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The Origins of the Basic Inventions Underlying Du Pont's Major Product and Process Innovations, 1920 to 1950

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E. I. du Pont de Nemours & Company is often cited as the leading and most successful practitioner of basic and applied research. In truth, its success as an innovator has made it a symbol of the deterministic doctrine which makes firm bigness a prerequisite to inventive capacity and success.

Its officials characterize Du Pont both as a firm grown big because of inventive superiority, and as an example of inventive superiority made possible by firm bigness. Du Pont President Crawford H. Greenewalt pointed this out when he said, "For the Du Pont Company and I believe this is also true for the chemical industry, I can say categorically that our present size and success have come about through the new products and new processes that have been developed in our laboratories."[1] Greenewalt further contended that Du Pont's record of laboratory accomplishment is itself based on Du Pont's size. As he puts it, the tasks confronting the firm a hundred years ago "were not very big, and a relatively small pool of talents and abilities could accomplish them. Today the tasks are correspondingly larger, and they require a larger pool of talent to accomplish them."[2]

Du Pont, of course, has been an innovator in many fields. But what were the sources of the basic inventions underlying its *most important* product and process innovations? Were these innovations rooted, as President Greenewalt contends, on "the new products and processes that have been developed in [its] laboratories?" It is the purpose of this paper to attempt to answer this question. Perhaps doing so will provide some additional empirical content for our scantily filled economic boxes labeled, "sources of inventive activity."

To answer this question for Du Pont, I shall restrict my analysis to the company's experience during the period 1920–50. For nearly all of its more than 100 years of growth before 1920 Du Pont was a manufacturer soley of explosives and related products. But shortly

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[1] *Study of Monopoly Power*, Hearings before the Subcommittee of the House Committee on the Judiciary, 81st Cong., 1st sess., p. 546.

[2] *Ibid.*, p. 59.

after the turn of the century it began diversifying into various fields not directly related to explosives; and by 1920 it had taken great strides toward becoming a diversified chemical firm.[3]

The definition of what constitutes important inventive activity at first sight seems beyond workable construction. It is impossible to state categorically where unimportant inventions end and important ones begin. All scientific inquiry and progress involve a continuing accretion of knowledge, with each piece of knowledge seemingly inseparably related to prior accumulations of knowledge.

But in reality we generally can identify inventions as being distinct from mere additional accumulations of scientific knowledge, because they result in something of unique economic importance. Thus, my definition of an important invention is based on its economic result. If a product or process resulting from a unique organization of scientific knowledge has been of significant economic importance to Du Pont's growth, I have considered it as being based on an important invention. I shall further avoid problems of defining what constitutes a really important Du Pont product or process by limiting the analysis to products and processes that have been of obvious economic significance.

It should be noted that this paper is concerned mainly with the inventions underlying *new* products and production processes, and *major* changes in existing products and processes. I recognize that the cumulative effects of many small changes in existing products and processes may have an important aggregate effect on product quality and production costs. The reason for placing special emphasis on the social and economic processes generating *new* products and processes is that they involve a basic breakthrough in scientific knowledge—often based on fundamental research—upon which subsequent product and process improvements are based. The justification for investigating the sources of technology underlying *new* products is that different economic and social forces may be responsible for generating the inventions underlying new products than for bringing about product improvements.

Table 1 lists twenty-five of Du Pont's most important product and process innovations from 1920 to 1950, and is based largely upon a similar list appearing in the October 1950 issue of *Fortune*.[4] All the

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[3] For a discussion of its growth before 1920 and the sources of the technology underlying that growth see Willard F. Mueller, "Du Pont: A Study in Firm Growth" (unpublished Ph.D. dissertation, Vanderbilt University, 1955).

[4] *Fortune*'s list included forty-eight products and processes illustrating Du Pont's

TABLE 1

Du Pont's Twenty-five Most Important Product and Process Innovations between 1920 and 1950, Rated From 1 to 5 on the Basis of Their Relative Commercial and Technological Importance

Year Introduced	Product and Process Innovations	Relative Importance (5 Denotes Greatest Importance)
1920	Viscose rayon	4[a]
1923	Duco lacquers	3
1923	Tetraethyl lead (bromide process)	3[a]
1924	Tetraethyl lead (chloride process)	2[a]
1924	Cellophane	4[a]
1926	Synthetic ammonia	1
1927	Moistureproof cellophane	3
1927	Methanol and higher alcohols	1
1928	Dulux finishes	2
1929	Acetate rayon	3[a]
1931	Freon	2
1931	Neoprene	2
1931	Titanium pigments	2[a]
1934	Cordura high-tenacity rayon	2
1936	Lucite acylic resin	1
1939	Nylon	5
1940	Polyvinyl acetate and alcohols	1
1941	Rutile titanium dioxide	1
1942	Fermate fungicides	1
1943	Teflon	1
1944	Alathon polyethylene plastic	1
1948	Orlon acylic fiber	3
1948	Titanium metal	3[a]
1949	Polymeric color film	1
1949	Fiber V (Dacron)	3[a]

Source: Based on "The Story of the Greatest Chemical Aggregation in the World: Du Pont," *Fortune*, October 1950, p. 114, except for viscose rayon, tetraethyl lead (chloride process), plain cellophane, acetate rayon, and titanium pigments which were added by the author.

[a] This is the author's estimate of the relative importance of these products and processes. In all other cases the relative importance is that given each product by *Fortune.*

"research and development record for three decades: 1920–49" ("The Story of the Greatest Chemical Aggregation in the World: Du Pont," *Fortune*, October 1950, p. 114). It rated each of these products and processes "with rough approximation" from one to six "on the basis of commercial importance and technical significance." Since little information is available on the items it ranked as least important (one), and since the significance of these items is debatable, the products and processes listed in Table 1 include only those ranked by *Fortune* as of two or above in importance. I have deleted one item, "improved X-ray film," included in *Fortune*'s "two" category, because no information about it is available and because according to Dr. James K. Hunt of Du Pont, "This product did not belong in quite the same category as the other items." (letter from technical advisor of Public Relations Department, Wilmington, Delaware, August 5, 1954). I have added five products not included in *Fortune*'s list: Viscose rayon, acetate rayon, and titanium pigments, because they are obviously more important than many of products and processes listed have contributed significantly to Du Pont's growth (in every case Du Pont was the first or one of the first American concerns manufacturing the product), and most are likely to continue to do so for some time. In 1948 these products and their closely related derivatives made up about 45 per cent of Du Pont's total sales. The circumstances surrounding the acquisition or development of these products and processes and their importance to Du Pont's growth are set forth below.

Product and Process Innovations

VISCOSE RAYON, 1920. Du Pont first became interested in rayon during its World War I diversification program. It conducted research to develop a nitrocellulose process for making artificial silk (later called rayon) but failed.[5] It also negotiated to purchase the highly profitable American Viscose Company, the country's sole viscose rayon producer, but it considered the price asked excessive.[6] Failing to develop its own rayon process and to buy the only rayon concern operating in America, Du Pont turned to Europe. In 1919 it executed an agreement with the Comptoir des Textiles Artificiels whereby the Comptoir gave exclusive rights to its viscose rayon technology to the newly created Du Pont Fibersilk Company. This company was owned jointly by Du Pont (60 per cent) and the Comptoir (40 per cent).[7] Only one other American concern (American Viscose) was in the field at the time Du Pont received access to patents protecting that valuable new product.

Viscose rayon has been one of Du Pont's major products ever since 1920. As late as 1948 rayon sales amounted to $102 million or about 10 per cent of total Du Pont sales.[8]

DUCO LACQUERS, 1923. According to Irénée du Pont, Du Pont accidentally discovered Duco Lacquer in 1920 while conducting research on photographic films. As he described it, on July 4, 1920, the power house was shut down shortly after a barrel of nitrocellulose

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the products included in *Fortune*'s list; tetraethyl lead using the ethyl chloride process, because Du Pont probably would have been forced out of tetraethyl lead production had it not obtained access to this process; and plain cellophane as well as moistureproof cellophane, because without the first the second would have been impossible.

[5] *U.S.* v. *E. I. du Pont de Nemours & Company*, 118 Fed. Supp. 48 (1953), Testimony, p. 5343 ff. Hereafter this case is referred to as the Cellophane Case.

[6] *U.S.* v. *E. I. du Pont de Nemours & Company*, 126 Fed. Supp. 235 (1954), GX 1244. Hereafter this case is referred to as the Du Pont-G.M. Case.

[7] Cellophane Case, Tr. 5343.

[8] Cellophane Case, GX 577, p. 7323.

solution had been prepared in connection with research on photographic films. The shut-down prevented experimentation with the solution for forty-eight hours. When the experimenters resumed their work, "to their amazement the contents of the drum had become so limpid and so fluid that you couldn't cast it on a wheel."[9] This suggested to them that they might "put some pigments into [it] and make lacquers with very heavy pigment carrying power . . . and they found it would work, and that was 'Duco'."[10] The nitrocellulose lacquer was a great improvement over existing nitrocellulose finishes.[11] It was of special commercial significance because it reduced the time required to finish a car from days to hours.[12] Although accurate estimates of Du Pont's Duco sales are not available from published sources, such sales have doubtless run into millions of dollars annually since the mid-twenties.

TETRAETHYL LEAD (BROMIDE PROCESS), 1923. Thomas Midgeley, Jr. of General Motors discovered the ethyl bromide process for making tetraethyl lead.[13] Du Pont and General Motors made an agreement on October 6, 1922, whereby Du Pont was to build a tetraethyl lead plant with a daily capacity of 1,300 pounds. The agreement set the initial price of the chemical made by Du Pont at $2.00 a pound, which the parties felt was adequate to enable Du Pont to amortize the cost of its plant in one year. A Du Pont report on the "Origins and Early History of Tetraethyl Lead Business" stated that "the intent was plainly . . . to be that the contract should be 'a continuing one,' the Du Pont Company undertaking to produce exclusively for General Motors, and General Motors agreeing to take its full requirements from the Du Pont Company, except in the event of the latter's inability or unwillingness to produce the entire quantities required."[14] The first Du Pont tetraethyl lead was sold in February 1923, and by the middle of the year the product had gained public acceptance.[15]

TETRAETHYL LEAD (ETHYL CHLORIDE PROCESS), 1924. Du Pont had just succeeded in getting tetraethyl lead production under way when Standard Oil of New Jersey discovered a superior manufacturing process—the ethyl chloride process. President Irénée du Pont, recognizing

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[9] Du Pont-G.M. Case, Tr. 2131.

[10] *Ibid.*

[11] Letter from James K. Hunt, dated July 30, 1954.

[12] "The Story of 'Duco' Nitrocellulose Lacquer," E. I. du Pont de Nemours & Company (mimeographed), p. 3.

[13] Du Pont-G.M. Case, Tr. 3525.

[14] Du Pont-G.M. Case, GX 773, p. 8.

[15] *Ibid.*

the superiority of Standard's process, wrote to Alfred Sloan of G.M. in June 1924 that "the ethyl chloride method will be found cheaper both as to construction cost and operating cost than the ethyl bromide method."[16] Had Standard manufactured and sold its own tetraethyl lead, Du Pont would have been in an inferior competitive position. Fortunately for Du Pont, however, it was able to make an agreement with Standard which gave it the right to the new process.[17] Between 1926 and 1948 Du Pont manufactured all of the country's tetraethyl lead. Its importance to Du Pont in recent years is indicated by its 1948 sales of tetraethyl lead which amounted to $30 million or about 3 per cent of total Du Pont sales.[18]

CELLOPHANE, 1924. Du Pont's association in rayon with the Comptoir des Textiles Artificiels was directly responsible for Du Pont's entrance into cellophane. During Du Pont's negotiations with the Comptoir on viscose rayon in 1919, a Comptoir official also introduced the company to a "transparent viscose film, known as cellophane." Cellophane was being manufactured by one of the Comptoir's associated companies, La Cellophane Société Anonyme.[19] La Cellophane had made cellophane since 1917, utilizing a process developed by Jacques E. Brandenberger, who in 1912 had begun producing a thin flexible cellulose film of the general type still manufactured today.[20] On January 6, 1923, Du Pont received an option from La Cellophane to acquire its rights to manufacture cellophane in North and Central America.[21] Cellophane has been one of Du Pont's most spectacular and profitable products.[22] By 1948 Du Pont's sales of it had grown to $74 million, or about 7.4 per cent of its total sales.

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[16] *Ibid.*, GX 660.

[17] *Ibid.*, GX 675.

[18] *Ibid.*, GX 837.

[19] Cellophane Case, GX 1, p. 4.

[20] Although the origins of cellophane chemistry date back to 1846, it was not until 1892 that two English chemists, G. F. Cross and E. J. Bevan, developed the viscose method of reducing cellulose to a solution. By using an acid, they regenerated the cellulose solution into films of pure cellulose. Not until 1908, however, did Brandenberger make sufficient improvements in that process to make it commercially significant. He began producing his transparent viscose film, which he called cellophane, shortly after (*ibid.*, GX 28, p. 142).

[21] *Ibid.*, GX 392, p. 5429. The option provided that, in the event Du Pont became interested in entering cellophane manufacture, a jointly owned subsidiary should be formed with Du Pont owning 52 per cent and La Cellophane 48 per cent of its common stock.

[22] For a discussion of Du Pont's earnings in cellophane see, George W. Stocking and Willard F. Mueller, "The Cellophane Case and the New Competition," *American Economic Review*, March 1955, pp. 29–63.

SYNTHETIC AMMONIA, 1926. Du Pont got its first technical information in this field in 1916 when it acquired the American rights to the Birkeland-Eyde arc process of fixing nitrogen which had been discovered in Norway. Du Pont never used that process and took no further steps toward entering the industry until 1924. In that year it acquired the American rights to the Claude process from the Société Anonyme l'Aire Liquide of France, for $2.8 million. Using the process it built its first plant at Belle, West Virginia, in 1925. At about the same time it also acquired four American ammonia concerns—three distributors and one manufacturer. Although Du Pont expanded its position in the market through these acquisitions, its technology remained inferior to that of some of its rivals—notably Allied Chemical and Dye Corporation. After having tried and failed to get the German technology on synthetic ammonia, it obtained the American rights to the important Casale process by purchasing the Niagara Ammonia Company in 1927. That process was superior to the Claude process and Du Pont constructed an entirely new plant to exploit it. Beginning in 1929, Du Pont further buttressed its technical position in synthetic ammonia by a patents and processes agreement with Imperial Chemical Industries, Ltd., England's leading chemical firm. With technology from these various sources Du Pont developed a modified Claude-Casale process subsequently known as the Du Pont process.[23] No breakdown is available of the amount spent by Du Pont in developing its modified process and for plant investment.

MOISTUREPROOF CELLOPHANE, 1927. Shortly after beginning production in 1924, Du Pont recognized as cellophane's greatest defect its imperfect resistance to moisture.[24] In October 1924 Du Pont made its initial appropriation authorizing research aimed at developing a moistureproof process, providing for hiring one researcher and the expenditure of between $5,000 and $10,000.[25] By 1927 Du Pont had found a satisfactory moistureproofing process and began commercial production. In 1929 it received its basic patents covering that development. The importance of the process is indicated by the fact that in recent years the bulk of Du Ponts' cellophane sales (80 per cent in 1948) have been of the moistureproof variety.

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[23] In 1948 sales of Du Pont's ammonia department amounted to $88 million (Du Pont-G.M. Case, DP 445). These sales included some products other than synthetic ammonia products, and no breakdown is possible. However, it seems quite likely that synthetic ammonia products constituted the greater part of these sales.

[24] Cellophane Case, DX 388.

[25] *Ibid.*, DX 393-94.

Uncertain that its initial moistureproof patents could be enforced against potential entrants into the cellophane field, Du Pont took steps to strengthen its moistureproof patent position. By 1930 it had patented "various modifications of moistureproof cellophane." A Du Pont employee explained that the patents were taken out "not only to strengthen the company's patent position, but also in an endeavour to prevent competition by a similar article."[26]

Between 1930 and 1934 Du Pont took additional steps to bolster its patent position when it authorized a research project for this specific purpose. In 1934 President Yerkes of Du Pont Cellophane reported on the success of this project.

> This work was undertaken as a defensive program in connection with protecting broadly by patents the field of moistureproofing agents other than waxes which were the only class of material disclosed in our original cellophane patents. The investigation on this subject did in fact lead to the discovery of a number of classes of materials which could serve equally well for moistureproofing agents, whether in lacquers or in other vehicles. Each of these classes has been made the subject of a patent . . . altogether 13 patent applications are being written as a result of the work done under this project, all in view of strengthening our Moistureproof Cellophane patent situation.[27]

The $19,503 spent on that research project was very likely more than was spent for the total research involved in developing the initial methods of moistureproofing cellophane used by Du Pont. As noted above, the first authorization for the earlier research was made in October 1924 with an appropriation between $5,000 and $10,000. That total expenditures for developing the initial process were not great is indicated by the fact that total "technical activities expenses," which included all types of technical work designed to improve production and process, came to only $32,048 during 1925 and 1926.[28]

Although Du Pont did not incur any of the expenses involved in the basic research leading to the invention of cellophane, and only modest expenses in developing its moistureproof process, it did spend large amounts in subsequent years for "research" aimed at cutting

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[26] Letter from the general manager of the Cellophane Department to W. S. Carpenter, Jr., Chairman of the Board of Du Pont Cellophane, August 26, 1938 (*ibid.*, GX 2469, p. 3161).

[27] *Ibid.*, GX 488, p. 6478.

[28] *Ibid.*, DX 387.

manufacturing costs and improving quality. The company estimates that between 1924 and 1950 it spent $24,361,065 on cellophane research and technical development.[29] Of this sum, almost 99 per cent was spent after 1929 and 75 per cent after 1939. Although no breakdown is given of how all that money was spent, in 1935 about 26 per cent of the cellophane research budget of $588,372 was spent on chemical control, 66 per cent on product and process improvements, and 7 per cent on the development of additions to established lines of products. None of that cellophane budget went for fundamental research.[30]

METHANOL AND HIGHER ALCOHOLS, 1927. Methanol was first synthesized by the great French chemist Sabatier in 1905. After the Germans developed synthetic ammonia shortly before World War I, another French scientist concluded that the principles employed in ammonia synthesis might be applied to synthesize methanol as well. His speculations proved correct and he was granted his first patent in 1921.[31] The Germans simultaneously developed a method for synthesizing methanol. In February 1925 the first German synthetic methanol arrived in the United States, and by May total American imports exceeded a quarter of a million gallons.[32]

Shortly after Du Pont learned of the French and German success in synthesizing methanol, it began work on a production process of its own. The close relationship between synthetic methanol and synthetic ammonia no doubt made Du Pont's know-how in the latter field helpful in developing a synthetic methanol process. After two years' concentrated work, Du Pont's efforts paid off in 1926 when it (accompanied almost simultaneously by Commercial Solvents) began producing the first American synthetic methanol.[33] When Du Pont hired Roessler and Hasslacher in 1930 it added somewhat to its methanol technology by getting access to the starch patents covering copper catalysts for the conversion of carbon dioxide and water to methanol.[34] Du Pont soon discovered that in making synthetic methanol it was possible to regulate conditions so that not only methanol

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[29] *Ibid.*, DX 387.

[30] *Ibid.*, GX 490, p. 6502. The breakdown of its 1934 cellophane research budget was about the same as in 1935 (*Ibid.*, GX 489, p. 6490).

[31] Williams Haynes, *American Chemical Industry, The Merger Era*, New York, Van Nostrand, 1948, Vol. IV, pp. 170–171.

[32] *Ibid.*, p. 172.

[33] *Ibid.*, p. 176.

[34] *Ibid.*

but also other higher alcohols could be obtained, e.g. propanol, izobutanol, active amyl alcohol, and di-isoprohyl carbinol.[35]

DULUX ENAMELS, 1928. Dulux enamels represented a substantial improvement in resin base finishes. William S. Dutton, in his biography of the Du Pont Company, reported that the basic resin essential for making Dulux was discovered by General Electric scientists.[36] Du Pont acquired the rights to General Electric's discovery and carried it into commercial production. These finishes have been used most extensively in refinishing automobiles and as original finishes for refrigerators. No estimates of the relative importance of dulux sales are available, but apparently they have contributed significantly to Du Pont's finish business for many years.

ACETATE RAYON, 1929. Acetate rayon is a fundamentally different and in many respects a superior product to viscose rayon.[37] Before 1929 the Celanese Corporation was the only American concern manufacturing it. Since Celanese was selling its acetate rayon at twice the price of viscose, profits probably were very high.[38] At any rate, Du Pont began looking about for a means of entering that industry during the mid-twenties. It again turned to France. In 1927 it acquired the manufacturing and sales rights to acetate flake from the Société Chimique Usines du Rhône, and in 1928 similar rights to the cellulose acetate yarn process were acquired from the Société Rhodiaceta. By 1948 Du Pont's total acetate rayon sales amounted to $32 million, about 3 per cent of its total sales.[39]

FREON, 1931. Thomas Midgely of General Motors, who had discovered tetraethyl lead about a decade earlier, discovered a revolutionary refrigerant in the late 1920's,[40] subsequently called Freon. Although General Motors had initially considered manufacturing the product itself,[41] Du Pont's close kinship with General Motors apparently paid off again. In August 1927, General Motors and Du Pont formed a jointly owned subsidiary, Kinetic Chemicals, Inc., in

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[35] "A Story of Progress," *Du Pont Magazine*, June 1939, p. 7.

[36] William S. Dutton, *Du Pont, One Hundred and Forty Years*, New York, Scribner, 1942, p. 300 n. *Fortune*'s study of Du Pont in 1950 also reported Dulux as not being a Du Pont original ("The Story of the Greatest Chemical Aggregation in the World: Du Pont," p. 114).

[37] Jesse W. Markham, *Competition in the Rayon Industry*, Harvard University Press, 1952, pp. 88–89.

[38] Haynes, *op. cit.*, p. 383.

[39] Du Pont-G.M. Case, GX 577, p. 7323.

[40] *Ibid.*, Tr. 3605.

[41] *Ibid.*, GX 838.

which Du Pont received a 51 per cent interest.[42] The importance of freon refrigerant is demonstrated by the fact that it has become the "almost universal refrigerant."[43] By 1944 Kinetic's sales amounted to $12 million.[44]

NEOPRENE, 1931. Neoprene, the first general purpose synthetic rubber made in this country, is another Du Pont original. Although Father Julius A. Nieuwland of Notre Dame University conducted the fundamental researches underlying neoprene,[45] he was "not even casually interested in the search for a satisfactory synthetic rubber," but in acetylene gas. The credit for applying his basic discoveries to synthetic rubber goes to Du Pont's brilliant chemist, Wallace Carothers, who also discovered nylon. Although public information is not available on Du Pont's neoprene sales, they undoubtedly have been substantial.

TITANIUM PIGMENTS, 1931. Shortly before 1920 American, Norwegian, and French researchers made the basic discoveries underlying commercial titanium compounds. But it was not until the late 1920's that titanium pigments—used chiefly in paints—became commercially important. In 1930 Du Pont recognized that titanium pigments were likely to replace lithopone to a large extent. To take immediate advantage of that new and growing field, in 1931 Du Pont acquired control of Commercial Pigments Corporation, one of the country's two producers.[46] Du Pont's subsequent growth in the field was rapid. By 1940 sales reached about $16 million.[47] No more recent sales information is available.

CORDURA HIGH-TENACITY RAYON, 1934. William H. Bradshaw, research director of the Du Pont Rayon Company, developed a stretched and twisted viscose fiber of exceptional strength.[48] Du Pont introduced

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[42] *Ibid.*, GX 850. Du Pont acquired G.M.'s interest in Kinetic in 1949 for $9.7 million (*Moody's Industrials*).

[43] Du Pont-G.M. Case, Tr. 3923.

[44] *Ibid.*, GX 886.

[45] Williams Haynes, *American Chemical Industry, Decades of New Products*, New York, Van Nostrand, 1954, vol. V, p. 390. Du Pont acquired rights to Father Nieuwland's basic patents in 1931 (Du Pont-G.M. Case, Tr. 4963).

[46] Commercial Pigments had acquired its basic titanium pigments patents and process from the Société de Produits Chimiques des Terres Rares on March 24, 1927. *U.S.* v. *E. I. du Pont de Nemours & Company*, 63 Fed. Supp. 513 (1945) (National Lead Case, GX 175, p. 974, hereafter referred to as the National Lead Case).

[47] In 1940 total American sales amounted to about $40 million. Du Pont supplied about 40 per cent of this, National Lead about 50 per cent, and American Zirconium Company and Virginia Chemical Company the remainder (National Lead Case, DP 92, pp. 4389–92).

[48] Haynes, *American Chemical Industry, Decades of New Products*, Vol. V, p. 371.

the fiber, which it called cordura yarn, for cord tire fabrics. Du Pont classifies the result of that development as an important product "improvement" rather than as a new product.[49] Du Pont rayon tire yarn sales in 1948 amounted to $40 million or about 4 per cent of its total sales.[50]

LUCITE, 1936. Du Pont received the vital technology for methyl methacrylate plastic, which it introduced as lucite,[51] from Imperial Chemical Industries, Ltd., of England. Beginning in the early 1930's, Du Pont received from I.C.I. seven methyl methacrylate patents, covering methacrylate monomers, lucite molding powder, lucite dentures, lucite molder sheets, lacquers, finishes, and adhesives and cements.[52] Du Pont paid I.C.I. only $121,680 for these vital product and process patents.[53] The importance of lucite to Du Pont is illustrated by its post-World War II sales, which amounted to between $20 million and $40 million a year.[54]

NYLON, 1939. Nylon was solely a Du Pont invention and doubtless ranks as one of the most outstanding accomplishments of modern industrial chemistry and private-industry sponsored research.

Du Pont research that ultimately led to nylon began about 1928. The year before, under the direction of C. M. A. Stine, Du Pont initiated a program of fundamental research. In accordance with the primary objective of this program, which was to discover scientific knowledge regardless of immediate commercial value, Du Pont began a number of chemical explorations. One of these projects was headed by Wallace H. Carothers, who continued work he had begun at Harvard on condensation polymers.[55]

His early work at Du Pont yielded considerable fundamental

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[49] Letter from James K. Hunt, August 3, 1954.

[50] Cellophane Case, GX 837.

[51] Lucite, which is called Plexiglas by Rohm & Haas, was used extensively during World War II in making bomber noses.

[52] *U.S.* v. *E. I. du Pont de Nemours & Company*, 100 Fed. Supp. 504 (1951), Tr. 3655 ff, hereafter referred to as the I.C.I. Case. Rohm & Haas, which had been engaged in methyl methacrylate research since the 1920's, applied for an American patent covering its discoveries in this field about the same time as I.C.I., thereby causing the Patent Office to declare an interference between these two claims. By 1935 seven interferences had been declared between Rohm & Haas and I.C.I. (representing Du Pont) claims. Rohm & Haas and I.C.I. settled these interferences on March 5, 1936 by agreeing to grant each other nonexclusive royalty free licenses under all their existing and future United States patents relating to the use, manufacture, and sale of acrylics and methacrylics. *Senate Committee on Patents*, 77th Cong., 2nd Sess., pp. 615, 685, 819–822.

[53] I.C.I. Case, DX 1532, p. 9160.

[54] *Ibid.*, Tr. 3655 ff.

[55] Testimony of Crawford Greenewalt, I.C.I. Case, Tr. 1881.

knowledge of polymerization (how and why small molecules unite to form "giant" molecules), which initially was only of "academic value."[56] Then, "quite by accident," one of his assistants made a fortunate discovery. President Greenewalt explained what happened as follows: "Well, one day one of Carothers' associates was cleaning out a reaction vessel in which he had been making one of those polymers, and he discovered in pulling a stirring rod out of the reaction vessel that he pulled out a fiber; and he discovered its unusual flexibility, strength, and the remarkable ability of these polymers to cold draw.[57] The discovery had obvious commercial implications for Du Pont, which already was in the textile business as a rayon maker. Although this particular fiber was not very strong or elastic and was softened by hot water, its discovery suggested that some related compound might possess characteristics suitable for producing commercial fibers.[58] There followed "a concentrated effort in the laboratory to synthesize a polyamide which might form the basis for a commercial textile fiber."[59] Carothers and his associates tried time and again, and at one time prospects were so dark that Carothers discontinued his investigations.[60] Fortunately, however, he resumed his search and on February 28, 1935, synthesized the superpolymer used in manufacturing the first nylon.[61]

The original nylon, polymer 66, was made in the laboratory by extruding a synthetic fiber through a spinneret improvised from a hypodermic needle. Du Pont scientists and engineers next tackled, during the following two years, "the development on a laboratory scale of the manufacturing processes for the intermediates, the polymer and nylon yarn, and the development on a semi-works scale of the chemical engineering data for the erection and operation of a large-scale plant."[62] Upon completing its semi-works plant and after pronouncing nylon commercially feasible, Du Pont announced on October 27, 1938, its intention to build a new commercial plant at Seaford, Delaware, with an annual capacity of 3 million pounds. Before the first unit of this plant began operating, late in 1939, Du

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[56] James K. Hunt, "Nylon: Development, Physical Properties, and Present Status," Wilmington, E. I. du Pont de Nemours & Company, undated, p. 1.

[57] I.C.I. Case, Tr. 1881.

[58] Hunt, "Nylon: Development, Physical Properties, and Present Status," p. 2.

[59] E. K. Bolton, "Development of Nylon," *Industrial and Engineering Chemistry*, January 1942, p. 5.

[60] Hunt, "Nylon, Development, Physical Properties, and Present Status," p. 2.

[61] Bolton, "Development of Nylon," p. 6.

[62] *Ibid.*

Pont decided to increase its capacity to 4 million pounds;[63] and before the plant was completed, its capacity was increased to 8 million pounds.[64] Early in 1940 the company announced plans to construct a second plant at Martinsville, Virginia; and in July 1948, it opened a third plant at Chattanooga, Tennessee.[65] By 1948 Du Pont's nylon sales had grown to $120 million; and Du Pont estimated its 1948 earnings before taxes at $37.9 million on an operating investment of $83.9 million.[66]

Public statements on the costs and risks of bringing nylon to the commercial stage are, at best, misleading and commonly inaccurate.[67] But a Du Pont document made public in a recent antitrust case sheds considerable light on this question. In 1938 a representative from Imperial Chemical Industries, Du Pont's leading international patents and processes partner, made two visits to Du Pont for the specific purpose of studying the discovery and development of nylon. He reported to I.C.I. that Du Pont's research expenditures in the early years of nylon research "were relatively modest, but as promising indications evolved the pace was quickened."[68] According to this source, by the time Du Pont had reached the point where it could build a pilot plant, expenditures amounted to $787,000. The pilot plant, which was completed in 1938, was designed and built at a cost of $391,000.[69] Another "development" cost cited by this source was approximately $782,000 (about the same as that spent on all pre-pilot-plant research) for sales development.[70] I.C.I.'s representative

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[63] Hunt, "Nylon: Development, Physical Properties, and Present Status," p. 4.

[64] Bolton, "Development of Nylon," p. 9.

[65] Hunt, "Nylon: Development, Physical Properties, and Present Status," p. 4.

[66] Cellophane Case, GX 577.

[67] Typical of the misrepresentations made of nylon's research costs is the following statement from *Time* ("The Age of Research," July 9, 1956, p. 75). "When Dr. Carothers found a way to simulate the long chain molecules found in natural silk, Du Pont applied his findings to the development of nylon, which reached mass production in 1939, after five years and $27 million spent on applied research."

[68] Imperial Chemical Industries memorandum from the chairman to Mr. Cushion, I.C.I. Case, GX 626, p. 2317. I believe the statements made by this individual can be accepted as an accurate account of the facts because of the close relations existing between these two concerns for about a half-century. There seems to be no reason to believe that Du Pont would have intentionally understated its research and development costs to I.C.I. After all, Du Pont wanted to impress I.C.I. with its value as a patent and process partner, and the record indicates the I.C.I. visitor was impressed. For a discussion of the close and continuing technical relations between I.C.I. and Du Pont, see Mueller, "Du Pont: A Study in Firm Growth," pp. 234–256, 318–324.

[69] These figures were originally expressed in pounds sterling. I converted them to dollars at the then current exchange rate of $4.89 per pound.

[70] *Ibid.*

concluded that "the total cost of research and development can thus be taken at [$1,960,000]."

The previously mentioned first commercial nylon plant, for which $8,600,000 was authorized for construction,[71] apparently did not represent much of a gamble or require great additional development expenditures. E. K. Bolton, Du Pont chemical director, later said of it, "Except in size, the Seaford plant was practically a duplication of the semi-works plant in all details. Each step of the process and the equipment for it had been worked out thoroughly on a pilot scale, and it was unnecessary to gamble with untried methods and equipment on a full-plant scale."[72] Moreover, the market development expenditure apparently indicated a satisfactory demand for nylon before work began on the full-scale plant. According to Bolton, "Hoisery manufacturers had evaluated the yarn and pronounced the stockings to be of commercial utility."[73]

POLYVINYL ACETATE, 1940. Polyvinyl acetate is used in manufacturing what is popularly known as safety glass. The resin formed from polyvinyl acetate is used as an interlayer in glass to prevent shattering. Du Pont received its basic patents for polyvinyl acetate from I.C.I., and has been manufacturing it since 1941.[74] Although available sources do not cite production figures, a company official claims it was one of the most important products Du Pont received as a result of its patents and processes agreements with Imperial Chemical Industries of England.[75]

RUTILE TITANIUM DIOXIDE, 1941. Because of this pigment's superior "hiding power and more concentrated capacity," it represented an important improvement over previous titanium pigments. Although hiding power had been increased consistently since titanium pigments were introduced, Du Pont's rutile titanium dioxide represented the first appreciable increase."[76] That important product improvement was the result of Du Pont's own research efforts, but almost simultaneously with its introduction by Du Pont, National Lead (Du Pont's only significant rival at the time) introduced a similar product as a result of independent research.[77] No information is available on

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[71] Haynes, *American Chemical Industry, Decades of New Products*, Vol. V, p. 36.

[72] Bolton, "Development of Nylon," p. 9.

[73] *Ibid.*

[74] I.C.I. Case, Tr. 3664.

[75] *Ibid.*

[76] "Titanium—The Common Rarity," Public Relations Department, E. I. du Pont de Nemours & Company (mimeographed), Wilmington, February 1952, p. 4.

[77] National Lead Case, DP 70, pp. 43, 52.

the research and development costs of this product or on its commercial importance.

FERMATE FUNGICIDES, 1942. Fermate, named after the first and last syllable of its chemical name, ferric dimethyl dithiocarbonate, is a fungicide and beetle repellant, for use in protecting many fruit, vegetable, and flower plants. Du Pont presumably developed the fungicide in its own laboratories,[78] but no information is available on its development costs or sales.

TEFLON, 1943. This remarkable plastic is "resistant to the attack of chemicals that would destroy gold or platinum," and "is a highly efficient electrical insulation, even at high temperatures, and particularly at the high frequencies of television and other electrical equipment."[79] *Fortune* described Teflon's discovery as a "research accident" growing out of Du Pont's systematic research efforts.[80] According to that account, Roy J. Plunkett was working with tetrafluoroethylene in the hope that it might have useful refrigerating properties. After synthesizing some tetrafluoroethylene he stored it in a cylinder for a few weeks. When he opened the cylinder he discovered that some of the compound had polymerized. Thus, "Accidently, Dr. Plunkett had turned up the most heat-resistant plastic and the most inert organic compound ever discovered."[81] No information is available about the subsequent development cost. *Fortune* expressed the view that after the discovery of its polymerization, Du Pont "had no difficulty devising a commercial process."

ALATHON POLYETHYLENE PLASTIC, 1944. Polyethylene is one of the lightest and most versatile of modern plastics. Its uses are numerous and *Fortune* referred to it as "the fastest growing plastic on the market."[82] Among its best-known uses today are ice-cube trays, food boxes, flexible refrigerator bowls, cosmetics containers, and plastic bags.[83] Imperial Chemical Industries invented and developed polyethylene shortly before World War II,[84] and disclosed the invention

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[78] News Release, Public Relations Department, E. I. du Pont de Nemours & Company, June 4, 1942.

[79] "Memorandum on 'Teflon,' Tetrafluoroethylene Resin," E. I. du Pont de Nemours & Company (mimeographed), Wilmington, June 1953, p. 2.

[80] "The Story of the Greatest Chemical Aggregation in the World: Du Pont," pp. 130–32.

[81] *Ibid.*

[82] *Ibid.*, p. 129.

[83] "Alathon Polyethylene Resin—Many Purpose Plastic, A Memorandum," E. I. du Pont de Nemours & Company (mimeographed), Wilmington, October 31, 1953. Alathon is the trade-mark name of the plastic.

[84] I.C.I. Case, GX 668, p. 2494.

to Du Pont under their patents and processes agreement. Upon learning of the great military importance of the plastic (used as an insulator in radar units), Du Pont immediately sent a mission to England to obtain the necessary technical information.[85] Soon after that, Du Pont began manufacturing polyethylene "entirely at the request of the United States Government and solely for war purposes,[86] I.C.I. having waived all claims for royalties on the plastic manufactured for war purposes.[87] After the war Du Pont received a formal license to manufacture polyethylene for commercial purposes, and up to May 31, 1950, it had paid I.C.I. royalties of $272,200 under that agreement.[88] Although Du Pont had conducted some independent work along similar lines, President Greenewalt pointed out that it could not have manufactured polyethylene without obtaining a license from I.C.I.[89] In 1948 Du Pont's polyethylene sales amounted to $1.3 million.[90]

ORLON ACRYLIC FIBER, 1948. Orlon is the second important discovery resulting from Du Pont's basic research in synthetic fibers. This fiber has outstanding resistance to sunlight, is quick drying, holds its shape, and is more resistant to outdoor exposure than any other preceding fiber.[91] Du Pont initiated its orlon research in 1941 when its rayon pioneering research section decided that acrylonitrile might polymerize into a good yarn.[92] These expectations proved well founded, and before the war ended it had turned out in a pilot plant some of the new fiber for limited use in the war effort. By 1947, after orlon's development had reached a point where full-scale production seemed warranted, Du Pont drew up plans for its first plant, costing about $17 million, located at Camden, South Carolina and with an estimated annual capacity of about 7 million pounds.[93] Even before operations began in October 1950, Du Pont completed plans to build a second plant (across the street from the first), costing about $25 million and with an estimated capacity of about 30 million pounds.[94]

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[85] *Ibid.*, DX 1193 and DX 1194.

[86] *Ibid.*, DX 673, p. 2545 and DX 1249, p. 8100.

[87] *Ibid.*, DX 1197, p. 675.

[88] *Ibid.*, DX 2219.

[89] *Ibid.*, Tr. 1871.

[90] I.C.I. Case, Tr. 1580, DX 1205, pp. 7887–92.

[91] "Facts About 'Orlon' Acrylic Fiber and the May Plant, Camden, S.C.," E. I. du Pont de Nemours & Company (mimeographed), Wilmington, undated, p. 1.

[92] "The Story of the Greatest Chemical Aggregation in the World: Du Pont," p. 112.

[93] *Ibid.*, p. 106.

[94] *Ibid.*

No detailed breakdown of the research and development costs of orlon are available. President Greenewalt mentioned $25 million as the total cost of research, development, and initial investment. That included $5 million for bringing orlon from the research stage through the pilot-plant and market-development stages, and $20 million for the initial plant investment.[95] Another Du Pont source stated that "Du Pont has invested more than eight years of intensive research and development work, and an estimated $22,000,000 in 'Orlon'."[96]

TITANIUM METAL, 1948. The discovery and introduction of titanium metal may well rank with that of aluminum. This remarkable metal is almost as strong as steel although weighing 40 per cent less.

In 1943 the United States Bureau of Mines obtained access to a German-owned titanium metal process seized by the Alien Property Custodian. A little later the originator of that process, Wilhelm Kroll, who had fled the Nazis in 1940, joined the Bureau of Mines where he continued his work. Under Kroll's direction the process was improved and by 1946 the Bureau of Mines had a titanium metal pilot plant in operation.[97] After the Bureau of Mines published its report, "Metallic Titanium and Its Alloys" in 1946, a number of American manufacturers manifested immediate interest. Du Pont and National Lead, now the country's two dominant titanium dioxide manufacturing concerns, began working on commercial processes immediately. By September 1948, Du Pont announced that it had a pilot plant in operation.[98] By 1950, its capacity had grown to 55 tons and it accounted for the bulk of the country's production of 75 tons in that year.[99] In 1951, Du Pont completed its first semicommercial plant, thereby pushing production to 700 tons during 1952.[100]

Mr. E. A. Gee of Du Pont's Pigment Department testified that the company had spent more than $4 million on titanium research up to November 1953, and that at the time it was continuing its research at a cost of about $1 million a year.[101] Du Pont's total investment for

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[95] Crawford H. Greenewalt, "A New Industry Comes to Town," Speech at the Opening of the May Plant at Camden, South Carolina, October 6, 1950, E. I. du Pont de Nemours & Company, p. 7.

[96] "Facts About 'Orlon'," p. 1.

[97] "Titanium: The New Metal," *Fortune*, May 1949, 124.

[98] *Ibid.*, p. 124.

[99] *Ibid.* Also, "Memo on Titanium." Public Relations Department, E. I. du Pont de Nemours & Company (mimeographed), p. 1.

[100] *Ibid.*

[101] Testimony before the Special Subcommittee on Minerals, Materials, and Fuel Economies, of the Committee on Interior and Insular Affairs of the U.S. Senate, November 23, 1953. Excerpts of testimony furnished the author by Du Pont.

research and initial production reportedly approximated $9 million as of that time. [102]

POLYMERIC COLOR FILM, 1949. Du Pont's polymeric film developed to compete with others used in the important colored motion picture film field, substitutes a synthetic polymer for a gelatin emulsion used in all other color films except Technicolor. The process, instead of dyeing the film, builds the color directly into the polymer.[103] This product is another first for Du Pont growing out of its pioneer work in polymers begun in 1928 by Carothers. However, although polymeric color film was included in *Fortune*'s list of important product discoveries, Du Pont still had not begun commercial production of it as of August 3, 1954.[104]

DACRON POLYESTER FIBER, 1949. Dacron fiber (first called Fiber V by Du Pont) possesses many qualities superior to those of any other fiber; for example, it is wrinkle resistant, even when wet, and has high resistance to stretch.[105] Du Pont introduced this new synthetic fiber commercially in the American market in the spring of 1953. Much of the basic chemistry underlying dacron goes back to Carothers' work on high polymers. Whereas Carothers first experimented with polyesters in his efforts to build giant molecules, he soon concluded that polyamides offered greater promise.[106] As noted above, his work in polyamides led to the discovery of nylon.

But while Du Pont concentrated on polyamides, English scientists made further investigations of polyesters. About 1940 Calico Printers' Association, Ltd., began research on polyesters in an effort to develop a synthetic fiber.[107] By 1941 they had prepared laboratory-scale quantities of polyethylene terephthalate polymer, called terylene, which could be used in making fibers, but World War II delayed further work on it.[108] Imperial Chemical Industries acquired Calico in 1947 and began pilot-plant production during 1948.[109]

When Du Pont learned about the new fiber from I.C.I. it "negotiated for the purchase of patent rights then owned by Calico Printers'

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[102] *Ibid.*

[103] "The Story of the Greatest Chemical Aggregation in the World: Du Pont," pp. 130–31.

[104] Letter from James K. Hunt, August 3, 1954.

[105] "The Du Pont Company and Its Products," E. I. du Pont de Nemours & Company (mimeographed), Wilmington, May 1953, p. 11.

[106] "Dacron Polyester Fiber," E. I. du Pont de Nemours & Company (mimeographed), Wilmington, August 27, 1953, p. 2.

[107] *Ibid.*

[108] *Ibid.*

[109] *Ibid.*

Association, Ltd."[110] Du Pont subsequently received eight different basic patents relating to dacron from I.C.I. under their patents and processes agreement,[111] and proceeded to develop the processes necessary for its production.[112]

Dacron has proven of even greater commercial importance than orlon. Du Pont reports its total research, development, and initial plant investment in dacron at about $65 million.[113] Of this amount, it reports that it spent between $6 and $7 million before it was able to begin building its first commercial plant.[114] This presumably includes expenditures for original research, development, and pilot plant.[115]

Summary and Conclusions

Of the twenty-five important product and process innovations discussed above (which together constituted about 45 per cent of Du Pont's total sales in 1948),[116] ten were based on the inventions of Du Pont scientists and engineers. If we break down these twenty-five innovations into new products and product and process improvements,[117] we find that of the eighteen new products, Du Pont discovered five and shared in the discovery of one other (see Table 2). Of the seven most important product and process improvements, Du Pont was responsible for five.

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[110] Mr. L. L. Larson, Textile Fibers Department, Du Pont Company. Talk before the American Association of Textile Technologists, New York City, May 2, 1951. Reprinted by Public Relations Department, E. I. du Pont de Nemours & Company (mimeographed).

[111] I.C.I. Case, DX 1549, p. 2999, DX 1543. Another Du Pont source states that Du Pont acquired the rights to dacron in 1946 ("The Du Pont Company and Its Products," p. 12).

[112] Emmette F. Izard, research associate of Du Pont's Film Department Research Laboratory, received the Jacob F. Schoellkopf medal for, among other things, his "contributions to the development of a process for the production of polyester fiber and film" ("News Release," Public Relations Department, E. I. du Pont de Nemours & Company, April 14, 1953).

[113] Andrew E. Buchanan, "The Outlook in Fiber Competition," Speech before the Denver Agricultural Club, May 25, 1953. Reprint by E. I. du Pont de Nemours & Company, p. 7.

[114] *Ibid.*

[115] If Du Pont followed the same means of estimating these costs as it did in the case of nylon (see above), they may also include initial sales promotion.

[116] Since Du Pont had not begun commercial production of "Dacron," "Orlon," and titanium metal in 1948, this may understate the present importance of the products and processes appearing in Table 1.

[117] This breakdown does not imply that the discovery of new products is necessarily more important than the discovery of major improvements in existing products or processes. Moreover, in some cases it is difficult to decide arbitrarily whether a particular discovery is a new product or an improvement in an existing one. Few products are ever completely new. The classification appearing in Table 2 is the author's.

TABLE 2

SUMMARY OF NEW PRODUCTS, AND PRODUCT AND PROCESS IMPROVEMENTS, INTRODUCED BY DU PONT, BY SOURCE OF BASIC INVENTION, 1920 TO 1949

New Products	Original Source of Basic Invention	Product and Process Improvements	Original Source of Basic Invention
Viscose rayon	Other	Duco lacquers	Du Pont
Tetraethyl lead (bromide process)	Other	Tetraethyl lead (chloride process)	Other
Cellophane	Other	Moistureproof cellophane	Du Pont
Synthetic ammonia	Other	Dulux finishes	Other
Synthetic methanel	Other and Du Pont[a]	Cordura high tenacity rayon	Du Pont
Acetate rayon	Other	Rutile titanium dioxide	Du Pont
Freon refrigerants	Other	Fermate fungicides	Du Pont
Neoprene	Du Pont		
Titanium pigments	Other		
Lucite	Other		
Nylon	Du Pont		
Polyvinyl acetate	Other		
Teflon	Du Pont		
Alathon polyethylene	Other		
Orlon	Du Pont		
Titanium metal	Other		
Polymeric color film	Du Pont		
Fiber V (Dacron)	Other		

SOURCE: These products and processes are classified on basis of discussion appearing in the text.

[a] Du Pont shared this discovery with others.

Of Du Pont's five new product discoveries, only neoprene, nylon, and orlon have achieved substantial commercial significance to date. On the other hand, most of the new products developed by others but introduced into the American market by Du Pont have been very important in Du Pont's growth. Especially important have been viscose rayon, tetraethyl lead, cellophane, synthetic ammonia, acetate rayon, freon, titanium pigments, lucite, polyethylene, and titanium metal. Many of these were big money makers before and during World War II, and practically all seem likely to continue to be important for some time. Du Pont enjoyed large innovator's profits in rayon during the 1920's[118] and grew rapidly in this field up to 1948. Its earning record in cellophane has been phenomenal over a twenty-five year period.[119] Since Du Pont had no competitors in tetraethyl lead between 1923 and 1948, this too must have been a profitable field. Freon, which had

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[118] See Stocking and Mueller, "Cellophane Case," p. 62.

[119] *Ibid.*

become the almost "universal refrigerant" by 1948, must also have been a profitable venture. By 1948 lucite sales already exceeded $20 million a year, and in polyethylene Du Pont had a stake in the "fastest growing plastic on the market." Titanium metal and dacron will doubtless be important factors in Du Pont's growth for years to come.

Of Du Pont's seven most important *product and process improvements,* five were Du Pont originals. Especially important were Duco, moistureproof cellophane, and cordura fiber. Duco has been an important seller ever since the mid-twenties. Most of the cellophane sold today is of the moistureproof variety. Du Pont sales of rayon tire yarn in 1948 came to $40 million; much of this presumably was cordura.

The above sample strongly suggests that Du Pont has been more successful in making product and process improvements than in discovering new products. Except for nylon, orlon, and neoprene, Du Pont's major product innovations have been based upon technology acquired from others. Next to be considered is the significance of these findings in relation to the frequent statement that Du Pont's bigness has created a perfect environment for inventive activity resulting in important *new* products and processes and *major* improvements in existing products and processes.

The record during the period of this study does not support such a generalization. Although Du Pont has expanded its research expenditures as it has grown—from slightly under $1 million annually shortly before 1920 to $38 million in 1950—there has not been a proportional acceleration in the number of *important* inventions (as defined herein) coming from its laboratories. Nylon still remains its greatest success story. Neoprene, discovered in 1931, probably has been exceeded only by nylon and orlon; and the latter was an outgrowth of its basic discoveries underlying nylon.

It is well to recall here that the basic research leading to the invention of nylon and neoprene was done during the late 1920's and early 1930's, when Du Pont's total research and technical budgets averaged $5 million a year, about one-sixteenth of its 1958 budget. Yes, the Du Pont that initiated the research leading to nylon and neoprene was truly a small firm by today's standards. Its sales in 1928 were only one-seventeenth as large as they were in 1959. Furthermore, by 1950 its nylon sales alone were larger than its 1928 sales of all products.

Du Pont's success in making major product and process improvements did not increase proportionately to its increasing research expenditures during 1920–50. Its greatest achievements of this kind were duco lacquers and moistureproof cellophane. Both of these were developed in the 1920's.

The above conclusions must be qualified in several important respects.

First, because I have concentrated my analysis on the inventions underlying Du Pont's most important innovations, I have left unmentioned many of Du Pont's successes. While I cannot quantify my judgment on this score, I believe that, if I had been able to identify the technical sources of Du Pont's many less spectacular innovations, the quantity of such accomplishments would be found to be more closely correlated with the size of Du Pont's research expenditures during 1920–50.

Second, it is possible that this analysis has treated too short a period in Du Pont's growth to permit generalizations.[120] Perhaps since 1950 Du Pont's inventive achievements have accelerated. But unfortunately it has not been possible to gain access to reliable information concerning the company's inventive activities since 1950.[121]

No opprobrium is intended by the preceding analysis of the sources of the inventions underlying Du Pont's most significant innovations. Du Pont's management must be commended for its aggressive and farsighted search for new products and processes, and for continually looking outside as well as within Du Pont's laboratories for them. It recognized new opportunities when they arose and backed them with a tremendous push of money, of product and process improvements, of mass production, and of salesmanship.

But a fundamental question is raised by these findings. To what extent can we as a nation rely on, and become dependent upon, the fundamental research efforts of a relatively few large industrial firms. Although such firms may be perfect vehicles of applied research and innovation, they may not have adequate economic incentives for

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[120] I have found, however, that during its growth as the country's largest explosive maker Du Pont relied even more heavily on the inventions of others than it has since becoming a diversified chemical concern (based on an unpublished paper by the author on the sources of Du Pont's innovations during its first 100 years of growth as an explosives manufacturer).

[121] I obtained much of the information concerning the sources of Du Pont's inventions during 1920–50 from Du Pont Company documents appearing in various antitrust cases. These documents often gave accounts of the sources of Du Pont's inventions which were substantially different from those in generally available secondary sources.

sponsoring the ideal environment for conducting the basic research leading to the inventions underlying important innovations, or they may not be able to create that environment.

Apropos the question of adequate incentives, Richard R. Nelson of the Rand Corporation concludes his excellent theoretical analysis of the economics of basic research by saying, "though private profit motives may stimulate the firms of private industry to spend an amount on applied research reasonably close to the figure that is socially desirable, it is clear . . . that the social benefits of basic research are not adequately reflected in opportunities for private profit, given our present economic structure."[122]

Apropos the environment which big businesses create for conducting basic research, Clarence Cook Little, Director of the Jackson Memorial Laboratory and former President of the University of Michigan put it this way: "Scientific research is an intensely personal effort . . . like the artist, the creative scientist must be permitted to pursue his own ideas unhampered by restrictions of organized groups. The large groups have made extremely important contributions only when an original discovery, made by a single individual, is already available for further technical development."[123]

Obviously, case studies alone cannot prove or disprove theories. But I hope this one will contribute to the slowly growing empirical evidence useful in testing what are still largely unverified theories of the sources of inventive activity.

COMMENT

ZVI GRILICHES

An economy can grow, in a per capita sense, either by an increase in the amount of available resources per head, or by an improvement in their quality and utilization, by getting "more" out of them. The latter has come to be known as "increases in productivity," and it is clear, by almost any conventional method of measurement, that it has been the most important component of economic growth in the United States in recent decades. The growth in productivity can in turn be

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[122] Richard R. Nelson, "The Simple Economics of Basic Scientific Research—A Theoretical Analysis," *Journal of Political Economy*, June 1959.

[123] Quoted with permission of T. K. Quinn, former vice-president of General Electric, in *Giant Business, Threat to Democracy: the Autobiography of an Insider* (New York, Exposition Press, 1953), p. 112.

divided into two parts: (1) the improvements in efficiency due to the elimination of various disequilibria, i.e., movements toward and along the known production boundaries; and (2) the expansion of the boundaries themselves due to the accretion of new knowledge. The first encompasses the diffusion of already known new techniques and the elimination of various inefficiencies, including taking advantage of existing economies of scale. The second includes advances in science in general, inventions and discoveries (patentable and unpatentable), and the development of practical versions and applications of more general inventions and new scientific principles.

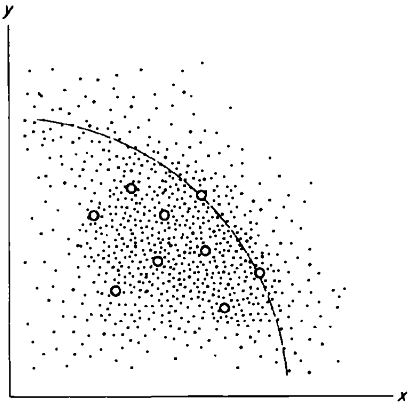
Economists have long been identified with the study of the efficient allocation of a given set of resources within the context of a particular, fixed state of the arts. Recently some attention has begun to be paid to factors affecting the rate of diffusion of new techniques. This conference, however, is concentrating on the even more difficult and challenging problem of the production frontier itself. Its focus is on the knowledge producing industry, its output, the resources available to it, and the efficiency with which they are being used. Thus we are faced with the problems of measuring the rate of accretion of new knowledge (the output of this activity), measuring the resources devoted to the production of new knowledge (the inputs), determining the existence and nature of the relationship between inputs and output (the production function), investigating the factors determining the rate of production and the composition of output in this industry (product and factor prices), and discovering and describing the social private arrangements that would be most conducive to productivity and increases in this industry.

For these purposes, however, inventions may be the wrong unit of measurement. What we are really interested in is the stock of useful knowledge or information and the factors that determine its rate of growth. Inventions may represent only one aspect of this process and be a misleading quantum at that. They are arbitrarily defined discrete large jumps in the stock of certain kinds of (largely patentable) knowledge. They may represent only a small fraction of the growth of knowledge in general, and their fluctuations may not be very well correlated with changes in the over-all rate of growth.

On the other hand, if we restrict our attention solely to the consideration of shifts in the production function, we may miss some very important contributions of invention to the process of economic growth. Inventions may affect the rate of economic growth not only by increasing the productivity of certain inputs but also by preventing a fall in their productivity. The latter influence may be very difficult to detect, even in the best of all statistical worlds. But the fact that the private rate of return has remained high enough for net investment to continue through so many decades is in itself a very important factor in economic growth and could be largely due to "inventions."

Turning, however, explicitly to shifts in the production frontier, I find the theoretical concepts in this area very unsatisfactory for our purposes. In what sense is this a fixed and inelastic frontier? What do we know about different previously unrealized points on it and about what is outside of it? Is the frontier equally impermeable throughout its length? I find the concept of a production function, frontier, or possibilities curve to be a very unsatisfactory tool of analysis when one tries to turn it around and use it to answer questions about itself.

FIGURE 1



Some of these problems are illustrated in Figure 1. Let x and y stand for quantities of different products or different kinds of performance levels that could be associated with a given, fixed set of resources. Let the circles stand for currently and previously achieved levels of productivity. Let the dots represent points that could be achieved, at some as yet undefined cost, given the current state of knowledge. The probability of achieving a given performance combination within a given time period and cost level would then vary from point to point and is represented in the figure by the frequency of the points. The denser the shading the higher is the probability of achieving it within a given cost-time constraint, and the lower is the expected cost achieving it (neglecting the time constraint). Presumably, points lying between, behind, or around already achieved levels could be "developed" with little uncertainty and cost. This is one interpretation of what is meant by development expenditures. Points further out may require substantial research expenditures to be realized, and the undotted area may be so unexplored and uncertain that even a subjective probability calculus would be of little help here. This, then, is the area of "basic" research.

Since all these distinctions are distinctions of degree rather than kind, the definition of what is "within the state of the arts" and the drawing of a production frontier becomes very difficult and arbitrary. One could define a production frontier, represented by the broken line in the figure, by putting to the left of it all the points that could be achieved (at some specified probability level) within a given time and cost constraint. But both this and the two-dimensional nature of the figure abstract from what may be the most important aspect of the problem—differences in the cost of achieving different productivity or performance levels.

Leaving the definition and measurement problems aside, the first substantive question to be asked is whether an increase in inputs in the knowledge producing industry would lead to more output. Is there any relationship between inputs and output here? Unless this question is answered in the affirmative, there is really no point in proceeding toward the usual prescription of economics, the manipulation of incentives and inputs to achieve particular goals. That there is such a relationship may appear self-evident to many of us, but actually there is very little evidence in support of it. Thus we are indebted to Minasian (and similar earlier work by Terleckyj) for showing that research and development expenditures seem to accomplish something, that more R and D implies more output, measured in this case by the growth in productivity. Since many firms are spending money on R and D, one would expect that they are getting something in return (at least on the average), but it is good to have one's preconceptions confirmed by a careful and detailed study of actual expenditures.

Similarly, Nelson's work shows the inventors of the transistor looking for, among other things, knowledge that would lead to better amplifying devices and finding it. In the same vein, Peck's study of the aluminum industry implies that different kinds of inventions are produced by those groups that are most likely to benefit from them. While none of these studies comes anywhere near supplying us with a production function for inventions, the Enos and the Marshall-Meckling papers emphasizing the large component of randomness and sheer uncertainty in it, nevertheless they do establish the existence of some relationships between input and output in this activity. These relationships are not very strong or clear, but they do tell us that there is something in the data, that there are regularities worth studying, and keep our hopes alive.

The next major area of discussion is the existence and identity of factors and incentives affecting the level and direction of inputs in inventive activity. It is quite clear that *successful* invention is a reasonably well paying activity; this can be inferred from the Enos and Minasian papers (it would be interesting to compute the private rate of return on R and D expenditures from Minasian's data). We know nothing, however, about the rate of return to inventive activity as a whole, including the unsuccessful efforts. Is it positive or negative? Even if it were negative, would that mean that we have too few inputs in this area? Not necessarily. Inventors may be tinged by megalomania and willing to risk investing in an activity whose average return is zero or negative, as long as the variance is high enough. This assumption may not be too far-fetched since it is probably true of such diverse groups as speculators on commodity and stock exchanges, investors in Broadway shows, and actors and artists in general. The question that has to be asked is not whether the private rate of return is low or high but whether it is too low and its variance too high to induce the "right" amount of inputs.

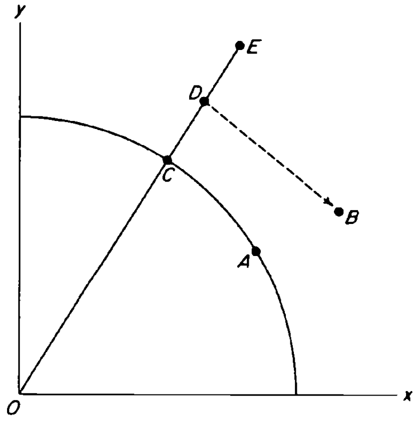
It is also quite clear that the direction of inventive activity is affected by the relative profitability of different lines of endeavour as perceived by the inventors. Peck's data, Nelson's study of the transistor, and Schmookler's study of the variations in the rate of inventive activity in different industries all point in that direction. If one conceives of a production-possibilities surface indicating the various combinations of commodities that could be produced from a given set of resources and within a given state of the arts; and if the term commodity is interpreted broadly to include different dimensions or performance characteristics of commodities—e.g., speed, volume of pay load, range, and achieved height for airplanes—there is little doubt that the relative prices of these different commodities and characteristics strongly affect the direction of inventive activity. It is probably no accident that little work is being done on increasing the speed of automobiles. Both the private and social returns from such work are likely to be low. On the other hand, work is continuing in an attempt to improve the fuel utilization of cars.

It is less certain that the direction of inventive activity is affected by relative factor prices except as these enter directly into the profitability calculations. Are inventions "neutral" on the average? Will different factor price ratios induce different kinds of invention? The theoretical answer given by Fellner implies no tendency away from neutrality in a competitive economy. Given the assumption that it costs the same to advance 10 per cent along any factor-ratio ray (this is effectively on equal ignorance assumption), the highest returns are to be had from an advance along the currently optimum ray. Even if inventors anticipate changes in factor prices and move out along another ray, the effect of this on factor shares is moot. It will depend on the form of the production function, on how it changes as it is pushed outward and upward, and on whether the anticipated factor price changes actually materialize.

Some support for Fellner's proposition is provided by Enos. On the basis of his data one cannot reject the hypothesis of the neutrality of invention in petroleum refining, at least in the "alpha" stage. The "beta" stage, the development and improvement stage, shows a somewhat larger drop in the labor coefficient than in the capital coefficient. Given the paucity of cases and the quality of data, one cannot make much out of it. Moreover, it is not at all clear what the theory would predict for petroleum refining. The relative shares of capital and labor in petroleum refining in 1929 were approximately 0.7 and 0.3. Thus a 10 per cent reduction in the capital coefficient would have been more profitable than a 20 per cent reduction in the labor coefficient, and one would have expected inventions to be "capital saving" there. Actually, we can say very little about it, since all our data concern average productivities, whereas our theory is about marginal productivities. In general, it is my hunch that relative factor prices play a much smaller role in determining the direction of inventive activity than differences in the relative returns from different kinds of inventions (relative product prices).

This conclusion gains force from considerations raised in the third area of concern: the most efficient way of using a given set of inputs. Noting the tremendous uncertainties involved, Klein proceeds to argue that the whole strategy of employing ones resources has to be different in this area. The basic idea is to stay flexible and search for significant new knowledge, rather than to try to produce a particular gimmick to perform a particular task. It may prove easier and more efficient to break through into a different area from the one originally desired. The cost of inventing may be lower there and once the production frontier has been pushed out, it will be relatively easy to colonize some intervening or neighboring areas and develop the desired gimmick. We may get farther if we do not care too much about where we are going. In other words, the cost of moving the production frontier may be different at different points along it, and lower for parallel and oblique than for ortagonal shifts in it. Thus if one wanted to achieve point *B* in Figure 2, it might be cheaper to break through along the ray *O C* to *D*, assuming that the frontier is more "permeable" at this point, and only then move from *C* to *B*. Moreover, it is possible that in trying to break out one actually achieves point *E*, making *B* suboptimal. *B* would now never be reached even though it was the original destination. In short, the differences in the cost of producing inventions utilizing particular factor combinations, the apparent inefficiency of having too definite a goal in the invention process, and the inherently large component of randomness in the final outcome, all lead to inventions that are not well correlated with base-period factor prices or price trends.

FIGURE 2



Granting the importance of Klein's point, I doubt, however, that the contrast between the efficiency minded manager and the inventor is as sharp as he makes it out to be. The true entrepreneur, one with some leeway in his decision making, also operates in a very uncertain environment. It may be optimal for him, too, to be flexible and searching (on this see the earlier work of Stigler and Simon).

Given the paucity of our knowledge about so many aspects of this problem, probably too much attention has been paid by economists to the relation between market structure and inventive activity. I do not deny that the relation between the form of industrial organization and inventiveness may be of interest to the industrial organization man, I only doubt its importance to the invention and economic growth oriented researcher. Whatever evidence we have (see the Mueller and Peck papers, Worley's paper, and the recent book by Jewkes *et al.*) points to no particular relationship between monopoly, oligopoly, or competition and inventive activity. Neither the empirical evidence nor the theoretical discussion has established the presumption of a correlation between the degree of market control and the rate of inventive activity. Even if there were some relationship between the two (positive or negative), it could at best have only a second order effect. It would be quite inefficient, I believe, to try to affect the rate of inventive activity in the United States by manipulating the antitrust laws.

COMMENT

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I would like to consider some theoretical implications of the case studies presented at this conference. My comments will be grouped under four heads: (1) the spread of information in the economic system; (2) the problems of appropriability and competition connected with the innovation process; (3) the optimal dynamics of invention; and (4) the implications for the estimation and meaning of macro-economic production functions over time.

Information

Invention is a process in which information is both the output and an input. The effectiveness of the invention process in a firm will depend then on the informational resources available to it, just as its productive effectiveness will depend in part on natural resources owned by it. Also, of course, the productive efficiency of the firm will depend on its acquisition of information, partly from its own inventive activity and partly from outside sources.

From the case studies, particularly those of Mueller and Peck, it can be inferred that the diffusion of information is by no means a cost-free process, even apart from artificial barriers in the form of patents and secrecy. As Mueller's example of dacron shows, even when information about new productive processes is supplied by another firm, a considerable investment must be made to make use of the knowledge. Further, it is not easy for Du Pont's rivals to develop competing products which deviate sufficiently from the original to avoid patent infringement, even when the fundamental knowledge can be inferred from Du Pont patents (e.g. nylon). Peck, in his discussion of the leadership of the primary producers in developing alloys, as opposed to their relative backwardness in other innovations, points to the fact that information about alloys is a by-product of the primary producing process. Other firms, for example, end-product manufacturers or independent fabricators, who would have an interest in new alloys, could acquire the background information only at a much greater cost.

To sum up, the transmission of information is costly, and certain types of information arise as a by-product of the basic production process of the firm. It follows that the information pool available to society is considerably greater than that available to any member or economic agent.[1]

The obstacles to the flow of information across company barriers are far from absolute, however. According to Mueller, many of Du Pont's innovations are derived from information supplied by others; Enos also cites several cases of patent transfers. Further, Peck has shown that in many cases end-product innovations and manufacturing techniques are developed by primary producers and given to the natural consumer of the information. Even when the information is not supplied officially, imitations can be devised, e.g., the rise of rival cracking processes. Imitation, which is a form of spreading of information, is, of course, costly, but it can be accomplished when sufficiently profitable.

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[1] A study of the social and individual informational pools for several cultures in the southwest United States has been carried out by John M. Roberts as part of the Harvard Values Study Project.

One interesting feature of all three of these studies is the relatively low price paid for information. Patent royalties are generally so low that the profits from exploiting one's own invention are not appreciably greater than those derived from the use of others' knowledge. It really calls for some explanation, why the firm that has developed the knowledge cannot demand a greater share of the resulting profits —ideally all except a competitive return on the capital invested. One possible explanation is that the costs of development are large and comparable to the costs of imitation, so that there is little to squeeze. Further, the high costs of development, being fixed costs, favor large firms and so create a monopsony or oligopsony situation.

Appropriability and Competition

The above observations suggest, though they do not prove, that the rewards for invention in the form of royalties are trivial. The basic reward must then come in the form of monopoly profits including, in many cases, those from market sharing to which patent exchanges may be auxiliary. Now the possibilities of monopolization vary among industries and, in particular, among different stages in a production process. This has been exemplified in the work of both Peck and Enos. The inventive activity may take place, not in the industry which benefits directly, but in supplying industries. Equipment makers appear to be in a peculiarly strategic position for invention to the extent that it is accompanied by differentiation of the equipment product. Primary producers operating under oligopoly can expect only a share of the market resulting from any innovation with respect to end-products, and so have a reduced incentive to innovate. In practice, this is offset in part by the expectation that the beneficiary of an innovation will give its trade to the innovating company for some period of time; this is an indirect form of royalty payment, though one that would be hard to capture statistically.

The appropriability of the results of invention may come about in one of two ways: either there may be, for other reasons, barriers to entry so that the rewards for invention can be appropriated by a firm which is, at least to some extent, in a monopolistic position; or the costs of imitation may be so high, for either technical or legal reasons, that competition cannot erode the profits from invention. In the second case, the invention may be appropriated either through monopoly or through patent royalties. The former possibility is certainly the more likely if the costs of transmission, including that of associated development, are high.

The typology sketched here and suggested by the papers of Enos, Mueller, and Peck may be useful in locating the industrial sectors in which the appropriability of invention is apt to be greatest. Of course, appropriability is not the sole determinant of the locus of inventive activity; the cost of production of the information also matters, and this will depend on the technological possibilities of the moment and the information available to a firm as a by-product of its usual activities.

Optimal Dynamics of Invention

The papers of Klein, Marschak, Marshall and Meckling, and Nelson are at a more micro-economic level than those of Enos, Mueller, and Peck. As in the usual rational theory of the firm, they are trying simultaneously to study how decisions are made and how they ought to be made. The primary stress is on the uncertainty of research and its implications for policy. Two factors dominate: the possibility of flexibility, through multiple lines of development and the cessation of unpromising lines, and the acquisition of information over time. These aspects are not completely unique to invention; they also appear in ordinary production processes under uncertainty in many cases, and the analysis of such situations was begun by Hart[2] many years ago.

One cautionary note on the implications of the view of Klein and his colleagues is in order. There is great stress on decentralization of decision making in research with a view to securing the parallel development of alternative approaches, since none is certain. But decentralization secured in this way is not identical with decentralization through the price system and, indeed, is in many respects incompatible with it. Parallel development of research projects, in order to be efficient, requires continuous interchange of the information accumulated during the process in order to permit elimination of inferior projects at the earliest possible time. In the absence of such interchange of information, for example, if it is prevented by competitive or interservice rivalry, there is liable to be either an excessive cost for retention of projects which are, in fact, inferior to others, or to avoid these costs an unwillingness to enter upon a sufficient number of projects.

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[2] A. G. Hart, *Anticipations, Uncertainty and Dynamic Planning*, New York, Kelley and Millman reprint, 1951, Chap. IV; "Risk, Uncertainty, and the Unprofitability of Compounding Probabilities," *Studies in Mathematical Economics and Econometrics*, O. Lange, T. O. Yntema, and F. McIntyre, editors, University of Chicago Press, 1942, pp. 110–118.

Implications for Estimation of Production Functions

The presence of innovations introduces a number of problems into the estimation of production functions, particularly, though not exclusively, estimation from time series. The technique, stemming from the pioneer work of Douglas, has been developed more recently, with greater reference to technological change, by Valavanis-Vail and Solow.[3] The production function itself is a relation between output and factors, usually capital and labor, but under competitive conditions marginal productivity relations imply that the parameters of the production function can, in part, be inferred from data on wages and profits, and this combination of methods has become standard. The papers of Enos, Peck, and Mueller suggest, however, some problems in the interpretation of these functions, a few of which I list here.

1. At any given moment of time the aggregate production function is supposed to reflect the technological knowledge then available. However, it appears from the case studies that the *distribution* of technical knowledge can also be a significant factor in the performance of the economy as a whole. If some criterion for measuring the accessibility of productive knowledge to individual entrepreneurs could be devised, it might be introduced as a relevant variable in explaining, for example, the differences in performance among countries at a given moment of time.

2. Invention and capital-labor substitution are hard to distinguish. If the capital-labor ratio changes, capital goods will tend to be embodied in different forms (bulldozers rather than shovels), which may be regarded as inventions only in the sense that no one had found it profitable to construct them previously. In this connection, one might offer an interpretation of Enos' observation that capital-labor substitution is not found in invention and development per se but only in the subsequent phase of improvement of the invention in practice. Possibly the latter phase might be regarded as adjustment to the optimum with respect to a given production function, while the former phase alone constitutes a shift in the production function. This suggests a model of neutral technological change with lagged adjustment to an optimum.

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[3] P. H. Douglas, "Are There Laws of Production?" *American Economic Review*, 1948, pp. 1–41; S. Valavanis-Vail, "An Econometric Model of Growth, U.S.A. 1869–1953," *American Economic Review*, Papers and Proceedings, 1955, pp. 215–218; R. M. Solow, "Technological Change and the Aggregate Production Function," *Review of Economics and Statistics*, 1957, pp. 312–320.

3. The rates of return on inventive activity as given by Enos seem very high and would be hard to reconcile with the marginal productivity assumptions used in the estimation of production functions. To the extent that they are valid, they support again the idea of a "dynamic" estimation of the production function in which there is a lag in the achievement of a maximum-profit position and also in the diffusion of technological knowledge throughout the economy. These effects have been demonstrated in the work of Griliches and Mansfield.[4] But there is reason to argue that the rates of return are too high; they disregard not only the capital invested but also the costs of unsuccessful innovations which should, properly speaking, be charged against the successful ones.

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[4] Z. Griliches, "Hybrid Corn: An Exploration in the Economics of Technological Change," *Econometrica*, 1957, pp. 501–522; E. Mansfield, "Technological Change and the Role of Imitation," presented at a meeting of the Econometric Society, December 1959.