

The Analytics of Technology News Shocks*

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Abstract

This paper constructs several models in which, unlike the standard neoclassical growth model, positive news about future technology generates an increase in current consumption, hours and investment. These models are said to exhibit procyclical news shocks. Two of the economies we study modify the neoclassical growth model to include, in turn: a complementarity between consumption and investment in production; labor externalities in utility. A third model we consider have two commonalities. There are mechanisms to ensure that: (I) consumption does not crowd out investment, or vice versa; (II) the benefit of forgoing leisure outweighs the cost. Our final model holds the greatest potential, we believe, for explaining procyclical news shocks. Its critical assumption is that news of the future technology also illuminates the nature of this technology. This illumination in turn permits economic actors to invest in capital that is forward-compatible, i.e. adapted to the new technology. On the technical side, our paper reintroduces the Laplace transform as a tool for studying dynamic economies analytically.

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1 Introduction

The optimal response of aggregate consumption, investment and hours in the neoclassical growth model to an unanticipated permanent (or near permanent) technology increase is well-understood. For most specifications used by researchers, all three variables increase.¹ A technology improvement increases capital's efficiency; thus, the desired capital stock increases. The increase in the capital stock is achieved by greater investment. Importantly, greater investment need not come at the cost of a drop in consumption. Rather, since the technology improvement shifts out the production frontier immediately, creating additional consumption and investment is feasible. Moreover, an hours increase is optimal because a higher marginal product of labor induces a substitution effect away from leisure that outweighs the wealth effect, which pushes in the opposite direction.

Next, consider the standard growth model's response to news of a future technology increase. The responses of these variables and the incentives that drive these responses are different. In the standard model, all three variables will not increase. Typically, labor falls upon the arrival of the news. The above-described wealth effect on leisure is operative; however, there is no offsetting substitution effect because the technology increase has not materialized immediately.

With a labor decline, the only way consumption can increase in response to the news is if investment falls. An investment decline is optimal because there is incentive to delay building additional capital stock until technology actually increases. Thus, in the standard model, positive news about future technology can cause a decline in labor and investment, and an increase in consumption.^{2,3}

This paper studies variants on the standard model that are capable of generating pro-

¹Campbell (1994) establishes this by simulation using several functional forms of preferences and model parameterizations. He does provide cases where, when preferences are non-separable in consumption and labor, that consumption declines in response to technology shocks.

²An alternative, but equally puzzling, response to good news about future technology is that labor and hours increase, while consumption declines. This occurs for a small region of growth model's parameter space.

³There is some support for procyclical news shocks in U.S. data. Systematic empirical work supporting the news shock explanation includes Schmitt-Grohe and Uribe (2012) and Beaudry and Portier (2006). The former estimate a business cycle model with news (anticipated) and current (unanticipated) shocks and find that news shocks explain a greater fraction of output volatility than current shocks. The latter estimate that the component of innovations to stock prices, not correlated to current productivity, is correlated with expected future productivity. Barsky and Sims (2009) using a different identification scheme deliver an opposite result. Other relevant empirical research supporting this explanation includes Beaudry, Dupaigne, and Portier (2008), Beaudry and Lucke (2010), and Khan and Tsoukalas (2012) as well as Leeper, Walker and Yang (2012).

cyclical responses. Each model has mechanism(s) to ensure that: (I) consumption does not crowd out investment, or vice versa; (II) the return to forgoing leisure is sufficiently high.

In our first model, we modify the neoclassical production function to have a convex production frontier between consumption and investment, i.e. production complementarity. In the standard model, the marginal rate of transformation between consumption and investment is fixed at one. Here, this marginal rate of transformation depends upon the consumption-investment ratio. We provide both sufficient and necessary conditions for the model to exhibit procyclical technology news shocks. These conditions depend upon the values of the model's underlying parameters.

With a convex production frontier, greater consumption (investment) increases the marginal product of labor towards the production of investment (consumption). This effect tends to increase investment and labor upon the arrival of the news if there is a consumption boom.⁴ This achieves Condition I: consumption does not crowd out investment.

Consumption-investment complementarity causes the two variables to comove; however, it is possible that the two variables might fall rather than increase in response to positive news. In this case, the planner takes leisure over consumption (and capital accumulation) in the short run. This arises if there is too much curvature in the utility function because, in this case, the intertemporal smoothing motive for leisure becomes too strong. As such, there must be sufficiently low curvature in order that hours, consumption and investment comove procyclically in response to positive news. The restriction ensures our Condition II, that the relative benefit of forgoing leisure is sufficiently strong.

Our second model contains a preference-based mechanism for generating procyclical technology news shocks.⁵ Here, we assume a preference externality such that the marginal disutility of own hours worked is falling in the economy-wide average hours worked.⁶ The preference externality acts, from each household's perspective, as a preference shock that expands each household's willingness to supply labor. This endogenous labor supply mechanism directly decreases the household utility cost of forgoing leisure (satisfying Condition II) and the increase in labor expands output sufficiently for both consumption and investment to increase (satisfying Condition I).

After proving a theorem for each model to exhibit procyclical news shocks, we conduct

⁴In an extreme but illustrative case, if consumption and investment are produced in a Leontief manner, then consumption and investment comove perfectly.

⁵That is, the production side of this second model is neoclassical.

⁶Despite being non-standard, the preferences are consistent with balanced growth and both consumption and leisure are normal goods from each household's perspective.

a quantitative analysis. Here, we find a drawback with both models. Each generates quantitatively small consumption booms in response to positive news. Consumption is nearly acyclical.

As a result of the near acyclicity of consumption, we develop two distinct extensions of the production complementarities model. First, we replace balanced-growth preferences with GHH preferences. Second, we add investment adjustment costs to the model. With either of these additions we are able to generate quantitatively larger consumption booms and also support procyclical news shocks with greater curvature in the utility function.

In our view, the greatest promise for explaining the phenomenon is a situation where Condition II, i.e. a strong return to forgoing leisure, is achieved because there is a benefit to starting investing early beyond that inherent in the basic neoclassical model. In our view, it is more plausible that this benefit is production-based rather than preference-based. To this end, we construct the final model of the paper, which introduces the concept of “forward-compatible investment.”

The starting point for the forward-compatibility model is a neoclassical economy with investment-specific technology (IST) shocks and production complementarity. In addition, we assume investment made between the news arrival and the actual IST increase is partially forward-compatible). This causes an investment boom upon the arrival of the news as the social planner builds capital in anticipation of the IST increase, even though there is no immediate technological improvement. This “preparatory-phase” investment is optimal because it allows the planner to smooth consumption while accumulating capital towards the eventual higher steady state.

It is beneficial, in our view, for a modification of the neoclassical model to be as minimal as possible. This makes it less likely that the resulting model does violence to existing theory of unanticipated shocks. To this end, we note that adding forward compatibility of investment is not a significant departure from the neoclassical model along two key dimensions. First, our solution adds no new state variables to the neoclassical model. This is useful because the lack of any new state variables allows for a thorough examination of the mechanism in a two dimensional space; each additional state variable would add two more dimensions to the model (a state and a co-state). Second, our model collapses to the standard neoclassical model with production complementarities when the exogenous driving process is a contemporaneous shock. That is, the forward compatibility does not operate when the business cycle is driven by contemporaneous shocks. This allows our model to be directly comparable to the basic neoclassical model, and m

To allow for a complete theoretical analysis, we use a continuous time model. A continuous time framework allows us to use the method of Laplace transform. The Laplace Transform is useful for studying linear differential equations with constant coefficients and exogenous (non-homogeneous) terms with discontinuities. The discontinuity is present of a forecastable jump in future technology. Once we log-linearize the growth model, our differential equations take exactly this form.

There are several existing papers on news-driven cycles in dynamic equilibrium models. Beaudry and Portier (2007) study the difficulty that the neoclassical model has in exhibiting procyclical news shocks; moreover, they calibrate model with one feature capable of generating news-driven cycles: production complementarities of the kind studied in our paper. Their theoretical work does not explore the analytics underlying the full dynamics of news-driven cycles. Beaudry and Portier (2004) generate news-driven cycles by modeling final consumption as a function of non-durables and the capital stock. Jaimovich and Rebelo (2009) generate large responses to news shocks, by adding variable capital utilization and two dynamic state variables to the neoclassical model: lagged investment through adjustment costs and time non-separable preferences. Christiano et. al.(2007) use investment adjustment costs and habit persistence to generate news-driven business cycles. Wang (2012) analyzes and compares three existing models generating procyclical news shocks via a labor market diagram. This graphical analysis is very useful for understanding the static relationships in these models, but not as useful for understanding the models' dynamics. In the same paper, he develops a model where an endogenous markup resolves this comovement puzzle.

Nah (2009) uses production complementarities and financial frictions to support procyclical news shocks. Gunn and Johri (2011) and Qureshi (2009) each develop a learning-by-doing model. In response to news about future technological improvement, forward-looking agents increase hours worked and investment immediately in order to build up their stock of knowledge to amplify the benefit of the future technology increase. Gunn and Johri (2009) show that learning-by-doing combined with variable capital utilization can generate procyclical stock prices. Qureshi (2009) shows that learning-by-doing along with an intratemporal adjustment cost can generate sectoral comovement in response to news about neutral and sector-specific technologies. Comin, Gertler and Santacreu (2009) develop a model with shocks to the number of new ideas capable of increasing the efficiency of capital and labor. However, resources must be allocated to transform ideas into actual technologies. In their model, news is the arrival of new ideas; whereas in our model, news is (in part) the arrival of

useful information about the nature of future technologies. Tsai (2009) uses variable capital utilization and preferences designed to minimize wealth effects on labor supply, along with fixed costs to adopt new vintages of capital. The latter feature in his model has a feel very similar to the forward compatibility assumption in our paper.

Our paper differs from the above numerical/simulation-based results, along with the theoretical results in Beaudry and Portier (2007), in that, to the best of our knowledge, it is the first paper to study the full dynamics of news shocks analytically. This allows us to shed light on the types of economic features, besides those presented in this paper, that may be plausible candidates to solve the news shock comovement problem.

In the next section, we describe the production complementarity model, characterize its optimal allocation and provide conditions under which the model supports procyclical technology news shocks. In Section 3, we do the analogous examination of a preference-based mechanism capable of supporting this type of news shocks. Section 4 analyses quantitative and calibration issues with the baseline production complementary model, and develops modifications to address these issues. Section 5 studies a model of forward-compatible investment, and Section 6 concludes.

2 Procyclical News Shocks via Production Complementarity

Consider the following variant of the continuous time, neoclassical growth model.

The Model

Consumption, $C(t)$, and investment, $I(t)$ are produced according to:

$$F[C(t), I(t)] = K(t)^\alpha (A(t) N(t))^{1-\alpha} \quad (1)$$

where $K(t)$ and $N(t)$ represent capital and hours respectively. Assume

$$F(C, I) = [\theta C^v + (1 - \theta) I^v]^{1/v} \quad (2)$$

where $\alpha, \theta \in (0, 1)$, $t \in [0, \infty]$ and $v \geq 1$.

Our sole departure from the neoclassical model pertains to the definition of $F(C, I)$, which represents the production possibility frontier for consumption and investment given the amount of inputs. We allow for the possibility of complementarities between the produc-

tion of consumption and investment goods. If $v = 1$, the equation collapses to the standard model. As v increases, the complementarity between the production of the two goods increases. If $v = \infty$, the production frontier takes a Leontief form. Figure 2 shows how the complementarity between consumption and investment as v changes.

We can interpret v as measuring the factor substitutability between the consumption and investment sectors of a more general model. In the basic neoclassical model ($v = 1$), factors are equally productive in both the consumption and investment sectors. As a result, the relative price of consumption to investment remains constant irrespective of how much resources are being devoted to producing consumption versus investment. In our model, factors are not equally productive in both sectors. As v increases, a factor in one sector is less and less productive in the other sector. For example, a worker that produces goods in the consumption sector, when moved to the investment sector will become less productive.⁷

The law of motion of capital is:

$$\dot{K}(t) = I(t) - \delta K(t) \quad (3)$$

where δ is the capital depreciation rate.

A social planner ranks utility over different consumption and hours time paths using:

$$U = (1 - \sigma)^{-1} \int_0^{\infty} e^{-\rho t} [C(t) \exp(-N(t))]^{1-\sigma} dt \quad (4)$$

where $\sigma \geq 0$ is the curvature parameter in the utility function and $\rho > 0$ is the discount rate.⁸

Next, a *positive technology news shock* is an increase in technology arriving at time T that becomes anticipated at time zero. Thus, at time zero, the perfect foresight time path for technology becomes:

⁷An alternative mechanism to the bowed-out production frontier in equation (1) is intersectoral adjustment costs. Suppose that in the planner problem we replace $F(C, I)$ with

$$F^{ADJ}(C, I) \equiv (C + I) \left[1 + \frac{\psi_Y}{2} \left(\frac{1}{\theta} \frac{C}{I} - 1 \right)^2 \right]$$

Given the above form, the intersectoral adjustment cost and production complementarity models are isomorphic up to the log-linearization.

⁸These preferences exhibit balanced growth. Holding fixed hours, σ is the inverse of the intertemporal elasticity of substitution for consumption.

$$A(t) = \begin{cases} \bar{A} & \text{for } t \in [0, T) \\ \bar{A} = \bar{A} + \epsilon & t \geq T \end{cases} \quad (5)$$

where \bar{A} denotes the initial steady-state technology level. A contemporaneous (or unanticipated) technology shock corresponds to the case when $T = 0$.

It is useful to define the following

Definition 1. *A model exhibits procyclical technology news shocks if an anticipated increase in future technology (i.e. a positive technology news shock) leads to an increase in current consumption, investment and hours.*

Because we only study technology shocks, we will often omit the word ‘technology’ when referring to technology news shocks.

The Planning Problem and Its Solution

The social planner chooses C , I , K and N to maximize U subject to (1), (2) and (3), taking as given the initial condition $K(0)$ and time path of technology given by (5).

The current value Hamiltonian associated with the problem is:

$$H = (1 - \sigma)^{-1} C^{1-\sigma} \exp[-(1 - \sigma)N] + \Lambda (I - \delta K) + \Phi (K^\alpha (AN)^{1-\alpha} - F(C, I))$$

The first-order necessary conditions at an interior solution satisfy the following:

$$-\frac{U_N}{U_C} = (1 - \alpha) \frac{F}{N} (F_1)^{-1} \quad (6)$$

$$\frac{U_C}{\Lambda} = \frac{F_1}{F_2} \quad (7)$$

$$\frac{\dot{\Lambda}}{\Lambda} - \rho = \delta - \alpha \frac{F}{K} (F_I)^{-1} \quad (8)$$

along with a initial condition on capital and a transversality condition on Λ .

Equation (6) is the intratemporal Euler equation between consumption and labor hours, equation (7) is the intratemporal Euler equation between consumption and investment, and equation (8) is the optimal capital accumulation equation. All of these equations are similar to their neoclassic counterparts. The sole difference is that $F_1 = F_2 = 1$ in the basic neoclassical model. With production complementarities F_1 and F_2 change with level of consumption and investment.

Log-linearizing these equations,⁹ we have the following three optimality conditions:

$$n = v s_I (i - c) \quad (9)$$

$$(v - 1) (i - c) = \lambda - (-\sigma c - zn) \quad (10)$$

$$\dot{\lambda} = -(\rho + \delta) [v(1 - s_I)(c - i) + i - k] \quad (11)$$

where $z = (1 - \sigma)(1 - \alpha) / (1 - s_I)$ and $s_I = (\alpha\delta) / (\rho + \delta)$.

Equation (9) ensures an efficient labor allocation. As consumption rises, the marginal utility of consumption falls and the planner increases leisure. An increase in investment shifts out labor supply. Labor does not depend on capital in the equation because we use balanced growth preferences.

Equation (10) ensures an efficient consumption-investment split. The left-hand side is the price of investment in units of consumption. Investment becomes more expensive when production of consumption is relatively low. The right-hand side is the marginal utility of investment minus the marginal utility of consumption.

Equation (11) is the intertemporal consumption Euler equation. It differs from the neoclassical model in that λ is not simply the derivative of the marginal utility of consumption. There is an additional relative price effect because of the convex production frontier.

The two resource constraints and the definition of output are given by:

$$(1 - s_I) c + s_I i = \alpha k + (1 - \alpha)(a + n) \quad (12)$$

$$\dot{k} = \delta (i - k) \quad (13)$$

$$y = \alpha k + (1 - \alpha)(a + n) \quad (14)$$

Equation (12) is the static resource constraint. Equation (13) is the law of motion for capital. Equation (14) gives the definition of output.

News-Driven Business Cycles

We next study under what conditions the model exhibits procyclical news shocks. We subdivide our proof into first establishing the procyclicality and comovement between the

⁹The system is log-linearized around the initial steady-state, which is consistent with the constant technology \bar{a} . A lower case letter denotes the log deviation of that variable from its upper case counterpart.

variables at time zero, and then the procyclicality and comovement between variables for time $t \in (0, T)$.

Lemma 1. *Suppose the economy experiences a positive technology news shock. Consumption, investment and hours will comove at time zero if and only if $v > v^* = (1 - \alpha)^{-1}$*

Proof. All proofs are contained in appendix A. □

Lemma 2. *Suppose the economy experiences a positive technology news shock. Consumption, investment and hours will comove procyclically, with respect to the expectations of future technology, at time zero if and only if $v > v^*$ and $\lambda(0) > 0$.*

The intuition for Lemmas 1 and 2 can be understood using Figure 3. Figure 3 plots the solution to the static consumption-investment decision holding fixed the marginal utility of investment. It plots this for the cases with and without production complementarity.

Substituting out the optimal hours from the production equation (12), we have:

$$\alpha k = (1 - \phi_I^{PC}) c + \phi_I^{PC} i \tag{15}$$

where $\phi_I^{PC} = (1 - v(1 - \alpha)) s_I$.

This is plotted as L_1 in Figure 3(a) and Figure 3(b). In the absence of production complementarity, this is a downward-sloping line, as seen in Figure 3(a).¹⁰ Intuitively, when consumption rises, hours cannot optimally rise because leisure is a normal good; therefore, investment must fall. With sufficiently strong complementarity, i.e. $v > (1 - \alpha)^{-1}$, L_1 is upward sloping as seen in panel (b).

With strong complementarity, an increase in investment raises the marginal product of labor in producing the consumption good. This higher marginal product of labor implies that both hours and consumption can increase. An investment decline, on the other hand, will go hand-in-hand with a reduction in consumption.

Next, consider L_2 , the consumption-investment Euler equation with optimal hours substituted out:

$$\gamma_I^{PC} i - (\sigma + \gamma_I^{PC}) c = \lambda \tag{16}$$

where $\gamma_I^{PC} = (v - 1) - [v(1 - \alpha)(1 - \sigma) s_I] / (1 - s_I)$.

¹⁰We are assuming that capital is predetermined at the steady-state level at time zero.

In general, the slope of L_2 can be either positive or negative. The slope depends most crucially on ν . To generate procyclical news shocks, ν must be large. To understand why L_2 can be upward-sloping, consider the consumption-leisure Euler equation. For the assumed utility function, consumption equals the real wage (ignoring complementarity in production). Because the real wage is simply labor's share in production, hours are a linear function of the output-consumption ratio. Thus, if the planner decided to increase investment relative to consumption, hours worked increases. This is seen in equation (9). Note that adding production complementarity (i.e. setting $\nu > 1$) increases the hours effect because it increases the marginal product of hours in producing the consumption good.

Next, suppose we consider an increase in the marginal utility of investment, λ , at time zero. For now, we take the increase in $\lambda(0)$ as given. Later, starting with Lemma 4, we provide a condition for which time zero news of a technology increase at time T results in an increase in $\lambda(0)$. First, an increase in $\lambda(0)$ does not shift L_1 .¹¹ Second, an increase in $\lambda(0)$ induces a shift leftward of L_2 either with or without complementarity. As the marginal utility of investment increases, the social planner shifts away from consumption for a given level of investment. Even though L_2 moves in the same direction in either case, the implication for the optimal investment-consumption pair is different between the two cases. Because L_1 is downward sloping without complementarity, investment rises but consumption falls; however, L_1 is upward sloping with complementarity and both investment and consumption rise. Intuitively, the increase in investment raises the marginal product of labor towards consumption when there is production complementarity. The fall in the relative price of consumption leads the planner to increase hours worked. Note that $a(0) = 0$, as the technology increase does not occur until time T .

Lemma 3. *Suppose the economy experiences a positive technology news shock. Also, assume that $\nu > \nu^*$. Consumption, investment and hours will comove procyclically for all time $t < T$ if $\forall t < T, \dot{\lambda} \geq 0$ and $\dot{k} \geq 0$*

Equation (15) implies that if k is increasing over time, then output also increases over time. As such, $\dot{k} \geq 0$ causes L_1 to progressively shift leftward, shifting out the production frontier. When $\dot{\lambda} \geq 0$, the marginal utility of investment is increasing over time. This causes the planner to shift production away from consumption into investment. This results in a rightward shift in L_2 . As illustrated in Figure 4, these two effects cause consumption and investment to continue increasing for all time $t < T$.

¹¹This is because our preferences imply that labor is stationary along a balanced growth path; the consumption-leisure Euler equation, and therefore L_1 does not depend on the co-state variable.

We have thus far studied what happens to c, i and n when $\lambda(0)$ increases in response to good news. We now provide conditions on parameters under which this increase in $\lambda(0)$ obtains.

The log-linearized dynamic system is:¹²

$$\begin{bmatrix} \dot{\lambda}(t) \\ \dot{k}(t) \end{bmatrix} = \begin{bmatrix} \Gamma_{\lambda,\lambda}^{PC} & \Gamma_{\lambda,k}^{PC} \\ \Gamma_{k,\lambda}^{PC} & \Gamma_{k,k}^{PC} \end{bmatrix} \begin{bmatrix} \lambda(t) \\ k(t) \end{bmatrix} + \begin{bmatrix} b_{\lambda,a}^{PC} \\ b_{k,a}^{PC} \end{bmatrix} a(t) \quad (17)$$

In the presence of a news shock, there is a discontinuous forcing term in the dynamic system. In equation (17), $a(t)$ is a step function which takes on the value zero for all time $t < T$ and a value of $\ln(1.01)$ for all time $t \geq T$, i.e. $\epsilon = .01\bar{A}$.

Laplace transforms lend themselves nicely here. Using these transforms, we can map our problem into the frequency domain where the problem is continuous and solvable using standard techniques. Once we have solved the dynamic system in this new domain we can then map the solution back into the time-domain (using the method outlined in Boyce and Diprima (1969)). The resulting time-paths of $k(t)$ and $\lambda(t)$ for our system are:

$$k(t) = \begin{cases} \frac{\Gamma_{k,\lambda}^{PC}\lambda(0)}{\mu_1 - \mu_2} e^{\mu_1 t} + \frac{\Gamma_{k,\lambda}^{PC}\lambda(0)}{\mu_1\mu_2} e^{\mu_2 t} & \text{for } t \in [0, T) \\ \frac{\Gamma_{k,\lambda}^{PC}\lambda(0)}{\mu_1 - \mu_2} e^{\mu_1 t} + \frac{\Gamma_{k,\lambda}^{PC}b_{\lambda,a}^{PC} - \Gamma_{\lambda,\lambda}^{PC}b_{k,a}^{PC}}{\mu_1\mu_2} + \frac{\mu_2 - \mu_1}{\mu_1(\mu_1 - \mu_2)} \Gamma_{k,\lambda}^{PC}b_{\lambda,a}^{PC} + (\mu_1 - \Gamma_{\lambda,\lambda}^{PC})b_{k,a}^{PC} e^{\mu_1(t-T)} & t \geq T \end{cases} \quad (18)$$

$$\lambda(t) = \begin{cases} \frac{(\mu_1 - \Gamma_{k,k}^{PC})\lambda(0)}{\mu_1 - \mu_2} e^{\mu_1 t} + \frac{(\mu_2 - \Gamma_{k,k}^{PC})\lambda(0)}{\mu_1\mu_2} e^{\mu_2 t} & \text{for } t \in [0, T) \\ \frac{(\mu_1 - \Gamma_{k,k}^{PC})\lambda(0)}{\mu_1 - \mu_2} e^{\mu_1 t} + \frac{\Gamma_{\lambda,k}^{PC}b_{k,a}^{PC} - \Gamma_{k,k}^{PC}b_{\lambda,a}^{PC}}{\mu_1\mu_2} + \frac{\mu_2 - \mu_1}{\mu_1(\mu_1 - \mu_2)} \Gamma_{\lambda,k}^{PC}b_{k,a}^{PC} + (\mu_1 - \Gamma_{k,k}^{PC})b_{\lambda,a}^{PC} e^{\mu_1(t-T)} & t \geq T \end{cases} \quad (19)$$

where μ_1 and μ_2 are the eigenvalues of the Γ^{PC} matrix.¹³ In Appendix B, we prove that μ_1 and μ_2 are real with one being positive and the other negative. Without loss of generality, let $\mu_1 < 0$ and $\mu_2 > 0$.

The solutions for the time paths of k and λ show that the dynamics of the system before time T are being determined not only by the stable eigenvalue, but also the unstable eigenvalue. This is important. Without a role for the unstable eigenvalue, the system would be on a new stable manifold, corresponding to a higher permanent level of $a(t)$, for all $t < T$. Along the stable manifold capital and the shadow value of investment do not comove. This

¹²The values of $\Gamma_{\lambda,\lambda}^{PC}$ and $b_{\lambda,a}^{PC}$ can be found in the Appendix B.

¹³The online Appendix B contains the derivation of (18) and (19)

will result in a negative comovement between the variables for $t \in [0, T)$. After time T , the system is on a new stable path and the dynamics are then determined by the new stable manifold alone.

The above solution has one undetermined variable $\lambda(0)$. We seek a path for (λ, k) that is not explosive. In order to achieve this, we choose $\lambda(0)$ such that the explosive root μ_2 does not determine the evolution of the system for $t > T$. This ensures that we are on the stable path. Otherwise, the path for k will be explosive. This restriction on $\lambda(0)$ is as follows:

$$\frac{\Gamma_{k,\lambda}^{PC} \lambda(0) + (\mu_2 - \Gamma_{\lambda,\lambda}^{PC}) k(0)}{(\mu_2 - \mu_1)} = - \frac{\Gamma_{k,\lambda}^{PC} b_{\lambda,a}^{PC} + (\mu_2 - \Gamma_{\lambda,\lambda}^{PC}) b_{k,a}^{PC}}{\mu_2 (\mu_2 - \mu_1)} e^{-\mu_2 T}$$

Studying the above equation in conjunction with the time paths for k and λ , it can be seen that the discontinuity of $a(t)$ does not cause a discontinuity in the time path of λ or k . Instead, the discontinuity of the exogenous process shows up in the time paths as a non-differentiability (kink) at time T .

Using the time paths of k and λ above, along with the restrictions for a stable solution, we have the following lemmas.

Lemma 4. *Suppose the economy experiences a positive technology news shock and $v > v^*$. $\dot{\lambda} \geq 0$ and $\dot{k} \geq 0 \forall t < T$ if and only if $\lambda(0) > 0$.*

Lemma 5. *Suppose the economy experiences a positive technology news shock and $v > v^*$. $\lambda(0) > 0$ if and only if $\sigma < \sigma^*$, where σ^* solves*

$$\mu_2^{PC} = (\rho + (1 - \alpha) \delta) v / (\gamma_I + \sigma)$$

and $\mu_2^{PC} = \mu_2^{PC}(\sigma)$ is the positive eigenvalue of Γ^{PC} .

The condition that $\sigma < \sigma^*$ implies that in order to generate procyclical technology news shocks the model requires a relatively low curvature parameter σ .

Lemmas 1 through 5 lead to the following theorem.

Theorem 1. *The production complementarity model exhibits procyclical technology news shock if and only if $v > v^*$ and $\sigma < \sigma^*$.*

To better understand this theorem, Figure 5 plots the phase diagram for four cases. For now, we focus on the first three: (a) no production complementarity, (b) complementarity

with a high curvature parameter, (c) complementarity with a low curvature parameter. Only case (c) results in procyclical news shocks. Initially before the news, as seen in in Figure 5(a), the capital-multiplier pair (k_{ss}, λ_{ss}) lies on the initial manifold \mathcal{M} and is at the initial steady state. Upon the time zero news arrival, the multiplier falls below λ_{ss} because there is an immediate consumption boom. Because capital is a stock variable, $k_0 = k_{ss}$. After time zero and before T (which is the instant of the technology arrival), the capital stock falls indicating that investment is below the steady-state. The consumption boom comes at the expense of investment. This is one indicator of the comovement problem in the standard model: investment declines upon the arrival of good news.

Note that between time zero and time T , the capital-multiplier pair flow in the opposite direction of the stable manifold. This is due to influence of the explosive root (μ_2) before the technology change occurs. At time T , the model is on the new stable manifold \mathcal{M}' and the system then converges monotonically to the new steady-state. The \mathcal{M} and \mathcal{M}' manifolds are parallel to each other because the technology shock does not change the coefficients multiplying the endogenous variables.

Figure 5(b) contains the phase diagram with production complementarity, but a high curvature parameter. As in the case without complementarity, investment initially falls in response to the news. Investment eventually increases once the technology change actually occurs. At this point, the system is on the manifold and capital converges monotonically to the new higher steady state. The desire for smooth consumption, due to the high curvature parameter, is evident in the path of the multiplier. It jumps downward on impact and then moves monotonically to the new steady state.

Figure 5(c) contains the phase diagram for the case of greatest interest. It represents the case when both conditions of Theorem 1 are satisfied: strong production complementarity and a low curvature parameter. Note that the marginal utility of investment jumps up rather than down in response to the good news.

Both σ and δ play important roles in affecting λ on impact, through equation (10).¹⁴ As a starting point, note first that according to the consumption-hours Euler equation (9), n increases if and only if $i - c$ increases.

Next, rewriting equation (10), we have:

$$\underbrace{\lambda}_{MU_I} = \underbrace{(v-1)(i-c)}_{price_I} + \underbrace{\left(-\sigma c - \frac{(1-\sigma)(1-\alpha)}{(1-s_I)}n\right)}_{MU_C} \quad (20)$$

¹⁴The L_2 line is exactly equation (10) once the labor term is substituted out using (9).

First, a good news shock that causes hours to rise is accompanied by an increase in the price of investment (in units of consumption) when $v > 1$. This works to raise the marginal utility of investment. Next, consumption also rises if the news shock is procyclical. The increases in both c cause the marginal utility of consumption to fall, which offsets the price effect on λ . This effect is dampened when σ is close to zero. This is a straightforward channel operating in the standard neoclassical model.¹⁵ Intuitively, when σ is close to zero the timing of investment is governed by production efficiency concerns and not a desire to smooth consumption.

Finally, n appears in the MU_C term because consumption and hours are non-separable in the utility function. σ plays a different role in the term premultiplying n . Here, it effects the degree of complementarity between n and c in preferences. If $\sigma = 1$, preferences are separable and the n term drops out. If $\sigma < 1$, then leisure and consumption are complements, which puts downward pressure on λ . It must be the case that effect of σ on c is dominates its effect on n .

Thus, a low σ (through a dampened consumption effect) and the production complementarity lead to an overall increase the shadow value of investment. This makes the return to forgoing leisure in order to produce the investment good, which is serves the requirement of Condition II.

Although investment jumps up at time zero, the new steady state must involve $k'_{ss} > k_{ss}$ and $\lambda'_{ss} < \lambda_{ss}$. This occurs in case (c) because the new manifold eventually crosses into the fourth quadrant of the phase space.

The conditions of Theorem 1 are independent of the value of T . As a result, the model preserves the ability to generate procyclical comovements in response to traditional time zero unanticipated shocks and news shocks for any time into the future.

In addition to providing both the necessary and sufficient conditions for solving the news shock puzzle, Theorem 1 provides insight into understanding how news shocks work. In particular, the analysis sheds light on other mechanisms that are capable of solving the news shock puzzle. We present our understanding via the following observation.

Main Observation¹⁶ *A variant of the neoclassical model will exhibit procyclical technology*

¹⁵If consumption and hours were separable, then σ is simply the inverse of the intertemporal elasticity of substitution of consumption.

¹⁶Lemma 2 and 4 tell us that $\lambda(0) > 0$ is both a necessary and sufficient condition to generate **procyclical technology news shocks** in a standard neoclassical model with production complementarities. However, most economic frictions/features that result in $\lambda(0) > 0$ have more than just that marginal effect on the model and also change the static and dynamic relationships in the standard neoclassical model with production complementarities. As a result of which we state this result as an observation rather than a theorem.

news shocks if it has one or more features that ensures:

I. consumption does not crowd out investment, or vice versa, and

II. the benefit to forgoing leisure is sufficiently strong.

Next, we consider the marginal effects of changing each of the model's remaining parameter. First, calibrating to a higher value of capital share, α , decreases the cost to forgoing leisure and thus now allows relatively higher values of σ required to generate procyclical news shocks.

Figure 6 plots the minimum curvature parameter needed for $\lambda(0) > 0$ when we parameterize $\nu = \infty$ in our production based model.¹⁷ As the capital share increases, the required utility curvature parameter falls. A higher capital share in production decreases the cost to forgoing leisure and thus allows a lower curvature parameter to generate $\lambda(0) > 0$.

Similarly, as ρ/δ increases, the minimum required intertemporal elasticity of substitution falls. An increase ρ/δ implies either an increase in ρ or a decrease in δ . An increase in ρ weakens the consumption smoothing motive and strengthens the returns to forgoing leisure. An increase in ρ/δ allows the model to exhibit procyclical news shocks with relatively low values of σ .

The second condition for a model to exhibit procyclical news shocks simplifies dramatically when the depreciation rate is near zero.

Lemma 6. *For δ sufficiently close to zero, the model exhibits procyclical news shocks if $v > v^*$ and $\sigma < 1$.*

What is the role of the depreciation rate? Intuitively, if the capital depreciation rate is high, then the benefit to forgoing leisure is low. This is because, upon the arrival of the news, forgoing leisure to increase investment is only optimal if investment undertaken right away has a positive effect on the capital stock once the technology actually increases; however, if the capital depreciation rate is too high, then much of the investment made at the arrival of the news will have depreciated by the time technology actually increases. A low depreciation rate implies that the forgone leisure used to produce the investment good is not depreciated away by the time of the technology arrival.

¹⁷ $\nu = \infty$ in the Leontief case. In this case $\lambda(0) > 0$ if and only if $\sigma < \sigma_c$. $\sigma_c = -\xi_A + \sqrt{\xi_A^2 + \xi_B}$, where $\xi_A = \frac{(2-3\alpha)(1-\alpha)+(3(1-\alpha)+\alpha^2)\frac{\rho}{\delta}+(\frac{\rho}{\delta})^2}{2(1-\alpha)\alpha}$ and $\xi_B = \frac{(1+\frac{\rho}{\delta})((1-\alpha)^2+\frac{\rho}{\delta})}{(1-\alpha)\alpha}$.

The importance of σ in Lemma 6 was explained previously in the discussion of Theorem 1. A low σ lessens the negative effect of the consumption boom on λ , allowing the positive price effect to dominate and thus increase λ .

Next, we plot the impulse responses for a specific model parameterization. Our model calibration meets the two conditions: $v > v^*$ and $\sigma < \sigma^*$. First, $v = 1.8$. Vall'es (1997) finds that $v = 1.8$ best matches the estimated responses of investment to various shocks. Sims (1989) uses a similar $F(C, I)$ function and chooses $v = 3$.

The value of σ in our baseline calibration is 0.5, which implies less curvature than the oft-used 1.0 (i.e. log utility). However, $\sigma = 0.5$ is within the range of some empirical estimates (e.g. Beaudry & Wincoop (1996), Vissing-Jorgensen & Attanasio (2003) and Mulligan (2002)). In Section 4, we consider modifications of the production complementarity model that allow for greater curvature in the utility function. The remaining parameters are less crucial and entirely in line with existing research. All parameters are reported in Table 1.

The impulse responses are given in Figure 7. At time zero, capital is at the initial steady state and agents receive news of an expected one-percent permanent increase in technology that will arrive at $T = 4$. Examining panels (b), (c) and (d), we see that consumption, hours and investment all increase on impact. Moreover, as our phase diagram and theorem dictate, the shadow value of investment λ increases upon the arrival of the news (see panel (f)).

The response of consumption, seen in panel (b), is positive but nearly zero. This may be viewed as a deficiency of the model, although we note that non-durable consumption, the closest analogue in actual data to consumption in our model, contributes very little to empirical business cycles. In Section 4, we examine how adding various features to the baseline production complementarity model can affect the impulse responses quantitatively.

Finally, the model exhibits a large increase in consumption, investment, and hours upon the actual technology increase.

3 Procyclical News Shocks via a Positive Labor Externality

This section modifies the preference side of the growth model as a way to sustain procyclical news shocks. Specifically, we replace the momentary utility function in equation (4) with:

$$W(C, N, \bar{N}) = (1 - \sigma)^{-1} [C \exp(-N\bar{N}^{-\gamma_N})]^{1-\sigma}$$

where $0 < \gamma_N < 1$ and \bar{N} is the average economy-wide labor input.¹⁸ Thus, there is an external effect of employment on utility. In particular, the marginal disutility of labor falls as average labor rises. From an individual's perspective, he would prefer to work additional hours when others are working. In turn, the labor externality will act, from the household perspective, similarly to a preference shock that shifts out labor supply. This mechanism will ensure a low relative cost of forgoing leisure

Also, we add investment adjustment costs by replacing (3) with

$$\dot{K} = I - \delta K - \frac{\psi_I}{2} \left(1 - \frac{I}{\delta K}\right)^2 I, \quad (21)$$

This is because no stable dynamic solution exists at low values of σ . With the employment externality, production complementarity is not necessary to support procyclical news shocks; as such, we set $\nu = 1$.

The log-linearized equations that characterize a solution to the constrained planner's problem are now:

$$n = \frac{s_I}{1 - \gamma_N} (i - c) \quad (22)$$

$$\underbrace{\lambda}_{MU_I} = \underbrace{\psi_I (i - k)}_{price_I} + \underbrace{(-\sigma c - zn)}_{MU_C} \quad (23)$$

$$\dot{\lambda} = -(\rho + \delta) [(1 - s_I)(c - i) + i - k] + \rho \psi_I (i - k) \quad (24)$$

as well as the resource constraints given by equations (12) and (13).

¹⁸To characterize the resource allocation in the presence of the externality, we have the social planner take the time path of \bar{N} as given when choosing the time paths of (C, I, K, N) . Thus, we are studying a constrained optimal plan. It is straightforward to show that this allocation is the same as what would obtain in a competitive equilibrium with the externality.

The term $\gamma_{\bar{N}}$ only appears in (22), the consumption-labor Euler equation.¹⁹ and the addition of investment adjustment costs, exactly like before, only alters equations (23) and (24).

We can substitute (22) into (12) to get a new consumption-investment production frontier (new L_1 line):

$$(1 - \phi_I^{LE})c + \phi_I^{LE}i = \alpha k + (1 - \alpha)a \quad (25)$$

Here, $\phi_I^{LE} = \left(1 - \frac{1-\alpha}{1-\gamma_{\bar{N}}}\right) s_I$. In this model, L_1 is upward sloping if $\phi_I^{LE} < 0$. This requirement, which simplifies to $\gamma_{\bar{N}} > \alpha$, is necessary and sufficient for comovement (although not necessarily procyclical) in response to a news shock.

Lemma 7. *Suppose the economy experiences a positive technology news shock. Consumption, investment and hours comove at time zero if and only if $\gamma_N > \gamma_N^* = \alpha$.*

Lemma 7 is the labor externality counterpart to Lemma 1 for the production complementarity model.

The steps in characterizing the allocation under labor externalities are very similar to those (previously done) under production complementarities. Two of the five equations, as noted above, are identical across the two cases. The remaining three equations contain nearly the same endogenous variables as in the previous model. Differences between the two sets of preferences are limited to the coefficients multiplying the endogenous variables. As such, we can apply the previous technique to this model.

The optimal solution satisfies the following conditions:

$$x = \tau_{x,k}^{LE}k + \tau_{x,\lambda}^{LE}\lambda + \tau_{x,a}^{LE}a \text{ for } x = c, i, n$$

$$\begin{bmatrix} \dot{k} \\ \dot{\lambda} \end{bmatrix} = \Gamma^{LE} \begin{bmatrix} k \\ \lambda \end{bmatrix} + b^{LE}a \quad (26)$$

The explicit formulas for $\tau_{x,\cdot}^{LE}$, b^{LE} and Γ^{LE} are given in Appendix B.

As mentioned previously for a model with labor externalities there exists no stable dynamic solution for low values of σ . The addition of investment adjustment costs alleviates

¹⁹In fact, if one were to replace $1/(1-\gamma_N)$ with the value ν on the left-hand side, the equation would be identical to (9) from the production complementarity model.

this problem. The next lemma holding fixed all other parameter values gives the minimum value of ψ_I , the investment adjustment cost parameter, under which a stable dynamic solution exists.

Lemma 8. *Suppose the economy experiences a positive technology news shock. Also, assume that $\gamma_N > \gamma_N^*$. Then a stable solution to equation (26) exists if*

$$\psi_I > \psi_I^+ = -\frac{\gamma_I^{LE} + \phi_I^{LE}\sigma}{1 - \phi_I^{LE}}$$

Lemma 9. *Suppose the economy experiences a positive technology news shock. Also, assume that $\gamma_N > \gamma_N^*$ and $\psi_I > \psi_I^+$. $\lambda(0) > 0$ if and only if $\psi_I > \psi_I^*$. where, ψ_I^* solves equality*

$$\mu_2^{LE} = \frac{\Gamma_{\lambda,\lambda}^{LE} b_{k,a}^{LE} - \Gamma_{k,\lambda}^{LE} b_{\lambda,a}^{LE}}{b_{k,a}^{LE}}$$

and $\mu_2^{LE} = \mu_2^{LE}(\psi_I)$ is the positive eigenvalue of Γ^{LE} .

Theorem 2. *The labor externality model exhibits procyclical technology news shock if: $\gamma_N > \gamma_N^*$ and $\psi_I > \text{Max}\{\psi_I^+, \psi_I^*\}$.*

Here is the intuition and relation to our main observation. As labor increases, the marginal product of labor falls, which reduces the incentive to work. Without an external effect, the marginal disutility of labor is increasing in labor. Thus, these two effects work in the same direction. On the other hand, with the external effect, then in a symmetric equilibrium, the effective marginal disutility of labor is falling in labor. If the labor externality, measured by γ_N , has a stronger positive labor supply effect than the negative diminishing returns to labor demand effect, measured by $1 - \alpha$, then the employment increase will be sufficiently large to support both a consumption and investment increase.²⁰ Thus, the labor externality mechanism achieves Condition I.

Next, equation (23) is critical for ensuring that the marginal utility of investment rises on impact. The intuition here is identical to that of the production complementarity model with one difference. In the current model, the price of investment (see the right-hand side

²⁰For parameter pairs (γ_N, α) that satisfy the comovement condition, note that there does not exist an interior solution to the first-best resource allocation. With $\gamma_N > 0$, the social marginal disutility of labor is declining, rather than rising, as labor increases. With $\gamma_N > \alpha$, this decline occurs more rapidly than the increase in marginal cost associated with diminishing returns.

of equation (23)) increases because of investment adjustment costs term, $\psi_I(i - k)$. In the production complementarity model, the price of investment (see the right-hand side of equation (20)) because of the production complementarity term, $v(i - c)$. The adjustment cost mechanism achieves Condition II.

Although the labor externality model has a different mechanism than the production complementarity model, the relevant diagrams for the two models are identical. Figure 5(c) is the correct phase diagram for the new model; Figures 3 and 4 illustrate the static relationships for the new model.

Next, we plot the impulse responses for a specific model parameterization. Our model calibration meets the requirement $\gamma_{\bar{N}} > \alpha$ and the two conditions on ψ_I . We set $\gamma_N = 0.332$, $\psi_I = 20$ and $\sigma = 1$. All parameters values are reported in Table 1.

The values of σ and ψ_I are in line with those of existing research. On the other hand, γ_N is chosen somewhat arbitrarily because existing research provides no guidance for choosing its value. This parameter choice is motivated by our desire to demonstrate one mechanism capable of supporting procyclical news shocks.

The impulse responses are given in Figure 8. Consumption, hours, investment as well as the shadow value of investment all increase upon the arrival of the news. Quantitatively, we view the results as disappointing. Each of the three main variables is nearly acyclical in response to the positive news.

4 Quantitative Issues and Calibration Issues

Section 2 established that adding production complementarity to the neoclassical growth model was sufficient to support procyclical news shocks. The mechanism, by itself, has two potential drawbacks: the resulting consumption boom is miniscule, the requires low curvature in the utility function. Both drawbacks are also present in the preference-externality model. This section restricts attention to the production complementarity model and shows how either changing preferences or adding investment adjustment costs can mitigate these difficulties.

Greenwood-Hercowitz-Huffman Preferences

Suppose we replace the King, Plosser and Rebello preferences (1988, hereafter KPR), used earlier in this paper, with those of Greenwood, Hercowitz and Huffman (1988, hereafter

GHH). The instantaneous utility function becomes

$$V(C, N) = \left(C - \xi \frac{N^{1+\psi}}{1+\psi} \right)^{1-\omega} / (1-\omega)$$

where $\omega, \xi, \psi > 0$. The set-up is otherwise identical to the production-complementarity model.

The critical feature of these preferences is that the marginal disutility of labor is falling in consumption. Recall that, in absence of a low σ under the KPR preferences, it was optimal for the planner to delay and hours boom until the new technology arrives. Under GHH preferences, the marginal disutility of work is falling in consumption; as such, there is an preference-driven incentive to work more during a consumption boom.

The log-linearized conditions for an optimum consists of five equations, three of which are identical to the baseline production-complementarity model.²¹ The first equation (that does change) is the intratemporal consumption-hours Euler condition. Under GHH preferences, it is:

$$n = v s_I (i - c) + c \tag{27}$$

For comparison, we restate the corresponding equation for the baseline preferences:

$$n = v s_I (i - c)$$

The production-complementarity effect, reflected by the $v s_I (i - c)$ term, is present in both equations. GHH preferences, additionally, imply that the planner works more hours when consumption is high. This augments the model's ability to achieve Condition I.

The second equation (that does change) is the consumption-investment Euler condition. Under GHH preferences, it is ²²

$$\lambda = (v - 1) (i - c) + \underbrace{\frac{1}{1 - s_n} [-\omega c + \omega s_n n]}_{MU_C} \tag{28}$$

²¹The unchanged equations are (11), (12), and (13).

²²Here $s_n = \frac{(1-\alpha)}{1-s_I}$

For the baseline preferences, we have

$$\lambda = (v - 1)(i - c) + \underbrace{\left[-\sigma c - (1 - \sigma) \left(\frac{1 - \alpha}{1 - s_I} \right) n \right]}_{MU_c}$$

Recall that in order for comovement to be *procyclical* with respect to positive news, λ must increase upon arrival of the news. This is an implication of our Condition II. Under the baseline preferences, we showed that this was qualitatively possible if v was sufficiently large and σ was sufficiently close to zero; however, quantitatively the consumption boom was nearly very small. Examining the KPR preferences, one sees that λ is decreasing in consumption. Roughly speaking, the planner attempts to allocate output to consumption and investment to equalize their marginal benefit. If consumption rises too much, then the marginal utility of consumption, MU_c , will fall too much. In turn, the marginal utility of investment would also have to fall.

GHH preferences help support an increase in λ in response to positive news. This is because, while MU_c is falling in consumption, it is rising in hours worked for any ω . Since labor and consumption comove, this leads to an offsetting effect of MU_c .

The steps in characterizing the optimal allocation under GHH preferences are very similar to those described previously. Three of the five equations, as noted above, are identical across the two cases. The remaining two equations, (27) and (28), for the GHH-preferences case, contain the same endogenous variables as in the KPR case. Differences between the two preference assumptions are limited to the coefficients multiplying the endogenous variables. As such, we can apply the previous technique.

The optimal solution satisfies the following conditions:

$$x = \tau_{x,k}^G k + \tau_{x,\lambda}^G \lambda + \tau_{x,a}^G a \text{ for } x = c, i, n$$

$$\begin{bmatrix} \dot{k} \\ \dot{\lambda} \end{bmatrix} = \Gamma^G \begin{bmatrix} k \\ \lambda \end{bmatrix} + b^G a$$

The explicit formulas for $\tau_{x,\cdot}^G$ and Γ^G are given in Appendix B. Appendix B also contains the conditions on the underlying parameters $(\alpha, \omega, \rho, \delta, \nu, \xi)$ required for the model to exhibit procyclical news shocks.

Next, we examine the quantitative implications of applying GHH preferences. The three new model parameters are set at $\omega = 0.5$, $\psi = 0.01$, and the scale parameter $\xi = 6.96$ to

match a steady state value of labor $N = 0.3$. We calibrate the remaining parameters at the values used in Section 2.

Investment Adjustment Costs

Condition II to generate procyclical news shocks requires a model feature that will ensure the benefit to forgoing leisure sufficiently outweighs the cost. Parameterizing our model with a high intertemporal elasticity of substitution led to us satisfy this condition in our basic production-based model. Further analysis of the marginal effect of other parameters in that model showed that increasing the marginal returns to investment, either by increasing the capital share in production or lowering the depreciation rate, also led to an increase in the benefit to forgoing leisure, albeit not large enough²³. The natural extension thus would be to include a feature that generates a very high returns to investment such as investment adjustment costs.

We make two modifications to the baseline production-complementarity model. First, we introduce investment adjustment costs by replacing (3) with (21). Second, we set $\sigma = 1$ to give us standard log utility in consumption.

This addition alter equations (10) and (11) in our log-linearized system by adding a new term:

$$\lambda = \underbrace{(v-1)(i-c) + \psi_I(i-k)}_{price_I} + \left(-\sigma c - (1-\sigma) \left(\frac{1-\alpha}{1-s_I} \right) n \right) \quad (29)$$

$$\dot{\lambda} = -(\rho + \delta) [v(1-s_I)(c-i) + i-k] + \rho \psi_I(i-k) \quad (30)$$

The remaining three equations are unchanged.

Equation (29) gives us the optimal consumption-investment decision. It is identical to the baseline production-complementarity model except there is an additional component to the price of investment, $\psi_I(i-k)$. This component is due to the investment adjustment costs, is increasing in i and works to increase λ . The phase diagrams in Section 2 showed why an increase in λ upon arrival of the news is required in order that a model support *procyclical* comovement. Adjustment costs help ensure that increase in λ , and, therefore, Condition II.

Equation (30) is the intertemporal consumption Euler equation. The sole difference in this equation from the baseline production-complementarity model is that the rate of change in the marginal utility of investment reflects the investment adjustment cost.

²³We still need higher than normal values of the intertemporal elasticity of substitution

Next, consider the impact of adjustment costs of Condition I. Even though the addition of investment adjustment costs alters equation (10), and thus the static system, it can be shown that the Lemmas 1 through 4 still hold. The L_1 line, equation (15), remains the same, and while the magnitude of the slope of L_2 changes qualitatively, there is no qualitative change. Figures 3(b) and 4 reflect (qualitatively) the static and required dynamic relationship in the adjustment cost model.

With investment adjustment costs the dynamic analysis is slightly altered. Lemma 5, and thus Theorem 1, now place a different parameter restriction required to generate a positive $\lambda(0)$. High investment adjustment costs lead to an increase in the returns to investment, which in turn leads to more capital, which further in turn leads to an increase in the benefit of supplying labor and forgoing leisure. Finally, the dynamic analysis in the (k, λ) space is qualitatively still given by Figure 5.

5 Forward-Compatible Investment

One observation, thus far, has been that in order to generate procyclical news shocks we require a feature or features that increases $\lambda(0)$, which is an alternative expression of Condition II. In this section, we describe how this can be achieved by introducing forward-compatible investment. Physical investment is forward-compatible if additions to the capital made between the arrival of the news and the actual technology increase are particularly well-suited to the future technology. For example, if an IT firm is laying down fiber optic cables and it knows a new, better standard will be in effect in a year then it may be able to ensure that the fiber optic cables currently being installed can take advantage of the new standard. This will mean that at least part of the investment done in the preparatory phase ($t \in [0, T)$) will be able to have an advantage of the new technology improvement once time T arrives.

The Model

Suppose that at time zero, news arrives of a future investment-specific technology shock. The technology increase will arrive at $T > 0$ and will be permanent:

$$Q(t) = \begin{cases} \bar{Q} & \text{for } t \in [0, T) \\ \tilde{Q} = 1.01 \times \bar{Q} & t \geq T \end{cases} \quad (31)$$

We shall refer to time between zero and T as the *preparatory phase*.

This shock appears in the capital law of motion:

$$\dot{K}(t) = Q(t)I(t) - \delta K(t) + (K(t) - e^{-\delta T} \bar{K}) P(\tilde{Q}, t, T, \epsilon) \quad (32)$$

where \bar{K} is the initial capital stock, which we assume is at the steady-state consistent with \bar{Q} .

The right-hand side of (32) decomposes the time derivative of capital into three terms. The first term is the contribution of investment multiplied by the current efficiency of investment. The second is the capital lost due to depreciation. The last term embodies the model's key assumption. It is the multiple of two functions. The first function is $K(t) - e^{-\delta T} \bar{K}$, representing the investment accumulated during the preparatory phase that has not depreciated. For convenience, define $\mathcal{K}(t) = K(t) - e^{-\delta T} \bar{K}$. The second function, $P(Q, t, T, \epsilon)$, is a positive technology shock. It will be constructed so that it permanently increases the productivity of investment made during the preparatory phase. Thus, investment made after the arrival of news will be forward-compatible with the yet-to-arrive technology.

This second function will be non-zero only in a small neighborhood of T . Thus, this positive shock will not come online until time T . Thus, the contribution of the third term in (32) will only apply to $\mathcal{K}(T)$. We refer to $\mathcal{K}(T)$ as *partially-adapted capital*. We plot the log deviations of the functions Q and P in Figure 10.

P depends on t because the forward-compatible effect is only operative for a certain interval of time. The term ϵ is a small positive number. It will define the neighborhood (of the time interval) in which the ‘‘forward-compatibility’’ shock occurs. Mathematically, $P(Q, t, T, \epsilon) \neq 0$ only if $t \in [T, T + \epsilon]$. A technical detail necessitates ϵ .²⁴ Later, we will drive ϵ to zero at the appropriate rate. We choose a particular form for P to aid calibration:

$$P(\tilde{Q}, t, T, \epsilon) = \begin{cases} 0 & \text{for } t \in [0, T) \cup (T + \epsilon, \infty) \\ \frac{\tau \tilde{Q}}{(1 - e^{-\epsilon}) Q} & t \in [T, T + \epsilon] \end{cases}$$

For notational simplicity, we will sometimes use $P_\epsilon(t)$ and suppress the function's dependence on \tilde{Q} and T .

Production of consumption occurs according to equations (1) and (2); that is, there is production complementarity between consumption and investment.²⁵ The utility function is (4), which is taken from the baseline model of Section 2.

²⁴If P were positive and finite only at one instant, then P will have zero effect on the capital capital. Instead, as we let ϵ approach zero, the P will become infinite at the instant T and cause K to jump upward. This technical detail is not needed in a discrete time model.

²⁵We assume that $A_t = 1$, since technology improvements are only investment specific in this model.

The Planning Problem and Its Solution

The social planner chooses C , I , K and N to maximize U subject to (1), (2) and (32), taking as given the initial condition $K(0)$ and time path of technology. The current value Hamiltonian for the problem is:

$$H = (1 - \sigma)^{-1} C^{1-\sigma} \exp[-(1 - \sigma)N] + \Lambda(QI - \delta K + P_\varepsilon \mathcal{K}) + \Phi(K^\alpha N^{1-\alpha} - F(C, I))$$

The log-linearized system that solves this Hamiltonian is given by five equations.²⁶ Two equations, (9) and (12), are identical to those from the baseline production complementarity model. These are the consumption-hours Euler equation and the production function. The three new equations are:

$$\lambda = (v - 1)(i - c) + (-\sigma c - z\nu) - q \quad (33)$$

$$\dot{\lambda} = -(\rho + \delta)[v(1 - s_I)c + q + i - k] - p_\varepsilon \quad (34)$$

$$\dot{k} = \delta(q + i - k) + (1 - e^{-\delta T})p_\varepsilon \quad (35)$$

Equation (33) ensures an efficient consumption-investment split. It is identical to the corresponding equation from the baseline production complementarity except for the final term on the right-hand side, $-q$. This is a relative price effect because technology is investment-specific. Before time T , however, $q(t) = 0$ because the technology improvement has not yet arrived.

Equation (34) is the intertemporal consumption Euler equation. It differs from the neoclassical model in two ways. First, λ is not simply the derivative of the marginal utility of consumption. There is an additional relative price effect because of the convex production frontier. Second, λ jumps down at T as a result of p_ε , that is in the limit as $\varepsilon \rightarrow 0$.

Equation (35) is the law of motion for capital. On the right-hand side, the first term is standard and the second reflects an increase in capital at time T . This occurs when the forward-compatible capital built during the preparatory phase becomes utilized with the new technology. Recall that p_ε is positive, and otherwise zero, only in a neighborhood of T . Below, we take the limit as $\varepsilon \rightarrow 0$. Then, p_ε becomes "infinite at an instant," causing an upward jump in the capital stock. The optimal solution also satisfies a standard transversality condition and an initial condition on capital.

²⁶The non-linear first-order conditions are presented in the appendix.

Recall that, in order to support procyclical news shocks, a model must have mechanism(s) that ensure: (I) consumption does not crowd out investment, and (II) a sufficiently large return to forgoing leisure.

Production complementarity is sufficient to ensure Condition I due to the derivations in the benchmark production complementary model. Following those derivations (detailed in the appendix), we have expressions for the jump variables (consumption, investment and hours) as functions of the state variables.

$$x = \tau_{x,k}^{FC} k + \tau_{x,\lambda}^{FC} \lambda + \tau_{x,q}^{FC} q \text{ for } x = c, i, n \quad (36)$$

Substituting (36) into the \dot{k} and $\dot{\lambda}$ equations, (34) and (35), we have:

$$\begin{bmatrix} \dot{\lambda}(t) \\ \dot{k}(t) \end{bmatrix} = \Gamma^{FC} \begin{bmatrix} \lambda(t) \\ k(t) \end{bmatrix} + b_q^{FC} q(t) + b_p^{FC} p(\tilde{q}, t, T, \varepsilon) \quad (37)$$

The explicit formulas for $\tau_{\cdot,\cdot}^{FC}$, Γ^{FC} , b_q^{FC} and b_p^{FC} are given in the appendix.

Next, we provide a theorem concerning procyclical news shocks in the forward-compatibility model.

Theorem 3. *The forward-compatible investment model exhibits procyclical technology news shocks if and only if $v(1 - \alpha) > 1$ and*

$$\tau > \frac{\Gamma_{k,\lambda}^{FC} b_{\lambda,q}^{FC} + (\mu_2^{FC} - \Gamma_{\lambda,\lambda}^{FC}) b_{k,q}^{FC}}{\Gamma_{k,\lambda}^{FC} \mu_2^{FC} b_{\lambda,p_\epsilon}^{FC} + (\mu_2^{FC} - \Gamma_{\lambda,\lambda}^{FC}) \mu_2^{FC} b_{k,p_\epsilon}^{FC}} \quad (38)$$

where μ_2^{FC} is the positive eigenvalue of Γ^{FC} .

Theorem 3 requires that there is both sufficient complementarity in production (Condition I) and the new capital accumulated between time Solving the differential equation (37), the time-paths of (k, λ) are:²⁷

$$k(t) = \begin{cases} \frac{\Gamma_{k,\lambda}^{FC} \lambda(0)}{\mu_1 - \mu_2} e^{\mu_1 t} + \frac{\Gamma_{k,\lambda}^{FC} \lambda(0)}{\mu_2 - \mu_1} e^{\mu_2 t} & \text{for } t \in [0, T) \\ \frac{\Gamma_{k,\lambda}^{FC} \lambda(0)}{\mu_1 - \mu_2} e^{\mu_1 t} + \frac{\Gamma_{k,\lambda}^{FC} b_{\lambda,q} - \Gamma_{\lambda,\lambda} b_{k,q}}{\mu_1 \mu_2} + \frac{\Gamma_{k,\lambda}^{FC} (b_{\lambda,q} + \tau \mu_1 b_{\lambda,p_\epsilon}) + (\mu_1 - \Gamma_{\lambda,\lambda}) (b_{k,q} + \tau \mu_1 b_{k,p_\epsilon})}{\mu_1 (\mu_1 - \mu_2)} e^{\mu_1 (t-T)} & t \geq T \end{cases} \quad (39)$$

²⁷The online Appendix B contains the derivation of (39) and (40)

$$\lambda(t) = \begin{cases} \frac{(\mu_1 - \Gamma_{k,k})\lambda(0)}{\mu_1 - \mu_2} e^{\mu_1 t} + \frac{(\mu_2 - \Gamma_{k,k})\lambda(0)}{\mu_2 - \mu_1} e^{\mu_2 t} & \text{for } t \in [0, T) \\ \frac{(\mu_1 - \Gamma_{k,k})\lambda(0)}{\mu_1 - \mu_2} e^{\mu_1 t} + \frac{\Gamma_{\lambda,k} b_{k,q} - \Gamma_{k,k} b_{\lambda,q}}{\mu_1 \mu_2} + \frac{\Gamma_{\lambda,k} (b_{k,q} + \tau \mu_1 b_{k,p_\epsilon}) + (\mu_1 - \Gamma_{k,k}) (b_{\lambda,q} + \tau \mu_1 b_{\lambda,p_\epsilon})}{\mu_1 (\mu_1 - \mu_2)} e^{\mu_1 (t-T)} & t \geq T \end{cases} \quad (40)$$

where μ_1 and μ_2 are the eigenvalues of the Γ^{FC} matrix.²⁸

The above solution has one undetermined variable $\lambda(0)$. We seek a path for (λ, k) that is not explosive. We choose $\lambda(0)$ such that the explosive root μ_2 does not determine the evolution of the system for $t > T$; otherwise, the path would be explosive. This restriction on $\lambda(0)$ is:

$$\frac{\Gamma_{k,\lambda} \lambda(0) + (\mu_2 - \Gamma_{\lambda,\lambda}) k(0)}{(\mu_2 - \mu_1)} = - \frac{\Gamma_{k,\lambda} (b_{\lambda,q} + \tau \mu_2 b_{\lambda,p_\epsilon}) + (\mu_2 - \Gamma_{\lambda,\lambda}) (b_{k,q} + \tau \mu_2 b_{k,p_\epsilon})}{\mu_2 (\mu_2 - \mu_1)} e^{-\mu_2 T}$$

Panel (d) of Figure 5 contains the phase diagram for the forward-compatibility model when the conditions of Theorem 3 are satisfied. Before the news shock, the economy is at its initial steady state (k_{ss}, λ_{ss}) . The initial capital stock is lower and the shadow value of investment is larger than their long-run, post-shock counterparts (k'_{ss}, λ'_{ss}) . \mathcal{M} is the pre-shock stable manifold and \mathcal{M}' is the corresponding manifold after time T .

At the instant of the news arrival, the shadow value of investment increases. This occurs because new investment will be more productive relative to previous investment, albeit not until time T . Capital does not jump instantaneously; however $\dot{k}(0) > 0$. This shows that investment increases in response to the shock—the first of three requirements for procyclical news shocks. The reader should return to Figure 3(b) to see graphically that the second requirement—that consumption rises—is satisfied. That figure shows that the increase in λ results in higher consumption.²⁹ The third requirement—that hours increase—holds because, otherwise, both consumption and investment could not increase.

At instant T , the actual increase in investment specific technology rises. All future investment produces an additional one percent of capital. Moreover, because of forward compatibility, investment made during the preparatory phase becomes τ percent more productive. This latter effect causes the capital to jump up at T . This latter effect also causes λ to jump down from T^- to T^+ . When the capital stock jumps up, the shadow value of

²⁸In the above expressions, we suppress the superscript FC from several variables to avoid notational clutter.

²⁹The intuition for this effect is discussed early in the paper.

investment, i.e. adding to that capital stock, declines in a discrete fashion. During the preparatory phase, the explosive root is operative, causing λ to rise.

Next, at after time T^+ , k and λ lie on the new stable manifold \mathcal{M}' . After the news arrives, the system is saddle path stable. If $(k(t), \lambda(t))$ did not lie on \mathcal{M}' for $t > T^+$, then the pair would diverge. Intuitively, going from T^+ onward, k and λ must be on the new manifold because technology has reached its new permanently higher level.

To close this section, we discuss the main restriction on the model parameters:

$$\tau > \frac{\Gamma_{k,\lambda} b_{\lambda,q} + (\mu_2 - \Gamma_{\lambda,\lambda}) b_{k,q}}{\Gamma_{k,\lambda} \mu_2 b_{\lambda,p_\epsilon} + (\mu_2 - \Gamma_{\lambda,\lambda}) \mu_2 b_{k,p_\epsilon}}$$

This restriction tells us that the preparatory investment must be sufficiently forward compatible. The two key parameters that determine the lower bound on τ are the curvature parameter, σ , and the degree of complementarity, ν . Figure 11³⁰ gives the regions of these parameters for which our model is able to generate procyclical news shocks.

In our above discussion, we have outlined that the dynamics crucially depend on the marginal return on investment relative to consumption. In particular, we need a sufficiently large return to induce the planner to increase investment. Both the curvature in the utility function and the degree of complementarity affect the size of the marginal return on investment. Low curvature lessens the consumption-smoothing motive and, thus, reduces the cost of allocating resources towards investment and away from consumption. In the extreme case when $\sigma = 0$, the planner no longer cares about consumption smoothing and his sole aim is to have capital at its new steady level at time T . This causes the return on investment to increase. Ideally, the planner would like to jump to the new capital level by only sacrificing consumption in a small neighborhood before T , however, production complementarity would cause the price of consumption at that instant to increase dramatically. This results in the planner smoothing the investment increase between time zero and $t = T$.

Quantitative Analysis of the Forward-Compatibility Model

The only new parameter is τ , the degree of forward compatibility. This is clearly a difficult parameter to calibrate. We set $\tau = 0.66$. The remaining parameters are set at values used earlier in the paper.

³⁰The graphs in 11 plot out the above equation, holding other parameters fixed. Alternatively, we could have used the above equation to directly do comparative statistics. The graphs allow for a more intuitive and thorough presentation of the results.

Figure 12 plots the responses of key variables to a positive news shock. As seen in panels (b)-(d), consumption, investment and hours all increase upon the arrival of the news. The three then increase smoothly until the beginning of quarter four. Then technology actually increases; each of the three jumps upward because the output cost of producing newly installed capital, $1/Q$, falls.

Note that consumption increases by less than investment on impact. The magnitude of the consumption response either is sensitive to parameter values. Specifically, the size of this response is increasing in the degree of forward compatibility, production complementarity and the curvature parameter.

Next, the relative price of investment to consumption, seen in panel (e), rises on impact due to production complementarity along with a larger increase in investment than an increase in consumption in response to the news. Panel (f) shows that the shadow value of investment is procyclical. This will imply that, in a decentralized version of the model, the value of the stock market is procyclical.

The dynamics of news shocks of every model in this paper are contained in Figure 5. All models discussed in the paper, excluding the forward-compatible model, achieve $\lambda(0) > 0$ by causing the stable manifold to shift upwards. With the forward compatibility, this is not necessary. We can maintain the stable manifold movements as in the standard neoclassical model and yet generate procyclical news shocks by instead adding in a friction that results in a discontinuity in the time path of the state and co-state variables. This allows a fair amount of flexibility in adding other non-related frictions and still generating procyclical news shocks.

Including a feature that adds a discontinuity to the state variable allows for a much richer set of dynamics and places fewer restrictions on the movements of the stable manifold vis-a-vis the inclusion of other economic frictions in the model.

6 Conclusion

In this paper, we have made the case that an analytic approach to understanding news shocks in stochastic growth models helps to generate important insights. Up to a first-order approximation, we have provided analytic solutions to five variants on the standard neoclassical model. In each case, we have provided conditions under which the model exhibits procyclical news shocks. For each model, we have provided a plausible calibration and then examined the quantitative features of the impulse response functions.

By examining several models, we have identified commonalities across models that resolve the news-shock comovement puzzle. Each model has a mechanism or mechanisms that ensure that consumption and investment do not crowd each other out and that the relative benefit of forgoing leisure outweighs its cost.

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Table 1: Parameterization for computing impulse responses from various models

Parameter	Value	Description
Production complementarity		
$\beta = \frac{1}{\rho+1}$	0.985	Subjective discount factor (quarterly)
α	0.33	Labor share in production is $(1 - \alpha)$
δ	0.025	Depreciation rate of capital
ν	1.8	Degree of complementarity between c and i ($> \nu_c = (1 - \alpha)^{-1}$)
σ	0.5	Utility curvature
θ	0.253	Calibrated to match a steady state price of investment of 1
T	4	Quarters between news and actual technology increase
Labor Externality		
σ	1	Utility curvature - separable Utility
γ_N	0.332	Degree of labor externality
ψ_I	20	Investment adjustment cost
GHH preferences		
ω	0.5	Utility curvature
$\frac{1}{\psi}$	100	Frisch Elasticity
ξ	6.96	Calibrated to match steady state labor of 0.3
Investment Adjustment Costs		
σ	1	Utility curvature - separable utility
ψ_I	10	Investment adjustment cost
Forward Compatible Investment		
σ	1	Utility curvature
τ	0.66	Degree of forward compatibility

Figure 1: Impulse Response to a Positive News Shock - Basic Neoclassical Model

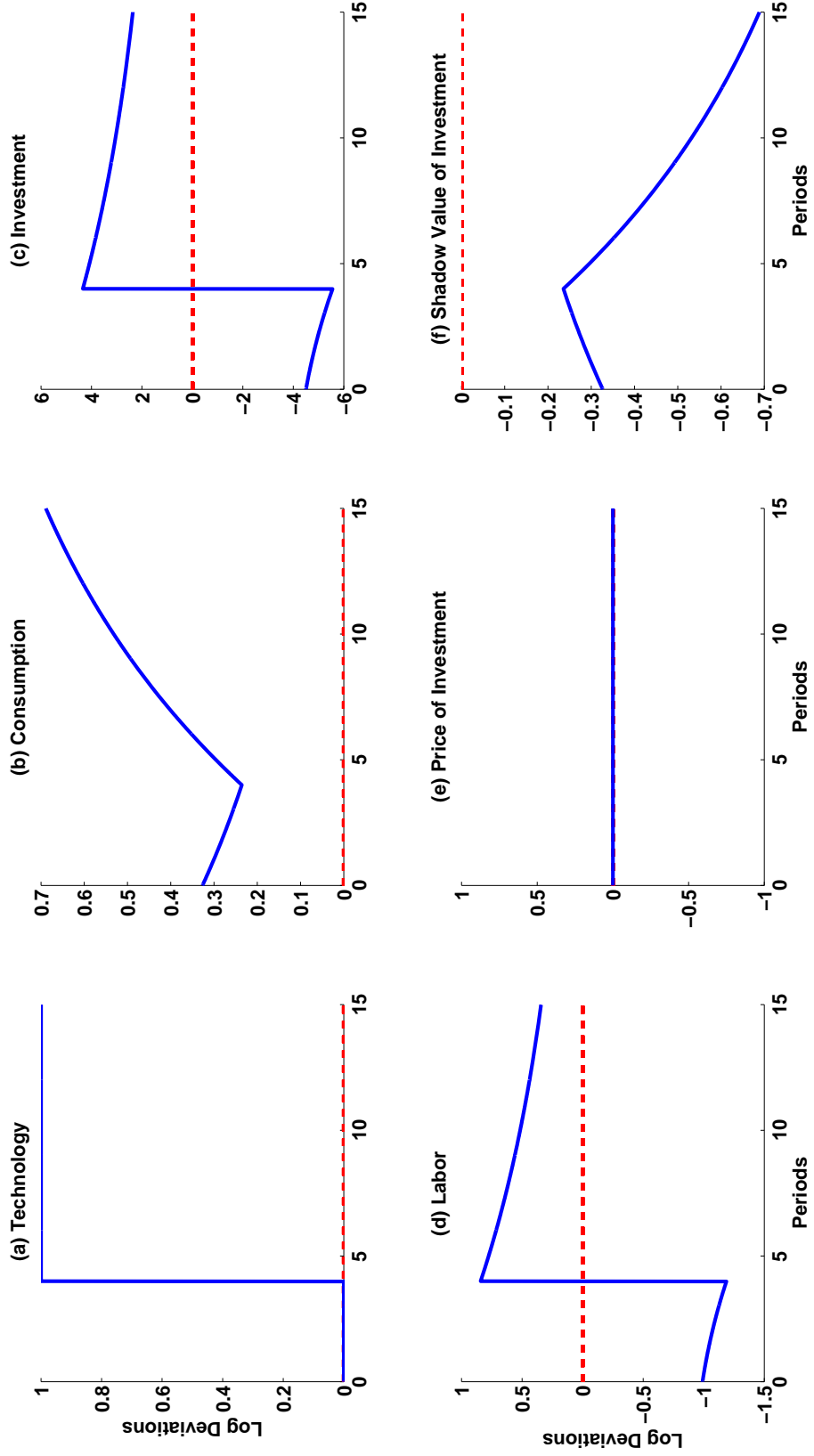
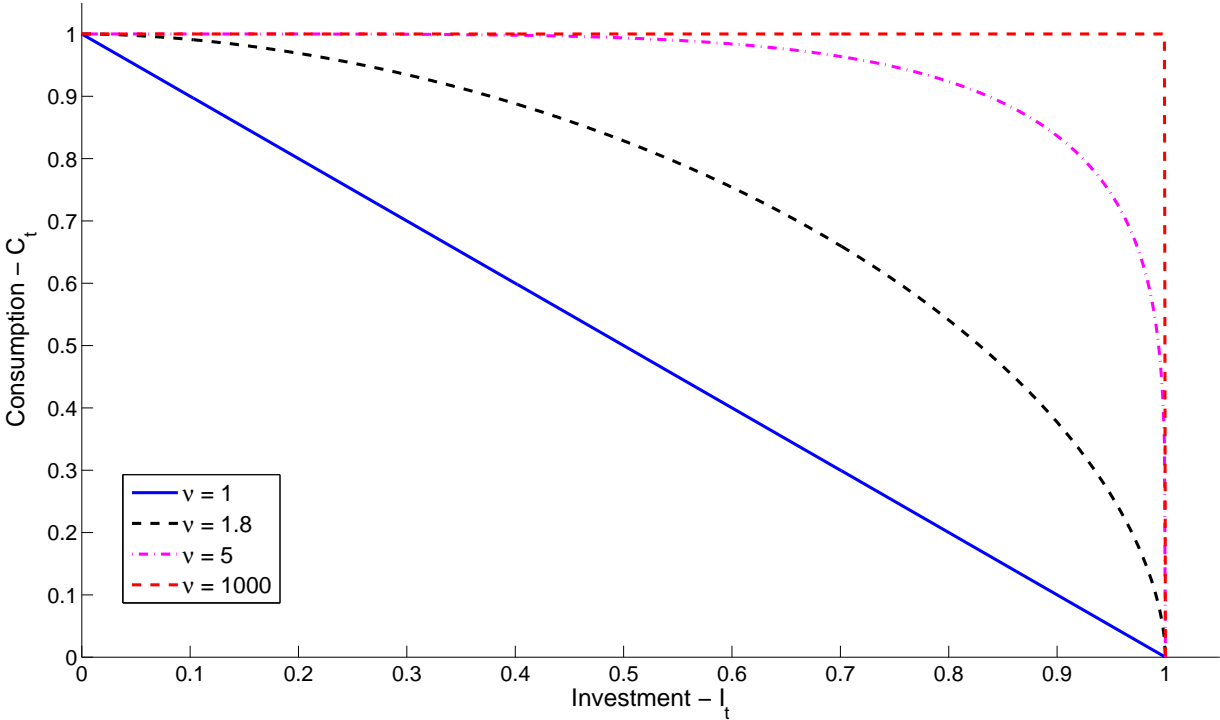
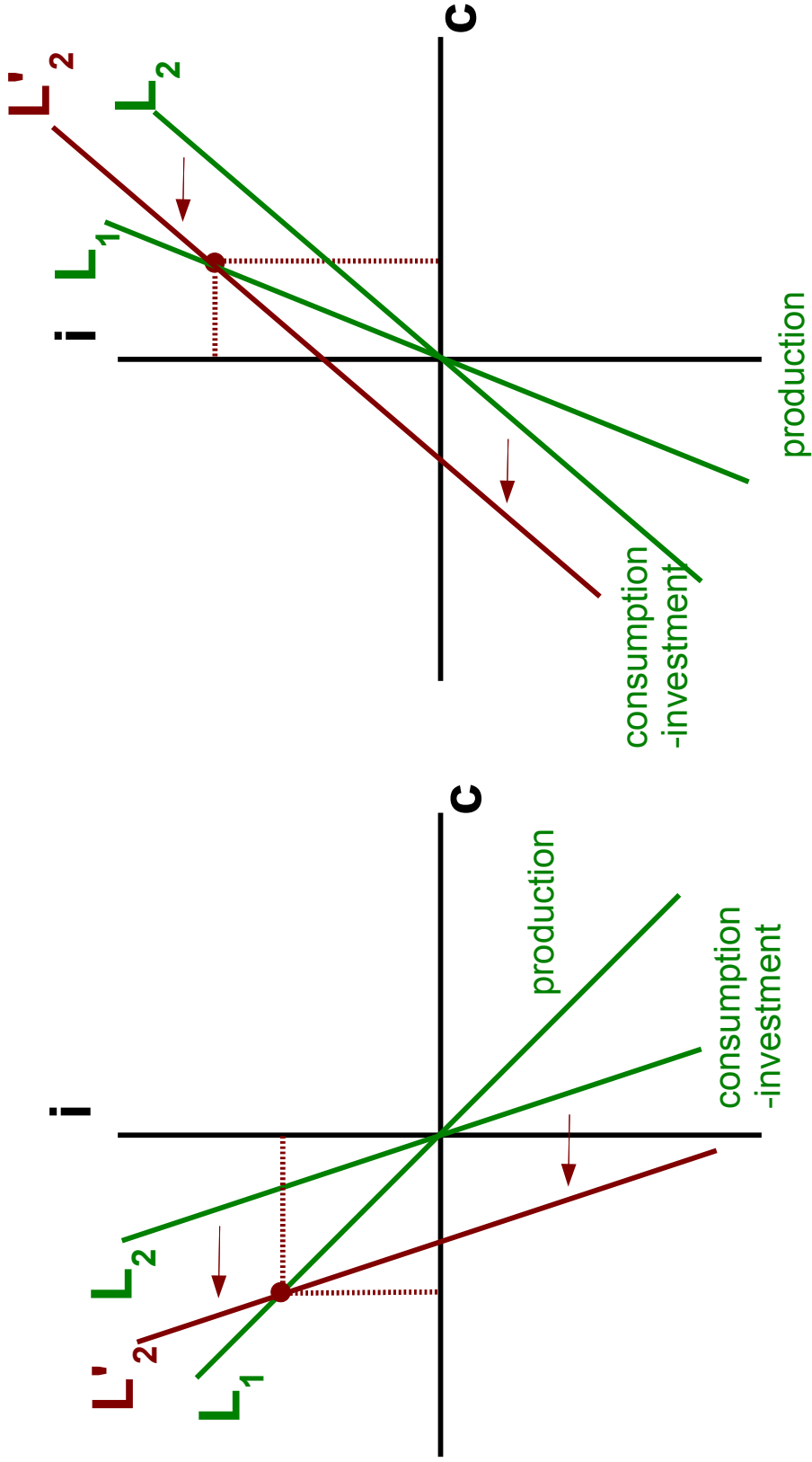


Figure 2: Production frontier between consumption and investment as ν changes.



Note: $\theta = 1/2$ and the fixed output level is equal to $(1/2)^{1/\nu}$.

Figure 3: L_1 and L_2 in i - c Space, and an increase in the marginal utility of investment (λ)



(b) with production complementarity

(a) without production complementarity

Figure 4: L_1 and L_2 in i - c Space, and an increase in both the marginal utility of investment (λ) and capital (k)

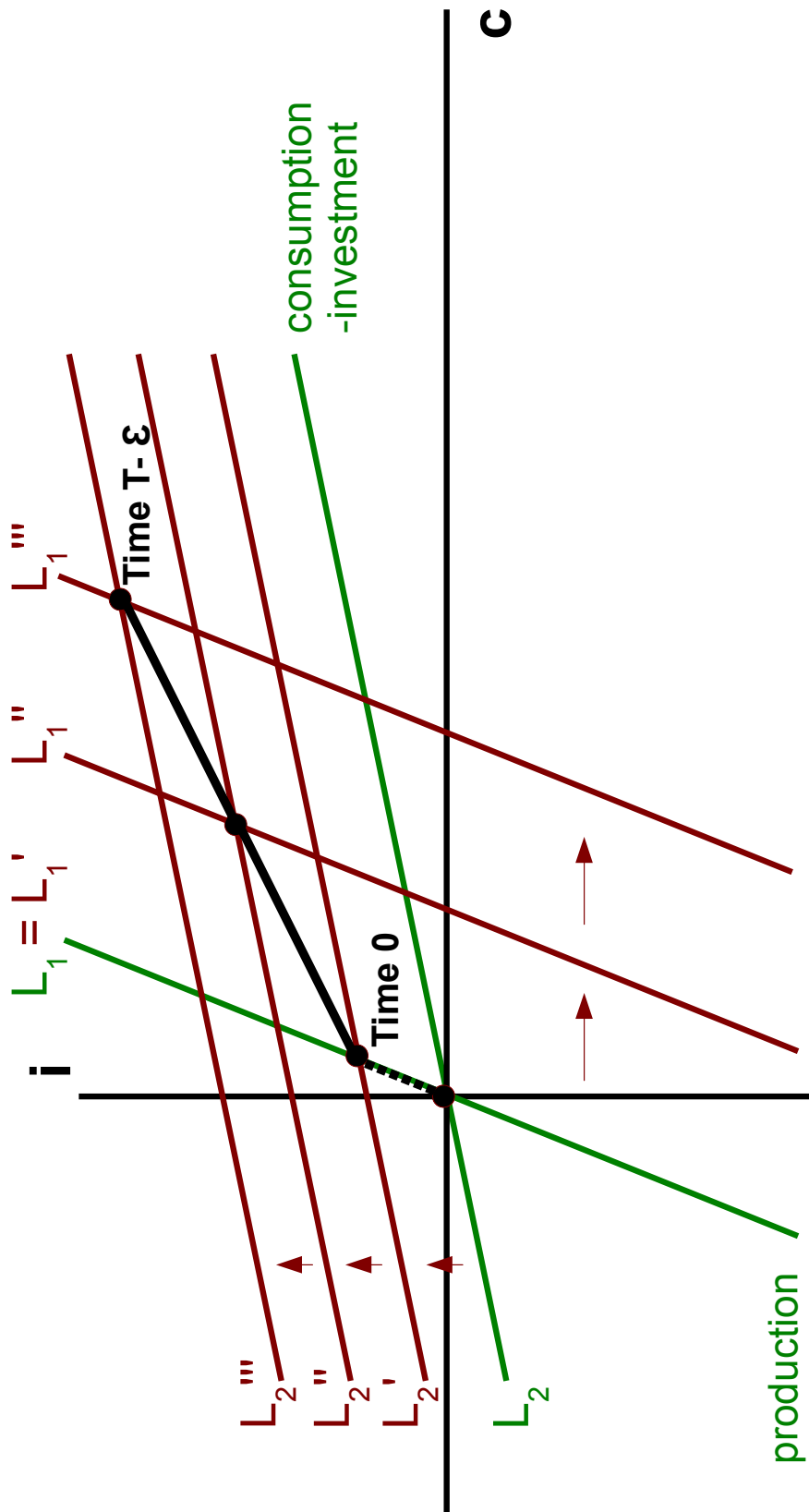
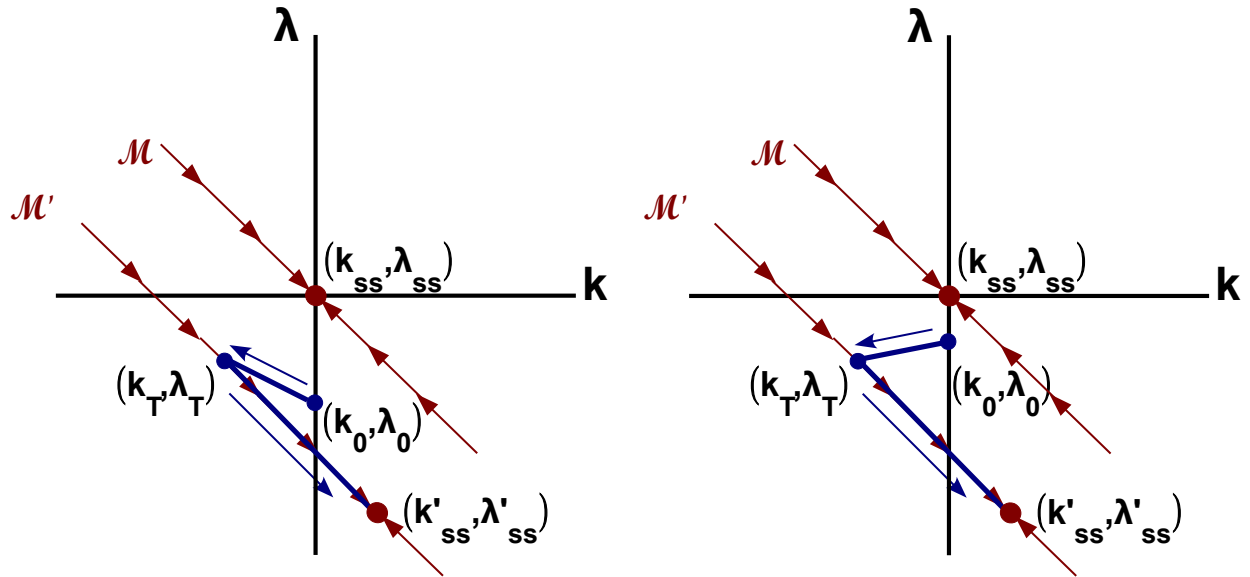
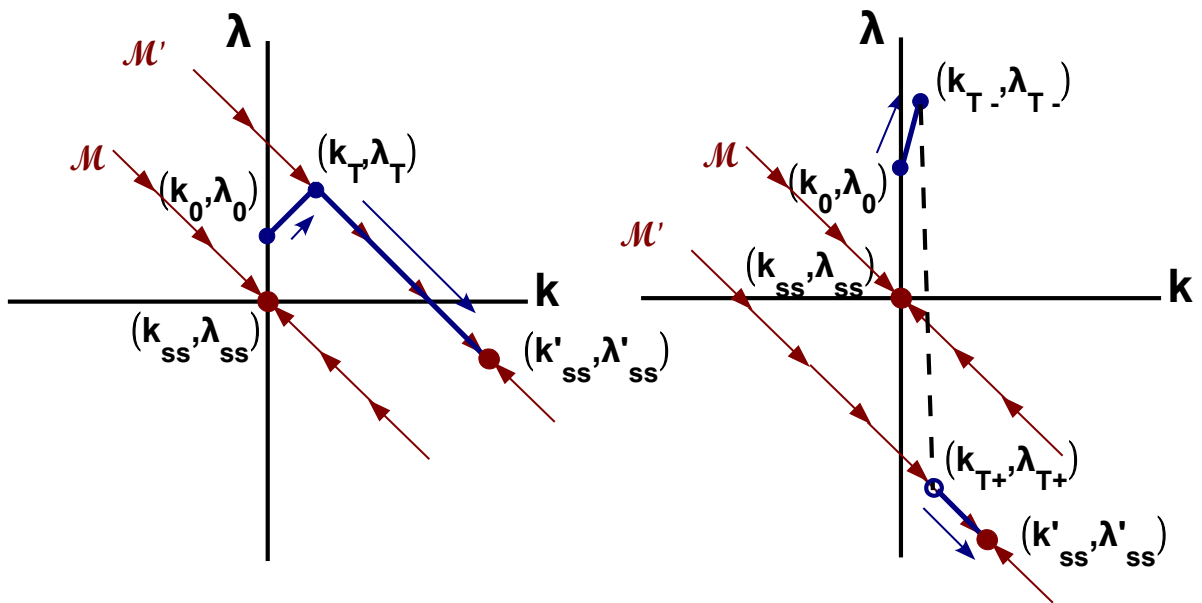


Figure 5: Phase diagrams in (k, λ) space for a positive news shock



(a) Standard Production, $\sigma = 1$

(b) Production Complementarities, High σ



(c) Production Complementarities, Low σ

(d) Production Complementarities, Partial Forward Compatibility

Figure 6: Critical Utility Curvature (σ^*) vs. Other Model Parameters

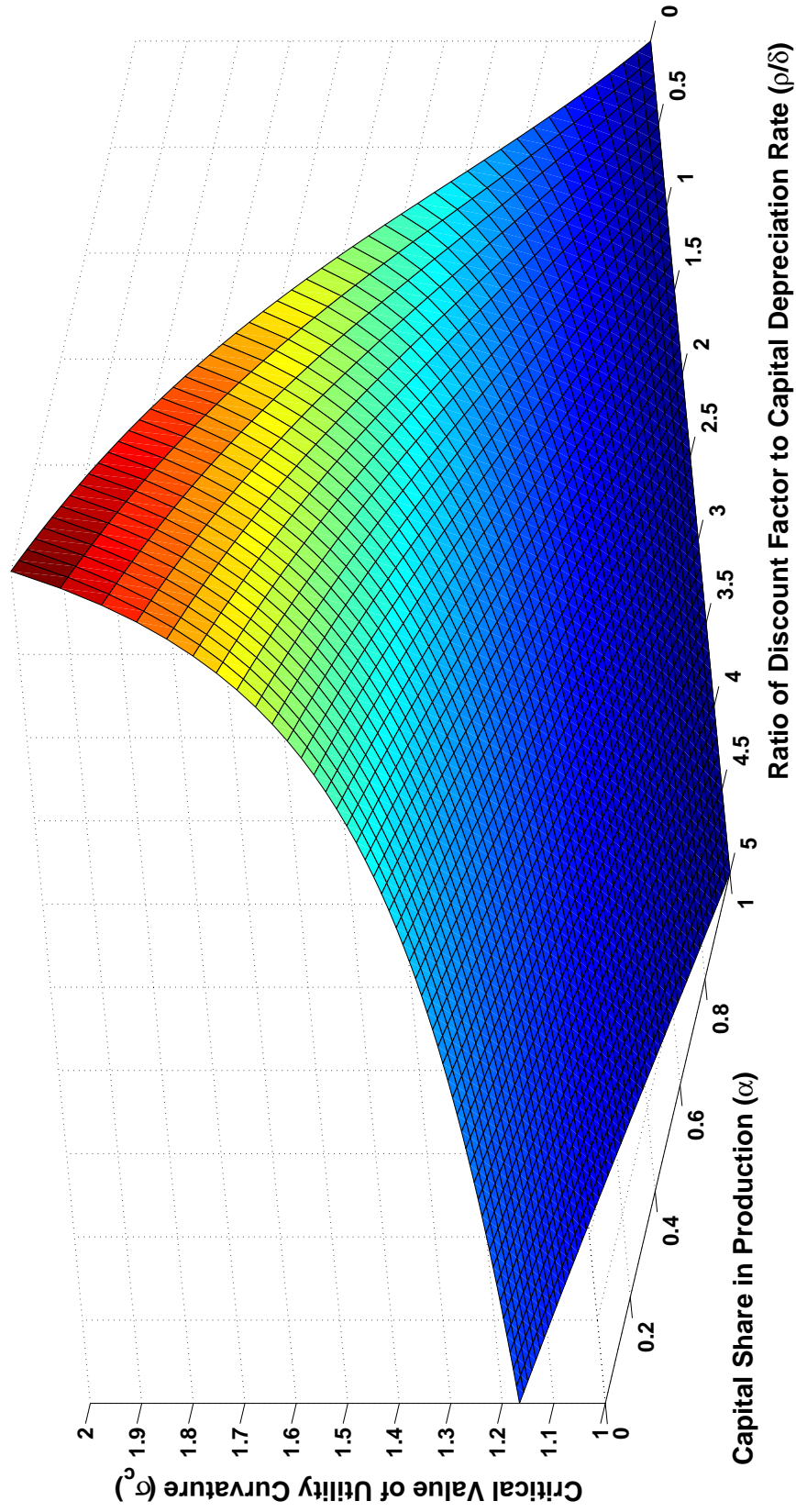


Figure 7: Impulse Response to a Positive News Shock - Benchmark Production Complementarity Model

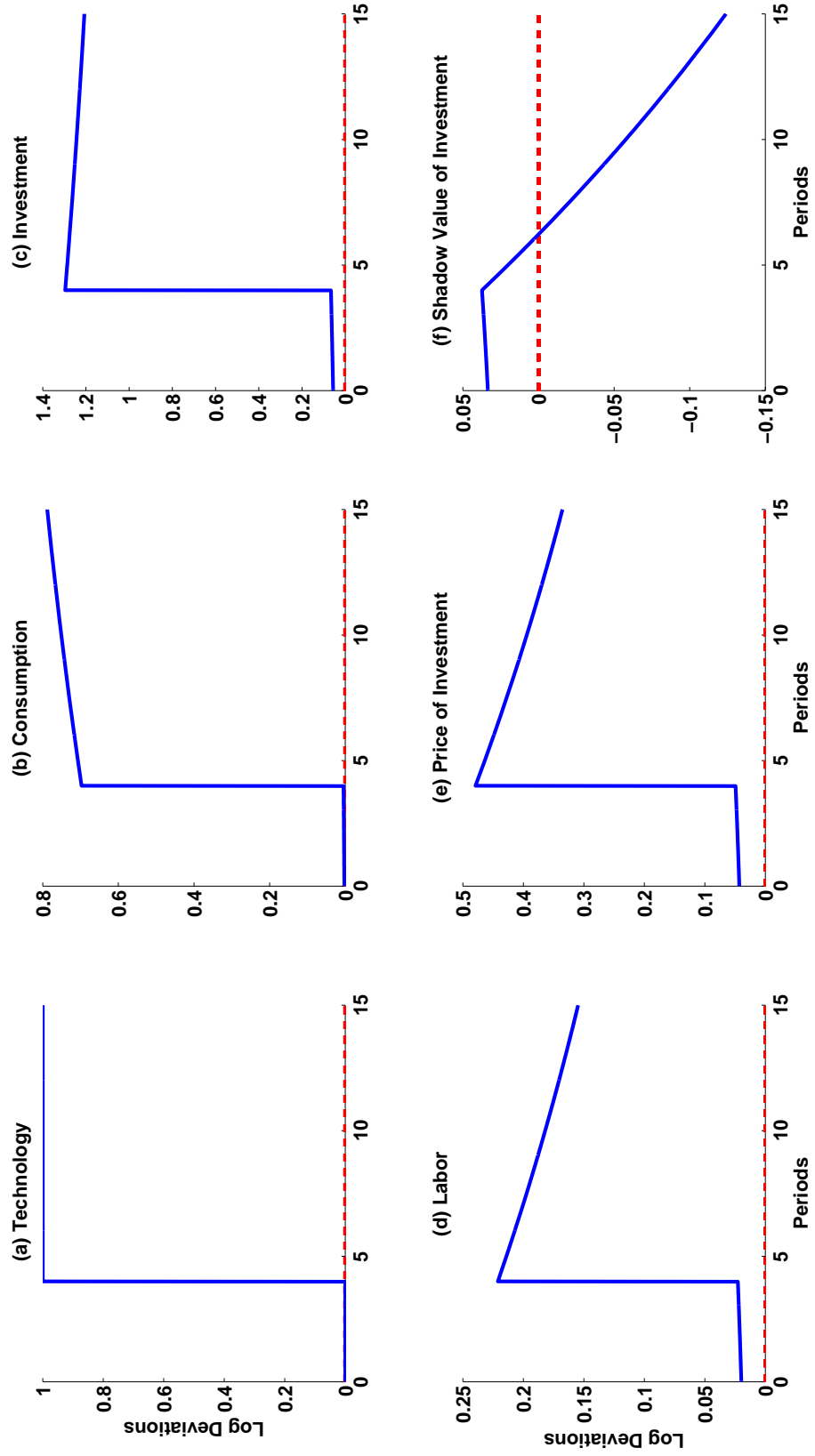


Figure 8: Impulse Response to a Positive News Shock - Labor Externality Model

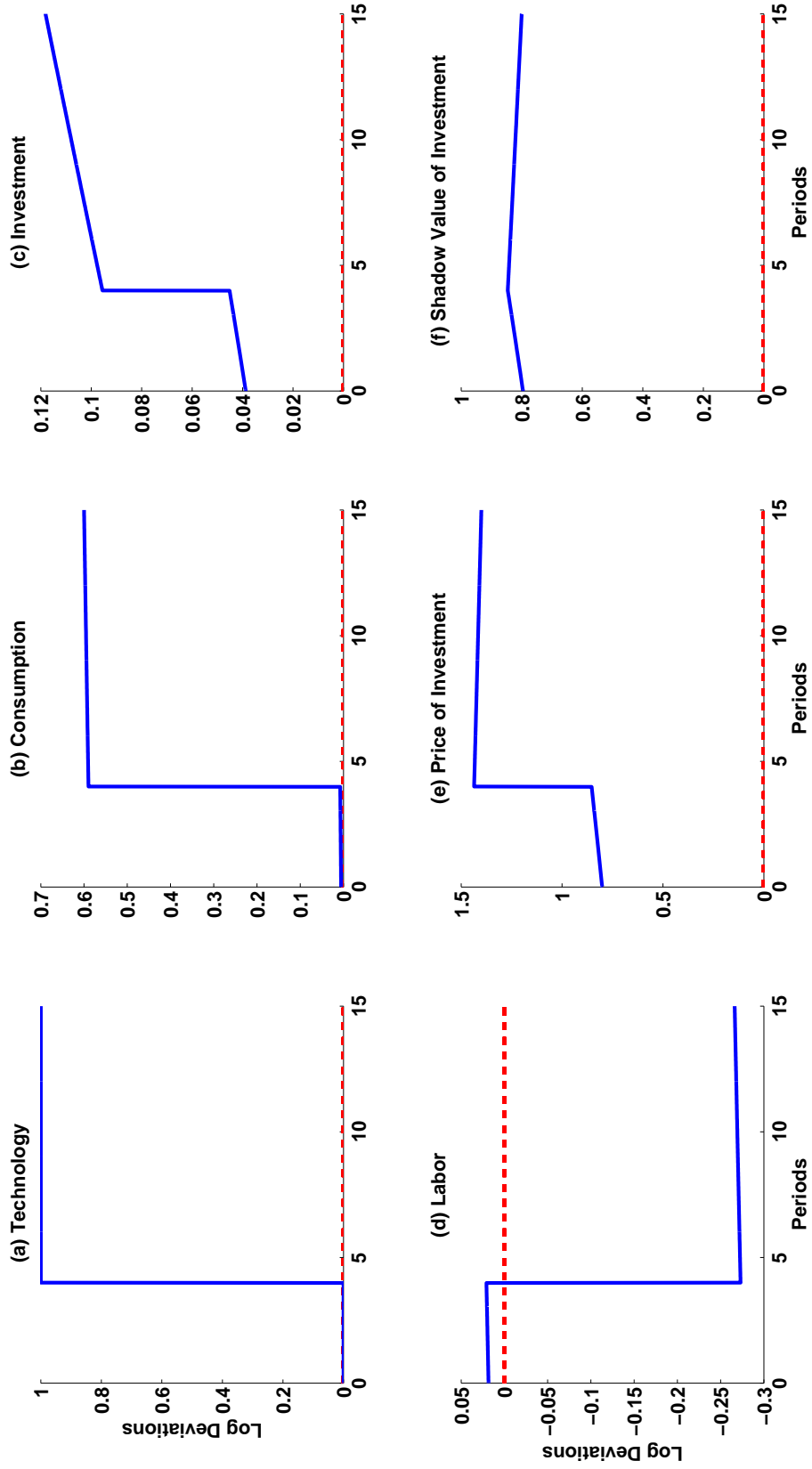


Figure 9: Impulse Response to a Positive News Shock - Variants on the Production Complementarity Model: GHH Preferences and Investment Adjustment Costs

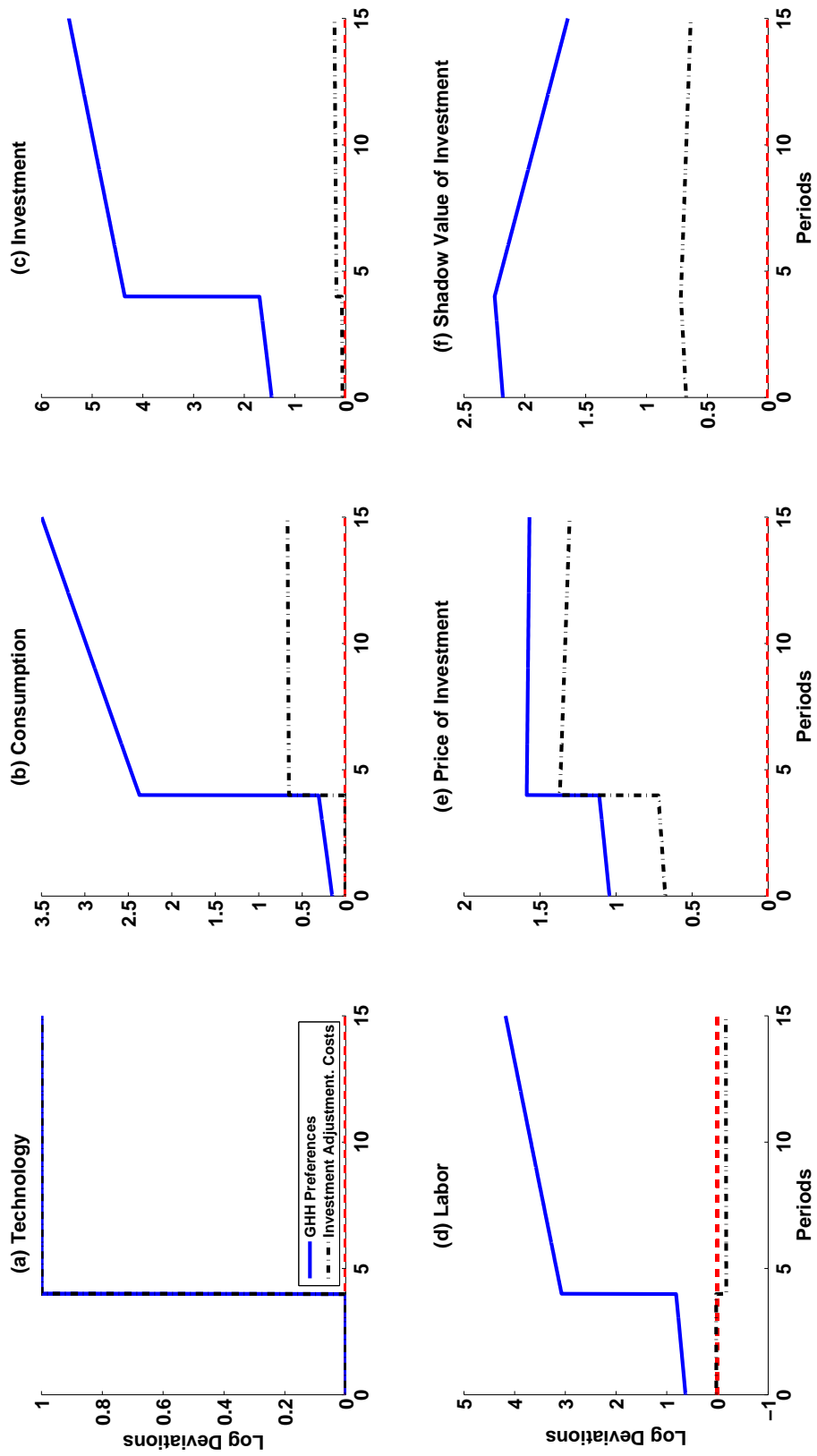
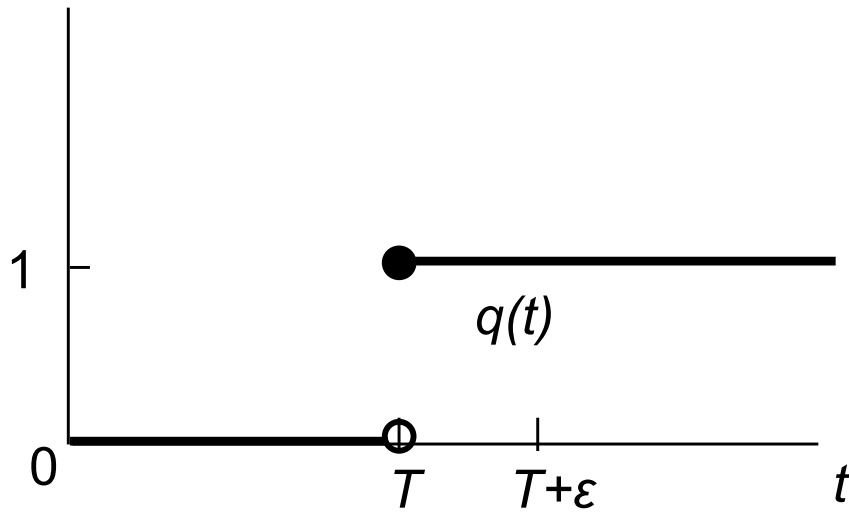


Figure 10: Efficiency of Different Types of Capital

(a) capital efficiency of post- T investment



(b) change in capital efficiency of investment (done in preparatory phase)

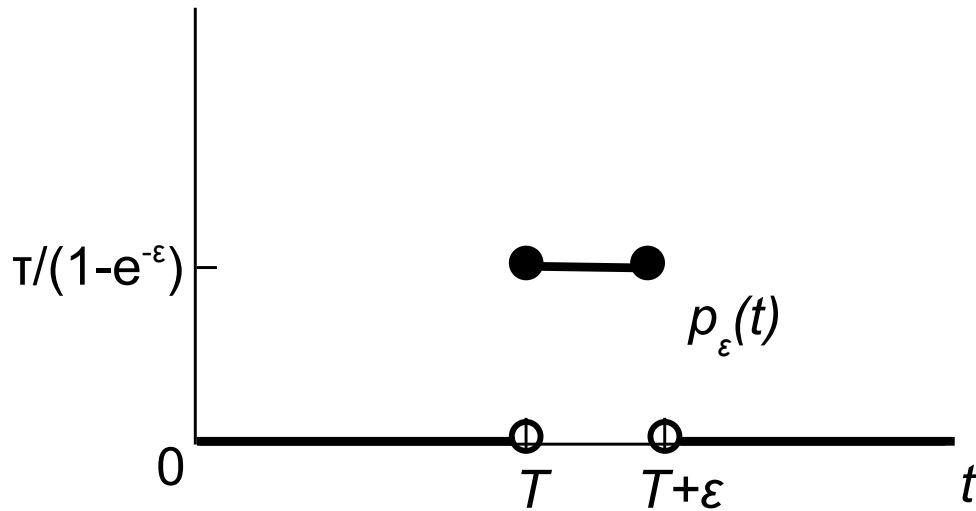
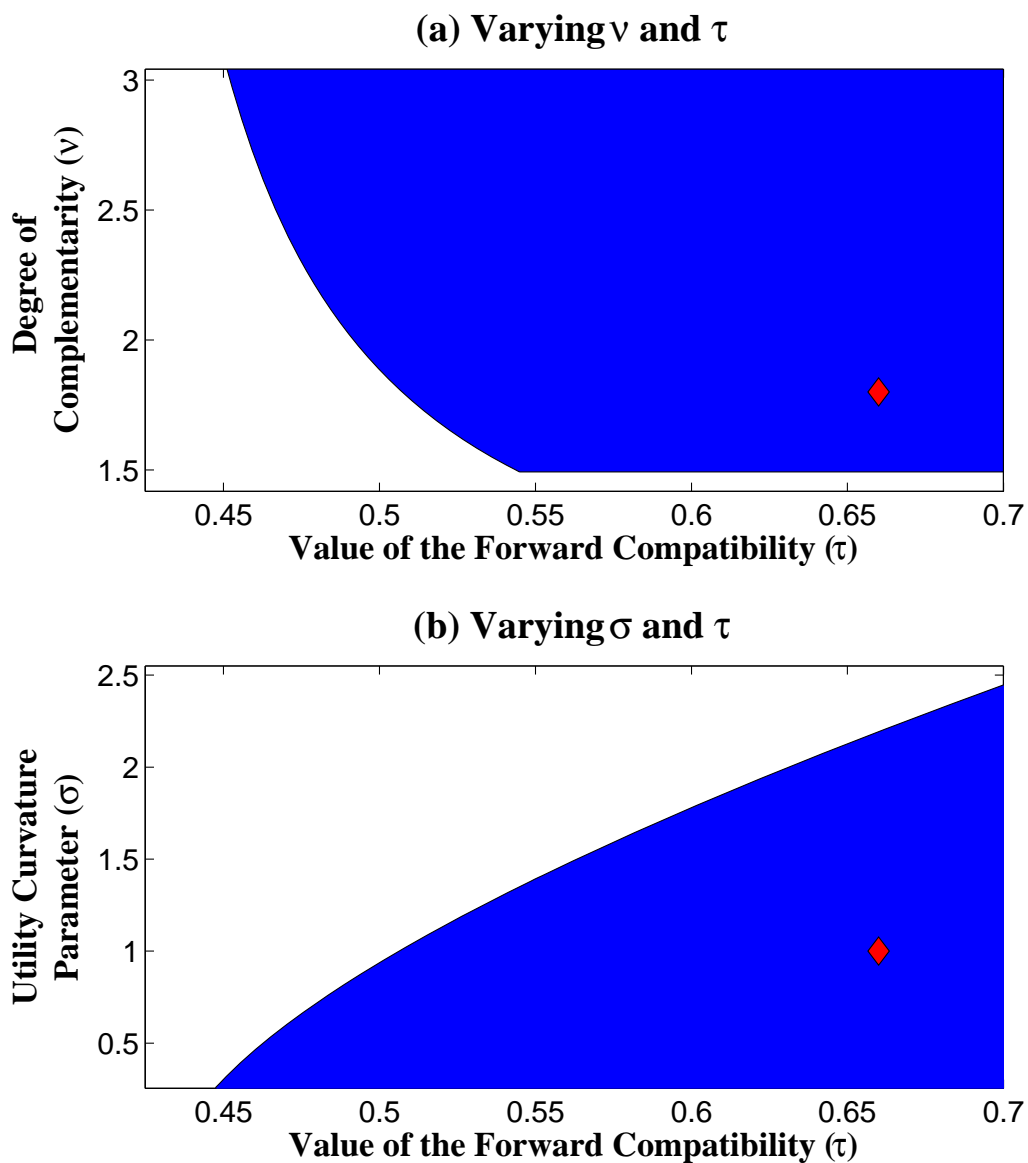


Figure 11: Parameter Configurations consistent with Procyclical News Shocks, shaded regions



Note: Diamonds indicate benchmark parameter values. All unvaried parameters are set equal to their benchmark values.

Figure 12: Impulse Response to a Positive News Shock - Forward Compatible Investment

