In-House R&D in a DSGE Model[*]

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Abstract

This paper examines the implications of in-house research and development (R&D) in a variety expansion model with common stochastic productivity disturbances. The crucial assumption of this model is that firms accumulate private knowledge that helps in-house R&D. The stock market and the level of productivity show interesting timing differences because the former reflects expected future innovations, whereas the latter is affected by past innovations. The following are three notable implications of the model: (i) the stock market is followed by measured total factor productivity with a time lag; (ii) with a recursive utility, the equity premium increases; and (iii) interest rates of safe assets decrease. With the model performing well in matching basic business-cycle facts, these additional improvements suggest the importance of private knowledge in in-house R&D.

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1 Introduction

The new growth theory identifies knowledge production as the source of endogenous technological improvement (Romer (1990), Grossman and Helpman (1991), and Aghion and Howitt (1997)). Much of the literature in this area focuses on the salient feature of the data, the balanced growth path on which important variables grow at constant rates. However, this body of literature pays limited attention to deviations from the trend; this is unfortunate because we can learn more about growth models by jointly studying knowledge production and economic fluctuations. For example, many variants of knowledge production functions have been proposed in the literature, but evaluating them is very difficult because direct observation is nearly impossible; in addition, we simply do not have many data points on the balanced growth path. Nevertheless, they may lead to distinct predictions about an economy's responses to recurrent shocks, and if so, we can choose a functional form of knowledge production function that concisely summarizes the actual knowledge production processes with that information. Model selection of this sort is common in the business cycle literature. For example, a form of investment adjustment cost proposed by Christiano, Eichenbaum, and Evans (2005) has become more popular because of its ability to match the cyclical properties of key macroeconomic variables.[1] Jointly studying knowledge production and economic fluctuations is also informative to business cycle studies because it allows us to assess the importance of the research and development (R&D) sector-specific productivity shocks, which were arguably an important source of the information technology boom in the late 90s and in other important events as well.

The current paper focuses on a particular topic, in-house R&D, studied by Smulders and van de Klundert (1995), Peretto (1996), and Peretto (1998). An important assumption of these papers

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[1] See Eberly, Rebelo, and Vincent (2011) for a recent discussion.

is that firms accumulate private knowledge that helps in-house R&D. Thus, the model intuitively explains why, in reality, most innovations are carried out by established firms that systematically conduct large scale R&D. These authors study long-run implications of in-house R&D in a deterministic environment. This paper embeds this crucial assumption in a stochastic model and examines the implications for impulse response functions, risk premium, interest rates of safe assets, and business cycle moments, all of which are especially interesting in the stochastic environment. In particular, I study a variety expansion model similar to Bilbiie, Ghironi, and Melitz (2007). But unlike these authors, I assume that ideas of new products are private knowledge, and firms develop products by advancing their own products, just as Apple computer innovations led to the iPhone by advancing the iPod, and then to the iPad by advancing the iPhone.

Three interesting implications emerge. First, the stock market is followed by total factor productivity (TFP) with a time lag, being consistent with the data (Beaudry and Portier (2006)). Unexpected changes in the common R&D productivity level produce this timing pattern. That is, when the productivity level increases, the stock market immediately increases because investors recognize that it will mainly benefit incumbent firms with experience in R&D. The measured TFP, however, improves slowly, awaiting product innovation, thus lagging behind the stock market.

Second, a large equity premium is observed. In my model economy, the equity premium is approximately one third of the actual equity premium in the U.S. economy, while in the one-sector version of the model equipped with the same utility function, the equity premium is almost nil. As discussed previously, the stock market immediately jumps up when a positive R&D shock hits the economy, but this means that the equity return is high at the point in time when investors anticipate a prolonged economic expansion, and vice versa. Because I assume that the representative household's utility function has a recursive form, as given by Epstein and Zin (1989), the household considers this price-fluctuation pattern to be risky and demands a large-risk compensation.

Third, interest rates of safe assets are low. In my model economy, the risk-free rate is larger than the actual rate by 42 basis points, while in the one-sector version of the model equipped with the same utility function, the risk-free rate is larger than the actual rate by 92 basis points. The risk-free rate is low because uncertainty originating from research productivity intensifies the self-insurance motive. Tallarini (2000) demonstrated that strong risk aversion lowers the risk-free rate in a one-sector standard real business-cycle model. The contribution of this study is quantitative, showing that R&D shocks in a two-sector model, where the persistence and volatility of these shocks are estimated using R&D spending data, further reduce the risk-free rate by a significant margin.

If in-house R&D has no special role, but instead, anyone can access the economy-wide common knowledge production function, the first two implications disappear. In such an environment, the stock market collapses when a positive R&D shock hits the economy because R&D is a zero-profit industry (consequence of free entry), but the incumbents only compete with new products. Because the stock market appreciation upon impact of a positive R&D shock was an important source of the resulting large-risk premium, the equity premium decreases without such a reaction.

Iraola and Santos (2009) and Comin, Gertler, and Santacreu (2009) study asset pricing and economic fluctuations in a dynamic stochastic general equilibrium (DSGE) model with endogenous technology diffusion. The current paper is complementary to their studies because, in their models, the production of ideas is exogenous but their adoption is endogenous; in my model, the production of ideas is endogenous but their adoption is costless. Another distinction is that, in their models, some agents are intrinsically good at adopting technologies; in my model, heterogeneity in knowledge production arises through a formal mechanism following the literature of in-house R&D. This formalization enables us to closely investigate its core mechanism with tight parameterization.

This work is also related to recent studies investigating the role of intangible capital, as exemplified by Danthine and Jin (2007), McGrattan and Prescott (2010), and Hou and Johri (2010). These authors assume that current intangible capital is an input of intangible capital production, but they introduce this feature into a typical business cycle model in which a representative firm operates constant returns to scale production technologies of both goods and intangible capital. The current paper introduces in-house R&D into a model in the growth-theory tradition, whose characteristics are monopolistic competition and increasing returns to scale for production technology. This modeling strategy is important not only because it facilitates comparison with the literature, but also because some important mechanisms are seen only in this framework, such as the effects of product composition on factor-share, productivity measures, and so on.

The remainder of the paper is organized as follows. Section 2 presents the model. Section 3 discusses the benchmark parameter values. Section 4 presents the main results. The final section presents the conclusions.

2 The Model

2.1 The aggregator's problem

The economy consists of three groups of agents: (i) a representative aggregator, (ii) multiproduct intermediate-goods firms, and (iii) a representative household. The aggregator produces composite good Z_t in period t with a given technology:

$$Z_t = \left[\int_0^{N_{t-1}} z_t\left(\omega\right)^{\frac{\theta-1}{\theta}} d\omega \right]^{\frac{\theta}{\theta-1}}$$

where N_{t-1} is the mass of intermediate products in period t, $z_t(\omega)$ is the input of intermediate product of index ω in period t, and $\theta > 1$ is the elasticity of substitution between every pair of products. This composite good is used for R&D as well as for consumption and investment. Therefore, it is gross output. The model counterpart of the value-added output (GDP) is gross output minus aggregate R&D spending because R&D is treated not as investment but as a business expenditure under the current national income accounting convention.

At the beginning of each period, the aggregator receives a price catalog from each intermediate-goods firm. Some products are sold by a single firm. In such cases, the aggregator simply purchases the product from that monopolistic supplier. Some products are sold by several firms. In that case, the aggregator purchases the product only from the firm offering the lowest price. If there are multiple firms offering the lowest price, I assume that the aggregator purchases an equal amount from each of them. Solving the cost minimization problem given these observations, we find that the per-product demand function is $\left(p_t^*(\omega)/P_t\right)^{-\theta} Z_t$, where $p_t^*(\omega)$ is the lowest price posted for product ω in period t, and P_t is the price index, defined as: $P_t \equiv \left[\int_0^{N_{t-1}} p_t^*(\omega)^{1-\theta} d\omega\right]^{\frac{1}{1-\theta}}$. Because the composite good market is competitive, the zero-profit condition implies that $P_t = 1$ in equilibrium.

2.2 The intermediate-goods firm's problem

There are two kinds of intermediate products: maturing products and innovative products. A maturing product is an *old* product (the precise definition is given later) and can be manufactured by any firm. An innovative product is a *new* product and is manufactured monopolistically by a single firm. Let $N_{M,t-1}$ denote the mass of maturing products in period t, and let $N_{I,t-1}^j$ denote the mass of innovative products firm j produces in period t. These are related with N_{t-1} in the following way:

$$N_{t-1} = N_{M,t-1} + \sum_{j=1}^{J_t} N_{I,t-1}^{j}$$

where J_t is the number of intermediate-goods firms in period t, which I assume is always greater than two. Further discussion on J_t will be given at the end of this subsection.

Each intermediate good is manufactured with an identical Cobb-Douglas technology with capital k_t and labor l_t; thus, $A_t k_t^{\alpha} l_t^{1-\alpha}$, where A_t is the goods-producing productivity in period t, which is common across products, and $\alpha \in [0, 1]$ is the capital elasticity. I assume that although firms manufacture multiple products, the pricing decision for each product is individually managed. In other words, a product manager is assigned to each product in each firm, and she sets the product price to maximize profit given all other prices. This assumption makes the goods market of this paper comparable with those in the existing literature and hence, allows us to focus on a new element in the R&D sector.[2] The monopoly rent of a typical innovative product in period t is:

$$\pi_t \equiv \frac{1}{\theta - 1} \left(\frac{\theta}{\theta - 1} \right)^{-\theta} \left[\frac{1}{A_t} \left(\frac{rental_t}{\alpha} \right)^{\alpha} \left(\frac{W_t}{1 - \alpha} \right)^{1-\alpha} \right]^{1-\theta} Z_t$$

where $rental_t$ is the rental price of capital in period t and W_t are the wages in period t. A maturing product's operating profits are zero in equilibrium because product managers engage in Bertrand competition.

An intermediate-goods firm also conducts R&D, aiming to invent new products. If firm j spends R_t^j of its gross output for R&D in period t, it acquires the mass $S_t \left(N_{I,t-1}^{j} \right)^{1-\nu} \left(R_t^j \right)^{\nu}$ of new innovative products at the end of the period, where S_t is the R&D productivity in period t,

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[2] An isomorphic modeling with single-product firms is also possible. In this case, I assume that (i) only those firms manufacturing an innovative product have the ability to develop new products, and (ii) once a firm succeeds in developing a product, it will sell out the exclusive production right of the product.

which is common across firms, and $\nu \in (0,1]$ is the research elasticity. $0 < \nu < 1$ is the case in which in-house R&D has a special role because current innovative products improve product innovation efficiency of the owner firm. If $\nu = 1$, in-house R&D has no special role, but instead, any firm can invent new products with the identical, linear knowledge production function of R&D input. The law of motion of firm j's innovative products is:

$$N_{I,t}^{j} = (1-\delta_N)(1-\sigma)N_{I,t-1}^{j} + S_t\left(N_{I,t-1}^{j}\right)^{1-\nu}\left(R_t^{j}\right)^{\nu} \tag{1}$$

where $\delta_N \in [0,1]$ is the rate of obsolescence—the share of products becoming permanently unavailable to the economy—and $\sigma \in [0,1]$ is the rate of maturation—the share $(1-\delta_N)\sigma$ of innovative products evolving into maturing products. Given this law of motion, firm j chooses a sequence of R&D inputs to maximize the firm value:

$$E_t\left[\sum_{\tau=0}^{\infty} M_{t,t+\tau}\left(N_{I,t+\tau-1}^{j}\pi_{t+\tau} - R_{t+\tau}^{j}\right)\right] \tag{2}$$

where $M_{t,t+\tau}$ is the stochastic discount factor. The first-order conditions are:

$$q_t \nu S_t\left(\frac{N_{I,t-1}^{j}}{R_t^{j}}\right)^{1-\nu} = 1 \tag{3}$$

$$q_t = E_t\left[M_{t,t+1}\left(\pi_{t+1} + q_{t+1}\left((1-\delta_N)(1-\sigma) + (1-\nu)S_{t+1}\left(\frac{R_{t+1}^{j}}{N_{I,t}^{j}}\right)^{\nu}\right)\right)\right] \tag{4}$$

where q_t is the Lagrange multiplier on the innovative products' law of motion (1).

I interpret these equations first when $0 < \nu < 1$. Equation (3) implies that a firm's R&D input is proportional to the firm's innovative products. Because a firm with more innovative products experiences higher productivity in product innovation processes, it leads to larger R&D input. Equation (4) implies that q_t is the present discounted value of two distinct sequences: future profits in the goods market and future marginal knowledge production of innovative products. Because an innovative product is not only a prototype of a monopolistic product but also a seed for new products, the price q_t reflects this dual role.

Now I interpret the same equations when $\nu = 1$. Equation (3) implies that an innovative product's value q_t is equal to its marginal cost of production. Hence, the net profit of R&D is always zero. Equation (4) implies that q_t is the present discounted value of a future profit stream alone.

Aggregation is easy. Combining (3) and (4) and substituting forward, we obtain

$$E_t \left[\sum_{\tau=1}^{\infty} M_{t,t+\tau} \left(N^j_{I,t+\tau-1} \pi_{t+\tau} - R^j_{t+\tau} \right) \right] = q_t N^j_{I,t}$$

This states that the ex-dividend firm value (the left-hand side) is the product of the price and the quantity of innovative products. Because of this linearity, the aggregate value of intermediate goods firms is simply $q_t N_{I,t}$, where $N_{I,t} \equiv \sum_j N^j_{I,t}$ denotes the mass of total innovative products at the end of period t. Let $R_t \equiv \sum_j R^j_t$ denote the aggregate R&D spending in period t. Because the ratio $R^j_t / N^j_{I,t-1}$ is identical across firms, the law of motion of the aggregate innovative products is:

$$N_{I,t} = (1 - \delta_N)(1 - \sigma) N_{I,t-1} + S_t (N_{I,t-1})^{1-\nu} (R_t)^{\nu} \tag{5}$$

I assume that the same obsolescence rate applies to maturing products. The law of motion of the maturing products is:

$$N_{M,t} = (1-\delta_N)\, N_{M,t-1} + (1-\delta_N)\, \sigma N_{I,t-1} \tag{6}$$

Adding (5) and (6) and recalling the definition of N_t, we find that the law of motion of the total products is:

$$N_t = (1-\delta_N)\, N_{t-1} + S_t \left(N_{I,t-1}\right)^{1-\nu} \left(R_t\right)^{\nu}$$

Notice the irrelevance of the number of firms and the firm-size distribution with respect to aggregation; the aggregation is not affected by these statistics as long as the number of firms is greater than two. This is because the knowledge production function has a Cobb-Douglas form. This irrelevance implies the neutrality of firm entry and exit in the following environment. Potential entrepreneurs can enter the market with the same technological constraints as incumbents face; i.e., a start-up firm can manufacture maturing products but needs innovative products to enter the R&D sector. An intellectual property rights market serves that need, where exclusive production rights for innovative products are traded at price q_t. This market also allows existing firms to exit. The number of intermediate-goods firms and the firm-size distribution can change accordingly, but as long as the assumption $J_t \geq 2$ is maintained, these changes do not affect aggregate variables.[3]

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[3] Smulders and van de Klundert (1995), Peretto (1996), and Peretto (1998) introduce the spillover in such a way that the market structure affects the aggregate economy. This paper does not analyze this issue for the sake of tractability because keeping track of the firm size distribution in the presence of the aggregate shocks is very difficult if not impossible with the technique developed by Krusell and Smith (1998). But I also notice that the spillover and sustained growth can be easily introduced in the current framework with keeping the great tractability intact by modifying the knowledge production function to $S_t \left(N_{I,t}\right)^{\nu} \left(N_{I,t-1}^{j}\right)^{1-\nu} \left(R_t^{j}\right)^{\nu}$, where the term $\left(N_{I,t}\right)^{\nu}$ is the spillover which individual firms treat exogenously.

2.3 The household's problem

The household maximizes the recursive utility of Epstein and Zin (1989):

$$U_t = u\left(C_t, L_t\right) + \beta E_t \left[U_{t+1}^{1-\gamma}\right]^{\frac{1}{1-\gamma}} \tag{7}$$

where $C_t \geq 0$ is consumption, $L_t \in [0,1]$ is the labor supply, $\beta \in [0,1]$ is the subjective time discount factor, and γ is the risk-aversion parameter. The utility kernel is

$$u\left(C_t, L_t\right) = \frac{\left[C_t\left(1-L_t\right)^{\varphi}\right]^{1-\frac{1}{\psi}}}{1-\frac{1}{\psi}}$$

where $\psi > 0$ is the intertemporal elasticity of substitution and φ is the elasticity of leisure. When $0 < \psi < 1$, I reformulate the recursion as $U_t = u\left(C_t, L_t\right) - \beta E_t \left[\left(-U_{t+1}\right)^{1-\gamma}\right]^{\frac{1}{1-\gamma}}$. The benefit of having the recursive utility is its flexibility in separately choosing the risk-aversion parameter γ and the intertemporal elasticity of substitution ψ.

The household maximizes the utility measure (7) by choosing sequences of consumption, labor supply, capital investment, and financial investment, subject to the budget constraint:

$$C_t + K_t + \sum_{j=1}^{J_t} \mu_t^j \left(q_t N_{I,t}^j\right) = W_t L_t + \left(1 - \delta_K + rental_t\right) K_{t-1} + \sum_{j=1}^{J_t} \mu_{t-1}^j \left[\Pi_t^j + \left(q_t N_{I,t}^j\right)\right] \tag{8}$$

and a no-Ponzi-scheme condition, where $K_t \geq 0$ is the capital stock at the end of period t, $\delta_K \in [0,1]$ is the capital depreciation rate, μ_t^j is the share in firm j at the end of period t, and $\Pi_t^j \equiv N_{I,t-1}^j \pi_t - R_t^j$ is firm j's profits in period t. The first-order conditions are:

$$W_t = \varphi \frac{C_t}{1-L_t}$$

$$1 = E_t \left[M_{t,t+1} \left(rental_{t+1} + 1 - \delta_K \right) \right]$$

$$q_t N_{I,t}^j = E_t \left[M_{t,t+1} \left(\Pi_{t+1}^j + q_{t+1} N_{I,t+1}^j \right) \right]$$

The first equation implies that the household is marginally indifferent in choosing between labor and leisure. The second equation implies that the household is marginally indifferent in choosing between consumption and capital investment. The third equation implies that the household is marginally indifferent in choosing between consumption and financial investment. $M_{t,t+1}$ is the stochastic discount factor, defined as:

$$M_{t,t+1} \equiv \beta \left(\frac{C_{t+1}}{C_t} \right)^{-\frac{1}{\psi}} \left(\frac{1 - L_{t+1}}{1 - L_t} \right)^{\varphi\left(1 - \frac{1}{\psi}\right)} \left(\frac{U_{t+1}}{E_t \left[U_{t+1}^{1-\gamma} \right]^{\frac{1}{1-\gamma}}} \right)^{-\gamma} \tag{9}$$

$M_{t,t+1}$ measures the rate at which the household is willing to substitute future consumption with current consumption. Note that when γ is positive (corresponding to the risk-averse case), future consumption in a state in which the continuation utility value is large is heavily discounted. In other words, the household does not appreciate receiving goods in a state in which it is optimistic about the future. This is an important observation when interpreting asset pricing results. $M_{t,t+\tau}$ for $\tau \geq 2$ is recursively defined as $M_{t,t+\tau} \equiv M_{t,t+\tau-1} M_{t+\tau-1,t+\tau}$.

2.4 Equilibrium

Equilibrium is defined in the usual way as a set of sequences of prices and quantities such that (i) they solve the optimization problems of the aggregator, intermediate goods firms, and the household and (ii) all the markets—gross output, labor, rental, and equity—clear in every period. There are three endogenous state variables $(K_{t-1}, N_{t-1}, N_{I,t-1}/N_{M,t-1})$ and two exogenous state variables

(A_t, S_t). I solve the model with the approximation method given by Swanson, Anderson, and Levin (2006).

3 Parameters

The benchmark parameter values are summarized in Table 1. The time unit is a quarter of a year. I set the capital depreciation rate to $\delta_K = .025$ and the subjective time discount factor to $\beta = .995$. These are standard values used in other macroeconomic studies. I set the intertemporal elasticity of substitution to $\psi = 1.5$, following Bansal and Yaron (2004), but I also check the sensitivity to this parameter. I set the obsolescence rate to $\delta_N = .01$. This value is based on empirical research on the product destruction rate (Broda and Weinstein (2010)). I set the maturation rate to $\sigma = .045$ so that $\delta_N = .01$ and $\sigma = .045$ together imply a 20% annual R&D depreciation rate (Corrado, Hulten, and Sichel (2009)). A value of $\sigma = .045$ also implies that 52% of innovative products are maturing within four years after their introduction, which is consistent with Mansfield, Schwartz, and Wagner (1981). I set the elasticity of substitution between every pair of products to $\theta = 3$. The selection of this value was guided by both empirical research on the price elasticity of branded products (Tellis (1988)) and empirical research on their markup (Hall (1988); Barsky, Bergen, Dutta, and Levy (2003)).[4] I set the capital elasticity to $\alpha = .31$ so that the steady-state labor share of GDP is 68%. I set the elasticity of leisure to $\varphi = 1.86$ so that the steady-state hours worked is one-third of the available time. I set the research elasticity to $\nu = .17$ so that the steady-state R&D share of GDP is 2%. Eaton and Kortum (1999) obtained almost identical research elasticity in their estimation using productivity, research employment, and international patent data. I set the risk-aversion

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[4] It is common to assume a 20% markup ($\theta = 6$), following Rotemberg and Woodford (1992); however, note that Rotemberg and Woodford (1992) state that their choice of markup is extremely conservative (see page 1,179).

Table 1. Benchmark Parameter Values.

Parameter	Description	Value	Source and reference
β	Subjective time discount factor	.995	Standard value
δ_K	Capital depreciation rate	.025	Standard value
ψ	Intertemporal elasticity of substitution	1.5	Bansal and Yaron (2004)
δ_N	Obsolescence rate	.01	Product destruction
σ	Maturation rate	.045	R&D depreciation
θ	Elasticity of substitution between products	3	Empirical research
α	Capital elasticity	.31	Labor share
φ	Elasticity of leisure	1.86	Hours worked
ν	Research elasticity	.17	R&D share
CRRA	Coefficient of relative risk aversion	75	Rudebusch et al. (2009)
ρ_A	Persistence of $\log A_t$	.99	GDP and R&D
ρ_S	Persistence of $\log S_t$	.97	GDP and R&D
$\Sigma_{11}^{1/2}$	Standard deviation of $\eta_{A,t}$	.0060	GDP and R&D
$\Sigma_{22}^{1/2}$	Standard deviation of $\eta_{S,t}$	.0093	GDP and R&D
$\Sigma_{21}/\left(\Sigma_{11}\Sigma_{22}\right)^{1/2}$	Correlation between $\eta_{A,t}$ and $\eta_{S,t}$	.045	GDP and R&D
$K^{corp}/\left(4Y\right)$	Corporate sector K-to-annual-GDP ratio	.65	Hall (2001)
Debt/Equity	Debt-to-equity ratio	1	Standard value

parameter γ using the implied coefficient of relative risk aversion as a guide. The relation of the two is complicated in the current model due to the elastic labor supply. Fortunately, Swanson (2010) derives the closed-form solution at the steady state. Using his result, I set γ so that the coefficient of relative risk aversion at the steady state is 75. This value is on the high side among those found in the literature but matches the value used by Rudebusch and Swanson (2009). In addition, Barillas, Hansen, and Sargent (2009) showed that this level of relative risk aversion can be justified with a robust control theory, using an isomorphic interpretation that the risk aversion measures the household's fear of model misspecification. More importantly, I subsequently show that the results are not driven by the large risk aversion alone, but by a combination of the large risk aversion and the R&D sector, as modeled.

With the calibrated parameters given above, I estimate the stochastic processes of two exogenous state variables. The estimation method is the maximum likelihood described by An and Schorfheide

(2007). I assume that they follow stationary AR(1) processes:

$$\log A_t = \rho_A \log A_{t-1} + \eta_{A,t},\ \ |\rho_A| < 1$$

$$\log S_t = \rho_S \log S_{t-1} + \eta_{S,t},\ \ |\rho_S| < 1$$

with $\eta_t \equiv \left(\eta_{A,t}, \eta_{S,t}\right)' \sim$i.i.d.$N\left(0, \Sigma\right)$ and calculate the likelihood by fitting the linearized model to the following data: linearly detrended quarterly GDP from the first quarter of 1950 to the second quarter of 2009 and the linearly detrended annual R&D spending performed by business from 1959 to 2007. The estimated persistence of goods-producing productivity is $\rho_A = .99$. The estimated persistence of R&D productivity is $\rho_S = .97$, implying that R&D shock has a half-life of approximately six years.

Finally, I consider a (hypothetical) competitive mutual fund with a balance sheet resembling an average balance sheet of the actual corporate sector. This is done for the convenience of constructing model counterparts for an average corporate equity and for safe bonds. Every period, the mutual fund issues equity and one-period bonds and purchases assets. In the next period, the fund liquidates the assets, makes the promised payments to the bond holders, and pays the residual to the equity holders. I assume that the equity holders bear unlimited liability, so that there is no default risk for the fund-issued bonds. On the asset side, I assume that the mutual fund purchases 26% of the economy's capital in every period. The value is chosen so that the mutual fund's steady-state capital holding is 65% of the annual GDP (Hall (2001)). I also assume that the mutual fund purchases all of the shares of intermediate-goods firms, which have steady-state values that are 54% of annual GDP.[5] On the liability side, I assume that the debt-to-equity ratio

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[5] The fund's total asset value is slightly larger than the estimate of the total financial claims of the nonfarm,

is constant at unity. This is a typical assumption in the literature. With these assumptions, the equity value in period t is $\left(K_t^{corp} + q_t N_{I,t}\right)/2$ where $K_t^{corp} \equiv (26\%)\, K_t$. The gross risk-free rate in period t is:

$$r_{f,t} \equiv \frac{1}{E_t\left[M_{t,t+1}\right]}$$

The gross equity return realized in period $t+1$ is:

$$r_{e,t+1} \equiv 2\left[r_{K,t+1}\left(\frac{K_t^{corp}}{K_t^{corp} + q_t N_{I,t}}\right) + r_{I,t+1}\left(\frac{q_t N_{I,t}}{K_t^{corp} + q_t N_{I,t}}\right)\right] - r_{f,t}$$

where $r_{K,t+1} \equiv 1 - \delta_K + rental_{t+1}$ is the gross tangible capital return realized in period $t+1$ and $r_{I,t+1} \equiv \left(\sum_j \Pi_{t+1}^j + q_{t+1} N_{I,t+1}\right)/q_t N_{I,t}$ is the gross intangible capital return realized in period $t+1$. Another variable of interest is the measured TFP, which is defined as:

$$TFP_t \equiv \frac{Y_t}{K_{t-1}^{\alpha} L_t^{1-\alpha}}$$

where Y_t is GDP in period t, which is gross output minus aggregate R&D spending: $Y_t \equiv Z_t - R_t$. In my model, TFP is an endogenous variable. In addition to exogenous goods-producing productivity, TFP is affected by R&D spending, product variety, and product composition.

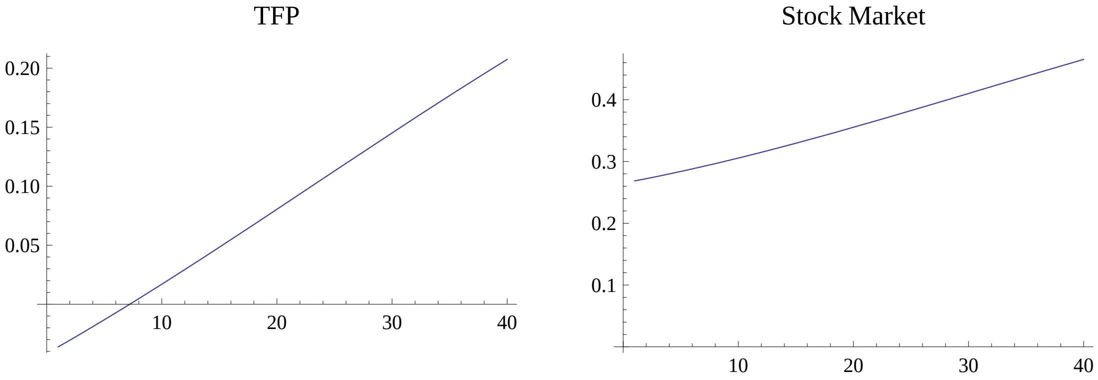

Figure 1: Benchmark model prediction. Impulse response functions to a one-standard-deviation positive R&D shock are plotted. The vertical axis is the percentage deviation from the steady state.

4 Results

4.1 The stock market and TFP

Figure 1 plots impulse response functions of the measured TFP and the equity value of the stock market after a one-standard-deviation positive R&D shock. Equity value immediately rises, and remains high for a prolonged period.[6] TFP initially drops slightly but then starts to grow, as if following the stock market. The other shock, the goods-producing productivity shock, does not generate such asymmetric responses, but it moves both TFP and equity value in the same direction, mostly on impact. Therefore, the stock market is followed by the measured TFP with a time lag. This is the first main result of this paper.

Figure 2 illustrates the same point with different technology. In this figure, I simulate 1,000 artificial data sets from the benchmark theoretical model, estimate a bivariate Vector Autoregression (VAR) of TFP and equity value, and plot the impulse response functions.[7] The same pattern

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nonfinancial corporate sector (Hall (2001)). However, if the financial sector is included, the two become close because this sector is intangible-capital intensive.

[6] This variable and all the other variables eventually return to their steady state values.

[7] Each set contains 212 data points. I estimate a VECM model, following Beaudry and Portier (2006), but other specifications yield similar results.

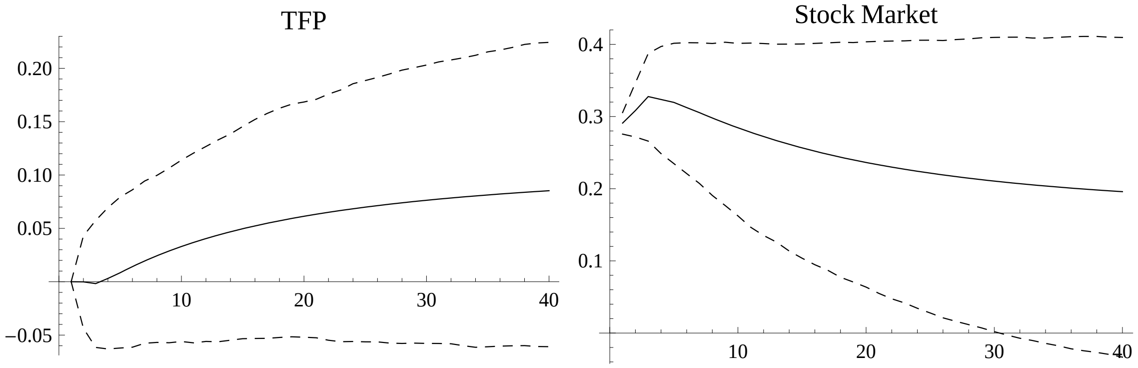

Figure 2: VAR with artificial data. Impulse response functions to a one-standard-deviation orthogonalized positive stock market innovation are plotted. The solid line is the mean, and the dotted lines are 16th and 84th quantiles, respectively, of the impulse response functions estimated with 1,000 sets of simulated data. The vertical axis is the percentage deviation from the steady state.

emerges again: a positive stock market innovation leads to an increase in TFP, but with a time lag. Moreover, the mean correlation between the R&D shock and the VAR innovation is 0.95 (with a standard error of 0.01) across the simulations. These results are interesting because the timing pattern seen in Figure 2 is consistent with the influential empirical work done by Beaudry and Portier (2006). Suggesting the importance of changes in expectations regarding future fundamentals, this empirical work draws much attention to news about future productivity realization.[8] But the typical work to date has assumed that productivity is exogenous. In my model economy, an R&D shock alters expectations about future TFP. In addition, an R&D shock generates an immediate stock market response followed by a change in the TFP level, whereas replicating this pattern with news is in general very difficult.[9] Therefore, my model offers an alternative to the phenomenon of news informing the public of future productivity and, additionally, overcomes the difficulty in replicating the timing of stock market appreciation.[10]

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[8] Prominent contributions include Beaudry and Portier (2004), Den Haan and Kaltenbrunner (2009), Eusepi and Preston (2009), Fujiwara, Hirose, and Shintani (2011), Jaimovich and Rebelo (2010), Schmitt-Grohe and Uribe (2009), and Walker and Leeper (2011).

[9] See Christiano, Ilut, Motto, and Rostagno (2008) for a more complete discussion of this topic.

[10] Much of the news-shock literature addresses the co-movement issue. That is, researchers attempt to construct

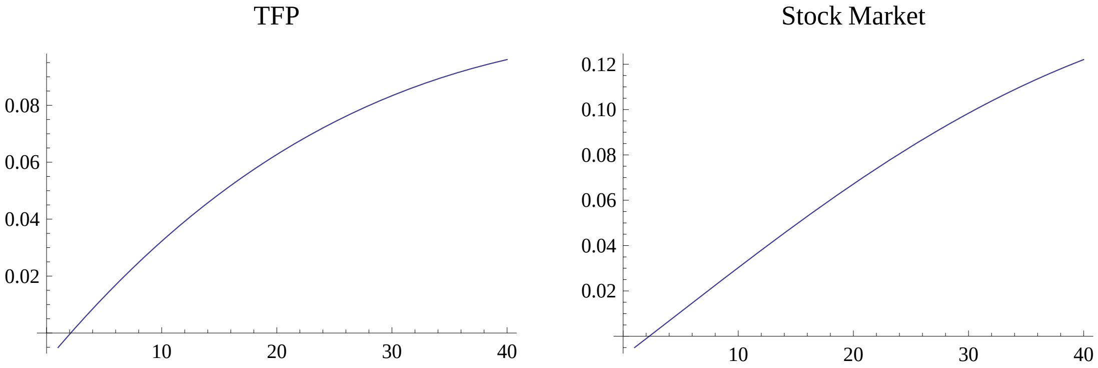

Figure 3: No special role in in-house R&D. Impulse response functions to a one-standard-deviation positive R&D shock are plotted. The vertical axis is the percentage deviation from the steady state.

I now discuss model mechanics. Clearly, it is not capital that generates the initial stock market appreciation because capital investment drops on impact due to the wealth effect. This response makes the initial stock market appreciation difficult. Nevertheless, the stock market appreciates because of intangible capital or, equivalently, innovative products. Remember that an innovative product is valued for its dual role: a prototype of a monopolistic product and a seed for new products. The stock market appreciates because a positive R&D shock increases the value of the latter role.

Figure 3 further clarifies this point. This figure plots impulse response functions in an alternative model in which in-house R&D has no special role, but instead, the economy-wide common knowledge production function exists. More specifically, any firm can create new products with a linear function with an effective R&D unit, which is produced by the household with a production function with elasticity ν. The curvature ν is introduced to the household's problem for making this

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a model in which major macroeconomic variables move in the same direction at the arrival of news. As noted by Cochrane (1994), this is not an easy task, but Beaudry and Portier (2004) accomplished it with highly complementary production sectors, as did Jaimovich and Rebelo (2010) with a novel utility function weakening the wealth effect. However, the empirical evidence is mixed. Namely, Beaudry and Portier (2006) originally supported conditional co-movement, but Barsky and Sims (2011) recently developed an alternative identification strategy and obtained a contradictory result. Given this empirical debate, in this work, I do not adopt a strong position on this issue but instead focus on the timing issue between the stock market and TFP, on which the empirical studies agree.

Table 2. Equity Premium and Risk-Free Rate.

	US data	benchmark	one sector	no R&D shock
Equity return	6.55	2.92	1.91	2.30
Equity premium	*5.57*	*1.52*	*0.01*	*0.74*
Equity return volatility	14.36	1.43	0.14	1.16
Risk-free rate mean	0.98	1.40	1.90	1.56
Risk-free rate volatility	0.65	0.13	0.12	0.12
Intangible capital return		3.28		2.38
Intangible capital return volatility		1.74		1.27
Tangible capital return		1.42	1.91	1.58
Tangible capital return volatility		0.14	.14	0.13

The US data are taken from CRSP. The coefficient of relative risk aversions is identical.

alternative model as close to the original as possible. Further details are given in the Appendix. As shown in Figure 3, the stock market drops on impact, in sharp contrast to the benchmark model. In this alternative model, R&D has to be a zero-profit industry in the equilibrium, because any firm can create new products with a linear knowledge production function. Therefore, the arrival of new products simply means the arrival of rival products from an existing product's point of view. Such an expectation lowers the values of existing products, causing a decline in the stock market.

4.2 Equity premium and risk-free rate

The upper panel of Table 2 reports the mean and volatility of the equity return.[11] In the benchmark model (the third column), the mean equity premium is 1.52% annually, which is approximately equal to one third of the actual (the second column). In a one-sector version of the model with the identical utility function (the fourth column), the mean equity premium is 0.01%. Because the utility functions are identical, clearly the large-risk aversion alone does not generate a large equity premium; rather, the combination of both the large-risk aversion and the R&D sector generates

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[11] I solve the model up to the second order. The reported model statistics are averaged across 1,000 simulations, each of which has a sample length of 240 quarters.

a large equity premium. The lower panel of Table 2 decomposes the equity return into asset categories. Intangible capital return is larger and more volatile than tangible capital return, which is roughly consistent with Chan, Lakonishok, and Sougiannis (2001), who reported that equity returns of R&D-intensive firms have these properties in the actual data.

The fifth column reports the results of an alternative simulation in which an R&D shock is shut down. The equity premium is 0.74% annually, implying that a goods-producing productivity shock alone can generate a relatively large equity premium. However, this also implies that more than half of the equity premium that is observed in the benchmark model is attributable to an R&D shock. The R&D shock raises the stock market and simultaneously starts a prolonged economic expansion. This combination means that the equity return is high precisely when the continuation utility value is high. The stochastic discount factor (9) implies that the household does not like this price-fluctuation pattern and demands compensation in the form of a large risk premium.

This mechanism is similar to the long-run risks of Bansal and Yaron (2004), but the mechanism does have several distinctions. First, with stationary exogenous state variables and rich amplification mechanisms, my model allows structural interpretation of the risk, i.e., where it comes from and how it propagates. Typical studies in the literature cannot address these issues because they treat crucial variables, such as consumption and profits (Bansal and Yaron (2004)) or TFP (Croce (2008); Ai, Croce, and Li (2010); Rudebusch and Swanson (2009)), as exogenous model inputs whose growth rates are positively serially correlated. Kaltenbrunner and Lochstoer (2010) is a notable exception to this in that they study the long-run risk originating from consumption smoothing.

Second, the qualitative results of the current paper are robust to changes in the value of the intertemporal elasticity of substitution (IES). Table 3 illustrates this point. The fourth column of

Table 3. Sensitivity to IES.

	IES 1.5		IES 0.5	
	both shocks	no R&D shock	both shocks	no R&D shock
Equity return	2.92	2.30	2.10	1.82
Equity premium	*1.52*	*0.74*	*0.93*	*0.66*
Equity return volatility	1.43	1.16	1.03	0.96
Risk-free rate mean	1.40	1.56	1.17	1.16
Risk-free rate volatility	0.13	0.12	0.15	0.11

The coefficient of relative risk aversion is identical.

Table 3 reports the results of a simulation in the economy in which the value of this parameter is reduced to 0.5, keeping the other parameter values identical. The equity premium is 0.93%, which is smaller than the equity premium observed in the benchmark model (the second column), but it is still large. The fifth column of Table 3 lists the results for the no-R&D-shock version of this small-IES economy. Here, the equity premium is 0.66%. Because this number is very close to its counterpart with a large IES (the third column), the risk premium associated with goods-producing productivity shock is not very sensitive to the value of this parameter. However, what is more interesting is the fact that the risk premium associated with R&D shock—the difference between the fourth column and the fifth column—is still positive, even though IES is less than one. This is in sharp contrast to what is usually found in the literature, i.e., that the long-run risk contributes to a negative risk premium if IES is less than one (Bansal (2007)), because the discount factor is too sensitive to consumption growth in this case. In my model economy, consumption growth and profit growth can diverge at a medium frequency due to product composition. This point is illustrated in Figure 4, which plots the impulse response functions of consumption and the aggregate profit of intermediate goods firms for 25 years after a positive R&D shock. Profit drops on impact due to large R&D spending but later grows rapidly because many new products are invented and also because new products are, on average, more profitable than old ones. In contrast, consumption

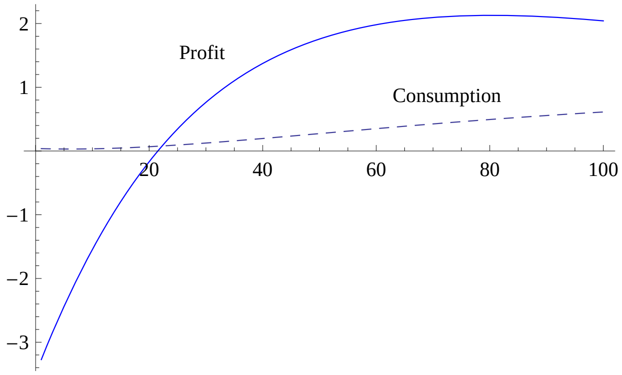

Figure 4: Profit and consumption after R&D shock. The solid line is the aggregate intermediate-goods firms' profits, and the dotted line is consumption. The vertical axis is the percentage deviation from the steady state.

growth is much slower than profit growth because it depends largely on the total product variety. These differential growth rates allow the stock market to rise on impact of an R&D shock even in an environment in which the discount factor is sensitive to the consumption growth. Because the household does not like this price-fluctuation pattern, a positive equity premium is demanded for it.[12]

The top panel of Table 2 also reports the risk-free rate. In the benchmark model, the mean rate is 1.40% annually. Because the risk-free rate in the one-sector version of the model with the identical utility function is 1.90%, again, it is not the large risk aversion alone but rather the combination of both the large risk aversion and the R&D sector that significantly reduces the risk-free rate. Because the household is risk-averse and because shocks are amplified in the R&D sector, the household strongly demands safe assets, thus reducing the risk-free rate. The interest rate is also stable in the benchmark model, as in the data, which is a distinguishing feature of the current model in contrast with other prominent contributions in the literature.[13]

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[12] See Danthine and Donaldson (2002) for the importance of factor-share movements in improving asset pricing implications in a different environment.

[13] E.g., Jermann (1998), Boldrin, Christiano, and Fisher (2001), Guvenen (2009), and Kaltenbrunner and Lochstoer

Table 4—Business Cycle Statistics

	U.S. data	benchmark	no R&D shock
GDP volatility	1.65	1.24	1.24
Consumption volatility	0.85	0.31	0.31
Investment volatility	4.73	4.33	4.30
Hours volatility	1.75	0.72	0.71
Consumption co-movement	0.77	0.62	0.64
Investment co-movement	0.79	0.99	0.99
Hours co-movement	0.87	0.98	0.97
R&D volatility	1.74	1.95	0.85
R&D co-movement	0.47	0.36	0.99

Source: BEA and BLS

4.3 Business cycle moments

Finally, I compare the unconditional second moments of the important macroeconomic variables in the data and in the model at the business-cycle frequency.[14] Table 4 reports the results. The benchmark model replicates the general movements of GDP, consumption, investment, and hours worked in the actual economy. The lower panel reports R&D spending, and the benchmark model also replicates the general pattern of this key variable. The fourth column reports the results for the no-R&D-shock case. Because the top panel does not change much, we can conclude that a goods-producing productivity shock will account for most of the business-cycle fluctuations of GDP, consumption, investment, and hours worked. But this does not mean that an R&D shock is unimportant to the economy. On the contrary, it is very important, but its full impact comes slowly at a medium frequency.[15] In addition, we see in the table that if an R&D shock is shut down, the volatility of R&D spending becomes less than half of the volatility of actual spending, and its correlation with GDP becomes almost one. Therefore, an R&D shock is an important factor in

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(2010).

[14] Using the band-pass filter of Christiano and Fitzgerald (2003), I extract cyclical components for up to 32 quarters for quarterly data and up to 8 years for annual data.

[15] These implications are consistent with the findings of Barsky and Sims (2011).

accounting for R&D spending fluctuations both at the business-cycle frequency and at a medium frequency.

5 Conclusions

This paper examines the implications of in-house R&D in a variety expansion model with stochastic productivity disturbances. The stock market and the level of productivity show interesting timing differences because the former reflects expected future innovations, whereas the latter is affected by past innovations. Three notable implications are the following: (i) the stock market is followed by measured TFP with a time lag; (ii) with a recursive utility, the equity premium increases; and (iii) interest rates of safe assets decrease. With the model performing well in matching basic business-cycle facts, these additional improvements support the model's crucial assumption that firms accumulate private knowledge that is helpful for in-house R&D.

I keep the model simple in order to focus on the new element in the R&D sector. The downside of this strategy is that, although the improvements are significant, some results fall quantitatively short of fully explaining the actual data. The level of equity premium and the volatility of the stock market are most notable. This problem, however, will be solved once I enrich the model in the directions that the body of literature in this area proves to be promising. For example, "disasterizing" the model will magnify the equity premium (Gabaix (2011); Gourio (2010)). Danthine and Jin (2007) and Hou and Johri (2010) showed that versions of intangible-capital models have the ability to generate volatile corporate profits. Matsumoto, Cova, and Pisani (2011) also showed that policy news can increase asset price volatility.

Some of the model's predictions are worth empirical scrutiny. An R&D shock in my model economy is observationally similar to a news shock. The prominence of an R&D shock as a source of the medium-term economic fluctuation is also worth further investigation. Cross-sectional implications should also be examined in an extended model, as Ngai and Samaniego (2011) showed that appropriateness is important for accounting for R&D growth across industries in the actual data.

A Alternative model

One way to eliminate the special role of in-house R&D is simply by setting the research elasticity ν to unity. However, doing so makes the steady state R&D share huge because the gross output becomes very productive in the R&D sector. Because I want to compare two cases around steady states with reasonable R&D shares, I take a different route: making the firm's knowledge production function linear and at the same time, introducing the curvature ν to the household's problem. In this way, any firm can create products with a linear knowledge production function for an effective R&D unit R_t^*. The effective R&D unit is traded in the market place at a competitive price $q_{R,t}$. Firm j's R&D problem is therefore:

$$\max_{\left\{R_t^{*j}\right\}_{t=0}^{\infty}} E_0\left[\sum_{t=0}^{\infty} M_{0,t}\left(N_{I,t-1}^j \pi_t - q_{R,t} R_t^{*j}\right)\right]$$

subject to

$$N_{I,t}^j = \left(1-\delta_N\right)\left(1-\sigma\right) N_{I,t-1}^j + S_t R_t^{*j}$$

The household produces the effective R&D unit with the production function $R_t^* = R_t^{\nu}$. It maximizes the utility (7) subject to the flow budget constraint:

$$C_t + K_t + R_t + \sum_{j=1}^{J_t} \mu_t^j \left(q_t N_{I,t}^j\right) = W_t L_t + (1 - \delta_K + rental_t)\, K_{t-1} + q_{R,t} R_t^* + \sum_{j=1}^{J_t} \mu_{t-1}^j \left[\Pi_t^j + \left(q_t N_{I,t}^j\right)\right]$$

Everything else is identical to the benchmark model.

B Data sources

GDP, consumption, investment, and R&D data are taken from BEA. Consumption is personal consumption expenditure on service and nondurable goods. Investment is personal consumption expenditure on durable goods and fixed private investment. These series are divided by a chain-type GDP deflator (from BEA) and the civilian noninstitutional population between 16 and 64 years old (from BLS). Hours worked are constructed from the average weekly hours (from BLS) multiplied by the number of employees in the private sector (from BLS) divided by the population. Financial data are taken from CRSP. Following Bansal and Yaron (2004), I construct equity return using the value-weighted NYSE return divided by realized inflation and construct the risk-free rate using the one month T-Bill rate divided by a trailing 12-month average of inflation.

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