RIETI Discussion Paper Series 24-E-013

Economic Growth through Basic Research by Firms: A science linkage approach

NIREI, Makoto
RIETI

OIKAWA, Koki
Waseda University

OROKU, Masahiro
Recruit Co., Ltd.

Research Institute of Economy, Trade & Industry, IAA

The Research Institute of Economy, Trade and Industry
https://www.rieti.go.jp/en/

RIETI Discussion Paper Series 24-E-013
January 2024

Economic Growth through Basic Research by Firms: A science linkage approach*

Makoto Nirei (University of Tokyo)
Koki Oikawa (Waseda University)
Masahiro Oroku (Recruit Co., Ltd.)

Abstract

Patents applied by private firms occasionally cite scientific papers. We regard these citations as a signal that the research project of the applying firms involves basic research, and examine the relationship between basic research and firm performance. Firms conducting basic research are more likely to earn higher profit margins, while no monotonic relationship is observed between basic research and sales size. We then construct an endogenous growth model incorporating the basic research investment by heterogeneous firms. Firms' decisions regarding basic research depend on firm size, the necessity for basic research for developing their products, and the degree of knowledge spillover from external basic research results. Quantitative analysis using this model reveals how basic research spillover effects impact economic growth, and how declining R&D efficiency, which has been reported in the literature in recent years, leads to lower growth. Furthermore, we compare public basic research investment with basic research subsidies and demonstrate that the latter is more efficient as a growth policy.

Keywords: economic growth; basic research; science linkage
JEL classification: O32, O40, L11

*This study is conducted as a part of the project "Innovation, Knowledge Creation and Macroeconomy" undertaken at the Research Institute of Economy, Trade and Industry (RIETI). The draft of this paper was presented at the DP seminar of the Research Institute of Economy, Trade and Industry (RIETI). I would like to thank participants of the RIETI DP Seminar for their helpful comments.

1 Introduction

The key to economic growth is technological progress, which is mainly driven by firms' R&D investments. Although the main body of research activities in firms is applied research and development aimed at yielding profits in the market, a non-negligible amount of resources is invested into basic research that does not directly generate commercial returns for firms.[1] The share of basic research expenditure in the business sector out of the total basic research expenditure in the United States and Japan (solid lines) is illustrated in Figure 1. In both countries, we observe increasing trends of basic research investments especially after the mid-2000s and the contribution of private firms accounts for more than 30% recently. The dashed lines show that the total basic research expenditure divided by GDP is also increasing over time. As elaborated in previous studies dating back to Griliches (1986), basic research generates significant private returns, and, more importantly, it has been increased over these years.

In this study, we first investigate firm-level basic research activities and their impacts on firm performance using the science linkage data, which is the collection of citations from patents to scientific papers. Frequent citations to scientific papers in patents applied by a firm imply that the firm is likely to be engaged in basic research. In the absence of data on the breakdown of basic and applied R&D expenditures at the firm level, the science linkage approach provides useful information. Of our sample of the US firms that applied at least one patent, 15-20% of firms cite scientific papers, depending on years. We estimate the impact of such paper citations on firm performance such as sales and profit rates (gross margin ratios) using the paper quality index as the instrumental variable, and we find that the science linkage increases profit rates, while the relationship with sales size is not monotonic.[2]

Second, we model the channel from basic research to firm's business performance in the form that they occasionally need basic research to develop their products further. We suppose that the amount of applications based on a given level of scientific knowledge

[1] In the OECD's Guidelines for Collecting and Reporting Data on Research and Experimental Development (OECD (2015)), basic research is defined as "experimental or theoretical work undertaken primarily to acquire new knowledge of the underlying foundations of phenomena and observable facts, without any particular application or use in view."

[2] Arora et al. (2017) use science linkages and report that firms invest in basic research when the research outcomes can be used in their inventions, focusing on within-firm citations from patents to scientific papers.

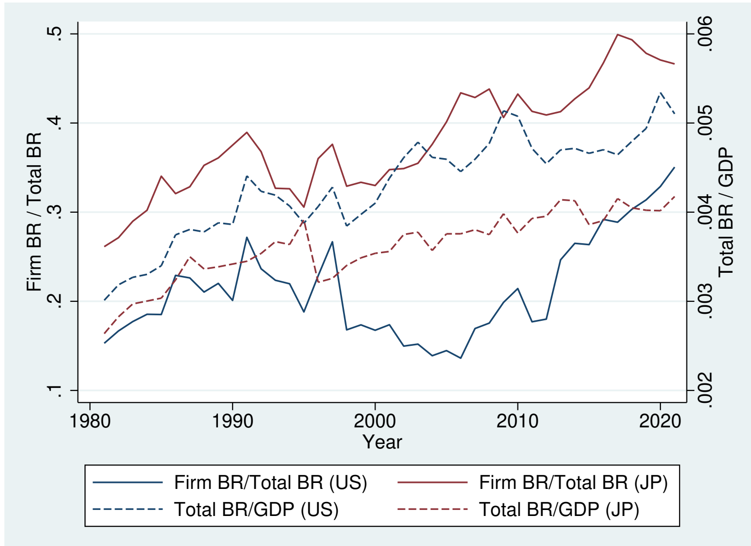

Figure 1: Share of basic research expenditure in the business sector out of the total basic research expenditure (solid lines, left axis), and the total basic research expenditure relative to GDP (dashed lines, right axis). Source: OECD Research and Development Statistics.

is limited and that basic research can enhance the potential pool of applications. This formulation is similar to Cozzi and Galli (2014), who assume basic research is a prerequisite for further applied research. The history of light-emitting diode (LED) development fits nicely into this assumption. To create a white light source with LED, which has a wide range of applications, a blue LED was needed. Such LED was developed by Nobel laureate Dr. Shuji Nakamura, who succeeded in growing high-quality Gallium Nitride (GaN) crystals when he worked for a private company. The method for manufacturing GaN opened up new possibilities for applications. The development of these applications provides an opportunity to generate profit.

Considering that the necessity for basic research varies across firms, we describe that even small firms actively engage in basic research if there is a sufficient need. Thus, the model is consistent with the finding of a non-monotonic relationship between basic research investment and firm size.

While basic research benefits the firm that conducts it, such research also opens the door to applications for other firms. In terms of the above example, GaN is not only the key to producing blue LEDs, but can also be applied in various devices that utilize power semiconductors. Because basic research is not aimed at a specific use, the spillover effect tends to be greater than that from applied research. Akcigit et al. (2020) highlight this point and demonstrate that a firm that operates in multiple sectors has a greater incentive to conduct basic research because they have relatively high possibility of utilizing the results within the firm. Our model shares the same spirit as in Akcigit et al. (2020) in the sense that firms supply multiple products and a strong spillover effect from basic research exists, while we keep our model much simpler. Firm heterogeneity is also an important feature of our model because some firms do not conduct basic research and become free riders on results derived by other firms. Such firm behaviors lead to inefficiency in the investment decisions. Firm-level basic research becomes socially suboptimal due to the spillover effect. We calculate the size of spillover effect by calibrating our model, and quantify the impacts of basic research subsidy and public basic research investment on the aggregate growth rate.

The model also provides an explanation for the declining R&D efficiency at macro and micro levels, reported by Bloom et al. (2020). As the necessity for basic research increases, the overall efficiency of R&D decreases because basic research is costly and generates no direct returns. We experiment its impact on the balanced growth path when the necessity for basic research increases.

The remainder of this paper is organized as follows. Section 2 summarizes the empirical results using science linkage and firm-level data. Section 3 presents the theoretical model. Section 4 shows quantitative results. Section 5 concludes.

2 Empirical Facts

2.1 Data Overview

Our analysis is based on comprehensive database of firms, patents and scientific papers in the United States from 2004 to 2011. The firm data including financial information are from Bureau van Dijk's Orbis database. The patent data are from the European Patent Office's PATSTAT database. The scientific paper data are from Clarivate Analytics' Web of Science (WoS) database. We constructed a combined database by linking these three datasets. Science linkages from patents to scientific papers are provided by Clarivate Analytics. Patent ownership information for firms are included in the Orbis database. Cases where one patent is owned by multiple firms were excluded.

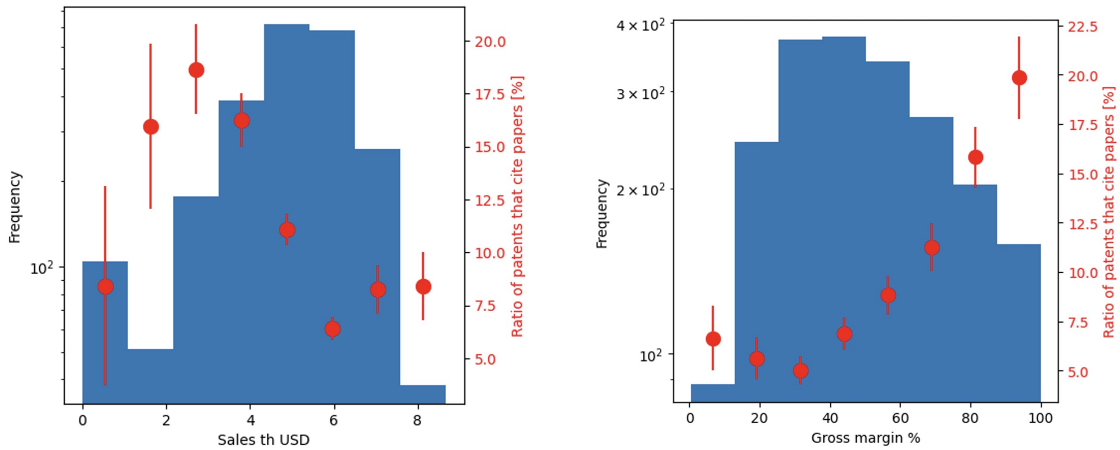

Figure 2: Paper citation ratio vs sales (left) and gross margin (right)

As a measure of firms' basic research intensity, we use *paper citation ratio*, which is calculated by the proportion of patents applied by a firm that cite scientific papers. Sales and gross margin are used as measures of firm performance. Sales value is real value, deflated by the producer price index of each industry. R&D expense divided by operating revenue is used as a measure of R&D intensity of the firm. We build a panel dataset by extracting the data of firms that have both patent application and financial information in the same year. The number of observations is about 1,300 (year×firm) in the following regressions. See Appendix A for more details regarding the data.

We illustrate the relationships between basic research and firm performance in Figure 2 following Oroku (2024), who uses basically the same dataset. The left panel presents the histogram of firm-level average sales in logarithmic form during the sample period with the average paper citation ratio among firms in each bin of the histogram (the vertical bar for each dot represents the 95% confidence interval). There are many relatively small firms that are engaged in basic research, although there is a lot of heterogeneity among them. The right panel illustrates the relationship between the paper citation ratio and the gross margin ratio (only for firms with positive margins). The panel clearly shows a positive correlation between the two indices: successful firms in terms of gross margin tend to have higher paper citation ratios. In other words, firms that invest in basic research tend to earn greater profits.

These simple observations suggest that basic research is related to firm-level performance although not directly determined by firm size in terms of sales. In the next subsection, we run regressions to see more detailed relationships observed in the current subsection.

2.2 Regression

Basic Research and Sales We investigate how the paper citation ratio relates to the patent holder's real sales. First, we regress one-year future log of real sales on the current year real sales (log), paper citation ratio, and R&D intensity using ordinary least squares (OLS) with robust standard errors. Second, we employ the instrumental variables (IV) method to deal with endogeneity issues such as the possibility that large sales are associated with large internal reserves that generate an environment conducive to basic research. Our instrument is the quality of scientific papers cited by each firm in each year, which is measured by the number of forward citations in scientific papers.[3] High quality papers are more likely to be cited by patents but they are unlikely to affect firm performance through other channels. The OLS and IV estimates are presented in Table 1, as well as the first stage estimation. The results show that the paper citation ratio is not significant in either regression. In other words, basic research does not directly enhance sales size as expected from the non-monotonic relation observed in Figure 2.

An interesting finding from this regression is observed in the first stage, the bottom of Table 1. The paper citation ratio is negatively correlated with sales size and R&D intensity. This finding is consistent with Arora et al. (2017), who document that basic research investments shift away from large firms over time in many industries. Rather, small start-up firms may represent a large percentage of basic research firms. The negative correlation with R&D intensity could be because R&D expense is the total of applied and basic research. If higher R&D intensity is associated with higher expenditures mainly on applied research, then it is natural that the higher the R&D intensity, the lower the ratio of basic research.

Basic Research and Profit We run similar regressions regarding the gross margin ratios. The dependent variable is the one-year future gross margin ratio, and the explanatory variables are the paper citation ratio, the same year log of real sales to control

[3]We made an adjustment that divides the number of forward citations of a paper by the average number of citations within the academic field for each year. This addresses the truncation problem of fewer citation opportunities for newer papers.

Table 1: Relevance of paper citation in sales

	F1.Sales(log)	
	(1) OLS	(2) IV second stage
Sales (log)	0.985***	0.992***
	(137.81)	(54.38)
R&D intensity	-0.047	-0.041
	(-0.782)	(-0.662)
Paper citation ratio	0.006	0.041
	(0.345)	(0.414)
Observation	1336	1336
R-squared	0.998	0.998
Cov. Est.	heteroskedastic	heteroskedastic
Application year FE	Yes	Yes
Technology field FE	Yes	Yes

First stage	Paper citation ratio
Sales (log)	-0.156***
	(-9.659)
R&D intensity	-0.158**
	(-2.320)
Paper quality	0.191***
	(4.205)
R-squared	0.728

*: $p < 0.10$, **: $p < 0.05$, ***: $p < 0.01$.

the size effect on the gross margin ratio, and R&D intensity. The OLS and IV estimation results using the same instrument as above are reported in Table 2. Unlike the results of the sales regressions, the coefficients for R&D intensity and paper citation ratio are significantly positive, which suggests that basic research contributes to profit rates. Note that the coefficient for the paper citation ratio in the IV regression, column (2), is greater than that in the OLS regression, column (1). It implies that the error term is negatively correlated with the paper citation ratio in the OLS regression, or the OLS estimate is biased downwardly. Such a bias occurs when low profit margins increase the incentive to conduct basic research. The measurement error in the relationship between paper citations and the true basic research activity also causes a downward bias.

Several possible reasons exist as to why basic research intensity is positively associated with profit while its relationship with sales is insignificant. One is that basic research improves productivity but the price may not move quickly because the pricing strategy depends on the elasticity of demand and the pricing of rival firms. If the price remains constant while productivity improves, profit must increase. Another possible reason is cannibalism within firm in the sense that a new product is a substitute for an old product supplied by the same firm (Arrow (1962); Igami (2017)). Because the firm with success in R&D produces an improved product and obtains new volume of sales, but simultaneously it loses sales from the substituted old product. The firm surely earns more profits but the total sales may not change significantly.

3 Model

We construct a growth model with firms' basic research investment. The fundamental structure of firm-level productivity and size dynamics follows a simplified version of that in Aoki and Nirei (2017). Our model differs from theirs in that product lines occasionally need a success in basic research to be improved further. We assume that each product alternates between the basic and the applied research stage, which is similar to Cozzi and Galli (2014), and that the products have positive productivity trends only in the latter stage.

Table 2: Relevance of paper citation in gross margin

	F1.Gross margin ratio	
	(1) OLS	(2) IV second stage
F1.Sales (log)	0.022***	0.069***
	(2.943)	(2.525)
R&D intensity	0.400***	0.446***
	(7.477)	(7.298)
Paper citation ratio	0.079***	0.388**
	(3.630)	(2.215)
Observation	1310	1310
R-squared	0.907	0.890
Cov. Est.	heteroskedastic	heteroskedastic
Application year FE	Yes	Yes
Technology field FE	Yes	Yes

First stage	Paper citation ratio
F1.Sales (log)	-0.157***
	(-9.431)
R&D intensity	-0.165**
	(-2.283)
Paper quality	0.205***
	(4.385)
R-squared	0.719

*: $p < 0.10$, **: $p < 0.05$, ***: $p < 0.01$.

3.1 Households and Firms

The household sector is homogeneous and standard. The representative household maximizes their expected utility such that

$$\max \mathbb{E}_t \int_t^{\infty} e^{-\rho(s-t)} \ln c_s ds \qquad \text{s.t. } \dot{a}_t = r_t a_t + \Pi_t + w_t - c_t \quad \forall t,$$

where a_t is the risk-free assets with the real interest rate of r_t, and Π_t is the dividends from firms. They inelastically supply fixed amount of labor, which is normalized to 1.

The final goods are supplied by competitive producers with the production function of

$$Y_t = \left[\int_0^I \int_0^{N_{i,t}} y_{n,i,t}^{\frac{\phi-1}{\phi}} dndi \right]^{\frac{\phi}{\phi-1}}, \qquad \phi > 1, \tag{1}$$

where $y_{n,i,t}$ is the intermediate product $n \in [0, N_{i,t}]$ that is supplied by firm $i \in [0, I]$ at time t. Intermediate goods firms are under monopolistic competition. We assume that the total measure of products is 1, that is, $\int_0^I N_{i,t} di = 1$ for any t.

Intermediate goods producers maximize the profits from each product,

$$\pi_{n,i,t} = p_{n,i,t} y_{n,i,t} - w_t \ell_{n,i,t} - (r_t + \delta) k_{n,i,t},$$

with the production function of

$$y_{n,i,t} = z_{n,i,t} k_{n,i,t}^{\alpha} \ell_{n,i,t}^{1-\alpha}, \qquad \forall n \in [0, N_{i,t}], \, \forall i \in [0, I], \tag{2}$$

where $p_{n,i,t}$, $z_{n,i,t}$, $k_{n,i,t}$, $\ell_{n,i,t}$ are the intermediate goods price, productivity, capital, labor, respectively, w_t is the wage rate, δ is the depreciation rate, and $\alpha \in (0, 1)$. Observing the demand function, $p_{n,i,t} = y_{n,i,t}^{-\frac{1}{\phi}} Y_t^{\frac{1}{\phi}}$, derived from the maximization for the representative final goods firm, the revenue from a product n supplied by firm i is

$$p_{n,i,t} y_{n,i,t} = Y_t^{\frac{1}{\phi}} \left[z_{n,i,t} k_{n,i,t}^{\alpha} \ell_{n,i,t}^{1-\alpha} \right]^{\frac{\phi-1}{\phi}}. \tag{3}$$

Assuming perfect competition in the factor markets, we have

$$w_t = \frac{\partial p_{n,i,t} y_{n,i,t}}{\partial \ell_{n,i,t}} = \frac{(1-\alpha)(\phi-1)}{\phi} Y_t^{\frac{1}{\phi}} z_{n,i,t}^{\frac{\phi-1}{\phi}} k_{n,i,t}^{\frac{\alpha(\phi-1)}{\phi}} \ell_{n,i,t}^{\frac{(1-\alpha)(\phi-1)}{\phi}-1}, \tag{4}$$

$$r_t + \delta = \frac{\partial p_{n,i,t} y_{n,i,t}}{\partial k_{n,i,t}} = \frac{\alpha(\phi-1)}{\phi} Y_t^{\frac{1}{\phi}} z_{n,i,t}^{\frac{\phi-1}{\phi}} k_{n,i,t}^{\frac{\alpha(\phi-1)}{\phi}-1} \ell_{n,i,t}^{\frac{(1-\alpha)(\phi-1)}{\phi}}, \tag{5}$$

implying

$$\begin{aligned} \ell_{n,i,t} &= \bar{\ell}_t z_{n,i,t}^{\phi-1}, \\ \bar{\ell}_t &\equiv \left[\frac{\alpha(\phi-1)}{\phi\left(r_t+\delta\right)} Y_t^{\frac{1}{\phi}}\right]^{\frac{\alpha(\phi-1)/\phi}{1-(\phi-1)/\phi}} \left[\frac{(1-\alpha)(\phi-1)}{\phi w_t} Y_t^{\frac{1}{\phi}}\right]^{\frac{1-\alpha(\phi-1)/\phi}{1-(\phi-1)/\phi}}. \end{aligned} \tag{6}$$

We also have

$$p_{n,i,t} y_{n,i,t} = \bar{py}_t \bar{\ell}_t z_{n,i,t}^{\phi-1}, \tag{7}$$

$$k_{n,i,t} = \bar{k}_t \bar{\ell}_t z_{n,i,t}^{\phi-1}, \tag{8}$$

$$\pi_{n,i,t} = \bar{\pi}_t \bar{\ell}_t z_{n,i,t}^{\phi-1}, \tag{9}$$

where

$$\begin{aligned} \bar{py}_t &\equiv \left[\frac{\alpha(\phi-1)}{\phi\left(r_t+\delta\right)}\right]^{\frac{\alpha}{1-\alpha}} \bar{\mathbb{E}}_t \left\{z_{n,i,t}^{\phi-1}\right\}^{\frac{1}{(\phi-1)(1-\alpha)}}, \\ \bar{k}_t &\equiv \left[\frac{\alpha(\phi-1)}{\phi\left(r_t+\delta\right)}\right]^{\frac{1}{1-\alpha}} \bar{\mathbb{E}}_t \left\{z_{n,i,t}^{\phi-1}\right\}^{\frac{1}{(\phi-1)(1-\alpha)}}, \\ \bar{\pi}_t &\equiv \bar{py}_t - w_t - \left(r_t+\delta\right) \bar{k}_t. \end{aligned}$$

The operator $\bar{\mathbb{E}}_t$ represents the cross-sectional average over all products in the economy at time t. Following Aoki and Nirei (2017), we assume that firms sell some fraction, θ_t, of their products at random at the price that is equal to the product value for the sellers to have a stationary firm size distribution. Note that the value of the products sold does not affect the value of the selling firm.

3.2 Productivity Dynamics: Basic and Applied Research

There are two possible stages for each product: the applied research (AR) stage and the basic research (BR) stage. The productivity growth of each product depends on the stages. Let $\mathcal{N}_{i,t}^A$ and $\mathcal{N}_{i,t}^B$ be the set of products supplied by firm i at t in the AR and BR stages, respectively ($\mathcal{N}_{i,t}^A \cup \mathcal{N}_{i,t}^B = [0, N_{i,t}]$). Product-level productivity, $z_{n,i,t}$, evolves according to

$$dz_{n,i,t} = \begin{cases} \mu z_{n,i,t}dt + \sigma_z z_{n,i,t}dW_{i,t} & \forall n \in \mathcal{N}_{i,t}^A, \\ \sigma_z z_{n,i,t}dW_{i,t} & \forall n \in \mathcal{N}_{i,t}^B, \end{cases} \tag{10}$$

where $\mu > 0$ is common across products. The productivity has a positive trend if the product is in the AR stage, while no trend in the BR stage. We assume that $W_{i,t}$ is the Wiener process that governs the firm-level productivity shock that is common across products supplied by firm i. Hence, $W_{i,t+dt} - W_{i,t} \sim N(0, dt)$ holds for any i.

The transition probability from the BR to AR stage in one unit of time, say $\lambda_{i,t}$, follows

$$\lambda_{i,t} = \begin{cases} \lambda(X_{B,t}) & \text{if not investing in basic R\&D} \\ \lambda_0 + \lambda(X_{B,t}) & \text{if investing in basic R\&D,} \end{cases} \tag{11}$$

where $\lambda_0 > 0$, $\lambda(\cdot) \geq 0$ is a continuous and increasing function, and $X_{B,t}$ is the total labor employed for basic research in the economy. Because basic research is not targeted at a specific product, we presume that it is conducted not at the product line level but at the firm level so that the probability of transition is common across the BR products for firm i. Basic research requires fixed labor of x_B per unit of time. Thus, $X_{B,t}$ equals x_B times the measure of firms that invest in basic research . The transition from the AR to BR stage occurs at an exogenous rate of $\eta > 0$ in a unit of time for each product. To focus on the role of basic research, the trend productivity growth in the AR stage, $\mu z_{n,i,t}dt$, is automatic without incurring any cost to the firm.

Because firms' production decisions depend on $z_{n,i,t}^{\phi-1}$ as in equation (6), it is convenient to convert equation (10) to the dynamics of $z_{n,i,t}^{\phi-1}$ such that,

$$dz_{n,i,t}^{\phi-1} = \begin{cases} \left[(\phi-1)\left(\mu - \frac{\sigma_z^2}{2}\right) + \frac{(\phi-1)^2\sigma_z^2}{2}\right] z_{n,i,t}^{\phi-1}dt + (\phi-1)\sigma_z z_{n,i,t}^{\phi-1}dW_{i,t} & \forall n \in \mathcal{N}_{i,t}^A, \\ \left[(\phi-1)\left(-\frac{\sigma_z^2}{2}\right) + \frac{(\phi-1)^2\sigma_z^2}{2}\right] z_{n,i,t}^{\phi-1}dt + (\phi-1)\sigma_z z_{n,i,t}^{\phi-1}dW_{i,t} & \forall n \in \mathcal{N}_{i,t}^B. \end{cases}$$

We now define the firm-level productivity as the sum of $z^{\phi-1}$ over products,

$$Z_{i,t} \equiv \int_0^{N_{i,t}} z_{n,i,t}^{\phi-1}dn.$$

The important state variable of a firm that determines the dynamics of $Z_{i,t}$ is the share of products in the BR stage, which we denote by $\beta_{i,t}$. We make a simplifying assumption that the research stages of products are randomly shuffled within firm in each instant. With this assumption, the productivity distribution in $\mathcal{N}^A_{i,t}$ is the same as that in $\mathcal{N}^B_{i,t}$. Hence, we do not need to track the stages of each product and the product-level average productivity is the same across stages. Because the measure of products in $\mathcal{N}^A_{i,t}$ and $\mathcal{N}^B_{i,t}$ are $(1-\beta_{i,t})N_{i,t}$ and $\beta_{i,t}N_{i,t}$, respectively, we have

$$Z_{i,t} = \frac{1}{1-\beta_{i,t}} \int_{\mathcal{N}^A_{i,t}} z^{\phi-1}_{n,i,t} dn = \frac{1}{\beta_{i,t}} \int_{\mathcal{N}^B_{i,t}} z^{\phi-1}_{n,i,t} dn. \tag{12}$$

We calculate the dynamics of firm-level productivity as follows:

$$\begin{aligned} dZ_{i,t} &= \int_{\mathcal{N}^A_{i,t}} dz^{\phi-1}_{n,i,t} dn + \int_{\mathcal{N}^B_{i,t}} dz^{\phi-1}_{n,i,t} dn - \theta_t Z_{i,t} dt \\ &= (\phi-1)\mu \int_{\mathcal{N}^A_{i,t}} z^{\phi-1}_{n,i,t} dn + \left[(\phi-1)\left(-\frac{\sigma_z^2}{2}\right) + \frac{(\phi-1)^2\sigma_z^2}{2}\right] Z_{i,t} dt \\ &\qquad + (\phi-1)\sigma_z Z_{i,t} dW_{i,t} - \theta_t Z_{i,t} dt. \end{aligned}$$

Note that the additional negative trend in $Z_{i,t}$ (the last term of the first line in the above equation) derives from our assumption that each firm sells some of its products randomly. Applying equation (12), we obtain

$$\begin{aligned} dZ_{i,t} &= \left[M(\beta_{i,t}) - \theta_t\right] Z_{i,t} dt + (\phi-1)\sigma_z Z_{i,t} dW_{i,t}, \\ M(\beta_{i,t}) &\equiv (1-\beta_{i,t})(\phi-1)\mu + \frac{(\phi-1)(\phi-2)\sigma_z^2}{2}. \end{aligned} \tag{13}$$

3.3 Basic Research Decision

The basic research investment is decided to maximize firm value, $q_{i,t} = q(Z_{i,t}, \beta_{i,t})$. Applying Itô's lemma, the Hamilton-Jacobi-Bellman equation satisfies

$$\begin{aligned} r_t q_{i,t} &= \bar{\pi}_t \bar{\ell}_t Z_{i,t} + \frac{\partial q}{\partial Z} M(\beta_{i,t}) Z_{i,t} + \frac{1}{2}\frac{\partial^2 q}{\partial Z^2}\left[(\phi-1)\sigma_z Z_{i,t}\right]^2 \\ &\quad + \max\left\{\frac{\partial q}{\partial \beta}\left[\eta - \beta_{i,t}\left(\eta + \lambda\left(X_{B,t}\right) + \lambda_0\right)\right] - x_B w_t,\ \frac{\partial q}{\partial \beta}\left[\eta - \beta_{i,t}\left(\eta + \lambda\left(X_{B,t}\right)\right)\right]\right\}. \end{aligned} \tag{14}$$

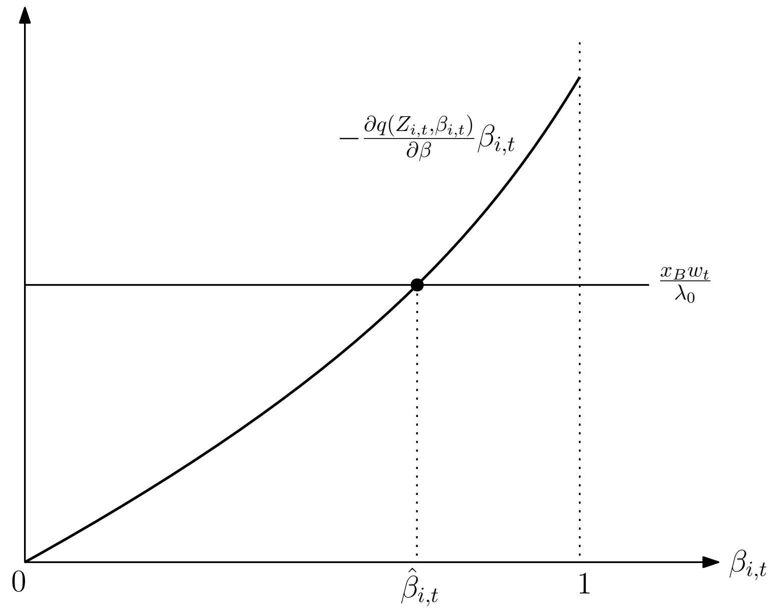

Figure 3: Basic research decision

The second line of equation (14) depends on the basic research decision. Firm i conducts basic research projects if

$$\begin{aligned} \frac{\partial q}{\partial \beta}\left[\eta - \beta_{i,t}\left(\eta + \lambda\left(X_{B,t}\right) + \lambda_0\right)\right] - x_B w_t &\geq \frac{\partial q}{\partial \beta}\left[\eta - \beta_{i,t}\left(\eta + \lambda\left(X_{B,t}\right)\right)\right] \\ \Leftrightarrow \quad -\frac{\partial q(Z_{i,t}, \beta_{i,t})}{\partial \beta}\beta_{i,t} &\geq \frac{x_B w_t}{\lambda_0}. \end{aligned} \tag{15}$$

The left and right-side of inequality (15) are depicted in Figure 3. Note that the $-\frac{\partial q(Z_{i,t},\beta_{i,t})}{\partial \beta}\beta_{i,t}$ is strictly increasing in $\beta_{i,t}$, or

$$\frac{\partial}{\partial \beta}\left[-\frac{\partial q}{\partial \beta}\beta\right] = -\frac{\partial q}{\partial \beta} - \frac{\partial^2 q}{\partial \beta^2}\beta > 0.$$

$\partial q/\partial \beta < 0$ because the drift of $Z_{i,t}$ is determined by $M(\beta_{i,t})$ in equation (13) and $M'(\beta_{i,t}) < 0$. This first-order impact becomes larger for greater β, so that $\frac{\partial^2 q}{\partial \beta^2} < 0$, because the decreased Z in the next instant implies even lower dZ in the future. Hence, $-q(Z_{i,t}, \beta_{i,t})$ is strictly convex and increasing in $\beta_{i,t}$ for given $Z_{i,t}$.

The intersection $\hat{\beta}_{i,t} = \hat{\beta}(Z_{i,t})$ is the threshold of basic research investment. Firm i invests in basic research at time t if and only if $\beta_{i,t} \geq \hat{\beta}(Z_{i,t})$. Note that the firm value

$q_{i,t}$ is increasing in $Z_{i,t}$ for any $\beta_{i,t}$, so that the curve, $-\frac{\partial q}{\partial \beta}\beta$, in Figure 3 shifts upward when $Z_{i,t}$ rises, implying that $\hat{\beta}_{i,t}$ declines as $Z_{i,t}$ increases. Moreover, $\hat{\beta}_{i,t}$ is increasing in w_t.

Proposition 1. *There exits unique threshold $\hat{\beta}(Z_{i,t})$ such that a firm with $\beta_{i,t} \geq \hat{\beta}(Z_{i,t})$ invests in basic research. Furthermore, $\hat{\beta}(Z_{i,t})$ is decreasing in $Z_{i,t}$ and increasing in $x_B w_t/\lambda_0$.*

Because basic research investment is determined by a single cutoff strategy, the firm value, $q_{i,t}$, can be divided into two segments: the values without and with basic research. Moreover, these two segments should be connected smoothly because basic research is an option available any time. To obtain the threshold $\hat{\beta}$, we consider the firm value without basic research. In this segment, equation (14) is simplified to

$$\begin{aligned} r_t q_{i,t} &= \bar{\pi}_t \bar{\ell}_t Z_{i,t} + \frac{\partial q}{\partial Z} M(\beta_{i,t}) Z_{i,t} + \frac{1}{2}\frac{\partial^2 q}{\partial Z^2}\left[(\phi-1)\sigma_z Z_{i,t}\right]^2 \\ &\quad + \frac{\partial q}{\partial \beta}\left[\eta - \beta_{i,t}\left(\eta + \lambda\left(X_{B,t}\right)\right)\right] \qquad \text{for } -\frac{\partial q}{\partial \beta}\beta_{i,t} < \frac{x_B w_t}{\lambda_0}. \end{aligned} \tag{16}$$

We can then solve $\hat{\beta}$ as in the next proposition.

Proposition 2. *Firm value without basic research investment has the form of $q_{i,t} = Q_t(\beta_{i,t})Z_{i,t}$ and the threshold $\hat{\beta}$ satisfies*

$$-Q_t'\left(\hat{\beta}(Z_{i,t})\right)\hat{\beta}(Z_{i,t}) = \frac{x_B w_t}{\lambda_0 Z_{i,t}},$$

where

$$\begin{aligned} Q_t(\beta) &= \left(-P_{2,t}(\beta) + C_{2,t}\right)e^{P_{1,t}(\beta)}, \\ P_{1,t}(\beta) &\approx -\frac{1}{\eta}\left[\left(r_t - M\left(\bar{\beta}_t\right)\right)\bar{\beta}_t \log\eta - \left(r_t - M\left(0\right)\right)\beta\right], \\ P_{2,t}(\beta) &\approx \frac{\bar{\pi}_t \bar{\ell}_t \eta^{\frac{1}{\eta}\left\{r_t - M\left(\bar{\beta}_t\right)\bar{\beta}_t\right\}}}{\frac{1}{\bar{\beta}_t} - \frac{1}{\eta}\left\{r_t - M\left(0\right)\right\}} e^{\left\{\frac{1}{\bar{\beta}_t} - \frac{1}{\eta}\left\{r_t - M(0)\right\}\right\}\beta}, \\ C_{2,t} &= \eta^{\frac{1}{\eta}\left\{r_t - M\left(\bar{\beta}_t\right)\right\}\bar{\beta}_t} Q_t(0) + P_{2,t}(0), \\ \bar{\beta}_t &\equiv \frac{\eta}{\eta + \lambda(X_{B,t})}. \end{aligned}$$

The proof is presented in Appendix B.[4] It should be emphasized that the cutoff strategy regarding basic research is two-dimensional. If $\beta_{i,t}$ is high, even a small firm (with low $Z_{i,t}$ and $\ell_{i,t}$) invests in basic research. This is consistent with our finding in Figure 2, where the relationship between firm size and basic research index is inconclusive.

3.4 Labor Market

Labor demand consists of production workers and researchers. Production workers in the aggregate economy are represented by

$$\int_0^I \int_0^{N_{i,t}} \ell_{n,i,t} dndi = \bar{\ell}_t \int_0^I \int_0^{N_{i,t}} z_{n,i,t}^{\phi-1} dndi = \bar{\ell}_t \bar{\mathbb{E}}_t \left[z_{n,i,t}^{\phi-1} \right].$$

Given the measure of researchers, $X_{B,t}$, which equals x_B times the measure of firms that have $(Z_{i,t}, \beta_{i,t})$ with $\beta_{i,t} \geq \hat{\beta}(Z_{i,t})$, the labor market clearing condition implies that

$$1 = \bar{\ell}_t \bar{\mathbb{E}}_t \left[z_{n,i,t}^{\phi-1} \right] + X_{B,t} \quad \Rightarrow \quad \bar{\ell}_t = \frac{1 - X_{B,t}}{\bar{\mathbb{E}}_t \left[z_{n,i,t}^{\phi-1} \right]}. \tag{17}$$

3.5 Stationary State Equilibrium

We focus on the stationary state equilibrium. A stationary state equilibrium of this economy has $r_t = \rho + g$, $\beta_t = \beta$, $X_{B,t} = X_B$, $\theta_t = \theta$, and constant growth rates for w_t, $\bar{\ell}_t$, $\bar{k}_t$, $\bar{py}_t$ $\bar{\pi}_t$, c_t, and Y_t. Firm distribution is represented by a stationary joint distribution, $f\left(\log \ell_{i,t}, \beta_{i,t}\right)$. Here, we consider stationary distribution of $(\log \ell_{i,t}, \beta_{i,t})$ instead of $(Z_{i,t}, \beta_{i,t})$ because $Z_{i,t}$ has a non-zero trend. Accordingly, we redefine the basic research threshold as employment-based such as $\hat{\beta}(\log \ell_{i,t})$, instead of $\hat{\beta}(Z_{i,t})$, abusing notation. Because $\log \ell_{i,t} = \log \bar{\ell}_t + \log Z_{i,t}$, $\hat{\beta}\left(\log \ell_{i,t}\right)$ is a strictly decreasing function for a given $\bar{\ell}_t$. Note that equation (17) with a constant X_B yields

$$d \log \bar{\ell}_t = -M(\beta) dt. \tag{18}$$

[4]Both functions $P_{1,t}$ and $P_{2,t}$ are approximated by $\log\left(1 - \beta/\bar{\beta}_t\right) \approx -\beta/\bar{\beta}_t$, regarding that $\beta/\bar{\beta}_t$ is sufficiently small. This approximation makes $P_{1,t}$ linear in β, and we can thereby obtain $P_{2,t}$ explicitly.

3.5.1 Employment Dynamics and Stationary Distribution

To derive the stationary joint distribution of $(\log \ell_{i,t}, \beta_{i,t})$, we formulate the system of differential equations regarding $d\log \ell_{i,t}$ and $d\beta_{i,t}$. Equation (13) in a stationary state and equation (18) implies that the dynamics of $\log \ell_{i,t}$ follows

$$\begin{aligned} d\log \ell_{i,t} &= d\log \bar{\ell}_t + d\log Z_{i,t} \\ &= \left[(\beta - \beta_{i,t})(\phi - 1)\mu - \theta^*\right] dt + (\phi - 1)\sigma_z dW_{i,t}. \end{aligned} \tag{19}$$

A stationary employment distribution exists if firms sell products at a rate of $\theta > 0$ and a minimum requirement of employment, $\ell_{\min} > 0$, exists to operate a firm. We assume that firms that reach $\ell_{\min}$ exit the market and are replaced by entrants, keeping the total measure of firms constant at I. The entrant firms are assigned a bundle of products consisting of those supplied by the exiting firms and those sold by the incumbents.[5]

An individual firm's ratio of BR products, $\beta_{i,t}$, follows a deterministic dynamics after deciding whether to invest in basic research,

$$d\beta_{i,t} = (1 - \beta_{i,t})\eta dt - \beta_{i,t}\lambda_{i,t} dt,$$

which implies that

$$d\beta_{i,t} = \begin{cases} \left(\eta - (\eta + \lambda(X_B) + \lambda_0)\,\beta_{i,t}\right) dt & \text{if } \beta_{i,t} \geq \hat{\beta}(\log \ell_{i,t}), \\ \left(\eta - (\eta + \lambda(X_B))\,\beta_{i,t}\right) dt & \text{otherwise.} \end{cases} \tag{20}$$

Equations (19) and (20) determine the dynamics of $(\log \ell_{i,t}, \beta_{i,t})$, which generates a stationary joint distribution.

[5] We assume that M&A can be coordinated between buyers (entrants) with smaller N and sellers (incumbents) with larger N. Such coordination is necessary for the following reason. Because basic research affects all products in the BR stage, the per-product cost of basic research is $\frac{x_B w_t}{\beta_{i,t} N_{i,t}}$, which is decreasing in $N_{i,t}$ for given $\beta_{i,t}$. This size effect generates an additional value of holding a product and the marginal benefit from an additional product is decreasing in $N_{i,t}$. Thus, the buyer's willingness-to-pay for a product is greater than the product value from the seller's perspective, if the latter owns more products than the former.

3.5.2 Aggregate Basic Research Investment and Growth Rate

Given a stationary joint distribution, we calculate the aggregate measure of workers engaged in basic research activities as

$$X_B = x_B I \int_{-\infty}^{\infty} \int_{\hat{\beta}(\log \ell)}^{1} f(\log \ell, \beta) d\beta d \log \ell.$$

The aggregate ratio of the products in the BR stage is the mean of β's across firms:[6]

$$\beta = \int_{0}^{1} \int_{-\infty}^{\infty} \beta f(\log \ell, \beta) d \log \ell d\beta.$$

The economic growth rate is

$$g = \frac{d \log Y_t}{dt} = -\frac{1}{(\phi - 1)(1-\alpha)} \frac{d \log \bar{\ell}_t}{dt} = \frac{M(\beta)}{(\phi - 1)(1-\alpha)}.$$

Because M is a decreasing function, the growth rate in the stationary state is higher if there are fewer products in the BR stage. A lower share of BR products is achieved by greater basic research investment, X_B.

4 Quantitative Analysis

In this section, we numerically compute the model in the previous section to illustrate (i) the spillover effect in basic research, (ii) the consequences of an increase in the necessity of basic research, and (iii) the policy experiment regarding public basic research investment and subsidy for firms. The benchmark parameter setting is the time preference $\rho = 0.05$, the capital share $\alpha = 1/3$, the depreciation rate $\delta = 0.05$, the elasticity of substitution $\phi = 1.5$, the switching rate from the AR to BR stage, $\eta = 0.05$, the success rate in individual basic research, $\lambda_0 = 0.05$, the fixed labor cost of basic research, $x_B = 1.5$, the productivity drift in the AR stage, $\mu = 0.1$, the standard deviation of the firm-level shock, $\sigma_z = 0.1$, the minimum level of workers $\log \ell_{\min} = -0.5$, and the total measure of firms, $I = 1$. For the function of λ, that represents the spillover effect of basic research,

[6] A distribution of $N_{i,t}$ exists but it is independent of the distribution of $\beta_{i,t}$ because $N_{i,t}$ is decreasing at a constant rate of θ in the stationary state.

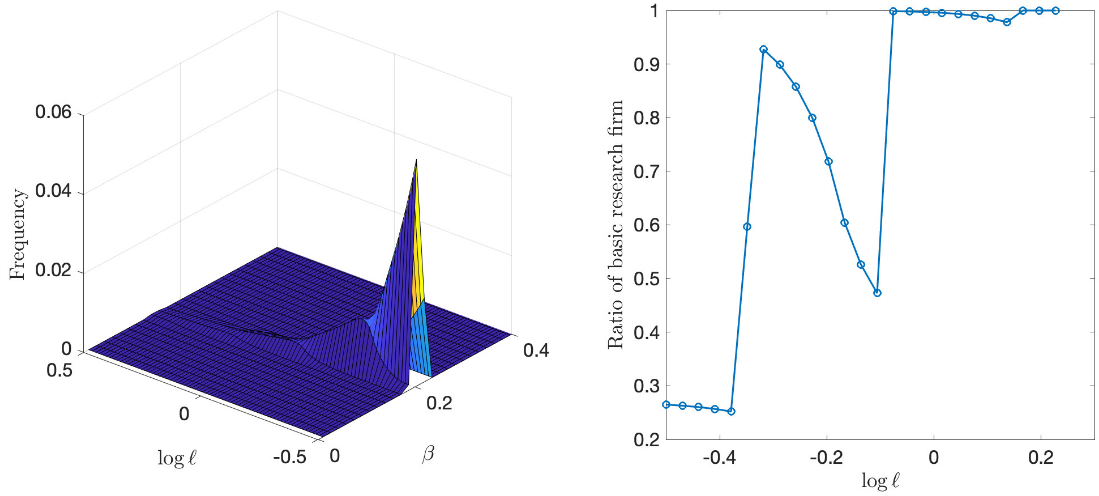

Figure 4: Joint density of firm employment and basic research ratio in the stationary state.

we use the form of

$$\lambda(X_B) = \lambda_1 X_B^{\lambda_2}, \qquad \lambda_1, \lambda_2 > 0. \tag{21}$$

The degree of spillover is measured by λ_1. We set the benchmark parameters as $\lambda_1 = 0.25$ and $\lambda_2 = 0.5$. The benchmark set of parameters gives 16.5% share of basic research firms among all firms, 19.9% share of products in the BR stage, 3.2% growth rate at firm-level on average, and an aggregate growth rate of 11.7%. The aggregate growth in the benchmark model is much higher than the actual growth rate because the model economy consists of only R&D firms. The left panel of Figure 4 presents the joint density of employment, $\log \ell_{i,t}$, and the share of products in the BR stage, $\beta_{i,t}$, in the stationary state for the benchmark parameter set.[7]

The figure also illustrates the shares of firms conducting basic research within the firm size groups. Consistent with the observed relationship between sales and basic research in the left panel of Figure 2, the share of firms with basic research is not monotonic with the firm size (employment and sales are parallel in the current model). A decreasing region exists in the middle range.[8] The hike in basic research firms in the region of relatively small firms occurs because they face more needs of basic research, that is, high

[7]We follow Achdou et al. (2022) to obtain the two-dimensional stationary joint distribution.

[8]The numbers in the right panel of Figure 4 are taken as the averages of basic research firm shares in the two adjacent size group grids in terms of log employment for smoothing.

β's, which lead to lower growth in firm size. We should note that the current model does not explain the right panel of Figure 2, the relationship between basic research and the gross margin, because it is common across firms at $\bar{\pi}_t/\bar{py}_t$ in the current model.

4.1 Impact of the Spillover Effect on Growth and Basic Research Investment

The first experiment concerns the parameter λ_1 to examine the impact of the spillover effect. A change in λ_1 can also be interpreted as a policy intervention regarding intellectual property rights. When a basic research result is patented with a strong restriction, it is costly for other firms to utilize the patented basic research knowledge, implying a low λ_1.[9] A higher λ_1 helps the economy grow because a basic research result that does not contribute to the researching firm may be utilized by another firm. However, it reduces the incentives for basic research at the firm level in two ways. First, a firm can free ride on basic research activities by the other firms. Second, the return on basic research investment becomes smaller when many firms are conducting basic research because the product-level profit depends on the productivity relative to the average productivity among all the products in the economy, which grows faster when more firms are active in basic research.

Figure 5 illustrates the changes in the aggregate basic researchers, X_B, and the aggregate growth rate, g, in the stationary states for various degrees of the spillover effect, $\lambda_1 \in [0, 0.5]$, where we set those values in the benchmark case as 1. Roughly speaking, X_B is decreasing and g is increasing over λ_1. Although the spillover effect raises economic growth through more effective utilization of basic research results, it reduces investment to generate the new knowledge from basic research. The impact on growth rate is sizable. Without the spillover effect ($\lambda_1 = 0$), the growth rate becomes lower by about 30%, relative to the benchmark, whereas the economy invests greater resources into basic research.

[9] In a study using a case of genetically engineered mice, Murray et al. (2016) highlight that entry to a research field is encouraged by weakened protection.

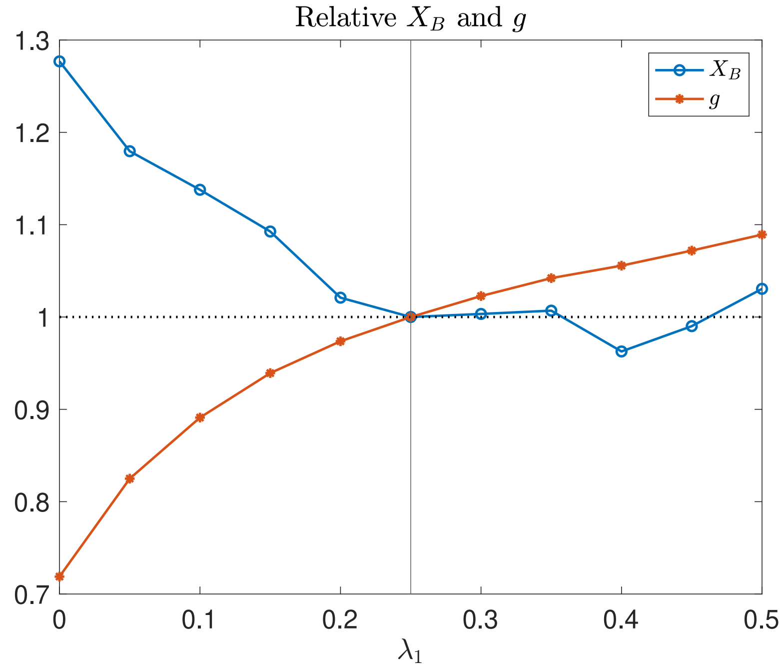

Figure 5: Spillover Effect

4.2 Impact of Higher Necessity of Basic Research

Next, we change the parameter of the switching rate from the AR to BR stage, η. We interpret that a higher η indicates a greater degree of necessity of basic research because products switch to the BR stage more frequently. A higher η leads to a lower aggregate growth, ceteris paribus, because it makes the share of products in the AR stage, which gives a positive trend in productivity, smaller. In other words, consistent with the result by Bloom et al. (2020), R&D efficiency, defined by R&D output divided by R&D investment, declines with η.

The results for $\eta \in [0.01, 0.1]$, where other parameters are the benchmark ones, are illustrated in Figure 6. Again, the vertical axis is the relative X_B and g with setting the values in the benchmark case as 1. Even though basic research is needed, the investment does not increase enough to compensate for the negative impact on growth rates. Firms do not see sufficient incentive to increase basic research, partly because they want to free ride, and partly because frequent return of products to the BR stage reduces the future payoff of successful basic research. Consequently, the growth rate monotonically decreases with η.

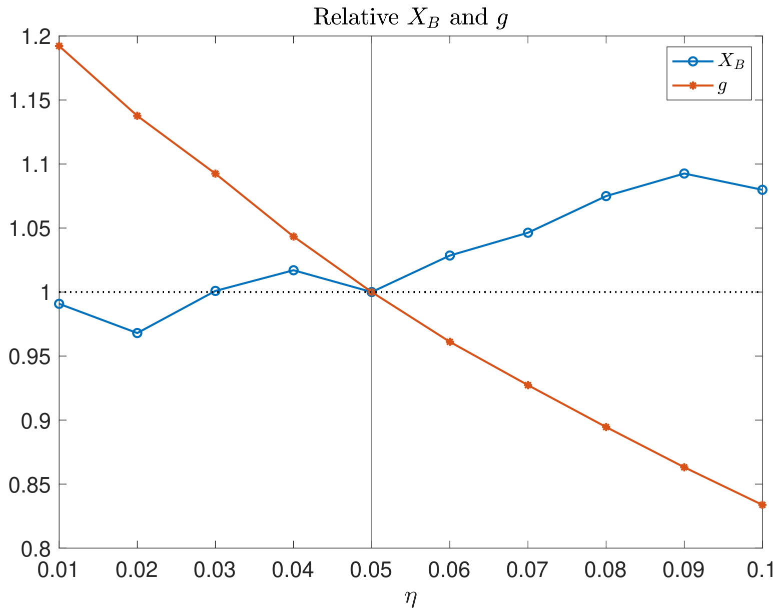

Figure 6: Increases in η

4.3 Public Basic Research vs. Basic Research Subsidy for Firms

The next analysis involves policy experiments regarding public basic research investment and basic research subsidy for private firms. Suppose that the government hires researchers, X_{PB}, to conduct basic research projects. We modify the spillover function such that

$$\lambda(X_B, X_{PB}) = \lambda_1 \left(X_B + X_{PB}\right)^{\lambda_2}. \tag{22}$$

The labor market clearing condition becomes $1 = \bar{\ell}_t \bar{\mathbb{E}}_t \left[z_{n,i,t}^{\phi-1}\right] + X_B + X_{PB}$. We assume that funding for public basic research expenditure is taken from the households in lump-sum tax.

The other policy is basic research subsidy. Suppose that the government subsidizes firms' basic research by the rate of s so that the cost of basic research is $(1-s)x_B$ in terms of labor. Again, the required resource is financed through lump-sum tax imposed on the households. Other factors are the same as in the basic model.

The impacts of those policies on relative g, compared to the benchmark case, are illustrated in Figure 7. The left and right panels present the results for public basic research and basic research subsidy, respectively. The figure also shows the total government spending in terms of labor units (right axis). The impact on growth rate, g, is greater in

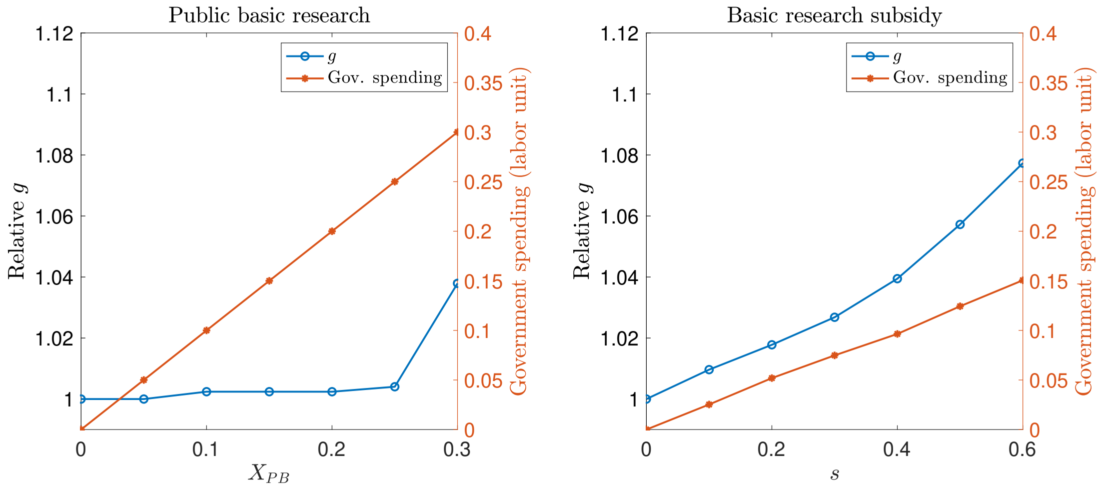

Figure 7: Basic research subsidy

the case of subsidy to firms' basic research activities. Furthermore, basic research subsidy can achieve higher growth rates at less government expense. The lower performance of public basic research investment derives from the free-rider problem brought by the spillover effect of basic research. Private firms quit basic research if they can find the active government-funded basic research results that can be used for their own business.

Complementarity between Private and Public Basic Research One may wonder whether private and public research are perfect substitutes, as is assumed in equation (22). What happens if they are complements?

To examine how complementarity works, we redefine the spillover function as a CES function such that

$$\lambda(X_B, X_{PB}) = \lambda_1 \left(aX_B^{\xi} + (1-a)X_{PB}^{\xi} \right)^{\frac{\lambda_2}{\xi}} \qquad a \in (0,1),\ \xi \leq 1,$$

where ξ represents substitutability between private and public basic research. We simulate the model with $\xi = \{-0.5, 0, 0.5, 1\}$ and $a = 0.5$ (the other parameters are the same as in the benchmark case). A lower ξ represents higher complementarity. Figure 8 illustrates the impacts of public basic research on the growth rates and private basic research investment relative to the case with $\xi = 1$ (perfect substitution) and $X_{PB} = 0$. The left panel shows that the growth rate is hump-shaped across X_{PB} when public and private research are complementary; moreover, the growth rates are lower under higher comple-

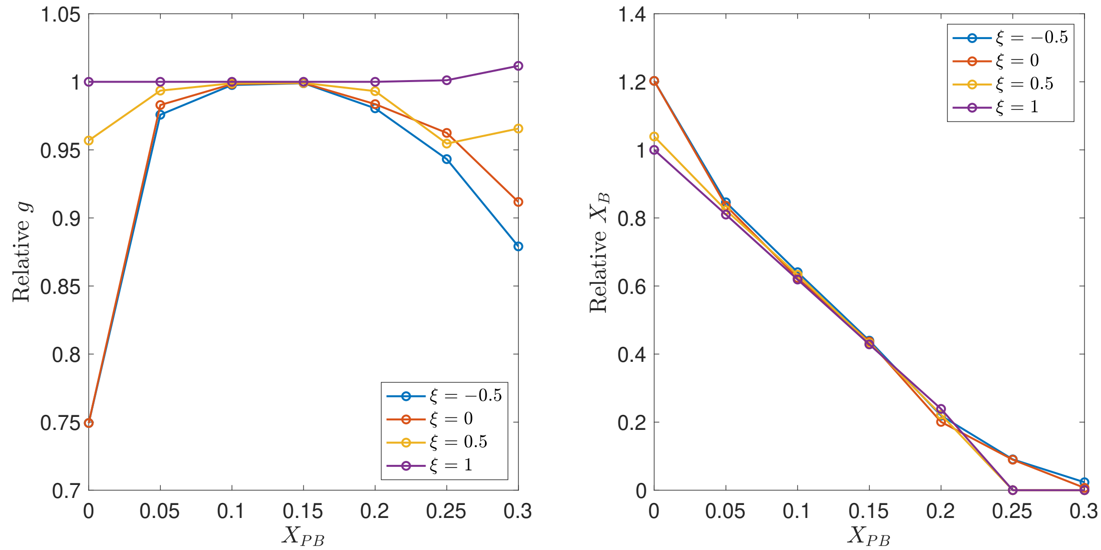

Figure 8: Public basic research and basic research subsidy

mentarity. Because both aggregate basic research investments, X_B and X_{PB}, are given for individual firms, each firm's basic research decision depends not on the interaction between X_B and X_{PB} but on the level of $\lambda(X_B, X_{PB})$. Since $\lambda(X_B, X_{PB})$ is increasing in X_{PB} for any ξ, they reduce private basic research investments under greater X_{PB} as illustrated in the right panel in Figure 8. Moreover, when complementarity exists, the function value of λ is pulled to the smaller elements, which generates the hump shape.

It should be noted, however, that the current model supposes that all basic research projects have equal possibility to lead to economic growth. In reality, some basic research projects are likely to lead to applications and development, while others are not, and it is the former category that firms are primarily engaged in. Given this heterogeneity in basic research projects, the present results suggest that basic research by public institutions should focus on projects that are far from commercialization, while projects closer to commercialization should be conducted by firms with appropriate subsidies.[10]

[10] Another experiment involves the change in the share parameter, a. If we consider that public basic research results are more likely to be open to public, the spillover effect through public research is greater even with the same level of investments. In this case, we have $a > 0.5$. Contrarily, if we consider that public basic research tends to be more fundamental and less likely to switch a product to the AR stage, its contribution is smaller than private basic research, which implies that $a < 0.5$. The results with a different from 0.5 are not essentially different from Figure 8 although an increase in X_{PB} has an additional positive (negative) impact on g for any ξ if $a > 0.5$ ($a < 0.5$).

5 Concluding remarks

If we have exhausted the fruit on the lower branches, we must make an effort to build a ladder to reach that on the higher branches. We need more efforts to find a new idea when technology advances, as theoretically suggested by Kortum (1997) and empirically documented by Bloom et al. (2020). One way to address the growing difficulties may be to increase investment in basic research because discoveries sometimes greatly broaden the range of product developments. As exemplified by blue LED, human genome analysis, IPS cells and so on, they expand applied research and product development in industries. We investigated the relationship between firm-level basic research activity and firm performance empirically and then constructed an endogenous growth model with heterogeneous firms and their basic research investment to formulate a channel from basic research to aggregate growth. We have quantitatively shown that the impact of basic research is highly dependent on knowledge spillovers. Such spillover also results in public basic research reducing firms' incentives to conduct it by allowing free-ride.

Although the current model captures some of the important features of basic research, we have not yet incorporated many aspects of research and development, which we leave for future research. For example, applied research is just an automatic productivity improvement in the current model. Clearly, applied research results are not low-hanging fruit and they also require efforts and funds. By incorporating investment decision for applied research into the model, the allocation of research resources to basic and applied research can be considered. Such an extension also contributes to the theoretical formulation of the complementarity of basic and applied research, which is empirically reported by Hottenrott et al. (2017) and Nagaoka et al. (2020).

References

Achdou, Y., J. Han, J.-M. Lasry, P.-L. Lions, and B. Moll (2022). Income and Wealth Distribution in Macroeconomics: A Continuous-Time Approach. *The Review of Economic Studies 89*(1), 45–86.

Akcigit, U., D. Hanley, and N. Serrano-Velarde (2020). Back to Basics: Basic Research Spillovers, Innovation Policy, and Growth. *The Review of Economic Studies 88*(1), 1–43.

Aoki, S. and M. Nirei (2017). Zipf's Law, Pareto's Law, and the Evolution of Top Incomes in the United States. *American Economic Journal: Macroeconomics 9*(3), 36–71.

Arora, A., S. Belenzon, and A. Patacconi (2017). The Decline of Science in Corporate R&D. *Strategic Management Journal 39*(1), 3–32.

Arora, A., S. Belenzon, and L. Sheer (2017). Back to Basics: Why do Firms Invest in Research? NBER Working Papers 23187, National Bureau of Economic Research, Inc.

Arrow, K. J. (1962). Economic Welfare and the Allocation of Resources to Invention. In R. Nelson (Ed.), *The Rate and Direction of Economic Activity*. N.Y.: Princeton University Press.

Bloom, N., C. I. Jones, J. V. Reenen, and M. Webb (2020). Are Ideas Getting Harder to Find? *American Economic Review 110*(4), 1104–1144.

Cozzi, G. and S. Galli (2014). Sequential R&D and Blocking Patents in the Dynamics of Growth. *Journal of Economic Growth 19*(2), 183–219.

Griliches, Z. (1986). Productivity, R&D, and the Basic Research at the Firm Level in the 1970's. *American Economic Review 76*(1), 141–154.

Hottenrott, H., C. Lopes-Bento, and R. Veugelers (2017). Direct and Cross Scheme Effects in a Research and Development Subsidy Program. *Research Policy 46*(6), 1118–1132.

Igami, M. (2017). Estimating the Innovator's Dilemma: Structural Analysis of Creative Destruction in the Hard Disk Drive Industry, 1981–1998. *Journal of Political Economy 125*(3), 798–847.

Kortum, S. S. (1997). Research, Patenting, and Technological Change. *Econometrica 65*(6), 1389–1419.

Murray, F., P. Aghion, M. Dewatripont, J. Kolev, and S. Stern (2016). Of Mice and Academics: Examining the Effect of Openness on Innovation. *American Economic Journal: Economic Policy 8*(1), 212–52.

Nagaoka, S., K. Edamura, K. Onishi, N. Tsukuda, Y. Naito, and R. Kadowaki (2020). Contributions of Corporate Basic Research and Research Collaboration with Academia to Innovation and Spillover Performance in Japan (Japanese). Discussion Papers (Japanese) 20001, Research Institute of Economy, Trade and Industry (RIETI).

OECD (2015). *Frascati Manual 2015: Guidelines for Collecting and Reporting Data on Research and Experimental Development.*

Oroku, M. (2024). Are Firms Able to Take Advantage of Academic Advances? Discussion papers, Research Institute of Economy, Trade and Industry (RIETI).

A Data Description

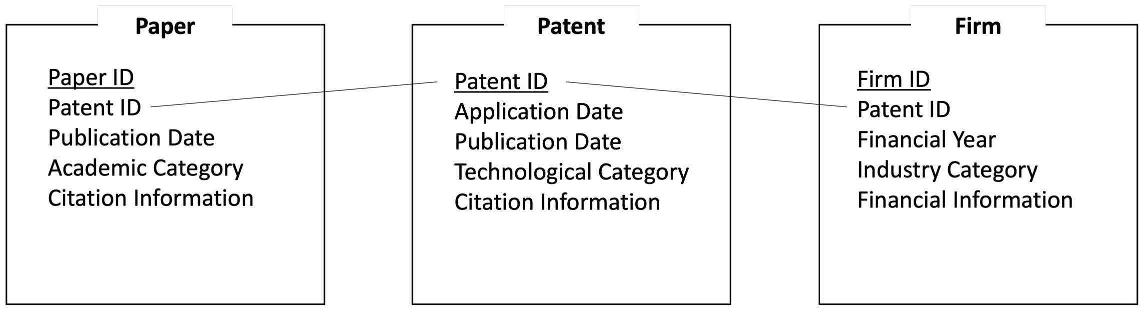

Figure A1: Overview of combined database

The overview of the database is as illustrated in Figure A1. Underlined columns represent the primary key of each database. Details of each column used in this analysis are as follows. Paper ID: WoS accession number (UT) as a unique identifier for scientific papers. Patent ID: United States Patent and Trademark Office (USPTO) publication number as a unique identifier for patents in US. Firm ID: Bureau van Dijk ID number as a unique identifier for firms. Our scientific categories are eight major categories aggregated from Essential Science Indicators (ESI) from the Web of Science. We use International Patent Classification (IPC) classified by the World Intellectual Property Organization (WIPO) as technological categories. Industrial categorizations are 3-digit NAICS codes. The list of variables and summary statistics are summarized in Table A1 and Table A2.

B Derivation of Q, P_1, and P_2

Suppose that $q\left(\beta_{i,t}, Z_{i,t}\right) = Q_t(\beta_{i,t})\bar{\pi}_t\bar{\ell}_t Z_{i,t}$ when firm i does not invest in basic research. Under this supposition, equation (16) becomes

$$r_t Q_t(\beta_{i,t}) = 1 + Q_t(\beta_{i,t})M(\beta_{i,t}) + Q_t'(\beta_{i,t})\left[\eta - \beta_{i,t}\left(\eta + \lambda\left(X_{B,t}\right)\right)\right] \quad \text{for } -Q_t'(\beta_{i,t})\beta_{i,t} < \frac{(\phi-1)(1-\alpha)x_B}{\lambda_1 \ell_{i,t}}, \tag{A1}$$

where we use the relationship

$$\frac{w}{\bar{\pi}_t} = (\phi - 1)(1-\alpha),$$

from equations (4) and (9). Equation (A1) is a first-order differential equation regarding β for a given t. Ignoring the time subscripts, it takes the form of

$$\left(a_1 + b_1\beta\right)Q = 1 + (a_2 + b_2\beta)Q' \quad \Leftrightarrow \quad Q' - \frac{a_1 + b_1\beta}{a_2 + b_2\beta}Q = -\frac{1}{a_2 + b_2\beta}, \tag{A2}$$

where

$$a_1 = r_t - (\phi-1)\mu - \frac{(\phi-1)(\phi-2)\sigma_z^2}{2}, \quad b_1 = (\phi-1)\mu,$$
$$a_2 = \eta, \qquad b_2 = -\left(\eta + \lambda\left(X_{B,t}\right)\right),$$

The solution for the differential equation is

$$Q = \left[-\int \frac{1}{a_2 + b_2\beta} e^{-\int \frac{a_1+b_1\beta}{a_2+b_2\beta}d\beta} d\beta + C_0\right] e^{\int \frac{a_1+b_1\beta}{a_2+b_2\beta}d\beta}.$$

Let P_1 and P_2 be the primitive functions for the integrands in the above equation such that

$$\int \frac{a_1 + b_1\beta}{a_2 + b_2\beta} d\beta \equiv P_1(\beta) + \text{Const.} \tag{A3}$$

$$\int \frac{1}{a_2 + b_2\beta} e^{-P_1(\beta)} d\beta \equiv P_2(\beta) + \text{Const.} \tag{A4}$$

We can write

$$Q(\beta) = e^{C_1} \left(-P_2(\beta) + C_2\right) e^{P_1(\beta)}, \tag{A5}$$

where C_1 and C_2 are some constants. By applying equation (A2) to equation (A5),

$$\begin{aligned}
Q'(\beta) &= e^{C_1} \left[-P_2'(\beta) + P_1'(\beta) \left(-P_2(\beta) + C_2\right)\right] e^{P_1(\beta)} \\
&= e^{C_1} \left[-\frac{1}{a_2 + b_2\beta} e^{-P_1(\beta)} + \frac{a_1 + b_1\beta}{a_2 + b_2\beta} \left(-P_2(\beta) + C_2\right)\right] e^{P_1(\beta)} \\
&= -\frac{e^{C_1}}{a_2 + b_2\beta} + \frac{a_1 + b_1\beta}{a_2 + b_2\beta} Q(\beta),
\end{aligned}$$

we should have $C_1 = 0$ to satisfy equation (A2).

P_1 is solved as follows. Ignoring the constant of integration,

$$\begin{aligned}
P_1(\beta) = \int \frac{a_1 + b_1\beta}{a_2 + b_2\beta} d\beta &= a_1 \int \frac{1}{a_2 + b_2\beta} d\beta + b_1 \int \frac{\beta}{a_2 + b_2\beta} d\beta \\
&= \frac{a_1}{b_2} \log|a_2 + b_2\beta| + b_1 \left(\frac{\beta}{b_2} \log|a_2 + b_2\beta| - \frac{1}{b_2} \int \log|a_2 + b_2\beta| d\beta\right) \\
&= \frac{a_1 + b_1\beta}{b_2} \log|a_2 + b_2\beta| - \frac{b_1}{b_2} \left(\frac{a_2 + b_2\beta}{b_2} \log|a_2 + b_2\beta| - \int 1 d\beta\right) \\
&= \frac{a_1 - a_2 b_1/b_2}{b_2} \log|a_2 + b_2\beta| + \frac{b_1\beta}{b_2}.
\end{aligned} \tag{A6}$$

Note that

$$\begin{aligned}
\frac{a_1 - a_2 b_1/b_2}{b_2} &= -\frac{1}{\eta} \left(r_t - M\left(\bar{\beta}_t\right)\right) \bar{\beta}_t, \\
a_2 + b_2\beta &= \eta \left(1 - \frac{\eta\beta}{\bar{\beta}_t}\right), \\
\frac{b_1\beta}{b_2} &= -\frac{\bar{\beta}_t}{\eta} (\phi - 1)\mu\beta,
\end{aligned}$$

where

$$\bar{\beta}_t \equiv \frac{\eta}{\eta + \lambda(X_{B,t})},$$

which the stationary value of β for given $X_{B,t}$ when a firm does not invest in basic research. To derive $P_2(\beta)$ explicitly, we assume that $\beta/\bar{\beta}_t$ is sufficiently small so that

$\log\left(1-\beta/\bar{\beta}_t\right) \approx -\beta/\bar{\beta}_t$. Then, we have

$$\begin{aligned}
P_{1,t}(\beta) &= -\frac{1}{\eta}\left(r_t - M\left(\bar{\beta}_t\right)\right)\bar{\beta}_t\left\{\log\eta\left(1-\frac{\beta}{\bar{\beta}_t}\right)\right\} - \frac{\bar{\beta}_t}{\eta}(\phi-1)\mu\beta \\
&\approx -\frac{1}{\eta}\left(r_t - M\left(\bar{\beta}_t\right)\right)\left\{\log\eta - \frac{\beta}{\bar{\beta}_t}\right\} - \frac{\bar{\beta}_t}{\eta}(\phi-1)\mu\beta \\
&= -\frac{\left(r_t - M\left(\bar{\beta}_t\right)\right)\bar{\beta}_t}{\eta}\log\eta + \frac{1}{\eta}\left(r_t - M\left(\bar{\beta}_t\right) - (\phi-1)\mu\bar{\beta}_t\right)\beta \\
&= -\frac{\left(r_t - M\left(\bar{\beta}_t\right)\right)\bar{\beta}_t}{\eta}\log\eta + \frac{1}{\eta}\left(r_t - (\phi-1)\mu - \frac{(\phi-1)(\phi-2)\sigma_z^2}{2}\right)\beta. \qquad \text{(A7)}
\end{aligned}$$

Using equation (A7), $P_2(\beta)$ is solved as follows:

$$P_{2,t}(\beta) = \frac{\eta^{\frac{r_t - M(\bar{\beta}_t)\bar{\beta}_t}{\eta}}}{\frac{1}{\bar{\beta}_t} - \frac{1}{\eta}\left\{r_t - (\phi-1)\mu - \frac{(\phi-1)(\phi-2)\sigma_z^2}{2}\right\}} e^{\left\{\frac{1}{\bar{\beta}_t} - \frac{1}{\eta}\left\{r_t - (\phi-1)\mu - \frac{(\phi-1)(\phi-2)\sigma_z^2}{2}\right\}\right\}\beta}. \qquad \text{(A8)}$$

We use the approximated equations (A7) and (A8) below.

To obtain C_2, we check the boundary at $\beta = 0$. From condition (15), any firm with $\beta = 0$ does not invest in basic research regardless of $Z_{i,t}$. Hence,

$$Q_t(0) = \left(-P_{2,t}(0) + C_{2,t}\right)e^{P_{1,t}(0)},$$

where

$$\begin{aligned}
P_{1,t}(0) &= -\frac{\left(r_t - M\left(\bar{\beta}_t\right)\right)\bar{\beta}_t}{\eta}\log\eta, \\
P_{2,t}(0) &= \frac{\eta^{\frac{r_t - M(\bar{\beta}_t)\bar{\beta}_t}{\eta}}}{\frac{1}{\bar{\beta}_t} - \frac{1}{\eta}\left\{r_t - (\phi-1)\mu - \frac{(\phi-1)(\phi-2)\sigma_z^2}{2}\right\}}.
\end{aligned}$$

The constant $C_{2,t}$ is determined by the boundary value $Q_t(0)$ such that

$$C_{2,t} = \eta^{\frac{1}{\eta}\left(r_t - M\left(\bar{\beta}_t\right)\right)\bar{\beta}_t} Q_t(0) + P_{2,t}(0).$$

Note that Q_t, $P_{1,t}$, $P_{2,t}$, and $C_{2,t}$ are stationary on a balanced growth path.

The value $q(Z_{i,t}, \beta_{i,t})$ should be connected smoothly at the threshold, $\hat{\beta}(Z_{i,t})$, $\frac{\partial q\left(Z_{i,t}, \hat{\beta}(Z_{i,t})\right)}{\partial\beta} =$

$Q_t'\left(\hat{\beta}(Z_{i,t})\right) Z_{i,t}$. From equation (15), $\hat{\beta}(Z_{i,t})$ is determined by

$$-Q_t'\left(\hat{\beta}(Z_{i,t})\right)\hat{\beta}(Z_{i,t}) = \frac{x_B w_t}{\lambda_0 Z_{i,t}},$$

In the stationary state,

$$-Q'\left(\hat{\beta}_{i,t}\right)\hat{\beta}_{i,t} = \frac{(\phi-1)(1-\alpha)x_B}{\lambda_0 \bar{\ell}_t Z_{i,t}} = \frac{(\phi-1)(1-\alpha)x_B}{\lambda_0 \ell_{i,t}}.$$

Table A1: List of variables

Name	Definition	Data source
Paper citation ratio	the proportion of patents owned by the firm that cite scientific paper	WoS, Orbis, Patstat
Paper quality	the logarithm of the average number of forward citations of papers cited by the patents owned by the firm	WoS
Sales (log)	logarithmic real sales of the firm	Orbis
Gross margin ratio	gross margin ratio of the firm	Orbis
R&D intensity	R&D expense / operating revenue of the firm	Orbis

Table A2: Summary Statistics

Sales regression

	Mean	Std. Dev.	Min	Max	Obs.
Paper citation ratio	0.339	0.305	0.001	1.000	1336
Paper quality	1.682	0.165	0.000	4.049	1336
F1.Sales (log)	3.861	0.994	0.000	6.25	1336
Sales (log)	3.826	0.998	0.493	6.288	1336
R&D intensity	0.125	0.166	0.000	1.000	1336

Gross Margin regression

	Mean	Std. Dev.	Min	Max	Obs.
Paper citation ratio	0.334	0.303	0.001	1.000	1310
Paper quality	1.679	0.661	0.000	4.049	1310
F1.Sales (log)	3.890	0.970	0.672	6.253	1310
F1.Gross margin ratio	0.509	0.205	-0.467	0.995	1310
R&D intensity	0.157	0.153	0.000	0.992	1310