Università degli Studi di Salerno
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SEMINAL CONTRIBUTIONS TO THE THEORY OF KNOWLEDGE AND TECHNOLOGICAL CHANGE***

WORKING PAPER 3.188

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***This note has been realized through the financial grants of the research project "The New Industry" realized thanks to P. Persico, Director of Dipartimento di Scienze Economiche e Statistiche (DISES), University of Salerno. We wish to thank P. Persico for this opportunity.

Contents

1 Introduction

There is a large and growing literature on endogenous growth process arising from technological change determined by research and development (R & D). The evolution of the production of new knowledge and technology is the core of R & D–based models.

Recent and important contributions can be found in Romer (1986, 1990), Lucas (1988), Grossman and Helpman (1991), Aghion and Howitt (1992, 1998), Jones (1995), and Abdih and Joutz (2006).

The objective of this paper is to illustrate the models and the growth results given in the seminal papers of Romer (1990), Aghion and Howitt (1992), and Jones (1995). These contributions are based on the following model, namely *the decentralized model*. The economy has three production sectors: a competitive final sector described by a representative firm, an intermediate sector represented by a collection of monopoly firms, and the R & D sector.

The final sector produces one consumption good using labor and a list of goods as inputs. The intermediate sector purchases designs discovered by the R & D sector, and using the purchased designs, transforms capital into goods which are used as inputs in the final production sector. The R & D sector uses the existing stock of knowledge and the labor engaged in R & D to produce new knowledge. Knowledge is the accumulation of designs for the goods that are produced by the intermediate sector.

In Section 2 we present the model given in Romer (1990). In Section 3, we focus on the one presented in Aghion and Howitt (1992). Finally, in Section 4, we analyze the model of Jones. In all of the sections, first, we describe the final production sector, the intermediate sector, and the R & D sector. Second, we provide the corresponding growth implications.

2 Endogenous Technological Change by Paul M. Romer

The model follows the one presented in [18] with technological change. But, in this article, the growth of the economy arises from the behavior of profit–maximizing agents. Therefore, technological change is endogenous rather than exogenous. One of the main contributions of this paper is that, at equilibrium, the stock of human capital devoted to research determines the rate of growth of the economy. The result follows from the fact that the new knowledge depends in a linear way on the existing knowledge, when the amount of research labor is fixed. Under this assumption, "... The model also suggests that low levels of human capital may help explain why growth is not observed in underdeveloped economies ..." (Romer, 1990).

2.1 The final sector

In this article, knowledge or technology is separated in private and public technology. Both are goods for the economy.

Private knowledge or technology is a rival and excludable good, public knowledge or technology is a nonrival and nonexcludable good. A rival good has the property that its use by one firm precludes its use by another firm. A good is excludable if the owner can prevent others form using it.

The stock of public knowledge or technology is a subset of $\mathbb{R}$ denoting the durable goods for which designs have been invented. Let $[0, A] \subseteq \mathbb{R}$ be the stock of public knowledge. A changes as new durable goods are invented. Durable goods are indexed by $i \in [0, A]$.

The final sector is represented by a single price-tacking firm. The final sector produces one output Y. Y is a function of the following variables: L denotes the physical labor used for the production of Y; H_Y is the private knowledge or technology which is represented by the human capital devoted to produce Y; physical capital. The physical capital consists of distinct types of durable goods $x := \{x_i\}_{i \in [0,A]}$, where $x_i \in \mathbb{R}_{++}$ is the quantity of durable good i. The labor L is measured by counts of people engaged to manufacture the final output. The human capital H_Y is measured by years of education or training. The production function is given by

$$Y(H_Y, L, x) := H_Y^{\alpha} L^{\beta} \int_0^A x_i^{1-\alpha-\beta} di \tag{1}$$

where $0 < \alpha + \beta < 1$. This production function is an extension of the Cobb–Douglas production function. The difference from the usual Cobb–Douglas production function is that different types of capital goods are substitutes for each other.

Several simplifications are considered. The first is that the population and the supply of labor are both constant. The second is that the total stock of human capital is fixed and that the fraction supplied to the market is also fixed. Then, H_Y and L are fixed. Therefore, when the price of Y is normalized to unity in every period, the firm's profit maximization problem is the following one.

$$\max_x \int_0^A [H_Y^{\alpha} L^{\beta} x_i^{1-\alpha-\beta} - p_i x_i] di$$

differentiating with respect to x_i, we obtain that for each $i \in [0, A]$

$$p_i = (1 - \alpha - \beta) H_Y^{\alpha} L^{\beta} x_i^{-\alpha-\beta} \tag{2}$$

2.2 The intermediate sector

The sector that produces durable goods is not described by a representative firm. This sector is represented by a collection of monopoly firms. For each durable good $i \in [0, A]$, there is a distinct firm i. Firm i will be the only seller of durable good i. Before commencing the production process, firm i purchases a design for the durable good i from the R & D sector. Moreover, each firm i can convert η units of final output into one unit of durable good i.

If firm i manufactures x_i units of the durable good i, it rents this durable good to the final sector for a rental rate price p_i. The cost is interest cost r on the ηx_i units of output needed to manufacture x_i. Therefore, firm i maximizes its revenue minus variable cost at each period,

$$\max_{x_i} p_i x_i - r\eta x_i$$

Since firm i is the only seller of the durable good i, it will face a downward-sloping demand curve for its durable good generated in the final sector. Then, by (2) we have that firm i's maximization problem becomes

$$\max_{x_i} (1-\alpha-\beta) H_Y^{\alpha} L^{\beta} x_i^{1-\alpha-\beta} - r\eta x_i$$

Differentiating with respect to x_i, the resulting monopoly price is

$$p_i = \bar{p} := \frac{r\eta}{1-\alpha-\beta} \tag{3}$$

for every i. Then, for each $i \in [0, A]$, x_i is associated to $\bar{p}$ by equation (2) in the following way

$$x_i = \bar{x} := \left[\frac{H_Y^{\alpha} L^{\beta}}{r\eta}\right]^{\frac{1}{\alpha+\beta}} \tag{4}$$

Then, each firm sets the same price $\bar{p}$ and sells the same quantity of its produced durable good $\bar{x}$. Since the total capital K is related to the durable goods that are used in the production final sector by the rule

$$K := \eta \int_0^A x_i di$$

then, (4) implies that

$$K = \eta \int_0^A \bar{x} di = \eta A \bar{x} \tag{5}$$

2.3 The R & D sector

One could assume that designs of new durable goods are produced by the same sector which produces durable goods. But, it seems economically reasonable to distinguish the research and development process as a separate firm which provides designs.

The R & D sector produces new knowledge or technology using human capital and the existing stock of public knowledge. Let $[0, A] \subseteq \mathbb{R}$ be the stock of public knowledge. The knowledge evolves according to

$$\dot{A} = \delta H_A A \tag{6}$$

where H_A is the human capital employed in the R & D sector and it is measured by years of education or training, and δ is a productivity parameter. Observe that the output of knowledge depends in a linear way on H_A and A.

One could weak the assumption on the linearity in H_A by considering, for instance, the case in which the new knowledge depends on different incomes for different participants in the research sector. Linearity in A implies that the total factor productivity growth

$$\frac{\dot{A}}{A} = \delta H_A$$

will be proportional to the amount of human capital devoted to R & D.

2.4 Growth implications

The strategy for characterizing the model is to solve for an equilibrium in which the growth rates of all variables (knowledge, total capital and final output) are constant, i.e., for an equilibrium in which the variables A, K and Y grow at a constant exponential rate. This is exactly the definition of *balanced growth equilibrium.* In according to Solow's model such an equilibrium exists if A grows at a constant exponential rate.

By equation (6) we know that

$$\frac{\dot{A}}{A} = \delta H_A$$

Since (5) implies $K = \eta \bar{x} A$, then we have that $\dot{K} = \eta \bar{x} \dot{A}$. Therefore, obviously one gets

$$\frac{\dot{K}}{K} = \frac{\dot{A}}{A} \tag{7}$$

Now, observe that from (1) and (5) we have that

$$Y = H_Y^{\alpha} L^{\beta} \eta^{(\alpha+\beta-1)} K^{(1-\alpha-\beta)} A^{\alpha+\beta}$$

Then, when H_Y and L are fixed, we get

$$\dot{Y} = H_Y^{\alpha} L^{\beta} \eta^{(\alpha+\beta-1)} \left[(1-\alpha-\beta) K^{(-\alpha-\beta)} \dot{K} A^{\alpha+\beta} + (\alpha+\beta) K^{(1-\alpha-\beta)} \dot{A} A^{\alpha+\beta-1} \right]$$

which implies that

$$\frac{\dot{Y}}{Y} = (1-\alpha-\beta)\frac{\dot{K}}{K} + (\alpha+\beta)\frac{\dot{A}}{A}$$

Finally, from (7) we have that

$$\frac{\dot{Y}}{Y} = \frac{\dot{K}}{K} = \frac{\dot{A}}{A}$$

3 A Model of Growth Through Creative Destruction by Phillipe Aghion and Peter Howitt

The model of endogenous growth studied in this paper is characterized by considering *vertical innovation* generated by a competitive R & D sector. Vertical innovation means that industrial innovation consists in improving the quality of existing produced goods. A firm can accumulate knowledge in many different ways, i.e., learning by doing, formal education, process innovations and others. In this paper, knowledge and technology increase improving the quality of existing produced goods. This model of economic growth is based on Schumpeter's process, whereas in Judd (1985), Romer (1990), and Jones (1995), the growth of the economy is based on *horizontal innovation*, in the sense that innovation means the creation of new goods.

3.1 The final sector

The final sector produces one consumption good using labor and one good produced by the intermediate sector. The final sector is represented by a single price-tacking firm and its production function is

$$Y(A, x) := AF(x)$$

where Y is the flow output of consumption good, x is the flow of intermediate good, A is a parameter of productivity of the intermediate input, and F is function such that $F' > 0$ and $F'' < 0$, i.e., F is strictly increasing and strictly concave.

Importantly, observe that the consumption good is produced using a fixed quantity of labor L_Y. For that reason, the above production function does not depend on the quantity of labor used in producing the final consumption good.

If the price of Y is normalized to unity in every period, the firm's maximization problem is

$$\max_x \quad Y - px \qquad \text{subject to} \quad Y = AF(x)$$

where p is the price (relative to the numeraire consumption good) of one unit of the intermediate good. Differentiating with respect to x, we obtain

$$p = AF'(x) \tag{8}$$

3.2 The intermediate sector

The sector that produces the intermediate good is represented by one monopoly firm.[1] Time is continuous. The subscript $t \in \mathbb{N}_0 := 0, 1, 2, ...$ denotes the interval $[t, t+1[$. Let x_t be the flow of the intermediate good produced by the monopolist during interval t. For each interval t, the intermediate good is produced using labor through the following linear production technology,

$$x_t = L_{x_t}$$

where L_{x_t} is the quantity of labor devoted to produce x_t.

Each innovation consists of the invention of a new intermediate good used in producing the final consumption good. Each innovation might consist of a new generation of intermediate good. New intermediate good increases the productivity parameter A previously defined by a real number $\gamma > 1$ as follows

$$A_t = A_0 \gamma^t \tag{9}$$

where A_0 is the initial value.

Since the monopolist is the only seller of the intermediate good, it will face a downward-sloping demand curve for the intermediate good generated in the final sector. Then, at each interval t, the monopolist's objective is to maximize the flow of profit π_t defined by

$$\pi_t := [p_t - w_t]\, x_t$$

where

$$p_t = A_t F'(x_t)$$

is given by (8), taking as given A_t and the wage w_t of labor L_{x_t}. Therefore, at each interval t, the monopolist's maximization problem becomes

$$\max_{x_t} \; [A_t F'(x_t) - w_t]\, x_t \tag{10}$$

[1] Observe that this simplifying assumption is relaxed in Section 8 of [2].

3.3 The R & D sector

Two categories of labor can be used in the research sector: skilled labor and specialized labor. The R & D sector produces innovations through a random process. The Poisson arrival rate of innovations in any interval t is given by

$$\lambda\phi(z, s) \tag{11}$$

where λ is a parameter, z is the flow of skilled labor, s is the flow of specialized labor, and ϕ is a constant–returns, concave production function from $\mathbb{R}^2$ to $\mathbb{R}$. The parameter λ and the function ϕ are connected to the technology of research. Moreover, $\phi(0, s) = 0$.

The aim of the R & D sector is to choose, at each interval t, z and s to maximize the following flow of expected profits from research,

$$\lambda\phi(z, s)V_{t+1} - zw_t - sw_t^s \tag{12}$$

where V_{t+1} is the value of the $t+1$–st innovation, w_t is the wage of skilled labor, and w_t^s is the wage of specialized labor.

For each t, denote (n_t, R_t) the solution of the above maximization problem. It can be shown that for each interval t, at equilibrium, $R_t = R$ where R is the total flow of specialized labor, and that the value V_{t+1} is given by

$$V_{t+1} = \frac{\pi_{t+1}}{r + \lambda\phi(n_{t+1}, R)} \tag{13}$$

where π_{t+1} is the flow of intermediate sector's profit and r is a parameter.

From the Kuhn–Tucker conditions associated with the maximization problem (12), it follows that

$$\phi'(n_t, R)\lambda V_{t+1} \leq w_t \text{ and } n_t \geq 0 \tag{14}$$

with at least one equality, where n_t is the flow of skilled labor used in research during interval t which solves problem (12). Observe that the function ϕ is increasing in the flow of skilled labor employed in the research sector, i.e., $\phi'(n_t, R) > 0$. By (13) and (14) we have that

$$\frac{\pi_{t+1}}{r + \lambda\phi(n_{t+1}, R)} \leq \frac{w_t}{\lambda\phi'(n_t, R)} \tag{15}$$

with at least one equality.

3.4 Equilibrium and evolution implications

An equilibrium is defined by a sequence $(x_t, n_t)_{t\in\mathbb{N}_0}$ such that, at each interval t, x_t solves the maximization problem (10), n_t satisfies equation (13), and the sum $x_t + n_t$ is constant, that is

$$x_t + n_t = N \tag{16}$$

for each interval t. It can be shown that, at equilibrium, condition (15) implies that the research employment at t is a function of the research employment at $t+1$, that is

$$n_t = \psi(n_{t+1})$$

where ψ is a strictly decreasing function from $[0, N)$ to $\mathbb{R}_+$.

It follows from the equilibrium condition (16) that at equilibrium x_t is univocally determined when n_t is known. Then, from now on we focus on two concepts of equilibrium that involve only $(n_t)_{t \in \mathbb{N}_0}$.

A perfect foresight equilibrium (PFE) is defined as a sequence $(n_t)_{t \in \mathbb{N}_0}$ such that

$$n_t = \psi(n_{t+1})$$

for each $t \in \mathbb{N}_0$. A stationary equilibrium corresponds to a PFE with n_t is constant. It is defined as the solution to

$$\hat{n} = \psi(\hat{n})$$

For a stationary equilibrium the flow of the consumption good produced by the final sector is given by

$$Y_t = A_t F(N - \hat{n}) \tag{17}$$

for each $t \in \mathbb{N}_0$. By (9) the flow of the consumption good produced during interval $t+1$ depends in a linear way of the flow of consumption good produced during interval t. Then, we obtain $Y_{t+1} = \gamma Y_t$.

4 R & D–Based Models of Economic Growth by Charles I. Jones

The model presented here is a modified version of the Romer (1990) model. Differently from Romer, the R & D–based growth is "semi-endogenous" in the sense that, at equilibrium, the growth of the economy is a function of parameters that are usually taken to be exogenous (including the growth rate of research labor). This key conclusion follows from the fact that the production of knowledge depends on parameters which measure the dependence of research productivity on the stock of existing knowledge and on the amount of research labor.

4.1 The final sector

The stock of knowledge is a subset of $\mathbb{R}$ denoting the durable goods for which designs have been invented. Let $[0, A] \subseteq \mathbb{R}$ be the stock of knowledge. A changes as new durable goods are invented. From now on, let these durable goods be indexed by $i \in [0, A]$.

The final sector is represented by a single price-tacking firm. The final sector produces one output Y using as inputs $x := \{x_i\}_{i\in[0,A]}$, where $x_i \in \mathbb{R}_{++}$ is the quantity of durable good i, and labor L_Y. L_Y is measured by counts of people engaged to produce output Y. Specifically, output is produced according to the following production function,

$$Y(L_Y, x) := L_Y^{\alpha} \int_0^A x_i^{1-\alpha} di \tag{18}$$

where $0 < \alpha < 1$. Observe that since invention of new designs corresponds to increase the stock of knowledge, then technology changes as knowledge increases.[2]

When the price of Y is normalized to unity in every period, the firm's profit maximization problem is the following one

$$\begin{array}{ll} \max\limits_{(L_Y,x)} & Y - (wL_Y + \int_0^A p_i x_i di) \\ \text{subject to} & Y = L_Y^{\alpha} \int_0^A x_i^{1-\alpha} di \end{array}$$

where w is the wage paid to labor in the final good sector and p_i is the rental price for the durable good i. Solving the above profit maximization problem, one deduces that

$$w = \alpha \frac{Y}{L_Y}$$

and

$$p_i = (1-\alpha) L_Y^{\alpha} x_i^{-\alpha} \tag{19}$$

4.2 The intermediate sector

As in [13], the sector that produces durable goods is represented by a collection of monopoly firms, and for each durable good $i \in [0, A]$, there is a monopoly firm i.[3] Differently from [13], it is assumed that the firm can transform each unit of capital into a single unit of the input and that the durable good produced can be transformed back into capital at the end of the period. Moreover, it is assumed that there is no depreciation for the durable goods.

Capital is rented at rate r for the period. If firm i produces x_i units of the durable good i, it rents this durable good to the final sector for a rental rate p_i. Then, the firm i solves the following maximization problem

$$\max_{x_i} \quad p_i x_i - r x_i$$

[2] Note that this production function is in the spirit of [5].

[3] See Subsection 2.2.

Since firm i is the only seller of the durable good i, it will face a downward-sloping demand curve for its durable good generated in the final sector. Therefore, by (19) we obtain the following equations for price and quantity.

$$p_i = \bar{p} := \frac{r}{1-\alpha}, \quad \text{for every } i$$

$$x_i = \bar{x} := \left[\frac{(1-\alpha)L_Y^{\alpha}}{\bar{p}} \right]^{1/\alpha}, \quad \text{for every } i \tag{20}$$

Then, as in [13], each firm sets the same price and sells the same quantity of its durable good. Since the capital stock is

$$K := \int_0^A x_i di$$

then, (20) implies that

$$K = \int_0^A \bar{x} di = A\bar{x} \tag{21}$$

4.3 The R & D sector

The R & D sector generates new knowledge or technology. Knowledge is the accumulation of ideas and designs which are developed by people attempting to discover new ideas and designs.

Let $[0, A] \subseteq \mathbb{R}$ be the stock of knowledge in the economy. The change in knowledge is given by

$$\dot{A} = \widetilde{\delta} L_A \tag{22}$$

where L_A is the number of people engaged to produce new knowledge and $\widetilde{\delta}$ is the rate at which R & D generates new knowledge. In this paper the rate $\widetilde{\delta}$ at which researchers discover new ideas depends on knowledge A in a non-linear way. Especially, it is analyzed the case in which

$$\widetilde{\delta} := \delta A^{\phi} \tag{23}$$

where δ and ϕ are constant parameters. The parameter ϕ measures the degree of dependence of current research productivity on the stock of ideas already discovered. When $\phi < 0$ ($\phi > 0$), the rate of innovation decreases (increases) with the stock of existing knowledge. When $\phi = 0$, the rate of new ideas is independent of the stock of ideas already discovered.

Finally, consider the case in which the rate of innovation given in (23) depends on the number of people engaged to produce new knowledge. In particular, suppose that

$$\widetilde{\delta} := \delta L_A^{\lambda-1} A^{\phi}$$

where $0 < \lambda \leq 1$. The parameter λ measures the degree of dependence of research productivity on the number of people engaged to produce new knowledge L_A. When $0 < \lambda < 1$, the rate of innovation $\widetilde{\delta}$ decreases with L_A.

By (22), we have that the change in knowledge is given by

$$\dot{A} = \delta L_A^{\lambda} A^{\phi}$$

Observe that for $\phi = 1$ and $\lambda = 1$, the knowledge evolves as in (6) which is the case considered in [13]. From the last equation, the growth of the stock of knowledge is

$$\frac{\dot{A}}{A} = \delta \frac{L_A^{\lambda}}{A^{1-\phi}} \tag{24}$$

4.4 Growth implications

Along the balanced growth path, the growth rate of knowledge is constant by definition.[4] Then, by (24) we have that

$$\frac{L_A^{\lambda}}{A^{1-\phi}} = \gamma$$

where γ is a constant. Differentiating both sides of the above equation allows to solve the balanced path growth rate of knowledge. Indeed, we have that

$$\lambda L_A^{(\lambda-1)} \dot{L}_A A^{(1-\phi)} - (1-\phi) L_A^{\lambda} A^{-\phi} \dot{A} = 0$$

If $\phi \neq 1$, then one obtains

$$\frac{\lambda}{(1-\phi)} \frac{\dot{L}_A}{L_A} = \frac{\dot{A}}{A}$$

that is

$$\frac{\dot{A}}{A} = \frac{\lambda n}{1-\phi} \tag{25}$$

where n is the growth rate of the labor force to produce new knowledge.

Since (21) implies $K = \bar{x}A$, then we get $\dot{K} = \bar{x}\dot{A}$, that is

$$\frac{\dot{K}}{K} = \frac{\dot{A}}{A} \tag{26}$$

Now, observe that from (18) and (21) we have that

$$Y = L_Y^{\alpha} K^{1-\alpha} A^{\alpha}$$

[4] See Subsection 2.4.

Then, when L_Y is fixed, one gets

$$\dot{Y} = L_Y^{\alpha}\left[(1-\alpha)K^{-\alpha}\dot{K}A^{\alpha} + \alpha K^{1-\alpha}A^{\alpha-1}\dot{A}\right]$$

which implies that

$$\frac{\dot{Y}}{Y} = (1-\alpha)\frac{\dot{K}}{K} + \alpha\frac{\dot{A}}{A}$$

Finally, from (25) and (26) we have that

$$\frac{\dot{Y}}{Y} = \frac{\dot{K}}{K} = \frac{\dot{A}}{A} = \frac{\lambda n}{1-\phi}$$

This equation states that along the balanced growth path, the growth rate of the economy depends on the growth rate of the labor force to produce new knowledge, and on the parameters λ and ϕ which determine the external returns in the R & D sector.

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Finito di stampare il 17 luglio 2007