary shocks and a hybrid Phillips curve (MBC2), the MBC model with cost-push shocks and a Calvo Phillips curve (MBC3), the MBC model with preference shocks and a Calvo Phillips curve (MBC4) and finally the MBC model with productivity shocks and a Calvo Phillips curve (MBC5).

I apply a generalized version of the Blanchard and Kahn (1980) approach, as formulated in Sims (2000), to solve for the unique bounded rational expectations equilibrium of the log-linear approximation to the model.[5] The log-linear approximation is a first-order Taylor series expansion around the non-stochastic steady state. The result is a system of first-order linear difference equations, which gives the law of motion for the economy. This system of equations can then be used to construct simulations given hypothetical shock processes, as well as theoretical means and variances.

4. There is a slight mechanical difference between my estimation approach and the one used by King and Rebelo (1999). To be consistent with the filtering procedure used for the other variables, I use the Hodrick-Prescott (HP)-filtered output series to estimate the stochastic process for the Taylor rule errors. King and Rebelo (1999) use linearly detrended data to estimate the autoregressive parameter in the productivity process rather than the HP-filtered data that are used in the remainder of their paper.

5. See Sims (2000) for a description of the Gensys program that I use to solve the model.

## V. SIMULATION RESULTS

King and Rebelo (1999) present the high correlations between the simulated and empirical series for the RBC model as dramatic evidence for the success of the RBC model driven by productivity shocks. Panel 1 of Table 1 shows that the simulation results for the MBC1-MBC5 models (with both the Calvo and hybrid Phillips curves) are equally dramatic. The correlations are at least .80 for consumption, .81 for investment, .88 for labor, and .59 for the Solow residual. The MBC2 model also explains the empirical series for inflation and the nominal interest rate quite well. The correlations between the simulated and empirical series are .91 for inflation and .74 for the nominal interest rate for the MBC2 model. The correlations have a similar magnitude for the RBC2 model, though the correlation for the Solow residual is slightly lower.

Figure 1 plots the simulated and empirical time series for the MBC2 model with the hybrid Phillips curve. The solid lines represent the empirical series, and the dashed lines represent the theoretical series. The plots show that the simulated and empirical time series are very similar, which is not surprising given the high correlations reported in Table 1. As discussed in the previous section, the perfect fit between the simulated and empirical output series is by construction—the monetary shocks are chosen to perfectly match the simulated and empirical output series. Similarly impressive plots could be constructed for all of the models for the consumption, investment, labor, and Solow residual variables. The success of the models at replicating the observed paths of these variables is robust to almost any changes in the parameters, given the procedure used to construct the shocks.

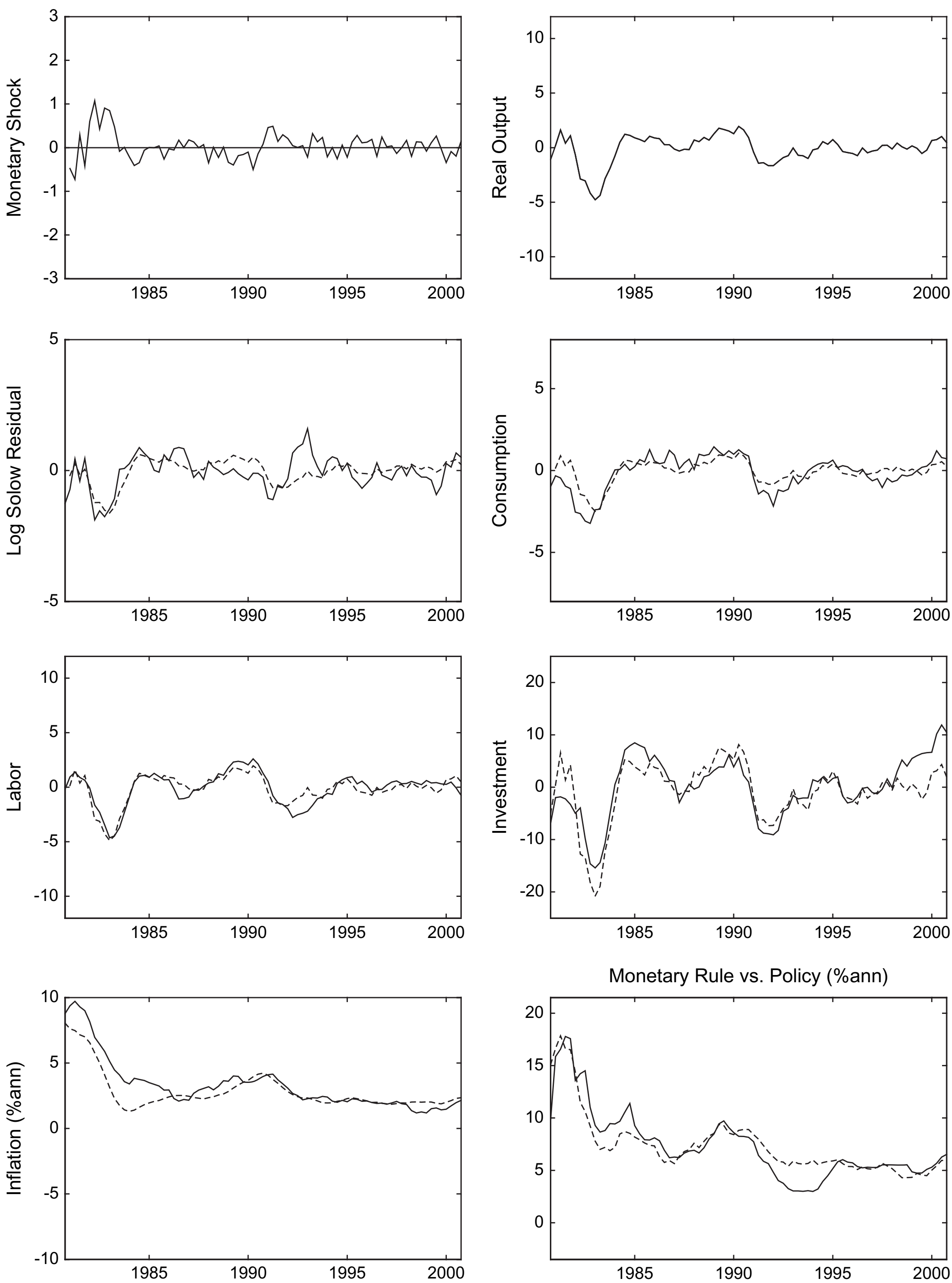
The simulations take as given the initial values of the state variables, capital and productivity, as well as the sequence of productivity shocks. I focus on the period spanning the

**TABLE 1**
Sample Correlations Between Simulated and Empirical Series

| | RBC1 | RBC2 | MBC1 Calvo | MBC2 Hybrid | MBC3 Calvo | MBC4 Calvo | MBC5 Calvo |
|---|---|---|---|---|---|---|---|
| *Panel A: 1980–2000* | | | | | | | |
| Consumption | 0.81 | 0.80 | 0.80 | 0.81 | 0.80 | 0.81 | 0.81 |
| Investment | 0.82 | 0.82 | 0.82 | 0.82 | 0.82 | 0.82 | 0.82 |
| Labor | 0.89 | 0.89 | 0.88 | 0.88 | 0.89 | 0.89 | 0.88 |
| Real wage | 0.10 | 0.06 | −0.08 | −0.02 | 0.06 | 0.20 | 0.03 |
| Inflation | | | 0.21 | 0.90 | 0.27 | 0.26 | 0.30 |
| Nominal interest rate | | | 0.27 | 0.73 | 0.01 | −0.01 | 0.07 |
| Output | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| Solow residual | 0.62 | 0.65 | 0.63 | 0.64 | 0.65 | 0.60 | 0.62 |
| *Panel B: 1947–2000* | | | | | | | |
| Consumption | 0.76 | 0.75 | 0.76 | 0.76 | 0.75 | 0.75 | 0.76 |
| Investment | 0.76 | 0.76 | 0.76 | 0.76 | 0.76 | 0.76 | 0.76 |
| Labor | 0.88 | 0.87 | 0.89 | 0.89 | 0.89 | 0.85 | 0.86 |
| Real wage | 0.07 | 0.00 | 0.08 | 0.08 | 0.06 | −0.01 | 0.07 |
| Inflation | | | 0.16 | 0.14 | −0.11 | −0.13 | −0.11 |
| Nominal interest rate | | | −0.01 | −0.08 | −0.11 | −0.01 | −0.12 |
| Output | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| Solow residual | 0.64 | 0.15 | 0.68 | 0.71 | 0.51 | 0.06 | 0.60 |

*Notes:* RBC1: Real Business Cycle model with remeasured Productivity Shocks; RBC2: Real Business Cycle Model with remeasured Preference Shocks; MBC1: Monetary Business Cycle model with remeasured Monetary Shocks, Calvo Philips Curve; MBC2: Monetary Business Cycle model with remeasured Monetary Shocks, Hybrid Philips Curve; MBC3: Monetary Business Cycle model with remeasured Cost Push Shocks, Calvo Philips Curve; MBC4: Monetary Business Cycle model with remeasured Preference Shocks, Calvo Philips Curve; MBC5: Monetary Business Cycle model with remeasured Productivity Shocks, Calvo Philips Curve. In all cases, the shocks are "remeasured" so that the theoretical output series perfectly matches its empirical counterpart.

**FIGURE 1**
Simulated versus Empirical Time Series for the Hybrid Monetary Business Cycle Model



third quarter of 1980 to the first quarter of 2000 in order to allow for a stable Taylor rule: it seems unreasonable to assume that the Federal Reserve Bank followed the same Taylor rule in earlier years.[6] For robustness, Panel 2 of Table 1 also presents results for the period 1947–2000. The results for the longer time series are broadly similar for the real variables, though the MBC models are considerably less successful at replicating the nominal variables over the longer time period. Following Taylor (1993), I use the four-quarter moving average of quarterly inflation as my empirical inflation series. As in RBC simulations, the data series for the real variables are constructed by logging and HP filtering the raw data, as described in Appendix A. The HP filter removes low-frequency fluctuations in the time series, for the purpose of isolating business cycle fluctuations.[7]

An important caveat to the success of the models along this dimension is, however, that the models' ability to explain the real variables falls as their correlation with output drops. Table 1 shows that the MBC2 model with the hybrid Phillips curve is far more successful than the other models at explaining the nominal interest rate and inflation (and has almost identical implications for the remainder of the variables).[8] However, this result is somewhat fragile. In particular, the MBC2 model's ability to replicate the nominal variables is much less robust to changes in the model than its ability to replicate the consumption, investment, labor, and Solow residual variables. The simulations of the nominal variables depend on the Central Bank's policy rule, whereas the simulations of the real variables do not. As I note above, the MBC model replicates the real variables almost equally well over the period 1947–2000, whereas the ability of the MBC2 model to replicate the nominal variables diminishes considerably over the longer time period. None of the models succeeds at all at explaining the real wage, which is least correlated with output among the real variables. The correlations between the simulated and empirical real wage series are close to zero or are negative.

Thus, the support provided by Table 1 for all of the business cycle models considered in this paper has an important caveat. Looking carefully at Figure 1, one can see that the simulated series for output, consumption, labor supply, and the Solow residual are very similar. The same is true of simulations of the RBC model. Table 2 shows that consumption, the labor supply, and the Solow residual are highly correlated with output in the long run. The success story of the RBC and MBC models (with respect to the real variables) is that the models are able to explain why certain variables covary so much over the business cycle, and at what amplitudes—not their idiosyncratic movements.

Another common RBC approach to evaluating the fit of the model is to compare the theoretical second moments of the model to the relationships observed in the data. Table 2 gives cross-correlations with output, and Table 3 gives the theoretical standard deviations relative to output for the RBC and MBC models. I compare the theoretical values to the corresponding empirical statistics for the periods 1947–2000 and 1980–2000.[9] Again, I find that the models have fairly reasonable, and remarkably similar, properties for consumption, investment, labor supply and the Solow residual.

Once again, the models differ in their implications for the nominal interest rate, inflation and the real wage. The RBC1, MBC3, and MBC5 models imply the most reasonable levels of volatility for the real wage—the real wage volatility for the other models is too low. (See Table 3.) However, the volatility of the real wage in the RBC1 model is very sensitive to the persistence parameter for productivity: a small reduction in this parameter causes a large reduction in the theoretical variance of the real wage.[10]

6. See Taylor (1999) for a discussion of the shift in monetary policy since the 1980s. Note, however, that there is some debate on whether, aside from the Volcker deflation, the changes in monetary policy were small relative to changes in the shock process. See, for example, Sims and Zha (2006).

7. RBC models generally attribute long-term growth to trend growth in productivity. This assumption could also be made in the MBC model.

8. The MBC2 model has some difficulty in capturing low-frequency movements in the nominal interest rate. One reason may be the HP filtering of the real variables: nominal interest rates fell over almost the entire period 1980–2000. According to the MBC2 model, low frequency variations in the nominal interest rate lead to low frequency variations in output. However, in the simulations, low frequency variations in the output series are removed by the HP filter.

9. The standard deviations presented here are calculated directly from the unconditional second moments of the model.

10. As the productivity shocks become less permanent, the incentives for intertemporal substitution rise. Therefore, a smaller change in the real wage is required to produce a given change in labor supply.

**TABLE 2**
Correlations with Output—Empirical Statistics versus Theoretical Predictions

| Model | 1947q1–2000q3 | 1980q1–2000q3 | RBC1 | RBC2 | MBC1 Calvo | MBC2 Hybrid | MBC3 Calvo | MBC4 Calvo | MBC5 Calvo |
|---|---|---|---|---|---|---|---|---|---|
| Consumption | 0.07 | 0.81 | 1.00 | 1.00 | 1.00 | 1.00 | 0.99 | 1.00 | 1.00 |
| Investment | 0.75 | 0.81 | 1.00 | 1.00 | 1.00 | 1.00 | 0.99 | 1.00 | 1.00 |
| Labor | 0.89 | 0.89 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.98 |
| Real wage | 0.08 | −0.18 | 0.10 | −0.80 | 0.24 | 0.17 | 0.27 | −0.99 | 0.10 |
| Inflation | 0.12 | −0.15 | | | 0.57 | 0.22 | −1.00 | −1.00 | −0.99 |
| Nominal interest rate | 0.13 | 0.01 | | | 0.58 | 0.33 | −0.99 | −0.99 | −0.98 |
| Output | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| Solow residual | 0.64 | 0.57 | 0.97 | 0.80 | 0.78 | 0.91 | 0.68 | 0.67 | 0.93 |

*Notes:* RBC1: Real Business Cycle model with remeasured Productivity Shocks; RBC2: Real Business Cycle Model with remeasured Preference Shocks; MBC1: Monetary Business Cycle model with remeasured Monetary Shocks, Calvo Philips Curve; MBC2: Monetary Business Cycle model with remeasured Monetary Shocks, Hybrid Philips Curve; MBC3: Monetary Business Cycle model with remeasured Cost Push Shocks, Calvo Philips Curve; MBC4: Monetary Business Cycle model with remeasured Preference Shocks, Calvo Philips Curve; MBC5: Monetary Business Cycle model with remeasured Productivity Shocks, Calvo Philips Curve. In all cases, the shocks are "remeasured" so that the theoretical output series perfectly matches its empirical counterpart.

The hybrid MBC model considerably underestimates the variance of the nominal interest rate, though the correlation between the theoretical and empirical series is quite high. (See Table 3.)

As noted above, the MBC2 model produces the most realistic implications for the nominal variables. All of the other MBC models imply correlations between the nominal variables and output that are unrealistically large in magnitude. Basically, this is a consequence of the use of the Calvo Phillips curve in the other MBC models. The lagged inflation term in the hybrid Phillips curve prevents inflation from moving in lockstep with output.

*Impulse Response Functions*

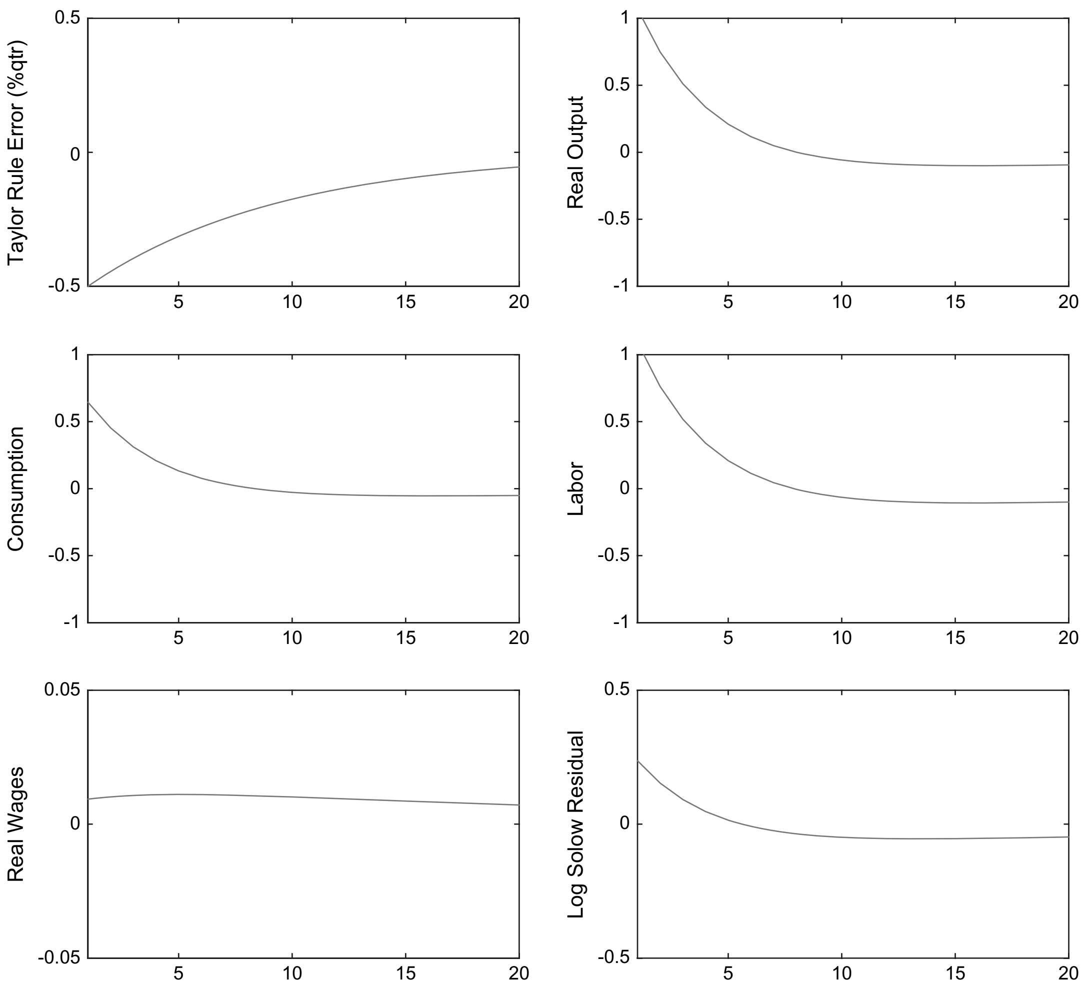
In order to provide some intuition for the results, Figures 2, 3, and 4 plot the impulse

**TABLE 3**
Relative Standard Deviations of Macroeconomic Series—Empirical Statistics versus Theoretical Predictions

| Model | 1947q1–2000q3 | 1980q1–2000q3 | RBC1 | RBC2 | MBC1 Calvo | MBC2 Hybrid | MBC3 Calvo | MBC4 Calvo | MBC5 Calvo |
|---|---|---|---|---|---|---|---|---|---|
| Consumption | 0.76 | 0.80 | 0.56 | 0.52 | 0.61 | 0.60 | 0.55 | 0.39 | 0.52 |
| Investment | 4.13 | 4.32 | 2.74 | 2.91 | 3.74 | 3.80 | 4.23 | 5.26 | 4.33 |
| Labor | 1.07 | 1.12 | 1.00 | 1.09 | 1.02 | 1.02 | 1.02 | 1.07 | 0.90 |
| Real wage | 0.41 | 0.63 | 0.04 | 0.11 | 0.07 | 0.03 | 0.09 | 0.15 | 0.10 |
| Inflation | 1.40 | 1.48 | | | 0.80 | 0.96 | 0.76 | 0.80 | 0.75 |
| Nominal interest rate | 2.04 | 2.49 | | | 0.75 | 0.95 | 0.66 | 0.70 | 0.64 |
| Output | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| Solow residual | 0.51 | 0.48 | 0.36 | 0.73 | 0.30 | 0.26 | 0.50 | 0.77 | 0.43 |

*Notes:* RBC1: Real Business Cycle model with remeasured Productivity Shocks; RBC2: Real Business Cycle Model with remeasured Preference Shocks; MBC1: Monetary Business Cycle model with remeasured Monetary Shocks, Calvo Philips Curve; MBC2: Monetary Business Cycle model with remeasured Monetary Shocks, Hybrid Philips Curve; MBC3: Monetary Business Cycle model with remeasured Cost Push Shocks, Calvo Philips Curve; MBC4: Monetary Business Cycle model with remeasured Preference Shocks, Calvo Philips Curve; MBC5: Monetary Business Cycle model with remeasured Productivity Shocks, Calvo Philips Curve. In all cases, the shocks are "remeasured" so that the theoretical output series perfectly matches its empirical counterpart.

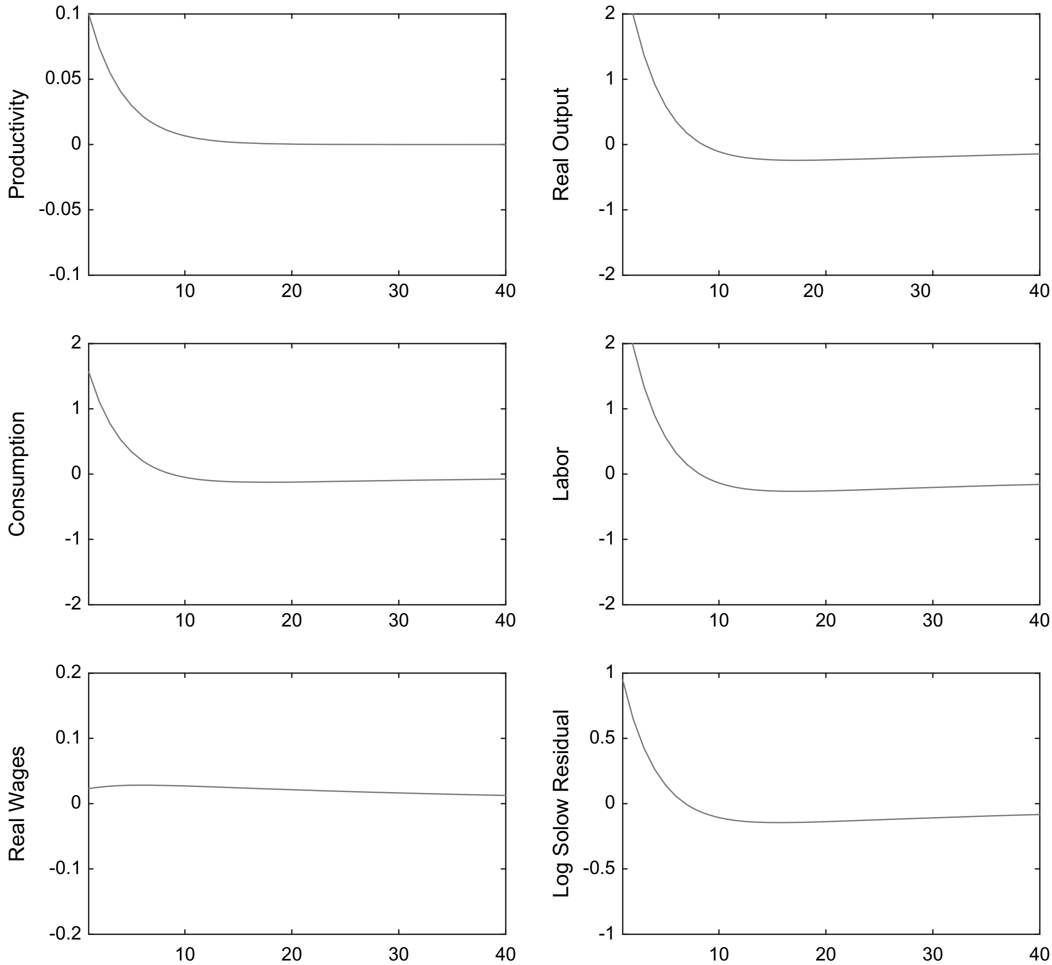
**FIGURE 2**
Impulse Responses to a Monetary Shock in the Hybrid Monetary Business Cycle Model




response functions for the MBC and RBC models. The monetary shock would, all else equal, reduce the nominal interest rate by half a percentage point in the MBC economy; the productivity shock would, all else equal, increase aggregate output by 0.1% in the RBC economy. The plots show that an economic boom in the MBC economy (induced by an expansionary monetary shock) appears very similar to a productivity-induced economic boom in the RBC economy. On the one hand, according to the MBC story, an economic boom occurs when unexpectedly low nominal interest rates lead to an expansion in demand, which is not undone by inflation (due to sticky prices). The resulting economic expansion leads to a measured increase in TFP, even though there is no productivity shock. (I explain the intuition for the measured increase in TFP below.)

On the other hand, according to the RBC story, an economic boom occurs when TFP is unusually high. The resulting increase in GDP leads to a measured decrease in the Taylor rule residual even though there is no monetary shock (holding fixed the nominal interest rate, which is indeterminate in the RBC model). From an MBC perspective, procyclical fluctuations in TFP are artifacts of a misspecified production function; from an RBC perspective, countercyclical fluctuations in the Taylor rule error are artifacts of a misspecified policy rule for the

**FIGURE 3**
Impulse Responses to a Productivity Shock in the RBC Model

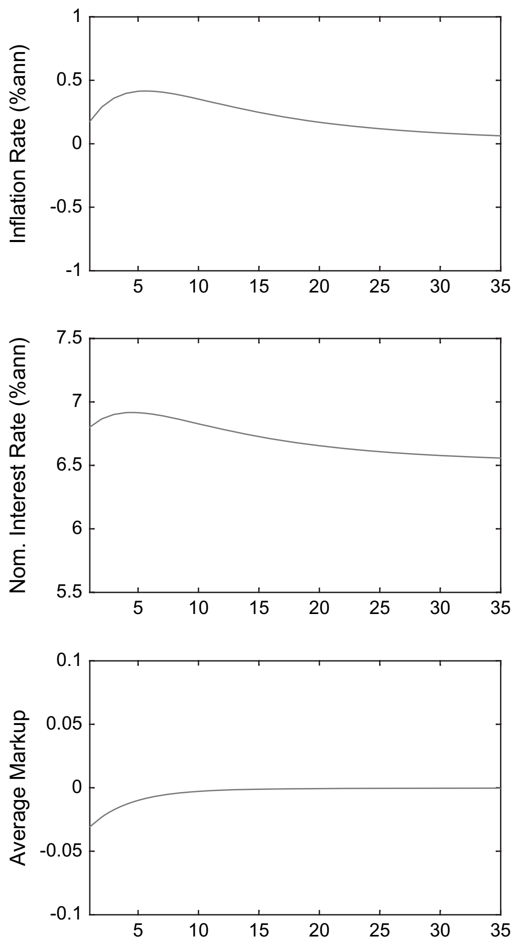



central bank. In the MBC model, the shocks also generate fluctuations in the nominal interest rate, inflation and the markup as depicted in Figure 4.

In the models without an assumed productivity shock (all of the models except the RBC model), one might wonder about the source of the observed procyclical variation in the Solow residual. There are two sources of the observed variation in the Solow residual aside from actual variation in TFP. The first is variable capital utilization, which is not accounted for in the standard version of the Solow residual. The second is a particular type of mismeasurement story that was first noted by Hall (1988).[11] The story goes as follows. If markets are monopolistic, then prices are no longer set equal to marginal costs. The traditional argument for calibrating the parameter $\alpha$ as the income share in the Cobb-Douglas production function breaks down. Given that the firms are monopolists in the MBC model, the correct calibration of the parameter $\alpha$ is as a markup over the income share, rather than the income share itself. The Solow residual thus underestimates the true contribution of

11. Hall (1988) shows that, with imperfect competition, movements in aggregate demand lead to changes in the Solow Residual. Rotemberg and Summers (1990) and Bernanke and Parkinson (1991) follow up on Hall's original contribution.

**FIGURE 4**
Impulse Response to a Monetary Shock in the Hybrid Monetary Business Cycle Model




labor to production. In the MBC model, economic booms result from expansionary monetary shocks rather than fluctuations in productivity. Since labor increases more than capital in booms, the Solow residual is procyclical even though productivity is constant.[12]

Finally, it is useful to provide some statistics on the assumed exogenous shocks in the various models. Table 4 presents some summary statistics for the remeasured shocks. In the case of the standard RBC and the MBC

12. Evans (1992) shows that the Solow residual is Granger caused by the nominal interest rate and the money supply.

**TABLE 4**
Descriptive Statistics for the Remeasured Shocks

| Model | RBC1 | MBC1 Calvo | MBC2 Hybrid |
|---|---|---|---|
| Standard deviation | 0.03 | 0.76 | 0.37 |
| Mean | 0.01 | 0.09 | 0.04 |

*Notes:* RBC1: Real Business Cycle model with remeasured Productivity Shocks; MBC1: Monetary Business Cycle model with remeasured Monetary Shocks, Calvo Philips Curve; MBC2: Monetary Business Cycle model with remeasured Monetary Shocks, Hybrid Philips Curve. The descriptive statistics for the productivity shocks are multiplied by 100. The descriptive statistics for monetary shocks are given in units of annualized percentage points.

models with monetary shocks (MBC1 and MBC2), it is possible to derive a direct empirical measure of the exogenous shocks as well as constructing the remeasured shocks investigated in this paper. As in King and Rebelo (1999), the remeasured shocks generally do not have a high correlation with the direct empirical measures of the shocks. The lack of correlation is not surprising, given the small magnitude of the shocks.

## VI. CONCLUSION

The simulation exercises in this paper show that the success of the RBC model according to standard RBC evaluation techniques arises primarily from the basic structure of the stochastic dynamic general equilibrium model, rather than from the specific role of the productivity shock. According to standard RBC evaluation techniques, there is a high degree of similarity between a broad variety of monetary and real business cycle models driven by productivity, monetary, cost-push, and preference shocks. These results emphasize the importance of the basic structure of the RBC model—common to most modern business cycle models in explaining the success of RBC models.

None of the models I consider provides a good explanation for variables not highly correlated with output such as the real wage and the real interest rate. Thus, as I discuss in Section V, the success story of the RBC and MBC models (with respect to the real variables) is that the models are able to explain why certain variables covary so much over the business cycle, and at what amplitudes—not their idiosyncratic movements. These results indicate strongly that a successful model of these variables must embody either complicated nonlinear dynamics that are able to generate shifting patterns of correlations across key macroeconomic variables, or multiple shocks. The disparate implications of the RBC and MBC models for the real wage and the interest rate suggest that the dynamics of these variables are likely to be particularly important in distinguishing between alternative sources of variation in models with multiple shocks. The similar implications of the RBC and MBC models in terms of standard RBC evaluation criteria also underscores the importance of techniques that make use of additional sources of data from micro-level studies, as well as more sophisticated econometric approaches for comparing the model and data.

## APPENDIX A: CONSTRUCTING THE DATA SERIES

This section describes the data series used in this paper. All of the series are from the Data Resources Inc. (DRI) website and span the period from the first quarter of 1947 through the third quarter of 2000. I indicate whether the series are seasonally adjusted (SA), seasonally adjusted at an annual rate (SAAR), or not seasonally adjusted (NSA). All of the series are quarterly unless otherwise indicated. For the monthly series, the average value over the quarter is used to create a quarterly series. All of the series, except those that correspond to nominal variables, are logged and then detrended by subtracting the HP trend series for $\lambda = 1{,}600$ (the standard value for quarterly data).[13] The variables are:

*Nominal GDP (in billions of dollars, SAAR):* GDP. Real GDP (in billions of 1992 chained dollars, SAAR): GDPQ. The HP-filtered version of this series is the estimate for $y_t$.

*Total Personal Consumption Expenditures (in billions of 1992 chained dollars, SAAR):* GCQ. The HP filtered version of this series is the estimate for $c_t$. The quarterly data are not available on the DRI website for the years prior to the fourth quarter of 1958 so annual data are used. The variable name for the annual consumption series is GAE.

*Total Fixed Investment (in billions of 1992 chained dollars, SAAR):* GIFQ. I use the data on investment to construct a series for the capital stock using the definition,

$$I_t = K_t - K_{t+1} + \delta K_t, \tag{17}$$

where $I_t$ is fixed investment. The initial value in the capital stock series is taken from the "Survey of Current Business" estimate for 1947. The HP-filtered version of the capital series is the estimate for $k_t$. In order to construct a consistent series for detrended investment, I apply the definition (17) to the $k_t$ series. (Another approach would be to HP filter the investment series, and then construct a capital stock series using Equation (17)).

*Total Hours of Employment of All Persons in the Nonfarm Business Sector (in billions of hours, SA):* LBMNU. The HP-filtered version of this series is the estimate for $N_t$.

*Total Capacity Utilization Rate in Manufacturing (percent of capacity, SA):* IPXMCA (monthly series). The HP filtered version of this series is the estimate for $Q_t$.

*Compensation per Hour in the Nonfarm Business Sector, (Scaled 1982 = 100, SA):* LBCPU. The HP-filtered version of this series is the estimate for $w_t$.

*Federal Funds Rate: (Percentage per Annum, NSA):* FYFF (monthly series). This series, transformed to give quarterly rates, is the estimate for $i_t$.

*Price Index:* I infer the price index series from the nominal and real GDP series.[14] I use the price index series to construct an inflation series, which is the estimate for $\pi_t$.

Solow residual

$$y_t - (1 - \alpha_{\mathrm{sh}})k_t - \alpha_{\mathrm{sh}} n_t. \tag{18}$$

## APPENDIX B: CALIBRATING THE MODEL

### *A. Households*

I set the real return on capital and the real interest rate to 6.5% and steady-state depreciation at 10% per annum. Following King and Rebelo (1999), I specify $\sigma = 3$ in the utility function (4).

The parameterization of $\theta$ determines the degree of monopoly power of the firms in the market. I chose a value $\theta = 7.88$, which implies a steady-state average markup of 15% over the marginal cost.[15]

### *B. Firms*

In the RBC framework, $\alpha$ is simply the steady-state labor income share. On the other hand, in a model with monopolistic competition, $\alpha$ is the labor income share scaled by the steady-state markup. The implied value of $\alpha$ is 0.7705, given a labor share of two-thirds.

I follow King and Rebelo (1999) in specifying the steady-state labor supply as $n = 0.2$, which they present as the fraction of available time engaged in work in the U.S. in the post-war period.

I set the steady-state value of capital utilization $Q = 1$. However, a different choice for $Q$ would simply define different units for capital.

The degree of amplification in the high substitution economy is very sensitive to the parameterization of the elasticity of $\delta(Q_t)$ with respect to $Q_t$. I follow King and Rebelo (1999) in calibrating this elasticity to be 0.1.

13. See Hodrick and Prescott (1980) for the details of the HP filter.

14. The GDP deflator is appropriate, since, in the model, I make the simplifying assumption that the prices of durable and consumption goods are the same.

15. This is the value for $\theta$ estimated in Rotemberg and Woodford (1997), although the assumptions in this paper are different from the ones we make here, so the parameter estimate should only be taken as a rough guide. A standard value in the literature is $\theta = 10$. For example, see Chari, Kehoe and McGrattan (2002).

Let $\gamma$ denote the probability that a firm is able to change its prices in a given period (according to the Calvo assumption). Gali and Gertler (1999) report estimates of $\gamma$ between .803 and .866. I use $\gamma = .6$ because this parameter implies a more realistic amount of high-frequency variation in the inflation series.

The remainder of the parameters in the model can be derived by exploiting the relationships among variables in the steady state.

## APPENDIX C: INDIVISIBLE LABOR

Rogerson and Wright (1988) suggest the following approach to modelling indivisible labor. Suppose that the labor force of the economy consists of a continuum of identical households. Each one has probability $p$ of working a shift of $H$ hours, and probability $1 - p$ of not working at all. As in Section II, the households seek to maximize their expected utilities. In this scenario, it seems natural for the households to enter into an efficient risk-sharing agreement—think of it as an Unemployment Insurance system. The Unemployment Insurance system allocates consumption in the two states to solve the problem,

$$\max_{C_u, C_e} pU(C_1, 1-H) + (1-p)U(C_e, H) \tag{19}$$

s.t.

$$pC_u + (1-p)C_e = C, \tag{20}$$

where $C_u$ is consumption in the unemployed state, $C_e$ is consumption in the employed state, and C is the expected consumption over the two states.

If household utility takes the CES form,

$$u(C, L) = \frac{1}{1-\sigma}\left\{[C\tilde{v}(L)]^{1-\sigma} - 1\right\}, \tag{21}$$

then expected utility is given by

$$u(C, L) = \frac{1}{1-\sigma}\left\{C^{1-\sigma}\left[\frac{1-L}{H}\tilde{v}\left(1-H\right)^{\frac{1-\sigma}{\sigma}} + \left(1 - \frac{1-L}{H}\right)\tilde{v}(1)^{\frac{1-\sigma}{\sigma}}\right]^{\sigma} - 1\right\}, \tag{22}$$

where $L$ is average leisure, defined as $L = 1 - pH$.

Thus, we can incorporate indivisible labor into the model simply by taking household utility to be (22).[16] See King and Rebelo (1999) for the details of the derivation.

16. To be consistent in interpretation, $C_t$, $L_t$, $B_t$, and $k_t$ (as used in Section I) must be expected values over employment states and likewise for the household's budget constraint.

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