Economics Department

Endogeneous Growth with a Declining Rate of Interest

LAVAN MAHADEVIA

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Abstract

This article shows that endogenous growth in capital is compatible with a decreasing rate of interest when investment is entirely financed by the earnings of the young and when there is an externality effect of capital on the productivity of their labour. And despite the presence of this externality effect, the demand curve for capital is downward sloping. So a decreasing rate of interest along a transition path can no longer be taken as invalidating endogenous growth and endogenous growth models do not necessarily imply upward sloping demand curves.
1. Introduction

In a neoclassical growth model, the return on capital (the rate of interest) declines to zero until there is no further incentive to invest in capital. In most endogenous growth models with a non-convex production function, the rate of interest does not decline and may even increase. This preserves the incentive to accumulate so that the capital stock and output grow forever. I show that it is possible to have a perpetually growing capital stock with a decreasing rate of interest. This happens in a plausible model where savings are financed entirely by labour income; where private capital and labour are substitutes and where the externality effect of capital is to make only labour productive. In the literature, a non-decreasing rate of interest which implies that the Inada condition is satisfied has been taken as being incompatible with endogenous growth (see for example Barro and Sala-i-Martin (1995) pp. 45). So this article proves that this inference is invalid.

I also show that endogenous growth is possible with a downward sloping demand curve for capital. But in many models where endogenous growth happens because of an externality or increasing returns to scale, a rise in the price of capital raises the gross demand for capital. To understand how this upward sloping gross demand curve for capital can come about, we have to consider the effect of a rise in its price on the gross demand for a factor input in some depth. Raising the price of capital causes a change in the overall level of output produced as well as substitution away from capital. These output and substitution effects are analogous to the income and substitution effects of a rise in the price of a consumption good. In a model with a non-convex production function, the rise in the price of capital leads to a higher level

That savings are financed by labour income jointly rests on the plausible propositions that savings are carried out by the young and the income of the young accrues largely from earnings. That the externality effect of capital is to raise the wage rate is supported by a large body of evidence on the complementarity between skilled labour and capital (see Goldin and Katz (1996) for references). In particular Krueger (1993) finds evidence of an externality effect between capital and labour.
of output overall as well as an incentive to substitute way from capital. The higher level of output requires more capital and the positive output effect more than offsets the negative substitution effect on the demand for capital.

That the gross demand for capital rises after a rise in its price is an untested assumption. If this were rejected as seems possible, then one could conclude that output and capital could not grow forever and the microeconomic behaviour of endogenous growth models with non-convex production functions would lead them to be rejected. I show that not only that capital can be perpetually accumulated even though the rate of interest goes to zero but also that this can happen with a downward sloping demand curve.

The economy I use as an example is one in which overlapping generations of finitely-lived agents choose how much to save to maximise a utility function which is separable over time. The agents behave competitively and take the rate of profit and their wage as given when making their decisions. When young each individual receives only a wage and when old, the total return on the savings he made in his youth. The old have no motive to save.

The salient features of this simple model arise from the fact that the representative individual of each generation receives income from two factors of production: labour and private physical capital in the form of a wage and interest on savings respectively. Although of these two, only physical capital is accumulable, labour is the only source of income when young and the young do all the saving. The return to labour must be sustained in order for savings and investment to keep increasing. As shown by Jones and Manuelli (1992) and Boldrin (1992), there must be a strong externality effect of capital on the wage to keep the economy growing. This paper considers the case proven by Boldrin (1992) that if this externality effect on the marginal product of labour is strong enough, growth in the capital stock can occur whilst the marginal product of private capital decreases towards zero.

The technology which gives growth with a decreasing rate of interest is non-normal.
A normal technology is one where the cross partial derivatives of the production function are all non-negative (Rader (1968)). So a non-normal technology is described by a production function where the marginal product of each factor declines in the quantity of any other factor.

In order for endogenous growth to take place the production function is non-convex with respect to all its inputs. It has been shown that either non-normality or non-convexity in the technology can produce an upward sloping gross demand curve. But in the presence of both features, I show that the factor markets continue to display similar gross demand behaviour to that implied by a convex and normal technology.

Section 2 proves that for endogenous growth to occur requires the satisfaction of certain straightforward assumptions on the technology and preferences. Section 3 presents a numerical example. Section 4 discusses the implications of the production function for demand behaviour.

2. The model

2.1. The consumers’ problem

Maximise \( U[c_t] + \beta U[c_{t+1}] \) \hspace{1cm} (2.1)

subject to,

\[ c_t^i + s_t \leq w_t, \] \hspace{1cm} (2.2)

\[ c_{t+1}^i \leq (1 + r_{t+1}) s_t, \] \hspace{1cm} (2.3)

\[ c_t^i \geq 0 \text{ and } c_{t+1}^i \geq 0, \] \hspace{1cm} (2.4)
The utility function is separable in the consumption over period one and two. In each period’s consumption it is strictly increasing and strictly concave. The separability and the concavity implies that the consumption goods are normal.

2.2. The producer’s problem

The entrepreneur maximises profits \( \pi[t] \) so as to equalise the wage \( w[k_t] \) and rental rate \( r[k_t] \) (both of which he takes as unaffected by his decisions) to the marginal products of labour and private capital. The production function is given by \( Y_t = F[k_t, l_t, x_t] \); such that output \( Y_t \) is a function of the private capital stock \( k_t \), labour \( l_t \) and social capital \( x_t \). Thus:

\[
r[k_t] = F_{kt} = F_k[k_t, l_t, x_t] \tag{2.5}
\]

\[
w[k_t] = F_{lt} = F_l[k_t, l_t, x_t] \tag{2.6}
\]

\[
\pi_t = F[k_t, l_t, x_t] - r_t k_t - w_t l_t \geq 0, \tag{2.7}
\]

It has to be assumed that any profit is consumed and not saved. There is market clearing in the goods market when 2.2 and 2.3 hold. The social capital arises as an externality effect of private capital although the representative producer takes it as given when making his decisions.

2.3. Assumptions on the technology

I make the following three sets of assumptions about the production function:

\[
F_{kt} \geq 0, F_{lt} \geq 0; \tag{2.8}
\]

\[
F_{kkt} < 0, F_{llt} < 0, F_{kkt}F_{llt} - F_{kt}F_{lt} > 0; \tag{2.9}
\]
and

\[
\frac{(F_{ikt} + F_{ixt})k_t}{w[k_t]} > 1, \quad F_{xt} > 0. 
\] (2.10)

The first assumption 2.8 must be satisfied in order to ensure that the rate of interest and the wage rate are both positive. The next assumption 2.9 ensure that the producer’s problem satisfies the sufficient conditions for an interior maximum. Note that the production function exhibits decreasing returns to scale in private capital and labour: the incomes from these factors will not be enough to exhaust total income. There must be a surplus of profit which goes to the owner of a fixed factor as rent which is never reinvested but is always consumed.

2.10 is necessary in order for the young to receive enough income to augment the current capital stock (as shown by Jones and Manuelli (1992) and Boldrin (1992)). These authors demonstrate that for the young to receive enough income to keep the economy growing, the elasticity of the wage with respect to the capital stock must be at least greater than unity. If the economy is growing and satisfying the first period budget constraint 2.2 then 2.10 implies that:

\[
1 \leq \lim_{k_t \rightarrow \infty} \frac{k_{t+1}}{k_t} \leq \lim_{k_t \rightarrow \infty} \frac{w[k_t]}{k_t}. 
\] (2.11)

and so satisfies the required condition\(^2\). To summarise, in order for this economy to support endogenous growth with competitive agents, it is necessary that the production function satisfies both of the last two inequalities 2.9 and 2.10.

Assumptions 2.8, 2.9 and 2.10 by themselves are not enough to rule out the possibility of an upward sloping gross demand curve for capital. Consider an example from the recent literature on endogenous growth with the production functions has an externality. Pelloni and Waldmann (1995) employ a production function which in my

\(^2\)That the wage rate is at least unitary elastic in the capital stock is incompatible with a convex technology. So in a single-sector economy with finitely lived agents, there must be a positive externality effect such that the non-convex technology is compatible with competitive behaviour.

5
terminology is given by \( Y = F(l_t x_t, k_t) \) where \( F(.,.) \) is convex and constant returns to scale in its two arguments \( (l_t x_t \text{ and } k_t) \). Then the change in the gross demand for capital following an increase in its price is given by \(-k_t F_{ltt}/F_{ktt}F_{lt} \) which is positive. But in their model the externality effect is large enough such that if the price of capital rises, the gross demand for capital will rise. That may indeed be a realistic feature of the market for capital. But as it is also not likely to be so, it is of worth to consider under what conditions this can arise.

The brief here is instead to describe a perpetually growing economy where the gross demand for each factor is inversely related to its price. This happens if the externality effect is not too large. So the production function also satisfies

\[ F_{kkt} + F_{kxt} < 0. \] (2.12)

By binding the externality in this way, I am ruling out situations in which a rise in the rate of interest with the wage rate constant could raise the gross demand for capital.

2.4. The first order conditions

The first order condition to the consumer's problem with \( s_t \) as the choice variable can be written as:

\[ U'[w[k_t] - s_t] = (1 + r[k_{t+1}])U'[((1 + r[k_{t+1}])s_t] \] (2.13)

Market clearing in the labour and capital markets and the simplest assumption for the externality imply:

\[ k_{t+1} - k_t = N_t s_t - k_t \] (2.14)

\[ l_t = N_t = 1 \] (2.15)
\[ x_t = k_t \] (2.16)

Substituting the market clearing conditions and the externality function into the first order condition and rearranging gives the savings function:

\[
k_{t+1} = \frac{w[k_t]}{1 + U^{-1}[(1 + r[k_{t+1}])]/(1 + r[k_{t+1}])} \equiv s[r[k_{t+1}], w[k_t]]
\] (2.17)

2.5. The assumptions on the preferences

The assumptions which describe this savings function, incorporating those already imposed on the utility function are:

\[ s \] is an increasing function of both its arguments;
\[ s[0, w] \geq 0 \text{ for all } w \geq 0 \text{ and } s[r, 0] = 0 \text{ for all } r \geq 0; \]
\[ \frac{\partial s}{\partial w} \in (0, 1). \] (2.18)

\( s \) is increasing in \( w \) by virtue of the two consumption goods being normal; (the utility function being separable in the two utilities and each utility being concave in its argument). For \( s \) to be increasing in \( r \) however requires us to assume that the substitution effect of a rise in the rate of interest dominates the income effect; ie that the elasticity of substitution between the consumption in the two periods is greater than one.

The result that endogenous growth can occur with a falling rate of interest follows readily if the intertemporal elasticity of substitution were less than one as the level of savings then increases as the rate of interest falls. But, in this case, a well-defined dynamic solution may not exist (see the explanation below and Galor and Ryder (1989)). Similarly if the intertemporal elasticity of substitution is equal to one, as would be the case if the utility function were logarithmic, then the level of savings would be
independent of the rate of profit and the endogenous growth result follows easily. So it seems better to assume that the intertemporal elasticity is greater than one; whilst noting that other values for the intertemporal elasticity are likely to strengthen the result rather than weaken it:

\[ \frac{\delta s}{\delta r} > 0. \]  

(2.19)

2.6. The steady state

The steady state solutions are given by:

\[ k^* = s[1 + r[k^*], w[k^*]] \equiv s[k^*]. \]  

(2.20)

Information on the multiplicity of steady states is contained in the function \( s[k^*] \). One possible outcome, that of a unique non-trivial steady state is described in the Fig. 1. below:

INSERT FIGURE 1 HERE

Note that:

\[ \lim_{{k^* \to -\infty}} s[k^*] = \lim_{{k^* \to -\infty}} w[k^*] \]

\[ = \frac{1}{1 + U^{-1}(\beta)}. \]

(2.21)

2.7. The dynamic solution and the condition for endogenous growth

Under what conditions does a continuous and single-valued dynamic solution to 2.17 of the form

\[ k_{t+1} = g[k_t] \]  

(2.22)

exist globally? A sufficient condition for this to occur is that:

\[ 1 - \frac{\delta s}{\delta r}(F_{kkt} + F_{kzt}) > 0, \]  

(2.23)

as shown by Nikaido (1968) among others. If the level of savings is increasing in the rate of interest as guaranteed by assumption 2.12, then a well-behaved dynamic

\[ ^3 \text{Information on the linear approximation stability properties of each steady state is contained in the function } s[w[k_t], r[k_{t+1}]], \text{ as shown below.} \]
solution exists. This is equivalent to a dominant substitution effect over an income effect of the rate of interest on savings.

In a model with a single capital stock where a well-behaved dynamic solution 2.22 exists, endogenous growth occurs when the economy begins growing at the largest steady state. This is because as the capital stock can never reach another steady state, it must grow thereafter. This is illustrated in Fig. 2. below.

So, for any savings function and production function, in order for endogenous growth to occur in an economy satisfying 2.2, 2.3 and 2.4, it is sufficient that:

\[ \text{at least one steady-state solution exists} \quad (2.24) \]

and

\[ \frac{dg[k_t]}{dk_t} \bigg|_{k_t = k_{t+1} = \hat{k}} = \frac{s_w[k_t]F_{kkt}}{1 - s_r[k_{t+1}](F_{kkt} + F_{kxt})} > 1 \quad (2.25) \]

where \( \hat{k} \) is the highest steady state.

I now show that for endogenous growth to occur with a declining rate of interest requires only that 2.8, 2.9, 2.10, 2.12, 2.18, and 2.19 are satisfied: I show that 2.25 is superfluous.

From inequality 2.25 above, endogenous growth occurs if assumptions 2.8, 2.18 and 2.19 hold and:

\[ \frac{\delta s[w[k^*], r[k^*]]}{\delta k^*} \bigg|_{k^* = k} = s_w[k^*]F_{ik} \bigg|_{k^* = k} + s_r[k^*](F_{kkt} + F_{kxt}) \bigg|_{k^* = k} > 1. \quad (2.26) \]

2.26 holds if and only if

\[ \lim_{k^* \to \infty} s[w[k^*], r[k^*]] > 1, \quad (2.27) \]

as demonstrated by the example in Fig. 1. From 2.21 it is sufficient that \( \lim_{k^* \to \infty} w[k^*] = \infty \) for 2.26 to hold. This is guaranteed if the wage is at least unitary elastic with respect to changes in the capital stock; i.e. (inequality 2.11 satisfied). Hence any problem
which satisfies assumptions 2.8, 2.9, 2.10, 2.12, 2.18, and 2.19 will give endogenous growth.

For this proof to be rigorous, I must show that assumptions 2.8, 2.9, 2.10, 2.12, 2.18 and 2.19 can be consistent with each other and with a decreasing marginal product of capital. That is done with a simple example.

3. An example

To illustrate the workings of this model in which endogenous growth can occur even if the production function exhibits strictly decreasing returns to the private capital stock, consider the following example. The preferences satisfy assumptions 2.8, 2.18 and 2.19. In particular, the elasticity of intertemporal substitution is equal to 2 in the utility function below.

Each individual born at time $t$ solves:

Maximise $\frac{(w_t - s_t)^{\frac{1}{2}}}{\frac{1}{2}} + \frac{((1 + r_{t+1})s_t)^{\frac{1}{2}}}{\frac{1}{2}}$, \hspace{1cm} (3.1)

subject to

\begin{align*}
\mathcal{C}_t + s_t &\leq w_t, \hspace{1cm} (3.2) \\
\mathcal{C}_{t+1} &\leq (1 + r_{t+1})s_t, \hspace{1cm} (3.3)
\end{align*}

and

\begin{align*}
\mathcal{C}_t &\geq 0 \text{ and } \mathcal{C}_{t+1} \geq 0; \hspace{1cm} (3.4)
\end{align*}

The first order condition gives:

\begin{align*}
s_t &= \frac{w_t}{1 + (1 + r_{t+1})^{-1}} \hspace{1cm} (3.5)
\end{align*}
Assume that output is produced according to:

\[ y_t = \frac{t_t^{0.8}(x_t)^{1.2}}{0.8} + k_t^{0.8} \]  \hspace{1cm} (3.6)

Note that this non-homogenous production function is not concave in total capital and labour together; it is homogenous of degree 0.8 and strictly concave in private capital and labour. Thus only eighty percent of output goes to the owners of capital and labour.

The wage and the rate of profit are given respectively by:

\[ w_t = l_t^{-0.2}k_t^{1.2} \]  \hspace{1cm} (3.7)

and

\[ r_t = k_t^{-0.2}. \]  \hspace{1cm} (3.8)

If the economy displays endogenous growth the rate of profit will decline towards zero.

As only the young work and earn a wage, market clearing in the capital and labour markets is now given by:

\[ s_t = k_{t+1}, x_t = k_t \text{ and } l_t = l = 1. \]  \hspace{1cm} (3.9)

Substituting the market clearing condition; the externality process and the wage and rate of profit equations into the first order condition gives:

\[ k_{t+1}(1 + (1 + k_t^{-0.2})^{-1}) = (k_t)^{1.2}. \]  \hspace{1cm} (3.10)

Assume as before that the solution to this equation can be written in the form:

\[ k_{t+1} = g(k_t), \]  \hspace{1cm} (3.11)
where \( g[.] \) is a single valued function. Although only an approximation to this solution can be obtained from the inverse function it can be seen that it exists as a single-valued function for all \( k_t \geq 0 \).

At any steady state, \( k_t = k^* \):

\[
k^*(1 + (1 + k^*-0.2)^{-1}) = k^{*1.2}.
\] (3.12)

Thus there exists steady states with a non-negative capital stock at \( k^* = 0 \) and \( k^* = \left(\frac{1+\sqrt{8}}{2}\right)^5 = 11.0902 \). The slope of the solution at the greatest steady state is given by:

\[
\left. \frac{dg[k_t]}{dk_t} \right|_{k_t = k_{t+1} = 11.0902} = \frac{(F_{k+t} + F_{k+1})s[w_t|k_t]}{1 - s_r[k_{t+1}][F_{k+1} + F_{k+t+1}]} \bigg|_{k_t = k_{t+1} = 11.0902}
= 1.16598 > 1.
\] (3.13)

Hence in this economy endogenous growth occurs for all initial capital stocks beyond the highest steady state value (11.0902) as shown in Fig. 3. below.

**INSERT FIGURE 3 HERE**

This proves that endogenous growth in the capital stock can occur even the rate of profit declines towards zero as accumulation takes place according to 3.12.

4. Gross demand behaviour

It is interesting to consider if this production function implies a downward sloping demand curve. Either a non-convexity in output or a 'non-normal' (Rader (1968)) production technology can independently produce different behaviour to that of the convex normal technology case. In this example both features are present and I show below that the net effect is to reproduce the upward sloping demand curve that would be implied by a convex normal technology.
4.1. The gross demand behaviour

I show that capital is a gross complement for labour but labour does not affect the gross demand for capital and that the gross demand for each factor is decreasing in its own price.

Consider the production function as $Y = F[k_t, l_t, x_t]$ as before with $x_t$ representing the externality effect of capital by the mechanism $x_t = k_t$.

Differentiating the solutions to the profit maximising problem yields:

$$
\begin{bmatrix}
\frac{\partial k}{\partial r} & \frac{\partial k}{\partial w}
\end{bmatrix} =
\begin{bmatrix}
F_{lt} & -F_{kt} \\
-(F_{ikt} + F_{ixt}) & F_{kkt} + F_{kxt}
\end{bmatrix} \Delta^{-1}
\begin{bmatrix}
-5k^{1.2} & 0 \\
-30k^{0.2} & -5k^{-1.2}l^{1.2}
\end{bmatrix},
\tag{4.1}
$$

where $k = k[r_t, w_t]$ and $l = l[r_t, w_t]$ are the gross demand functions for capital and labour respectively and $\Delta = F_{kkt}F_{ltt} - (F_{ikt} + F_{ixt})F_{klt} = 0.04l^{-1.2} > 0$. The gross demand for labour is negatively affected by the rate of interest whereas the gross demand for capital is not affected by changes in the wage. Thus the two factors are not gross substitutes. Note that the gross demand for each factor of production is also decreasing in its own price as would be observed in the ‘normal’ case.

Consider a rise in the rate of profit with the wage rate fixed, given that the economy is already at a competitive equilibrium with the individual receiving a return equal to the marginal private product for each factor. The demand for physical capital would fall, as its marginal private product is decreasing in total capital. The lower capital stock lowers the marginal private product of labour below the wage. The demand for labour would thus have to fall until the marginal product of labour rises to equal the wage (given the decreasing marginal product of labour). Thus the effect of a higher rate of interest with the wage rate fixed is a lower gross demand for labour.
The gross demand behaviour of the factor market is that of a (strictly) concave production function without externalities such as a Cobb Douglas function. In this case, when output exhibits decreasing returns to scale in labour and capital together ($F_{klt} < 0$, $F_{ult} < 0$ and $\Delta > 0$) then labour and capital cannot be gross substitutes in demand when the technology is normal (Rader (1968)). Giordano (1986) shows how the gross demand behaviour is different from this case when non-convexities are allowed for in a normal technology and Takayama (1985) provides an illustration by showing that a minimum wage rate can increase the employment of labour when technology is non-convex in capital and labour. Adapting the results of Bear (1965), Rader (1968) and Sakai (1974) it is easy to see how the introduction of a non-normal but still convex technology will alter gross demand behaviour in a similar fashion. The example above by containing elements of both deviations from the convex, normal technology case presents the same gross demand behaviour as can be observed in this usual technology.

5. Conclusions

This result is of most interest for its empirical implications; for it means that a non-decreasing rate of interest is no longer a necessary condition for endogenous growth. So estimation of the aggregate production function which shows decreasing returns to the accumulated factor including any externality effects should not be taken as evidence against the existence of endogenous growth.

The model predicts a declining share of capital; an increasing share of labour; and a constant share of profits as rent from total income. There is some empirical support for these predictions (Atkinson (1975)) although they contradict Kaldor’s famous empirical regularity on the constancy of factor shares.

Another implication of this model is of course that policies to redistribute income

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4The note in the text in Takayama (1985) shows how the technology typically assumed by endogenous growth models implies that a minimum wage rate policy can increase the demand for labour.
from the owners of capital to those of labour may enhance growth, if the production function including the externality effects are of the appropriate form.

6. References


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