New Directions in Schumpeterian Growth Theory*

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Abstract

Schumpeterian growth is a particular type of economic growth that is based on the endogenous introduction of new products and/or processes and is governed by the process of creative destruction described by Joseph Schumpeter (1942). This paper provides an exposition of the scale-effects property in the context of Schumpeterian growth models. In particular, the paper outlines the three distinct solutions to the scale-effects problem, discusses their implications and offers an assessment of scale-invariant Schumpeterian growth models.

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1. Introduction

Schumpeterian growth is a particular type of economic growth which is based on the process of creative destruction. The process of creative destruction was described in the writings or Joseph Schumpeter (1928, 1942) and refers to the endogenous introduction of new products and/or processes. For instance, in *Capitalism, Socialism and Democracy*, chapter 8, Schumpeter states:

> The essential point to grasp is that in dealing with capitalism we are dealing with an evolutionary process…The fundamental impulse that sets and keeps the capitalist engine in motion comes from the new consumer goods, the new methods of production, or transportation, the new forms of industrial organization that capitalist enterprise creates…In the case of retail trade the competition that matters arises not from additional shops of the same type, but from the department store, the chain store, the mail-order house and the super market, which are bound to destroy those pyramids sooner or later. Now a theoretical construction which neglects this essential elements of the case neglects all that is most typically capitalist about it; even if correct in logic as well as in fact, it is like *Hamlet* without the Danish prince.

In other words, the essential feature of Schumpeterian-growth models is the incorporation of technological progress which is generated by the endogenous introduction of product and/or process innovations. The term "endogenous" refers to innovations that result from conscious actions undertaken by economic agents (firms or consumers) to maximize their objective function (profits or utility). Although Schumpeterian-growth theory formalizes only a subset of Schumpeter's ideas, it is much closer to the concept of creative destruction than other existing economic growth theories.[1]

The birth of Schumpeterian growth theory started in the late 1980's and early 1990s with the publication of four articles and its rapid development has followed the general evolutionary process of creative destruction.[2] The merit and robustness of key assumptions of earlier models have been questioned; certain implications have been tested and rejected; and state-of-the-art analytical techniques have resulted in new and more versatile models. Until the mid 1990s, growth theory witnessed a renaissance fueled by a rapidly expanding Schumpeterian growth literature under the label of "endogenous"

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[1] For instance, the neoclassical growth model assumes exogenous technological progress, the AK growth model focuses on the role of physical capital accumulation, and the Lucas (1988) model of growth emphasizes the importance of knowledge spillovers in the process of human-capital accumulation.

[2] The four studies that developed the foundations of Schumpeterian growth theory are Romer (1990), Segerstrom, Anant and Dinopoulos (1990), Grossman and Helpman (1991a) and Aghion and Howitt (1992). Dinopoulos (1994) provides an overview or earlier Schumpeterian-growth models, and Romer (1994) offers an excellent account on the origins of this theory.

growth. Hundreds of articles and at least three textbooks analyzed various features of the "new" growth theory focusing on the effects of policies on long-run growth and welfare.[3]

By mid-1990s, the development of the theory reached a blind intersection. In two influential articles, Jones (1995a, 1995b) argued that earlier Schumpeterian growth models incorporate a scale-effects property: The rate of technological progress is assumed to be proportional to the level of R&D investment services (which in turn are produced with a standard constant-returns-to-scale production function). For instance, if one doubles all R&D inputs, then the level of R&D investment doubles as well. This scale-related property implies that an economy's long-run per capita growth rate increases in its size, measured by the level of population. In the presence of positive population growth, the scale-effects property implies that per capita growth rate increases exponentially over time and it becomes infinite in the steady-state equilibrium. Jones argued that the scale-effects property is inconsistent with time-series evidence from several advanced countries. This evidence shows that resources devoted to R&D have been increasing exponentially, but the growth rates of total factor productivity and per capita output remain roughly constant over time.

The Jones critique raises the following fundamental questions: Is the scale-effects property empirically relevant? Can one construct Schumpeterian growth models with positive population growth and bounded long-run growth? Can one develop scale-invariant Schumpeterian growth models which maintain the policy endogeneity of long-run growth? Affirmative answers to these questions are crucial for the evolution of Schumpeterian growth theory for the following reasons. First, removal of the scale-effects property enhances the empirical relevance of the theory. Second, scale-invariant Schumpeterian growth models with endogenous technological change represent one more step towards a unified growth theory which would eventually combine the insights of neoclassical and Schumpeterian growth theories. Third, the development of scale-invariant long-run endogenous growth theory enhances their policy relevance and brings the theory closer to the spirit of Joseph Schumpeter (1937) who stated: "There must be a purely economic theory of economic change which does not merely rely on external factors propelling the economic system from one equilibrium to another. It is such theory…that I have tried to build …[and that] explains a number of phenomena, in particular the business cycle, more satisfactorily than it is possible to explain them by means of either the Walrasian or the Marshalian apparatus".

This paper intends to introduce the reader to the recent developments in Schumpeterian growth theory and to provide several useful insights on the scale-effects property. The rest of the paper is organized as follows. Section 2 uses a simple analytical framework borrowed from Dinopoulos and Thompson (1999) and Jones (1999) to highlight the mathematics and economics of the scale-effects property and to illustrate three basic approaches to generating scale-invariant Schumpeterian growth. Section 3 offers an assessment of scale-invariant Schumpeterian growth models. Section 4 offers several concluding remarks and suggestions for further research.

[3] A survey of this literature lies beyond the scope of this paper. The interested reader is referred to Grossman and Helpman (1991), Barro and Sala-i-Martin (1995) and especially Aghion and Howitt (1998) for more details.

2. An Anatomy of Scale-Effects

The scale-effects property in Schumpeterian growth models is related to two fundamental modeling building blocks: an economy's knowledge production function and its resource constraint. The former links the growth rate of knowledge (which is identical to the growth rate of technology) to R&D resources via a constant-returns-to-scale production function.[4] The latter requires that the sum of resources devoted to all activities must not exceed the available supply of these resources at each instant in time.

We can illustrate the role of the knowledge production function and the resource constraint by considering the simplest possible version of a Schumpeterian growth model. Consider an economy in which final output is produced by the following production function:

$$Y(t) = A(t)L_Y(t), \tag{1}$$

where $Y(t)$ is the economy's final output at time t, $A(t)$ is the level of technology and $L_Y(t)$ is the amount of labor devoted to manufacturing of $Y(t)$. The following knowledge production function governs the evolution of technological progress

$$g_A \equiv \frac{\dot{A}(t)}{A(t)} = \frac{L_A(t)}{X(t)}, \tag{2}$$

where g_A denotes the growth rate of technology, $L_A(t)$ is the amount of aggregate resources devoted to R&D (i.e., the economy's scientists and engineers), and $X(t)$ is a measure of R&D difficulty. Higher values of $X(t)$ imply that the same amount of R&D resources generates a lower growth rate of technology.[5] In other words, the inverse of $X(t)$ is the total factor productivity in R&D. As will become clear below, assumptions that govern the evolution of $X(t)$ play a crucial role in regulating the scale-effects property and in conditioning the nature of long-run Schumpeterian growth.

For the time being, assume that labor is the only factor of production, and that the production of $X(t)$ does not require any economic resources. Under these two assumptions, the economy's resource constraint can be expressed by the following full-employment-of-labor condition

$$L_Y(t) + L_A(t) = L(t); \tag{3}$$

where $L(t) = L_0 e^{tg_L}$ denotes the level of labor force (population) at time t, which is one measure of the economy's size; and $g_L > 0$ is the rate of population growth. The resource

[4] The reason that the growth rate of technology (as opposed to just the change in the level of technology) enters on the left-hand-side of the knowledge production function can be traced to the non-rivalry of ideas. Romer (1990) provides an excellent discussion on this basic difference between the production of goods and the generation of ideas.

[5] Segerstrom (1998) was the first to introduce variable $X(t)$ in the knowledge production function of a scale-invariant Schumpeterian growth model based on quality improvements.

condition states that at each instant in time the amount of labor devoted to manufacturing plus the amount of labor devoted to R&D equals the economy's labor force.

Denote with $s(t) = L_Y(t)/L(t)$ the share of labor force employed in manufacturing. Equation (1) implies that the economy's per capita income is $y(t) = Y(t)/L(t) = A(t)s(t)$. Since $s(t)$ is bounded from above by one and from below by zero, it must be constant at the steady-state equilibrium (i.e., $s(t) = s$) and thus the long-run growth rate of output per capita is given by

$$g_y \equiv \frac{\dot{y}(t)}{y(t)} = \frac{\dot{A}(t)}{A(t)} = (1-s)\frac{L(t)}{X(t)} \ , \tag{4}$$

where equations (2) and (3) along with $s(t) = L_Y(t)/L(t)$ were used to derive the right-hand-side of equation (4). Equation (4) states that the steady-state growth rate of output per capita equals the growth rate of technology. The latter is directly proportional to the economy's size, measured by the level of population $L(t)$, and inversely proportional to the level of R&D difficulty $X(t)$.

Dividing both sides of the resource condition (3) by the level of population and substituting $L_A(t) = g_A X(t)$, (see equation (2)) yields the following per capita resource condition:

$$s + g_A \frac{X(t)}{L(t)} = 1 \, . \tag{5}$$

Equations (4) and (5) illustrate the basic building blocks of Schumpeterian growth models and hold at each instant in time independent of market structure considerations and independent of whether technological progress takes the form of variety accumulation or quality improvements. In the steady-state equilibrium, the share of labor devoted to manufacturing, s, and the growth rate of technological progress, g_A, must be constant over time. Consequently, the level of per capita R&D difficulty captured by the ratio $X(t)/L(t)$ must be constant in the long run.

2.1. Earlier Schumpeterian Growth Models

Earlier models of Schumpeterian growth generate endogenous long-run growth by adopting two basic assumptions. First, they assume that the labor force is constant over time, i.e., $g_L = 0$, and thus $L(t) = L_0$ in equations (4) and (5). Second, they typically assume that the R&D difficulty is a constant parameter, i.e., $X(t) = X_0$. These two assumptions imply that $X(t)/L(t) = X_0 /L_0$ is constant over time and therefore equations (4) and (5) hold. In addition, it is obvious from equation (4) that long-run Schumpeterian growth is bounded and that any policy that alters the level of R&D resources, $L_A = (1-s)L_0$, affects the rate of long-run growth g_A. Consequently, long-run Schumpeterian growth is endogenous in these models.

Romer (1990) developed such an endogenous Schumpeterian growth model based on horizontal product differentiation in which variety accumulation in intermediate capital goods drives the evolution of technological change. Segerstrom, Anant and

Dinopoulos (1990), Aghion and Howitt (1992) and Grossman and Helpman (1991a, 1991b) set up the foundations for the development of the quality-ladders Schumpeterian growth model in which quality improvements based on stochastic and sequential R&D races constitute the source of endogenous growth. An extensive body of literature further developed the insights of these earlier Schumpeterian growth models.[6]

Jones (1995a) criticized the empirical relevance of this class of Schumpeterian growth models by focusing on the above-mentioned assumptions. He pointed out that various measures of per capita growth—such as the growth rate of total factor productivity, the flow of patents, and even the growth rate of income per capita—have remained roughly constant over time, whereas resources devoted to R&D—such as the number of scientists and engineers—have been increasing exponentially over time.

In the presence of positive population growth, i.e., $g_L > 0$, the right-hand-side of (2) and (4) grows exponentially over time at the rate of population growth, but this leads to unbounded long-run growth of per capita output. In other words, under the assumption that $X(t) = X_0$, as the scale of the economy increases, so does the *rate* of long-run Schumpeterian growth. This unrealistic prediction is evident in the knowledge production function (4) and the resource condition (5), which represent two sides of the scale-effects-property coin. Following Jones' (1995a) critique, it became clear to growth theorists that there are strong theoretical and empirical arguments that called for the removal of scale effects from earlier Schumpeterian growth models.

2.2. Exogenous Schumpeterian-Growth Models without Scale Effects

The first approach to the removal of scale effects employs the notion of *diminishing technological opportunities*. Jones (1995b) adopted this notion in a variety-expansion growth model a la Romer (1990), Segerstrom (1998) used the same approach in a quality-ladders Schumpeterian growth model, and Kortum (1997) provided theoretical foundations for the assumption of diminishing technological opportunities. The present framework can illustrate this approach by assuming that the level of R&D difficulty $X(t)$ increases over time as the level of technology $A(t)$ rises:

$$X(t) = A(t)^{1/\varphi} \ , \tag{6}$$

where $\varphi > 0$ is a constant parameter that captures the degree of diminishing technological opportunities. In Schumpeterian growth models of vertical product differentiation, the scale-effects property is removed by assuming that the level of R&D difficulty increases as R&D investment accumulates over time in each industry during an R&D race (Segerstrom, 1998) or when the R&D race ends and innovation occurs (Li, 2003). It is obvious from equations (4) and (5) that since $X(t)/L(t)$ must be constant over time in the steady-state equilibrium, the growth rate of R&D difficulty must be equal the exogenous growth rate of population, that is $\dot{X}(t)/X(t) = \dot{L}(t)/L(t) = g_L$. Equation (6) implies that the rate of growth of $X(t)$ is proportional to the rate of growth of technology:

[6] Aghion and Howitt (1998) provide and excellent exposition of this body of literature.

$\dot{X}(t)/X(t) = g_A/\varphi$. Combining these two expressions yields the basic result of this strand of literature:

$$g_A = \varphi g_L. \tag{7}$$

The growth rate of technology (and per capita income) is proportional to the exogenous population growth rate with the proportionality factor given by the parameter φ. The economic intuition associated with equation (7) is as follows: In the steady-state equilibrium because of diminishing returns to R&D efforts, individual researchers become less productive as the level of knowledge increases over time. To maintain a constant rate of innovation and growth, there must be an expansion in the employment of researchers. This is possible only if the economy's population is growing at a positive rate. If φ approaches zero, the level of R&D difficulty approaches infinity and economic growth stops. If φ approaches infinity, the level of R&D difficulty approaches unity and is time invariant. In this case, as the level of population increases exponentially, long-run Schumpeterian growth approaches infinity.

Since the population growth rate g_L and the parameter φ are not affected by policies by assumption, this class of models generates exogenous Schumpeterian growth without scale effects. It should be emphasized though, that, unlike the neoclassical model in which the rate of technological change is assumed to be constant in the short and long run, exogenous Schumpeterian growth models generate changes in the rate of technological change during the transition to the steady-state equilibrium. To see this, define per capita R&D difficulty as $x = X(t)/L(t)$, which implies that $\dot{x}/x = (g_A/\varphi) - g_L$. Notice that the resource condition defines the steady-state value of x as a function of the model's parameters. If a change in a policy-related parameter increases the steady-state value of x, then during the transition to the new long-run equilibrium, $\dot{x} > 0$. This means that $g_A(t) > \varphi g_L$, that is, there must be a temporary acceleration in the rate of technological change.[7] In addition, these models are relatively simple to handle and generate interesting welfare results.

2.3. Endogenous Scale-Invariant Schumpeterian-Growth Models

The second approach to the scale-effects problem employs a two-dimensional framework with horizontal and vertical product differentiation: Horizontal product differentiation takes the form of variety accumulation and removes the scale-effects property from these models in a way similar to the one used by exogenous Schumpeterian growth models. Vertical product differentiation takes the form of quality improvements or process innovations and generates endogenous long-run growth. This approach postulates a proportional relationship between (aggregate) R&D difficulty and the

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[7] Since policy changes have *temporary effects on growth*, Dinopoulos and Segerstrom (1999) christen this specification as the TEG specification of R&D difficulty. Segerstrom (1998) and Dinopoulos and Segerstrom (1999) provide more details on the implications of the TEG specification for transitional dynamics.

number of varieties. Under the right market structure assumptions the number of varieties, in turn, can be shown to be proportional to the size of population.

Consequently, a linear relationship emerges between R&D difficulty and the size of population which removes the scale-effects property and hence establishes the *variety-expansion* mechanism. The variety-expansion approach was suggested independently by Peretto (1998), where vertical product differentiation takes the form of process innovations, and Young(1998), where vertical product differentiation is modeled as quality improvements. Aghion and Howitt (1998, chapter 12), Dinopoulos and Thompson (1998) and Howitt (1999) have further developed this approach.

To illustrate the variety-expansion approach to the scale-effects problem, we need to introduce a bit of additional economic structure to the basic framework. Consider an economy consisting of *n(t)* structurally identical industries (firms) producing horizontally differentiated products (varieties). Assume that each industry's output is given by $z(t) = A_\iota(t)\ell_z$, where *z(t)* is the industry specific output, $A_\iota(t)$ is the industry-specific level of technology and ℓ_z is the number of manufacturing workers employed in a typical industry. The knowledge production function in a typical industry is

$$g_\iota \equiv \frac{\dot{A}_\iota(t)}{A_\iota(t)} = \ell_A, \tag{8}$$

where g_ι is the rate of industry-specific technological change, and ℓ_A is the number of R&D researchers employed in a typical industry. Equation (8) implies that the evolution of technological change *within* an industry exhibits scale effects: If the number of researchers ℓ_A doubles, then the growth rate of technology doubles as well.

The aggregate level of output in this economy is given by $Y(t) = z(t)n(t) = A_\iota(t)\ell_z n(t)$. Therefore, the growth rate of per capita output *y(t) = Y(t)/L(t)* is given by

$$g_y \equiv \frac{\dot{y}(t)}{y(t)} = \frac{\dot{A}_\iota(t)}{A_\iota(t)} + \frac{\dot{n}(t)}{n(t)} - g_L = \ell_A + \frac{\dot{n}(t)}{n(t)} - g_L. \tag{9}$$

Observe that constant steady-state growth rate g_Y requires that both ℓ_A and $\dot{n}(t)/n(t)$ remain constant over time.

We follow Aghion and Howitt (1998, chapter 12) and propose a simple mechanism to determine to determine the evolution of *n(t)*. Assume that the number of varieties *n(t)* grows over time as a result of serendipitous imitation. Each imitation results in a new industry with the same technology level as the other industries. Each person in the economy has the same exogenous instantaneous probability of imitation ξdt, where ξ is the intensity of the Poisson process that governs the arrival of new varieties. This implies that $\dot{n}(t) = \xi L(t)$. For $\dot{n}(t)/n(t) = \xi L(t)/n(t)$ to be constant, *n(t)* must grow at the rate of *L(t)*, which equals the population growth rate g_L. This implies that the per capita number of varieties *n(t)/L(t)* converges to the constant ξ/g_L, which establishes

$$n(t) = [\xi/g_L]L(t) = \beta L(t), \qquad (10)$$

where $\beta = \xi/g_L$ is used to simplify the expression. It is important to emphasize that the linear relationship between the number of varieties and the level of population is derived from a market-based mechanism with solid micro foundations. For instance, Young (1998, equation (17)) generates a version of equation (10) under the standard assumptions of monopolistic competition and fixed-entry costs.[8]

Adopting the Aghion and Howitt (1998) mechanism, we can write the economy-wide resource constraint as $\ell_z n(t) + \ell_A n(t) = L(t)$, which states that at each instant in time the amount of manufacturing and R&D labor must be equal to the size of population. Substituting (10) in this expression yields the following per capita resource condition:

$$\ell_z + \ell_A = \frac{1}{\beta} \quad . \qquad (11)$$

In the steady-state equilibrium, the amount of labor devoted to manufacturing ℓ_Z and R&D ℓ_A activities within each industry must be constant over time. This implies that the increase in the level of population is absorbed by the proportional expansion of varieties (industries). Substituting $\dot{n}(t)/n(t) = g_L$ in (9) implies that the long-run growth rate of per capita output is:

$$g_y = \frac{\dot{A}_\iota(t)}{A_\iota(t)} = \ell_A . \qquad (12)$$

Any policy that changes the allocation of labor between manufacturing and R&D within each industry affects long-run growth. In this sense, the removal of scale effects through the variety-expansion approach generates endogenous scale-invariant long-run Schumpeterian growth. If final output is given by a CES production function, say

$$Y = \left(\int_0^n z(i)^{1/\rho} di \right)^{\rho} ,$$

where $\rho > 1$, then substituting the corresponding expressions for z(t), and using (12) yields the following expression for long-run Schumpeterian growth: $g_y = \ell_A + (\rho - 1)g_L$. In addition to the endogenous component of long-run growth, an

[8] A similar result has been obtained by Kelly (2001) in a Schumpeterian growth model that distinguishes between innovating and non-innovating industries and allows for spillovers from innovating industries to neighboring industries. In this model, knowledge spillovers from innovating industries located on the border of the industry space results in the creation of a new industry. Kelly finds that scale effects are removed if and only if the growth rate in the number of industries equals the growth rate of population.

exogenous component, proportional to the rate of population growth, is added to the long-run growth expression.

The relationship between the level of R&D difficulty $X(t)$ and the number of varieties $n(t)$ can be readily established if one assumes an aggregate knowledge production function as before

$$g_A \equiv \frac{\dot{A}(t)}{A(t)} = \frac{L_A(t)}{X(t)} = \frac{\ell_A n(t)}{X(t)} \qquad , \tag{13}$$

where $A(t)$ is the economy-wide level of technology and $L_A(t) = \ell_A n(t)$ is the economy-wide amount of labor devoted to R&D. If ℓ_A is constant, then bounded steady-state growth requires that the level of R&D difficulty grow at the rate of variety expansion, which in turn equals the rate of population growth; that is, $\dot{X}(t)/X(t) = \dot{n}(t)/n(t) = g_L$. This implies a linear relationship between the level of R&D difficulty and the size of population

$$X(t) = \kappa L(t), \tag{14}$$

where $\kappa > 0$ is an inconsequential positive parameter. It is clear from the above discussion that R&D is becoming more difficult as the number of varieties expands in such a way that the amount of resources per industry remains constant over time.

The third approach to the removal of scale effects employs the notion of Rent Protection Activities (RPAs). This novel approach has been proposed by Dinopoulos and Syropoulos (2006) in the context of a quality-ladders Schumpeterian-growth model developed by Grossman and Helpman (1991a). In quality-ladders models, there is a continuum of structurally-identical industries covering the unit interval. In each industry the state-of-the-art quality product is produced by an incumbent monopolist who earns temporary economic profits (rents). Challengers raise claims to these rents by engaging in R&D investment to discover a higher-quality product and replace the incumbent monopolist. The latter has strong incentives to devote resources in various activities to protect her/his intellectual property and prolong the duration of temporary monopoly rents. Examples of RPAs include investments in trade secrecy, increasing the complexity of the product to reduce knowledge spillovers to potential challengers, expenditures to sustain legal teams to litigate patent infringement disputes and so on. In models that adopt the rent-protection approach to the removal of scale effects, the discovery of new products in each industry is governed by sequential stochastic innovation contests (as opposed to R&D races). Challengers choose the level of R&D investment and incumbents choose the level of RPAs. The level of R&D difficulty $X(t)$ is assumed to be directly proportional to the level of RPAs, and therefore it is endogenous.

We can illustrate the RPA approach to scale-invariant endogenous Schumpeterian growth by using our basic framework. Following Dinopoulos and Thompson (1999), one can model the level of technology in quality-ladders growth models as $A(t) = \lambda^{q(t)}$, where $\lambda > 1$ is a parameter measuring the size of each innovation and $q(t)$ is the expected number of innovations at time t in a typical industry. There is a continuum of independent, structurally-identical industries covering the unit interval. The expected flow of innovations per unit (instant) of time is governed by a Poison process with intensity $I(t)$. Following Segerstrom (1998), we model the intensity of the Poisson process as $I(t) = L_A(t) / X(t)$, where $L_A(t)$ is the industry (and economy) wide level of resources devoted to R&D, and $X(t)$ is the level of R&D difficulty. The assumption of a continuum of industries implies that aggregate growth is deterministic and the number of economy-wide innovations $q(t)$ obeys the differential equation $\dot{q}(t) = I(t)$. Taking logs and differentiating the level of technology $A(t)$ and substituting the above derived expressions yields an aggregate knowledge production function in quality-ladders Schumpeterian growth models:

$$g_A \equiv \frac{\dot{A}(t)}{A(t)} = [\log \lambda] I(t) = [\log \lambda] \frac{L_A(t)}{X(t)}. \tag{15}$$

Assume now that rent-protection services are produced using labor only that is specific to the production of these activities, say, lawyers. For simplicity of exposition, suppose that one unit of lawyer produces one unit of RPAs. The aggregate supply of lawyers $H(t)$ is an exogenous fraction of population; thus, $H(t) = \theta L(t)$, where $0 < \theta < 1$ is a parameter. The remaining fraction of the labor force $1 - \theta$ constitutes the supply of non-specialized labor which is allocated between manufacturing and R&D activities: $L_Y(t) + L_A(t) = (1 - \theta) L(t)$. Let $R(t)$ represent the level of industry-wide (and economy-wide) RPA. If one assumes that $X(t) = \beta R(t)$ with $\beta > 0$, which means that the level of R&D difficulty $X(t)$ is proportional to level of RPAs, then the full-employment condition for specialized labor is given by

$$X(t) = [\beta\theta] L(t). \tag{16}$$

Substituting equation (16) into (15) yields the main result of the RPA approach

$$g_A \equiv \frac{\dot{A}(t)}{A(t)} = \left[\frac{\log \lambda}{\beta\theta}\right]\left[\frac{L_A(t)}{L(t)}\right]. \tag{17}$$

Dividing both sides of the full-employment condition for non-specialized labor by the level of population and using (15) yields, with the exception of inconsequential constant parameters, equation (5). Equation (16) assures that the per capita full-employment condition for non-specialized labor holds independently of whether or not there is positive population growth.

In the steady-state equilibrium, as the supply of labor increases exponentially, both the equilibrium number of R&D researchers employed by challengers and the number of lawyers employed by incumbents rise exponentially. The two effects cancel each other and the scale-effects property is removed. Notice that (17) does not depend on the population growth rate and holds even if the level of population is constant over time. The long-run growth rate of technology (and per capita utility) depends positively on the size of innovations, and on the share of labor devoted to R&D. Any policy that shifts resources from manufacturing to R&D activities increases the level of long-run

Schumpeterian growth. In addition, changes in the effectiveness of RPAs (captured by β) or changes in the fraction of population engaged in RPAs (captured by θ) affect the rate of long-run growth.

3. An Assessment

In this section we offer a few remarks which provide an admittedly subjective assessment of scale-invariant Schumpeterian growth models. The first remark has to do with a somewhat exaggerated criticism directed at the functional robustness of scale-invariant Schumpeterian growth models. Notice the striking similarity between equations (14) and (16). In both classes of endogenous Schumpeterian growth models, the level of R&D difficulty is a linear function of the level of population. This linear functional form has been characterized as a “knife-edge” property that is unsatisfactory because it lacks functional robustness (see Jones 1999, and especially Li, 2000 and 2002).

We believe that the emphasis on functional robustness is rather misguided and it is largely based on a natural tendency to differentiate newly developed models from old ones. Even if one views (14) and (16) as knife-edge features, there are many examples of knife-edge properties and assumptions in economic theory. A case in point is the assumption of constant returns to scale, which requires that, if all inputs of production double then output exactly doubles. This assumption has been used routinely to support perfectly competitive markets in a variety of contexts including neoclassical growth theory.[9] Another well accepted knife-edge property is the saddle-path stability condition as shown in the Cass-Koopmans-Ramsey version of the neoclassical growth model and in Segerstrom’s (1998) scale-invariant growth model (among numerous others).

Finally, Temple (2003) points out that in the steady-state equilibrium, the neoclassical growth model allows only labor-augmenting technological progress or the employment of a Cobb-Douglas aggregate production function.[10]

Another defense for the linear relationship between the level of R&D difficulty and the level of population is based on the following conjecture: *For any approach that generates scale-invariant endogenous Schumpeterian growth, there exists a market-based mechanism that determines endogenously the evolution of R&D difficulty.* In the variety-expansion approach, profit-maximization considerations coupled with market-driven free entry of monopolistically competitive firms establish the required linearity between $X(t)$ and the level of population $L(t)$. In the rent-protection approach, the optimal choice of RPAs by the typical monopolist to maximize expected discounted profits

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[9] Incidentally, the argument that endogenous Schumpeterian growth models require knife-edge conditions can be equivalent to criticizing the constant returns to scale property of the knowledge production function. To see this, consider for instance, the variety expansion model of section 2.3. and assume that $\dot{n}(t) = \xi[(L(t)]^{\alpha}$, with $\alpha \neq 1$. It is straightforward to show that the rate of per capita income growth would then equal to $g_y \equiv \ell_A + [\dot{n}(t)/n] - g_L = \phi L(t)^{(1-\alpha)} + (\alpha - 1)g_L$; hence, the scale-effects property would emerge. More specifically, if $0 < \alpha < 1$, then growth increases exponentially as t goes to infinity. If $\alpha = 1$, then $\ell_A = \phi$, and growth is endogenous so long as ϕ can be affected by policy (original case). Finally if $\alpha > 1$, then $g_Y = (\alpha - 1)g_L$ as t goes to infinity. These results are similar to the ones presented in Jones (1999, p.142)

[10] Jones (2003) provides an excellent discussion of this issue.

generates this linear relationship. In contrast, exogenous Schumpeterian growth models assume that the level of R&D difficulty is tied to the level of technology and, therefore, is not directly market determined.

The following remark on the "functional robustness" debate is borrowed from Temple (2003), who offers an excellent and insightful discussion on the long-run implications of growth theory. In the conclusion section of his paper he states the following "Five Obvious Rules for Thinking about Long-Run Growth":

> 1) Remember that the long-run is a theoretical abstraction that is sometimes of limited practical value. 2) Do not assume that a good model of growth has to yield a balanced growth path, or that long-run growth has to be endogenous. 3) Do not dismiss a model of growth because the long-run outcomes depend on knife-edge assumptions. 4) Remember that long-run predictions may be impossible to test. It will be extremely difficult to distinguish between models based on their predictions about long-run outcomes. 5) Do not undervalue level effects.

We fully agree with Temple's point of view that the knife-edge assumptions of endogenous growth models should be seen in a forgiving light and the emphasis should be placed on their comparative statics and especially the welfare properties of Schumpeterian growth models.

These remarks lead us to the following suggestion. Analyzing the steady-state equilibrium properties of Schumpeterian growth models is still very useful because it is simply easier to analyze long-run equilibrium than analyzing the transitional dynamics. We propose a shift from debating the robustness of particular assumptions in specific models to assessing the robustness of policy changes across various models, including those that carry the scale-effects property. For example, consider the current controversial issue of the dynamic effects of globalization on relative wage income inequality between advanced (North) and poor (South) countries. If one models globalization as an increase in the size of the South (motivated by China's entry into the world trading system), then the following three quality-ladders growth models of North-South product-cycle trade provide specific answers to this question: Grossman and Helpman (1991c) using an endogenous Schumpeterian growth model with scale effects find that an increase in the size of the South does not affect the relative wage of Northern workers.[11] Şener (2006) uses a scale-invariant endogenous Schumpeterian growth model based on RPAs to establish that globalization increases the relative wage of Northern workers. Dinopoulos and Segerstrom (2006) employ a scale-invariant exogenous Schumpeterian growth model to establish that an increase in the size of the South reduces the relative wage of Northern workers. Could one trace these different predictions to knife-edge assumptions? We seriously doubt that this can be achieved without examining in more detail the structure of each model.

Our final remark has to do with the terminology employed in the present paper compared to that used by other growth researchers. Following the path-braking work of

[11] They actually consider two regimes: efficient and inefficient followers regimes. Each one has different wage implications. In the efficient followers regime (the more general case), an increase in the size of the South does not change the relative wage. In the inefficient followers regime, the relative wage of North moves in an ambiguous direction as the size of the South expands.

Romer (1990), earlier Schumpeterian growth models established what was called endogenous growth theory. This normative (policy-related) term became quickly popular because it accurately captured the property that in these earlier Schumpeterian growth models policy changes affected long-run per capita growth. In contrast, the neoclassical growth model predicts that per capita long-run growth is policy invariant. The development of scale-invariant growth models generated a class of growth models in which policy changes do not affect long-run growth making the term "endogenous" growth somewhat fuzzy and inaccurate. We believe that the policy-neutral term "Schumpeterian" growth describes accurately and clearly all four classes of growth models and offers the well-deserved and long overdue credit to Joseph Schumpeter.

4. Conclusions

The present paper provided an overview of recent developments in Schumpeterian growth theory, which envisions economic growth through the endogenous introduction of new products and/or processes. A simple theoretical framework was utilized to illustrate the scale-effects property of first-generation Schumpeterian growth models and to describe somewhat more formally the new directions of the theory. Three classes of Schumpeterian models generate scale-invariant long-run growth depending on how the R&D difficulty is modeled. The diminishing technological opportunities approach generates exogenous long-run Schumpeterian growth, whereas the variety-expansion and the rent-protection approaches yield endogenous long-run growth. We offered our own conjecture on what we believe is the distinguishing feature of endogenous and exogenous scale-invariant Schumpeterian growth models: For any endogenous scale-invariant growth approach, there exists a market-based mechanism that directly determines the evolution of R&D difficulty endogenously. One interesting direction of future research is to establish formally the validity of this conjecture.

The development of scale-invariant Schumpeterian growth models draws legitimacy from three important considerations: First, the scale-effects property embodied in earlier models yields the counterfactual prediction that increasing R&D inputs generate higher long-run growth. This prediction is inconsistent with time-series evidence from several advanced countries. Second, in the presence of positive population growth, models with scale effects generate infinite per capita long-run growth. This is clearly unsatisfactory for researchers who are interested in analyzing the long-run properties of growth models. Third, scale-invariant growth models represent another important step towards a unified growth theory that combines the robustness and empirical relevance of the neoclassical growth model and the Schumpeterian mechanism of creative destruction. For instance, Jones (1995b) and Aghion and Howitt (1998, chapter 12) have already developed such integrated-growth models. More work in this exciting and important direction is needed.

We view the first and second generation Schumpeterian growth models as horizontally differentiated approaches to Schumpeterian-growth theory. Time and more research will tell which of these new directions will survive the process of creative destruction. This process has already started with the development of scale-invariant growth models that offer new insights in the fields of public policy, macroeconomics, international economics and economic development. Space limitations do not allow the survey of this rapidly expanding strand of growth literature, and therefore we have to classify this important task as a direction for future research in the field of Schumpeterian economics.

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