GROWTH, DEVELOPMENT AND TECHNOLOGICAL CHANGE

Volker Grossmann
University of Fribourg; CESifo, Munich; Institute for the Study of Labor (IZA), Bonn

Thomas M. Steger
ETH Zurich; CESifo, Munich

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Summary

The theory of endogenous technical change has deeply contributed to our understanding of the fundamental sources of economic growth and development. In this chapter we survey important contributions in the field by focusing on the basic structure of endogenous growth models with horizontal as well as vertical innovation and emphasizing important implications for growth policy. We address issues like the scale effect problem, directed technological change to understand the evolution of wage inequality, long-run divergence between the innovating North and the imitating South due to inappropriate technology in the South, the relationship between trade and growth, competition and R&D, and the role of imperfect capital markets for R&D-based growth.

1. Introduction

Sustained and significant growth in average world per capita income started roughly with the first era of the industrial revolution (Jones, 2005, Section 5). There is little doubt that technological progress through process innovations played the key role in initiating, accelerating, and sustaining economic growth in the modern era (e.g. Mokyr, 2005).

Even according to neoclassical growth theory, long-run growth in income and physical capital per worker is entirely driven by productivity growth (more precisely, by the rate of labor-saving technological progress). Unfortunately, however, neoclassical growth models treat this growth rate as exogenous. They focus on transitional dynamics where the prime engine of income growth per worker is capital accumulation, depending on rates of investment and population growth in addition to the productivity growth rate.
Thereby, neoclassical growth theory predicts falling growth rates within countries over time and convergence between countries, conditional on economic fundamentals. However, as shown in Figure 1, historical evidence points to a relative stability of growth rates for more than a century in the U.S. Moreover, there is long-run divergence in per capita income between major regions in the world. Figure 2 illustrates that economic divergence is not a recent phenomenon but started roughly with the beginning of the modern era, characterized by relatively fast growth in Western countries and slow growth in Africa in the last two centuries. By allowing for accumulation of human capital in the basic model of Solow (1956), Mankiw, Romer and Weil (1992) argue that, using data from the period 1960-85, about 80 percent of the cross-country variation in income can be explained by focusing on the steady state of the augmented Solow-model, through differences in investment rates and the population growth rate. However, they do not address the overwhelming evidence on long-run divergence. Moreover, Bernanke and Gürkaynak (2001) find that, inconsistent with the Solow-model, the long-run growth rate depends on behavioral variables, particularly on the rate of investment of physical capital. From this brief discussion, it is evident that models which endogenize technological change are highly desirable to understand the process of economic development in the long-run. In this survey, we outline in some detail important theoretical approaches in which technological progress is driven by deliberate R&D investments of private agents in response to market incentives. This literature, starting with Romer (1990), rests on the basic premise that intentional innovations require resources spent prior to both production of goods and product market competition.
It thereby abandons the neoclassical paradigm of perfect competition and constant-
returns to scale in the production process, which (as we point out in more detail in
Section 2) runs into the fundamental problem that it leaves no resources for the private
sector to finance the search for innovations. The second premise of endogenous growth
theory is that technological knowledge, in the form of a set of instructions how to
produce goods and services (called “idea”, “blueprint” or “design” in the literature), is a
non-rival good; that is, an innovation can be used by others without diminishing the
knowledge of the innovator. This implies that, without ways to exclude others from
(some of) the newly created knowledge, in a large society no agent would have an
incentive to incur any costs to innovate. (At least this is true when potential innovators
are motivated alone by material benefits which accrue from applying the innovation.)
An innovation would then be a pure public good, which suffers from underprovision
when privately supplied (with zero provision when the number of agents goes to
infinity). Although still under debate from an historical point of view (Khan and
Sokoloff, 2001; Mokyr, 2005), intellectual property rights protection, which emerged in
Britain already in the seventeenth century, may thus play an important role for
stimulating innovations.

In sum, endogenous growth theory captures the notion that knowledge accumulates
through the arrival of new ideas which are an outcome of profit-oriented R&D
investments. By outlining basic approaches of this theory we demonstrate that it
generates a wide range of interesting hypotheses and policy implications.
Our survey is structured into three main parts. In Section 2, we present models where growth is driven by new intermediate inputs (“horizontal innovations”), capturing specialization gains. The section builds on the seminal paper by Romer (1990). One major issue which has arisen from early models of endogenous technical change is the prediction of “scale effects” in growth rates, meaning that economies which possess a larger workforce that is capable to conduct R&D have higher per capita income growth rates. However, this result is inconsistent with the evidence that the U.S. economy is characterized by a fairly balanced (at least clearly non-accelerating) long-run growth path (recall Figure 1) despite large increases in the number of employed scientists and engineers during the second half of the twentieth century (Jones, 1995a,b, 2005). We discuss how Jones (1995a,b) eliminates the prediction of scale effects in growth rates. In his so-called semi-endogenous growth model, positive long-run growth is possible only if there is positive population growth. We then turn to three applications of the basic framework with horizontal innovations. First, following Acemoglu (1998, 2002), we allow for technological change which is directed to various skill types, thereby addressing the widely-discussed evidence on rising skill premia in many developed countries, despite increasing relative supply of skilled labor, in the last few decades. Second, we present a two-economy (“North” and “South”) model, where economies differ in their relative endowment of skilled labor. We show that, although the South can imitate the technology of the innovating North at a small cost, output per worker is larger in the North, due to different factor endowments (Acemoglu and Zilibotti, 2001). Third, we highlight the role of horizontal innovations for the impact of liberalization of goods trade on economic growth (Rivera-Batiz and Romer, 1991). In Section 3, we turn to models of “vertical innovations”, where growth is driven by quality-improvements of intermediate goods. We first present a version of the “creative destruction” model by Aghion and Howitt (1992). As many models of endogenous technical change, in addition to scale effects in growth rates, the model predicts that higher market power is unambiguously conducive to R&D expenditure. As the scale effects prediction, this result is refuted by empirical evidence (e.g. Blundell, Griffith and van Reenen, 1999; Aghion, Bloom, Blundell, Griffith and Howitt, 2005, Aghion, Blundell, Griffith, Howitt and Prantl, 2006). Following Aghion and Howitt (2005), we therefore present a model with vertical innovations which modifies this result and has interesting implications for industrial R&D policy. In Section 4, we allow for horizontal differentiation in a model of vertical innovations, like Peretto (1998) and Young (1998), among others. This class of models eliminates the scale effect in growth rates like semi-endogenous growth models but at the same time allows for positive income growth even in absence of population growth. Finally, we introduce borrowing constraints for financing R&D into this model. The resulting model suggests an important role of credit market imperfections for long-run divergence, as recently emphasized by Aghion, Howitt and Mayer-Foulkes (2005).

2. Horizontal Innovation

The models considered in this section explain economic development to result from the interplay between capital accumulation and endogenous technological change. Private firms engage in R&D which results in new varieties of intermediate (or capital) goods. (In the Grossman-Helpman (1991, chapter 3) model, not considered here, technological change takes the form of new varieties of consumer goods.) Since new intermediate
goods are of the same quality as previously invented goods, technological change here takes the form of horizontal innovations.

2.1. The Romer Model

2.1.1. The Challenge of modeling Technological Change

The neoclassical growth model relies on exogenous technological progress as the ultimate engine of long-run economic growth (Solow, 1956; Swan, 1956). Romer (1990) was the first who formulated an explicit and rigorous growth model with endogenous technical progress. His analysis is based on three premises: (i) economic growth is driven by technological progress as well as capital accumulation; (ii) technological progress results from deliberate actions taken by private agents who respond to market incentives; (iii) technological knowledge is a non-rivalrous input. We will see below how these premises are formalized within the model.

Formulating a general equilibrium model with endogenous technological change, as required by premise (ii) above, is all but trivial. Earlier contributions modeled technical progress as a by-product of capital accumulation (Arrow, 1962; Romer, 1986). The major theoretical difficulty can be sketched as follows. Consider an economy producing a final output good \( Y \) according to the production technology \( Y = F(A,K,L) \), where \( A \) denotes the state of technology, \( K \) the stock of physical capital, \( L \) labor input, and \( F(.) \) is \( C^2 \) with \( \frac{\partial F(.)}{\partial X} > 0 \) and \( \frac{\partial^2 F(.)}{\partial X^2} < 0 \) for all \( X \in \{A,K,L\} \). It is further assumed that \( F(.) \) exhibits constant returns to scale (CRS) in capital and labor, i.e. \( \lambda Y = F(A,\lambda K,\lambda L) \) for any \( \lambda \geq 0 \). Neoclassical theory relies on perfect competition such that all factors are rewarded according to their marginal product. This in turn implies that output is completely exhausted, i.e. \( Y = F_k(.)K + F_L(.)L \) with \( F(.) := \frac{\partial F(.)}{\partial K} \) denoting the marginal product of capital etc. Now it becomes obvious that any theory which rests on perfect competition together with CRS and should fulfill premise (ii) runs into a fundamental problem. Those agents who bring technical change about are assumed to react to market incentives and must therefore be rewarded somehow. Since output is, however, completely used up by paying wages to labor and rental prices to capital owners, nothing is left to reward researchers.

2.1.2. The Structure of the Model

We consider a simplified version of the Romer (1990) model in that there is only one type of labor. (Romer (1990) distinguishes between unskilled labor and skilled labor (human capital). This distinction is, however, not essential for the derived results; it merely relabels the relevant scale variable, as explained below.) The household side is identical to the Ramsey model of optimal growth (see, for instance, Barro and Sala-i-Martin, 2004, chapter 2). On the production side there are three sectors: a final output sector, a producer durables sector, and a research sector.

**Households.** The economy is populated by a continuum of mass one identical households. Each household is endowed with \( L \) units of labor services per unit of time, which are inelastically supplied (independent of the wage rate) to the market.
Households are assumed to choose the time path of consumption \( C(t) \) so as to maximize the present discounted value of an infinite utility stream 
\[
\int_{0}^{\infty} C(t)e^{-\rho t} dt ,
\]
where \( \sigma > 0 \) and \( \rho > 0 \) is the time preference rate. The optimal consumption path obeys the well-known Keynes-Ramsey rule (KRR)
\[
\frac{\dot{C}(t)}{C(t)} = r(t) - \rho ,
\]
where \( \dot{C}(t) := dC(t)/dt \) denotes the rate of change of consumption and \( r(t) \) is the interest rate in \( t \).

**Final output sector.** Firms in the final output sector produce a homogenous good \( Y \) that can be either consumed or used as an input in the production of differentiated capital goods. The market for the final output good is perfectly competitive. The technology is given by (the time index \( t \) is often suppressed to simplify the notation)
\[
Y = \int_{0}^{A} x(i)^\alpha di ,
\]
where \( L_y \) is the amount of labor devoted to \( Y \)-production, \( x(i) \) is the amount of capital good \( i \in [0, A] \), and \( 0 < \alpha < 1 \). In equilibrium \( x(i) = x \) for all \( i \) and hence the above technology can be expressed as \( Y = L_y^{-\alpha} Ax^\alpha \). Moreover, if we define aggregate capital as \( K := Ax \), one may write
\[
Y = (AL_y)^{1-\alpha} K^\alpha .
\]
This formulation shows that Eq. (2) boils down to a Cobb-Douglas technology with labor-augmenting technical change and hence makes an important implication obvious: Even if one holds the total amount of capital \( K = Ax \) constant, an increase in the "number" of varieties \( A \) boosts the productivity of labor. Hence, technology (2) captures the basic idea that specialization, as reflected by an increasing number of intermediate goods \( x(i) \), makes the production process more and more efficient (Smith, 1776, Book I, chapter I; Ethier, 1982; Solow, 2000, chapter 9). Final output is chosen as the numeraire, its price is set equal to unity \( p_y = 1 \).

**Producer durables sector.** Producers in this sector manufacture differentiated capital goods \( x(i) \), also labeled "producer durables" or simply "machines". As a technical and legal prerequisite for production, firms must at first purchase a blueprint (design). Technology (2) implies that the \( x(i) \) are imperfect substitutes in \( Y \)-production; this assumption is crucial for monopolistic competition in the market for producer durables. As regards the production technology for \( x(i) \), it is assumed that it takes one unit of "raw capital" (output not consumed) to create one unit of any type of durables (Romer, 1990, p. S82). This modeling assumption is further explained in Rivera-Batitz and Romer (1991, p. 534): "This does not mean that consumption goods are directly
converted into capital goods. Rather, the inputs needed to produce one unit of consumption are shifted from the production of consumption goods into the production of capital goods. The constant marginal production cost of \( x \) therefore equals the interest rate \( r \). As regards the institutional structure, it is assumed that \( x \)-producers rent their machines to \( Y \)-producers by charging a rental price.

**R&D sector.** Firms in the research sector search for new and economically valuable ideas. An "idea" is a blueprint (design) for a new producer durable. The market for designs is perfectly competitive and characterized by free entry. In the words of Romer (1990, p. S85) "anyone engaged in research can freely take advantage of the entire existing stock of designs in doing research to produce new designs". R&D is modeled as a deterministic process. The R&D technology is given by

\[
\dot{A} = \eta AL, \tag{4}
\]

where \( \dot{A} := dA/dt \) denotes the rate of change in the number of blueprints \( A \) per period of time \( dt \), \( L \) the amount of labor devoted to R&D, and \( \eta > 0 \). Notice that the productivity of researchers \( L \) increases with technological knowledge \( A \); see premise (iii) above.

It should be noted that there is a double knife-edge restriction implicit in this formulation: (i) \( \frac{\partial \ln A}{\partial \ln L} = 1 \) and (ii) \( \frac{\partial \ln A}{\partial \ln Y} = 1 \). The first is needed for sustained growth to be feasible. (For a critical discussion of this linearity assumption see Solow (2000, chapter 9).) The second is required for a consistent microeconomic structure, i.e. a perfectly competitive market requires CRS in the single private input \( L \). It is further assumed that, once a new idea is found, its producer obtains perfect and perpetual patent protection.

Equilibrium in the labor market requires \( L = L_A + L_Y \). Equilibrium in the capital market requires that the household’s financial capital equals the total physical capital employed by final output firms \( K \).

**The long run growth rate.** The final output technology (3) indicates that, along the balanced growth path (BGP), this model is equivalent to a neoclassical growth model with labor-augmenting technical progress. This implies that the following relations must hold along the BGP: \( \dot{Y} = \dot{K} = \dot{C} = \dot{A} = g \), where \( \dot{X} := X/X \) for all \( X \in \{Y, K, C, A\} \). Moreover, the R&D technology (4) implies that the long run growth rate of \( A \) is

\[
\dot{A} = \eta L_A, \tag{4}
\]

where \( L_A^* \) denotes the constant amount of labor devoted to R&D. The economically interesting question then concerns the determination of \( L_A^* \). This is the issue we consider at next.
2.1.3. The Decentralized Solution

To determine the long run growth rate of the market economy we start with the equilibrium condition stating that the wage rate of labor employed in \( Y \)-production (\( w_Y \)) must equal the wage rate of labor employed in R&D (\( w_{R&D} \)). The competitive wage rates in both sectors equal the respective value marginal product of labor. From (2) and (4) one therefore gets

\[
w_Y = (1 - \alpha) L_Y^{-\alpha} A x^\alpha
\]
\[
w_{R&D} = p_A \eta A
\]

where \( p_A \) is the price of a blueprint. Operating profits of the typical \( x \)-producer are

\[
\pi = (p_D(x) - r)x \quad \text{with} \quad p_D(x) \quad \text{denoting the demand price (or inverse demand function)}
\]

of \( x \), which is given by

\[
p_D(x) = \alpha L_Y^{1-\alpha} x^{\alpha - 1}.
\]

The typical \( x \)-producer faces constant marginal cost, equal to \( r \), and a constant elasticity demand curve with a price elasticity equal to \( \frac{1}{\alpha - 1} < -1 \). It is well known that, in this case, the optimal supply price is a mark-up over marginal cost according to \( p_R = \frac{z}{\alpha} \). Moreover, using \( r = \alpha p_S \) we have \( \pi = (p_D - \alpha p_S)x \). From equilibrium in the \( x \)-market, \( p_D = p_S = p \), and plugging (5) into the profit function one gets

\[
\pi = (1 - \alpha) px = (1 - \alpha) \alpha L_Y^{1-\alpha} x^\alpha.
\]

Assuming that the economy grows along a BGP, which implies that both \( \pi \) and \( r \) are constant, the price of a blueprint may be expressed as \( p_A = \frac{\pi}{\alpha} \). Hence, the price of a blueprint may be written as \( p_A = (1 - \alpha) L_Y^{1-\alpha} x^\alpha \). Now evaluating the equilibrium condition \( w_Y = w_{R&D} \) yields

\[
(1 - \alpha) L_Y^{-\alpha} A x^\alpha = \frac{\eta A (1 - \alpha) L_Y^{1-\alpha} x^\alpha}{r},
\]

which immediately gives \( r = \eta \alpha L_Y \). (the preceding condition can be expressed as \( \frac{z}{\alpha} = \frac{\pi}{\eta A} \) and hence is equivalent to the free entry condition, implying zero profits, in the R&D sector. To see this, note that under (4), profits are given by \( P_A \eta A L_A - w_A \) and use \( P_A = \frac{z}{\eta} \).) Plugging \( L_Y = L - L_A \) (labor market equilibrium) and \( L_A = \frac{z}{\eta} \) (from (4)) into the preceding equation leads to a condition describing equilibrium on the supply side of the economy.
\[ r = \eta a L - \alpha g. \]  

(6)

The economic reason for the negative relationship between \( r \) and \( g \) is that an increase in \( r \) lowers \( \frac{p_L}{r} \) and therefore R&D firms employ a lower amount of labor. Equilibrium on the demand side is described by the KRR, Eq. (1), which may be expressed as

\[ r = \sigma g + \rho. \]  

(7)

The positive association between \( r \) and \( g \) captures the fact that an increase in \( r \) motivates households to save more which boost growth. Solving (6) and (7) for \( g \) yields \( g = \frac{\eta a L - \rho}{\sigma + \alpha} \). (One can equivalently solve (6) and (7) for \( r \) and then evaluate \( r = \eta a (L - L_g) \), which gives \( L_g \). Plugging the result into \( g = \frac{\eta a L - \rho}{\sigma + \alpha} \) yields, of course, the same solution.) Since growth cannot become negative in this model, the long run growth rate of the market economy, denoted \( g_M \), reads

\[ g_M = \begin{cases} \frac{\eta a L - \rho}{\sigma + \alpha} & \text{for } \eta a L > \rho, \\ 0 & \text{for } \eta a L \leq \rho. \end{cases} \]  

(8)

Long run growth obviously requires that the economy is large enough in the sense that \( \eta a L > \rho \). Moreover, the preceding solution shows a scale effect since, provided that \( \eta a L > \rho \), larger economies (with size being measured by \( L \)) do grow at a higher rate. The economic reason for this scale effect implication is that, along the BGP, a constant fraction of the labor force is devoted to R&D. More researchers produce more knowledge, which in turn improves the productivity of the R&D sector such that long run growth accelerates. This effect does, however, depend critically on the strength of the intertemporal knowledge spillover, as will be discussed below.

### 2.1.4. Market Imperfections and Policy Implications

So far we have focused on the decentralized economy. Turning to the social planner’s solution, it can be readily shown that the optimal long run growth rate, \( g_S \), is given by (Chiang, 1992)

\[ g_S = \begin{cases} \frac{\eta L - \rho}{\sigma} & \text{for } \eta L > \rho, \\ 0 & \text{for } \eta L \leq \rho. \end{cases} \]  

(9)

Comparing this result to (8) shows that \( g_M < g_S \). The market economy grows at a pace which is too low compared to the social optimum. This is due to two imperfections inherent in the market economy, which bias the private allocation decisions (Jones and Williams, 2000; Steger, 2005): First, the R&D technology (4) exhibits an intertemporal
knowledge spill-over since the productivity of current researcher $L_d$ increases with the stock of knowledge, as measured by $A$, which has been accumulated in the past. This social benefit is not reflected in the market price for designs $p_d = \pi$ and, consequently, R&D incentives are too low. Second, the typical producer durable firm realizes a monopoly profit by selling a differentiated capital good. It cannot, however, appropriate the entire "consumer surplus". The gain to society resulting from a new innovation is larger than the private profits earned by the monopolist. This static distortion leads once more to a price of blueprints which falls short of its social value. Hence, the Romer (1990) model unambiguously exhibits underinvestment in R&D. (There are other R&D-based growth models with positive and negative R&D externalities such that the amount of resources devoted to R&D might be too high in the market equilibrium (Jones and Williams, 2000; Steger, 2005). Also horizontal innovation models do not capture another important externality associated with private R&D, namely the business stealing effect; see Section 3 of this article.) This basic implication is in line with empirical studies on the gap between the private and the social rate of return on R&D. Griliches (1991) reviews this literature and reports social rates of return of about 40 to 60 percent, which are much higher than private rates of return.

What are appropriate public policies to correct these market failures? One possible scheme of public policies is as follows. The positive knowledge spill-over can be neutralized by a subsidy on the sales of blueprints. The "consumer surplus" effect can be corrected by subsidizing the sales of producer durables (Steger, 2005, Section II).

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Biographical Sketches

Volker Grossmann studied Economics at the University of Bonn and received his Ph.D. from the University of Regensburg (both Germany). Subsequently, he was assistant professor (Oberassistent) at the University of Zurich (Switzerland). Currently, he holds a chair for Macroeconomics at the University of Fribourg (Switzerland). He is also research fellow at the Institute for the Study of Labor, Bonn (Germany) and research affiliate at CESeifo, Munich (Germany). His major fields of research comprise Growth Economics, Development Economics, International Economics, and Public Economics. He has published in journals such as Journal of Economic Growth, Journal of Macroeconomics, International Journal of Industrial Organization, Journal of Economic Psychology, European Journal of Political Economy and Oxford Economic Papers.

Thomas M. Steger studied Economics at the University of Giessen and received his Ph.D. from the University of Siegen (both Germany). During 2000/01 he gained experiences in the commercial banking sector. Subsequently, he was senior research fellow (wissenschaftlicher Assistent) at the University of Greifswald (Germany) and visiting researcher and lecturer at Tilburg University (Netherlands) and University of Washington (Seattle, USA). Since January 2003, he is assistant professor (Oberassistent) at the Center of Economic Research at ETH Zurich (Switzerland). He is also research affiliate at CESeifo, Munich (Germany). His major fields of research comprise Dynamic Macroeconomics, Growth Theory & Growth Empirics, International Economics, and Development Economics. He has published in journals such as Journal of Economic Dynamics and Control, Macroeconomic Dynamics, Scandinavian Journal of Economics, Journal of Development Economics, Economics Letters, and German Economic Review.