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The Appearance of Knowledge in Growth Theory

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Abstract
The paper analyzes the appearance of knowledge in growth theory in relation to some fundamental notions in epistemology and the philosophy of science. Based on a brief account of epistemological theory, I discuss the treatment of knowledge in growth models starting from Solow (1956). My results suggest that although some important insights have been made - for instance the distinction between propositional and procedural knowledge and between knowledge gained by experience and by education - there are still confusions in the literature regarding the vital difference between the known and the knowing. Growth theorists have also largely overlooked that knowledge tends to be uncertain and evolves in a discontinuous fashion. Future growth modeling might benefit from empirical patent research at the micro level.

1. Introduction

ONE of the basic themes of modern growth theory is the view of knowledge as the engine of economic development. Although it is not the only source of rising living standards, the unprecedented rate of growth during the last two centuries would not have occurred without the spectacular advances made within science and technology. In consequence, knowledge formation has been put at the forefront of economic growth theory. But what do economists really know about knowledge and knowledge formation? Are the analytical tools developed by economics suited to explain the emergence of skills, blueprints, and scientific principles?

In this essay, I will present a critical survey of the appearance of knowledge in modern growth theory, in the light of some fundamental insights derived from epistemology and the philosophy of science.[2] The basic motivation for this undertaking is the impression that some models of knowledge formation in growth theory would benefit from a closer connection with epistemological thought. Recent work on economic growth has gained significantly from contributions by economic historians (Landes, 1969; North, 1990; Mokyr, 1990) and from students of technological change (Dosi, 1988; Rosenberg, 1994). I suggest that much less has been learned from epistemologists. In the paper, I briefly present some of the main ideas within epistemology and the philosophy of science, as they appear from the perspective of a trained economist.

The survey will primarily deal with *theory* and only occasionally refer to the equally important field of empirical *growth accounting*.[3] It will focus on growth models from the last five decades, starting with Solow (1956). The neoclassical theory of growth is a useful benchmark in many regards and in particular for its explicit treatment of a technology variable. The overview will be selective, treating in some depth a relatively small number of contributions of outstanding importance. The selection of such contributions is of course to a large extent subjective, although the aim has been to pick out the works that appear to be widely regarded as seminal.

The main conclusions from my analysis are that modern growth theory has recognized the important differences between *propositional* and *procedural* knowledge and between knowledge gained by experience and through education. The uncertainty and potential obsolescence of existing knowledge have been less recognized, as has the discontinuous nature of technological change. The failure to see the important difference between the *known* and the *knowing* has led to some confusion in the literature which might have been avoided with a better acquaintance with epistemological thinking. The modeling of knowledge is complicated by the fact that there are several logical problems involved in the construction of a knowledge variable. The future analysis of knowledge and growth should try to explain macro phenomena such as long waves of economic development, but in order to do so, it will be necessary to start from the micro perspective and the relation between individual elements of knowledge. Empirical research on patent data might prove very useful in this regard.

Section two gives a brief account of some issues in epistemology which are relevant for knowledge-based growth theory. Section three introduces a broad non-technical overview of the relations between epistemology and concepts used in growth theory. Section four presents a technical survey of the appearance of knowledge in growth models from Solow (1956) to Weitzman (1998), while section five analyzes and concludes the results from the previous sections.

2. *Epistemology*

Prior to analyzing the appearance of knowledge within economic growth theory, it is necessary to discuss the meaning of the term 'knowledge'. This is admittedly no simple task. Epistemology is a sizable field of its own within philosophy and nearly every great philosopher since the ancient Greeks have contributed to its literature. The discipline is concerned with the 'nature, origin, and limits of human knowledge' (Britannica, 2000a). A close relative of epistemology is the philosophy of science. The two fields are often discussed under the same heading, and so they will be in this section, and the brief survey will only deal with some particular aspects that are relevant to economics and growth theory.

There are essentially two meanings of the word knowledge; *that which is known* and the *state of knowing*.[4] The first meaning of knowledge concerns the mental images which are regarded as knowledge by at least one individual. It incorporates ideas, propositions, and theories of various kinds. In mathematical notation, if A_i is the set of such pieces of knowledge carried by individual i, then $\bigcup_{i=1}^{I} A_i$ is that which is *known* among the I individuals. Usually, I is thought of as the world population so that A is what is universally known. The *known* is thus a collection of ideas that can be analyzed independently from its users. It is the body of accumulated facts and theories about the world.[5]

The *knowing*, on the other hand, is the act by individuals of storing parts of *that which is known* in their minds. This meaning of knowledge is more focused on the taking and maintaining possession of ideas rather than on the ideas themselves. It describes knowledge as a dynamic process. Note that if *the known* is described as $\bigcup_{i=1}^{I} A_i = A$ then A in itself gives us no information about the distribution of knowledge among the I individuals. If, for example, we imagine a society of two individuals, called Al and Beatrice, where Al knows the true proposition a and Beatrice the true propositions a,b,c,d, then the union of their individual knowledge sets is simply a,b,c,d. If we have another society of two individuals Carol and David where Carol knows a,b,c,d and David a,b,c,d, then the known is identical in the two societies, whereas knowing as a mental state must be described as superior in Carol and David's society since they store eight true propositions in their minds while Al and Beatrice only store five. In the English language, the term *knowledge* refers to both the *known* and the *knowing*, which sometimes confuses discussions on the subject. In the subsequent discussion, it will be necessary to bear in mind the distinction between the two meanings.

Among the many constituents of what is known are two different kinds of knowledge, which are often described by the two expressions *knowing that* and *knowing how*.[6] *Knowing that* refers to knowledge in the form of ideas or propositions like: 'Boston is a city in the state of Massachusetts' and 'A computer's main source of power is electricity'. This kind of knowledge is therefore often called *propositional knowledge*. *Knowing how* reflects skills and practical abilities, about how to *do* things (*procedural knowledge*). If person *X* knows that *Y* can swim, then that is a piece of propositional knowledge that is different from *Y*'s actual ability to swim, which is procedural knowledge. Unlike propositional knowledge, specific skills and abilities can not be fully described by language.

One of the greatest controversies within epistemology is concerned with the proper way of conducting the search for new (propositional) knowledge. In this important issue, there are proponents of two fundamentally different methodologies: *rationalism* and *empiricism*.[7] Rationalists believe that the ultimate source of knowledge is to be found in human reason. This tradition goes back to Plato and Heraclitus. The main assertion that rationalists make is that there is a correspondence between reason and reality which makes it possible for the former to apprehend the true nature of the latter. Empiricism, on the other hand, has its roots partly in Aristotelian thinking but most of all in the writings of British philosophers like John Locke and David Hume. Although Locke and Hume acknowledged that some trivial knowledge was *a priori* - that is possible to reach through reasoning alone - the bulk of all important knowledge was seen as *a posteriori*, in other words reached after having experienced it. Reaching knowledge by experience means that it is received by the senses rather than through thinking. The mind is essentially passive in this process. Knowledge gained from experience can never be certain; at best, it is *probable*.

A fundamental aspect of propositional knowledge in general, and of the philosophy of science in particular, is the determination whether propositions are true or not. As pointed out by Boulding (1966), the English word 'knowledge' has some tendency to approach the meaning of 'truth'. By definition, something that is true cannot be false, and thus knowledge cannot be false. However, theories that science has embraced as knowledge during different periods have repeatedly been proven to be false or at least not totally correct (Kuhn, 1962). Boulding (1956) therefore suggests the term 'image' instead of knowledge to reflect the cognitive content of people's minds which might or might not be true knowledge, but which nevertheless serves as the basis of human action.

Most often, people are inclined to view the determination of the 'trueness' of a statement as dichotomous; it must be either true or false. A central issue in epistemology is whether knowledge is a kind of *belief* or if knowledge and beliefs are two different things (Machlup, 1980). Those who regard knowledge as a kind of belief stress the uncertainty and inexactness of all knowledge. Truth can only be a strong belief in a statement (Russell, 1907). No knowledge and no truths can ever be perfect and hence concepts like truth and falsehood only indicate the quality of belief in some idea. The contending view is of course that 'a truth is a truth' and not a quality of some belief.

The most influential writer on the nature of scientific knowledge is probably Karl Popper.[8] Popper's point of departure is the empiricist view that all knowledge is uncertain. According to Popper, science should be defined by its *falsifiability* - its ability to come up with empirically falsifiable statements with at least one potential falsifier, i.e. a statement that conflicts with the basic statement logically. Scientific inquiry should be a matter of trying to refute established conjectures. All knowledge is by nature conjectural and all scientific statements are forever tentative, but we might at least be able to falsify untrue propositions.

Popper's approach to science is often described as prescriptive since it attempts to formulate a methodology for scientific research. In his famous book *The Structure of Scientific Revolutions*, Thomas Kuhn (1962) gives a quite different picture of the evolution of science. In Kuhn's descriptive historical analysis, new knowledge evolves as a result of two different processes. In the normal case, science proceeds incrementally, one small step at a time along already familiar paths. These 'mopping-up' or 'puzzle-solving' operations are the tying up of loose ends that previous research has left undone. Nothing revolutionary comes out of such *normal science*, as Kuhn refers to it. However, as new discoveries are made that are not in correspondence with the predominant pattern of scientific thinking, a sense of anomaly arises which makes researchers question the relevance of the foundations of the old theory. A *paradigm shift* eventually occurs, a revolutionary new way of thinking which destroys much of the conventional wisdom upon which earlier science was developed. As examples of such paradigm shifts, Kuhn mentions the shifts from Ptolemaic to Copernican astronomy, and from Aristotelian to Newtonian dynamics. When a new paradigm is in place, normal science once again ensues. Knowledge formation is thus characterized by revolutions followed by periods of more stable development.

As one might expect, the Popperian and Kuhnian views have been widely discussed and elaborated. One of the more well-known contributions in this respect is offered by Imre Lakatos (1970) who in some sense achieves a synthesis of the prescriptive and descriptive approaches. In Lakatos' view, scientific disciplines are made up of *Scientific Research Programs* (SRPs), which are groupings of related theories that evolve through time and are similar to Kuhn's notion of paradigms. An SRP comprises a *hard core* of fundamental, more or less irrefutable axioms. Surrounding the hard core is the *protective belt* where all empirical testing is carried out. All progress takes place in the protective belt. When testing the hypotheses that follow from the axioms in the core, Lakatos de-emphasizes the importance of refutation in Popper's sense. Lakatos even argues that several competing SRPs might be in place within the same discipline.[9]

3. Knowledge in growth theory

Far from all kinds of knowledge are analyzed in the theory of economic growth. The most widely discussed kind of knowledge is *technology*. The encyclopedic definition of technology is 'the application of scientific knowledge to the practical aims of human life.' (Britannica, 2000b). Technology is thus normally seen as a relatively advanced form of knowledge which is used in production of some kind.

It is also necessary to recognize that there is a distinction between *science* and technology. Science is a systematic attempt to understand and interpret the world whereas technology is oriented towards products and production processes. Although science and technology today are highly interrelated, this has not always been the case. The first attempts at scientific activity did not occur until societies had reached a state of civilization. Technology, on the other hand, is as old as Man. Not until the religious and philosophical gestalt-switch of the Renaissance - inspired by thinkers such as Leonardo da Vinci, Christian Wolff, Gottfried Wilhelm Leibnitz, and Francis Bacon - were science and technology brought more closely together (Reinert and Daastøl, 1997).

In ordinary microeconomic textbooks, however, technology is the formula for combining inputs to produce output. In this sense, the concept has almost the same meaning as the nature of the production function. We say that some production function uses, for example, a Cobb-Douglas or a Leontief technology to describe the process whereby inputs are transformed into outputs. In this text, we will adhere to the meaning of technology as a kind of knowledge that might be treated as an input alongside capital and labour.[10]

In the modern growth literature, a clear distinction is also made between technology and *human capital* (Nelson and Phelps, 1966; Romer, 1990). Human capital is the skills and competencies embodied in individual workers. It is acquired through education or through experience. Human capital is similar to physical capital in the sense that it is enhanced through investments (in time and effort) and is subject to depreciation (since people tend to forget). Like other forms of capital, skills and competencies might also become obsolete as technology advances. A piece of human capital can not exist independently from its holder, i.e. skills are always *embodied* in some individual. This is not the case for technological propositions or ideas. Ideas can exist independently from humans and the same idea can be used by two or two thousand individuals at the same time. They are therefore often described as *disembodied*.[11]

In a famous discussion, Romer (1990) elaborates on the differences between technology and human capital by discussing their degree of *rivalry* and *excludability*. A rivalrous good is a good such that its use by one individual to a high degree physically precludes its simultaneous use by another person. Indeed, most goods have this characteristic. Excludability concerns both the physical and legal characteristics of a good. A good is excludable if the owner can prevent other people from using it. An ordinary good, like a pair of shoes, is both rivalrous and excludable to a high degree. Two people cannot use a shoe at the same time and theft of the shoe can be prevented because of enforceable property right laws. Romer (1990) argues that human capital has these characteristics, whereas technology in the form of ideas has not. An idea is nonrivalrous by nature since it can be used by many people as soon as it has been presented. Ideas can be excludable, but only partially so since property right arrangements for ideas - such as patents, copyrights, etc - can never be perfect. Although some researcher might have the patent to some invention, she can never prevent other researchers from keeping the idea behind the invention in their minds.

Disembodied technological knowledge and embodied human capital as they are used in growth theory have their obvious terminological counterparts in the epistemological notions of propositional and procedural knowledge. Propositional knowledge, or *knowing that*, is indeed what characterizes technological ideas like 'Crop rotation enhances yields' or 'Steam engines can be used in transportation'. Such ideas are propositions about how individual elements are related to each other. Pieces of human capital, such as the ability to calculate the area of a circle or to steer a ship, are examples of *knowing how* to carry out certain actions. Although never explicitly recognized, this distinction between propositional and procedural knowledge is well established in growth theory.

One of the major problems of macroeconomic growth theory is how to construct an actual or even an imagined aggregated measure of technological knowledge in a society. Should such a measure capture *the known*, i.e. the accumulated body of technological propositions, or should it reflect *the knowing*, the distribution of propositional knowledge across individuals? As a first reflection, note that if

$\bigcup_{i=1}^{I} A_i = A$ is a pure public good that immediately spills over to all agents in the economy, then all we need information about is the known since

$$A_1 = A_2 = ... A_I = \bigcup_{i=1}^{I} A_i$$

implies that the known and the knowing are identical. However, if this is not the case, as suggested by many of the key works in growth theory, then the distribution of technological knowledge across individuals seems highly relevant. As will be demonstrated in the technical survey section, there appears to be some confusion in the literature arising from the failure to see the important distinction between the known and the knowing.

But even if growth theory was able to clarify the above-mentioned aspect, how should one think of $\bigcup_{i=1}^{I} A_i = A$ as a variable? Does it assume values in $\mathbf{R}$ so that it is possible to construct a cardinal measure of the level of technology? Most growth modelers implicitly make this rather strong assumption. The variable is then often thought of as some index of the level of technology. Alternatively, it might be thought of as the number of intermediate goods so far invented (Romer, 1990) or as the number of 'idea-cultivars' which might be recombined to give new ideas (Weitzman, 1998). In the latter two cases, a cardinal measure seems to be logically defensible, although empirically very difficult to obtain.

How then is knowledge in its various forms created? The earliest formulations of a coherent growth theory tended to regard knowledge as altogether exogenous to the economic system (Solow, 1956). Early endogenous growth models include Arrow (1962) and Shell (1966), but the real upswing in theories on endogenous technological change did not appear until the late 1980s with the contributions of Romer (1986, 1990) and Lucas (1988). At first sight, one might imagine that endogenous knowledge creation in growth theory should have important similarities with the empiricist view. Improved technology is after all often a result of trial-and-error experiments on nature that have as their goal the introduction of a new product or a new idea about how to combine physical production factors. Arrow's (1962) 'learning-by-doing', which arises as a by-product when people work with physical capital, is indeed an example of a model in the empiricist tradition. However, highly influential models such as those of Romer (1990) and Aghion and Howitt (1992), are more difficult to reconcile with empiricist thinking. The choice of terminology in these models, emphasizing knowledge 'production' rather than 'acquirement', is suggestive. As will be shown in the survey section, in this production of ideas or designs for new goods, all that is required is human capital and the accumulated body of technological knowledge acquired so far. Existing knowledge can therefore create new knowledge all by itself. There is really no need for careful observation of the surrounding world. This assumption seems to be well in line with the rationalist view of *a priori* knowledge that is possible to reach through mere reasoning.

Whereas the determination of what is true and what is false is a central issue in the writings of for instance Locke and Popper, this is not a controversial issue in growth theory. One reason why this is so is probably that 'trueness' is not an aspect that is obviously relevant when analyzing technological change. New technologies are not implemented because older technologies have proven to be 'false', rather because a new technology simply gives a better result with a given level of other resources and a given goal that the agent strives to achieve. However, even with this reservation in mind, growth theory is remarkably silent on the inherent uncertainty of what is perceived to be knowledge at some point in time. The long tradition of using Bayesian mathematics in economics should make it possible to include uncertainty to a greater extent in the analysis of knowledge formation.

Uncertainty is also related to the issue of major technological change. In the philosophy of science, we have already encountered Kuhn's (1962) famous description of how normal science proceeds in an incremental fashion until a sense of anomaly gradually arises and a revolutionary paradigm shift eventually introduces a completely new way of thinking which makes many older theories obsolete. Among economic historians, it has long been recognized that technological change is sometimes drastic, causing 'macroinventions' (Mokyr, 1990), but most often non-drastic, following predictable trajectories (Dosi, 1988). In economics, the key figure in this field of research is of course Joseph Schumpeter who argued that radical 'new combinations' of resources tended to appear '...discontinuously in groups or swarms' (Schumpeter, 1934, p 223), thereby causing technological and economic cycles of varying periodicity. These swarms of new innovations also destroy parts of the existing monopoly rents, human skills, and physical investments in a process of 'creative destruction'.

This observed pattern of drastic and non-drastic innovations has left very few marks in orthodox growth theory. Hardly any of the models in the neoclassical or endogenous growth tradition discusses or makes any distinction between major and minor technological change. A plausible explanation for this neglect might be that growth theorists did not wish to be associated with the 'long-wave' tradition of Kondratieff and Schumpeter that was sometimes regarded as unscientific and even an inspiration to Marxist theory. Only recently, a few contributions have appeared, notably Aghion and Howitt (1998, ch 8) and Helpman (1998). This new tradition apparently seeks to reinvent its unorthodox predecessor by introducing new concepts such as 'General Purpose Technologies' (GPT) and by (consciously or unconsciously) disregarding most of the older literature.[12] Whether the emerging literature on GPTs will have a lasting influence on thinking about economic growth, remains to be seen.

4. A Technical survey of the growth literature

A natural point of departure for any review of modern growth theory is Robert Solow (1956) upon which all neoclassical growth theory builds. The main motivation of Solow's paper was to provide an extension of an earlier model suggested by Harrod (1939) and Domar (1947) in which aggregate output is produced according to a fixed-proportions production function with no substitutability between capital and labour. Only as one of several extensions of his basic model, Solow introduces a cardinal technology variable $A(t)=\exp(g_A t)$ where $g_A>0$ is the proportional growth rate of A and t is time. We thus have a completely exogenous and constant rate of growth in the technology variable. Solow (1956) does not at all specify what he considers A to be. However, in his empirical paper the following year, he writes:

> It will be seen that I am using the phrase 'technical change' as a short-hand expression for any kind of shift in the production function. Thus slowdowns, speedups, improvements in the education of the labor force, and all sorts of things will appear as technical change. (Solow, 1957, p 312).

Solow followed up his 1956 article with an empirical paper where he reached the famous result that the accumulation of labour and capital accounted for less than twenty percent of total growth of net per capita output (Solow 1957). In line with his earlier theory, the remaining part - later to be called 'the Solow residual' - was interpreted as reflecting technological change. At about the same time, Abramovitz (1956) reached similar empirical results. Abramovitz was not equally convinced that the residual necessarily was technological change and coined the much-quoted phrase that it was rather 'a measure of our ignorance'. The kind of growth accounting that Solow and Abramovitz initiated was continued by many researchers who managed to decrease the residual considerably by including new variables and using expanded data sets. The residual was also given a new name: *Total Factor Productivity* (TFP).

Whereas Solow makes an explicit distinction between knowledge and physical capital, Kaldor (1957) views such a distinction as arbitrary and artificial. Kaldor argues that an increase in capital per worker inevitably is associated with the introduction of superior techniques and hence the capital stock also reflects the level of existing knowledge. Kaldor then specifies a 'technical progress function' which relates the rate of output and productivity growth to the rate of capital investment. The particular relationship between output and capital per capita depends on underlying factors such as society's adaptability of new ideas. Regardless of the specific form, the 'prime mover' in the growth process is the readiness to absorb technical change and the willingness to undertake capital investments.

The links between capital and knowledge are apparent also in Arrow (1962). Arrow motivates his research by pointing at the shortcomings of the neoclassical model that empirical research had made clear:

> ...a view of economic growth that depends so heavily on an exogenous variable, let alone one so difficult to measure as the quantity of knowledge, is hardly intellectually satisfactory. From a quantitative, empirical point of view, we are left with time as an explanatory variable. Now trend projections, however necessary they may be in practice, are basically confessions of ignorance, and, what is worse from a practical viewpoint, are not policy variables. (Arrow, 1962, p 155)

Arrow further calls for a more thorough analysis of the concept knowledge since it appears to play such a major role. In Arrow's view, knowledge has to be acquired, and people acquire knowledge through learning. Technical change is indeed '...a prolonged process of learning about the environment...' (Arrow, 1962, p 155). Not even psychologists are in full agreement about the nature of this learning process, but one generalization that appears to be generally agreed upon, according to Arrow, is that knowledge must be the product of experience, of *learning by doing*.

What variable should then be used to capture the extent of experience? Arrow takes the view that cumulative gross investment in capital goods might be considered as an index of experience. Hence, as in Kaldor (1957), technical change is completely embodied in new capital goods. Arrow then continues to derive the implications of his model. Among many other things, he shows that due to the learning effect that new capital goods give rise to, the production function might display increasing returns in capital and labour. He also discusses the implications of assuming rational expectations among investors and analyzes the divergence between the social and private productivity of capital that arises since the learning effect of an investment - which spills over to the rest of the economy - is not compensated in the market. Both the increasing returns and the private/social aspects of knowledge would decades later be important components of New Growth Theory.

Arrow's (1962) treatment provides a much more precise analysis of knowledge than what had previously been suggested in the literature. The view of new knowledge as a result of experience from using new capital goods, has important similarities to the empiricist view of knowledge formation. It describes an essentially passive individual who 'learns' (not 'invents') only when a new physical object is presented to him or her. Knowledge is seen as a by-product of capital accumulation and not something which is sought on purpose. The nature of this knowledge is unclear. Is it propositional knowledge in the form of theories and ideas, or is it procedural knowledge in the form of skills, as the choice of terminology ('learning by doing') would indicate? This is not obvious in Arrow's model.

One of the earliest models in which knowledge is completely endogenous is provided by Shell (1966). Aggregate output is assumed to be a function of technical knowledge $A(t)$ and of physical capital per capita $k(t)$. Technical knowledge grows according to the differential equation

$$\dot{A}(t) = \sigma\alpha(t)y(t) - \rho A(t) \qquad (1)$$

where $\dot{A}(t)$ is the time derivate of A, α is the share of ordinary output y that is saved for innovative activity, σ is the fraction of resources for innovation αy that are successfully turned into increases in technical knowledge, and ρ is the rate of depreciation. Note that (1) is very similar to the standard equation of motion for capital per worker in the neoclassical model, the primary difference being that A has replaced k.

There are several important things to note about this equation. First, new knowledge is explicitly modeled as being created endogenously and intentionally. A certain share α of total output y is devoted to this activity. In Shell's view, there is a tradeoff between investment in capital and in knowledge (a fraction $(1-\alpha)y$ is used for consumption and capital investment). Second, the 'stock' of technical knowledge behaves very much like the stock of capital. A fixed fraction σ of total investment αy is always successful and the stock always 'depreciates' at the rate ρ. Although no reference is made to Schumpeter, Shell's idea of knowledge growth is very similar to the 'late' Schumpeter's description of highly routinized R&D taking place in the research laboratories of large firms. Third, Shell's model is about the invention of new goods which immediately become public knowledge. There is very little of individually based 'learning' involved. Shell's kind of knowledge thus appears to be propositional rather than procedural. Furthermore, Shell's knowledge formation process is activity-oriented and, in fact, even mechanic. If physical resources are devoted to this process, there are definite results. This is far from the empiricist view of inexact, uncertain and passively acquired knowledge.

As we have seen, no distinction has so far been made between different kinds of knowledge. What Solow (1956), Arrow (1962), and Shell (1966) all seemed to have in mind was technological knowledge, in other words ideas or blueprints about products and production methods. Nelson and Phelps (1966), on the other hand, distinguish between three different kinds of knowledge. The first one is the theoretical level of technology T, or the best-practice level that would prevail everywhere if diffusion were instantaneous. It is the '...body of techniques that is available to innovators.' (Nelson and Phelps, 1966, p 71). The growth rate of this kind of knowledge is assumed to be exogenous at a level $\lambda>0$. The second kind of knowledge is the actual level of technology at some time $A(t)$, which is determined according to:

$$A(t) = T\left(t - w(h)\right) = T_0 \cdot \exp\left(\lambda\left[t - w(h)\right]\right) \quad (2)$$

where t is time, $w(h)$ is a negative function of h, and where h is the third kind of knowledge, the 'average educational attainment' or 'the degree of human capital intensity'. This is one of the earliest explicit inclusions of human capital in growth theory. The theory of human capital was introduced only a few years earlier by the writings of Schultz (1960) and Becker (1964). Human capital h enters (2) in that it affects the time lag $(t-w(h))$ in the diffusion of the best-practice technology. Since it is assumed that $w'(h)<0$, $A(t)$ increases with increases in h and the time lag in diffusion shrinks.

What Nelson and Phelps (1966) describe as the worldwide, theoretical level of technology T, might in epistemological terminology be equated with *the known* whereas A is an indication of the *knowing* in the specific country. Furthermore, both T and A are by nature propositional knowledge, which is free for anyone to use, given a sufficient level of procedural knowledge in the form of human capital. This distinction between three kinds of knowledge provides an intuitively attractive explanation to why productivity levels in poor countries often are low despite the public good character of technological knowledge.

The revival of growth theory, after about one and a half decades of stagnation, is usually considered to have started with Romer (1986, 1990) and Lucas (1988). Romer (1986) suggests a production function of the form

$$F(A_i, T, x_i) \qquad (3)$$

where A_i is a variable describing the level of firm i:s disembodied knowledge ('knowledge in books') and where x_i is firm i:s input of all other physical production factors such as capital and land. The most important variable, however, is the total stock of knowledge

$$T = \sum_{i=1}^{N} A_i$$

aggregated over all the N firms. The total stock of knowledge T is a part of firm i:s production function since private knowledge only can be partially kept secret and can not be patented and therefore has a public good-character.

Furthermore, Romer assumes that if the level of A_i is identical across all i, then the production function can be expressed as $F(A,NA,x_i)$ where the social marginal product is

$$\partial F(\bullet)/\partial A = F_1(\bullet) + N \cdot F_2(\bullet) > 0$$

and

$$\partial^2 F(\bullet)/\partial A^2 > 0$$

implying that the production function exhibits increasing marginal productivity of knowledge from a social point of view. However, since the individual firm does not value the positive spillovers to other firms which come about due to increases in its own knowledge stock, the private returns to knowledge is simply $F_1(\bullet) > 0$ and $NA=T$ is taken as exogenously given. There is therefore a discrepancy between the private and the social marginal products, leading to the familiar result that if the level of each A is determined through individual optimization, the socially optimal level is not reached. This result is well in line with the discussion in Arrow (1962).

As in Shell (1966), the creation of new knowledge in Romer (1986) is a function of investments, i.e. of forgone consumption. The creation of knowledge is thus highly deliberate and depends endogenously on the consumption/investment choices of the agents. An important difference from Shell (1966) is that whereas the growth rate of knowledge in Shell is independent of the level of knowledge, Romer (1986) considers the growth rate of A to be a decreasing function of A. Another difference is that in Romer's model, knowledge does not depreciate.

The kind of knowledge that Romer (1986) considers is undoubtedly propositional knowledge. It is reached through a smooth, production-like process which is far from the empiricist view of knowledge and there are no elements of discontinuous jumps, knowledge obsolescence or destruction. An interesting feature is further the assumption that the total stock of knowledge in society is simply the sum of individual knowledge stocks $\left(T = \sum_{i=1}^{N} A_i\right)$ However, if the N firms have at least one piece of knowledge in common, which seems to be reasonable given the assumed public good-character of A, then summing the knowledge stocks in the above manner means that the same piece of knowledge is accounted for N times. Hence, the measure T overestimates what is *known* in society. This logical inconsistency, in part acknowledged by Romer (1994), seems to have arisen from a failure to recognize the distinction between the knowing and the known. If total knowledge instead had been thought of as the union of all technological ideas among the N firms, $\bigcup_{i=1}^{N} A_i$, this problem would have been avoided.

While the emphasis in Romer (1986) is on disembodied, propositional knowledge, Lucas (1988) follows in the tradition of Schultz and Becker in focusing on human capital. An individual's human capital is defined simply as her level of skill, whereas 'technology' is modeled as '...something common to all countries, something 'pure' or 'disembodied' whose determinants are outside this inquiry.' (Lucas, 1988, p 15). Output is produced according to the production function

$$A \cdot F\left(X, uhN, h_a\right) \qquad (4)$$

where A is the constant level of technology, X is physical capital, u is the fraction of the labour force's time used in the final output sector, h is the identical skill level of all N members of the workforce, and ha is the average level of human capital. uhN is thus the 'effective workforce' in the final goods sector. As in Romer (1986), Lucas assumes that there is an internal and an external effect of knowledge on output; the h-term in the effective workforce is individual knowledge while h_a is meant to capture the public good part of human capital.[14] The idea is that an individual with a given level of skill will produce more in an environment of highly skilled co-workers. This view of human capital as having positive externalities is not a common assumption in growth theory.

Lucas (1988, p 19) also emphasizes that '...human capital accumulation is a social activity, involving groups of people in a way that has no counterpart in the accumulation of physical capital.' His model describes a completely separate learning or education sector. This kind of human capital formation is very different from Arrow's (1962) learning by doing which suggests that individuals learn by using capital goods in the manufacturing sector. Lucas explicitly recognizes the distinction between human capital gained by experience and by education. Lucas' human capital is clearly procedural knowledge, or know-how, and the central thing is not the body of accumulated facts about the world but rather individual capabilities.

In maybe the most important article in New Growth Theory, Romer (1990) combines the insights from his own previous work and from Lucas (1988). The model builds upon three premises: (1) Technological change lies at the heart of economic growth. (2) Technological change is a result of intentional actions in response to market incentives. (3) Ideas are inherently different from other economic goods. The last point is discussed in terms of the *rivalry* and *excludability* of knowledge. As was mentioned in the previous section, Romer considers human capital to be rivalrous and excludable like most other goods, whereas ideas are nonrivalrous but partially excludable due to patents.

Final output in this economy is produced according to the following production function:

$$F\left(H_Y, L, \int_{i=0}^{A} x_i di\right) \qquad (5)$$

H_Y is the stock of human capital used in the manufacturing or final goods sector, L is the number of workers, and $\int_0^A x_i di$ is the input of intermediate capital goods. Human capital is defined as 'a distinct measure of the cumulative effect of activities such as formal education and on-the-job training.' (Romer, 1990, p.79). The 'product diversity'-specification of physical capital stems from Dixit and Stiglitz (1977) and has become a central tool in modern growth theory. Knowledge enters the production function as the upper limit A to the continuous range of intermediate capital goods. The model therefore explicitly treats two kinds of knowledge; nonrivalrous and partially excludable technology and rivalrous and excludable human capital. Romer assumes that the quantity of each capital good is identical so that $x_i = x_{i+1} = x$ for all i. Hence, $\int_0^A x_i di = Ax$. In Romer's view, one might think about A as the number of designs of intermediate goods. New designs are created in a separate R&D sector where researchers are driven by the prospects of monopoly profits.

From the perspective of the present analysis, Romer (1990) is important because of his explicit recognition of two kinds of knowledge with very different economic characteristics. Another important aspect is the assumption of knowledge formation as a response to market incentives. The treatment of human capital is very similar to the notion of procedural knowledge discussed in epistemology. The definition of technological knowledge as the number of intermediate capital goods, is, however, rather restrictive. It rules out productivity improvements which are the result of more efficient methods of production. The manufacturing sector's absorption capability of new ideas is also independent of the level of human capital in the manufacturing sector, unlike in Nelson and Phelps (1966).

A model which is in many ways similar to Romer (1990) is Aghion and Howitt (1992). The setup is inspired by Schumpeter's (1942) idea of 'creative destruction'. Like Romer (1990), Aghion and Howitt model a competitive research sector producing patents for new intermediate products, with the important difference that each new innovation destroys the monopoly rents enjoyed by the former innovator (thereby causing 'creative destruction' and 'business-stealing effects'). The aggregate production function is simply $y = A_t F(x)$ where A_t is productivity and x is an intermediate good. The invention of a new intermediate good increases productivity in the final goods sector. The intertemporal relation between the productivity levels A_t and A_0 is $A_t = \gamma^t A_0$ where $\gamma > 1$ is the fixed 'size' of innovations. An important novelty in Aghion and Howitt's model is that innovations are assumed to arrive randomly at a Poisson arrival rate δH_A where δ is a research productivity parameter and H_A is the human capital employed in the research sector. The expected rate of knowledge and output per capita growth during a given time interval is therefore an increasing function of the human capital devoted to the process.

Although there is a continuing destruction of monopoly rents through the invention of new intermediate goods, there is not really any destruction of knowledge since all new products contribute positively to the stock of knowledge used in the final goods sector. The randomness of knowledge acquisition in Aghion and Howitt's model must be regarded as an improvement in terms of realism in comparison to the more mechanical models above. The random arrival of innovations also implies that the growth rate evolves discontinuously over time. However, even if the arrival rate of new knowledge is uncertain, the size or importance of each innovation (γ) is not.[16]

A growing part of the recent literature is concerned with the relations between different kinds of knowledge. One motivation for this line of research is the recognition that not only human capital varies across regions but also the state of nonrivalrous technology appears to vary (Nelson and Phelps, 1966; Romer, 1993). As Basu and Weil (1996, p.1) write:

> Do all countries in the world use the same technology? Many would view even the posing of this question absurd. In India, fields are harvested by bands of sweating workers, bending to use their scythes. In the United States, one farmer does the same work, riding in an air-conditioned

combine. Yet an economist might argue that the countries do have access to the same technology and simply choose different combinations of inputs (points along an isoquant) due to differences in factor prices. But this stance raises a new problem when one considers technological change: do technology improvements that raise the productivity of combines in America also improve the productivity of farmers in India? The answer must be 'No'.

Several different explanations have been suggested in the literature why technologies and productivity levels vary. Andersson and Mantsinen (1980) suggest that the diffusion of knowledge from some geographical location to another is subject to 'spatial frictions' so that the degree of diffusion decreases with distance between the locations. Parente and Prescott (1994) argue that barriers to technology adoption such as '...regulatory and legal constraints, bribes that must be paid, violence or threat of violence, outright sabotage, and worker strikes...' might be part of the explanation (Parente and Prescott, 1994, p 299). Basu and Weil's (1996) answer to the paradox lies in their notion of 'appropriate technology'. Even if recent technological innovations are available to underdeveloped countries, the new technology is not employed since it is inappropriate for usage together with the existing stock of capital. Basu and Weil therefore assume that any given capital stock is associated with one particular set of technologies. Acemoglu and Zilibotti (2000) refine this argument by proposing that it is essentially the poor level of human capital in underdeveloped countries that keeps these countries from attaining better technology. Technological progress in developed countries tends to be 'skill-biased', i.e. requiring a high level of human capital, which leads to a mismatch between innovations from the North and existing skills in underdeveloped regions.[17]

Most of these recent attempts at understanding the paradox of technological variance across geography use the same basic idea as in Nelson and Phelps (1966), who, in turn, make an implicit distinction between the known and the knowing of propositional knowledge. The known in the form of leading edge 'Northern' technology is basically there for the taking, but since procedural knowledge and physical capital in developing countries are not suited to the knowledge produced in the developed world, the knowing in these countries is different from what's known elsewhere.

The underlying issue in many of these discussions is whether technology and human capital are mainly substitutes or complements in production (in technical terminology, the slope of the isoquant in A,H-space). The typical Cobb-Douglas setup $y = AH^{\alpha}K^{1-\alpha}$ implies that A and H are imperfect substitutes since the slope of the corresponding isoquant is negative, continuous and convex. Helpman and Rangel (1998) define *technology-human capital complementarity* as a situation when a new technology requires a greater level of human capital than the previous technology ('skill bias'), whereas there is *technology-human capital substitutability* if a new technology requires a lower level of skills. It is sometimes argued that new technologies are mostly skill-biased (Galor and Weil, 1998) although this is not necessarily always the case (Acemoglu, 1998).

The literature on major technological change analyzes the effects on wages, output and human capital formation of the introduction of a fundamentally new method of production, often referred to as a new General Purpose Technology (GPT).[18] Examples of such revolutionary innovations include the wheel, the steam engine, electricity, and nuclear power. The basic idea in models of such long waves of development stems from Schumpeter's analysis of business cycles. However, the nature of a GPT, as defined in Helpman (1998), is also similar to Kuhn's (1962) concept of a scientific paradigm. As in Kuhn (1962), a period of fundamental change (paradigm shifts) is assumed to be followed by a period of secondary advances (normal science). But whereas Kuhn spends much effort in describing how 'a sense of anomaly' and a period of crises lead to a scientific revolution and the emergence of a new paradigm, the mechanism behind the appearance of a new GPT is rarely analyzed. GPTs are usually assumed to be more or less exogenously given (Aghion and Howitt, 1998, ch.8; Helpman, 1998).

It has been shown above how notions in New Growth Theory such as 'creative destruction' and 'long waves' have been derived from the works of Joseph Schumpeter, a circumstance which has induced some authors to label the whole field Schumpeterian Growth Theory (Aghion and Howitt, 1998). Weitzman (1998) makes use of yet another Schumpeterian thought; the view of innovations as new combinations of existing ideas (Schumpeter, 1934). As a motivation for his model, Weitzman criticizes earlier idea-based growth models (Weitzman, 1998, p 332):

> 'New ideas' are simply taken to be some exogenously determined function of 'research effort' in the spirit of a humdrum conventional relationship between inputs and outputs.[…] It seems to me that something fundamentally different is involved here. When research effort is applied, new ideas arise out of existing ideas in some kind of cumulative interactive process that intuitively seems somewhat different from prospecting for petroleum. To me, the research process has at its center a sort of pattern-finding or combinatoric feel.

Instead of a conventional production function approach, the core of Weitzman's (1998) model uses combinatorial mathematics. Weitzman's metaphor for knowledge creation is an agricultural research station where pairs of existing 'idea-cultivars' are combined to give new 'hybrid ideas'. Given that there are A idea-cultivars, $C_2(A)$ is the number of different binary pairings that can be made out of the A ideas. By using combinatorial theory, it is shown that this function is given by

$$C_2(A)=\frac{A!}{(A-2)!2!}=\frac{A(A-1)}{2} \qquad (6)$$

Given $A=2 \Rightarrow C_2(2)=1$, $A=3 \Rightarrow C_2(3)=3$, $A=4 \Rightarrow C_2(4)=6$ and so on. The production function for new ideas is further modeled as assuming a fixed-proportions feature

The growth rate of new ideas is thus deter-

$$\begin{aligned} g_A &= \frac{A(t+1)-A(t)}{A(t)} \\ &= \min\left\{\frac{\delta\big(C_2(A(t))-C_2(A(t-1))\big)}{A(t)}, s\beta\right\} \end{aligned} \qquad (7)$$

mined by the minimum of two arguments; the expected number of successful recombinations of ideas and the resources spent on the combinatory process. The first argument (to the left inside the parenthesis) contains the number of hybrid ideas in period t created by binarily combining all the ideas in $A(t)$ not previously combined $\big(C_2(A(t))-C_2(A(t-1))\big)$, multiplied by the probability δ of turning the hybrid ideas into useable form, divided by $A(t)$. The right-hand side argument is given by the fraction of total resources s spent on the recombination process with β as a productivity parameter.

It can be easily shown that the left-hand side expression inside the parenthesis is an increasing function of A. At some period in time, it will therefore be the case that the expected number of successful recombinations is greater than the level of resources devoted to the process, implying that the growth rate of knowledge (and of output) settles at its steady-state level $s\beta$. Hence it turns out that '…the ultimate limits to growth may lie not so much in our ability to *generate* new ideas, so much as in our ability to *process* an abundance of potentially new seed ideas into useable form.' (Weitzman, 1998, p.333). Furthermore, in Weitzman's view, this result is also well in line with the general pattern of world history where growth for thousands of years was near zero due to shortage of ideas, whereupon growth rates during the last millennium rapidly increased as the stock of ideas increased, only to settle at a trendless level during the last century.

A more subtle point, related to the history of growth theory, is that '...crossing the neoclassical Solow growth model with a recombinant innovation process recreates part of the basic 'look' of a Harrod-Domar landscape - from which the Solow model was originally invented to escape...everything comes back full circle to steady-state growth rates being linearly proportional to aggregate savings...' (Weitzman, 1998, p.354).

If this is indeed so, what have we learned from almost fifty years of modern growth theory?

5. Analysis and concluding remarks

Although some recent economic growth models almost can be seen as reformulations of the works of Schumpeter, Marshall, Harrod, and Domar, it is undoubtedly the case that modern analysis of the links between knowledge and economic development has made great progress. A list of the most important insights might include the divergence between the private and social benefits of knowledge creation, the distinction between nonrivalrous ideas and rivalrous skills and between human capital formation through experience and through learning, the modeling of purposeful R&D activities as a response to market incentives, and the view of new ideas as arising out of recombinations of older ideas.

Even though one must conclude that the explicit links between growth theory and epistemological thinking are very weak, some epistemological notions such as the distinctions between propositional and procedural knowledge, and between knowledge by experience and by reasoning, are at least implicitly recognized in growth modeling. However, growth theory often seems to confuse the crucial difference between the known and the knowing. A summation of the stocks of nonrivalrous knowledge as in Romer (1986) might be said to give a description of the quality of knowing, but if all individuals have at least one piece of knowledge in common, a summation of individual knowledge stocks will grossly overstate what is *known*. A practice of using unions of individual knowledge sets, as suggested in Olsson (2000), might have many advantages in this regard.

Whereas it is relatively straightforward to view the sum of all individual skill levels in society as a human capital stock with characteristics similar to physical capital, it is much more problematic to get a grip of what a variable describing a societal stock of nonrivalrous technological ideas might be. Is it the unweighted sum of all production-oriented ideas that are used at some particular time in a geographically bounded area, or is it the number of intermediate goods used in the final goods sector? One might certainly argue that some ideas or innovations are more important than others and should be given a greater weight in the construction of a technology variable. Some attempts at measuring the actual quality of ideas have been made in the patent literature (Lanjouw and Schankerman, 1999). Furthermore, ideas seem to be intertwined with each other in a manner that, for instance, machines or other factors of production, are not, which further complicates things.

As was discussed above, philosophers like Popper and Russell and empiricists like Locke and Hume regard all knowledge as uncertain to a greater or smaller extent. Thomas Kuhn even asserts that all scientific paradigms sooner or later will be regarded as anomalous by the scientific community. This potential obsolescence or destruction of knowledge is rarely discussed in modern growth theory, in part probably because the trueness of propositions is less relevant in technological research. However, the research process itself - in science as well as in commercial R&D - is characterized by a high degree of inherent uncertainty which is not easily captured by more or less mechanical knowledge production functions. As Solow (1994, p 51-52) writes in an overview of Endogenous Growth Theory:

> ...there is probably an irreducibly exogenous element in the research and development process, at least exogenous to the economy. Fields of research open up and close down unpredictably, in economics as well as in science and technology. This is reflected, for instance, in the frequency with which research projects end up by finding something that was not even contemplated when the initial decisions were made. There is an internal logic - or sometimes non-logic - to the advance of knowledge that may be orthogonal to the economic logic. This is not at all to deny the partially endogenous character of innovation but only to suggest that the 'production' of new technology may not be a simple matter of inputs and outputs.

The practice of using production functions for describing idea creation usually misses the empirical nature of the search for better technologies. The growth rate of research output is often simply modelled as a function of the level of human capital (Romer, 1990; Aghion and Howitt, 1992). The level of this output is regarded as independent of the surrounding nature and there is no indication that the opportunities for technological advance might differ across sectors and time. The patent literature has come further in this area and has shown that technological opportunity might indeed be very different from field to field (Jaffe, 1986).

A research area in growth theory that seems to be relatively underdeveloped is the study of long waves in economic development. Although the existing literature on GPTs analyzes the economic consequences of major technological revolutions, very little is known about the causes of drastic technological changes. Modern growth theory has almost nothing to say about, for instance, the reasons behind the Industrial Revolution. Such a research agenda seems particularly relevant considering the general perception that the breakthrough of IT-technology during the end of the 1990s, indeed constitutes a significant paradigm shift. Economic thinking about long waves has so far been associated with Schumpeter, but would presumably benefit from insights from philosophers of science such as Kuhn and Lakatos.

In order to get further inside the 'black box' of knowledge formation, it will probably also be necessary to develop more advanced methods for measuring different kinds of knowledge. On the human capital side, measures such as years of schooling, degree of population with primary, secondary, or tertiary education, years of experience within an industry, literacy rates, and international test scores, used by Barro (1999) and others, give at least a rough picture of the state of human capital within a country. With disembodied, propositional knowledge, empirical measurements are a far more complicated matter. The unexplained part in growth regressions is often interpreted as the state of technical knowledge, following Solow (1957), although Abramovitz (1956) is maybe more correct in labeling it a measure of our ignorance.

The best approximation for measurements of technological innovations is probably found in patent statistics. Research on patent data has a long tradition with well-known contributions such as Schmookler (1966), Griliches (1979), and Jaffe (1986), to name only a few. The results from this literature regarding knowledge spillovers, knowledge obsolescence, technological opportunity and the value of technological ideas, could be used in growth modeling to a greater extent. Ambitious attempts in this direction are Caballero and Jaffe (1993) and Kortum (1994). As suggested by Solow (1994), it appears that a theory of knowledge growth, based upon a closer study of empirical regularities at the micro level, might prove to be the road ahead for future research on the role of knowledge in economic development.

Endnotes

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2. Literature overviews with somewhat different approaches include McCallum (1996), Kurz (1997) and Aghion and Howitt (1998).

3. For recent surveys, see Barro (1998) or Temple (1999).

4. The following two paragraphs rely on Machlup (1980).

5. A referee correctly noted that since 'that which is known' is not necessarily equivalent to 'that which is true' (see the discussion below on this distinction), the union of all individual A_i might in principle contain both a proposition and its negation. For instance, one individual might 'know' that 'the earth is flat' while someone else might 'know' that 'the earth is round'.

6. Much of the discussion of *knowing that* versus *knowing how* has been inspired by the British twentieth century philosopher Gilbert Ryle (Machlup, 1980).

7. Britannica (2000a).

8. See Caldwell (1991) or Popper (1959).

9. Remenyi (1979) has offered an extension of Lakatos' SRP and discusses the possibility of 'demi-cores' within the protective belt.

10. Since the production function itself has the character of a formula, it must be considered as a piece of propositional knowledge.

11. Note, however, that many models assume that technology is either capital- or labour-augmenting.

12. In Helpman (1998) - the so far most important collection of papers on GPTs - not a single reference is made to either Schumpeter or Kuhn.

13. At least not according to his own later account (Abramovitz, 1993).

14. Since the individual level of h is identical across workers, $h=h_a$. Lucas keeps the distinction for analytical reasons.

15. Lucas also discusses the possibility of incorporating learning by doing in his model.

16. As an extension, the authors even make the size of innovations endogenous.

17. There is also a large non-growth oriented 'innovation literature' that focuses on the determinants of technological change. Dosi (1988) and Karlsson and Olsson (1998) present overviews of this tradition.

18. See Helpman (1998) for a survey and some important contributions.

19. A sketch of a similar model, based on combinatorics, can be found in Schmookler (1966).

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