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Economics of Technology
O. Granstrand (Editor)

CHAPTER 1

Economics of Technology —An Introduction and Overview of a Developing Field[1]

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Chapter contents:

Abstract

The basic motive behind the study of economics of technology in general and behind this book specifically is outlined. It is argued that technology has historically penetrated the economy far more than it has penetrated economics for various reasons. However, the chapter demonstrates that economics of technology has established itself recently as a true field of scientific inquiry with all its tangible and intangible paraphernalia. The history of economic thought on technology is briefly described in general while the neglected pioneering contributions of C. Babbage are described in more detail. Schumpeter is the leading figure, however, as is generally recognized. The chapter also presents a literature survey and a citation analysis of the developments in economics of technology since the 1970s.

Finally, the chapter outlines the contents of the book.

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1.1 Technology and Economy in Interaction

If the historians of the 21st century were to name those 3 to 5 "events" in the second half of the 20th century that they considered most important for their own times, a reasonable bet is that they would include (a) the disintegration of the USSR political empire and economic system, (b) the rise of Japan into an economic and technological superpower, and perhaps also (c) the European economic and political integration process. Further down the list would probably come events like the rise of oil-based wealth in the Middle East with all its repercussions, growth of instabilities in the international finance system and possibly also space exploration (Sputnik, Apollo etc.). The first three events demonstrate the outcomes of various ways in which technology and economy have interacted. In terms that must be brief and sweeping here, the rise of Japan's economic power has been largely technology-based, while the fall of the USSR can be viewed as resulting in no small measure from the failure, relative to the West, to link the economic system to the science and technology (S&T) system domestically and abroad. European integration in turn was largely gaining momentum as a defensive move towards the economic and technological power of the US and Japan, with the perception that increased integration was a way to increase Europe's capabilities and relative power in these respects.

Turning to 20th-century views on history, the decisive importance at macro level of having science, technology and economy interact closely can be illustrated by the case of ancient Greece. Farrington [33] argues that one strong reason why industrialization did not start in ancient Greece, where many required conditions were present at the time, was the separation of science from technology and the economy, and a technology too weak to spur industrialization (see also [34]). The prolific and important interactions between technological changes and economic changes during various subsequent periods in history have also been documented by economic historians and historians of technology.[2] Examples are White [149], Mantoux [86], Usher [144], Landes [75]. However, although giving accounts of the interactions, works on histories of technology and economy usually have emphasized either technological or economic changes in the analysis.[3]

Thus, interaction between technology and economy is an old phenomenon; it has been important not only in connection with modern industrialization, and it does not seem to lose in importance, to say the least. This is hardly a revelation but nevertheless gives a natural argument for studying the phenomenon in question.

A further elaboration of examples of the importance of interactions between economy and technology, including examples at the micro level, could of course be given, but that is what this book is largely about.

[2] Needless to say, the causes and consequences of technological changes are not confined to economic ones but include social, political and cultural ones as well. The focus here is, however, confined to economic causes and consequences of technological changes or, alternatively speaking, technological causes and consequences of economic changes.

[3] Several significant works on the history of technology and economy have also been published by authors in this volume, e.g. Dahmén, David, Hughes and Rosenberg.

1.2 The Need for Technology and Economics in Interaction

1.2.1 *Purpose of this Book*

This book is deeply intended to stimulate the generation of more knowledge about the economics of technology and its scientific underpinnings through both teaching and research.

More specifically the purpose of this book is to contribute to the analysis of interactions between technological changes and economic changes as an area of growing importance and concern and to further raise the interest in this area, especially among new generations of researchers, teachers and students. To achieve this purpose the book attempts to reflect the state of the art in the area and to illustrate different and partly new research approaches and disciplinary perspectives. The book will moreover identify generally promising directions for future research and teaching in the area.

The book has been produced in the belief that there is an urgent but long-felt need to narrow an intellectual gap between the economics, engineering and natural science professions, a gap which has been forged by intellectual divergence and sustained by academic priorities and institutional separation. It is then necessary to make adequate pleas for cooperative efforts among scholars, especially among economists and technologists.

Before going further, a tentative definition of the subject of concern for this book will be offered.

1.2.2 *Definition of Economics of Technology*

Tentatively defined here, Economics of Technology is the field of inquiry that focuses on the causal nature of the interactions between changes in various technologies and natural sciences on one hand and economic changes of various kinds on the other. Put somewhat differently, Economics of Technology encompasses the economic analysis of technological change as well as the analysis of economic change, focusing on technology.

From a narrow logical point of view, it does not necessarily follow from this definition of Economics of Technology that the field should be considered a branch of economics. In fact, many practicing engineers and applied scientists have worked so closely with economic analysis that it could be considered an integral part of their work. Often this has been done in a reductionist way, suitable for a specific situation, by defining costs and benefits in terms of material savings, energy conversion efficiency, stability of motion, reliability, and so on. Improvements and optimizations of designs have been made in such terms but have nevertheless been inherently economic in nature, although not to an extent that would justify viewing engineering as just a branch of economics, just as all economics is not about engineering. However, technology and engineering is primarily not an end in itself but a means for improving economy in a wide sense. This reason, as well as historic reasons, justify the view that Economics of Technology is primarily a branch of economics. In turn, this view does not imply that technology is the concern primarily of economics among the social sciences, nor does it imply that economics of technology is the concern solely of economists among scientists. On the contrary, as will be argued in several of the following chapters, there is a strong need for interdisciplinary work in the field.

1.2.3 Separation of Technology and Economics

Has not economics dealt satisfactorily with technology since long ago, just as technology has long interacted with the economy? The common standpoint nowadays is that it has not for diverse reasons, one being relative neglect of technology among most economists until recently. As S&T and economics have established specialized intellectual disciplines and professions, they have become intellectually and institutionally separated for various reasons, which cannot be covered in any depth here. (Cf. Snow [130].) The institutional separation is deep, wide, old and conspicuous with separate colleges, schools, universities, libraries, academies, societies, ministries, departments, institutes etc. The intellectual separation, which to some extent is inherent in the natural course of specialization, has been cause and consequence of this institutional separation.

The intellectual separation also has visible signs such as the scarcity of technology-related entries in indices to economic textbooks and vice versa. More importantly, the intellectual separation can be illustrated by the ways technology and economics have been conceptualized and the problems they have attended to. There are naturally several definitions of economics, but a highly influential and widespread definition is the one by Robbins [109], stating that: "Economics is the science which studies human behavior as a relationship between ends and scarce means which have alternative uses." Conceptualizations of the central concern of economics along these lines are natural and reasonable and lead into resource allocation problems under scarcity. However, a next step commonly taken, but in relation to technology less reasonable, is to assume fixed ends or preferences and fixed scarcity or resources rather than focusing on processes of growth, development and transformation of resources. It is not primarily the resource allocation perspective per se that is inadequate but a static rather than a dynamic perspective. "After two centuries of being concerned with the growth of resources and the rise of wants, economics after 1870 became largely a study of the principles that govern the efficient allocation of resources when both resources and wants are given" [13, p. 4]. The latter orientation of economics has since been reinforced by its amenability to a certain body of static optimization theory, available at the time.[4]

On the other hand, "as the word itself implies technology is simply a body of knowledge about techniques" as pointed out by Freeman [36, p. 18], with techniques roughly referring to industrial crafts and methods.[5] The employment of such techniques improves resource utilization, but in so doing they also transform resources to an extent that essentially

[4] One must not fall victim to simply criticizing past developments in economics as not catering to all past and current needs at the same time. In fact the problems attended to by late 19th-century economists, leading to the establishment of much of the neo-classical economics paradigm, were perhaps more pressing at the time, e.g. resource waste; malfunctioning markets, firms and trade; business cycles, unemployment etc. One special need was also to establish economics as a science for which mathematics was seen as an important means. (See Darnell [22, Vol. 1].)

[5] Technology will be taken in a broad sense here and the conceptual and empirical relations between natural science and technology will not be elaborated upon in this chapter. (See further e.g. Price [107] and Rosenberg in Chapter 12.)

implies the generation and redefinition of resources as well as needs and wants. Moreover, the techniques and their associated artefacts have themselves been generated by human beings for whom it is all but natural to continue such endeavors. For them, whom we can call engineers, technologists, scientists, inventors and the like, it is a contradiction *par excellence* to suggest that the level of techniques employed and technology achieved will remain fixed. Even the notion of a limited and exhaustible set of technological opportunities and advances bears little resemblance to their past experience and anticipated future.

Take the case of the human need for communication as a further illustration. In a quite basic sense this need may not have changed very much. The technical means to satisfy it have changed dramatically, however, and as a result so has the expression of human communication needs, as derived from the means available at any time. In let us say 1870, these means amounted to direct communication with no intermediate media, communication by mail and simple optical means (lamps, flags, fires), communication through the telegraph etc. A century or so later, the available means had expanded considerably to include also the telephone, the telefax, electronic mail, mobile radio, optical fibres, and satellite microwave communication. Further means are under way or envisaged for the future, like the compact "wallet terminal" (with electronic keys, credit cards, watch, computer, data storage, audio, video and mobile communications functions), interactive multi-media, virtual reality applications, "telepresence" and 3-D real time holography.

To claim that the only thing these means have accomplished is a better utilization of given resources for given needs for communications, and that *the* central problem to work on in economics still is how to allocate given resources for given needs, is in fact to misallocate intellectual resources.[6] This, of course, does not mean that static resource allocation problems are always unimportant.[7] They may still be of relevance in many settings involving possible resource waste, agricultural settings as well as industrial and ecological ones. In many cases resource limits are changing so slowly in relation to the time frame employed for a particular analysis that they could in all fairness be treated as fixed; in some cases, resources really are fixed and even exogenously exhaustible.[8]

However, static resource allocation problems do not in general constitute the most important problem area in economics and certainly not when the economics of technology is concerned. Many other examples may be given, showing how resource limits rapidly recede due to technological change, which also alter the notion of what constitutes the resource in question. Think, for example, of how silicon in sand, one of the earth's most common substances, has through a series of innovations provided us with information-processing capabilities unconceived of two generations ago; think of how optical fibres provide transmission capacities that for all current practical purposes could be considered almost unlimited; think of how the electromagnetic frequency spectrum, theoretically

[6] Those economists who do not agree with this should - as a mere consequence of their standpoint - try to prove the opposite.

[7] Time itself has strict resource limitations when viewed as a resource. The length of the day is 24 hours and human life is (still) finite and only slowly increasing. However, to the modern engineering student, many of the traditional economics textbook elementary examples, some of them rooted in agriculture, appear unrepresentative of the dynamic heterogeneity of economic ends and means.

[8] E.g. in the case of irreversible processes preventing renewing transformations; see further Dosi and Metcalfe [32] on irreversibilities.

unlimited, provides land mobile, broadcasting and satellite communications catering to human needs in a way unconceived of, and perhaps inconceivable, in the times of the marginal revolution in economics and the emergence of utility theory in the late 19th century[9]; think of how many needs for physical well-being could be catered to by pharmaceuticals, often without utilizing many natural resources, partly because of synthetic chemistry; think of the abundance of energy, harmful or not available through nuclear physics and engineering; think of the abundance of atomic material that modern physics is developing ways to transform into new materials with new properties. This does not mean that there are no ultimate limits to growth, only that focusing on current limits is normally misleading. Neither does it mean that growth could be pursued without any considerations of resource constraints and risks involved; only that such considerations must be analyzed in a more proper dynamic framework, taking into account the variability of human needs and the allocation of current resources for the future generation and transformation of resources under uncertainty.

What has so far been said about resource allocation only serves as an illustration of the intellectual separation of economics from technology, not as an explanation. There are other illustrations as well[10] and many factors account for the separation. In general terms, the establishment of the neo-classical micro-economic paradigm and the macro-economic paradigms came to neglect many (but not all) technology-related issues, partly because these issues did not present themselves at the time as importantly as other issues, such as the functioning of prices and markets, economic stability, international trade and unemployment. Before World War II economists, in academia and in governments, were not particularly interested in the wider economic aspects of technology.[11] Similarly on the S&T side there has been an intellectual, even a moral, separation from economics, among many professionals, relegating the wider economic aspects of their work to others.

1.2.4 The Need for Technology and Economics in Interaction

Given a historical separation of the fields of technology and economics, is there a need for increased interaction and integration? The mere importance of technology and its interactions with economy justifies its attention in economics, as mentioned in the introductory section 1.1. However, aside from being a phenomenon of growing importance, the interactions between technology and economy are surrounded by some special circumstances that increase the need for economics to attend to them, and the need for economics to interact with engineering sciences.

First, science and technology communities worldwide today command large and powerful resources and R&D activities become increasingly resource-consuming, as do the investments induced by new technologies. At the same time the large and growing stock of technical knowledge is a most powerful means for creating wealth and well-being, although with inherent risks that are increasingly recognized. This circumstance should naturally fit the traditional interest in resource allocation among economists, just as it should fit such interests among scientists and engineers. Second, technical changes are proliferating and increasingly penetrating our lives. These changes are both positively and negatively valued, often with values that are unpredictable, extreme and unequally distributed in and among societies. Third, the technological and technical changes are interacting with each other and with economic changes so intrinsically that they are extremely difficult to separate. Thus, technology has an intrinsic feature of more or less inseparable value-duality, which moreover is unpredictable and redistributive. These technology-related circumstances present challenges to the real economy and therefore also to economics as a science. The differences in the ability of various economic systems and policies to deal with this fundamental type of challenge from technology have meant a fundamental difference for various countries, companies, professions and citizens. The challenge to economics from technology may very well alter significant parts of the established framework of economics, the framework into which a great many economic problems are cast and which consumes a great deal of the intellectual resources of economists in academia and elsewhere. This is especially so if common reductionist approaches in economics do not work satisfactorily, that is, if technological and technical changes cannot be adequately analyzed and governed through reducing all characteristics of the phenomena to traditional economic variables.

1.3 The Emergence of Economics of Technology

1.3.1 Old Phenomenon, New Academic Field

As illustrated above, the interaction between economy and technology is an old phenomenon while there has not been a corresponding field of academic inquiry.[12] As will be described below, it is justified in the 1990s to say that such a field has emerged. It does not have an established label but 'Economics of Technology' may be sufficiently descriptive. Table 1.1 gives in a simple way examples of economic and technological factors that are commonly studied and related to each other. Together they give an idea of the kind of phenomenological and causal perspective hitherto often used in studies in the field.

[9] Incidentally, the frequency spectrum is often characterized as a fixed, natural resource which should be allocated as such by public authorities. Naturally, frequency allocation is necessary and not an easy problem to cope with, but the possibilities of utilizing the frequency spectrum have increased considerably through new technologies and more possibilities to remove limitations can be expected to emerge.

[10] Another illustration is given by the uncritical application of the principle of division of labor to intellectual work and to S&T and Economics professionals themselves.

[11] It is sometimes said that the classical economists Smith, Ricardo, Mill etc. attended to technology, and that the real sin of omission was on behalf of traditional neo-classical economics. This is a qualification that easily becomes exaggerated. Although the observations and debate on technology were there, the classical economists did something but not a great deal about it, and especially not any theoretical work. Much the same may be said about neo-classical economists' work in relation to technology, although it had another orientation in general. See further Section 1.3.

[12] Curiously enough, however, several economists or major contributors to economics have been natural scientists and engineers by training, for example, L. Walras (1834-1910) in mining engineering, K. Pareto (1848-1923) in civil engineering, A. Cournot (1801-1877) and J. Keynes (1883-1946) in mathematics, and J. Hicks (1904-1989) in mathematics and engineering.

Table 1.1 Examples of Factors Commonly Related and Studied in Economics of Technology

Level[1] of observation/analysis	Economic factors/variables/ activities/processes/ phenomena	Technology factors/variables/ activities/processes/ phenomena
A. Macro (national, international)	Welfare Growth Employment Investment Income distribution Business cycles Trade Inflation Interest rate Productivity Development etc.	S&T institutions Patent system National systems of innovation R&D system Technology system Innovation clusters Innovativeness etc.
B. Micro (markets, industries, firms, products, technologies etc.)	Market structure Concentration Size of firm Growth Profitability, rate of return Productivity Competitiveness Investments Organization etc.	Creativity Discovery Invention R&D Innovation, innovativeness Imitation Adoption Diffusion Patenting Licensing Technology diversification Different technologies A,B,... Different technical performance Parameters Trajectories Paradigms etc.

1 There is also a time dimension and studies focus to varying degrees on historical, present and future conditions, falling into categories such as history of technology, economic history, and economic/technological forecasting.

Studies dealing mainly with indicators and measurement of economic and technological variables fall into the categories labelled as econometrics, technometrics (and also scientometrics).

1.3.2 Overview of Prior Research in Europe and the USA

1.3.2.1 Classics

A comprehensive work on the history of technology in economic thought is unfortunately lacking, as is a corresponding work on something like the history of economics in engineering thought. This is not the place for such an undertaking,[13] but a few highlights

[13] A bibliometric survey and requests for help from key participants in the field through a questionnaire survey have resulted in so much material and kind suggestions that the only way to do justice to the field and its many participants is to perform the task independently of this book.

seem necessary, directed to the field of economics as recognized in Western literature. For general histories of economic thought, see e.g. Hutchison [65] and Blaug [13]. For specific histories of economic thought on technology and innovation, see various works of Rosenberg, e.g. Rosenberg [114, 115].

Pre-Schumpeter economists

References to technology among economists before Adam Smith (physiocrats, mercantilists etc.) were scarce and casual.[14]

Adam Smith (1723-90) dealt explicitly with invention and improved machinery, when elaborating upon what he saw as the main determinant behind labor productivity increases, namely the division of labor. This in turn he saw as resulting from a principle that applied solely to human beings, namely the propensity for exchange, which was constrained only by the size of the market and, as one of its consequences, led to inventions and improved machinery by both users and producers, as well as by the particular class of "philosophers or men of speculation", to whom division of labor also applied, with its benefits of improved dexterity, time efficiency and inventions, e.g. of scientific instruments, that is, inventions to improve the work of inventing.[15] Considering how immersed Smith was in the dominating agricultural economics of his time, his writing on technology, while brief, was insightful and anticipatory, although he may have drawn on much of the vivid economic discussion of his time, also addressing the role of inventions in machinery and manufacturing.

However, the first scholar who really dug wholeheartedly into what, by any reasonable interpretation, can be called Economics of Technology was Charles Babbage (1791-1871) with his work "On the Economy of Machinery and Manufactures", published in London in 1832 [8].[16] This remarkable work and author, and his treatment of economics in general and economics of science and technology in particular, certainly deserve a scholarly study in its own right. Babbage published extensively in various fields, including what was formally his own as a Lucasian Professor of mathematics in Cambridge. He also became obsessed by theoretical and practical work on a computing machine, as is well known. Already before this obsession arose, he became interested in political economics and in science and its economic implications. Of relevance in this context is also his book "Reflections on the Decline of Science and Some of its Causes", published in 1830 [7]. Incidentally he suggested in this work, true to his inclination towards constructivism,

[14] However, economic ideas about technology did exist, although not confined solely to the slowly emerging economics profession, and perhaps more so than we are inclined to think. For example, the idea of conducting collective R&D in a branch of industry was a mercantilist idea of the 17th century. Another example is the patent institute. The idea that a temporary monopoly would serve as an economically justified incentive to generating technical inventions had its first clear expression in the "Statute of Monopolies" in England in 1623 that granted temporary monopoly rights to inventors under certain conditions, i.e. patent rights as we know them today. A peculiar expression of a contrary idea is the forbidding of technical inventions in 18th-century Japan by the ruling powers in their belief that they would be threatened by such inventions.

[15] In this way A. Smith identifies an important mutually reinforcing mechanism in his economics of division of labor in which both manual and intellectual labor is improved by its division and moreover both utilizes and generates inventions for its further improvements and possible division. In a sense A. Smith may be said to have recognized the importance of learning and R&D (see Boulding [14]).

[16] For a more thorough presentation, see Granstrand [53].

reform campaigning and attention to details along with visions, a reformed university curriculum which combined natural science studies with 'Political Economy' and, nota bene, 'Applications of Science to Arts and Manufacture' (see also Chapter 19 in this book).

Although today largely forgotten, the role of his 1832 book could from the point of view of industrial economics and its extension into the economics of technology to some extent be considered to correspond to the role of Smith's "The Wealth of Nations" in general economics. Babbage's ideas of a "calculating engine" or a "difference engine" provided the prime motive for undertaking the main empirical investigation behind the book, which was to survey the state of mechanical and industrial technology in order to realize his design, conceived of as being realizable based on mechanical principles.[17] However, Babbage in a way misjudged the mechanical technology and its economics; this became his great mistake in life, a kind of misjudgement of technology that has been common in history. (See Lindgren [77].) His forgotten outstanding academic achievement and well-remembered practical failure in economics of technology are an excellent but sad case of history's irony.

In surveying the state of the art, his gifted scientific mind urged him to write a book on economics in its own right. (Perhaps this shows that Babbage was more of a scientist than an entrepreneur.) Babbage was acquainted with several economists of his time and some of their works. Apart from a few references to Adam Smith [129] in his 1832 book, in which he elaborated a great deal on the principle of division of labor, especially extending it also to division of mental labor, he referred hardly at all to works of other economists but mostly to government investigations. His search for scientific principles, also in economics, was typical of this time. In fact, many of his principles and observations (e.g. economies of scale and increasing size of the firm) have surfaced in economics much later. Of particular interest here is his emphasis not only on techniques but also on technical change and inventions, referred to as "contrivance of machinery", and its economic causes and consequences. His methodology is also of interest, emphasizing detailed empirical and statistical studies inside the firm, on the shop floor, making e.g. work studies but with automation more in mind than work rationalization of the type developed by F.W. Taylor half a century later under the label "Scientific Management" [137]. (See Granstrand [52, Ch. 12].) He urged other economists to engage in the same type of empirical studies, and even proposed a detailed questionnaire in the book to be used by others ([137, pp. 94-96]). He was trained in mathematics and esteemed theory, but insisted that it should be based on facts and promoted the use of statistics and in particular the "science of calculation" as he called it ([137, p. 316]). The following passage is typical (and some would argue that it still applies):

> "Political economists have been reproached with too small a use of facts, and too large an employment of theory. ...let it be remembered that the closet-philosopher is unfortunately too little acquainted with the admirable arrangements of the factory..." (ibid. p. 119).

[17] The difference engine was not built as planned in Babbage's days, but was built in 1991 at the Science Museum, London, in commemoration of Babbage's bicentennial, using the technology available to Babbage. This prototype works and thereby does away with the previously most common explanation behind Babbage's failure, that the state of mechanical technology of his time was insufficient.

What make Babbage's work so original in the field of economics of technology and industry are, in general terms, its focus and method of inquiry. For the first time during industrialization, industry and its employed technologies (mainly mechanical at the time) were systematically studied and put in the center of a scholarly analysis[18] rather than agriculture, banking or trade. The perspective was certainly not static or ahistorical, focusing on developments in general, including inventions and technical progress. The approach was engineering-economics-like in the sense that it was oriented around machinery and manufacturing, detailed observation, quantification, cost and quality, work processes, labor saving etc. In this sense Babbage's approach foreshadowed much later developments such as scientific management, cost engineering, management science, and operations research. In addition, he addressed a number of technology and industrial policy issues.

Babbage was a true believer in the general merits of the scientific method. He formulated a number of issues and principles[19] which have later and independently attracted much attention, such as: static and dynamic economies of scale, the learning curve (even specified with coefficient 0.2 in a given case), increasing firm size and market concentration, transaction costs, technology classification, the concept of invention, international transfer of technology, technology-induced unemployment, R&D costs, technological substitution, links between science, technology and industry, the role of science in the national economy, professionalization of science, government intervention and even the fundamental merits of a joint-stock limited liability company, later to be considered such an important innovation in capitalism (which by the way Babbage took for granted and implicitly advocated).

Thus, as an outsider just like Cournot, Babbage entered economics with new spirit and ideas, but originally motivated mainly by other needs than to produce new economics. However, in his writings he hardly returned to economics apart from some smaller works.[20] This fact may explain why his impact, which was considerable for some time after the book was published, never became sustained and generated followers. An "incumbent" scholar such as J.S. Mill (1806-1873) extensively used Babbage's ideas, as did K. Marx (1818-1883), and J. Schumpeter acknowledged the greatness of Babbage's work [125], although just in a footnote. Beyond this Babbage's work in economics was overshadowed by other research, including his own on the difference engine and later on

[18] Certainly there were other studies of industry and technology at the time, but not equal to Babbage's in terms of scholarly analysis.

[19] Babbage distinguished clearly between economic principles and mechanical principles and then tried to relate them to each other.

[20] See Hyman [66] for a somewhat panegyrical account of Babbage's work and Campbell-Kelly [16] for an edited series of volumes of the entire published works by C. Babbage.

his "analytical engine", known as the first conception of a computer, and Babbage's contribution to economics gradually fell into oblivion.[21] (See also the bibliometric survey below.)

The next major pre-Schumpeter author with a bearing on economics of technology was definitely Karl Marx. It is fair to judge him as the first economist who explicitly dealt with technological change in a macro-analysis of economic and political change. This he did in quite another manner and with quite another personality compared to Babbage, although he was well acquainted with Babbage's work, and to some degree influenced by it. Marx' role, as an economist being a careful student of technology, has without doubt been sufficiently well dealt with by N. Rosenberg to refer the reader to his work [115, Ch. 2]. See also Mac Kenzie [80] and Schumpeter [126].

Finally, Thorstein Veblen (1857-1929) deserves mention in this context for his pioneering emphasis on the importance of machinery and the engineering class[22] as well as his plea in Veblen [146] for an evolutionary approach in economics, a plea given at the time when economics began to establish marginal analysis and other parts of the coming neo-classical paradigm. Although not principally opposed to mathematics, Veblen had much of a sociological and behavioral perspective on technology and economics, a perspective which clashed with marginal and static analysis. For further reading on Veblen, see Dorfman [27].

Schumpeter

Joseph Schumpeter (1883-1950) lived through two world wars, one major revolution and one major depression, which sensitized him to the dynamics of economic and political changes as they should have sensitized any economist of his time. Yet he was relatively unusual in his day, with his thinking on the dynamics of economic development and particularly his emphasis on innovations and entrepreneurial activities as major factors in the dynamics of competition and institutional evolution. It is difficult, impossible perhaps, to make a brief description of Schumpeter's contributions to economics of technology. One complicating factor is that Schumpeter's writings are voluminous, addressing numerous issues, mostly brilliant but not always entirely clear or consistent, with changing perspectives and standpoints over time.[23] Another complicating factor is that Schumpeter's many followers[24] together with their appreciation have criticized him on a number of accounts as being weak on theory, weak on systematic empirical studies,

[21] Blaug [13] has only a mention of Babbage [8] *en passant*. Berg [11] puts his work in its historical context of the discussion of "the machinery question" and its relation to labor developments, but is mainly focusing on Ricardo's contributions on that issue. In comparison to Babbage's contributions to economics of technology and industrial economics, Ricardo's contributions (mainly in Ricardo [108]) are insignificant, though. Finally, G. Stigler wrote an appreciative but brief article 1991, commemorating Babbage's bicentennial (Stigler [132]).

[22] The importance of the engineering profession had been recognized earlier by Auguste Comte, who saw engineers as constituting an important link between science and society. However, Comte was mainly a sociologist, in fact commonly referred to as the founding father of sociology. (See Coser [20].)

[23] The latter has given rise to the reference to the young and the old Schumpeter models of technological change, firstly succinctly described in Phillips [104].

[24] Some label themselves 'Schumpeterians', some 'Neo-Schumpeterians', although the prefix 'neo', implying a revival, seems questionable as there does not seem clearly to be any generation of classical Schumpeterians or the like (except for Schumpeter himself).

inconsistent etc. This is quite in contrast to Marx, whose followers rather became victims of dogmatism. A third factor is that it is always difficult to assess the role or impact of a scholar's writings apart from mere recognition. Schumpeter received early on (before World War I) a strong and lasting positive reputation, not only in Europe, but also in the US and Japan; but his ideas and works did not become incorporated in mainstream economics, or in economic policy-making. This was again in contrast to Marx, who regardless of political preferences might be considered one of the individual economists with the largest impact ever. However, while Marx's influence is definitely on the decline, Schumpeter's is strongly increasing, partly because of its ability to provoke academic work.

Today there is an overwhelming consensus that Schumpeter has been the leading author of the 20th century on Economics of Technology. His writings have been so widely documented and acknowledged that there is no point in elaborating further on them here.[25] Of course he did not appear in a vacuum, and his impact, which was mainly post-Schumpeter, may be interpreted in various ways, some not matching Schumpeter's intentions. Some may even exaggerate his academic achievements, although they lacked a good deal in terms of systematic empirical studies and rigorous theory formation.[26] An indisputable achievement, however, is his path-breaking focus on and analysis of entrepreneurial activities as a primary dynamic factor, mediating technological and economic changes.

Except for Schumpeter's own works and various historical works, there was not much research done on economics of technology before World War II by economists, at least not theoretically oriented. The work by Sir John R. Hicks (1904-1989) and others on technical progress, focusing on process innovations and classifying technical change as neutral, factor-saving or capital-saving, deserves mention in this brief overview. There were of course others as well (e.g. Marxists, historians), addressing various issues (e.g. technology and employment, technology and long waves). The economists' neglect of technical change is dominant in the picture, however (see [13, 41]).

1.3.2.2 Post-Schumpeter and Post-World War II

It was not until after World War II that economics of technology "took off" as a field of inquiry, in the sense that groups of scholars, rather than scattered individual ones, attended to it with works related to each other in an increasingly coherent way. Causes of the long period of relative neglect, and what finally triggered a collective interest among economists in technology, could be speculated about. Suggested explanations of the relative neglect include emergence of a dominant neo-classical paradigm, committed to optimization and equilibrium analysis but with a rudimentary representation of technological change, pre-occupation with other issues like business cycles, unemployment, trade and government policy, and/or conceptions of technology and engineering as of little relevance to economics. Suggested factors that triggered economic research in the field include military

[25] See further e.g. Freeman et al. [43] and Rosenberg [114].

[26] Schumpeter has also become something of a symbolic figure among a current generation of scholars, sharing a discomfort with neo-classical theory and its neglect of technology and entrepreneurs as primary dynamic factors in the economy. A future generation may very well downplay some of Schumpeter's achievements.

R&D programs in the US in the 1950s, concomitant growth of R&D in industry, and OECD initiatives in the 1960s.[27]

One triggering event in particular was the publication of works by Schmookler, Abramowitz and Solow in the 1950s. These works showed that aggregate output could not be explained very well by increases in capital and labor, leaving most of the explanation in a residual in the aggregate production function framework.[28] Particularly Solow's work directed attention to economics of technology, partly because his framework was neo-classical, partly because he named the residual "technical change", a perhaps somewhat arbitrary but nevertheless successful choice of label.[29] An account of "the history of the residual" will be published elsewhere, to which the reader is referred.[30]

The various other developments in the field that took place in the 1950s and onwards are too complex to be justly accounted for in brief here. Besides, there are several good reviews and survey articles that the reader may be referred to. For some recent surveys of general literature related to economics (rather than management and organization) of technology (including invention, innovation, R&D), see e.g. Thirtle and Ruttan [139], Dosi [29], Verspagen [148] and Freeman [42]. For older ones, see Nelson [93] (one of the earliest), Blaug [12], Pavitt [102], Kennedy and Thirlwall [72]. For more specific surveys, see Baldwin and Scott [10], Mowery and Rosenberg [90].[31] The classic surveys of literature on diffusion of innovations, in itself a large, growing, interdisciplinary field intersecting with economics and engineering, are Rogers [110, 111]. In fact the increasing number of various surveys creates a need for a survey of surveys on economics of technology, a sign of the growth of the field.

Table 1.2 displays the books (in English) that explicitly refer in their titles to economics and technology or closely related terms. Table 1.2 also includes some early seminal articles and some related books of major influence on the field. Finally, there are several journals addressing the field, and several of them have started since the 1970s.[32]

1.3.2.3 A Bibliometric Survey of the Field

A bibliometric analysis of scientific articles on Economics of Technology was undertaken in order to learn something about the current structure of the field and its recent trends on

[27] A number of scholars have provided suggestions of this sort, many in response to a questionnaire survey, as reported in Granstrand and Persson [55]. I here gratefully acknowledge the assistance of E. Dahmén, G. Dosi, C. Freeman, Z. Griliches, H. Hanusch, B. Klein, E. Mansfield, S. Metcalfe, R. Nelson, K. Pavitt, F.M. Scherer, P. Stoneman and P. Swann.

[28] This framework goes back to Say, who made the distinction between land, labor and capital as factors of production; Wicksell, who formulated the notion of a production function; and Cobb and Douglas, who supplied a specification of the function; all of them without a specific notion of technology, however.

[29] Other labels were used as well. Abramowitz [2] carefully called it a measure of ignorance.

[30] Professor Griliches, written communication.

[31] See also Rosenberg [113, 114, 115] and Jantsch [67].

[32] Examples are *Research Policy*, *Journal of Evolutionary Economics*, and *Economics of Innovation and New Technology*. The bibliometric survey reported in the following showed that *Research Policy* was the most central journal to the field. (See further [55].)

Table 1.2 Overview of Books and Early Seminal Works Mainly on Economics of Technology[1]

Mainly European Origins[2]	Decade	Mainly USA/North America Origins[2]
(**Smith, A.** 1776, The Wealth of Nations)[129] [3] (**Marx, K.** 1867-1894, Das Kapital) [88][3] **Babbage, C.** 1832, On the Economy of Machinery and Manufactures [8] **Schumpeter, J.** 1912, Theorie der Wirtschaftlichen Entwicklung [124]	pre-1950	(**Veblen, T.** 1904, The Theory of Business Enterprise and other works) [147][3]
Carter, C.F. and Williams, B.R. 1958, Investment in Innovation [17] **Jewkes, J. et al.** 1958, The Sources of Invention [68][6]	1950	**Abramovitz, M.** 1956, Resource and Output Trends in the United States since 1870 [2] **Solow, R.** 1957, Technical Change and the Aggregate Production Function [131][5] **Griliches, Z.** 1957, Hybrid corn: an exploration in the economics of technological change [56] [5] **Nelson, R.** 1959, The Simple Economics of Basic Scientific Research [94]
Salter, W.E.G. 1960, Productivity, Growth and Technical Change [117] **Sylos Labini, P.** 1962, Oligopoly and Technical Progress [136] **Jantsch, E.** 1967, Technological Forecasting in Perspective [67][4] [5] **Williams, B.R.** 1967, Technology, Investment and Growth [150]	1960	**Mansfield, E.** 1961, Technical Change and the Rate of Imitation [81] **Arrow, K.** 1962, Economic Welfare and the Allocation of Resources for Invention [5] **Nelson, R. ed.** 1962, The Rate and Direction of Inventive Activity [95] **Tybout, R.A. ed.** 1965, Economics of Research and Development [142] **Brown, M.** 1966, On the Theory and Measurement of Technological Change [15] **Hamberg, D.** 1966, R&D: Essays on the Economics of Research and Development [59] **Schmookler, J.** 1966, Invention and Economic Growth [122][5] **Marschak, T. et al.** 1967, Strategy for R&D. Studies in the Microeconomics of Development [87] **Nelson, R. et al.** 1967, Technology, Economic Growth and Public Policy [97] **Mansfield, E.** 1968, Industrial Research and Technological Innovation: An Econometric Analysis [82] **Mansfield, E.** 1968, The Economics of Technological Change [83][5] **Nordhaus, W.D.** 1969, Invention, Growth and Welfare: A Theoretical Treatment of Technological Change [100]

[1] Although the table is intended to be more comprehensive than illustrative it is difficult to make it exhaustive. Only scholarly, research-oriented books in English that deal mainly with economics (rather than management) of technology, innovation, R&D etc. in general as expressed in the title are included, regardless of their impact. In addition a few early seminal works have been added. The selection of these is even more difficult to make in a fairly objective way.

[2] Classified according to location (in the first place) and nationality of author(s) or editor(s) at the time of the work.

[3] These works contain seminal chapters on technology, inventions etc. Many other pre-1950 economists have also dealt with technology and related matters, but in a far less pioneering or seminal way, e.g. Ricardo, Mill, Hicks, and Harrod.

[4] This is not a work mainly on Economics of Technology but it involves many economic aspects of S&T and is also a widely cited work. Being an OECD study it is not really a work originating solely in Europe.

[5] Among the most cited works in SSCI in the field.

[6] The work was carried out by one US and two UK authors.

Table 1.2 Overview of Books and Early Seminal Works Mainly on Economics of Technology (cont.)

Mainly European Origins	Decade	Mainly USA/North America Origins
Musson, A.E. ed. 1972, Science, Technology and Economic Growth in the Eighteenth Century [92] **Taylor, C. and Silberston, A.** 1973, The Economic Impact of the Patent System [138] **Williams, B.R. ed.** 1973, Science and Technology in Economic Growth [151] **Freeman, C.** 1974, The Economics of Industrial Innovation [36] **Heertje, A.** 1977, Economic and Technical Change [60]	1970	**Lederman, L.L. ed.** 1971, A Review of the Relationship Between Research and Development and Economic Growth/Productivity [76] **Phillips, A.** 1971, Technology and Market Structure [104] **Rosenberg, N. ed.** 1971, The Economics of Technological Change [113] **Wilson, G.W. ed.** 1971, Technological Development and Economic Growth [152] **Schmookler, J.** 1972, Patents, Invention and Economic Change [123] **David, P.** 1975, Technical Choice, Innovation and Economic Growth [24] **Rosenberg, N.** 1976, Perspectives on Technology [114][5] **Gold, B.** 1977, Research, Technological Change, and Economic Analysis [48] **Piekarz R.R. ed.** 1977, Relationships Between R&D and Economic Growth/Productivity [105] **Johnson, P.S.** 1978, The Economics of Invention and Innovation [69] **Gold, B.** 1979, Productivity, Technology, and Capital [49] **Hill, C. and Utterback, J. eds.** 1979, Technological Innovation for a Dynamic Economy [63] **Walker, W.B.** 1979, Industrial Innovation and International Trading Performance [145]

more objective grounds.[33] There are several important caveats in such an analysis, but these are fairly well-known and many are obvious, so they are left aside here. The field was defined through a search profile, which was applied to the online version of Social Science Citation Index (SSCI) for the equidistant publication years 1976, 1984 and 1992.[34] The year 1991 was added mainly for sensitivity analysis.[35]

Some of the results of the bibliometric analysis are shown in Figure 1.1 (visualizing parts of the "invisible college" in the field) and Tables 1.3 and 1.4. These results indicate

33 This section draws heavily on the work by Dr. Olle Persson, Inforsk, University of Umeå, Sweden in conjunction with the author and reported in Granstrand and Persson [55]. The co-citation analysis was made using the BIBMAP software, developed by O. Persson.

34 The search profile used was: (TECHN* + SCIEN* + INNOV* + INVENT* + RESEARCH* + ENGINEE* + PATENT*) x (ECON* + MARKET + CAPITAL + COMPET* + GROWTH + PRODUCTION + PRODUCTIVITY + DIFFUS* + SUBSTIT* + COST* + ENTERPRISE* + FIRM* + COMPANY + COMPANIES + CORPORATION* + EMPLOYMENT + DEMAND + SUPPLY) where +, x and * denote union, intersection and truncation respectively. A few variations of the search profile were made for sensitivity analysis but the results did not vary much. (Cf. also Table 1.1.)

35 The period of observation was stretched as far back as possible, but the SSCI online version data were judged too unreliable for pre-1976 years. For 1991 and 1992 a CD-ROM version was used to retrieve articles. There is a slight time delay between publication date and date of inclusion in the CD-ROM version, and thus some works published in 1990 are included while some published in 1992 are excluded. This dating mismatch is indeed minor, however.

Table 1.2 Overview of Books and Early Seminal Works Mainly on Economics of Technology (cont.)

Mainly European Origins	Decade	Mainly USA/North America Origins
Pavitt, K. ed. 1980, Diversification by Regulated Monopolies and Incentives for Cost-Reducing R&D [103] **Sahal, D.** 1981, Patterns of Technological Innovation [116][5] **Freeman, C.** (1982), The Economics of Industrial Innovation [37] **Freeman, C. et al.** 1982, Unemployment and Technical Innovation: A Study of Long Waves and Economic Development [43] **Giersch, H. ed.** 1982, Emerging Technologies: Consequences for Economic Growth, Structural Changes and Employment [46] **Stoneman, P.** 1983, The Economic Analysis of Technological Change [133] **Dosi, G.** 1984, Technical Change and Industrial Transformation [28] **Clark, N.** 1985, The Political Economy of Science & Technology [18] **Thwaites, A.T. and Oakey, R.P. eds.** 1985, The Regional Economic Impact of Technological Change [140] **Amin, M. and Goddard, J.B. eds.** 1986, Technological Change, Industrial Restructuring and Regional Development [4] **Freeman, C. ed.** 1986, Design, Innovation and Long Cycles in Economic Development [38] **Hall, P.H.** 1986, Technology, Innovation and Economic Policy [58] **Wyatt, G.** 1986, The Economics of Invention. A Study of the Determinants of Inventive Activity [153] **Baldwin, W.L. and Scott, J.T.** 1987, Market Structure and Technological Change [10] **Coombs, R. et al.** 1987, Economics and Technological Change [19] **Link, A.N.** 1987, Technological Change and Productivity Growth [78] **Freeman, C.** 1987, Technology Policy and Economic Performance, Lessons from Japan [39] **Stoneman, P.** 1987, The Economic Analysis of Technology Policy [134] **Amendola, M. and Gaffard, J-L.** 1988, The Innovative Choice [3] **Artus, P. et al.** 1988, Innovation, Technology, and Finance [6] **Dosi, G. et al., eds.** 1988, Technical Change and Economic Theory [30][5] **Heertje, A.** 1988, Innovation, Technology and Finance [61] **Menshikov, S.M. and Klimenko, L.A.** 1989, Long Waves in Economy. When Society Changes Its Skin [89]	1980	**Gold, B. Rosegger, G. and Boylan Jr., M.G.** 1980, Evaluating Technological Innovations [50] **U.S. Congress, Joint Economic Committee** 1980, Special Study on Economic Change [143] **Machlup, F.** 1980, Knowledge: Its Creation, Distribution, and Economic Significance [79] **Kamien, M.I. and Schwartz, N.L.** 1982, Market Structure and Innovation [71][5] **Nelson, R. and Winter, S.** 1982, An Evolutionary Theory of Economic Change [99][5] **Mansfield, E. et al.** 1982, Technology Transfer, Productivity and Economic Policy [85] **Rosenberg, N.** 1982, Inside the Black Box: Technology and Economics [115] **Sato, R. and Suzawa, G.** 1983, Research and Productivity: Endogenous Technical Change [118] **Griliches, Z.** 1984, R&D, Patents and Productivity [57] **Scherer, F.M.** 1984, Innovation and Growth [119] **Landau, R. and Jorgenson, D. eds.** 1986, Technology and Economic Policy [73] **Landau, R. and Rosenberg, N. eds.** 1986, The Positive Sum Strategy: Harnessing Technology for Economic Growth [74] **Rosegger, G.** 1986, The Economics of Production and Innovation - An Industrial Perspective [112] **Abetti, P.A. et al., eds.** (1987), Technological Innovation and Economic Growth [1] **Dasgupta, P. and Stoneman, P. eds.** 1987, Economic Policy and Technological Progress [23] **Nelson, R.** 1987, Understanding Technical Change as an Evolutionary Process [96] **Bailey, M. and Chakrabarti, A.** (1988), Innovation and the Productivity Crisis [9] **Cyert, R.M. and Mowery, D.C. eds.** 1988, The Impact of Technological Change on Employment and Economic Growth [21] **Smilor, R.W. et al.** 1988, Creating the Technopolis: Linking Technology Commercialization and Economic Development [128] **Jorgenson, D.W. and Landau, R. eds.** 1989, Technology and Capital Formation [70] **Mowery, D. and Rosenberg, N.** 1989, Technology and the Pursuit of Economic Growth [91] **Silberston, A. ed.** 1989, Technology and Economic Progress [127]

Table 1.2 Overview of Books and Early Seminal Works Mainly on Economics of Technology (cont.)

Mainly European Origins	Decade	Mainly USA/North America Origins
De la Mothe, J. and Ducharme L. M. eds. 1990, Science, Technology and Free Trade [26] **Dosi, G. et al.** 1990, The Economics of Technical Change and International Trade [31] **Gaffard, J.-L.** 1990, Economie industrielle de l'innovation [45] **Glaziev, S.Yu.** 1990, Economic Theory of Technical Development [47] **Gomulka, S.** 1990, The Theory of Technological Change and Economic Growth [51] **Freeman, C. ed.** 1990, The Economics of Innovation [40] **Freeman, C. and Soete, L. eds.** 1990, New Explorations in the Economics of Technical Change [44] **Heertje, A. and Perlman, M. eds.** 1990, Evolving Technology and Market Structure [62] **Freeman, C.** 1992, The Economics of Hope. Essays on Technical Change, Economic Growth and the Environment [41] **Deiaco, E. et al.** (1991), Technology and Investment: Crucial Issues for the 1990s [25] **OECD** 1992, Technology and the Economy: The Key Relationships [101] **Foray, D. and Freeman, C. eds.** 1992, Technology and the Wealth of Nations [35] **Stoneman, P. ed.** 1993, Handbook on the Economics of Innovation and Technical Change [135]	1990 -1993	**Trajtenberg, M.** 1990, Economic Analysis of Product Innovation [141] **Howard Jr., W.G. and Guile, B.R. eds.** 1992, Profiting from Innovation [64] **Scherer, F.M.** 1992, International High-Technology Competition [120] **Scherer, F.M. and Perlman, M. eds.** 1992, Entrepreneurship, Technological Innovation, and Economic Growth [121] **Mansfield, E. ed.** 1993, Economics of Technical Change [84]

that during 1976-1992 the field has grown in absolute number of articles,[36] as have the number of cited works per article, the number of multi-cited authors per article, the median age of cited works, and the connectivity of the field as indicated by the number of times the same pair of authors is cited by an article in the field.[37]

Observations like these show that (a) the rate of growth of the "intellectual base" of the field has stabilized somewhat; (b) the intellectual base made explicit through citation in each article has grown on an average[38] and so has its span of historical attention; (c) the field has become integrated and has established a fairly stable core of key participating authors. The latter is supported by Figure 1.1 and the ranking lists in Table 1.4 of most cited authors. The ranking lists show a stabilizing top with a layer of upwardly and downwardly mobile authors below. Most names on the top and in the mobile layer next-to-top also appear on the co-citation map in Figure 1.1, which then indicates the existence of a stabilized, connected intellectual core of the field. A few names on the top are not on

[36] The field has grown very rapidly by various measures since the 1960s, even "exploded". In terms of annual number of articles the growth has levelled off somewhat towards the end of the 1980s, perhaps indicating the establishment of the field with stable growth.

[37] Connectivity could be indicated in various ways but the main result still obtains.

[38] This growth is not proportional to the growth of the field, however, which could result from a growing body of "commonized" knowledge, i.e. knowledge for which the propensity to cite has gone down. Also there are common conventions formed about reasonable limits on the total number of citations for an article of a certain size, which in turn has not grown on an average. The attention of an individual scholar is moreover not growing as fast as the aggregate attention of the growing collection of scholars active in the field.

the map, notably R. Solow. This author is certainly prominent but not sufficiently integrated with other prominent authors in the particular field of Economics of Technology.[39]

A more detailed examination, not displayed here, suggests that cited works collectively span over an increasing number of fields other than economics of technology (indicating increasing external diversification), as well as an increasing number of nationalities of institutions and authors (i.e. increasing internationalization) and an increasing historical integration, indicated by increasing age of the oldest cited works and increasing median age of cited works. Moreover, it appears as if the field is also increasing its internal structural diversity (internal diversification) with new clusters of authors having stronger connectivity among themselves than between other author clusters in the field. At the same time the core appears to be "hardened" by stabilizing citation patterns, giving the overall picture of a field that is getting increasingly structured but with a preserved and even strengthened core.

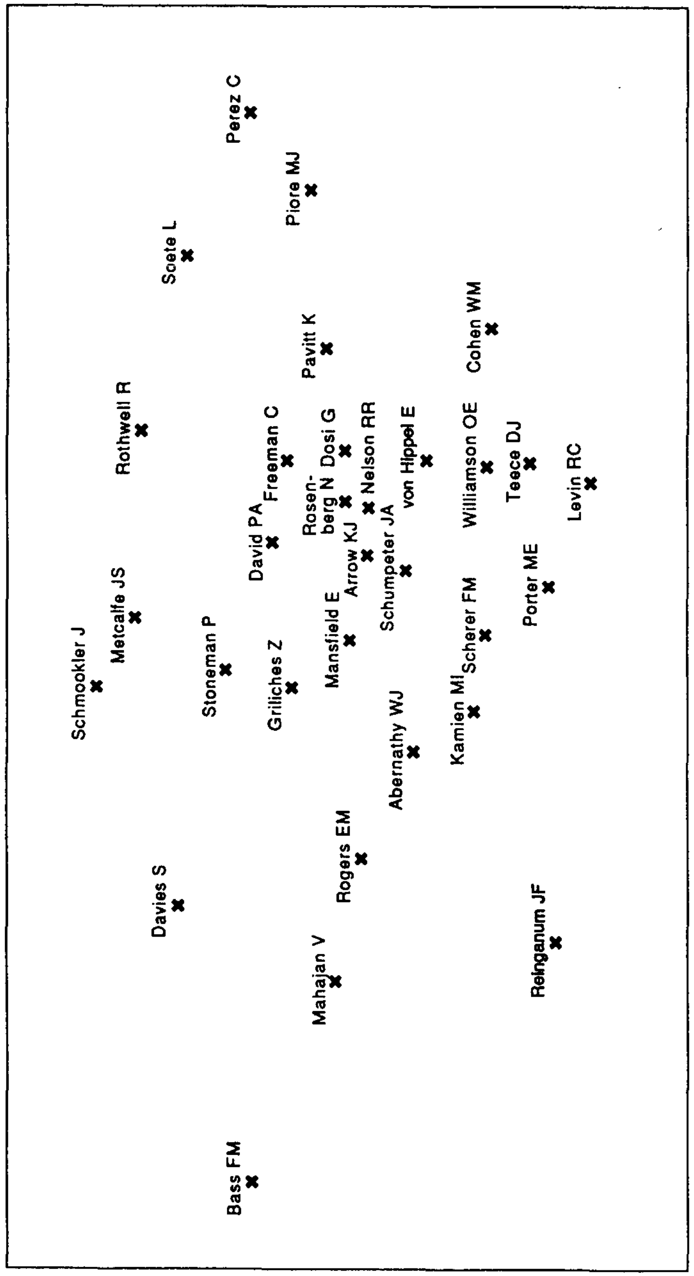
It is difficult to characterize the internal field structure by labels solely on the basis of a bibliometric analysis. For that purpose a questionnaire survey was also undertaken, directed to key participants in the field as mentioned earlier. The results cannot be reported extensively here. A few comments may suffice in connection with Figure 1.1 and Table 1.4.

J. Schumpeter is without doubt the father of the field in terms of citation appearance and influence upon others, as is widely acknowledged.[40] His prolific writings also span many facets of the field, and in fact may be said to have generated some of them. In his role of being of outstanding originality and preserved centrality in the field he is unique. Another original participant in the field but of far less significance than Schumpeter on the whole is J. Schmookler with his path-breaking use of patent statistics to advance the hypothesis that innovation was essentially demand-led, which was in sharp contrast to at least the young Schumpeter's view, namely that innovation was essentially pushed by exogenous science and technology. This early appearance of clear but conflicting hypotheses spurred several subsequent activities in the field. Except for Schumpeter and Schmookler, all key

[39] The Nobel Prize Winners appearing in the top citation ranks are:
Kenneth Arrow, Harvard and Stanford University, and John Hicks, Oxford University (joint prize winners 1972 with the official motivation: "for their pioneering contributions to general economic equilibrium theory and welfare theory"); Herbert Simon, Carnegie-Mellon University (prize winner 1978 with the official motivation: "for his pioneering research into the decision-making process within economic organization"); George Stigler, University of Chicago (prize winner 1982 with the official motivation: "for his seminal studies of industrial structures, functioning of markets and causes and effects of public regulation"); Robert Solow, MIT (prize winner 1987 with the official motivation: "for his contributions to the theory of economic growth"); and Gary Becker, University of Chicago (prize winner 1992 with the official motivation: "for having extended the domain of microeconomic analysis to a wide range of human behavior and interaction, including nonmarket behavior"). Of these it is only K. Arrow and H. Simon who also appear in the co-citation core of the field.

[40] A co-citation analysis was done especially for C. Babbage as a test. Although Babbage linked up with authors like A. Smith, J. Schumpeter etc. he did not enter the field in terms of citation. In fact Babbage [8], as well as Babbage as an author in the field, must be classified as an almost forgotten singularity.

Figure 1.1 Most Co-cited Authors in Articles on Economics of Technology from Social Science Citation Index 1991-1992.



Source: Grandstrand and Persson [55]

Table 1.3 Basic Data on the Set of Articles in Social Science Citation Index on Economics of Technology

	1976	1984	1992
No. of articles identified for analysis	164	252	263
No. of citations	3641	5700	6912
No. of works cited at least twice	245	487	673
No. of author pairs co-cited at least twice	724	1765	2927
Percent connected	5.42	5.58	8.50
Median year of cited work	1970	1975	1983
Average number of cited works per article	15	18	23
Average number per article of multi-cited authors (defined as cited by at least two articles)	1.5	1.9	2.6
Number of articles clustering at the level of 5 co-citations (integration index)	0	9	25
Pre-WW2 works cited	Stratton 1941 Schumpeter 1939 Say 1819	Stigler 1939 Schumpeter 1939 Allen 1938 Coase 1937 Keynes 1936 Hicks 1932 Hotelling 1932	Schumpeter 1942 Bernal 1939 Schumpeter 1939 Coase 1937 Keynes 1936 Schumpeter 1934 Lotka 1926 Veblen 1919 Schumpeter 1912 Ravenshear 1908 Gompertz 1825

participants in the field in 1993 were then alive, which supports Derek de Solla Price's thesis that by far most (>80%) scientists in a field are alive (Price [106, p. 1]).[41]

The micro-economic type of modelling and econometric analysis of R&D, innovation and diffusion, spurred by increased US spending on R&D, especially military R&D, has

[41] A similar type of calculation shows that with a 40-year working lifetime and a 10-year doubling time of knowledge in a given field, over 90% of the existing stock of knowledge will be produced by scientists and engineers still alive and active [54, p. 368].

Table 1.4 Most Cited Authors by Articles in Social Science Citation Index on Economics of Technology[1] in 1976, 1984, 1991, 1992. (The number of citations is given after the author name.)

1976		1984		1991		1992	
Mansfield E	19	Mansfield E	22	Mansfield E	31	Mansfield E	27
Vernon R	10	Nelson RR	21	Freeman C	26	Nelson RR	25
Rogers EM	9	Arrow KJ	17	Nelson RR	26	Rosenberg	24
Solow RM	9	Griliches Z	15	Rosenberg N	26	Schumpeter JA	23
Nelson RR	8	Schumpeter JA	14	Schumpeter JA	20	Griliches Z	19
Griliches Z	6	Freeman C	12	Arrow KJ	19	Arrow KJ	18
Kuhn TS	6	Stigler GJ	11	Porter ME	19	Freeman C	18
Marx K	6	Berndt ER	10	Scherer FM	19	Dosi G	16
Pavitt K	6	Rosenberg N	9	von Hippel EA	18	Kamien MI	16
Schmookler J	6	Becker GS	8	Dosi G	17	Rogers EM	16
Schumpeter JA	6	Rothwell	8	Griliches Z	15	Porter ME	15
Vaitsos CV	6	Solow RM	8	Mowery DC	15	Scherer FM	15
Baumol WJ	5	Binswanger HP	7	Rogers EM	15	Williamson OE	15
Fedorenko NP	5	Galbraith JK	7	Teece DJ	15	von Hippel E	13
Hamberg D	5	Hicks JR	7	Williamson OE	15	David PA	11
Johnson HG	5	Kmenta J	7	Pavitt K	13	Baumol WJ	10
Simon HA	5	Kuhn TS	7	Rothwell R	12	Mahajan V	10
Arrow KJ	4	Lall S	7	David PA	11	Abernathy WJ	9
Becker GS	4	Simon HA	7	Kamien MI	11	Cohen WM	9
Behrman JN	4	Vernon R	7	Levin RC	10	Pavitt K	9

1 'Economics of Technology' as defined by the search profile described earlier, applied to Social Science Citation Index (SSCI).

occupied a prominent role throughout the years with E. Mansfield as a leading author in terms of citations but also with authors like Z. Griliches, R. Nelson[42] and F.M. Scherer. Younger US scholars have appeared with some influences from this US tradition (e.g. D. Teece, R. Levin, W. Cohen). Diffusion research with a more sociological (e.g. E. Rogers) or marketing orientation (e.g. F.M. Bass) has also been present, but somewhat isolated. Economic historians (e.g. N. Rosenberg, P. David) have been present all the time, while historians of technology have been absent.[43]

Macro-economic works have less presence than micro-economic ones. However, developmental economics entered the field early (e.g. S. Lall, C. Vaitsos) as did international trade economics (e.g. R. Vernon).

Economic works with inexact labels, i.e. more qualitative and empirical, often historic, analytical at both micro and macro levels, often originating outside the mainstream economics profession, have emerged in Europe, especially around SPRU with C. Freeman

[42] Richard Nelson, however, is nowadays mainly referred to as a central figure in evolutionary theory and criticism of neo-classical theory. See e.g. Nelson and Winter [98, 99].

[43] This is not necessarily a reason for criticism of any sort. It may rather be a result of the analytical procedure employed here.

as a central figure among several others (G. Dosi, K. Pavitt, C. Perez, R. Rothwell, L. Soete). Much of evolutionary economics is associated with this type of economics. As evolutionary economics is evolving, with R. Nelson as one seminal author, it also embraces other types of economists (e.g. S. Metcalfe), often distinguishing themselves from "orthodox economics".

A few works and authors appearing in the field have been in management and organization studies rather than in economics (e.g. M. Tushman, E. von Hippel). Few if any, however, have been recruited from typical business economics (accounting, finance etc.).

Authors who, in their writings, apparently have worked more outside than inside the field, but still appear in the field's revealed intellectual base, are K. Arrow, R. Solow, and O. Williamson.

Authors who apparently work in the field but do not appear in its intellectual base as revealed by citations are conceivable, of course. A category which is missing, apart from historians of technology and business economists, is active rather than converted engineers, an observation that could be taken as somewhat surprising. Some of them appear in works in the operations research tradition, in the R&D management tradition, in the cost engineering or engineering economics tradition, but not at all connected to the core of the field.[44] The field is in fact dominated by economists, trained as such. Although the field includes authors with origins in some other disciplines as well, it is not typically interdisciplinary from this point of view. Nor is it truly international, being dominated by an Anglo-Saxon tradition with key authors missing from e.g. Russia and Japan.[45] A certain shift of relative emphasis from the US to Europe seemed to take place in the 1980s.

1.3.3 Summary

In summary, economics of technology has displayed a delayed but recently rapid growth into a sizeable field of academic inquiry, with recent decades showing: fairly stable growth, some diversification and internationalization with an Anglo-Saxon dominance and an apparent relative shift recently from the US to Europe, increasing historical rooting, increasing internal diversity, formation of common knowledge, integration and establishment of a central intellectual core having a dominant discipline (economics) but with a heterogeneous theoretical base and new approaches (especially Schumpeterian and evolutionary ones) emerging, partly in cooperation, partly in competition with old ones (especially neo-classical ones), the latter being originally developed primarily for applications outside the economics of technology.

The size of the field is not small, as one could perhaps have expected. In fact it is probably approaching the limits of being possible to command and continually survey by

[44] A similar search was carried out in SCI (Science Citation Index) but did not reveal much.

[45] This is particularly surprising, considering the conscious attention paid to the economics and management of technology in practice in Japan. In a planned economy, similar attention would have been natural. See also Chapter 16 for an account of Russian works spurred by N.D. Kondratieff.

a single individual.[46] Moreover, the establishment of a core of incumbents tends to stimulate a growing amount of inward looking in a field, thereby paving the way for radical renewal coming from outside in a manner not unlike what happens in "real" markets (as opposed to "intellectual" markets).[47] A renewal of the field would then not be unlikely and, if it is initiated by new entrants, these have to come e.g. from other countries than those currently dominating (e.g. from Japan or some other Asian country), from other disciplines (e.g. engineering or mathematics), from other theoretical approaches (e.g. evolutionary approaches or systems theory) and/or from a new generation of scholars.[48] Influences outside academia could of course be instrumental as well, such as environmental concern or political or corporate concern over competitiveness.[49]

1.4 Outline of the Book

The various authors and chapters in this book represent a wide variety of backgrounds, perspectives and research problems. This is by design. They were selected not because they coherently treated a narrow theme, but because their scholarly work dealt with the indeed complex and many-faceted phenomenon of technology from diverse angles and perspectives of economics, technology and history. There are no natural clusters among them and instead of sorting the chapters into various constructed parts of the book, they are sorted alphabetically by author's name.

The authors represent economists, who constitute the largest group of contributors, technologists and historians, both economic historians (E. Dahmén, P. David, N. Rosenberg) and historians of technology (T. Hughes, S. Lindqvist, U. Wengenroth). History studies and approaches were at the outset considered to be important in themselves, but also as a means to strengthen the links between economics and technology.

Moreover, the authors represent various levels of analysis (macro, micro). Most of them present empirical studies, but to varying degrees also together with theoretical perspectives. Pure theory has not been emphasized, as it was felt that a field like economics of technology should grow mainly from its empirical roots.

Although scholarly variety has been attempted in order to illuminate many techno-economic relations, a book like this cannot cover everything and should never pretend to do so. Thus, a number of areas and perspectives are more or less missing, notably military technology (perhaps the largest case of R&D over-investment ever), environmental economics of technology (which should be an exciting and important sub-field), geographic perspectives and regional economics (which is a large subject, some of it dealing with

[46] The field currently grows by roughly one article per day with several hundreds of participants, whose number also grows. It has been hypothesized by de Solla Price that an invisible college would start to disintegrate when its number of participants grows beyond a few hundred members (Price [106, p. 72]).

[47] An academic field could be viewed in a stylized way as an intellectual market or rather an intellectual exchange economy with highly differentiated products exchanged among agents, acting in the dual roles of users and producers, paying each other with recognition (expressed in terms of e.g. citations). This analogy could be carried further, of course, just as it has limitations.

[48] A look at the age structure of authors in the core of the field suggests that there will be a generation shift in the coming years.

[49] Environmental concern is in fact a good example of a concern that involves both economics and technology in a close way.

technology, innovation, and diffusion), legal aspects of economics of technology, e.g. intellectual property rights (which should grow in importance in an emerging information society with increasing competition for intellectual resources), policy-oriented studies, e.g. regarding technology and unemployment, or technology and regulation, and finally studies oriented more towards management of technology. Policy and management aspects of technology feature occasionally in the book as a perspective but not as a main focus.

Bo Carlsson and his co-authors in Chapter 2 exemplify a highly justifiable research undertaking in economics of technology. They try to trace specific economic effects—productivity and growth in Swedish engineering industry—of a specific technology, factory automation technology, through the use of various methods and data sets: interview data, survey questionnaire data and simulation data. The interaction between changes in factory automation and economic changes in productivity and growth turns out to be more complex than a simple strong, positive, directed causation. However, the latter is often assumed both for factory and office automation but then on questionable grounds, which has been emphasized by several other studies as well. A multi-method approach, as used by Carlsson, is then particularly valuable, since absence of evidence may result from bluntness of a particular method or from absence in reality itself. The more the same relation is investigated by different methods, the more any repeated absence of evidence can be taken to support the proposition that there is no relation, at least not on an average in a short, specific time period in a specific context.

Paul David in Chapter 3 proceeds, as some other pioneering economists do as well, from opening the once "black box" of technology to opening the "black box" of science. David demonstrates not only the feasibility of doing economic research—investigating productivity etc.—within the realm of science but also the feasibility of applying a particular type of stochastic, dynamic modelling, that ought to trigger much continued research along promising lines. In this way David is able not only to extend and combine econometrics, scientometrics and technometrics but he will also be able to create significant contributions to the science of science, more specifically the economic science of science.

In Chapter 4 Giovanni Dosi and Luigi Orsenigo take a comprehensive view of an entire economic system and embark on the venture of testing evolutionary and non-evolutionary modelling against a set of stylized facts. Their research strategy is particularly interesting and relevant since they have chosen to perform the modelling at micro level and test at macro level against facts, some of which are technology-related. It can be argued that a good map or model at some level of analysis should always leave out some amount of detail at a lower level of analysis, but it should be compatible with a variety of important facts[50] and should not produce anything that evidently has no foundation in facts.

A comprehensive view of an economy from micro and macro levels of perspective is also taken in Chapter 5 by Gunnar Eliasson. Rather than testing received modelling approaches, Gunnar Eliasson proposes several elements of a theory that has been developed together with a simulation model. Although not yet fully developed, the theoretical approach is rich in ideas and has many attractive features, one being its

[50] Emergent properties being possible exceptions, i.e. properties that emerge at a higher level of analysis without being deducible from aggregation.

potential coherence, which is supported by the simulation model and its partial calibration to the Swedish economy. The approach is in line with, and extends, much contemporary thinking about innovations, economic organization and development, thinking rooted in especially the young Schumpeter's ideas and work.

In Chapter 6 Martin Fransman presents the thinking of some leading Western economists on the problem of knowledge segmentation and integration, together with the practice in some leading Japanese companies of dealing with the problem, e.g. in relation to R&D. Apparently, there is no reason to assume that this is just another case of Western thinking successfully applied in Japanese practice. Nevertheless it is striking when reading Fransman's in-depth account of how well suited the Japanese organizational practice currently is to deal with this universal problem. Considering other reported virtues of Japanese industry in dealing with many technology-related problems, one is wondering whether Japan has a better experimentally organized economy in Eliasson's terms.

An attempt to formally represent technology and construct a cardinal knowledge measure is presented in Chapter 7 by Ove Granstrand. A systems-theoretic framework for analysis of technological, technical and economic changes is moreover presented, and then used to probe the question of how technological and technical change affects market structure. The entire approach is new in its explicit modelling of how technical developments interact with market evolution.

Hariolf Grupp in Chapter 8 combines modelling, statistical analysis and case studies in a concerted attack on the question of how much science is involved in various technological areas. Aside from the merit of being a multi-method approach, Grupp's chapter also illustrates the merits of using patent and publication statistics. As such statistics constantly become richer and more amenable to what can be called computer-integrated research, the stock of research results based on such data can be expected to grow rapidly. Hariolf Grupp is well positioned in this development with his research.

The focus of Håkan Håkansson in Chapter 9 is on business relationships. To consistently apply this focus in economic research is at the core of the so-called network modelling approach in economics, organization and marketing management studies, an approach to which Håkansson among others has made many contributions. This approach is also quite fruitful since it focuses on a fundamental element in building economic organizations and in building an organization theory. At the same time it can be argued that business relationships have traditionally been dealt with in a highly stereotyped manner, assuming away much of their cognitive, social and dynamic features. As more knowledge is gathered about the dynamics of the evolution of a business relationship in itself, its power as an explanatory factor in more aggregate evolutionary processes among agents in an economy will most likely increase.

The first historian of technology in the book, Svante Lindqvist, argues in Chapter 10 that much of our commonly applied focus in economics of technology is distorted. It is distorted in the sense that there is too much focus on new technologies and recent changes in technological levels and too little focus on what Svante Lindqvist calls the technological volume, that is, the existing stock of technology already embedded in men and their machinery. Fresh technologies and their significant R&D efforts attract significant economic research efforts as well, while the stock of existing and declining technologies determines much more of the current economy. Lindqvist's plea is to some extent related to the plea made by several economists for more studies of technology diffusion and substitution, but Lindqvist goes further, putting more emphasis on the late stages of diffusion and decline, and especially on the decline or persistence of whole technological systems.

Almarin Phillips and his co-workers focus on the relation between technological innovation and market structure in Chapter 11. In contrast to what used to be the common approach in economics, namely to focus on how market structure influences the rate of technological innovation, they focus on how a market is formed and how technological innovation influences its formation process and structure. They contribute a piece of business and technology history with a strong Schumpeterian flavor. Moreover, Almarin Phillips does not do history solely for its own sake but in addition presents rich food for thought about a multitude of pending issues in economics of technology.

The connection of science with technology is returned to in Chapter 12 by Nathan Rosenberg, with quite another approach compared to Hariolf Grupp's in Chapter 8. Nathan Rosenberg's more qualitative approach allows his historical light to illuminate from a variety of angles the interactive nature of science, technology and economy with all its time delays, uncertainty and complexity, which constitute the feedback structure. This feedback structure has an important fine structure at micro level in the sense that there is quite a lot of interaction among various S&T disciplines themselves. Moreover, there is evidence that this interdisciplinary interaction is of growing importance, economically as well as scientifically. However, we know little about the dynamics of this interaction, how specialties and disciplines evolve, and how they "move", combine and transform in an expanding knowledge universe. At the same time we know how easily the economic organization with its institutional structure hampers interdisciplinary interaction. Nathan Rosenberg does not do history solely for its own sake either, but deals as well with the web of organizational problems and policy issues arising from the diverse complex relations in the science, technology and economy system.

Mike Scherer gives an illustration in Chapter 13 of how much a combination of methods can achieve when intelligently and systematically applied. The results from his microeconomic "triathlon" analysis give exhaustive answers to many theoretically as well as practically pressing questions at micro level about the strategic behavior of companies facing technological innovation. Moreover, Scherer is able to identify several highly interesting consequences at macro level regarding international competitiveness and trade and international division—and possible international duplication—of R&D labor.

Also Luc Soete in Chapter 14 addresses technology and international competitiveness and trade, but with the main focus on national policy level and on strategic behavior of nations facing technological innovation as well as facing increasingly internationalized firms and technology flows. In fact, international trade theory is one of the areas of economics in which technology considerations have significantly transformed traditional economic theory, i.e. the theory about free trade, which has also been a theory fairly free from technology. However, Luc Soete, as well as Mike Scherer in the preceding chapter, point out possible distortion effects internationally from strategic behavior of companies and nations. One could then argue, as Luc Soete does, in favor of supranational policy-making in order to avoid such effects. This in turn would call for further theoretical developments in the area, which will be highly interesting to watch in the future.

In Chapter 15 Ulrich Wengenroth gives a detailed history of steel-making technology and history. Like Almarin Phillips' history in Chapter 11, Ulrich Wengenroth's history is interesting in itself but also gives food for thought experiments and economic theorizing. For example, how do the cases of UK and German steel industry compare with the cases of US and Japanese industries as described by Mike Scherer in Chapter 13? How would various UK and German steel companies have fared 1870-1970 with different mixes of Scherer's submissive and aggressive R&D and technology strategies? How would the UK and German steel industries as a whole have fared under various combinations of free trade and strategic trade regimes in their respective home markets? Is path-dependency, which is generally important as argued by Paul David, Giovanni Dosi and others, weakened or even removed and a new path-dependent process restarted when technological paths bifurcate between two periods of technological dominance or technological monopoly as in the Wengenroth case?

Certainly, it may be enormously difficult to assess various technological trajectories in terms of long-run optimality, even ex post with in-depth historical studies as demonstrated by Ulrich Wengenroth. Appraising long-run investments in new technologies is a far cry from one-shot net present value calculations.

Chapter 16 by Yuri Yakovets is a bold and stimulating attempt to extract patterns of regularity in the long-run interaction of technical and economic changes. Cyclicity, periodic or not, has always attracted the interest of philosophers and men of speculation, including scientists such as Yuri Yakovets. It is a bit of history's irony, or perhaps more a bit of evidence of the force of cyclicity, that research interest in economic cycles, with Kondratieff as a portal name, grew so strong in an economic system designed to counteract them. Yuri Yakovets may have many dissidents in his area since his approach is thought-provoking as well as non-Popperian in its disregard for falsifiability. But so is much of the very interesting field of astronomy.

In Chapter 17, Erik Dahmén embarks, with life-long experience as economist and scholar, on a judgmental Odyssey in economics from what were originally intended to be some summary remarks upon the symposium behind this book and its topic. This resulting chapter reflects his deep concern over economics as a subject, with its sins of commission to politics and mathematics and its sins of omission of technology and industrial transformation explicitly pointed out. Dahmén's chapter and his constructive proposals also reflect his engagement for the development of economics in new, promising directions. Schumpeter is the main source of inspiration behind Erik Dahmén's proposed conceptualizations and meso level of analysis (development block etc.).

Finally, Thomas Hughes in Chapter 18 continues Dahmén's Odyssey beyond economics and puts economics and technology in perspective. His case of military technology should give sobering thoughts in the wake of economics of technology to all who might be tempted to believe there is something like a "technological fix" in the economy as well as in the subject of economics. Thomas Hughes actually points at limitations of two kinds pertaining to economics of technology. First, a lion's share, perhaps half, of the world's technology is generated outside the regular economy, that is, in the military sector. Second, the current concepts and tools of economic analysis are too dull for comprehending and analyzing the complexities of technology properly.

Hopefully—indeed—these limitations will recede.

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CHAPTER 2

Factory Automation and Economic Performance: A Micro-to-Macro Analysis

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Chapter contents:

Abstract

Swedish industry is among the most highly automated in the world. The reasons why Sweden has attained a position of leadership in factory automation are explored in the research project "Sweden's Technological System and Future Development Potential." The purpose of this paper is to examine the implications of automation for various aspects of economic performance.

The first part of the paper reports the results of a series of interviews at the firm and plant level concerning the context of various automation decisions and their consequences. The second part analyzes the results of a questionnaire survey of automation in about 350 Swedish manufacturing entities. The third part is based on a set of simulations on the Swedish micro-to-macro model in which an attempt has been made to model automation.

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