# Innovation-based growth theory
# Peter Howitt

Report by Egbert L.W. Jongen*

## Introduction

Peter Howitt (Brown University), one of the leading researchers in the field of endogenous growth, gave a series of lectures at the NAKE-workshop at the Free University Amsterdam in June 2000. Below we report the main insights and ideas handed to us by Professor Howitt during these lectures. Peter Howitt and his continual collaborator Philippe Aghion view economic growth as a process of creative destruction, where leading innovators are continually displaced by the next leading innovator.

The outline of this report follows the outline of the lectures. In the first lecture we consider the limitations of 'exogenous' growth theory and the so-called AK-model of economic growth. In the second lecture we outline the bare bones model of innovation dirven by creative destruction. Lecture 3 takes a closer look at general purpose technologies, whereas Lecture 4 considers the topical issue of competition and growth. The final lecture, Lecture 5, seeks to explain the development of the world income distribution using the creative destruction approach of Aghion and Howitt, and deals with some criticisms of endogenous growth theory.

## Lecture 1 - Exogenous growth and AK models

During the 1950s, Solow (1956) and Swan (1956) constructed the first general equilibrium models of economic growth.The striking implications of what came later to be known as 'exogenous' growth theory was that capital accumulation and population growth are

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insufficient for a continual rise in per capita income, and policy can not affect the long-run per capita growth rate. Below we briefly consider the bare-bones of the Solow-Swan model of economic growth.

Let the production function be of the Cobb-Douglas type

$$Y(t) = K(t)^{\alpha}(A(t)L(t))^{1-\alpha}, \tag{1}$$

where $Y(t)$, $K(t)$, $L(t)$ and $A(t)$ denote aggregate output, the capital stock, labor supply and the level of technology, respectively. $\alpha$ is a production parameter. Note that labor in production equals labor supply, i.e. no unemployment, and technological progress is labor-augmenting. Labor supply and technology grow exogenously at the rates $n$ and $\gamma$, respectively. Define $k(t) = K(t)/(A(t)L(t))$ and $y(t) = Y(t)/(A(t)L(t))$, where capital and output are now per effective unit of labor.The change in the stock of capital is endogenous, via the behavioral equation

$$\dot{k}(t) = sy(t) - (\delta + n + \gamma)k(t), \tag{2}$$

where the behavioral assumption is the constant saving rate $s$. $\delta$ denotes an exogenous depreciation rate. Note that $n$ and $\gamma$ effectively raise the depreciation rate of capital per efficiency unit of labor, as more effective labor units have to work on the same stock of capital accumulated in the past.

First, consider what happens when $n = \gamma = 0$. For low $k(t)$ the marginal productivity of capital (times the savings rate) is higher than the depreciation rate, whereas for a sufficiently high $k(t)$ the reverse is true. By the behavioral equation for capital accumulation this implies that there exists a unique steady state stock of capital $k^*$ (next to the degenerate case $k^* = 0$). A higher savings rate or a lower depreciation rate will sustain a higher capital level, but output will cease to grow (or fall) once the capital stock settles down.

By introducing population growth, $n > 0$, output and capital can grow in line with the growth in labor supply, Following the same reasoning as before we find that the capital-labor ratio will eventually settle down at some $k^*$. At $k^*$ $K(t)$ and $L(t)$ will grow at the same rate $n$, so output will grow at rate $n$ as well. However, once again per capita growth can not be sustained.

When we introduce labor-augmenting technological change, $\gamma > 0$, the economy will again settle down at some $k^*$. Capital and output will now grow at the rate of effective labor supply $n+\gamma$. However, as labor supply in persons grows only at $n$, the economy can 'escape' from the presence of diminishing marginal product of capital. Per capita growth can be sustained. However, as $\gamma$ is exogenous, policy can not affect the long-run growth rate of per capita income.

Another way to escape the ever present diminishing marginal product of capital is to eliminate this barrier to per capita growth directly, the so-called AK-approach to economic growth (Frankel (1962), Romer (1986)). In the AK-approach no labor augmenting technological change is required to sustain per capita growth. Suppose that aggregate output is given by

$$Y(t) = AK(t), \tag{3}$$

whereas the capital accumulation is the same as before. Effective labor supply is normalized to 1. One can readily show that capital and output will grow at the rate $sA - \delta$. Provided that $sA > \delta$ per capita income will grow without bound. Furthermore, by raising the savings rate policy can raise per capita income growth indefinitely.

## Lecture 2 - Endogenous growth with creative destruction

The exogenous growth model could account for the 'stylized facts' of economic growth of Kaldor (1961) like i) sustained growth; ii) a constant capital-output ratio; iii) a constant labor share; and iv) the constancy of the interest rate on capital. However, the exogenous growth model does rather poorly in terms of more recent 'stylized facts' of economic growth. Furthermore, exogenous growth models leave the single engine of per capita growth, technological change, unexplained. Finally, no one is compensated for technological progress, whereas market forces seem to lie at the heart of the innovative process.

It would take quite some time before 'endogenous' growth entered the stage though. From 1970 to the early 1980s normal science continued, but no really new and interesting ideas on economic growth appeared (see Solow (2000)). However, the thesis of Paul Romer (published in 1986) sparked the research into economic growth models. During the late 1980s/early 1990s various seminal papers appeared in the leading journals that showed how technological change can be endogenized (i.e. Romer (1986), Lucas (1988), Grossman and Helpman (1991) and Aghion and Howitt (1992)). In endogenous growth models technological innovations are driven by the profit motive. Furthermore, policy re-enters the stage, as policies can affect the long-run growth rate. Indeed, policy plays a central role in endogenous growth theory, as with the endogenization of the growth rate came along various market failures. Below we consider the bare-bones version of the Aghion and Howitt (1992) model of economic growth.

Output is given by

$$Y(t) = A(t)(x(t))^{\alpha}, \tag{4}$$

where $A(t)$ denotes the technology level at time $t$. Let $L$ be the (constant) labor force, and let $n$ denote share of the labor force devoted to R&D. $L - n$ of labor units are devoted to producing the intermediate input $x$ (one unit of labor generates one unit of $x$ each period). One unit of labor devoted to R&D generates a innovation in $A(t)$ at rate $\lambda$. The stepsize of innovations is denoted by $\gamma$ $(> 1)$. Denote by $A(\tau)$ the level of technology after $\tau$ innovations. Free entry into R&D implies

$$w(\tau) = \lambda \frac{\pi(\tau + 1)}{r + \lambda n}, \tag{5}$$

where $w(\tau)$ denotes the wage rate after $\tau$ innovations, $\pi(\tau+1)$ denotes the profits arising from the next innovation, and $r$ denotes the interest rate. Profits follow from the monopoly price for units of $x$ by the leading innovator $(w(\tau)/\alpha)$. The wage rate has to equal the rate at which an innovation occurs times the discounted value of the profits associated with this innovation. Profits are discounted by the interest rate and the rate at which the incumbent is displaced by the next innovation, creative destruction occurs at rate $\lambda n$ (in equilibrium $n$ will be independent of $\tau$).

The equilibrium share of labor devoted to R&D is independent of the level of $A(t)$. Define the growth corrected wage rate by $\omega(\tau) = w(\tau)/A(\tau)$. $n$ can be found from the free entry condition of R&D (with the right and left hand side divided by $A(\tau)$) given above and labor the market equilibrium condition

$$n + x(\omega) = L. \tag{6}$$

A higher share of labor devoted to R&D is associated with a higher 'wage rate' $\omega$ via the labor market clearing condition. From the free entry condition for R&D a higher share of labor devoted to R&D is associated with a lower $\omega$ (profits are discounted more heavily due to increased creative destruction). Equilibrium is a pair $(n, \omega)$ that satisfies both conditions.

One can readily verify that $x$ is constant in equilibrium (as $\omega$ is constant). Hence, by standard growth accounting we have $g_Y = g_A$. From the poisson distribution with parameter $\lambda n$ we find $g_A = \lambda n \ln \gamma$. Note that a higher labor force will raise $n$ and hence the growth rate (the model is 'scale dependent'), and so will a R&D subsidy (effectively lowering labor costs for R&D). Policy can influence the long-run growth rate. Howitt further showed how the model can be extended to allow for an infinitum of sectors and capital accumulation (see Chapter 3 in Aghion and Howitt (1998)). As a result of the continuum of sectors growth will loose its stochastic character at the aggregate level. Furthermore, capital accumulation becomes an essential ingredient for growth, as capital is one of the resources required for innovation. The endogenous growth results are unaffected, with a higher savings rate now also raising the growth rate of the economy.

## Lecture 3 - General purpose technologies

The Schumpeterian view of endogenous technological change can be used to examine the response of the economy to the invention of general purpose technologies (GPTs). The Schumpeterian model creates an interesting link between growth and cycles. GPTs, like the steam engine and computers, seem to generate higher output in the long-run at the cost of a lower output in the short-run.

The first shot on the time path of an economy to the invention of a GPT comes from an adapted version of the Helpman and Trajtenberg (1994) model, where the adaptation is in the endogeneity of technological change. The arrival rate of a GPT is exogenous. Before the GPT can be used to produce (higher) output, components have to be discovered so as to facilitate its implementation. The discovery of components depends on the resources devoted to R&D. Output goes through three stages. In stage 1 all firms produce at the old GPT, with the components already discovered. Stage 2 begins with the arrival of a new GPT. Resources are directed towards R&D to generate the necessary components. Measured output falls. Stage 3 begins with the arrival of the necessary components. All firms produce with the higher GPT. Measured output rise above the level of stage 1. As the development of the necessary components is driven by the profit motive, the arrival rate of new GPTs has an ambiguous effect on the growth rate. A higher arrival rate implies more chances to upgrade to a better technology, but lowers the incentive to invest in R&D due to higher creative destruction.

The simple setup outlined above seems to have two main limitations: i) output jumps down when a GPT arrives, then jumps up when the necessary components are discovered, and remains stable in between jumps, this hardly seems in line with the data; and ii) the fall in output is due to the divertion of resources towards R&D, with a share of R&D of only 2.5 percent of output this seems insufficient to generate the more dramatic swings in observed output. Therefore we generalize (see Chapter 8 in Aghion and Howitt (1998)).

The first limitation can be met by extending the model towards a continuum of sectors where innovation is characterized by 'social learning'. Let $n_0$ be the share of sectors that produce at the old GPT, $n_1$ be the share of sectors that are performing R&D to adopt the new GPT, and $n_2$ the share of sectors that succeeded in adopting the new GPT. The crucial assumption is that sectors can learn from each other, in the sense that the rate at which a given sector starts doing R&D depends on the share of firms that succeeded in adopting the GPT. A typical time pattern for the share of $n_0$, $n_1$ and $n_2$ is given in Figure 1. At some exogenous rate sectors enter into R&D, a move from $n_0$ to $n_1$. Initially the share is low and rising slowly, but as sectors engage in R&D and start succeeding into adopting the new GPT, a move from $n_1$ to $n_2$, the sectors that are drawn into R&D starts to rise more steeply. The share of sectors performing R&D eventually falls again, as more and more sectors succeed in adopting the new GPT, the terminal state. The corresponding time path for output is given in Figure 2. With few sectors performing ('unproductive') R&D output initially falls, with the rise in R&D output falls more steeply, but output eventually rises above its initial level as more and more sectors adopt the new GPT.

The second limitation can be met by enhancing the adoption costs to the new GPT. As outlined in Chapter 8 of Aghion and Howitt (1998) the costs of adoption may go beyond the costs of resources devoted (directly) to R&D. One may envisage reallocation costs of labor, for example costly search by workers moving from firms with the old GPT to sectors with the new GPT. Furthermore, the new GPT may require a different capital stock than the capital stock currently in place, tailor-made for the old GPT. The obsolecence of capital increases the costs of adoption. A calibration with realistic parameter values for osbsolence may generate the observed dramatic initial drop in output.

Aghion and Howitt (1998, Chapter 8) and Aghion (2001) further consider the impact of a new GPT on the wage distribution. They argue that Schumpeterian growth theory can explain the productivity slowdown over recent decades and the wage compression during the 70s and the subsequent rise in the between- and within-dispersion in wages across skill-levels. The adoption to a new GPT (information technology) outperforms the explanations based on trade liberalization, exogenous skill-biased technological change and deunionization.

## Lecture 4 - Competition and economic growth

The basic Schumpeterian model outlined in Lecture 2 predicts that more competition lowers growth. Indeed, one can readily verify that a higher elasticity of demand, an increase in $\alpha$, lowers the profits from an innovation and hence R&D expenditures. However, this

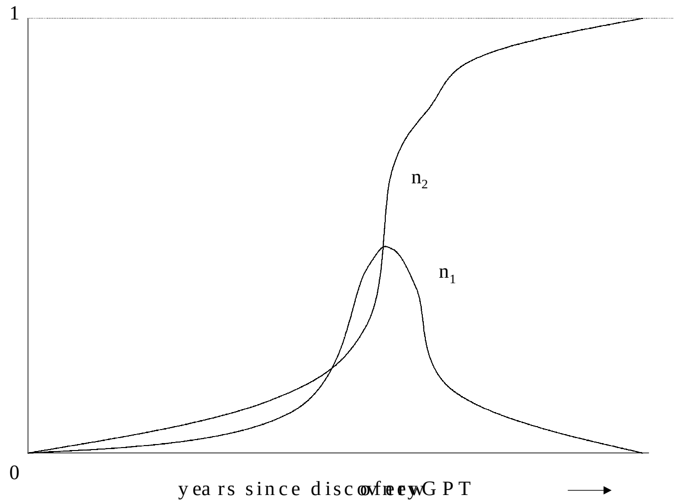


Figure 1: Shares of firms

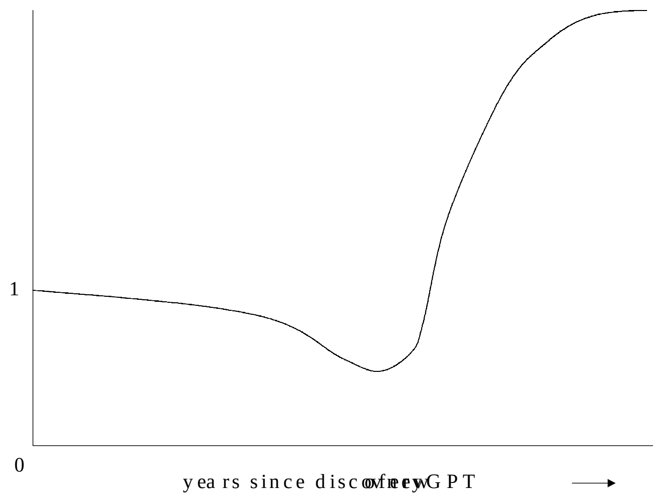


Figure 2: Measured output

seems to be at odds with the data (see e.g. Nickell (1996) and Blundell et al. (1995)). There are several ways to enrich the basic Schumpterian model to create a positive link between competition and economic growth.

First, more competition in the research sector may lead to higher growth. a) An entry cost for all firms to do research will lower the entry into R&D, a lower entry cost will stimulate R&D and hence growth. b) Suppose that R&D is done by a monopolist (asymmetric entry costs). The monopolist has a lower incentive to do R&D because his surplus (profits) rise only by the increment of technology, whereas an outside competitor would capture the increment of the surplus and the old surplus (the Arrow-effect). However, on the other hand the monopolist has a higher incentive to do R&D because an innovation raises the profitability of future R&D (a positive intertemporal spillover). Free entry into R&D may thus raise R&D and hence growth, depending on whether the Arrow-effect dominates the intertemporal spillover effect.[1]

Second, more competition in the product market may lead to higher growth. a) Increased competition may speed up the innovation process when the managers do not maximize profits but control rights (Aghion et al. (1997)). Higher competition increases the risk of being displaced. One way to avoid being displaced is to stay ahead, i.e. speed up the innovation process. b) An increase in the substitutability between old and new product lines will induce workers to move more speedily from the old to the new product line (the Lucas effect, see Aghion and Howitt (1996)). This induces a higher level of research and hence growth. c) Finally, neck-to-neck competition may foster growth (see Aghion and Howitt (1998, Chapter 7) and Aghion et al. (2001)). Following Howitt we consider this case in more detail.

The basic neck-to-neck model considers a sector with two competitors. The main difference with the basic Schumpeterian model is that sectors can be 'leveled' where both competitors have the same technology level, whereas they leapfrog in the basic Schumpeterian model. When a firm makes an innovation the competitor can costlessly acquire the previous technology. Hence, there are two cases to consider. The sector may

[1] It is sometimes argued that the Arrow-effect also exists in competitive markets (e.g. Barro and Sala-i-Martin (1995)). According to the author this is an error. The argument in favor is that an outside competitor captures the surplus of the incumbent and the additional surplus from the innovation, whereas the incumbent captures only the additional surplus from an innovation. However, free entry into R&D implies that total resources into R&D are fixed in equilibrium. Hence, an incumbent with rational expectations will realize that R&D will raise his or her probability of making an innovation and capture the additional surplus, and will reduce the probability that the incumbent loses his current surplus to an outside competitor. Hence, the incentive for R&D is the same for the incumbent and the outside competitor.

be unleveled, with one firm being one step beyond its competitor, or the sector may be leveled, with both firms having the same technology level. Due to the setup of the model both firms have an incentive to innovate when the sector is leveled, whereas the incumbent does not innovate when the sector is unleveled (the level of technology does not affect the level of innovation). Innovation costs are of a quadratic form. Hence, the same innovation rate can be achieved with less resources when both firms engage in R&D relative to the case where only one (the lagging) firm performs R&D. Leveled sectors perform more R&D than unleveled sectors. Higher product market competition lowers R&D expenditures in unleveled sectors (as in the basic Schumpeterian model). However, higher product market competition enhances R&D in leveled sectors. Hence, higher product market competition may stimulate growth. Note that there is an additional caveat as the rates at which sectors become leveled and unleveled are endogenous. Indeed, the model suggests that more product market competition enhances growth when competition is not too intense already. Aghion et al. (2001) further show (in a richer model) that some imitation will raise growth, whereas a lot of imitation reduces growth. Furthermore, the model predicts an important role for the complementarity between patent and anti-trust policies, with the impact of changes in the imitation rate and in product market competition being intimately linked.

## Lecture 5 - Accounting for growth

The final lecture of Howitt dealt with the empirical challenges for Schumpeterian growth models. Mankiw et al. (1992) show that the standard Solow-Swan model seems to do rather well in explaining the cross-country distribution of per capita income growth, and the convergence rates of countries to their steady state growth rate. Furthermore, Jones (1995) shows that per capita growth shows no tendency to rise over a long time horizon, despite the rise in R&D expenditures. Finally, Evans (1996) shows that the developed countries seem to converge to the same growth rates, once again at odds with the basic Schumpeterian model which does not imply convergence. However, Howitt (2000) shows that an adapted Schumpeterian model of endogenous growth can meet these challenges.

First, consider the claim that endogenous growth theory seems to have little to add in explaining the distribution of per capita income growth rates and convergence rates over the Solow-Swan model. Recall from Lecture 1 above that according to the Solow-Swan model we have along the steady state path income per efficiency unit of labor as

$$y = \frac{Y}{AL} = k^{\alpha} = \left(\frac{\delta + n + \gamma}{s}\right)^{\frac{\alpha}{\alpha-1}}.$$

Taking logs, and adding a random error term $\varepsilon_i$ where the index $i$ denotes country $i$, we arrive at the following linear estimation equation of Mankiw et al. (1992)

$$\ln(Y/L)_i = \frac{\alpha}{\alpha - 1}(\ln s_i - \ln(\delta + g_{l,i} + \gamma)) + \ln A + \varepsilon_i, \quad (7)$$

where $g_{l,i}$ denotes the growth in the labor force ($n_i$ denotes resources devoted to R&D by country $i$ in the Schumpeterian model). The variations in labor force growth and savings rates lead to an $R^2 \simeq .75$. Not bad for a cross-section estimation. However, the share of capital in aggregate output (under perfect competition) $\alpha$ seems rather high at $\approx 2/3$. Linearizing the behavior of per capita income around the steady state yields a convergence rate of $(1 - \alpha)(\delta + n_i + \gamma) \simeq .02$, which seems to accord with the data, for the same high value of $\alpha$.

Howitt (2000) presents a hybrid Solow-Swan Aghion-Howitt model of per capita growth. As in the previous two lectures we will present the model in an informal manner. Countries produce output using a range of intermediate goods whose quality can be improved by engaging in R&D. A research success in country $i$ in sector $j$ occurs at rate $\lambda n_{j,i}$. A research success implies that the sector will jump to some exogenous frontier that grows at rate $\gamma$ (at the end of the paper Howitt (2000) shows how the exogenous growth rate of the frontier can be endogenized by assuming $\gamma = \sum_{j=1}^{m} \sigma_j \lambda_j n_j$ where $m$ denotes the number of countries). From this we can deduce that the growth rate of technology in country $i$ is given by $\dot{A}_j(t) = \lambda n_{j,i}(A^{\max}(t) - A_j(t))$ where $A^{\max}(t)$ denotes the technological frontier. The level of R&D depends positively on capital per efficiency unit of labor (R&D is a fraction of output, hence capital enters into R&D) and on any (positive) subsidies to R&D. The capital intensity depends positively on the savings rate, hence R&D depends positively on the savings rate. Following the same steps as before we arrive at the following log-linear specification for per capita income for the adapted Schumpeterian model

$$\ln(Y/L)_i = \frac{\alpha}{\alpha - 1}(\ln s_i - \ln(\delta + g_{l,i} + \gamma)) + \frac{\kappa}{1 - \kappa}\left(\ln\left(\frac{R\&D}{Y}\right)_i + g_{l,i}\right) + \text{constant} + \varepsilon_i, \quad (8)$$

where $\left(\frac{R\&D}{Y}\right)_i$ denotes the R&D intensity in country $i$. Hence, the Schumpeterian model yields an equation for per capita growth similar to the Solow-Swan model, but in addition suggests that R&D has explanatory power in per capita income growth. Lichtenberg (1993) shows that inclusion of the R&D variable reduces the estimate of $\alpha$, the share of capital in income, which is desirable as noted above. Similarly, one may derive a convergence rate from the Schumpeterian model to the steady state level of output per efficiency unit of labor. A similar convergence rate to the Solow-Swan model can be achieved with a lower $\alpha$, which once again seems to favor the Schumpeterian extention to economic growth. Furthermore, whereas the Solow-Swan model is silent on productivity differences across countries, these differences arise naturally in the Schumpeterian model. Indeed, countries that do less R&D will lag more behind the technological frontier than other countries.

The third criticism, Schumpeterian models do not lead to so-called 'club-convergence', i.e. the industrialized countries seem to have converged to the same growth rate, is invalidated in the model outlined above. Indeed, the law-of-motion governing the growth in a countries technology $\dot{A}_j(t) = \lambda n_{j,i}(A^{\max}(t) - A_j(t))$ suggests that the adapted Schumpeterian model does lead to 'club convergence'.

The adapted model can also meet the Jones (1995) criticism. In the adapted model labor force growth leads to an increase in varieties (sectors). However, with the appropriate choice of the aggregate production function (see Aghion and Howitt (1998), Chapter 12) one can counterbalance the implied rise of output by increasing varieties. Indeed, Aghion and Howitt (1998) argue that the gains from specialization do not obviously dominate any increase in complexity and errors that may occur as a result. This puts their model at the opposite extreme of Romer's (1990) expanding varieties model where all growth results from the increase in varieties. Consequently, R&D will rise, but its returns dissipate horizontally by the increase in product variety. The rise in R&D induced by population growth does not affect the growth rate.

Jones (1995) challenged the presence of endogenous growth on empirical grounds. However, Solow (2000) has challenged endogenous growth theory on theoretical grounds. Indeed, endogenous growth models typically need "a Santa Claus assumption to determine the growth rate endogenously." (Solow (2000), p. 105) An innovation in the basic Schumpeterian model raises $A(\tau)$ to $A(\tau+1) = \gamma A(\tau)$, hence every improvement is assumed to lead to an equal proportionate increase in the current technology. This is the Santa Claus assumption. Indeed, when technology improvements are not in proportion to existing technology (for example $A(\tau+1) = A(\tau) + \gamma$) per capita income growth will either fall to zero (as in the example) or explode as time goes to infinity. However, as noted by Howitt during his final lecture, even the Solow-Swan model needs to make a Santa Claus assumption, technological growth can only be purely labor-augmenting for the model to exhibit balanced growth. Hence, the arbitrariness in the technological process is a challenge for both endogenous and exogenous growth theory.

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