# GROWTH, DEVELOPMENT AND TECHNOLOGICAL CHANGE

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## Contents



## 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.

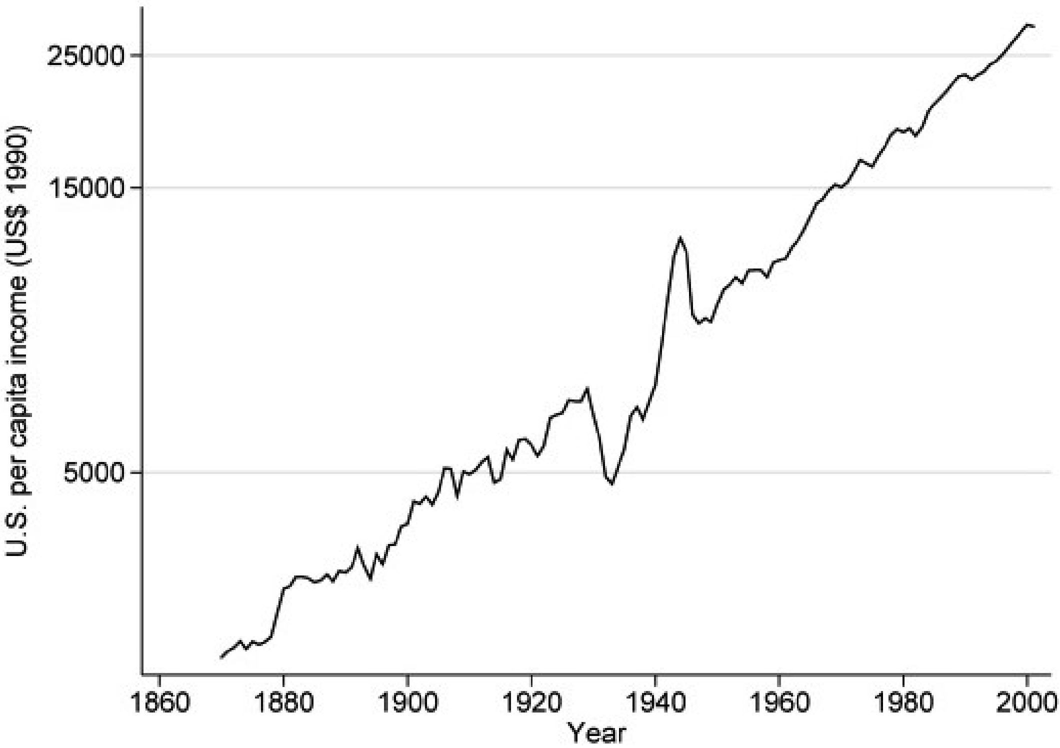


Figure 1: U.S. per capita GDP (log scale), 1870-2001. Note: Data from Maddison (2003).

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.

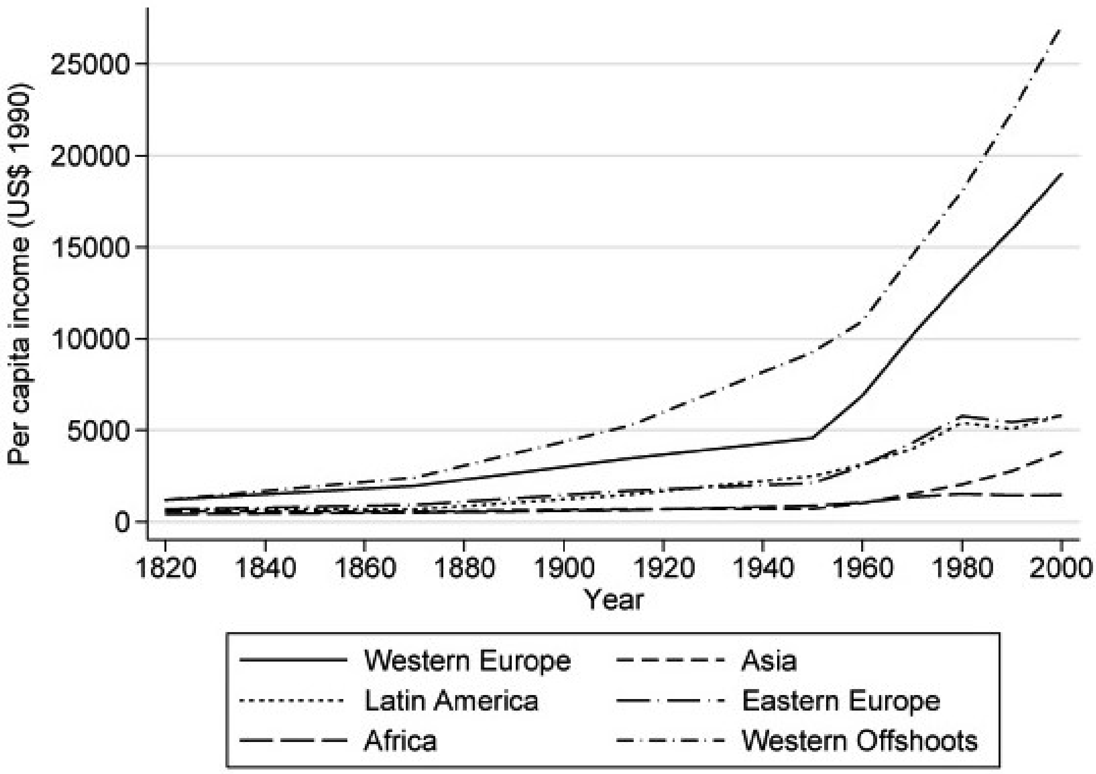


Figure 2: Divergence in per capita income, 1820-2001. Note: Data from Maddison (2003).

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 $F_K(.) := \frac{\partial F(.)}{\partial K}$ 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 $\int_0^\infty \frac{C(t)^{1-\sigma}-1}{1-\sigma} e^{-\rho t} dt$, where $\sigma > 0$ and $\rho > 0$ is the time preference rate. The optimal consumption path obeys the well-known Keynes-Ramsey rule (KRR)

$$\frac{\dot{C}(t)}{C(t)} = \frac{r(t) - \rho}{\sigma}, \qquad (1)$$

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)

$$Y = L_Y^{1-\alpha} \int_0^A x(i)^\alpha di, \qquad (2)$$

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 $Y = L_Y^{1-\alpha} A x^\alpha$. Moreover, if we define aggregate capital as $K := Ax$, one may write

$$Y = (AL_Y)^{1-\alpha} K^\alpha. \qquad (3)$$

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

$$\dot{A} = \eta A L_A, \qquad (4)$$

where $\dot{A} := dA/dt$ denotes the rate of change in the number of blueprints $A$ per period of time $dt$, $L_A$ the amount of labor devoted to R&D, and $\eta > 0$. Notice that the productivity of researchers $L_A$ 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) $\frac{\partial \ln \dot{A}}{\partial \ln A} = 1$ and (ii) $\frac{\partial \ln \dot{A}}{\partial \ln L_A} = 1$. 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 $L_A$. 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: $\hat{Y} = \hat{K} = \hat{C} = \hat{A} = g$, where $\hat{X} := \dot{X}/X$ for all $X \in \{Y, K, C, A\}$. Moreover, the R&D technology (4) implies that the long run growth rate of $A$ is

$$\hat{A} = \eta L_A^*,$$

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 ($w_{\text{R\&D}}$). The competitive wage rates in both sectors equal the respective value marginal product of labor. From (2) and (4) one therefore gets

$$w_Y = (1-\alpha) L_Y^{-\alpha} A x^{\alpha}$$

$$w_{\text{R\&D}} = p_A \eta A,$$

where $p_A$ is the price of a blueprint. Operating profits of the typical $x$-producer are $\pi = (p_{\text{D}}(x) - r)x$ with $p_{\text{D}}(x)$ denoting the demand price (or inverse demand function) of $x$, which is given by

$$p_{\text{D}}(x) = \alpha L_Y^{1-\alpha} x^{\alpha-1}. \qquad (5)$$

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 $p_{\text{S}} = \frac{r}{\alpha}$. Moreover, using $r = \alpha p_S$ we have $\pi = (p_{\text{D}} - \alpha p_{\text{S}})x$. From equilibrium in the $x$-market, $p_{\text{D}} = p_{\text{S}} = p$, 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 $p_A = \frac{\pi}{r}$. Hence, the price of a blueprint may be written as $p_A = \frac{(1-\alpha)\alpha L_Y^{1-\alpha} x^{\alpha}}{r}$. Now evaluating the equilibrium condition $w_Y = w_{\text{R\&D}}$ yields

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

which immediately gives $r = \eta \alpha L_Y$. (the preceding condition can be expressed as $\frac{\pi}{r} = \frac{w}{\eta A}$ 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 $P_A \eta A L_A - w L_A$ and use $P_A = \frac{\pi}{r}$.) Plugging $L_Y = L - L_A$ (labor market equilibrium) and $L_A = \frac{g}{\eta}$ (from (4)) into the preceding equation leads to a condition describing equilibrium on the supply side of the economy

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**Bibliography**

Acemoglu, D. (1998). Why do new technologies complement skills? Directed technical change and wage inequality, Quarterly Journal of Economics 113, 1055-1090. [The seminal contribution on directed technical change with a focus on the evolution of the skill premium]

Acemoglu, Daron (2002). Directed technical change, Review of Economic Studies 69, 781-809. [A synthesis of the directed-technical-change approach with a discussion of different applications]

Acemoglu, D. and F. Zilibotti (2001). Productivity differences, Quarterly Journal of Economics 116, 563-606. [This paper represents an important application of the directed-technical-change approach to the phenomenon of persistent underdevelopment]

Aghion, P., G.-M. Angeletos, A. Banerjee and K. Manova (2005). Volatility and growth: Credit constraints and productivity-enhancing investment, Harvard University (mimeo). [An attempt to build a bridge between macroeconomic fluctuations and economic growth]

Aghion, P., N. Bloom, R. Blundell, R. Griffith and P. Howitt (2005). Competition and innovation: An inverted U relationship, Quarterly Journal of Economics 120, 701-728. [Theory and evidence on the relationship between R&D activity and the degree of product market competition]

Aghion, P., R. Blundell, R. Griffith, P. Howitt and S. Prantl (2006). The effects of entry on incumbent innovation and productivity, NBER Working Paper No. 12027. [Theory and evidence on the relationship between R&D activity and the entry regulations]

Aghion, P., D. Comin and P. Howitt (2006). When does domestic saving matter for economic growth?, Harvard University (mimeo). [Theory and evidence on the link between savings and innovations]

Aghion, P. and Howitt, P. (1992). A model of growth through creative destruction, Econometrica, 60, 323-352. [A seminal paper in endogenous growth theory with vertical innovations]

Aghion, P. and Howitt, P. (1998). Endogenous Growth Theory, MIT Press, Cambridge (Ma.). [A book on endogenous growth theory which provides many applications of the creative-destruction model]

Aghion, P. and Howitt, P. (2005). Growth with quality-improving innovations: An integrated framework, in: P. Aghion and S. Durlauf (eds.), Handbook of Economic Growth, North-Holland, Amsterdam. [A survey chapter on theory and evidence of endogenous growth theory with vertical innovations]

Aghion, P., P. Howitt and D. Mayer-Foulkes (2005). The effect of financial development on convergence: theory and evidence, Quarterly Journal of Economics 120, 173-222. [Links differential evolution in per capita income of countries to different degree of credit market imperfections]

Arrow, K.J. (1962). The economic implications of learning by doing, Review of Economic Studies 29, 155-173. [One of the first contributions to endogenous growth theory, where technical progress is modeled as a side effect of capital accumulation]

Backus, D., K., P. J. Kehoe, and T. J. Kehoe (1992). In search of scale effects in trade and growth, Journal of Economic Theory 58, 377-409. [This paper discusses the different mechanisms behind scale effects and provides a comprehensive empirical analysis]

Barro, R. J. and X. Sala-i-Martin (2004). Economic Growth, MIT Press, Cambridge (Ma.). [A comprehensive and technically advanced textbook on economic growth]

Bernanke, B.S and R.S. Gürkaynak (2001). Is growth exogenous? Taking Mankiw, Romer, and Weil seriously, NBER Macroeconomics Annual. [Discusses predictions of neoclassical growth theory in light of empirical evidence]

Blundell, R., R. Griffith and J. van Reenen (1999). Market share, market value and innovation in a panel of British manufacturing firms, Review of Economic Studies 66, 529-554. [Important empirical contribution on the relationship between the degree of product market competition and innovations of firms]

Caselli, F. (2005). Accounting for cross-country income differences, in: P. Aghion and S. Durlauf (eds.), Handbook of Economic Growth, North-Holland, Amsterdam. [An accessible and in-depth survey of the basic concept of development accounting and the main results of the empirical research]

Chiang, A.C. (1992). Elements of Dynamic Optimization, McGraw Hill, New York. [This textbook represents the perfect starting point for economists and economics students who start to learn the methods of dynamic optimization]

Cohen, W.M. and S. Klepper (1996a). A reprise of firm size and R&D, Economic Journal 106, 925-951.

[Empirical study on the link between size of firms and their R&D activity]

Cohen, W.M. and S. Klepper (1996b). Firm size and the nature of innovation within industries: The case of process and product R&D, Review of Economics and Statistics 78, 232-243. [Empirical study on the link between size of firms and different kinds of R&D activity]

Cohen, W.M. and R.C. Levin (1989). Empirical studies of innovation and market structure, in: Schmalensee, R., Willig, R. D. (eds.), Handbook of Industrial Organization, Vol. II, North-Holland, Amsterdam, ch. 18. [Survey chapter on the link between market structure and innovation]

Devereux, M.B., Lapham, B.J. (1994). The stability of economic integration and endogenous growth, Quarterly Journal of Economics 109, 299–305. [An important extension of the Rivera-Batiz and Romer (1991) model to trade among asymmetric economies]

Dixit, A. and J.E. Stiglitz (1977). Monopolistic Competition and Optimum Product Diversity, American Economic Review 67, 297-308. [A seminal contribution on the modeling of imperfect product market competition in general equilibrium models]

Eicher, T.S. (1996). Interaction between endogenous human capital and technological change, Review of Economic Studies 63, 127-44. [Studies the interplay of two fundamental sources of growth, human capital and R&D]

Eicher, T.S. and C. Garcia-Penalosa (2006). Endogenous strength of intellectual property rights: Implications for economic development and growth, University of Washington (mimeo). [Addresses the sources of different intellectual property rights across countries and their impact on the process of development]

Eicher, T.S. and S.J. Turnovsky (1999), Non-scale models of economic growth, Economic Journal 109, 394–415. [This paper provides a thorough discussion of non-scale growth models and shows that, in general, the long run growth rate is determined by the technologies of the engine-of-growth sector and the final output sector]

Ethier, W.J. (1982). National and international returns to scale in the modern theory of international trade, American Economic Review 72, 389-405. [This paper shows how the basic idea of gains of specialization can be modeled by applying the Dixit-Stiglitz setup to the production sphere]

Föllmi, R. and J. Zweimüller (2006). Income distribution and demand-induced innovations, Review of Economic Studies 73, 941-960. [Proposes a mechanism how the income distribution affects the demand for new goods and therefore for R&D-driven economic growth]

Gancia, G. and F. Zilibotti (2005). Horizontal Innovation in the Theory of Growth and Development, in: P. Aghion and S. Durlauf (eds.), Handbook of Economic Growth, North-Holland, Amsterdam. [An in-depth and comprehensive survey of macroeconomic models with horizontal innovation]

Griliches, Z. (1991). The search for R&D spill-overs, Scandinavian Journal of Economics 94, 29-47. [This paper reviews the basic model of R&D spillovers and then focuses on the empirical evidence for their existence and magnitude]

Grossman, G. and E. Helpman (1991). Innovation and Growth in the Global Economy, MIT Press, Cambridge (Ma.). [An important book on endogenous growth theory, which first sets up the so-called Grossman-Helpman growth model and then applies this model to analyze growth in the open economy]

Grossmann, V. (2007a). Advertising, in-house R&D, and growth, Oxford Economic Papers, forthcoming. [Argues that even combative advertising may positively affect R&D activity and social welfare through its interactions with firm size]

Grossmann, V. (2007b). How to promote R&D-based growth? Public education expenditure on scientists and engineers versus R&D-subsidies, Journal of Macroeconomics, forthcoming. [Shows that education policy may be superior to R&D subsidies when innovative activity requires specific skills and education is publicly financed]

Hornstein, A., P. Krusell, and G. Violante (2005). The effects of technical change on labor market inequalities, in: P. Aghion and S. Durlauf (eds.), Handbook of Economic Growth, North-Holland, Amsterdam. [A thorough survey of the economic mechanisms through which technological progress shapes the degree of inequality among workers in the labor market]

Jones, C.I.. (1995a). R&D-based models of economic growth, Journal of Political Economy 103, 759–784. [In this paper the author points to the fact that the so-called scale effect is empirically problematic and subsequently modifies the Romer model to eliminate the scale effect]

Jones, C.I. (1995b). Time series tests of endogenous growth models, Quarterly Journal of Economics 110, 495-525. [This paper provides time series evidence against the scale effect for a number of industrialized economies]

Jones, C.I. (1999). Growth: with or without scale effects?, American Economic Review 89, 139-44. [Provides a review of the literature on idea-based models and scale effects and presents various recent idea-based growth models and analyzes their implications for the relationship between scale and growth]

Jones, C.I. (2002). Sources of U.S. economic growth in a world of ideas, American Economic Review 92, 220-239. [Argues that economic growth in the U.S.A. during the post-WWII period is probably a transitional phenomenon with the implication of declining growth in the near future]

Jones, C.I. (2005). Growth and ideas, in: P. Aghion and S. Durlauf (eds.), Handbook of Economic Growth, North-Holland, Amsterdam. [A comprehensive survey on R&D-based growth with special emphasis on horizontal innovation models]

Jones, C. I. and Williams, J. C. (2000), Too much of a good thing? The economics of investment in R&D, Journal of Economic Growth 5, 65–85. [Based on a comprehensive macroeconomic R&D-based growth model the authors investigate whether the market economy is likely to conduct too much or too little R&D]

Khan, B.Z. and K.I. Sokoloff (2001). The early development of intellectual property rights institutions in the United States, Journal of Economic Perspectives 15, 1-15. [Discusses the role of intellectual property rights for innovations from a historical perspective in the U.S.]

Kremer, M. (1993). Population growth and technological change: One million B.C. to 1990, Quarterly Journal of Economics 108, 681-716. [Discusses the plausibility of scale effects in the very long run perspective]

Lainez, C.A. and P.F. Peretto (2006). Scale effects in endogenous growth theory: an error of aggregation not specification, Journal of Economic Growth 11, 263-288. [Provides evidence in support of models with both horizontal and vertical differentiation which remove scale effects in growth rates]

Maddison, A. (2003). The World Economy: Historical Statistics, OECD, Paris. [A comprehensive data set on time series for long run GDP per capita and a broad sample of countries]

Mankiw, N.G., D. Romer and D.N. Weil (1992). A contribution to the empirics of economic growth, Quarterly Journal of Economics 107, 407-437. [A classical paper which argues that the Solow model, extended by human capital accumulation, can account for a large share in international per capita income differences]

Mokyr, J. (2005). Long-term economic growth and the history of technology, in: Aghion, P. and S.N. Durlauf (eds.), Handbook of Economic Growth, North-Holland, Amsterdam. [A comprehensive discussion of the sources of the industrial revolution]

OECD (1999). Science, Technology and Industry Scoreboard 1999: Benchmarking Knowledge-based Economies, Paris. [Collection of data on sources and expenditures on innovation activity]

Rivera-Batiz, L.A. and P.M. Romer (1991). Economic integration and endogenous growth, Quarterly Journal of Economics 106, 531-555. [In this paper the basic Romer (1990) model is used to investigate the consequences of economic integration among symmetric economies]

Romer, P.M. (1986). Increasing returns and long-run growth, Journal of Political Economy 94, 1002-1037. [This paper models economic growth to result from knowledge spill overs due to capital accumulation]

Romer, P.M. (1990). Endogenous technological change, Journal of Political Economy 98, 71-101. [This is the first paper which formulates an explicit and rigorous growth model with endogenous technical progress]

Schumpeter, J.A. (1942). Capitalism, Socialism and Democracy, reprinted 1994, Routledge, London. [Seminal book on the economic of technological change]

Smith, A. (1776). An Inquiry into the Nature and Causes of the Wealth of Nations, Fifth edition (1789), republished from: Edwin Cannan's annotated edition, 1904, Methuen & Co., Ltd. First edition: 1776. [In this truly classical book Smith has not only discussed a number of fundamental economic questions but has also established "economics" as a scientific discipline]

Solow, R.M. (1956). A contribution to the theory of economic growth, Quarterly Journal of Economics 70, 65-94. [In this classical paper, Solow sets up the neoclassical growth model, which has since then been labeled the Solow growth model]

Solow, R.M. (2000). Growth Theory: An Exposition, Oxford University Press, Oxford. [A concise and extremely valuable summary of the main contributions to old and new growth theory]

Steger, T. M. (2005). Welfare implications of non-scale R&D-based growth models, Scandinavian Journal of Economics 107, 737–757. [Using a comprehensive two-sector R&D-based growth model this paper investigates whether the market economy is likely to invest too many or too little resources in capital accumulation and R&D]

Swan, T. (1956). Economic growth with capital accumulation, Economic Record 32, 344-361. [Simultaneously with Solow (1956) Swan formulated the principles of neoclassical growth theory and hence the neoclassical growth model is sometimes labeled the Solow-Swan model]

Young, A. (1998) Growth without scale effects, Journal of Political Economy 106, 41-63. [Representative for a class of models without scale effects in growth rates due to horizontal and vertical differentiation of goods]

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