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R&D, Specific-Training Human Capital, and Growth

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Abstract

This paper incorporates the complementarity property between intermediate goods and specific-training human capital into Schumpeterian R&D-based growth model. The use of innovated intermediate capital goods required the specific-trained human capital to operate it. Moreover, the innovative firm has the incentive to train workers of the intermediate goods purchasing firms from which a lump sum of training fee may charged. Like tie-in sale, innovative firm sells intermediate goods and trains workers for the purchasing firms. The steady state growth rate is determined by both the ratio and level of the intermediate goods and specific-training human capital. Hence even countries converge to same steady-state ratio of intermediate goods and specific-training human, the differential long-run growth rate across countries may exist provided that countries have different levels of intermediate goods or specific-training human capital. Like Solow growth model, during the transitional path conditional convergence will prevail. As for external shocks, the model can generates profound growth effects depends on the property of shocks. The temporary adverse (favorable) shocks on both intermediate goods and specific-training human capital will produce permanent adverse (favorable) effect. However, temporary shock on only one type of capitals will generate asymmetric effect. The temporary adverse shocks on either types of capitals will have no long-run growth effect, while the temporary favorable shocks on either types of capitals will generates positive long-run growth effect. Therefore, the policy implications of the model are that government should encourage the accumulation of intermediate capital goods or specific-training human capital or both. The effects will be permanent!

R&D, Specific-Training Human Capital, and Growth

I. Introduction

Since the surge of endogenous growth models in the mid- 1980s, R&D-based growth model has been the mainstream thinking of the process of economic growth, see, for example, Romer (1990), Aghion and Howitt (1992, 1998), and Grossman and Helpman (1991). Numerous empirical studies provide concrete evidence for R&D as the engine of growth. The so-called " New Economy" fueled by computer innovations and made a sharp contrast to the " Old Economy" reflects this R&D phenomenon. However, the fundamental of the R&D activity are people who invent it and also people who can operate it. This specific type of people is called human capital, they are the core of the development process. In world with rapid international trade and globalization, once the technology is invented it can be easily obtained or imported from the advanced technology frontier countries; however, it is the people or human capital of the technology-imported country that determines the use and the success of the technology adoption and application. Based on the Schumpeterian growth model, this paper emphasizes the role of on-the-job training and tries to incorporate the specific-training human capital in conjunction with the innovated intermediate goods to explain the growth process. Human capital needs to be trained in order to be able to adopt and use new intermediate goods efficiently. Unlike the conventional R&D model, the innovative firm has double incentive in doing R&D, one from charging a price markup for its innovated intermediate goods and the other from training of the worker to use the new technology embodied in the intermediate goods. Like two-capital or two-sector growth models, this model can generate conditional convergence. However, both the ratio and level of intermediate goods and specific-training human capital affect a country long-run growth rate. Therefore the model allows differential growth rate across countries in the steady state. Moreover, temporary external shocks may provide profound growth effects depends on the property of the shocks, weather it' s favorable or adverse, it' s on one type or two types of capitals. The temporary adverse shock on one type of capital has no permanent growth effect, while temporary favorable shock has positive growth effect. The main policy implication of the model is that government should encourage the accumulation of intermediate capital goods or skilled or well-trained human capital or both. The growth effects will be permanent!

The rest of the paper is organized as follows. Section II present the R&D model with the specific-training human capital. Section III characterizes the transitional dynamics and steady-state properties of the model. Section IV discusses the effects of external shocks and main policy implication of the model. Concluding remarks are followed in Section V.

II. The Model

2.1 Production

Assume the economy produces one final product in the competitive market using two inputs, intermediate good and specific-training human capital. The aggregate production function has a Cobb-Douglas form and defined as

$$Y_t = A_t X_t^{\alpha} Z_t^{1-\alpha}, \quad 0 \le \alpha \le 1 \tag{1}$$

where t denotes time, Y is the output, X is the intermediate good, Z is the stock of specific-training human capital, and A is the highest technology level attainable. The market of the intermediate good is a monopoly market, firm that develops leading-edge technology at each period enjoy the monopoly power. The leading– edge technology is also embodied in the production of intermediate good and specific training of human capital. The production function of specific training of human capital is define as

$$Z = G(\underset{-}{A}, \underset{+}{H}), \tag{2}$$

where, H is the stock of human capital. Equation (2) implies that the specific training of human capital depends negatively on the leading-edge technology and positively on the current stock of human capital. That is, the training is specific in the sense of applying leading-edge technology so that human capital can be combined with the intermediate good to produced current output. As human capital is homogenous, the higher the leading-edge technology the smaller the amount of the transformed specific-training human capital available for a given stock of human capital. In other words, the higher the leading-edge technology the larger the amount of human capital is required to produced one unit of specific-training human capital. Other things being equal, the more units of specific-training human capital the higher the amount of human capital required. We further assume the production of specific-training human capital has following functional form

$$Z_t = B^{\gamma} \frac{H_t}{A_t}, \quad \text{and } B > 1, \ \gamma > 0, \tag{3}$$

where B is a technology parameter. H_t/A_t can be seen as technology-adjust human capital or human capital in efficiency unit, and the specific training of human capital increases the productivity of human capital in efficient unit by B^{γ} time.

The production function of the intermediate good is a function of leading-edge technology and current stock of physical capital and specifies as

$$X_t = \frac{K_t}{A_t}, \tag{4}$$

where K is the stock of physical capital. Equation (4) implies that the production intermediate good is rather capital intensive and uses the leading-edge technology available at the time of production. For given stock of physical capital, the higher the leading-edge technology the smaller the amount of intermediate good being produced.

Assume the price of final good P_Y at time t equals one, the profit maximization decision of the representative firm in the final good market at time t becomes

$$\max_{X,Z} \qquad \pi_{ti} = Y_{ti} - P_X X_{ti} - W_Z Z_{ti} \tag{5}$$

$$s.t. \qquad Y_{ti} = A_t X_{ti}^{\alpha} Z_{ti}^{1-\alpha} \tag{6}$$

where, P_X is the price of intermediate good at time t and W_Z is the wage of specific-training human capital. Noted that the leading-edge technology is a common technology and thus is available for all firms at current time t. From first order conditions of equations (5) and (6) we can derived the firm' s inverse demand function for both intermediate good and specific-training human capital and thus the market demand as

$$P_x = \alpha A_t \left(\frac{X_t}{Z_t}\right)^{\alpha-1} \tag{8}$$

$$W_Z = (1-\alpha) A_t \left(\frac{X_t}{Z_t}\right)^{\alpha} \tag{9}$$

For the monopoly firm that own the leading-edge technology, it not only produces intermediate good but also train human capital into specific-training human capital that can apply intermediate good to jointly produced final good. Therefore, for the monopoly it is a tie-in sale of intermediate good plus training of human capital. How is the pricing of this intermediate good monopoly under tie-in sale situation? As labor market is competitive and human capital is homogenous, the wage of human capital thus equals to the marginal product of human capital in efficiency unit, i.e.

$$W_t = (1-\alpha)\frac{A}{B^{\gamma(1-\alpha)}}\left(\frac{X}{Z}\right)^{\alpha} \tag{10}$$

Compare (9) and (10) yields

$$\frac{W_Z}{W_t} = B^{\gamma(1-\alpha)} \tag{11}$$

As shows in Figure 1, the difference between the two marginal products is equal to the wage differentials.

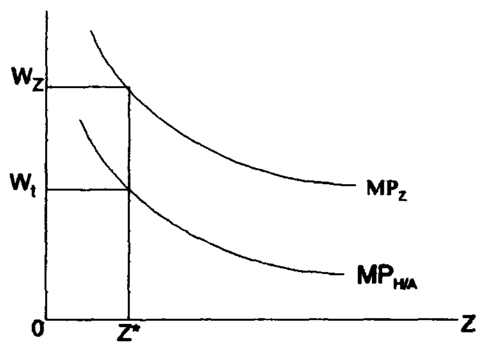

Figure 1. Wage differentials of human capital and specific-training human capital

For given level of specific-training human capital Z*, the total training cost paid by the final product firms equals

$$(W_Z - W_t)Z^* = (1-\frac{1}{B^{\gamma(1-\alpha)}})(1-\alpha)A_t X^{\alpha} Z^{1-\alpha}. \tag{12}$$

Hence the revenues of the monopoly of intermediate good include the sale of intermediate good plus the training fee charge for human capital employed by the producer of the final good. Thus the profit maximization problem of the monopoly of the intermediate good becomes

$$\max_{X} \quad \pi^X = P_X X + (W_Z - W_t)Z - P_K K$$

$$\text{s.t.} \quad P_X = \alpha A_t X^{\alpha-1} Z^{1-\alpha}$$

$$X = \frac{K}{A_t}$$

$$(W_Z - W_t)Z = (1-\frac{1}{B^{\gamma(1-\alpha)}})(1-\alpha)A_t X^{\alpha} Z^{1-\alpha}$$

First order conditions of the problem renders

$$\alpha A_t X^{\alpha-1} Z^{1-\alpha}\left[1-\frac{1}{B^{\gamma(1-\alpha)}}(1-\alpha)\right]=P_K A_t \tag{13}$$

$$\Rightarrow P_X=\frac{P_K A_t}{1-\frac{1}{B^{\gamma(1-\alpha)}}(1-\alpha)} \tag{14}$$

As $P_K A_t$ is the marginal cost of intermediate good, equation (13) implies a price markup by the intermediate good producer. Note that the markup is positively related to the production efficiency of the specific-training human capital. This implies that the greater the production efficiency from specific-training of human capital the larger the training fee that the intermediate good producer can charge (see equation (12)) and thus the lower the price markup of the intermediate good. This is consistent with the economic theory that by lowering the price of intermediate good to induced larger demand for intermediate good and thus greater quantity of human capital need to be trained, which generates greater amount of revenues from receiving training fee provided that the production efficiency is high for the specific-training human capital. This is a common pricing strategy in tie-in sale practice. Compare with the pricing of intermediate good in the conventional R&D-base growth model, see for example Romer (1990), Grossman and Helpman (1991, Ch3), we have

$$\frac{P_K A_t}{1-\frac{1}{B^{\gamma(1-\alpha)}}(1-\alpha)}<\frac{P_K A_t}{\alpha} \tag{15}$$

The markup in this model is actually lower than that implied by conventional models. The total profit of the intermediate good producer is

$$\pi^X=(1-\alpha)A_t X^{\alpha} Z^{1-\alpha}\left[1-\frac{1}{B^{\gamma(1-\alpha)}}(1-\alpha)\right] \tag{16}$$

2.2 R&D

In the model at every time period there exists a leading-edge technology. How does the leading-edge technology evolve? It' s by research and development. There are many intermediate good firms compete in the market by doing R&D to find new technology. At each time period only the one who develops the new technology, i.e. the leading-edge technology, wins the whole market of the intermediate good and gains the monopoly power. This is like the patent race described in Tirole (1988) and Reinganum (1989). As in Aghion and Howitt (1988, Ch), we adopt the Schumpeterian Approach of the innovation process. Assume final good is the only input in R&D

activity and denotes as N. The emerge of innovations is a Poisson process and has a entering rate defined as

$$\phi_t = \lambda n_{it}, \lambda > 0 \tag{17}$$

$$n_{it} = \frac{N_{it}}{A_t}, \quad A_t \equiv \max\{A_{it} | i \in [0,1]\} \tag{18}$$

where ϕ_t is the emerging rate of innovations, n_{it} is the amount of technology-adjusted final good input in R&D activity by each firm, and λ is the technology parameter of R&D production. Equation (18) implies that the greater the leading-edge technology the larger the amount of final good required to put into R&D activity,[1] while equations (17) implies that the great the amount of resources in turns of technology-adjusted final good engage in R&D and the higher the R&D production efficiency the higher the emerging rate of innovations. As final good is a function of physical and human capitals, R&D activity thus also influence by physical and human capital.[2] In equilibrium, as the expected profit of each firm is the same by symmetry the input of resources in R&D will be the same across firms, i.e., $n_{it} = n_t$. As the R&D activity of each firm is mutually independent with equal opportunity of generating innovations, at each time period there is a rate of λ n_t of innovations in the whole economy. There also exist a distribution of A_{it} from 0 to A_t and the distribution shifts rightward as the leading-edge technology evolve at each time period. Following the specification of leading-edge technology by Caballero and Jaffe (1993), the leading edge-technology is a common knowledge and its growth rate is proportional to the aggregate emerging rate of innovations in the economy. Thus we define the growth rate of leading-edge technology as

$$g_t \equiv \frac{\dot{A}_t}{A_t} = \sigma\lambda n_t, \sigma > 0 \tag{19}$$

For R&D investment, the equilibrium no-arbitrage condition required that the marginal cost of R&D investment equals the expected marginal benefit from R&D. As $n_t = \frac{N_t}{A_t}$, additional one unit increase of n_t requires A_t units final consumption N_t. Therefore the marginal cost of R&D equals A_t. The expected return of R&D is the discounted expected payoff from time of innovation to the time that next innovation emerge. Thus the expected return is defined as

$$V_t = \int_t^{\infty} e^{-\int_t^s r_u du} e^{-\int_t^s \lambda n_u du} \pi_x dx \tag{20}$$

where s is time that the innovation have not been replaced. The effective discount rate

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[1] This formulation also prevents the case of explosive growth of R&D activity.

[2] From equation (), (),and (), $Y_t = A_t X_t{}^{\alpha} Z_t{}^{1-\alpha} = B^{\gamma(1-\alpha)} K_t^{\alpha} H_t^{1-\alpha}$

equals to interest rate plus the emerging rat of new technology. The greater the emerging rate of innovations the shorter the monopoly period enjoyed by the incumbent firm and hence less expected profit is. Equation (20) also implies that incumbent monopoly firm will not engage in R&D as its marginal cost is the same as other potential firms but its revenue is equal to V_{t+1}-V_t, which is apparently less then V_{t+1}. In equilibrium, no entry condition for R&D requires $\lambda V=A$. Let $v=V/A$, divide A from both sides of equation (20) and then differentiate with respect to t which yields

$$\dot{v}_t = -\left[1-\frac{1}{B^{\gamma(1-\alpha)}}(1-\alpha)\right](1-\alpha)X_t^{\alpha}Z_t^{1-\alpha} + (r_t+\lambda n_t)v_t \tag{21}$$

Substitute $v=1/\lambda$ and let $\dot{v}_t = 0$ obtains a R&D no-arbitrage condition

$$1=\lambda\frac{\left[1-\frac{1}{B^{\gamma(1-\alpha)}}(1-\alpha)\right](1-\alpha)X_t^{\alpha}Z_t^{1-\alpha}}{r_t+\lambda n_t} \tag{21}$$

Equation (21) holds for both steady-state or off steady-state.

2.3 Consumption

Let the economy is full with consumers of infinite life time. The representative consumer has a utility of constant intertemporal elasticity of substitution over consumption of final good and defined as

$$u(c_t)=\frac{c_t^{1-\varepsilon}-1}{1-\varepsilon}, \varepsilon>0 \quad \text{...} (22)$$

where c is the consumption of final good at time t and 1/ represents the elasticity of intertemporal substitution. The larger the ε, the less the consumer is willing to substitute consumption across time. Under one sector technology assumption, final good can be used for consumption, investment of physical and human capital, and R&D and express as

$$Y_t = C_t + I_{Kt} + I_{Ht} + N_t = B^{\gamma(1-\alpha)}K^{\alpha}H^{1-\alpha} \tag{23}$$

where I_K and I_H are gross investment of physical and human capital, respectively. Let the depreciation rate of two capitals is the same as δ and $0<\delta<1$. The accumulation of physical and human capital is assumed having following forms

$$\dot{K}_t = I_{Kt} - \delta K_t \tag{24}$$

$$\dot{H}_t = I_{Kt} - \delta H_t, \tag{25}$$

The representative consumer maximizes equation (22) subject to equations (23), (24), (25), and (19). The equilibrium condition for the investment of two capitals requires the equalization of the marginal revenue product of the two capitals, i.e.

$$\alpha B^{\gamma(1-\alpha)}K^{\alpha-1}H^{1-\alpha} = (1-\alpha)B^{\gamma(1-\alpha)}K^{\alpha}H^{-\alpha} \tag{26}$$

Rearrange we have

$$\frac{K}{H} = \frac{\alpha}{1-\alpha}, \tag{27}$$

or in terms of intermediate good X and specific-training human capital Z

$$\frac{X}{Z} = \frac{1}{B^{\gamma}}\left(\frac{\alpha}{1-\alpha}\right). \tag{28}$$

Therefore in equilibrium, the ratio of two capitals or the ratio of intermediate good to specific-training human capital is constant. Moreover, the ratio is positively correlated with the output elasticity of the intermediate good and negatively correlated with the production efficiency of the specific training of human capital. The larger the output elasticity of the intermediate good the more important the intermediate good relative to specific-training human capital, and hence the greater the ratio is. While the more productive the training in specific human capital, the more investment in specific-training human capital, and hence the less the ratio is.

While the growth rate of consumption is

$$\frac{\dot{C}}{C} = \frac{1}{\varepsilon}(r-\rho) = \frac{1}{\varepsilon}\left[B^{\gamma(1-\alpha)}\alpha^{\alpha}(1-\alpha)^{1-\alpha} - \delta - \rho\right]. \tag{29}$$

III. Steady-State Analysis

In steady state, all the sectors are in equilibrium which imply solving following equations

$$\frac{X}{Z} = \frac{1}{B^{\gamma}}\left(\frac{\alpha}{1-\alpha}\right) \tag{30}$$

$$1 = \lambda\frac{(1-\alpha)X^{\alpha}Z^{1-\alpha}\left[1-\frac{1}{B^{\gamma(1-\alpha)}}(1-\alpha)\right]}{r+\lambda n} \tag{31}$$

$$r = \rho + \varepsilon g \tag{32}$$

$$g = \sigma\lambda n \tag{33}$$

Substituting (32) and (33) into (31) yields

$$1=\lambda\frac{(1-\alpha)X^{\alpha}Z^{1-\alpha}\left[1-\frac{1}{B^{\gamma(1-\alpha)}}(1-\alpha)\right]}{\rho+\lambda n(1+\varepsilon\sigma)} \tag{34}$$

let $\theta\equiv\frac{X}{Z}$, the system reduced to

$$\theta=\frac{1}{B^{\gamma}}\left(\frac{\alpha}{1-\alpha}\right) \tag{35}$$

$$n=\frac{(1-\alpha)\left[1-\frac{1}{B^{\gamma(1-\alpha)}}(1-\alpha)\right]\theta^{\alpha}}{1+\varepsilon\sigma}Z-\frac{\rho}{\lambda(1+\varepsilon\sigma)} \tag{36}$$

$$\text{or }=\frac{(1-\alpha)\left[1-\frac{1}{B^{\gamma(1-\alpha)}}(1-\alpha)\right]\theta^{\alpha-1}}{1+\varepsilon\sigma}X-\frac{\rho}{\lambda(1+\varepsilon\sigma)}$$

From (35) and (36), in steady state the ration of intermediate good and specific-training human capital is a constant hence does not affect long run growth rate. However, from (36) the level of intermediate good or specific-training human capital may affect long run growth rate of the economy. Solving (35) and (36) obtains

$$n^{*}=\frac{\alpha^{\alpha-1}(1-\alpha)^{\alpha}\left[B^{\gamma(1-\alpha)}-(1-\alpha)\right]}{1+\varepsilon\sigma}X-\frac{\rho}{\lambda(1+\varepsilon\sigma)} \tag{37}$$

$$\text{or }n^{*}=\frac{\alpha^{\alpha}(1-\alpha)^{1-\alpha}\left[\frac{B^{\gamma(1-\alpha)}-(1-\alpha)}{B^{\gamma}}\right]}{1+\varepsilon\sigma}Z-\frac{\rho}{\lambda(1+\sigma\varepsilon)} \tag{38}$$

Figure 2 depicts determination of the steady state.

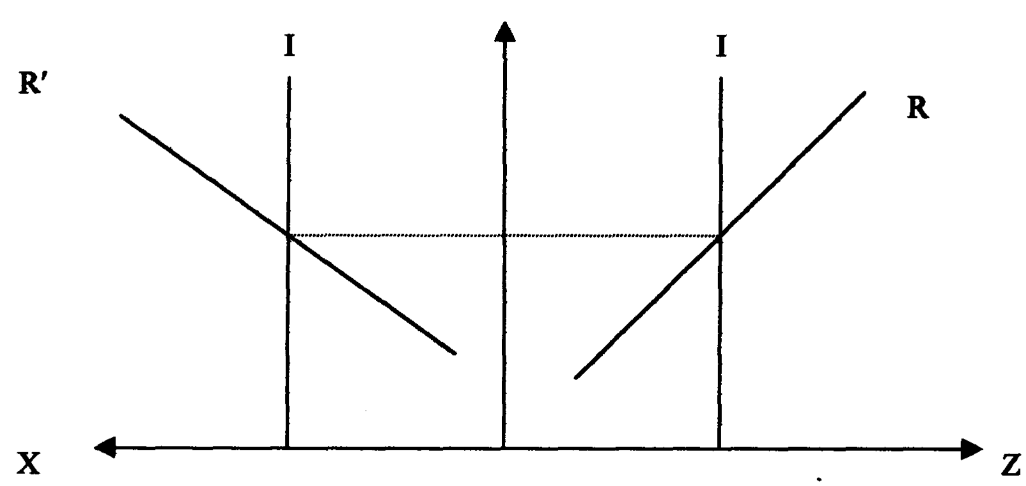


Figure 2 The determination of Steady state

3.2 Comparative Analysis

The steady state growth rate is negatively correlated with time preferences and elasticity of marginal utility, and positively correlated with relative proportion of innovation rate with respect to aggregate productivity growth, R&D productivity, and productive efficiency in specific human capital training. Table 2 lists relationship between the parameters and productivity growth rate.

Table 2

Parameter	Relationship with growth rate
ρ	-
ε	-
σ	+
λ	+
B	+

The higher the time preference or elasticity of marginal utility imply that consumers value more on current consumption and thus are less willing to substitute future consumption for current consumption, and hence accumulate less capital and invest less input in R&D. This actually retards long run growth. The greater the proportion of innovation rate relative to aggregate productivity growth the greater the impact of innovation on economic growth, the greater the productivity in R&D activity the larger the rate of innovations for given inputs in R&D sector, and the higher the production efficiency in specific human capital training the larger the expected return from R&D as intermediate good firm can receive higher training fee. This helps to foster long run economic growth.

A common feature of one sector economy of common technology is that in steady the share of physical and human capital is constant and all countries converge to the same steady state regardless the level of accumulated capitals. In our model the share of intermediate good relative to specific-training human capital (or the share of physical capital relative to human capital) is also constant in steady state. However, the level of intermediate good or specific-training human capital does affect long run growth. From

(37) and (38), the level of intermediate good or specific human capital positively affect the input in R&D activity even though the ratio of the two is constant. Therefore, for countries with same ratio of intermediate good and specific-training human capital in the steady state can still have different long run growth rate provided they have different level of intermediate good or specific-training human capital. The above discuss renders proposition 1.

Proposition 1: Assume a world with n countries and in steady state all countries has same ratio of intermediate good and specific-training human capital. However, if the steady-state level of the stock of intermediate good or specific-training human capital is different, the long run growth rate will be different across countries.

For example, let $\left(\frac{X_1}{Z_1}\right)^* = \left(\frac{X_2}{Z_2}\right)^* = \dots\dots = \left(\frac{X_n}{Z_n}\right)^* = \theta *$. However, if the orders of the stock of intermediate good and specific-training human capital are

$$X_1^* < X_2^* < \dots\dots < X_n^*$$
$$Z_1^* < Z_2^* < \dots\dots < Z_n^*,$$

then steady state productivity growth and the long run economic growth rate will be different across countries and preserve the order that

$$g_1 < g_2 < \dots\dots\dots < g_n$$

$$\text{or } \frac{\dot{Y}_1}{Y_1} < \frac{\dot{Y}_2}{Y_2} < \dots\dots\dots < \frac{\dot{Y}_n}{Y_n}.$$

Therefore, in steady state even with same ratio in the intermediate good and specific-training human capital, a country with lower level of stock of intermediate good or specific-training human capital will result in lower long run growth rate.

3.3 Transitional Dynamics

The transitional dynamics of the system depends on the initial ratio of intermediate good relative to specific-training human capital. Form (), it also depends on the ratio of physical relative to human capital.

(1) if $\frac{X_0}{Z_0} < \frac{\alpha}{B^{\gamma}(1-\alpha)}$, then $\frac{K_0}{H_0} < \frac{\alpha}{1-\alpha}$ and the condition $I_H - \delta = 0$ must be binding.

This initial condition implies that physical capital is small relative to human capital, so the marginal product of physical capital is higher than that of human capital. Physical capital will keep accumulate so is the intermediate good.

The Hamiltonian equation of the consumer optimization becomes

$$J = \frac{C^{1-\varepsilon} - 1}{1-\varepsilon} e^{-\rho t} + v\left(B^{\gamma(1-\alpha)} K^{\alpha} H^{1-\alpha} - C - \delta K - \delta H - nA\right) + \mu(\sigma\lambda nA)$$

Let $\theta \equiv \frac{X}{Z} = \frac{1}{B^{\gamma}}\frac{K}{H}, \chi \equiv \frac{C}{K}$, and $\phi \equiv \frac{N}{K}$, solving the Hamiltonian we obtain[3]

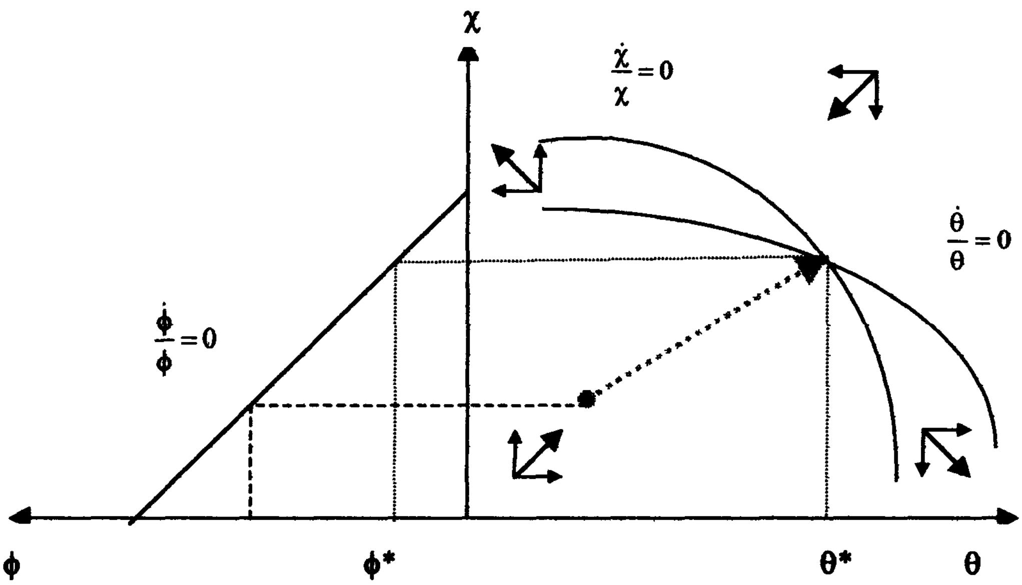
$$\frac{\dot{\theta}}{\theta} = \frac{\dot{K}}{K} - \frac{\dot{H}}{H} = \theta^{\alpha-1} - \delta(\theta B^{\gamma})^{-1} - \frac{C}{K} - \frac{N}{K} = \theta^{\alpha-1} - \delta(\theta B^{\gamma})^{-1} - \chi - \phi \qquad \text{(A.7)}$$

$$\frac{\dot{\chi}}{\chi} = \frac{\dot{C}}{C} - \frac{\dot{K}}{K} = \frac{1}{\varepsilon}\left[\alpha\theta^{\alpha-1} - \delta - \rho\right] - \left[\theta^{\alpha-1} - \delta(B^{\gamma}\theta)^{-1} - \chi - \phi\right] = \theta^{\alpha-1}\left(\frac{\alpha}{\varepsilon} - 1\right) + \delta(B^{\gamma}\theta)^{-1} + \chi + \phi - \frac{(\delta+\rho)}{\varepsilon} \qquad \text{(A.8)}$$

$$\frac{\dot{\phi}}{\phi} = \frac{\dot{N}}{N} - \frac{\dot{K}}{K} = g - (\theta^{\alpha-1} - \delta(B^{\gamma}\theta)^{-1} - \chi - \phi) \qquad \text{(A.9)}$$

Note that for finite utility function, $\alpha<1-\varepsilon$. Let $\theta^{*} = \frac{\alpha}{B^{\gamma}(1-\alpha)}$ be the steady state value of θ.

Figure 4 depicts the phase diagram of transitional dynamics. When $\theta < \theta^{*}$, θ, χ, and ϕ will all increase monotonically along the saddle path until it reaches steady state θ^{*}, χ^{*}, ϕ^{*}.



[3] See Appendix.

Figure 4. Transitional Dynamics: When $\theta < \theta^*$

As $\frac{\dot{C}}{C} = \frac{1}{\varepsilon}\left[\alpha\theta^{\alpha-1} - \delta - \rho\right]$, the growth rate of consumption is governed by the evolution process of θ, so during the transitional period the growth rate of consumption will increase over time. Moreover, the greater the initial θ_0 away from θ^*, the larger the growth rate of the economy. Therefore, the model also has the property of conditional convergence as found in the traditional Slow growth model.

(2) If $\frac{X_0}{Z_0} > \frac{\alpha}{B^\gamma(1-\alpha)}$, then $\frac{K_0}{H_0} > \frac{\alpha}{1-\alpha}$ and the condition $I_K - \delta = 0$ must be binding. In contrast, this initial condition implies that human capital is small relative to physical capital, so the marginal product of human capital is higher than that of physical capital. Human capital will keep accumulate so is the specific-training human capital.

Let $\tilde{\chi} \equiv \frac{C}{H}$. and $\tilde{\phi} \equiv \frac{N}{H}$, by the same token, we obtain three equations of the dynamic system

$$\frac{\dot{\theta}}{\theta} = \frac{\dot{K}}{K} - \frac{\dot{H}}{H} = -B^\gamma\theta^\alpha + \delta B^{\gamma\theta} + \tilde{\chi} + \tilde{\phi} + \delta \quad \text{(A.16)}$$

$$\frac{\dot{\tilde{\chi}}}{\tilde{\chi}} = \frac{\dot{C}}{C} - \frac{\dot{H}}{H} = B^\gamma\theta^\alpha\left[\frac{(1-\alpha)}{\varepsilon} - 1\right] + \delta B^\gamma\theta + \tilde{\chi} + \tilde{\phi} - \frac{(\delta+\rho)}{\varepsilon} \quad \text{(A.17)}$$

$$\frac{\dot{\tilde{\phi}}}{\tilde{\phi}} = \frac{\dot{N}}{N} - \frac{\dot{K}}{K} = g - B^\gamma(\theta^\alpha - \delta\theta) + \tilde{\chi} + \tilde{\phi} + \delta \quad \text{(A.18)}$$

Note that for finite utility function, 1-α<1-ε. Figure 5 depicts the phase diagram of transitional dynamics. When $\theta > \theta^*$, θ will decrease monotonically while χ and ϕ increase monotonically along the saddle path until it reaches steady state θ^*, Therefore, during the transitional period the growth rate of consumption will increase over time. Moreover, the greater the initial θ_0 away from θ^*, the larger the growth rate of the economy, again the conditional convergence prevails.

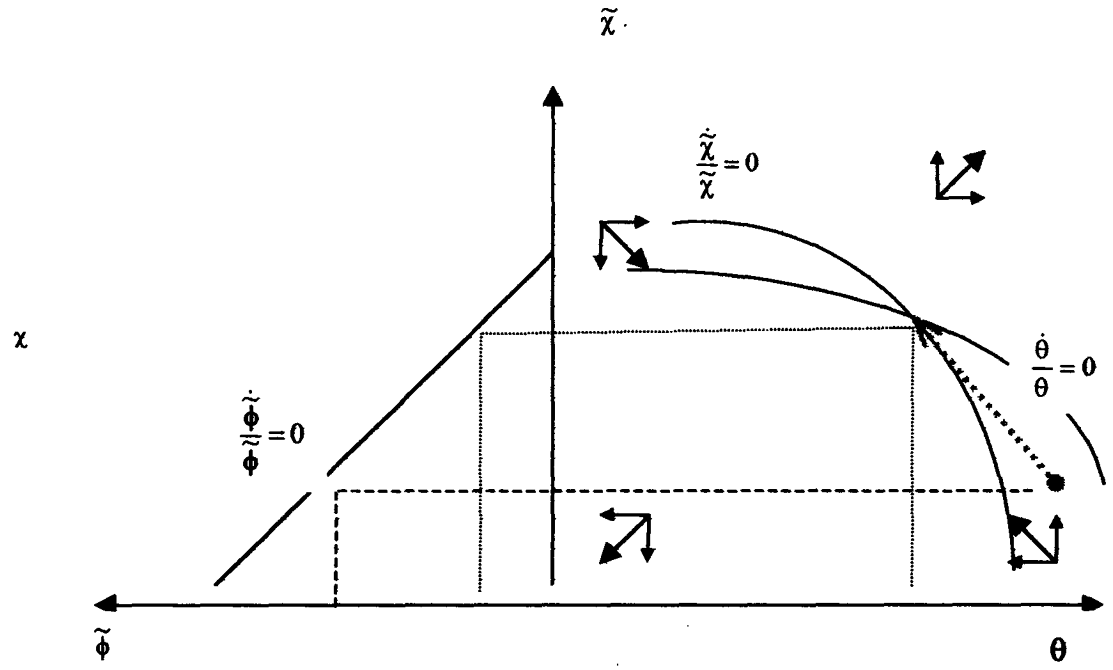


Figure 5. Transitional Dynamics: when $\theta > \theta*$

Figure 6 shows the transitional path of an economy' s growth rate.

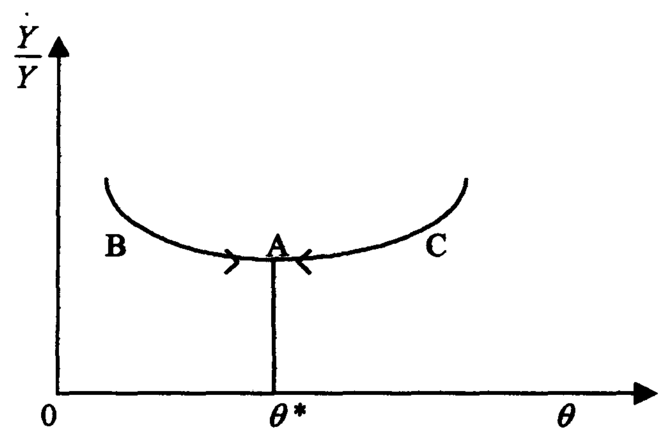


Figure 6. Transitional Path of an Economy' s growth rate

IV. External Shocks and Policy Implications

Will external shocks affect steady state growth rate of an economy? If yes, is the effect temporary or permanent? Suppose initially a country is in its steady state, a war destroys most of its intermediate good or physical capital but leaves human capital intact. Then the economy off steady state transitional path will move like from point B to point A as in Figure 7. Likewise, if an epidemic disease kills most of human capital but leaves physical capital intact. Then the transitional dynamics will follow the path from point C to point A as in Figure 7. Therefore, destruction of either one of the capitals has only temporary effect. However, if both physical and human capitals are destroyed, then it may affect both transitional dynamics as well as steady state even if the decrease amounts of the two capitals are the same, i.e. the ratio of the two capitals remain constant. Suppose that the ratio of the two capitals remain the same after shocks, the steady state growth rate drops directly from point A to point D. However, if the magnitude of the drop is larger for physical capital relative to that of human capital, then the transitional path will first shift from point A to point E and then converge to new steady state point D. If the magnitude of the drop is larger for human capital relative to physical capital, the transitional path will first shift from point A to point F and then converges to point D. Note also that although the new steady state growth rate at D is definitely smaller than that at A, the transitional growth rate may likely be higher than the growth rate at point A in the early period right after shocks. That is, the growth rate at E or F may be higher than that at A.

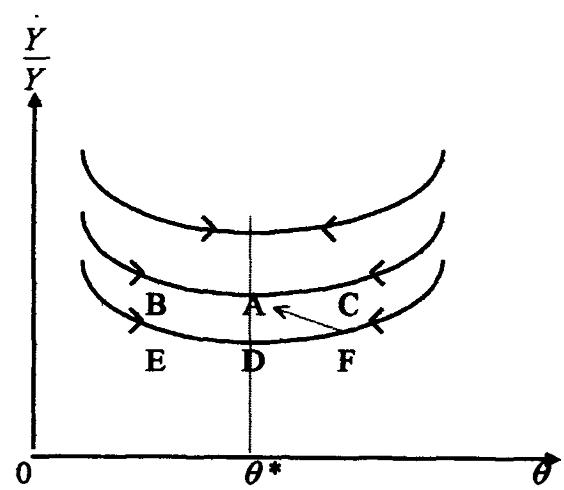


Figure 7. Transitional Dynamics of destruction in both physical and human capitals

However, the temporary increase of either type of capitals will stimulate both shortand long-run growth rates of the economy. Suppose that the inflow of foreign aid or foreign direct investment increases the level of intermediate capital goods so that $\theta > \theta*$. This will stimulate the accumulation of human capital to restore the value of $\theta*$ and reach at a higher steady state as the level of both capitals are higher after the shocks. Hence the transitional dynamics following the path from D to C and then from C to A. If instead a huge flow of high quality immigrants increases the stock of specific-training human capital, then it will stimulate the accumulation of intermediate good to restore the equilibrium value $\theta*$. Hence the transitional dynamics following the path from D to B and then from B to A. Hence, the policy implications of the above discussion are that government may encourage accumulation of physical or human capital or both. The effect will be permanent!

In summary, temporary adverse shock on either one of capitals have only temporary adverse effect; however, temporary favorable shock on either one of capitals can generate positive and permanent effect. However, the temporary adverse (favorable) shocks on both types of capital will produce permanent adverse (favorable) effect.

V. Concluding Remark

This paper incorporates the complementarity property between intermediate goods and specific-training human capital into Schumpeterian R&D-based growth model. The use of innovated intermediate capital goods required the specific-trained human capital to operate it. Moreover, the innovative firm has the incentive to train workers of the intermediate goods purchasing firms from which a lump sum of training fee may charged. Like tie-in sale, innovative firm sells intermediate goods and trains workers for the purchasing firms. As there is profit trade-off between selling intermediate goods and charging specific-training fee for the workers using the intermediate goods. To maximize profit, in our model the innovative firm will charge intermediate goods at a lower markup than conventional models predict.

The steady state growth rate is determined by both the ratio and level of the intermediate goods and specific-training human capital. Hence even countries converge to same steady-state ratio of intermediate goods and specific-training human, the differential long-run growth rate across countries may exist provided that countries have different levels of intermediate goods or specific-training human capital. Like Solow growth model, during the transitional path conditional convergence will prevail. As for external shocks, the model can generates profound growth effects depends on the property of shocks. The temporary adverse (favorable) shocks on both intermediate goods and specific-training human capital will produce permanent adverse (favorable) effect. However, temporary shock on only one type of capitals will generate asymmetric effect. The temporary adverse shocks on either types of capitals will have no long-run growth effect, while the temporary favorable shocks on either types of capitals will generates positive long-run growth effect. Therefore, the policy implications of the model are that government should encourage the accumulation of intermediate capital goods or specific-training human capital or both. The effects will be permanent!

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Appendix:

Case 1: $\frac{X_0}{Z_0} < \frac{\alpha}{B^{\gamma}(1-\alpha)}$ $\left(\frac{K_0}{H_0} < \frac{\alpha}{1-\alpha}\right)$, i.e., $\dot{H} = 0$

Hamiltonian equation:

$$J = \frac{C^{1-\varepsilon} - 1}{1-\varepsilon} e^{-\rho t} + v\left(B^{\gamma(1-\alpha)} K^{\alpha} H^{1-\alpha} - C - \delta H - N - \delta K\right) + \omega(\lambda\sigma N) \tag{A.1}$$

Differentiating (A.1) with respect to C, K, and N and let $\theta \equiv \frac{X}{Z} = \frac{1}{B^{\gamma}} \frac{K}{H}$ yield

$$\frac{\partial J}{\partial C} = C^{-\varepsilon} e^{-\rho t} - v = 0 \tag{A.2}$$

$$\frac{\partial J}{\partial K} = v\left[\alpha\theta^{\alpha-1} - \delta\right] = -\dot{v} \tag{A.3}$$

$$\frac{\partial J}{\partial N} = \omega\lambda\sigma - v = 0 \tag{A.4}$$

From (A.3) and (A.4)

$$\frac{\dot{\omega}}{\omega} = \frac{\dot{v}}{v} = -(\alpha\theta^{\alpha-1} - \delta) \tag{A.5}$$

From (A.2)

$$\frac{\dot{C}}{C} = \frac{1}{\varepsilon}\left[-\frac{\dot{v}}{v} - \rho\right] = \frac{1}{\varepsilon}\left[\alpha\theta^{\alpha-1} - \delta - \rho\right] \tag{A.6}$$

Hence, the evolution path of θ governs the economy' s transitional path. Let $\chi \equiv \frac{C}{K}$.

and $\phi \equiv \frac{N}{K}$, therefore

$$\frac{\dot{\theta}}{\theta} = \frac{\dot{K}}{K} - \frac{\dot{H}}{H} = \theta^{\alpha-1} - \delta(\theta B^{\gamma})^{-1} - \frac{C}{K} - \frac{N}{K} = \theta^{\alpha-1} - \delta(\theta B^{\gamma})^{-1} - \chi - \phi \tag{A.7}$$

$$\frac{\dot{\chi}}{\chi} = \frac{\dot{C}}{C} - \frac{\dot{K}}{K} = \frac{1}{\varepsilon}\left[\alpha\theta^{\alpha-1} - \delta - \rho\right] - \left[\theta^{\alpha-1} - \delta(B^{\gamma}\theta)^{-1} - \chi - \phi\right] = \theta^{\alpha-1}\left(\frac{\alpha}{\varepsilon} - 1\right) + \delta(B^{\gamma}\theta)^{-1} + \chi + \phi - \frac{(\delta+\rho)}{\varepsilon}$$

(A.8)

$$\frac{\dot{\phi}}{\phi} = \frac{\dot{N}}{N} - \frac{\dot{K}}{K} = g - (\theta^{\alpha-1} - \delta(B^{\gamma}\theta)^{-1} - \chi - \phi) \tag{A.9}$$

Case 2: $\frac{X_0}{Z_0} > \frac{\alpha}{B^{\gamma}(1-\alpha)}$ $(\frac{K_0}{H_0} > \frac{\alpha}{1-\alpha})$, i.e., $\dot{K} = 0$

Hamiltonian equation:

$$J = \frac{C^{1-\varepsilon} - 1}{1-\varepsilon} e^{-\rho t} + \mu\left(B^{\gamma(1-\alpha)} K^{\alpha} H^{1-\alpha} - C - \delta K - N - \delta H\right) + \omega(\lambda \sigma N) \quad \text{(A.10)}$$

Differentiating (A.1) with respect to C, K, and N and let $\theta \equiv \frac{X}{Z} = \frac{1}{B^{\gamma}} \frac{K}{H}$ yield

$$\frac{\partial J}{\partial C} = C^{-\varepsilon} e^{-\rho t} - \mu = 0 \quad \text{(A.11)}$$

$$\frac{\partial J}{\partial K} = \mu\left[\alpha \theta^{\alpha-1} - \delta\right] = -\dot{\mu} \quad \text{(A.12)}$$

$$\frac{\partial J}{\partial N} = \omega \lambda \sigma - \mu = 0 \quad \text{(A.13)}$$

From (A.3) and (A.4)

$$\frac{\dot{\omega}}{\omega} = \frac{\dot{\mu}}{\mu} = -\left[(1-\alpha) B^{\gamma} \theta^{\alpha} - \delta\right] \quad \text{(A.14)}$$

From (A.2)

$$\frac{\dot{C}}{C} = \frac{1}{\varepsilon}\left[-\frac{\dot{\mu}}{\mu} - \rho\right] = \frac{1}{\varepsilon}\left[(1-\alpha) B^{\gamma} \theta^{\alpha} - \delta - \rho\right] \quad \text{(A.15)}$$

Hence, the evolution path of θ governs the economy' s transitional path. Let $\tilde{\chi} \equiv \frac{C}{H}$.

and $\tilde{\phi} \equiv \frac{N}{H}$, therefore

$$\frac{\dot{\theta}}{\theta} = \frac{\dot{K}}{K} - \frac{\dot{H}}{H} = -B^{\gamma} \theta^{\alpha} + \delta B^{\gamma\theta} + \tilde{\chi} + \tilde{\phi} + \delta \quad \text{(A.16)}$$

$$\frac{\dot{\tilde{\chi}}}{\tilde{\chi}} = \frac{\dot{C}}{C} - \frac{\dot{H}}{H} = B^{\gamma} \theta^{\alpha}\left[\frac{(1-\alpha)}{\varepsilon} - 1\right] + \delta B^{\gamma} \theta + \tilde{\chi} + \tilde{\phi} - \frac{(\delta+\rho)}{\varepsilon} \quad \text{(A.17)}$$

$$\frac{\dot{\tilde{\phi}}}{\tilde{\phi}} = \frac{\dot{N}}{N} - \frac{\dot{K}}{K} = g - B^{\gamma}(\theta^{\alpha} - \delta\theta) + \tilde{\chi} + \tilde{\phi} + \delta \quad \text{(A.18)}$$