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INSTITUTIONAL STRUCTURE AND TECHNOLOGICAL CHANGE

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I. Introduction

This study began as a survey of the literature on institutional change as it related to research and development. Since the survey was to exclude the literature on patents and on industrial organization, it was completed very quickly. That literature is practically nonexistent. The relationship, however, remains an interesting one. There is a significant and growing body of literature that bears on the theory of institutional change.[1] In addition economic historians have assigned technical change a central role in their studies of economic growth, and have produced an extensive literature of the history of invention and innovation. Since institutional change is by its very nature a long-term process, work in economic history provides a laboratory for the study of that process. This survey uses some of the recent developments in the theory of economic change to examine more traditional work by economic historians in the hope of providing some insight into the relationship between institutional structures and technical progress.

1. Lance E. Davis and Douglas C. North, Institutional Change and American Economic Growth (Cambridge, Mass.: Cambridge University Press, 1971). See also, J. Buchanan and Gordon Tullock, The Calculus of Consent (Ann Arbor, Mich.: University Press, 1962), and Mancur Olson, The Logic of Collective Action (Cambridge, Mass.: Harvard University Press, 1965).

There is no attempt to provide conclusive answers. Instead the purpose is to generate a few tentative hypotheses and to suggest some areas where further research might provide more concrete results. The paper is in three parts. The first attempts to cast the problem in a framework that is amenable to the theory and to the data provided by the economic historians. The second surveys some portions of the economic history literature that appear relevant. The third presents a few observations suggested by the history and outlines areas for further research.

II. The Problem and the Economic Historians

Despite the number of pages that have been written on the subject, the theory of technical change is not well worked out and even the taxonomy is not precise. It is possible to define technical progress as the force that accounts for changes in the level of income that cannot be explained by changes in measurable inputs.[2] That such a definition is precise, one cannot argue; however, if the problem involves explaining those forces, that definition is hardly helpful. Moreover, this *ex post* definition has taken on a life of its own, a life that seems to mask the need to push behind that definition to a study of the causes of technical progress. For those that do choose to look for causes, the analysis is built on concepts, like, for example, invention and innovation. But in this instance (and perhaps, in general) differences between the two are seldom specified and when specified seldom operational. To Schumpeter, inventions are the discovery of new techniques while innovation is the act of applying those techniques to economic production.[3] The acts are

2. Edward Fulton Denison, The Sources of Economic Growth in the United States and the Alternatives Before Us (New York: Committee for Economic Development, 1962).

3. Joseph Schumpeter, The Theory of Economic Development: An Inquiry into Profits, Capital, Interest and the Business Cycle (Cambridge, Mass.: Harvard University Press, 1911).

separable and Schumpeter's theory turns on that distinction. Inventions occur randomly over time but innovations are concentrated in periods of low uncertainty and explain the distinctive cyclical nature of growth. Any examination of the real world, however, shows that invention and innovation are frequently inseparable and at times indistinguishable. Schumpeter may be excused because he wrote half a century ago but recent work has helped little if at all. It is possible to talk precisely about shifts in and movements along specified production functions, but in practice, it is difficult to distinguish one from another. Moreover, Salter has shown that the concept of a well specified production function has few empirical counterparts.[4] Even if one is willing to accept the traditional formulation as useful, it helps little in understanding technical change that takes the form of new products rather than improved processes.[5]

In the course of this review no attempt is made to distinguish between inventions and innovations nor to build a taxonomy that permits product innovation to the treated symmetrically with process innovation. (This failure leads to both confusion and ambiguity, but it also suggests the possible productivity of research directed toward these basic questions.)[6] Instead, the concern is with institutional structures and the associated rates of technical change defined to include both changes in technique and the introduction of new products. It is necessary, however, to realize that observed rates may be attributed to differences in the rates of production of new processes or products, to differences in the rate of diffusion of products and processes or to a combination of the two.

4. W. E. Salter, Productivity and Technical Change (Cambridge, Mass.: Cambridge University Press, 1968).

5. Edward Ames and Nathan Rosenberg, "The Enfield Arsenal in Theory and History," Economic Journal 78 (December 1968).

6. Gerald Flueckiger, "Observation and Measurement of Technical Change," Explorations in Economic History 9 #2 (Winter 1971-2).

Although this focus attempts to finesse the problem of operational definitions, the avoidance is more apparent than real. In the literature the distinction between product and process innovation is frequently implicit, and from an analytical point of view some distinction is important. Any new process or product involves a certain amount of technological uncertainty, but a new product involves not only technological but also market uncertainty. As long as the innovator is his own consumer, the market uncertainty is reduced or perhaps eliminated. Empirically, however, it is very difficult to distinguish between a product and a process innovation. In the case of the machine tool industry, for example, textile firms at first produced specialized tools as modifications of existing equipment (clearly a process innovation) and then gradually began to invent and market more general machines (clearly new products).[7] It is, however, almost impossible to identify the point in development at which process changes become product changes. It probably makes sense, therefore, to focus not on the process-product distinction but on the question of the degree of market uncertainty; and it appears that the literature can be more easily interpreted if the distinction is made in this manner.[8]

7. George S. Gibb, The Saco-Lowell Shops: Textile Machinery Building in New England, 1813-1949 (Cambridge, Mass.: Harvard University Press, 1950). See also, Duncan M. McDougall, "Machine Tool Output 1861-1910," Purdue Faculty Papers in Economic History 1956-1966, (Illinois: Richard D. Irwin, Inc., 1967), and Nathan Rosenberg, "Technological Change in the Machine Tool Industry, 1840-1910," Journal of Economic History 4 (December 1963), pp. 414-446.

8. W. Paul Strassman has studied a series of nineteenth century technological innovations in light of this question. His method involves distinctions between various types of risk (e.g., production, timing consumer) and their possible influence upon the decisions of innovators/businessmen during this period. See W. Paul Strassman, Risk and Technological Innovation: American Manufacturing Methods During the Nineteenth Century, (Ithaca, New York: Cornell University Press, 1959).

Given these caveats about taxonomy, let us turn to the questions of alternative institutional arrangements and the governmental policies that have affected the rate at which these institutions produce technology. Economic history contains examples of governmental institutional arrangements that have acted directly on research output, that have affected research output by altering its profitability, and that have indirectly affected the profitability of expenditures on research and development. At times government has affected output by acting as a consumer of research and at other times they have socialized the research function. Profitability has been affected by the innovation of policies that guarantee markets for new products, by patents and other devices that confer some monopoly profits on the innovating firm, and by indirect subsidization of research and development when that activity was a joint product with government expenditures made for other purposes. Finally, there have been institutional changes that have promoted joint research, granted exemptions from anti-trust prosecution or preferential tax treatment, enacted laws protecting innovating firms from attacks by other institutions, and reduced information costs.

While economic history provides numerous examples of alternative institutional structures, economic historians have seldom directed their research in that direction. Substantial work has, however, been focused on trends and fluctuations in innovative and/or inventive activity, and a portion of this conventional wisdom is relevant to a discussion of institutional productivity. Schumpeter in The Theory of Economic Development argued that invention was exogenous, and that economic growth occured when uncertainties were reduced sufficiently to induce a wave of innovation.[9] Later

9. Schumpeter, The Theory of Economic Development.

in Capitalism, Socialism, and Democracy he focused on the speed of imitation and on the need for monopoly profits to foster the commitment of resources to research and development.[10] While his later work has been the basis for intellectual exploitation by others, his earlier work has not had the same impact. Kuznets was particularly concerned with the cost saving attributes of innovation, and he argued that it was the first major invention in any industry that triggered the greatest rise in productivity.[11] His primary interest was not with problems arising from the economic environment but with the sources of inventive activity.[12] While not explicitly discussing the productivity of various institutional structures, he was less concerned with appropriability, and less worried about uncertainty than was Schumpeter. It is worth noting that his concern was almost entirely with process rather than product innovation. Both Kuznets and Schumpeter were interested in explaining the process of economic growth, but Kuznets' focus on process innovation may explain his relative lack of interest in the scientific basis of technical development. Schumpeter's preoccupation with new products, however, tended to focus his attention on the need for formalized research. The different

10. Joseph Schumpeter, Capitalism, Socialism and Democracy, (Harper & Row, 3rd Edition, 1950).

11. Simon Kuznets, Secular Movements in Production and Prices, (1930).

12. Kuznets argues that later inventions were less important and tended to follow from the profits engendered by the imbalances produced by earlier innovations. This conclusion appears to rest in part on his relatively narrow definition of an industry and in part on certain assumptions about the elasticity of demand, Kuznets, Secular Movements.

weights they assign to product and process development can probably be best explained in terms of their areas of experience. Kuznets, drawing on a wide ranging historical background, recognized that most developments were in fact process innovations. Schumpeter, impressed by those few developments that had a massive impact on the economy, turned his attention to new product breakthroughs. Both points should be kept in mind if one is interested in innovating structures that are conducive to technical change. As causes of innovations, ex ante entrepreneurial rewards are important to both authors, but reductions of uncertainties are more important to Schumpeter and likely to questions of product innovation in general. Since rewards from new product innovation tend to be less certain and longer delayed, Schumpeter's policies are designed to provide temporal protection for those rewards.

In the past decade, Jacob Schmookler and W. Paul Strassman have examined the historical work underlying the views of Kuznets and Schumpeter in more detail. Schmookler's interest is in questions of economic growth, and therefore in both product as well as process innovation.[13] For the empirical portion of his study he uses patents as a surrogate for technical change.[14] His conclusions support Kuznets to some extent. They indicate that inventors tend to invent that which is profitable, and that inventions do not appear to flow directly from developments in pure science. On the other hand, his work implies that the type of invention (as opposed to its purpose) is dependent on the state of science and technology. Thus the greater complexity of modern inventions probably reflects the "better quality" of science.

13. Jacob Schmookler, Invention and Economic Growth, (Cambridge, Mass.: Harvard University Press, 1966).

14. The patent statistics cover both process and product inventions; however, the "patentability" criterion biases the series toward product innovations. As a result, a railroad with the wheels on the ground and the rails on the car was granted a patent, but the Ford-Sorenson assembly line was not patentable.

Strassman attempts to test Schumpeter's conclusions concerning the importance of uncertainty reductions in fostering innovations.[15] He concludes that the risks run by inventor-innovators in the nineteenth century were less than Schumpeter believed. In this regard he also supports Kuznets' position, but again the support may be the product of the bias toward process inventions in the history of any technology. Taking the four works together, one can conclude that anticipated profits are important in the production of new technologies. For process changes, however, there is little evidence to support the contention that these profits must be protected from competitors. No one has shown that uncertainties are not a major barrier for product innovation, nor that the quality of inventions may be a function of the stock of science and of applied engineering techniques. As to whether, as Schumpeter feels, the rates of accumulation of these stocks can be increased by policies aimed at protecting the profits of inventors is less clear.

Schmookler's work is just one example of a spate of literature that uses patents as a proxy for technical change.[16] The criticisms of the patent data are well known and need not be touched on at any length here. Utilization of patents as a measure of technical change not only involves very strong assumptions about the inter-patent distribution of productivities and the industrial distribution of the inventions but also about the movement over time in the costs and revenues derived from the act of patenting. Despite the weaknesses inherent in that choice, patents are used because other measures are not easily available. Our survey however indicates that at least two authors have

15. Strassman, Risk and Technological Innovation.

16. Jacob Schmookler, "The Level of Inventive Activity," Review of Economics and Statistics 36 (May 1954), pp. 183-190.

suggested alternative measures, both based upon engineering data. Enos, in a study of the petroleum industry, utilized physical measures of productivity.[17] In comparing six process innovations he measures progress by the fall in the number of units of input required per unit of output. Since the innovations in question appear to have saved on all inputs he is not even faced with the problems of weighting the inputs. These results indicate that a micro focus, when possible, provides a superior measure of technical change. Ames' study of Bell Labs tends to support the same conclusions, even though he finds his data will not support direct measures of productivity change.[18] Working from engineering specifications and catalog descriptions, Ames is able to distinguish between major and minor developments, to follow the process of technical diffusions, and to compute life expectencies of particular technical developments. The role of engineering surrogates for technical progress is, of course, limited to process changes where comparisons of productivity have some meaning. It is difficult if not impossible to conceive of how engineering data might be used to measure the contributions of new product innovation to technical progress. Perhaps when some empirical counterpart of the concept of consumer surplus is developed the way will be opened, but there is no indication that this is likely to occur in the near future.

Despite these alternatives, patent data have provided the basis for a substantial proportion of the work done in economic history. The problems inherent in this approach are at least severe. Consider, for example, the alternative implications drawn from the observation that the number of patents issued has declined since the early 1940s. To some it has been interpreted as a decline in national creativity; to another group merely a reflection of the institutionalization of research (a reduction in the profits accruing to patenting intermediate steps);[19] and to others, an indication only that technology itself is changing.

17. John L. Enos, Petroleum Progress and Profits: A History of Process Innovation (Cambridge, Mass.: M.I.T. Press, 1962).

18. Edward Ames, "Observing the Effects of Research on Business," Purdue Faculty Papers in Economic History 1956-1966, (Illinios: Richard D. Irwin, 1967.)

19. Schmookler, "The Level of Inventive Activity," p. 185.

(A single patent is now sought to cover increasingly complex developments where in years passed a number of simpler developments would have each been covered by a single patent.)[20] If patents are to be used as the major data source, and if there is any expectation that the results of such utilization are to be useable, it appears necessary to go below the aggregate numbers and discover something about differential productivities and life expectancies.

Comanor's study of the pharmaceutical industry, for example, suggests that the useful life of a patented invention is very short (not much over two years).[21] The Bell inventions, on the other hand, live for much longer periods, and more complicated developments once innovated, tend to survive longer than simpler ones.[22] It seems likely that the contrasting experiences can be traced to differences in the industrial structure of the industries involved, but regardless of the cause such discrepancies cast serious doubt on the use of raw patent series.

Ames' work is important not only because it is rooted in engineering data and therefore provides some clues about the cost savings potential of particular technical developments, but also because it provides information on the economic life of those developments. The substitution of a catalog of offered technologies for a list of patents is productive in measuring inventive-innovative activity, although it is appropriate to only a small subset of potential studies. Since the profits attached to any innovation are a function not only of the size

20. Ames, "Effects of Research on Business," p. 402.

21. William S. Comanor, "Research and Competitive Product Differentiation in the Pharmaceutical Industry in the United States," Economica 31 (November 1964) pp. 372-384.

22. Ames, "Effects of Research on Business."

of potential earnings but also the time distribution of those earnings, patent data must be adjusted to reflect both returns and that distribution. This constraint is particularly binding if the concern is with the design of institutional structures. If the patent series are adjusted for productivity and life expectancy it would be possible to discuss such topics as the optimal life of a patent or to compare the efficiencies of policies designed to increase appropriability with those designed to speed diffusion in a systematic fashion. Similarly, such adjustments might make it possible to explore the relationships between technical change and such exogenous institutional developments as industrial structure or the state of the capital markets.

Two observations seem appropriate. Given the difficulty of making the suggested adjustments in the patent data, for process innovations at least, it may be easier to go immediately to a more direct measure of technology by generating at the firm level measures similar to those produced either by Enos or Ames.[23] If patents are to be used, some adjustments must be made. At the most general level the patents could be more carefully read and finer classifications produced even if no attempt is made to research the underlying data.[24] In addition, a project designed to sample the patent universe and then to examine the engineering and economic foundation for each patent in the sample appears to be both feasible and of substantial value.

III. Technological Change and the Economic Historians

It is possible to turn to history for evidence to help answer questions that have interested students of technical changes. These

23. Business history includes an extensive amount of data as yet virtually unmined as a source of technical measurement, which could be utilized by future researchers for studies in the manner of Enos and Ames.

24. Cyril Grant, "Sources of Regional Technological Change as Indicated by Patent Granted Statistics," PhD Dissertation, 1967 (Purdue University). See also, J. Schmookler and O. H. Brownlee, "Determinants of Inventive Activity," American Economic Review, Papers and Proceedings 52 # 2 (May 1962), pp. 165-176.

questions include first appropriability. The greater the degree of appropriability permitted by an institutional structure, the greater are the proportion of the profits that accrue to the inventor/innovator; however, this conclusion does not lead to any firm policy recommendations. We know very little about the elasticity of technical change with respect to profits, nor about the relative importance of invention versus diffusion in the determination of the rate of economic growth. We would like, for example, to compare the returns earned by institutional structures that increase appropriability with those produced by structures that socialize the research function and make the output available at a subsidized price to potential innovators.

Second is the optimal size of the inventing/innovating unit. Again the economic history literature provides no certain answers but some evidence. In the literature we find evidence of increasing returns to scale flowing from (1) learning by doing,[25] (2) the importance of team research,[26] and (3) the reduction of uncertainties arising in the production and marketing experience of integrated firms even when that experience is not directly relevant to the research in question.[27] At the same time there is some evidence that decreasing returns may exist since creativity may be inversely correlated with firm size, and sunk market cost may reduce the potential profits from competitive technologies.

25. Kenneth Arrow, "The Economic Implications of Learning by Doing," Review of Economic Studies 29 (June 1962) pp. 155-73. See also Paul David, "Learning by Doing and Tariff Protection: A Reconsideration of the Case of the Ante-Bellum United States Cotton Textile Industry," Journal of Economic History 30 # 3 (September 1970), pp. 551-601.

26. Guy Hartcup, The Challenge of War: Britain's Scientific and Engineering Contributions to World War II, (New York: Taplinger Publishing, 1970).

27. Strassman, Risk and Technological Innovation.

Third is the difference between product and process innovation. Economic historians frequently assign product innovation a major role in their studies of economic growth; however, most of the technological history is written about process innovation. Since product innovation may involve marketing uncertainties not present in process development, there is no reason to believe that all institutions will prove equally efficient in promoting both. Industry studies and work done on scientific effort on wartime provide some information on this subject, even when the technological literature does not.

The following section provides a thumbnail review of the economic history literature of certain periods, industries, and sectors. There is no attempt to provide symmetry or complete coverage. Although they constitute only a small part of total historical experience, the survey of the economic history literature indicated that the selected areas had been the subject of historical investigation and appeared to yield some interesting insights into the question of the relationship between institutional change and technical progress.

1. The Industrial Revolution: No set of subjects, let alone a single subject of a technological nature, has occupied economic historians more than the study of the century of British history that spanned the years 1725 to 1825. Despite the effort, that research tells us relatively little about the process of technical change, although it makes it clear that there was a great deal of change. The literature suggests that the economic environment was highly competitive, and appropriation of the gains from inventions difficult. Patent laws existed, but were seldom a barrier to the diffusion of technology. Information costs must have been low and the patent laws more observed in the breech. The breakdown of feudal monopolies

and the movement towards freer trade were characteristics of the economic environment; an environment that was particularly conducive to rapid innovation.[28] The history of technical change within this environment adds confirmation to the belief that expected profits rooted in innovation and application of that innovation to new markets, even if no barriers prohibit competitors from seeking those same profits, are sufficient to encourage rapid innovation.

While one might think that an economic revolution would involve the introduction of a wave of new products, the technological developments that have received the most study were almost all process innovations. Both Kuznets and Mantoux have observed that productivity gains were concentrated in textiles, iron making, and pottery.[29] All had markets marked by a high degree of price elasticity, and the *ex ante* profits to be produced by cost saving innovations must have seemed high. It is possible that the steam engines and machine tools were examples of product innovations, but even that conclusion is not clear. The history of the machine tool industry is a history of gradual movement from pure process to product innovation, and the latter was effected only after the market for the new products was known to exist.[30] In the case of the steam engine, its use as a stationary power source (the original basis for development) should properly be viewed as a process innovation in the energy industry, if the focus is on market

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28. R. M. Hartwell, "The Causes of the Industrial Revolution: An Essay on Methodology," *Economic History Review* 18 #1 (1965).

29. Paul Mantoux, *The Industrial Revolution in the 18th Century* (London, 1928). See also, Kuznets, *Secular Movements*.

30. Nathan Rosenberg (ed.), *Great Britain and the American System of Manufacturing* (Edinburgh University Press, 1968).

uncertainty. The later application to transport may be best viewed as product innovation, but it also can be argued that it was nothing but process innovation in transportation. Under any conditions, research expenditures were small since most of the work had been done in the development of the stationary engine. The period was characterized by changes in the institutional structure that probably increased the rate of capital accumulation and certainly made capital mobilization much less expensive. Since most of the technical progress was embodied in the capital stock, it is difficult to sort out the effects of accumulation-mobilization and technical change. This difficulty may explain the failure of economic historians, despite their preoccupation with the period, to provide an adequate scenario of the actual process of invention and diffusion.

As Kuznets has suggested, the inventions of the industrial revolution were based on experience, and science played almost no role. Thus the period contributes little to an understanding of the relationship of institutions to science based change. Perhaps the competitive institutional structure so productive in that period is less useful when basic research and its accompanying externalities are important. The history of both the textile and the iron industry suggests that inventions were closely linked to perceived profits and that lack of appropriability was not a significant barrier to new developments. In this regard the industrial revolution appears to foreshadow Schmookler's conclusions about a much later period. For process innovation at least the prospects of profits (even when imitation is swift) arising from assured markets appears sufficient to underwrite a high rate of technical progress. The period did not, however, produce substantial product innovation, a result that might be taken as negative evidence on the productivity of the totally free institutional structure in that dimension. It may, on the other hand,

merely reflect the differing productivity of process versus product innovation in the eighteenth century.

2. The USA 1860 to 1910: Jewkes has termed this the "Heroic Age of Invention in the United States," but he may have confused productivity changes with inventiveness.[31] The economic history literature indicates that it was certainly a period of marked economic change, rapid income growth, and substantial innovations.[32] However, while there were some important American inventions, growth was largely postulated on the importation of foreign technologies.[33] Kelly discovered a blast steel process and that process was used in the nation's first steel mill; but the bulk of the American steel industry was based on the importation of the Bessemer Technology.[34] Agriculture was revolutionized by the opening of the wheat belt in the upper plains, but the crucial postbellum technical development[35] was the introduction of Hungarian reduction milling.[36] It was the growth in the railroad network that made a national market possible;[37] however, while there were American technical contributions, growth was largely based on process innovations on an already existing

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31. J. Jewkes, D. Sawers and R. Stillerman, The Sources of Invention (London: Macmillan & Co., Ltd., 1958).

32. Victor S. Clarke, History of Manufacturers in the United States, Vol. I & 2 (Washington: Carnegie Institution, 1929).

33. There is a substantial body of literature about British and American technology in the nineteenth century, but the focus has not been on technical change. Instead the argument has revolved around the differences in the two technologies, as reflections of the response to different factor prices. The discussion is of some interest from the point of view of diffusion of technology, but there is little that is relevant to an understanding of institutional structures.

34. Duncan Burn, The Economic History of Steelmaking 1867-1939, (Cambridge, Mass.: Cambridge University Press, 1961).

35. The mechanical reaper, first patented by Obed Hussey in 1833 and later improved substantially by Cyrus McCormick, was being marketed extensively prior to the Civil War.

36. John Storck and William Dorwin Teague, Flour for Man's Bread (Minneapolis: University of Minnesota Press, 1952) p. 196.

37. Albert Fishlow, "Productivity and Technological Change in the Railroad Sector, 1840-1910," in Output, Employment and Productivity in the United States after 1800. Studies in Income and Wealth, Vol. 30 (New York: NBER, 1966).

and well proved technology.[38] Still there were some major American inventions and they do provide us with some clues as to the relationship between institutional structure and technical progress.

The conventional wisdom, both economic and historical, suggests that the rate of technical progress was in part dependent upon the degree of uncertainty that faced nineteenth century innovators. Strassman's study of manufacturing methods in the period reveals that technological innovation was relatively free from high-risk factors.[39] He argues that interference risks from labor were negligible since workers were neither threatened to any great extent by labor-saving inventions[40] nor sufficiently organized to pose a threat themselves. The government at all levels was generally sympathetic to the interests of the business sector and passed tax and tariff laws which served to stimulate innovation. Consumers were on the whole open to new methods and products, reducing marketing uncertainties. Furthermore, production risks especially those involving chemical processes became less insuperable as scientists and scientifically trained engineers became more and more involved in the process of innovation.

The developments that concern Jewkes were in electricity (Edison and Brush), petroleum, and communications (the telephone). Of the group the telephone is clearly a new product, a case can be made that certain parts of the electric industry (lighting) should be put in the same category, but, while kerosene is a new product it almost certainly ought to be considered a process innnovation in illumination. Still in the period there was a grouping of new product innovation about which we do have some historical evidence. Perhaps

38. The Westinghouse air brake, the automatic coupler and the consolidation type steam engine were important technical breakthroughs in the railroad industry. All of the above, however, were antedated by similar patented devices. See Schmookler, Invention and Economic Growth, pp. 269-274.

39. Strassman, Risk and Technological Innovation.

40. Strassman is not quite correct in terms of the threat to labor. There are certainly examples of skilled craftsmen whose position was undercut by technical advance. The cordwainers, cigar makers and glass blowers (to cite only three) certainly fall into this class. Their total numbers, however, may have been small, and certainly they were not strong enough to prevent the innovation of new technology.

equally important there appears for the first time to be some connection between inventions and scientific development.[41]

Edison was a great inventor, but he knew very little about science in general or electricity in particular. Most of his electrical inventions were based on reasoning by analogy from natural gas to electricity.[42] A cursory examination of his contributions appears to add weight to Kuznets' argument about the relation of invention to science. A more careful reading suggests that conclusion is probably erroneous. Edison's lack of scientific training put him on the wrong side of the AC-DC controversy and ultimately cost him his position at General Electric. Moreover, even Edison recognized that at times science was important, and he built an organization that would permit him to draw on the abilities of people with scientific training. His laboratory at Menlo Park was an example of one of the first attempts to institutionalize the research function.

Bell had a much better understanding of the role of science, and his recognition of the importance of that field can be seen in his support of the pure science done at the Volta Laboratories.[43] He also, however, explicitly recognized the appropriability problem, and viewed his support of pure science not as a profit making venture but as largely an exercise in philanthropy. Even so, the degree of appropriability must have been much greater for natural monopolies like the telephone industry than it was for Edison under constant competitive pressure from Westinghouse

41. Schmookler, Invention and Economic Growth.

42. Harold C. Passer, The Electrical Manufacturers 1875-1900 (Cambridge, Mass.: Harvard University Press, 1953).

43. Jewkes, et al, The Sources of Invention, p. 56.

and a handful of other firms. Bell was not the only science trained inventor of importance in the period. Both Brush and Elihu Thomson came to Technology with some scientific background.[44] Times had begun to change, and these, perhaps, were the changes Schumpeter saw. The changes also had an institutional counterpart with the emergence of technical schools (Coopers Union, for example) and scientific institutes (The Franklin Institute). However the precise contribution of early formal scientific education to the process of technical development has not been the subject of substantial historical inquiry.

Finally, the petroleum industry provides examples of research based on science, but also examples of the older purely empirical developments. The close temporal connection between Silliman's 1855 scientific paper and the invention of fractional distillation must be one of the earliest examples of a development in science leading directly to technical change.[45] Conversely, it appears that the development of destructive cracking was a purely unintentional byproduct of refiners' attempts to squeeze more and more output from a given capital stock,[46] and provides one more piece of evidence for those who believe that "learning by doing" accounts for a major portion of process innovation.[47]

44. Jewkes, et al, The Sources of Invention, p. 57. See also, Passer, The Electrical Manufacturers 1875-1900.

45. Harold F. Williamson and Arnold R. Daum, The American Petroleum Industry, Vol. I, The Age of Illumination (Evanston, Illinios: Northwestern University Press, 1959.)

46. Harold F. Williamson, Ralph L. Andreano, Arnold Daum and Gilbert Close, The American Petroleum Industry: The Age of Energy 1899-1956 (Evanston, Illinois: Northwestern University Press, 1963).

47. Schmookler, Inventions and Economic Growth.

What then can we deduce about institutional development from the technological history of this period? There was a constellation of product developments and these may have been related to a number of changes in the institutional structure that appear to have reduced market uncertainties. For example, the period saw the emergence of a truly national market for both inputs and final products. This development not only increased the total profit potential of an innovation, but also reduced uncertainties about prices and tastes in regions far removed from the innovators' immediate ken. At the same time, both the electric generation and the telephone system were natural monopolies, so the period may provide some evidence in support of the Schumpeterian conclusion. Again, the emergence of a science based technology appears to have engendered some economies of scale in research. Even Edison admitted that a little mathematics was an efficient substitute for complicated mechanical models. The result was the innovation of a new institutional form -- the research laboratory. In the period the legal structure made patents increasingly enforceable, although the courts tended to hold that an unused patent was no patent at all.[48] Finally, innovation in the United States was still largely concentrated in process changes where market uncertainties were negligible and in industries that were natural monopolies. As a result, there is little evidence that an institutional structure that did not prohibit rapid imitation inhibited development in the way Schumpeter believed. Such a structure does not appear to discourage process developments based on learning by doing, since the technological developments were to a large extent embodied and

48. Strassman, Risk and Technological Innovation, p. 192.

so in part at least appropriable. Equally important, since they were produced in the normal course of business, their marginal development costs were probably close to zero.

3. World War II: Although the era of the second world war has drawn less attention from economic historians than the two earlier periods, it was a period of rapid technological progress. By all accounts World War II produced a wave of product innovation, but the history also suggests that the rate of new product development was not high until market uncertainties were reduced. Radar, considered a miracle by many, languished for ten years until the government made the decision to innovate that form of aircraft defense. The basic research on penicillin had been completed by the early 1930s, but production difficulties made innovation appear unprofitable until the approach of war greatly increased the potential demand for a broad spectrum antibiotic. A similar lag with less positive results from the point of view of product innovation can be seen in the case of German jet aircraft development. In the case of both radar and jet aircraft development, the government was the dominant potential demander. Often development appears to await the recognition of profitable employment for the product, and history suggests that when there is little competition for that product, that wait may be very long indeed. The wartime experience also brings to light another problem that has not been so well investigated. While the decision to "go ahead" with some technical development frequently produced rapid technical advance by concentrating all attention on a single line of development, it also tended to reduce diversity and may, in the long run have resulted in slower development. Britain's experience with the jet engine is a case in point. The government's decision to reduce the role of Jet Power Company and turn a substantial amount of development work over to Rover froze technology and contributed to the failure of Britain to get an operational aircraft by the war's end.[48a]

48a. Jewkes, et al, The Sources of Invention, pp. 314-317.

An examination of history also contributes to our understanding of the productivity of a variety of research organizations. The literature frequently stresses the importance of the "research team."[49] It is argued that continuing existence apparently generates externalities not only through "learning by doing" but also through the development of interpersonal relationships that make the group more productive than the sum of the individuals. In addition, a comparison of British-American research efforts with those in Germany suggests that institutions that produced feedback between research and development personnel, units devoted to production, and those groups charged with utilizing the product were much more productive than those structures without analagous mechanisms. The Americans and British had scientific personnel involved in all of the "follow-through" operations but the Germans tended not to follow that practice. The allies were much quicker to assess production bottlenecks and market failures and suggest modifications than was the Axis power.

Not all wartime research and development was successful, and history suggests that the mere existence of guaranteed markets or a socialization of the research function does not guarantee that the research will be successful or if successful that the output will be productive. Once a market had been guaranteed, the development of radar was swift, but similar guarantees even though supported by a substantial resource commitment did not produce a successful aerial mine. Moreover, there were numerous examples of research decisions that show that in the absence of a market test for productivity, expenditures in research and development may result in inventions, that while technically feasible, have no "commercial value." Operation

49. James Phinney Baxter, Scientists Against Time (Boston, Mass.: Little, Brown, 1946). See also Hartcup, The Challenge of the War.

Habbakkuk, the Pykecrete project, is a case in point.[50] Technically it was feasible to produce an almost unsinkable ship two miles long made of frozen water and sawdust, but how did its development shorten the war? These wartime research experiences concerning the process of technical change suggests certain hypotheses: some organizational structures appear more productive than others, and the success of team research implies that there were economies of scale in R&D. A reduction of market uncertainty appears to increase the levels of new product invention-innovation and full subsidization of research almost certainly increases the output of that activity. Reduced uncertainty and subsidization are, however, not panaceas. Institutions with these characteristics can increase research output, but they do not guarantee solutions to any particular problems. Moreover, since resources are finite, such structures may lead to inferior choices when decisions must be made between alternative lines of research and they may produce a technology that has little relevance to anything. Finally, the decision of the monopsonist in the market for technology (the government) to subsidize a particular development almost certainly tends to eliminate competing technologies and this reduction of diversity may in the long run retard development.

4. Agriculture: Economic historians have not only been intrigued by certain periods in the past, but they have also written extensively about particular firms and industries. While the focus has seldom been technological change, they have been concerned with both organization and the response of the units to governmental policy. We have made no attempt to survey all of the literature in the fields of industrial and business history, but we have examined

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50. Hartcup, The Challenge of the War, pp. 258-262.

several industries in some detail, and it appears that two are particularly relevant.

Recent work in theory has suggested that optimum levels of expenditure in research and development decline as the number of firms in the industry increase.[51] Agriculture is a competitive industry, and its history provides some evidence on this question. It indicates that early attempts to organize research on a voluntary cooperative basis were never very successful;[52] the free rider problem was clearly apparent in the nineteenth century. Most of the productivity increases since the 1860s have come either from socialized research activities or from private firms able to appropriate the gains of their research by selling products embodying these developments. The research experience of the Department of Agriculture is particularly interesting since it is one of the few American examples of government financed research not carried out under the pressure of war. The Department has been highly successful in producing process developments but less successful in increasing the rate of invention-innovation in new products.

Over the past century and a quarter the Department evolved an institutional structure very similar to that which proved so productive for military research during the Second World War. In fact, the chroniclers of the war would almost certainly have been less generous with their praise of the British-American effort had they noticed that the structure that finally evolved was very similar to structure that the Department had already developed. The early

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51. L. E. Ruff, "Research and Technological Progress in a Cournot Economy," Journal of Economic Theory (December 1969), pp. 397-415.

52. Wayne Rasmussen, (ed.) Readings in the History of American Agriculture (Urbana, Illinios: University of Illinios Press, 1960).

period of organizational experimentation could probably have been reduced had the government innovated the already proven structure.

By the end of the nineteenth century, the Department was organized with an administrative group in Washington, agricultural experiment stations located in the areas where the output of the research was likely to be used, and a group of subsidized agents who could supervise innovation and report results from the field.[53] In the twentieth century, the structure was modified to centralized basic research in a single laboratory, but the responsibility for applied research and development still rested with the experiment stations. Thus whatever economies of scale existed in team research were realized while the feedback mechanism was probably superior to those developed during the Second World War. Applied work was done close to the areas of use, and the agents not only provided a continual source of information on the actual productivity of new developments but also disseminated new technical developments quickly and cheaply. Although the objective function of the Department has never been clearly articulated, the structure at least permits it to be exercised. It is less clear that the wartime structure had this capability. Finally, the output of basic research was made easily available not only to the experiment stations but to any private firms that wanted to pursue further research and development themselves. Such low information costs certainly increased the rate of technological diffusion. Moreover, by opening up applied research to a number of potential users, it permits parallel research paths to be followed. It seems at least possible that the diversity so engendered could prove more productive in the long run than the single channel development

53. A. Hunter Dupree, Science in the Federal Government (Cambridge, Mass.: Belknap Press, 1957). See also Rasmussen, History of American Agriculture.

that was characteristic of so much wartime research. Basic research is centralized and it would be interesting to estimate the scale gains from the team and compare them with the diversity losses from centralization. The Department has in part recognized this problem and continues to underwrite some basic research through university contracts.

Griliches' work in hybrid corn measures both the productivity of the investment in research and development and the speed at which this technical development was diffused through the economy.[54] For one crop, at least, it can be used to provide a measure of the effectiveness of the Department's institutional structure. In that instance, at least, rapid imitation did not stand in the way of development, and a substantial portion of the gains were accrued by the consumers rather than the business sectors.

Although the Department of Agriculture has made major contributions in the area of process innovation, their performance in the area of product innovation has been less spectacular. In its early years, the Department did promote new products, but most were "exotic" and foredoomed to failure.[55] The commitments to silk and tea fall into this category. The goal in most of these cases was American economic self-sufficiency, not increased productivity. It is interesting to note that these excursions antedated real farmer inputs into the decision-making process of the USDA. In the periods of the Department's greatest activity, two major "new" products have become important, peanuts and soybeans; however, the Department contributed little to their original development,

54. Zvi Griliches, "Hybrid Corn: An Exploration in the Economics of Technological Change," Econometrica (October 1957). See also, Zvi Griliches, "Research Cost and Social Return - Hybrid Corn and Related Innovations," Journal of Political Economy (October 1958).

55. Paul W. Gates, The Farmer's Age 1815-1860 Vol. III The Economic History of the United States (New York: Holt, Rinehart, and Winston, 1960).

nor have they added much to the R&D that was required to produce marketable products. A similar conclusion is reached from an examination of the Department's contribution to those technological developments embodied in the capital stock. The USDA has developed improved ploughs, cotton gins, spraying machines and a host of other devices that have increased productivity. In almost every case, however, the innovations have been process improvements on already existing equipment. The crop dusting apparatus patented in the early thirties is one of the few examples of a new product innovation.

As a comment on institutional structure, it is interesting to note that in some dimensions at least, the feedback mechanism has proved almost counterproductive. In part this problem arises from the failure of society to articulate clearly the Department's research goals. The Department is largely a political creature and, as such, responsive to its constituents. The feedback mechanisms so useful in reporting successes and failures are equally efficient in conveying the opinions of the farmers to the decision-making units in Washington. These constituents are interested in increasing the productivity of their agricultural capital not the total agricultural stock of society. This criteria may well account for the bias toward innovations geared to improving existing technology other than developing new products. The farmers have proved almost unconcerned with possible long-term developments (their rate of discount may well be above society's) and in addition they appear to recognize that the profits from the new products might accrue to a different group of people.[56]

56. Charles Rosenberg's work on scientists in the early agricultural experiment stations has examined the problems of research geared to satisfying the relatively scientifically unsophisticated farmer. See "Science, Technology and Economic Growth: The Case of Agricultural Experiment Station Scientist, 1875-1914," Agricultural History Vol. 45, (January 1971).

Despite the obvious importance of this institutional structure, we still know relatively little about the activities of the Department. Griliches' productivity studies could be duplicated for other products (particularly for new products, fertilizers and pesticides). It appears that research aimed at discovering the criteria behind the assignment of research priorities within the Department would be very valuable and the total institutional structure could be examined to determine if it is , in fact, as productive as it appears from a reading of its history. (It is clear that in this area more than most of the history has been written by the propagandists of the institution itself.)

5. The Petroleum Industry in the Twentieth Century: The early history was touched on in our discussion of the "Heroic Age of American Invention," the more recent history, illuminated by the work of the Hidys, Enos, and Andreano and Williamson, is particularly suggestive as to the research productivity of alternative institutional structures.[57] The period spans the years 1910 to 1940, and the change involves the development of the continuous catalytic cracking process. Before the 1890s profits came from kerosene sales, but the widespread innovation of electricity and the discovery of oil in Russia had greatly reduced the industry's traditional markets. With the movement to auto transportation, the industry's demand again began to increase, but the technology was not well suited to the production of gasoline.

In 1913, the discovery of the Burton process made it possible to crack heavy petroleum and produce gasoline at a substantial cost

57. Enos, Petroleum Progress and Profits; Ralph W. Hidy and Muriel E. Hidy, Pioneering in Big Business, 1882-1911: History of Standard Oil Company (New Jersey), (New York: Harper & Brothers, 1955). See also Williamson, et al, The American Petroleum Industry.

savings. The monopoly rents demanded by Standard of Indiana for licensing its process touched off an intensive search for alternative technologies not covered by the original patent.[57a] The increased level and more highly focused research produced a series of inventions that were themselves improvements on the Burton process.[58] As a result, in a period of only slightly over three decades the industry moved from thermal cracking, to continuous thermal cracking, to catalytic cracking. In that process the resource inputs per 100 gallons of gas fell from 396 to 170 gallons of raw petroleum, $8,600 to $320 of capital equipment, 1.6 to .02 man-hours of labor, and 8.4 to 1.1 million BTU's of energy.[59]

The history of the industry suggests that, first, within the context of the American business environment, the decision to engage in research is a very delicate one. In every case, developments were the products of research groups nurtured and protected by a single individual in some position of authority. When

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57a. Williamson et al, The American Petroleum Industry.

58. To a certain extent this argument sounds like the one frequently made in studies of economic development where latecomers are assumed to have substantial advantages because they have no fixed capital. No such assertion is made in this case. Instead the argument merely infers that there are more than one possible solutions to the problem and there are gains from being first even if that first solution is not necessarily the best. At a later time further research may produce improved technical solutions, but there is more incentive for firms forced to pay high licensing fees than for firms who are deriving their income from those licenses to continue the search. Had the new developments been economically inferior, they would not have been adopted since monopoly rents would have fallen sufficiently to keep the Burton process competitive.

59. Enos, Petroleum Progress and Profits.

that person moved or lost his interest, the research group languished and productivity ceased. Second, although it must have been clear that the bulk of the technical capital was embodied in the research group and while this capital, though perhaps specialized to the industry, was certainly not specialized to any firm, there were few attempts to raid these groups. Raiding was not an unfamiliar institutions technology since the Tube and Tank process was discovered by a research group at Jersey Standard that had been bid away from Standard of Indiana.[60] No other firm, however, attempted to duplicated that coup. The explanation of this behavior is not obvious. It may reflect something about the structure of the industry (the evidence of any cheating on a cartel decision would be easy to discover) or about the substitutability of research groups. Third, in these examples at least, the attempts to research around a process patent produced a series of superior technical solutions. Fourth, the twentieth century market for research is characterized by the same types of failures that marked the nineteenth century capital market; but, economic pressures have not produced a set of institutional innovations similar to those that underwrote the improvement in the market for funds.

This last part raises more general questions. Why are there no institutions designed to arbitrage the market for research personnel? Is it because knowledge is too specialized or because there are overwhelming economies of scale in group research? If such economies exist, why are there so few companies specializing in research? There are, after all, no legal barriers similar to the National Banking Act that prohibit the development of national research corporations. It is possible that knowledge is too specialized, or such arrangements are subject to industrial espionage, or, perhaps, that there is little research on new products and most of the capital for process research is embodied in the existing processes and their operators. Whatever the explanation, the question warrants further study. Fourth, the most

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60. Enos, Petroleum Progress and Profits. p. 231.

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60. Enos, Petroleum Progress and Profits. p. 231.

radical departures were made by researchers operating on the periphery of the industry, but the laboratories of the large companies, while not proving creative have been very efficient in adapting and applying the inventions of others. This latter observation tends to confirm the lessons drawn from the experience of the Department of Agriculture, but it makes the absence of specialized research companies even more difficult to explain.

One explanation for such an absence may be that the university as a center for federal and industrial sponsored research is too strong a competitor. A profit-oriented research company would have to shoulder the total cost, at least initially, for personnel and equipment -- a cost which for most university research is shared jointly by the university and sponsoring agency. Professional societies and journals provide information and feedback mechanisms. The cost of this structure is relatively low compared to that which would have to be invested by a research company if it were to achieve similar ends. In addition, there is an appropriability problem. Since most universities are not profit-oriented, they have not aggressively pursued the profits inherent in much of their research activities. Instead they have allowed researchers to move their successful experiments "off campus" and capture a substantive portion of the profits. If it is the case that universities are in part responsible for the absence of specialized research firms, perhaps future work in this area should examine more closely the movement of on-campus research into the profit-making sector.

IV. CONCLUDING OBSERVATIONS

1. On Appropriability: While there may have been some improvements in the more recent past, it has been difficult to appropriate the profits of a process innovation. Often the change comes from the stock of skills acquired through learning by doing, and other firms in the industry tend to have similar inventories of skills. Nor have patents worked well to protect the profits of the process inventor, whether he was Eli Whitney or the steel innovators Cort, Heath and Mushet.[61] In the more recent past, patents have provided better protection, but the gains have not been substantial. In the case of the petroleum industry, an example of a development into a "new" area, the skills of other research teams underwrote successful counter innovation in a relatively short time. The Burton process innovated in 1913 had one hundred percent of the market until 1919, but by 1928 was the technology of choice for the producers of only ten percent of gasoline output.[62] A similar story is found in the recent history of the computer software industry.[63] A team can produce a new software system (a process innovation), but despite the copyright laws, the economic life of the innovation is relatively short and appears to be becoming shorter as the requisite skills become more widely dispersed. In other industries, where an entire technology is not in question, the period of successful appropriability has been even less. The brief effective lifetime of these legally protected monopolies probably explains why industrial secrecy has become so important.

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61. Who are known in the literature as the metallurgical martyrs. Alan Birch, The Economic History of British Iron and Steel Industry, 1784-1879 (London: Frank Cass, 1967), p. 317.

62. Enos, Petroleum Progress and Profits.

63. Electric Computers: Gaps in Technology, presented at the Third Ministerial Meeting on Science of OECD Countries (March 11 & 12, 1968)

In the case of product innovation, institutional instruments designed to permit appropriability appear to have worked only slightly more effectively. In the case of pharmaceuticals, Comanor's work implies that even with patents duplication time is extremely short but that in the absence of patents it is unlikely that a firm could expect monopoly profits for any period of time.[64] Even with patents' protection, counter research appeared to produce substitute products within two or three years. While this example is likely extreme, the history of other industries seems to suggest that the difference is of degree, not kind.

The history of both product and process innovation suggests that a significant part of the research potential is embodied in the research establishment. Even with patents and copyrights the extent of appropriability rests in large part on the speed with which results can be duplicated. Speed depends in part upon the substitutability of research groups or the possibility of acquiring the skills of the superior group. The ability of existing firms to produce substitute technology has been demonstrated in a number of cases, and it may account for the failure of research firms to emerge. For such firms, a sales talk may well provide sufficient clues to an alert research team to permit duplication without any further collaboration. In an industry where the ability to copy and adopt is still lacking, research teams do have a positive price. The takeovers of software firms can be viewed merely as purchases of research capability. Increases in the degree to which research skills are transferable may also account for the recent decline in patenting activity and the increased emphasis on industrial secrecy and espionage.

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64. Comanor, "Product Differentiation in the Pharmaceutical Industry."

From the point of view of the design of optimal R&D structures, this study suggests that future research should focus in part on "learning by doing" and the externalities inherent in team research with particular emphasis on interindustry differences in the ability to produce substitute technologies. In this last regard, it appears impossible to ignore the effects of the industry's organization. It should surprise no one that Bell Laboratories are supported by an almost totally monopolized industry but historians have written relatively little about the research efforts of more oligopolistic industries.

2. <u>On Returns to Scale:</u> Historically returns to scale were important in process innovation. In the machine tool industry, for example, there was a tendency for the firms to innovate an institutional structure that made process innovation easy. Over time, however, these structures often produced new products as well. In process innovation learning by doing and the feedback mechanisms that have proven themselves so efficient elsewhere were an almost natural part of the institutional structure provided by the producing unit. Within the same firm are the inventors and the engineers who oversee the use of the innovation (in many cases these are the same groups of people) and even salesmen who are in contact with the users of the final product. Internally the firms naturally reproduce the structure that had to be innovated at some cost in both the wartime laboratories and the Department of Agriculture. Moreover, since the feedback functions are natural byproducts of the day to day activities of the integrated firm, their marginal costs are almost certainly less than they would be to any firm that cannot combine such functions. It has been argued that there are not necessarily economies of scale in "learning by doing" since vertical disintegration should allow small firms each specializing in some small phase of the operation to develop

the same learning skills as could be done in a large integrated firm. In the case of product innovation, this allegation may be true. In the case of process innovation, however, it was not always true. For process development, to the extent the learned skills sometimes involved in-house tasks, such gains may have been captured in smaller specialized firms. Often, however, the innovations involved the movement of products through the production process and for a specialized firm these activities may occur outside the producing unit. In these cases, for specialized firms there would be no doing and therefore no learning. (Perhaps in this case the activity would be better called learning by watching.) Whatever it is called, however, it should be no surprise that highly specialized firms in the British textile industry produced few assembly innovations while such developments were very common in the larger and less specialized American firms. Similarly, it was the American not the British auto industry that produced the assembly line.

The machine tool industry provides an interesting example of both feedback and learning by doing processes and, thus, provides some evidence on the question of optimal institutional structure. In the early nineteenth century there were no machine tool companies, but there were groups of "engineers" in textile companies who were charged with the repair and modification of the existing capital stock. Building on their experience in maintenance and repair, these men began to produce new as opposed to modified machines. The new machines at first merely replaced already existing ones in the traditional process and therefore the economies engendered from easy feedback and learning by doing accrued within the existing institutional structure. From time to time, however, these early "research teams" produced machines that were less specialized to the individual process, and in these cases there were fewer benefits

and some actual costs in maintaining the existing structure. The gains from learning by doing flowed not only from traditional activities, but also from their experience with the less specialized machines. The number of such mutations increased over time. As the economies of scale declined (there was no feedback mechanism for machines sold to some other firm), and as some organizational costs increased (the administration of the producing unit often had a comparative disadvantage in machine sales), the repair and maintenance departments tended to spin off into separate machine tool companies. These companies then attempted to capture the economies of scale within a different organizational structure. Feedback was frequently provided by salesmen cum technical representative, and the gains from learning by doing accrued to the now smaller group who were specializing in the production of non-specialized machines.

The written histories of the automobile industry[65] do not focus on the slow rate of technical change nor on the almost total absence of expenditures on research and development, but they do provide some, perhaps unintentional, insights into the question of the relationship between institutional structure, returns to scale, and technical progress. We have already seen that the nature of process innovation is such that there may be substantial cost savings if it is undertaken by the firm that expects to utilize the process. The auto industry is really not an auto manufacturing but an automobile assembly industry. While its overall technical leadership is open to question,[66] it has been among the leaders in innovations relating to assembly line

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65. John Rae, The Automobile Industry (Chicago: University of Chicago Press, 1965). See also, Allan Nevins and F. E. Hill, Ford: The Times, the Man, the Company (New York: Charles Scribner's Sons, 1954).

66. Jonathan Hughes, The Vital Few (New York: Oxford University Press, 1965).

techniques.[67] There is no activity where learning by doing is more productive than the assembly process, and even the innovation of the assembly line did not represent an independent breakthrough but merely the culmination of a number of small process changes. Outside of assembly techniques, other innovations have tended to come from supplying firms, but this division too is in line with our general understanding of institutional productivity. Those firms are specialists in the products they produce, and if there are economies of scale in the production of these new products (arising either from learning by doing or from feedbacks), they will most likely accrue to the specializing firm.

The history of the petroleum industry provides additional support for the hypothesis that economies of scale are sometimes associated with learning by doing. The established firms were the major source of innovation when those were modifications or adaptations of existing technologies or even new products that came from within the existing paradigm. The farther development moved away from existing technologies, however, the more likely it was to come from a source outside the existing large firms. Compare this result with the experience of the machine tool companies. The evidence on the optimal size of research units producing new products is much less clear.[68] Burton Klein argues that the rate of technological

67. It was Henry Ford who when asked about the source of his invention of the assembly line said that he had seen a modern slaughter house, thought of it as a disassembly line, and merely reversed the process.

68. Daniel Hamberg studied the sources of 27 major inventions in the period of 1946 to 1955 and discovered only 7 were the result of research done in large industrial laboratories. "Invention in the Industrial Research Laboratory," Journal of Political Economy 71 (April 1963) p. 96. Willard Mueller's work on the origins of 25 major product and process innovations of DuPont between 1920-1950 revealed that of the 18 new products only 5 were discovered by DuPont. "The Origins of the Basic Inventions Underlying DuPont's Major Product Innovations, 1920-1950," in R. Nelson (ed.) The Rate and Direction of Inventive Activity NBER, (Princeton, New Jersey, 1962).

progress is frequently dependent upon the internal structure of the firm and that tightly structured firms are oftentimes less able to engage in the type of risk-taking necessary for innovation.[69] This may explain in part why older firms which have, in many cases, evolved into highly structured organizations restrict themselves to improving and modifying inventions already in existence rather than developing new products.[70]

3. On Product Innovation: Despite the lip service paid by historians to growth through product innovation, we know very little about the subject. Although a great number of business histories have been written, there is very little usable industrial history on, for example, the polymer industry, the early years of the automobile industry, the computer industry, nor that portion of the electrical industry that was concerned with new product innovation.[70a] Further work in these areas should certainly prove productive. At the simplest level, it would be very useful to know whether the source of innovative activity has come from established firms or from newly created enterprises.

69. Burton Klein, "Competition and Progress" (unpublished paper, California Institute of Technology, 1974).

70. Arthur Stinchcombe, an expert in the area of organizational theory, has examined the relationship between the date of birth of an organization and its present internal structure. Although his work may be of no direct use, it suggests that a study of the timing of a firm's entry into a particular sector and its present internal structure could prove fruitful in predicting its innovating capabilities. See A. Stinchcombe, "Social Structure and Organizations," in James G. March (ed.) Handbook of Organizations (Chicago: Rand McNally, 1965). In a similar vein Lance E. Davis has explored the relationship between date of birth and sources of finance and his methodology appears to complement Stinchcombe's work. "Sources of Industrial Finance: The American Textile Industry - A Case Study," Purdue Faculty Papers in Economic History 1956-1966 (Illinios: Richard D. Irwin, 1967). This type of analysis could be expanded to an analysis of other research institutions (e.g., universities and non-profit laboratories).

70a. The major exception is W. R. Maclaurin's study of the radio industry. Invention and Innovation in the Radio Industry, (New York: Macmillan, 1949).

A cursory examination of the literature that does exist suggests that the results are mixed, but there appears to be some economic logic to the institutional division. In the case of polymers, existing chemical firms provided the bulk of the technological development. These firms already had research groups with the skills necessary to exploit developments in chemistry, and they should have been able to capture economies arising both from the externalities inherent in existing groups and from their ability to use those groups both in the new product development and in whatever other work was of current interest. Thus they were able to divide an otherwise lumpy research investment and operate profitably at a lower level of research output than would have been possible for any firms not "in the business." In the case of the electric durable industry, most product innovation also came from already existing firms. Westinghouse and General Electric together organized the Radio Corporation of America and introduced the mass-produced radio receiver.[71] Similarly, those companies took the lead in the introduction of refrigerators and washing machines. Both firms had a stake in increasing the demand for electric power because the success of the new products would permit them to capture not only the direct profits of the innovation but also indirect profits arising from their position in the market for electricity and for electric generating equipment. Given identical costs, innovation must look more profitable to them than to a firm in the position to capture only the direct returns. Costs, however, were not identical, since those two firms also had research departments with a stockpile of skills at least partly applicable to the new developments. Finally, in the case of the auto industry, innovation was by a very large number of firms, many new, but a few with origins in coach making. The product was almost entirely new, and not based on any development in pure science. Firms in the coach industry had little specialized stock of developmental capital, and the other existing industry most likely to benefit from the development, petroleum, neither recognized

71. Jewkes et al, The Sources of Invention.

its importance (their major product was kerosene not gasoline), nor had any inventory of skills that were particularly relevant. Moreover, the technical problems laregly involved only the assembly of already existing components. Under these conditions, it is likely that existing firms had few cost advantages, and new firms may have represented the institutional technology of choice.[72] These historical vignettes are interesting, but hardly conclusive. They do, however, suggest yet another avenue for potentially productive research.

Market uncertainty is certainly a barrier to new product innovation, but the evidence suggests that the level of profitability is also important. Wartime guarantees induced a spate of product innovation, but the guaranteed markets for pharmaceuticals that resulted from the innovation of the National Health scheme in Britain reduced the amount of new product innovation.[73] In the latter case, market guarantees were coupled with a change in market structure that replaced patent protected monopolies with a bilateral monopoly marked by a great deal of bargaining power on the other side of the table. In this regard it might be particularly interesting to compare DuPont's decision to enter the polymer market with its decision to move more heavily into smokeless powder.[74] Similar comparison could be made of, for example, Westinghouse and General Electric's decision to enter the radio industry with their wartime experience in radar and sonar, or IBM's wartime with its peacetime experience. These studies could provide the basis for comparison of the reaction of private firms to various governmental market guarantees.

72. If creativity declines with age it is not surprising that it was the Ford Motor Company that first conceived of the $750 car and the assembly line. Nor should it be surprising that thirty years later Ford continued to produce only black autos.

73. Michael H. Cooper, Prices and Profits in the Pharmaceutical Industry (Oxford: Pergamon Press, 1966).

74. Although their study does not address this question directly, Chandler and Salsbury's work on the DuPont Corporation does provide sufficient material to make an analysis of this type of decision possible. See Alfred D. Chandler, Jr. and Stephen Salsbury Pierre S. DuPont and the Making of the Modern Corporation (New York: Harper & Row, 1971).

4. On Alternative Organizational Structures: In the Calculus of Consent, Buchanan and Tullock categorize organizations as individual, voluntary cooperative, and governmental. In this section our focus is on the latter two classes. The "Heroic Age of Invention" has largely passed, and from the point of view of policy most of the most interesting examples of institutional structures are from one of the "super individual" classes. These examples provide some insight into the research productivity of various institutional structures and suggest some areas for further research.

i. Cooperative Research Ventures: In the late 1920s an attempt was made to enlist the support of private firms for a voluntary cooperative venture in basic research. The nascent institution was given the august title, "The National Endowment for Science," and was launched with vocal support from both the business and political communities. The attempt was almost a total failure. The free rider problem proved insuperable. While almost every major corporation affirmed the goals of the institution, very few were willing to match their words with dollars, and the enterprise passed out of existence with the Depression.[74a] In Great Britain a part of research in the steel industry is organized on a cooperative basis.[75] This venture has been more successful than the NES, although contributions are voluntary. The work is jointly supported by government and the private sector, and the tied benefits derived from the government's contribution are apparently sufficient to induce provate firms to contribute. The structure provides tied benefits similar to the free insurance that has proven so necessary in holding together other

75. (About fourteen percent in 1963.) See, J. A. Allen, Studies in Innovation in the Steel and Chemical Industries (New York: Augustus M. Kelley, 1968), pp. 176-177.

74a. See Lance Davis and Daniel Kevles, "The National Research Fund: A Case Study in the Industrial Support of Academic Science," Minerva, forthcoming.

voluntary cooperative groups (for example, nineteenth century trade unions and the American Medical Association). In Germany, cooperative research in steel has been even more successful; however, in that country the organization has the power to tax its members.[76] A survey of these three structures suggests that, in the absence of some coercive power, the free rider problem makes cooperative ventures economically unfeasible unless the research is so specialized that the gains to a single (or small set of) firm(s) is sufficient to pay all the costs. Even if the legal problems were solved and cooperative ventures granted coercive powers over their members, the structure would likely prove useful only in industries characterized by few firms and substantial barriers to entry.

ii. Government Guarantees of the Demand for Final Output: Radar and penicillin provide impressive examples of the speed at which technical advance can take place when the profitability of the advance is guaranteed. But technical advance in the engineering sense cannot be the goal of any reasonable policy. In the wartime case, the government as the consumer of final or intermediate products had some notion of the productivity of the advances in question, although the history of American planes, tanks, and torpedos suggests that, even in those instances, the productivity signals were not very good. It is less clear that there exists a structure to provide a set of signals about the differential productivity of technical progress in areas where the government is not a market participant: It is not clear, for example, that the signals produced by the parity price program in agriculture led to an optimal mix of research and development expenditures. Research on this question might involve a more

76. The Verein Deutsher Eisenhutteleute. See Allen, Studies in Innovation.

careful study of the wide range of historical experience, perhaps the development of anti-smog devices or even of railroad land grants in the nineteenth century.

iii. Socialization of the Research and Development Function: The history of the Department of Agriculture suggests that socialized research has, in that area at least, been productive. Even in that instance, however, we have no clear measure of the meaning of "productive," since we know little about what might have been achieved if the same resources had been deployed in a different manner. In a similar vein, a cursory reading of wartime and postwar experience might be used to support the view that government sponsored research has also been "highly productive." Government funded research laboratories both here and in Britain produced a wide variety of new products during the war, and in the past decade and a half NASA has managed to land a man on the moon and send a rocket to Mars. In few of these cases, however, has there been any attempt to match costs against revenues, and in some instances the evidence suggests that the net productivity may have been zero even if the costs had been at that level as well. Operation Habakkuk (the two-mile long Pykecrete ship) seems to fall into the latter category. On the other hand, many of the new products did help shorten the war, and the heavily funded British and American research operations seem to have been more productive than those in Germany where the commitment to socialized research was less. The question of productivity signals leads to the question of the research departments' decision criteria. When research is socialized, the usual division is after all a political unit, and it is likely to respond to its constituents. As we have seen in the case of the Department of Agriculture, the goals of that constituency are not necessarily the goals of society. In particular, the political links appear to produce a research bias towards process as opposed to product development. The constituents

prefer research that bestows extra profits on their capital stock and oppose development that makes that stock obsolete. In addition, they are interested in maximizing their income, not in supporting developments whose benefits might accrue to someone else. Finally, to the extent that the constituents' discount rate is above society's, there is a natural tendency to favor change that is more immediately profitable (in the case of research, frequently process rather than product development). In the case of the agricultural sector, at least, the farmers' behavior suggests a very high rate of discount.

Given the ambiguity of the evidence, more clarity might be provided if some future research were to focus not on military R&D (where the problems of providing adequate productivity measurement must be close to insuperable), but on the histories of the Department of Agriculture, the National Science Foundation, and the National Institute of Health.

iv. Research Produced as a Joint Product: A significant quantity of research has been produced as a by-product of government expenditures. Although the wartime experiences come immediately to mind, the process antedates even the first World War. In the early nineteenth century, many of the civil engineering developments that underwrote the construction of the railroad network were subsidized by the government in its efforts to train military engineers,[77] and half a century later it was the Bureau of the Census that helped pay for the development of the earliest precurser of the modern computer. Moreover, the political rhetoric over private appropriability has been substantial. Putting aside questions of welfare, we know very little about the mechanism of "by-product research" nor has there even been a systematic census of the improvements that have been financed in this fashion. The structure is inherently an interesting one, since some signals of the productivity of the primary

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77. Daniel Calhoun, American Civil Engineer: Origins and Conflict (Cambridge, Mass.: Harvard University Press, 1960).

activity at least are available, and it appears fruitful as an object for further research. It seems useful to attempt to explain technological spinoffs by relating those spinoffs to some policy variable (e.g., to the method of financing research, to the structure of the industries involved, or the system of letting the original contracts) in some systematic fashion. In short, is it possible to explain why twenty years of expenditure on space research, largely of the high technology variety, has produced only Corningware?

Economic historians have been concerned with technical change, but their work is subject to the same weaknesses, criticisms and lack of operationality that is characteristic of the work of other economists working on the same problem. The body of literature they have produced, however, provides an important data source for studies attempting to link institutional development to technical change. The focus has, however, been on process changes, and new product innovation has not received the attention it deserves. In fact, the Schumpeter-Kuznets debate over the relative importance of product and process innovation has still to be resolved. Furthermore, while the work of Ames and Enos has suggested, for at least a subset of these questions, that these questions might be better answered with engineering data rather than patents, work along these lines has hardly begun.

Despite these caveats, it appears that, if understanding the relationship between institutions and technology is the goal, economic history provides a fruitful area for further research. The costs of organizing the existing work which bring to bear on the primary question should be both inexpensive and productive. Extensions into periods and industries not already covered would be more costly, but given the focus provided by recent theory and the ability to narrow that focus to those areas not otherwise covered, that project is probably economically viable as well. In short, the structure provided by

economic historians appears to provide a heretofore largely ignored but potentially productive technology for further research into the institutional aspects of the process of technical change.

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