A Survey on Modeling Economic Growth
With Special Interest on Natural Resource Use

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Abstract

The purpose of this paper is to survey the contributions to economic growth theory. We focus on the basic models and literature that link resource economic and economic growth, in order to reveal the main differences on how the different aspects are incorporated into growth models. As economic science is not a hard science, all economic activities must always be considered against the background of the economy, the political and social institutions, and technical capabilities at that time (as already mentioned by Solow (1985), p. 328). That is why many of the first growth models, fitted to contemporary state, when they were developed, are not transferable to remote periods. Furthermore, natural resources as input factors, which influence economic growth, were neglected for a long time, whereas today they are one of the most discussed factors influencing economic growth.

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1 Why is Growth so Important?

There are 215 countries in the world, whose GDPs (gross domestic product) are growing at different rates. Even small differences in the growth rates lead to enormous differences in real terms, if running with the same start value (after 100 years, a growth rate of 0.7 percent leads to twice the starting GDP, a rate of 1.7 percent leads to an increment of 5.4 times). Some countries, like Qatar and Paraguay, are growing rapidly with an inflation adjusted increase of the GDP of about 15 percent a year, some are not growing at all, others, like Puerto Rico, Anguilla and San Marino, are even dwindling by more than five percent a year (cf. CIA - Central Intelligence Agency (2010)). The GDP does not represent in full the real state of the individual welfare of people living in those countries, but it is one of the best ways to compare countries quantitatively. The income per person is a useful index, highly correlated to quality of life. According to the scientific approach it may be reasonable to add further indicators, e.g. public welfare or working lifetime.

But why do growth rates differ ever so much? Every country has a different starting point. The supply of labor, the stock of resources, capital and human capital, the level of infrastructure, and the climate conditions are some of the main aspects influencing the development of countries. Further aspects affecting the process of growth are the political and institutional environment, the volume of international trade and the current GDP. Growth models try to capture these facts to show the relationships and the development of the variables. They try to reveal how decisions made by economic agents, the value of the variables in the past, present and future, as well as specific implications affect the growth rates.

Studies in economic growth want to make a contribution to solutions on economic-political problems. So it is important to keep in mind the implications, the adequacy to the purpose and the suitability of instruments. Even similar problems often need specific methods, and even the same problem cannot be solved in the same way in each country because in a specific situation there are a lot of interdependencies between different political issues.

Generally in political and public discussions only a growth rate above two percent is regarded as sufficient; in some countries a satisfying growth rate is even claimed by law, e.g. Germany (cf. Bundesministerium der Justiz (1967) paragraph 1). This is accounted for by the general definition of growth. Growth is understood as a sustained extension of good-production, so that the average household may use more products and achieve a greater level of satisfaction and happiness. The importance of a growth rate not only greater than zero, but even larger, is determined by the fact that the growth rate must be higher than the inflation rate to achieve this goal.

Alongside of the direct goal of economic growth, there are more indirect goals of economic policies, seeing economic growth only as a means to an end (cf. Meyer et al. (1998) pp. 1-2). While technical improvement leads to higher average labor productivity, the employment rate can only be kept constant or be raised if more goods can be distributed. Another goal, a fairer income distribution, is usually more easily achievable if there is additional income as basis for the reallocation.

In addition, growth has to be evaluated. It influences many fields that often are not directly included in economic questions. It is relevant which impact it has on the individual utility and on the society. The positive effects have to be balanced with the cost of growth, like, for example, environmental destruction or less leisure time. Keeping in mind that we are dealing with production functions, which include the development of resources, it must be guaranteed that not only one generation benefits from economic growth, but that it is long lasting and sustainable. Especially, the exhaustion of non-renewable resources must be taken into account. Here technical progress and a substitution progress are important to keep on the economy growing.

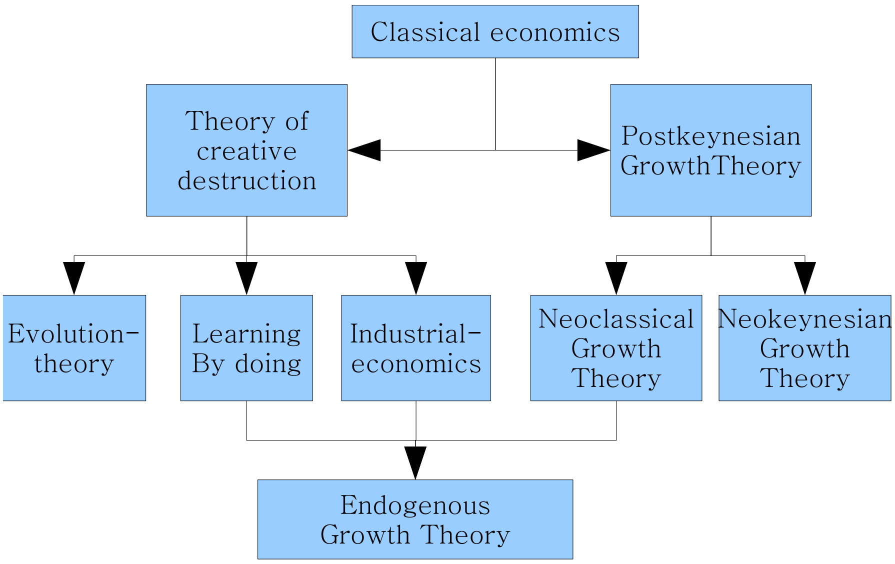

Fig. 1: Evolution of the new growth theory (cf. Bretschger (2004) p. 8)

The purpose of this paper is to give an overview of the main influences and contributions to the theory of economic growth. There are already quite a lot of reviews, overviews and surveys dealing with economic growth. They mostly concentrate on special topics or aspects. The growth theory from Harrod to Neumann is already summarized quite detailed by Hahn and Matthews (1964), the endogenous growth theory with all its aspects by Aghion and Howitt (1998), who even introduce new ideas. Of course, many textbooks recapitulate the main aspects of economic growth as well (e.g. Barro and Sala-i Martin (1995) or Bretschger (2004)). Additionally, Rogers (2003) gives a really short overview on the standard models (neo-classic and endogenous growth) and skims further fundamental factors determining societies, like institutions, geography and international openness. He underlies his arguments by a summary of empirical evidence (cf. Rogers (2003) pp.

122-128). Rostow (1959) looks on economic growth from a different perspecitve. In his review he concentrates on the stages of growth in a describing non-theoretical context, depending on the different stages of the development of societies (cf. Rostow (1959) p. 1).

The main aim of the paper is to show how the different schools of economic build on one another and influence todays dealing with economic growth and its presentation in theoretical literature (see Fig. 1). This survey is arranged in five main sections and proceeds as follows. At first, a short historical overview of the theory of growth is given. We discuss the historical background of growth theory, followed by the main basic theories of economic growth. In a further section the fundamentals of endogenous growth theory are discussed. Section five introduces factors influencing economic growth, thereby concentrating on resources and the differences in research design. We conclude by giving an outlook on further research requirement.

2 Some Background of Growth Models

We start with the classical economists of the 18th and 19th century, who made important discoveries in their grand theories, building the basis of further research. Influenced by this, Schumpeter made a first step to a new field of research by his theory of creative destruction, and coevally the idea of accelerators and multiplicators was introduced.

2.1 Fundamentals of Growth Theory

The Tableau économique, educed by **François Quesney** (1694-1774), can be interpreted as first growth model (later translated edition, see Quesney (1965)). Quesnay states that only land is net-productive; the land lords will invest all their income (production Y less consumption C). Assuming constant prices, the amount of goods produced depends only on the consumption rate c, and therefore, determines whether production grows, declines or is stationary (formally written $g = 0.5\,(c - 0.5) - 2/3\,(c - 0.5)^2$, see Eltis (1975) p. 333).

The classical economics, replacing the physiocratic body of thought, included in their grand theories many aspects which were later used as science base of the first attempts to describe long-run economic growth in more detail. The main aspects of these grand theories relevant for economic growth will be described shortly in the style of current formal models. As a basis of the classical economics Adam Smith's "An Inquiry into the Nature and Causes of the Wealth of Nations" (Smith (1776)) can be seen. Most principals are mentioned there, even though there are still many discrepancies between the different elements of his book (cf. Stavenhagen (1969) pp. 52 ff.).

Adam Smith (1723-1790) concentrates mainly on the definition of wealth, how it arises and why it grows. In contrast to the physiocrates, he points out that the labor performed by the nation is the source of wealth and not the agricultural, primary production. The efficiency of labor depends on the division of labor, and the division of labor needs functioning markets. Smith's production function may read roughly like this: $Y = Y(K, L, T)$ where T is usable land with $T \leq T_{max}$ (see Meyer et al. (1998) pp. 52 et seqq.). As long as there is a lot of usable land uncultivated, the enlargement of the production is determined by the capital accumulation and population growth. If at the same time the division of labor is growing, the returns to scale are growing, too. The closer the economy reaches the limit of population growth (N_{max}), depending on the natural endowment of the economy (land, climate, etc.), and has reached a high level of labor division, the more the returns to scale decrease. In the long-run, economies, following Smith, reach a steady state.

In the different editions of "An Essay on the Principle of Population" **Thomas Robert Malthus** (1766-1834) mainly develops a population theory, where the population growth (geometric series $n_{t+1} = n_t \cdot 2$) is always stronger than the growth of food production (arithmetic series $y_{t+1} = y_t + 1$) (see Malthus (1798), chapter 2). Therefore, there is a limit to population growth, even under the condition of technological progress. Savings, and consequently, waiver of consumption were the determining factors for economic growth. But there was the risk of a lack of demand, which would induce a negative cycle. In summary, Malthus puts forward the assumption that there is a stationary final state without growth, when the optimal size of population is reached. But this state would only be achieved after a long period of time.

A further important classical economist is **David Ricardo** (1772-1823). In his studies, compiled in "On the Principles of Political Economy and Taxation" (Ricardo (1821)), he mainly dealt with the allocation of income between capital, labor and land (cf. Eltis (1989) p. 202). As long as only fertile soils are used, the tenants achieve a higher rent (for capital). Those profits are normally invested in production, more land can be cultivated, more workforce employed. At some point in time, the less fertile pieces of land have to be used by the tenants to enlarge the production. At this time, the tenants' profits are reduced because they have to pay a higher rent for the best soils to the landowners. As long as they receive a bit more than the minimum rent, the tenants will invest, and it is possible that the population of the economy grows or that the workers can enlarge their demand for goods. If the minimum rent is reached, the economy reaches a stationary state. The price of goods is controlled by the amount of labor used for the production. To overcome the stationary state, Ricardo advocated international trade, so that every economy could specialize in the product where they have an advantage regarding the costs of production in comparison to the other countries (cf. Heertje and Wenzel (2008) p. 51). The wealth of the economies can be increased in this way.

In 1848 **John Stuart Mill** (1806-1873) tried to summarize the current state of the economic theory in his publication "Principles of Political Economy". He subdivides the economic theory in five categories "Production", "Distribution", "Exchange", "Influence of the progress of society on Production and Distribution", and "Influence of Government" (Mill (1848)). Until today his structure is important in economic research. At the same time he developed the ideas of earlier acting economists and introduced new modifications. He tried to keep in touch with the reality and the consequences on political proceedings, by trying to introduce a reform party (cf. Marchi (1989) p. 272). He kept the idea of a stationary final state, welcomed by him because it may lead to a fair and cultivated social existence (cf. Holub (2010) p. 233). A further important aspect of Mill's research was that he concentrated on the maximization of utility and fortune, in contrast to profit maximization (cf. ibidem pp. 229-230).

Friedrich List (1798-1846) encourages this idea as well. He assumed that each nation had to develop itself, using investments and technological progress, to reach a higher productivity. Prohibitive taxes may be used by nations which have not reached the maximum level of industrialization yet (cf. List (1841) p. 18).

An important contribution is the fact that factor aggregation, associated with increasing or diminishing returns to scale, which is crucial to many growth models, was introduced by Alfred Marshall (1842-1924) and introduced into growth economy (see Romer (1994) p. 14). He summarizes that "every increase of wealth and every increase in the numbers and intelligence of the people increased the facilities for a highly developed industrial organization, which in its turn adds much to the collective efficiency of capital and labor" (Marshall (1980) book 4, chap. 13, paragraph 1).

In total, one could say that these economists were more interested in development in the long-run than in short-term changes. They mostly assumed that there is a stationary limit to which all initially growing economies convert, accounted for by different mechanisms.

2.2 From the Theory of Long-period Equilibrium to the Theory of Growth

In contrast to the former theories, **Joseph Alois Schumpeter** (1883-1950) sees innovations as the main driving force for economic growth. A constant evolution and modification of products and production processes, new customers and suppliers, and even changes in the political settings lead to new market structures and temporary monopoles (Schumpeter (1934)). At the same time old ideas become inefficient, and the economic cycle, the possible finale state and the equilibrium are changed. Schumpeter had in mind innovations like e.g. the steam-engine or the railroad system, which occur as episodes.

Using the idea of **Albert Aftalion** (1874-1956), the accelerator principle was developed by **John Bates Clark** (1847-1938) (cf. first published in French 1913, Aftalion (1927) and Clark (1917)). It states that investment depends on consumption and a constant accelerator c, that is why a change in consumption leads to an over-proportional change in investments, formally $I = c \cdot \frac{dC}{dt}$ with $c > 1$, which leads to economic growth (cf. Clark (1917) p. 223).

In contrast to J. B. Clark, **John Maynard Keynes** (1883-1946) states that the amount of investments is independently set, and the total income is given by $Y = C + I$. The national income may either be consumed C or saved for investments S, consequently consumption is a function of the total income. If the marginal propensity to consume c' is constant, the multiplier results from $\frac{dY}{dt} = \frac{1}{1-c'} \cdot \frac{dI}{dt}$; a change in the amount of investments leads to a change of the total income, subject to the multiplier $\frac{1}{1-c'}$ (Keynes (1936)). If the equilibrium of $S = I$ is disturbed, additional national investments have to be made to restore the equilibrium. However, his theory does not lead to suggestions concerning long-run growth, rather to guidance in different phases of the economic cycle (cf. Murad (1962) p. 57).

Karl Marx (1818-1883) uses theoretical considerations, concerning two different economic sectors. Equilibrium is reached if and only if both sectors grow at the same rate. Formally the growth rate g is defined by the ration of savings and investment rate s to the capital coefficient z, where z is determined by the ratio of fixed and variable capital to wages and the income of the capitalists. If s and z are constant, continuous balanced growth is possible (see Marx (1962) with an example in chapter 21, section 3, III). Originally, Marx states that the composition of capital z grows because of the capitalization of the capitalists' income, and therefore, the total growth rate will sink and finally stagnate. The case of continuous balanced growth is only a random exceptional state.

Not being a specialist in growth theory **Allyn Abbot Young** (1876–1929) wrote one single paper dealing with the understanding of economic growth as a presidential address to the British Association in September 1928 on "Increasing Returns and economic Progress" (Young (1928)). His main idea is that inventions of any kind, which entail an economic progress, will lead to changes elsewhere, and therefore, expedite themselves in a cumulative way. He sees no limits to the process of expansion as long as the demand is elastic and returns of production are increasing (see Young (1928) pp. 533-534). He describes the trend of the growth rate and the differences between countries, which are influenced by the growing size of the market, and therefore, enhance the economics of scale (cf. Currie (1981) p. 53). It is a theory of self-perpetuating, demand-induced growth. The paper had been neglected for a long time because it was written at the wrong time (Great depression, followed by the Second World War), when the focus concentrated on different aspects, but especially not on increasing returns (cf. ibidem p. 54).

3 The First Growth Theories

In the post-keynesian era the first separate theories of growth. Today's theory of growth is mostly influenced by neoclassical theory, amended by the industrial economics and the macroeconomic contributions to the relevance and design of human capital. Schumpeter's theory of creative destruction became the starting point for three further research areas, the evolutionary approach, the industrial economic and the area of human capital research.

3.1 Postkeynesian Growth Theory

The idea was to combine the ideas elaborated by Marx (expanded reproduction) and by Keynes (solving the equilibrium by driving consumption with additional investments) and additionally, take into account the capacity effect and not only the income effect of investments. **Roy Harrod** (1900-1978) assumes an exogenous constant saving rate $s = \frac{S}{Y}$ and uses a function for the demand of investments, depending on the investment coefficient $v' = \frac{I_t}{\Delta Y_t}$. v' is determined by the technological progress and the behavior of the firms. From the equilibrium condition $I = S$ follows that the "warranted rate of growth" must be $g* = \frac{s}{v'}$ (see Harrod (1939) p. 18). In contrast to this, **Evsey Domar** (1914-1997) determines the capacity effect by the marginal capital coefficient $v' = \frac{\Delta K_t}{\Delta Y_t *}$ (with $\Delta Y_t* =$ change in production capacity). In this model equilibrium is reached if the investments create as much new capacity as new demand is generated. This is given if investment grows at the constant rate of $g_I* = \frac{s}{v}$ (see Domar (1946) p. 145). Determined by these equations of both models, all growth rates must grow at the same rate in an equilibrium $g_Y = g_K = g_L$. Otherwise if the real investment rate differs from the optimal one, it will, following the models, collapse. As these models were unveiled shortly after the Great Depression, the basic ideas were favorably accepted, but do not have great influence on current growth theory (cf. Barro and Sala-i Martin (1995) p. 10).

These ideas are supplemented by the assumption of a constant labor coefficient. It is assumed that factor prices are quite inflexible and substitution of factors is nearly impossible. Therefore, a Leontief production function is used, which implies that equilibrium with full employment of all input factors is only possible when all factors grow at the same rates. If the growth rate of population n is constant, all other factors also have to grow with the rate of n, which is called the natural growth rate in Harrod's terminology (see Hahn and Matthews (1964) pp. 783-784). It must not equal the "warranted rate of growth", but if differing from this rate, the level of satisfaction may be over- or under-fulfilled.

Later the ideas of Harrod and Domar were developed to the "Harrod-Domar-Theory". The main improvement was that investments were divided into induced investments I_{ind} and autonomous investments I_{aut}. The induced investments are determined by the accelerator principle $I_{ind} = v' \cdot \frac{dY_t}{dt}$ if $\frac{dY_t}{dt} > 0$, and the autonomous ones grow at an exogenous constant rate (cf. Hamberg and Schultze (1961) p.60-62).

3.2 Neo-keynesian Growth Theory

At the same time as Harrod, **Paul Samuelson** (1915-2009) developed a quite similar model (Samuelson (1939)). He adds governmental expenditures as another input factor of the national income, but it is set constantly to $G = 1$. Depending on the relation of consumption to private investments, he reveals four different states of the economy, either growing but with decreasing growth rate, reaching a steady state, oscillating around zero income, or a steadily growing state.

Nicolas Kaldor (1908–1986) uses a consumption function, in which he distinguishes between two categories, the wage income and the capital income, as basis for consumption. He assumes that according to the type of income there are different saving rates; the capital income recipients' one are higher than the wage income recipients' one. The total savings S are the arithmetical average of both categories of savings, weighted with the income quotes. To achieve the equilibrium of $S = I$, income has to be shifted from capital income to wage income if S is higher than the optimal level, or the other way around if S is lower than the optimal level (Kaldor (1957)).

3.3 Neoclassical Growth Theory

To overcome the criticisms of the post-keynesian growth theories, a new approach was developed. In contrast to Harrod and Domar, **Robert Merton Solow** (born 1924) uses an aggregated production function where substitution between labor and capital is possible, and therefore, the capital coefficient becomes variable (Solow (1956)). But the returns of scale are still assumed to be constant, and the savings and consumption rates are still exogenously given. The main equation describes the change of the per capita capital intensity with respect to time $\dot{k} = s \cdot f(k) - (n + \delta) \cdot k$, where $n + \delta$ describes the effective discount rate. The model describes the growth rate during the adjustment to the steady state. Differences from the optimal capital intensity are autocratically adjusted.

Balanced growth is reached if $s \cdot f(k^*) = (n + \delta) \cdot k^*$, with a constant k^*. In balanced growth Y, K, C all have to grow with the same rate of n. **Trevor Swan** (1918-1989) developed a quite similar model using different sets of illustrations (see Swan (1956)). That is why models using this approach are referred to as the Solow-Swan-Model (cf. Diamand and Spencer (2009)).

Solow did not specify the size of the saving rate s. With a high s the economic reaches a higher income, but consumption at the same time is quite low; with a small s there is a lot of consumption, but capital intensity is quite low, and therefore, production and income are quite low. The golden rule of accumulation was developed by different economists, including **Edmund Phelps** (born 1933). They state that the optimal capital intensity in the balanced growth has to maximize per capita consumption and not per capital production. The optimal saving rate, than, is determined by $s = \frac{dY}{dt} \cdot \frac{k}{y}$, in other words, savings, and therefore investments, must equal the income of interests (see Phelps (1961) pp. 641-642). To reach the balanced growth, savings may differ from the optimal rate to reach the optimal stock of capital. The problem is that, in this modeling approach, it is not decisive at what point of time consumption is possible. As already stated by **Eugen von Böhm-Bawerk** (1851-1914), people prefer current consumption to future consumption (cf. Böhm-Bawerk (1921) pp. 328-334).

An increase of the income in the steady state is only possible, if there is exogenous technological progress A, which leads to a shift in production and in this way in the level of the value of the output (cf. Solow (1957) p. 313). Technological progress may influence the production function in different ways. Hicks-neutral technological progress leads to a bigger the amount of products produced with the same amount of input factors $Y = A \cdot F(K, L)$. In contrast to this, Harrod-neutral technological progress leads to growing efficiencies on labor input. Producing the same amount of output needs less input of labor $Y = F(K, A \cdot L)$. Just like this, Solow-neutral technological progress affects the efficiency of capital input (for further details see Hahn and Matthews (1964) pp. 825-832). Compatible to the neoclassical concept is only the Harrod-neutral technological progress because, with a constant saving rate, the capital coefficient has to be constant as well (cf. Uzawa (1961) pp. 117-118).

In chronological perspective, **Frank P. Ramsey** (1903-1930) had to be mentioned first in this chapter, but his ideas were neglected until the 1960s (see Barro and Sala-i Martin (1995) p.10). Already in 1928, Ramsey published his ideas on how the optimal amount of savings is determined, so that the total (undiscounted) utility of the economy is maximized (see Ramsey (1928) p. 544). Furthermore, he applied techniques of dynamic optimization to encourage his idea. Mainly **David Cass** (1937–2008) and **Tjalling Koopmans** (1910-1985) picked up this idea and developed it to the well-known Ramsey-Rule. The difference to Solow's model is that they endogenize the determination of the optimal amount of savings and explicitly model the consumer side (see Cass (1965) and Koopmans (1963)). Koopmans uses a discounted utility function with an infinite time horizon to determine the optimal path of consumption and investment under the individuals' budget constraint (see Koopmans (1963) pp. 22-23). Specific information on the behavior of the optimal saving rate can only be given with additional assumptions concerning the utility and the production function (see Cass (1965) p. 238), but generally it can be said that the saving rate is now determined by the interest rate and is not given exogenously. Beginning with a given stock of capital, there is only one existing optimal allocation path to reach the steady state, where stock of capital grows with the same intensity as the labor input. Keeping in mind that the utility is now discounted, the optimal stock of capital per capita in the steady state is smaller than in the Solow model.

Using Samuelson's idea, **Peter Diamond** (born 1940) introduced the overlapping generations in neoclassical growth theory (Samuelson (1958) and Diamond (1965)). He extended the set-up used by Cass and Koopmans by introducing individuals with finite time horizon. Individuals are continuously dying, and new agents are born. Individuals have different saving rates in different stages of life. It is assumed that individuals save an amount of their income in the first period of life, which generates the capital stock in the next period. During the second period of life, they receive income from the capital stock, which is completely consumed. The decision of the saving rates, which depends on the time preferences, has to be made, taking into consideration the growing population and the growing demand.

John von Neumann (1903-1957) develops a linear economic model of growth. His main contribution was the mathematical approach to prove the existence and uniqueness of equilibrium of an expanding economy. In contrast to the other models, Neumann (1945) uses a production function, where the final goods are produced with the same products as input factors, and a decision has to be made which of the different available production technologies is used. The important parameter is to define with which intensity the chosen technologies have to be used to maximize total production (cf. Neumann (1945) p. 2). The fact of producing and developing these technologies is not considered. The difficulty is to find the set where the demand for all goods (for production and consumption) and the supply of these goods are balanced. The equilibrium is reached, when the economy expands without any change in the production structure (cf. Hahn and Matthews (1964) p. 855).

3.4 Evolutionary Theory

In the 1980s a new approach of explaining the technological change influencing economic growth was developed. The evolutionary theory designs the economic process similar to the biological evolution. There is one market, and the ongoing competition between products, companies and even economic systems leads to the situation that only those will survive which fit the needs best and adjust themselves best to changing conditions. Based on the ideas published by **Friedrich von Hayek** (competition as discovery of new possibilities (see v. Hayek (1969)) and by **Schumpeter** (1883-1950) (theory creative destruction (see chapter 2.2 of this paper)), it is possible that changes and innovations will cause the destruction of ideas and products. The evolutionary theory was established as a separate research field after the critique of **Nelson and Winter** on the basic question of how firms and industries change overtime, giving an answer with evolutionary theory background (see Nelson and Winter (1982)).

4 Endogenous Growth Theory

The neoclassical approaches were quite unsatisfactory because the main variable explaining economic growth, the rate of technological progress, was exogenously given. The results did not fit to the empirical data and the economical insight that technological progress depends on economic decisions. Furthermore, if the rate of technological progress is exogenously given, it must be the same for all countries, and differences between countries would vanish. A new field of research, a new neoclassical approach or the endogenous growth theory, developed, trying to explain technological progress endogenously. The main problem was how to deal with the possibility of increasing returns, keeping in mind that under these conditions not all factors can be paid the marginal factor product (see Aghion and Howitt (1998) p. 23). The different ideas to overcome these problems are already listed an assorted by Romer (1994) and described in detail by Jones and Manuelli (1997). In the next sections the main aspects are explained, concentrating on the authors' different assumptions.

4.1 Leading Towards Endogenous Growth

Young can be seen as one of the forerunners of endogenous growth (see chapter 2.2 of this paper). He already insists on the assertion that growth is endogenous and cumulative and the main source of growth is growth itself (cf. Sandilands (2000) p. 309). Already **Nordhaus** (born 1941) stated that it is not satisfying or rather not correct to say that economic growth is induced by technological progress because it cannot be determined what leads to economic growth. It is more precise to say that the growth of the input factors cannot fully explain the growth of the output and that there have to be other driving forces (see Nordhaus (1969) p. 18). As a consequence, he claims for theories that explain the generation and transmission of new knowledge and for that reason are able to define the forces leading to productivity changes. In a first attempt to achieve this aim, Nordhaus defines technological change as depending on the number of inventions made, which in turn depend on the amount of output devoted to invention. A new result is that a rising technological change leads to reduction of the capital stock. The problem of this model is that there has to be population growth in a first step to start the process of a growing number of inventions. A growing amount of output in real terms must be devoted to invention production because diminishing returns are assumed; otherwise technology will stagnate (ibidem p.23). **Karl Shell** (born 1938) introduced an invention sector in almost the same manner, thereby concentrating on the organizational matters as monopoles and the properties of pure public goods (Shell (1973)).

4.2 Endogenous Growth Using Capital Accumulation

One of the simplest ideas to overcome the exogenous explanation of economic growth is relaxing some assumptions of the Solow model. Now the marginal productivity of capital convergences to a positive value $A > 0$, and therefore, production becomes a linear equation depending on capital, in the Cobb-Douglas case this reads $Y = AK$. This kind of model is known as the AK-approach. **Sergio Rebelo** (born 1959) chooses this approach in his basic growth model, using a very wide capital definition including both physical and human capital (cf. Rebelo (1991) pp. 502-503). In this case, growth is professed by always positive marginal returns to capital, which seems to be unrealistic. As in the linear Neumann Model, technological progress is completely left out of consideration. **Larry Jones** and **Rodolfo Manuelli** add to the production function a further term to incorporate further input factors, $Y = AK + f(K, L)$ (cf. Jones and Manuelli (1990) p. 1014). But these factors cannot be essential to production because otherwise the assumption of steady positive values of the marginal productivity cannot be maintained. It might decrease in the beginning, but with rising capital intensity it convergences to A again.

4.3 Technological Progress Using Spillover Effects

The main idea is that there must be a difference between productions seen from the point of view of an individual firm compared to the perspecitve of the whole economy. From the individual's view, the state of the technology is exogenously given, and even the progress might seem to be exogenous because discoveries may be accidental and not always based on individual decisions. But from an external view, the technological progress is endogenous because it is influenced by the decisions and efforts made by individuals (cf.

Romer (1994) pp. 13-14). There are externalities from the individual behavior to the total stock of knowledge and reverse.

One of the first endogenous growth models is "Increasing Returns and Long-Run Growth" (1986) introduced by **Paul M. Romer** (born 1955). He models technological progress as depending on the total amount of investments to knowledge $A(R)$, which is determined by individual decisions of each competitive firm j. Investments can be either done in the capital of the firms or in individual research, increasing private knowledge R_j. Investing one unit into research enlarges the stock of knowledge not only by one unit, but rather more, depending on the current stock of private knowledge (cf. Romer (1986) p. 1019). The output of the individual firms then reads $Y_j = A(R) \cdot F(R_j, K_j, L_j)$, depending on the total stock of knowledge and the individual inputs, including investments to knowledge (cf. Romer (1994) p. 15). To prevent the production function from increasing returns, the private stock of knowledge is assumed to be rival, and therefore, has to be enlarged to achieve more output. The spillovers from the private stocks of knowledge R_j to the total stock of knowledge R describe the endogenization of the technological progress. For the individual firm, the stock of total knowledge is exogenously given, but it is determined by individual decisions.

Another early and quite similar model was developed by **Kenneth J. Arrow** (born 1921). He stated that the technological progress is influenced by the investments to capital in each period and called it the experience generated by using the goods acquired by the capital stock (cf. Arrow (1962) p. 157 and p. 172). The production function changes to $Y_j = A(K) \cdot F(K_j, L_j)$. In this case the endogenization of the technological progress is a by-product of the production process and the choice of the investment rate, and not directly influenced by an individual decision. **Robert Lucas** (born 1937) developed a similar model, distinguishing between physical capital K and human capital H. In this case, there are two individual investment decisions. Investments in human capital are generated by devoting time to learning and reaching a higher skill level (cf. Lucas (1988) p. 18). The technological progress is determined by the individual investments into human capital, therefore $Y_j = A(H) \cdot F(K_j, H_j)$ (see additionally for the whole section and especially the equations Romer (1994) p. 15).

The idea of the following models was to explain the differences of income per capita in different countries. To explain the different growth rates the assumption that the same technological opportunities are available at all times for everyone must be dropped (see Romer (1994) p. 4). He also gives one of the first solutions to model this. He predicates that the technological progress depends positively on the amount of capital in the respective country and negatively on the amount of labor. The negative effect results from the fact that, with a higher amount of labor it becomes unattractive to drive technological progress in labor saving innovations $A(K, L) = K^{\gamma} L^{-\gamma}$. Using a

Cobb-Douglas production function, as $Y = A(K, L) \cdot K^\alpha \cdot L^{1-\alpha}$, the total output reads $Y = K^{1-\beta} L^\beta$ with $\beta = \alpha - \gamma$. Now the size of β is determining if and to what extend different economies converge (Barro and Sala-i Martin (1992)). Additionally, they explain the differences in the possible steady state by further variables included in A, like e.g. the school enrollment rates and political revolutions (ibidem p. 242, Table 3). Mankiw et al. (1992) assume that the technological level is the same in all economies, but that there is a further input factor of human capital, which represents the additional variables. Those were also used by **Robert J. Barro** (born 1944) and **Xaviar Sala i Martin** (born 1962) (Mankiw et al. (1992) p. 11).

4.4 Innovation as Engine of Growth

A further approach in endogenous growth theory, which is mainly used today, is to model explicitly technological innovation and investments to research and development. There are two different manners how this influences the production, either by increasing the variety of products or by improving the quality of products. A characteristic of these models is that they take into account that the firms will only invest in research and development if there is a chance to use the innovation exclusively and that they have at least a temporary monopoly.

One of the best known models is introduced by Paul Romer in 1990. Using the production variety theory of **Avinash Dixit** (born 1944) and **Joseph E. Stiglitz** (born 1963), he creates a model where innovations lead to new products or new technologies; the variety of products is increasing (horizontal innovation) (Dixit and Stiglitz (1977), Romer (1990)). To overcome the critique that obsolescence is not taken into account, vertical innovations, where the qualities of products and processes are improved, and therefore, old products substituted, are considered (Grossman and Helpman (1991) and Aghion and Howitt (1992)). **Gene Grossman** (born 1955) and **Elhanan Helpman** (born 1946) introduce quality ladders for each product, which are followed during the innovation process. **Philippe Aghion** (born 1956) and **Peter Howitt** (born 1946) take up again Schumpeter's idea of creative destruction (see chapter 2.2 of this paper).

The main setup of these models is quite similar. The economy consists of three sectors, one producing innovations, the second producing intermediates and the third one manufacturing the final output. Using human capital, a distinction between working people's individual knowledge H, which is rival in use, and the technological level A, which is non-rival, has to be made (see Romer (1990) p. S79). In the research sector a share of human capital H_A and the current stock of knowledge are used to produce new ideas and templates (in the case of Romer) or new prototypes with better qualities (in the other case), $\dot{A} = F(A, H_A)$. Then a different firm in the sector of the intermediates bids to get the right to combine the output of the research sector with further investment goods (foregone output) to produce goods required by the final production x_i. In this case, the intermediates producer has at least a temporary monopoly and the innovations can be paid (see Aghion and Howitt (1992) p. 328). The remainder of human capital H_Y, labor L and physical capital K, which consist of the different intermediates x_i, are the input used for final production, therefore total output is $Y = F\left(H_Y, L, \sum x_{i}{}_{i=0}^{\infty}\right)$.

The growth engine of these models is that there are sectors which use their own output as input. In the research sector mainly labor or a share of human capital is used as direct input, combined with the total stock of the technical knowledge of the society influencing the productivity of the used labor. The output of the research sector is the new technical knowledge which is added to the current stock. Additionally, the assumption of non-decreasing returns to the direct or indirect inputs is needed to generate positive growth per capita (see Groth (2007) p. 130). Due to the fact that Schumpeter was one of the first to have the idea that a temporary monopoly is essential to motivate innovations and that new inventions may make old technologies inefficient, growth models incorporating this are called models of neo-Schumpeterian growth (see Aghion and Howitt (1998) chapter 2).

4.5 Further Endogenous Growth Models

Today, the theory of endogenous growth is the main theory used to analyze economic growth. It is used as a basis for further research in many fields and focusing on many different concrete aspects (for an overview on the different aspects in endogenous growth theory see Jones and Manuelli (1997)). Researchers try to incorporate more input factors into the production function to reach more realistic results and to reveal different coherences between growth and the assumptions made to model these input factors. For example, the human capital sector is more specified by incorporating inelastic supply, leisure time, education or unemployment. Another field of economic research incorporates the government as a further producing sector, producing public goods, or as political institution, making different requirements or giving assistance. Different market structures and sizes and even open economies, including international trade, are considered as well. In recent years, quite a lot of research deals with the effect of natural resources, keeping sustainability and environmental facts in mind (see next section).

Different sectors are added to reflect the economy of a single country or region with the intention to receive more realistic models. The different sectors react differently on economic decisions, and different production coefficients are assumed (for an introduction to multisector growth models see Roe et al. (2010)). The rising complexity of these models requires computational methods. They are introduced in economic growth theory in order to solve these problems and make numerical simulations possible. Additionally, not only deterministic models are solved; stochastic parameters are introduced. Doing so, the normal uncertainty of economic development and further uncontrollable influencing factors are incorporated. Now the expected utility becomes the object of maximization (see Heer and Maußner (2009) pp. 27-33 for an example of a stochastic Ramsey model).

A further field of research deals with supplementary empirical studies, which are made to confirm or refuse these expansions to the models and to verify the accompanying assumptions. Testing the theoretical results in comparison to real data sets leads to better assumptions concerning the different variables. Today more and more data are gathered and edited for research purpose. With the help of today's computer capacities, it is possible to test huge sets of data and compare the results of different sets of variables to each other. Additionally, the value of the different variables may be estimated. It is possible to isolate unusual and non-recurrent events, and therefore, future predictions become more stalwart, as far as they are determined by the past.

5 Natural Resources and Growth

In recent decades the inter-temporal allocation of exhaustible resources has been a frequently discussed topic, especially in the context of sustainable economic growth. In this context, sustainability is defined as leading to inter-generational justice, meaning that future generations may not be put into a worse position. But that does not mean that all resources have to be kept untouched and cannot be used; rather all consequences of the use (like finiteness and environmental impact) and all substitution possibilities should be taken into account (for a further definition see Aghion and Howitt (1998) p. 155-157). During the last years the use of renewable resources is as well discussed critically because of the competition of land used for cultivation of renewable energy resources and the land used for food production.

5.1 Beginning of Resource Theory

The economists who developed the first economical theories were confronted with a completely different set of production. Agricultural products were the main goods produced by using natural resources. The concern that resources would not last forever and might be fully exploited was of no vital significance. In the classical perspective, land was the main scarce factor, which would lead to diminishing returns and economic stagnation (see Ricardo chapter 2.1 and cf. Groth (2007) p. 127). This period is followed by the first systematic approaches to resource theory keeping in mind both, nonrenewable resources and renewable resources. In 1849 **Martin Faustmann** (1844-1876) formulates one of the first optimal rules for reforestation (timber as renewable resource), while trying to determine the maximum value of forest floor (Faustmann (1849)); but it was not until 1921 that **Bertil Ohlin** (1899-1979) formulated the mathematical conditions describing this rule (Ohlin (1995)). An early approach to the economics of nonrenewable resources, which is seldom cited, is evolved by Gray in 1913. He points out the importance of conservation of resources, especially of those which are exhausted by use and non-restorable after exhaustion, and the conflict between present and future use (cf. Gray (1913) pp. 499-501). His work is followed by **Harold Hotelling**'s (1895-1973) famous work on the economics of exhaustible resources, where he revealed the still used Hotelling Rule. He provided a rule to maximize the present value of all future profits for the owner of an exhaustible supply (cf. Hotelling (1931) p. 140). The amount extracted has to be chosen in a way that the price of the resource increases at the rate of interest. This leads to the result that the stock of the resource is not extracted completely as soon as possible.

In the beginning, neoclassical economics dealing with economic growth almost completely neglected natural resources. Until the 1970s, the pessimistic Malthusian view that the limited stock of non-renewable resources would restrict the economic growth was dominant. Especially the predictions of the Club of Rome emphasized these negative predictions (see Meadows et al. (1972)). They warn that the optimistic assumptions of economic growth will not last for long, due to the rising world population and the associated rising food demand. Additionally, they focus on the increasing environmental damage and the limited stocks of important resources. By introducing resources as essential input to production in the neoclassical growth framework, this view could be overcome to some extent because economic growth now was seen as possible as long as there was a sufficient rise in the technical progress. Until then, land was seen as the restricting factor for growth (see Ricardo in chapter 2.2 of this paper). Land is introduced as a non-reproducible factor, the same amount of which is available in each period (cf. Rebelo (1991) p. 502). Using land as an input factor in the Solow model (see chapter 3.3 of this paper), leads to the result that the growth rates of output and technological progress now differ from each other. The growth rate of total output is now depending on the exogenous technological growth less the production coefficient of land β times the population growth n ($gY = g\,(P, -\beta \cdot n)$, cf. Jones (2002) pp. 172-173). In this model land exhibits diminishing returns because it is used as a fixed factor; technological progress, if high enough, may compensate this.

But in the neoclassical view definitve answers could not be given as long as technological progress was seen as exogenous. The increase of research, including the dealing with natural resource, was driven by the oil crisis in the mid-1970s. In a symposium issue of Review of Economic Studies in 1974, the basic articles considering non-renewable resources R in economic growth models were published (for a summery see Krautkraemer

(1998) pp. 2091-2095). They are all starting from the same main assumptions and then concentrate on different aspects (cf. Groth (2007) pp. 135-142). A neoclassical production function with constant returns to scale and exogenous technological progress is used. There is a fixed amount of cumulative resource extraction for all times. If population growth is considered, the largest consumption per head which lasts to eternity must be found, keeping in mind the finiteness of the non-renewable resource (cf. Solow (1974) p. 35). There are different possibilities to do so; the non-renewable resource may be substituted by capital or other resources, there might be resources-augmenting technical progress, or increasing returns to scale (cf. Neumeyer (2000) p. 307).

There is only one state where the capital-output ratio K/Y and the ratio of used resource to resource stock R/S are constant. It can only be reached if the rate of technical progress is greater than the share of the resource multiplied by the rate of population growth, which means resource augmenting technological progress (Stiglitz (1974a,b)). In case the economy departs from this path, there exists a finite time horizon after which consumption stops growing and the resource is fully exhausted. Furthermore, it is not certain whether resource augmenting technical progress is permanently possible and is sufficient to replace the declining stock of the resource (cf. Neumeyer (2000) p. 325).

Dasgupta and Heal (1974) use a quite different approach to solve the same problem. They use a CES production function; in the case of the substitution parameter $\sigma \leq 1$ the non-renewable resources are essential to production. The production and consequently the consumption level first rises, but tends to zero during time. If $\sigma > 1$, there is no problem because the resource is inessential for production. To overcome the result of declining output, technical change is introduced at a specific date T, when a perfect substitute for the non-renewable resource, in form of a flow of services at a constant rate, is discovered (cf. Dasgupta and Heal (1974) p. 7). At point T the economy switches, and production and consumption rise again.

5.2 Including Resources in Economic Growth Models Today

Again the approach, starting from the assumption that technological progress is only exogenously given, is not satisfying. That is why models postulating endogenous technological progress and including natural resources were developed. The different basic ideas are summarized by Aghion and Howitt (1998), chapter 5.They incorporate a non-renewable resource to the AK-model (see chapter 4.2 of this paper) and to the Schumpeterian approach (see chapter 3.4 of this paper); and at the same time they take into account the state of the environment. In all approaches innovations and technological progress are used as a necessary input in order to be able to reach an optimal sustainable growth path. This is seen to be possible; but the question is, how it can be reached and which institutions have to be introduced (cf. Aghion and Howitt (1998) pp. 164-165). Grimaud and Rougé (2003) develop a model using the approach of Aghion and Howitt (1992) incorporating a non-renewable resource and using labor either for final production or for research. Under certain conditions an equilibrium growth path can be revealed, but the outcome may either be positive or negative, depending on the discount rate of the economy in relation to the parameters of the research function (cf. Grimaud and Rougé (2003) p. 452). Further approaches were made for example by Scholz and Ziemes (1999) and Schou (2000). The basic results of these models are all quite similar to those, when no non-renewable resource is used, because the resources do not enter the growth engine, the research sector (cf. Groth (2007) p. 150). An idea to solve these critiques is presented by Groth (2005). He introduces the non-renewable resource not only into the production function of the final output but also as input to the research activity (see ibidem pp. 3-4). In this case there must be population growth and a high elasticity of output to knowledge to compensate for the declining resource input.

It seems that when using renewable resources in an economic growth model instead of non-renewable ones there are no big differences to a model where resources are not considered. As long as the regeneration capacity of the resource η_A is higher than the demand of the resource for production, and no further input or output is observed, this is true (cf. Aznar-Márquez and Ruiz-Tamarit (2005) p. 180). But in the context of renewable resources further extensions have to be kept in mind. Depending on the chosen production function, a higher input of a resource leads to a higher output and therefore to higher growth. It would be reasonable to use as much renewable resource as possible, but in the context of sustainable growth, the regeneration capacity is a limiting factor. Additionally, a further influencing factor is the allocation of labor between harvesting the resource and its use in the final output sector (cf. Elíasson and Turnovsky (2004) pp. 5-6). Another approach is to model the sensitiveness of the resource regeneration to environmental pollution arising from final good production (cf. Tahvonen and Kuuluvainen (1991) pp. 651-652). But pollution may also be generated by the production and use of the resources (both by renewable or by non-renewable ones). Furthermore, it is discussed if a growing use of renewable resources and therefore, an expansion of production, is after all desirable because the land used for resource production is in competition to the land used for food production (cf. Kuhn et al. (2013) p. 471).

6 Outlook

We can see that for a long time the basic theories for economic growth were subject to enormous changes, influenced by the different stages of the societies. As the existing theories were not satisfying in the new context or did not fit to undergone experiences,

	Production function	Saving rate	Technological progress	Further implications
Classical Economists (Chapter 2.1.1)	Quite general, specification introduced later		Only specialization	Stationary limit
Keynes, Marx and Co. (Chapter 2.1.2)		Exogenous, equal investments		Accelerator, Multiplicator
Postkeynesian growth theory (Chapter 2.3.1)	Production induces additional investments	Exogenous and constant, equal investments		Capacity effect of investments
Neokeynesian growth theory (Chapter 2.3.2)		Equal investments, but different depending on income		
Neoclassical growth theory (Chapter 2.3.3)	Specific formulation, using low of motions	Equal the income of interests	Exogenous; hicks-, harrod-, or solow-neutral	Steady state
Creative destruction (Chapter 2.3.4)			Only those survive which fit best	
Endogenous growth theory		Equal investment, but endogenous determined by I=Y-C	Defining the forces which lead to changes	
- with capital accumulation (Chapter 2.4.2)	Y=AK, always positive marginal returns to capital		Evolution not considered	
- with spillover effects (Chapter 2.4.3)	Y=A(X)·F(K,L,R,H), where X is the input determining the technological progress		Determined by private knowledge, capital input or stock of human capital	
- with innovation (Chapter 2.4.4)			Separate innovation sector, using labor and knowledge as input	

Fig. 2: Summary of the presented growth theories

they were adjusted and extended. Fig. 2 shows a summary of the presented growth theories. Since the endogenous approach to economic growth theory, science concentrated on the extension of these models. In endogenous growth theory not only the direct influence of agents' economic decisions, being either consumers, firms or the state, made at time t, on growth is revealed. Furthermore, the implicit effects on the other agents, variables determined by the past and exogenous unplanned effects are considered (cf. Novales et al. (2010) pp. 27-28). In the beginning, growth theory was almost entirely a macroeconomic theory. Today the structure of growth models is completely micro-economic founded, to include specific and detailed assumptions. Especially with the usage of computer technologies, it is possible to solve even more complex models. Today's research is focused on the incorporation of more aspects influencing economic growth, either in a positive direction or limiting economic growth.

Since the beginning of the 21st century, non-renewable but also renewable resources become more and more an important input factor to models of economic growth. Against the background of scarce resource, sustainable development and environmental issues, it is essential to integrate the economic resource theory into growth theory to reveal the influences on economic growth.

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