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A Critical Investigation of Long-run Properties of Endogenous Growth Models

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Abstract

This paper presents a critical investigation of long-run properties of endogenous growth models. A growth model is said to have desirable long-run properties when there is a unique steady state with sustained growth and when expressions of the steady state growth rates are robust for changes in values of parameters. It is shown that endogenous growth models never have the desirable long-run properties, whereas exogenous growth models do have them. These results reinforce the argument of Solow's skepticism about new growth theory and establish that the Solow model is still the standard model of economic growth.

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This paper presents a critical investigation of long-run properties of endogenous growth models. A growth model is said to have desirable long-run properties when there is a unique steady state with sustained growth and when expressions of the steady state growth rates are robust for changes in values of parameters. It is shown that endogenous growth models never have the desirable long-run properties, whereas exogenous growth models do have them. These results reinforce the argument of Solow's skepticism about new growth theory and establish that the Solow model is still the standard model of economic growth.

I. INTRODUCTION

Just half a century ago Robert M. Solow presented a simple and highly influential model of economic growth — without doubt a monument in growth theory. The Solow model of growth with exogenous technological change — old growth theory — is sometimes called the exogenous growth model at the present period. As is well known many models of growth with endogenous technological change — new growth theory — have appeared since then.

Historically, endogenous growth models emerged intensively two times in the past. The first wave was appearance of pioneering work of Arrow[1962], Uzawa[1965], Shell[1966, 1967] and others. After two decades the second wave arose vigorously. P. Romer[1986, 1990], Lucas[1988], Grossman and Helpman[1991], Aghion and Howitt[1992] and succeeding others constructed the golden age of endogenous growth theory. In the powerful stream of this new theory many growth theorists seemed to believe that the theory was a dream theory of growth and that it overcame the Solow model of exogenous growth. At the present time they seem to believe in the superiority of the new theory over the Solow model.

Should we simply believe the victory of endogenous growth theory or should we rely upon the Solow model? The purpose of this paper is to answer this question — the greatest question in macroeconomics — in a simple and general manner.

A revolution causes a counterrevolution. In the enthusiastic surge of endogenous growth theory Solow[2000] describes skepticism about the new theory calmly. To put it briefly, his counterattack is done by showing that major models of endogenous growth lack robustness dangerously and, therefore, they do not succeed as growth models.

Is the Solow model truly obsolete? Is endogenous growth theory a great advance from the Solow model, or a mare's nest? We now need to make an appraisal of the new theory. In this paper I shall support the Solow model resolutely, because endogenous growth models do not have desirable long-run properties that are indispensable to successful growth models. In other words, I shall argue that endogenous growth theory should be dismissed, because despite seemingly rich content it is a fragile theory without robustness.

Desirable properties that successful growth models should have are not necessarily confined to only the robustness of the models (that is, insensitivity of results obtained to changes in values of parameters of the models). Then what are desirable properties of a growth model? They are as follows:

P1. (Existence of a Unique Steady State) There is a unique steady state.[1]

P2. (Sustained Growth along the Steady State) The steady state growth rates of per capita quantities are positive and finite.

P3. (Global Stability of the System) A growth path starting from a given initial point approaches the steady state path.

P4. (Robustness of the Steady State Growth Rates) Expressions of the steady state growth rates are robust for changes in values of parameters.

These are the main properties. We will refer to some other properties later. (Besides, it is required that a model is simple, clear and elegant.) If a growth model lacks at least one of these desirable properties, then the model is not desirable as a growth model. In the above properties P1, P2 and P4 are long-run properties, whereas P3 is a property of a transition path. In this paper I shall focus my attention only on long-run properties of growth models, because examining them suffices to show the desirability of exogenous growth models and the undesirability of endogenous growth models.[2]

Surely endogenizing technological change appears the admirable extension of the Solow model. However, our examination demonstrates that endogenous growth models fail to generate the desirable long-run properties against expectation. In contrast, exogenous growth models — that is, the Solow model and the Mankiw-Romer-Weil model — succeed perfectly in generating all the desirable properties. Thus, the argument of the present paper implies that the Solow model (correctly, exogenous growth theory including the Mankiw-Romer-Weil model) is the standard model (or theory) of economic growth, and in addition, that the Solow model will still be the standard model of growth in the future.

The paper is organized as follows. Section 2 and 3 review the Solow model and the Mankiw-Romer-Weil model respectively. Succeeding sections consider endogenous growth models critically. Section 4 deals with two kinds of models of growth with endogenous knowledge capital accumulation — learning by doing model and endogenous R&D-based models. Section 5 treats an integrated model of endogenous knowledge and human capital accumulation. Section 6 is a visual guide to the simplest social planner problem.

Table 1 summarizes crucial assumptions and long-run properties of the models examined in the paper.

II. THE SOLOW MODEL

In this and the next sections I show that exogenous growth models have the desirable long-run properties. A starting point and a benchmark of our argument is the Solow model of growth with exogenous technological change. Consider a competitive market (i.e., decentralized) economy without government. Long-run motion and properties of the Solow model (with the Cobb-Douglas production function) are determined (only) by the following three equations:

(1) $$Y = K^{\alpha}(AL)^{1-\alpha}, \qquad 0<\alpha<1$$

(2) $$\dot{A} = mA,$$

(3) $$\dot{L} = nL,$$

where Y = the quantity of output of the final good, K = the stock of physical capital, A = the level of technology, L = the supply of labor force. A dot over a variable stands for time derivative. (1) is the production function with Harrod neutral technological change. (2) stands for exogenous technological change at a constant growth rate . We regard A simply as the stock of knowledge capital. (3) stands for exogenous labor force growth at a constant rate. For simplicity we ignore depreciation of the physical capital stock.

Let $y = Y/L$ and $k = K/L$. Let g_x denote a steady state (long-run) growth rate of a variable x designated by a subscript. Logarithmic differentiation of equation (1) yields an equation $g_y = \alpha g_k + (1-\alpha)g_A$. Solutions to this equation are given by

(4) $$g = g_y = g_k = g_A = m.$$

Obviously, the Solow model has a steady state with sustained growth at the exogenously given constant rate m. (Of course, it is usually assumed that $0 < g = m < \infty$.)

III. THE MANKIW-ROMER-WEIL MODEL

The Mankiw-Romer-Weil[1992] model is a simple integrated model of exogenous technological change and endogenous human capital accumulation. (This model itself was developed to explain cross-country differences in incomes. In contrast, they interpreted the Solow model as a model of worldwide economic growth.)

Long-run properties of their model are determined by the following three equations:

(5) $$Y = K^{\alpha} H^{\beta} (AL)^{1-\alpha-\beta}, \qquad 0 < \alpha + \beta < 1$$

(6) $$\dot{A} = mA,$$

(7) $$\dot{L} = nL,$$

where H= the stock of human capital. Let $h = H / L$. Equation (5) yields an equation $g_y = \alpha g_k + \beta g_h + (1 - \alpha - \beta) g_A$. Solutions to this equation are given by

(8) $$g = g_y = g_k = g_h = g_A = m.$$

The Mankiw-Romer-Weil model also has a steady state with sustained growth at the rate m.[3]

IV. MODELS OF ENDOGENOUS KNOWLEDGE CAPITAL ACCUMULATION

This section deals with two kinds of models of growth with endogenous knowledge capital accumulation. The first model is a learning by doing model and the second one is endogenous R&D-based models.

IV. A. Learning by Doing Model

First, I examine long-run properties of Sheshinski[1967]'s model as the simplest model of growth with learning by doing. Long-run properties of the Sheshinski model (with the Cobb-Douglas production function) are determined by the following three equations:

(9) $$Y = K^{\alpha}(AL)^{1-\alpha}, \qquad 0 < \alpha < 1$$

(10) $$A = K^{\eta}, \qquad 0 < \eta < 1$$

(11) $$\dot{L} = nL.$$

(The notation is mine.) The production function of the final good, (9), yields an equation $g_y = \alpha g_k + (1-\alpha) g_A$. The relation of available knowledge to learning by doing, (10), yields an equation $g_A = \eta(g_k + n)$. We see that long-run growth rates

(12) $$g = g_y = g_k = g_A = \frac{\eta n}{1-\eta}$$

satisfy both equations. Therefore, the Sheshinski model has a steady state.

However, the model is not desirable. The reasons are as follows:

R1. The expression of (12) means that the steady state growth rates, g, are proportional to the rate of growth of labor force, n. This implies that faster growth of population leads to that of per capita quantities. This is obviously unrealistic.

R2. Furthermore, (12) means that $n = 0$ (constant population) causes $g = 0$ (stopping growing). This result can not explain sustained growth observed in some advanced countries (such as West European countries and recent Japan) where the populations are approximately constant.

R3. Lastly, (12) means that the steady state growth rates increase rapidly as η approaches unity and that they explode as $\eta = 1$.

R3 implies that the steady state growth rates are very sensitive to changes in values of the parameter η especially in the neighborhood of $\eta = 1$. In other words, the expression of the steady state growth rates lacks robustness.

Thus, the learning by doing model of endogenous growth fails to have the desirable long-run properties that are indispensable to successful growth models. We therefore conclude that the learning by doing model of growth is an undesirable model of growth.

IV. B. Endogenous R&D-Based Models

I consider models of economic growth driven by endogenous R&D investment — the mainstream of the current endogenous growth models — next. Long-run properties of models of growth with endogenous R&D are determined by the following three equations:[4]

$$(13) \qquad Y = F(K_Y, A, L_Y) = F^*(K_Y, AL_Y) = F^*(K, AL_Y) = K^{\alpha}(AL_Y)^{1-\alpha}, \qquad 0 < \alpha < 1$$

$$(14) \qquad \dot{A} = G(K_A, A, L_A \text{ or } l_A = L_A / L)$$
$$= G(0, A, L_A \text{ or } l_A),$$

$$(15) \qquad \dot{L} = N(K, A, L; \cdots\cdots) = N(0,0,L;0,0,\cdots,0) = nL,$$

where $K_Y =$ the stock of physical capital installed in the final good sector, $L_Y =$ labor force employed in the final good sector, $K_A =$ the stock of physical capital installed in the R&D sector, $L_A =$ labor force employed in the R&D sector. $K_Y + K_A = K =$ the total stock of physical capital, $L_Y + L_A = L =$ the total supply of labor force and $0 \leq l_A \leq 1$ hold.

(13) stands for the production function of the final good. (For simplicity we assume the Cobb-Douglas form.) (14) stands for the production function of new knowledge. (15) implies that we exclude endogenous fertility.[5]

Let $l_Y = L_Y / L$. $0 \leq l_Y \leq 1$ and $l_Y + l_A = 1$ hold. Note that labor force allocation ratios, l_Y and l_A, are kept to be constant in a steady state. (13) yields an equation $g_y = \alpha g_k + (1-\alpha) g_A + (1-\alpha) g_{l_Y}$. If there is a steady state, then $g_{l_Y} = 0$. We now need to specify the R&D equation, (14), to know whether there is a steady state or not, and to obtain the steady state growth rates (if the steady state exists).

I shall examine the following functional forms of $G(\cdots\cdots)$ in turn.

$$(16) \qquad \dot{A} = \delta L_A,$$

$$(17) \qquad \dot{A} = \delta L_A A,$$

$$(18) \qquad \dot{A} = \delta L_A^{\lambda} A^{\phi}, \qquad 0 \leq \lambda \leq 1, \quad -1 \leq \phi \leq 1$$

(19) $$\dot{A} = \delta l_A^{\lambda} A, \qquad 0 \le \lambda \le 1$$

(20) $$\dot{A} = \delta l_A^{\lambda} A^{\phi}. \qquad 0 \le \lambda \le 1, \quad -1 \le \phi \le 1$$

(i) The Case of (16)

The functional form (16) is used by Funke and Strulik[2000]. This R&D equation yields $g_A = n.$ Equation (16) generates a steady state with the growth rates

(21) $$g = g_y = g_k = g_A = n.$$

These results are not desirable by the same reason as one mentioned in the learning by doing model (R1 and R2).

(ii) The Case of (17)

This form is used by Romer[1990]. Equation (17) generates a steady state only if $n = 0$, i.e., $L =$constant. The steady state growth rates are given by

(22) $$g = g_y = g_k = g_A = \delta L_A = \delta l_A L. \qquad \text{only if } n = 0$$

This expression exhibits scale effects, which are not supported by empirical evidence. When $n \ne 0$, (17) can not generate a steady state. Therefore, equation (17) does not yield the desirable long-run properties.

(iii) The Case of (18)

This form is used by Jones[1995] and Arnold[1998]. Equation (18) generates a steady state with the growth rates

(23) $$g = g_y = g_k = g_A = \frac{\lambda n}{1-\phi}.$$

It is obvious that (23) has the same drawbacks as those of the learning by doing model (R1, R2 and R3).

(iv) The Case of (19)

This form is used by Uzawa[1965]. Equation (19) generates a steady state with the growth rates

(24) $$g = g_y = g_k = g_A = \delta l_A^{\lambda}.$$

We see that $0 \leq g \leq \delta$ holds. Although equation (19) generates sustained growth at the positive rate, regrettably, this property is a fragile one. This fact is shown in the next case.

(v) The Case of (20)

This form is a simple extension of (19). Equation (20) generates an undesirable steady state with the growth rates

(25) $$g = g_y = g_k = g_A = 0. \qquad \phi \neq 1$$

Seeming success of equation (19) is due to hiding a parameter ϕ. As soon as ϕ takes a slightly different value from unity the economy fails to achieve sustained growth at a positive rate.[6] In this sense the results derived from (19) are not robust ones.

Finally, does introducing the physical capital stock into the R&D equation yield the desirable long-run properties? As is easily expected, the answer to this question is negative. Let (13), (14) and (15) be:

(26) $$Y = F(K_Y, A, L_Y) = F^*(K_Y, AL_Y) = K_Y^{\alpha}(AL_Y)^{1-\alpha}, \qquad 0 < \alpha < 1$$

(27) $$\dot{A} = G(K_A, A, L_A) = K_A^{\theta} L_A^{\lambda} A^{\phi}, \qquad 0 < \theta < 1$$

(28) $$\dot{L} = nL.$$

(Of course, this formulation requires introducing an additional rule for allocation of investment in the physical capital stock between the final good sector and the R&D sector.) (26) yields an equation $g_y = \alpha g_{K_Y/K} + \alpha g_k + (1-\alpha) g_A + (1-\alpha) g_{l_Y}$. In a steady state K_Y / K and $l_Y = L_Y / L$ must be constant. The system (26), (27) and (28) has a steady state with the growth rates

(29) $$g = g_y = g_k = g_A = \frac{(\theta+\lambda)n}{1-(\theta+\phi)}.$$

Clearly these results show that the modified system is undesirable.

In sum, unfortunately, models of growth with endogenous knowledge accumulation fail to yield the desirable long-run properties, though an attempt to endogenize technological change is admirable. It seems that endogenous growth theorists opened Pandora's box. (The hope left is the Solow model.)

V. INTRODUCING HUMAN CAPITAL

This section extends the R&D-based models of growth. An important theme for study in recent endogenous growth theory is to construct integrated models of endogenous R&D and endogenous human capital accumulation. Major contributors to this field are Arnold[1998], Funke and Strulik[2000], Blackburn, Hung and Pozzolo[2000] and Zeng[2003]. Do the integrated models of growth have the desirable long-run properties?

In order to answer this question consider the following equations:

(30) $$Y = F(K_Y, H_Y, A, L_Y) = F^*(K_Y, H_Y, AL_Y) = K^{\alpha} H_Y^{\beta} (AL)^{1-\alpha-\beta},$$

(31) $$\dot{H} = M(K_H, H_H, A, L_H) = M(0, H_H, 0, 0) = \xi H_H,$$

(32) $$\dot{A} = G(K_A, H_A, A, L_A) = G(0, H_A, A, 0) = \delta H_A^{\lambda} A^{\phi},$$

(33) $$\dot{L} = nL,$$

where H_Y = the stock of human capital employed in the final good sector, K_H = the stock of physical capital installed in the education sector, H_H = the stock of human capital employed in the education sector, L_H = labor force employed in the education sector, H_A = the stock of human capital employed in the R&D sector. $K_Y + K_H + K_A = K$ = the total stock of physical capital, $H_Y + H_H + H_A = H$ = the total stock of human capital and $L_Y + L_H + L_A = L$ = the total supply of labor force hold respectively. In previous studies, it is usually assumed that $L = 1$ (that is, $n = 0$).

The production function (of the Mankiw-Romer-Weil type) of the final good sector, (30), yields an equation $g_y = \alpha g_k + \beta g_{H_Y/H} + \beta g_h + (1-\alpha-\beta) g_A$, where $h = H/L$. In a steady state H_Y/H is kept to be constant. The steady state growth rates satisfy

(34)
$$g = g_y = g_k = g_h = g_A.$$

The production function (of the Arnold/Funke-Strulik type) of the education sector, (31), yields

(35)
$$g_h = \xi\left(\frac{H_H}{H}\right) - n.$$

The production function of the R&D sector, (32), yields

(36)
$$g_A = \frac{\lambda\left(g_h + n\right)}{1-\phi}.$$

This model has a steady state with the growth rates

(37)
$$g = g_y = g_k = g_h = g_A = \frac{\lambda n}{1-(\lambda+\phi)}.$$

Substituting (37) into (35) we have the ratio of the stock of human capital employed in the education sector to the total stock of human capital along the steady state path

(38)
$$\frac{H_H}{H} = \frac{n}{\xi}\left(\frac{1-\phi}{1-\phi-\lambda}\right).$$

Clearly the expression of the steady state growth rates, (37), shows that the integrated model also lacks the desirable long-run properties. (Note that $g=0$ as $L=1$.) In addition, this model may yield boundary optima, $H_H = 0$ (i.e., $H=$constant) and/or $H_A = 0$ (i.e., $A=$constant), which are pointed out by Funke and Strulik.[7]

Thus, an ambitious attempt to integrate endogenous R&D and endogenous human capital accumulation yields the miserable results again.

VI. AN INTRODUCTION TO THE SOCIAL PLANNER PROBLEM: A VISUAL GUIDE

In this section I explain the simplest social planner problem relying on the phase diagram analysis.[8] In order to draw diagrams in a two-dimensional space we assume here that the stock of physical capital, K, the stock of human capital, H, and the supply of labor force, L, are constant respectively. Therefore, only the stock of knowledge capital (the level of technological knowledge), A, is a state variable. The purpose of our explanation is to give visual understanding of the problem and to show that the problem has not the desirable long-run properties. In particular, our illustration may be useful for aiming at pedagogical effects except that the calculation is somewhat complicated.

VI. A. The Simplified Solow Model

Before proceeding to the social planner problem I would examine the Solow model both with the constant stock of physical capital and with the constant supply of labor force. The Solow model in which economic growth is driven only by technological progress is written as:

(39) $$Y = C = K^{\alpha}(AL)^{1-\alpha} = (AL)^{1-\alpha}, \qquad K = 1$$

(40) $$\dot{A} = mA,$$

(41) $$L = \text{constant.}$$

This model has a steady state with the growth rates

(42) $$g = g_Y = g_C = (1-\alpha)g_A = (1-\alpha)m.$$

An observed value of $(1-\alpha)$ is about 0.7. As shown in section 2 the steady state growth rates of per capita quantities in the general Solow model is equal to the given rate of technological progress, m. (42) means that the steady state growth rates (of per capita quantities) in the Solow model without physical capital deepening is equal to about seventy per cent of those in the general Solow model. Thus the Solow model still can achieve sustained growth at the positive rate only by technological progress, even though both physical capital accumulation and labor force growth vanish.

In what follows we draw phase diagrams for some simplified social planner problems with endogenous knowledge accumulation.

VI. B. The Problem with the Funke-Strulik Knowledge Production Function

First, we deal with the simplest social planner problem in which the new knowledge production function is of the Funke-Strulik form. Consider a two-sector planned economy which consists of the final good sector and the scientific research sector.[9]

Optimal growth in the economy is formulated as follows:

(43) $$\text{Maximize} \int_0^\infty e^{-\rho t} U(C) dt$$

(44) $$\text{subject to } Y = C = K^\alpha \left(AL_Y\right)^{1-\alpha} = \left(AL_Y\right)^{1-\alpha}, \qquad K = 1$$

(45) $$\dot{A} = \delta L_A.$$

(43) is a usual social welfare function. The instantaneous utility function is assumed to be $U(C) = \frac{1}{1-\sigma} C^{1-\sigma}$, $\sigma > 0$, $\sigma \neq 1$. As before, we assume that $K = 1$ and $L_Y + L_A = L =$ constant. The initial condition is $A(0) = A_0 =$ given. The transversality condition is $\lim_{t\to\infty} e^{-\rho t} U'(C) = 0$.

The Euler-Lagrange equation for this problem is given by

(46) $$\frac{\dot{L}_Y}{L_Y} = \frac{\delta\left[1-(1-\alpha)(1-\sigma)\right]L_Y - \rho A + \delta(1-\alpha)(1-\sigma)L}{\left[\alpha+\sigma(1-\alpha)\right]A}.$$

We draw a phase diagram in $\left(A, L_Y\right)$ plane. From (45) we see that $\dot{A} > 0$ as $L_A = L - L_Y > 0$, i.e., $L_Y < L$, and that $\dot{A} = 0$ as $L_A = 0$, i.e., $L_Y = L$. From (46) $\dot{L}_Y = 0$ as

$$L_Y = \frac{\rho A - \delta(1-\alpha)(1-\sigma)L}{\delta\left[1-(1-\alpha)(1-\sigma)\right]}.$$

The denominator of this expression is always positive. Hence, the $\dot{L}_Y = 0$ locus is an upward sloping straight line. We see that $\dot{L}_Y > (<) 0$ in a domain above (below) the $\dot{L}_Y = 0$ locus. Thus we obtain a phase diagram Figure I. A positively sloped heavy curve represents an optimal path satisfying the transversality condition. The optimal path starts from the given initial value A_0 and approaches a steady state (A^*, L). In the steady state the economy can no longer grow.

From (44) we have $g_Y = g_C = (1-\alpha)g_A + (1-\alpha)g_{L_Y}$. From (45) we have $g_{L_A} = g_A$. Since $g_{L_Y} = g_{L_A} = g_L = 0$, we have the steady state growth rates

(47) $$g = g_Y = g_C = (1-\alpha)g_A = 0.$$

That is, this model fails to generate sustained growth at a positive rate (which is possible in the simplified Solow model).

VI. C. The Problem with the Romer Knowledge Production Function

Second, we examine the problem with the Romer knowledge production function. Let

(48) $$\dot{A} = \delta L_A A$$

instead of equation (45). The Euler equation is given by

(49) $$\frac{\dot{L}_Y}{L_Y} = \delta\left(L_Y - L_Y^*\right),$$

where

(50) $$L_Y^* = \frac{\rho - \delta(1-\alpha)(1-\sigma)L}{\delta\left[1-(1-\alpha)(1-\sigma)\right]}.$$

The phase diagram for this case is depicted in Figure II. A horizontal heavy straight line represents an optimal path. Labor force allocation between the two sectors along the optimal path is kept to be constant over time. The optimal path is a steady state with the growth rates

(51) $$g = g_Y = g_C = (1-\alpha)g_A,$$

(52) $$g_A = \delta L_A^* = \delta\left(L - L_Y^*\right).$$

Therefore, fortunately, the economy can grow at the positive rate forever. This seemingly fine performance crucially depends on hiding possible parameters of the knowledge production function, however.

VI. D. The Problem with the Jones Knowledge Production Function

Finally, we examine the problem with the Jones knowledge production function

(53) $$\dot{A} = \delta L_A^{\lambda} A^{\phi}.$$

Since the calculation of the Euler equation for the Jones equation is complicated, I would use here the logarithmic utility function $U(C) = \ln C$ for simplification. Then, the Euler equation is given by

(54) $$\dot{L}_A = -\frac{\left(\delta\lambda L_Y - \rho L_A^{1-\lambda} A^{1-\phi}\right) L_A^{\lambda}}{\left(1-\lambda + L_A / L_Y\right) A^{1-\phi}}.$$

The phase diagram is drawn in Figure III. $\dot{L}_A = 0$ holds when

(55) $$\delta\lambda L_Y = \rho L_A^{1-\lambda} A^{1-\phi}.$$

A locus of (A, L_A) satisfying (55) is a downward sloping curve that starts from a point $(0, L)$ and approaches the horizontal axis as A goes to infinity. The reason is understood by drawing (55). I leave this work to Appendix. In the phase diagram a negatively sloped heavy curve shows the optimal path. Along the optimal path, the knowledge capital stock increases unlimitedly, whereas the optimal labor force devoted to the research activity decreases toward zero. Thus, the economy approaches a steady state in which the total labor force is devoted to the production of the consumption good.

The problem has the steady state with the growth rates

$$g = g_Y = g_C = (1-\alpha)g_A = 0. \tag{56}$$

That is, the model fails to generate endogenous sustained growth at a positive rate. Clearly the performance of this model is inferior to that of the simplified Solow model.

Why ever do we take the trouble to construct endogenous growth models that are more complicated than the Solow model? A major reason is that we expect endogenous growth models to reveal better performance — that is, achievement of faster long-run growth with or without the assistance of appropriate policies. However, our investigation strongly shows that the Solow model is undoubtedly superior to sophisticated models of endogenous growth.

VII. THE KEY TO CONSTRUCTING A SUCCESSFUL MODEL OF GROWTH

Our examination of models of economic growth in the previous sections leads to an undoubted conclusion. That is, work of constructing a successful growth model (correctly, a growth model with the desirable long-run properties) must start from accepting the following three assumptions:

A1. (Harrod Neutral Technological Change) Technological change is Harrod neutral.

A2. (Exogenous Technological Change at a Constant Growth Rate) The stock of technological knowledge grows at an exogenously given constant rate.

A3. (Exogenous Labor Force Supply at a Constant Growth Rate) The supply of labor force grows at an exogenously given constant rate.

Needless to say, any attempt to construct endogenous growth models violates A2.

Mathematically, these assumptions are expressed as follows:

$$Y = F(K_Y, A, L_Y) = F^*(K_Y, AL_Y) = F^*(K, AL), \tag{57}$$

$$\dot{A} = G(K_A, A, L_A) = G(0, A, 0) = mA, \tag{58}$$

$$\dot{L} = N(K, A, L; \cdots\cdots\cdots) = N(0, 0, L; 0, 0, \cdots, 0) = nL, \tag{59}$$

$$K_Y + K_A = K,$$
$$L_Y + L_A = L.$$

These equations are just (a part of) the Solow model itself.[10]

Now what is the endogenous growth theory "revolution"? Its meaning is as follows: The "revolution" reminds again us that only the Solow model is a good model of economic growth. In that sense the "revolution" is a revolution betrayed (that is, not an unfinished revolution but a failed one) and ironically leads to a favorable reappraisal of the Solow model after all.

VIII. CONCLUSION

In this paper I have investigated the essential nature of endogenous growth theory. Specifically, I have examined the existence of a steady state, the possibility of sustained growth and the robustness of expressions of the steady state growth rates. As a result of examination I have confirmed that endogenous growth models do not have the desirable long-run properties, that is, that incorporating the R&D equation with the fine explanatory power into a growth model never ensures success of the model. In contrast, the Solow model has the desirable long-run properties. In addition, it is simple and clear. Therefore, I do not regard endogenous growth theory as the successful theory and as the legitimate successor to the Solow model.

Endogenous growth theory certainly seems revolutionary. (Frankly speaking, when I began to study this theory, I also felt the theory epoch-making.) Why on earth do endogenous growth models fail to have the desirable properties? Why does the Solow model work very well? This is a great mystery in economics. I do not know whether Heaven is spiteful or not.

We now encounter serious difficulty. What is generalization or extension of theories in our discipline at all? Does generalization (or extension) always yield useful and fruitful (that is, successful) results? Or is it unusual for generalization to succeed? I would introduce here an example in mathematics into our argument. I quote the last paragraph from Kunihiko Kodaira's essay.[11]

What is fruitful generalization of theories?

In general, mathematicians like generalization instinctively. Consider a fruitful system of theory S derived from a system of axioms A. Then, every mathematician wants to obtain a system of theory T that is more general than S starting from a new system of axioms B made by removing some axioms from A. T appears a system that is more fruitful than S, because T is generalization of S. But in many cases we are disappointed that the content of T is too poor against expectation. In this case

T is not generalization of S but making S thin. Of course, every generalization does not cause making theories thin. Mathematics has been evolving by virtue of generalization. In recent mathematics it is a mysterious phenomenon that generalization sometimes causes making theories thin.

What are features of the generalization that evolves into fruitful theories then? Moreover, what are features of the systems of axioms that can be starting points of fruitful systems of theories? Contemporary mathematics is cool toward this question. For example, clearly group theory is a system that is more fruitful than lattice theory. Then what are respects in which a system of axioms of group theory is superior to that of lattice theory? Furthermore, a starting point of sheaf theory which is basic to topological geometry, algebraic geometry, function of many variables etc. is seemingly quite trivial generalization that constant coefficients of cohomology group are replaced by functions. Why is it very fruitful generalization? In contrast, why doesn't continuous geometry that is thought to be amazing generalization of projective geometry have evolved? There are many questions of this kind in mathematics. Are they stupid questions that are not worth considering? Can phenomenology of mathematics to answer these questions exist? I do not know. It must be a very interesting subject if it can exist. An obvious difficulty is that studying the phenomenology of mathematics requires understanding all of major fields of mathematics. This work needs much of time. The reason contemporary history of mathematics is not written is due to the same reason. —— Kodaira, Kunihiko, "Impression of Mathematics", Seki, Setsuya, Shoji Maehara and Tamotsu Murata Ed., *Invitation to Mathematics* (in Japanese) (Tokyo: Chikuma Shobo, 1969), 272-281.

I do not know whether the situation of mathematics is the same as that of economics or not, because mathematics is not science but logic.

However, the fact quoted above gives us serious suggestion. Difficulty often caused by generalization may be inevitable fate in disciplines using mathematics. The failure in an attempt at endogenization of the Solow model — probably the greatest failure in economics — may be such an example. I think that the admirable success of the Solow model is due to the stoicism against temptation to complicate the model. Constructing successful models in economics is a kind of art that finds out an unknown watershed lying between simplification and complication.

A main conclusion that emerges from our critical investigation, is that the tremendous rise of endogenous growth models is not a genuine and hopeful breakthrough in growth theory. Many growth theorists may think that even so we should continue to study endogenous growth theory believing future possible evolution. In contrast, other theorists may think that we should withdraw immediately from the fragile theory and should turn back to the Solow model. I believe that return to the Solow model is wise.

I have been thinking about a question: Is the Solow model alive or dead? My answer is as follows: The Solow model is still alive. And only the Solow model will continue to live. It is surprising that both the starting point and the final destination for growth theory are the Solow model.

Enthusiasm and self-satisfaction will be over sooner or later. What will appear before us then? I would like to expect it.

APPENDIX: THE SLOPE OF THE $\dot{L}_A = 0$ LOCUS

(55) is drawn in Figure V. In this figure $L_A = L - L_Y$ is measured along the horizontal axis. The left-hand side of (55), $\delta\lambda L_Y = \delta\lambda(L - L_A)$, is a downward sloping straight line. The right-hand side of (55) for a given value of A is an upward sloping and concave curve starting from the origin. The horizontal coordinate of a point of intersection of both curves gives a value of L_A satisfying $\dot{L}_A = 0$. If $A = 0$, then the right-hand side of (55) equals 0 and its graph coincides with the horizontal axis. Hence L_A satisfying (55) for $A = 0$ is L. As A increases the right-hand side of (55) shifts upward and the horizontal coordinate of a point of intersection of both sides of (55) decreases. That is, L_A satisfying $\dot{L}_A = 0$ decreases as A increases. If $A = \infty$, then the right-hand side of (55) equals ∞ and its graph coincides with the vertical axis. Hence L_A satisfying (55) for $A = \infty$ is 0. A region in which $\dot{L}_A > 0 (< 0)$ holds (that is, in which the left-hand side $<$ $(>)$ the right-hand side holds in (55) instead of the equality) is the one above (below) the $\dot{L}_A = 0$ locus.

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TABLE I

FOUR KINDS OF GROWTH MODELS

Model	Physical capital accumulation	Knowledge capital accumulation (Technological change)	Human capital accumulation	Long-run properties of the model
Solow model	endogenous	exogenous	________	desirable
Mankiw-Romer-Weil model	endogenous	exogenous	endogenous	desirable
Models of endogenous knowledge capital accumulation	endogenous	endogenous	________	undesirable
Integrated models of endogenous knowledge and human capital accumulation	endogenous	endogenous	endogenous	undesirable

[1] In growth models with multiple steady states (for example, in some kind of monetary growth model) the so-called indeterminacy problem of growth paths sometimes arises. However, in the development economics the idea of growth with multiple steady states — for example, the poverty trap equilibrium and the self-sustained growth equilibrium — may be useful and fruitful.

[2] Note that long-run properties of growth models are independent of microeconomic foundation — that is, optimizing behavior of households and firms — of the models. Therefore we do not refer to the intertemporal optimization of agents. (Of course, the saving/investment decisions derived from the dynamic optimizing behavior of individual agents influence the transition dynamics of the model.)

[3] Note that their equation for human capital accumulation, $\dot{H} = s_H Y$, which yields $g_y = g_h$, is a redundant one for examining long-run properties of the model.

[4] See Christiaans[2004]. I owe the conceptual framework of the long-run growth analysis to Christiaans' insight into growth models.

[5] The function $N(\cdots\cdots)$ represents a change in labor force supply generated by birth, death and a change in the rate of labor participation. $N(\cdots\cdots)$ is the most mysterious function in economics. No one knows an exact form of this function. Christiaans[2004] points out that exogenous labor force growth at a constant rate is required for existence of a steady state. (p. 257, p. 258)

[6] Disappearance of sustained growth at a positive rate seen in (25) implies that the costly R&D effort generates no performance in the long-run. Obviously, this is a failure as an R&D-based model of growth. As Solow[2000, p. 145] notes, endogenous growth models are meaningful only when they can achieve the long-run growth that is faster than that in the exogenous growth model.

[7] If $H_H = 0$ and $H_A = 0$, then a rise in labor productivity is driven only by physical capital deepening. But, no country can become an advanced country with high income level only by physical capital deepening. See Maddison's impressive statistics. (Maddison[1995, Table K-2, Comparative Growth Performance of the USA, UK and Japan, 1820-1992, p. 255].

[8] A pioneering study of the social planner problem is Uzawa[1965]. Recent works in this field are Eicher and Turnovsky[1999], and Turnovsky[2000, pp. 522-535].

[9] In the social planner problem it is assumed that universities and laboratories financed by government produce free new knowledge. (In contrast, in the decentralized model it is assumed that private laboratories perform profit-making R&D.) The new knowledge in the social planner problem is a non-marketable good, that is, a public good. Therefore, the government levies tax on the final good sector to pay wage costs of researchers employed by the research sector. Hence, the optimal allocation of human resources between the two sectors is equivalent to the optimal taxation/subsidization.

[10] The rest of the Solow model are an equation for physical capital accumulation expressing "saving = physical investment" and initial conditions ($k(0) = k_0 = K_0 / L_0$ and $A(0) = A_0$). In many textbooks economists draw a phase diagram for the dynamics of the Solow model using the amount of physical capital per unit of efficiency (effective) labor (K / AL) as a state variable. But this manner of drawing the diagram is not necessarily appealing for students. I propose here drawing

the diagram in a $(k = K / L, A)$ plane instead of the above manner. This manner seems easy to understand the motion of the system intuitively. See Figure IV. In this figure an upward-sloping straight line SS shows a steady state path. All transition paths converge toward the steady state path SS. (In contrast to the case of the Solow model drawing a phase diagram in $(h = H / AL, k = K / AL)$ plane is convenient for understanding the Mankiw-Romer-Weil model.)

[11] Kodaira(1915-1997) is a Japanese mathematician who won the Fields prize in 1954.

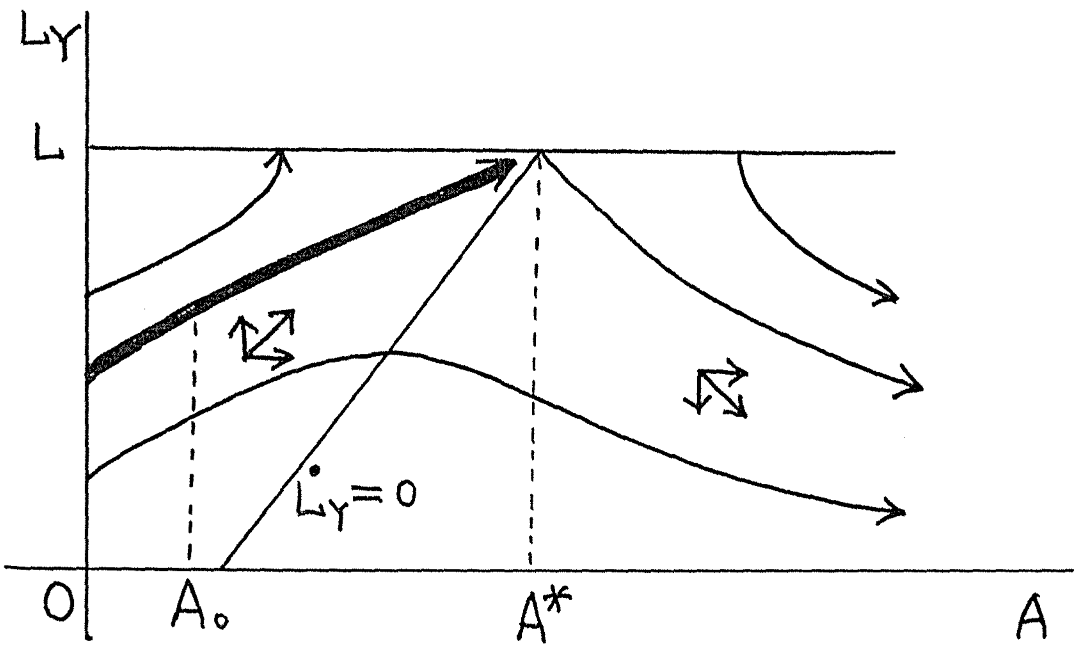
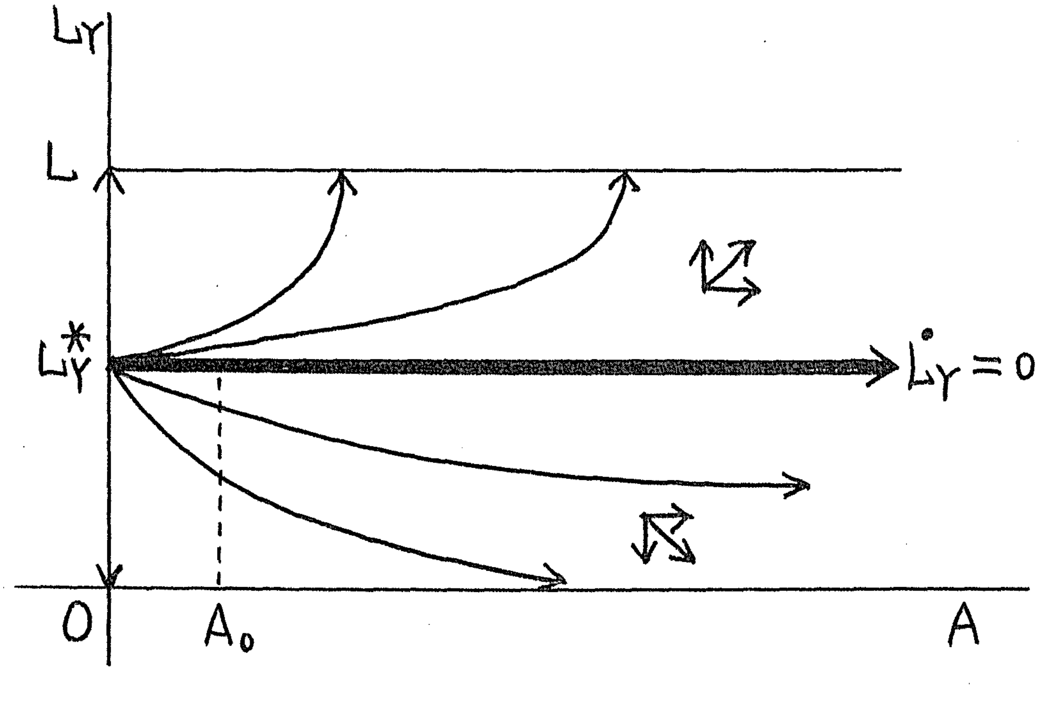


FIGURE I



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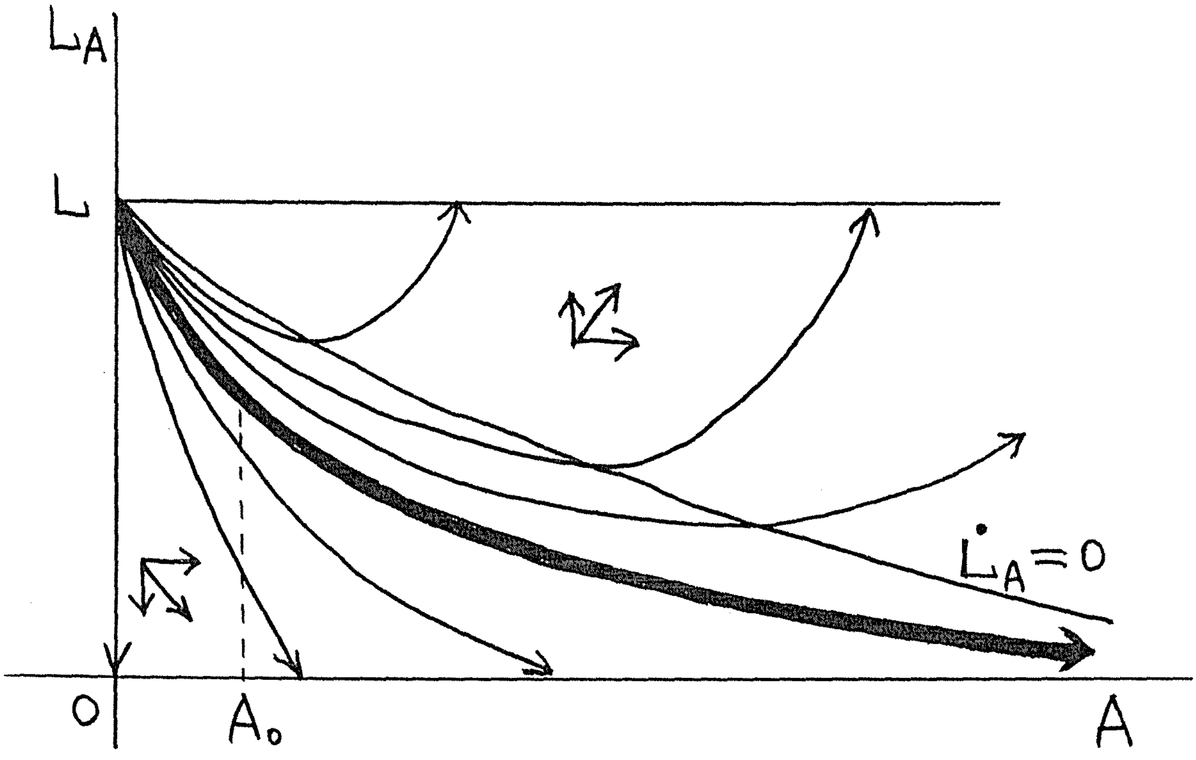

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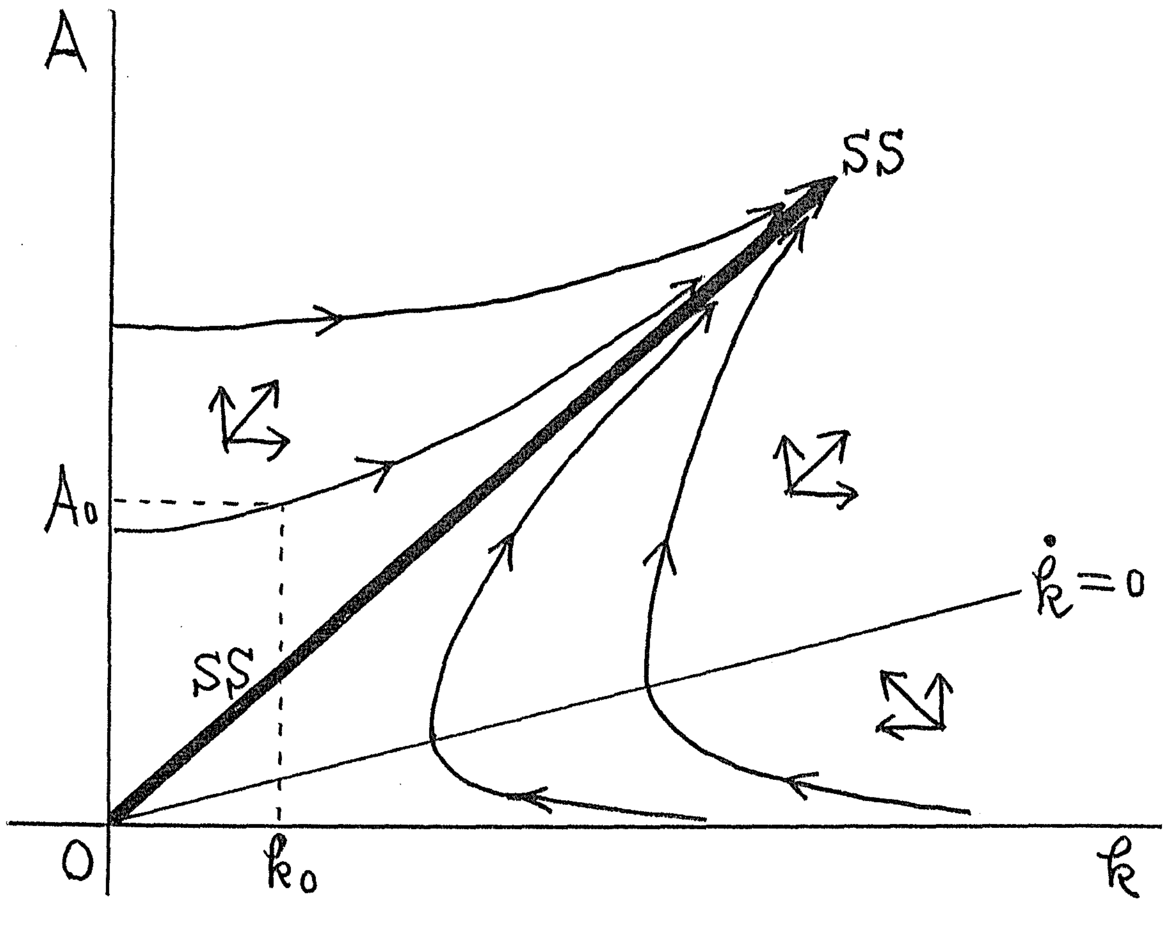

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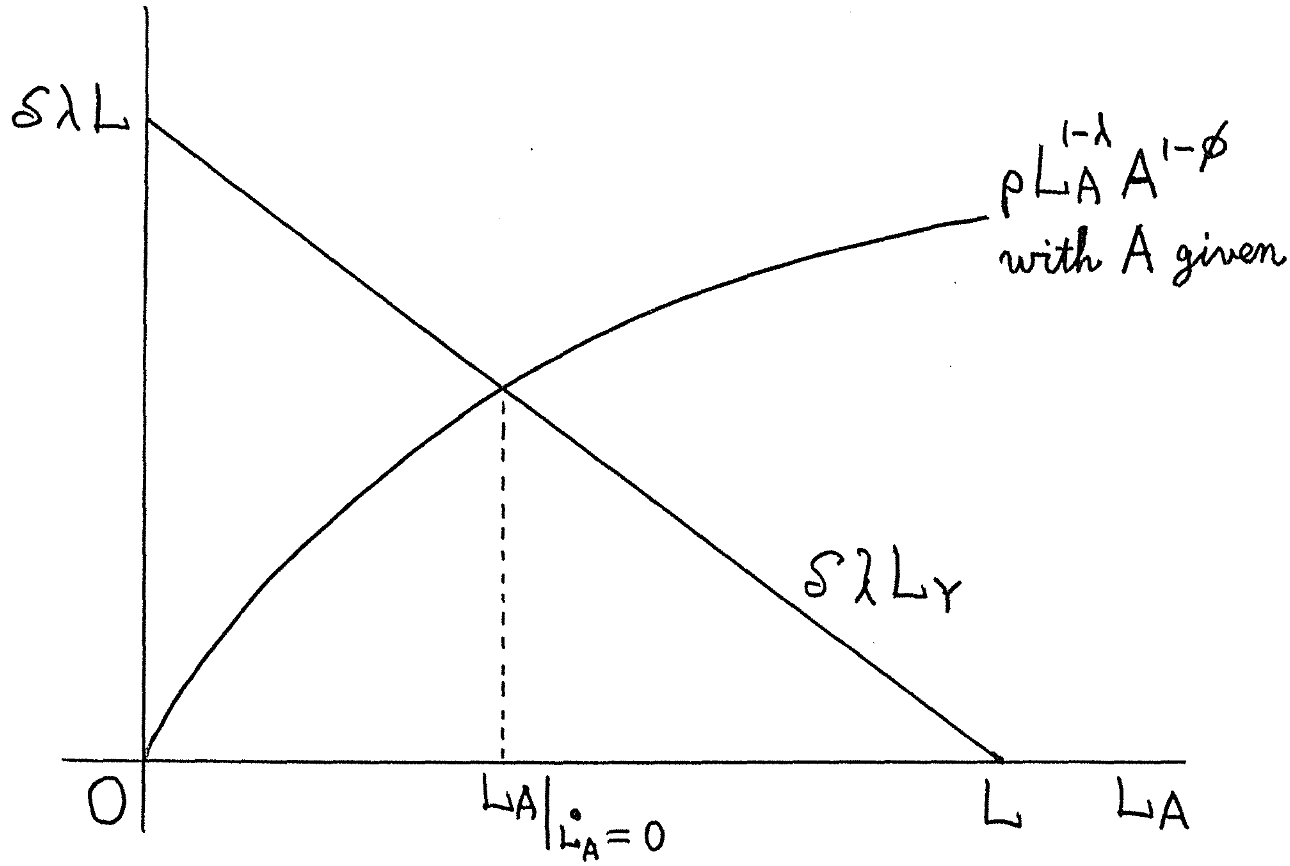

$\delta\lambda L$
$\rho L_A^{1-\lambda} A^{1-\phi}$
with A given
$\delta\lambda L_Y$
O
$L_A|_{\dot{L}_A=0}$
L
L_A

FIGURE V

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