Technological Change

What do Technology and Change stand for?

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Abstract

Technological change is a loose concept that has multiple meanings. The concept originates in the 1930s from issues concerning unemployment. It was subsequently applied to the study of economic growth, namely productivity.

This paper documents the origin and subsequent uses of the concept through the main theoretical contributions made. The concept has two broad meanings, a restricted and a large one: change in methods or techniques of industrial production and diffusion of new invention or technology through society. These meanings are explained according to the scholars' interests, namely the 'agent' studied. From the very beginning, the study of technological change was concerned with the effects of technology on *people*'s lives (unemployment, culture), hence a large meaning. Over time, the concept was distinguished or separated from these issues and achieved 'autonomy'. It concerns *firms* and techniques of production as tool for maintaining or increasing productivity.

Over the twentieth century, the concept of technology gave rise to two phrases that crept into the vocabulary of scholars and laymen alike: technological change and technological innovation. This paper is concerned with the former. Technological change is a phrase that emerged in the interwar years and that, by the 1950s, was "a modern sounding term", as a US Commission put it in 1960.

In November 16, 1960, a Commission on National Goals transmitted its report *Goals for Americans* to US President Eisenhower. Asked to identify the main goals and public programs for the next decade, the commission included in the report one chapter titled "technological change", an indication of the importance of the issue to Americans. Written by Thomas Watson, President of IBM, the chapter is concerned, among other things, with automation and the problem of unemployment. "Technological change has not always brought a better life for all in the past … If not controlled, [technological change] causes real displacement in the working population. [Yet] automation can, if properly applied and understood, give us the opportunity to put more production people into better jobs" (President's Commission on National Goals, 1960: 193-94).

Among the recommendations the Commission made, one was the creation of a commission to study the effects of technological change upon people. The said Commission, whose members included sociologist Daniel Bell and economist Robert Solow, was set up in December 1964 as the National Commission on Technology, Automation and Economic Progress. After one year of work, the Commission submitted its report *Technology and the American Economy* to Congress. The report is a huge one, considering a series of contracted studies included as appendices. It deals entirely with with technological change and the "belief that technological change is a major source of unemployment". To the Commission, "technology has, on balance, surely been a great blessing to mankind". The task of the next decades is to better align technological change to the fulfillment of human purposes (National Commission on Technology, Automation and Economic Progress, 1966: xii-xii).

What is technological change? To the Commission on National Goals, technological change is "the development of a better way of doing a known job or the discovery of how to do a previously impossible one" (President's Commission on National Goals, 1960: 193). To the Commission on Technology, Automation and Economic Progress, technological change is "new methods of production, new designs of products and services, and new products and new services" (National Commission on Technology, Automation and Economic Progress, 1966: xi). Briefly stated, these definitions sum up to what others call invention or technological innovation. What then is the difference, if any, between technological change and technological innovation?

This paper is a conceptual history of the concept of technological change. It studies the origin and subsequent uses of the concept through the main theoretical contributions made. The period covered is c.1930-60s, namely from the emergence of the phrase to that of its competitor: technological innovation.

To many, "Change in technology and technological change are used interchangeably …", as economist Edwin Mansfield does (Mansfield, 1968b: 4). One idea developed in this paper is that there is a difference between the two. In 1972, in a long review of the economic literature on "technical progress" (60 pages), Charles Kennedy and Anthony Thirlwall, Kent University, England, suggested that technical progress refers either to the *effects* of changes in technology on the economic growth process, or to "*changes* in technology itself [technical change], defining technology as useful knowledge pertaining to the art of production" (Kennedy and Thirlwall, 1972). There are also two uses made of technological change. One is the study of the diffusion or use of technology in society and economy. Here, 'change' refers less to technology than to social and economic effects, like change in productivity and unemployment. The other use made of the concept of technological change is the study of change in or generation of technology. 'Change' refers to new technology and the process of generation of technology.

A Diversity of Meanings

Technological change is a very loose concept that has diverse meanings, depending on the discipline (Table 1). One meaning is a large one. Technological change is *technological* "*advance*" or *"improvement"* or "*progress*", terms often used as synonyms for technological change in the literature. True, a few scholars make a difference between technical progress and technical change, like Kennedy and Thirlwall do. But in general, both progress and change are used interchangeably.

Table 1.

Technological Change: Meanings

- New technological inventions
  - Used to discuss effects of technology on society and culture (change)
- New production techniques (industrial processes)
  - Used to study the role of technology as a factor of economic growth (productivity)
- Change in the production function
  - Used for measurement

In line with this first meaning, technological change refers to new technologies – tools, facilities, services – and their effects on society and culture: how people adapt or *adjust*, to use William Ogburn's term, to new technologies. Such is the use anthropologists make of the concept (e.g.: Hodgen, 1952; Mead, 1953; Spicer, 1952; Foster, 1962). To Margaret Mead, technological change is "the introduction of new tools and new technical procedures" (Mead, 1953: 9). Mead's interest is the study of technological change on cultures. To Margaret Hodgen, technological change is "alterations in the customary occupational habits of a group, expressed in the willingness of one or more individuals to adopt new tolls or techniques, to improve old products, or to manufacture objects hitherto not made in the local community", or "technological changes are envisaged as having taken place when a tool, a device, a skill or a technique, however unknown or well-known elsewhere, is adopted by an individual in a particular community and is regarded as new by the members of that community" (Hodgen, 1952: 44-45).

Sociologists use the phrase in a large sense too (Ryan and Gross, 1950; Colum Gilfillan, 1946, 1952; Eugene Wilkening, 1956; Everett Rogers, 1958, and Rogers and Beal, 1958), as most of us do. [1] For example, to Everett Rogers, technological change is the adoption of a new farm practice: "technological change is defined as the degree to which individuals [farmers] accept new technological practices": new seed varieties, fertilizers, machines, livestock feeds, etc. "The adoption of farm practices scale is the operational measure of the concept of technological change" (Rogers, 1958: 137). In this sense, technological change is more or less a synonym for technological innovation, although some scholars make a distinction with innovation: technological change refers to the *result* or *outcome* of innovation; innovation is the *action* leading to technological change (Marquis, 1969; Gerstenfeld, 1979).

To economists, technological change has a more restricted meaning related to changes in *production techniques* or methods of production (industrial processes), of which mechanization ("changes in mechanization", Jerome, 1934), then assembly line, then automation were emblematic in the 1930s and after. [2] This is the main theoretical meaning of the phrase: "A change in technique, in the wider sense of the term, as referring to changes in the methods of production" (Kaldor, 1932: 184); "Changes in techniques … result[ing] from discoveries of new methods of production" (Robinson, 1937: 131-32). The concept focuses on industrial techniques as factors of economic growth or productivity.

From this conceptualization came a prolific literature from management and policy concerned with "technological unemployment" and labour-management relations on the one side, and technological change (introduction of new methods of production in enterprises) on the other. This issue is one of the main factors leading to a large and non-

[1] A few occurrences in William Ogburn (1933), Bernhard Stern (1937), Talcott Parson (1951).
[2] One early use of the term in this sense is Alvin Hansen. Hansen uses both technical change and technological change, yet with no theorization (Hansen, 1921).

specialist use of the term technological change. Such is the conception of the two American commissions discussed above, of various hearings before committees of the US Congress (US Congress, 1941, 1955, 1961), of the American Assembly (Columbia University) (Dunlop, 1962) and of organizations like the Industrial Relations Research Association (Somers, Cushman and Weinberg, 1963).

Some make a distinction between technical and technological change. To Jacob Schmookler, technological change is "change in knowledge" and technical change is "change in technique" (change in practice). The latter is "the ultimate purpose of technological change" (Schmookler, 1966: 2). [3] To Edwin Mansfield**,** the technical (technique) refers to "a utilized method of production" and the technological or technological change to "advance in knowledge to the industrial arts" or "advance in technology" or technique "first discovered" (Mansfield, 1968b: 3, 10, 11). To Irwin Feller, technological change (or technological progress) "involves the creation of a new set (which includes the old one) of production alternatives"; technical change (or shift in technique) is "a change in production method out of the existing (technological) set of alternatives" (Feller, 1972: 155). To Chris Freeman, the technical (of technical innovation) refers to "the commercialization and spread of new and improved products and [industrial] processes in the economy", and the technological to techniques or "advances in knowledge" (a body of knowledge) (Freeman, 1974: 18, footnote 1). Yet, the uses of the two concepts are far less differentiated than these authors lead us to believe. Most of the time, both terms are used interchangeably. If there is a distinction, it is that between processes and products. Technological change focuses on industrial processes, at least among economists. Technological change as new products for the customers is another concept that gave rise to that of technological innovation.

Finally, a third meaning is mathematical. In operational terms, technological change is defined as change in productivity due to changes in input (factors of production: capital

[3] In a long essay on definitions, Schmookler introduces the followings: Technological progress is "the rate which new technology is produced" (as contrasted to the "rate of replication", or diffusion and imitation). Technological change is "change in knowledge" (of which invention is only one aspect) and technical change is "change in technique" (change in practice). "When an enterprise produces a good or service or uses a method or input that is new to it, it makes a technical change" (Schmookler, 1966: 1-9).

and labor) used to produce output, or substitution of machinery for labor. “Technological change is here considered as synonymous with modifications of [“a schedule which gives the outputs corresponding to different factor inputs”], i.e. changes in the production function” (May, 1947: 52). Put otherwise: Technological change is a *shift* in the production function (new combination of factors) – as contrasted to movement along the production function or mere growth in the quantity of existing inputs to produce a given output (Rosenberg, 1963: 414). Such a definition serves formalization and measurement.

The three conceptions above are used for the study of social and economic change due to technology or techniques. Change in technology remains a black box, as some call it: how technology is generated is not studied over the period studied here, with a few exceptions. “We are usually concerned”, claimed two Canadian scholars in 1963, “with the effects of technical change upon the whole of an economic system rather than with technical change *per se*” (Asimakopulos and Weldon, 1963: 374).

Key Moments in the Origin of the Concept

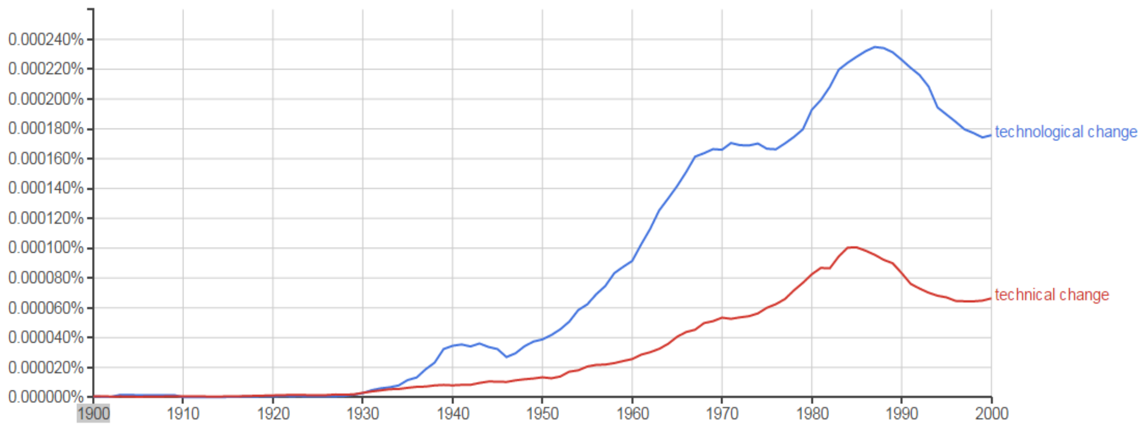
The literature surveyed in this paper is limited to economics. The phrase technical or technological change appeared somewhere in the late 1920s-early 1930s, jointly with technological (or technical) progress (Figure 1). [4] In *Retardation of Industrial Growth*, economist Simon Kuznets looked at the characteristics of the process of industrial growth, and identified “technical changes” (including organizational changes) as the most important factor: invention of machines in the manufacturing sector; discovery of new sources and uses of a commodity in the extractive sector (Kuznets, 1929). However, in the following years, the phrase was used mainly in regard to “technological unemployment”.

[4] To be sure, one may find a few isolated occurrences before that date: “technical change” in the nineteenth century, and “technological change” in the early twentieth century (e.g. Veblen, 1908), but with no theorization.

Figure 1.

Technological Change

(Google Ngram)



Reemployment Opportunities and Recent Change in Industrial Techniques

Use of the phrase technological change can be traced back to the years following the Great Depression, when the bicentennial debate on the role of mechanization on employment re-emerged (Fano, 1991; Bix, 2000). [5] There were optimists, like the economic advisers and sociologist William Ogburn (Ogburn, 1933), and pessimists like the German economist Emil Lederer (Kaldor, 1932) and labor unions. [6] Paul Douglas, professor of economics, University of Chicago, puts the case of optimists – the long-term winners in the debate – perfectly well: "In the long run …. the improved machinery and greater efficiency of management do not throw workers permanently out of employment nor create permanent technological unemployment ... [But] technological and business change creates a considerable amount of temporary unemployment which *in the short run* [only; my italics] creates havoc" (Douglas, 1930a: 938, 942). Douglas was not without critics (e.g. Hansen, 1931). Therefore, in the 1930s efforts began to be invested into

[5] For bits of history on classical and neoclassical economic theories on technological unemployment, see Gourvitch (1940) and US Temporary National Economic Committee (1941).

[6] The first pessimist is David Ricardo in his *Principles*, chapter on machinery.

measuring the “dark prophecies” on technological unemployment, as economist David Weintraub called it (Weintraub, 1937).

The issue of technological unemployment is really at the origins of the concept of technological change. Machines and unemployment – an issue that has occupied economists for some centuries – gave rise to a series of influential theoretical classifications of technologies, among others, as to whether they are capital-saving or labour-saving or neutral (Pigou, 1924; Hicks, 1932; Robinson, 1938) and to quantitative analyses of productivity. Changes in labor productivity (defined as output) due to changes in factors of production (input) came to be equated with invention and were called technological change: productivity is witness to technology’s use in production.

Forerunners in such studies were the US Bureau of Labor Statistics, with a *Digest of Materials on Technological Change,* among others (1932), the National Bureau of Economic Research (NBER) (Weintraub, 1932; Mills, 1932; 1936; 1938; Jerome, 1934; Altschul and Strauss, 1937), the US Department of Agriculture – concerned about the declining share of agriculture (as opposed to manufacturing) in the economy (e.g. US Department of Agriculture, 1940; Hopkins, 1941) –, and the US Work Progress Administration.

The Work Progress Administration was quite influential, with over sixty studies conducted between 1935 and 1940 (e.g. Weintraub, 1937; Weintraub and Kaplan, 1938; Magdoff et al., 1938; Gill, 1940; Gourvitch, 1941). We owe to the organization a large part in the widespread use of the term “technological change”. To the organization, technological change is “change in industrial techniques”. Yet, the purpose of the organization is not the study of change in technology but the impact on employment. Weintraub, as director of the project on “Reemployment Opportunities and Recent Change in Industrial Techniques”, thought, in line with a study he conducted for the NBER in 1932, that measuring labour productivity as a ratio of “quantity output per employee man-year” would answer the question on technology and unemployment (Weintraub, 1937: 67):

> Since the net effects of the underlying economic factors find their quantitative expression in the net changes of the volume of production and employment, a statistical analysis of the relationship between the total volume of goods and services produced in the country and the number of hired workers engaged in the production offers an approach toward a better understanding of the nature of a problem which has come to be referred to popularly as that of technological unemployment.

To Weintraub, "the unit-labor-requirement ratio indicates changes in man-years employed per unit of total output" (Weintraub, 1937: 72). If the same number of workers or less is required to produce the same level of output or more, it means that technology (technological change) causes the increased productivity (and therefore unemployment). Such a measurement did last for some time. "Perhaps the best known of the partial indicator of technological change", stated Irving Siegel in the mid-fifties, "is labor productivity" (Siegel, 1953). For example, it was used in *Technology in our Economy*, a study conducted for the Temporary National Economic Committee and the Congress Hearings on Concentration of Economic Power in 1941, and in diverse scholarly studies in the 1940s – Siegel himself is co-author of a study for the National Research Project of the Work Progress Administration (Magdoff, Siegel and Davis, 1938). But the indicator soon got criticized. "It seems rather unlikely", claimed economist Vernon Ruttan in 1956, "that many economists actually view change in labor productivity as an adequate indicator of technological advance" (Ruttan, 1956: 62, footnote 7).

The Economics of Technological Change

"Change in industrial techniques" is just one representation of technological change of the time. In the early 1940s, economic historian William Rupert Maclaurin from MIT approached the Social Science Research Council's (SSRC) Committee on Research in Economic History, itself interested in promoting investigation of the entrepreneur's role in American industry, with a proposal to jointly sponsor an investigation of technological and industrial expansion. Supported by a grant from the Rockefeller Foundation, Maclaurin initiated the first systematic and long-term research program on "The Economics of Technological Change" (see Annex 1). Under Maclaurin's guidance, MIT's department of economics launched a series of economic studies on technological change that addressed two major problems: "determining the principal economic factors responsible for the rate of technological progress in various industries, and determining the conditions in industry that are most conductive to steady technological progress with a minimum of frictional unemployment". By the early 1950s, Maclaurin and colleagues had developed a whole program of research, which led to several publications on various industries such as glass, paper, electricity (lamp) and radio, and which all arrived at similar conclusions (e.g. Scoville, 1948; Bright, 1949; Maclaurin, 1949) (see Annex 2). From this program came Maclaurin's sequential model, the 'linear model of innovation': pure science, invention, innovation, finance, acceptance (or diffusion) (Maclaurin, 1953).

To Maclaurin, technological change or technological progress – both terms are used interchangeably –, never defined explicitly, is inventions coming out of the application of science or research and development (R&D), what with time he came to call innovation (Godin, 2008). Maclaurin is concerned with technological change as a "process", from basic research to applications and how firms generate technological change. Maclaurin conceived technological change as a change in technology, not limited to industrial techniques. He remains one of the few to examine technological change in this sense prior to the 1960s.

At about the same time, economist Yale Brozen from Northwestern University published many papers on technological change, including a review of studies on "technological change" (Brozen, 1951b). [7] To Brozen, "Technological change … means a change in a production function … We will define technological change as any change in production methods in an enterprise or industry. Most changes will show as a change in the ratio in which resource services are combined" (Brozen, 1953: 288). This definition he developed beginning with a paper produced for a conference on technological change discussed in the next section. [8] Such a view of technological change and the production function is exceptional before Brozen. I will come back to this below.

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[7] Brozen completed a PhD thesis on *Some Economic Aspects of Technological Change* at the University of Chicago, Department of Economics, in 1942.

[8] "Investigation of the role of technological change in economic growth is made easier if we examine it at three different levels: at the level of invention, of innovation, and of imitation. We are led to this approach quite naturally through the circumstance that movement in technology have been defined as a change in the production function and that this may have any one of three different meanings. The production function, as an expression relating the quantity produced of a good (or goods) to quantities of output, may be used to express (1) what is technologically possible (the maximum output obtainable from any of many sets of

In parallel to his pure economic papers, and in contrast to Maclaurin, Brozen was mainly concerned with social change due to technology and the social control of technological change. He produced papers on the social impact of technological change (Brozen, 1950), underdeveloped areas (Brozen, 1951c), public policy (Brozen, 1951e), values and technological change (Brozen, 1952) and ideology and productivity (Brozen, 1955). Together with a definition of technological change defined in terms of the production function, Brozen included in the study of technological change any study concerned with invention: economics (e.g. Works Progress Administration), history (e.g. Abbot Usher and Maclaurin) and sociology (e.g. William Ogburn, Colum Gilfillan and Sjoberg Gideon) (Brozen, 1951b)

Quantitative Description of Technological Change

The emerging interest in technological change from diverse sources in 1930-40s (scholars; public organizations like the Works Progress Administration; Congressional hearings; government reports) [9] led to a major conference, the first ever on technological change. In April 1951, the SSRC organized a conference on “Quantitative Description of Technological Change” at Princeton. It is at this conference that Maclaurin presented his linear model (not called as such at the time). The idea for the conference came from discussions at two committees of the SSRC: the Committee on Economic Growth, chaired by the economist Simon Kuznets, and the Committee on the Social Implication of Technological Change. Following a meeting held in October 1949, Kuznets had circulated a memorandum of suggested topics for the conference. He proposed looking at measurements such as: patents, lags in technology use, the censuses of machines (or mechanization surveys of industries), the counting of new (consumer) products, and input/output ratios. Comments were received from several researchers. All shared their enthusiasm for a conference, and proposed to present their own methodology.

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factors or the minimum inputs required for any level of output with any ratio between inputs), (2) what is possible with techniques that are (or have been) used in firms which are technological leaders, or (3) what is occurring in the economy as a whole. The level of technological possibilities [invention], the level of the technological leaders [innovation], and the average technology of the society [imitation] may move at different rates and in different directions” (Brozen, 1951a: 239).

[9] National Resources Committee (1937), *Technological Trends and National Policy*; Temporary National Economic Committee (1941), *Technology in Our Economy*.

Thirteen papers were prepared (see Annex 3), and about sixty people attended the conference, among them Oskar Morgenstern, Gerald Debreu, Solomon Fabricant, Moses Abramovitz, Wassily Leontief, Jean Fourastié, Fritz Machlup, Irving Siegel, Jacob Schmookler, Rupert Maclaurin, Yale Brozen, Abbott Usher, Joseph Rossman and Colum Gilfillan. There had been a project to publish the proceedings as a book, but this was abandoned because "the papers [were] in most cases of a very exploratory character, with quite different points of view and without a sufficient thread of unity to be published in a single volume". [10] In fact, the closing session concluded that "thus far research efforts on many of the most significant aspects of technological change have failed to produce conclusive results". But "there was agreement that persistent efforts must be made to develop and test new research approaches". [11] Instead of attempting to publish the very diverse set of papers, it was decided to "distill" them into a shorter publication that would include discussions. Kuznets committed to such a paper his thoughts on "technological change", making use of the conference, but he never completed his preliminary draft (Kuznets, 1951). [12] Kuznets's draft dealt with measuring the contribution of technology to production, mainly through input-output analyses. The paper was of a methodological nature, discussing what technological knowledge is and how to measure it, the problem of subtracting technology as a residual from other factors or changes, [13] and the problem of attribution. Kuznets concluded that "we may be doomed to a position in which we can measure only economic growth, but not its causes".

In retrospect, the fact that the conference was "inconclusive" (Siegel, 1953: 143) and that the organizers did not publish the proceedings appears as a rather severe judgment. Many speakers published their paper independently in academic journals – Yale Brozen

[10] Letter from A. J. Coale to J. L. Fisher, 6 July 1951. The Rockefeller Archive Center: Social Science Research Council Archives, Accession Two, Box 148, Folder 1690.
[11] Attachment to letter from P. Webbink to R. R. Nelson, 5 August 1960. The Rockefeller Archive Center: Social Science Research Council Archives, Accession Two, Box 148, Folder 1690.
[12] Many of Kuznets' thoughts from 1951 may be found in Kuznets (1959; 1962).
[13] To the best of my knowledge, this is the first occurrence of the term "residual" in economic studies of technological change: "securing a measure of technological change by subtracting [non-technological change] from total production changes" (Kuznets, 1951: 10).

(1951a), Colum Gilfillan (1952), Rupert Maclaurin (1953), Joseph Fisher (1953), Jacob Schmookler (1952) – and books (Anne Grosse-Carter, in Wassily Leontief, 1953). The papers presented offered analyses, methodologies and data that would define the field in the decades to come, particularly the concept of the production function, as discussed in the next section.

What is technological change to the organizers and speakers at the conference? Like any conference, the scope of the subject is very wide. I discussed Maclaurin and Brozen above. To Joseph Fisher, member of the staff of the US Council of Economic Advisers, technological change is the "application of new and improved technologies in industry" (Fisher, 1953: 57). In a similar vein, to sociologist Colum Gilfillan, "technological change … practically means inventions, and their adoption" (Gilfillan, 1946: 172; 1952; 1953). Other conferees held a more specific view. To Jacob Schmookler, "the index of output per unit of total input … describe[s] the pattern and magnitude of technical change" (Schmookler, 1952: 214). To Wassily Leontief, in his comments on the topics of the conference: "The narrowly defined economic aspects of technological knowledge can be described in terms of quantitative input-output relationships". [14] In spite of the caveats Kuznets made on the existing methods of measurement, some described the change in ratio inputs to outputs and the production function as "the main measuring device" (Tjalling Charles Koopmans, Cowles Commission) [15] and "a conceptual framework in pretty good shape" (Wassily Leontief). To Kuznets, technological change is "part of change in production practices, presumably that assignable to addition to knowledge" (Kuznets, 1951: 7).

[14] Wassily Leontief, Memorandum on the Problems Connected with the Study of Technology and Technological Change, 2 December 1949. The Rockefeller Archive Center: Social Science Research Council Archives, Accession Two, Box 148, Folder 1690.

[15] Tjalling Charles Koopman, Comments on Suggested Topics for the Conference on The Measurable Aspects of Technological Change, 7 February 1950. The Rockefeller Archive Center: Social Science Research Council Archives, Accession Two, Box 148, Folder 1690.

Formalization of the Concept

In 1959, looking at two decades of work on technological change, Vernon Ruttan felt the need to revisit the concept of technological change, among others. He recommended a "restrictive" definition of technological change, as one critic called it. Ruttan suggested "that we employ the term technological change in a functional sense – to designate changes in the coefficients of a function relating inputs to outputs resulting from the practical application of innovation in technology and in economic organization" (Ruttan, 1959: 606). The critic is Paul Schweitzer from the US Department of Labor, Economics and Research Branch, who understands technological change as change in technology. To Schweitzer, not every technological change involves a change in the production function itself: "It would surely be more useful to define technological change in the wider sense of including any change in production techniques" (Schweitzer, 1961: 154). Yet, it is Ruttan's definition that economists decided to follow in the following decades.

Where does this definition come from? The embryo of it comes from Paul Douglas, "followed by an impressive series of econometric studies" (Schumpeter, 1954: 1042, footnote 36). The production function is a concept, and formula that links the quantity produced of a good (output) to quantities of input (Cobb and Douglas, 1928). In respect to technological change, the idea reads as follows: there are, at any given time factors or inputs (labour, capital) available to the firm, and a large variety of techniques by which these inputs can be combined to yield the desired (maximum) output. As Joseph Schumpeter put it in his *History of Economic Analysis*: the production function "expresses the technological relation that exists between the quantity of product and the quantities of the 'factors' that co-operate in varying proportion to produce it" (Schumpeter, 1954: 260, footnote 5). Technological change is "change in the production function" (Mansfield, 1968a: 2). "The production function shows, for a given level of technological change, the maximum output rate which can be obtained from a given amount of inputs" (Mansfield, 1968b: 2, 13). Over the period studied in this paper, this definition is espoused by every mainstream economist.

It took some time before the Cobb-Douglas production function got into the analysis of technological change. In spite of papers on technical change and technological unemployment (Douglas, 1930a; 1930b; Douglas and Director, 1931: 119-164), Douglas never did apply the production function to technological change specifically. True, every empirical analyzes conducted on technological change and productivity until then was put within an input-output framework. The early economic studies of "invention" are conducted in terms of factors of production too (labor and capital-saving inventions). [16] But the vocabulary of a production function and the formalization is not there.

Joseph Schumpeter is a step in the genealogy. [17] To be sure, technological change is not part of Schumpeter's vocabulary. It does not appear in *The Theory of Economic Development* (1934) and Schumpeter uses it only once in *Business Cycles*. [18] As a matter of fact, to Schumpeter, invention (technological change) is not part of innovation. Yet, Schumpeter defines innovation "rigorously", as he put it, as "the setting up of a new production function", namely changes in production according to changes in factors of production, and it is this definition that got into that of technological change in subsequent years. [19] To Schumpeter, "this historic and irreversible change in the way of doing things we call 'innovation' and we define: innovations are changes in production functions …" (Schumpeter, 1935: 4). Schumpeter's theory of innovation (Schumpeter, 1939: 87-102) is a theory of technological change.

> Technological data may be expressed, for every firm, by a function which links quantities of factors, such as … means of production … to the quantity of the product which it is possible to produce … (Schumpeter, 1939: 38).

[16] "Invention may change the parts played by capital and labour in production" (Pigou, 1924: 629); "we can classify inventions according as their initial effects are to increase, leave unchanged, or diminish the ratio of the marginal product of capital to that of labour" (Hicks, 1932: 121);."all types of innovation can be described in terms of the changes in the quantities of labour and capital required to produce a given rate of output" (Robinson, 1952: 42).

[17] In his *History of Economic Analysis*, Schumpeter devotes a long section to the production function (Schumpeter, 1954: 1026-53).

[18] "Technological change in the production of commodities" is one type of "doing things differently" or innovation (Schumpeter, 1939: 84).

[19] Schumpeter applies the term function to many other things: entrepreneur function, managerial function, social function. The economic literature abounds in the use of the term function. As examples from the literature on technological change, see: engineering production function (Chenery, 1949; Pearl and Enos, 1975), manufacturing progress function (Hirsch, 1952), decision function (Dillon and Heady, 1958), innovation function (Massell, 1962), investment function (Mansfield, 1965b).

> Whenever at any time a given quantity of output costs less to produce than the same or a larger quantity did cost or would have cost before, we may be sure, if prices of factors have not fallen, that there has been innovation somewhere (Schumpeter, 1939: 89).

> [The production function] describes the way in which quantity of product varies if quantities of factors vary. If, instead of quantities of factors, we vary the *form* [my italics] of the function, we have an innovation … Innovation [is] the setting up of a new production function … Innovation combines factors in a new way (Schumpeter, 1939: 87-88).

Almost every paper on "innovation" from economists published in the following two decades defined innovation in terms of factors of production or technological change, often citing Schumpeter explicitly (Lange, 1943; Goodwin, 1946; Griffin, 1949; Hendrix, 1951; Scoville, 1951; Solo, 1951; Hunter, 1955; Bruton, 1956; Fellner, 1958; Dillon, 1958; Penn, 1958; Hamberg, 1959). The impact of Schumpeter on the study of innovation is in the first place through his use of the production function, an equation subsequently used in the literature on technological change (e.g. May, 1947; Ruttan, 1956; Solow, 1957; Massell, 1962; Rosenberg, 1963; Brown, 1966; Mansfield, 1968a), but discredited later by evolutionary economists (see below). Schumpeter's impact on the evolutionary framework of innovation came much later.

But Schumpeter is not the whole story. Other inputs to the study of technological change among economists need to be mentioned. There was the Cowles Commission, whose president was present at the SSRC conference of 1951, and which supported and published several scholarly papers on technological change, most of the time of a very mathematical nature: Kenneth May, Herbert Simon, Gerard Debreu, William Nordhaus, Benton Massell, Sydney Winter (see Annex 4). [20] There was the NBER too, which continued its studies of the 1930s on productivity and the factors (labor, capital) responsible for it (Fabricant, 1954; Abramovitz, 1956; Kendrick, 1961). And there was a conference on invention, or rather a spin-off from that conference. In 1960, the NBER organized a conference on the "Rate and Direction of Inventive Activities", in collaboration with the SSRC. The latter was a natural partner, having organized the 1951 conference. [21] The main purpose of the NBER was to open the "black box" of invention,

[20] Five years before the SSRC conference (December 1946), Kenneth May organized a seminar at the Cowles Commission on *Tentative Methods for Dealing with technological Change*. May did not attend (or was not invited to?) the SSRC conference.
[21] On the history of the conference, see Godin (2010).

so it was claimed. [22] In a certain sense, the conference was narrowly focused on invention or R&D, as Richard Nelson put it in the introduction to the book. It did not deal with the process of innovation or that of diffusion (NBER, 1962: 3-4). [23] In another sense, invention was understood as a large category that included any study concerned with the economics and management of science and technology, but technological change as understood until then (the black box). [24]

Yet, the study of technological change "has been an important ingredient" to the conference (NBER, 1962: 3). One big impetus was Robert Solow's article on technical change, showing that most of productivity growth was not due to capital but an unexplained residual that he called "technical change" (Solow, 1957), "a confession of ignorance rather than a claim to knowledge" (Solow, 1960: 90) – over the years, or rather in a matter of a few years (1960), Solow started to used interchangeably technical change and technical progress. Unfortunately, Solow did not attend the conference, and neither did Paul Samuelson, whose name was suggested by Solow. Solow formalized earlier works on growth accounting (decomposing GDP into capital and labor), and equated the residual in his equation with "technical change" – although it included everything that was neither capital nor labor – as "a shorthand expression for any kind of shift in the

[22] To be sure, there were precursors, from a psychological (Abbot Usher, Joseph Rossman), sociological (Colum Gilfillan) and economic (Maclaurin) perspective, but few testified of his knowledge at the conference but Gilfillan (Usher and Maclaurin have passed away).

[23] This is partly true. The speakers in the 1960s who dealt most with innovation in the sense that the category would acquire later in non-mainstream economics were W. F. Mueller and J. L. Enos. Certainly, some others used the term innovation (Minasian, p. 95; Feller, p. 171; Siegel, p. 451). However, the use had no consequence for their analysis. Mueller looked at innovation defined as commercialized invention. Mueller was here concentrating on a meaning of innovation as products of inventive activities introduced to the market. Enos for his part followed Maclaurin, preferring to define innovation as a whole process from invention to commercialization (For a similar distinction with regard to invention, see Siegel, p. 441-42). Enos in fact produced one of the first economic studies on time intervals, or lags, between invention and commercialized invention (innovation) (The very first such studies came from sociologist Gilfillan (Ogburn and Gilfillan, 1933; Gilfillan, 1935; 1952; the latter paper was produced for the 1951 conference on technological change. Later such studies from economists are Posner (1961), Mansfield (1961), Lynn (1966), Mansfield (1968: chapter 4), and Gold et al. (1970). The study gave rise to studies on gaps between countries in terms of innovating (defined as both inventing and adopting).

[24] Most of the papers presented at the conference came from economists and researchers interested in the management of research, like RAND. Among the speakers, four were present at both the 1951 and 1960 conferences: Brozen, Gilfillan, Kuznets and Schmookler. Sociologists and historians were absent as speakers, but a psychologist (D. W. Mackinnon) was invited to speak on invention as creativity, and Gilfillan and T. S. Kuhn attended as commentators.

production function".[25] Integrating technological change into the economic equation was thus not a deliberate initiative, but it soon became a fruitful one. In the following years, researchers began adding variables (factors like education, R&D and new technology) into the equation in order to reduce the "beast" (the residual), as Zvi Griliches called it, and better isolate the components of technological change (e.g. Denison, 1962; 1967; Griliches, 1963; 1964; Jorgenson and Griliches, 1967). Since these first calculations, the literature on measuring technological change and productivity has grown exponentially, becoming an "industry".[26]

In retrospect, the NBER conference can undoubtedly be qualified as influential.[27] It discussed the then-emerging ideas on technological invention in economics, using multiple statistics and methodologies (see Annex 5).[28] Long after other disciplines, economists were finally beginning to look at invention seriously. As Burton Klein put it at the conference, "while economists have probably had little influence on business practices in research and development, the same cannot be said of cost accountants, management experts, and the growing army of business school graduates in general. And to their influence must be added the influence of the engineers" (NBER, 1962: 497).

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[25] "Both Solow's conclusions and method actually appeared in the literature much earlier; the former in Abramovitz (1956) and the latter in Tinbergen (1942)" (Lave, 1966: 4).

[26] For early surveys of the field, see Brown (1966), Lave (1966) and Nadiri (1970).

[27] Two years after the NBER conference, another conference on the economics of invention was held at the Ohio State University. The book that came out of this conference elected *The Rate and Direction of Inventive Activity* as "the most recent definitive compendium" and claimed that "in less than a decade, the subject of economics of technological change has come into its own as a research area" (Tybout, 1965: 4). Many of the speakers at this conference were present at the NBER conference too: Griliches, Klein, Markham, Nelson, Scherer, Schmookler.

[28] Like the 1951 conference, measurement was a challenging issue to the conference. There were as many statistics used – expenditures on R&D (Minasian, Brozen), labor (Machlup, Worley), patents (Schmookler, Thompson) – and many methodologies – production function (Minasian, Fellner), case-studies (Peck, Mueller, Nelson), and pure theory (Arrow). However, very few statistics were said to be without limitations, which led Jacob Schmookler to conclude that "no one will dispute that accurate measures of a thing are always better than an uncertain index of it … In the meantime, much as we might prefer caviar, we had better settle for plain bread when that is all we get" (NBER, 1962: 78). In every of his thoughts concerned with invention, technological change and innovation, as well as his contribution to the NBER conference, Kuznets was definitively a pessimist as regards measurement (Kuznets, 1951; 1959; 1972; 1974). At the NBER conference, he has been criticized on that count. The NSF representative, H. I. Liebling, accused Kuznets of applying "somewhat more rigorous standards to the R&D series than he does to the national income category we have learned from him" (NBER, 1962: 89). To Liebling, "in the construction of any complex set of statistics, attention must be given to its operational requirements in obtaining a successful measure, often requiring the adoption of certain conventions" (NBER, 1962: 88).

Table 2.

Some Key Authors and Institutions

on Technological Change

1930-50s	1950s	1960s
Joan Robinson	Moses Abramovitz	John Kendrick
Harry Jerome	Solomon Fabricant	Wilfred Salter
US BLS	Rupert Maclaurin	Jacob Schmookler
WPA	Yale Brozen	Edwin Mansfield
NBER	Robert Solow	Nathan Rosenberg
Cowles Commission	Zvi Griliches	
	Vernon Ruttan	

A few years after the NBER conference (1963), a group that called itself "Inter-University Committee on the Microeconomics of Technological Change", members of which were Alf Conrad, Zvi Griliches, Edwin Mansfield, Jesse Markham, Richard Nelson, Merton Peck, Frederic Scherer and Jacob Schmookler, got a $150 000 grant from the Ford Foundation to pursue studies on technological change. It enabled the group of young economists (most of them present at the NBER conference) to meet together from time to time. The meetings helped build a sense of community. The work culminated in a 1966 conference held in Philadelphia, attended by most of the Americans who would work on technological change problems in coming years (Scherer, 2005: 5). By that time, technological change "has become one of the most fashionable areas of economics", wrote Mansfield in one of the output from the members of the inter-university committee on technological change (Mansfield, 1968a: 1). Mansfield was right. Titles on technological change (and technical change) were voluminous for some decades (Table

2). And from the 1960s, technological change was defined operationally, by way of the production function.

In spite of the formalization, by the late 1960s and into the early 1970s, some economists started using technological change in a new sense: change in technology, or technological innovation as some call it. In their survey on the economics of "technical progress" cited above, Kennedy and Thirlwall subsumed under technological change ("change in technology") the kind of studies that occupied the NBER conference – invention and research and development, plus innovation and diffusion (Kennedy and Thirlwall, 1972). Technological change is no longer (not only) economic change due to technology, but change in technology or technological innovation. The interest of (some) scholars shifts to the inside of the black box and scholars start using another concept to this end: technological innovation. Mansfield's works are an ideal example to examine the shift but also the interchangeability between the concepts of technical change and change in technology or technological innovation. Some papers are titled technical change but innovation is the main concept used (e.g. Mansfield, 1965). Mansfield's process of technical change is similar to what he and others call the process of technological innovation: the "process by which new processes and products are invented, developed, commercialized, and accepted" (Mansfield, 1965: 136). [29] In 1968, Mansfield published *The Economics of Technological Change*, a companion to *Industrial Research and Technological Innovation*, published the same year. The two books are quite similar in content – the first one "dealing with a much wider spectrum of topics" (impact on employment; government funding of R&D; public policy) –, but with different titles.

Mansfield is not alone. In 1971, Nathan Rosenberg published *The Economics of Technological Change: Selected Readings*, a collection of articles produced in the previous years on technological change, but also on invention and innovation (Rosenberg, 1971). The proceedings of a meeting on *Economics and Technical Change*

[29] Mansfield's *Industrial Research and Technological Innovation* is framed into a sequence from invention (research) (Part I) to commercialization or innovation (Part II) to imitation or diffusion (Part III) (Mansfield, 1968a). Similarly, *The Economics of Technological Change* frame the discussion in terms of invention (chapter 3) to innovation to diffusion (chapter 4) (Mansfield, 1968b).

held at the 1968 annual meeting of the British Association for the Advancement of Science offer the same breath (e.g. Hugh-Jones, 1969).

The fuzziness of the vocabulary was thus widespread in the 1960s and 1970s. One final example, to complicate things further: Richard Nelson and his colleagues, in *Technology, Economic Growth and Public Policy* – one more output from the members of the inter-university committee on technological change –, talk of "technological advance" in the same way others talk of technological change (Part I) – "advances in knowledge which, when put to work, result in an increase or improvement in output" (Nelson, Peck and Kalachek, 1967: 22) – and reserve the phrase technological change for automation, the problem of unemployment and the mechanisms of adjustment (Part II). [30]

Not surprisingly, more than a decade after Ruttan, some felt the need to revisit the concepts again. There is "ambiguity", stated Irwin Feller, "occasioned by treating technology and technique, technological change and technical change, and invention and innovation as synonymous terms, and using the analytical tools of the production function and the production isoquant interchangeably in the handling of these concepts" (Feller, 1972: 155). Feller was right.

What happened that could explain the shift or conflation in the meaning of the concept, in spite of over a decade of formalization?

Contesting the Concept

In 1961, Evsey Domar qualified the concept of technological change as a mysterious factor, and suggested to talk of a "residual", a more appropriate term: technological change includes "a whole group of factors" explaining productivity, that part not measured by increases in capital per man (Domar, 1961: 711). A few years later, Mark Blaug wrote (Blaug, 1963: 31):

> No one has yet managed to measure the state of technical knowledge, much less the rate of change of technological knowledge. The neoclassical idea of a given state of

[30] Fifteen years later, Nelson understood technological change critically in the sense studied in this **paper** (Nelson and Winter, 1982).

> knowledge is admittedly an abstract one. But the concept of a given rate of change of knowledge is almost metaphysical.

As a matter of fact, very early on the production function – and incidentally technological change defined as a production function and the econometrics on which it relies – got criticized: "By concentrating upon the question of the proportion of factors [the concept of a production function] has distracted attention from the more rewarding questions of the influence governing the supplies of the factors and of the causes and consequences of changes in technical knowledge" (Robinson, 1953-54: 81). "There is thinness of studies [on the process of technical change]", claimed Kennedy and Thirlwall, "as compared to macro-economic production function studies" (Kennedy and Thirlwall, 1972: 62).

At the NBER conference, Jora Minasian analyzed invention as such a factor or input to economic growth and productivity and concluded "beyond a reasonable doubt, causality runs from research and development to productivity, and finally to profitability" (NBER, 1962: 95). According to Richard Nelson, Minasian's paper presented "encouraging evidence that classical economic theory can be applied fruitfully to inventive activity" (NBER, 1962: 8). However, according to many attendants to the conference like Zvi Griliches, the production function was "a very unsatisfactory tool of analysis" (NBER, 1962: 348). To Griliches, "none of these studies [Minasian, Nelson, Peck, Enos] comes anywhere near supplying us with a production function for inventions": the relationships between input and output "are not very strong or clear" (NBER, 1962: 350) – thirty six years later, Griliches concluded again that "the quantitative basis for these convictions [links between technological change and economic growth] is rather thin", and pleaded for realism (Griliches, 1998: 41). [31] To Fritz Machlup, the production function is "only an abstract construction designed to characterize some quantitative relationships which are regarded as empirically relevant" (NBER, 1962: 155). [32]

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[31] From the early 1960s to the late 1980s, Griliches was one of the most productive researchers working to improve the measurement of technological change according to the production function. From 1979, Griliches directed the National Bureau of Economic Research's *Productivity and Technical Change Studies Program*, which published a large volume of working papers.

[32] In **19??**, the NBER organized a conference on production functions, whose participants were, among others, Paul Douglas, Robert Solow, Zvi Griliches and Richard Nelson. "A significant part" of the conference, claimed Murray brown, editor of the book, "was characterized by dissatisfaction and dissidence", particularly regarding the difficulty of measuring technological change (Brown, 1967: 3-4).

In the following decades, the criticisms continued. Wassily Leontief argued that "elaborate aggregative growth models can contribute very little to the understanding of processes of economic growth, and they cannot provide a useful theoretical basis for systematic empirical analysis" (Leontief, 1970: 132). Mansfield qualified the mathematics behind economists' models as "not strong enough to permit very accurate estimates … At best, the available estimates are rough guidelines" (Mansfield, 1972: 478). Similarly, Nathan Rosenberg called the production function a "fiction" (Rosenberg: 1976: 63). Economists writing on "technical progress" focus on the *use* of existing goods (processes) and exclude the *generation* of new products, a thought reminiscent of Joan Robinson's (Rosenberg, 1982). Solow himself concluded in 1978: "No way has been found to measure directly the contribution of technological progress to the growth of output" (Solow and Temin, 1978: 26).

To continue: to Chris Freeman, "Most economists have given up now on the purely statistical attempts to aggregate the production function and the disaggregation of the components of technical change"; the accuracy of these estimates is poor (Freeman, 1982: 196). Richard Nelson, in contrast to his thoughts of the 1960s, positions his theory of innovation against orthodoxy or "a narrow set of criteria that are conventionally used as a cheap and simple test" (Nelson and Winter, 1982: 6), namely the presumptions of maximization and equilibrium, and the formalization in terms of the production function.

In brief, the economic conception of technological change is limited to "a few reasonably narrow and well-defined situations" (Warner, 1974: 434). From then on, the concept of innovation became a substitute to that of technological change, at least in a certain part of the literature. In fact, technological change is a synonym to technological innovation (or rather a certain kind of technological innovation), even a precursor term to technological innovation, both being used interchangeably. Such was the case for Maclaurin and Mansfield, as mentioned above, but also others. Joan Robinson's "technical progress" in her 1937 and 1938 papers becomes innovation in 1952, and the classification of inventions (labour-saving, capital-saving or neutral) becomes categories of innovation (capital cost, labour cost). [33]

One of the early extensive uses of the concept of innovation among mainstream economists is “induced innovation” (Fellner, 1961; Kennedy, 1964; Samuelson, 1965). Induced innovation is defined as changes in input prices which induce changes in capital-labor ratios. Many of the issues studied are not really different from those of technological change (innovation is understood as invention used and the method used is econometrics and the production function) and invention (the study of economic factors, in the present case prices). [34] The concept of ‘induced innovation’ is a relabeling and adaptation of “induced invention” from John Hicks as “change in the relative *prices* of factors of production” conducting to invention (labor-saving or capital-saving depending on prices) (Hicks, 1932: 22). Up to then ‘invention’ was the term used to talk of labor-saving and capital-saving innovations (Pigou, 1920; Hicks, 1932; Robinson, 1938). ‘Induced innovation’ was first used by Schumpeter (1939: 101), with a totally different meaning, as subsequent improvements on first innovations by copiers and users, [35] then by Weir Brown (1946).

Even though the concept was used in these ways, innovation remained a contested term to most mainstream economists. Innovation was too subjective a category. As a matter of fact, those who had studied innovation extensively until then, namely the sociologists, defined it as any idea *perceived as new* by its adopter (Rogers, 1962). As a result of this view, economists criticized the term and were reluctant to use it. Some of the participants to the NBER conference also has the same reaction. To Machlup, “we shall do better without the word innovation” (Machlup, 1962: 179). To others, the term is in need of a more rigorous definition, because it “has come to mean all things to all men” (Ames, 1961: 371). In the 1970s, the skepticism continued: the “use of the term innovation is

[33] Technical progress (“change in techniques” in 1937 and 1938) is innovation defined as “changes in methods of production, whether due to new inventions or to any other change in circumstances … [A]n innovation involves stepping from one combination [of factors of production] to another” (Robinson, 1952: 33-34). “All types of innovations can be described in terms of the changes in the quantities of labour and capital required to produce a given rate of output” (Robinson, 1952: 42).
[34] See Binswanger and Ruttan (1978) for a survey.
[35] Schmookler framed the debate on technology-push *versus* demand-pull using the term ‘induced’: inventions are “knowledge-induced or demand-induced” (Schmookler, 1966: 12).

counterproductive", claimed the authors of a survey conducted for the US National Science Foundation, because each individual has his or her own interpretation (Roberts and Romine, 1974: 4).

Yet, over time (technological) innovation has become a concept competing with technological change in the vocabulary, even THE concept per excellence. A contrast is often made in the literature, particularly by evolutionary economists, between the study of or tradition on technological change and that on technological innovation. The former treats technology as exogenous, so it is said, while the latter considers it as endogenous and study the process or generation of technology. This paper suggested that a fundamental contrast is between the 'agent' studied. From the very beginning, the study of technological change was concerned with the effects of technology on *people*'s lives (unemployment, jobs deskilling, etc.), and continued to be studied as such much later (e.g. Freeman and Soete, 1987). This issue gave rise to early measures of technological change as change in labor productivity. But over time, in 'pure' economics, the measurement was to be distinguished or separated from the issue of unemployment and achieved 'autonomy' through the production function. The economic study of technological change also came to be dissociated from the issues of social change proper, thereafter discussed as an element of context only (e.g. Stoneman, 1983). In contrast to the tradition on technological change, that on technological innovation emerged from scholars' interest in how *firms* generate technology for maintaining or increasing their competitiveness.

Conclusion

"Technical progress is difficult to discuss in precise language", claimed Joan Robinson in 1952. As a matter of fact, "Over the years the term technical progress has been given a wide range of meanings and interpretations" (Kennedy and Thirlwall, 1972: 12). One is technological change, itself defined with a wide range of meanings and interpretations: inventions, production techniques, shifts in production function. The uses of the concept oscillate between the large and the restricted, from social (including economic) change due to technology to change in technology. Technological change is also a concept that is much valued, with terms such as progress and advance in place of change. [36]

The concept originates from issues concerning unemployment, including management-labor relations, as discussed in the United States in the 1930s. It was subsequently applied to the study of economic growth. Here, technological change got quantified with measures of productivity output and formalized through an equation called the production function, linking quantities of inputs to quantities of output. At about the same time, the concept started to be used, with a very broad meaning (anthropology, sociology) and migrated outside the United States.

Technological change is part of a semantic field composed of many concepts concerned with a type of changes many believed was a major factor of 'progress' of modern societies: machines, mechanization, automation, technology, invention, innovation. The discourses on technological change make use of all of these concepts. Technological change is a direct precursor concept to that of technological innovation, both as a substantive and a verb: it concerns one type of invention (industrial processes); it applies to the study of invention used (rather than the generation of invention). Last but not least, the concept is used interchangeably with that of innovation.

[36] The synonymy started very early in the economic literature. John Hicks: "inventions and improvement" (that Hicks also calls "technical change") is "one kind of progress" (Hicks, 1932: 114); Nicholas Kaldor: "A change in technique [that he calls "technical change" too] … can be initiated by … three causes [inventions, scarcity of factors, prices]… Only [inventions] can be properly called technical progress" (Kaldor, 1932: 184). As stated above, very few authors make a difference between change, progress and advance (or improvement). Besides Charles Kennedy and Anthony Thirlwall (1972) discussed above, there is Harold Lydall: technical progress is "a shift in one or more of the parameters" of the production function; technical change is "a change in the basic form of the production function" (Lydall, 1968: 809). And there is, again, Kennedy (in another paper): a technical improvement "consists of a more productive use of an existing machine"; the term "technical progress" is reserved for the economy as a whole (Kennedy, 1962).

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Annex 1.

The MIT Research Program on

“The Economics of Technological Change”

- Determine the principal economic factors responsible for the rate of technological development in various types of industries
- Determine the conditions in industry which are more conductive to steady technological progress with a minimum of frictional unemployment

Source: Bright and Maclaurin (1943: 429, footnote 1).

More specifically:

- What has been the relationship between fundamental scientific research and invention? - between invention and innovation?
- What are the strengths and weaknesses of the large corporation in bridging the gap between scientific research and the introduction of new commercial products?
- What is the role of new firms in introducing technological innovations? Does our economy require a stream of new concerns to pioneer in the untried and speculative?
- What generalizations can we make concerning the personality requirements for successful invention and innovation? Are inventive talent and entrepreneurial skill rarely found in one man? If so, what kind of team management is likely to be most effective?
- How is the patent system working? Does it provide an effective inducement to invention? - to investment in research? Are there patent abuses that retard economic progress?
- And, finally, is there a discernible relationship between technological innovation and the business cycle?

Source: Maclaurin (1949: xvi).

- How are decisions involving innovation in industry actually reached?
- What are the factors which account for the time lag between the conception stage (frequently marked by a patent application) and a successful innovation?
- What is the typical relationship in a firm between gradual technological change and major innovations? Are different sets of people involved? Are the decisions made on a different basis?
- What effect does the structure of an industry have on the nature and rate of inventions?
- Is there a discernible relationship between the size of a firm and its capacity to innovate?

- What are the general characteristics of innovator firms and imitator firms? How does one account for the differences?
- Is there an optimum rate of innovation for a firm - e.g., how many innovations in a decade can a firm make and still keep its organization running smoothly?
- How far down into an organization does the process of innovation actually penetrate? Is the diffusion of entrepreneurial decision making within an organization leading to emphasis on minor rather than major changes (and to capital saving rather than capital consuming change)?
- Are there certain types of innovations that require a much longer period of gestation than others? Why?
- What kind of relationship does one find empirically between innovations and cyclical fluctuations?

Source: Maclaurin, *Memorandum on Research on Technological Change*, prepared for the Conference on Measurement of Technological Change, 1951.

Annex 2.

Publications from the MIT Program on

"The Economics of Technological Change"

Books

W. C. Scoville (1948), *Revolution in Glassmaking: Entrepreneurship and Technological Change in the American Industry, 1880-1920*, Cambridge (Mass.): Harvard University Press. [37]

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[37] Scoville's work on technological change started as part of a joint project between the committee on Research in Economic History of the Social Science Research Council, chaired by Arthur H. Cole, and Maclaurins's group.

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[38] *Explorations in Entrepreneurial History* was a series from the Research Center in Entrepreneurial History (1948-58), founded and directed by A. Cole, Harvard University.

Annex 3.

Papers Presented at the Conference on

"Quantitative Description of Technological Change"

(1951)

Jacob Schmookler (Michigan State College), Inventive Activity, Technical Knowledge and Technical Change as Seen through Patent Statistics.

Alfred B. Stafford (University of Wyoming), An Appraisal of Patent Statistics.

William Rupert Maclaurin (Massachusetts Institute of Technology), The Sequence from Invention to Innovation, With Emphasis on Capital Supply and the Entrepreneur.

S. Colum Gilfillan (University of Chicago), The Lag Between Invention and Application.

Anne P. Grosse (Harvard University), Innovation and Diffusion.

Yale Brozen (Northwestern University), Invention, Innovation and Diffusion.

Ansley J. Coale (Princeton University), The Measurement of Changes in Industrial Processes.

W. Duane Evans (Bureau of Labor Statistics), Index of Labor Productivity as a Partial Measure of Technological Change.

Gerard Debreu (Cowles Commission for Research in Economics), Effects of Technological Change on Production Potential.

Wassily W. Leontief (Harvard University), Structural Change.

Joseph L. Fisher (Council of Economic Advisers), Natural Resources and Technological Change.

Simon Kuznets (University of Pennsylvania), Ratio of Capital to Product and Technological Change.

William M. Capron (University of Illinois), Changes in Household Equipment as a Partial Measure of Technological Change.

Annex 4.

Cowles Commission Discussion Papers

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[39] Available at http://cowles.yale.edu/search/node/technological%20change).

Annex 5.

Papers Presented at the Conference on

"The Rate and Direction of Inventive Activity"

(1960)

S. Kuznets (Harvard University), Inventive Activity: Problems of Definition and Measurement.

B. S. Sanders (George Washington University), Some Difficulties in Measuring Inventive Activity.

J. R. Minasian (RAND), The Economics of Research and Development.

F. Machlup (Princeton University), The Supply of Inventors and Inventions.

W. Feller (Yale University), Does the Market Direct the Relative Factor-Saving Effects of Technological Progress?

J. Schmookler (University of Minnesota), Changes in Industry and the State of Knowledge as Determinants of Industrial Invention.

J. S. Worley (Vanderbilt University), The Changing Direction of Research and Development Employment Among Firms.

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