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Innovation and growth: What have we learnt from the robustness debate?

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Abstract

The recurrent issues of "non-robustness" and "scale effects" are discussed within a unified framework for the presentation of different generations of innovation-based growth models. With a certain proviso robust innovation-based growth models tend to end up with the long-run per capita growth rate pinned down by population growth. That is, the long-run prospect seems to be semi-endogenous growth. This is so also when essential non-renewable resources are taken into account. Semi-endogenous growth need not imply policy-invariant growth. Non-renewable resources may imply instability problems of an unfamiliar kind. The projected slowdown of population growth is likely to decrease future per capita growth as well as the discount rate relevant for evaluation of long-term environmental projects.

Keywords: Endogenous growth; non-renewable resources; instability; limits to growth; discounting the distant future.

JEL Classification: O4, Q3.

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1 Introduction

This paper reviews the development of innovation-based endogenous growth theory. The emphasis is on the recurrent issues of "non-robustness" and "scale effects" and their implications for the limits-to-growth debate.

Economists agree that ideas are different from most economic goods in that they are *nonrival*: their usage by one agent does not in itself limit their usage by other agents. This leads to increasing returns to scale when knowledge is included in the total set of inputs. Yet there is scope for alternative assumptions about the size of the returns to *producible* inputs, including knowledge.

Standard endogenous growth theory (Lucas 1988, Romer 1990, Aghion and Howitt 1992) has suspended the neoclassical presupposition of diminishing returns to producible inputs and replaced it with the assumption of exactly constant returns to producible inputs. This has far-reaching implications. It is possible for economic policy not only to lift the level of the path along which growth occurs, but also to tilt the path. This nourishes many economist's belief that knowledge creation is likely to overcome the limits to growth implied by limited natural resources.

Without implicating the limits-to-growth debate, other economists (Solow 1994, Jones 1995a, 1995b) argue that the presumption of non-diminishing returns to producible inputs lacks empirical support as well as theoretical plausibility.

There is a tight relationship between these conflicting viewpoints and the debate about "non-robustness", "scale effects" and all that. The problem of "non-robustness" arises because of the knife-edge character of the assumption of constant returns to producible inputs. And the "scale effect" problem arises because, when a non-rival good − like technical knowledge − is one of the producible inputs, then standard endogenous growth models lead to counterfactual predictions like: (i) The larger is the economy, ceteris paribus, the larger is the long-run per-capita growth rate; and (ii) sustained growth in population should be associated with a forever rising per-capita growth rate. Fortunately, the whole debate about these matters has helped us climb up the quality ladder of growth models. Further, it turns out that taking non-renewable natural resources into account puts the debate in a new perspective. A crucial question is here whether the non-renewable resources are essential inputs (directly or indirectly) in the growth-generating sector.

The rest of the paper will discuss these issues within a unified framework for the presentation of the different "generations" of innovation-based growth models. The next section provides the necessary background: the first-generation models. In Section 3 the "Jones critique" is presented, and the "semi-endogenous growth" alternative as well as the different responses to the Jones critique are described. Section 4 portrays the second-generation models which consider innovations on *two* dimensions. Section 5 introduces the third-generation models where both the rate and *direction* of technical change is determined. Repercussions of the presence of essential non-renewable resources are depicted in Section 6, and the concluding Section 7 draws out implications for the prospect of future growth.[1]

2 First-generation models

It is common to divide the models of the endogenous growth literature into two broad classes: accumulation-based models and innovation-based models. The first class of models is based on the idea that the combination of physical capital and human capital accumulation may be enough to sustain long-run productivity growth (Lucas 1988, Rebelo 1991). The second class of models, which will be our focus here, attempts to explain how technological change comes about and how it shapes economic growth.

The origin of the innovation-based growth models goes back to Romer (1987, 1990), where growth is driven by specialization and increasing division of labour. That is, here the focus is on *horizontal innovations:* the invention of new intermediate or final goods giving rise to new branches of trade. The invention of micro-processors is an example. Shortly after the Romer papers came out, Grossman and Helpman (1991, Chapter 4) and Aghion and Howitt (1992) proposed theories where growth is driven by *vertical innovations.* This strand of endogenous growth theory concentrates on the invention of better qualities of existing products and better production methods that make previous qualities and methods obsolete. Improvement in the performance of microprocessors provides an example. The two strands of models are often called "increasing variety" models and "increasing quality" models (or "quality ladder" models), respectively. We begin with an account of the increasing variety models.

[1] In several respects this review is heavily inspired by Jones (1999) and Jones (2004a). However, we discuss the non-robustness arising from arbitrary parameter values and parameter links in a broader context, including directed technical change and non-renewable resources. Further, we provide a more symmetric treatment of the "increasing variety" approach and the "increasing quality" approach.

2.1 Horizontal innovations

The following is a simplified version of Romer (1990). There are two production sectors. Sector 1 supplies "basic goods" under perfect competition. Aggregate output of basic goods is

$$Y = \left(\sum_{i=1}^{N} x_i^{\alpha} \right) L_Y^{1-\alpha}, \qquad 0 < \alpha < 1, \tag{1}$$

where x_i = input of capital good variety i, N is the number of different varieties of capital goods, and L_Y is labour input. The output of basic goods is used for consumption, C, and investment in "raw capital". The stock of raw capital, K, grows according to

$$\dot{K} = Y - C - \delta K, \qquad \delta \geq 0, \tag{2}$$

where δ is the depreciation rate.

In Sector 2, the innovative sector, two activities take place. Firstly, there is investment in R&D in the sense that labour, L_R, is applied to invent new capital varieties, i.e., new kinds of specialized capital goods. There is free entry to this activity. The number of new varieties invented per time unit is assumed proportional to R&D input. Ignoring indivisibilities, we have

$$\dot{N} = \tilde{\mu} L_R. \tag{3}$$

The individual research lab, which is "small" relative to the economy as a whole, takes R&D productivity, $\tilde{\mu}$, as given. At the economy-wide level, however, this productivity depends positively on the stock of technical knowledge in society, proxied by N. In fact, Romer assumes linearity:

$$\tilde{\mu} = \mu N, \qquad \mu > 0, \tag{4}$$

where μ is a constant.

Secondly, once the technical design (blueprint) of a new variety has been invented, the inventor takes out, free of charge, an infinitely-lived patent and starts supplying the new capital good under conditions of monopolistic competition. Given the technical design, it takes one unit of raw capital, K, to produce one unit of the new specialized capital good. In view of the symmetric cost structure and the concavity in (1), profit maximizing firms in the basic-goods sector choose $x_i = x = K/N$ for all i, so that the aggregate production function becomes

$$Y = K^{\alpha}(NL_Y)^{1-\alpha}. \tag{5}$$

We see that increased N implies increased productivity: variety is productive. This is how Romer formalizes the idea that specialization and division of labour increase productivity.

Total labour force (population) is L, a constant, and $L_Y + L_R = L$. At the societal level there are two allocation problems, how to divide the labour force into L_Y and L_R and how to divide Y into consumption and investment. Adding perfect competition on the labour market and a description of households' behaviour the model can be solved.

For any positive variable x let $g_x \equiv \dot{x}/x$, and let $y \equiv Y/L$. Then, along a balanced growth path or, for short, in a steady state we have

$$g_y = \mu s_R L, \qquad \text{where } s_R \equiv \frac{L_R}{L}. \tag{6}$$

Here, the share of the labour force employed in R&D, s_R, will depend on parameters such as α, μ and those describing the household sector (here left out for brevity). When parameter values are such that $0 < s_R < 1$, we get:

(i) Growth is *strictly endogenous* in the sense that the long-run growth rate in per-capita output is positive without the support of growth in any exogenous factor.[2] The key to this is the assumption of non-diminishing returns to the producible input (N) in the "growth engine": $\dot{N} = \mu N L_R$.

(ii) Via affecting incentives, policy can affect s_R (by a research subsidy, say) and thereby the long-run growth rate.

(iii) Under laissez-faire the market economy always does too little R&D.

It is generally recognized that at least result (iii) is not robust. As Benassy (1998) and Groot & Nahuis (1998) argued, there is an arbitrary link in the Romer model between gains to specialization (i.e., the exponent, $1 - \alpha$, to N in (5)) and the share of capital, α. With more general specifications of (1) this link is disentangled and "too much R&D" in the market economy is possible. Further, Alvarez & Groth (2003) argued that there is yet another arbitrary parameter link, that between market power, $1/\alpha$, in the supply of specialized capital goods and the capital share, α. When this link is removed, Romer's original "too little R&D" conclusion is in fact vindicated as the empirically relevant case. In addition, this parameter separation is needed in order

[2] Within the broad class of "endogenous growth" models the complementary sub-class is that of "semi-endogenous" growth, to which we return below.

not to blur effects of increased monopoly power by offsetting effects from decreased capital share.

Before we discuss the possible non-robustness of result (i) and (ii) let us take a look at the "increasing quality" model.

2.2 Vertical innovations

Here we present a simplified version of Aghion & Howitt (1992, 1998) comparable to the above version of Romer (1990). Again there are two sectors (broadly defined), the basic-goods sector and the innovative sector. But now the number of different specialized capital goods, $\bar{N}$, is fixed (and "large"), and we have

$$Y = \left(\sum_{i=1}^{\bar{N}} Q_i x_i^{\alpha} \right) L_Y^{1-\alpha}, \quad 0 < \alpha < 1, \tag{7}$$

where Q_i = productivity ("quality") attached to the latest vintage of capital good i. Because of its (sufficiently) superior quality this vintage outperforms previous vintages ("creative destruction"). Further, raw capital can be converted into this vintage according to

$$x_i = \frac{K_i}{Q_i}, \tag{8}$$

that is, succeeding vintages of the specialized capital good are increasingly capital intensive. The symmetric structure leads to $x_i = x = K/(\bar{N}Q)$ for all i, where

$$Q \equiv \frac{\sum_{i=1}^{\bar{N}} Q_i}{\bar{N}}. \tag{9}$$

Hence,

$$Y = K^{\alpha}(\bar{N}QL_Y)^{1-\alpha}. \tag{10}$$

The aggregate outcome of R&D activity in the different branches of the innovative sector is described by

$$\dot{Q} = \tilde{\mu} L_R, \tag{11}$$

$$\tilde{\mu} = \mu Q, \qquad \mu > 0, \tag{12}$$

which are analogous to (3) and (4).

In steady state, again

$$g_y = \mu s_R L, \tag{13}$$

but now growth is driven by increasing quality of a fixed spectrum of inputs.

Results 1 and 2 from the previous section go through, but result 3 is modified. Indeed, there are now three market failures, two of which tend to generate too little R&D in the market economy (the positive intertemporal spillover in research and the surplus appropriability problem, that is, the inability of the innovator to capture the whole contribution to output of the innovation). But a third market distortion works in the opposite direction, namely the "business stealing" effect, i.e., the failure of the innovator to internalize the loss to the previous innovator caused by inventing a better quality. Because of this effect, under laissez-faire the market economy *may* generate too *much* research. Empirically, this does not seem to be the case, rather the contrary (Jones and Williams, 1998).

3 Non-robustness and the semi-endogenous alternative

Two features of the conclusion $g_y = \mu s_R L$ stand out: (i) There is a scale effect on growth, $\partial g_y/\partial L > 0$.[3] (ii) By affecting incentives, policy can affect s_R and thereby the long-run growth rate.

3.1 The Jones critique

In two important papers Charles Jones (1995a, 1995b) claimed:

(a) Both conclusions are rejected by time-series evidence for the industrialized world.

(b) Both conclusions are theoretically non-robust (i.e., they are very sensitive to small changes in parameter values).

To see point (b), take the Romer model as an example.[4] From (3) and (4) the aggregate invention production function is $\dot{N} = \mu N L_R$. A more general specification would be

$$\dot{N} = \mu N^{\varphi} L_R, \qquad \varphi \leq 1, \tag{14}$$

where the parameter φ is the elasticity of research productivity with respect to the level of technical knowledge. In the Romer model the value of this parameter is arbitrarily put equal to one. One could easily imagine, however, this parameter being negative ("exhaustion of new ideas", "the easiest ideas are found first"). Even when

[3] Indeed, $\partial g_y/\partial L = \mu(s_R + L\partial s_R/\partial L) \geq \mu s_R$, since increasing L does not tend to diminish relative research effort, s_R.

[4] An analogue argument goes through for the vertical innovation model.

one assumes $\varphi > 0$ (i.e., the case where the subsequent steps in knowledge accumulation become easier and easier to reach), there is neither theoretical or empirical reason to expect $\varphi = 1$.[5] Even worse, $\varphi = 1$ is a knife-edge case. If φ is slightly above 1, then explosive growth arises – and does so in a very dramatic sense: infinite output in finite time! This was pointed out by Solow (1994). The numerical example he gives corresponds to $\varphi = 1.05$, $s_R = 0.10, \mu L = 1$ and $N_0 = 1$. Then the Big Bang – the end of scarcity – is only 200 years ahead! The fact that this occurs only a hair's-breath from the presumed unit value of φ tells us something about how strong and optimistic that assumption is. To paraphrase Solow, it is too good to be true.[6]

On the other hand, with φ slightly less than 1, productivity growth peters out, unless assisted by growth in some exogenous factor, say population. Indeed, let $L = L_0 e^{nt}$, where $n \geq 0$ is a constant. Then, deriving from (14) an expression for $\dot{g}_N / g_N$ we find that in steady state (i.e., when $\dot{g}_N = 0$),

$$g_y = \frac{n}{1 - \varphi}. \tag{15}$$

Hereby, the unwelcome scale effect on growth has disappeared. Still, from (14) it is obvious that a scale effect on the *level* of y remains. In view of the nonrival character of technical knowledge this was to be expected. The nonrivalry of knowledge also explains the feature that the rate of productivity growth is an increasing function of the rate of population growth. This trait should not be seen as a prediction about individual countries in an internationalized world, but rather as pertaining to larger regions, perhaps the global economy. Finally, unless policy can affect φ or n (often ruled out by assumption[7]), long-run growth is independent of policy as in the old neoclassical story. Of course, "independence of policy" should not be interpreted as excluding that the general social, political and legal environment can be a *barrier* to growth.

The case $\varphi < 1$ constitutes an example of *semi-endogenous growth.* We say there is semi-endogenous growth when a) per capita growth is driven by some internal mechanism (as distinct from exogenous technology growth), but b) sustained per capita growth requires the support of growth in some exogenous factor. In innovation-based growth theory this factor is typically population size. For a constant growth rate of

[5] The standard replication argument for constant returns with respect to the complete set of *rival* inputs is not usable.

[6] The knife-edge is not only a property of innovation-based endogenous growth models, but also of accumulation-based endogenous growth models, e.g., Lucas (1988).

[7] Exceptions include Cozzi (1997) who develops a model in which R&D can follow different directions and where short-term gains may conflict with long-term growth prospects. By taxes and subsidies it is possible to shift research to directions with high growth potential.

knowledge to arise, the diminishing returns to knowledge must be offset by a rising number of researchers. Note that in our terminology, the distinction between strictly endogenous growth (defined in Section 2.1) and semi-endogenous growth is not the same as the distinction between policy-dependent and policy-invariant growth. This becomes important below.[8]

3.2 Different responses to the Jones critique

The Jones critique provoked at least four different kinds of responses.

3.2.1 The knife-edge models may be handy approximations

No doubt the knife-edge models are useful as simplifying devices (as emphasized by McCallum 1996, Temple 2003). Yet they may yield an acceptable approximation only for a somewhat limited period of time. To get a flavour, consider the Cobb-Douglas version of the well-known Learning-By-Investing model without scale effect (Barro and Sala-i-Martin 2004, p. 235, 237). Let σ be a subsidy to purchases of capital services. Departing from steady state, consider an unanticipated increase in σ from 0.40 to 0.56. Let the "true" learning parameter λ be as high as 0.8, and compare the effect of the shock to that in the simplified (knife-edge) model where $\lambda = 1$. For standard parameter values one may end up with, after 60-70 years, an aggregate capital intensity in the knife-edge model double to that in the "true" model, a difference that may be important for, e.g., the evaluation of welfare effects.

3.2.2 Anyway, *some* linearity is needed

That is, as noted by Romer (1995), in order for steady growth to be possible a growth model must yield a differential equation that is linear:

$$\dot{x} = \text{constant} \cdot x \tag{16}$$

Growth models differ according to a) what variable takes the role of x, and b) what determines the constant.[9] The key to having policy impinging on long-run growth is to have the constant determined such that policy affects it. In Solow (1956) we

[8] In Jones (1995b) (14) takes the extended form, $\dot{N} = \mu N^{\varphi} L_R^{\varepsilon}$, $0 < \varepsilon \leq 1$, in order to represent a likely congestion externality of research (duplication of effort); but this externality is not crucial for the discussion here. For more elaborate variants of the semi-endogenous approach, see Kortum (1997) and Segerstrom (1998). An early example is Arrow (1962). A somewhat different way to aleviate or eliminate scale effects is based on *adoption costs* (Jovanovic 1997).

[9] If the model contains more than one state variable, the simple proportionality in (16) takes the form of a vanishing determinant.

have $\dot{T} = \tau T$, where T is the technology level, and τ is exogenous; hence, long-run growth is policy-invariant. In the AK model of Rebelo (1991), $Y = AK$, so that $\dot{K} = (A - C/K - \delta)K$, where C/K is constant in equilibrium and can be affected by tax policy. The human-capital model of Lucas (1988) has $\dot{h} = \mu e h$, where h is per capita human capital, and e is per capita educational time.[10] Romer (1990) and Aghion and Howitt (1992) were described above. Jones (2003) proposes $\dot{L} = (b-d)L \equiv nL$, where b is the birth rate and d is the death rate. He argues that this demographic candidate seems the least arbitrary among the different candidates. After all, people reproduce in proportion to their number.[11] No convincing explanation has as yet been given for any of the other candidates. In Section 6 we shall meet yet another candidate.

3.2.3 One can do with only *asymptotic* linearity

Larry Jones and Rodolfo Manuelli (1990, 1997) pointed out that *asymptotic* linearity with respect to capital can be enough for strictly endogenous growth to arise. Dalgaard and Kreiner (2003) followed up, by applying the same principle to the invention production function. It is not clear, however, that the empirical evidence for asymptotic linearity is essentially better than that for exact linearity.

The fourth response to the Jones critique is more elaborate and constitutes what may be called the second generation innovation-based models.

4 Second generation models

Young (1998), Peretto (1998), Aghion & Howitt (1998, Ch. 12), Dinopoulos & Thompson (1998) and Howitt (1999) (for short: the Y/P/AH/DT/H models) try to establish that it is possible to get rid of the scale effect on growth and at the same time maintain that policy affects long-run growth. The following is only a rough description that does not do justice to all the interesting insights and differing details of these papers.

The basic idea is to combine the quality ladder approach with the increasing variety approach by letting innovations occur along *both* dimensions, the vertical as well as the horizontal. Aggregate output of basic goods is

$$Y = K^{\alpha}(NQL_Y)^{1-\alpha} , \tag{17}$$

[10] Combining innovations along one or more dimensions with linearity in human capital formation, Dalgaard and Kreiner (2001) and Strulik (2004) remove the scale effect and at the same time restore strictly endogenous growth.

[11] Most of the Jones papers take n as given, but Jones (2003) deals with the very long run and provides a theory of endogenous fertility.

where now the number of varieties, N, is increasing over time. Indeed, total research effort is, as before, $L_R = s_R L$, but the fraction $1 - s_Q$ of this is devoted to horizontal innovations,

$$\dot{N} = \mu(1 - s_Q)s_R L, \tag{18}$$

and the remaining part is devoted to vertical innovations within the existing N product lines,

$$\dot{Q} = \xi Q \frac{s_Q s_R L}{N}, \qquad \xi > 0. \tag{19}$$

If s_R and s_Q are constant, (18) gives $\dot{g}_N/g_N = n - g_N$ so that in steady state $g_N = n$. Further, by (17),

$$g_Y = \alpha g_K + (1 - \alpha)(g_N + g_Q + n),$$

which, in steady state, where $g_K = g_Y = g_y + n$, gives

$$\begin{aligned} g_y &= g_N + g_Q = \mu(1 - s_Q)s_R \frac{L}{N} + \xi s_Q s_R \frac{L}{N} \\ &= (1 + \frac{\xi}{\mu} \frac{s_Q}{1 - s_Q})n, \end{aligned} \tag{20}$$

in view of $g_N = n$. Similar results are obtained if the vertical innovations take the form of cost-reducing process innovations as in Peretto (1998).

Notice that in this version, population growth is necessary to sustain positive per capita growth in the long run.[12] Hence, this is a case of semi-endogenous growth according to the definition given above. More importantly, we see that:

- Long-run growth is not policy-invariant; policy can affect g_y via affecting s_Q.
- There is no scale effect on growth, hence, population growth does not imply accelerating growth.

Jones (1999), Li (2000) and others rejoined that, though interesting,

(i) these results rely on *several* knife-edge conditions;

(ii) a generic model with innovations along two dimensions is semi-endogenous.

Indeed, the above model is special: There are no knowledge spillovers *within* horizontal innovations, there are no knowledge spillovers *between* horizontal innovations and vertical innovations, and the parameter for the spillovers within vertical innovations has a very particular value.

[12] Yet, within the second generation models there are also contributions that generate strictly endogenous growth, e.g., Young (1998) and Dinopoulos and Thompson (1998).

A more general (and symmetric) model would be (essentially Chol-Won Li, 2000):

$$\dot{N} = \mu N^{\varepsilon_1} Q^{\varphi_1} \frac{(1-s_Q)s_R L}{Q}, \qquad \varepsilon_1 \geq 0, \varphi_1 \geq 0, \tag{21}$$

$$\dot{Q} = \xi N^{\varepsilon_2} Q^{\varphi_2} \frac{s_Q s_R L}{N}, \qquad \varepsilon_2 \geq 0, \varphi_2 \geq 0. \tag{22}$$

In steady growth (g_N and g_Q constant) the numerator and the denominator in expressions for g_N and g_Q, derived from (21) and (22), must grow at the same rate. This implies

$$\begin{aligned}(1-\varepsilon_1)g_N + (1-\varphi_1)g_Q &= n,\\ (1-\varepsilon_2)g_N + (1-\varphi_2)g_Q &= n.\end{aligned}$$

By (17), $g_y = g_N + g_Q$ in steady growth, so that, with $D \equiv (1-\varepsilon_1)(1-\varphi_2) - (1-\varphi_1)(1-\varepsilon_2) \neq 0$, we get

$$g_y = \frac{(\varphi_1 - \varphi_2 + \varepsilon_2 - \varepsilon_1)n}{D}. \tag{23}$$

We see that in the generic case, $D \neq 0$, long-run growth is semi-endogenous. On the other hand, in the Y/P/AH/DT/H models the spillover parameters happen to be:

$$\begin{aligned}\varepsilon_1 &= \varepsilon_2 = 0 \qquad \text{(spillovers from horizontal innovations)},\\ \varphi_1 &= \varphi_2 = 1 \qquad \text{(spillovers from vertical innovations)}.\end{aligned} \tag{24}$$

This knife-edge case implies $g_N = n$, leaving room for s_Q in (20), hence g_Q, to be determined by policy, via R&D incentives and households' preferences.

Chol-Won Li (2002) generalizes the model and shows that if intermediate goods have k quality attributes, which can be improved through R&D, then policy-dependent growth requires $k+1$ knife-edge conditions to be satisfied. Otherwise long-run growth is independent of policy.

Well, this conclusion is true for this model. But a richer model could contain economic mechanisms affecting the spillover coefficients. The models proposed by Cozzi (1997) and Peretto and Smulders (2002) are steps in this direction. In the Peretto and Smulders paper the vertical innovations are "in-house" (no business-stealing effect), and the horizontal innovations raise technological distance. This reduces the effective spillovers originating in horizontal innovations. Indeed, the model can be interpreted as the case: $\varepsilon_1 \to 0, \varepsilon_2 \to 0$ for $N \to \infty$. Similarly, Weitzman (1998b) may coarsely be interpreted as showing how (24) can arise generically in the long run.[13]

[13] It should be recognized, however, that neither Peretto and Smulders (2002) or Weitzman (1998b) fit utterly well into our framework since both models lead to strictly endogenous growth rather than semi-endogenous growth as in (20).

5 Third generation models: Directed technical change

Until recently, almost all growth models, whether with endogenous or exogenous technical change, relied on either the knife-edge assumption of an elasticity of substitution between capital and labour exactly equal to 1 (the Cobb-Douglas production function) or the knife-edge assumption that all technical change is purely labour-augmenting − capital-augmenting technical change being, by assumption, excluded. With an elasticity of substitution less than 1 (as the empirical evidence suggests), technical change must be purely labour-augmenting in order that balanced growth paths with constant income shares of labour and capital can exist. But what mechanisms can possibly explain that technical change should tend to be purely labour-augmenting, i.e., Harrod-neutral, in the long run?

In a series of papers Acemoglu (1998, 2002, 2003) succeeded integrating the somewhat ad-hoc theory from the 1960's about the "innovation possibility frontier"[14] with the microfounded endogenous growth theory of the late 1980's. The outcome is a theory where the same economic forces − profit incentives − that affect the *rate* of technical change will also shape the *direction* of technical change. Here we outline how the theory works in the horizontal innovation framework.[15]

Assume output of basic goods is given by the CES function

$$Y = \left[\alpha(MK)^{(\sigma-1)/\sigma} + (1-\alpha)(NL_Y)^{(\sigma-1)/\sigma}\right]^{\sigma/(\sigma-1)}, \tag{25}$$

where $\sigma > 0$ is the constant elasticity of substitution between K and L_Y. There are now *two* technology terms: M, which measures the range of capital-enhancing intermediate goods, and N, which measures the range of labour-enhancing intermediate goods. The technologies for invention of new varieties of the two kinds of intermediate goods are

$$\dot{M} = \hat{\psi} s_M L_R - \eta M, \quad \text{and} \quad \dot{N} = \hat{\mu}(1-s_M)L_R - \eta N, \tag{26}$$

where s_M denotes the fraction of research effort devoted to invention of new varieties of capital-enhancing intermediate goods, and $\eta > 0$ represents the rate of evaporation of varieties.[16] At the economy-wide level the research productivities are given as

$$\hat{\psi} = \psi M(s_M L_R)^{\varepsilon-1}, \quad \text{and} \quad \hat{\mu} = \mu N\left[(1-s_M)L_R\right]^{\varepsilon-1}, \tag{27}$$

where $\varepsilon \in (0,1)$ captures crowding effects not internalized by the individual R&D firm.[17]

[14] For a summary and critical assessment, see Nordhaus (1973).
[15] Fitting the theory to vertical innovations is also possible, but is slightly more complicated.
[16] The assumption $\eta > 0$ is invoked in order to avoid multiplicity of balanced growth paths.
[17] By having $\varepsilon < 1$, inconvenient discontinuities in the behaviour of s_M is avoided.

Embedding this production structure in a standard representative-agent framework, Acemoglu (2003) essentially shows the following. An income share of capital above its long-run equilibrium makes capital-augmenting innovations more favorable, i.e., s_M is increased. Thereby the "effective" capital intensity, $k \equiv MK/NL_Y$, increases, and with $\sigma < 1$ this implies decreasing income share of capital. Similarly, a rate of interest above its long-run equilibrium spurs capital accumulation, thereby decreasing the rate of interest. The system approaches a BGP with constant k and constant rate of interest. The constancy of the remuneration to capital is obtained when s_M is at a level low enough to just maintain a constant M. On the other hand, N, and the thereby the real wage, keeps growing along with K/L_Y, without stimulating labour supply, which is not a function of wages. In this way technical change becomes purely labour-augmenting in the long run.

Although here formulated as a strictly endogenous growth model, i.e., the spillover parameters in (27) are exactly one, seemingly the theory works just as well in the semi-endogenous growth case, where the spillover parameters are less than one (Acemoglu 2002, p. 795). The essential point is that the knife-edge condition of Harrod-neutral technical progress is replaced by a theory of induced Harrod-neutrality in the long run. Of course, when one problem is resolved, new problems appear. Acemoglu's theory relies on the knife-edge condition that there are no knowledge spillovers *between* the M and N promoting endeavours, cf. (27). A next task will be to either relax this assumption or provide a microfoundation for it.

The theory of endogenous directed technical change has shown its usefulness in many applications. Different elaborations embrace topics such as skill-biased technical change (Acemoglu 1998, Kiley 1999), the long-run constancy of the capital income share despite large changes in fiscal policy and labour market policy (Acemoglu 2003) and cross-country differences in pollution (Di Maria and Smulders 2004). Of particular interest in relation to the limits-to-growth debate is the modelling of induced energy-saving technical change in André and Smulders (2004).

A problem with the Acemoglu directed-technical-change framework is its quite abstract nature. As noted by Stokey (2003) it is not easy to identify what N, M and S_M correspond to empirically. Jones (2004b) offers an alternative approach to the problem of the shape of the aggregate production function, implying that the question about Harrod-neutrality looses its importance. Indeed, Jones provides a microfoundation for the production function being Cobb-Douglas in the long term, though the short-term elasticity of substitution may be less than one.

6 Non-renewable resources and growth

It is not always recognized that already the literature of the 1970's on macro implications of essential non-renewable natural resources (Solow 1974, Stiglitz 1974a, 1974b, Suzuki 1976) laid the groundwork for a theory of endogenous, policy-dependent growth. These contributions typically considered a one-sector model with technology and resource constraints at macro level described by:

$$Y = AK^{\alpha}L^{\beta}E^{\gamma}, \qquad \alpha, \beta, \gamma > 0, \ \beta, \gamma < 1, \tag{28}$$

$$\dot{K} = Y - cL - \delta K, \tag{29}$$

$$\dot{S} = -E \equiv -eS, \qquad \int_0^{\infty} E(t)dt \leq S(0). \tag{30}$$

The new symbols are: E = input of the non-renewable resource, S = remaining resource stock, and e = extraction rate. The non-renewable resource is *essential* in the sense that $Y > 0$ is possible only if $E > 0$. The finite upper bound on cumulative resource extraction is shown by (30). For simplicity, costs of extraction are ignored. Solow and Stiglitz focused mostly at constant returns to scale ($\alpha + \beta + \gamma = 1$) and exogenous technical progress, that is, total factor productivity, A, growing at a constant positive rate τ. But still, the long-run per capita growth rate g_y turned out to depend on preferences and was therefore capable of being affected by some kinds of policy. The explanation is that (28), transformed into growth rates, yields

$$g_Y = \tau + \alpha g_K + \beta n + \gamma g_E, \tag{31}$$

and in steady state $g_K = g_Y \equiv g_y + n$ and $g_E = g_S = -E/S \equiv -e$, so that (31) gives

$$(1 - \alpha)g_y + \gamma e = \tau + (\alpha + \beta - 1)n. \tag{32}$$

It is seen that:

(i) A steady state with $g_y > 0$ can exist only if

$$\tau + (\alpha + \beta - 1)n > 0 \qquad \text{or} \qquad \alpha > 1. \tag{33}$$

(ii) Policies which decrease (increase) the long-run extraction rate e will (for $a < 1$) increase (decrease) the long-run per capita growth rate.

The key to this strong policy conclusion is that any balanced growth path has to comply with the linear differential equation $\dot{S} = -eS$, which is the form here taken by

(16). The conventional wisdom in the endogenous growth literature is that interest income taxes impede economic growth and investment subsidies promote economic growth. Interestingly, this is not so here. Generally, only those policies that interfere with the extraction rate in the long run (like a capital-gains tax or a time-dependent tax on resource use) can affect long-run growth.[18]

An interesting corollary of result (i) is that if $\tau = 0$ (no exogenous technical progress), then $g_y > 0$ is possible only if there are either increasing returns to the capital-*cum*-labour input combined with population growth *or* increasing returns to capital itself. At least one of these conditions is required in order that capital accumulation can offset the effects of the inevitable decline in resource use over time.[19] And only if $\alpha > 1$, is strictly endogenous growth possible; further, the potentially explosive effects of $\alpha > 1$ can, if α is not *too* large, be held back by the strain on the economy imposed by the declining resource input.

In some sense this is "good news": Strictly endogenous steady growth is theoretically possible, and no knife-edge assumption is needed. But the "bad news" is that increasing returns to capital is probably a too strong and optimistic assumption: An α only slightly above 1 implies that, from a technological point of view, *any* per capita growth rate can be sustained − there is no upper bound on g_y.[20] Too good to be true!

It is noteworthy that these conclusions differ somewhat from those of the existing literature explicitly dealing with non-renewable resources and endogenous growth (Robson 1980, Jones and Manuelli 1997, Aghion and Howitt 1998, Chapter 5, Schou 2000, Schou 2002, André and Smulders 2004). This literature typically has a separate sector where a fraction of the labour force is employed in research (or education). The crucial feature is that this sector, the "growth engine", is assumed not to use the non-renewable resource (not even indirectly in the sense of physical capital being used). Therefore, the conclusions reached are pretty much in conformity with those of the strictly endogenous growth models without non-renewable resources.[21] In particular, as in Section 2, strictly endogenous steady growth again requires the knife-edge

[18] This is further explored in Groth and Schou (2004). Notice, that this policy result holds whether $g_y > 0$ or not and whether growth is exogenous, semi-endogenous or strictly endogenous.

[19] In this context K is to be interpreted as "broad capital", including technical knowledge and human capital.

It is another thing that the predicted decline in resource use has not yet shown up in the data. Indeed, the per capita use of, e.g., fossile fuels in the period 1950-2000 shows an increasing trend (Jones 2002, p. 184), probably due to better extraction technology and discovery of new deposits. But in the long run this tendency inevitably will be reversed.

[20] See Groth (2004a).

[21] And the scale effect on growth tends to pop up again, though sometimes hidden by the labour force being normalized to one.

assumption that the growth engine has exactly constant returns to producible inputs.

In reality, however, most sectors, including educational institutions and research labs, use fossil fuels for heating and transportation purposes, or minerals and oil products for machinery, computers, etc. With $\tau = 0$ and $(\alpha+\beta-1)n > 0$ or $\alpha > 1$, the technological set-up above sketches an endogenous growth model which *does* take this into account: The resource enters the growth engine, which is the manufacturing sector itself. Embedding this set-up into a Ramsey representative-agent optimal growth framework Groth and Schou (2002) show:

(iii) There is no scale effect on growth, but higher n generates higher g_y (anti-Malthus). Indeed, in steady state

$$g_y = \frac{(a + \beta + \gamma - 1)n - \gamma\rho}{1 - \alpha + (\theta - 1)\gamma}, \tag{34}$$

where the denominator is assumed positive (which is necessary for stability), θ being the elasticity of marginal utility and ρ the rate of time preference.

(iv) Existence of a *stable* balanced growth path with $g_y > 0$ requires population growth.

A corollary of result (iv) is that stable strictly endogenous growth does not exist. That is, the knife-edge problem of strictly endogenous growth has waned, but only to reappear as an instability problem. To get a glimpse of what is involved, notice that population growth tends *ceteris paribus* to raise the level of the marginal product of capital required for balanced growth. When $\alpha > 1$, the "snowball effect" from $\alpha g_K > g_K$ need to be offset by the spur to capital accumulation being so low that in the absence of population growth the required marginal product is negative, which is impossible.

Are these results just an artifact of the one-sector set-up? Groth (2004b) studies a horizontal-innovation-based two-sector model where the non-renewable resource is a necessary input in both the manufacturing sector and the R&D sector. Results analogous to the above go through. In particular sustained per capita growth requires a higher elasticity of research productivity with respect to knowledge than when the growth engine does not need the resource as an input. Further, in the one-sector model the knife-edge assumption of an elasticity of substitution equal to one (the Cobb-Douglas case) was needed in order to ensure that the non-renewable resource is essential ($Y > 0$ possible only if $E > 0$), but does not *a priori* rule out non-decreasing consumption in the long run. But no such knife-edge condition is needed in the two-sector model. Indeed, in that model, featuring endogenous resource-augmenting technical progress, an elasticity of substitution between capital and the resource less than one is allowed.

Of course, it is possible that in the long run the elasticity of substitution turns out to be larger than one so that the strain on economic growth implied by non-renewable resources disappears. We simply do not know.

7 Outlook

The last two decades have deepened our understanding of mechanisms that influence the amount and direction of technical progress. The theoretical advances contain far more insight and subtlety than portrayed in this selective review. And the burgeoning empirical literature has completely been passed over.

With a certain proviso alluded to at the end of Section 4, the conclusion I am inclined to draw is the following. Robust innovation-based growth models tend to end up with the long-run per capita growth rate pinned down by population growth. If non-renewable resources are not essential for any sector of the economy, long-run growth takes a form similar to that in formula (23) above and is independent of policy. If non-renewable resources are essential at least for the manufacturing sector, preference parameters also enter the growth formula, as in (34) above, and certain kinds of policy affects long-run growth. If non-renewable resources are essential for the growth engine, strictly endogenous growth tends to be unstable.

In the last 55 years world population growth reached its peak rate of 2 percent per year in the 1965-1970 period and since then it has declined to 1.3 percent between 1995 and 2000 (United Nations, 2003). The general view seems to be that economic and cultural conditions are likely to put an end to population growth within 40-80 years and already within 20-25 years in the now more developed regions. Although this does not necessarily mean that the n of the model will be approaching zero equally soon, it suggests that if growth is semi-endogenous, then a slowdown of long-run per capita growth must be expected. Of course, such a prediction is very uncertain, because many exogenous factors can change. Nonetheless, the indication is that the likelihood of a slowdown should carry relatively more weight than its opposite. In addition to the uncertainty argument, according to which the social discount rate should be smaller the longer is the time horizon as seen from "now" (Weitzman 1998a), this is yet another reason why the warranted discount rate for long-term environmental projects (like measures to mitigate the problems of global warming) is likely to be considerably smaller than an average of past rates of return to capital.

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