

Economics Department
Working Papers in Economics

Boston College

Year 2006

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Real Business Cycle Model

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Productivity and U.S. Macroeconomic Performance: Interpreting the Past and Predicting the Future with a Two-Sector Real Business Cycle Model*

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April 2006

Abstract

A two-sector real business cycle model, estimated with postwar U.S. data, identifies shocks to the levels and growth rates of total factor productivity in distinct consumption- and investment-goods-producing technologies. This model attributes most of the productivity slowdown of the 1970s to the consumption-goods sector; it suggests that a slowdown in the investment-goods sector occurred later and was much less persistent. Against this broader backdrop, the model interprets the more recent episode of robust investment and investment-specific technological change during the 1990s largely as a catch-up in levels that is unlikely to persist or be repeated anytime soon.

JEL: E32, O41, O47.

*All data and programs used in this research are freely available at <http://www2.bc.edu/~irelandp>. The authors would like to thank Susanto Basu, Jeff Fuhrer, Jordi Galí, Giovanni Olivei, Charles Steindel, and seminar participants at the Federal Reserve Bank of New York and the National Bureau of Economic Research for extremely helpful comments and suggestions and Suzanne Lorant for expert editorial assistance. Some of this work was completed while Peter Ireland was visiting the Federal Reserve Bank of Boston; he would like to thank the Bank and its staff for their hospitality and support. This material is also based on work supported by the National Science Foundation under Grant No. SES-0213461 to Peter Ireland. Any opinions, findings, and conclusions or recommendations expressed herein are the authors' own and do not reflect those of the Federal Reserve Bank of Boston, the Federal Reserve System, the National Bureau of Economic Research, or the National Science Foundation.

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1 Introduction

Two pictures motivate this analysis. First, Figure 1 traces out the evolution of total factor productivity in private, nonfarm, U.S. businesses as measured by the Bureau of Labor Statistics. This first graph reveals that there have been large and extended swings in the level, and possibly the growth rate, of total factor productivity. In particular, productivity growth slowed during the 1970s but revived more recently in the 1990s. Persistent fluctuations in total factor productivity such as these play a key role in Kydland and Prescott's (1982) real business cycle model. But what, more specifically, can a real business cycle model tell us about the recent increase in productivity growth? Looking back with the help of this model, how does the recent productivity revival relate, if at all, to the earlier productivity slowdown? And looking ahead, how long might the productivity revival last?

Second, Figure 2 displays in its top two panels the behavior of real, per-capita consumption and investment in the U.S. economy. This second graph highlights the fact that growth in real investment has outpaced growth in real consumption throughout the entire postwar period but especially during the most recent aggregate productivity revival. Differential growth rates of consumption and investment play a key role in multi-sector extensions of the real business cycle model, like those developed by Greenwood, Hercowitz, and Huffman (1988); Greenwood, Hercowitz, and Krusell (1997, 2000); and Whelan (2003), that distinguish between improvements to consumption- versus investment-goods-producing technologies. But what, more specifically, can a multi-sector real business cycle model tell us about the nature of the recent investment boom, the coincident revival in aggregate productivity growth, and the links, if any, between these recent phenomena and the earlier productivity slowdown?

To answer these questions, this paper applies a two-sector real business cycle model directly to the postwar U.S. data, estimating its parameters via maximum likelihood. This extended real business cycle model allows for distinct shocks to both the levels and the growth rates of total factor productivity in distinct consumption- and investment-goods-producing sectors. According to the model, these different types of technology shocks—

to levels versus growth rates and to the consumption- versus investment-goods-producing sectors—set off very different dynamic responses in observable variables, including those used in the estimation: aggregate consumption, investment, and hours worked. Although some of these differences have been noted before, for example, by Kimball (1994) and Lindé (2004), this study exploits them more fully to identify with aggregate data the historical realizations of each type of shock and thereby estimate parameters summarizing the volatility and persistence of each type of shock—parameters that help to describe the past and forecast the future.

Through these estimates, the econometric results provide answers to the questions raised above. They provide insights into the relative importance of shocks to the levels and growth rates of productivity in the consumption- and investment-goods-producing sectors in generating the slowdown of the 1970s and the revival of the 1990s. They draw surprising links between these two important episodes in postwar U.S. economic history. And they help in guessing how long the recent productivity revival might last.

In previous work, Greenwood, Hercowitz, and Krusell (1997, 2000); Fisher (2003); and Marquis and Trehan (2005) use data on the relative price of investment goods to distinguish between technology shocks to the consumption- and investment-goods-producing sectors. Hobijn (2001) emphasizes that these price data, though informative under certain assumptions, do not always lead to reliable conclusions about the rate of investment-specific technological progress. Motivated partly by the difficulties highlighted by Hobijn (2001), Basu, Fernald, Fisher, and Kimball (2005) construct sector-specific measures of technological change without the help of price data, relying instead on industry-level figures to distinguish between outputs that are used primarily for consumption and those that serve chiefly for investment.

This paper takes an alternative approach to complement these existing studies. As noted above, it uses data on aggregate quantities only and exploits the dynamic implications of the multi-sector real business cycle model to disentangle the effects of shocks to consumption-

and investment-goods-producing technologies and to distinguish, further, between shocks to the levels and growth rates of productivity in these two sectors.

In other related work, DeJong, Ingram, and Whiteman (2000) use aggregate quantity data to estimate a version of Greenwood, Hercowitz, and Huffman's (1988) model of neutral versus investment-specific technological change, but allow shocks to impact only the level, and not the growth rate, of productivity in each sector. Pakko (2002, 2005), on the other hand, studies versions of Greenwood, Hercowitz, and Krusell's (2000) model with shocks to both the levels and growth rates of neutral and investment-specific productivity; those models, however, are calibrated and simulated rather than estimated. Finally, Roberts (2001), Kahn and Rich (2004), and French (2005) use less highly constrained time-series models to detect and characterize persistent shifts in labor or total factor productivity growth in the postwar U.S. economy. The present study addresses similar issues, but using a more tightly parameterized theoretical model that distinguishes, as well, between productivity developments in separate consumption- and investment-goods-producing sectors. Thus, the present study contributes to the recent literature on productivity and postwar U.S. macroeconomic performance through its use of new data, new methods, and new identifying assumptions, in hopes of shedding new light on these enduring issues.

2 The Model

2.1 Overview

This two-sector real business cycle model resembles most closely the one developed by Whelan (2003), in which a logarithmic utility function over consumption and separate Cobb-Douglas production functions for consumption and investment goods combine to allow nominal expenditure shares on consumption and investment to remain constant along a balanced growth path, even as the corresponding real shares exhibit trends driven by differential rates of technological progress across the two sectors. As suggested by the data shown in Fig-

ure 2 and as discussed more fully by Whelan (2003, 2004), these basic features—constant nominal and trending real shares of expenditure on consumption versus investment goods—characterize most accurately the postwar U.S. data. Whelan (2003) also describes how this two-sector model reinterprets Greenwood, Hercowitz, and Krusell’s (1997, 2000) earlier formulation by recasting their distinction between neutral and investment-specific technological change alternatively as one between consumption-specific and investment-specific technological change.

The model used here elaborates on Whelan’s (2003) in a number of ways, so as to enhance its empirical performance and thereby make it more suitable for a structural econometric analysis of productivity shifts in the consumption- and investment-goods-producing sectors of the postwar U.S. economy. In particular, the model extends Whelan’s by allowing leisure as well as consumption to enter into the representative household’s utility function; hence, the extended model has implications for the behavior of aggregate hours worked as well as for consumption and investment. Here, a preference shock also appears in the utility function. As discussed below, this preference shock competes with the various technology shocks in accounting for fluctuations in consumption, investment, and hours worked so that the extended model, when applied to the data, need not attribute all or even most of the action observed in those variables to the effects of technology shocks.

Here, as well, Whelan’s Cobb-Douglas production structure is generalized to allow for heterogeneity in factor shares across the consumption- and investment-goods-producing sectors; Echevarria (1997) and Huffman and Wynne (1999) present evidence of sectoral heterogeneity of this kind. The extended production structure also incorporates two additional features—adjustment costs and variable utilization rates for sector-specific capital stocks—that enrich the model’s dynamics and break what might otherwise be an excessively tight link between sector-specific outputs, capital stocks, and labor inputs. Finally, to allow for a detailed focus on the persistence of sector-specific technology shocks, the extended model borrows from Pakko’s (2002) specification by introducing shocks to both the levels and the growth rates

of productivity in the consumption- and investment-goods-producing sectors.

2.2 Preferences and Technologies

The infinitely-lived representative household has preferences described by the expected utility function

$$E_0 \sum_{t=0}^{\infty} \beta^t [\ln(C_t) - (H_{ct} + H_{it})/A_t], \quad (1)$$

where C_t denotes consumption, H_{ct} and H_{it} denote labor supplied to produce consumption and investment goods, respectively, and the discount factor β lies between zero and one. The representative household's utility is logarithmic in consumption to make the model consistent with the balanced-growth properties mentioned above. The representative household's utility is linear in leisure; this specification can be motivated, following Hansen (1985) and Rogerson (1988), by assuming that the economy consists of a large number of individual households, each of which includes a potential employee who either works full time or not at all during any given period.

The preference shock A_t in (1) impacts on the marginal rate of substitution between consumption and leisure; it enters the utility function in a way that associates an increase in A_t with an increase in equilibrium hours worked. Parkin (1988), Baxter and King (1991), Bencivenga (1992), Holland and Scott (1998), and Francis and Ramey (2005) also consider preference shocks of this kind in real business cycle models, while Hall (1997), Mulligan (2002), Chang and Schorfheide (2003), Galí, Gertler, and Lopez-Salido (2003), Comin and Gertler (2004), Kahn and Rich (2004), Chang, Doh, and Schorfheide (2005), and Galí (2005) all emphasize that preference shocks of this kind can stand in for a wide variety of non-technological disturbances that potentially play a role in driving aggregate fluctuations at short, medium, and long horizons. Here, A_t serves in this broader sense as a general competitor to technology shocks as a source of business-cycle dynamics so that, as noted above, the estimated model is not forced to attribute all or even most of the action found in the

postwar U.S. data to the various technology shocks.

During each period $t = 0, 1, 2, \dots$, the representative household produces consumption and investment according to the stochastic technologies described by

$$\left[1 - \frac{\phi_c}{2} \left(\frac{I_{ct}}{K_{ct}} - \kappa_c \right)^2 \right] (u_{ct} K_{ct})^{\theta_c} (Z_{ct} H_{ct})^{1-\theta_c} \geq C_t \quad (2)$$

and

$$\left[1 - \frac{\phi_i}{2} \left(\frac{I_{it}}{K_{it}} - \kappa_i \right)^2 \right] (u_{it} K_{it})^{\theta_i} (Z_{it} H_{it})^{1-\theta_i} \geq I_{ct} + I_{it}. \quad (3)$$

In (2) and (3) as in (1), C_t denotes consumption and H_{ct} and H_{it} denote labor used to produce, respectively, the consumption and investment good. Likewise, K_{ct} and K_{it} denote capital stocks allocated to the two sectors, u_{ct} and u_{it} denote the corresponding rates of capital utilization, and Z_{ct} and Z_{it} denote sector-specific technology shocks. The Cobb-Douglas share parameters θ_c and θ_i lie between zero and one.

In (2) and (3), capital adjustment costs subtract from output in each of the two sectors according to a specification adapted from Basu, Fernald, and Shapiro (2001). These costs apply to all investment I_{ct} or I_{it} that is allocated to the consumption- or investment-goods-producing sectors; hence, the household incurs these costs regardless of whether it is installing newly produced units of capital or reallocating existing units of capital across sectors. The nonnegative parameters ϕ_c and ϕ_i govern the magnitude of the capital adjustment costs, and the parameters κ_c and κ_i will eventually be set equal to the steady-state investment-capital ratios in the two sectors so that steady-state adjustment costs equal zero.

Finally, capital stocks in the two sectors evolve according to

$$[1 - (1/\omega_c)u_{ct}^{\omega_c}]K_{ct} + I_{ct} \geq K_{ct+1} \quad (4)$$

and

$$[1 - (1/\omega_i)u_{it}^{\omega_i}]K_{it} + I_{it} \geq K_{it+1} \quad (5)$$

for all $t = 0, 1, 2, \dots$. These capital accumulation constraints associate higher rates of capital utilization with faster rates of depreciation, a specification originally suggested by Taubman and Wilkinson (1970), first introduced into a real business cycle model by Greenwood, Hercowitz, and Huffman (1988), and later used by Greenwood, Hercowitz, and Krusell (2000) to examine the consequences of investment-specific technological progress. In this specification, the parameters ω_c and ω_i both exceed one.

2.3 Equilibrium Allocations

Since the two welfare theorems apply, Pareto optimal and competitive equilibrium resource allocations correspond to those that solve the social planner's or representative household's problem: choose contingency plans for $C_t, H_{ct}, H_{it}, I_{ct}, I_{it}, u_{ct}, u_{it}, K_{ct+1}$, and K_{it+1} for all $t = 0, 1, 2, \dots$ to maximize the utility function (1), subject to the constraints imposed by (2)-(5) for all $t = 0, 1, 2, \dots$. Letting Λ_{ct} and Λ_{it} denote the nonnegative multipliers on the production possibility constraints (2) and (3) and Ξ_{ct} and Ξ_{it} denote nonnegative multipliers on the capital accumulation constraints (4) and (5), the first-order conditions for this problem can be written as

$$1 = \Lambda_{ct} C_t, \tag{6}$$

$$H_{ct} = (1 - \theta_c) \Lambda_{ct} A_t C_t, \tag{7}$$

$$H_{it} = (1 - \theta_i) \Lambda_{it} A_t I_t, \tag{8}$$

$$\Xi_{ct} = \Lambda_{it} + \phi_c \Lambda_{ct} (I_{ct}/K_{ct} - \kappa_c) (1/K_{ct}) (u_{ct} K_{ct})^{\theta_c} (Z_{ct} H_{ct})^{1-\theta_c}, \tag{9}$$

$$\Xi_{it} = \Lambda_{it} [1 + \phi_i (I_{it}/K_{it} - \kappa_i) (1/K_{it}) (u_{it} K_{it})^{\theta_i} (Z_{it} H_{it})^{1-\theta_i}], \tag{10}$$

$$\theta_c \Lambda_{ct} C_t = \Xi_{ct} u_{ct}^{\omega_c} K_{ct}, \tag{11}$$

$$\theta_i \Lambda_{it} I_t = \Xi_{it} u_{it}^{\omega_i} K_{it}, \tag{12}$$

$$\begin{aligned}\Xi_{ct} &= \beta E_t \{ \Xi_{ct+1} [1 - (1/\omega_c) u_{ct+1}^{\omega_c}] \} + \beta \theta_c E_t (\Lambda_{ct+1} C_{t+1} / K_{ct+1}) \\ &+ \beta \phi_c E_t [\Lambda_{ct+1} (I_{ct+1} / K_{ct+1} - \kappa_c) (I_{ct+1} / K_{ct+1}) (1 / K_{ct+1}) (u_{ct+1} K_{ct+1})^{\theta_c} (Z_{ct+1} H_{ct+1})^{1-\theta_c}],\end{aligned}\tag{13}$$

$$\begin{aligned}\Xi_{it} &= \beta E_t \{ \Xi_{it+1} [1 - (1/\omega_i) u_{it+1}^{\omega_i}] \} + \beta \theta_i E_t (\Lambda_{it+1} I_{t+1} / K_{it+1}) \\ &+ \beta \phi_i E_t [\Lambda_{it+1} (I_{it+1} / K_{it+1} - \kappa_i) (I_{it+1} / K_{it+1}) (1 / K_{it+1}) (u_{it+1} K_{it+1})^{\theta_i} (Z_{it+1} H_{it+1})^{1-\theta_i}],\end{aligned}\tag{14}$$

and (2)-(5) with equality for all $t = 0, 1, 2, \dots$, where aggregate investment has been defined as

$$I_t = I_{ct} + I_{it}\tag{15}$$

and aggregate hours worked can be defined similarly as

$$H_t = H_{ct} + H_{it}.\tag{16}$$

Intuitively, (6) indicates that Λ_{ct} measures the representative household's marginal utility of consumption during each period $t = 0, 1, 2, \dots$; (7) and (8) then equate the value of the marginal product of labor in each sector to the household's marginal rate of substitution between consumption and leisure. Equations (9) and (10) show how capital adjustment costs drive a q -theoretic wedge between the shadow price Λ_{it} of newly produced investment goods and the shadow prices Ξ_{ct} and Ξ_{it} of installed capital in both sectors. Equations (11) and (12) balance the marginal benefit of producing more units of the consumption or investment good by increasing the rate of capital utilization in either sector with the marginal cost of depreciating that sector's capital stock at a faster rate. Finally, when solved forward, (13) and (14) equate the shadow prices Ξ_{ct} and Ξ_{it} of installed capital in either sector to the present discounted value of the additional output produced by an additional unit of capital in that sector after accounting for depreciation and adjustment costs.

2.4 Driving Processes

The model is closed through assumptions about the stochastic behavior of the preference and technology shocks: A_t , Z_{ct} , and Z_{it} . To allow for a detailed analysis of the persistence properties of each of these shocks, suppose, in particular, that each contains two separate autoregressive components, one that is stationary in levels and the other that is stationary in growth rates, so that

$$\ln(A_t) = \ln(a_t^l) + \ln(A_t^g), \quad (17)$$

$$\ln(a_t^l) = \rho_a^l \ln(a_{t-1}^l) + \varepsilon_{at}^l, \quad (18)$$

$$\ln(A_t^g/A_{t-1}^g) = (1 - \rho_a^g) \ln(a^g) + \rho_a^g \ln(A_{t-1}^g/A_{t-2}^g) + \varepsilon_{at}^g, \quad (19)$$

$$\ln(Z_{ct}) = \ln(z_{ct}^l) + \ln(Z_{ct}^g), \quad (20)$$

$$\ln(z_{ct}^l) = \rho_c^l \ln(z_{ct-1}^l) + \varepsilon_{ct}^l, \quad (21)$$

$$\ln(Z_{ct}^g/Z_{ct-1}^g) = (1 - \rho_c^g) \ln(z_c^g) + \rho_c^g \ln(Z_{ct-1}^g/Z_{ct-2}^g) + \varepsilon_{ct}^g, \quad (22)$$

$$\ln(Z_{it}) = \ln(z_{it}^l) + \ln(Z_{it}^g), \quad (23)$$

$$\ln(z_{it}^l) = \rho_i^l \ln(z_{it-1}^l) + \varepsilon_{it}^l, \quad (24)$$

and

$$\ln(Z_{it}^g/Z_{it-1}^g) = (1 - \rho_i^g) \ln(z_i^g) + \rho_i^g \ln(Z_{it-1}^g/Z_{it-2}^g) + \varepsilon_{it}^g \quad (25)$$

for all $t = 0, 1, 2, \dots$, where the autoregressive parameters ρ_a^l , ρ_a^g , ρ_c^l , ρ_c^g , ρ_i^l , and ρ_i^g all lie between zero and one. Suppose, in addition, that the innovations ε_{at}^l , ε_{at}^g , ε_{ct}^l , ε_{ct}^g , ε_{it}^l , and ε_{it}^g are serially and mutually uncorrelated and normally distributed with zero means and standard deviations σ_a^l , σ_a^g , σ_c^l , σ_c^g , σ_i^l , and σ_i^g . In the short run, of course, both components of each shock impact simultaneously the level and the growth rate of that shock. In the long run, however, only the “growth rate” component (that is, the component that is stationary in growth rates), and not the “level” component (that is, the component that is stationary in

levels), can account for the nonstationary behavior of consumption, investment, and hours worked in the U.S. data.

This specification adapts Pakko's (2002) approach to apply to this two-sector framework with consumption and investment-specific shocks as opposed to Greenwood, Hercowitz, and Krusell's (2000) model of neutral versus investment-specific shocks; as noted above, Whelan (2003) discusses the connections between these two alternative depictions of sector-specific technological change in more detail. This specification also extends Pakko's approach to apply to the preference shock as well as to the technology shocks. Hence, the estimated model can potentially attribute nonstationary behavior in consumption, investment, and hours worked to the preference shock instead of or in addition to the technology shocks. Finally, to account for the differential trends in real consumption, real investment, and hours worked per capita shown in Figure 2, the specification allows for differential average growth rates a^g , z_c^g , and z_i^g of A_t , Z_{ct} , and Z_{it} , respectively.

2.5 Solution and Estimation Procedures

Equations (2)-(25) now describe the behavior of the model's 24 variables: C_t , H_t , H_{ct} , H_{it} , I_t , I_{ct} , I_{it} , u_{ct} , u_{it} , K_{ct} , K_{it} , Λ_{ct} , Λ_{it} , Ξ_{ct} , Ξ_{it} , A_t , a_t^l , A_t^g , Z_{ct} , z_{ct}^l , Z_{ct}^g , Z_{it} , z_{it}^l , and Z_{it}^g . In equilibrium, these variables grow at different average rates, and some inherit unit roots from the nonstationary components of the shocks. However, the transformed (lower-case) variables $c_t = C_t/[A_{t-1}^g(Z_{it-1}^g)^{\theta_c}(Z_{ct-1}^g)^{1-\theta_c}]$, $h_t = H_t/A_{t-1}^g$, $h_{ct} = H_{ct}/A_{t-1}^g$, $h_{it} = H_{it}/A_{t-1}^g$, $i_t = I_t/(A_{t-1}^g Z_{it-1}^g)$, $i_{ct} = I_{ct}/(A_{t-1}^g Z_{it-1}^g)$, $i_{it} = I_{it}/(A_{t-1}^g Z_{it-1}^g)$, u_{ct} , u_{it} , $k_{ct} = K_{ct}/(A_{t-1}^g Z_{it-1}^g)$, $k_{it} = K_{it}/(A_{t-1}^g Z_{it-1}^g)$, $\lambda_{ct} = A_{t-1}^g (Z_{it-1}^g)^{\theta_c} (Z_{ct-1}^g)^{1-\theta_c} \Lambda_{ct}$, $\lambda_{it} = A_{t-1}^g Z_{it-1}^g \Lambda_{it}$, $\xi_{ct} = A_{t-1}^g Z_{it-1}^g \Xi_{ct}$, $\xi_{it} = A_{t-1}^g Z_{it-1}^g \Xi_{it}$, $a_t = A_t/A_{t-1}^g$, $a_t^l = A_t^l/A_{t-1}^g$, $z_{ct} = Z_{ct}/Z_{ct-1}^g$, $z_{ct}^l = Z_{ct}^l/Z_{ct-1}^g$, $z_{it} = Z_{it}/Z_{it-1}^g$, $z_{it}^l = Z_{it}^l/Z_{it-1}^g$ remain stationary, as do the growth rates of consumption, investment, and hours worked, computed as

$$g_t^c = C_t/C_{t-1} = a_{t-1}^g (z_{it-1}^g)^{\theta_c} (z_{ct-1}^g)^{1-\theta_c} (c_t/c_{t-1}), \quad (26)$$

$$g_t^i = I_t/I_{t-1} = a_{t-1}^g z_{it-1}^g (i_t/i_{t-1}), \quad (27)$$

and

$$g_t^h = H_t/H_{t-1} = a_{t-1}^g (h_t/h_{t-1}). \quad (28)$$

Equations (2)-(28) then imply that in the absence of shocks, the model converges to a balanced growth path, along which all of the stationary variables are constant. Equations (26)-(28) imply, more specifically, that along the balanced growth path consumption, investment, and hours worked grow at different rates, with

$$g_t^c = a^g (z_i^g)^{\theta_c} (z_c^g)^{1-\theta_c}, \quad (29)$$

$$g_t^i = a^g z_i^g, \quad (30)$$

and

$$g_t^h = a^g \quad (31)$$

for all $t = 0, 1, 2, \dots$

When log linearized around the stationary variables' steady-state values, (2)-(28) form a system of linear expectational difference equations that can be solved using the methods of Blanchard and Kahn (1980) and Klein (2000). These linear methods provide an approximate solution to the nonlinear real business cycle model that quite conveniently takes the form of a state-space econometric model. In this case, the solution links the behavior of three observable stationary variables—the growth rates of aggregate consumption, investment, and hours worked—to a vector of unobservable state variables that includes the six autoregressive shocks a_t^l , a_t^g , z_{ct}^l , z_{ct}^g , z_{it}^l , and z_{it}^g . Hence, the Kalman filtering algorithms outlined by Hamilton (1994, Ch.13) can be used to estimate the model's structural parameters via maximum likelihood and to draw inferences about the behavior of the unobserved shocks, most importantly the shocks to the levels and growth rates of productivity in the two sectors.

The quarterly U.S. data used in this econometric exercise are those displayed in Figure

2. The sample period runs from 1948:1 through 2005:1. Readings on real personal consumption expenditures in chained 2000 dollars provide the measure of C_t ; readings on real gross private domestic investment in chained 2000 dollars provide the measure of I_t ; and readings on hours worked by all persons in the nonfarm business sector provide the measure of H_t . All three series are seasonally adjusted and expressed in per-capita terms by dividing by the civilian noninstitutional population, ages 16 and over. Since the theoretical model allows nonstationary components to be present in the preference shock A_t and the sector-specific technology shocks Z_{ct} and Z_{it} , it also allows for nonstationarity in the levels of all three observable variables and, unlike the simpler one-sector model of King, Plosser, Stock, and Watson (1991), does not generally imply that real consumption and investment, if nonstationary, will be cointegrated. Hence, as indicated above, the growth rates of all three variables are used in the estimation; after this logarithmic first-differencing, however, the data are not filtered or detrended in any other way.

The model has 24 parameters describing preferences, technologies, and the stochastic behavior of the exogenous shocks: β , θ_c , θ_i , ϕ_c , ϕ_i , κ_c , κ_i , ω_c , ω_i , a^g , z_c^g , z_i^g , ρ_a^l , ρ_a^g , ρ_c^l , ρ_c^g , ρ_i^l , ρ_i^g , σ_a^l , σ_a^g , σ_c^l , σ_c^g , σ_i^l , and σ_i^g . Of these, κ_c and κ_i are set equal to the model's implied steady-state investment-capital ratios in the two sectors so that, as mentioned above, capital adjustment costs equal zero in the steady state. The discount factor β is notoriously difficult to estimate with data on aggregate quantities only. Here, the setting $\beta = 0.99$ is also imposed prior to estimation so that, consistent with the frequency of the data, each period in the model can be interpreted naturally as one-quarter year in real time.

In addition, as shown in (29)-(31), the parameters a^g , z_c^g , and z_i^g serve primarily to determine the steady-state growth rates of aggregate consumption, investment, and hours worked along the model's balanced growth path. However, a^g and z_i^g also enter into the log-linearized versions of (2)-(28) that describe the model's dynamics. Constrained by these cross-equation restrictions, the maximum likelihood estimates of these parameters need not act to equate the steady-state growth rates of C_t , I_t , and H_t with the corresponding average

values of these variables as measured in the data. The danger then arises that the maximum likelihood routine, when in effect confronted with observable variables that appear to depart systematically from their steady-state values, will overstate the true degree of persistence in the exogenous shocks. Guarding against this possibility takes high priority here, where much of the focus is on obtaining accurate measures of the persistence in the sector-specific technology shocks. Hence, values for $a^g = 0.9999$, $z_c^g = 1.0050$, and $z_i^g = 1.0066$ are also fixed in advance, so that each of the three observable variables gets accurately de-measured prior to estimation. Finally, preliminary attempts to estimate the model lead consistently to values of θ_i , capital's share in the Cobb-Douglas production function for investment, lying near or up against the lower bound of zero. Once again, with a view towards making the model and its implications more sensible and easier to interpret, the setting $\theta_i = 0.15$ is also imposed prior to estimation.

3 Results

Table 1 shows maximum likelihood estimates of the model's 17 remaining parameters. The standard errors, also shown in Table 1, come from a parametric bootstrapping procedure similar to those used by Cho and Moreno (2005) and Malley, Philippopoulos, and Woitek (2005) and described in more detail by Efron and Tibshirani (1993, Ch.6). This procedure simulates the estimated model in order to generate 1,000 samples of artificial data for aggregate consumption, investment, and hours worked, each containing the same number of observations as the original sample of actual U.S. data, then re-estimates the model 1,000 times using these artificial data sets. The standard errors shown in Table 1 correspond to the standard deviations of the individual parameter estimates taken across these 1,000 replications.

The estimate of $\theta_c = 0.28$ for capital's share in the consumption-goods-producing sector lies above the value $\theta_i = 0.15$ that is preassigned to the corresponding parameter for the

investment-goods-producing sector, consistent with findings from previous work. In particular, Huffman and Wynne (1999) use sectoral U.S. data to estimate a factor income share for capital in producing consumption goods that is larger than the corresponding share for capital in producing investment goods. Similarly, Echevarria (1997) finds that across OECD countries, capital's factor income share in producing nondurables and services consistently exceeds capital's share in durable manufacturing.

The estimates of $\phi_c = 46.20$ and $\phi_i = 0.29$ imply that capital adjustment costs are much more important in the consumption-goods-producing sector, while the estimates of $\omega_c = 2.65$ and $\omega_i = 2.18$ imply that capital utilization is more elastic in the investment-goods-producing sector. While their standard errors are quite large, these point estimates themselves suggest that production processes are generally more flexible for investment goods than for consumption goods. In addition, the estimates of ω_c and ω_i imply a steady-state depreciation rate of 1.01 percent per quarter for capital used to produce consumption goods versus a steady-state depreciation rate of 1.41 percent per quarter for capital used to produce investment goods.

Of special interest here, of course, are the parameter estimates summarizing the volatility and persistence of each of the six shocks. The estimates $\sigma_a^l = 0.0038$, $\sigma_a^g = 0.0036$, $\sigma_c^l = 0.0050$, and $\sigma_c^g = 0.0049$, all of the same order of magnitude, suggest that disturbances to both the levels and growth rates of the preference shock A_t and the consumption-specific technology shock Z_{ct} have been important over the postwar sample period. But whereas the growth rate components of both shocks appear equally persistent, as reflected in the nearly identical estimates of $\rho_a^g = 0.5707$ and $\rho_c^g = 0.5711$, the level components differ considerably in their properties: the estimate of $\rho_a^l = 0.96$ indicates that disturbances to the level of the preference shock are highly persistent, while the estimate of $\rho_c^l = 0.00$ implies that disturbances to the level of the consumption-specific technology shock are serially uncorrelated.

Meanwhile, the investment-specific technology shock exhibits distinctive behavior of its

own. In particular, the estimates $\rho_i^l = 0.95$, $\sigma_i^l = 0.04$, and $\sigma_i^g = 0.00$ indicate that the data prefer a version of the model in which the investment-specific shock has a level component that is highly volatile and persistent but lacks altogether a stochastic growth rate component. Broadly consistent with the results obtained by Marquis and Trehan (2005), therefore, those shown here in Table 1 attribute the diverging evolution of productivity across the U.S. consumption- and investment-goods-producing sectors primarily to highly persistent consumption-specific, as opposed to investment-specific, technology shocks.

What lies behind these estimates, which assign very different properties to the various shocks? Here, it should be noted, the model's structural disturbances are identified based not on the timing assumptions, described by Hamilton (1994, Ch.11), that are frequently invoked in studies that work with less highly constrained vector autoregressive time-series models, but instead on the dynamic effects that the real business cycle model itself associates with each distinct type of shock. Thus, Figures 3-5 trace out the estimated model's implied responses of each observable variable to each of the shocks: Figure 3 collects the impulse responses to the preference shocks, while Figures 4 and 5 display the impulse responses to the consumption and investment-specific technology shocks.

As noted previously by Kimball (1994) and as shown in Figure 4, the two-sector real business cycle model has the striking implication that consumption-specific technology shocks impact only consumption, leaving investment and hours worked completely unchanged. Here, therefore, the two components of the consumption-specific technology shock are identified precisely as those that affect either the level or the growth rate of consumption itself without changing investment and employment. Figures 3 and 5 show that, by contrast, the preference and investment-specific technology shocks impact simultaneously all three observable variables. But whereas the shock to the level of A_t affects consumption, investment, and hours worked by roughly equal amounts, the shock to the level of Z_{it} generates a response in investment itself that is an order of magnitude larger than the coincident movements in consumption and hours worked.

The estimate of $\sigma_i^g = 0.00$ shown in Table 1 suggests that no shocks to the growth rate of investment-specific technology have hit the postwar U.S. economy, but the theoretical model can still be used to trace the effects those shocks would have had under the counterfactual assumptions that $\rho_i^g = 0.50$ and $\sigma_i^g = 0.01$ (these are the impulse responses shown in the second column of Figure 5). Lindé (2004) observes that in a standard one-sector real business cycle model, persistent shocks to the level of total factor productivity can be distinguished from persistent shocks to the growth rate of productivity based on their differing short-run effects on investment and hours worked: level shocks cause these variables to increase on impact, whereas growth-rate shocks cause these variables to fall. Figure 5 shows that this same result carries over to describe the effects of investment-specific technology shocks in this two-sector real business cycle model. Figure 3 reveals that investment also falls on impact following a growth-rate shock to preferences; in this case, however, hours worked increase immediately. In addition, while growth-rate shocks to preferences and investment-specific technology both have permanent effects on the levels of consumption and investment, the preference growth-rate shock permanently raises hours worked as well, whereas the investment-specific growth-rate shock leaves this variable unchanged in the long run. Hence, the estimate of $\sigma_i^g = 0.00$ obtained here ultimately reflects the fact that the maximum likelihood procedure cannot find evidence in the postwar U.S. data of any shocks that increase consumption but decrease investment and hours worked in the short run and increase consumption and investment but leave hours worked unchanged in the long run.

In light of this underlying intuition, one might suspect that the result indicating the absence of growth-rate shocks to investment-specific productivity hitting the postwar U.S. economy could have been anticipated: it might seem highly unlikely that any econometric method would find evidence of favorable technology shocks that reduce hours worked in the short run. Interestingly, however, a number of recent studies, including Galí (1999), Basu, Fernald, and Kimball (2004), and Francis and Ramey (2005), find that various identification procedures associate technology shocks with precisely this perverse property: they move pro-

ductivity and hours worked in opposite directions. Christiano, Eichenbaum, and Vigfusson (2003) and Chari, Kehoe, and McGrattan (2005) dispute these findings—the purpose here is not to help resolve this dispute, as Erceg, Guerrieri, and Gust (2005), Fernald (2005), and Galí and Rabanal (2005) attempt to do, but simply to point out that in light of this previous work the results obtained here are by no means preordained. Here, the extended real business cycle model with shocks to both levels and growth rates of productivity in distinct consumption- and investment-goods-producing sectors makes clear that different types of technology shocks have different short-run effects on hours worked: level shocks to the investment sector increase hours worked, level and growth-rate shocks to the consumption sector leave hours worked unchanged, and growth-rate shocks to the investment sector decrease hours worked on impact. Only after it is estimated with the postwar U.S. data does the model minimize the importance of the growth-rate shock to investment that initially moves productivity and hours worked in opposite directions.

The various insights gleaned from the impulse-response analysis also help explain the results shown in Table 2, which decomposes the forecast error variances in consumption, investment, and hours worked into percentages due to each of the model’s six shocks. Since consumption-specific technology shocks impact only on consumption, these shocks play no role in accounting for the variability in investment and hours worked. And since σ_i^g is estimated to be zero, investment-specific growth-rate shocks contribute nothing to the volatility of any variable. Instead, level shocks to investment-specific productivity and growth-rate shocks to preferences join together to explain most of the variability in both investment and hours worked.

Figure 6 goes a step further by plotting estimates that show how the various shocks themselves have evolved over the postwar period. All of these estimates reflect information contained in the full sample of data; that is, they are constructed using the Kalman smoothing algorithms described by Hamilton (1994, Ch.13) and generalized by Kohn and Ansley (1983) to accommodate cases like the one that arises here, in which the covariance matrix of

the unobserved state vector turns out to be singular. Consistent with the results derived by Basu, Fernald, Fisher, and Kimball (2005) and Marquis and Trehan (2005), the estimates shown in Figure 6 point to the consumption-goods-producing sector as the most significant source of the aggregate productivity slowdown of the 1970s. Here, in particular, the estimated level of total factor productivity in the consumption-goods-producing sector remains essentially unchanged from the beginning of 1973 through the middle of 1982. More generally, movements in the level of consumption-specific productivity appear to be enormously persistent, reflecting the importance of the growth-rate component of that sector-specific shock: the estimates of Z_{ct} lie above their deterministic trend for an extended period beginning in 1953 and ending in 1979, then spend nearly all of the period since 1979 below trend.

The investment-specific technology shock, by contrast, crosses over its deterministic trend line much more frequently over the full sample period. Like the results from Basu, Fernald, Fisher, and Kimball (2005) but unlike the results from Marquis and Trehan (2005), the estimates derived here show evidence of a productivity slowdown in the investment-goods-producing sector as well as the consumption goods sector. But whereas Basu, Fernald, Fisher, and Kimball's (2005) estimates suggest that the productivity slowdown occurred contemporaneously across the two sectors, here the investment-specific slowdown begins later—in fact, after the consumption-specific slowdown ends—and appears much less persistent as well: the level Z_{it} of productivity in investment peaks in the middle of 1984 and bottoms out in 1990. Viewed against this broader backdrop, the more recent period of robust growth in investment-specific productivity appears as a snap-back to trend following the earlier, transitory slowdown.

In Figure 6, consumption-specific productivity Z_{ct} , though persistent in its movements, ends the sample period growing at a rate that is quite close to its postwar average. Meanwhile, investment-specific productivity Z_{it} is less persistent and ends the sample period quite close to its long-run deterministic trend. Thus, when Figure 7 extends the series for these

two variables with forecasts running out through 2011, it shows that both are predicted to grow at average rates going forward. The estimated model, therefore, offers up a mixed view of the future. The good news is that the productivity slowdown appears to have ended in both sectors of the U.S. economy. The not-so-good news is that the model interprets the more recent episode of robust growth in investment and investment-specific productivity as largely representing a catch-up in levels after the previous productivity slowdown—hence, the model predicts that this recent episode of unusual strength is unlikely to persist or to be repeated anytime soon.

4 Summary and Extensions

The two-sector real business cycle model studied here implies that different types of technology shocks—to the levels versus the growth rates of productivity in distinct consumption-versus investment-goods-producing sectors—have very different effects on observable variables, including aggregate consumption, investment, and hours worked. Hence, when the model is estimated via maximum likelihood, these theoretical implications help to identify the realizations of these various shocks in the postwar U.S. data. The results of this estimation exercise point to the consumption-goods-producing sector as the principal source of the productivity slowdown of the 1970s. The results also show evidence of a productivity slowdown in the investment-goods-producing sector, but this investment-specific slowdown occurs later and is much less persistent than its consumption-specific counterpart. Viewed against this broader backdrop, the more recent episode of accelerated growth in investment and investment-specific technological change appears largely as a snap-back in levels to a long-run deterministic trend rather than a persistent shift in growth rates. Thus, the results offer up a mixed outlook for the future. The estimated model confirms that the productivity slowdown of the 1970s has ended. But it also suggests that the productivity revival of the 1990s is not likely to persist or be repeated. Instead, the model points to future productivity

growth rates in both sectors that match their healthy but unexceptional longer-run averages from the entire postwar period.

In work that relates most closely to this present study, Marquis and Trehan (2005) use data on investment goods prices as well as on aggregate quantities to distinguish between consumption and investment-specific technological change in the postwar U.S. economy. Basu, Fernald, Fisher, and Kimball (2005) exploit industry-level quantity data to pursue the same goal. The results obtained here echo some of those presented in these earlier studies. Consistent with earlier findings, for instance, the results obtained here highlight the central role played by the consumption-goods-producing sector during the productivity slowdown of the 1970s. But unlike results from Marquis and Trehan (2005), which suggest that the investment-goods-producing sector largely escaped the productivity slowdown, and unlike the results from Basu, Fernald, Fisher, and Kimball (2005), which suggest instead that productivity growth slowed coincidentally across the two sectors of the U.S. economy, the results obtained here point to a slowdown in investment-specific technological progress that came later and was less severe than the downturn in the consumption-specific sector. In addition, neither Marquis and Trehan (2005) nor Basu, Fernald, Fisher, and Kimball (2005) distinguishes between level and growth-rate shocks to the consumption and investment goods sectors in an effort to generate forecasts of future productivity growth that can be compared to those presented here.

Before closing, mention should be made of several possible extensions of the present analysis. First, the model developed here allows private agents to always distinguish perfectly between shocks to the levels and growth rates of sector-specific productivities. Edge, Laubach, and Williams (2004), by contrast, argue that private agents in the U.S. economy were slow to recognize the persistent shifts in productivity growth that occurred first during the 1970s and then again during the 1990s. Using a calibrated real business cycle model similar to the one that is estimated here, they also show that growth-rate shocks to consumption- and investment-specific technologies can have different effects when private agents lack full

information and instead must gradually learn about the magnitudes of those shocks. These results suggest that it would be fruitful to extend the present analysis by allowing for learning behavior on the part of U.S. households and firms.

Second, the model developed here treats the United States as a closed economy and therefore abstracts completely from the large and growing current account deficits that accompanied the most recent period of robust investment and investment-specific technological change. But Guerrieri, Henderson, and Kim (2005) calibrate an open economy real business cycle model with both level and growth-rate shocks to consumption- and investment-specific technologies and find that these different shocks also have different implications for the behavior of the trade balance. These results suggest that estimating an open-economy version of the model developed here ought to be another high priority for future research.

Third, the model developed here, like most other variants of the basic real business cycle model, includes a single, homogeneous capital stock that can be reallocated, albeit subject to adjustment costs, across distinct sectors of the economy. However, Tevlin and Whelan (2003) argue that in explaining the investment boom of the 1990s it is helpful to distinguish between different types of capital goods and to account more specifically for the special features of information technology capital. Tevlin and Whelan's results suggest additional insights could be found by estimating an extended version of the model developed here that disaggregates the total capital stock and assigns a key role to the capital goods associated with the information technology sector. Importantly, the results from such an exercise would also speak more directly to the issues debated by Gordon (2000) and Oliner and Sichel (2000) concerning the role of information technology in the productivity revival of the 1990s and the potential for that information-technology-driven growth to persist into the future.

A final caveat: the results derived here come from a model that is estimated with data extending back nearly six decades to 1948. This model captures the effects of structural changes of one particular kind by allowing for persistent shocks to both the levels and growth rates of total factor productivity in distinct consumption- and investment-goods-

producing sectors, but abstracts from the wider array of shifts in tastes, technologies, and government policies that may have influenced the evolution of the postwar U.S. economy. Precisely because it is based on the entire postwar sample, the analysis here can and does draw unexpected links, for instance, between the productivity slowdown of the 1970s and the subsequent revival of the 1990s. But to the extent that the “new economy” is truly new, data from the more distant past become less useful for understanding the present, and even greater optimism for the future may be called for.

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Table 1. Maximum Likelihood Estimates and Standard Errors

Parameter	Estimate	Standard Error
θ_c	0.2841	0.0374
ϕ_c	46.2019	36.1088
ϕ_i	0.2929	33.3471
ω_c	2.6524	1.5895
ω_i	2.1780	18.1582
ρ_a^l	0.9630	0.0938
ρ_a^g	0.5707	0.0760
ρ_c^l	0.0000	0.0465
ρ_c^g	0.5711	0.1519
ρ_i^l	0.9529	0.0320
ρ_i^g	—	—
σ_a^l	0.0038	0.0014
σ_a^g	0.0036	0.0007
σ_c^l	0.0050	0.0008
σ_c^g	0.0049	0.0012
σ_i^l	0.0397	0.0040
σ_i^g	0.0000	0.0023

Notes: During the estimation, the constraints $\beta = 0.99$ and $\theta_i = 0.15$ are imposed, κ_c and κ_i are set to make steady-state capital adjustment costs equal to zero, and a^g , z_c^g , and z_i^g are set to de-mean the series for the growth rates of consumption, investment, and hours worked. The parameter ρ_i^g is unidentified, given the point estimate of $\sigma_i^g = 0.0000$.

Table 2. Forecast Error Variance Decompositions**Consumption**

Quarters Ahead	ε_a^l	ε_a^g	ε_c^l	ε_c^g	ε_i^l	ε_i^g
1	18.6	22.4	28.9	28.1	2.1	0.0
4	10.6	30.9	4.2	46.2	8.1	0.0
8	7.5	31.7	1.6	48.4	10.9	0.0
12	6.1	32.6	0.9	48.5	11.9	0.0
20	4.6	34.9	0.5	48.3	11.7	0.0
40	2.8	39.9	0.2	48.2	8.9	0.0

Investment

Quarters Ahead	ε_a^l	ε_a^g	ε_c^l	ε_c^g	ε_i^l	ε_i^g
1	0.2	4.4	0.0	0.0	95.3	0.0
4	0.4	14.0	0.0	0.0	85.6	0.0
8	0.4	22.7	0.0	0.0	76.9	0.0
12	0.4	27.1	0.0	0.0	72.5	0.0
20	0.4	33.0	0.0	0.0	66.6	0.0
40	0.4	40.1	0.0	0.0	59.5	0.0

Hours Worked

Quarters Ahead	ε_a^l	ε_a^g	ε_c^l	ε_c^g	ε_i^l	ε_i^g
1	84.2	7.1	0.0	0.0	8.7	0.0
4	13.5	68.9	0.0	0.0	17.6	0.0
8	8.9	74.4	0.0	0.0	16.7	0.0
12	7.8	77.9	0.0	0.0	14.3	0.0
20	6.6	83.2	0.0	0.0	10.2	0.0
40	4.7	88.8	0.0	0.0	6.5	0.0

Note: Entries decompose the forecast error variance of each variable at each horizon into percentages due to each of the model's six shocks.

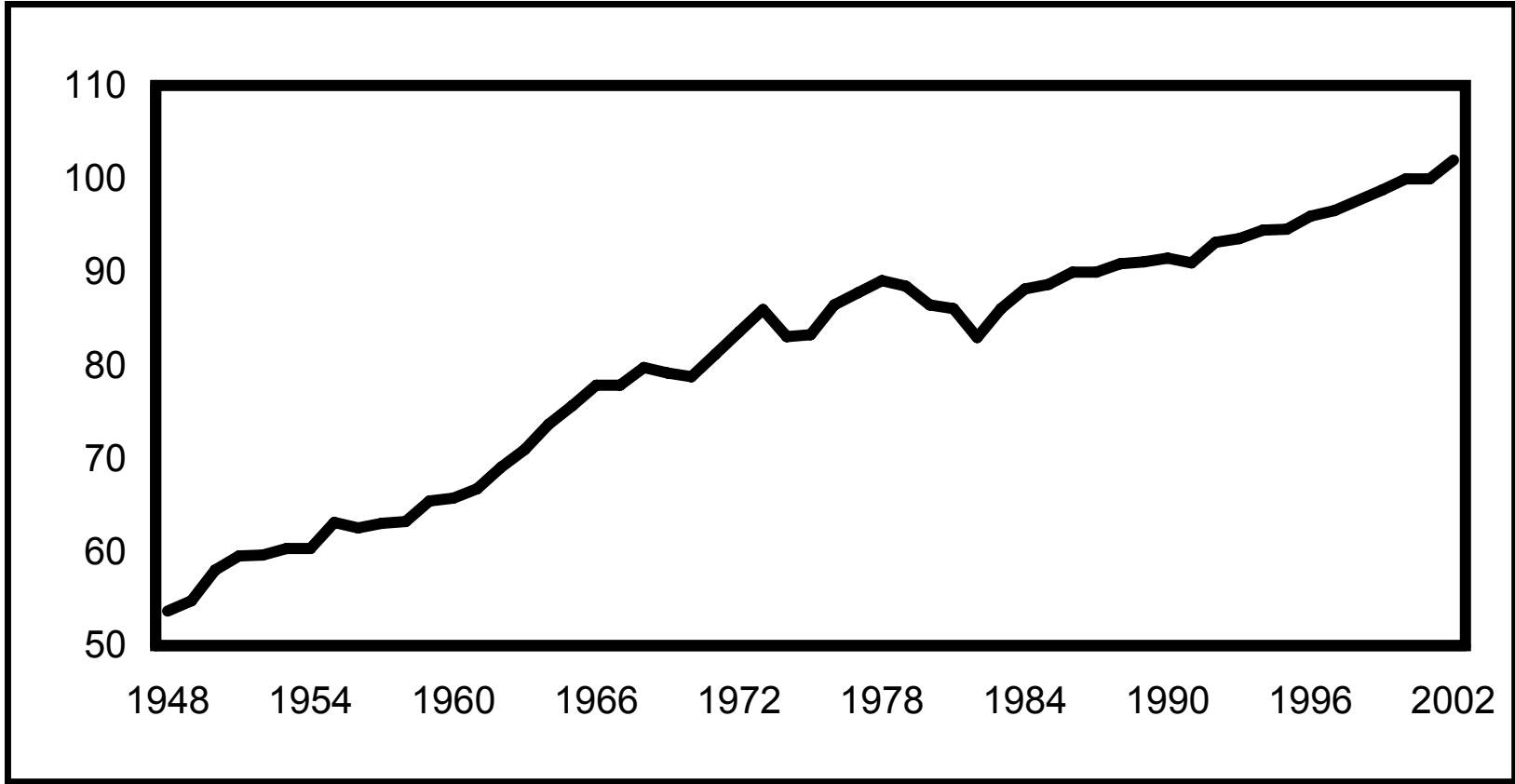


Figure 1. Multifactor Productivity, U.S. Private Nonfarm Business Sector (Index, 2000=100).

Source: Bureau of Labor Statistics.

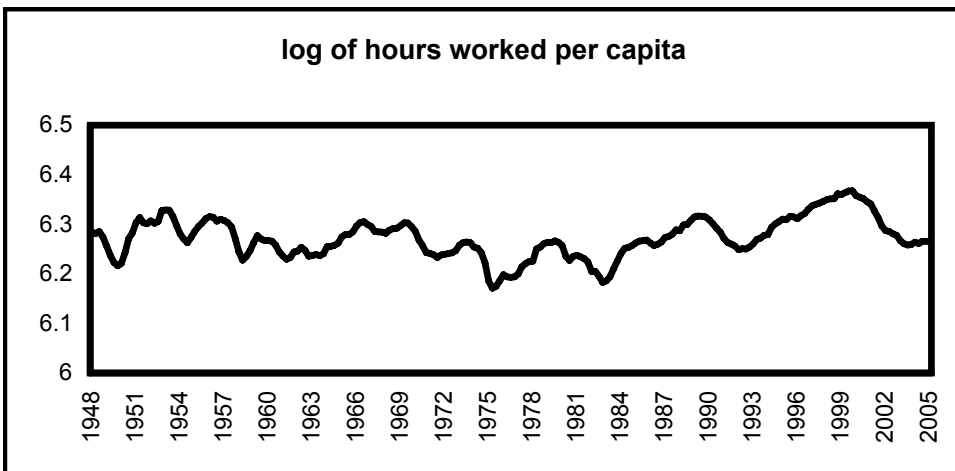
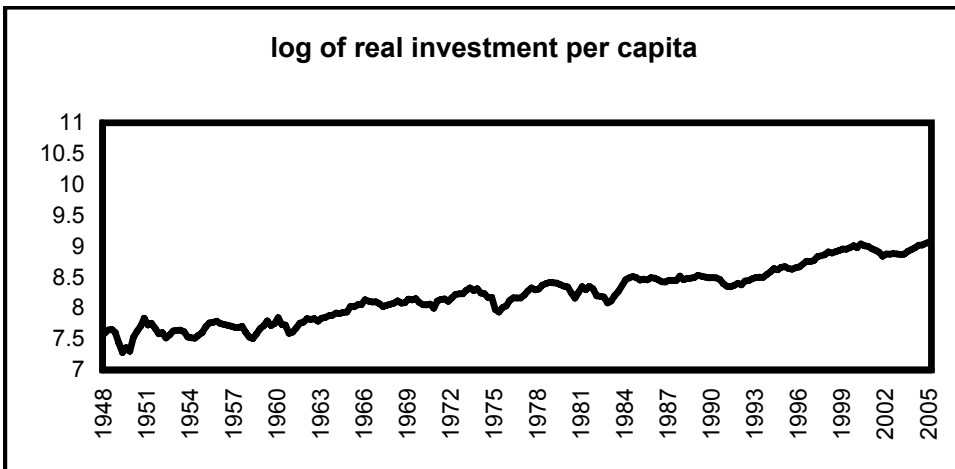
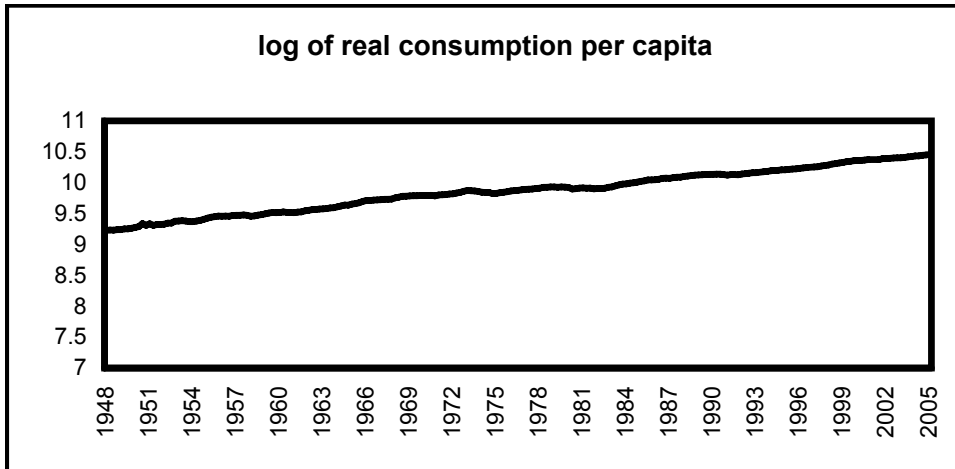


Figure 2. Postwar U.S. Data. Consumption and investment are expressed in chained 2000 dollars. Hours worked are indexed, 1992=100. Source: Federal Reserve Bank of St. Louis.

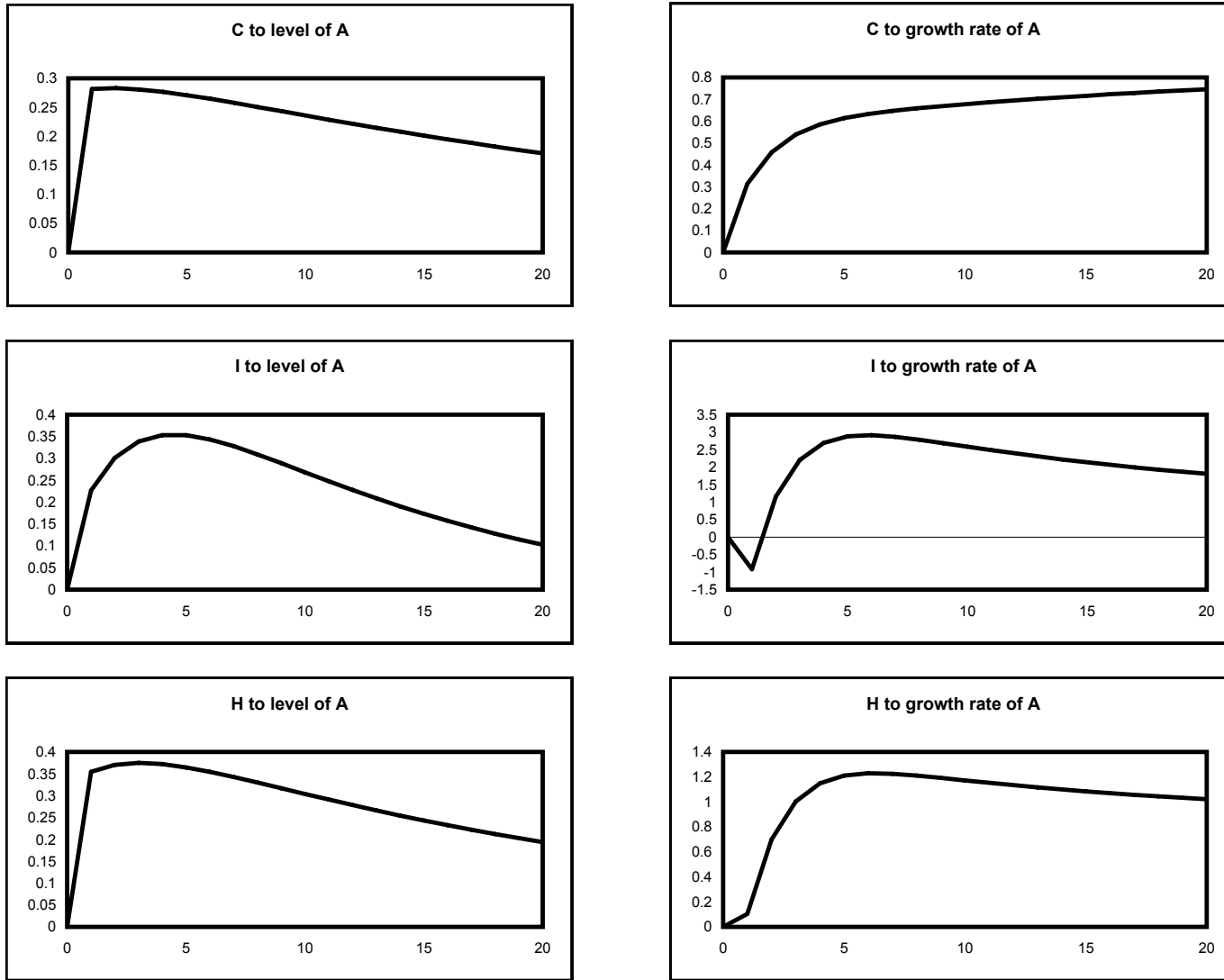


Figure 3. Impulse Responses to Preference Shocks. Each panel shows the percentage-point response of aggregate consumption (C), investment (I), or hours worked (H) to a one-standard-deviation shock to the level or growth rate of the preference parameter A.

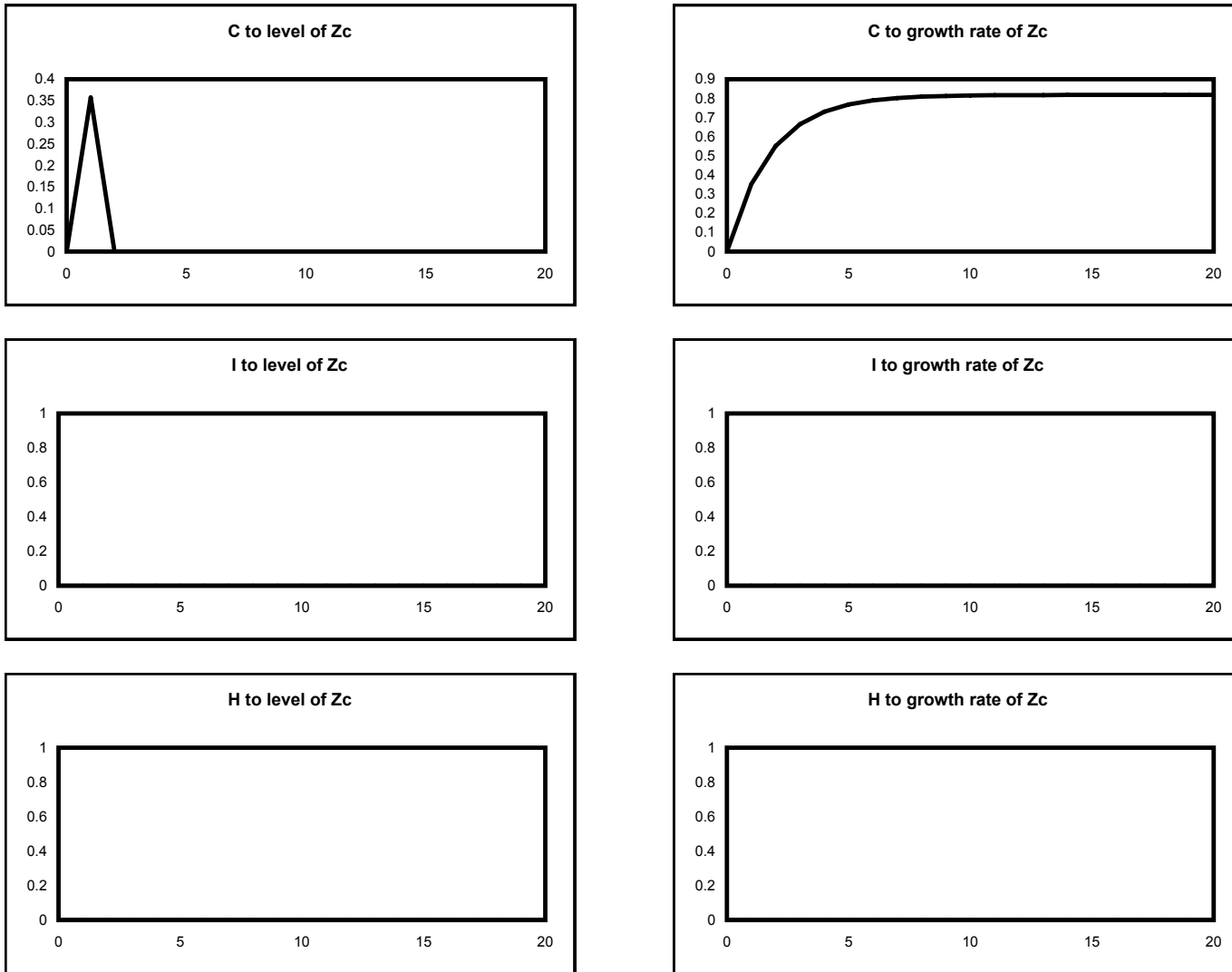


Figure 4. Impulse Responses to Consumption-Sector Technology Shocks. Each panel shows the percentage-point response of aggregate consumption (C), investment (I), or hours worked (H) to a one-standard-deviation shock to the level or growth rate of productivity Z_c in the consumption-goods-producing sector.

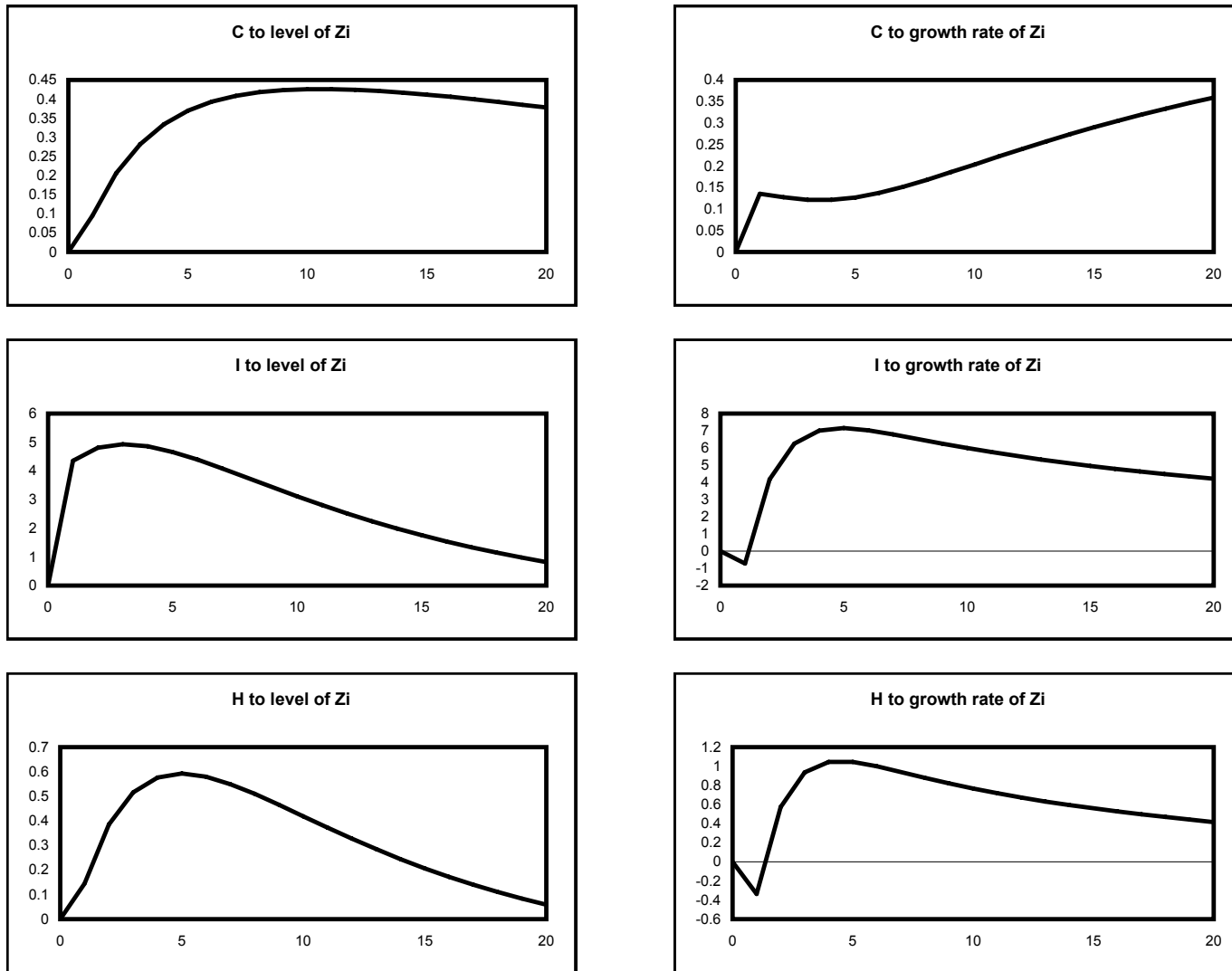


Figure 5. Impulse Responses to Investment-Sector Technology Shocks. Each panel shows the percentage-point response of aggregate consumption (C), investment (I), or hours worked (H) to a one-standard-deviation shock to the level or growth rate of productivity Z_i in the investment-goods-producing sector.

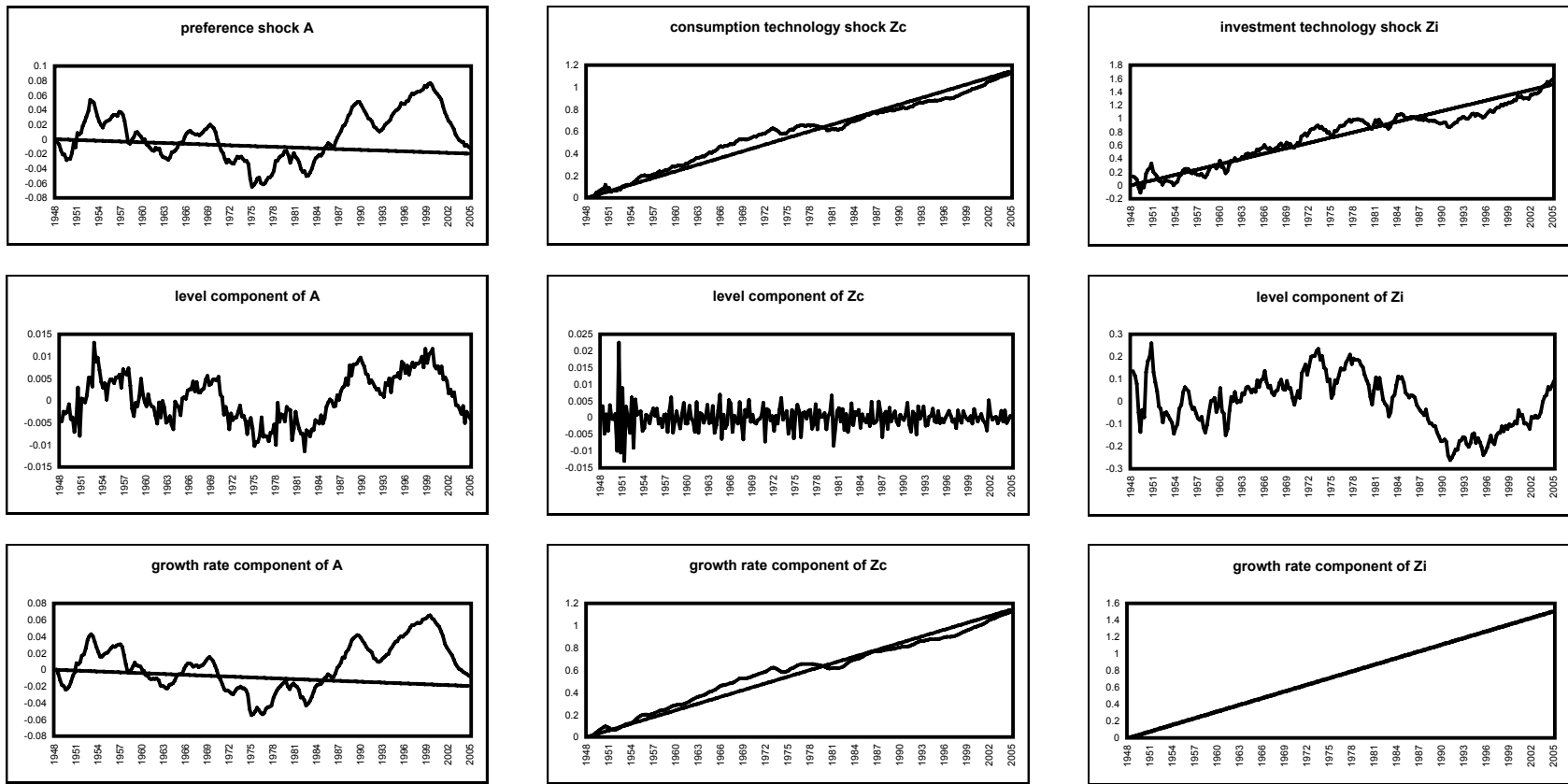


Figure 6. Smoothed (Full-Sample) Estimates of Preference and Technology Shocks, Decomposed into Level and Growth-Rate Components. All variables shown in logs.

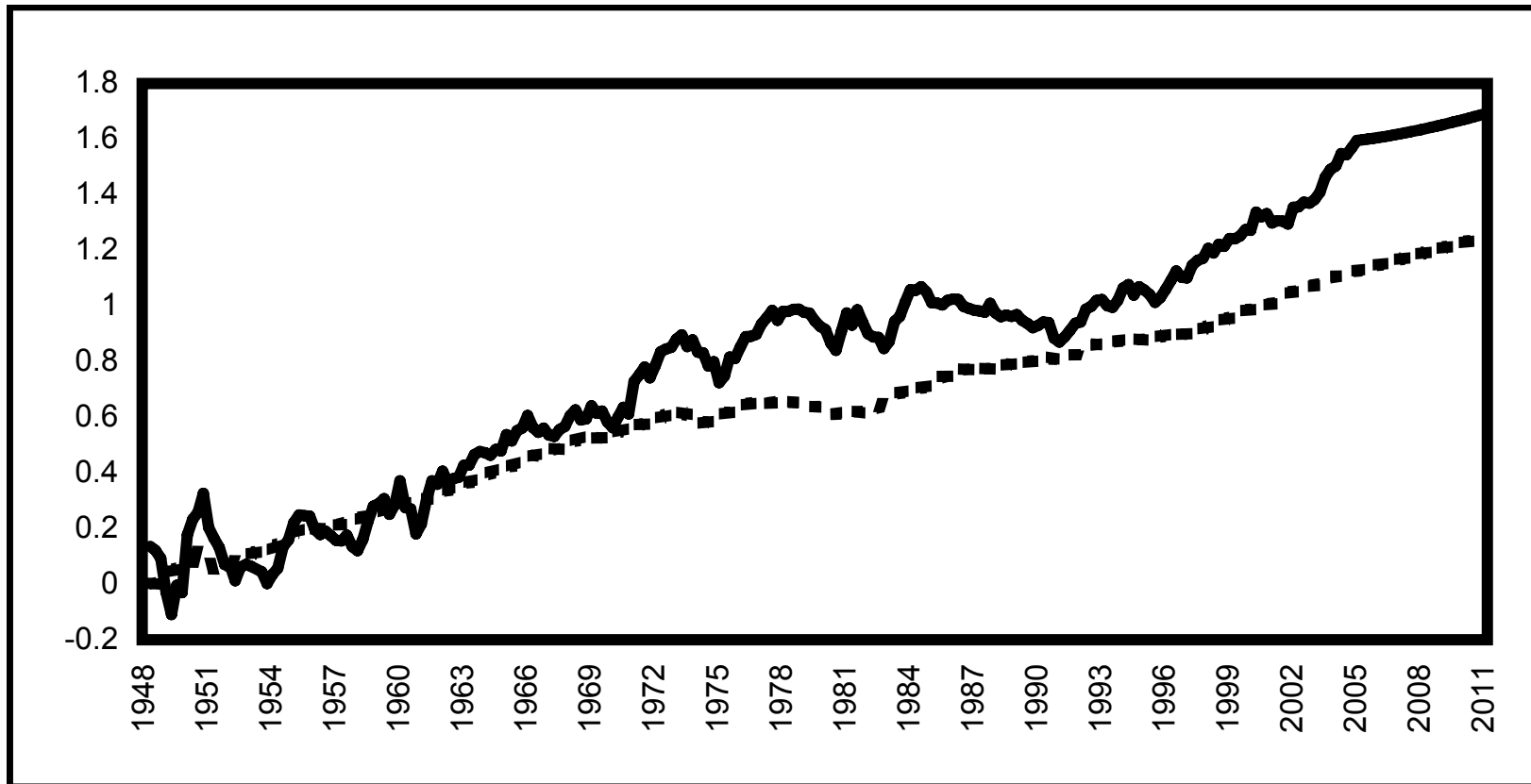


Figure 7. Logs of Productivity in the Consumption- (Z_c , dotted line) and Investment- (Z_i , solid line) Goods-Producing Sectors. Estimated through 2005:1 and forecast through 2011:1.