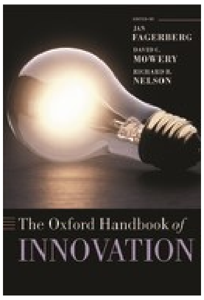

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CHAPTER

18 Innovation and Economic Growth

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Abstract

Economic history addresses the issue of the way in which the record of economic growth is related to historical developments. This article argues that technological and organizational innovation are responsible for this lengthy period of gradually accelerating growth. Although this argument is appealing, in fact economic theories explaining any such relationship are far from straightforward. Growth theory is a field characterized by spirited scholarly debate. An important current debate is that between the evolutionary approach and the more neoclassically inspired "endogenous growth theory". This article argues that the gap between these two approaches is rooted in fundamental differences in their basic worldviews. While the neoclassical tradition adheres to a worldview in which cause and effect are clearly separable, and growth is a steady state phenomenon, the evolutionary worldview is one of historical circumstances, complex causal mechanisms, and, turbulent growth patterns that appear to be far from a steady state.

Keywords: economic growth, organizational innovation, economic theories, growth theory, endogenous growth theory

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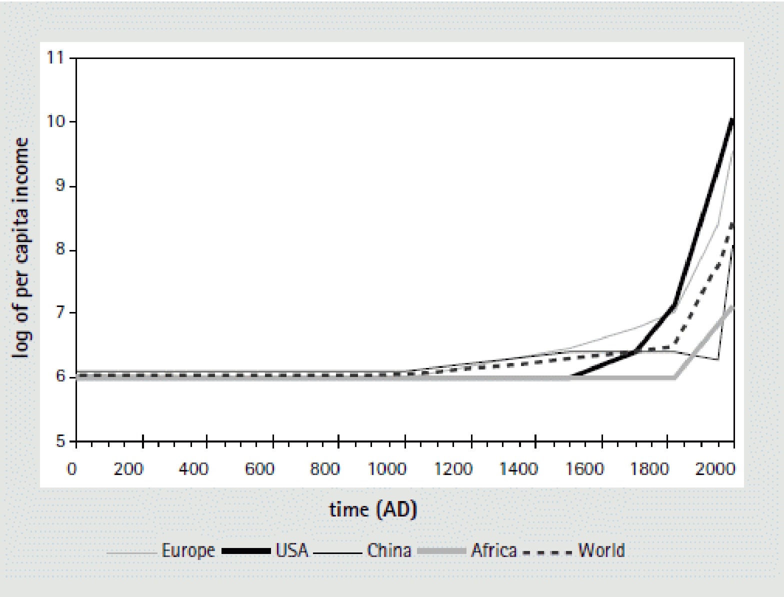
18.1 Introduction

ACCORDING to Maddison (2001), the world economy began to grow in roughly the year AD 1000 following a long period of stagnation (Figure 18.1).[1] A marked increase in growth rates occurred in the period 1600–1800, and, as the figure suggests, growth has been increasing ever since.

Economic history addresses the issue of the way in which the record of economic growth in Figure 18.1 is related to historical developments such as the Industrial Revolution (see also Bruland and Mowery, Ch. 13 in this volume). Although the exact impact that this has had on growth rates, particularly at the sectoral level, remains a subject of debate (e.g. Crafts 1985), it seems beyond dispute that a change of technology in the pure sense, coupled with organizational changes at various levels of aggregation, are the main driving factors behind the continuous increase of living standards entailed by this process.

The historical perspective also nicely illustrates the fact that there is much more to economic growth than just the data on per capita income that are so widely used by economists. Economic growth is an historical
p. 488 process of structural change in the ↳ broadest sense, and only the most elementary aspects of this process can be measured by the data on production and income. The form of structural change most visible in the statistics is the changing sectoral mix of the economy. Chenery, Syrquin, and Robinson (1986) have illustrated the regularity between the changing sectoral composition of the economy and the increasing level of productivity, while a "deeper" manifestation of structural change in the long-run process of economic growth remains largely the domain of historical research.

Fig. 18.1



Long-run growth in the world economy, according to the data in Maddison (2001)

Although the argument that technological and organizational innovation are responsible for this lengthy period of gradually accelerating growth is appealing, in fact economic theories explaining any such relationship are far from straightforward. Growth theory, especially when focused on the issue of technology, is a field characterized by spirited scholarly debate. An important current debate is that between the evolutionary approach and the more neoclassically inspired "endogenous growth theory".

This chapter argues that the gap between these two approaches is rooted in fundamental differences in their basic worldviews. While the neoclassical tradition adheres to a worldview in which cause and effect are
p. 489 clearly separable, and growth is an ordered, steady state phenomenon, the evolutionary worldview is one of ↳ historical circumstances, complex causal mechanisms that change over time, and, above all, turbulent growth patterns that appear to be far from a steady state.

Before these two approaches are compared (in Section 18.3), I discuss some of the perspectives found in the earlier literature (Section 18.2). This discussion includes both highly applied methods from the mainstream toolbox of economics (growth accounting and the literature on R&D and productivity) and applied work from a post-Keynesian or Schumpeterian perspective. Section 18.4 outlines a few lines for future research.

18.2 Growth and Technology: Traditional Economics Approaches

While technological change and economic growth were at the core of the work of the classical economists (think of Adam Smith or Karl Marx), these topics largely vanished from the scene with the neoclassical revolution in economic thinking in the late nineteenth and early twentieth centuries. The neoclassical growth models that appeared half a century ago (Solow 1956) treated technological change as an exogenous phenomenon. Technology was an explanatory factor "of last resort," in the sense that growth not explained by the variables included in the model was assumed to be the result of exogenous technological change. However, when empirical work—so called "growth-accounting" (Abramovitz 1956; Solow 1957)[2]—indicated that the unexplained share of long run economic growth tended to be very high, the interest in technological change and other possible explanatory factors not taken into account by the modelers increased.

Following Solow (1957), growth accounting commonly starts from the assumption of so-called "neutral technological change," implying that technological change improves the productivity of both labor and capital equally. Moreover, all markets are assumed to be "perfectly" competitive and in equilibrium. Economies of scale are assumed to be insignificant.

These assumptions support the following approach to calculating the contribution of "technological progress" to economic growth: subtract from the growth rate of GDP the weighted growth rates of the capital stock and employment, using the share of wages in GDP as a weight for employment, and subtract from one to get the weight for the capital stock. What remains, the "residual," is labeled "total factor productivity" (TFP) growth. This should, following Solow, be seen as the result of technological progress. Although convenient, the strong assumptions underlying these calculations are likely to be violated in practice, and the residual almost p. 490 ↳ certainly includes many more factors than just the contribution of technology. This is why Abramovitz (1956) called the residual "a measure of our ignorance."

Over the years, the growth accounting method has been greatly refined. First, the collection of more refined statistical data allowed more production factors to be distinguished, e.g. human capital, various types of labor (different by educational level), different types of capital, etc. In this way, the residual shrinks, attributing a larger part of it to the factors that are now better measured (Denison 1962).[3] The secondline of extensionhas been to refine the concept in a theoreticalway, for example by assuming that some factors (capital) are quasi-fixed, i.e. cannot be reduced or increased as a result of short-run fluctuations in output growth (e.g. Morrison 1986).

The TFP concept remains important in studies of growth by economists, as it provides a "proximate" indicator of the impact of technological change on growth. Nonetheless, the problems that remain in conceptualization and measurement have made many scholars in the field critical of its use. Perhaps the most fundamental critique is that many of the factors going into the growth accounting calculations are interrelated by causal links not accounted for by the underlying theory.[4]

Growth theory in the 1950s and 1960s was based on a simplistic view of technology as a "public good." Technological knowledge obviously has some characteristics of a public good, i.e. more than one firm can use the same piece of knowledge at the same time (non-rivalry), and once knowledge is in the open, it is hard to exclude specific firms from using it (non-excludability). In its extreme form, this view leads to the conclusion that all knowledge can be acquired externally as "general knowledge," and firms need not develop knowledge themselves.

Other important aspects of technology, however, make it a private rather than a public good (see also Fagerberg, Ch. 1 in this volume). Pure public goods do not require any special effort or special skills on the side of the consumer or receiver of the services of the good. This is obviously not the case for technological knowledge. Using technological knowledge, even if it stems from the public domain, requires considerable skills and efforts on the side of the receiver of this knowledge. The reason for this is that knowledge has a strongly cumulative and often tacit character. Every piece of new knowledge builds to a large extent on previous knowledge, and to apply knowledge requires that one have command over the older knowledge on which the new knowledge builds.

A number of models developed during the 1950s and 1960s made technology endogenous. In Kaldor (1957) this took the form of a so-called "technical progress function," which assumed a linear relation between growth of labor productivity and the growth of capital per worker. Kaldor's work gave rise to a specific tradition, often labeled "Post-Keynesianism." Work in this tradition takes the role of demand into account explicitly.[5]

The Post-Keynesian tradition also emphasizes the role of "cumulative causation" or "positive feedback." Contrary to the neoclassical idea of knowledge as a public good, these models assume that knowledge is
p. 491
specific to the agents that develop it ↳ and does not spill over easily to other agents or nations. This idea was applied to regional growth in Kaldor (1970), and goes back to Verdoorn (1949), Fabricant (1942) and Young (1928). In this view, generating knowledge is mainly a learning process deeply rooted in gaining experience with specific production processes and products: learning-by-doing and learning-by-using are key concepts. Only those engaged in the actual learning experiences will gain from it, and others, who do not profit from experience, will be left behind.

The consequence of this is a tendency for "success to breed success": those nations (or regions, or agents) that are growing rapidly accumulate experience and hence learn faster than others. This leads to a better competitive position for those already ahead and enables them to move further ahead. Hence, the crucial tendency here is one of divergence, in which some nations (regions) are able to grow rapidly while others are left behind. A model of regional growth along these lines was presented in Dixon and Thirlwall (1975).[6]

An important contribution in this post-Keynesian tradition is Cornwall (1977), who argues that manufacturing is the leading sector in economic growth because of the externalities it generates for other sectors. The motivation for this hypothesis is consistent with the Schumpeterian idea that large innovations have a broad impact across many sectors (see also Section 18.4.2 below). This is coupled with a view that, for many countries, the inflow of knowledge from abroad is paramount (see also Fagerberg and Godinho, Ch. 19 in this volume).

Attempts to generate models of endogenous technological change were also formulated in the neoclassical tradition in the 1960s. Arrow (1962) introduced a model of learning-by-doing as the source of technological progress, and Uzawa (1965) and Shell (1967) formulated full-fledged growth models with endogenous technological change, which in many respects can be considered as the front-runners of the wave of "endogenous growth models" that emerged in the late 1980s and early 1990s (see Section 18.3.3).

The work on growth accounting also contributed to the emergence during the 1970s of a purely empirical approach to the issue of growth and technology that formulated and estimated econometric models of the relationship between GDP and R&D investment (e.g. Griliches 1979, 1984). These studies employ a production function that adds a "knowledge stock" measure (typically, cumulative, depreciated R&D investment) to the traditional factors of labor and capital. Estimates of the elasticities of output with regard to the various production factors suggest that knowledge (R&D) has a significant impact on productivity growth. This approach has been used at various levels of aggregation: firms (e.g. Griliches and Mairesse 1984), sectors (e.g. Verspagen 1995) or countries (e.g. Griliches 1986).

An important issue in this literature is the empirical identification of so-called R&D spillovers. This goes back to the notion that knowledge is at least partly a public good and can be used by others than the firm that developed it. In the context of a production function, spillovers are incorporated by introducing two

p. 492 R&D ↳ knowledge stocks: one formed by R&D undertaken by the firm (or nation, or sector) itself, and another one formed by R&D undertaken by other firms (nations, sectors; see Los and Verspagen 2000, for a micro-level application). These studies generally conclude that the social rate of return to R&D is larger than the private rate of return, at any level of aggregation. Firms thus tend to benefit from other firms' R&D, and the same holds at the international level: one nation's productivity growth is to an important extent determined by that of others. Despite their econometric sophistication, however, these studies reveal little about the exact channels through which spillovers operate. These channels may include traded goods, employee mobility, technology alliances, or even knowledge that is "simply in the air."[7]

18.3 Competing Paradigms for Explaining the Relation between Growth and Technology

Two major approaches emerged during the 1980s and 1990s as the dominant approaches to the analysis of the relationship between technology and growth. These are the neoclassical approach, which is also dominant in other fields of economics, and the neo-Schumpeterian or evolutionary approach. While the neoclassical approach consists of a relatively homogenous set of interrelated sub-approaches (models), the field of neo-Schumpeterian or evolutionary economics consists of a more loosely connected set of contributions. The evolutionary approach includes formal models as well as more "appreciative" or historical approaches, as will be explained in more detail below. Even the label used to describe this approach is not yet common understanding. Here, we will use, mainly for convenience, the short description of "evolutionary economics," but we include under this heading a broad category of work, including what some have called neo-Schumpeterian economics.

Both of these approaches agree on basic issues such as the importance of innovation and technology for economic growth, as well as the positive role that can be played by government policy for science and technology. Yet they disagree on the behavioral foundations underlying these respective theories. These differences can be characterized by saying that the neoclassical theory sacrifices a significant amount of realism in terms of describing the actual innovation process in return for a quantitative modeling approach that favors strong analytical consistency, while the evolutionary approach embraces the micro
p. 493 complications of the innovative ↳ process and applies a more eclectic approach. Given these differences, it is useful to start with an overview of their analytics in terms of the microeconomic aspects of endogenous technological change and innovation.

18.3.1 Microeconomic Aspects of Technology and Innovation of Importance for the Analysis of Economic Growth

We focus in this section on two important aspects of the micro-foundations of innovation and technological change: uncertainty and differences in the significance of innovations. Economists typically deal with uncertainty by postulating a probability distribution for a certain range of events. Using these probability distributions, the economic consequences of decisions can be weighted by their probability. Rational actors can make calculations that are more complex than those in an environment of certainty, but the results do not differ appreciably. We refer to such a situation as a case of weak uncertainty.

The situation changes, however, when the possible outcomes of an uncertain process are not known in advance, i.e. the events for which a probability distribution is needed cannot be identified. Arguably, this is a better description of the innovation process, at least where more radical innovations are concerned (Box 18.1 discusses some examples of this in the history of computing). We will refer to the situation in which the possible outcomes of an uncertain process are not known in advance as strong uncertainty. Under strong uncertainty, the elegant calculations using probability-weighted outcomes to calculate the expected value of a stochastic process no longer apply. As will be seen below, the treatment of uncertainty as either weak or strong is an important distinction between neoclassical and evolutionary approaches to economic growth.

The second issue to be discussed in this section is the technological or economic significance of innovations. The history of technology is filled with innovations that have transformed the world—a non-exhaustive list includes the steam engine, electricity, the automobile, the computer, and genetic engineering. Each of these innovations had an almost immeasurable impact on the economy. But there are many examples of less significant innovations that have had far less economic significance.

One may argue that the above comparison is not a fair one, since “the computer” or “the steam engine” never existed. All of the above examples of radical innovations took decades to develop, and were the result of a combination of radical technological breakthroughs as well as many cumulative incremental innovations. Although one can therefore not speak of “the computer” or “the steam engine,” it still remains true that some innovations, no matter at which level they are defined, are much more valuable than others. p. 494 In fact, a large share of innovations eventually ↳ turns out to be useless, simply because a promising technological idea never makes it into a successful commercial application.

Box 18.1 Technological change and uncertainty

Uncertainty with regard to technologies may be understood in different degrees. Consider, for example, the difference between the first conception of a computer in the days of Turing, Mauchly, and Eckert (i.e. the 1940s and early 1950s), and the introduction of the Pentium chip by Intel in 1992. In the first case, according to a history of the early days of computers in the United States (Katz and Philips 1982), the leading business men of the day saw no commercial possibilities for the computer. They quote Thomas J. Watson Sr., CEO of IBM, as having expressed the feeling that “the one SSEC machine which was on exhibition in IBM's New York offices could solve all the scientific problems in the world involving scientific calculations.” The same T. J. Watson, by the way, quickly led IBM into leadership in the global computer industry in the late 1950s.

These pessimistic views of the commercial potential of computers reflect the fact that businessmen such as Watson had no familiarity with computer technologies in their modern form. Under such circumstances, it was impossible to appreciate the many new uses that were to be found, or the possibility that the functions and capabilities of the room-sized computers of the early 1950s could be made to fit in the space of a desktop. One of several problems in recognizing the commercial opportunities of a major technological breakthrough, and a factor contributing to uncertainty, is the lack of any frame of reference for judging these impacts.

The situation was very different in respect of the introduction of the Pentium chip by Intel in 1992. By that time, Intel and other firms, as well as users, had accumulated knowledge about the applications for computers and the devices attached to them. Intel also knew that its products were a major input in the small computers that were being purchased by a large population of consumers and firms. But Intel still faced some degree of technological uncertainty, because of the complex nature of the new design. Indeed, Intel's engineers had made a small mistake that could produce errors in the Pentium's calculations. The publicity over the so-called “Pentium Bug” eventually forced Intel to take back all faulty chips and offer free replacements. The example shows that even for a relatively mature technology, some degree of uncertainty remains.

This has given rise to a distinction in the literature between incremental and radical innovations. But this distinction obscures the fact that the size distribution of innovations is not a dichotomy, but instead covers a continuous range of innovation sizes. Moreover, there is an important interaction and interdependence between radical and incremental innovations. For example, the first workable steam engine (the so-called Newcomen engine) was very large and had a limited applicability as well as efficiency. It took more than fifty years for the next step to be taken, i.e. James Watt's engine with a separate condenser. If we can characterize the impact of some innovations as “major,” “basic,” or “radical,” it is only because of a continuous streamof incremental innovations following the introduction of a basic new design.

p. 495

Box 18.2 Evolution and the blind watchmaker

Let us use Richard Dawkins's metaphor of the blind watchmaker to illustrate the general idea behind economic growth as an evolutionary process. Dawkins's story starts from the idea of William Paley, an eighteenth-century theologian. Paley argued that certain objects, like a watch, are by their nature obviously created by conscious design, whereas for others, like a rock, it is easy to believe that they "have always been around." His argument then went on to stress that nature contains many such objects that are obviously created by conscious design. The most famous of such objects discussed by Paley is the human eye. He then used this argument to offer the proposition that the world must have been created by a conscious being (God).

Dawkins uses Paley's examples to argue that the watch may look as if it was carefully designed (and in the case of a watch it really was), but it might just as well have been created by an evolutionary process that can be thought of as a *blind watchmaker*. This blind watchmaker is unable to design the watch by carefully planning it on a drawing board and then implementing it using precision instruments. Instead, he operates through the processes of random mutation and natural selection. His approach is to start with a simple device and add small and simple changes in a random way. These changes are subjected to a real-world test, i.e., whether or not they lead to an improvement in keeping the time. Only if they do so are they kept; otherwise they are discarded. From a new design that incorporates such a successful small change, the process may start again, and step-by-step a more complicated design emerges. In the end, after a long and gradual process, a complicated artifact such as a watch may result. Although this artifact looks as if it were carefully designed, it was instead the blind watchmaker and his tools of random mutation and natural selection that created it.

Carrying the metaphor over to economic growth and technology, our watchmaker is blind because of the strong uncertainty facing the individual economic decision maker. No businessman can perfectly foresee the huge potential of a new innovation when it first emerges. But it is through a process of incremental innovations, each one of which is implemented by an entrepreneur who sees some market for the newly resulting artifact, that the full potential of the technology unfolds. The incremental innovations are the economic counterpart of biological mutation. Natural selection has its counterpart in economic selection, i.e. markets that decide whether or not certain innovations become successful. Just as in biology, many of the "mutations" (incremental innovations) are not successful, and the selection process erases them from history.

The metaphor is thus concluded by arguing that, although the individual entrepreneur has to cope with strong uncertainty and therefore cannot design a process that we may call a technological revolution, the capitalist system, working by means of a combination of the creation of novelty (innovation) and economic selection (markets), can create "objects" that seem as if they have been carefully designed. With hindsight, technological revolutions, such as the diffusion of steam power or Information and Communication Technologies (ICTs) may look as if they were planned from the very beginning to create a "new economy," but in reality, so it is argued by evolutionary theory, these technological systems were created by the trialand-error method of the blind watchmaker.

p. 496 ## 18.3.2 The Evolutionary Approach to Technology and Growth

18.3.2.1 The Evolutionary Philosophy

The evolutionary approach to the analysis of economic growth is based in part on the axiom that individual humans are unable to cope in a fully maximizing way with the complexities of technology that were discussed in Section 18.3.1. A single economic decision maker, be it an entrepreneur from the early days of the Industrial Revolution or a large multinational corporation from the twenty-first century, simply cannot see all business opportunities that result from technological possibilities and/or manage them in a way that maximizes profits. These decision makers thus operate under a scheme of bounded rationality, in which relatively simple and occasionally adaptive behavioral rules ("rules of thumb" or "routines") are used to make decisions. These are not fixed, but can be changed over time, especially so under the influence of feedback from economic performance.

Although these simple behavioral rules help economic decision makers in a turbulent and complex world cope with strong uncertainty, their role sheds little light on the mechanisms through which complex modern economies remain on a path of constant technological improvement that we call economic growth. The explanation of aggregate economic performance in evolutionary economics relies on two forces: selection and the generation of novelty. Over time, the variety present in the system is reduced by selection —i.e. the growth of those entities that are better adapted to circumstances, and the decline of those that are not. Novelty is constantly added to the system, however, and thus evolution is the outcome of a constant interaction between variety and selection. Innovation is an important noveltygenerating process, and the market and other economic institutions are among the most important selection mechanisms in modern economies.

In biology, the generation of novelty (mutation) is purely random, and there is no way in which the mechanism of mutation itself can learn to generate "smarter" mutations. Each mutation is truly "blind" in the sense that there is no *ex ante* way of telling whether or not it will improve the performance of the organism. In economic evolution, however, decision makers at the micro level are not "completely blind"—they plan their actions in order to generate potentially successful innovations in a process that more closely resembles the Lamarckian view of evolution. Thus, innovations introduced by profit-seeking, "satisficing" entrepreneurs will have at least some commercial potential; in other words, they are most likely biased in a "positive" direction. Nevertheless, uncertainty remains important, since it is difficult to foresee the cumulative effects of numerous small, incremental improvements, and because of the systemic nature of knowledge that results from knowledge spillovers among fields. An actor operating in one field may invent something for which he does not see the full potential in other fields.

The evolutionary approach is particularly suited for analyzing historical processes. Evolution and history
p. 497 are both a complex mixture of random factors, or ↳ contingencies, and more systematic tendencies. It is a well-known error to think that the biological evolutionary process is goal-oriented, i.e. that is strives to achieve a predefined aim. Our discussion of the blind watchmaker metaphor may have misled the reader into thinking that such a goal exists, i.e. that it would be the aim of evolution to create a complex artifact such as a watch or a human eye. Instead, it is only the individual mutation that has a sense. The accumulation of incremental innovations may seem to have a purpose, but in fact there is no force in the system that has formulated or even tried to achieve such a goal. The same applies to economic evolution.

Such a view of the world as a mixture between chance and necessity is shared between the historical view of the world, the evolutionary view of the world, and the dialectic (Hegelian) view of the world. It is opposed to the Newtonian or Laplacean view that portrays the world as a clockwork in which future states of the system can be predicted with full accuracy if only enough information about the present state is known. We will argue below that the neoclassical economic growth theory is much more similar to the latter view.

18.3.2.2 Non-Formal Evolutionary Theorizing about Economic Growth and Technology

The evolutionary approach to economic growth also draws heavily on economic history and the history of science and technology in its analysis of economic development. Historical analysis often is used by evolutionary scholars to develop heuristic patterns that can be used to describe and categorize these developments in a more general way. “In the appreciative and applied evolutionary literature much has been made of the concepts of technological paradigm (Dosi 1982) and natural trajectories (Nelson and Winter 1982). This is indeed an attempt to impose additional structure on technology and differentiate discrete interrelationships in technological space from one another, if only ex post ... This should be contrasted with the smooth, substitutable, unbounded production possibility sets of neoclassical theory” (Silverberg 2001: 1277).[8]

Dosi (1982) defines a technological paradigm as a “model and pattern of solution of selected technological problems, based on selected principles from the natural science and on selected material technologies.” The term is borrowed from Kuhn's philosophy of science (Kuhn 1962), which posits that the normal development path of scientific knowledge relies heavily on a dominant framework jointly adhered to by the leading scientists in the field. The paradigm thus limits the possible directions technological development may take.

In the interpretation of Freeman and Louçã (2001), a small number of basic innovations set out a technological paradigm that may dominate techno-economic developments for a long time. Within the paradigm, the basic design of the innovation is constantly altered by incremental innovations, but the direction of ↳ technological development is limited by the paradigm. Still, there is some room for choice within the paradigm, and these choices are governed by the specific circumstances (e.g., scarcity of a particular resource) in which the technology develops. This development is termed a “technological trajectory.”

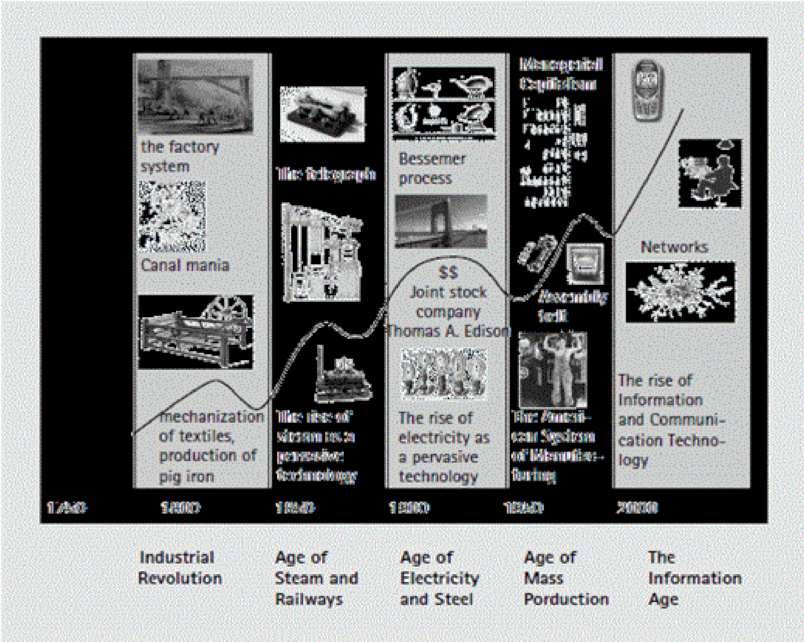
p. 498

Thus, in the paradigm/trajectory heuristic, a basic innovation can be thought of as setting out developments in the techno-economic domain for a number of years to come, but the success of the paradigm, and hence of the basic innovation, depends crucially on how well incremental innovation is able to adapt the paradigm to local (e.g. industry, geographical and temporal) circumstances. These circumstances include the skills and capabilities of the workforce that has to work with new machinery, as well as factors such as cultural aspects of the society in which the paradigm develops.

Another set of heuristics developed in the historical part of evolutionary economics relates to the temporal clustering of innovations. This part of the literature starts from Schumpeter's observation that innovations “are not evenly distributed in time, but that on the contrary they tend to cluster, to come about in bunches, simply ↳ because first some, and then most firms follow in the wake of successful innovation”(Schumpeter 1939: 75). Although Schumpeter was in fact referring to a tendency for incremental innovations to cluster following a large innovation (this is an idea not incompatible with the paradigm view summarized above), his idea has been interpreted in the literature as implying that large (or “basic”) innovations cluster in time (e.g. Mensch 1979: Kleinknecht 1987). In this view, some historical periods are characterized by an above average rate of (basic) innovations, while other periods show a relatively low rate of such activity.

p. 499

Figure 18.2



Approximate chronology of technological revolutions, based on Freeman and Soete (1997) (dates are approximate)

Together, these two sets of heuristics have interesting implications for growth. They suggest that technological innovation can introduce an uneven temporal pattern into economic growth. In the early, exploratory stages of a paradigm, the technology progresses rapidly, but the pace of change slows when the paradigm goes into its phase of "normal" development, and slows still further when technological opportunities become less numerous (and the paradigm may start to break down as a result of this). The clustering-heuristic suggests variations over time in the rhythm of growth simply because the rate at which large, influential innovations occur differs over time.

One extreme interpretation of this temporal pattern of innovation is the idea of a "long wave" in economic growth, in which periodicity is bounded in a short range of 50–60 years (e.g. Kleinknecht 1987; Freeman and Louçã 2001). Another view claims that growth patterns are inherently turbulent, but with little regularity in terms of strict cycles. In any case, the evolutionary view argues that the uneven temporal rates of technological change mean that the economy is almost always away from anything that could be characterized as a steady state.

Theories and historical analyses of this type propose a view of the interactions among technology, the economy, and the institutional context. The institutional environment is important because it is both a facilitator of and an impediment to technological change. Moreover, the institutional context is itself an endogenous factor that changes under the influence of technological and economic developments. Although it is sometimes claimed that theories of this type suffer from "technological determinism" (i.e. a tendency for one-way causality from technology to growth: see e.g. Bijker et al. 1987), work such as that of Perez (1983) proposes an interactive relationship among institutions, the economy, and technology that emphasizes mutual causality.

18.3.2.3 Formal Evolutionary Growth Models

Evolutionary ideas have also been used to formulate models of economic growth and technology. The starting point of this tradition is the model in Nelson and Winter (1982), in which heterogeneity is defined in terms of firms, using production techniques that employ a fixed ratio of labor and capital (so-called
p. 500 Leontieftechnology). The generation of novelty (new fixed proportion techniques) occurs ↳ as a result of search activities by firms, but search is initiated only when the firm's rate of return falls below a certain (arbitrarily set) value. Search may take two different forms: local search or imitation. In the first case, firms search for new, yet undiscovered techniques, each of which has a probability of being discovered which linearly declines with technological distance from their current technology (hence the term *local* search). In the second search process, imitation, a firm searches for techniques currently employed by other firms but not yet used in its own production process.

Like most models in this tradition, the Nelson and Winter model has to be simulated on a computer to obtain an impression of its implications. The model, which is calibrated with the Solow (1957) data on total factor productivity for the United States in the first half of the century, yields an aggregate time path for capital, labor input, output (GDP), and wages (or labor share in output) that corresponds in a qualitative sense to those observed by Solow. Based on these results, Nelson and Winter argue that "it is not reasonable to dismiss an evolutionary theory on the grounds that it fails to provide a coherent explanation of … macro phenomena" (p. 226). More specifically, they argue that although both the neoclassical explanation of economic growth offered by Solow and the Nelson and Winter model seem to explain the same empirical trends, the causal mechanisms underlying the two perspectives differ greatly:

> the neoclassical interpretation of long-run productivity change … is based upon a clean distinction between "moving along" an existing production function and shifting to a new one. In the evolutionary theory … there was no production function.… We argue … that the sharp "growth accounting" split made within the neoclassical paradigm is bothersome empirically and conceptually. (Nelson and Winter 1982: 227)

Evolutionary models following Nelson and Winter (1982), such as Chiaromonte and Dosi (1993) and Silverberg and Verspagen (1994), extend these conclusions. A more complete overview is in Silverberg and Verspagen (1998). The model by Chiaromonte and Dosi shows how growth rates in a cross-section of nations may differ. The models by Silverberg and Verspagen show how "routines" of R&D investment may arise endogenously in a population of firms, and how growth patterns vary along the history of an economy that learns in such a "collective" way.

One of the rare models in this tradition that is solved analytically rather than by numerical simulation is that of Conlisk (1989). Under the assumption that technology advances are random, Conlisk constructs a model in which the growth rate of the aggregate economy is a function of three variables: the standard error of the productivity distribution of new plants (which can be interpreted as the average innovation size), the savings rate (which is defined somewhat unconventionally), and the speed of diffusion of new knowledge. Moreover, by changing some of the assumptions about the specification of technical change, the model emulates three standard specifications of technical change found in growth models in the neoclassical
p. 501 tradition. In this case, the first and third factors no longer have an impact on ↳ growth (they are specific to the "evolutionary" technical change specification of the model). However, the impact of the savings rate can be compared between the various model setups. Conlisk finds that using purely exogenous technical change (as in the Solow model), or learning by doing specifications (as in Arrow 1962), the savings rate does not have an impact upon (long-run) economic growth. This result, which is in fact also well known from standard neoclassical growth theory, marks an important difference between these models and his more evolutionarily-inspired specification.

The recent so-called "history-friendly models" (Malerba et al. 1999) aim to bring evolutionary models closer to empirical reality by reproducing the historical evolution of a particular industry, e.g. the computer industry. To this end, they start with a descriptive analysis of industry variables such as growth, concentration, and employment, and incorporate the insights from this analysis into a model the behavioral foundations of which are consistent with the evolutionary view. This model is calibrated and simulated to reproduce real-world trends as closely as possible. While this approach generates empirically relevant models, the simulations employ a relatively narrow set of parameter values. The work devotes little attention to a more open-ended investigation of which *minimal* set of assumptions is necessary to generate certain aspects of the structural evolution of specific industries.

These more open-ended uses of evolutionary micro models could lead to a new class of models that employ relatively simple, evolutionary microeconomic foundations to generate a broader range of phenomena in the evolutionary interpretation of technology and growth, rather than increasing the sophistication of the microfoundations. A much clearer focus on the salient macro features and what really drives them at the micro level may result from this approach, which is necessary to close the gap between the historical, evolutionary view and model building.

18.3.3 Neoclassical Views of Economic Growth and Technology

18.3.3.1 Endogenous Growth Models

How has mainstream economic theory coped with the complexity of technological change? The literature on neoclassical models of endogenous technology grew rapidly in the 1980s and 1990s following the publication of Romer (1986). Romer's model and others in this tradition were motivated by the apparent flaws associated with the assumption in the Solow model of decreasing marginal returns to capital: holding all other production factors (labor, land, infrastructure, buildings) fixed, the productivity of an extra (marginal) unit of investment would fall with growth in the existing capital stock. Decreasing marginal
p. 502 returns to investment could cause ↳ growth to slow down or even cease in the long run. As growth proceeds, capital accumulates, i.e. the capital stock increases, and hence an extra unit of investment generates less and less growth. Exogenous growth or productivity (knowledge) had been the traditional answer, but Romer (1990) and Grossman and Helpman (1991) proposed to make technology endogenous by modeling the R&D process. Abstracting from technicalities (a survey is provided by Verspagen 1992), this can be summarized as follows.

All the models assume that R&D is essentially a lottery in which the prize is a successful innovation. In the model by Aghion and Howitt (1992), this innovationprize buys the firm a temporary monopoly of supplying the best-practice capital good used for production of consumption goods. The temporary monopoly vanishes when the next firm makes an innovation. Hence, the innovation process is modeled as a "quality ladder" of innovations, in which each new innovation supersedes the old one. In the industrial organization literature, this is called "vertical differentiation" of products.

In the model by Romer (1990), the innovation prize buys the successful firm a new variety of capital that will be demanded by producers of consumption goods forever, but has to compete with all other varieties (invented in the past, with the range continuing to expand in the future as a result of R&D). In this model, varieties of goods (innovations) do not go out of the market. Substitution between variations of goods is governed by a utility function or production function (depending on whether innovation takes place in consumer goods or intermediate goods) with a "constant elasticity of substitution." This is called "horizontal differentiation."

More tickets for the R&D lottery can be bought by doing more R&D, which is of course a costly process. Relative to the evolutionary models considered above, the crucial assumption is that the outcomes of the R&D process can be characterized realistically by weak uncertainty, i.e. the firm is able to estimate the probability that it will get the innovation-prize given its level of R&D spending. With expected benefits and costs of R&D known, the firm may make a cost–benefit analysis and derive an optimal level of R&D spending. This will, on average, correspond to a given amount of innovation, and produce a given growth rate. Although additional assumptions are necessary (e.g. with regard to the working of capital markets in which R&D expenditures have to be financed), this mechanism is the key to generating endogenous growth.

Before endogenous growth is possible in these models, there is one essential assumption about the nature of technology that needs to be made. This is related to the (partly) public good nature of technology. In the new growth models, this is represented by the assumption that there are technology spillovers between firms in the R&D process. The assumption takes two forms, depending on which flavor of model is used. In the horizontal differentiation type models (also called "loveof-variety" models), each innovation increases the level of general knowledge available in the economy, and this increases the productivity of the R&D process ↳ itself (Romer 1990). This assumption is necessary because of the ever more severe competition between the varieties of capital goods, and the falling profit rates that this causes. A tendency for R&D to be more productive (i.e. the costs of R&D to fall) offsets this falling profit rate, and keeps R&D feasible in the long run (see Grossman and Helpman 1991).

In the quality ladder models (vertical differentiation), each new innovation destroys the monopoly of the old innovator. However, the new innovator also builds on the previous innovation, because the quality of the new capital good is a fixed increase over the previous one. In other words, each new innovator is "standing on the shoulders of giants," and knowledge spills over intertemporally from one innovator to the next one. Without this spillover, endogenous growth would not be possible.

The technological spillovers in endogenous growth models lead to increasing returns to scale at the aggregate level. Even though the production functions of firms at the micro level are characterized by constant returns to scale, the R&D spillovers that flow from one firm to the rest of the economy imply increasing returns at the aggregate level. In terms of the expression for the aggregate growth rate of the economy, this feature of the endogenous growth models implies that growth at the country level depends (*ceteris paribus*) on the size of the country. Taken literally, this means that (*ceteris paribus*) larger countries will grow more rapidly. Related to this issue is the fact that the basic endogenous growth models are quite sensitive to small changes in the model specification with regard to technology spillovers. A slightly different specification of the impact of "general knowledge" on R&D productivity will lead to either zero growth in the long run, or to increasing growth rates in time (Grossman and Helpman 1991).

Technological spillovers make endogenous growth possible, but pose a challenge for policy makers. When technology generates positive externalities, the social benefits of R&D are larger than the private benefits (a rational firm investing in R&D does not consider the benefits of its R&D for its competitors). Hence the amount of R&D investment "generated by the market" will be too low from a social point of view. Technology policy in the form of R&D subsidies may bring the economy to a higher, socially optimal growth path. A similar conclusion is reached in a model of human capital and growth in Lucas (1988). In Aghion and Howitt (1992), there is also a negative externality: each new innovator destroys the rents of the existing monopolist (this is called "business stealing," or, in line with Schumpeter (1939), "creative destruction"). In this model, private R&D investment also can be too high from a social welfare perspective, depending on which of the two forms of externalities (creative destruction or standing on the shoulders of giants) is stronger.

The development of this new class of models raises promise and problems. On the positive side, it can be argued that this new growth theory takes seriously a number of arguments about technological change

p. 504 previously championed by evolutionary ↳ theorists but ignored by mainstream economists. These include the notion that R&D and technology are essentially stochastic phenomena (although evolutionary theory would argue that the type of uncertainty, i.e. weak uncertainty in which the probability distribution is known, is still not very adequate), and the importance of technology flows between agents (spillovers) for growth in the long run. The implication in many of these models that technology policy matters for growth also is relatively consistent with evolutionary theory, but may be less easily accommodated by mainstream economic theories that emphasize the efficiency of market forces.

On the negative side, these new growth models still propose a view of the interaction between economic growth and technology that differs substantially from that of evolutionary theory. The evolutionary view is one in which contingence and more systematic factors blend together in the dialectical process of historical time, but the new growth theory is still much closer to a Newtonian clockwork world in which there is a certain degree of "weak" uncertainty. In other words, the new growth theory still portrays the relationship between technology and growth as one of a steady-state growth pattern, which can be "tweaked" relatively easily by turning the knobs of the R&D process.

The evolutionary inclination, on the other hand, is that the nature of the growth process is more complex and variable over time. While the importance attached to the technology factor is shared with the new growth models, the belief that the relation between technology and growth is easily tweaked is not. In the evolutionary view, it is hard to predict exactly the impact of a policy measure, because it impacts on a complex range of interrelated factors. Moreover, while relations between a number of factors may have been revealed by careful research for a specific instance in time, it is to be expected that the nature of this relationship will change over time, exactly because of the (co)evolutionary nature of the process.

A more recent branch of new growth theory is the group of models that comes under the heading of "general purpose technologies" (GPT, Helpman 1998). A GPT is defined in essentially the same way as a basic innovation or paradigm in the evolutionary tradition. It consists of a basic technology (radical breakthrough), but this needs to be developed in the form of a range of intermediate (capital) goods. Within each GPT, the determinants of productivity are essentially the same as in one of the variants of the new growth models discussed above: technological change takes the form of an ever-expanding range of capital goods, but this is time-specific to the GPT. Thus, we see that at least two ideas from the evolutionary tradition are captured: the idea of differences in innovation size, and the idea that incremental innovations are responsible for the diffusion of a basic technology.

The GPT model generates cyclical growth. In its simplest form, the cycle consists of two phases. In the "low growth phase," the new GPT has been discovered, but is not yet in operation. New capital goods are being developed for it, and this activity has been halted for the old GPT. Thus, economic growth is low, because
p. 505 the main ↳ technology in use is no longer being developed. Once enough capital goods are available for the new GPT, its productivity outperforms that of the old GPT, the old GPT vanishes, and the economy shifts into a "high growth phase."

The GPT model resembles the evolutionary, Schumpeterian idea of long waves in economic growth. But scholars in the latter tradition have moved away from the fixed and deterministic cycle that characterizes the GPT model. Its clockwork view of economic growth has been dominant in the neo-classical tradition since the Solow model. One illustration of the limitations resulting from this view is the fact that, in the GPT view of the world, there is only room for substitution between subsequent paradigms. But economic and technological histories are filled with examples of the adaptation and survival, often in modified form, of old paradigms. For example, although the automobile is typical of the mass-production paradigm, it still plays a crucial role in the modern "Information Economy," although ICT has indeed been applied in the production of cars.

In conclusion, the evolutionary tradition and the neo-classical tradition have converged somewhat in the phenomena deemed central within each analytic approach. But they disagree on the essential nature of the growth process. The neoclassical theory conceptualizes growth as a deterministic process in which causality is clear-cut, and policies can be built on an understanding of time-invariant determinants of growth patterns. In the evolutionary view, on the other hand, contingencies and specific historical circumstances play a larger role, and causal mechanisms that prevail in one period may be subject to endogenous change in the next. In such a world, designing policy is harder, but not impossible.

18.3.3.2 Empirical Work on Growth and Technology Following the Endogenous Growth Models

The new growth models led to a tidal wave of empirical work on growth. Temple (1999) provides a detailed overview of this literature. The source of data for nearly all of this work was either the data by Maddison (1995) or the so-called Penn World Tables (PWT, Summers and Heston 1991). The PWT provides a broad cross-section of data for over a hundred countries. A crucial topic in the empirical debate following the endogenous growth models is the respective roles of steady state growth rates and convergence toward them. While the Solow model predicts that countries will converge to identical steady states (dependent on the exogenous rate of technological progress available to everyone), endogenous growth models predict that steady states will generally differ between countries. Empirical work on this issue has used a wide range of variables in regressions of growth rate differentials between countries, in order to examine cross-national differences in steady state growth rates.

Unfortunately, this approach is data-driven rather than theory-driven: an overall framework that governs p. 506 and justifies the selection of factors is lacking. Also, many of ↳ the estimation results are sensitive to a small number of observations in the large sample (Levine and Renelt 1992). Nonetheless, this work leads to the conclusion that steady state growth rates differ between nations. Growth rates may converge toward a country-specific steady state growth path at best (so-called conditional convergence), leading to the divergence of growth paths among countries. Growth seems to be heterogeneous among countries starting from low levels of GDP per capita, with some countries falling behind, and some countries being able to catch up. This phenomenon is discussed in more detail in Fagerberg and Godinho (Ch. 19 in this volume).

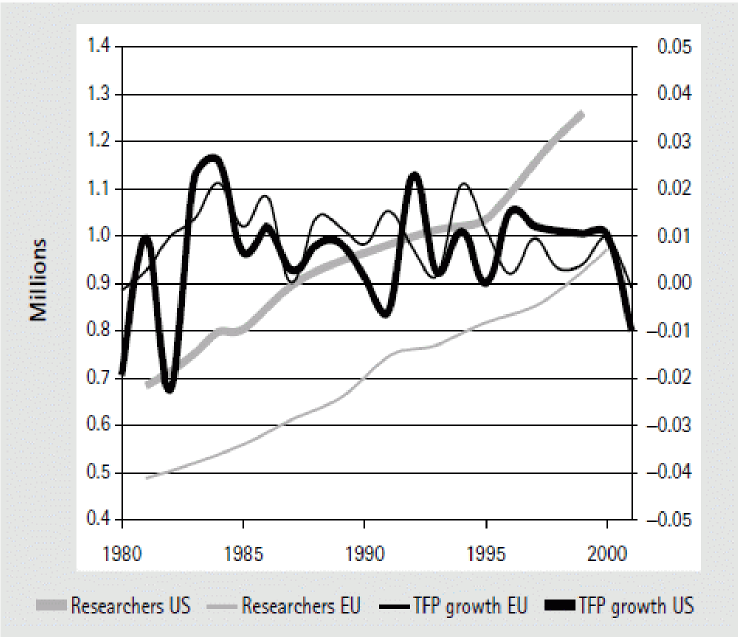
Jones (1995*a* and *b*) has argued that the observed empirical record on R&D and growth is inconsistent with the theoretical predictions of endogenous growth models (see Box 18.3 on the "Jones critique" and semi-endogenous growth models). He observes that the postwar empirical evidence does not confirm the relationship proposed by R&D-based endogenous growth models that an increase in the number of R&D workers leads to higher rates of economic growth. Jones notes that the number of R&D workers has increased since the 1960s, but growth rates (of total factor productivity) have either been constant or declining during the same period. The so-called "Jones critique" has led to still more work in the endogenous growth tradition since its publication. Jones (1995*a*) suggests a so-called semi-endogenous growth model, which appears to be more consistent with the empirical facts, but in which endogenous growth only takes place when the population grows.

Box 18.3 The “Jones critique” and semi-endogenous growth models

Figure 18.3 illustrates the Jones critique for the United States and the European Union during the 1980s and 1990s. The R&D-based endogenous growth models predict that the growth rate of an economy, which is here approximated by total productivity factor growth, depends on the number of researchers in R&D. We see a steady increase in the latter, both in the US and the EU, but total factor productivity growth does not display a clear trend—instead it fluctuates widely around a roughly constant level. Does this constitute evidence against the relationship between innovation and economic growth?

Jones suggests an alternative model, which differs from the R&D-based endogenous growth models by Romer, Grossman and Helpman, and Aghion and Howitt by a different specification of the invention process. Whereas these original R&D-based growth models assumed that the growth rate of knowledge depends on the number of R&D workers in a linear way, Jones assumes that there are decreasing returns to R&D labor. This assumption is based on the idea that “the most obvious ideas are discovered first, so that the probability that a person engaged in R&D discovers a new idea is decreasing in the level of knowledge … [and] the possibility that at a point in time the duplication and overlap of research reduce the total number of innovations” (Jones 1995*a*: 765). In this so-called semi-endogenous growth model, endogenous growth is only possible when the population grows.

Fig. 18.3



The Jones critique. Total factor productivity growth trends are flat while the number of researchers in R&D increases (R&D researchers on left scale, tfp on right scale).

Source: Source for tfp data: Groningen Growth and Development Centre Total Economy Growth Accounting Database. Source for R&D researchers data: OECD Main Science and Technology Indicators Database.

From the point of view of evolutionary growth theory, the Jones critique appears to be the result of the misguided emphasis on steady-state growth states in the R&D-based endogenous growth models. The assumed relationship between R&D labor, the number of innovations, and resulting economic growth is based on assumptions of equilibrium behavior and weak uncertainty. In the less mechanistic evolutionary world, innovation, R&D, and growth are linked in a less rigid relationship that may change over time as a result of new and radical technological developments. In this view, the specific relationship between R&D labor and TFP growth observed by Jones may well be specific to the historical circumstances of the period, and may be subject to change in the future.

p. 507 International endogenous growth models have provided other new inputs for the empirical tradition of research on R&D and productivity initiated by Griliches. This recent research focuses on the channels for international transmission of R&D spillovers. The assumption by Coe and Helpman (1995) is that these R&D
p. 508 spillovers ↳ are embodied in traded goods, and, hence, that R&D weighted by trade flows may be used to measure them. The empirical analysis by Coe and Helpman shows that the correlations between TFP growth and this measure are indeed strong, suggesting that trade is an important source of knowledge spillovers. However, subsequent contributions show that other weighting schemes may provide different interpretations. For example, Lichtenberg and Van Pottelsberghe (1996) show that Foreign Direct Investment (FDI) may be a carrier of spillovers and Verspagen (1997) shows the importance of inter-sectoral spillovers, while Keller (1998) is critical of the various weighting schemes and benchmarks them against a random weighting scheme. These results also are sensitive to the measurement by empirical researchers of absorptive capacity in the spillover-receiving countries.

An interesting "merger" between the empirical tradition on productivity and R&D, on the one hand, and new growth theory on the other hand, is the empirical model by Eaton and Kortum (1999). This paper provides a model in which innovation and technology diffusion are both drivers of country-level growth. The model is motivated by empirically observed trends, and is estimated with data on technology indicators (patents, R&D) and growth. The results of the estimations show that both endogenous R&D and the diffusion of knowledge between countries contribute to growth, although the mix between these two sources differs greatly between countries and time periods. This approach and its conclusions also has much in common with earlier technology gap models such as that of Nelson (1968), as surveyed by Fagerberg and Godinho (ch. 19 in this volume). Fagerberg and Verspagen (2002) recently reassessed the post-war evidence for these types of models, and concluded that, over time, innovation has become a more important source of growth as compared to the "pure" imitation of foreign technology. Models such as that of Eaton and Kortum thus have great promise to guide new growth theory in a direction that has much in common with the historically-inspired evolutionary approach.

18.4 Outlook for Theoretical Research on Innovation and Growth

Neoclassical work in "new growth" or "endogenous growth" recently has shifted toward more "realistic" models that can accommodate a range of phenomena previously of interest only in the evolutionary
p. 509 tradition. Heertje described this convergence as follows: ↳

> neo-Schumpeterians [i.e., the evolutionary tradition] have been productive in their criticism of the neoclassical scheme on the basic of an evolutionary approach, but the questions they have raised have been addressed more or less successfully by many scholars, who have close links with the neoclassical tradition … Iwould not be surprised to see the present Schumpeterian mood to be part of mainstream economics before the end of this century. (Heertje 1993: 273–5)

Is further convergence of the two traditions likely, as Heertje predicted for the end of the (previous) century? One avenue for convergence is in the further analysis of the intertemporal variability of growth patterns. At least some new growth models (e.g. Aghion and Howitt 1992) argue that time series of economic growth show variability, and this is a main topic in evolutionary models. The application of Pareto-type probability distributions, in which very large innovations have nonnegligible probability, may bring the two approaches closer together, since they provide an intuitive way of modeling "strong uncertainty" (see e.g. Sornette and Zajdenweber 1999).

Each of the two approaches also contains a range of important and interesting lines of research to be pursued. In the endogenous growth tradition, the returns to purely theoretical work seem to have slowed down, but important empirical challenges remain open. The most fruitful avenue of research here seems to be further theoretical refinement induced by empirical work on technology and growth, with the explicit aim of developing empirically relevant models instead of new explorations motivated by technical problems with the existing models. For a long time, empirical research has led the way in the mainstream analysis of technology and growth, and this approach still seems to be the way forward.

Two main challenges confront the evolutionary tradition. The first is to develop a research program that goes beyond just emulating, although with a more plausible micro-foundation, the results of neoclassical analysis. Such an extension of the evolutionary research agenda could benefit from closer interaction with the non-formal work in the evolutionary tradition and greater reliance on historical research. Evolutionary modelers could seek to explain observed historical regularities in the relation between growth and technology.

A second challenge for evolutionary theorists is the development of more practically relevant models, for example, with regard to specific policy advice. Evolutionary theory rarely generates precise policy advice (see also Lundvall and Borrás, Ch. 22 in this volume), mostly as a result of the nature of the theory that points to complex interactions and rather unpredictable dynamics as important ingredients of the economic environment. To a certain extent, evolutionary theory will argue for a change in the way policy is viewed, but more precise work on how this can be implemented to achieve higher or more sustainable economic growth remains crucial.

Notes

1. The (older) data are necessarily rather imprecise, but the general trends are plausible on the basis of historical evidence. Note that since the vertical axis displays the logarithm of per capita income, a straight line would correspond to growth at a fixed rate, the slope of the line indicating the growth rate.

2. Solow (1957) is often quoted as the standard reference on growth accounting, but the ancestry of the method lies earlier (e.g. Tinbergen 1943 and Abramovitz 1956; for an overview see Abramovitz 1989: 13–15).

3. Well-known studies in this tradition are Denison (1962, 1966), Jorgensen (1967) and Maddison (1987, 1991): see Nadiri (1970) for an early overview of the methodology.

4. Critical surveys of the method can be found in Nelson (1973, 1981) and Fagerberg (1988*b*).

5. Pasinetti 1993 analyzes growth and technology from a demand perspective.

6. An elaborate overview of (empirical as well as theoretical) work on growth in the post-Keynesian tradition is in McCombie and Thirlwall (1994). A specific application to the issue of technology dynamics and growth is in Fagerberg (1988*a*).

7. Griliches (1992) provides a broad overview of empirical studies estimating R&D spillovers; Cincera and Van Pottelsberghe (2001) provide a survey on international spillovers, Van Pottelsberge (1997) on intersectoral spillovers.

8. An early attempt to develop a heuristic similar to the ones cited by Silverberg is in Sahal (1981).

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