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RESEARCH ARTICLE

Elias Dinopoulos · Constantinos Syropoulos

Rent protection as a barrier to innovation and growth

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Abstract We build a model of R&D-based growth in which the discovery of higher-quality products is governed by sequential stochastic innovation contests. We term the costly attempts of incumbent firms to safeguard the monopoly rents from their past innovations *rent-protecting activities*. Our analysis (1) offers a novel explanation of the observation that the difficulty of conducting R&D has been increasing over time, (2) establishes the emergence of endogenous scale-invariant long-run innovation and growth, and (3) identifies a new structural barrier to innovation and growth. We also show that long-run growth depends positively on proportional R&D subsidies, the population growth rate, and the size of innovations, but negatively on the market interest rate and the effectiveness of rent-protecting activities.

Keywords Schumpeterian growth · Scale effects · R&D · Innovation contests · Barriers to innovation

JEL Classification Numbers D2 · D7 · O3 · O4

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E. Dinopoulos
Department of Economics, University of Florida, Gainesville, FL 32611, USA
E-mail: elias.dinopoulos@cba.ufl.edu

C. Syropoulos (✉)
Department of Economics and International Business, LeBow College of Business,
Drexel University, 503-N Matheson Hall,
32nd and Market Streets, Philadelphia, PA 19104, USA
E-mail: c.syropoulos@drexel.edu

1 Introduction

Technological progress and innovation occur amidst uncertainty and insecurity. Incumbent firms with state-of-the-art production processes or products, for example, rarely remain unchallenged. Though patents afford them some protection, their past innovations are often claimed and captured by competitors through direct imitation, if not overt appropriation. As a consequence, their profits rarely remain intact over time and typically are eroded by further innovation. Thus, to protect their intellectual property and prolong the duration of their economic rents, incumbent firms may find it worthwhile to expend resources to frustrate imitation or to retard the pace of innovations by challengers.

The industrial organization literature has paid considerable attention to the above ideas primarily in the context of partial-equilibrium models and empirical studies. For instance, a growing body of research has been concerned with the nature, extent, and evolution of appropriability conditions regarding R&D, as well as with incumbent firm strategies to preserve their economic rents.[1] Such strategies aim to limit the flow of knowledge spillovers to potential competitors and include investments in trade secrecy and camouflaging of their innovations through technological complexity of their products; expenditures in creating and maintaining legal teams to litigate disputes over patent infringements; choosing weak future competitors through strategic technology licensing.[2] Besides delaying the introduction of new products, lengthy litigation (actual or potential) on patent infringement may deter the invention of similar or higher-quality products by competitors.[3] In markets characterized by network externalities, where first-mover advantages are important, incumbent firms may use advertising strategically to improve customer loyalty, or expand manufacturing capacity and distribution systems to their advantage.[4] Further, in the case of complex products like computers and other electronic

[1] Levin et al. (1987) and Cohen et al. (2002) identify and supply survey-based evidence on the extent of these activities.

[2] Coca Cola has expended resources to maintain the secrecy of its formula; Microsoft has been adding new features to its Windows operating system, rendering it more complex and thus more difficult to imitate; and Intel has been producing increasingly smaller, more sophisticated and, arguably, more resistant to reverse engineering microprocessors. Rockett (1990) develops a model of patent licensing where incumbents choose weak (as opposed to strong) potential competitors in an effort to prolong their monopoly rights. He also presents case-study evidence based on the development and licensing of polyester, cellophane and nylon.

[3] In his review of Baumol (1993), Pecorino (1995, pp. 390–391) states: "As for patent law, Baumol documents the fact that inventions are often met with costly and lengthy legal battles over patent rights. What is amusing and somewhat instructive is that Baumol's examples run from Robert Fulton and Eli Whitney up through Henry Ford and Thomas Edison. Eli Whitney, for example, earned almost no return on the invention of the cotton gin and was involved in numerous infringement suits over a period of many years Baumol (1993, pp. 87–88). These examples indicate that the problem of excessive litigation is not an entirely recent phenomenon, and that the inventive spirit is not such a delicate flower as to be crushed by the legal difficulties which inventors typically face." Lerner (1995) provides empirical support for the hypothesis that the patenting behavior of firms is affected by the presence of costly litigation. He shows that in the area of biotechnology firms with high litigation costs forego the opportunity to patent their products in subclasses populated by incumbents whose litigation costs are low.

[4] Eisenhardt and Brown (1998, p. 8) provide several examples of time-pacing strategies (i.e., strategies that aim to expand manufacturing capacity in regular intervals independently of the pace of new product discoveries): "For example, about every nine months, Intel adds a new fabrication facility to its operations. According to Intel's CEO Andy Groves, 'We build factories

equipment, incumbent firms may engage in "patent blocking"– i.e., build a fence around a major invention by obtaining patents in several other related secondary inventions but with no intention to ever introduce them to the market–to discourage the circumvention of existing patents by potential challengers and to deter competing innovations from entering the market.[5] Lastly, firms may expend resources to enforce a variety of confidentiality clauses with their employees, control the flow of knowledge spillovers through the labor market and possibly improve their own chances of discovering better goods.

The aforementioned activities entail considerable resource costs. According to Lerner (1995, p. 470), the direct patent litigation costs for the year 1991 accounted for more than 25% of total R&D expenditures for that year. Two excellent studies (Levin et al. 1987; Cohen et al. 2002) document the nature, extent and importance of these activities for US and Japanese manufacturing R&D labs. But what is the link between these activities, economic growth and welfare? What are the implications of different policies in environments where ownership of intellectual property is inherently insecure?

A small but growing strand of development and growth literature has formally analyzed the growth effects of special interest groups. For example, Tornell (1997), Tornell and Lane (1999), and Van Long and Sorger (2006) have used the AK model of growth through capital accumulation to examine the effects of interest groups on the redistribution of capital stock and economic growth; and Parente and Prescott (1999, 2000) and Parente and Zhao (2005) have introduced rent-seeking coalitions that monopolize the supply of productive factors and create considerable barriers to the adoption of superior technology.

The present paper combines the insights of the above two distinct strands of literature by introducing a new mechanism that creates barriers to the accumulation of knowledge and R&D-based growth: resource-using activities by incumbent firms that produce state-of-the-art quality products (as opposed to interest groups that aim at redistributing capital or monopolizing the supply of labor, or institutions that protect the monopoly rights of rent-seeking coalitions) aiming to protect their innovation-based monopoly rights. We analyze the effects of these activities in the context of a standard Schumpeterian (R&D-based) growth model without physical capital accumulation but with positive population growth. Schumpeterian growth is a type of economic growth that is based on the introduction of new goods or processes as envisioned in Schumpeter's (1934) notion of creative destruction – as opposed to physical or human-capital accumulation.

We term the costly attempts of incumbent firms to safeguard the monopoly rents from their past innovations *rent-protecting activities*. These activities can retard or delay the innovation of better products by reducing the flow of knowledge spillovers from incumbents to potential challengers, and/or increase the costs of copying existing products – in most cases rent-protecting activities actually do

two years in advance of needing them, before we have the products to run in them and before we know that the industry is going to grow.' By expanding its capacity in this predictable way, Intel deters rivals from entering the business and blocks them from gaining a toe hold should Intel be unable to meet demand. Small and large companies, high and low tech alike, can benefit from time pacing, especially in markets that will not stand still. Cisco Systems, Emerson Electric, Gillette, Netscape, SAP, Sony, Starbucks, and 3 M all use time pacing in one form or another."

[5] According to Cohen et al. (2002) firms may use patent fences to increase the R&D costs of other firms in a broad technological domain.

both. While this distinction is analytically important, in this paper we focus on the growth effects of rent-protecting activities that in effect delay the introduction of better quality products.[6] In addition to relating rent-protecting activities directly to economic growth, an important motivation for not investigating their impact on imitation here is to preserve continuity and relate our work to the recent literature on growth without scale effects that has been exclusively concerned with the process of innovation. Furthermore, because these activities appear to play a significant role in the process of economic growth, we find it natural to initiate this line of research by focusing on the innovation process itself. Recognizing that the analysis of imitation-targeting rent-protecting activities is also important, we leave its formal exploration to future research.

For simplicity, we incorporate rent-protecting activities into the standard quality-ladders framework of Schumpeterian growth developed by Grossman and Helpman (1991, chapter 4). Earlier Schumpeterian growth models were not concerned with the impact of rent-protecting activities and assumed that the growth rate of technological change depends positively only on the level of R&D resources devoted to innovation at each instant in time. As population growth causes the size (scale) of the economy to increase exponentially over time, R&D resources also grow exponentially, and so does the long-run growth rate of per-capita real output. In other words, long-run Schumpeterian growth in these models exhibits scale effects.[7] An important objective of this paper is to demonstrate that the presence of rent-protecting activities can help remove the scale effects property of earlier Schumpeterian growth models.

Our approach to modeling rent-protecting activities has three features. First, for simplicity and tractability, we abstract from possible differences in the nature of different rent-protecting activities. Second, we assume that a firm may engage in rent protection only after it discovers the state-of-the-art quality product and becomes an incumbent monopolist. In other words, we presume that the firm knows its product with certainty before it engages in rent protection. Third, we suppose rent-protecting activities aim to reduce the productivity of R&D investments by potential competitors (perhaps by reducing the flow of knowledge spillovers or the expected returns to such investments). In short, our model postulates that R&D may become more difficult as the size of the economy grows because incumbent firms may allocate more resources to rent-protecting activities. The discovery process is modeled as an R&D contest in which challengers engage in R&D and incumbent firms allocate resources to rent-protecting activities.

In the model there are two factors of production, "specialized" and "non-specialized" labor. Each factor is proportional to the level of population, which grows at an exogenously given rate. Final consumption goods are produced by a continuum of structurally identical industries. However, in each industry three broad activities stand out: manufacturing of final goods, production of rent-protecting services, and provision of R&D services. The technology for each of these processes exhibits constant returns to scale. Production of manufacturing output and R&D ser-

[6] In Dinopoulos and Syropoulos (1998), we analyze the implications of such rent-protecting activities for firm conduct, market structure, and welfare in the context of a static duopoly model.

[7] See Dinopoulos and Sener (2006) and Jones (1999) for overviews of recent theoretical models of Schumpeterian growth with scale effects. These studies also review theoretical approaches to growth models without scale effects.

vices requires the employment of non-specialized labor. Specialized labor ("lawyers") is used exclusively for the production of rent-protecting services. We focus on a two-factor economy for two reasons: to highlight the role of factor markets and to capture key features of the wage-income distribution in the context of long-run growth in the simplest possible way.

The arrival of innovations in each industry is governed by a memoryless Poisson process whose intensity depends positively on R&D investments and negatively on the level of rent-protecting activities. At each instant in time, the incumbent in each industry and challengers choose their respective expenditure levels on rent protection and R&D strategically to maximize their individual expected discounted profits. We model this interaction as a stochastic differential game for Poisson processes. Its solution determines the equilibrium value of the expected rate of innovation in each industry, which is proportional to the long-run rate of growth.

The model has a unique steady-state equilibrium in which per-capita consumption expenditure (unadjusted for quality) and the relative wage of specialized labor are constant over time. However, the rate of new product creation, and therefore the long-run Schumpeterian growth, are endogenous, bounded, and constant over time. The levels of resources devoted to R&D and rent protection increase exponentially at the same rate as the constant rate of population growth. In addition, the presence of rent-protecting activities creates structural barriers to long-run innovation and growth that depend on virtually all the model's parameters (Proposition 1).

A novel and important insight of the paper is that the equilibrium long-run growth is proportional to the unit costs of rent-protecting services divided by the unit costs of R&D services; that is, long-run growth is proportional to the "relative price" (the opportunity cost) of rent-protecting services expressed in units of R&D services. As a consequence, a proportional R&D subsidy that reduces the opportunity cost of R&D investments (i.e., a subsidy that lowers the relative price of R&D) fuels long-run growth. Further, because the opportunity cost is proportional to the relative wage of specialized labor, any permanent changes that raise the relative wage of specialized labor (e.g., an increase in the rate of population growth or the size of innovations, or a fall in the market interest rate or the effectiveness of rent-protecting activities) also raise the opportunity cost of rent-protecting activities and thus growth. If one followed the current literature (which assumes the presence of only one factor of production so that all three activities use only non-specialized labor), then proportional R&D subsidies affect long-run growth directly but not indirectly through changes in relative factor prices. In other words, the incorporation of rent-protecting activities into the model implies that growth is proportional to a "relative price" (which, in models with one factor of production, is fixed by productivity parameters).

The analysis generates several additional findings. First, as in the original quality-ladders growth model, there are no transitional dynamics here (Proposition 1). Second, long-run growth is endogenous: it depends positively on proportional R&D subsidies, the size of innovations, the labor productivity in R&D services, and the rate of population growth; it also depends negatively on the fraction of population engaged in rent protection, the effectiveness of rent-protecting activities, and consumers' subjective discount rate (Proposition 2). Third, the welfare ranking between the market and social rates of innovation is ambiguous. While the introduction of rent-protection activities into Schumpeterian growth theory does not eliminate the welfare ambiguities caused by the presence of several distortions, it amplifies the magnitude of the "intertemporal spillover" effect and reduces challengers' incentives to engage in R&D. In other words, the presence of insecure intellectual property and rent protection amplifies the rationale for R&D subsidies (Proposition 3).

Some of the above findings (e.g., the absence of transitional dynamics, the endogeneity of long-run growth, and the welfare ambiguity between the market and social rates of growth) are inherited from the original quality ladders framework of Schumpeterian growth. However, several ideas are entirely new. They include the modeling of innovation as a contest, the proposed micro-foundations of why the difficulty of R&D has been increasing over time, the effects of population growth, the consequences of the effectiveness of rent-protecting activities and their relative supply, the existence of structural barriers to long-run growth, and the welfare analysis of rent protection. Lastly, our analysis broadens the literature on insecure property rights and barriers to technology adoption by exploring the implications of insecure intellectual property rights in a growth-theoretic environment.

Section 2 develops the model and solves the stochastic differential game that determines the optimal levels of resources allocated to innovative R&D and rent protecting activities. Section 3 describes the steady-state equilibrium and its properties. Section 4 summarizes our key findings and suggests possible extensions. The Appendix contains the formal proof to a proposition.

2 The model

In traditional quality-ladders models of Schumpeterian growth the discovery of a new product is the outcome of an R&D race in which the "prize" is the discounted stream of profits the state-of-the-art quality product is expected to generate. This prize induces firms – the "challengers"– to invest in R&D that aims to discover the next higher-quality product that will ultimately replace the incumbent firm. By contrast, in this paper we view the discovery of a new product as the outcome of an *innovation contest* between the incumbent monopolist and the challengers.[8] As in the standard quality-ladders models, challengers invest in R&D. However, the incumbent monopolist does not remain passive here. To prolong the duration of its monopoly it invests in rent protection. Thus, the instantaneous probability of the next discovery increases with the industry-wide R&D level and decreases with expenditure on rent protection (see below).

2.1 The knowledge-creation process

There is a continuum of structurally identical industries indexed by $\theta \in [0, 1]$. In each industry θ there are sequential stochastic R&D contests of the type described above. To simplify the notation of the model we will omit index θ because all industries are structurally identical. In addition, we will use the time argument t as

[8] See Skaperdas (1996) for a discussion of contests and an axiomatic approach to contest success functions.

an identifier of variables and functions that grow over time, and will omit it from variables and functions that are time-invariant.

More specifically, a challenger j that invests in R&D discovers the next higher-quality product with instantaneous probability $I_j \mathrm{d}t$, where $\mathrm{d}t$ is an infinitesimal interval of time and

$$I_j = \frac{R_j(t)}{D(t)}. \tag{1}$$

$R_j(t)$ captures firm j's R&D outlays; $D(t)$ captures the difficulty of R&D in a typical industry (and thus $1/D(t)$ is a measure of the "efficiency" of R&D services). The returns to R&D investments are independently distributed across challengers, across industries, and over time; therefore, the industry-wide probability of innovation can be obtained from (1) by summing the levels of R&D across all challengers; that is,

$$I = \sum_j I_j = \frac{R(t)}{D(t)}, \tag{2}$$

where $R(t) \equiv \sum_j R_j(t)$. In each industry, the arrival of innovations follows a memoryless Poisson process with intensity I which we will henceforth refer to as "the rate of innovation." (As will be shown later, this rate or innovation is proportional to long-run Schumpeterian growth.)

Earlier models of Schumpeterian growth assumed $D(t)$ is constant over time. This is unsatisfactory because in the presence of population growth the rates of innovation and long-run growth increase exponentially as the scale of the economy (measured by the size of its population) grows exponentially.[9] Furthermore, the scale-effects property embodied in (2) when $D(t)$ is considered constant is inconsistent with post-war time-series evidence presented in Jones (1995).

Several recent studies developed models of Schumpeterian growth without scale effects.[10] One class of models removes the scale effects property by assuming that proportional increases in knowledge become more difficult over time as the level of knowledge expands with the discovery of new products. These models generate long-run Schumpeterian growth that is proportional to the rate of population growth, and therefore exogenous in the traditional sense. Another class of models assumes that economy-wide R&D becomes more difficult over time as R&D effort is diffused over more firms, and that there are localized R&D spillovers. In these models, free entry in the creation of new product lines (e.g., varieties) implies that the economy-wide level of R&D difficulty in (2) is endogenous and proportional to the economy's scale; as a result, quality-enhancing effective R&D per firm is endogenous in the steady state equilibrium.

In this paper, we propose an alternative solution to the scale-effects problem and one that generates endogenous Schumpeterian growth without requiring the

[9] See Aghion and Howitt (1992), Grossman and Helpman (1991) (chapter 4), and Segerstrom et al. (1990), among others, who developed early Schumpeterian growth models based on quality improvements. Identical considerations apply to Romer (1990) type growth models based on variety expansion, where $I(t) = \dot{A}(t)/A(t)$, with $A(t)$ capturing the measure of designs at time t.

[10] Dinopoulos and Sener (2006) and Jones (1999) provide a more detailed exposition of several models of growth without scale effects.

introduction of new varieties. We do this by postulating that $D(t)$ in (1) and (2) depends positively on the incumbent monopolist's rent-protecting outlays; that is,

$$D(t) = \delta X(t), \tag{3}$$

where $X(t)$ denotes the level of rent-protecting services in a typical industry at time t and $\delta > 0$ is a parameter capturing the effectiveness of rent-protecting activities. Since, for a given level of rent protection, lower values of δ are associated with a lower level of R&D difficulty, δ could be viewed as a proxy of the extent to which existing institutions protect intellectual property; alternatively, δ can be interpreted as the (constant) productivity level of resources devoted to rent protection. As will become clear below, higher values of this parameter are associated with higher barriers to innovation and Schumpeterian growth. To keep the analysis simple and direct, we suppose all rent-protecting activities are similar.[11] Note that if $X(t) \to \infty$, or if $R(t) = 0$, the innovation process comes to a halt.

2.2 Labor and production

Each industry contains three production processes: manufacturing of final goods, production of rent-protecting services, and R&D investment. As mentioned earlier, labor is partitioned into two types: specialized workers with skills of use only in the production of rent-protecting services, and non-specialized workers employed in manufacturing and R&D. The assumption of activity-specific labor is not necessary for the main results of the paper. However, this assumption places factor markets at center stage and thus allows us to study in a direct way the connection between the functional distribution of income and economic growth.[12]

Let $N(t)$ be the population at time t and assume that it grows over time at a constant exogenous rate $\dot{N}(t)/N(t) = g_N > 0$. The economy's endowments of specialized and non-specialized labor at each instant in time are defined as $H(t) = sN(t)$ and $L(t) = (1-s)N(t)$, respectively, where s is fixed. It follows that both factors grow at the rate of population growth, i.e., $\dot{H}(t)/H(t) = \dot{L}(t)/L(t) = \dot{N}(t)/N(t) = g_N$.

[11] There are several alternative modeling specifications of rent-protecting activities. For example, one could replace (3) by $\dot{D}(t) = \partial D(t)/\partial t = \delta X(t)$, where $D(t) = D_0 > 0$ is the level of R&D difficulty in industry θ at time zero. Equation (3) implies that the level of R&D difficulty is a flow and that there is no link between past efforts to protect rents and their present level. This alternative specification treats the level of R&D difficulty as a stock that can be increased through further levels of rent-protecting services. The stock specification of R&D difficulty assumes that there is no depreciation of rent-protecting expenditures; the flow specification is meant to capture the notion of instantaneous depreciation of past rent protection expenditures. Instead of (3), one could assume that $D(t) = \kappa + \delta X(t)$, where $\kappa > 0$ is a parameter. This specification introduces transitional scale effects and makes the welfare analysis considerably more complicated. The main results of the paper are robust to either specification, but the treatment of the level of R&D difficulty as a flow (as in Equation (3)) proportional to the level of rent-protecting activities simplifies the algebra and results in the absence of transitional dynamics, a property that is shared by earlier quality-ladders growth models. For simplicity and comparability with previous work, we use (3) throughout this paper.

[12] In the context of the model, specialized workers could be interpreted as lawyers, who usually do not manufacture products and can be hired by companies to use legal means or lobby the government to protect the innovation rents of incumbents.

A firm that produces $Z(t)$ units of manufacturing output incurs the cost

$$w_L \alpha Z(t), \tag{4}$$

where w_L denotes the wage of non-specialized labor, α is the (constant) non-specialized labor requirement per unit of final output, and $w_L\alpha$ is the unit cost of production.

Firm j produces $R_j(t)$ services of R&D also under constant returns to scale. Its cost function is

$$w_L \beta R_j(t), \tag{5}$$

where parameter $\beta > 0$ is the unit-labor requirement in R&D production and $w_L\beta$ is the cost of producing one unit of R&D output.

Lastly, rent-protecting services, $X(t)$, are produced by the incumbent monopolist in a typical industry at time t with specialized labor, again under constant returns to scale. The corresponding cost function of this activity is

$$w_H \gamma X(t), \tag{6}$$

where parameter $\gamma > 0$ is the associated unit-labor requirement, and w_H is the wage of specialized labor.

2.3 Households

There is a continuum of identical households of measure one. Each household consists of infinitely lived members and is modeled as a dynastic family whose size grows at the rate of population growth g_N. We normalize the number of members in each household to unity at time $t = 0$. Thus the population of the economy, as well as the number of members in each household, at time t is $N(t) = \mathrm{e}^{g_N t}$. Every household maximizes the discounted utility

$$U \equiv \int_0^\infty \mathrm{e}^{g_N t}\mathrm{e}^{-\rho t} \log u(t)\mathrm{d}t \equiv \int_0^\infty \mathrm{e}^{-(\rho - g_N)t} \log u(t)\mathrm{d}t. \tag{7}$$

where $\rho > 0$ is the (constant) subjective discount rate. In order for U to be bounded, we assume that the effective discount rate is positive (i.e., $\rho - g_N > 0$). Expression $u(t)$ captures per-capita utility at time t and is defined as follows:

$$\log u(t) \equiv \int_0^1 \log\left[\sum_i \lambda^i Z(i, \theta, t)\right] \mathrm{d}\theta. \tag{8}$$

Variable $Z(i, \theta, t)$ in Equation (8) is the quantity consumed of a final product that has experienced i quality improvements in industry $\theta \in [0, 1]$ at time t. Parameter $\lambda > 1$ measures the size of a quality improvement between two consecutive innovations.

At every instant in time, and for given product prices, each household allocates its income so as to maximize (8). The solution to this optimization problem yields the demand function for a typical product

$$Z(t) = \frac{cN(t)}{p}, \tag{9}$$

where c is per-capita consumption expenditure and p is the market price of the good considered. Within each industry, goods adjusted for quality are by assumption identical and only the good with the lowest quality-adjusted price is consumed. The quantity demanded of all other goods is zero because the firm that owns the state-of-the-art product practices limit pricing.

Maximizing (7) subject to the standard intertemporal budget constraint and taking (9) into account yields

$$\frac{\dot{c}}{c} = r - \rho, \tag{10}$$

where r is the instantaneous market interest rate.

2.4 R&D contests

To keep the analysis simple and to highlight the role of rent-protecting activities, we assume that every firm has access to the technologies of all goods that are at least one step below the state-of-the-art quality product in each industry. This assumption renders further investments in R&D by incumbents unappealing and generates the familiar inertia incumbency hypothesis (due to Arrow 1962). In other words, incumbent monopolists produce rent-protecting services whereas challengers produce R&D services.[13] At each instant in time, the incumbent monopolist produces the state-of-the-art quality product and earns a flow of profits

$$\pi(p, X, t) = [p - w_L\alpha]\frac{cN(t)}{p} - w_H\gamma X(t), \tag{11}$$

where p is the price charged; the term in square brackets denotes the per-unit profit; $Z(t) = cN(t)/p$ is the quantity demanded that was described in (9); the last term in (11) captures the cost of rent-protecting activities that was defined in (6).

Because the arrival of innovations is governed by a Poisson process with intensity I, the strategic interactions between incumbents and challengers can be modeled as a differential game for Poisson jump processes.[14] Let $q(t)$ denote the state variable that takes the value $q(t) = 0$ when it refers to variables and functions

[13] If an incumbent firm discovers the next higher-quality product, say product $k + 1$, the technology of product k becomes common knowledge and, consequently, the monopolist continues to earn the same flow of profits as before. Thus there is no incentive for the monopolist to engage in further R&D investment to discover product $k + 1$. The motivation for this assumption is based on our intention to keep the analysis simple and comparable to the original quality-ladders growth model built by Grossman and Helpman (1991, chapter 4).

[14] See Malliaris and Brock (1981, pp. 123–125) for applications of stochastic dynamic programming to Poisson jump processes. We are indebted to Peter Thompson for suggesting this methodology.

of challengers, and the value $q(t) = 1$ when it refers to variables and functions of an incumbent. Variable $r_c(t) = \int_0^t r(s)\mathrm{d}s$ denotes the cumulative interest rate at time t (i.e., $r_c(t) = \rho t$ in the steady-state equilibrium). Then, the expected present value of a firm at time t is given by

$$J(q(t), t) = \max\ E_t \int_t^{\infty} \mathrm{e}^{-r_c(s)} \pi(q(s), X(s), s)\mathrm{d}s \tag{12}$$

where E_t denotes the expectation operator and $\pi(\bullet)$ is the flow of profits defined in (11). The solution concept employed in this stochastic differential game is that of the non-cooperative equilibrium (closed-loop solution) in which the incumbent maximizes (12) for $q(t) = 1$ with respect to the price p and the level of rent-protecting services, $X(t)$, and each challenger j chooses the amount of R&D investment, $R_j(t)$, to maximize (12) for $q(t) = 0$.

Since the flow of profits $\pi(\bullet)$ grows over time at the rate of population growth, the differential game can be modeled as a non-autonomous stochastic optimal control problem. Thus, the solution to the incumbent's optimization problem will satisfy the following Jacobi-Bellman equation:

$$-\dot{J}(1, t) = \max_{p, X} \left\{ \mathrm{e}^{-r_c(t)} \pi(p, X, t) + \frac{R(t)}{\delta X(t)} [J(0, t) - J(1, t)] \right\}. \tag{13}$$

At each instant in time, the incumbent monopolist enjoys the present value of instantaneous profits $\mathrm{e}^{-r_c(t)}\pi$. With instantaneous probability $I = R(t)/\delta X(t)$ this monopolist is replaced by a successful challenger who discovers the next higher-quality product and the value of the firm drops by $[J(0, t) - J(1, t)]$, which is equal to the difference between the market value of a challenger and the value of the incumbent. Thus the right-hand side (RHS) of (13) is the optimal expected change in the value of the incumbent due to a change in the state variable, $q(t)$. By the principle of optimality, this change must be equal to the fall in the firm's value over an infinitesimal period of time dt for any given value of the state variable along the optimal path.

The corresponding Jacobi-Bellman equation for each challenger j is given by:

$$-\dot{J}(0, t) = \max_{R_j} \left\{ -e^{-r_c(t)} (1 - \tau) w_L \beta R_j(t) + \frac{R_j(t)}{\delta X(t)} [J(1, t) - J(0, t)] \right\}. \tag{14}$$

During an R&D contest, challenger j incurs a cost equal to $e^{-r_c(t)}(1-\tau)w_L\beta R_j(t)$, where $\tau > 0$ is an exogenously given ad valorem R&D subsidy that reduces the cost of R&D services.[15] With instantaneous probability $I_j = R_j(t)/\delta X(t)$, challenger j wins the contest, becomes an incumbent monopolist, and the firm's value jumps by a factor $[J(1, t) - J(0, t)]$.

[15] Since challengers perform only R&D services while incumbents manufacture final goods and invest in rent protection, the implementation of R&D subsidies is straightforward here. For instance, the government could subsidize the output of R&D labs that do not engage in manufacturing.

Utilizing (11) in (13), maximization of the RHS of (13) with respect to price p implies the monopolist will engage in limit pricing; therefore, the monopolist will charge a price (approximately) equal to the unit cost of manufacturing a product times the quality increment λ; that is,

$$p = \lambda w_L \alpha. \tag{15}$$

One the other hand, maximization of the RHS of (13) with respect to $X(t)$ yields the first-order condition

$$e^{-r_c(t)} \gamma w_H = \frac{\delta I}{D(t)}[J(1,t) - J(0,t)], \tag{16}$$

where $D(t) = \delta X(t)$ is the level of R&D difficulty defined in (3) and $I = R(t)/\delta X(t)$.

Each challenger chooses the level of R&D investment R_j to maximize the RHS of (14). The condition that guarantees a strictly positive and bounded from above solution requires the RHS of (14) to equal zero–this is so because the RHS of (14) is linear in R_j – or, equivalently,

$$\mathrm{e}^{-r_c(t)}(1-\tau)\beta w_L = \frac{J(1,t) - J(0,t)}{D(t)}. \tag{17}$$

Multiplying both sides of (17) by $R(t)$ yields the familiar free-entry condition into each R&D contest whereby the present-discounted value of innovation equals the discounted cost of R&D. Thus the expected present discounted value of each challenger must be equal to zero, i.e., $J(0,t) = 0$.

Equations (13) through (17) determine the evolution of the endogenous variables p, $X(t)$, $R(t)$, $J(1,t)$, and $J(0,t)$ over time.

Denote with $V(1,t) = \mathrm{e}^{r_c(t)} J(1,t) = V(t)$ the current (as opposed to the present) value of monopoly profits earned by an incumbent. Taking logs and differentiating the resulting expression with respect to time yields

$$-\dot{J}(1,t) = J(1,t)\left[r(t) - \frac{\dot{V}(t)}{V(t)}\right].$$

Now substitute this expression into (13), set $J(0,t) = 0$ and use the definition $I = R(t)/\delta X(t)$ to obtain

$$J(1,t)\left[r(t) - \frac{\dot{V}(t)}{V(t)}\right] = \mathrm{e}^{-r_c(t)}\pi(p,X,t) - I(t)J(1,t). \tag{18}$$

Utilizing $J(1,t) = V(t)\mathrm{e}^{-r_c(t)}$ in (18), simplifying the resulting expression and rearranging terms yields

$$V(t) = \frac{\pi(p,X,t)}{r + I(t) - \dot{V}(t)/V(t)} = \frac{(p - w_L\alpha)cN(t)/p - w_H\gamma X(t)}{r + R(t)/\delta X(t) - \dot{V}(t)/V(t)}. \tag{19}$$

(The expression in the far RHS of (19), was derived with the help of (11), (2) and (3).) Equation (19) states that value of the expected discounted profits of a successful innovator (incumbent firm) at time t equals the flow of monopoly profits discounted by the instantaneous interest rate and adjusted by a term that captures the difference between the risk of default due to a new innovation, $I(t)$, and the growth rate of the firm's market value $\dot{V}(t)/V(t)$.[16]

Furthermore, setting $J(0,t) = 0$ in (16) and (17) yields the following two additional equations:

$$\frac{V(t)}{D(t)} = \frac{e^{r_c(t)}J(1,t)}{D(t)} = \frac{\gamma w_H}{\delta I}, \tag{20}$$

$$\frac{V(t)}{D(t)} = \frac{e^{r_c(t)}J(1,t)}{D(t)} = (1-\tau)\beta w_L. \tag{21}$$

2.5 Factor markets

We assume that wages are fully flexible and adjust instantaneously to equalize the demand and supply of each factor of production. The full-employment condition for non-specialized labor is derived as follows. At time t the supply of non-specialized labor is $(1-s)N(t)$. The demand for this type of labor consists of two components. *First*, by (9) and (15), each incumbent monopolist produces $Z(t) = cN(t)/\lambda\alpha w_L$ units of final output. But each unit of $Z(t)$ requires α units of non-specialized labor. Consequently, the aggregate demand for non-specialized labor in each manufacturing industry is $cN(t)/\lambda w_L$. *Second*, from (5), the demand for non-specialized labor in the production of R&D services in each industry is $\beta R(t)$, where β is the unit labor requirement and $R(t)$ is the level of R&D investment at time t. Since, by assumption, the measure of industries equals the unit interval, the demand for non-specialized labor in each industry is equal to the economy-wide demand for this input. Consequently, the full-employment condition for non-specialized labor is

$$(1-s)N(t) = \frac{cN(t)}{\lambda w_L} + \beta R(t). \tag{22}$$

Similar logic applies for the full-employment condition for specialized labor, which is

$$sN(t) = \gamma X(t). \tag{23}$$

3 Equilibrium

The dynamic behavior of the economy is governed by two equations that determine the evolution of per-capita consumption expenditure c and the rate of innovation I. To facilitate the interpretation and understanding of our main results we begin by deriving expressions for the long-run per-capita real output and its long-run

[16] Equation (19) can be derived by considering the stock-market valuation of monopoly profits and assuming the absence of profitable arbitrage opportunities for investors. The latter assumption requires the expected rate of return on holding stocks issued by a successful innovator to equal the interest rate of a riskless bond, $r(t)$. See, for instance, Grossman and Helpman (1991, pp. 93–94) for a stock-market-based derivation of (19).

growth. Following the standard practice of Schumpeterian growth models, one can obtain the following deterministic expression for sub-utility $u(t)$, which is the appropriately weighted consumption index and corresponds to real per-capita income

$$\log u(t) = \log\left[\frac{c}{\lambda \alpha w_L}\right] + tI \log \lambda, \tag{24}$$

where $c/\lambda\alpha w_L$ is per-capita consumption expenditure expressed in units of manufacturing output.

The economy's long-run Schumpeterian growth is defined as the rate of growth of sub-utility $u(t)$, $g_U = \dot{u}(t)/u(t)$. Differentiation of (24) with respect to time yields

$$g_U = I \log \lambda, \tag{25}$$

which is a standard expression for long-run growth in quality-ladders growth models. Because the size λ of each innovation is constant over time, long-run Schumpeterian growth g_U can be affected only through changes in the rate of innovation I. Combining (20) with (21) and solving for I gives

$$I = \frac{\gamma w_H}{\delta(1-\tau)\beta w_L} = \frac{\gamma \omega}{\delta(1-\tau)\beta}, \tag{26}$$

where $\omega \equiv w_H/w_L$ is the relative wage of specialized labor.

Equation (26) identifies the channels through which parameter changes affect long-run innovation and growth. For example, the long-run level of effective R&D, I, (and, therefore, the growth rate g_U) is increasing in the relative wage of specialized labor ω and the proportional R&D subsidy τ, but decreasing in the effectiveness of rent-protecting services δ and in the productivity of R&D services β.

In the presence of rent-protecting activities, the rate of innovation is proportional to the (subsidy-adjusted) relative price of rent-protecting services $\gamma\omega/(1-\tau)\beta$. Thus, any change that causes this relative price to rise (and thus renders these growth-suppressing activities more "expensive" relative to productive R&D investments) raises long-run growth.[17]

Let us now choose non-specialized labor as the numeraire by setting

$$w_L \equiv 1. \tag{27}$$

Combining the full employment conditions (22) and (23) with (2) and (3) and taking into account (27) yields the resource condition[18]

$$1 - s = \frac{c}{\lambda} + \frac{\beta\delta s}{\gamma} I, \tag{28}$$

[17] Even if the ratio of the two unit-cost functions (i.e., γw_H and βw_L) did not depend on wages (as would be the case, for example, if there were only one type of labor that resulted in $w_H \equiv w_L$), long-run growth would depend positively on the ad-valorem R&D subsidy, but other policies would not have any long-run growth effects. In other words, a linear production structure (associated with a one-factor model) implies that the relative price of rent-protecting services is proportional to the fixed labor productivity coefficients of rent-protecting and R&D services. The presence of two factors of production creates a link between the endogenous relative wage ω and long-run growth. In other words, the presence of two production factors increases the range of parameters that affect long-run growth.

[18] The resource condition is obtained as follows. Substitute $X(t)$ from (23) into (3), use (2) to solve for R&D investment, $R(t) = s\delta IN(t)/\gamma$, and substitute the resulting expression in (22).

which defines a negative linear relationship between per-capita consumption expenditure, c, and the rate of innovation, I. This resource condition holds at each instant in time because, by assumption, factor markets clear instantaneously.

We now derive the differential equation that determines the growth rate $\dot{c}/c$ of per-capita consumption expenditure as a function of its level and the rate of innovation. Equations (3), (21) and (23) will hold at each instant in time; therefore, $\dot{V}(t)/V(t) = \dot{D}(t)/D(t) = \dot{X}(t)/X(t) = g_N$. In other words, the value of expected discounted profits $V(t)$, the level of R&D difficulty $D(t)$, and the level of rent-protecting services $X(t)$ all grow at the constant rate of population growth, g_N. Equations (26) and (27) imply $w_H = \delta(1-\tau)\beta I/\gamma$. Substituting these expressions into (19) and dividing both sides of the resulting expression by the level of population $N(t)$, yields

$$\frac{V(t)}{N(t)} = \frac{c(\lambda-1)/\lambda - I\delta(1-\tau)\beta s/\gamma}{r - g_N + I}. \tag{29}$$

Equations (3) and (23) imply $D(t) = \delta s N(t)/\gamma$; therefore, the level of R&D difficulty is proportional to the size of the market, $N(t)$. Substituting this expression into (20) gives $V(t)/N(t) = \delta(1-\tau)\beta s/\gamma$ which together with (29) allows us to obtain the following expression for the market interest rate r:

$$r = \frac{(\lambda-1)\gamma}{\lambda\delta\beta(1-\tau)s}c - 2I + g_N. \tag{30}$$

Substituting (30) into (10) yields the following differential equation:

$$\frac{\dot{c}}{c} = r - \rho = \frac{(\lambda-1)\gamma}{\lambda\delta\beta(1-\tau)s}c - 2I - (\rho - g_N). \tag{31}$$

Equations (31) and (28) determine the evolution of the two endogenous variables of the model, per-capita consumption expenditure c and the rate of innovation I. As suggested in (25), bounded long-run growth requires the rate of innovation to be constant over time. In turn, this implies that per-capita consumption expenditure must also be constant over time–otherwise the resource constraint (28) would be violated.

Setting $\dot{c} = 0$ in (31) yields the equilibrium R&D condition

$$c = \frac{\lambda(1-\tau)\beta\delta s}{(\lambda-1)\gamma}[\rho - g_N + 2I] \tag{32}$$

which defines a positive linear relationship between per-capita consumption expenditure c and the rate of innovation I. It also implies the familiar condition $r = \rho$ which requires the market interest rate to be equal to the subjective discount rate in the steady-state equilibrium.

Let a tilde "$\sim$" over variables denote their market value in a steady-state equilibrium. The resource condition (28) and the equilibrium R&D condition (32) determine simultaneously the long-run equilibrium values of per capita consumption expenditure $\tilde{c}$ and the rate of innovation $\tilde{I}$.

From (28) and (32), we can obtain the following explicit solution for the steady-state rate of innovation:

$$\tilde{I} = \frac{(1-s)\gamma/(s\delta\beta) - ((1-\tau)(\rho - g_N)/(\lambda-1))}{1 + 2(1-\tau)/(\lambda-1)}. \tag{33}$$

Equation (33) relates the market rate of innovation $\tilde{I}$ to virtually all the parameters of the model, including the ad valorem R&D subsidy, τ. The reader can obtain an explicit solution for the long-run level of per-capita consumption expenditure by substituting (33) into the resource condition (28). A necessary and sufficient condition for non-negative long-run Schumpeterian growth is that the numerator in (33) be non-negative. This condition will be satisfied if, for example, the relative supply of non-specialized labor, $L(t)/H(t) = (1-s)/s$, the size of innovations, λ, the unit-labor requirement in rent protection, β, or the rate of population growth, g_N, are sufficiently large. Moreover, because per-capita consumption expenditure and R&D investment are choice variables, the model does not exhibit transitional dynamics. We thus arrive at

Proposition 1 *There exists a unique steady-state market equilibrium such that*

(a) the long-run rate of innovation $\tilde{I}$, the relative wage of specialized labor $\tilde{\omega}$, per-capita rent-protecting services $\tilde{x}$, and per-capita consumption expenditure $\tilde{c}$ are all bounded and constant over time;
(b) long-run Schumpeterian growth $\tilde{g}_U$ is bounded, does not exhibit scale effects, and is strictly positive if and only if the model's parameters satisfy the following condition:

$$\frac{\lambda - 1}{\rho - g_N} > (1-\tau)\frac{\beta\delta}{\gamma}\frac{s}{1-s}; \tag{34}$$

(c) the economy does not exhibit transitional dynamics.

Proof See the Appendix. □

The removal of scale effects from the long-run growth rate $\tilde{g}_U$ crucially depends on the endogenous determination of rent-protecting services. At the steady-state equilibrium, the level $\tilde{X}(t) \equiv \tilde{x}N(t)$ of these services and the level $\tilde{R}(t) = \delta\tilde{I}\tilde{X}(t)$ of R&D services increase exponentially at the rate of population growth g_N (i.e., $\dot{X}(t)/X(t) = \dot{R}(t)/R(t) = g_N$), as can be ascertained from (23). In other words, as the size of the economy $N(t)$ grows exponentially over time, resources injected into R&D and rent protection also grow exponentially.

The removal of growth scale effects is consistent with postwar time-series evidence from several industrial economies showing exponential increases in R&D resources and constant per-capita real GDP growth rate (Jones 1995). In the present model, the flow of innovations (i.e., patents) per researcher equals $\tilde{I}/[\beta\tilde{R}(t)]$ and decreases monotonically over time.

Part (b) of Proposition 1 clarifies how parameter values that lead to the violation of (34) can create a structural barrier to long-run rate of innovation and growth. For example, if condition (34) is not satisfied, the numerator of (33) will be non-positive and the economy will be unable to sustain long-run growth. Moreover, starting at a steady-steady equilibrium, if parameter changes reverse the inequality in (34), Schumpeterian growth will come to halt and, as a result, the economy will be populated by incumbent monopolists who enjoy an infinite stream of monopoly profits.

It is therefore worthwhile to identify the nature of this growth barrier – which nay differ across countries – and its dependence on the model's parameters. The

LHS of condition (34) identifies demand-based growth barriers. It captures the discounted marginal return to each innovation and depends positively on the size of innovations λ and negatively on the effective discount rate $\rho - g_N$. The RHS of (34) identifies the following supply side barriers to innovation and growth: Low R&D subsidies (or high R&D taxes), captured by $1-\tau$; high relative abundance of a factor that is used specifically (or intensively) in rent-protecting activities, captured by $s/(1-s)$; weak protection of intellectual property (or, equivalently, high productivity effectiveness of rent-protecting activities), captured by δ; and low relative productivity of (non-specialized) labor in R&D as compared to (specialized) labor productivity in rent protection, captured by the ratio β/γ.

The identification of these growth barriers addresses, at least partially, the concerns expressed by Parente and Prescott (1919, p. 1217) that Schumpeterian growth theory cannot explain why some countries are poor and some countries rich. Country-specific differences in all these structural barriers to innovation can account for differences in the long-run growth rates of total factor productivity across countries. Further, if one is willing to interpret the present model as one of technology adoption (rather than as one of technology generation), the framework could be readily modified to address the nature of barriers to technology adoption and growth in developing countries.

The following proposition identifies several determinants of long-run Schumpeterian growth, including R&D subsidies:

Proposition 2 *The market equilibrium long-run Schumpeterian growth rate* $\tilde{g}_U$ *depends*

(a) *positively on the subsidy rate* τ*, the population growth rate* g_N*, the size of innovations* λ*, and the unit-labor requirement in the production of rent-protecting activities* γ*;*
(b) *negatively on the fraction of specialized labor s, the consumer's subjective discount rate* ρ*, the unit-labor requirement in the production of R&D services* β*, and the degree of insecurity in intellectual property* δ*.*

Proof Substitute the expression for $\tilde{I}$ determined by (33) into (25) and differentiate the resulting expression with respect to the appropriate parameter. □

The comparative steady-state properties outlined in Proposition 2 differentiate our model from several others in its class.[19] An increase in the R&D subsidy τ raises the relative price of rent-protecting services and directly stimulates the rate of innovation I, relative to per-capita consumption expenditure c. In other words, a larger R&D subsidy reduces the per-unit cost of conducting R&D and thus induces the long-run Schumpeterian growth rate to rise. Conversely, in the case of an ad valorem tax on R&D (i.e., $\tau < 0$), an increase in τ reduces the rate of innovation and long-run Schumpeterian growth. Thus, the model preserves the policy endogeneity of long-run growth found in earlier models of Schumpeterian growth with scale effects. This stands in sharp contrast to several recent models of long-run growth that imply ad valorem R&D subsidies are ineffective in altering the level of long-run growth.[20]

[19] Howitt (1999) has obtained comparative steady-state properties similar to those of Proposition 2 in a model of Schumpeterian growth with horizontal and vertical product differentiation.
[20] See, for instance, Jones (1999).

An increase in the rate of population growth g_N operates through a decrease in the effective discount rate $\rho - g_N$, thus resulting in a higher rate of innovation $\tilde{I}$ and higher long-run growth $\tilde{g}_U$.[21] Even in the absence of population growth (e.g., $g_N = 0$), the economy enjoys positive rates of innovation and long-run Schumpeterian growth (see (25) and (33)).[22]

By raising the relative supply of specialized labor, an increase in the fraction of specialized workers, s, reduces their relative wage, thereby yielding lower innovation and long-run growth rates.

4 Welfare

The absence of transitional dynamics and the structural symmetry across industries render the analysis of the welfare properties of the equilibrium path feasible and simple. The economy jumps to the balanced-growth equilibrium at time zero and the social planner allocates the same amount of non-specialized labor across all industries. Substituting real per-capita income, given by (24), in (7) and performing the requisite integration yields the following expression for the level of welfare discounted to time zero:

$$U = \frac{1}{\rho - g_N}\left(\log\left[\frac{c}{\alpha\lambda}\right] + \frac{I \log\lambda}{\rho - g_N}\right). \tag{35}$$

Expression (35) was obtained under two additional assumptions regarding the feasibility of public policy instruments. First, we assumed that each incumbent charges a price equal to $\alpha\lambda w_L$, where $w_L = 1$ by choice of the numeraire. In other words, the social planner permits limit pricing by incumbents, which generates temporary monopoly profits, instead of setting each price equal to marginal cost and engaging in public R&D financed by taxation. Second, we assumed that it is not feasible to identify and tax directly the resources allocated to rent protection. If this were possible the social planner would be able to reduce the per-capita level of rent protection by creating unemployment among specialized workers or by driving the level of rent-protecting services down to zero. (In the latter case, the long-run rate of innovation would exhibit scale effects, the expression in (35) would approach infinity, and the social planner's problem would not be well-defined.) Similar considerations apply with regards to the ability of the social planner to alter the fraction of the population engaged in the production of rent-protection services, s. If s is a choice variable, the social planner would be able to generate unbounded growth by setting $s = 0$, which would drive the level of rent-protection services down to zero and would reintroduce growth scale effects. In reality, the fraction of specialized

[21] In more general settings, where specialized and non-specialized labor may be employed both in rent-protection activities and R&D, parameters that affect long-run growth through the relative wage of specialized labor operate in a manner that depends on the factor-intensity ranking between the two activities according to the Stolper and Samuelson (1941) mechanism. The assumption that specialized labor is used only in rent-protecting activities is equivalent to assuming that these activities use this factor input intensively relative to production of R&D services and manufacturing of final consumption goods.

[22] In contrast, models of exogenous R&D-based growth without scale effects (e.g., Jones 1995 and Segerstrom 1998) generate zero long-run per-capita growth if the economy's market size (measured by the level of population) remains fixed.

labor depends on education, specialized training, or learning by doing which are all affected by demand and supply considerations. We conjecture that, in the present context, one must model the endogenous determinants of the division of population between specialized and non-specialized labor before analyzing the welfare effects of treating the fraction of specialized workers as a choice variable.[23]

Given the above considerations and following the spirit of earlier Schumpeterian growth models, we assume that the social planner chooses the levels of per-capita consumption expenditure and the rate of innovation to maximize the discounted utility in (35) subject to the full employment conditions (22) and (23). Using (2) and (3), we can express the social planner's resource constraint as

$$1 - s = \frac{c}{\lambda} + \frac{\beta\delta s}{\gamma} I, \tag{36}$$

which is identical to the market-resource condition (28).

Because U is concave in per-capita consumption expenditure c, U defines convex social indifference curves in the $(I,\ c)$ space. The social optimum can thus be obtained by setting the slope of a typical social indifference curve $dc/dI = -c(\log\lambda)/(\rho - g_N)$ (i.e., the marginal rate of substitution) equal to the slope of the resource constraint $dc/dI = -\lambda\beta\delta s/\gamma$ (i.e., the marginal rate of transformation) to obtain

$$\frac{[\log\lambda]c^*}{\lambda(\rho - g_N)} = \frac{\beta\delta s}{\gamma}. \tag{37}$$

where an asterisk "*" denotes the value of an endogenous variable at the social optimum. Equations (36) and (37) define the optimum values of per capita consumption and the rate of innovation. The latter is given by

$$I^* = \frac{(1-s)\gamma}{s\beta\delta} - \frac{\rho - g_N}{\log\lambda} \tag{38}$$

In the presence of rent-protection activities, does the socially optimum level of innovation exceed the market rate of innovation, when the latter is generated without any government intervention? In other words, does welfare maximization require an R&D subsidy or a tax? Setting $\tau = 0$ in (33) and subtracting the resulting free-market rate of innovation from (38), yields the following explicit expression for the difference between the socially optimal and laissez-faire rates of innovation:

$$I^* - \tilde{I} = \frac{1}{\lambda + 1}\left[\frac{2(1-s)\gamma}{s\beta\delta} - (\rho - g_N)\left(\frac{\lambda + 1 - \log\lambda}{\log\lambda}\right)\right]. \tag{39}$$

If the RHS of (39) is positive, the optimum rate of innovation will exceed the free-market rate of innovation. This is a case, then, in which the social planner should provide incentives for higher levels of R&D investment and subsidies can accomplish that. On the other hand, if the RHS of (39) is negative, the market generates over investment in R&D (too much of a good thing!) and the social planner should

[23] Dinopoulos and Segerstrom (1999) have developed a model with endogenous skill formation. However, the presence of endogenous skill formation in that model introduces complicated transitional dynamics which render intractable the welfare analysis.

provide incentives for lower levels of R&D investment in the form of R&D taxes. Generally, in economies with a high fraction of non-specialized labor $1 - s$, a low level of resource requirement per unit of effective R&D, $\beta\delta s/\gamma$, and a low effective discount rate $\rho - g_N$, the market level of R&D should be subsidized. In addition, the term in square brackets in (39) becomes negative for low and high values of parameter λ (i.e., the parameter that captures the size of innovations), and remains positive for intermediate values of λ. Consequently, economies with low and very high values of λ should tax R&D investment.[24]

The following proposition summarizes the model's main welfare property.

Proposition 3 *In the presence of rent-protection activities and scale-invariant growth, the welfare ranking between the social and market rates of innovation is ambiguous.*

The economic intuition for this welfare ambiguity is driven by the presence of multiple forces that create a divergence between social and private incentives towards innovation. One way to compare the optimum to the market equilibrium is to observe that in both cases the resource constraints are identical. In the absence of an R&D subsidy, the R&D condition can be written as

$$\frac{(\lambda - 1)\tilde{c}}{\lambda(\rho - g_N + 2\tilde{I})} = \frac{\beta\delta s}{\gamma}, \tag{40}$$

where, again, a tilde "$\sim$" denotes the market value of an endogenous variable in the absence of government intervention. Equations (36) and (40) define the market equilibrium values of consumption expenditure per capita and the rate of innovation.

Now observe that the RHS of (40) is identical to the RHS of (37). This expression measures the opportunity cost of transforming the rate of innovation, I, into quantity consumed, $q = c/\lambda$ (see (36)). The LHS of (40) captures the per-capita expected discounted profits of a successful innovator. The LHS of (37) can be interpreted as the per-capita "social" discounted profits. There are two key differences between the LHS expressions of (37) and (40). First, the term $\lambda - 1$ appears in the numerator of (40) which is larger than $\log \lambda$ which appears in the numerator of (37). This difference has been christened by Aghion and Howitt (1992) the "*monopoly-distortion*" effect. The winner of each R&D race is concerned about the instantaneous profit margin $\lambda - 1$ of each new product, where as the social planner is interested in the change in consumer surplus caused by an innovation

[24] See section 4.3 of Grossman and Helpman (1991) for an excellent discussion of the welfare properties of the original quality-ladders growth model, where the difference between the social and market rates of innovation is given by their (4.38) which can be stated, using the notation of this paper, as

$$I^* - \tilde{I} = \frac{1}{\lambda}\left(\frac{N(t)}{\beta} - \rho\frac{[\lambda - \log\lambda]}{\log\lambda}\right).$$

While the removal of scale effects in the model of this paper does not eliminate the ambiguity in the ranking of the social and market rates of innovation, it introduces several additional considerations that do not arise in the original quality-ladders model. Notice that the fraction of non-specialized labor $1 - s$ measures the economy's "per-capita" scale and plays the same role as the level of population in earlier models of Schumpeterian growth.

that equals $\log\lambda < \lambda - 1$ for $\lambda > 1$. The monopoly-distortion effect creates a tendency for over-investment in R&D relative to the socially optimal level.

Second, the "*intertemporal spillover*" effect is reflected in the difference between the denominators of the LHS of (40) and (37). This effect creates a tendency for the private sector to under-invest in R&D. The social planner discounts the benefits of each innovation by the social discount rate $\rho - g_N$, instead of $\rho - g_N + 2I$, which corresponds to the effective private market discount rate. The social planner takes into account the fact that consumers benefit from an innovation forever; in contrast, recognizing that they are not infinitely lived, private firms take into account the probability that they will be replaced in the future by challengers. In the absence of rent protection, the market discount rate equals $\rho - g_N + I$ (Segerstrom 1998). The presence of rent-protecting activities doubles the economy's resources devoted to innovation and augments the private discount rate. As a result, the intertemporal spillover effect tends to reduce the market rate of innovation relative to the socially optimum level by increasing the market above the social discount rate.

In general, the welfare ranking between social and market rates of innovation is ambiguous and depends on the strength of the monopoly-distortion effect relative to the intertemporal spillover one. If the latter effect dominates, then an appropriate R&D subsidy can achieve the social optimum.

5 Concluding Remarks

Underscoring the notion that throughout history "insecure property" has been a salient feature of economic life, recent contributions to the literature on property rights (e.g., Tornell 1997, Tornell and Lane 1999, Parente and Prescott 1999, 2000, Anbarci et al. 2002, Skaperdas and Syropoulos 2001, 2002) have paid special attention to agents' incentives to expend resources on private protection and how this matters for efficiency. Noting that intellectual property is insecure and that, as a result, incumbent firms may safeguard their past innovations through rent protection, this paper has attempted to shed light on the implications of this condition for technical change and welfare. The removal of scale effects from early Schumpeterian growth models represents an important step in growth theory because it improves its empirical relevance and makes it more likely to integrate neoclassical and new growth theories. The paper contributes to this development by showing that rent-protecting activities may help remove scale effects and explain why R&D becomes more difficult over time. In addition, the paper contributes to the literature on barriers to technological progress by identifying the role of structural parameters that may slow down and even stop the long-run rate of innovation.

Our analysis has generated several novel insights. In the steady-state equilibrium, Schumpeterian growth is directly proportional to the relative price of rent-protecting services. The more expensive is rent protection relative to R&D, the higher is the long-run rate of Schumpeterian growth. Importantly, long-run growth is endogenous and does not exhibit scale effects. Moreover, policies that affect the relative price of rent protection directly (as in the case of proportional R&D subsidies) or indirectly (through changes in the returns to factor inputs) affect long-run growth. Thus, unlike other models of Schumpeterian growth, where income distribution is a byproduct of the growth process, the present model highlights the direct link between growth and income distribution. Lastly, several key predictions of the model based on its comparative steady-state properties are consistent with time series and international cross-sectional evidence on economic growth.

The aforementioned insights complement those of other quality-ladder growth models without scale effects. Several growth models that removed the scale effects property did so by assuming that R&D becomes more difficult over time because of diminishing technological opportunities (e.g., Kortum 1997, Segerstrom 1998, and Dinopoulos and Segerstrom 1999). These models generate exogenous long-run growth because the assumption of diminishing technological opportunities implies that in some sense R&D difficulty increases exogenously over time. Our research complements other models of endogenous long-run growth without scale effects (e.g., Young 1998; and Howitt 1999) by introducing a new mechanism based on partial (as opposed to localized) R&D spillovers. The rent-protecting activities mechanism relies on the notion that R&D within each product line becomes more difficult over time endogenously, whereas models that employ the notion of localized R&D spillovers assume that R&D within each product line does not.

Appendix

Proof of Proposition 1 Part (a): Equations (28) and (32) define a unique steady-state equilibrium in which $\tilde{c}$ and $\tilde{I}$ are bounded and constant. Equation (23) determines the constant value of $\tilde{x} = s/\gamma$, and (26) determines the value $\tilde{\omega}$ as a function of $\tilde{I}$ which is constant over time in the steady-state equilibrium.

Part (b): It follows from requiring the numerator of (33) to be strictly positive.

Part (c): As in the original quality-ladders model of growth, our model does not exhibit transitional dynamics. To see this, note that the resource condition (28) must hold at each instant in time because factor markets clear instantaneously. Solving the resource condition for the rate of innovation, I, and substituting the resulting expression in (31) yields a differential equation in consumption per-capita:

$$\dot{c} = \left\{ \frac{\gamma}{\lambda\beta\delta s}\left[\frac{\lambda-1}{1-\tau}+2\right]c - \left[\frac{2(1-s)\gamma}{\beta\delta s}+\rho-g_N\right]\right\}c \tag{41}$$

The resource condition (28), which for convenience we reproduce as

$$1-s = \frac{c}{\lambda}+\frac{\beta\delta s}{\gamma}I, \tag{42}$$

determines the evolution of the rate of innovation I for any value of c.

Setting the square-bracket expression in (41) equal to zero defines the steady-state per-capita consumption expenditure $\tilde{c} > 0$, which is consistent with the positive rate of innovation in Equation (33). Because consumption expenditure, R&D services and rent-protecting services are all choice variables, the economy jumps instantaneously to this steady-state equilibrium at time zero. Any other trajectory leads eventually to an inconsistency with respect to profit-maximizing behavior of firms.

For values of per-capita consumption that are less than $\tilde{c}$ the RHS of (41) is negative and the economy approaches a steady-state with zero per-capita consumption expenditure. This trajectory implies that, with $\tilde{c} = 0$, firms engage in R&D

investment even if the flow of profits $\pi(t)$ is zero and the reward to innovation $V(t)$ is negative (see (29)). This behavior contradicts the assumption that firms maximize expected discounted profits when investing in R&D.

Similarly, for values of per-capita consumption higher than $\tilde{c}$ the RHS of (41) is positive, the market interest rate is higher than the subjective discount rate and $\dot{c}(t)/c(t) > 0$. In this case, (42) implies that the economy experiences positive growth in per-capita consumption expenditure but no innovation. The trajectory with $\tilde{I} = 0$ implies that the level of R&D investment is zero, per-capita consumption expenditure grows exponentially, and all non-specialized labor is allocated in manufacturing final consumption goods. Equation (29) implies that the per-capita reward to innovation $V(t)/N(t)$ increases over time. Consequently, expression $V(t)/D(t) = [\gamma/\delta s][V(t)/N(t)]$ also increases over time, and thus challenger j's expected discounted profits, which can be written as $[V(t)/D(t) - (1-\tau)\beta]R_j(t)\mathrm{d}t$ increase over time as well, even though firms do not engage in R&D! □

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