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William D. Nordhaus

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SOME SKEPTICAL THOUGHTS ON THE THEORY OF INDUCED INNOVATION *

WILLIAM D. NORDHAUS

A. The process of accumulating knowledge, 208.—B. Growth with non-stationary innovation possibility function, 213.—C. Conclusion, 218.

Neoclassical growth theory has never been very comfortable with technological change. Until recently, only Harrod-neutral (or purely labor-augmenting) technological change could be introduced into neoclassical growth without leading to bizarre results. Neoclassical growth models were "saved" from such restrictiveness by the introduction of the theory of induced innovation. Under the usual neoclassical assumptions, and in addition when the innovation possibility curve takes the form assumed by Kennedy and Samuelson, the system settles down into a balanced-growth path exactly like that of the purely labor-augmenting case.¹ This result is so remarkable that it even merits a place in the leading introductory textbook.² Recently, the theory has been tested empirically³ and even appears as the basis for a study of class conflict.⁴

However remarkable the theoretical, empirical, and sociological results may be, I think the model is too defective to be used in serious economic analysis. The present paper outlines some reasons for this skepticism.

A. THE PROCESS OF ACCUMULATING KNOWLEDGE

Behind the theory of induced innovation is, implicitly, a microeconomic description of the generation and accumulation of knowledge. The first question that must be answered is whether this description is acceptable.⁵

* This research was supported by the National Science Foundation and the Ford Foundation.

1. This is proved in Paul A. Samuelson, "A Theory of Induced Innovation along Kennedy-Weizsacker Lines," *Review of Economics and Statistics*, XLVII (Nov. 1965), 343-56.

2. See Paul A. Samuelson, *Economics*, 7th ed. (New York: McGraw-Hill, 1967), pp. 271ff.

3. William Fellner, "Empirical Support for the Theory of Induced Innovation," this *Journal*, LXXXV (Nov. 1971), 580-604.

4. Samuel Bowles and David Kendrick, *Notes and Problems in Microeconomic Theory* (Chicago: Markham Press, 1970), Section 6.7, "Class Interests and Induced Technical Change," pp. 196-200.

5. To my knowledge, S. Ahmad ("On the Theory of Induced Investment," *The Economic Journal*, LXXVI (June 1966), 344-57) is the only person who has attempted to formulate the model from a microeconomic point of view.

The generally accepted formulation of the model is roughly as follows.⁶ Production is (with time subscripts omitted) given by

$$(1) \quad Y = F(AK, BL),$$

where Y is output, K is capital services, L is labor services, A is efficiency of capital, and B is efficiency of labor. F is a neoclassical production function, having among other properties constant returns to scale.

The new twist of the theory of induced innovation is an innovation possibility function (IPF) showing how new techniques affect productive efficiency. It is represented functionally by

$$(2) \quad a = g(b) \quad g'(b) < 0, \quad g''(b) < 0,$$

where $a = d(\ln A)/dt$ = the rate of capital-augmenting technological change and $b = d(\ln B)/dt$ = the rate of labor-augmenting technological change.

This is also shown in Figure I. The question arises, what kind of microeconomic framework is represented by (1) and (2)? In the

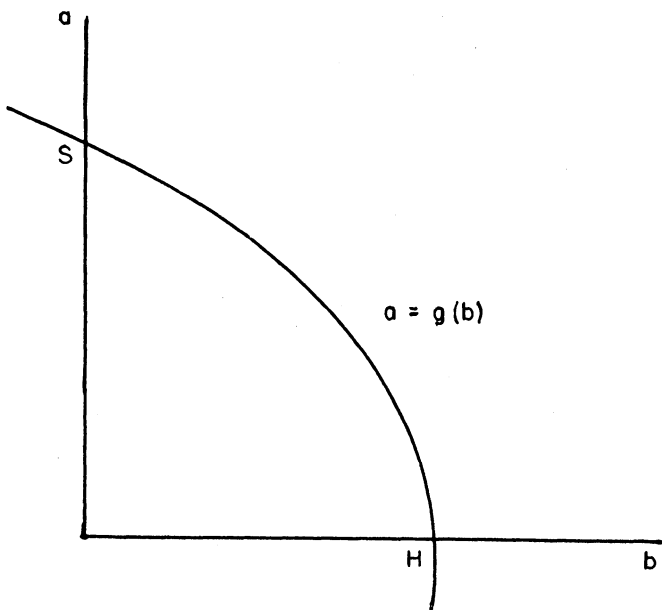


FIGURE I

The Innovation Possibility Function

6. Charles Kennedy ("Induced Bias in Innovation and the Theory of Distribution," *The Economic Journal*, LXXIV (Sept. 1964), 541-47; and "Samuelson on Induced Innovation," *Review of Economics and Statistics*, XLVIII (Nov. 1966), 442-44) eschews the production function approach, but does not seem able to replace it with an acceptable model.

first place, note that there will probably be decreasing costs; we return to this below. Second, note that the position of g is independent of A and B ; this very significant question will occupy us in Section B below.

The further questions that are bothersome about (2) will be discussed in this section.

Where does the IPF come from, and is it exogenous or endogenous? I have argued elsewhere that the IPF is not a true case of induced innovation or invention as usually defined.⁷ The true case of induced invention requires at least two productive activities, production and invention. If there is no invention, then the theory of induced innovation is just a disguised case of growth theory with exogenous technological change.

This may seem a semantic distinction, but it is much more fundamental than just the question of exogeneity. For, if the inventions are really exogenously given to the firm, they are costless

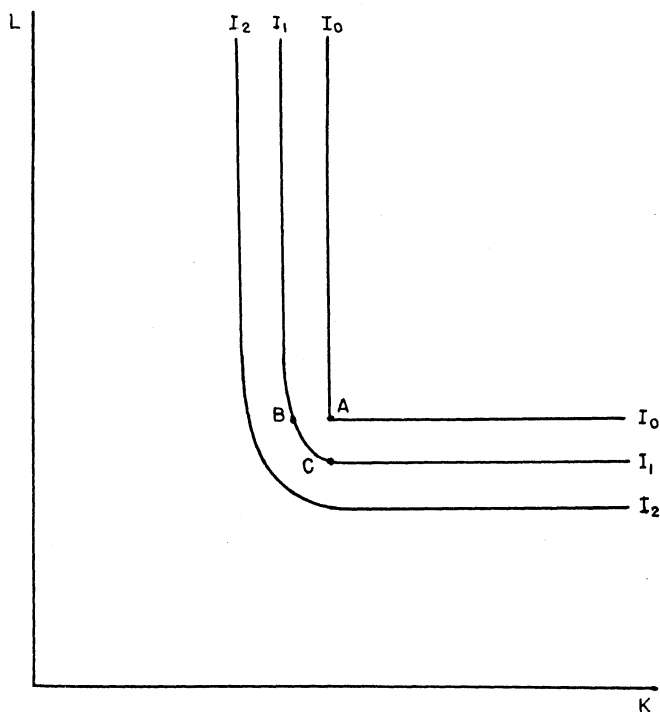


FIGURE II

7. The essence of the argument is in William D. Nordhaus, *Invention Growth and Welfare* (Cambridge: M.I.T. Press, 1969), Ch. 6.

activities. Introducing new techniques involves setup or fixed costs. If technological change (pure research, development, or engineering) involves setup costs, then firms have declining average costs. This is, of course, inconsistent with the competitive assumptions on which the model is based.

It will be useful to consider an alternative formulation of the IPF. The important distinctions to be made in the theory of production are, usually, between movement along the production function and shifts of the production function: the distinction is useful in that it allows for the distinction between costless and costly changes in techniques, respectively. In treating research as endogenous, it would seem sensible to recognize that to "move" to a different technique requires resources and the further the move, the greater the cost. Ignoring uncertainty temporarily, we call the set of techniques attainable with a given cost C the C -isotech. The conventional production function is the zero-isotech. Figure II shows a hypothetical set of isotechs under conditions of regularity. Figure III

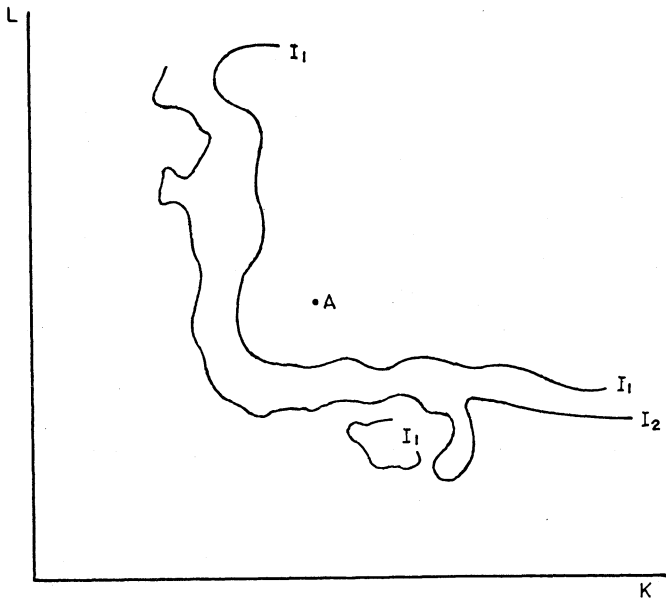


FIGURE III

gives an "irregular" case. Consider an economy currently operating at A . Under free disposal this means that at least any technique northeast of I_0I_0 is available at no cost. Now by devoting resources

of, say, $R(I_1)$, we can get any *one* technique on $R(I_1)$ -isotech, I_1I_1 , and so forth. We would generally assume that the progress of technology displays time dependence, or memory, in that the invention possibilities at time $t+1$ depend on whether the system has at time t moved from A to B or from A to C .⁸

This model of the process can be enriched by adding uncertainty. Just as the change in techniques has cost, it also has uncertainty. We can describe isovariance loci similar to the isocost loci described in Figures II and III.⁹

In this framework, it is easy to understand the assumptions behind the IPF in Figure I. It is easiest to examine the case when the production function, F in equation (1), is fixed proportions. Consider that we start from point A in Figure IV, with capital requirement K_0 and labor requirement L_0 . According to Figure IV, we then move to the point B , where labor requirements are the same and capital requirements are $K_0/(1+S)$. Or we can move to C with requirements K_0 and $L_0/(1+H)$. Or we can have any combination given in Figure IV and shown by the isotech $I_A I_A$, where this is the curve

$$\{L_0/(1+b), K_0/[1+g(b)]\}.$$

Once a point is chosen on the isotech $I_A I_A$, a new choice is faced for the next period. If in the first period B was chosen, the new isotech is $I_B I_B$; if C , $I_C I_C$ is relevant. The important point is that whatever is the initial point, (L_t, K_t) , the next period's isotech is

$$\{L_t/(1+b_t), K_t/[1+g(b_t)]\}.$$

To summarize, we thus see that the theory of induced innovation assumes: (1) that from any technique (say B or C), the new normalized isotechs are identical; there is no "memory" in the process of innovation;¹ (2) that only a single isotech is available at

8. This is a possible defect in the analysis of Ahmad (*op. cit.*), who postulates "neutrality," or lack of memory. In his model whether the system had moved to B or C is irrelevant. The "new" set of isotechs in the next period would be the same. This greatly simplifies the problem, since the firm or economy can minimize short-run costs without worrying about long-run costs.

9. The model proposed here has not, to my knowledge, been formally proposed before. It has been used informally by Richard R. Nelson, Merton J. Peck, and Edward D. Kalachek (*Technology, Economic Growth, and Public Policy* (Washington, D.C.: The Brookings Institution, 1967), especially Ch. 2); Burton H. Klein ("The Decision Making Problem in Development" in Richard R. Nelson, ed., *The Rate and Direction of Inventive Activity* (Princeton, N.J.: Princeton University Press, 1962), pp. 477-97); A. W. Marshall and W. H. Meckling ("Predictability of the Costs, Time, and Success of Development," in Nelson, *ibid.*, pp. 461-75). The conventional approach is a special case of this: the "production function" represents the isotech with zero acquisition cost and zero uncertainty.

1. This, clearly, is where Ahmad would disagree, since the *model* used here is definitely not neutral in his sense. After renormalizing $K_1=L_1=1$, the

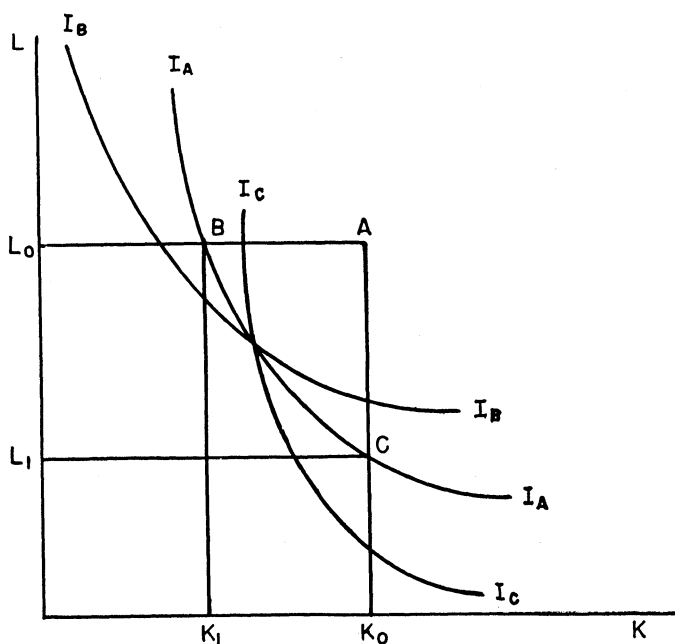


FIGURE IV

any point of time; and finally (3) that the isotech can be attained costlessly.

B. GROWTH WITH NONSTATIONARY INNOVATION POSSIBILITY FUNCTION

The assumptions outlined above are very restrictive. Can they be relaxed without changing the results?

I think the answer is no. The induced innovation (InIn) model has let a very restrictive assumption slip in the back door. When the back door is shut, all the same dilemmas remain, and the model does not explain the stylized facts of economic growth.

The crucial assumption is the stationary nature of equation (2): that is, that the shape of the frontier is independent of the path. Clearly (2) is only a very special case of a more general function:

$$(3) \quad a = h(b, A, B),$$

shape of the curve $I_A I_A$ is exactly the same independent of where K_1, L_1 are on $I_A I_A$.

where the function depends on the levels of A and B attained. Thus it might be harder to increase A if A had been raised very rapidly in the past. In (2), the InIn model, g is not affected by the last two terms. What is the property of the solution where h depends on A and B ?

It does not appear possible to solve the system replacing (2) with (3) under the most general conditions. We will proceed in two steps. First, we will show the necessary conditions for the InIn solution to hold for (3). In the next steps we will proceed to analyze two special cases of (3) to get explicit solutions.

Recall that in the InIn model we define efficiency units, Z , as

$$Z = AK/BL,$$

and $Y = BLf(Z)$. We assume a proportional savings rate:

$$\frac{dK}{dt} = sY.$$

The stable long-run solution to the model with labor growing exogenously at rate n is

$$(4) \quad \begin{cases} z = 0 & b = H \\ a = 0 & g'(b) = -(1-\sigma)/\sigma, \end{cases}$$

where $z = d(\ln Z)/dt$. We call (4) the *balanced-growth* equilibrium to the induced innovation model, where σ (= the competitively determined relative share of capital) is constant. Equation set (4) represents the "stylized facts" of economic growth. Using (3) instead of (2), we have

$$\begin{aligned} z &= a + sY/K - n - b \\ &= h + \frac{sAf}{Z} - n - b. \end{aligned}$$

For an InIn equilibrium like (4) to exist, $z = 0$, so

$$h + \frac{sAf}{x} = n + b.$$

Set $sf/Z = c$:

$$a + cA = n + h(a, B, A).$$

If a balanced-growth equilibrium is to exist, $a = 0$, so $A = A^*$ and

$$(5) \quad cA^* = n + h(0, B, A^*),$$

where $B(t) = \exp\left[\int_0^t h[0, B(v), A^*] dv\right]$.

Since this holds for all B , differentiate (5) with respect to B :

$$(6) \quad \frac{\partial h}{\partial B} = 0.$$

Therefore a necessary condition for the induced-innovation equilibrium is that the function h in (3) behave according to (6) at every B . Equation (6) says that the *rate* of capital-augmenting technological change is *everywhere* independent of the level of labor augmentation. Thus as technological change accumulates, there is no effect on the tradeoff between labor and capital-augmenting technological change. There are additional restrictions on the way A affects h , but these are more complicated. Faced with this result, the chances for the balanced growth equilibrium must be dubious: the necessary conditions are too stringent to be generally applicable.

A second approach will be to assume particular forms for (3) to get explicit results. There are two kinds of restrictions that come to mind. The first and more interesting is that there is a "natural drift" to technology, given by the direction of exogenous scientific discovery and invention. The idea of natural drift was proposed by Samuelson in the following passage:

Until now, I have gone along with the assumption that there are no discernible exogenous trends in technical development. This is of course not true. Any scientist can tell you, after some breakthrough has been made, that there is likely to be "pay-dirt" in pursuing a certain line of invention rather than another. . . . Hence it is not realistic to assume that new discoveries are random. . . .

We might in a formal way allow for a "natural drift" of technical change by introducing exogenous functions $A^*(t)$ and $B^*(t)$ with certain specifiable properties, and then rewrite (2) in the form

$$\frac{a}{A^*} = g\left(\frac{b}{B^*}\right).$$

Then certain patterns of invention become more profitable than others, depending on what is known about the $A^*(t)$ and $B^*(t)$. (An interesting hypothesis might make the latter neutrally exponential.) . . . The absence of zero serial correlation in innovation gives this notion of natural drift operational content.²

Clearly, there is no reason why the natural drift should be in any particular direction, labor or capital saving. It is an interesting hypothesis that A^* is roughly constant and B^* is roughly exponential.

A general way of describing the natural drift is to say that potential technology can be described by the exogenous movement of $A^*(t)$ and $B^*(t)$. Thus write the IPF as

$$b = (a, B, A, B^*, A^*).$$

Clearly we must have $B < B^*$ and $A < A^*$. Moreover, one might think that the closer one gets to the potential technology (e.g., as

2. Samuelson, *op. cit.*, 1965, p. 353. Changes in notation and the equation number were made to conform with that used in the present paper.

$A \rightarrow A^*$), the harder accumulation becomes. A case of this would be

$$(7) \quad b = h \left(a, \frac{A^* - A}{A^*}, \frac{B^* - B}{B^*} \right). \quad h_1 < 0, h_2 > 0, h_3 > 0.$$

This means that as long as both A and B are staying a constant percentage behind A^* and B^* , the growth can continue forever.

We need not spend much time worrying about the solution, since we already know the long-run solution to one version of the function. First, assume that technology is always at the maximal or potential levels because technology flows costlessly. Then $A = A^*$ and $B = B^*$; there is no choice available. This solution is then ex-

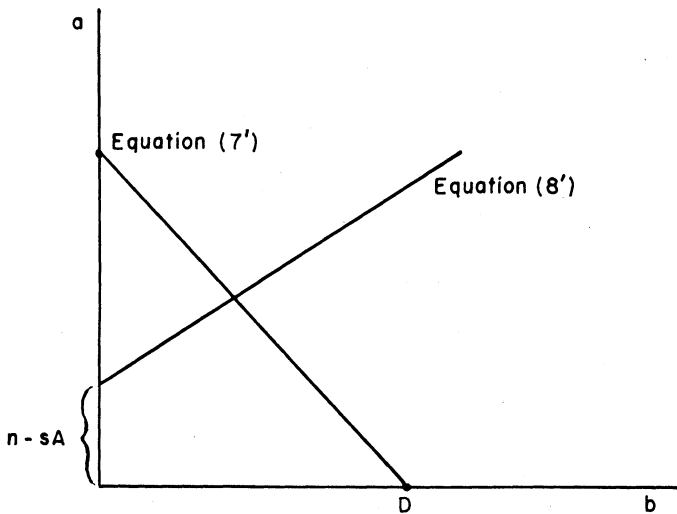


FIGURE V

actly the same as the neoclassical model with exogenous technological change. It follows that *the balanced-growth equilibrium holds only when the natural drift of technology is Harrod-neutral.*

The case where actual technology lags behind potential in a variable way is more difficult. We can see from the fixed-coefficients model, however, that essentially the same result holds. Assume that $F = \min(AK, BL)$. We then know that if accumulation is efficient, $AK = BL$, and

$$a + k = b + n,$$

where $k = d(\ln K)/dt$ and $n = d(\ln L)/dt$, or since $k = sAK/K = sA$,

$$(8) \quad a + sA = h + n.$$

If the natural drift is Harrod-neutral (so $a^* = 0$), then (4) is clearly

the solution with $b = b^*$. If $a^* > 0$, however, then by (7) either $a > 0$, or $\frac{dh}{dt} > 0$. But if $a = 0$ and $\frac{dh}{dt} > 0$, then by (8) $a > 0$. Therefore $a > 0$ —and in fact, a is bounded above zero—so the balanced-growth equilibrium cannot hold. A similar argument holds if $a^* < 0$.

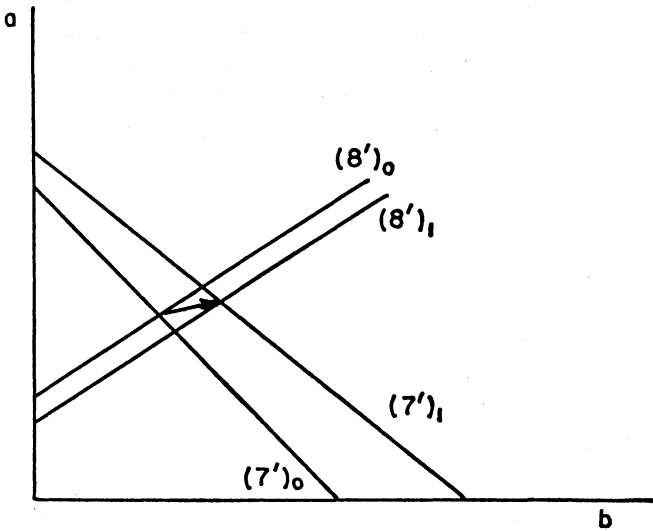


FIGURE VI

The solution with a natural drift of technology thus generally rules out the balanced-growth equilibrium except in the special case where the natural drift of technology is purely labor-augmenting. When the elasticity of substitution is less than unity, the share of labor tends to zero and not a constant. Nor is the capital-output ratio constant.

For those who find the “natural drift” idea implausible, a third model is used. Again we assume production has fixed coefficients, but instead of assuming a natural drift, we allow a more general choice function. The restriction we make is to limit the function to the first quadrant and to assume it linear.

Thus

$$(7') \quad a = c_0 - c_1 b \quad \begin{aligned} c_0 &= \phi(A, B) \\ c_1 &= \psi(A, B). \end{aligned}$$

c_0 and c_1 are assumed to be affected by the level of A and B according to some pattern. Equations (8) and (7') then form the laws of

motion of the economy. We can rewrite (7') and (8'):

$$(7') \quad a = c_0 - c_1 b$$

$$(8') \quad a = b + n - sA.$$

We can show the instantaneous solution in Figure V by simply graphing (7') and (8'). First consider the case where c_0 and c_1 are constant, as in the IPF in equation (2). In the balanced-growth solution, if a is positive (or negative), (8') moves down (or up). Clearly the only stable solution is at the point D .

Things are otherwise if (7') moves around because c_0 and c_1 change. There are several possibilities. In FIGURE VI, (8') moves

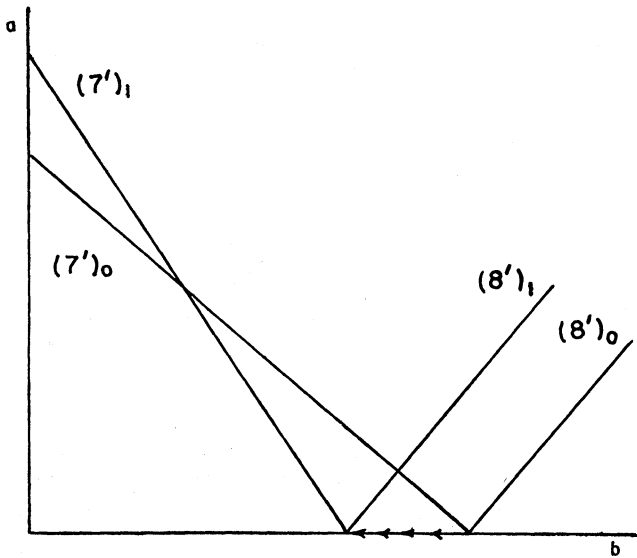


FIGURE VII

out more than (9') so that a increases over time. A second possibility is that as a tends to zero, purchase of b is more expensive. The frontier may move to the left and be steeper, as in Figure VII. In this case, a will always be near zero, but there will be no long-run equilibrium of the balanced-growth variety.

C. CONCLUSION

We have argued above as follows: (A) The theory of induced innovation rests on dubious microeconomic foundations. Although

it is a *possible* way for technological change to proceed, it is only a very special case. (B) There is little ground for the belief that a general form of innovation possibility schedule — such as in equation (3) — will lead to a state of balanced growth. Only when the natural drift of technology is Harrod-neutral will this be the case.

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