

# News Shocks and Learning-by-doing\*

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## Abstract

The idea that expectations about future economic fundamentals can drive business cycles dates back to the early twentieth century. However, the standard real business cycle (RBC) model fails to generate positive comovement in output, consumption, labor-hours and investment in response to news shocks. This paper proposes a simple and intuitive solution to this puzzling feature of the RBC model, based on a mechanism that has strong empirical support: learning-by-doing (LBD). First, we show that the one-sector RBC model augmented by LBD can generate aggregate comovement in response to news shock about technology. Second, we show that in the two-sector RBC model, LBD along with an intratemporal adjustment cost can generate sectoral comovement in response to news about three types of shocks: i) neutral technology shock, ii) consumption technology shock, and iii) investment technology shock. We show that these results hold for contemporaneous technology shocks and for different specifications of LBD.

*Keywords:* News Shocks, Learning-by-Doing, Pigou Cycles.

*JEL Classification:* E3.

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# 1 Introduction

The idea that expectations about future economic fundamentals can drive business cycles dates back to the early twentieth century (e.g. Pigou (1927) and Clark (1934)). Recently there has been a renewed interest in expectation shocks (the so-called “news shocks”) as a source of business cycle fluctuations. However, the standard real business cycle (RBC) model fails to generate an economic expansion in which consumption, investment and labor-hours all rise relative to their trends, in response to positive news about future technology. On the contrary, it generates a recession today in response to positive news. Good news generates a positive wealth effect today causing households to increase their consumption and leisure. Hence labor-hours and consequently output decrease. The decline in output along with an increase in consumption requires investment to decrease. Thus consumption increases while labor-hours, investment, and output decrease in response to positive news. This counterintuitive characteristic of the RBC model was first documented by Barro and King (1984) and later examined by Beaudry and Portier (2004, 2008).

This paper proposes a simple and intuitive solution to this puzzling feature of the RBC model, based on learning-by-doing (henceforth, LBD). Several micro-studies, including Bahk and Gort (1993), Benkard (1997), and Imai (2000) have estimated LBD and have found strong empirical support. Recent studies have also investigated the role of LBD in generating richer macroeconomic dynamics. Two prominent works in the macroeconomic literature that incorporate LBD into general equilibrium models are those by Chang, Gomes and Schorfheide (2002) (CGS (2002)), and Cooper and Johri (2002) (CJ (2002)). CGS (2002) model learning through skill accumulation (LBD via Skill) that captures the effects of past work experience on labor productivity. CJ (2002) model learning through the accumulation of organizational capital (LBD via Organizational Capital), which is a by-product of the production process; the idea being that production activity creates information about the organization which improves future productivity. Hence, learning in CGS (2002) is associated with labor-hours while learning in CJ (2002) depends on the overall production activity or output. These studies find empirical evidence for LBD and show that it can provide an important propagation mechanism in business cycle models. We introduce LBD along the lines of these studies into the standard one-sector RBC model and show that the model, under both these specifications of LBD, is capable of generating an economic expansion in response to positive news about future technology. Such news increases the value of LBD immediately, which induces the economic agents to accumulate it by increasing production as soon as the news arrives. Hence the LBD mechanism provides a countervailing force to the negative wealth effect on labor supply from positive news. The resulting increase in output is large enough to accommodate increases in both consumption and investment. As learning increases the productivity of factor-inputs, labor-hours and investment continue to rise in subsequent periods. Consequently, the model generates an expansion in response to the positive news.

We also investigate the role of LBD in generating sectoral comovement in response to news about three types of shock: neutral technology shock, investment technology shock, and consumption technology shock. Several studies including Lucas (1977), and Burns and Mitchell (1946) emphasize the importance of sectoral comovement in developing a single unified theory of business cycles. Huffman and Wynne (1999) document that labor-hours and investment across sectors comove and are procyclical. However, the two-sector version of RBC model cannot generate sectoral or aggregate comovement in response to contemporaneous shocks or news shock about future technology. As a result of the the infinite elasticity of substitution between investment across sectors and between labor in the two sectors, investment and employment across sectors are very volatile and move in opposite direction in the benchmark model. Consequently, we follow Huffman and Wynne (1999) and introduce an intratemporal investment adjustment cost, which helps in generating comovement in response to contemporaneous shocks, but not news shocks. This is because the model still lacks any propagation mechanism that can compensate for the negative wealth effect on labor supply from positive news about future technology. We show that LBD can provide a countervailing force that can offset this negative wealth effect in the two-sector model. Accordingly, LBD along with intratemporal investment adjustment cost can generate sectoral and aggregate comovement in response to contemporaneous and news shocks about technology.

Our paper is related to the emerging literature on news driven business cycles. Prominent works include Beaudry and Portier (2004), who propose a multi-sectoral durable and non-durable goods model that can produce an expansion in response to positive news about technology in the non-durable goods sector. Jaimovich and Rebelo (2008) generate news driven expansions by appending three features into the RBC model: variable capital utilization, investment adjustment cost, and special type of preferences that reduce the negative wealth effect on labor supply. Christiano et al. (2007) add habit formation and investment adjustment costs in their benchmark model, while including additional nominal frictions into their full model. Schmitt-Grohe and Uribe (2008) estimate a structural Bayesian model that incorporates both anticipated and unanticipated components of various shocks, and find that anticipated (news) shocks to technology can account for more than two-thirds of business cycle fluctuations in the U.S.<sup>1</sup> A recent study that is closest to our paper is by Christopher Gunn and Alok Johri (2009) (GJ (2009), henceforth).<sup>2</sup> They show that ‘knowledge capital,’ which is produced through a learning-by-doing process, can generate a boom in the aggregate economy and equity prices. While there are obvious similarities, we believe there are at least two differences in our paper. First, GJ (2009) model knowledge capital associated with labor-hours,

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<sup>1</sup>Other papers in this literature include the early works of Beveridge (1909), Pigou (1927), and Clark (1934) with more recent work done by Dupor and Mehkari (2009), Mehkari (2008), Nah (2009), Beaudry and Portier (2008), Li and Mehkari (2009), Den haan and Kaltenbrunner (2007), Eusepi (2008), and Lorenzi (2005).

<sup>2</sup>I had written the first draft of my paper and had presented it before I became aware of GJ (2002).

which corresponds to the ‘LBD via Skill’ specification. In addition to this specification, we examine another specification of LBD that is popular in the macroeconomic literature, namely ‘LBD via Organizational Capital’. Second, and more importantly, while GJ (2009) examine aggregate comovement in response to news about a neutral technology shock in a one-sector model, this paper, in addition to the one-sector model, also examines sectoral comovement in a two-sector model in response to news about three types of shocks: neutral technology shock, consumption technology shock, and investment technology shock.

The rest of the paper is organized as follows. In Section 2 we explore the role of LBD in generating news driven expansions in a one-sector economy. We examine two different specifications of learning that are popular in the macroeconomic literature and show that the model with both the specifications of LBD can generate news driven booms. In section 3 we present a two-sector version of our model that can generate sectoral and aggregate comovement with respect to contemporaneous and news shocks about future technologies. The final section concludes.

## 2 The One-Sector Economy

In this section we explore the ability of learning-by-doing in generating news driven expansions in a one-sector RBC model. Several empirical studies have examined LBD and have found substantial evidence for it in micro datasets, in that production costs decrease and productivity increases with cumulative output. Some recent studies have also examined aggregate implications of LBD by incorporating it in dynamic general equilibrium models. Two prominent works in the macroeconomic literature that incorporate LBD into general equilibrium models are those by Chang, Gomes and Schorfheide (2002) (henceforth, CGS (2002)), and Cooper and Johri (2002) (henceforth, CJ (2002)).

CGS (2002) examine LBD associated with labor effort. They model a skill accumulation process that captures the effects of past work experience on labor productivity. They estimate the LBD parameters using a Bayesian approach that combines the micro-level panel data with the aggregate time-series data. They find that the LBD mechanism is capable of generating richer macroeconomic dynamics. CJ (2002) model LBD through organizational capital, which is a by-product of the production process; the idea being that production activity creates information about the organization which improves future productivity. They estimate the LBD parameters using sector and plant-level data and find that LBD can provide an important propagation mechanism in business cycle models. The key difference in the LBD mechanism of CGS (2002) and CJ (2002) is that while in the former learning is only associated with labor-hours, learning in the latter depends on the overall production activity or output.

In this section, we augment the standard one-sector RBC model with LBD along the lines of

these studies. We first introduce learning through skill accumulation as outlined in CSG (2002), *LBD via Skill*. Next, we follow CJ (2002) and introduce learning through the accumulation of organizational capital, *LBD via Organizational Capital*. Subsequently, we examine the role of these LBD mechanisms in generating aggregate comovement in response to news shocks.

## 2.1 Model

The model economy is populated with many identical agents who maximize their expected discounted lifetime utility defined over consumption,  $c_t$ , and labor-hours worked,  $n_t$ :

$$U = E_0 \sum_{t=0}^{\infty} \beta^t \left[ \frac{c_t^{(1-\sigma)}}{(1-\sigma)} - \psi n_t \right] \quad (2.1)$$

The physical capital evolution is given by:

$$k_{t+1} = I_t + (1 - \delta_k)k_t \quad (2.2)$$

where  $\delta_k$  is the depreciation rate of the capital stock. Output is the economy can be used for production or consumption:

$$c_t + I_t = y_t \quad (2.3)$$

### 2.1.1 LBD via Skill

We follow CGS (2002) and assume that experience from past employment is identified with skill level,  $x_t$ . The skill accumulation process is given by:

$$\ln \left( \frac{x_{t+1}}{x} \right) = \phi \ln \left( \frac{x_t}{x} \right) + \mu \ln \left( \frac{n_t}{n} \right) \quad 0 \leq \phi < 1, \mu \geq 0 \quad (2.4)$$

where variables without the time subscript denote the steady-states. This process captures that skill level is augmented by labor-hours worked in the past and it depreciates over time ( $\phi < 1$ ). Output in the economy is produced using constant-returns-to-scale Cobb-Douglas technology in physical capital,  $k_t$ , and labor-input,  $h_t$ :

$$y_t = k_t^\alpha h_t^{(1-\alpha)} a_t \quad (2.5)$$

where  $a_t$  is an exogenous technology shock. The labor-input in the production function consists of labor-hours worked and the skill level:

$$h_t = n_t x_t \quad (2.6)$$

Hence skill raises the effective unit of labor supplied. Combining (2.3) with (2.5) and (2.6), the recourse constraint becomes:

$$c_t + I_t = k_t^\alpha (n_t x_t)^{(1-\alpha)} a_t \quad (2.7)$$

The social planner's problem for this economy with skill accumulation is to maximize (2.1) subject to (2.2), (2.4), and (2.7).<sup>3</sup>

The first order conditions to the planner's problem are:

$$c_t^{-\sigma} = \lambda_t \quad (2.8)$$

$$\psi = \lambda_t (1 - \alpha) \left( \frac{k_t}{n_t} \right)^\alpha x_t^{(1-\alpha)} a_t + \Lambda_t \frac{\mu}{n} \left( \frac{x_t}{x} \right)^\phi \left( \frac{n_t}{n} \right)^{(\mu-1)} \quad (2.9)$$

$$\lambda_t = \beta \lambda_{t+1} \left( (1 - \delta_k) + \alpha \left( \frac{x_{t+1} n_{t+1}}{k_{t+1}} \right)^{(1-\alpha)} a_{t+1} \right) \quad (2.10)$$

$$\frac{\Lambda_t}{x} = \beta \frac{\Lambda_{t+1}}{x} \phi \left( \frac{x_{t+1}}{x} \right)^{(\phi-1)} \left( \frac{n_{t+1}}{n} \right)^\mu + \beta \lambda_{t+1} (1 - \alpha) \left( \frac{k_{t+1}}{x_{t+1}} \right)^\alpha n_{t+1}^{(1-\alpha)} a_{t+1} \quad (2.11)$$

where  $\lambda_t$  and  $\Lambda_t$  are the Lagrange multipliers associated with the aggregate constraint (2.7) and skill accumulation (2.4), respectively.

The first-order condition for labor-hours (2.9) differs from that of a standard RBC model by the second term in (2.9), which captures the marginal value of skill generated by an extra labor-hour. This second term, which is absent in the standard RBC model, is crucial in generating positive comovement in labor-hours and consumption in response to news shock about future technology. To see this, consider (2.9) without the second term and substitute out  $\lambda_t$ :

$$\psi c_t^\sigma = (1 - \alpha) \left( \frac{k_t}{n_t} \right)^\alpha x_t^{(1-\alpha)} a_t \quad (2.12)$$

This would correspond to the first-order condition for labor-hours in the RBC model, except for the skill term. The above equation shows that it is not possible to get positive comovement between labor-hours and consumption when the news shock occurs. When positive news about future productivity arrives, technology remains at steady-state. Skill and physical capital are state variables and are thus predetermined; they also remain at the steady-state level. Hence as consumption increases, labor-hours must decrease. This explains why the standard RBC model fails to generate positive comovement between labor-hours and consumption. The economics behind increase in consumption and decrease in labor-hours in response to positive news is as follows. The economic agents feel wealthier today as the good news about future technology arrives. Thus they

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<sup>3</sup>CSG (2002) present a decentralized version of this economy. It is straightforward to verify that the solution to the planner's problem is identical to that of the decentralized economy.

increase their consumption and work less hours. The addition of the second term in (2.9) allows for the possibility of positive comovement since the shadow value of skill,  $\Lambda_t$ , increases in response to positive news, as we will discuss shortly. Rewriting (2.9) gives:

$$\frac{\psi}{\lambda_t} = (1 - \alpha) \left( \frac{k_t}{n_t} \right)^\alpha x_t^{(1-\alpha)} a_t + \frac{\Lambda_t \mu}{\lambda_t n} \left( \frac{x_t}{x} \right)^\phi \left( \frac{n_t}{n} \right)^{(\mu-1)} \quad (2.13)$$

The above equation shows that the planner equates the marginal rate of substitution between consumption and labor-hours to the sum of the marginal product of labor and the marginal value of skill (in terms of consumption) generated from increasing labor-hours by one unit.

The first-order condition for physical capital (2.10) is the same as that in standard RBC model, except for the skill term. First-order condition for skill (2.11) shows that the marginal value of skill,  $\Lambda_t$ , depends on next period's technology. Log linearizing (2.11) around the non-stochastic steady state and rearranging shows that the shadow value of skill depends on the discounted sum of expected future technology. Consequently, marginal value of skill increases immediately in response to positive news about future technology. As we will discuss shortly, this increase in marginal value of skill induces the social planner to invest in skill when the positive news arrives, which leads to a boom in macroeconomic aggregates.

### 2.1.2 LBD via Organizational Capital

So far we have introduced LBD through skill accumulation. We now explore the second specification of LBD that is popular in the literature: LBD through the accumulation of organizational capital. CJ (2002) model organizational capital as a by-product of the production process; the idea being that production activity creates information about the organization which improves future productivity. In this specification learning depends on the overall production activity (labor-hours, physical capital and productivity) as opposed to only labor-hours in case of LBD via Skill.

The organizational capital is accumulated indirectly through the production process and its evolution is given by:

$$\ln(x_{t+1}) = \gamma \ln(x_t) + \tau \ln(y_t) \quad (2.14)$$

where  $x_t$  is the stock of organizational capital. The production technology converts its inputs of physical capital, labor-hours, and organizational capital into output:

$$y_t = k_t^\theta n_t^\nu x_t^\omega a_t \quad (2.15)$$

where  $a_t$  represents an exogenous technology shock. Substituting (2.15) into the organizational capital accumulation equation (2.14), we obtain:

$$x_{t+1} = x_t^{\gamma_x} n_t^{\gamma_n} k_t^{\gamma_k} a_t^{\gamma_a} \quad (2.16)$$

where  $\gamma_x = \gamma + \tau\omega$ ,  $\gamma_n = \tau\nu$ ,  $\gamma_k = \tau\theta$ , and  $\gamma_a = \tau$ . The aggregate constraint can be written as:

$$c_t + I_t = k_t^\theta n_t^\nu x_t^\omega a_t \quad (2.17)$$

We solve the model with organizational capital as a social planner's problem.<sup>4</sup> The planner maximizes (2.1) subject to (2.2), (2.16), and (2.17). The first-order conditions to the planner's problem are:

$$c_t^{-\sigma} = \lambda_t \quad (2.18)$$

$$\psi = \lambda_t \nu n_t^{\nu-1} k_t^\theta x_t^\omega a_t + \Lambda_t x_t^{\gamma_x} \gamma_n n_t^{\gamma_n-1} k_t^{\gamma_k} a_t^{\gamma_a} \quad (2.19)$$

$$\lambda_t = \beta \lambda_{t+1} \left( (1 - \delta_k) + \theta k_{t+1}^{(\theta-1)} n_{t+1}^\nu x_{t+1}^\omega a_{t+1} \right) + \beta \Lambda_{t+1} x_{t+1}^{\gamma_x} n_{t+1}^{\gamma_n} \gamma_k k_{t+1}^{\gamma_k-1} a_{t+1}^{\gamma_a} \quad (2.20)$$

$$\Lambda_t = \beta \Lambda_{t+1} \gamma_x x_{t+1}^{\gamma_x-1} n_{t+1}^{\gamma_n} k_{t+1}^{\gamma_k} a_{t+1}^{\gamma_a} + \beta \lambda_{t+1} k_{t+1}^\theta n_{t+1}^\nu \omega x_{t+1}^{(\omega-1)} a_{t+1} \quad (2.21)$$

where  $\Lambda_t$  and  $\lambda_t$  are the Lagrange multipliers corresponding to (2.16) and (2.17), respectively. The first-order condition for labor-hours differs from that of a standard RBC model by the second term in (2.19), which captures the value of organizational capital generated by an extra labor-hour. It shows that the planner equates the marginal rate of substitution between consumption and labor-hours to the sum of the marginal product of labor and the marginal value of organizational capital (in terms of consumption) generated from increasing labor-hours by one unit.

The first-order condition with respect to physical capital can be rewritten as:

$$\frac{\lambda_t}{\lambda_{t+1}} = \beta(1 - \delta_k) + \beta \theta k_{t+1}^{(\theta-1)} n_{t+1}^\nu x_{t+1}^\omega a_t + \beta \frac{\Lambda_{t+1}}{\lambda_{t+1}} x_{t+1}^{\gamma_x} n_{t+1}^{\gamma_n} \gamma_k k_{t+1}^{\gamma_k-1} \quad (2.22)$$

The above equation differs from that of the standard RBC model or the model with skill accumulation by the last term in (2.22), which captures that physical capital also contributes to the accumulation of organizational capital. Hence increasing physical capital by one unit today results in discounted undepreciated capital tomorrow, increases output, and raises the organizational capital. The planner, therefore, equates the inter-temporal marginal rate of substitution in consumption to the discounted sum of discounted undepreciated capital, the marginal product of capital, and the marginal value of organizational capital (in terms of consumption) generated from increasing

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<sup>4</sup>CJ (2002) solve their model as a social planner's problem since it allows them to be agnostic about the question of whether the organizational capital is firm-specific or worker-specific.



physical capital by an additional unit.

The first-order condition for organizational capital is similar to that of skill discussed above, in that the marginal value of organizational capital,  $\Lambda_t$ , depends on future technology. Consequently, marginal value of organizational capital increases immediately in response to positive news about future technology. As we will discuss shortly, this increase in the value of organizational capital induces the economic agents to investment in it by increasing production immediately, which results in a news driven expansion.

## 2.2 Results

We now present numerical results to the one-sector economy that is calibrated to standard values found in the literature. We interpret one model economy period to be a quarter.

### Structure of News Shocks

The structure of the shock to future productivity, news shock, takes the following form introduced by Christiano et al. (2007):

$$\ln(a_t) = \rho_a \ln(a_{t-1}) + \widetilde{e_{t-p}} - e_t \quad (2.23)$$

where  $\widetilde{e_{t-p}}$  represents a news shock and  $e_t$  represents a contemporaneous shock. Under this specification, in period 1 the planner (unexpectedly) gets the news that productivity will change after  $p$  periods. However, depending on the value of  $e_{t+p}$ , this news may or may not turn out to be true in period  $p+1$ , which is the period of expected change in productivity. In the benchmark case, the news turns out to be true,  $e_t = 0$ ; hence, the news is realized. If  $e_t = \widetilde{e_{t-p}}$ , then the news is false; thus the news is not realized.

### Calibration

Model is calibrated to standard values used in the literature. We set share of capital in the production function,  $\alpha$ , to 0.34, and set the capital depreciation rate,  $\delta_k$ , to 0.025. The subjective discount rate,  $\beta$ , is set to 0.99, implying an annual steady-state real interest rate of 4 percent. Following Christiano et al. (2007), we set  $\rho_a$  to 0.83 and  $p$  to 4 so that the news about technology is four quarters into the future.

The LBD parameters are based on empirical estimates in CGS (2002) and CJ (2002). In the skill accumulation specification, we set the LBD parameters to the posterior means in CGS (2002):  $\phi$  and  $\mu$  are set to 0.8 and 0.11, respectively. In the organizational capital specification, the LBD parameters  $\omega$ ,  $\gamma$ , and  $\tau$  are based on empirical estimates in CJ (2002) and are set to 0.3, 0.5, and 0.5, respectively. The capital share,  $\theta$ , and labor share,  $\nu$ , in the production process under this specification are also 0.34 and 0.66, respectively. Setting the LBD parameters to zero under both the specifications reduces the models to the RBC model. This allows us to compare the responses

of the LBD model with the RBC benchmark.

The relative risk aversion,  $\sigma$ , is set to 0.6, which is lower than the usual value of unity for log utility; however, it is well within the range of empirical estimates in the literature (Beaudry and Wincoop (1996), Vissing-Jorgensen and Attanasio (2003), and Mulligan (2002)). The choice of  $\sigma$  less than 1 (higher intertemporal elasticity of substitution) implies a smaller wealth effect on labor supply in the model. Nevertheless, the model can generate an expansion in response to positive news with log utility if the learning effect is amplified. For example, setting  $\mu$  to  $(1 - \phi)$ , so that there is CRS in the skill accumulation process, can produce a new driven expansion with log utility.

## Numerical Results

We start out by examining the impulse responses to a positive news shock to the model without any LBD mechanism. The model is calibrated to the values discussed above except that the LBD parameters are set to 0. Consequently, the model reduces to the standard RBC model. Figure 1 shows that the RBC model generates a recession today in response to positive news about future technology; output, investment and labor-hours all decrease until period 4 as the positive news arrives in period 1. Consumption, on the other hand, increases due to the positive wealth effect. The wealth effect also causes a decrease in labor supply. Since capital is fixed in period 1 and productivity is expected to increase in the future but does not change when news arrives in period 1, the decrease in labor-hours causes output to decline. As output decreases and consumption increases, investment must decrease. Consequently, the RBC model generates a recession in response to positive news. In period 5 if the news turns out to be true, the macroeconomic variables rise with the technology, whereas if the news turns out to be false they return to their steady-state level. This puzzling feature of the standard RBC model has been documented by Beaudry and Portier (2004, 2008).

Figure 2 plots the impulse responses to a news shock in the model with LBD via skill. The figure shows that the RBC model augmented by LBD can generate an expansion in response to positive news about future technology. Output, labor-hours, investment, and consumption all rise until period 4. The figure shows that the marginal value of skill,  $\Lambda_t$ , increases in response to the news. This induces the planner to invest in LBD immediately by increasing labor-hours. The resulting increase in output is large enough to accommodate increases in both consumption and investment. As increasing skill raises productivity of factor-inputs, labor-hours and physical capital continue to increase until period 4. In period 5 if the news turns out to be true, labor-hours, investment, consumption and output continue to increase, thus the expansion persists. If the news turns out to be false, all the variables decrease and revert to the steady-state level, hence causing a recession. This explains how introducing skill accumulation into the standard RBC can generate news driven business cycles.

Figure 3 shows the impulse responses in the model with organizational capital. The figure

reveals that the RBC model with organizational capital can also generate an expansion in response to positive news about future productivity. Output, labor-hours, investment and consumption rise until period 4 in response to the positive news in period 1. The reason why organizational capital can generate a news driven expansion is similar to that of skill. The marginal value of organizational capital,  $\Lambda_t$ , increases as soon as the positive news arrives, which induces the planner to invest in it. This is accomplished by increasing labor-hours and physical capital, both of which are inputs into the organizational capital accumulation process. However, physical capital being predetermined does not contribute to the accumulation of organizational capital or the production process until one period after the news shock. Increase in labor-hours raises output substantially so that both consumption and investment can increase. Consequently, labor-hours, output, consumption and investment rise until period 4. If the news turns out to be true, the expansion continues. Otherwise, all the variables decrease to the steady-state level.

Next, we examine the responses to contemporaneous shock. Figure 4 plots the impulse responses to contemporaneous technology shocks under both the specifications of LBD. Impulse responses in the figure reveal that both the LBD specifications are capable of generating positive comovement in response to contemporaneous shock as well.<sup>5</sup>

### 3 The Two-Sector Economy

To study sectoral comovement we consider a two-sector version of our model with a consumption sector and an investment sector. Several papers including Lucas (1977) and Burns and Mitchell (1946) have underscored the importance of sectoral comovement in developing a single unified theory of business cycles. Huffman and Wynne (1999) document that labor-hours and investment across sectors comove and are procyclical in the data. Therefore in this section we explore the ability of LBD in generating sectoral comovement in response to news shocks. We introduce learning-by-doing in both the sectors. In the interest of brevity, we focus on LBD through skill accumulation from hereon.<sup>6</sup>

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<sup>5</sup>While both the specifications can generate positive aggregate comovement, only the model with organizational capital can generate hump-shaped responses in labor-hours and output. For a discussion on responses to contemporaneous shocks, see CSG (2002) and CJ (2002).

<sup>6</sup>Our two-sector model with organizational capital can also generate sectoral and aggregate comovement in response to the three shocks considered in this paper. These results are available upon request.

### 3.1 Model

The model economy constitutes of a consumption sector and an investment sector. The production technology in the two sectors has the standard Cobb-Douglas functional form:

$$c_t = k_t^{c\alpha} h_t^{c1-\alpha} a_t z_t^c \quad (3.1)$$

$$I_t^c + I_t^i = k_t^{i\alpha} h_t^{i1-\alpha} a_t z_t^i \quad (3.2)$$

where the superscripts “c” and “i” denote variables specific to the consumption and investment sectors, respectively.<sup>7</sup>  $z_t^c$  and  $z_t^i$  are the sector-specific technology shocks while  $a_t$  is the neutral technology shock. The consumption sector produces consumption goods from capital,  $k_t^c$ , and labor-input,  $h_t^c$ , which is the product of labor-hours worked,  $n_t^c$ , and skill  $x_t^c$ . The investment sector produces investment goods for both the sectors using capital,  $k_t^i$ , and labor-input,  $h_t^i$ , which consists of labor-hours worked,  $n_t^i$ , and skill level  $x_t^i$ .

Following the literature, we assume that capital is not mobile across sectors. The idea here is that capital used in the production of industrial machinery cannot easily be used to produce food. This assumption is formalized by specifying separate equations for capital evolution in each sector:

$$k_{t+1}^c = I_t^c + (1 - \delta_k)k_t^c \quad (3.3)$$

$$k_{t+1}^i = I_t^i + (1 - \delta_k)k_t^i \quad (3.4)$$

Similarly, we assume that skill is sector-specific and cannot easily be used in the other sector. The logic is the same; skill in producing industrial machinery cannot easily be used for producing food. Hence we specifying separate equations for the skill accumulation process in each sector:

$$\ln \left( \frac{x_{t+1}^c}{x^c} \right) = \phi \ln \left( \frac{x_t^c}{x^c} \right) + \mu \ln \left( \frac{n_t^c}{n^c} \right) \quad (3.5)$$

$$\ln \left( \frac{x_{t+1}^i}{x^i} \right) = \phi \ln \left( \frac{x_t^i}{x^i} \right) + \mu \ln \left( \frac{n_t^i}{n^i} \right) \quad (3.6)$$

where  $0 \leq \phi < 1$  and  $\mu \geq 0$ . Finally, aggregate labor-hours is the sum of labor-hours in the two sectors.

$$n_t = n_t^c + n_t^i \quad (3.7)$$

The planner solves (2.1) subject to the aggregate constraints, (3.1) and (3.2), and the capital and skill accumulation equations, (3.3) through (3.6). The first-order conditions to the planner’s

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<sup>7</sup>The above two equations replace the resource constraint (2.3) in the one-sector economy.

problem are:

$$c_t^{-\sigma} = \lambda_t^c \quad (3.8)$$

$$\psi = \lambda_t^c (1 - \alpha) \left( \frac{k_t^c}{n_t^c} \right)^\alpha x_t^{c(1-\alpha)} a_t z_t^c + \Lambda_t^c \frac{\mu}{n^c} \left( \frac{x_t^c}{x^c} \right)^\phi \left( \frac{n_t^c}{n^c} \right)^{(\mu-1)} \quad (3.9)$$

$$\psi = \lambda_t^i (1 - \alpha) \left( \frac{k_t^i}{n_t^i} \right)^\alpha x_t^{i(1-\alpha)} a_t z_t^i + \Lambda_t^i \frac{\mu}{n^c} \left( \frac{x_t^i}{x^i} \right)^\phi \left( \frac{n_t^i}{n^i} \right)^{(\mu-1)} \quad (3.10)$$

$$\frac{\Lambda_t^c}{x^c} = \beta \frac{\Lambda_{t+1}^c}{x^c} \phi \left( \frac{x_{t+1}^c}{x^c} \right)^{(\phi-1)} \left( \frac{n_{t+1}^c}{n^c} \right)^\mu + \beta \lambda_{t+1}^c (1 - \alpha) \left( \frac{k_{t+1}^c}{x_{t+1}^c} \right)^\alpha n_{t+1}^{c(1-\alpha)} a_{t+1} z_{t+1}^c \quad (3.11)$$

$$\frac{\Lambda_t^i}{x^i} = \beta \frac{\Lambda_{t+1}^i}{x^i} \phi \left( \frac{x_{t+1}^i}{x^i} \right)^{(\phi-1)} \left( \frac{n_{t+1}^i}{n^i} \right)^\mu + \beta \lambda_{t+1}^i (1 - \alpha) \left( \frac{k_{t+1}^i}{x_{t+1}^i} \right)^\alpha n_{t+1}^{i(1-\alpha)} a_{t+1} z_{t+1}^i \quad (3.12)$$

$$\lambda_t^i = \beta \lambda_{t+1}^i (1 - \delta_k) + \beta \lambda_{t+1}^c \alpha \left( \frac{x_{t+1}^c n_{t+1}^c}{k_{t+1}^c} \right)^{(1-\alpha)} a_{t+1} z_{t+1}^c \quad (3.13)$$

$$\lambda_t^i = \beta \lambda_{t+1}^i (1 - \delta_k) + \beta \lambda_{t+1}^i \alpha \left( \frac{x_{t+1}^i n_{t+1}^i}{k_{t+1}^i} \right)^{(1-\alpha)} a_{t+1} z_{t+1}^i \quad (3.14)$$

where  $\lambda_t^j$  and  $\Lambda_t^j$  are the Lagrange multipliers with respect to the resource-constraints and the skill accumulation equations in the two sectors ( $j = c, i$ ). The first-order conditions in this two-sector economy are analogous to those in the one-sector model. For instance, the first-order conditions for labor-hours in the two sectors (3.9) and (3.10) are similar to (2.9) and show that the social planner equates the marginal-rate-of-substitution between labor-hours and consumption (investment) to the sum of the marginal product of labor in the consumption (investment) sector and the marginal value of skill in terms of consumption (investment) generated from increasing labor-hours by one unit in the respective sector.<sup>8</sup> Similarly, the first-order conditions with respect to skill in the two sectors (3.11) and (3.12) are analogous to (2.11), in that the marginal value of skill in the two sectors depend of future technology.<sup>9</sup>

### Intratemporal Adjustment Cost

In the two-sector model, there is an infinite elasticity of substitution between investment across sectors, which makes it very easy to switch from the production of one type of capital good to that of another. Specifically, by cutting back the production of new capital goods for one sector by one unit, it is possible to increase production of new capital goods for the other sector by one unit without any need to increase overall production of new capital goods. Huffman and Wyne

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<sup>8</sup>As in (2.9), these first-order conditions differ from the standard two-sector RBC model by the second terms in (3.9) and (3.10), which capture the marginal value of skill in the respective sectors.

<sup>9</sup>In the same way, the first-order conditions for physical capital in the two sectors (3.13) and (3.14) are analogous to (2.10).

(1999) argue that while an economy can alter its capacity for producing heavy capital equipment for industrial use and alternative capital goods for service sector use, it can be costly to do so quickly in practice. Consequently, they introduce an intratemporal investment adjustment cost in a standard two-sector model and show that this modification can generate sectoral comovement in response to contemporaneous shock. We follow Huffman and Wyne (1999) and introduce intratemporal investment adjustment cost in our model.<sup>10</sup> The production technology in the investment sector (3.2) will then be replaced by:

$$\left(I_t^{c-\rho} + I_t^{i-\rho}\right)^{-\frac{1}{\rho}} = k_t^{i\alpha} \left(n_t^i x_t^i\right)^{1-\alpha} a_t z_t^i \quad (3.15)$$

The central assumption behind this specification is that it is costly to alter the composition of capital goods produced in the economy. This formulation generates a convex production possibility frontier between investment in the two sectors.<sup>11</sup> Setting  $\rho = -1$  would result in the standard resource constraint for the capital-goods producing sector in a two-sector model. Thus, it is easy to understand the implications of introducing this adjustment cost.

## 3.2 Results

We now present numerical results to the two-sector economy. We follow Jaimovich and Rebelo (2008) and calibrate the two-sector model with the same parameter values used for the one-sector model.<sup>12</sup> We set the intratemporal investment adjustment cost,  $\rho$  to -1.4.<sup>13</sup>

### Numerical Results

We now discuss the impulse responses of sector-specific and aggregate variables to news about three types of shocks. The first shock is a neutral technology shock,  $a_t$ . The second is a sectoral shock to technology in the consumption sector,  $z_t^c$ , and the third is a sectoral shock to technology in the investment sector,  $z_t^i$ . The timing is as follows. The economy is in the steady-state at time zero. At time one the economy learns that there is a one-percent increase in one of the three shocks after four periods.

Figure 5 shows that the model with LBD and intratemporal investment adjustment cost can

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<sup>10</sup>We introduce the intratemporal adjustment costs since LBD by itself cannot reduce the rapid movement of factor across sectors.

<sup>11</sup>For a detailed motivation for this form, refer to Huffman and Wyne (1999).

<sup>12</sup>Jaimovich and Rebelo (2008) calibrate their two sector growth model with the same parameter values as their one sector version of the model. Huffman and Wyne(1999), on the other hand, use different depreciate rates, labor capital shares and persistent parameters in the two sector. Hence an alternative to the Jaimovich and Rebelo (2008) would be to follow Huffman and Wyne(1999).

<sup>13</sup>Huffman and Wyne (1999) estimated  $\rho$  in the range of -1.1 and -1.3. While  $\rho$  of -1.4 is slightly larger (in absolute value), the results are essentially the same when  $\rho$  is set to -1.3.

generate both sectoral and aggregate comovement in response to news about all three shocks. The positive news increases the marginal value of skill in the two sectors,  $\Lambda_t^c$ , and,  $\Lambda_t^i$ , immediately. This induces the planner to invest in skill by increasing labor-hours in both the sectors, which raises aggregate consumption and aggregate investment. The intratemporal investment adjustment cost restricts the movement of investment across sectors and as a result investment in both the sectors increase. As skill accumulation raises the productivity of factors-inputs, labor-hours and investment continue to increase in both the sectors. Consequently, aggregate consumption, investment, labor-hours and output also continue to increase in subsequent periods. Hence the model generates both sectoral and aggregate comovement in response to positive news about neutral and sector-specific technology shocks. The next figure shows the effects of the corresponding three contemporaneous shocks. The timing is as follows. The economy is in the steady-state at time zero and the shock occurs at time one. Figure 6 shows that the model generates both aggregate and sectoral comovement in response to all three shocks.

To better understand the dynamics of the model, we first examine the responses to contemporaneous and news shocks about investment-specific technology in the two-sector version of standard RBC model. Subsequently, we will add the intratemporal investment adjustment cost and LBD one at a time to examine their relative contribution in generating a news driven expansion. Figure 7 shows the response to contemporaneous shock and news shock in the benchmark model without skill accumulation or intratemporal adjustment cost. The figure shows that in response to contemporaneous shock, aggregate output and investment rise immediately and in subsequent periods, while consumption falls for several periods. This is because as investment productivity increases, investment (and subsequently capital) in the investment sector will increase to take advantage of the increased productivity. Later, as decreases to the steady-state level, capital and investment will also decrease. Since investment in the investment sector has increased by so much, the corresponding investment in the consumption sector will fall immediately upon the rise in technology, and consequently consumption falls in the following periods. As more capital goods are accumulated, capital in the investment sector falls and capital in the consumption sector grows as agents desire more consumption. The figure also plots responses to positive news about investment technology. In response to this positive news, the planner increases labor-hours and capital in the consumption sector immediately in order to build consumption before the investment-specific technology arrives. However, due to the negative wealth effect on labor supply there are more than offsetting decreases in the investment sector, which cause aggregate labor-hours, output and investment to decline. Subsequently, the planner reallocates the factors to the investment sector in order to take advantage of the increased productivity when the actual investment technology arrives.<sup>14</sup> After the shock, the planner reallocates the factor to the consumption sector to increase consumption. As

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<sup>14</sup>Since capital is predetermined, the planner increases investment one period in advance to ensure that capital in the investment sector is at a higher level in the next period when the investment technology arrives.

the technology subsequently reverts to its steady-state level, so do the investments and labor-hours in the two sectors. It is clear from the figure that the benchmark two-sector model fails to generate sectoral or aggregate comovement in response news and contemporaneous shocks.

Next we examine the impulse responses when the two key elements are introduced to the benchmark two-sector model: skill accumulation and intratemporal investment adjustment cost. Figure 8 shows that introducing intratemporal adjustment costs substantially reduces the volatility in the factors as there is no longer an infinite elasticity of substitution between the two types of investment goods. The figure confirms that introducing this adjustment cost leads to positive sectoral and aggregate comovement in response to contemporaneous shock. However, the adjustment cost by itself cannot produce an expansion in response to positive news about future investment technology. Labor and investment decrease in the consumption sector, causing aggregate consumption to decline. While investment increases slightly in the investment sector, the decrease in labor causes aggregate investment to decrease. The figure shows that all the sectoral variables (except for investment in the investment sector) and all aggregate variables decline, hence causing a recession in response to the positive news. The reason why the two-sector model with only intratemporal investment adjustment cost fails to generate comovement in response to news shock is because there are no forces in the model that can compensate for the negative wealth effect on the labor supply from news about future productivity.

We now examine the impulse responses when the model is augmented with LBD. Introducing LBD via skill in the two sectors increases the marginal value of skill when the positive news arrives. This induces the planner to invest in skill, which is accomplished by an increase in labor-hours. Hence the LBD mechanism provides a countervailing force to the negative wealth effect on labor supply. The figure shows that when skill accumulation is added into the model both the sector-specific variables and the aggregate variables rise in response to the positive news.<sup>15</sup> Hence skill accumulation combined with intratemporal adjustment can produce both sectoral and aggregate comovement in response to news shock.

Figure 9 shows the response in the benchmark two-sector model to news and contemporaneous shocks in the consumption sector. Once again, the responses are volatile as the factors are moved freely across sectors to where their marginal products are higher. Introducing intratemporal investment adjustment cost leads to comovement in response to contemporaneous shock. While in this case adding the adjustment cost can also generate comovement in response to news about consumption technology, initial increase in labor in the consumption sector and aggregate consumption is negligible. Introducing LBD substantially increases the size of this initial boom.

Finally, we examine responses to news and contemporaneous shocks to neutral technology. Fig-

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<sup>15</sup>The impulse responses when only skill is added to the benchmark two-sector model are still volatile because of the infinite elasticity of substitution between investment and labor in the two sector. Hence learning-by-doing by itself is not sufficient to generate an expansion in response to positive news.



ures 11 and 12 show that the benchmark two-sector model fails to generate sectoral or aggregate comovement and introducing intratemporal investment adjustment cost helps in case of contemporaneous shock. However, adjustment cost by itself fails to produce an expansion in response to positive news about neutral technology. Investment and labor shrink in the consumption sector, resulting in a decrease in aggregate consumption. While investment increases in the investment sector, the corresponding decrease in labor-hours cause aggregate investment to shrink. As a result aggregate output also decreases. The figure shows that except for investment in the investment sector all the aggregate and sector-specific variables decline, thus causing a recession in response to positive news. Introducing learning-by-doing via skill in the two sectors induces the planner to invest in it by increasing labor-hours, which leads to increases in both sectoral and aggregate variables.

## 4 Conclusion

It is well documented that the standard RBC model fails to generate positive comovement in output, consumption, investment, and labor-hours in response to news about future technology. This paper proposes a solution to this puzzling feature of the RBC model based on learning-by-doing. We examine two specifications of LBD that are popular in the literature and show that both these specifications can generate aggregate comovement in response to news shocks about technology. Furthermore, we show that LBD plays a crucial role in generating sectoral comovement in response to news shocks. While several other recent studies have added features to the RBC model to account for aggregate comovement in response to news shocks, we believe that the primary virtue of our approach is that it provides a simple and intuitive solution based on a mechanism that has strong empirical support. In addition, we show that our model can generate sectoral comovement in response to news about three types of shocks: neutral technology shock, consumption technology shock, and investment technology shock.

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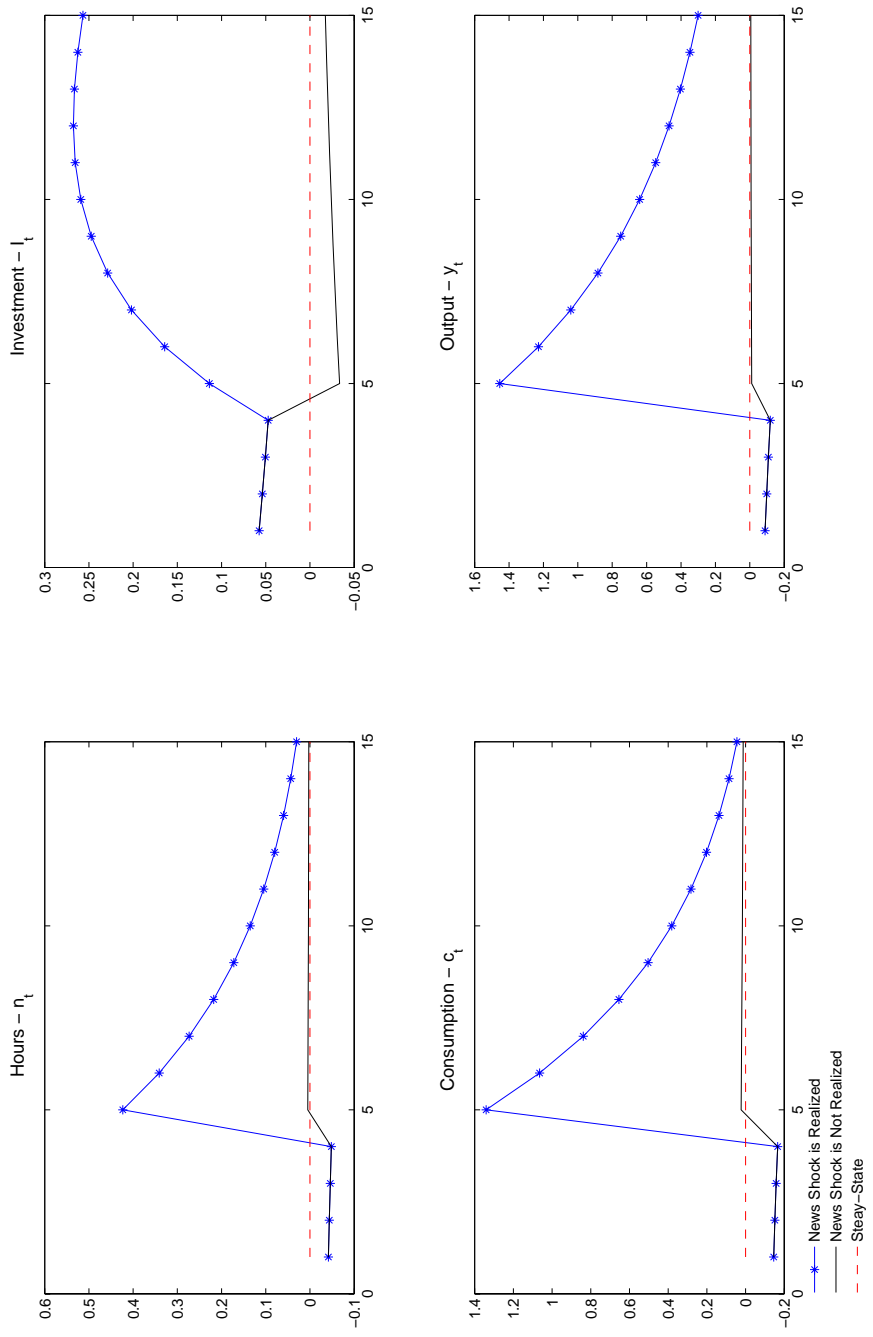


Figure 1: RBC Model - News Shock

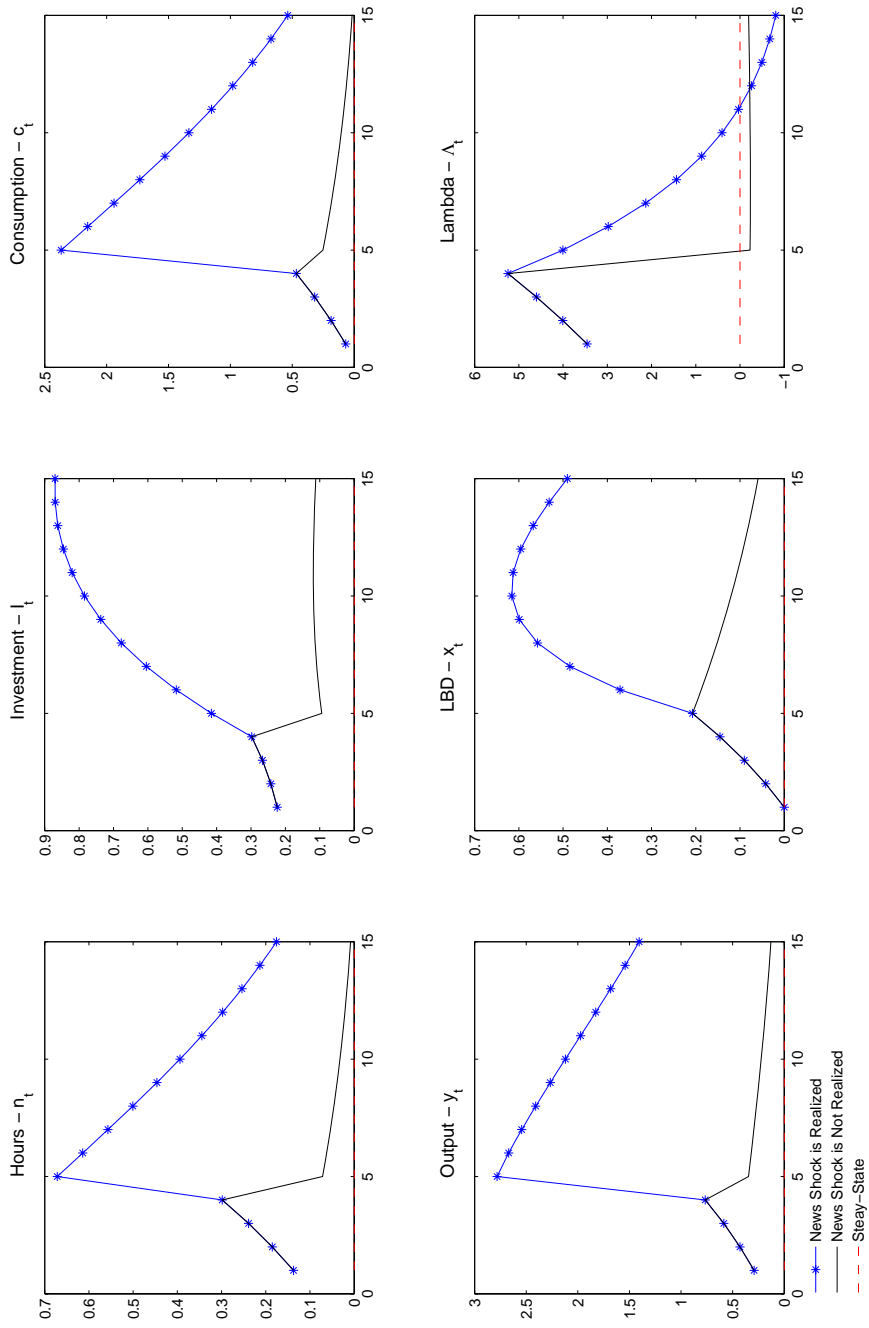


Figure 2: LBD via Skill - News Shock

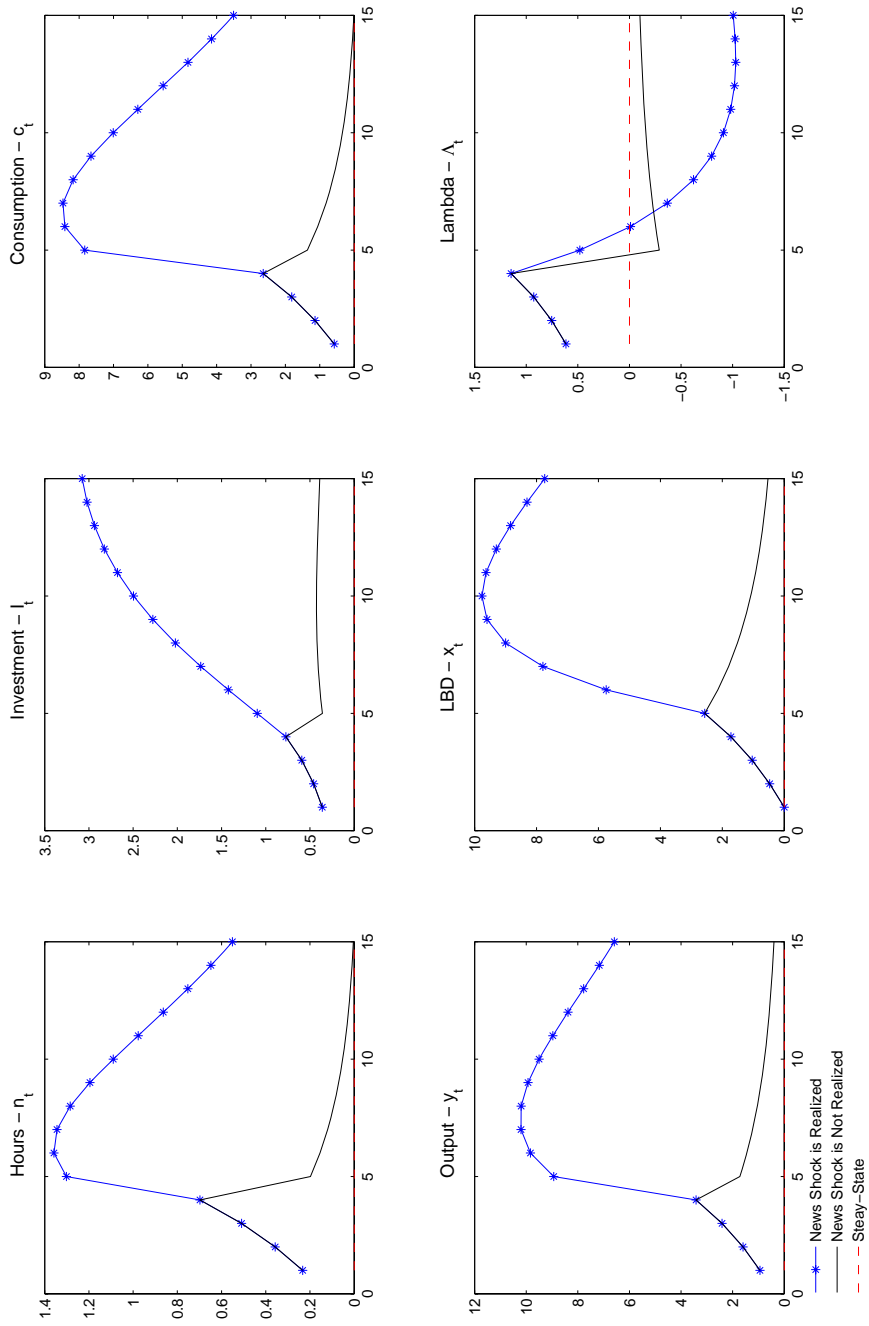


Figure 3: LBD via Organizational Capital - News Shock

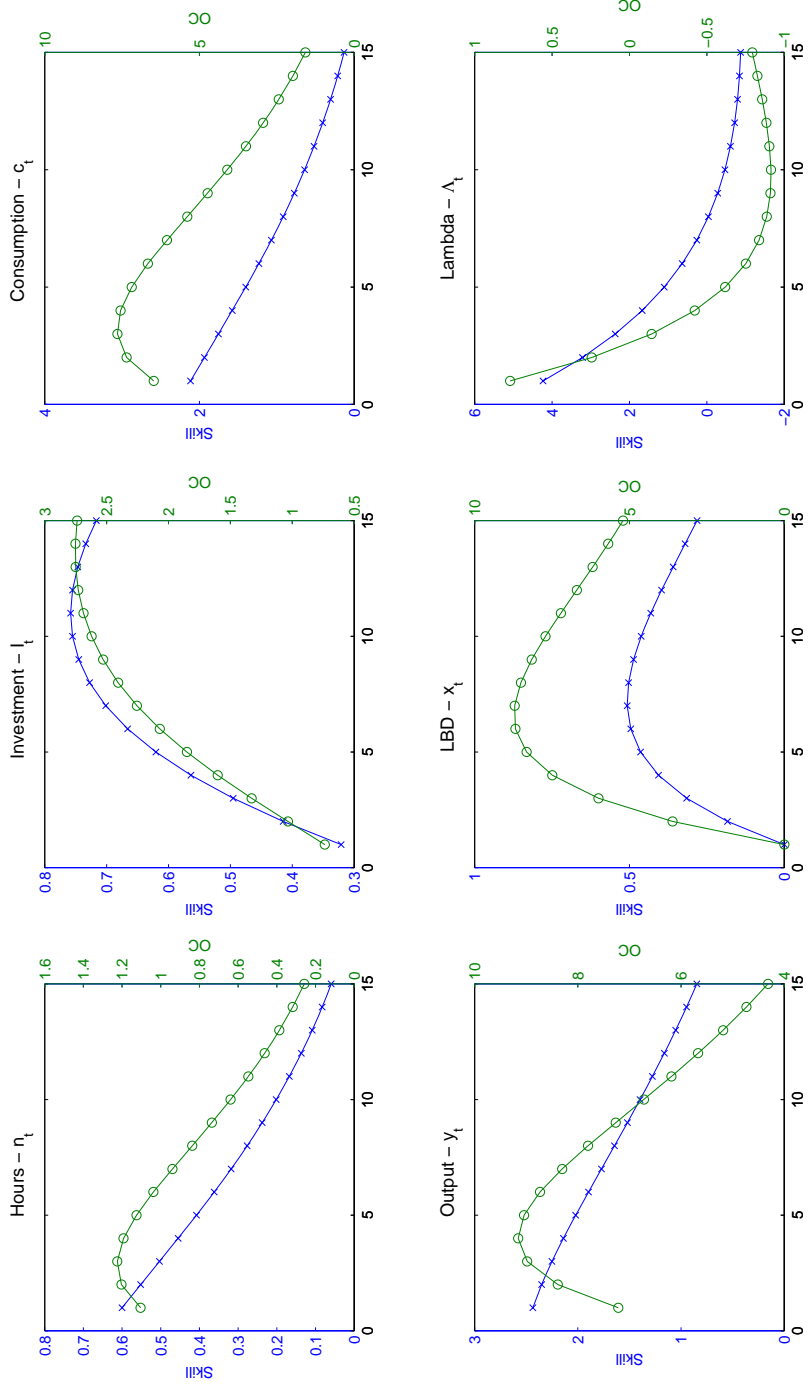


Figure 4: LBD - Contemporaneous Shock

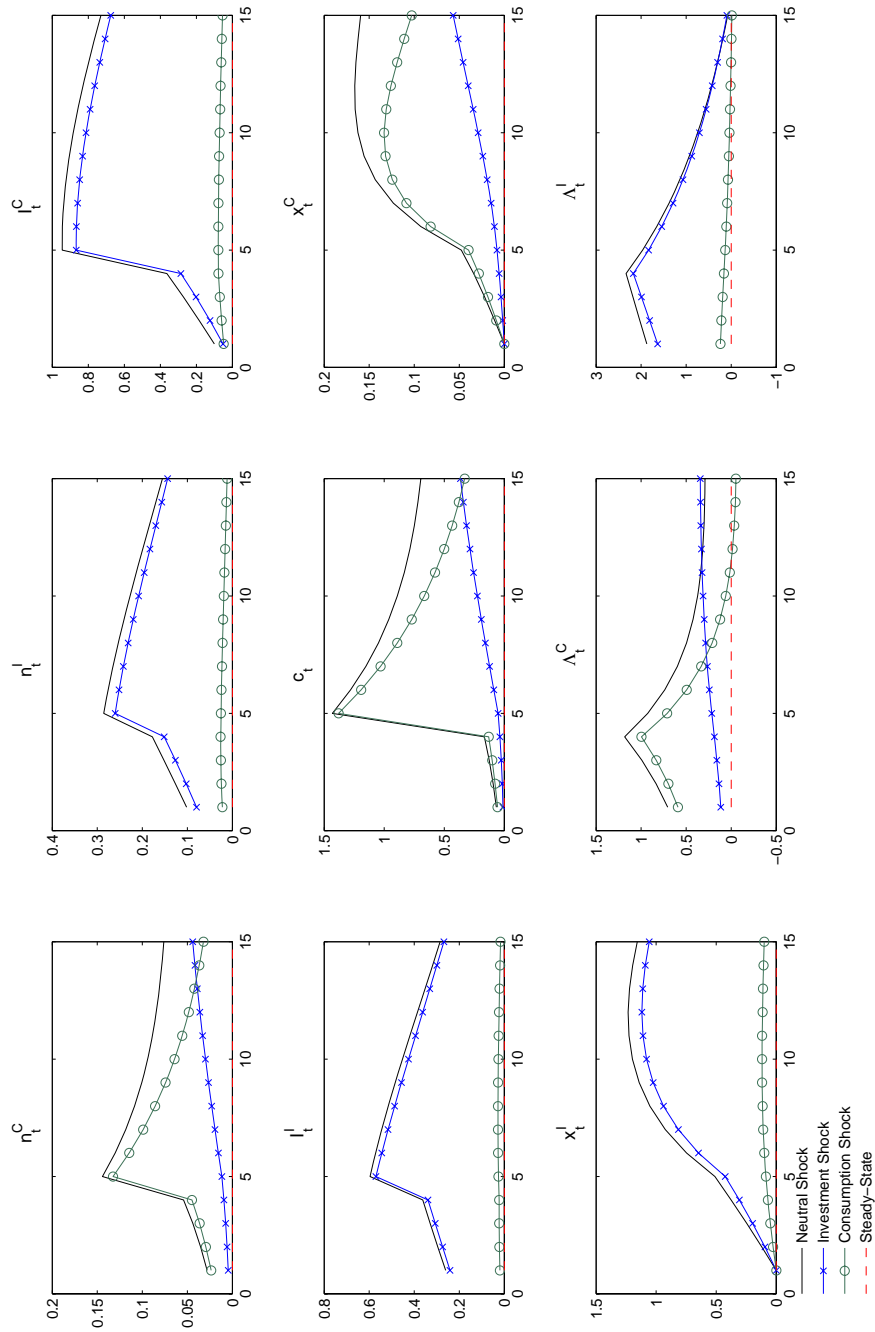


Figure 5: News Shocks in Our Two-Sector Model



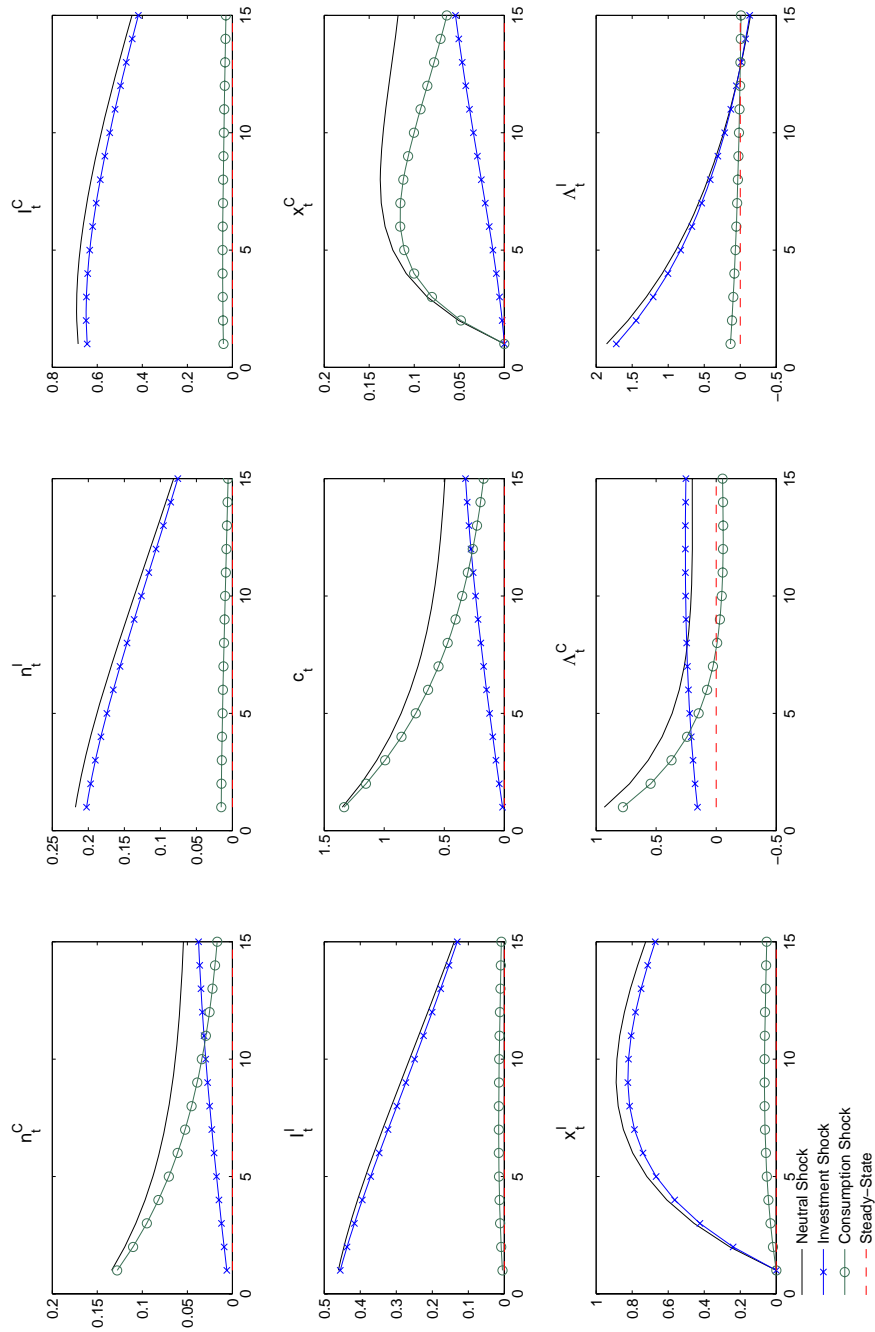


Figure 6: Contemporaneous Shocks in OUR Two-Sector Model

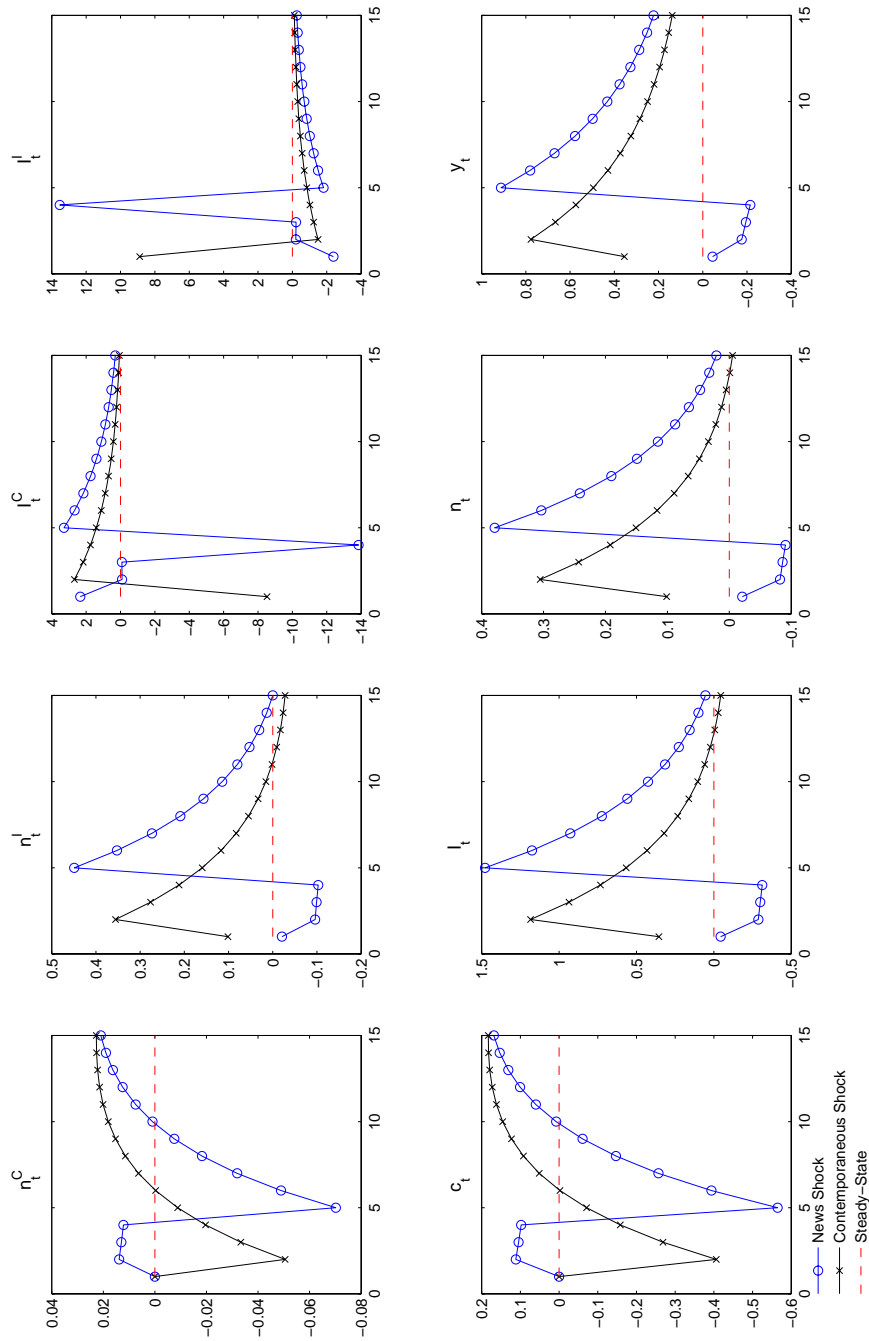


Figure 7: Investment Technology Shock in BENCHMARK Two-Sector Model

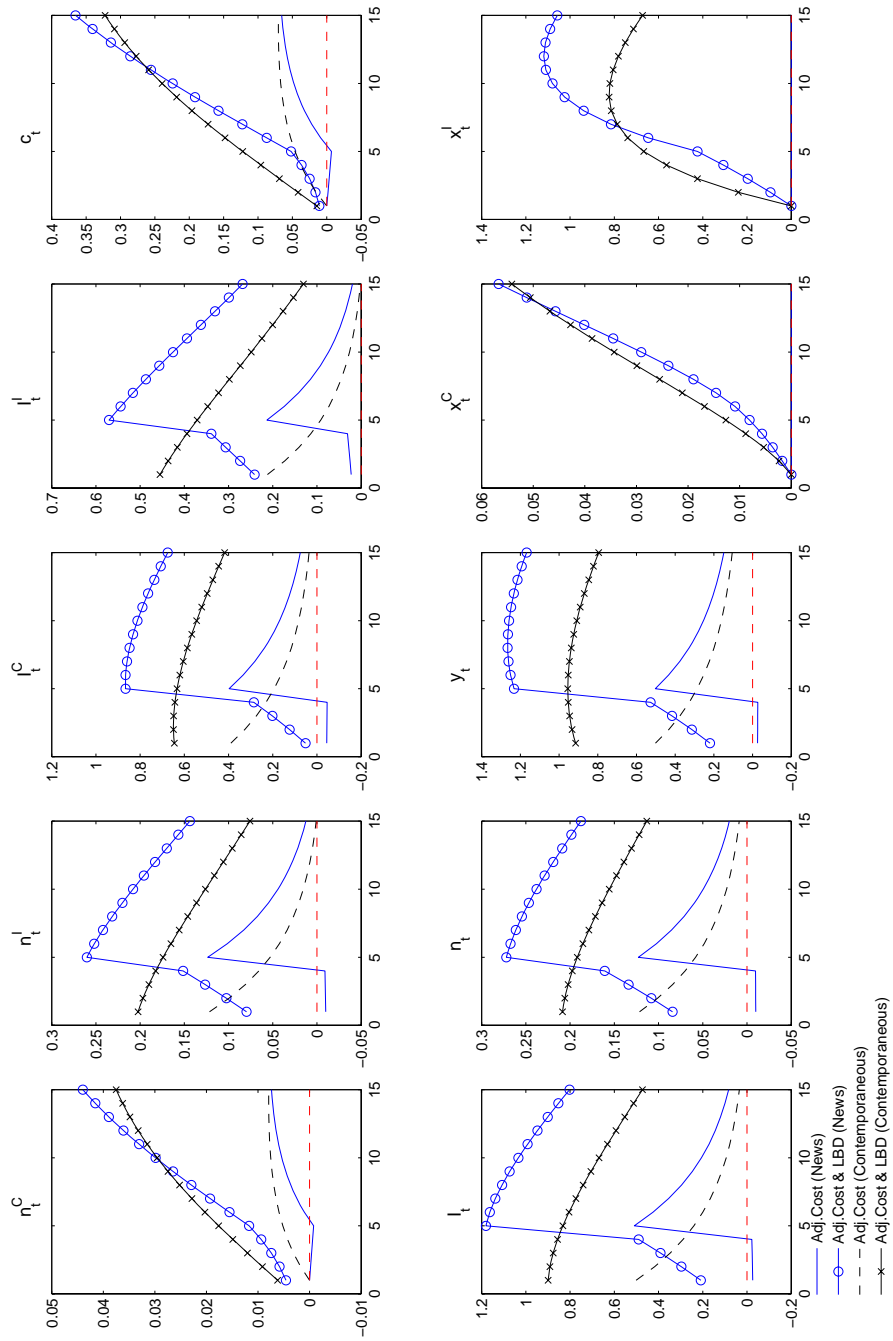


Figure 8: Investment Technology Shock in Our Two-Sector Model

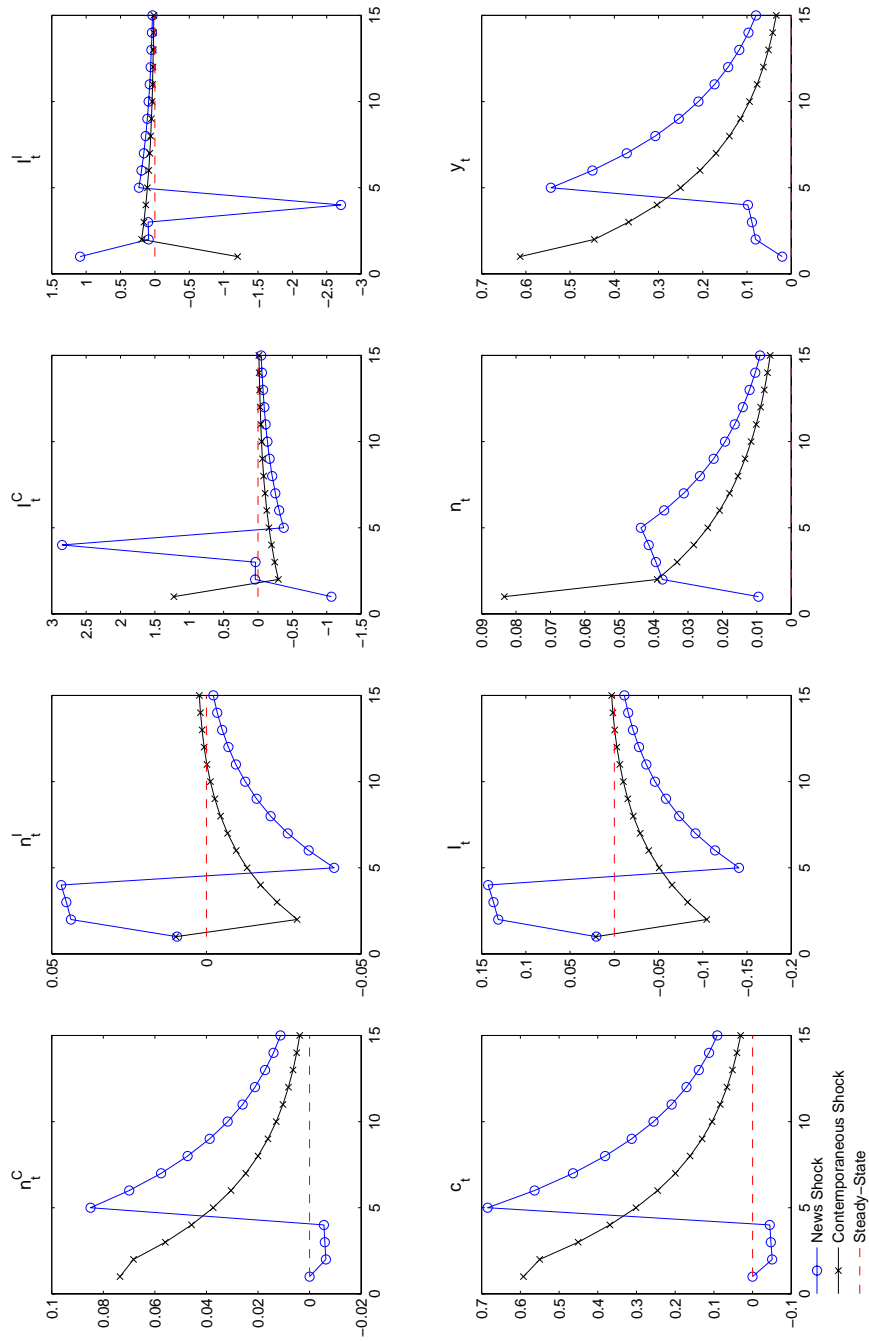


Figure 9: Consumption Technology Shocks in BENCHMARK Two-Sector Model

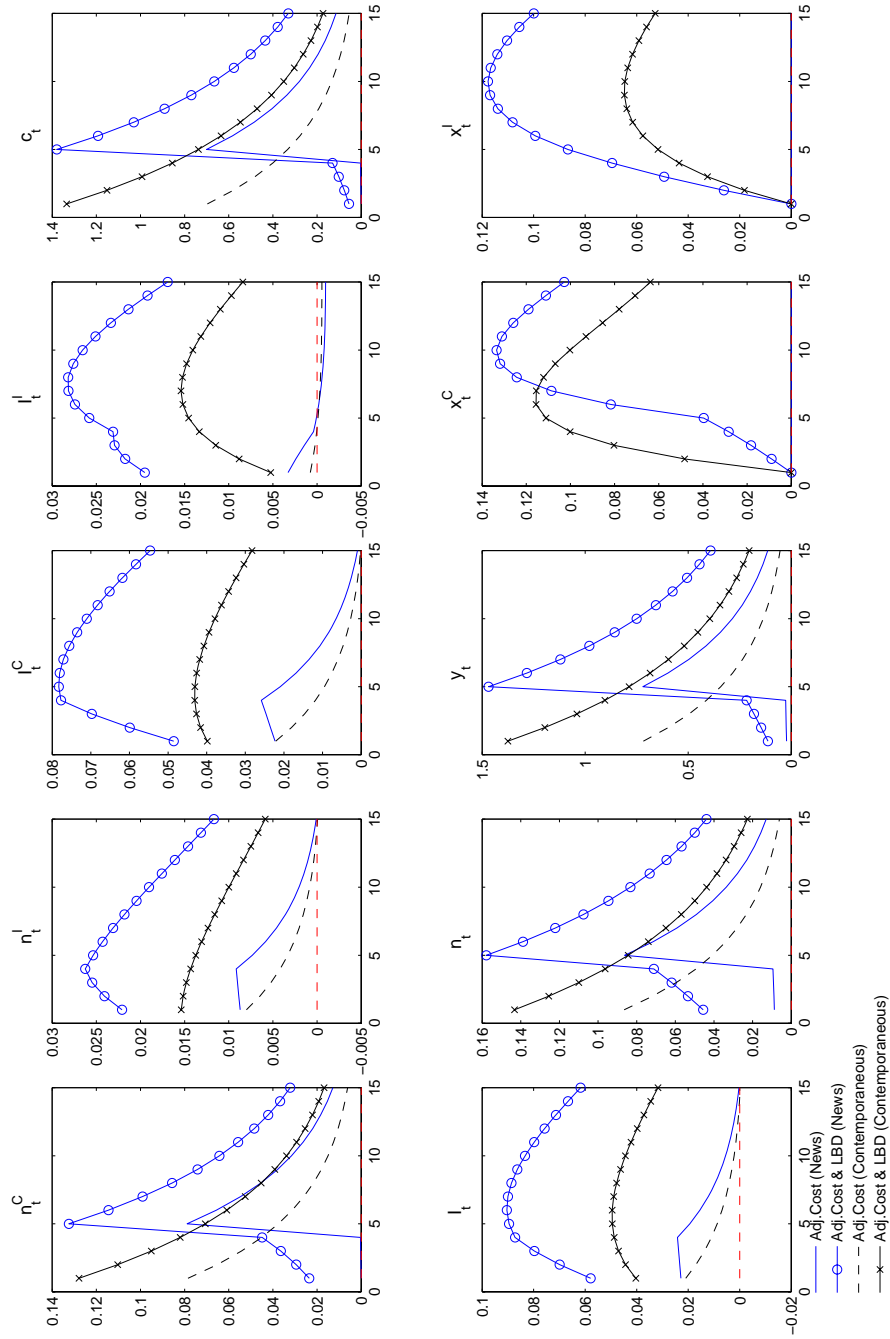


Figure 10: Consumption Technology Shock in OUR Two-Sector Model

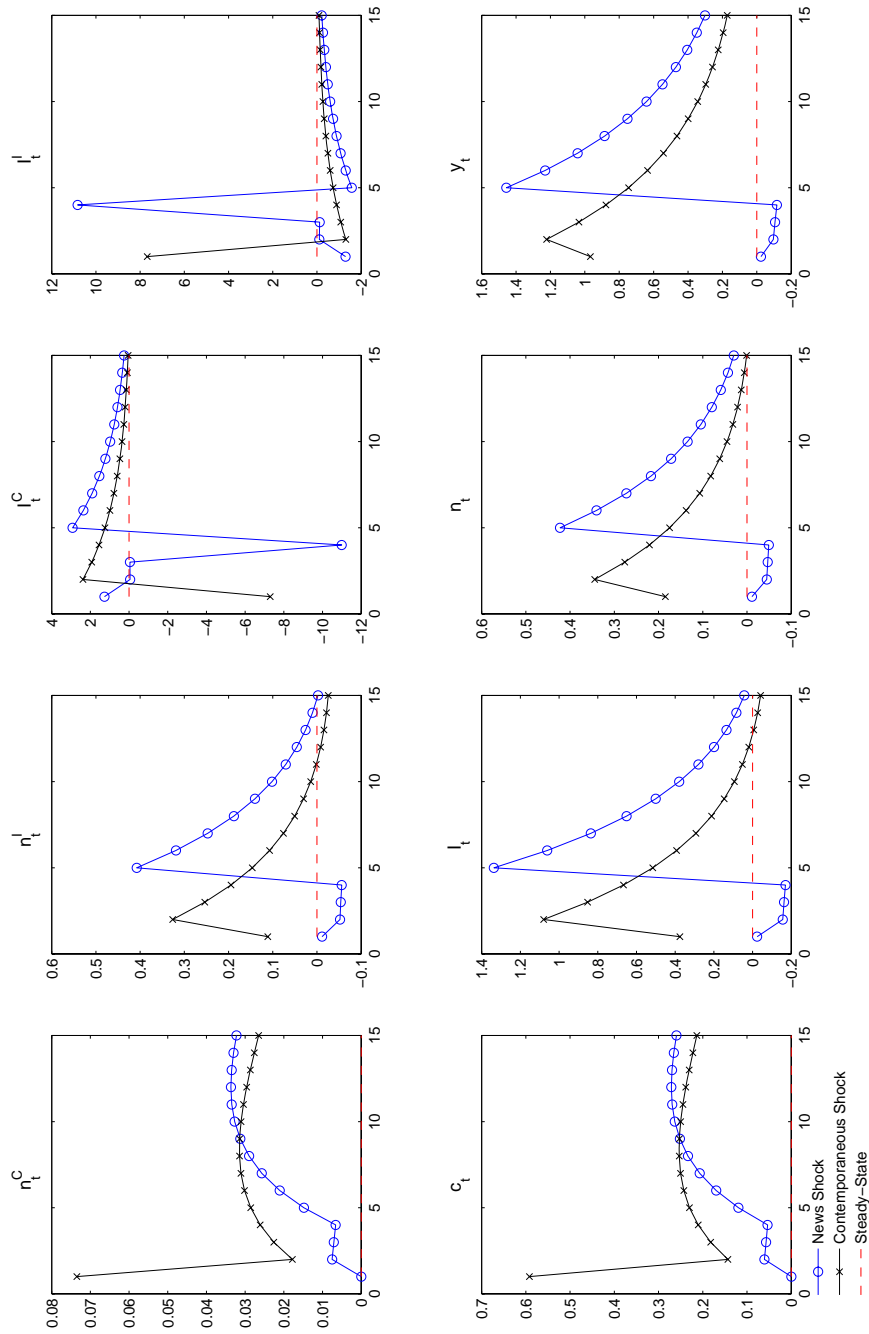


Figure 11: Neutral Technology Shock in BENCHMARK Two-Sector Model

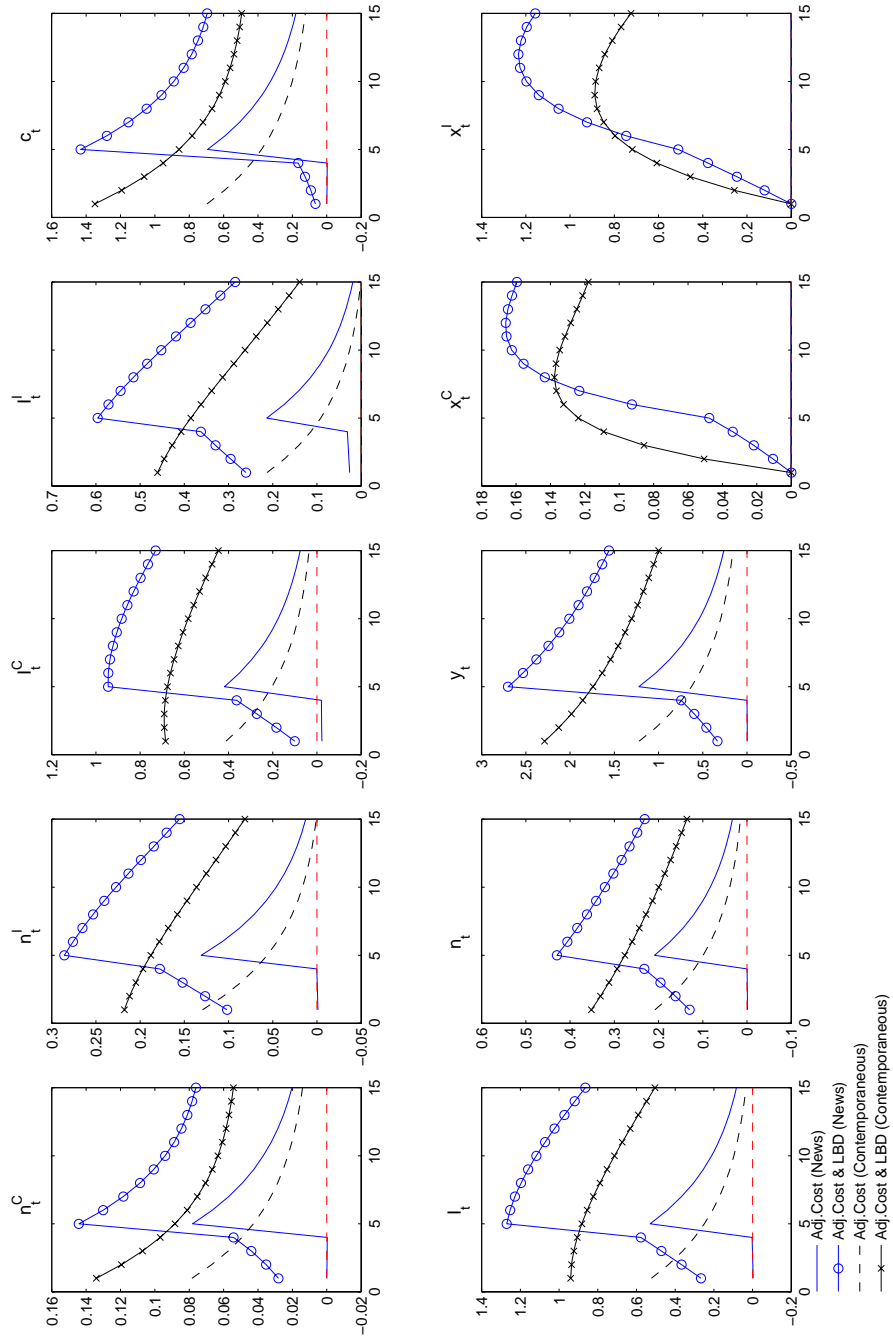


Figure 12: Neutral Technology Shock in Our Two-Sector Model