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Abstract

What are the effects of blocking patents on R&D and consumption? This paper develops a quality-ladder growth model with overlapping intellectual property rights and capital accumulation to quantitatively evaluate the effects of blocking patents. The analysis focuses on two policy variables (a) patent breadth that determines the amount of profits created by an invention, and (b) the profit-sharing rule that determines the distribution of profits between current and former inventors along the quality ladder. The model is calibrated to aggregate data of the US economy. Under parameter values that match key features of the US economy and show equilibrium R&D underinvestment, I find that reducing the extent of blocking patents by changing the profit-sharing rule would lead to a significant increase in R&D, consumption and welfare. Also, the paper derives and quantifies a dynamic distortionary effect of patent policy on capital accumulation.

***Keywords*:** blocking patents, endogenous growth, patent breadth, R&D

***JEL classification*:** O31, O34

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"Today, most basic and applied researchers are effectively standing on top of a huge pyramid… Of course, a pyramid can rise to far greater heights than could any one person... But what happens if, in order to scale the pyramid and place a new block on the top, a researcher must gain the permission of each person who previously placed a block in the pyramid, perhaps paying a royalty or tax to gain such permission? Would this system of intellectual property rights slow down the construction of the pyramid or limit its heights? … To complete the analogy, *blocking patents* play the role of the pyramid's building blocks." – Carl Shapiro (2001)

1. Introduction

What are the effects of blocking patents on research and development (R&D)? In an environment with sequential innovations, the scope of a patent (i.e. patent breadth) determines the level of patent protection for an invention against imitation and subsequent innovations. This latter form of patent protection, which is known as leading breadth in the literature, gives the patentholders property rights over future inventions. Because of the resulting overlapping intellectual property rights, an infringing inventor may have to share her profits with the infringed patentholders and have less incentive to invest in R&D. This negative dimension of overlapping intellectual property rights is known as blocking patents.

The main contribution of this paper is to develop an R&D-driven endogenous-growth model to quantitatively evaluate the effects of blocking patents. To the best of my knowledge, this paper is the first to perform a quantitative analysis on patent policy by calibrating a dynamic general equilibrium (DGE) model that combines the following features (a) overlapping intellectual property rights emphasized by the patent-design literature, (b) multiple R&D externalities commonly discussed in the growth literature, and (c) endogenous capital accumulation that leads to a dynamic distortionary effect of patent protection on saving and investment. As Acemoglu (p. 1112, 2007) writes, "… we lack a framework similar to that used for the analysis of the effects of capital and labor income taxes and indirect taxes in public finance, which we could use to analyze the effects… of intellectual property right polices… on innovation and economic growth."

The analysis focuses on two policy variables (a) patent breadth that determines the amount of profits created by an invention, and (b) the profit-sharing rule that determines the distribution of profits between current and former inventors along the quality ladder. Because of overlapping intellectual property rights, the current inventor, who infringes the patents of some former inventors, has to share her profits with the infringed patentholders and extract profits from future inventors. As a result, the income stream received by an inventor is delayed. If the growth rate of profits is lower than the interest rate, then the stream of profits received by an inventor has a lower present value, which reduces the incentive to invest in R&D. In other words, overlapping intellectual property rights have a positive effect as well as a negative effect on R&D. On one hand, the consolidation of market power between patentholders increases the amount of profits created by an invention that leads to a positive effect on R&D. On the other hand, the lower present value of profits received by an inventor due to profit sharing leads a negative effect. For the rest of the paper, I will refer to the positive (negative) dimension of overlapping intellectual property rights as patent breadth (blocking patents). Although the two effects are interrelated, it is possible to have a reduction in the extent of blocking patents without changing the level of patent breadth, and vice versa.

In order to quantify the effects of blocking patents and other externalities associated with R&D investment, the model is calibrated to aggregate data of the US economy. The key equilibrium condition, which is used to identify the effects of blocking patents on R&D, can be derived analytically without relying on the entire structure of the DGE model. In particular, it can be derived from two conditions (a) a zero-profit condition in the R&D sector, and (b) a no-arbitrage condition that determines the market value of patents. The DGE model serves the useful purpose in providing a structural interpretation on this equilibrium condition.

The main result is the following. Blocking patents have a significant and negative effect on R&D. Holding patent breadth constant, minimizing the effects of blocking patents would increase the steady-state R&D share of GDP by at least over 10% (percent change). This result has important policy implications. Given previous empirical estimates on the social rate of return to R&D, the market economy underinvests in R&D relative to the social optimum, and the reduction in the extent of blocking patents helps increasing R&D towards the socially optimal level. It is important to emphasize that the DGE model has been made rich enough to be consistent with either R&D overinvestment or underinvestment by combining blocking patents with multiple R&D externalities. Whether the market economy overinvests or underinvests in R&D depends crucially on the degree of externalities in intratemporal duplication and intertemporal knowledge spillovers, which in turn is calibrated from the balanced-growth condition between long-run total factor productivity (TFP) growth and R&D. The larger is the fraction of long-run TFP growth driven by R&D, the larger are the social benefits of R&D and the more likely for the market economy to underinvest in R&D. I use previous empirical estimates for the social rate of return to R&D to calibrate this fraction.

Furthermore, when the effects of blocking patents are mitigated, the balanced-growth level of consumption increases permanently by a minimum of 3% (percent change). Taking into account the transition dynamics, social welfare (defined as the lifetime utility of the representative household) increases by a minimum of 1.7%. Finally, I identify and analytically derive a *dynamic* distortionary effect of patent protection on saving and investment that has been neglected by previous studies on patent policy, which focus mostly on the *static* distortionary effect of markup pricing.[1] The dynamic distortion arises because the monopolistic markup in the patent-protected industries creates a wedge between the marginal product of capital and the rental price. Proposition 1 shows that (a) the market equilibrium rate of investment in physical capital is below the socially optimal level if there is underinvestment in R&D, and (b) an increase in the markup would lead to a further reduction in the equilibrium rate of investment in physical capital. The numerical exercise also quantifies the discrepancy between the equilibrium

[1] Laitner (1982) is the first study that identifies in an exogenous growth model with overlapping generations of households that the existence of an oligopolistic sector and its resulting pure profit as financial assets creates both the usual static distortion and an additional dynamic distortion on capital accumulation due to the crowding out of households' portfolio space. The current paper extends this study to show that this dynamic distortion also plays an important role and through a different channel in an R&D-growth model in which both patents and physical capital are owned by households as financial assets.

capital-investment rate and the socially optimal level and shows that reducing the extent of blocking patents helps to decrease this discrepancy slightly.

Literature Review

This paper provides an effective method through the reduction in the extent of blocking patents to mitigate the R&D-underinvestment problem suggested by Jones and Williams (1998) and (2000). Also, the calibration exercise takes into consideration Comin's (2004) critique that long-run TFP growth may not be solely driven by R&D. Furthermore, the current paper complements the qualitative partial-equilibrium studies on leading breadth from the patent-design literature,[2] such as Green and Scotchmer (1995), O'Donoghue et al. (1998) and Hopenhayn et al. (2006), by providing a quantitative analysis on the effects of blocking patents. O'Donoghue and Zweimuller (2004) is the first study that merges the patent-design and endogenous-growth literatures to analyze the effects of patentability requirement and patent breadth on economic growth in a canonical quality-ladder growth model. The current paper complements and extends their study by quantifying the effects of blocking patents on R&D and by generalizing their model in a number of dimensions in order to perform a quantitative analysis. Other DGE analysis on patent policy includes Li (2001), Goh and Olivier (2002), Grossman and Lai (2004) and Futagami and Iwaisako (2007). These studies are also qualitatively oriented and do not feature capital so that the dynamic distortionary effect of patent policy is absent.

In terms of quantitative analysis on patent policy, this paper relates to Chu (2007). Using a variety-expanding model similar to Romer (1990), Chu (2007) finds that whether or not extending the patent length would lead to a significant increase in R&D depends crucially on the patent-value depreciation rate. At the empirical range of patent-value depreciation rates estimated by previous studies, extending the patent length has limited effects on R&D. Therefore, Chu (2007) and the current paper together provide a comparison on the relative effectiveness of extending the patent length and reducing

[2] The seminal work on optimal patent length is Nordhaus (1969). Some other recent studies on optimal patent design include Tandon (1982), Gilbert and Shapiro (1990), Klemperer (1990), O'Donoghue (1998), Hunt (1999) and Scotchmer (2004). Judd (1985) provides the first DGE analysis on optimal patent length.

the extent of blocking patents in mitigating the R&D-underinvestment problem. The crucial difference between these two policy instruments arises because extending the patent length increases future profits while reducing the extent of blocking patents raises current profits for an inventor.

The rest of the paper is organized as follows. Section 2 describes the model. Section 3 defines the equilibrium and analyzes its properties. Section 4 calibrates the model and presents the numerical results. The final section concludes with some policy implications.

2. The Model

The model is a generalized version of Grossman and Helpman (1991) and Aghion and Howitt (1992). The final goods, which can be either consumed by households or invested in physical capital, are produced with a composite of differentiated intermediate goods. The monopolistic intermediate goods are produced with labor and capital. The markup in these monopolistic industries drives a wedge between the marginal product of capital and the rental price. Consequently, it leads to a dynamic distortionary effect that causes the equilibrium rate of investment in physical capital to deviate from the social optimum. The R&D sector also uses both labor and capital as factor inputs.

To prevent the model from overestimating the social benefits of R&D and the extent of R&D underinvestment, the long-run TFP growth is assumed to be driven by R&D as well as an exogenous process as in Comin (2004). The class of first-generation R&D-driven endogenous-growth models, such as Grossman and Helpman (1991) and Aghion and Howitt (1992), exhibits scale effects and is inconsistent with the empirical evidence in Jones (1995a).[3] In the model, scale effects are eliminated as in Segerstrom (1998). The various components of the model are presented in Sections 2.1–2.6.

[3] See, for example, Jones (1999) for an excellent discussion on scale effects.

2.1. Households

There is a unit continuum of identical infinitely-lived households, who maximize life-time utility that is a function of per-capita consumption c_t (numeraire). The standard iso-elastic utility function is given by

(1) $$U = \int_0^{\infty} e^{-(\rho - n)t} \left(\frac{c_t^{1-\sigma}}{1-\sigma} \right) dt \,,$$

where $\sigma > 0$ is the inverse of the elasticity of intertemporal substitution and ρ is the subjective discount rate. The representative household has $L_t = L_0 \exp(nt)$ members at time *t*. The population size at time 0 is normalized to one, and $n > 0$ is the exogenous population growth rate. To ensure that lifetime utility is bounded, it is assumed that $\rho > n + (1-\sigma) g_c$, where g_c is the balanced-growth rate of per-capita consumption. The household maximizes (1) subject to a sequence of budget constraints given by

(2) $$\dot{a}_t = a_t (r_t - n) + w_t - c_t \,.$$

Each member of the household inelastically supplies one unit of homogenous labor in each period to earn a real wage income w_t. a_t is the value of risk-free financial assets in the form of patents and physical capital owned by each household member, and r_t is the real rate of return on these assets. The familiar Euler equation derived from the household's intertemporal optimization is

(3) $$\frac{\dot{c}_t}{c_t} = \frac{1}{\sigma} (r_t - \rho) \,.$$

2.2. Final Goods

This sector is characterized by perfect competition, and the producers take both the output and input prices as given. The production function for the final goods Y_t is a standard Cobb-Douglas aggregator over a unit continuum of differentiated quality-enhancing intermediate goods $X_t(j)$ given by

(4) $$Y_t = \exp\left(\int_0^1 \ln X_t(j) dj \right).$$

The familiar aggregate price index is

(5) $$P_t = \exp\left(\int_0^1 \ln P_t(j)dj\right) = 1 .$$

2.3. Intermediate Goods

There is a unit-continuum of industries producing the differentiated quality-enhancing intermediate goods. Each industry is dominated by a temporary industry leader, who owns the patent for the latest R&D-driven technology in the industry. The production function in each industry has constant returns to scale in labor and capital inputs and is given by

(6) $$X_t(j) = z^{m_t(j)} Z_t K_{x,t}^{\alpha}(j) L_{x,t}^{1-\alpha}(j) .$$

$K_{x,t}(j)$ and $L_{x,t}(j)$ are respectively the capital and labor inputs for producing intermediate-goods *j* at time *t*. $Z_t = Z_0 \exp(g_Z t)$ represents an exogenous process of productivity improvement that is common across all industries and is freely available to all producers. $z^{m_t(j)}$ is industry *j*'s level of R&D-driven technology. $z > 1$ is the exogenous step-size of each technological improvement. $m_t(j)$ is the number of inventions that has occurred in industry *j* as of time *t*. The marginal cost of production in industry *j* is

(7) $$MC_t(j) = \frac{1}{z^{m_t(j)} Z_t}\left(\frac{R_t}{\alpha}\right)^{\alpha}\left(\frac{w_t}{1-\alpha}\right)^{1-\alpha} ,$$

where R_t is the rental price of capital.

2.4. Patent Breadth

Before providing the underlying derivations, this section firstly presents the Bertrand equilibrium price and the amount of profits created by an invention under different levels of patent breadth η.

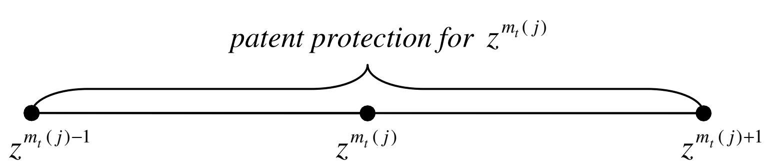
(8) $$P_t(j) = z^{\eta} MC_t(j) ,$$

(9) $$\pi_t(j) = (z^{\eta} - 1) MC_t(j) X_t(j),$$ [4]

for $\eta \in \{1,2,3,...\}$. I will use $\mu(z,\eta) \equiv z^{\eta}$ to denote the markup. The expression for the equilibrium price is consistent with the seminal work of Gilbert and Shapiro's (1990) interpretation of "breadth as the ability of the patentee to raise price." A broader patent breadth corresponds to a larger η. Therefore, an increase in patent breadth increases the amount of profits created by an invention and *potentially* enhances the incentives for R&D. This is the positive effect of overlapping intellectual property rights emphasized by the patent-design literature.

The patent-design literature has identified and analyzed two types of patent breadth in an environment with sequential innovations (a) lagging breadth, and (b) leading breadth. In a canonical quality-ladder growth model, lagging breadth (i.e. patent protection against imitation) is assumed to be complete while leading breadth (i.e. patent protection against subsequent innovations) is assumed to be zero. The following analysis assumes complete lagging breadth and focuses on non-zero leading breadth, and the formulation originates from O'Donoghue and Zweimuller (2004).[5]

The level of patent breadth $\eta = \eta_{lag} + \eta_{lead}$ can be decomposed into lagging breadth denoted by $\eta_{lag} \in (0,1]$ and leading breadth denoted by $\eta_{lead} \in \{0,1,2,...\}$. In the following, complete lagging breadth is assumed such that $\eta = 1 + \eta_{lead}$. Nonzero leading breadth protects patentholders against subsequent innovations and gives the patentholders property rights over future inventions. For example, if $\eta_{lead} = 1$, then the most recent inventor infringes the patent of the second-most recent inventor. The following diagram illustrates the concept of complete lagging breadth and nonzero leading breadth with an example in which the degree of leading breadth is one.



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[4] The current inventor may capture only a fraction of these profits due to profit sharing with former inventors.
[5] See Li (2001) for a discussion on incomplete lagging breadth.

In this example, a leading breadth of degree one facilitates the most recent inventor (i.e. $z^{m_t(j)+1}$) and the second-most recent inventor (i.e. $z^{m_t(j)}$) to consolidate market power through a licensing agreement that results into a higher markup against the third-most recent inventor (i.e. $z^{m_t(j)-1}$).[6]

The share of profit obtained by each patentholder in the licensing agreement depends on the profit-sharing rule (i.e. the terms in the licensing agreement). Following O'Donoghue and Zweimuller (2004), a stationary and exogenous bargaining outcome is assumed.

Assumption 1: *The set of profit-sharing rules* $(\Omega^1, \Omega^2, ...)$ *is symmetric across industries. For a given degree of patent breadth* $\eta \in \{1,2,...\}$, $\Omega^\eta \equiv (\Omega_1^\eta, ..., \Omega_\eta^\eta) \in [0,1]^\eta$, *where* Ω_i^η *is the share of profit received by the i-th most recent inventor, and* $\sum_{i=1}^{\eta} \Omega_i^\eta = 1$.

The profit-sharing rule determines the present value of profits received by an inventor. The two extreme cases are (a) *complete frontloading* $\Omega^\eta = (1,0,...,0)$ and (b) *complete backloading* $\Omega^\eta = (0,...,0,1)$. The effects of blocking patents can be reduced by raising the share of profits received by the current inventors while holding patent breadth constant. Complete frontloading (if feasible) maximizes the incentives on R&D by maximizing the present value of profits received by current inventors.

2.5. Aggregation

Define $A_t \equiv \exp\left(\int_0^1 m_t(j) dj \ln z \right)$ as the aggregate level of R&D-driven technology. Also, define total labor and capital inputs for production as $K_{x,t} = \int K_{x,t}(j) dj$ and $L_{x,t} = \int L_{x,t}(j) dj$ respectively. The aggregate production function for the final goods is

[6] See O'Donoghue and Zweimuller (2004) for a more detailed discussion on market-power consolidation through licensing agreements.

(10) $$Y_t = A_t Z_t K_{x,t}^{\alpha} L_{x,t}^{1-\alpha}.$$

The market-clearing condition for the final goods is

(11) $$Y_t = C_t + I_t,$$

where $C_t = L_t c_t$ denotes aggregate consumption and I_t denotes investment in physical capital. The factor payments for the final goods can be decomposed to

(12) $$Y_t = w_t L_{x,t} + R_t K_{x,t} + \pi_t.$$

$\pi_t = \int \pi_t(j)dj$ is the total amount of monopolistic profits and given by

(13) $$\pi_t = \left(\frac{\mu - 1}{\mu}\right) Y_t,$$

where $\mu \equiv z^{\eta}$. Therefore, the growth rate of monopolistic profits equals the growth rate of output. The factor payments for labor and capital inputs employed in the intermediate-goods sector are respectively

(14) $$w_t L_{x,t} = \left(\frac{1-\alpha}{\mu}\right) Y_t,$$

(15) $$R_t K_{x,t} = \left(\frac{\alpha}{\mu}\right) Y_t.$$

(15) shows that the markup drives a wedge between the marginal product of capital and its rental price. As will be shown later, this wedge creates a dynamic distortionary effect that decreases the rate of capital investment. Finally, the correct value of GDP should include R&D investment such that

(16) $$GDP_t = Y_t + w_t L_{r,t} + R_t K_{r,t}.$$[7]

$L_{r,t}$ and $K_{r,t}$ are respectively the number of workers and the amount of capital for R&D.

[7] In the national income account, private spending in R&D is treated as an expenditure on intermediate goods. Therefore, the values of investment and GDP in the data are I_t and Y_t respectively. The Bureau of Economic Analysis and the National Science Foundation's R&D satellite account provides preliminary estimates on the effects of including R&D as an intangible asset in the national income accounts.

2.6. R&D

Denote $V_{i,t}(j)$ as the market value of the patent for the *i*-th most recent invention in industry *j*. The Cobb-Douglas specification in (4) implies that $\pi_t(j) = \pi_t$ for $j \in [0,1]$. This fact together with the symmetry of the profit-sharing rule across industries implies that $V_{i,t}(j) = V_{i,t}$ for $j \in [0,1]$. Lemma 1 derives the law of motion for $V_{i,t}$.

Lemma 1: *For $i \in \{1,2,...,\eta\}$, $V_{i,t}$ evolves according to a sequence of laws of motion given by*

(17) $$r_t V_{i,t} = \Omega_i^\eta \pi_t + \dot{V}_{i,t} - \lambda_t (V_{i,t} - V_{i+1,t}),$$

where $V_{\eta+1,t} = 0$.

Proof: See Appendix A.

(17) can also interpreted as a no-arbitrage condition. The left-hand side is the return of holding $V_{i,t}$ as an asset. The first term on the right-hand side is the amount of profits captured by the patent for the *i*-th most recent invention in an industry. The second term is the capital gain due to growth in profits. The third term is the expected capital loss/gain due to creative destruction, and λ_t is the Poisson arrival rate of the next invention. When the next invention occurs, the *i*-th most recent inventor losses $V_{i,t}$ but gains $V_{i+1,t}$ as her invention becomes the $i+1$-th most recent invention in the industry. When an invention is no longer included in any licensing agreement, its market value becomes zero (i.e. $V_{\eta+k,t} = 0$ for any $k \geq 1$).

The arrival rate of an invention for an R&D entrepreneur $h \in [0,1]$ is a function of labor input $L_{r,t}(h)$ and capital input $K_{r,t}(h)$ given by

(18) $$\lambda_t(h) = \overline{\varphi}_t K_{r,t}^{\alpha}(h) L_{r,t}^{1-\alpha}(h).$$

$\overline{\varphi}_t$ captures R&D productivity that the entrepreneurs take as given. The expected profit from R&D is

(19) $$\pi_{r,t}(h) = V_{1,t}\lambda_t(h) - w_t L_{r,t}(h) - R_t K_{r,t}(h).$$

The first-order conditions for any R&D entrepreneur h are

(20) $$(1-\alpha)V_{1,t}\overline{\varphi}_t(K_{r,t}/L_{r,t})^{\alpha} = w_t,$$

(21) $$\alpha V_{1,t}\overline{\varphi}_t(K_{r,t}/L_{r,t})^{\alpha-1} = R_t,$$

in which $K_{r,t}/L_{r,t} = K_{r,t}(h)/L_{r,t}(h)$ for $h \in [0,1]$.

To eliminate scale effects and capture various externalities, I follow previous studies to assume that R&D productivity $\overline{\varphi}_t$ is a decreasing function in A_t and given by

(22) $$\overline{\varphi}_t = \varphi(K_{r,t}^{\alpha}L_{r,t}^{1-\alpha})^{\gamma-1}/A_t^{1-\phi},$$

where $K_{r,t} = \int K_{r,t}(h)dh$ and $L_{r,t} = \int L_{r,t}(h)dh$. $\gamma \in (0,1)$ captures the negative externality in intratemporal duplication. $\phi \in (-\infty,1)$ captures the positive $\phi \in (0,1)$ or negative $\phi \in (-\infty,0)$ externality in intertemporal knowledge spillovers. Given that the arrival of inventions follows a Poisson process, the familiar law of motion for R&D-driven technology is given by

(23) $$\dot{A}_t = A_t\lambda_t \ln z,$$

where the aggregate arrival rate of an invention is

(24) $$\lambda_t = \varphi(K_{r,t}^{\alpha}L_{r,t}^{1-\alpha})^{\gamma}/A_t^{1-\phi}.$$

3. Decentralized Equilibrium

In this section, I firstly define the decentralized equilibrium. Then, Section 3.1 summarizes the system of equations that characterizes the transition dynamics. Section 3.2 derives the balanced-growth path. Section 3.3 discusses the effects of blocking patents. Section 3.4 derives the socially optimal allocations and the dynamic distortionary effect of patent protection.

The equilibrium is a sequence of prices $\{w_t, r_t, R_t, P_t(j), V_{1,t}\}_{t=0}^{\infty}$ and a sequence of allocations $\{a_t, c_t, I_t, Y_t, X_t(j), K_{x,t}(j), L_{x,t}(j), K_{r,t}(h), L_{r,t}(h), K_t, L_t\}_{t=0}^{\infty}$ such that they are consistent with the initial conditions $\{K_0, L_0, Z_0, A_0\}$ and their subsequent laws of motions. Also, in each period,

(a) the representative household chooses $\{a_t, c_t\}$ to maximize utility taking $\{w_t, r_t\}$ as given;

(b) the competitive final-goods firms choose $\{X_t(j)\}$ to maximize profits taking $\{P_t(j)\}$ as given;

(c) each industry leader for intermediate goods j chooses $\{P_t(j), K_{x,t}(j), L_{x,t}(j)\}$ to maximize profits according to the Bertrand price competition and taking $\{R_t, w_t\}$ as given;

(d) R&D entrepreneur chooses $\{K_{r,t}(h), L_{r,t}(h)\}$ to maximize profits taking $\{V_{1,t}, R_t, w_t\}$ as given;

(e) the market for the final goods clears such that $Y_t = C_t + I_t$;

(f) full employment of capital such that $K_t = K_{x,t} + K_{r,t}$; and

(g) full employment of labor such that $L_t = L_{x,t} + L_{r,t}$.

3.1. Aggregate Equations of Motion

The transition dynamics of the model is characterized by a system of differential equations. The capital stock is a predetermined variable and evolves according to

(25) $$\dot{K}_t = Y_t - C_t - K_t\delta .$$

R&D-driven technology is also a predetermined variable and evolves according to (23). Per-capita consumption is a jump variable and evolves according to the Euler equation in (3). The market value of the patent for the *i*-th most recent invention in an industry is also a jump variable and evolves according to (17) for $i \in \{1,2,...,\eta\}$, and $V_{\eta+1,t} = 0$. To close this system of differential equations, the endogenous variables { Y_t, π_t, R_t, λ_t, r_t, $L_{x,t}$, $L_{r,t}$, $K_{x,t}$, $K_{r,t}$ } need to be determined by the following static equations: (10) for Y_t; (13) for π_t; (15) for R_t; (24) for λ_t; $r_t = R_t - \delta$ for r_t; $L_t = L_{x,t} + L_{r,t}$, (14) and (20) for $L_{x,t}$ and $L_{r,t}$; and $K_t = K_{x,t} + K_{r,t}$, (15) and (21) for $K_{x,t}$ and $K_{r,t}$. Given this system of equations, the transition dynamics can be simulated using numerical methods, such as the relaxation algorithm developed by Trimborn et al. (2008), despite the large number of differential equations.

At the aggregate level, the generalized quality-ladder model is similar to Jones's (1995b) model, whose dynamic properties have been investigated by a number of recent studies. For example, Arnold (2006) analytically derives the uniqueness and local stability of its steady state with certain parameter restrictions. Steger (2005) and Trimborn et al. (2008) numerically evaluate its transition dynamics.

3.2. Balanced-Growth Path

On the balanced-growth path, c_t increases at g_c, so that the steady-state real interest rate from (3) is

(26) $$r = \rho + g_c \sigma .$$

Using (23) and (24), the balanced-growth rate of R&D technology $g_A \equiv \dot{A}_t / A_t$ is given by

(27) $$g_A = \frac{(K_{r,t}^{\alpha} L_{r,t}^{1-\alpha})^{\gamma}}{A_t^{1-\phi}} \varphi \ln z = \gamma \left(\frac{\alpha g_K + (1-\alpha)n}{1-\phi} \right).$$

Then, the steady-state rate of creative destruction is $\lambda = g_A / \ln z$. The balanced-growth rate of per capita consumption is

(28) $$g_c = g_Y - n .$$

From the aggregate production function (10), the balanced-growth rates of output and capital are

(29) $$g_Y = g_K = n + (g_A + g_Z)/(1-\alpha) .$$

Using (27) and (29), the balanced-growth rate of R&D-driven technology is determined by the exogenous labor-force growth rate n and productivity growth rate g_Z given by

(30) $$g_A = \left(\frac{1-\phi}{\gamma} - \frac{\alpha}{1-\alpha} \right)^{-1} \left(n + \frac{\alpha}{1-\alpha} g_Z \right).$$

Long-run TFP growth denoted by $g_{TFP} \equiv g_A + g_Z$ is empirically observed. For a given g_{TFP}, a higher value of g_Z implies a lower value of g_A as well as a lower calibrated value for $\gamma/(1-\phi)$, which in turn implies that R&D has smaller social benefits and the socially optimal level of R&D is lower.

3.3. Blocking Patents

Equating the first-order conditions (14) and (20) and imposing the balanced-growth condition on R&D-driven technology yield the steady-state R&D share of factor inputs given by

$$\text{(31)} \qquad \frac{s_r}{1-s_r} = (\mu-1)\left(\frac{\lambda}{\lambda+r-g_Y}\right)\nu(\Omega^\eta),$$

where $s_r = s_K = s_L$, $s_K \equiv K_{r,t}/K_t$ and $s_L \equiv L_{r,t}/L_t$. The backloading discount factor is defined as

$$\text{(32)} \qquad \nu(\Omega^\eta) \equiv \sum_{k=1}^{\eta}\Omega_k^\eta\left(\frac{\lambda}{\lambda+r-g_Y}\right)^{k-1} \in (0,1]$$

that will be discussed in further details below. Using (13) – (15), (31) becomes

$$\text{(33)} \qquad \frac{w_t L_{r,t} + R_t K_{r,t}}{Y_t} = \frac{\mu-1}{\mu}\left(\frac{\lambda}{\lambda+r-g_Y}\right)\nu(\Omega^\eta).$$

The left-hand side of (33) is simply R&D as a share of GDP, whose data is readily available in the US. Provided that μ, λ, r and g_Y can be probably calibrated, (33) provides an equilibrium condition that can be used to identify the value of ν in the US economy. A small value of ν indicates a severe problem of blocking patents. An advantage of this approach is that it does not require the knowledge of η or Ω^η. However, a potential criticism is that the equilibrium condition is derived from the DGE model, whose structure may not be a realistic description of the real economy.

Fortunately, Appendix B shows that (33) does not rely on the entire structure of the DGE model and can be derived from (a) a zero-profit condition in the R&D sector, and (b) a no-arbitrage condition that determines the market value of patents. The DGE model serves the useful purpose in providing a structural interpretation on ν as the backloading discount factor, which captures the effects of blocking patents caused by overlapping intellectual property rights. (32) shows that holding the level of patent breadth (i.e. η) constant, increasing the profit share of a more recent inventor (e.g. increase Ω_k^η) and decreasing the profit share of a less recent inventor (e.g. decrease Ω_{k+i}^η for any $i \geq 1$) by an equal amount would increase v because $\lambda/(\lambda + r - g_Y)$ is less than one given that $r = \rho + g_c\sigma > g_c + n = g_Y$.

I define a reduction in the extent of blocking patents as an increase in v holding η constant. For example, for a given η, an increase in v can be achieved by raising Ω_1^η subject to $\sum_{i=1}^{\eta} \Omega_i^\eta = 1$. In the numerical analysis, I firstly use (33) to identify the value of v in the US economy. Then, I consider a hypothetical policy experiment by raising the value of v to one (i.e. setting $\Omega_1^\eta = 1$ that is the complete-fronting profit-sharing rule) holding η (i.e. the markup) constant. However, I should emphasize that this extreme profit-sharing rule may not be achievable in reality because it requires the previous patentholders to let the current inventor use their technology free of charge. A more realistic policy reform would be to improve the bargaining position of the current inventor. A hypothetical example is $\Omega^\eta = (1-\bar{\varepsilon}, \varepsilon, ..., \varepsilon)$, where $\bar{\varepsilon} \equiv (\eta - 1)\varepsilon$ and ε is set to a very small value through policy enforcement. From a policy perspective, this kind of profit-sharing rules that favor the current inventor can be enforced by the patent authority through (a) compulsory licensing with an upper limit on the amount of licensing fees charged to current inventors, and (b) making patent-infringement cases in court favorable to current inventors. The policy experiment in Section 4 based on the complete front-loading profit-sharing rule should be viewed as an approximation to the more realistic rules, such as $\Omega^\eta = (1-\bar{\varepsilon}, \varepsilon, ..., \varepsilon)$, where ε is very small.

3.4. Socially Optimal Allocations

This section firstly characterizes the socially optimal allocations and then derives the dynamic distortion of patent policy on capital accumulation. To derive the socially optimal capital-investment rate and R&D share of factor inputs, the social planner chooses $i_t \equiv I_t / Y_t$ and $s_{r,t}$ to maximize the household's lifetime utility subject to (a) the aggregate production function, (b) the law of motion for capital; and (c) the law of motion for R&D-driven technology. After deriving the first-order conditions, the social planner solves for i^* and s_r^* on the balanced-growth path. The socially optimal R&D share of factor inputs is

(34) $$\frac{s_r^*}{1-s_r^*}=\left(\frac{\gamma g_A}{(1-\phi)g_A+r-g_Y}\right).$$

The socially optimal capital-investment rate is

(35) $$i^*=\alpha\left(1+\frac{s_r^*}{1-s_r^*}\right)\frac{g_K+\delta}{r+\delta},$$

and the market equilibrium capital-investment rate is

(36) $$i=\frac{\alpha}{\mu}\left(1+\frac{s_r}{1-s_r}\right)\frac{g_K+\delta}{r+\delta}.$$

Comparing (31) and (34) indicates the various sources of R&D externalities: (a) the negative externality in intratemporal duplication given by $\gamma\in(0,1)$; (b) the positive or negative externality in intertemporal knowledge spillovers given by $\phi\in(-\infty,1)$; (c) the static consumer-surplus appropriability problem given by $(\mu-1)/\mu\in(0,1]$, which is a positive externality; (d) the markup distortion in driving a wedge of $\mu>1$ between the payments for factor inputs and their marginal products; (e) the net externalities of creative destruction and business-stealing effects given by the difference between $g_A/(g_A+r-g_Y)$ and $\lambda/(\lambda+r-g_Y)$; and (f) the negative effects of blocking patents on R&D through the backloading discount factor $\nu\in(0,1]$. Given the existence of positive and negative externalities, it requires a numerical calibration that will be performed in Section 4 to determine whether the market economy overinvests or underinvests in R&D.

If the market economy underinvests in R&D as also suggested by Jones and Williams (1998) and (2000), the government may want to increase patent breadth to reduce the extent of this market failure. However, the following proposition states that even holding the effects of blocking patents constant, an increase in η mitigates the problem of R&D underinvestment at the costs of worsening the dynamic distortionary effect on capital accumulation.

Proposition 1: *The equilibrium rate of capital investment is below the socially optimal level if there is underinvestment in R&D. Holding the backloading discount factor constant, an increase in patent breadth leads to a reduction in the equilibrium rate of capital investment.*

Proof: (35) and (36) show that $s_r < s_r^*$ is sufficient for $i < i^*$ because $\mu > 1$. Holding ν constant, an increase in η increases the markup. Substituting (31) into (36) shows that $\partial i / \partial \mu < 0$.■

A higher aggregate markup increases the wedge between the marginal product of capital and the rental price. This effect by itself reduces the equilibrium rate of capital investment; however, there is an opposing positive effect from the R&D share of capital. The second part of Proposition 1 shows that the negative effect dominates. As for the first part of Proposition 1, the discrepancy between the equilibrium rate of capital investment and the socially optimal rate arises due to (a) the markup, and (b) the discrepancy between the market equilibrium R&D share of capital and the socially optimal share. Because the equilibrium capital-investment rate is an increasing function in s_r, the underinvestment in R&D (i.e. $s_r < s_r^*$) is sufficient for $i < i^*$.

4. Calibration

Using the framework developed above, this section provides a quantitative assessment on the effects of blocking patents. Figure 1 shows that in the US, private spending on R&D as a share of GDP has been rising sharply since the beginning of the 80's. Then, after a few years, the number of patents granted by the US Patent and Trademark Office also began to increase as shown in Figure 2. Given the changes in patent policy in the 80's,[8] the structural parameters are calibrated using long-run aggregate data of the US's economy from 1953 to 1980 to examine the extent of R&D underinvestment and the effects of blocking patents before these policy changes. The goal of this numerical exercise is to quantify the effects of eliminating blocking patents on R&D, consumption, welfare and capital investment.

4.1. Backloading Discount Factor

The first step is to calibrate the structural parameters and the steady-state value of the backloading discount factor v. The average annual TFP growth rate g_{TFP} is 1.33%,[9] and the average labor-force growth rate n is 1.94%.[10] The annual depreciation rate δ on physical capital and the household's discount rate ρ are set to conventional values of 8% and 4% respectively. For the markup μ, Laitner and Stolyarov (2004) estimate that the markup is about 1.1 (i.e. a 10% markup) in the US; on the other hand, Basu (1996) and Basu and Fernald (1997) estimate that the aggregate profit share is about 3%. To be conservative, I set μ to the lower value at 1.03.[11] Some empirical studies have estimated the arrival rate λ of inventions, and I consider a wide range of values $\lambda \in [0.04, 0.20]$ that cover the usual estimates.[12] (33) shows that holding other variables constant, an increase in λ must be offset by a decrease in v to hold the level of R&D constant. Therefore, at higher values of λ, the calibrated effects of blocking patents would be even more severe.

For $\{v, \alpha, \sigma\}$, the model provides three steady-state conditions for the calibration (a) R&D share of GDP in (37), (b) labor share in (38), and (c) capital-investment rate in (39).

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[8] See, for example, Jaffe (2000), Gallini (2002) and Jaffe and Lerner (2004) for a discussion.
[9] Multifactor productivity for the private non-farm business sector is obtained from the Bureau of Labor Statistics.
[10] The data on the annual average size of the labor force is obtained from the Bureau of Labor Statistics.
[11] A higher markup would imply a more severe effect of blocking patents. Intuitively, a higher markup means increased profitability which must be offset by a stronger effect of blocking patents in order to hold the level of R&D in the data constant. In this case, eliminating blocking patents would lead to a more significant increase in R&D and consumption.
[12] For example, Caballero and Jaffe (2002) estimate a mean rate of creative destruction of about 4%. Lanjouw (1998) estimate a patent renewal model using patent renewal data from Germany for a number of industries, and the estimated probability of obsolescence ranges 7% for computer patents to 12% for engine patents.

(37) $$\frac{wL_r + RK_r}{Y} = \frac{1}{\mu}\left(\frac{s_r}{1-s_r}\right),$$

(38) $$\frac{wL}{Y} = \frac{1}{1-s_r}\left(\frac{1-\alpha}{\mu}\right),$$

(39) $$\frac{I}{Y} = \frac{\alpha}{\mu(1-s_r)}\left(\frac{n + g_{TFP}/(1-\alpha) + \delta}{\rho + \sigma g_{TFP}/(1-\alpha) + \delta}\right),$$

where $\frac{s_r}{1-s_r} = \frac{(\mu-1)\lambda\nu}{\lambda + \rho - n + (\sigma-1)g_{TFP}/(1-\alpha)}$ from (31). On average, private spending on R&D as a share of GDP is 0.0115.[13] Labor share is set to a conventional value of 0.7, and the average ratio of private investment to GDP is 0.203.[14]

Table 1 presents the calibrated values for the structural parameters along with the real interest rate $r = \rho + \sigma g_{TFP}/(1-\alpha)$ for $\lambda \in [0.04, 0.40]$.

Table 1: Calibrated Structural Parameters

λ	0.04	0.06	0.08	0.10	0.12	0.14	0.16	0.18	0.20
ν	0.85	0.70	0.62	0.58	0.54	0.52	0.51	0.49	0.48
α	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29
σ	2.36	2.36	2.36	2.36	2.36	2.36	2.36	2.36	2.36
r	0.084	0.084	0.084	0.084	0.084	0.084	0.084	0.084	0.084

Table 1 shows that the calibrated values for $\{\alpha, \sigma, r\}$ are roughly invariant across different values of λ. The calibrated value for the elasticity of intertemporal substitution (i.e. $1/\sigma$) is about 0.42, which is closed to the empirical estimates suggested by Guvenen (2006). The implied real interest rate is about 8.4%, which is slightly higher than the historical rate of return on the US's stock market, and this higher interest rate implies a lower socially optimal level of R&D spending in (34) and a higher steady-state value of the backloading discount factor in (33). As a result, the model is less likely to overstate the extent of R&D underinvestment and the degree of blocking patents. Furthermore, the fact that the calibrated

[13] The data is obtained from the National Science Foundation and the Bureau of Economic Analysis. R&D is net of federal spending, and GDP is net of government spending. The data on R&D in 1954 and 1955 is not available.
[14] The data is obtained from the Bureau of Economic Analysis, and GDP is net of government spending.

values of $\nu \in [0.48, 0.85]$ are smaller than one suggests a severe degree of blocking patents in the US economy. Therefore, reducing the extent of blocking patents may be an effective method to stimulate R&D. After calibrating the externality parameters and computing the socially optimal level of R&D spending, the effects of reducing the extent of blocking patents on consumption will be quantified.

4.2. Externality Parameters

The second step is to calibrate the values for the externality parameters γ (intratemporal duplication) and ϕ (intertemporal knowledge spillovers). To do this, I need to first determine the value of g_A by setting $g_A = \xi g_{TFP}$ for $\xi \in [0,1]$. The parameter ξ captures the fraction of long-run TFP growth driven by R&D, and the remaining fraction is driven by the exogenous process Z_t such that $g_Z = (1-\xi) g_{TFP}$. For each value of ξ, g_{TFP}, n, and α, the balanced-growth condition (30) determines a unique value for $\gamma/(1-\phi)$, which is sufficient to determine the effects of R&D on consumption in the long run. However, holding $\gamma/(1-\phi)$ constant, a larger γ implies a faster rate of convergence to the balanced-growth path. Therefore, to determine the socially optimal level of R&D, it is important to consider different values of γ. To reduce the plausible parameter space of γ and ϕ, I make use of the empirical estimates for the social rate of return to R&D. Following Jones and Williams' (1998) derivation, Appendix C shows that the net social rate of return $\tilde{r}$ to R&D can be expressed as

$$\tilde{r} = \frac{1+g_Y}{1+g_A}\left(1+g_A\left(\frac{\gamma}{s_r}+\phi\right)\right)-1. \tag{40}$$

After setting $\tilde{r}$ to the lower bound of 0.30 as in Jones and Williams (1998, 2000), (30) and (40) pin down a unique value of γ and ϕ for each value of ξ.

Table 2 presents the calibrated values of γ and ϕ for $\xi \in [0.25, 1.0]$ that correspond to $\tilde{r} = 0.3$. For lower values of ξ, the implied social return to R&D would be less than 0.3. Table 3 shows that as ξ

increases, $\gamma/(1-\phi)$ increases as shown in (30) and the intratemporal duplication effect can become more severe while maintaining the social return of R&D in (40) at 0.3. When ξ equals 0.25, a social return of 0.3 implies that there must be negligible duplication externality. When all the TFP growth is driven by R&D, the duplication effect can be as severe as $\gamma = 0.23$.

Table 2: Calibrated Externality Paramaters									
ξ	0.25	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00
γ	0.98	0.80	0.59	0.47	0.39	0.33	0.29	0.26	0.23
ϕ	-6.29	-3.98	-1.75	-0.74	-0.20	0.12	0.33	0.47	0.57
γ/(1-ϕ)	0.13	0.16	0.21	0.27	0.32	0.38	0.43	0.48	0.54

4.3. Socially Optimal Level of R&D Spending

This section calculates the socially optimal R&D share of GDP in (34). Figure 3 plots the socially optimal R&D share for each set of parameter values in Table 2 that corresponds to $\tilde{r}$ equal 0.30.

[insert Figure 3 here]

Figure 3 shows that there was underinvestment in R&D in the US over the entire range of parameters. In a sense, this finding is not surprising given the large estimated social return to R&D. Optimal R&D share increases in ξ in Figure 3 because a larger ξ implies a larger $\gamma/(1-\phi)$ in Table 2. Applying the log approximation $\ln(1+x) \approx x$ to (C4) and combining it with (34), it can be shown that

$$\text{(41)} \qquad \frac{s_r^*}{1-s_r^*} \approx \left(\frac{\gamma}{1-\phi}\right) \Bigg/ \left(1 + \frac{r-g_Y}{\tilde{r}-g_Y}\left(\frac{1}{s_r}\left(\frac{\gamma}{1-\phi}\right)-1\right)\right).$$

Therefore, for a given social return $\tilde{r}$ of R&D, $s_r^*/(1-s_r^*)$ increases in $\gamma/(1-\phi)$ so long as $\tilde{r} > r$.

4.4. Eliminating Blocking patents

Given the calibrated parameter values, this section quantifies the effects of eliminating blocking patents on R&D and consumption. Table 3 shows that eliminating blocking patents (i.e. setting $\nu = 1$) would lead to a substantial increase in the R&D share of GDP in (33). The model predicts that R&D share of GDP in the US would increase from 0.0115 in the data to a minimum of 0.0136 (i.e. an increase of 18%) in Table 3. For a large value of λ, R&D share of GDP may even double. Table 1 shows that the calibrated values for ν decrease in λ; therefore, as λ increases, the increase in ν to eliminate blocking patents is larger and hence leads to a more significant effect on R&D.

Table 3: R&D Shares without Blocking Patents									
λ	0.04	0.06	0.08	0.10	0.12	0.14	0.16	0.18	0.20
R&D	0.0136	0.0165	0.0185	0.0200	0.0211	0.0219	0.0226	0.0232	0.0237

Next, we quantify the effects of eliminating blocking patents on the level of consumption in the long run. Along the balanced-growth path, per capita consumption increases at an exogenous rate g_c. Therefore, after dropping the exogenous growth path and some constant terms, long-run consumption can be derived as a function of the steady-state value of the backloading discount factor ν through the capital-investment rate $i(\nu)$ and the R&D share $s_r(\nu)$ of factor inputs. It can be shown that in the case of a change in ν, the percent change in long-run consumption can be expressed as

$$(42)\qquad \Delta\ln c(\nu) = \left(\begin{array}{l} \left(\dfrac{\alpha(1-\phi+\gamma)}{(1-\alpha)(1-\phi)-\alpha\gamma}\right)\Delta\ln i(\nu) + \Delta\ln(1-i(\nu)) + \\ \left(\dfrac{\gamma}{(1-\alpha)(1-\phi)-\alpha\gamma}\right)\Delta\ln s_r(\nu) + \left(\dfrac{(1-\phi)}{(1-\alpha)(1-\phi)-\alpha\gamma}\right)\Delta\ln(1-s_r(\nu)) \end{array} \right).$$

I consider the most conservative case that only one quarter of the TFP growth in the US is driven R&D (i.e. $\xi = 0.25$). A value of 0.25 for ξ implies a very small value of 0.13 for $\gamma/(1-\phi)$ in Table 2.[15] Figure 4 shows that even in this conservative case, eliminating blocking patents would raise the balanced-growth level of consumption by at least 3% (percent change) and up to over 12% if the change in v is large enough. Also, the change in consumption mostly comes from $(\gamma/((1-\alpha)(1-\phi)-\alpha\gamma))\Delta\ln s_r(\nu)$ in (42) that is the direct effect of R&D on consumption through technology; in other words, the other general-equilibrium effects only have secondary impacts on long-run consumption.

[insert Figure 4 here]

[15] Note that the coefficients in (42) are determined by $\gamma/(1-\phi)$ rather than the individual values of γ and ϕ.

In addition to examining the effects of blocking patents on long-run consumption, I also consider the transition dynamic effects. I use the relaxation algorithm developed by Trimborn et al. (2008) to compute the transition path of consumption.[16] For the set of parameter values considered before (i.e. $\xi = 0.25$ in Table 2 and $\lambda \in [0.04, 0.20]$ in Table 3), upon eliminating blocking patents, consumption falls slightly on impact and then gradually rises to the new balanced-growth path.[17] I use the consumption path up to 100 years after the policy change to calculate the representative household's utility (1) on this new transition path and compare it to the household's original utility on the old balanced-growth path. Table 4 reports the percent changes in welfare (i.e. the household's lifetime utility).[18]

Table 4: Percent Changes in Welfare

λ	0.04	0.06	0.08	0.10	0.12	0.14	0.16	0.18	0.20
U	1.7%	3.2%	3.9%	4.2%	4.4%	4.6%	4.7%	4.7%	4.8%

To have a sense on how important these changes are, an increase of 1.7% (4.8%) in the household's lifetime utility requires a permanent increase in consumption of 1.3% (3.7%).

4.5. Dynamic Distortion

Proposition 1 derives the condition under which the equilibrium rate of investment in physical capital is below the socially optimal level. The following numerical exercise quantifies this wedge. Figure 5 presents the socially optimal rates of capital investment in (35) along with the US's investment rate, and the wedge is about 0.014 on average.

[insert Figure 5 here]

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[16] I would like to thank Timo Trimborn for his advice on the relaxation algorithm.

[17] In fact, consumption does not necessarily fall on impact but instead gradually rises to the new balanced-growth path over a wide range of parameters that correspond to a higher social return to R&D (i.e. larger ξ, γ and ϕ). In other words, in a model with capital, it is possible for households to avoid short-run consumption losses by running down the capital stock, and this finding is different from models without capital accumulation. See, for example, Kwan and Lai (2003) for an interesting analysis on the transition dynamic effects of patent policy in a variety-expanding model without capital accumulation.

[18] Because the value of the household's utility is negative given that $\sigma > 1$, the percent change in the household's utility is defined as $(U^{new} - U^{old}) / | U^{old} |$, where $| U^{old} |$ is the absolute value of U^{old}.

The equilibrium rate of investment in physical capital is increasing in the R&D share of capital. Therefore, eliminating blocking patents also increases the capital-investment rate. Table 5 shows that upon eliminating blocking patents, the steady-state capital-investment rate increases from 0.203 in the data slightly toward the socially optimal level.

Table 5: Capital-Investment Rates without Blocking Patents

λ	0.04	0.06	0.08	0.10	0.12	0.14	0.16	0.18	0.20
I/Y	0.204	0.204	0.205	0.205	0.205	0.205	0.206	0.206	0.206

4.6. Discussion

The numerical analysis is based on a number of calibrated parameters and variables. The key parameter is ξ and the key variable is ν. The calibrated values for ξ imply R&D underinvestment. A lower bound of 0.25 for ξ is based on the previous empirical estimates on the social return to R&D. If R&D has little social values, then the actual value of ξ would be smaller and hence there may be no underinvestment in R&D. However, even if R&D is not underinvested, reducing the extent of blocking patents would allow the policymakers to lower the breadth (i.e. the markup) that reduces the distortionary effects of patent policy while keeping the level of R&D constant.

The calibrated values for ν imply a significant effect of blocking patents. An upper bound of 0.85 for ν is based on a number of assumptions. The first assumption is that the data on R&D investment is reasonably accurate. If there is a large amount of R&D spending not recorded, then the identification of ν using (33) would imply a downward bias on ν (i.e. an overestimate of blocking patents). Secondly, applying (33) to aggregate data requires an assumption that monopolistic profits in the economy are created by patent protection. To the extent that only a small fraction of profits is created by patent protection, the identification of ν using (33) would also imply a downward bias on ν. However, using a very small aggregate markup of 1.03 (i.e. 3% markup) in the calibration reduces this bias. In patent-protected and R&D-intensive industries, the markup and the profit share should be much larger.[19] Thirdly, when λ is below the lower bound of 0.04, (33) would indicate a less significant effect of blocking patents (i.e. a larger ν). However, such a small value of λ implies that the average time between arrivals of inventions would be longer than 25 years. On the other hand, for larger values of λ (e.g. Acemoglu and Akcigit (2008) consider an average arrival rate λ of 0.33), the calibrated values for ν would be smaller (i.e. an even more severe effect of blocking patents).

Finally, the numerical analysis is performed on a semi-endogenous growth model, in which increasing R&D investment has no effect on long-run growth. In the case of a fully endogenous-growth model, raising R&D through the elimination of blocking patents would increase the long-run growth rate of consumption. For example, doubling R&D would increase the R&D-driven TFP growth rate by a factor of 2^{γ} in the first-generation quality-ladder growth models. So long as ξ and γ are not negligible, this kind of increase in the long-run growth rate would have tremendous effects on welfare. Therefore, the calibrated effects from a semi-endogenous growth model are likely to be conservative.

5. Conclusion

This paper has attempted to accomplish three objectives. Firstly, it develops a quantitative framework that can be applied to evaluate the effects of blocking patents. Secondly, it applies the model to aggregate data to perform hypothetical policy experiments. Thirdly, it identifies a dynamic distortionary effect of patent policy on capital accumulation that has been neglected by previous studies. The numerical exercise suggests the following findings. If a non-trivial fraction of TFP growth in the US is driven by R&D, there is underinvestment in R&D in the economy. Then, provided that blocking patents have a significant and negative effect on R&D, reducing this negative effect of overlapping intellectual property rights while keeping its positive effect (i.e. patent breadth) constant can help mitigating the R&D-underinvestment problem. The resulting increase in R&D could lead to a substantial increase in consumption.

[19] For example, Comin (2004) considers that a reasonable markup in these industries should be around 1.5.

The readers are advised to interpret the numerical results with some important caveats in mind. The first caveat is that although the quality-ladder growth model has been generalized as an attempt to capture more realistic features of the US economy, it is still an oversimplification of the real world. Furthermore, the finding that eliminating blocking patents has substantial and positive effects on R&D and consumption is based on the assumptions that the empirical estimates on the social return to R&D and the data on R&D investment are reasonably accurate. The validity of these assumptions remains as an empirical question.

Finally, I conclude this paper with some policy implications. The changes in patent policy in the 80's are conventionally believed to include a broadening of patent breadth. The theoretical analysis suggests that a broader patent breadth increases R&D at the costs of worsening the distortionary effects on patent protection. In other words, there exists a welfare tradeoff using this policy instrument. On the other hand, holding patent breadth constant, reducing the extent of blocking patents would stimulate R&D without worsening the distortionary effects. This reasoning suggests that for the purpose of stimulating R&D, reducing the extent of blocking patents would have been a less harmful policy instrument than increasing patent breadth. Even if the current level of R&D is socially optimal, it would be beneficial for the society to reduce the level of patent breadth and the extent of blocking patents simultaneously to keep R&D constant. A lower level of patent breadth would reduce the distortionary effects of patent protection while the decrease in the incentives for R&D can be offset by reducing the extent of blocking patents.

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Appendix A: Proof for Lemma 1

The market value of the patent for the *i*-th most recent invention in an industry is

$$\text{(A1)} \qquad V_{i,t} = \int_t^{\infty} \left(\int_t^{s} \Omega_i^{\eta} \pi_u \exp\left(-\int_t^{u} r_v dv \right) du \right) f(s) ds + \int_t^{\infty} V_{i+1,s} \exp\left(-\int_t^{s} r_v dv \right) f(s) ds \,,$$

where $f(s) = \lambda_s \exp\left(-\int_t^{s} \lambda_\tau d\tau \right)$ is the density function of *s* that is a random variable representing the time when the next invention occurs and follows the Erlang distribution. The first term in $V_{i,t}$ is the expected present value of monopolistic profits captured by the *i*-th most recent inventor in the current licensing agreement. The second term in $V_{i,t}$ is the expected present value when the *i*-th most recent inventor becomes the $i+1$-th most recent inventor in the next licensing agreement. To derive (17), I differentiate (A1) with respect to *t*. To simplify notations, I define a new function such that (A1) becomes

$$\text{(A2)} \qquad V_{i,t} = \int_t^{\infty} g(t,s) ds \,,$$

where $g(t,s) = \left(\int_t^{s} \Omega_i^{\eta} \pi_u \exp\left(-\int_t^{u} r_v dv \right) du + V_{i+1,s} \exp\left(-\int_t^{s} r_v dv \right) \right) f(s)$. Then, using the formula for differentiation under the integral sign,

$$\text{(A3)} \qquad \dot{V}_{i,t} \equiv \frac{\partial V_{i,t}}{\partial t} = -g(t,t) + \int_t^{\infty} \frac{\partial g(t,s)}{\partial t} ds \,,$$

where $g(t,t) = \lambda_t V_{i+1,s}$, and

$$\text{(A4)} \qquad \frac{\partial g(t,s)}{\partial t} = \left((\lambda_t + r_t) \left(\int_t^{s} \Omega_i^{\eta} \pi_u \exp\left(-\int_t^{u} r_v dv \right) du + V_{i+1,s} \exp\left(-\int_t^{s} r_v dv \right) \right) - \Omega_i^{\eta} \pi_t \right) f(s) \,.$$

After a few steps of mathematical manipulation, (A3) becomes (17) after setting $\int_t^{\infty} f(s) ds = 1$.■

Appendix B: An Intuitive Derivation of the Equilibrium Condition for R&D

This appendix shows that the equilibrium condition for R&D in (33) that identifies the effects of blocking patents can be derived from (a) a zero-profit condition in the R&D sector, and (b) a no-arbitrage condition that determines the market value of patents. The zero-profit condition in the R&D sector implies that

(B1) $$wL_r + RK_r = \lambda V_1 .$$

V_1 is the market value of the most recent invention in an industry, and λ is the Poisson arrival rate of an invention. $wL_r + RK_r$ is the spending on R&D. The zero-profit condition states that the expected benefit of creating an invention equals its cost. The no-arbitrage condition implies that the market value of an invention is the expected present value of the stream of profits π_1 received by the inventor such that

(B2) $$V_1 = \frac{\pi_1}{r + \lambda - g_\pi},$$

where r is the real interest rate, so $r + \lambda$ is the effective discount rate due to creative destruction. g_π is the growth rate of profits. Because of blocking patents, an inventor may only capture a fraction ν of the total amount of monopolistic profits π created by her invention such that

(B3) $$\pi_1 = \nu \pi,$$

where $\nu \in (0,1]$. The DGE model provides a structural interpretation of ν as the backloading discount factor. Substituting (B2) and (B3) into (B1) yields

(B4) $$wL_r + RK_r = \pi\left(\frac{\lambda}{\lambda + r - g_\pi}\right)\nu .$$

Appendix C: The Social Rate of Return to R&D

Jones and Williams (1998) define the social rate of return to R&D as the sum of the additional output produced and the reduction in R&D that is made possible by reallocating one unit of output from consumption to R&D in the current period and then reducing R&D in the next period to leave the subsequent path of technology unchanged. To conform to their notations, I rewrite the law of motion for R&D technology as

(C1) $$\dot{A}_t = G(A_t, \tilde{R}_t) \equiv A_t^{\phi} \tilde{R}_t^{\gamma} \varphi \ln z ,$$

where $\tilde{R}_t \equiv K_{r,t}^{\alpha} L_{r,t}^{1-\alpha}$. The aggregate production function is rewritten as

(C2) $$Y_t = F(A_t, \tilde{X}_t) \equiv A_t Z_t \tilde{X}_t ,$$

where $\tilde{X}_t \equiv K_{x,t}^{\alpha} L_{x,t}^{1-\alpha}$. Using the above definition, Jones and Williams (1998) show that the gross social rate of return to R&D is

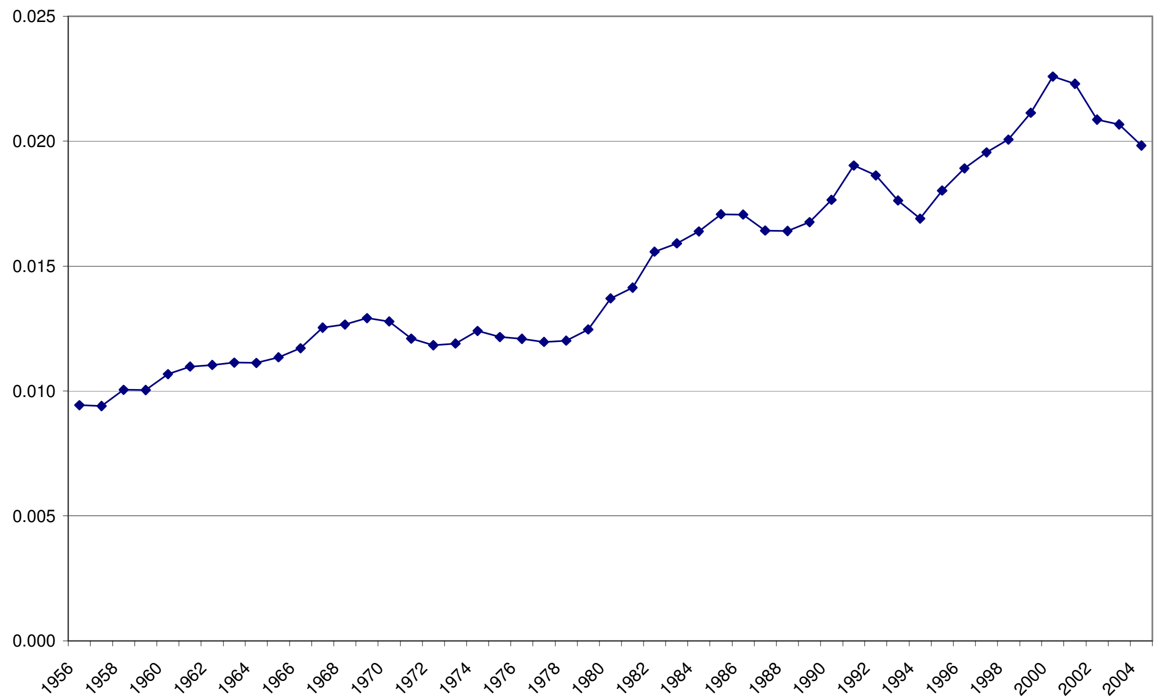
(C3) $$1 + \tilde{r} = \left(\frac{\partial G}{\partial \tilde{R}} \right)_t \left(\frac{\partial F}{\partial A} \right)_{t+1} + \frac{(\partial G / \partial \tilde{R})_t}{(\partial G / \partial \tilde{R})_{t+1}} \left(1 + \left(\frac{\partial G}{\partial A} \right)_{t+1} \right) .$$

After imposing the balanced-growth conditions, the net social rate of return to R&D becomes

(C4) $$\tilde{r} = \frac{1 + g_Y}{1 + g_A} \left(1 + g_A \left(\frac{\gamma}{s_r} + \phi \right) \right) - 1 .$$

Appendix D: Figures

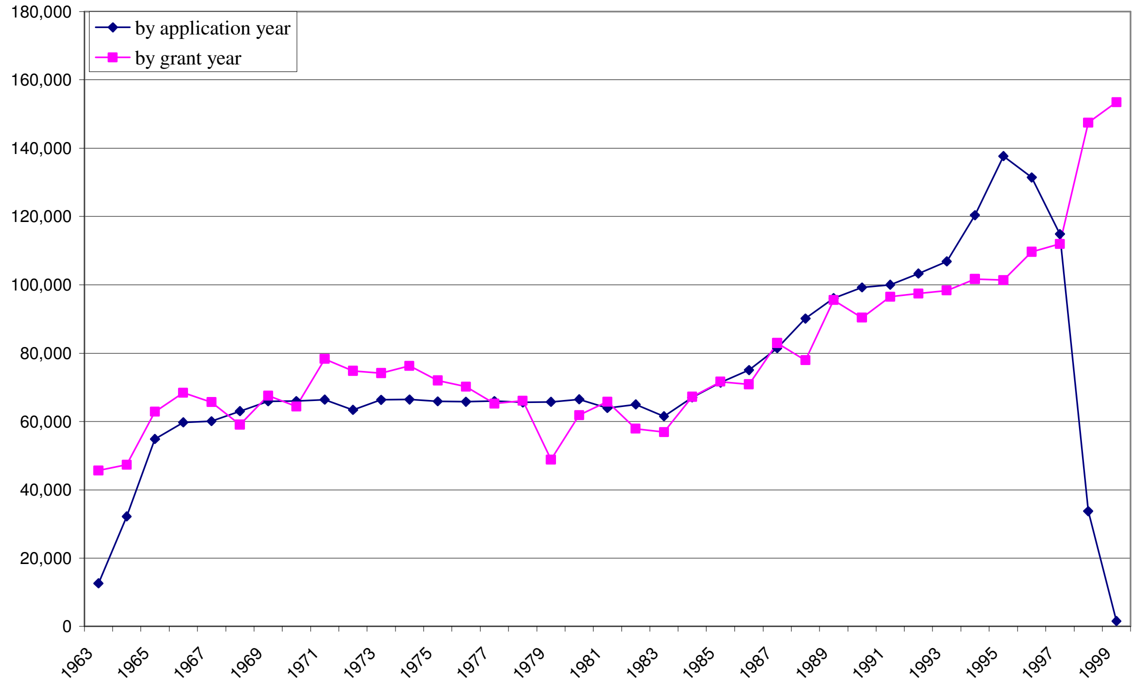
Figure 1: Private Spending on R&D as a Share of GDP



Data Sources: (a) Bureau of Economic Analysis: National Income and Product Accounts Tables; and (b) National Science Foundation: Division of Science Resources Statistics.

Footnote: R&D is net of federal spending, and GDP is net of government spending.

Figure 2: Number of Patents Granted



Data Source: Hall, Jaffe and Trajtenberg (2002): The NBER Patent Citation Data File.

Figure 3: Socially Optimal R&D Shares

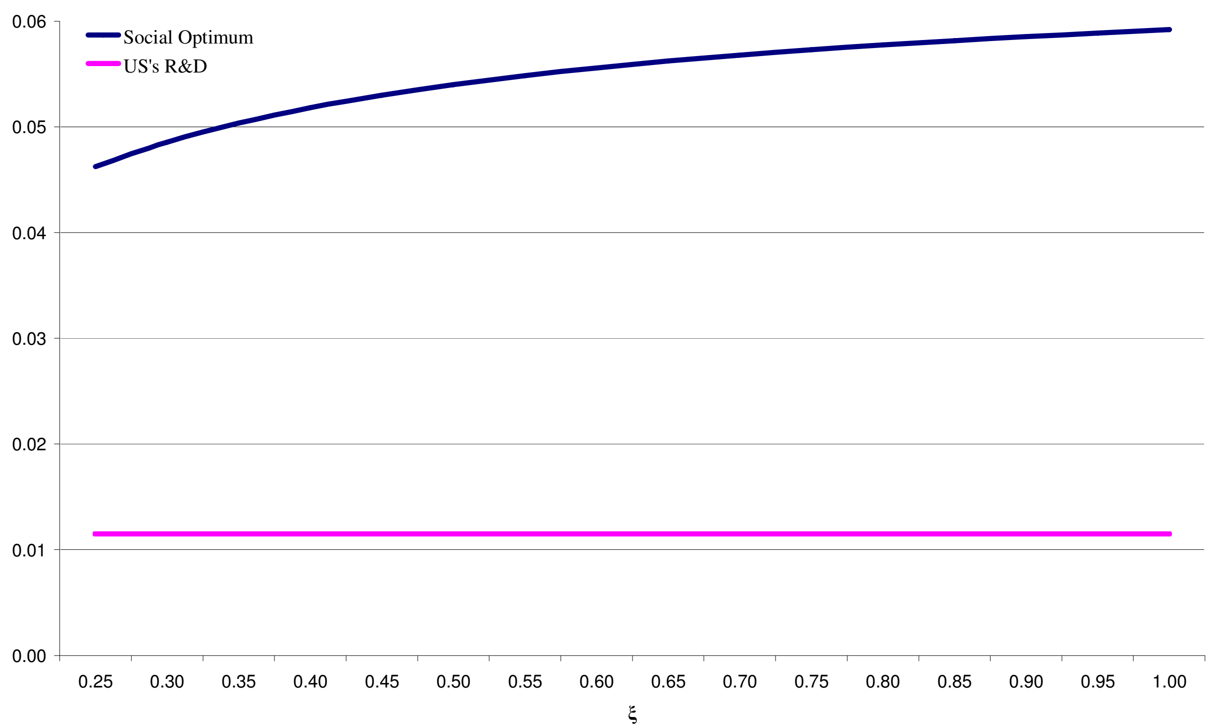


Figure 4: Percent Changes in Long-Run Consumption from Eliminating Blocking Patents

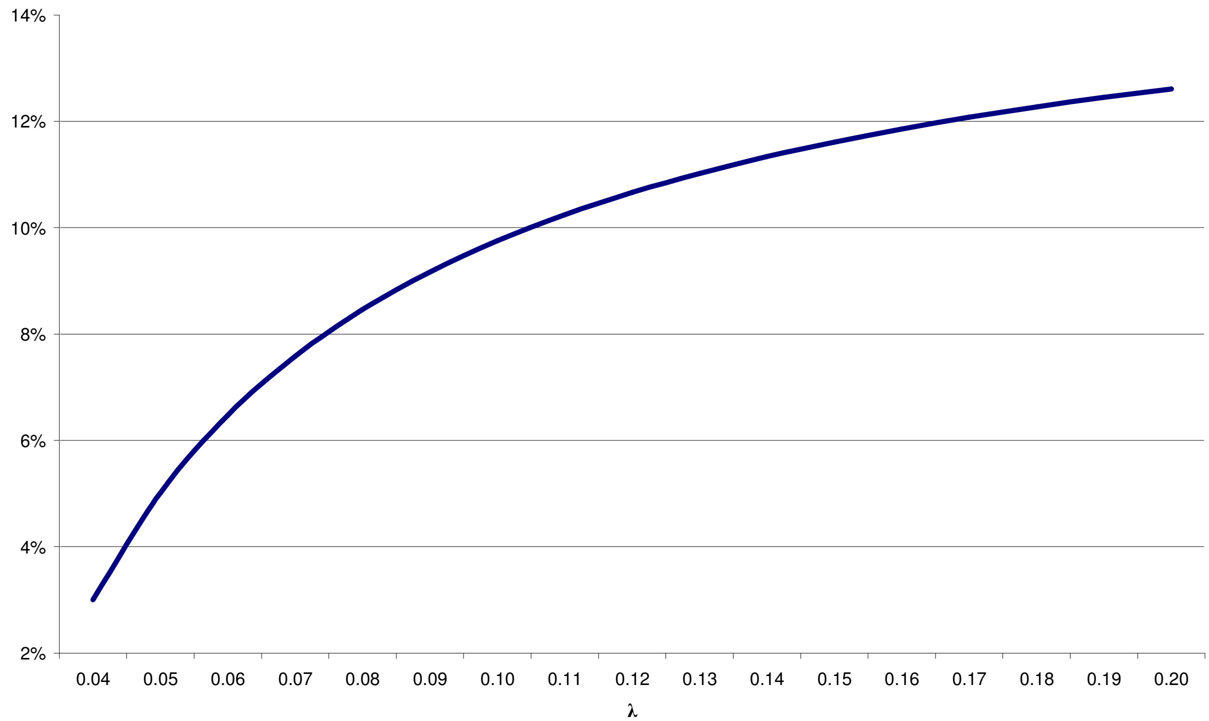


Figure 5: Socially Optimal Capital-Investment Rates