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Changes in Industry and in the State of Knowledge as Determinants of Industrial Invention

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THIS is a progress report on a larger study of the growth of technical knowledge. The study as a whole centers on the course of patented inventions in many American industries from 1836 to 1957. This paper, however, will deal with only four of the most important industries—railroading, farming, paper making, and petroleum refining, with primary emphasis on the railroad industry, the industry for which our data are most complete.

Before our preliminary findings are described, it seems worth while to say a few words about the conceptual framework of the project as a whole. We assume that the growth of modern western industrial technology has been primarily the result of the interplay of (1) changes in the state of knowledge and (2) changes in industry. The "state of knowledge" includes not only science and technology but also any other aspects of thought, e.g., art and religion, which affect man's perception of the material universe. "Changes in industry" presumably change, among other things, the benefits expected from a potential change in technical knowledge. The "benefits expected" from changing the stock of technical knowledge are those anticipated and valued by the unit seeking to make the change. Presumably, in a private enterprise economy these benefits usually take the form of profit to the inventor or his backer.[1]

Changes in the state of knowledge can influence inventive activity by affecting either (1) the prospective cost of making an invention and

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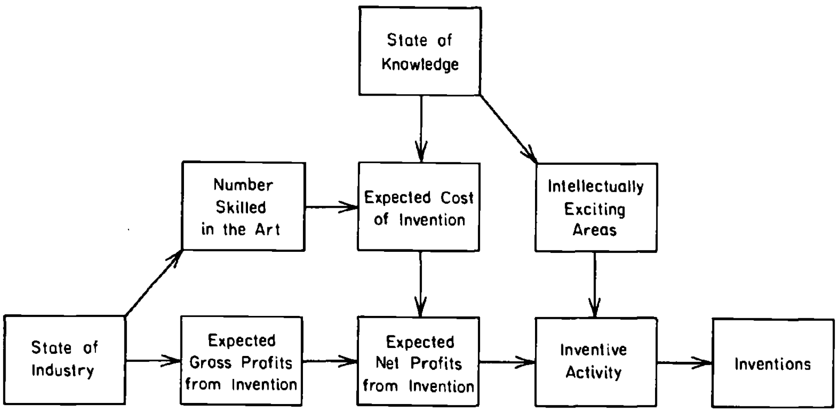
[1] Cf. Jacob Schmookler, "The Level of Inventive Activity," *Review of Economics and Statistics*, May 1954.

thereby the *net* profit anticipated from it; or (2) the intrinsic interest of explorations in different fields of technology. While analytically distinct, (1) and (2) are probably often impossible to differentiate in practice: though an employer may finance the pursuit of an idea because new knowledge reduces its prospective cost, his hired inventors may pursue the idea mainly because they find it interesting.

The conceptual framework of the project, which is naturally subject to change as our work progresses, is summarized in the following diagram, in which the arrows signify "determines".



At any moment the existing state of knowledge wholly determines the set of all conceivable inventions by definition of the latter. Since increases in technical knowledge change the state of knowledge always, and the state of industry often, the process described in the diagram is continuous. It is not a closed process because other factors affect both industry and the state of knowledge. Because it is so difficult to get data on the variables in the interior of the diagram, we concentrate our analysis on those on or near the boundaries—the state of knowledge, the state of industry, inventions and inventive activity.[2]

In emphasizing the role of expected benefits, changes in which are assumed to arise from economic change, this conception of events stands in marked contrast to that which views technological progress exclusively as an automatic outgrowth of the state of knowledge itself. In the latter view, the growth of technology takes on the character of a

[2] We hope to give special attention, in our project but not in this paper, to the number skilled in the art.

process which, given some indispensable minimum institutional framework, is largely independent of economic life.

Two variants of the latter interpretation may be distinguished. According to the more sophisticated version, which seems implicit in many sociological and anthropological analyses, new inventions can be adequately explained by reference to the state of prior knowledge, because every new invention grows out of existing knowledge, whether that knowledge be scientific, technological, or otherwise. The more popular version, the application of which is usually limited to recent times, differs from the sophisticated only in that the relevant knowledge base consists wholly of science. In this variant, therefore, new inventions are considered adequately explained by reference to the scientific discoveries from which they allegedly grow.

The persuasiveness of both variants derives from the genetic logic evident in the history of ideas, for each new idea does build on earlier ideas. Yet neither variant can answer two crucial questions: (1) What determines the lag between the formation of the indispensable prior knowledge and the emergence of the new ideas based on it? (2) Since, one must suppose, only some of the useful ideas which could evolve from a given knowledge base actually appear, what is the nature of the selection process?[3]

Our central hypothesis assumes that the answers to these two questions will be found primarily in the anticipated costs and benefits —with risk preferences, intellectual curiosity, and purely random factors undoubtedly also playing a part. The problem may be stated in the parlance of traditional economics. The supply of inventions is in a sense determined by the number of creative individuals skilled in the technical arts, and by the state of knowledge which affects the conversion of inventive effort into inventive output. The demand for inventions, in turn, is presumably determined by economic conditions.

Those who, like Ogburn and his followers, have emphasized the dependence of new inventions on the prior art to the point where the whole process takes on an inevitable character, appear to believe that the supply of new inventions at any moment is completely inelastic, and that the new knowledge gained from one moment to the next

[3] The popular variant is not only unable to answer these questions but ignores the frequent instances in which inventive activity either flows into channels unaffected by scientific discovery, or fails to flow into channels which have been so affected. Likewise, it overlooks the influence of industrial technique on scientific inquiry and, like the sophisticated variant, has no apparent regard for the effect of instrumental considerations on the direction and level of scientific work.

causes the supply curve to shift (exponentially) rightward. By contrast, Gilfillan[4] and the present writer[5] have stressed factors on the demand side.[6]

In a sense, therefore, the problem before us is the relative influence of changes in (1) demand conditions and (2) supply conditions on the production of inventions.

Of the variables noted affecting the supply of inventions in a field—the number of workers skilled in the art and the state of knowledge—we shall consider in this paper only the latter, and of the many factors which might affect the demand for inventions we shall consider only investment here. Obviously, any statements to be made about the relative influence of investment and the state of knowledge apply only to the four industries covered. Even for these industries any statements made must be regarded as tentative.

The study of our four industries is continuing, we are studying other industries as well, and the underlying data are not in final form. While the patent statistics presented here are for patents counted at the time of granting, our study will ultimately be based on patents counted at the time of application for the patent right. Such data are superior to those used here, which are affected by significant variations between fields and over time in the interval between the date of application and the date of granting. Such variations inevitably obscure the inventive process which it is our purpose to study. Yet, the data presented below do provide indications of the long-term trends and long swings[7] (if any) in invention in the industries covered. The highly interesting results reported justify their use.

The findings are tentative for still another reason, however: they traverse territory so novel that important features of the landscape may easily escape notice. The data have been available only briefly,

[4] S. Colum Gilfillan, *The Sociology of Invention*, Chicago, 1935.

[5] Schmookler, *op. cit.*

[6] For a more extensive discussion of the literature in this context, cf. Richard R. Nelson, "A Survey of the Literature on Invention," *Journal of Business*, April 1959.

[7] Long swings are alternating phases of expansion and contraction, either in absolute terms or relative to trend, whose combined duration exceeds that of business cycles, i.e. four to eleven years. Their maximum duration is shorter than that of the trends about which they move. They, thus, characteristically exceed a decade and may last over half a century. Cf. Simon Kuznets, "Long Swings in the Growth of Population and in Related Economic Variables," *Proceedings of the American Philosophical Society*, Vol. 102, No. 1, pp. 25–52; Moses Abramovitz, "Long Swings in U.S. Economic Growth," and Richard A. Easterlin, "Long Swings in the Growth of Population and Labor Force," in *The Study of Economic Growth*, National Bureau of Economic Research, Thirty-ninth Annual Report, New York, 1959, pp. 23–27 and 27–30, respectively.

and further study and the consideration of other variables may well reveal significant characteristics as yet unobserved.

Subject to the foregoing qualifications the evidence presented below suggests the following: (1) The trends and long swings in patented invention tend to match those in investment. (2) Both investment and invention quite clearly move together with prospective profits in railroading, the only industry for which we have an index of the latter. (3) There is some tendency for important inventions to lead run-of-the-mill inventions, but this tendency is slight and its significance is unclear. (4) Scientific discoveries played no appreciable and obvious role in triggering important inventions in our four industries. However, scientific discoveries undoubtedly sometimes played a permissive role, particularly in the case of petroleum refining and papermaking inventions, many of which necessarily depended on the growth of chemical science. Moreover, if plant improvements, e.g., hybrid corn, were included in our list of important agricultural inventions, the triggering effect of scientific discoveries might seem greater than our present evidence suggests.

Important Inventions, Run-of-the-Mill Inventions, and Investment in the Railroad Industry

Because our economic data are most complete and the case seems clearest for railroading, we consider it first. Chart 1 shows the course of railroad stock prices, capital formation, and patents. The patents cover equipment and structures. The stock prices have been adjusted for changes in the general level of wholesale prices.[8] Net additions to road are taken as representative of capital formation during the early years when a more suitable index is not available.[9] These three variables are shown as seven-year moving averages. Gross capital formation is presented in the same form as in the source, i.e., as a five-year moving average.

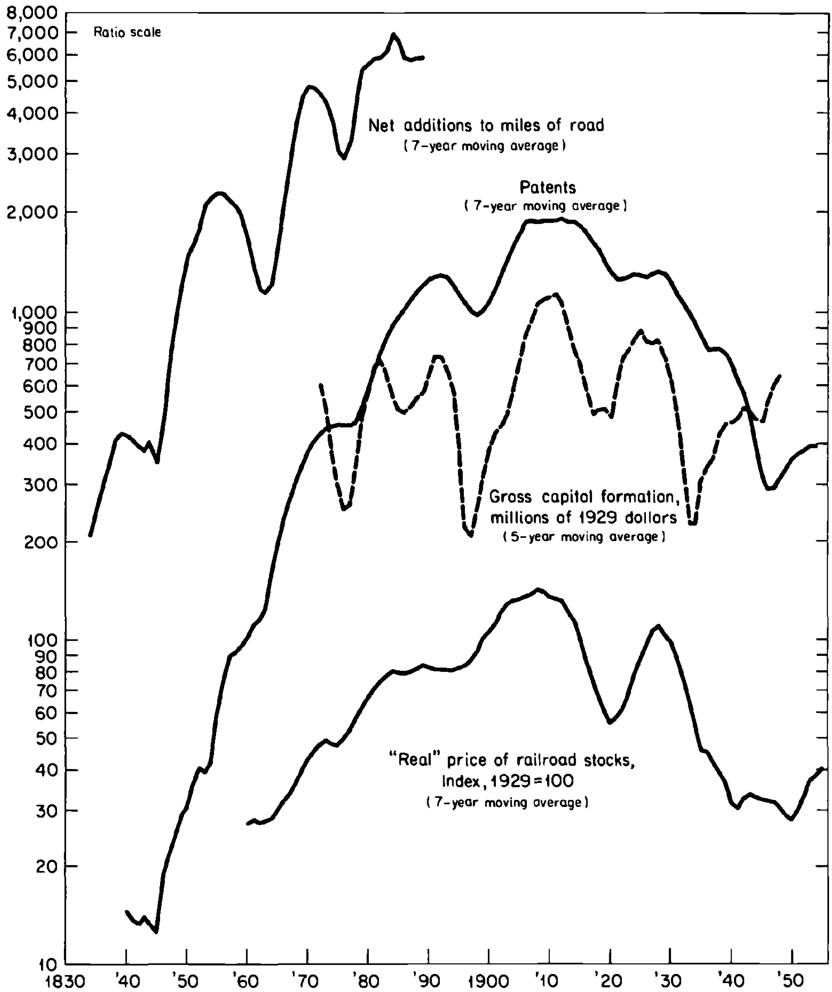
The general impression conveyed by Chart 1 is unmistakable. The trends and long swings in railroad stock prices, capital formation, and patenting are very similar. Net additions to miles of road decline from

[8] If railroad stock prices were adjusted for changes in the general level of stock prices, or not adjusted at all, the net impression created would be much the same.

[9] Cf. Melville J. Ulmer, *Trends and Cycles in Capital Formation by United States Railroads, 1870–1950*, Occasional Paper 43, New York, NBER, 1954, p. 54, which suggests, by implication at least, that this series is a tolerable indicator of capital formation in this period.

CHART 1

Railroad Stock Prices, Capital Formation, and Patents



SOURCE: Gross railroad capital formation in 1929 prices: Melville J. Ulmer, *Trends and Cycles in Capital Formation by United States Railroads*, 1870–1950, Occasional Paper 43, New York, National Bureau of Economic Research, 1954, Table A-1. Net additions to miles of road: calculated from *Historial Statistics of the United States*, Series K-1. The "real" price of railroad stocks: calculated by taking stock prices from F. R. Macauley, *Some Theoretical Problems Suggested by Interest Rates, Bond Yields, and Stock Prices in the United States Since* 1856, New York, NBER, 1938, App. Table 10; and from *Moody's Transportation Manual*, 1959, p. a3; and adjusting for changes in the BLS index of wholesale prices, *Historical Statistics*, Series L-15, and *Statistical Abstract of the United States*, 1959.

1839 to 1845. Patents granted decline from the start in 1840 to 1845. Both series then rise rapidly after 1845, with additions to road suffering a check in the rate of climb from 1850 to 1851 and patents declining absolutely in 1852–53. After a further rise additions to road decline absolutely from 1855 through 1863, while patents undergo marked retardation in the rate of climb from 1857 to 1863.

Rail stock prices begin rising in 1862, additions to road and patents, in 1863. Additions to road reach a peak in 1870, stock prices in 1873, and patents in about 1875. Stock prices start rising again in 1875, capital formation in 1876, and patents in 1877. The next set of peaks are difficult to locate. In investment, in fact, there are two peaks. Stock prices appear to reach their high in 1889, capital formation in 1891, and patents in 1892. Stock prices then reach a trough between 1891 and 1893, capital formation in 1897, and patents in 1898. The next series of peaks, which happen also to constitute all-time highs, occur in 1908 in stock prices, 1911 in capital formation, and 1912 in patents.

Stock prices, which generally led during the trend expansion, move into second place or tie for third during the trend contraction. Capital formation reaches a low in 1917–20, stocks in 1920, and patents in 1921. Capital formation then moves to a high in 1925, with stock prices and patents reaching their highs in 1928. Capital formation then falls to a low in 1933–34, stocks in 1935, and patents in 1936, with both of the latter falling thereafter but at a slower rate. The subsequent timing relations are not clear, perhaps because the recent swings are incomplete.[10]

One of the striking features of the relation between railroad patents and the other variables shown in Chart 1 is its substantial invariance over the whole period. *During a century in which inventive activity itself changed drastically, and in which the railroad industry moved from an unregulated to a regulated status and from growth to decline, patents continued to rise and fall with the level of railroad investment and expected profit as represented by stock prices.*

What is the explanation of this striking phenomenon, this covariation of patents, investment, and expected profits? Clearly, the rise of highway transportation explains the long-term decline which began around 1910 in all three railroad variables. With the growth of rival forms of transportation, investors and inventors simply turned to more remunerative fields. Thus, in a sense, one might argue, a major

[10] Obviously, if trends were eliminated the timing estimates might change somewhat, but not enough to affect the general picture of synchronization of movement.

invention, the automobile with its variants—the truck and bus—was responsible for the secular decline of railroad investment, invention, and stock prices. (We shall discuss this argument later.) This argument provides us with a clue to a possible and obvious line of further inquiry: Can it be that the long swings in railroad stock prices and investment also reflect the implementation of railroad inventions, just as the secular decline in railroad investment reflects the implementation of a major rival invention? In short, are the waves of railroad investment generated by the waves of railroad invention? This is a natural question, and we shall consider it first.

The first point to note is that the long swing turning points in patents generally lagged from one to three years behind the turning points in the two capital formation series. Only at the two earliest troughs, 1845 and 1863, did patents manage to turn as early as investment. Since the interval between application and granting of patents was generally about a year or less before World War I, and about two years in the interwar period, and since our investment data pertain to installations, not decisions, the most that can be plausibly inferred from the data is that the long swings in railroad inventing and patenting coincided with those in railroad investing. This suggests that whatever effect the waves of potentially useful invention had on the concurrent waves of investment was probably superimposed on the latter and not a cause of them.

Conceivably, however, a given swing in invention could cause the next swing in investment. Yet, if this is the case, why do the trend peaks in both variables occur practically simultaneously? If a given swing in invention causes the next swing in investment, the all-time high in investment should have come in the 1920's, not around 1910. Secondly, according to this hypothesis one would expect variations in the duration of the swings in invention to reappear, with a lag of one cycle, in the swings of investment. Yet, Table 1 shows duration of a swing in invention is usually more like that of its companion swing in investment than like that of the next swing in investment.

Inspection of the table reveals that in only one case, Cycle III in patents, is a given patent cycle matched as well by the next investment cycle as by its companion investment cycle. Thus Cycle III lasts 21 years in patents and 23 years in investment, compared to 19 years in Cycle IV in investment. In the other four cases, the duration of each patent cycle is much closer to that of the concurrent cycle in investment than to the succeeding cycle of the latter.

TABLE 1

DURATION OF LONG SWINGS IN RAILROAD PATENTS AND CAPITAL FORMATION

Cycle	*Date of Initial Trough* Patents	Capital Formation	*Cycle Duration* Patents	Capital Formation
I	1845	1845	18	18
II	1863	1863	14	13
III	1877	1876	21	23
IV	1898	1899	23	19
V	1921	1918	15	17
VI	1936	1935		

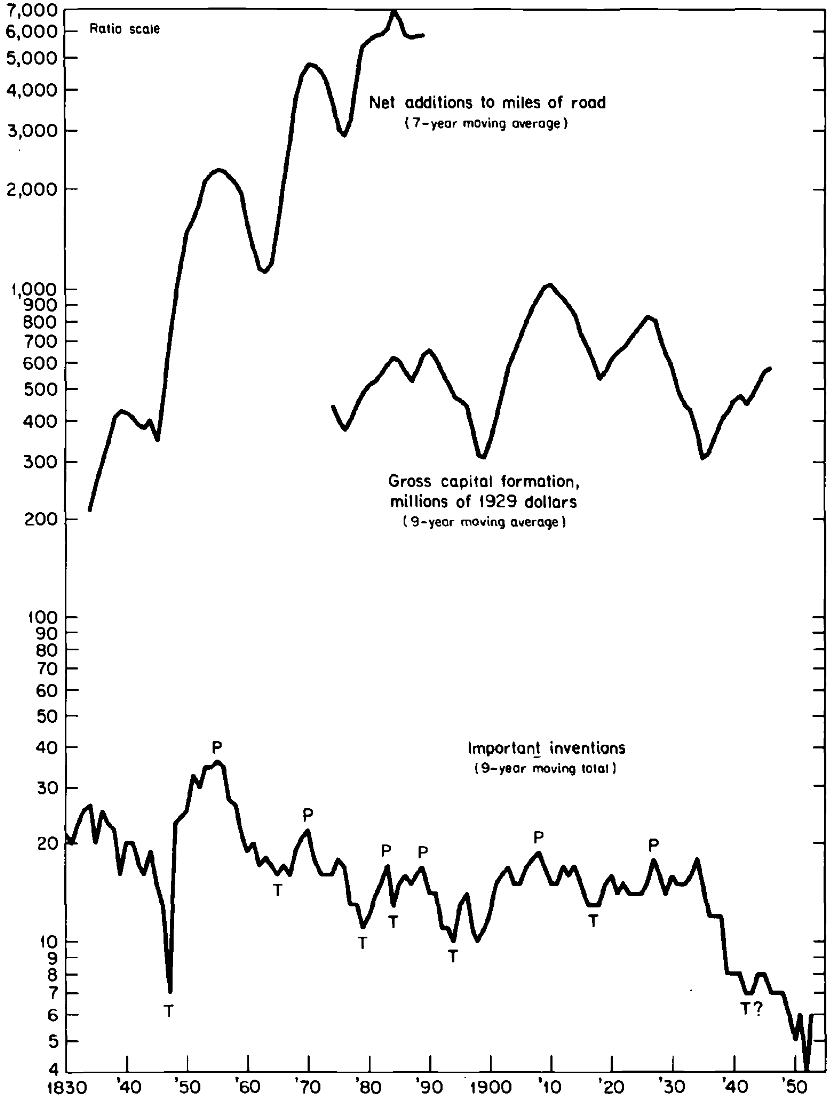
SOURCE: Patents: Chart 2. Cycles I and II in capital formation: from net additions to miles of road in Chart 2. The timing of subsequent cycles in capital formation is for nine-year moving averages of the same presented in Melville J. Ulmer, *Capital in Transportation, Communications, and Public Utilities* (Princeton University Press for National Bureau of Economic Research, 1960), p. 120. Using the timing indicated by Chart 2 for all the cycles would not affect the results.

Given the simultaneous trend peaks and the good matching of durations of simultaneously matched long swings, the evidential basis for the hypothesis that a given swing in invention causes the next swing in investment does not seem strong. Moreover, since the waves in patents either coincide with, or lag behind, the waves in investment, the notion that a given wave in invention causes the companion wave in investment likewise seems rather improbable.

The next point along this line of inquiry is plain. Inventions, obviously, are not all the same. While the swings in investment were apparently not responsive to the swings in invention generally, were they generated by waves of *important* inventions?

Chart 2 provides us with a basis for answering this question tentatively. As part of our project we compiled a chronology of about 250 of the most important railroad inventions made since 1800. Unlike the inventions covered by our patents, these are dated, so far as possible, at the time the inventions were actually made. They are shown in the Chart, starting with 1826, in the form of nine-year moving *totals*. The heroic, if not foolish, act of marking off long swings in this series, which from 1870 to 1938 fluctuates between 10 and 19, was performed in order to, and in such a fashion as to, give the hypothesis the most favorable "test" within the stringent limitations imposed by this whole approach. The long swings in the two capital formation series were used as a guide in determining the swings in important inventions, and whenever a choice existed in selecting turning points, doubts were resolved so as to give the important invention series the lead. For

CHART 2
Important Inventions and Investment in Railroading



SOURCE: Gross railroad capital formation in 1929 prices: Ulmer, *Capital in Transportation, Communications, and Public Utilities: Its Formation and Financing*, Princeton for NBER, 1960, Table K-2. Net additions to miles of road: same as for Chart 1.

example, a trough in important inventions was dated in 1894 instead of 1898, and a peak dated in 1927 instead of 1934, though the later dates would have been perhaps more defensible. Again, by dividing in two the major swing in capital formation from the middle 1870's to the late 1890's and recognizing thereby the small decline from 1884 to 1887 in that series, two instances were created in which the important invention series lead.

Given the limitations imposed by our data and general approach, the hypothesis that long swings in important inventions generate similar movements in capital formation could hardly receive more advantageous treatment. The results are summarized in Table 2. At

TABLE 2

LONG SWINGS IN IMPORTANT RAILROAD INVENTIONS AND CAPITAL FORMATION

					SEQUENCE AT TURNING POINTS			
	IMPORTANT INVENTIONS		CAPITAL FORMATION[a]		*Important Inventions*		*Capital Formation*	
CYCLE	*Trough*	*Peak*	*Trough*	*Peak*	Trough	Peak	Trough	Peak
I	1847	1855	1845	1855	2	1.5	1	1.5
II	1865	1870	1863	1870	2	1.5	1	1.5
IIIA	1879	1883	1876	1884	2	1	1	2
IIIB	1884	1889	1887	1890	1	1	2	2
IV	1894	1908	1899	1910	1	1	2	2
V	1917	1927	1918	1926	1	2	2	1
VI	1942+	?	1935	1949[b]	2	2	1	1
MEAN RANK AT TURNING POINTS					1.6	1.4	1.4	1.6

SOURCE: see Chart 3.

[a] The timing through 1870 is derived from seven-year moving averages of net additions to miles of road. After 1870 it is derived from 9-year moving averages of gross capital formation in 1929 dollars.

[b] Estimate of Ulmer based on annual data (Melville J. Ulmer, *Capital in Transportation, Communications, and Public Utilities*, Princeton University Press for National Bureau of Economic Research, 1960, Table 39, p. 125).

the troughs, the important invention series lags four times and leads three times. At the peaks, the important invention series lags twice, leads three times, and ties for the lead twice. The mean rank at the troughs is 1.6 for the important inventions, compared with 1.4 for capital formation. At the peaks, these mean ranks are reversed. Even if we ignore the fact that the test was rigged in its favor, the hypothesis receives little support from this evidence. On the contrary, to the degree that the swings in the important invention series are bona fide, they seem to be synchronized with those in investment as much as are those in railroad invention generally. (We recognize, of course, that the fundamental inventions which establish an industry—in this case made almost entirely abroad—must come first. Our discussion here is limited to the later important inventions.)

A legitimate objection to this conclusion is that our analysis, while taking into account important inventions, has failed to differentiate among them. Conceivably, when properly weighted in terms of economic potential, the important inventions would be found to lead the investment swings. This possibility is given consideration next, although obviously full consideration could be given to it only by a much more extensive investigation.

Bruschke, who prepared the chronology of important railroad inventions, undertook to determine the 100 most important among them. He then ranked this more select group according to two criteria: economic importance and technological importance.[11] (The distinction between the two arises from the fact that an invention, whether or not it has an appreciable economic impact, may lead to other economically important inventions. Inventions possessing this seminal quality were designated as technologically important.) Thus, each invention was assigned a rank running from 1 to 100 under each standard, the more important inventions under each standard being assigned the higher numbers.

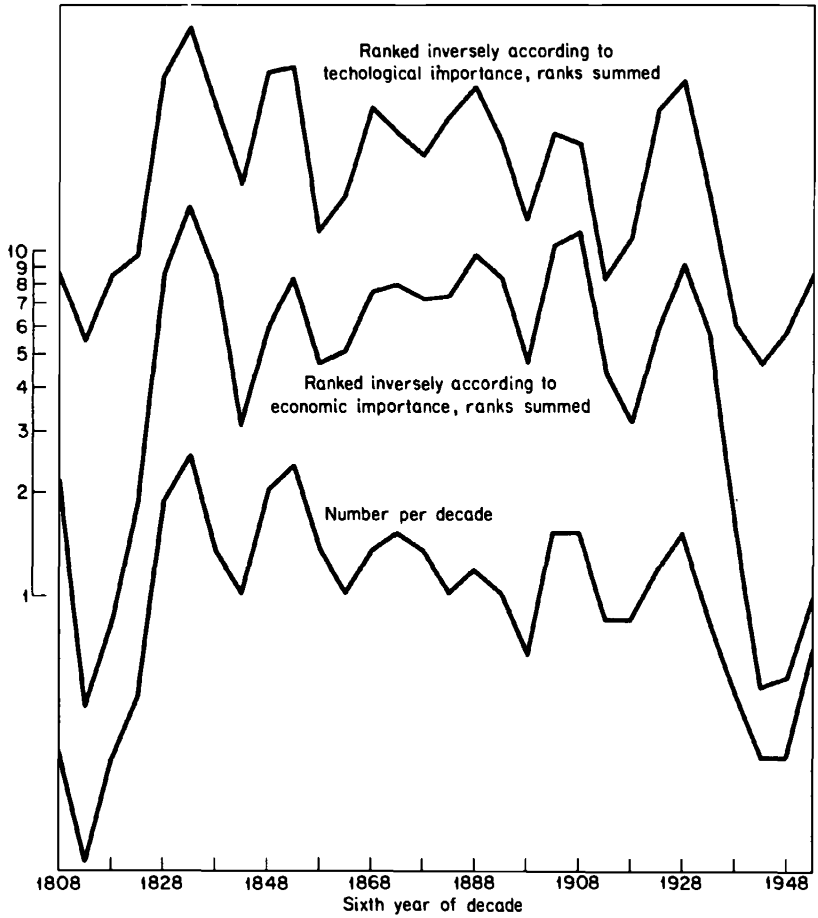
The ranks under each criterion were summed for overlapping decades with results as shown in Chart 3. Given the lack of anything like adequate data for fixing a firm value for each invention in each category, the results are, of course, based only on impressions from the literature and are only suggestive. The general impression conveyed by the chart is that, on the whole, it makes little difference whether the inventions are weighted or unweighted, or whether they are weighted according to their economic or technological importance.[12] Moreover, when weighting does make a difference, it postpones turning points by about five years. Possibly a weighting scheme which ran from 1 to 1,000 or 1 to 1,000,000 would have altered the picture but Bruschke did not think so. Finally, as with the patent series, the duration of a given swing in the important invention series bears no special relation to the duration of the next swing in investment.

[11] These correspond to two of the dimensions of an invention discussed in Kuznets' paper in this volume.

[12] These conclusions are confirmed by similar operations performed on the 100 most important inventions in petroleum refining and papermaking, respectively. We have not attempted to weight the important farm inventions.

CHART 3

The One Hundred "Most Important" Railroad Inventions, Overlapping Decade Totals, 1803–1957



In short, there is little present basis for assuming that the waves of minor or major inventions, once the industry is established, cause the swings in railroad investment, either immediately or with a lag. Of course, this does not mean that the major and minor railroad inventions had no effect on railroad investment. Presumably, really useful inventions go through, first, a period of increasing use as their value becomes known, initial defects are eliminated, and occasions for adoption arise; and then, a period of declining use as superior inventions or changed economic conditions make them obsolete. If this "life cycle" of an invention is approximately correct, then investments embodying the inventions probably follow a similar pattern. Other inventions may, of course, never be used, or used only until fatal defects are revealed in practice. The pattern of investment in inventions of the latter sort presumably is one of swift decline from a low initial level. These patterns, however, apply only to investment embodying specific inventions. The effect of these inventions on the aggregate level of investment is indeterminate a priori, for the expansion of investment embodying a given invention obviously may depress total investment in the industry below what it would otherwise have been.

If the foregoing is correct, the association between the waves of investment and invention in the railroad industry would appear to be of two sorts. On the one hand, either the waves of investment induce the waves of invention, or both variables respond to the same external forces. On the other hand, the waves of investment provide the occasion for the introduction and diffusion of inventions, new and old.[13] But *the introduction and diffusion of inventions in the industry seem merely to accompany but not to cause the waves of investment.*

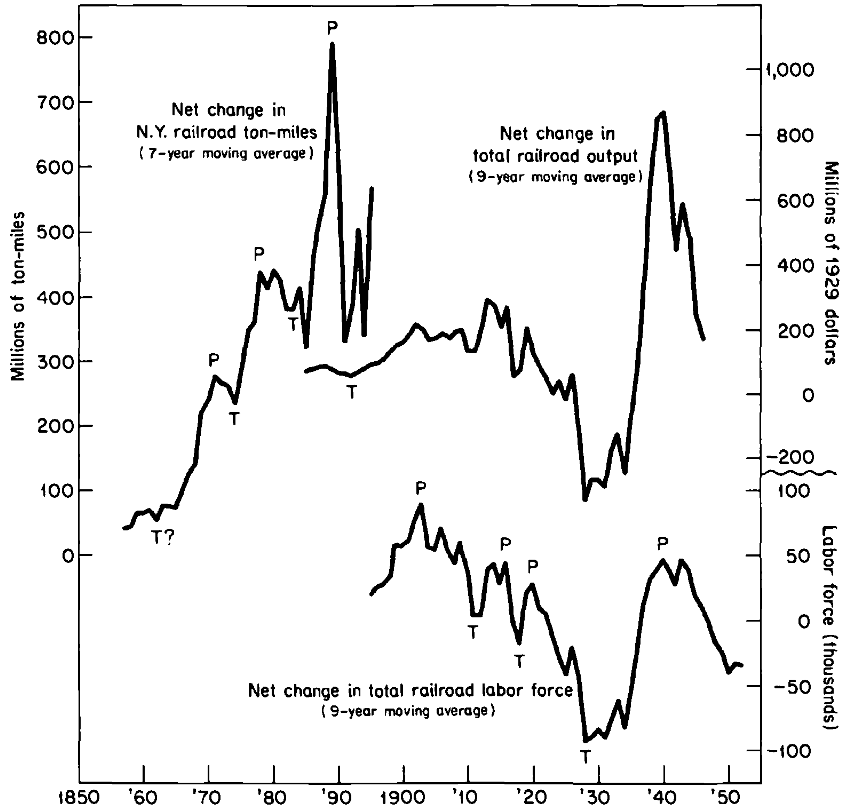
One important implication of the failure of important inventions to lead investment is that, once past the fundamental pioneer inventions, at least, important inventions also fail to lead the run-of-the-mill inventions which dominate the patent statistics. Indeed, a comparison between the trough dates of patents in Table 1 and the corresponding dates of important inventions in Table 2 shows that patents lead in four long swings while important inventions lead only in two. This does not mean that the minor inventions did not build on the major ones—or vice versa, for that matter. It does suggest that the timing of such "building" was governed by the factors that controlled the general level of inventive activity in the industry, and not by factors arising directly out of the growth of knowledge. In short, the role of changes in the state of knowledge as a determinant of inventive activity in this industry does not seem overwhelming, if the number of either major or minor inventions or both are taken as representing changes in the state of knowledge.

The proposition that the swings in railroad investment are not

[13] That investment constitutes either innovation or diffusion of new or old inventions is, obviously, little more than a truism. Each kind of equipment must have been invented sometime. (Only when a worn-out machine is replaced by an identical one can we say that neither innovation nor diffusion has occurred.)

CHART 4

Net Changes in Railroad Output and Labor Force



SOURCE: Net change in New York railroad ton-miles: calculated from *Historial Statistics of the United States*, Series K-169. Net change in railroad labor force: calculated from Harold Barger, *The Transportation Industries, 1889–1946: Output, Employment, and Productivity*, New York, NBER, 1951, Table B-1; and from *Statistical Abstract of the United States*. Net changes in output: calculated from Ulmer, *Capital in Transportation, Communications, and Public Utilities . . .*, Table 1-13.

caused by invention and innovation is supported by careful students of the phenomenon. Thus, Ulmer writes, "Second—and more important—it seems impossible to provide an explanation for each of the three and one-half swings during the 1870–1950 period in terms of specific transportation innovations."[14]

[14] Ulmer, *op. cit.*, p. 137. Ulmer treats the period from 1876 to 1899 as one long swing in this quotation, which is based on his data in the form of nine-year moving averages. However, he identifies two long swings for this period when he uses annual data (*Ibid.*, Table 39, p. 125).

Similarly, Cootner writes, "The key railroad innovations were adopted in response to explicit economic demands. The railroad investment . . . was specifically motivated by the growth of industrial requirements, and that motivation was repeated in the early sixties and eighties, while building in the fifties and in the post-Civil War period was induced by the need for the expansion of primary production."[15] Cootner's suggestion that the long swings in railroad investment arose from the ebb and flow of pressure on railroad capacity is borne out by the fact that long swings in the rate of growth of gross national product precede by a few years those in railroad investment.[16] It is further supported by the fact that major peaks and troughs in net additions to railroad output and to railroad labor force generally occur one to seven years before the long-swing peaks and troughs, respectively, in railroad investment, as shown in Chart 4.

While changes in output and labor force are not nearly as smooth as are those in investment, and the existence of long swings in the former two variables is debatable, the evidence that changes in output and labor force lead changes in capital stock nonetheless seems clear. The long-swing peaks and troughs marked off in these two series are compared in Table 3 with the related dates in capital formation.

Whether or not long swings exist in changes in railroad labor force and output is probably not important. That these variables exhibit major peaks and troughs well ahead of the long-swing peaks and troughs in railroad investment probably is important, however. A major peak in additions to output implies impending or actual pressure on capacity and therefore a rising incentive to invest. By the same token, a major trough in additions to output is a signal to reduce the rate of investment. That the waves in investment are not nearly as choppy as are those in increments to output and employment probably results from the character of the investment process in the industry.[17]

The trend and long swings in railroad investment are, therefore, probably not caused by the trend and long swings in railroad invention. If this is correct, then the similarity between the two variables must be explained either by (1) a highly improbable degree of coincidence, (2) a tendency for variations in investment in the industry to induce corresponding variations in invention, or (3) a tendency for inventors

[15] Paul H. Cootner, "Transport Innovation and Economic Development," Unpublished Ph.D. Thesis, Massachusetts Institute of Technology, 1953, Ch. IX, p. 4 of azograph copy kindly supplied by Mr. Cootner.

[16] Cf. Ulmer, *op. cit.*, Table 44, p. 133.

[17] Cf. Ulmer, *op. cit.*, p. 140.

TABLE 3

MAJOR PEAKS AND TROUGHS IN CHANGES IN RAILROAD OUTPUT (OR LABOR FORCE) AND CAPITAL FORMATION

Cycle	*Changes in Output (or Labor Force)* Trough	Peak	*Capital Formation* Trough	Peak	*Lag of Capital Formation Behind Changes in Output (or Labor Force)* (years) Trough	Peak
	(1)	(2)	(3)	(4)	(5)	(6)
II	1862 or earlier	1871	1863	1870	1 or more	−1
IIIA	1874	1878	1876	1884	2	6
IIIB	1883	1889	1887	1890	4	1
IV	1892	1903	1899	1910	7	7
VA	1911	1916				
VB	1918	1920				
V			1918	1926	0–7[a]	6–10[a]
VI	1928	1940	1935	1949	7	9

SOURCE: Cols. (1) and (2): Chart 5. Dates shown are from output through 1892, from labor force thereafter. Cols. (3) and (4): Table 2.

[a] The first figure is the interval between the date for capital formation and that for Cycle VIB in labor force. The second figure is for the interval between the former and that for Cycle VIA in the labor force.

to respond similarly to the conditions which govern investment. The first explanation can be rejected not only on the basis of the evidence presented for this industry but also in the light of the evidence to follow for other industries.

Whether invention responds primarily to investment or to the conditions which govern the latter cannot be determined yet for lack of evidence. Whichever explanation is ultimately accepted will have to apply to the activities of independent and captive inventors alike, for the association between investment and invention is observable when first one and then the other was predominant.

Perhaps clues to the nature of the association can be found in two elementary facts. First, investment in the railroad industry consists of sales—by the railroad equipment makers and the construction industry. Second, independent inventors, for whom invention is generally an avocation rather than a vocation, do their inventing when they encounter, or hear of, a technical condition which dissatisfies them and which they think they can remedy. (These two properties identify the potential inventor.) We may, therefore, surmise that the timing relations between invention and investment arise from circumstances connected with either (1) the identification of a technical problem, or (2) the activity of remedying the problem, or both.

The identification of a problem can occur at any time during the use, or observation of the use, of an article or piece of equipment. And the man with an irrepressible urge to improve things may, without any special economic motivation, begin inventing as soon as he "recognizes" the problem. The problem may be solved in minutes. In this case—except for the circumstances to be noted later—there need be no association between the given act of invention and the level of investment. On the other hand, as often happens, the solution may take years. In the latter case, the internal drive is likely to slacken and the work put aside and taken up time and again. Under these circumstances, economic motives (or the desire for the recognition which economic success brings) are likely to become relatively more powerful as the first surge of enthusiasm wanes. Now, if sales of the product the inventor wishes to improve are high, he is likely to push harder to finish his improvement and make money from it, while if sales are low, his efforts may subside. Thus, there will tend to be some positive correlation between the sales of a product and the timing of difficult improvements, even when the initial stimulus to the inventor was noneconomic.

Moreover, prolific but equally irrepressible inventors may have several problems with half-finished solutions in their minds. And while their underlying drives may also be noneconomic, it seems reasonable to suppose that the economic prospects of the different incomplete inventions will affect the direction of their efforts, other things being equal.[18]

In addition to this tendency for the solution of technical problems to be stimulated or inhibited by the level of sales of the products involved, there is the possibility that the very recognition of a problem —the initial stimulus to invention—may come when the inventor or an acquaintance of his is shopping for the article which later becomes the object of the inventor's efforts. This may happen particularly if the article turns out to be (1) more costly than anticipated or (2) lacking in

[18] Following the same line of reasoning, there will be tendencies for (1) the proportion of inventions patented to rise and fall with the industry's sales, and (2) inventors to try to juggle the issue dates of their patents in accord with the state of business. Of course, these tendencies cannot account for the marked trend of the railroad patents. The possible effect of (2) will be eliminated from our data for the period beginning with 1874 when application dates rather than granting dates will provide the basis of the time series. (1) creates the real possibility that minor deviations about the trend reflect changes in patenting rates and not changes in inventing. However, since the economic incentives to invent are the same as the incentives to patent, appreciable movements in patenting—including appreciable deviations about trend—should ordinarily be construed as reflecting movements of invention in the same direction.

performance requirements of the customer. If the article is too expensive, the price itself may make the inventor feel he can design a cheaper one. If his requirements are more exacting than can be met by the product already on the market, he may feel he can design a better one.[19] If these surmises are correct, the number of dissatisfied customers may tend to vary directly with the volume of an industry's sales—with the result that the amount of inventing may rise and fall with sales.

The foregoing conjectures are transferable to the activities of captive inventors. The economic considerations which are perhaps marginal with independent inventors become central in the calculations of businessmen. The common corporate practice of setting research and development budgets at a fixed percentage of sales practically assures a high correlation between invention and sales. Far from being a mere convention, this practice has an intelligent rationale, part of which is that inventing a given improvement in the firm's product will entail a certain expected cost which is unrelated to the product's sales volume, and will probably increase the firm's market share by a given percentage. Hence, if the industry's sales are high, the absolute amount resulting from an enlarged market may be great enough to warrant the cost of the invention, and the project will be pursued. But if the industry's sales are low, the increase in the relative market share may promise a revenue from the invention that is too small to justify the project. In addition to these considerations, the higher the firm's sales, other things being equal, the more it can afford research and the farther ahead it can plan, by means of research and other activities.

The general relation of the foregoing to the association between investment and invention in railroading seems clear, but how much is fancy and how much fact remains to be determined. As indicated above, investment in the railroad industry consists primarily of sales to it by the equipment and construction industries. The independent inventors presumably are both railroad employees and outsiders; the captive inventors, the engineers and research men of the locomotive and car companies, rail manufacturers, etc. Some technical problems arose or were recognized in the daily operation of the business, and independents or representatives of suppliers tried to solve them. When equipment purchases were high these efforts were increased—partly

[19] Alternatively, recognition of the problem may come before shopping begins, but the decision to solve it inventively may not be made until the inventor discovers that none of the goods on the market constitute a solution.

because, from the buyer's standpoint, the problems would be longer-lived if incorporated in brand-new equipment, partly because the problems may have been recognized for the first time when the very expensive purchases were being considered, and partly because it would be most profitable for the seller to solve the problems then.

Two other considerations may be mentioned relating to the possible timing of the inventor's recognition of the problem to be solved. We noted earlier that increments to output and labor force tended to lead increments to plant by several years. Conceivably, technical problems may be created by the changing capital-output and capital-labor ratios which result. Particularly, a fall in either or both of these ratios below a certain minimum (which, of course, changes with changes in the technique of production) would indicate a strain on plant capacity, a condition which might stimulate some to invent improvements to relieve the pressure on capacity. This would assume a lag of several years between the recognition of the problem and the completion of the invention—a lag as long as that between the pressure on capacity and the consequent increase in capacity represented by the upturn in investment which coincides with the upturn in patenting.

A somewhat different timing in recognizing the problem to be solved is suggested by the presumption, suggested previously, that the waves of investment in the industry determine the timing of waves of innovation and diffusion. If this is correct, one would expect that the new equipment introduced during expansion will exhibit defects under special, local circumstances, or otherwise evoke dissatisfaction in the breasts of inventive men. Thus, the hypothesized environment of relatively rapid technical change may stimulate invention among those who make, sell, use, or service the new equipment. The disproportionately large contribution of "new men" or outsiders—Quakers, Huguenots, etc.—to invention and innovation has been noted by scholars in the past. The proposition here is the other side of the coin—a changing environment can make new men out of old ones. In this case, inventing and patenting these inventions takes little time, given the similarity of timing between the swings in investment and those in patenting.

In both cases supposed in the preceding two paragraphs, recognition of the problem to be solved is associated with the level of investment in some way. In the first case, it is the low level of the latter relative to increments in output or labor. In the second case, it is the high level of investment with the high rate of technical change assumed to be associated with it. How serious these possibilities or the alternative possibility that the problem tends to be identified when the purchase is under consideration may be, we do not know. Moreover, in an industry as large as railroading inventors probably are continually recognizing problems. The question then is presumably one of the relative frequency of each kind of timing and not whether one kind exists and the others do not.

The one argument which seems persuasive, at present, is that the prospective profit from invention tends to vary with equipment purchases and construction, i.e. with the sales of the product being improved, so that regardless of when the idea was conceived, an inventor—or the firm employing him—will tend to press for a solution when sales are high and slacken his efforts when sales are low. (While an inventor could still profit, even if the industry planned to invest nothing, by making such a drastic improvement that, for a given level of output, the total cost with his invention would be lower than the total variable cost with existing installations, this is stacking the cards against himself. His task is much less demanding, especially in a high fixed-cost industry like railroading, when the industry is buying equipment anyway. In this case, total production costs with his invention need only be less than total costs with other new equipment.)

Let us now try to summarize what can be said at present about the relation of invention and investment in the railroad industry. (1) The trend and swings in invention probably do not cause the trend and concurrent swings in investment. (2) A given swing in invention does not constitute the cause of the next swing in investment. These tentative judgments seem as valid for major railroad inventions as for run-of-the-mill inventions. (3) Rather, the trend and swings in railroad investment appear to reflect, fundamentally, the industry's response to changes in the demand for railroad service. This statement, of course, applies to the industry only after the pioneer inventions essential to its establishment have been made. (4) The trend and swings of invention are probably caused in some fashion by those in investment or by the same forces which dominate the latter.

The next question we may ask is whether the concordance between invention and investment found in the railroad industry exists in other industries as well. The other industries for which we have data are petroleum refining, papermaking, and farming, and we turn to them next.

Investment, and Important and Run-of-the-Mill Inventions in Petroleum Refining, Papermaking, and Farming

Comparisons of the sort presented for the railroad industry are, for the present at least, impossible for the other three industries because the necessary data on investment are lacking. What we have instead are estimates of annual rates of net investment between several dates. Given the kind of reasoning developed in the preceding section, gross investment seems by far the more relevant variable. However, since the direction of change is likely to be the same for net as for gross investment, we can still gain some impression of whether or not gross investment and invention rise and fall together in these industries as in railroading.

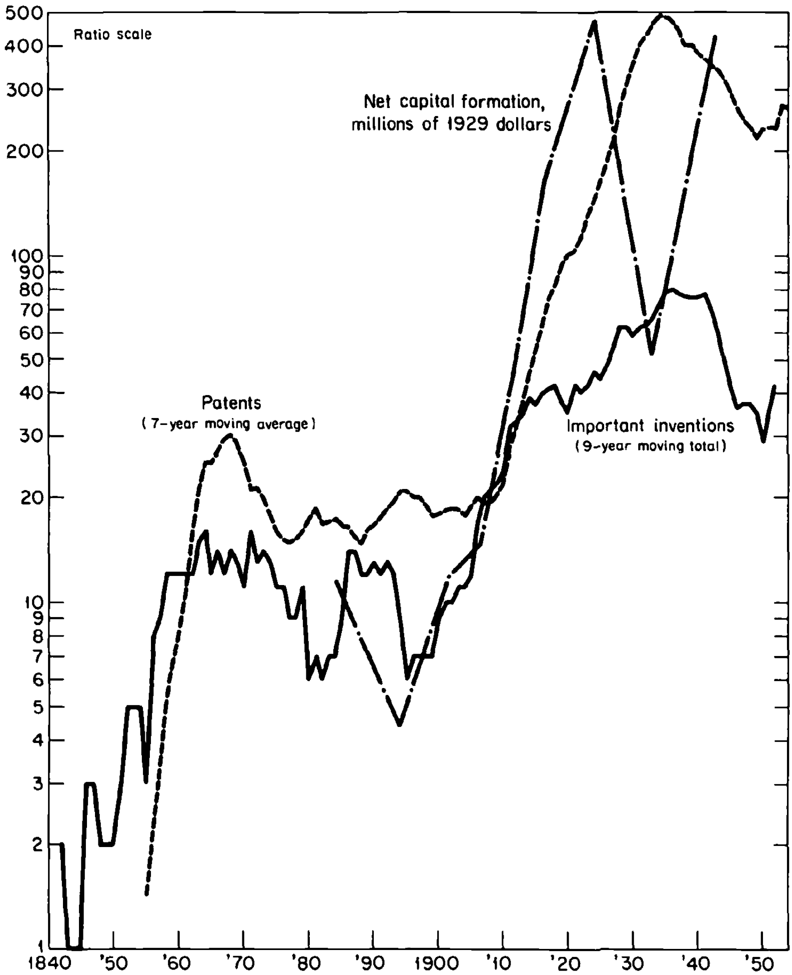
A more serious difficulty is that our estimates of annual net investment cover only nine time intervals in petroleum refining and papermaking, and only eleven intervals in farming. Moreover, five of the intervals in the two manufacturing industries are approximately decades, and only four are for quinquennia. Hence, impressions as to long swings generally cannot be formed. In farming, five are for decades, and six are for quinquennia, which is a little better. Another consequence of this type of data is that the resulting values naturally must be plotted at the mid-points of the intervals to which they relate and this creates at least one serious distortion for petroleum refining and papermaking. Specifically, the annual rate of investment from 1919 to 1929 is plotted at 1924, and the rate from 1929 to 1937 is plotted at 1933–34. As might be expected, an impression of a great decline in investment from 1924 to 1933–34 is conveyed. Yet the true peak in investment even for, say, a seven-year moving average, probably occurred in these industries sometime around 1927–29.

The comparison between invention and investment for these industries is further distorted by the increased lag between application for and granting of patents which occurred after World War I, at least in rapidly growing fields like petroleum refining and papermaking. Preliminary studies show that in the early 1930's, the average lag was about four and one-half years in petroleum refining. The lag in papermaking patents, at least for chemical inventions, was probably comparable. When our data have been converted to an application date basis, this difficulty will be eliminated.

With these precautionary statements in mind, we turn to Chart 5 which shows the course of patents, net investment, and important

CHART 5

Important Inventions, Patents, and Capital Formation in Petroleum Refining



SOURCE: Net capital formation: calculated from Daniel Creamer, Sergei Dobrovolsky, and Israel Borenstein, with the assistance of Martin Bernstein, *Capital Formation in Manufacturing and Mining: Its Formation and Financing*, Princeton for NBER, 1960, Table A-1.

inventions in petroleum refining. The two invention series apply almost entirely to process and equipment inventions. The number of product inventions covered is trivial. The most important single impression from the chart is that all three variables show two distinct growth cycles—the first associated with the kerosene stage of the industry and the second, with the gasoline stage. The presence of these two growth cycles is clearly indicated in both invention series. In the case of patents the second cycle of growth appears to start at about 1908. In the case of the important inventions, the start of the second cycle could be either 1895 when the series reaches a low point, or about 1904 when it returns to approximately the same trend level as had characterized it earlier. The existence of two distinct growth phases in the investment series can reasonably be inferred, since investment must have risen rapidly after Drake's well in 1859 and then levelled off until the demand for gasoline began to swell with the coming of the automobile. The assumption of a second growth cycle is supported by an absolute decline in investment from the 1880's to the 1890's, followed first by a recovery to the old level, and then by a sharp rise after 1906–07. The second growth phase in investment thus began probably in the 1900's, when the gasoline powered automobile came on the scene in large numbers.

If we divide the secular movements in the three variables into rapid growth and retardation (flat or falling trend) phases for each growth cycle, the order of secular turning points seems to be as follows:

Start of first phase of rapid growth: important inventions (before 1840), run-of-the-mill inventions (c. 1850), investment (1859)

Start of first retardation phase: important inventions (1864–71), run-of-the-mill inventions (1868), investment (unknown)

Start of second phase of rapid growth: important inventions (1895–1904), investment (1900's), run-of-the-mill inventions (1908)

Start of second retardation phase: investment (late 1920's), run-of-the-mill inventions (late 1920's), important inventions (late 1930's)[20]

It seems clear that important inventions led run-of-the-mill inventions at two out of four of the secular turning points, while lagging behind at the last one. It is, moreover, inevitable that important inventions led investment during the phase of rapid growth in the first growth cycle. On the other hand, at the start of the second retardation phase, investment led at least the important invention series, and it is not clear whether investment led or lagged behind the important invention series at the start of the second phase of rapid growth. In any case, the important invention which "caused" the second phase of rapid growth in refining investment was obviously the internal-

[20] The timing indicated for investment and run-of-the-mill inventions reflects consideration of the factors discussed earlier in this section.

combustion engine (and its diffusion), and not the refining inventions per se.

Given the nature of our data, no possibility exists for detecting long swings, if such exist, in investment. However, the 1890's and the 1930's were periods of subnormal investment, and there seem to have been more or less matching declines in both invention series. Marking off long swings in the invention series is neither easy nor necessarily warranted. Neither invention series exhibits the smooth variation characteristic of the railroad patents. Hence, such variation about the trend as exists may be largely random or a reflection of changed patenting propensities. In the first growth cycle there is, however, some suggestion that fluctuations in important inventions led those in run-of-the-mill inventions, and this impression tends to carry over until, but not including, the second retardation phase in the 1930's. Yet, given the low amplitude of most of these fluctuations about trend, attributing any statistical significance, let alone causal association, to this weak pattern seems hazardous at this stage.

In brief, in petroleum refining two successive growth cycles probably occurred in each variable. As might be expected, important inventions led the other two variables during the first phase of rapid growth, but they lagged in the last phase of retardation. These are the only timing relations we can be sure of at present. Since the entire first growth cycle in each variable was induced by the rising demand for illuminants[21] and kerosene in particular, and the second, by the rising demand for gasoline, the pattern of responsiveness of investment and invention to underlying demand conditions suggested in the preceding section on the railroad industry appears to have been repeated here.

The situation in farming is shown in Chart 6 where, because during two quinquennia net disinvestment occurred, it has been necessary to use an arithmetic scale. The important inventions[22] presented are restricted to mechanical equipment in order to make them comparable with the inventions represented by the patent statistics. Thus, important agricultural advances like hybrid corn are left out. For the same reason, the investment data pertain only to implements and machinery and not to farm real estate, livestock, or inventories.

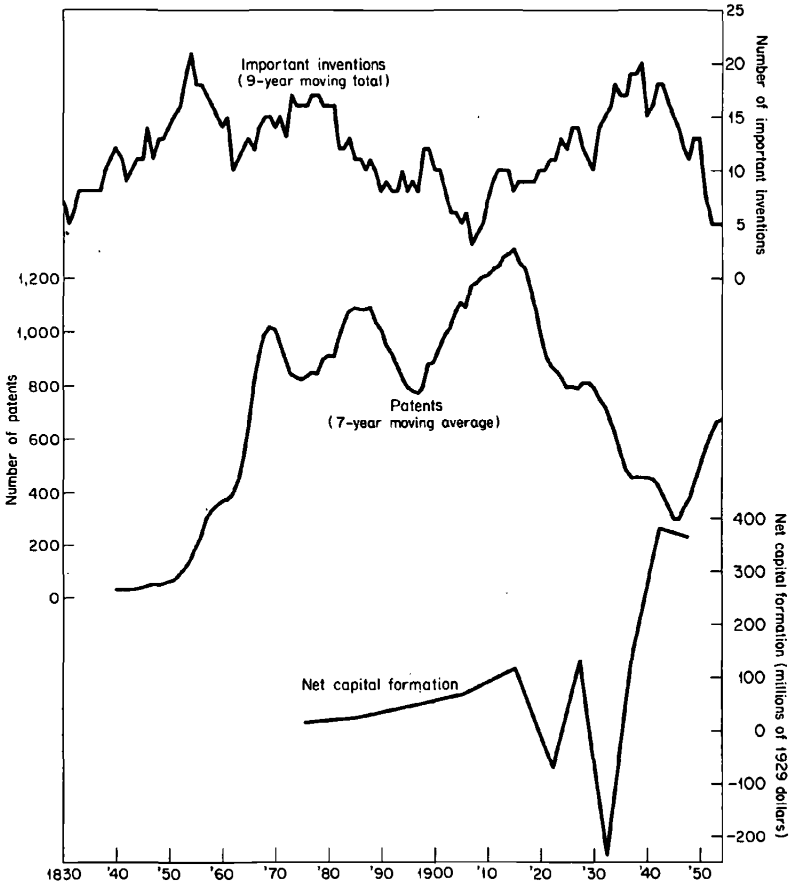
The free wheeling, not overly critical imagination can find many

[21] Cf. H. R. Williamson and A. R. Daum, *The American Petroleum Industry*, Evanston, 1959, Chaps. 2–5.

[22] Makers of important farm inventions, unlike inventors in the other industries, were primarily American from the start. In the other industries Americans dominated after the first few decades.

CHART 6

Important Inventions, Patents, and Capital Formation in Farm Implements and Machinery



SOURCE: Net capital formation calculated from Alvin S. Tostlebe, *Capital in Agriculture: Its Formation and Financing Since 1900*, Princeton for NBER, 1957, Table G-1.

suggestive phenomena in Chart 6. Two long-term growth cycles in important inventions, the first ending and the second beginning in 1907, seem fairly clear. The first of these could be the cause of the entire movement in the run-of-the-mill inventions reflected in the patent statistics. This is, in one sense, not a very remote possibility since many of the latter are made by farmers who may not be abreast of the industry's needs and technology, as well as by equipment makers who presumably are more up-to-date. On the other hand, the deep decline of agricultural patenting in the 1890's suggests that perhaps there were two long-term growth cycles in this series, too. If so, while important inventions led run-of-the-mill inventions in the first growth cycle, run-of-the-mill inventions led the important ones in the second cycle. The long swings in the patent series seem quite pronounced, and while this seems also to be the case with the important invention series, the fact that only about 150 items appear in the latter (far fewer than in the comparable series for our other three industries), or slightly less than one per year, should make us treat the minor fluctuations in this variable with considerable skepticism. Be that as it may, except for the obvious lead of important over run-of-the-mill inventions at the outset, the timing relations between the two are not constant. Only some kind of content analysis of the inventions involved seems likely to disclose the kind and degree of interdependence of the two series.

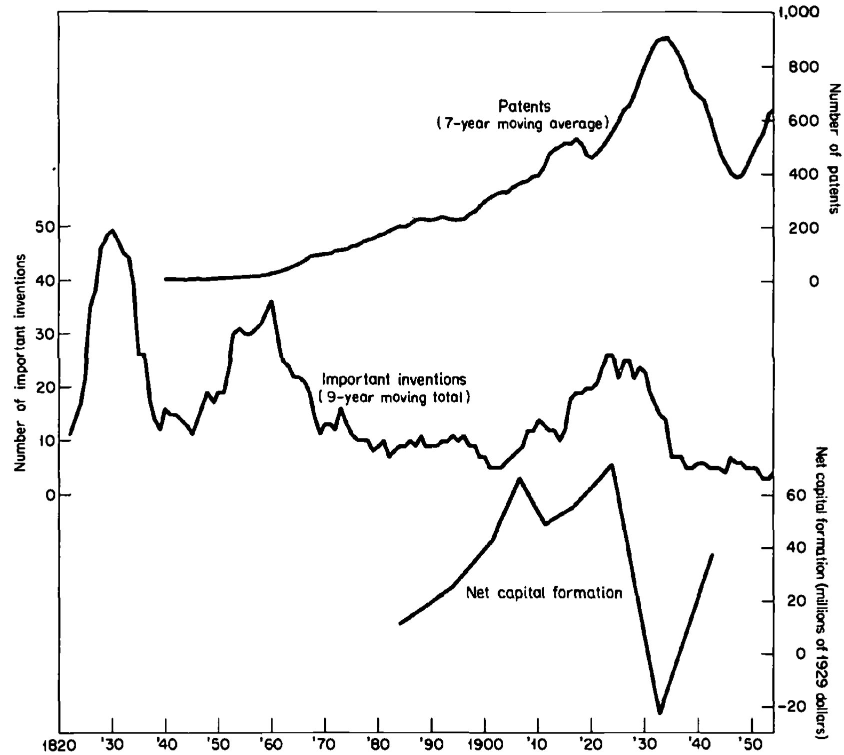
The investment-invention relationship, however, seems more stable in some respects, and indeed is like that found earlier in railroading. Until 1920 the investment data are only for decade intervals, but the trend is upward like that in patents.[23] After 1915, however, the trend of patents is downward, while that of investment is generally rising, despite big drops. On the other hand, with quinquennial average rates of investment available after 1920 we can compare the long swings in the variables, and these are similar. Starting with a peak in 1915 in patents and in 1910–20 in investment, we have next a trough in investment in 1920–25 and in patents in 1925; a peak in investment in 1925–30 and in patents in 1929; a trough in investment in 1930–35 and in patents in 1937; and finally, a peak in investment in 1940–45 and in patents around 1941. Interestingly enough, at the last three turning points the important invention series seems to lead, with dates at 1926, 1930, and 1939. However, the low level of farm investment in the early 1930's certainly reflected the depression, and the high level in the early 1940's, war-time demand and labor shortage, and not the changing rate of important inventions.

The same variables in papermaking are shown in Chart 7. Equipment, processes, and products are all reflected in the two invention series. When the data are decomposed, this combination may prove

[23] This remark applies only to the trend in investment in implements and machinery. The trend for total farm investment was down during the period, and the fluctuations in it run directly counter to those in farm patents. Starting with 1910–20, investment in implements and machinery and total farm investment move together.

CHART 7

Important Inventions, Patents, and Capital Formation in Papermaking



SOURCE: For net capital formation, same as for Chart 6.

to have been a mistake. In particular, we do not yet know what the timing pattern is between improvements on products and improvements on the machines that make them. Since the investment series pertains by definition to plant and equipment, it would have been preferable, in the light of the discussion in the previous section, to have had a separate series on equipment inventions.

The over-all impression conveyed by Chart 7 is that the trends in investing and general inventing were similar in timing and direction. This statement is made on the basis of the contentions advanced earlier in this section that the all-time peak in investment occurred not in the early but in the late 1920's, and that the all-time peak in run-of-the-mill inventions occurred not in the early 1930's but in the late

1920's. If these arguments are correct, then on the whole patents rose when investment rose and declined when investment declined. On the other hand, it is doubtful that the bulge in patenting from about 1910 to 1920 is tied to the earlier bulge in investment from 1899–1904 to 1909–14, for the average lag between application for and granting of patents then could hardly have been ten or eleven years.

In addition, the long swings in important papermaking inventions seem similar to later movements in the patent series. Conceivably, the first phase in patenting ending in 1895 was associated with the rise and fall in important inventions from 1845 to about 1869; the period of steady rise in patenting from 1895 to about 1910 with the nearly stationary level of important inventions between 1870 and 1903; the patent swing from 1910 to 1920 with the swing in important inventions from 1903 to 1915; and the patent swing from 1920 to 1947 with the swing in important inventions from 1915 to the close. Obviously, however, whether the temporal association between the run-of-the-mill inventions and the important ones is that suggested by the graph could be ascertained only by means of a content analysis of both.

Without wishing to spin out still another speculative thread, one may suggest that this industry may be one in which the chain of direct causality runs mainly from major inventions to the level of investment and from the latter or both to run-of-the-mill inventions. That is, important inventions in this industry may conceivably dominate the level of investment, and inventing generally may respond to investment in this industry in the ways suggested earlier for the railroad industry. The hypothesis that important inventions dominate investment would become tenable if it could be shown that the paper industry—perhaps because its products on the average occupied a smaller share of their respective markets than was the case with the products of the other three industries—faced a product demand that was more responsive to cuts in price and to new and improved products than the demand confronting the other three industries was. In that event, innovations would tend to stimulate aggregate investment in the industry. When such conditions do not exist, the level of investment in an industry is likely to be dominated by the external factors that govern demand.

In brief, the trend movements of patents and investment run roughly parallel in railroading, petroleum refining, and papermaking. In farming, however, these variables rise together until the mid-1910's but then patents decline while investment in implements and machinery pursues a choppy but slightly rising course. The long swings in patents and investment seem approximately synchronized in both railroading and farming. In petroleum refining and papermaking, however, long swings in investment, if they exist, are not observable in our data. Nor is the existence of long swings in patenting in petroleum refining at all certain.

Important inventions lead at the outset in all four industries, but their subsequent relation to the other two variables seems unclear. In petroleum's second growth cycle, they lead patents and may lead investment at the start but in the same growth cycle they later decline absolutely after both investment and patents. In railroading, the later long swings in important inventions are approximately concurrent with those in patents and investment. In farming, where the number of important inventions in our chronology is relatively small, no obvious relation between these inventions and the other two variables appears. In papermaking, however, the graph suggests the possible existence of three or four long swings in important inventions which lead somewhat similar movements in patents.

The variety of the relations thus far observed indicates the desirability of decomposing some of our variables in an effort to determine whether the differences actually exist or merely result from incomparabilities in the underlying data, e.g. the inclusion of product and process patents in papermaking, and process patents in petroleum refining.

For the present, at least, the evidence and the reasoning developed earlier suggest that inventive activity tends to rise and fall with the sales of the product which the inventions improve, although other factors undoubtedly also play a role. In industries like railroading where investment lags behind sales, one would therefore anticipate a tendency for product inventions to lead equipment inventions. While the bearing of this line of reasoning on process inventions is not clear, where process inventions entail equipment changes, one may conjecture that their timing will tend to be the same as that of equipment sales.

Note on the Role of Science in the Four Industries

In light of the common belief that modern inventions represent the industrial application of prior scientific discoveries, a belief reflected in some of the other conference papers and partially justified by examples too well known to warrant repeating, the four researchers who compiled the chronologies of important inventions were instructed to note any suggestion in the literature that a particular scientific discovery or any other factor prompted a particular invention included in their chronologies.

For most of the roughly 1,000 inventions in our four chronologies, the records unfortunately omit mention of stimulating factors, but the subject is mentioned in a number of cases, almost always referring to industrial problems the inventors sought to solve. In only one or two cases in petroleum refining and papermaking did prior scientific discoveries appear to constitute a direct stimulus. At present, therefore, the direct influence of individual scientific discoveries, even in industries like petroleum refining and paper with their strong dependence on chemistry, seems to have been nominal. Possibly careful research into unpublished materials would raise this estimate.

This, however, should not be interpreted as meaning that scientific discoveries may not have played a crucial role in many of the major and perhaps minor inventions in these four industries. It merely means that in our industries science has been like a book on a reference shelf—taken down when needed and enriching and perhaps even making possible what is accomplished. The point is only that scientific discoveries per se have apparently seldom constituted a direct stimulus to the making of important (and presumably unimportant) inventions in these four industries.

Finally, it may be suggested that more powerful than individual scientific discoveries as a general precondition for invention in these industries has been the pervasiveness of an empirical, experimental attitude, an attitude characteristic of modern society and reflecting a popular belief in the efficacy of experimental science. But, of course, this general and indispensable precondition can hardly explain the temporal variations in invention in these or other industries.

Concluding Remarks

Why should economists be interested in patent statistics since unpublished attempts by Sanders, Griliches, and the present author to compare these data for individual industries with data on output per unit of input in the same industries reveal no consistent relationships? This is a fair question and one which was raised at the Conference in connection with the first draft of this paper.

Two answers, at different levels, can be given to the question. The most important in the present context is the light which a study of the data has already cast on fundamental questions of social theory and the theory of economic development. Many, if not most, economists, historians, sociologists, and anthropologists find in scientific discovery and invention a pair of exogenous variables which together or separately largely explain long-term social change and economic growth. A whole theoretical superstructure has been built around this postulate by one school of sociologists. In economics, anthropology, and history, system building is uncommon, but it would be easy to cite authors in these fields who make the same facile technologically deterministic assumption. Much more important, the same assumption seems to serve as a tacit article of faith and point of departure for both laymen and many social scientists.

In public and in the universities, we are constantly told that science shapes our lives, and that the rest of culture lags behind changing technology. In economics, waves of investment are often, if not usually, in certain contexts construed as waves of innovation and imitation *a la* Schumpeter. The half-truth of these statements is hardly ever made whole by correlated statements showing how our lives shape science, how technology lags behind the rest of culture, and how economic change induces waves of innovation. The atomic bomb and advances in nuclear science are imputed to non-Euclidean geometry, Einstein ($e = mc^2$), and a few foreign born physicists. The obvious role of World War II and its aftermath, of a system of dangerously entangled rival nation-states, and of the expenditure of several billion dollars a year on research is hardly mentioned. High farm surpluses are accounted a consequence of the lag of culture behind technological change, because the farm population has failed to adjust to higher productivity. Yet, the lag is just as much in the opposite direction. Farm technology, after all, has failed to develop new uses for farm products which would eliminate the surpluses.

Finally, let me cite just one example of a wave of innovation induced by economic change. While Schumpeter is correct in assigning a large role to the automobile industry in the so-called Kondratieff which began around the turn of the century, it seems almost obvious, to this writer at least, that the automobile came when it did more because of economic and social changes than because of technological change as such. In the first place, in the automobile, prestige, flexibility, privacy, recreation, and utility are combined in ways which only an individualistic high-per-capita-income society could afford or develop. (The so-called bicycle craze of the 1890's was part of the same phenomenon.) The automobile, after all, did not and has not revolutionized life in low-income India or China. Its effects have been confined primarily to the United States and other industrialized countries, roughly in proportion to income. A good case can be made for the contention that among the indispensable conditions for the coming of the automobile age were relatively high levels of income, at least for the middle-income classes, and an individualistic society.[24]

Secondly, there is no warrant for supposing that the advent of the automobile depended on the development of the internal combustion engine. At the turn of the century, after the industry was thoroughly launched, experts were still divided over whether the automobile of the future would be driven by steam, electricity, or gasoline. Each type was heavily represented in the market. Even more important, the first "locomotives" over a century and a half ago were not locomotives at all but automobiles—engine-driven road vehicles. Had the wealthy of that day wanted mechanical playtoys as did those of a century later, the automobile industry could have come nearly a hundred years before it did. Even so, steam-powered buses operated for a few years in the first half of the nineteenth century on some of the highways of England, until driven from them by vested interests. Putting the vehicle on rails, hitching cars behind it, and converting the whole into a means of public transportation was as much a reflection of the political and socio-economic elements of the situation as of the technological characteristics of the machine. (One implication of this analysis is that our earlier imputation of the decline in railroad investment and invention after about 1910 to the invention of the automobile was a conventional over-simplification.)

The antidote urged here for the popular conception of the role of science and technology is far from new. Bagehot said long ago, "Most men of genius are susceptible and versatile, and fall into the style of their age." The same view has been cogently argued by Gilfillan,[25] and by others. It has been overdone by those Marxists who seek to substitute economic determinism for the currently more popular scientific and technological determinism. The antidote merely recognizes the wholesale interdependence of changes in society and changes in the state of knowledge. It regards the two somewhat like blades of a

[24] Khrushchev's statement on looking at our west coast's jammed freeways comes to mind.

[25] *Op. cit.*

scissors. One is not an inert material on which the other operates ad libitum.

The lack of currency of this alternative and more appropriate construction of events is explained primarily by the absence of substantial objective evidence of a two-way flow between the variables. Such evidence has already begun to come from the study of patent statistics, as this paper indicates. If the study of the data accomplishes no more than a righting of the balance and an elimination of the present serious distortion in social theory; if it does no more than persuade social scientists and through them the public that men shape science and technology as much as these forces shape men, that the production of knowledge, though doubtless in lesser measure than the production of goods, responds to social pressures including those of the market, as well as to the exigencies of genius; then the study of patent statistics will have contributed its fair share to the advancement of social science.

These considerations pave the way for the second answer to the question with which this section began. After socioeconomic forces have directed the activities of inventors, similar though even greater forces affect the fate of their brain children. Between the discovery of new knowledge and its filtration through industry lie the processes of innovation and diffusion. These processes in turn are drastically altered by depression and prosperity, war and peace, the advent of rival and complementary inventions, and the secular rise and fall of the industries concerned. Hence, there is little reason to suppose that the economic impact of the average invention in an industry will be the same over time. The invention of a new product or process is but the first link in a long, poorly-understood chain of events.

The study of patent statistics is consequently but one stage in the study of that chain.[26]

[26] A further point in answer to the question which opened this section of the paper may be mentioned here. It is not logical to assume that the average invention of a given period should yield the same increase in output per unit of input as does the average invention of some other period. If we suppose as a first approximation that the cost of making the average invention is constant over time, then as an industry (or firm) grows, it will pay it to seek inventions which yield increasingly smaller increases in output per unit of input. Similiarly, as an industry declines, inventions which yield increasingly large increases in output per unit of input will be sought. In brief, it is the saving in total cost, or the increase in total output, that is likely to provide the incentive for invention, and not the increase in output per unit of input.

It was this line of reasoning, following his failure to find any clear relation between patenting and later changes in output per unit of input, which led the author to seek and find a positive association between the volume of patent applications and the volume of employment of all resources in the United States from 1869 to 1938 (Cf., Schmookler, "The Level of Inventive Activity"). Whether the association observed is to be explained

APPENDIX

Note on Statistics of Patents Granted by Industry

Anyone wishing to use statistics of patents classified by industry must recognize that he will be able to find out little concerning temporal changes in (1) the propensity to patent in each industry, (2) the quality of the average patented invention, or (3) the quantity of inventive inputs actually employed per patented invention. About all that can be said with confidence at present is that, roughly since 1940, there has apparently been a decline in the ratio of patents granted to corporations to inventions made by corporations. The economic input per patented corporate invention may also have increased since 1940. The reasons for suspecting that these changes have occurred are mentioned in the author's comment on Sanders' paper in this volume and will be discussed by him in a forthcoming critique and review of the literature on patent statistics. Simon Kuznets and Barkev Sanders discuss some of the possible difficulties in interpreting patent statistics in their papers in this volume.

Yet, despite these largely insoluble difficulties, it seems very reasonable to believe that far more railroad inventions were made around 1910 than in the decades before or after, that far more petroleum refining inventions were made in the 1920's than in earlier years, and that the number of papermaking inventions grew fairly continuously until the depressed 1930's. Given common knowledge about the economic growth patterns of the industries concerned, acceptance of the data as indicative of the trends and long swings in inventive output places no strain on one's credulity. (On the other hand, the author's very limited knowledge about the growth of agriculture provides him with no similar assurance in the case of farm patents.) By the same token, declines in patenting in wars and deep depressions and increases in patenting with the return of peace or prosperity can be readily accepted as indicative of the behavior of the output of inventions and the input of inventive effort (except, of course, for war-associated industries).

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by this reasoning is not clear. However, this finding, in conjunction with a recognition that the processes of innovation and diffusion occur in a changing environment, suggests that the lack of correspondence between inventions patented and later changes in output per unit of input does not diminish the utility of patent statistics in the study of economic growth.

PREPARATION OF THE SPECIFIC SERIES USED

The conceptual and operational difficulties associated with the compilation of statistics of patents issued by industry deserve more attention than can be afforded here. On the conceptual side lies the problem of choosing the criteria for assigning a given invention to one industry instead of to another. This choice is naturally affected by the purpose at hand: one industry may inspire the invention, another manufacture it, and a third use it.

In each case the assignment might differ depending on whether the interest is in the industry immediately, or the industry ultimately inspiring, producing, or using the invention. Whatever the purpose, the implementation of the criteria chosen is impeded by the host of inventions that cut across many industries (whether the latter be inspirers, makers, or users), and which therefore cannot be properly assigned to a single industry.

In the present study the investigator assigned inventions to the current main producing or using industry. If, in the case of a given invention, both the producing and using industries were to be included in the project, the invention was assigned to both. Silos, for example, were assigned to both construction and agriculture. Inventions with significant multiple industry application, such as bearings, motors, engines, etc. were simply excluded. Any alternative treatment of this significant group of inventions requires more knowledge than the author has.

In practice these criteria had to be compromised. For any individual or small group to assign to specific industries each of the nearly 3 million patents issued by the United States Patent Office since 1836 (or, for that matter, any sample large enough to be useful for our purpose) would be impractical. Instead the author assigned whole Patent Office subclasses to specific industries. The subclass is the elementary unit of the classification system designed by the Patent Office to facilitate the search of the prior art. Nearly 50,000 such subclasses exist, each a member of one or another of more than 300 main classes. The average subclass has slightly more than 50 patents in it.

Each subclass has its own definition, typically of a technological-functional character. When the definition clearly implied that nearly all the inventions in a given subclass would be made or used, if at all, by a single industry the whole subclass was allocated to that industry. When, as often, the definition provided an insufficient basis for such a decision but implied a reasonable possibility that at least two-thirds of the patents might be assignable to a given industry, the investigator sampled the patents included in the subclass in the files of the Patent Office search room. If, on the basis of this sampling, at least two-thirds of the patents seemed to apply to the industry, the whole subclass was so assigned. The 10,000 subclasses ultimately assigned to 88 four-digit industries were then reviewed by a group of principal examiners in the Patent Office, and corrections in our industrial classification were made in accordance with their suggestions.

The resulting statistics of patents issued classified by industry thus necessarily include some inventions that do not belong to the industry to which they have been credited and exclude some that do. As is common in life, however, the signs of omission probably outweigh those of commission. In all likelihood, at least 95 per cent of the inventions covered by the series for our four industries belong to the industries to which they have been assigned. On the other hand, an indeterminate number of equally pertinent inventions have been omitted because they were in highly heterogeneous subclasses. But perhaps even more serious than the omission of inventions with primary applicability to a given industry is the absence of inventions with substantial multiindustry application. Whether our concern is with the causes or with the effects of invention in an industry, such lacunae are troublesome. Inventors traditionally seek to maximize the generality of their inventions, and patent applicants, the generality of their patents. A man who starts by trying to improve the woodsawing art may end by improving the sawing art generally. Such examples could be multiplied easily. Ideally, to study the inventions affecting or affected by an industry one would want to know not only those inventions pertinent to that industry alone, but also those inventions which relate to the given industry and others as well. Unfortunately, to determine which electric motor, for example, belongs to which industry or group of industries was simply not feasible.

Because of the exclusion of inventions which, though primarily applicable to a given industry, are classified in excessively mixed subclasses, and because of the exclusion of inventions with a substantial multiindustry application, the resulting time series of patents by industry provide an incomplete record of the patented inventions arising from or affecting the industries in our project. Perhaps by sampling all the patents issued in some years we may later be able to measure and correct some of the bias present because of the first deficiency. The task of remedying the second deficiency seems hopeless.

FIELDS COVERED IN THE FOUR INDUSTRIES

The farm patents are primarily for inventions pertaining to plows, harvesters, harrows, manure spreaders, cultivators, threshers, etc.—bins and silos, tools, and plant husbandry. Farm tractors are omitted because inventions relating to them are mixed in many subclasses with technologically related nonfarm inventions. However, inventions induced by the tractor in the fields covered are naturally included. Little government agricultural research is reflected since patents seldom result from it. The aggregate farm series presented is a summation of dozens of separate time series, each series pertaining to a specific phase of farm technology and covering at least six Patent Office subclasses. The patents number 83,000.

The railroad patents cover locomotives, passenger and freight cars, draft appliances, brakes, wheels and axles, rail cleaning and snow removing, track laying, ties, rails, switches, signals, crossing gates, and railway mail delivery. Altogether the data reflect over 90 individual time series and 90,000 patents. Those power plant inventions are included which apply only to railroading and which were, in consequence, classified in one of the subclasses covered. The development of steam and diesel engines per se is not directly represented, although some of their indirect effects undoubtedly are.

The papermaking inventions, which number 38,000, relate to the disintegrating and grinding of wood; bleaching, preparing, and working pulp; forming and delivering the web; coating, finishing, and drying paper; and special products such as boxes and envelopes, and machines for making them. Twenty-seven individual series underlie the aggregate for this industry.

The petroleum refining patents, 12,000 in number, pertain to bubble towers, refining with paraffin, refining with solvents, refining with chemicals, distillation, cracking, and petroleum products. This aggregate is a summation of twelve separate time series.

The four industries collectively represent roughly 3,500 subclasses, over a third of those included in the major study.