OLD AND NEW THEORIES OF ECONOMIC GROWTH (II Part)

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Abstract: *In this article an attempt has been made to give comparative analysis of old and new theory of economic growth. The field of economic growth has became again very dynamic and very interesting after appearance of seminal Romer's 1986 and Lucas's 1988 articles, which initiated so called new theory of economic growth, sometime termed as theory of endogenous technological progress. This new theory, in some very important issues, stands in a sharp contrast with the old neoclassical version of theory of economic growth, which similarly can be termed as the theory of exogenous technological progress Apart from the introduction and the concluding section, core of the article is presented in four sections. In first of them exposition of old version of neoclassical growth theory is given. In the following 3 sections survey of new theory is given. Version that eliminates assumption of diminishing returns to capital is discussed first. Than, version that uses human capital as engine of growth is presented. After that, models that use R&D as engine of growth is discussed. Models with spillovers from international trade are also shortly presented.*
Key words: *Economic growth, Endogenous models, Diminishing returns, Human capital*

Apstrakt: *U ovom članku je učinjen pokušaj da se da komparativna analiza stare i nove teorije privrednog rasta. Disciplina ekonomskog rasta je ponovo postala vrlo dinamična i interesantna nakon pojavljivanja odlučujućih članaka Romera iz 1986 i Lukasa iz 1988, koji su inicirali takozvanu novu teoriju privrednog rasta, ponekad nazivanu i teorija endogenog tehnološkog progresa. Ova nova teorija, u nekim vrlo važnim pitanjima, stoji u oštrom kontrastu sa starom neoklasičnom verzijom teorije privrednog rasta, koja slično može biti nazvana teorija egzogenog tehnološkog progresa. Pored uvodnog i zaključnog odeljka jezgro članka je dato u četiri odeljka. U prvom od njih izložena je stara verzija neoklasične teorije privrednog rasta. U naredna tri odeljka dat je pregled nove teorija rasta. Verzija koja eliminiše opadajuće prinose na kapital je prva prezentirana. Zatim, je data verzija kod koje ljudski kapital predstavlja mašinu rasta. Nakon toga je data verzija kod koje su ulaganja u istraživanje i razvoj mašina rasta. Modeli sa prelivanjima iz međunarodne trgovine su takođe ovde kratko prezentirani.*
Ključne reči: *ekonomski rast, endogeni modeli, opadajući prinosi, ljudski kapital*

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4. Endogenous models with R&D capital

1. In order to understand meaning of *knowledge* and *capital of knowledge* it is very important to make distinction between *knowledge* and *human capital*. Very often two terms are used as synonyms. However, there is an important difference. Knowledge refers to society's understanding about how the world function. Human capital, on the other hand, refers to cumulative of all resources devoted to transferring this understanding to the labor force. Or, to put it more illustratively, knowledge can be seen as the quality of society's textbooks, while human capital can be viewed as amount of time that has been spent (by population) reading this books [Mankiw (1995)]. More importantly, it seems that, while accumulation of human capital can be reasonably assumed to exhibit diminishing return, accumulation of knowledge does not encounter this problem. Consequently, accumulation of knowledge can be regarded to be most important sources of perpetual sustained growth.

It is also important to make distinction between autonomous research, mainly basic, fundamental research and part of applied research, on the one side, and those research that are mainly devoted to discovery of new and / or modification of old products and / or production process (R&D), on the other side. Results of basic research are regarded to be entirely *non-rivalry* goods (use of this goods from one agent do not have influence on quantity of goods used by other agents) and *non-excludable* goods (producer / owner can not exclude other agents from using them). In other words, results of basic research are regarded as *pure public goods*. For those reasons, possible private investors are not able to appropriate benefits from investment in basic research. Private rate of return is negligible compared to social rate of return, which is enormously large. In other words, although socially desirable, investments in basic research are impossible under private arrangements and market mode of transaction. For that reason, investments in autonomous and basic research are responsibility of government and public sector. Great economic importance of investment in basic research come from a fact that results of a basic research represent main input of R&D activities.

On the other hand, R&D investments are usually left to private sector and market mode of transaction. It doesn't mean, however, that *excludability* is absolute, and that, therefore, apropriability of benefits is satisfactory here. On the contrary, apropriability is far from being satisfactory. There are always possibilities to imitate new products and production process and to overcome different property rights limitations (patents). External effects in the form of spillovers are overwhelming phenomena here. For that and some other reason (increase in consumer surplus that is appropriated by consumers, for example), private rate of return are smaller than social rates of returns. Consequently, level of R&D investment is sub-optimal under purely private arrangements. Government intervention, in form of subvention, is necessary in order to increase level of R&D investment. Facts speak by itself: approximately 20% to 30% of all R&D performed by private sector in modern market economies are financed by federal or local governments.

Earlier mentioned point on non-diminishing returns of knowledge accumulation, is important not only in making distinction between human capital and knowledge, but also in making distinction between new and *traditional approach in analyzing of R&D influences on economic growth*. In fact, first efforts to explain growth rate and especially to break Solow's residual by usage of some sort of R&D capital had been made by traditional theorist like Mansfield (1968, 1971, 1977), Kendrick (1973, 1981), Griliches (1980, 1984) and other. However, their efforts have two important shortcomings. First is already mentioned: they implicitly assumed that investment in R&D knowledge exhibit *diminishing return* like conventional investment in physical capital. In fact they introduced R&D capital in production function in exactly the same way in which physical capital is introduced. They simply added it as new factor of production. Its influence on growth rate is than measured as a multiple of its growth rate and elasticity of production with respect to R&D capital. R&D elasticity is, like in the case of conventional factors, measured as share of R&D in GNP. Such procedure, of course, involves certain changes in accounting of gross domestic product, capital and so on. Obvious consequence of this growth accounting practice is augmentation of contribution of overall capital (conventional + human + R&D) to economic growth. However, owing to diminishing rate of return property, R&D capital introduced in that way cannot be regarded as a source of sustained, perpetual growth.

Second shortcoming, which is in fact connected with previous one, is even much less understandable. The way in which R&D capital is measured is wrong. It can even produce negative rate of growth of knowledge and it is obviously impossible. R&D capital is measured using *perpetual inventory procedure*, that is, it is measured as a cumulative of investment in R&D committed in the past which positive influences are still present now. Problems lay in a fact that they assumed, and in same cases calculated using fancy econometric technique, that R&D capital exhibit depreciation. So, if gross investments in R&D in certain period are less than depreciation of R&D capital, result will be negative rate of growth of knowledge and it is, as we already mentioned, impossible. Justification for accounting of R&D depreciation is found in a fact that owners (producers) of some innovation, because of external effects and spillovers, by passage of time lose ability to appropriate benefits from his investment in that innovation. Eventually their profit from that investment drops to zero. It is clear that this procedure can be legitimately used in explaining inter-firm differences in efficiency. But it cannot be used in sources of growth analysis. Changes in distribution of benefits from innovations have noting to do with changes in quantity of knowledge. Attenuation of property rights of initial owners of innovations is not depreciation of productive power of knowledge. To see the mechanism of endogenous models with R&D investment, in what follow we will present celebrated Romer (1990) model of growth.

2. Inclusion of the theory of technological progress into the neoclassical framework was not easy task because standard competitive assumptions were not easy to maintain. In fact, the return to scale of the production function tends to increase if technology A_t is introduced as factor of production, like in original Solows' model, $Y_t = K_t^a (A_t L_t)^{(1-a)}$. Different earlier attempts to overcome this difficulty by Shell, by treating knowledge as publicly provided good, or by Arrow and Shesinski, by treating knowledge as a by product of "learning by doing", have not captured the basic idea of deliberate efforts of economic agents to develop new products and technologies. Introduction of intentional R&D activities in analysis of growth and the fact that firm may enjoy exclusivity of their inventions via the usage of patent based or other kind of intellectual property rights should be followed with departure from competitive assumptions framework characteristic for neoclassical growth theory. In other words, appropriate market (decentralized) theory of technological progress requires basic changes in neoclassical model in order to introduce imperfect competition. This was first time done in models of growth developed by Paul Romer (1986, 1987, 1990, 1994, 1997). In what follow, we will present somewhat modified, see Ribeira, Maria-Joao, 2003, Romers' celebrated 1990 model.

As far as consumer preferences are regarded, Romer (1990) assume that representative consumer, faced with his budget constraint, maximize same function used earlier in this article (equation (14) and (15))

$$Max \int_0^\infty U(C_t) e^{-\rho t} dt \;\; ; \; U(C_t) = \frac{C_t^{1-\sigma}}{1-\sigma} \qquad \sigma > 0$$

Representative consumer faced with constant interest rate, *r,* chooses to have consumption that grows at constant rate g_C derived from Euler equation[1]

$$g_C = \frac{\dot{C}}{C} = \frac{1}{\sigma}(r - \rho) \tag{69}$$

Production, on the other side, is described in the following way. There are 3 sectors of production in this model: the final good sector, the capital goods sector, and the R&D sector. The *final good sector* uses as inputs fraction of labor that work in final goods sector, L_Y, and number of durable goods from set of A_t differentiated durable capital goods. Number of differentiated durable goods, A_t, increases with technological progress. In other words, technological progress is understood as a process of differentiation of capital goods used by final god producers. Each of durable goods, *i*, is produced in quantity *x(i)*. All those capital goods have additively separable effects on output.

Having above in mind production function is of the form

[1] For proof se Appendix 1 of this article (Part I).

$$Y_t = L_{Yt}^{(1-a)} \int_0^{A_t} x_t(i)di \qquad (70)$$

This production function obviously, for constant A_t, shows constant return to scale in L_Y and $x(i)$, and diminishing return to scale in $x(i)$, for fixed L_Y. However, A_t is in this model not constant. This is produced by third sector (R&D), so that increase in A_t prevent the tendency for diminishing returns in $x(i)$ for constant L_Y. This is what delivers endogenous growth in the model. Capital accumulation, that is development of capital goods, is given as usual by

$$\dot{K}_t = Y_t - C_t$$

Under assumption that it takes one unit of foregone consumption to produce one unit of any type of capital good, K_t is related with capital goods following next equation

$$K_t = \int_0^{A_t} x_t(i)di$$

Accumulation of new knowledge in the form of new design, that is production function of R&D is given in following way

$$\dot{A}_t = bL_{At}A_t \qquad (71)$$

where L_A presents fraction of labor engaged by R&D sector, while b present efficiency parameter of R&D sector. Let's stress again that technological progress is understood here as a process of differentiation of capital goods used by final god producers. This idea is obviously borrowed from theory of monopolistic competition, and it seems to be very good description of what is really happening here. Whole history of technological progress, especially from industrial revolution seems like never ending process of differentiation of human activities. This differentiation is sometimes termed as deepening of division of labor. It is known and very often stressed that it has been causing development of market – domestic and international. But it also has been causing development, what was not very often noticed, of hierarchical structure within companies. Last fact become evident with newest IT revolution which, on the one side, bring flattering of hierarchical structure of existing companies, and, on the other side, started developing new fields of division of labor. So, both, development of market and increase of hierarchical structure had been results of differentiation of human activities.

Variables L_Y and L_A are obviously related in following way that present constraint in model

$$L_t = L_{At} + L_{Yt}$$

From equation (71) it follow that all researchers have free access to the total stock of knowledge A_t. Obviously, knowledge influences production process in two different ways. First, a new design enters final goods production function via new capital goods used in this sector. Second, it stands as input in R&D sector production function: new design increase stock f total knowledge and in that way increase productivity of workers engaged in R&D sector.

The owner of design has property rights over the production of particular designed capital good, but not over the usage of particular design that is over the knowledge embodied in it. All researchers in R&D sector can freely use this knowledge. In other words, knowledge is *non-rival good* that is *partially excludable* and *privately provided.* This interpretation seems to disregard previously mentioned problem of apropriability, which limit even owner's rights over the production of particular designed capital good, but this would not be difficult to introduce this assumption as well.

To conclude, equation (71) is based on tree assumptions. First, it assume that devoting more labor to R&D sector leads to higher growth rate of A_t. Second, higher total stock of knowledge, A_t, implies higher marginal productivity of researchers. Finally, third, production function of R&D sector is linear in A_t. This is assumption that makes possible the existence of a balanced growth path.

Assuming now perfect competition environment, we can imagine final good producers renting each capital good according to next profit maximization rule

$$\frac{dY_t}{dx_t(i)} = R_t(i)$$

where $R_t(i)$ stands for the rental price of i-th capital good. Consequently, each capital good producer is faced with inverse demand curve of the following form

$$R_t(i) = aL_{Yt}^{(1-a)} x_t(i)^{(a-1)} = a[L_{Yt} / x_t(i)]^{(1-a)} \quad (72)$$

With given value of r and L_Y , each capital good producer has already made the fixed cost investment in a design, P_A. Of course, he has a patent protection on it, and he will maximize its revenue minus variable cost at every date. Formally

$$Max\pi_t(i) = R_t(i)x_t(i) - r_t x_t(i)$$

This monopolistic competitor is faced with constant marginal cost and constant elasticity demand curve. He will solve his problem by charging monopoly prices, which are markups over marginal costs. The markup is defined by the elasticity of demand *(a-1)*

$$Max\pi_t(i) = aL_Y^{(1-a)} x(i)^a - rx(i)$$

$$\frac{d\pi(i)}{dx(i)} = a^2 L_Y^{(1-a)} x(i)^{(a-1)} - r = 0$$

$$R(i) = \frac{r}{a}$$

The point is that firm incurs a fixed cost when it produces a new capital good. It recovers the cost later when it sells its good for a price $R_t(i)$ that is higher than its constant marginal cost. Obviously, decision to produce new capital good depends on comparison between discounted stream of net revenues which the patent on this good will bring in the future and the cost, P_A, of the initial investment in design. This R&D costs are supposed to be entirely paid in the initial point of time, before profit can be earned. This is what brings natural dynamics in the model.

If market for design is competitive, than at every date t the price for design will be equalized to the present value of the future revenue that monopolist can extract. Consequence is that capital good producers earn zero profit in the present value sense. The dynamic zero-profit condition (free entry condition) is than

$$P_{At} = \int_t^{+\infty} e^{-r(\tau-t)} \pi_\tau(i) d\tau \quad (73)$$

$$\dot{P}_{At} = r_t P_{At} - \pi_t(i)$$

This equation can be arranged in bit proper way to give

$$r_t P_{At} = \pi_t(i) + \dot{P}_{At}$$

It can be interpreted in following way. Firm can choose between two options. First, it can put the monetary value P_A in bank and earn interest on deposit, $r_t P_{At}$. Second, firm can buy a patent for the same value and earn the return of producing differentiated good, $\pi_t(i)$, plus the capital gain (loss) of owing that value, $\dot{P}_{At}$. This presents, well-known Fischer equation in this model.

According to Euler equation (69) in the balanced growth path interest rate should be constant. Consequently, same applies for *R(i)*.

Since all producers have same technology and face the same market conditions they will choose the same equilibrium. This implies that $R(i) = \overline{R} = R$ and $x(i) = \overline{x} = x$. Than expressions for R_t and x_t can be rewritten as

$$R_t = aL_{Yt}^{(1-a)} x_t^{(a-1)}$$

and from (72) and maximizing conditions

$$x_t = L_{Yt} \left[\frac{a^2}{r} \right]^{\frac{1}{1-a}}$$

From those equations we can conclude that at balanced growth path, with L_Y constant, x is also constant.

Since, by assumption, all capital goods producers produce same quantity of capital goods, total physical capital should be equal to

$$K_t = \int_0^{A_t} x_t(i) di = A_t x_t$$

and, consequently, production function can be rewritten as

$$Y_t = L_{Yt}^{(1-a)} A_t x_t^a$$

With L_Y and x constant than, from this two equation, we can conclude that output and capital should grow at the rate of growth of A, g_A.

Production function can further be transformed to give

$$Y_t = L_{Yt}^{(1-a)} A_t x_t^a = L_Y^{(1-a)} (Ax)^a A^{(1-a)}$$

$$Y = K^a (L_Y A)^{(1-a)}$$

which is similar to original Solow's (1957) production function.

The marginal productivity of capital is here equal to

$$\frac{dY}{dK}=\frac{aL_Y^{(1-a)}A^{(1-a)}}{K^{(1-a)}}$$

It is obvious that for L_Y constant and for capital growing at the same rate as A, marginal productivity of capital should be constant. So, model brings sustained balanced growth in the same way as Solow's model. It is the role of technological progress to overcome the diminishing returns of capital. However, while in Solow's model technological progress is exogenously determined in Romer model it is determined within model. So, let us see how its rate of growth is endogenously determined.

As we know the engine of growth is given by equation (71), which implies

$$g_A=bL_{At}$$

meaning that rate of growth of technological progress, apart from technological efficiency (b), depends on the number of people employed in R&D sector. From equation (71) we conclude that balanced growth path solution, that is solution with constant rate of growth, require that L_A remains constant. Consequently, balanced growth path solution requires that prices and wages are such that L_A and L_Y remain constant as A, K, Y and C grow at a constant rate of growth.

Having in mind competitive labor market, wages in both sectors should be same. In the final good sector the wages paid to L_Y should be

$$w_{Yt}=\frac{dY_t}{dL_{Yt}}=(1-a)L_{Yt}^{-a}A_t x_t^a$$

while in research sector they should be

$$w_{At}=\frac{d\dot{A}_t}{dL_{At}}P_{At}=bA_tP_{At}$$

Their equality imply that

$$P_{At}=\frac{1-a}{b}L_{Yt}^{-a}x_t^a \tag{74}$$

From (74) it follows that, since L_Y and x are both constant, P_{At} must also be constant, that is $(dP_A/dt)=0$. Having this in mind we conclude that zero-profit condition (73) implies

$$0=r_tP_{At}-\pi_t(i)$$
$$r=\frac{\pi}{P_A} \tag{75}$$

Now, from equation (72) and the markup rule $R(i)=r/a$, we can rewrite the profit expression as

$$\pi=Rx-rx=(1-a)aL_Y^{(1-a)}x^a \tag{76}$$

Replacing expressions (76) and (74) in expression (75) we get

$$r=\frac{\pi}{P_A}=\frac{(1-a)aL_Y^{(1-a)}x^a}{\frac{1-a}{b}L_Y^{-a}x^a}$$
$$r=baL_Y \tag{77}$$
$$L_Y=\frac{r}{ba}$$

From above it follows that rate of growth of technology must be

$$g_A=bL_A$$
$$g_A=b(\overline{L}-L_Y) \tag{78}$$
$$g_A=b\overline{L}-\frac{r}{a}$$

As already told output and physical capital should grow at the same rate as A_t. From capital accumulation equation we can see that consumption C_T should also grow at the same rate. In fact, from capital accumulation equation $\dot{K}=Y-C$, it follows that $\frac{\dot{K}}{K}=\frac{Y}{K}-\frac{C}{K}$

Constant K, $dg_K/dt=d\left(\frac{\dot{K}}{K}\right)/dt=0$, implies that $\frac{\dot{Y}}{K}=\frac{\dot{C}}{K}$. Now because of $g_Y=g_K$, we arrive at

$$\frac{\dot{C}}{C}=\frac{\dot{K}}{K}$$

Finally, with constant population and labor force we will have balanced path rate of growth to be

$$g_c = g_y = g_k = g_A = g_K = g_C = g_Y = g$$

which, as we know, is

$$g = g_A = b\overline{L} - \frac{r}{a} \tag{79}$$

Equation (79), which represents *(r, g)* pairs of balanced growth path on production side and which shows negative relationship between growth rate and interest rate, can be termed as Technology curve. To understand this relationship recall that firms benefits from investing labor in R&D activity can be presented as a discounted, present value of a stream of net-revenue that new design generate into the future. On the other hand, its' opportunity cost can be measured with wage rates in final goods sector. If the interest rate increases, present value of net revenue stream decrease (because of higher discount rate) and consequently labor shift from R&D to final good sector causing decrease of growth rate.

Euler equation (69), on the other hand, represents *(r, g)* pairs of the balanced growth path on the consumer side. Relationship between interest rate and growth rate is here positive and this curve can be called the Preference curve.

General equilibrium growth path for the economy is now obtained where two curve intersect (see Figure 4).

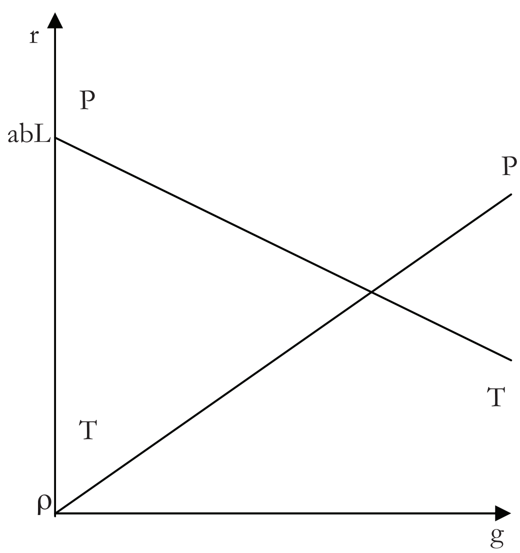

Figure 4.

In order to avoid growth rate to be greater than the interest rate, otherwise present value of benefits would not be finite, certain restriction on parameters should be imposed (Rivera-Batiz and Romer, 1991). These restrictions always hold if $\sigma \geq 1$, which means that preference curve (P) lies above or on 45° line.

The equilibrium growth rate is solution of system of two equations, (69) and (79), and two unknown, *r* and *g*.

$$\begin{cases} g = b\overline{L} - \dfrac{r}{a} \\ g = \dfrac{1}{\sigma}(r - \rho) \end{cases}$$

Solution is

$$g = \frac{ab\overline{L} - \rho}{a + \sigma} \tag{80}$$

It is clear from this solution (80) that balanced path growth rate depend, first, on preference parameters, ρ and σ. If any of them decrease Preference curve from above figure will shift to the left and growth rate will increase. Second, it depend on the technology parameter *a* which present elasticity of production with respect to capital. Third, it depends on parameter *b,* which present efficiency of R&D sector. Finally, and most interestingly, growth rate is proportional to the total labor force, *L*. This proportionality is known as scale-effect property. Source of this effect is in equation (71) for R&D production function, which assumes technological progress to be proportional to labor force allocated at R&D sector. Matched with assumption that constant share of labor force is dedicated to R&D activity, this gives proportionality of total labor force and rate of growth. This property is in contradiction with empirical reality. For example, it implies that integration of two economies with equal population will, more than realistically, increase growth rate of newly integrated economy by twice. New generations of R&D models are avoiding this problem.

It can be shown that above described equilibrium growth rate is not optimal[2]. There are two reasons or sources of this non-optimality.

[2] Derivation of the "Solution for the social planner version of this model" is given in the Appendix at the end of the paper (Part I).

First, source lays in the fact that capital goods producers impose prices, which are higher than their marginal costs. Markup rule is, as we know, $R = r / a$. We also know from expression (72) that $R = aL_Y^{(1-a)} x^{(a-1)}$. Marginal productivity of capital is

$$\frac{dY}{dK} = \frac{aL_Y^{(1-a)} A^{(1-a)}}{K^{(1-a)}} = \frac{aL_Y^{(1-a)} A^{(1-a)}}{(Ax)^{(1-a)}}$$

$$\frac{dY}{dK} = aL_Y^{(1-a)} x^{(a-1)}$$

From above it follows that

$$r = aR = a\frac{dY}{dK}$$

In other words, capital is paid less than its' marginal productivity.

Second source of non-optimality in this model is the presence of externality generated by the fact that the individual decision to invest in R&D does not take into the account fact that ongoing research will benefit other R&D activities and projects, which is obvious from R&D production function..

3. Newest generations of endogenous growth models are much more radical than those outlined previously. In fact, it can be stated, following Romer (1994), *that all above given models belong to Marshalian tradition,* while those of newest generation belong to *Shumpeterian traditions*. All models of Marshalian tradition, more or less, recognize following four facts:

First, there are *many firms* in economy (competition and price taking);

Second, discoveries are *non-rival* goods;

Third, it is possible to *replicate physical activities* (it is not necessary to replicate discoveries in order to replicate output, because of their non-rival nature);

Finally, forth, discoveries and corresponding *technological advance comes from peoples deliberate activities* (they are not function of time).

In order to preserve above assumptions and to overcome, at the same time, pessimistic prediction of Ricardo and especially Maltus, Marshal introduced concept of increasing returns that were regarded to be external to individual firms. (Needless to say, this concept of externality differs from modern one.) In this way, using concept of increasing returns, Marshal secured downward sloping shape of supply (marginal cost) curve for an industry with many firms. Downward sloping shape of supply curve, on the other hand, was guarantee for sustained growth. In Solow's (1956) model same role - sustained growth - is played by exogenously given technological progress. However, this exogenity violates above given fact no. four, and, in that way, makes theory less realistic.

Previously developed endogenous growth models, as we already know, recognize all four facts. It can be stated that Arrow's (1962) model of learning by doing presents first attempt to formalize Marshal's ideas recognizing those four facts. In order to make comparison with Solow's and Neo-Shumpetarian models easier, his model, following Romer (1994), can be stylized and simplified to

$$Q_i = A(\sum_0^t I_v) F(K_i, L_i) = A(\sum_0^t I_v) K_t^a L_t^{(1-a)}$$

where subscript i stand for specific firm. Obviously, output of some firm, Q_i, is, in this model, determined not only with firms labor, L_i, and capital, K_i, but also by the externally determined level of technological knowledge $A(\sum_0^t I_v)$. As we can see, level of knowledge, in this model of learning by doing, is *endogenously defined*: it is determined by *cumulative of investment of all firms in industry* and not just by existing capital of corresponding firm. More importantly, it is available to all firms in industry: it has *property of non-rivalry*. Following same manner, Lucas (1988) model can be described as one in which externally determined level of knowledge is function of all human capital in society, *A(H)*. In Romer's (1986) first version of spillover growth model externally determined level of knowledge is function of all R&D committed by society, *A(R)*, while in one latter version of spillover growth model it is function of society's labor and capital.

We already noted that newest generations of endogenous growth models are much more radical than those outlined above.[3] They belong to so called *Shumpeterian tradition*. In fact, following Romer (1994), we can say that those models of growth are trying to recognize facts

[3] Most prominent of those kind of works are contribution by Judd (1985), Romer (1990), Aghion and Howitt (1992), Grossman, and Helpman (1989, 1991), and other.

that *many individuals and firms have market power and earn monopoly rents on discoveries.* This is, according to Romer (1994), fifth important fact that must be taken in consideration in order to get realistic picture of growth. It is important to note that, although those models leave assumption of perfect competition, they do it by not violating fact 1, that is assumption of existence of many firms in a market economy. They belong to a class of aggregate models with many firms (fact 1), each of which could have market power (fact 5).

Basically R&D undertaken by the firm and resulting innovations, as seen in this class of models, can help firm to become *temporary market leader* and, in that way, to earn *stream of monopoly rent* as a reward for it's research investment. It can be done in several ways. First, it can *improve quality of intermediate or final goods* produced by firm. In that way, innovating firm can increase it's profit either via increase in it's relative prices, or by redirecting demand from competitors to it's product (increase in market share), or, most commonly, in both ways. Second, it can lead to invention of *entirely new products*, redirecting, in that way, consumers and producers demand from some old needs to entirely new one (mobile phone or internet, for example). Third, it can help *improvement of old production process* that makes less costly production of existing products. Finally, it helps *discovery of entirely new, less costly, production processes.*

Stream of monopoly rent that firm earn in that way is what motivate firms to invest in R&D. But rent earned in that way is just temporary. On the one hand, since it is not possible to protect fully property right on innovations (some innovations, although very profitable, are even not patentable), innovator is assumed to share results of his research investment with other agents in that industry. He is supposed to experience attenuation of property right and dissipation of rent. By passage of time this dissipation of rent becomes total: results of his research become totally shared among all agents in economy. On the other hand, and it is most important in Shumpeter's story, rival firms are also engaged in R&D activity. They are, therefore, very likely to bring new generation of product and process that are even more profitable than old one. Those new product and processes are, consequently, very likely to reduce share of old products, if not to discard them from market altogether. So, firms are not only motivated to invest in R&D in order to earn temporary monopoly rent: they are persuaded to invest in innovations in order to secure pure survival. And it is what market economy is about to be, according to Shumpeterian approach. Not only that new generations of technologies replace old one, but, as a result of a same process, new firms replace old one, sometimes taking just leading role from them and sometimes destroying them entirely. It is what Shumpeter called *creative destruction.* Aggregation mask this micro-level survival war and the macro economy grow at the steady peace, provided that number of innovations is large.

Neo-Shumpetarian growth models with monopolistic competition, obviously, can easily provide sustained, long run growth in per capital output. *Long-term growth rate* in this model is dependent on *expected cost and benefits on investment in R&D* and innovation. More specifically, level of R&D investment is determined by the point where *marginal cost of additional inputs into R&D* equals the *expected gain* provided by those inputs, later being equal to increased probability of success multiplied by the market value of new products. Changes in expected values of those cost and benefits will change incentives for investment in R&D, and therefore long run rate of growth. For example, some sudden, unexpected theoretical discovery (after all this is activity full with Knightian uncertainty and can't be totally endogenized), by increasing expected number of innovations and by boosting expected stream of benefits from that innovations, is most likely to increase investment in R&D and, consequently long run as well as transitory rate of growth. Similar is effect of increase in households' inclination toward saveing, that is effect of decrease in required rate of return as a cost of R&D capital.

4. To present mechanism of Shumpeterian kind of process we will present Agnionm and Howit (1992) celebrated model of economic growth is. In this model, like in Romer's model, growth and technological progress are generated by intentional and persistent investment in uncertain R&D activities and sequences of quality improving innovations that results from it. Their model generates two kinds of externalities. First are negative externalities that follow from the fact that new generations of innovations replace older one and make them obsolete. Second, and more important, there are also two positive kinds of externalities: first one is the result of the fact that monopoly rents are smaller than the consumer surplus; second kind of positive externalities are results of the fact that older generations of inventions make possible newer generation of inventions. In what follow Agnion and Howit (1998, ch. 2) interpretation of model is given.

In their model there is no capital accumulation. Society is made of number of individuals, L_t, which also present labor force. Utility function that is maximized by individuals is kind of a linear inter-temporal preference

$$U(Y)=\int_0^\infty Y_t e^{-rt}dt \qquad (81)$$

where r stands for the rate of time preference which is here equal to interest rate, while Y_t presents final goods production.

Labor force, L_t, produces capital goods, x, in one-to-one technology manner. Capital goods are then used in production of final goods, Y_t, according to the production function of the form

$$Y_t = Ax^a \qquad 0<a<1 \qquad (82)$$

where x^a stand for capital goods at present moment. Innovation is made of inventing new intermediate good. If successful, those intermediate goods make the old one obsolete and increase A_t parameter by constant factor γ. Formally

$$\frac{A_{i+1}}{A_i}=\gamma>1$$

where i refers to the number of innovations that have occurred up to the present moment.

Innovations arrive randomly according to Poisson process with arrival rate λL_A. Value $L_A=n$ presents number of workers dedicated to R&D activities, while $\lambda>0$ stands for productivity of R&D activity. So, probability of an innovation is given by $\lambda L_A=\lambda n$.

Economy's total labor force is allocated between capital goods producing sector and R&D sector. Market clearing condition is than

$$L=L_x+L_A=x+n \qquad (83)$$

Note that here $L_x=x$ number of workers in capital producing sector is equal to capital, because of the assumption that capital is produced by labor according to one-to-one technology.

Number of workers allocated to R&D is determined following arbitrage conditions

$$w_i=\lambda V_{i+1} \qquad (84)$$

where w_i stands for wage rate, whereas V_{i+1} stands for the present value of expected stream of benefits from innovation (discounted expected payoff) of the *(i+1)*-th innovation. This arbitrage condition determines dynamics of the economy over the successive innovations. In the equilibrium, worker must be indifferent between working one hour in capital producing, w_i, and working one hour in R&D sector. Value to worker of one hour working in R&D sector is equal to the flow of probability of one innovation, λ, multiplied by the value of that innovation, V_{i+1}.

The value of V_{i+1} is determined by the asset condition of the form

$$rV_{i+1}=\pi_{i+1}-\lambda n_{i+1}V_{i+1} \qquad (85)$$

which postulate that expected income generated by a patent on the *(i+1)*-th innovation during the unit of regarded time interval, that is rV_{i+1}, should be equal to the flow of profit that the producer of the *(i+1)*-th innovation earn, π_{i+1}, minus the expected loss that occurs when the next innovation replaces *(i+1)*-th innovation. Expected loss is in this case equal to multiplication of the flow probability of the innovation occurring (λ), the amount of labor dedicated to research after the *(i+1)*-th innovation (n_{i+1}), and the value that will be lost (V_{i+1}), that is to $\lambda n_{i+1}V_{i+1}$. In other words there must be indifference between investing in R&D and reaching a patent of an intermediate good to produce it, and investing money in bank deposit and earning interest rate on it.

From (85) it follows that

$$V_{i+1}=\pi_{i+1}/(r+\lambda n_{i+1}V_{i+1}) \qquad (86)$$

So called Shumpeterian effect of creative destruction can be clearly seen from this equation: the greater number of researchers in R&D activity, that is the greater investment in R&D, the smaller the payoff to innovation in *i*-th good. More specifically, more researchers after the *(i+1)*-th innovation, $n_{(t+1)}$, the smaller is going to be payoff of on *i*-th innovation.

Let us now specify the profit flow (π_{i+1}) and the flow of demand for manufacturing labor (x_i). Final good sector uses each intermediate goods following profit maximization rule according to which

$$\frac{dY}{dx_i} = p_i$$

where p_i present price of x_i. Having in mind above given production function (82) it follow that

$$aAx^{(a-1)} = p_i$$

$$x = \left(\frac{a}{p_i / A_i}\right)^{\frac{1}{1-a}} \qquad (87)$$

Now, let us see profit maximization problem of the intermediate good producers that use *i*-th innovation. This kind of monopolist can be assumed to be either the innovator, who is at the same time producer of good *i,* or the producer who buys the patent at price V_i. His problem can formally presented as

$$Max...\pi_i = p_i x - w_i x$$

Its' solution bring markup rule

$$p_i = \frac{w_i}{a}$$

which, when substituted in (87) bring specification for x_i

$$x_i = \left(\frac{a^2}{w_i / A_i}\right)^{\frac{1}{1-a}} \qquad (88)$$

Now, we can provide expression for π_i

$$\begin{aligned}\pi_i &= p_i x - w_i x \\ &= (1-a) p_i x \qquad (89) \\ &= (1-a) a A_i \left(\frac{a^2}{w_i / A_i}\right)^{\frac{a}{1-a}}\end{aligned}$$

Using arbitrage condition expression (84) can be rewritten as

$$w_i = \lambda V_{i+1} = \lambda \frac{\pi_{i+1}}{r + \lambda n_{i+1}}$$

$$= \lambda \frac{(1-a) a A_{i+1} \left(\frac{a^2}{w_{i+1} / A_{i+1}}\right)^{\frac{a}{1-a}}}{r + \lambda n_{n+1}}$$

Having in mind that $A_{i+1} / A_i = \gamma > 1$, the productivity adjusted wage rate, $\omega_i = w_i / A_i$, can be written to be

$$\omega_i = \frac{w_i}{A_i} = \lambda \frac{\gamma (1-a) a \left(\frac{a^2}{w_{i+1} / A_{i+1}}\right)}{r + \lambda n_{i+1}}$$

so that new arbitrage condition become

$$\omega_i = \frac{\gamma \lambda \tilde{\pi}(\omega_{i+1})}{r + \lambda n_{i+1}} \qquad (90)$$

where $\tilde{\pi} = \dfrac{\pi_{i+1}}{A_{i+1}}$.

Labor clearing condition (83) can now be rewritten as

$$L = n_i + \tilde{x}(\omega_i) \qquad (91)$$

The steady state or balanced growth equilibrium is defined as a solution of the system made of equations (90) and (91) where $\omega_i = \omega$ and $n_i = n$. This means that both ω and n remain constant over time. Consequently, ω, π, and Y are all scaled up by the same $\gamma > 1$ factor each time new invention occur.

To sum up, in a steady state the system to be solved is

$$\begin{cases} \omega = \dfrac{\gamma\lambda\tilde{\pi}(\omega)}{r+\lambda n} \\ L = n + \tilde{x}(\omega) \end{cases} \tag{92}$$

In the (ω, n) space, first, arbitrage condition, equation is downward sloping because rise of n increase denominator of the ratio. On the other hand, second, market clearing equation is upward sloping: with constant L, if n increase $\tilde{x}(\omega_i)$ must fall, which happens if ω rises. Since one equation is upward sloping and other is downward sloping, the balanced growth path solution (ω^*, n^*) is unique. This equilibrium is illustrated at Figure 5.

Replacing now $\tilde{\pi}$ with workable expression and solving this system we get

$$\pi = p_i x - w_i x = \frac{1-a}{a} wx$$
$$\tilde{\pi} = \frac{\pi}{A} = \frac{1-a}{a}\omega\tilde{x} = \frac{1-a}{a}\omega(L-n)$$

Then, replacing $\tilde{\pi}$ in arbitrage condition (90) we get equilibrium value of n

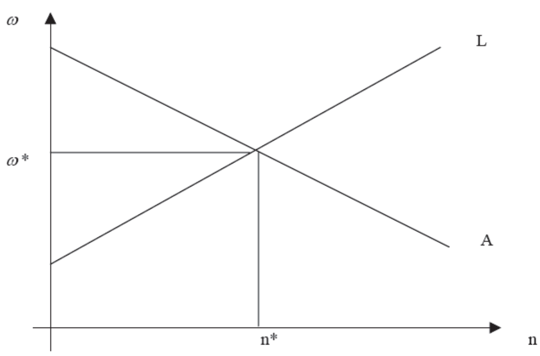

Figure 5.

$$\omega = \frac{\gamma\lambda\left(\dfrac{1-a}{a}\right)\omega(L-n)}{r+\lambda n}$$
$$r+\lambda n = \gamma\lambda\left(\frac{1-a}{a}\right)(L-n) \tag{93}$$
$$n^* = \frac{\gamma\lambda\left(\dfrac{1-a}{a}\right)L - r}{\lambda\left(\dfrac{a+\gamma(1-a)}{a}\right)}$$

Now that we have value of n^* we can use market clearing condition to derive equilibrium value of ω^*.

We are now left with determination of the equilibrium growth rate of the economy. In steady state, the flow of the final good, Y_t, produced between innovations *i*-th and *(i+1)*-th is

$$Y_i = A_i(x^*)^a = A_i(L-n^*)^a$$

This imply that

$$Y_{i+1} = A_{i+1}(L-n^*)^a$$

so that

$$Y_{i+1}/Y_i = A_{i+1}/A_i = \gamma \tag{94}$$

From this equation it can be seen that each time an innovation occur $\ln Y_i$ increases by the amount equal to $\ln\gamma$. However, since the real time between two innovations is random, the time path of $\ln Y_i$ must also be random step function whose each step size must be equal to $\ln\gamma > 0$. The time interval between each step is exponentially distributed with parameter λn^*. Assuming unit time interval between t and $(t+1)$ we have

$$\ln Y(t+1) = \ln Y(t) + (\ln\gamma)\varepsilon(t)$$

where $\varepsilon(t)$ presents number of innovations between t and $(t+1)$. Since $\varepsilon(t)$ has Poisson distribution with parameter λn^* we have that

$$\begin{aligned} E[\ln Y(t+1) - \ln Y(t)] &= \lambda n^*(\ln\gamma) \\ g_Y &= \lambda n^*(\ln\gamma) \end{aligned} \tag{95}$$

where g_Y presents the average growth rate of output.

As can be seen growth rate is, first, determined with value of n^* that is with number of workers engaged in R&D sector. Second, economy is in this model also characterized with scale effect we met at Romer's model. From (93) we see that n^* rises with L and therefore increase g_Y. Third, rate of growth depends on parameter λ that is on productivity of R&D sector. Finally, interest rate (r) and elasticity of production with respect to capital (a) have both negative impacts on value of n^* (equation 93) and therefore on the rate of growth of economy.

5. Spillovers from international trade

1. Relationship between R&D investment and rate of growth of total factor productivity is not so straightforward as one would expect relying solely on consideration of endogenous growth with R&D capital. Most interesting in that respect is a fact that *some small and less developed countries exhibit much larger rate of technological progress than would be suggested regarding data on absolute and relative magnitude of their domestic R&D investment*. Explanation of this phenomenon is most commonly found in the fact that those countries base their development strategy not only, and not even primarily, on knowledge developed within the country, but on knowledge developed worldwide. We have seen earlier that knowledge can be regarded either as a pure *public good* (basic knowledge) or as semi public good, that is as a good with high degree of external effects (R&D knowledge embodied in all kinds of innovations). At the same time, and for the same reason, it can be regarded as *fugitive good* too: knowledge does not recognize international borders; *externalities and spillovers from knowledge do not stop at international borders; they overspread quickly from one country to another*. With certain, not so high, price every country can afford access to this worldwide pool of knowledge. From the formal point of view, all it means that worldwide pool of knowledge must be somehow taken in account in explaining growth of nations: it's influence on economic growth of different nations should be formalized; worldwide stock of knowledge should become additional argument, apart from domestic stock of knowledge, in aggregate production function. If we equip production function of some less developed small country with this additional factor of production, than, according to previously developed theory, model of growth based on it will show exactly the same behavior as one we very often have in reality: because of a large magnitude of newly introduced factor of production, ratio of others factors of production relative to worldwide stock of R&D is well below it's stationary level; in this circumstance, it is possible to accumulate for a long time other factors of production without experiencing any sign of diminishing return; consequently, transitory / medium run rate of global factor productivity is higher than would be suggested regarding just stock of domestic R&D capital; it is also higher than its stationary / long run rate of global factor productivity; finally, transitory period lasts for a longer time than in other circumstances. All this is quite acceptable and understandable even at the very informal and intuitive level: under developed countries do not need to discover what is already discovered and to invent what is already invented; they just need to imitate those already invented production process and products or simply to buy those modern technologies; cost of imitation are not small, of course, but they are negligible compared to cumulative of R&D investment that have been committed in the past by developed countries in order to create all those modern technologies and to discover all theories underlying them.

2. Above hypothesis seems to offer perfect explanation for, already mentioned, cases of some small and less developed countries that, for a couple of decades, have experienced much larger rate of growth of global factor productivity than would be suggested solely on the basis of their own R&D investment. Apart from this, hypothesis is theoretically so neat and so convincing that above empirical fact becomes in quite another way intriguing and immediately attracts our attention: why just some countries behave in described way; *why all other small and less developed countries do not exploit from worldwide stock of knowledge, and, in that way, provide higher rate of technological advance*; this behavior would be more theoretically acceptable. Obviously, *openness of an economy* is what determines which portion of worldwide stock of knowledge is being used and exploited by particular country. Different level of openness of small and underdeveloped countries is intriguing, especially in the light of, earlier mentioned, fact that access to this lucrative worldwide stock of knowledge is not very expensive. Answer to this question can be complicated and difficult one: political economy of openness must include not only analysis of behavior of different interest group within particular country (domestic producers, importers, exporters and so on), but also analysis of behavior of world system and international order. We are not supposed to deal with this question here. Instead, to shed bit a more light on convergence problem, we will now see what are possible *transmission channels of R&D spillovers* that have been stressed by recent theory of economic growth.[4] As we will se, all these channels boost domestic productivity either by making available products that embody superior foreign knowledge, or by making available useful information that would be otherwise costly to acquire.

First channel reefer to *direct exchanges of peoples and ideas*. This exchange is partially autonomous and independent on any economic relations between countries (universities exchange, international research, movement of people across border and so on), but most important part of this exchange goes hand by hand with international trade. International trade is by itself channel of communication that enormously stimulates cross-border learning of production methods, product design, information system design, organizational design, marketing methods and similar. In that way it facilitates more efficient employment of domestic resources, on the one side, and / or adjustment of prod-ucts mix in a way to obtain more value added per unit of input, on the other side.

Second channel refers to different form of *legally allowed imitation of foreign technology*. *International contracts* enable country to copy foreign technology and modify them to suit domestic needs. Imitation is widespread phenomena. It has played most important role in the growth of most fast growing economies after Second World War. Examples of Japan and the newly industrializing economies of East Asia are most commonly quoted. Needless to say, this form of learning has been implied by increased level of foreign trade: export orientation and proliferation on a foreign market have very often been prerequisite for implementation of new technology.

Third channel is *international trade* by itself. It is obvious that *import of better foreign machinery and intermediate goods* can contribute enormously to efficiency of domestic economy: first, because of their superior quality they make domestic production directly more efficient; second, import of machinery and intermediate goods facilitates process of learning and transfer of information by itself. But note that *import of consumption goods* also contributes to increase of welfare of nation: imported consumption goods are either less expensive than domestic, or of a better quality, or both. All this is possible because of the fact that R&D improvement embodied in consumption goods are not entirely appropriated by investor / producer, in this case by foreign producer. We have already seen that part of that benefits are appropriated by other producer imitators. But they are also partially appropriated by consumers in the form of increased consumer surplus. How much is appropriated by consumers, on the other hand, depends on the shape of supply and demand function on a particular market. Impact of *enlarged export*, as a result of increased international trade, on productivity of exporting country is even larger than impact of import. It enables exporting country to exploit fully its comparative advantages. Finally, by exposing domestic firms to foreign competition, international trade also diminishes rent-seeking behavior and improves motivational structure of economy in general.

Fourth channel refers to *direct foreign investment*. Transmission of knowledge is most obvious here: first, direct investment are by itself most direct transfer of best technologies, information systems, modern organizations and foreign markets; second, it is not rare case that newly established foreign affiliates, joint venture, or other form of units organize its' own R&D activities, contributing in that way even more to transfer of knowledge. This kind of transfer of knowledge is becoming especially important now, and is supposed to become even more widespread as processes of globalization continue. Like other channels, this one is also regarded to be conditional on the level of international trade: export and foreign market is most of the time prerequisite for direct investment. On the other hand, we can say that, in the era of globalization, direct investments are also substituting inter-

[4] Notable are in this respect contributions given in works by Grossman and Helpman (1991), Helpman (1992), Coe and Helpman (1995), Coe, Helpman and Hoffmaister (1997).

national trade and contractual transfer of knowledge.[5]

3. We have already told that, in order to be as realistic as possible, models of economic growth and its' underlying production function should, apart from domestic stock of knowledge, include stock of worldwide knowledge. We also know that, because of the fact that portion of world R&D stock used by particular country depends on it's economic openness, this worldwide R&D stock should be conceptualized and measured in a way to reflect openness of the country that is being analyzed. From the above analysis of main channels of knowledge transmission, we can conclude, first, that value of international trade relative to value of GDP in particular country can be used as a best possible proxy for measurement of openness of that country. No doubt countries with larger trade to GDP ratio are more likely to exploit from worldwide stock of knowledge. But, and it is second important point in constructing models with international R&D spillovers, quality and structure of that openness also matters: countries that import more from most developed nations are, other things being equal, likely to capture more from world wide stock of knowledge than countries that import mainly from less developed countries.

Above can be formalized, first, by allowing elasticity of total / global factor productivity of particular country (A_i) with respect to foreign R&D capital to depend on it's share of import in GDP (m_i), and, second, by constructing country specific foreign R&D stock (F_i) in a way to reflect quality of country's openness [Coe and Helpman (1995), Coe, Helpman and Hoffmaister (1997)]. Relation between total factor productivity of some country (A_i) on the one side and it's domestic (D_i) and foreign (F_i) stock of R&D can be expressed using form of Cobb-Douglas function. Its' linear, logarithmic transformation, which is basically used in empirical research, has following form

$$\ln A_i = \alpha_{i0} + \alpha_{id} \ln D_i + \alpha_{if} m_i \ln F_i \qquad (96)$$

[5] Connected with those questions of channels of international spillovers is question of *dynamic comparative advantage,* and especially question of *influence of north-south spillovers on product cycle.* More elaborate discussion on that topics can be find in Grosman and Helpman (1991, ch. 8-12) and (1994).

where i stands for index of particular country, α_{id} stands for elasticity of total factor productivity with respect to domestic R&D, $\alpha_{if}\, m_i$ stands for elasticity of total factor productivity with respect to foreign R&D, while α_{io} presents free coefficient. Stock of domestic R&D (D_i) can be, as we mentioned in previous consideration, constructed as cumulative of R&D investment committed in the past by particular country.

$$D_i = \sum_{v=0}^{t} R \,\&\, D_{iv} \qquad (97)$$

On the other hand country specific foreign stock of R&D is measured as weighted sum of R&D stock of all other world countries with which respecting country has economic relations, where share of import from some country in value of total import of respecting country is used as a corresponding weight. Formally

$$\begin{aligned} F_i &= \sum_{j=0}^{n} w_{ij} D_j \\ w_{ij} &= m_{ij} / m_i \\ m_i &= \sum_{j=1}^{n} m_{ij} \end{aligned} \qquad (98)$$

where m_{ij} stands for import of country i from country ***j***.

It is interesting that above given expressions allow for further decomposition of rate of growth of some country GNP. First, it allows contribution of foreign R&D capital to be distinguished from contribution of domestically generated knowledge. Second, it allows contribution of every country's R&D stock to the GDP growth of respecting country to be distinguished. So, we can get, for example, influence of USA stock of R&D on Kenya's rate of growth, or influence of France R&D stock on Kenya's rate growth, and so on. More interestingly, it is possible to measure magnitude of spillovers between developed and less developed countries [Coe, Helpman and Hoffmaister (1997)].

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