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Discoveries, Innovations, and Business Cycles

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ABSTRACT

There is considerable evidence that the density of basic innovations is peaked at definite periods with intervals of about 40–60 years. This has been used as support for the behavior of economic cycles as postulated by Kontradieff and amplified by Schumpeter. Recently some economists have used this model to forecast economic recovery in the middle or late 1980s.

This paper points out that the shape of the clusters of innovation or inventions are different and sharper than those of economic depression or economic recovery. The transfer of knowledge from basic inventions to industrial innovations shortens as one moves from the 18th to the 20th century, and some probable explanations for this are offered. The importance of discoveries and limited discoveries to the process of invention and innovation is discussed. Also shown is that discoveries reveal cluster phenomena which are functionally related to the clusters of invention and innovation.

1. Introduction

There has been considerable conjecture regarding the evidence on economic cyclic behavior as postulated by Kontradieff [8]. Some of this evidence has been reviewed by Kuznets [10], and, more recently, by Van Duijn [21,22]. Schumpeter, in his book on business cycles [18,19], has advanced a thesis that technical innovations are the prime generators for economic recovery and economic upturn. An important corollary of Schumpeter's theory is that major innovations should occur in spurts, in clusters, at well defined periods, and, in particular, at the time when the economy is depressed or stagnant or just at the beginning of a recovery. It is, therefore, of importance to investigate statistically whether there are clusters of important innovations at well defined periods. It should be stated immediately that finding such clusters does not necessarily prove the correctness of Schumpeter's analysis (or its modification by neo-Schumpeterian disciples). However, the absence of this continuity would throw serious doubts on the theory itself [10].

In an important study, Mensch [16] has shown from a restricted amount of data that there are three distinct periods which show a bunching of important innovations of all kinds. These periods occur near the years 1825, 1880, and 1930 and seem to correspond to the economic depressions in the industrialized nations (World Economic Crises of 1825, 1873, 1929).

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This paper deals with a closer analysis of the data presented by Mensch and modified by other authors. It will be shown that these data contain some additional information. The inference from this information correlated with the data of government and industrial expenditure and research in the 20th century throw considerable doubt on any economic theory that links uniquely and exclusively the clustering of innovation with economic activity.

In the next section we will discuss the differences between scientific discovery, limited scientific discovery, basic invention, basic innovations, and diffusion of innovation. In the third section we will give a brief summary of Mensch's data and the criticism advanced against the data. It will be shown that all authors agree essentially on the existence of peaks and troughs in innovations. The nature of these peaks and troughs and their relation to peaks and troughs of basic inventions are significant data. In the fourth section an analysis of the data will be given. This analysis will throw some doubt on the conclusion of Mensch, Van Duijn and others. It will be shown that scientific discoveries show some bunching.

Some conclusions are drawn in the last section. In particular it will be shown that basic discoveries seem to bunch at definitive periods. Some conjectures regarding the causes of these peaks and the interrelationships are presented.

2. Discovery, Invention, and Innovation

Mensch [14, 15] makes the distinction between basic innovation and improvement innovation. *Basic innovations* are those that produce new markets and new industrial branches and activities, open up new vistas in cultural spheres, in public administration, and in social and medical services. *Improvement innovations* give rise to a cheaper or improved quality product, or to a cheaper or better production method. Improvement innovation does not change radically the economic structure.

Mensch also recognizes the importance of inventions. Inventions are the basic ideas for more efficient technologies. An example is the invention of the telephone in 1842 by Alexander Graham Bell. The basic innovation occurred forty years later, about 1881, when the first central exchange was opened in Berlin, creating a viable network of telephone users.

The nature of industrial inventions depends critically on scientific basic research and discoveries. Scientists may come up with a new theory, a new law, a new interpretation of well known phenomena. The theory does not only explain existing facts. A new theory has to predict additional new phenomena, that can be tested in principle, and the predictions must be verified. Hence, a new theory, a new law, or a new basic discovery has hidden within its sphere of influence new advances both in science and in instrumentation, as well as in inventions and in basic innovations. These may in the long run result not only in new branches and sub-branches of science, but also in new technologies and new industries. Very often the practical utilization of new ideas is not limited by the lack of a market pull. It is limited because the practical instruments that make a commercial utilization possible are not available at the time. A merging of ideas, discoveries, and advances in technical instrumentation can give rise to industrial inventions and new industrial activities.

Two examples from physics of this evolution process come to mind. The theory of general relativity is a new and revolutionary interpretation of basic physical phenomena of space and time. It contains within itself formulas such as $E = mc^2$. Several decades passed before this formula itself could be tested. More decades passed before its profound

The data sampled by Mensch have been criticized. However, regardless of the sampling used, the fact remains that there is a considerable bunching of innovations in well defined periods. This observation is accepted by his critics. It is, therefore, not much of a surprise that these data have been used by various economists to support a potential link between the peaks of innovation and the "long wave theory" in economics. Mensch himself advocated this theory, in which industrial firms are more prone to promote and to adopt basic innovations in times of depression. During an economic crisis there is a pressure—in a sense, an "accelerator mechanism"—which promotes the applications of basic inventions in order to solve, by means of technical innovation, industrial problems. Hence, this causes a bunching of industrial or social basic innovations. This, in turn, stimulates prosperity.

In a recent paper, Graham and Senge [5], following an earlier suggestion of Forrester [2, 3], had developed a System Dynamics analysis showing the inverse—that is to say, that economic behavior has a dominant influence on the density and the frequency of innovations. In a sense, the economy is the driving force and the cause, rather than the effect.

Their argument is that the pattern of both basic innovations and of general economic behavior occurs in waves. This correlation is dependent, like most other economic factors, according to the System Dynamics theory, on capital-producing sectors. These sectors have a cyclic, wavelike behavior. The economy shows expansion, overexpansion and overshoot, leading finally to relative decline and to a depression. The simulation methods used by the System Dynamics theory seem to reproduce the times of economic depression that occurred in industrialist countries around 1830, 1880, and 1930.[1]

Innovations peak in density and frequency during the times when the economy is just on the upturn, on the "mend." At that time, industry is willing to forego outdated technology and to begin to invest in capital and new innovations that have been lying dormant for some time. As the economy picks up, there is a further increase in the utilization of innovative technology. When full economic activity is realized, new innovations cannot be easily absorbed. Hence, there is no stimulus to create new innovations. Their numbers decline, although there may be some improvement of innovation, leading to more efficient ways of production or to better products. By the time the downtrend has begun, the innovation has become institutionalized. Therefore, the trend toward depression is not a good climate for inventors; the prevailing atmosphere essentially opposes any change. The economic recovery prompts innovations, rather than innovations prompting the recovery.

The theory suggests a clustering of basic innovation out of phase with the peak of economic activity and in phase with the long wave of economic activity.

It is possible that some of these authors have fallen into the pitfall Forrester repeatedly has warned against. It is questionable and dangerous to equate correlation with a causal relation. There may be, indeed, a correlation between the peaks in basic innovations and peaks in economic activity; possibly there may be a partial causal connection between these two. However, one cannot exclude that there may be additional driving forces causing the peaks and the troughs in innovation and that, therefore, the correlation is in part noncausal and accidental.

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[1] The System Dynamics approach has been summarized in number of papers, i.e., J.W. Forrester, Growth Cycles, *De Economist*, pp. 125, 525 (1977); J.W. Forrester, N.J. Mass, and R.J. Ryan, "The System Dynamics National Model," *Technological Forecasting and Social Change* 9:51 (1976).

influence on many technologies—from space travel to nuclear power plants—was seen. The digestion of a new theory takes a finite time before it reaches even the beginning of a basic invention. The implication of such a theory to practical life becomes important only when the necessary tools are at hand. Many decades ago the necessary tools for utilization of relativity theory had not yet been created. Eventually, new techniques are used in diverse ways, based on basic innovations.

Another example is the discovery of the phenomenon of *superconductivity*, or infinite electrical conductivity at very low temperatures. This was discovered by Kamerling Onnes in Leiden. Leiden was one of few places where liquid helium at low temperatures was available. For decades many scientists knew about superconductivity and could measure its behavior, although they had no theory to explain this phenomenon. No immediate practical applications were apparent. It was like a Pirandello effect.[2] There were many diverse data in search of a theory, and in search of an application. It took nearly 40 years before a creditable theory was formed. Diverse applications are now emerging since there are new commercial superconductivity materials and liquid helium is commercially available.[3]

Basic discoveries often result from a crisis atmosphere in existing theories. Many data show small deviations from predicted behavior. While each set of data may have an *ad hoc* explanation, the totality of these data indicates that there may be something fundamentally wrong in the present theory. This cumulative process slowly creates scientific crisis and the stimulus for a new theory [9].

In addition to basic revolutionary discoveries, there are limited discoveries, which are usually a step closer to an invention or to a basic innovation. These limited discoveries do not necessarily deal with a basic theory or law; they are often a realization of some aspect of the prevailing theories that had not been noticed or had been overlooked. These limited discoveries give rise to a better and deeper understanding of matter.

Two examples of limited discoveries are nuclear magnetic resonance (N.M.R.) and electron spin resonance (E.S.R.), and the laser. The discovery of N.M.R. and E.S.R. after World War II could have been made many years before because the basic knowledge of electromagnetic theory and the magnetic properties of liquids and solids were already available before then. However, the war effort prompted research by physicists at such institutions as the Radiation Laboratory of M.I.T. that led to new techniques in radio and radar instrumentation and, in particular, in the generation and detection of low level signals. This intimate knowledge of instrumentation allowed for successful experimentation leading to N.M.R. and E.S.R. Several new industries have emerged from the discovery of N.M.R. and E.S.R. These techniques are important analytical tools in chemistry and biology; N.M.R. also has applications as a medical diagnostic tool for cancer detection. This example illustrates both the need for cultural acclimatization of

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[2] Pirandello wrote a play called *Six Characters in Search of an Author*.

[3] One of the newer applications is the Josephson junction. It is the theoretical result of reinterpretation of quantum mechanics. The tunneling effect in a superconducting junction can be used as an extremely fast switch and hence as an element in a computer. This is a far cry from the original discovery of superconductivity and would be classified as a "limited discovery." The technological innovation is an obvious corollary, but was in need of some sophisticated technology and some reinterpretation. The delay time from discovery to innovation in this case was 15–20 years. (See D.C. Gazis, "Influence of Technology on Science: A comment on some experiences at I.B.M. Research," *Research Policy* 8:251 (1979).)

some discoveries so that they can be exploited and also the need for proper instrumentation which, in turn, stimulates new limited discoveries or innovations.

Another example of a limited discovery is the laser. This tool has become an important ingredient in many different types of industries. The coherent properties of light have been used for telecommunications (fiber optics). The property of high density of energy has been used in many different applications—for example, in drilling or cutting of materials. The monochromaticity of the light is used both as a diagnostic tool and as a catalyst to initiate chemical reactions.

The main theory of the laser was embodied in electromagnetic theory and in atomic physics that was known for many years earlier. (Indeed, a major ingredient of the laser is the concept of inverted population, a necessary but not sufficient condition for the light to lase. This phenomenon had been observed previously by many atomic spectroscopists.) The particular jump in the thought process occurred only in 1950, after scientists were exposed to phenomena and to experiments using coherent oscillators such as microwave tubes and masers. The analogy to optical coherent sources followed.

This limited discovery of the laser, the reinterpretation of basic laws, resulted from cultural acclimatization with known phenomena. This gave rise, after a somewhat slow start, to many new innovations that produce new markets and industrial branches [14].

A look at the density of fundamental discoveries and limited discoveries will show peaks and troughs similar to the wavelike characteristic of basic inventions described by Mensch.[4] This wave pattern will be, of course, superimposed on a random noise pattern, since men of genius probably arise stochastically. Nevertheless, it is likely that basic scientific discoveries are also conditioned by a number of external factors. One of these factors already mentioned is slow evolution, a convergence, towards a scientific crisis, when existing theories are not sufficient and are problematic. A need for change arises as scientists become polarized and dissatisfied. But Kuhn has also shown that there is some analogy between political and scientific crisis development [9].

Another factor that may give rise to bunching—in particular, a bunching of limited discoveries and innovations—is the intersecting in time of a number of technologies. If some different technologies become mature roughly at the same time, their interaction will give rise to new experiments and new, novel processes and ideas, which will lead to new discoveries and innovations. These discoveries, in turn, bring about other innovations, as a result of the utilization of merged technologies.

Often the quest for new experimentation and the study of new phenomena will, in itself, lead to a scientific innovation in instrumentation not necessarily related to the prime objective of research. The experiments in molecular beams by Stern and co-workers, which resulted in new and profound knowledge about molecular and atomic phenomena, would not have been possible without the construction of a good vacuum diffusion pump. Simultaneous with his research of atomic and molecular beams, Stern made this pump in order to obtain the high vacuum required to conduct his experiments. As a result of his work the new branch of vacuum technology was formed. Similarly, the discovery of the transistor and the silicon chip with a high density of memory could not have been made without a parallel development of new materials and a controlled deposition of thin films, of etching, electroplating, etc. Industries were built up around these new processes. Hence, a critical factor in creating new innovations is the timing and bunching of a number

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[4] See section entitled "Discussion of Data" and Figure 4.

of discoveries or of the bunching of sophisticated techniques and instrumentation, which prompt or permit the realization of new ideas.

The transition from theory to practical realization in an industrial process does not always follow a uniform pattern. The development of the modern communication industry illustrates one form of such a pattern. In the late 1880s Hertz demonstrated the feasibility of generating radio waves—the Hertzian waves. This was an extension of Maxwell's equation. One can classify Hertz's experiments and theory as a *basic discovery*. On the other hand, Marconi demonstrated in 1901 the possibility of practical transmission of radio waves. This could be classified as a *basic invention*. However, without the technical developments during the next few years (e.g., the diode in 1904 and the triode in 1907) practical radio transmission could not have been made in 1920. The innovation of radio transmission and reception brought about a vast—and still ongoing—expansion of the total communications industry. Many new innovations were brought about: in 1936, frequency modulation and television; in 1940, the practical high frequency radar set. At the same time, discoveries in different fields have given rise to offshoots that merged with the mature communication technology. Advances in semi-conducting scientific knowledge during and after World War II gave rise, in 1951, to the practical transistor. The transistor was a necessary tool for the total miniaturization of the electronics industry, the reduction of electric power, the reduction in cost, and, hence, numerous practical innovations. This caused, in turn, a change and an expansion in the communications industry; different discoveries were merging to give rise to further advances and applications.

Often, however, there is only a small time lag between a discovery and an invention. For example, the discovery of the laser in 1960, which threw new light on some fundamental properties of optical coherent phenomena, was at the same time a practical invention. Hence, the time scale for different innovations, such as the development of the solid state or the gas laser, was very short indeed. The basic technology for this development had already existed at the time of the discovery of the laser; therefore, only a limited amount of research and materials was necessary for further development. The multitude of applications resulting from such an innovation is often called the "swarming of technological innovations." This development is strongly dependent on the availability of the necessary technology at a particular time.

3. Analysis and Discussion of Bunching of Basic Innovations

The relative frequency of innovations and inventions as a function of time has been studied by Mensch [16]; his data are reproduced in Figures 1 through 3. The data show

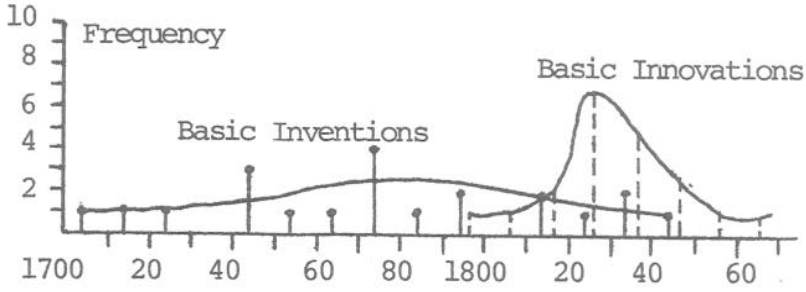

Fig. 1. Frequency distribution of basic inventions and basic innovations as a function of time, referring to the first half of the 19th century [16, pp. 140–146].

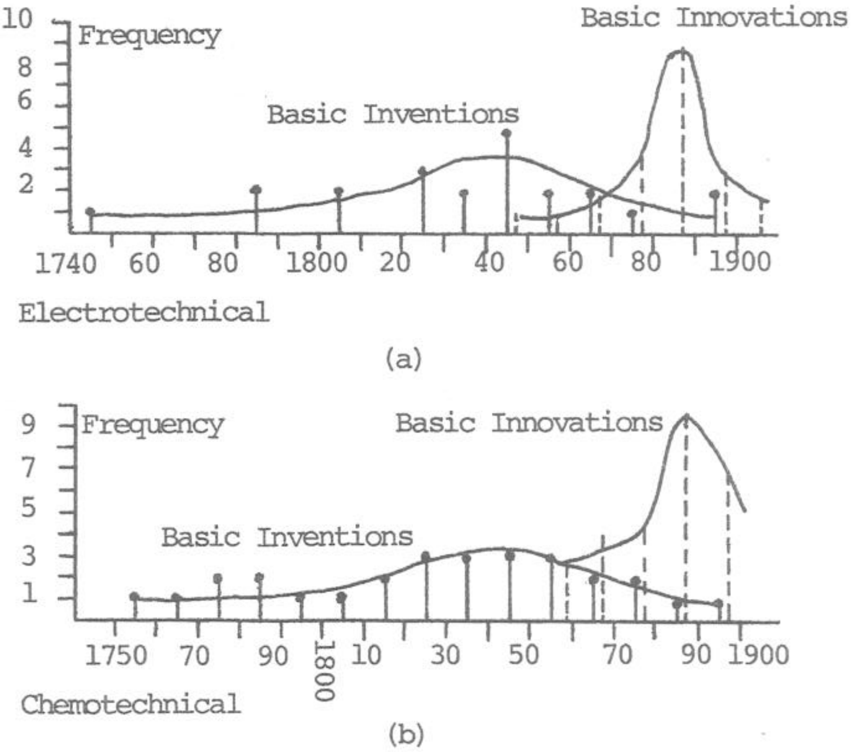

Fig. 2. Frequency distribution of basic inventions and basic innovations as a function of time, referring to the second half of the 19th century [16, pp. 140–146].

peaks and pronounced troughs at definite periods. The peaks are so sharp that, even allowing for inaccuracy in sampling, the main features of these graphs would not be changed drastically.

Criticism of Mensch's data has followed along several lines. Some of the criticism dealt with the sampling of the data. It was claimed that the set of innovations that were included in the sample was not complete. Another criticism dealt with the question of

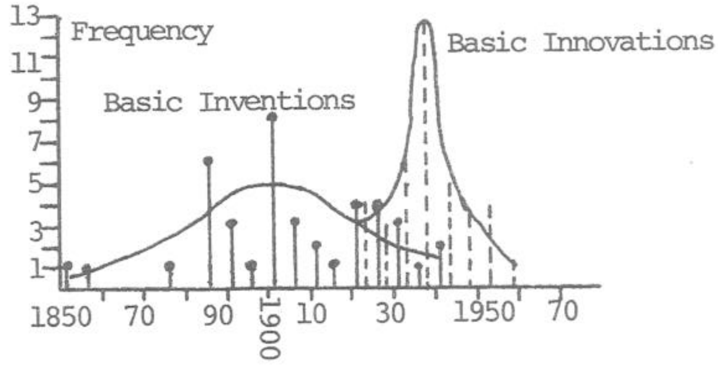

Fig. 3. Frequency distribution of basic inventions and basic innovations as a function of time, referring to the first half of the 20th century [16, pp. 140–146].

value, of attaching relative weight to different innovations. Mensch distinguishes between basic innovation and minor improvement. But, within each category, there are differences in the relative importance of innovations, although, as far as the intellectual exercise is concerned, both may demand the same original thought process, a similar quantum jump.

A large percentage of the criticism has been levied on the data reproduced in Figure 3 and deal with the 20th century. Mensch derived his data mainly from Jewkes et al. in his book *The Sources of Invention* [6], and, to some extent, from Schmookler's data on patents [17]. Clark et al. [1] claimed, with some degree of justice, that Jewkes' data are not complete and, hence, are not sufficient to make a good base for sampling. Similar criticism has been levied against Schmookler's list. Furthermore, Schmookler has data for the period up to the middle of 1950, just beyond which there seemed to be a resurgence of new innovations. Finally, Clark et al. criticized the weighting factor in basic innovations. Mensch does not attach any importance to the relative impact of innovations. For example the ball point pen and the nuclear reactor have the same weight on his scale. The ball point pen may be important; but, certainly, as far as industry is concerned the nuclear reactor was of far larger importance. It is true, however, that the ball point pen was probably the product of innovation of one or a few persons, whereas the nuclear reactor required a team, a cooperative venture, to produce with a practical operating reactor.

Clark et al. conducted an analysis of product and process innovation during the 20th century [1]. They found that there is a sharp peak around 1935 and, in addition, another wider peak around 1965. Their analysis is based on the number of patents applied for and granted in the United States from 1940 to 1979. There is a peak in the number of patents in the years 1930–35, and considerable growth in the number of patents from immediately after World War II until 1975. Naturally these findings can be criticized; patents do not necessarily represent in an intelligent way the nature of an invention. Not each patent granted reflects the importance of the invention. The tendency to patent may, indeed, be conditioned by a trend in industrialization, with many patent applicants "jumping on the bandwagon." Certainly the number of patents in the United States in the period from 1930 to 1940 was very much influenced by the immigration of talented persons from Germany, who fled from the Nazis, and who brought along with them many new ideas and latent scientific discoveries. The number of patents as a function of time from 1930 to 1970 in the United States reflects the tremendous intellectual activity created in part by this immigration [23]. The data on patents of Clark et al. confirm, nevertheless, the essentials of Mensch's conclusion.

Kleinknecht [7] analyzed the data collected by Mahdavi [11]. These data have the advantage that Mahdavi was not concerned with proving or disproving a theory, and, hence, there was no statistical bias.[5] In addition, Mahdavi's sample is diverse and deals with discoveries and innovations of many different disciplines, ranging from instrumentation to practical innovations. Statistical tests of these data, according to Kleinknecht, give strong support of clustering of radical product innovations during the period between World War I and World War II (that is to say, from 1920 to 1940), with a peak in 1935.

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[5] The question of statistical bias has been raised by W.C. Priest and C.T. Hill in *Identifying and Assessing Discrete Technological Innovations*. They state: "It is not quite proper to have a tenable hypothesis for a statistical test to be encouraging if that hypothesis is formed only after 'combing' the data." In general it can be stated that four do not give a reliable statistical test to determine a causal relationship. They may be accidental occurrences. One has to eliminate all other parameters that might influence the data, a task that is insurmountable.

The study of the plastic industry by Clark et al. shows a sharp peak in innovations and inventions near 1935. This seems to be true, in general, for the frequency of innovations in synthetic materials. Mandel also seems to concur with the main conclusions of Mensch [12].

All data and analyses point to the same phenomena: there are significant clusters at definite periods. Mensch's data may be somewhat inaccurate. (We can assume, however, that, if there is an error, it will be a systematic error in classification, in the 17th, the 18th, the 19th and the 20th centuries.) We shall assume, therefore, that the nature of the graphs in Figures 1–3 is not violently changed if there are some relative inaccuracies of Mensch's data. Even if the data were inaccurate by as much as 25–30% it would not significantly change our conclusions. With this assumption, we shall investigate the shape of the different curves in Figures 1–3.

We shall define a measure of time, Δ, called the half-width, which gives the time span between points corresponding to half the frequency of innovation. Basic innovations will be represented by Δ_1; Δ_2 will refer to basic inventions. To have a more quantitative measurement of Δ_1 and Δ_2, one has to know the background frequency of random innovations or inventions. We shall assume that this background is independent of time. We approximate that by drawing a straight horizontal line with the arbitrary frequency scale of 1.0 for basic inventions and 1.2 for basic innovations. The exact number is not relevant to our conclusions, since these are independent of the height of the background. Table 1 gives a measure of Δ_1 and Δ_2 for the three significant Kontradieff periods. It also gives a lead time, δ; the time from the peak of the frequency of basic inventions to the time of the peak of the frequency of basic innovations.

As mentioned before, we shall not be concerned with the exact numbers in this table, but rather with the trend. It is clear from a casual observation of the Figures 1–3 and Table 1 that the peak of basic innovations sharpens up as we move into the 20th century. This is also confirmed from data collected by Freeman et al., who, in a recent book, plotted 195 radical innovations in the United Kingdom from the period 1920–1980 [4, Figure 3.1]. From this curve, we see that the number of radical innovations peaked at about 1935, with a half-width of approximately 6–8 years. This coincides with the trend shown in Table 1. The same authors also show the variation of the frequency of technical innovation and inventions for different countries as a function of time. An analysis of their data [4, Figure 9.1] indicates a cluster at about 1870 with a half-width of 20 years, consistent with data in Table 1.

We can draw the following conclusions from these graphs and Table 1.

1. There are pronounced peaks of innovations at well defined periods separated by approximately 55 years. The structure of these peaks differs for each period. The

TABLE 1

Half-Width of Peaks of Innovation and Invention (in years)

	lst Cycle	2nd Cycle	3rd Cycle
Δ_1[a]	12–14	8–10	6
Δ_2[b]	75–65	55–45	28–26
δ[c]	50–45	40–35	25–20

[a] Δ_1 is the half-width referring to innovation.

[b] Δ_2 is the half-width referring to invention.

[c] δ is the delay time, in years, the difference in time beween peaks in invention and peaks in innovation.

half-width, Δ_1, decreases (by a factor of approximately 2 in a decade) as one moves from the 18th century to the 20th century. Hence the sharpening of the peaks and the bandwagon effect of basic innovation become more pronounced in the 20th century.

2. Similar clusters are observed for basic inventions. However, these clusters are spread over much longer periods than the innovation clusters. The same phenomenon of sharper clusters in the 20th century is apparent, with Δ_1 decreasing by a factor of 2.
3. The time delay of the utilization of innovations, δ (i.e., a measure of the transfer of knowledge from basic inventions to basic innovations) seems to decrease at a nonlinear rate as you move from the 17th century to the 20th century. It appears that industry is able to absorb the cumulative knowledge from basic inventions much faster and to utilize it more quickly for industrial purposes.

Similar trends had been noticed in 1980 by Marchetti [13]. Instead of using the measure Δ, the half-width, Marchetti fits a set of limited data to a function

$$\log \frac{F}{1 - F} = at + b,$$

where F is the cumulative number of innovations or inventions reported, normalized over the total set under the peak, t is the time variable, and a and b are constant. The slope of these curves is measured by the time to move from $F = 0.1$ to 0.9 and this time increment substantiates our conclusions. The innovation time constant is shorter than the invention time constant, and both decrease by a factor of approximately 2, between 3 cycles or in a century.

One would assume *a priori* that the frequency of fundamental or limited discoveries should not be profoundly influenced by economic factors or cycles. They should not show strong peaks of activity at definitive economic periods. They should be more influenced by what Kuhn calls "the crisis environment," and by general advances in instrumentation as well as by cultural forces. Inventions and product and process innovations are no doubt causally dependent on the frequency of discoveries. On the other hand, inventions and innovations are more susceptible to economic pressures. They may be either the cause or the effect, the stimulus for, or be stimulated by, economic activity.

These conclusions have to be viewed against a changing background of employment of scientists and engineers during the last 100 years. In the 19th century, many engineers were probably not much more than glorified technicians. In the twentieth century, how-

TABLE 2
Chronology of Kontradieff Cycles

	I	II	III	IV
Prosperity	1782–1792	1845–1857	1892–1903	1948–1957
Prosperity	1792–1802	1857–1866	1903–1913	1957–1966
Recession	1815–1825	1866–1873	1920–1929	1966–1973
Depression	1825–1836	1873–1883	1929–1937	1973–1984
Recovery	1836–1845	1883–1892	1937–1948	

Source: Data are from J. J. Van Duijn, *Prospects of Economic Growth,* Chapter 20,(S. K. Kuipers and G. J. Lanjouw, eds.), North Holland Press (1980), p. 223; J. J. Van Duijn, *Futures* 13(4)268 (1981).

TABLE 3
Duration of Kontradieff Periods (in years)

	I		II		III		IV
Prosperity	20	(13)	21	(14)	21	(13)	18
Recession	10	(12)	7	(11)	9	(12)	7
Depression	11	(13)	10	(14)	8	(13)	10
Recovery	9	(14)	9	(12)	11		

Sources: J. J. Van Duijn, *Prospects of Economic Growth,* Chapter 20, (S. K. Kuipers and G. J. Lanjouw, eds.), North Holland Press (1980), pp. 223–233; numbers in brackets from S. Kuznets, *Technological Innovation and Economic Growth,* San Francisco Press, San Francisco (1978).

ever, engineers were already employed in advanced R & D work. Furthermore, during the last 100 years, there was a considerable increase in the number of scientists and engineers employed in industry and in government work. In 1940, there were about 10,000 scientists; by 1950, the number had increased ten-fold (see Figure 6).

We should consider also these curves and take into account the background of the emergence of organized science, of government-sponsored R&D, often for defense purposes. Government sponsorship brought about a change in social and cultural attitudes toward science and technology. We shall discuss this in the next section.

4. Discussion of Data

An analysis of the data presented in Section 3 and some of the conclusions drawn from them have a definite relation to fundamental questions relating innovation cycles to economic cycles.

Protagonists of the long wave theory have found correlations between the Kontradieff cycles and the bunching of innovations as discussed in Section 1. There is some controversy regarding the historical onset of various periods of Kontradieff cycles, of prosperity, recession, depression, and recovery. Van Duijn [21, 22] recently has reviewed his evidence, which is presented in Table 2. In Table 3 we show the lengths of these various periods. The numbers in brackets are taken from Kuznets [10]. There is a reasonable consistency between the data of Van Duijn and Kuznets, if you lump prosperity and recovery together. The main discrepancy is in the interpretation of when recovery ends and when prosperity begins, since both periods refer to economic growth.

The evidence of the position of the peaks of basic innovations seems to support the main correlations with economic cycles found by Mensch and others. The peaks of innovation and the clusters tend to occur during the end of the recession or the beginning of the recovery. We shall deal separately with the peak near 1935, when we discuss a similar peak in scientific discoveries at about the same time.

Freeman, et al. [4] have found another peak in innovation about 1960. They use this as convincing evidence against Mensch's hypothesis that clusters of innovations occur during depression. The 1960s was a period of relative prosperity.

We are reluctant to attribute this peak only to standard economic factors, such as market considerations. No doubt they play a role in the increased innovation activity. The removal of economic barriers, such as price controls and the marshalling of industry to the "war effort" resulted in a spurt of new economic activity that was restrained for a long period. However, the aftereffects of World War II have to be taken into account. These are the reconstruction of Europe, the Cold War, and the sudden awareness by government and by corporate industrial leaders of the new and important role of scientists and engineers. This resulted in a stronger commitment to R&D, and probably to the surge in innovations in the 1960s.

One possible theory is that this peak measures, to some extent, the transfer of scientific engineering talent from Germany, under Nazi rule, to the United States and Europe. In the early 1930s, Hitler expelled 1,600 scientists; many of them left for the United States and Great Britain. This may account for the sudden decrease of scientific activity in Germany by over 100% between 1920 and 1940, despite the massive government support of R&D for military industrial purposes. This is also borne out, to some extent, by the striking number of Nobel Laureates in basic sciences as shown in Table 4. Many of the Nobel Awards from 1950 to 1966, were given for research done in the early 1930s, and a significant fraction of them were of European origin and had migrated to the United States. No doubt this immigration stimulated U.S. R&D in engineering and basic sciences and helped establish U.S. supremacy. We can, therefore, consider the peak around 1935 as simply a continuation of the activity of the early 1900s that was interrupted by World War I and its aftereffects.

The interesting aspect of the numbers in Table 3 is that the periods are nearly constant for all the three or four cycles. The period of prosperity, according to Van Duijn, is approximately 12 years; the period of depression is approximately 10 years.

In contrast to this constancy, we find that the duration of the periods of basic innovations gets shorter, as seen in Table 1. The same seems to hold true for major inventions. Obviously, a simple economic pull or push on innovations cannot be the only explanation, since the shape of the curve of innovation, (its half-width) does not correspond with the shape of the periods of economic depression or recovery (although its detailed shape has not been investigated).

A partial explanation of the change in Δ_1 and Δ_2 with the various periods, compared with the constancy of Δ of the economic cycles may be found in the fact that modern industry is more aware of inventions and innovations. A major innovation will induce many industries to capitalize on it, to jump on the bandwagon, so as not to be left behind. This is particularly true if the breakthrough seems to be practical and profitable. This, in turn, will create what Schumpeter describes so vividly as *the swarming effect*. Many industries will take up a very promising idea; one major innovation will give rise to many other innovations. This was found in the 1860's in the chemical industry—particularly

TABLE 4
Nationality of Nobel Prizes in the Sciences

Country	1901–30	1931–50	1951–66
United States	5	24	44
Belgium	1	1	0
Canada	1	0	0
France	14	2	4
Germany	26	12	7
Japan	0	1	1
Netherlands	7	1	1
Great Britain	16	13	18
USSR	2	0	7
Other countries	22	17	0

Sources: N. Rosenberg, "Role of Science and Technology in the National Development of the United States," in *Science Technology and Economic Development,* (William Baranek, Sr. and Gustav Ranis, eds.), Praeger Publishers, (1978); the data are taken from *Encyclopedia Britannica* XVI, pp. 549–51 (1967).

in the dye industry—and, similarly, in the 1930s in synthetic materials. A cumulative effect was clearly to be discerned.

Modern communication, scientific journals, and informal conferences have contributed significantly to the rapid dissemination of knowledge. This brings about related additional advances in innovations. This is particularly pronounced once a profitability of a technical development has been clearly demonstrated. A good example of such a trend is the modern development of technical and semi-fundamental innovations in Silicon Valley, based on the progressive development of the micro-chip as a basic element for microprocessors and computers.

Mensch [16] has also discussed in detail the evidence of the lead time from basic invention to basic innovation. He concludes that the tendency toward a shorter time span exists in some technological areas and only in certain periods. This means that the delay time, δ_1, for one industry may be fairly long compared with δ_2 for another industrial sector where inventions are being utilized in a brief time. Each industrial sector has its own problems, hurdles, and obstacles to overcome before it will take the risk of modernization, and investment in new inventions and innovations. A detailed study would, therefore, take into account each sector separately.

However, if one looks at the composite picture of all the economic activity it becomes clear that there is a definite trend. The time lag, δ, the uptake of inventions so as to transform them into industrial innovations, which, in turn, gives rise to new economic growth, is shortened considerably as one moves from the 17th to the 20th century, by about a factor of 2.2 between the first and second (δ_1) cycle compared with the period between the third and fourth cycle.

One may conclude, therefore, that it is naive to assume that only market forces are the source for the surge and the duration of innovations and inventions. Other additional forces, such as social and cultural changes, educational changes, wars and their after-effects, and government intervention, may produce contributory effects, which may account, at least in part, for the emergence of these peaks and their duration. The economic cyclic behaviour seems to be superimposed on some long-term effects as well as some additional fluctuations which may lie outside standard economic theories.

5. Evidence of Clusters of Fundamental Discoveries

We have indicated previously that basic innovations are to a large extent determined by basic scientific discoveries, and these seem to cluster, as well, at definite times. The evidence can be derived from data collected by Streit [20] who investigated major scientific and social innovations by country of origin over the last 200 years. Freeman, et al. [4] have used these data to plot a 10-year moving average of the number of major discoveries by country of origin (see Table 9.1 and Figure 9.2 in their recent book.) We have used their data to plot the composite of all scientific discoveries of the major industrial countries (France, Germany, Great Britain, and the United States, from 1765–1945). This is shown in Figure 4.

The data compiled by Streit are somewhat limited and, like all data of this type, somewhat subjective. However, even allowing for considerable inaccuracy (say, up to 30%) of these data, a few salient and surprising features emerge. There are definite and well established peaks or clusters of discoveries at four periods. The first peak is about 1805 and is a composite of two peaks in leadership of two countries. France dominated scientific discoveries in the Napoleonic era (about 1795); England led soon afterwards (about 1810). Germany took a dominant lead about 1850 and accounted for about 40% of all major discoveries, particularly in the chemical sciences. This gives rise to the

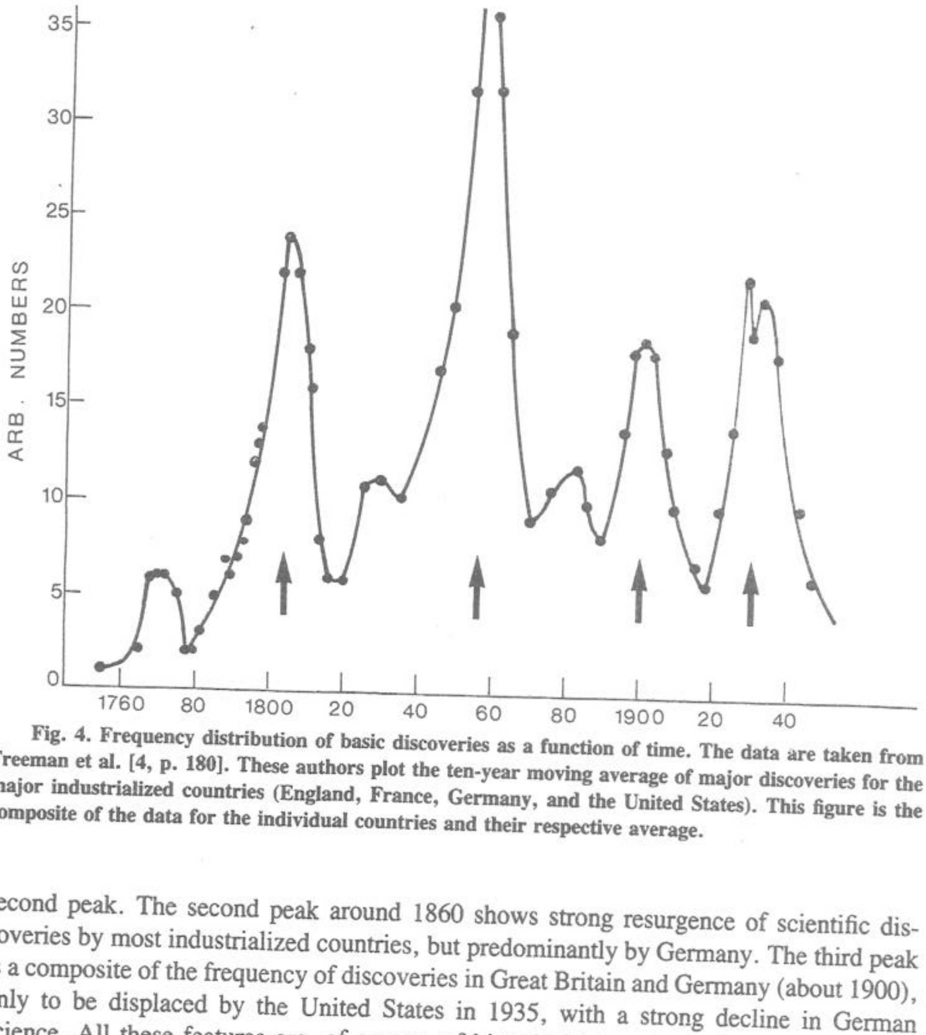

Fig. 4. Frequency distribution of basic discoveries as a function of time. The data are taken from Freeman et al. [4, p. 180]. These authors plot the ten-year moving average of major discoveries for the major industrialized countries (England, France, Germany, and the United States). This figure is the composite of the data for the individual countries and their respective average.

second peak. The second peak around 1860 shows strong resurgence of scientific discoveries by most industrialized countries, but predominantly by Germany. The third peak is a composite of the frequency of discoveries in Great Britain and Germany (about 1900), only to be displaced by the United States in 1935, with a strong decline in German science. All these features are, of course, of historical interest and show that scientific effort gravitates from one country to the next.

It should be noted in this context that in the period 1820–1830 most bigger European cities founded Polytechnic Institutes similar to the original Ecole Polytechnique in Paris (e.g., Prague, 1806; Vienna, 1815; Karlsruhe, 1825; Munich, 1827). The competition among these institutions was strong. Eventually the majority achieved full academic accreditation and were recognized as technical universities. Their influence on the universities, and vice versa, as well as on industry, was very pronounced. No doubt that the graduates of these technical universities have contributed to the emergence of the peaks of the 19th century, particularly in Germany where many of these institutions existed.

It seems an inescapable conclusion that scientific discoveries cluster similarly to industrial inventions or innovations, with a certain time separation. It is of similar interest to note that the peaks in discovery fall approximately at the end of a period of relative prosperity (see Table 2). The period of prosperity may be an important factor which permits talented people to indulge in fundamental science. Positive economic consideration, such as support of R&D, may be more easily made during the periods of prosperity.

However, this conjecture needs further substantiation. It seems unlikely—and even, to some extent, unreasonable—that only economic pull and push have a strong influence on basic scientific discoveries.

If one compares these peaks with all the peaks of basic innovations and inventions, one is tempted to detect a transfer of knowledge delay time which is more or less constant. The peaks of innovative activity seem to be delayed from the peaks of scientific discovery by about 30 years, unlike δ, which decrease rapidly. However, we feel reluctant to draw any definitive conclusions from these data and this just may be accidental.

The peak near 1935, however, is different. It falls at the time of economic depression in the United States and throughout the rest of the world. The main contribution to this peak of scientific discovery is from the United States. At about the same time there is also a peak and cluster of basic innovations. Here, again, the main contribution comes from the United States. In Figure 5, we present data of government and industrial expenditures in science and engineering. U.S. government spending increased very little during the period from 1930 to 1950. Basic research received larger grants only after the war. A study by the National Science Foundation estimates of R&D show a somewhat larger increase, shown in Figure 6. The National Science Foundation's data contain a significant amount of money given to agricultural research. Industrial support increased in the period from 1930 to 1940, although not very radically. The National Research Council estimates that there were about 1000 industrial laboratories in 1927, about 1600 in 1931, and close to 5000 in 1956. However, these industrial laboratories in the 1930s did very little basic research and, in most cases, they were only concerned with small

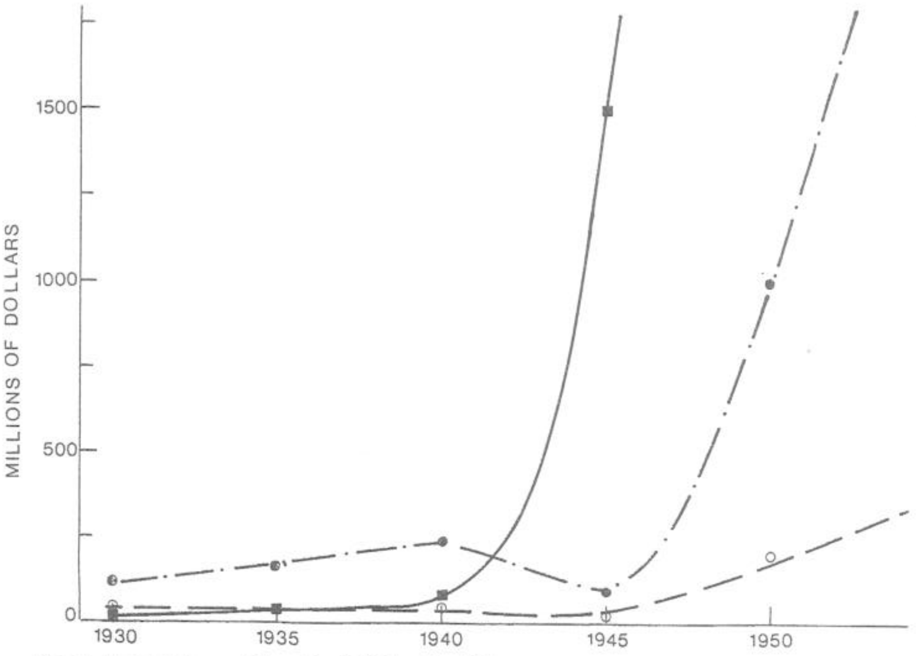

Fig. 5. Financial expenditure for R&D by the U.S. government, industry, and universities during the period 1930–1955. The basic data are taken from Warren Weaver, *Scientific American* 199, Sept. 1958, page 171. (Note: ■ = Expenditure by government in millions of dollars; ● = Expenditure by industry; ○ = Expenditure for basic research.)

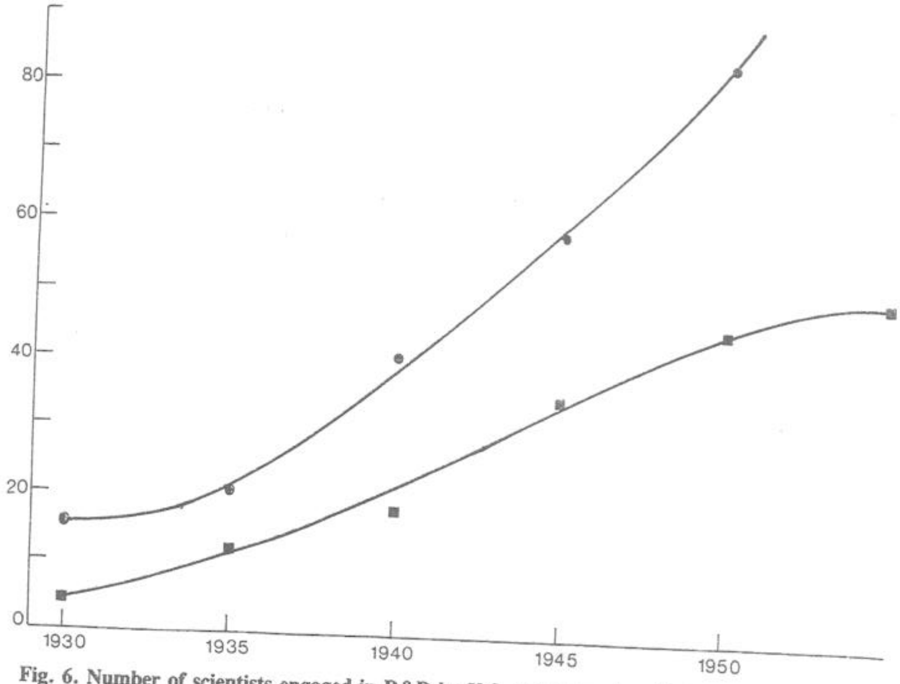

Fig. 6. Number of scientists engaged in R&D by U.S. government and industry during the period from 1930–1955. The basic data are taken from Warren Weaver, *Scientific American* 199, Sept. 1958, page 173. (Note: ■ = Number of scientists in government in thousands; ● = Number of scientists in industry in thousands.)

technical innovations or with testing. The number of scientists employed in government or in industry started to increase only at about 1940, and is shown in Figure 7. Hence, none of these data seem to support unusually strong industrial or government activity between 1930 and 1940, which would prompt a peak in scientific discoveries or in innovations in 1935. We, therefore, do not consider this peak as evidence for any theory which links peaks in innovation.

6. Conclusions

There seems to be abundant evidence that innovations and inventions cluster at definite periods of history. There is a correlation of these clusters with cyclic economic activities, although a causal relationship cannot be definitely established from these data alone. There is also good evidence that the transfer of knowledge from the periods of invention to industrial innovations shortens as one moves to modern times. The peaks and the shapes of the clusters become sharper and more pronounced in the 20th century than they were in the 18th or 19th century. The evidence for these clusters on the whole is even stronger than the evidence for the long wave, the Kontradieff waves. This is indicative of a cumulative, amplifying effect in modern times.

It has been pointed out that a breakthrough in a given technical area, in a well defined scientific field, leads to an avalanche of basic innovations. At a somewhat later stage, it may lead to a considerable amount of activity in somewhat less basic innovations, in instrumentation, in product and process control and improvement. It is very likely that this bandwagon effect of the swarming of innovations is caused, to a large extent, by

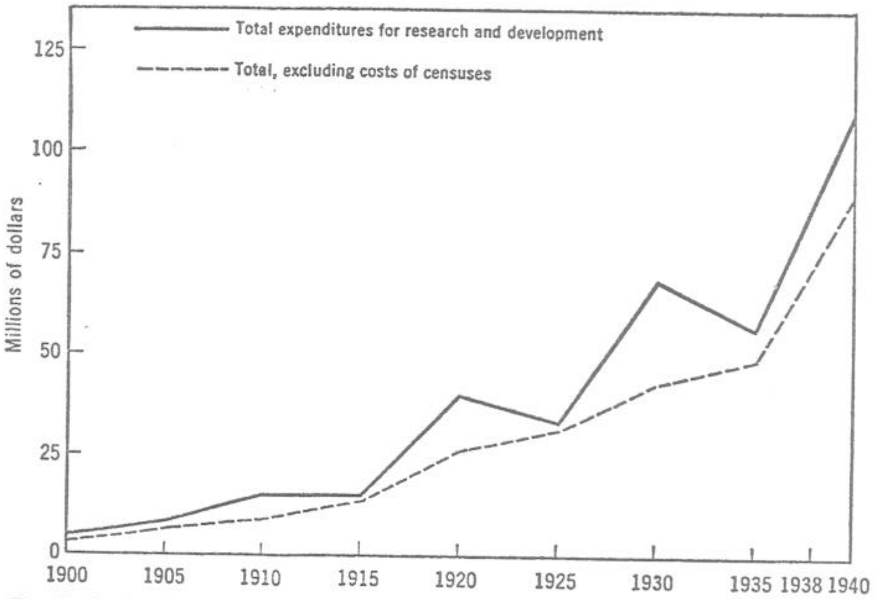

Fig. 7. Total U.S. government expenditure for R&D from 1900–1940. The data are taken from *Science in Federal Government,* A. Hunter Dupree, Harvard University Press (1957), page 331. The data themselves are courtesy of Mrs. Mildred C. Allen, The National Science Foundation. (Note: the dotted curve refers to the expenditure excluding the costs of the censuses.)

economic considerations. These may be either because of expectation of industrial profits or the fear of being left behind in a rapidly developing market. Modern communication and transfer of knowledge may be, in part, the reason for sharper peaks.

Traditional economic theories, whether they are monetarist or neo-Keynesian, cannot ignore the data—that is to say, the structure of the peaks, their half-widths, the shortening of the delay time from invention to innovation as one moves from the 18th to the 20th century. It cannot treat the changes in patterns of innovation and in discoveries only as exogenous variables. These variations in the frequency of innovations and inventions, and their structural time dependents, have to be incorporated in a larger, more total, and, at the same time, more dynamic, economic theory.

We have shown that there is also some evidence that discoveries cluster at definite periods. It is difficult to correlate a link of these clusters with economic activity or economic cycles. There is, of course, a functional relationship between discoveries and inventions and, in turn, with industrial innovations. Without basic discoveries there will be few, if any, new inventions. Hence it may be suggested that there is some transfer of knowledge from the peaks of discoveries to create peaks of inventions, after an appropriate time of digestion. On the other hand one can also postulate that periods of stronger industrial activity giving rise to innovation may well be a psychological trigger for new intellectual activities that lead to what we have called limited discoveries.

One is faced with a partial dilemma. There seems to be no strong explanation of why discoveries should occur at well defined clusters. There is an obvious functional relationship of discoveries with innovations; yet it has been conjectured that economic factors are responsible for these peaks of basic innovations. Theories have been advanced that relate causally the cycles of innovation to cycles of depression or the onset of recovery and to the related theories of the Kontradieff cycles.

In the absence of a complete theory and additional data one can only conjecture some possible reasons which are in need of further investigations.

Kuhn [9] has already pointed out the connection between social and political forces and its effects on crisis situations in fundamental science phenomena. The first peak in scientific discoveries falls roughly around the time of the French Revolution and of the Napoleonic wars. This period had an atmosphere of social revolution, in which the basic tenets of government were challenged. In addition, the French government—probably the first time a government has done this—organized pure and applied science for both military and cultural national resources. Similarly, the strong peak in scientific discoveries in 1860, many of which stemmed from Germany, may be connected to the social problems and aborted attempts at bourgeois democratic revolutions in 1848. In addition, as we have pointed out, the effect of the creation of many polytechnic institutes and universities may have also helped in creating the strong peak in scientific discoveries in 1880. This has to be related, of course, to the close relations of German industries—in particular, in the chemical industry, in the dye and petrochemical sectors—with professors of universities and polytechnic institutes. Similarly, the inventions and scientific discoveries around 1905 seem to correlate with social and cultural unrest in Europe.

A full analysis would also have to take into account the emergence of organized science and technology. Government intervention is sometimes massive, particularly for defense needs; this leads as a by-product, and very often an unpredicted by-product, to new discoveries and inventions. It is fallacious, however, to think that government spending in defense oriented areas is the only contributing factor. Government sponsored cultural and medical research are probably among the prime movers in the fundamental and applied activities in these fields.

The total interplay of economic factors, of social and cultural forces and attitudes, the emerging of technologies and their advances, and, in particular, instrumentation, as well as the effect of organized science and massive government support, the awareness that scientists and engineers are a national asset, all of these factors have to be taken into account before a more complete theory can be formulated, or economic decisions or projections be made solely on such data.

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