The Linear Model of Innovation:
The Historical Construction of an Analytical Framework

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Abstract

One of the first (theoretical) frameworks developed in history for understanding science and technology and its relation to the economy has been the linear model of innovation. The model postulated that innovation starts with basic research, followed by applied research and development, and ends with production and diffusion.

The precise source of the linear model remains nebulous, having never been documented. Several authors who have used, improved or criticized the model in the last fifty years rarely acknowledged or cited any original source. The model was usually taken for granted. According to others, however, it comes directly from V. Bush's *Science: The Endless Frontier* (1945).

This paper traces the history of the linear model, suggesting that it developed in three steps, corresponding to as many scientific communities looking at science from an analytical point of view. The paper argues that statistics is one of the main reasons explaining why the model is still alive, despite criticisms, alternatives, and having been proclaimed dead.

The Linear Model of Innovation:
The Historical Construction of an Analytical Framework

Introduction

One of the first (theoretical) frameworks developed for historically understanding science and technology and its relation to the economy has been the "linear model of innovation". The model postulates that innovation starts with basic research, then adds applied research and development, and ends with production and diffusion:

Basic research → Applied research → Development → (Production and) Diffusion

The model has been very influential. Academic organizations as a lobby for research funds, [1] and economists as expert advisors to policy-makers, [2] have disseminated the model, or the understanding based thereon, widely, and have justified government support to science using such a model. As a consequence, science policies carried a linear conception of innovation for many decades, [3] as well as academics studying science and technology. Very few people defend such an understanding of innovation anymore: "Everyone knows that the linear model of innovation is dead", claimed N. Rosenberg [4] and others. But is this really the case?

In order to answer the question, one must first trace the history of the model to the present. The precise source of the linear model remains nebulous, having never been documented. Several authors who have used, improved or criticized the model in the last fifty years have rarely acknowledged or cited any original source. The model was usually

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[1] National Science Foundation (NSF) (1957), *Basic Research: A National Resource*, Washington: NSF.

[2] R.R. Nelson (1959), The Simple Economics of Basic Scientific Research, *Journal of Political Economy*, 67: 297-306.

[3] D. C. Mowery (1983), Economic Theory and Government Technology Policy, *Policy Sciences*, 16, pp. 27-43.

[4] N. Rosenberg (1994), *Exploring the Black Box: Technology, Economics, and History*, New York: Cambridge University Press, p. 139.

taken for granted. According to others, however, it comes directly from, or is advocated clearly in V. Bush's *Science: The Endless Frontier* (1945). [5] One would be hard pressed, however, to find anything but a rudiment of this model in Bush's manifesto. Bush talked about causal links between science (namely basic research) and socio-economic progress, but nowhere did he develop a full-length argument based on a sequential process broken down into its elements, or that suggests a mechanism whereby science translates into socioeconomic benefits.

In this paper, I trace the history of the model, suggesting that it developed in three stages. The first, from the beginning of the twentieth century to *circa* 1945, was concerned with the first two terms, basic research and applied research. This period was characterized by the ideal of pure science, and people began developing a case for a causal link between basic research and applied research. This is the rhetoric in which Bush participated. Bush borrowed his arguments directly from his predecessors, among them industrialists and the US National Research Council. The second stage, lasting from 1934 to *circa* 1960, added a third term to the discussion, namely development, and created the standard three-stage model of innovation: Basic research → Applied research → Development. Analytical as well as statistical reasons were responsible for this innovation. The analysis of this stage constitutes the core of this paper. The last stage, starting in the 1950s, extended the model to non-R&D activities like production and diffusion. Business schools as well as economists were responsible for this extension of the model.

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[5] J. Irvine and B. R. Martin (1984), *Foresight in Science: Picking the Winners*, London: Frances Pinter, p. 15; G. Wise (1985), Science and Technology, *Osiris*, 1: p. 231; C. Freeman (1996), The Greening of Technology and Models of Innovation, *Technological Forecasting and Social Change*, 53, pp. 27-39; D.A. Hounshell (1996), The Evolution of Research in the United States, in R.S. Rosenbloom and W.J. Spencer (eds.), *Engines of Innovation: US Industrial Research at the End of an Era*, Boston: Harvard Business School, p. 43; D. C. Mowery (1997), The Bush Report after Fifty Years – Blueprint or Relic?, in C. E. Barfield (ed.), *Science for the 21st Century: The Bush Report Revisited*, Washington: AEI Press, p. 34; D. E. Stokes (1997), *Pasteur's Quadrant: Basic Science and Technological Innovation*, Washington: Brookings Institution, p. 10; P. Mirowski and E.-M. Sent (2002), *Science Bought and Sold: Essays in the Economics of Science*, Chicago: University of Chicago Press, pp. 21-22; Godin, B. (2003), Measuring Science: Is There Basic Research Without Statistics, *Social Science Information*, 42 (1): 62; Schmoch, U. (2007), Double-Boom Cycles and the Comeback of Science-Push and Market Pull, *Research Policy*, 36: 1002. More recently, P. Mirowski has attributed the model to P. Samuelson, based on the (slight) evidence that the economist contributed to the drafting of the Bush report: P. Mirowski and E.-M. Sent (2008),

The main thesis of this paper is that the model owes little to Bush. It is rather a theoretical construction of industrialists, consultants and business schools, seconded by economists. The paper also argues that the long survival of the model, despite regular criticisms, is due to statistics. Having become entrenched with the help of statistical categories for counting resources and allocating money to science and technology, and standardized under the auspices of the OECD and its methodological manuals, the linear model functioned as a "social fact". Rival models, because of their lack of statistical foundations, could not easily become substitutes.

This paper is divided into four parts. The first discusses the core of the linear model and its source, that is, the political rhetoric, or ideal of pure science, that made applied research dependent on basic research. The second part discusses the first real step toward the construction of a model by looking at the category and the activity called "development" and its place in industrial research. The third part documents the crystallization of the standard three-stage model via statistics. It argues that statistics has been one of the main factors explaining why the model gained strength and is still alive, despite criticisms, alternatives and a proclaimed death. The last part documents how economists extended the standard model to include innovation.

The paper focuses on the United States, although it draws on material from other countries in cases where individuals from these countries contributed to the construction of the model or to the understanding of the issue. Two factors explain this focus. First, American authors were the first to formalize the linear model of innovation and to discuss it explicitly in terms of a sequential model. Second, the United States was the first country where the statistics behind the model began to be systematically collected. Although limited, this focus allows one to balance D. Edgerton's recent thesis that the linear model does not exist: "the linear model is very hard to find anywhere, except in

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Commercialization of Science and the Response of STS, in E.J. Hackett et al. (eds.), *The Handbook of Science and Technology Studies*, Cambridge (Mass.): MIT Press, p. 676 (endnote 4).

some descriptions of what it is supposed to have been" (p. 32). [6] To Edgerton, the model does not exist in Bush's writings, and here Edgerton and the present author agree, but neither does it exist elsewhere. As this paper implies, only if one looks at the term itself can one supports Edgerton's thesis. The model, whatever its name, has been THE mechanism used for explaining innovation in the literature on technological change and innovation since the late 1940s.

A Political Rhetoric

From the ancient Greeks to the present, intellectual and practical work have always been seen as opposites. The ancients developed a hierarchy of the world in which *theoria* was valued over practice. This hierarchy rested on a network of dichotomies that were deeply rooted in social practice and intellectual thought. [7]

A similar hierarchy existed in the discourse of scientists: the superiority of pure over applied research. The concept of pure research originated in 1648, according to I. B. Cohen. [8] It was a term used by philosophers to distinguish between science, or natural philosophy, which was motivated by the study of abstract notions, and the mixed "disciplines" or subjects, like mixed mathematics, that were concerned with concrete notions. [9] The term came into regular use at the end of the nineteenth century, and was usually accompanied by the contrasting concept of applied research.

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[6] D. Edgerton (2004), The Linear Model did not Exist, in K. Grandin, N. Worms, and S. Widmalm (eds.), *The Science-Industry Nexus: History, Policy, Implications*, Sagamore Beach: Science History Publications, pp. 31-57.

[7] H. Arendt (1958), *The Human Condition*, Chicago: Chicago University Press; G. E. R. Lloyd (1966), *Polarity and Analogy: Two Types of Argumentation in Early Greek Thought*, Cambridge: Cambridge University Press; N. Lobkowicz (1967), *Theory and Practice: History of a Concept From Aristotle to Marx*, London: University of Notre Dame.

[8] I. B. Cohen (1948), *Science Servant of Men*, Boston: Little, Brown and Co., p. 56.

[9] R. Kline (1995), Construing Technology as Applied Science: Public Rhetoric of Scientists and Engineers in the United States, 1880-1945, *ISIS*, 86: 194-221.

The ideology of pure science has been widely documented in the literature, and will not be discussed here. [10] Suffice it to say that pure science was opposed to applied science on the basis of motive (knowledge for its own sake). The dichotomy was a rhetorical resource used by scientists, engineers and industrialists for defining, demarking and controlling their profession (excluding amateurs), for financial support (scientists), for raising the status of a discipline (engineers), and for attracting scientists (industrialists). It was also a rhetoric, particularly present in Great Britain, that referred to the ideal of the freedom of science from interference from the State, with an eye to the counter-reference and negative experiences in Nazi Germany and to some extent in the Soviet Union. [11]

Although generally presented as opposing terms, however, basic and applied research were at the same time being discussed as cooperating: basic research was the seed from which applied research grew: [12] "to have the applications of a science, H. A. Rowland argued, the science itself must exist" (p. 594). Certainly, the relationship was a one-way cooperation (from basic to applied research), but it gave rise to a whole rhetoric in the early twentieth century, one supported by the industrialists, among others.

Industrial research underwent expansion after World War I. Several big firms became convinced of the necessity to invest in research, and began building laboratories for the purpose of conducting research. [13] Governments accompanied them in these efforts. In

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[10] G. H. Daniels (1967), The Pure-Science Ideal and Democratic Culture, *Science*, 156, pp. 1699-1705; E. T. Layton (1976), American Ideologies of Science and Engineering, *Technology and Culture*, 17 (4), pp. 688-700; D. A. Hounshell (1980), Edison and the Pure Science Ideal in 19th Century America, *Science*, 207: 612-617.

[11] Congress for Cultural Freedom (1955), *Science and Freedom*, London: Martin Secker & Warburg.

[12] H. A. Rowland (1902), A Plea for Pure Science, in *The Physical Papers of Henry Augustus Rowland*, Baltimore: Johns Hopkins University Press, pp. 593-613; N. Reingold and A. P. Molella (1991), Theorists and Ingenious Mechanics: Joseph Henry Defines Science, in N. Reingold (ed.), *Science: American Style*, New Brunswick: Rutgers University Press, pp. 127-155.

[13] On the emergence of industrial research, see: National Research Council (1941), *Research: A National Resource (II): Industrial Research*, National Resources Planning Board, Washington: USGPO; G. Wise (1985), *W. R. Whitney, General Electric, and the Origins of US Industrial Research*, New York: Columbia University Press; L. S. Reich (1985), *The Making of American Industrial Research: Science and Business at GE and Bell, 1876-1926*, New York: Cambridge University Press; D. A. Houndshell and J. K. Smith (1988), *Science and Corporate Strategy: Du Pont R&D, 1902-1980*, New York: Cambridge University Press; A. Heerding (1986), *The History of N. V. Philips' Gloeilampenfabriken*, New York: Cambridge University Press; J. Schopman (1989), Industrious Science: Semiconductor Research at the N. V. Philips' Gloeilampenfabriken, 1930-1957, *Historical Studies in Physical and Biological Sciences*, 19 (1), pp. 137-172; M. B. W. Graham and B. H. Pruitt (1991), *R&D for Industry: A Century of Technical Innovation at*

Great Britain, for example, the Department of Scientific and Industrial Research aided and funded industries in their efforts to create industrial research organizations. [14] In the United States, it was the newly created National Research Council that gave itself the task of promoting industrial research. The close links between the National Research Council and industry go back to the preparations for war (1916). Industrialists were called upon for the World War I research efforts coordinated by the National Research Council. After the war, the National Research Council, "impressed by the great importance of promoting the application of science to industry (…), took up the question of the organization of industrial research, (…) and inaugurated an Industrial Research Division to consider the best methods of achieving such organization (…)." [15] "In the 1920s, the division had been a hotbed of activity, preaching to corporations the benefits of funding their own research". [16] The division conducted special studies on industrial research, arranged visits to industrial research laboratories for executives, organized conferences on industrial research, helped set up the Industrial Research Institute – an

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Alcoa, New York: Cambridge University Press; J. K. Smith (1990), The Scientific Tradition in American Industrial Research, *Technology and Culture*, 31 (1), pp. 121-131; M. A. Dennis (1987), Accounting for Research: New Histories of Corporate Laboratories and the Social History of American Science, *Social Studies of Science*, 17, pp. 479-518; D. Mowery (1984), Firm Structure, Government Policy, and the Organization of Industrial Research: Great Britain and the United States, 1900-1950, *Business History Review*, pp. 504-531; G. Meyer-Thurow (1982), The Industrialization of Invention: A Case Study from the German Chemical Industry, *ISIS*, 73, pp. 363-381; T. Shinn (1980), The Genesis of French Industrial Research, 1880-1940, *Social Science Information*, 19 (3), pp. 607-640. For statistical analyses, see: D. C. Mowery and N. Rosenberg (1989), The US Research System Before 1945, in D. C. Mowery and N. Rosenberg, *Technology and the Pursuit of Economic Growth*, New York: Cambridge University Press; D. C. Mowery (1983), Industrial Research and Firm Size: Survival, and Growth in American Manufacturing, 1921-1946: An Assessment, *Journal of Economic History*, 63 (4), pp. 953-980; D. E. H. Edgerton and S. M. Horrocks (1994), British Industrial Research and Development Before 1945, *Economic History Review*, 67 (2), pp. 213-238; S. M. Horrocks (1999), The Nature and Extent of British Industrial Research and Development, 1945-1970, *ReFresh*, 29, Autumn, pp. 5-9; D. C. Mowery (1986), Industrial Research, 1900-1950, in B. Elbaum and W. Lazonick, *The Decline of the British Economy*, Oxford: Clarendon Press; D. E. H. Edgerton (1993), British Research and Development After 1945: A Re-Interpretation, *Science and Technology Policy*, April, pp. 10-16; D. E. H. Edgerton (1987), Science and Technology in British Business History, *Business History*, 29 (4), pp. 84-103; M. Sanderson (1972), Research and the Firm in British Industry, 1919-1939, *Science Studies*, 2, pp. 107-151.

[14] Committee on Industry and Trade (1927), *Factors in Industrial and Commercial Efficiency*, Part I, chapter 4, London: Majesty's Stationery Office; D. E. H. Edgerton and S. M. Horrocks (1994), British Industrial R&D Before 1945, *Economic History Review*, 47, pp. 213-238, pp. 215-216.

[15] A. L. Barrows, The Relationship of the NRC to Industrial Research, in National Research Council (1941), Research: A National Resource II: Industrial Research, *op. cit*. p. 367.

[16] G. P. Zachary (1997), *Endless Frontier: Vannevar Bush, Engineer of the American Century*, Cambridge (Mass.): MIT Press, 1999, p. 81.

organization that still exists today [17] – and compiled a biennial repertory of laboratories from 1920 to the mid 1950s. [18]

In Europe as well as in North America, industrialists reproduced the nineteenth-century discourses of scientists on the utility of science: pure research was "of incalculable value to all the industries". [19] The *Reprint and Circular Series* of the National Research Council in the 1910s and 1920s was witness to this rhetoric by industrialists. J. J. Carty, vice-president, ATT, was a typical purveyor of the rhetoric. In 1924, speaking before the US Chamber of Commerce, he proclaimed: "The future of American business and commerce and industry is dependent upon the progress of science". [20] To Carty, science was composed of two kinds: pure and applied. To him, the pure scientists were "the advance guard of civilization. By their discoveries, they furnish to the engineer and the industrial chemist and other workers in applied science the raw material to be elaborated into manifold agencies for the amelioration of mankind, for the advancement of our business, the improvement of our industries, and the extension of our commerce" (pp. 1-2).

Carty explicitly refused to debate the contested terms "pure" and "applied" research: "the two researches are conducted in exactly the same manner" (p. 7). To Carty, the distinction was one of motives. He wanted to direct "attention to certain important relations between purely scientific research and industrial research which are not yet sufficiently understood" (p. 1). In an article published in *Science*, [21] Carty developed the first full-length rationale for public support to pure research. To the industrialist, "pure" science was "the seed of future great inventions which will increase the comfort and convenience and alleviate the sufferings of mankind" (p. 8). But because the "practical

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[17] The Institute was launched in 1938 as the National Industrial Research Laboratories Institute, renamed the next year as the Industrial Research Institute. It became an independent organization in 1945.

[18] See A. L. Barrows (1941), The Relationship of the NRC to Industrial Research, *op. cit*; R. C. Cochrane (1978), *The National Academy of Sciences: The First Hundred Years 1863-1963*, Washington: National Academy of Sciences, pp. 227-228, 288-291, 288-316.

[19] J. J. Carty (1916), The Relation of Pure Science to Industrial Research, *Reprint and Circular Series*, No. 14, National Research Council, p. 8.

[20] J. J. Carty (1924), Science and Business, *Reprint and Circular Series*, No. 24, National Research Council, p. 1.

[21] J. J. Carty (1916), The Relation of Pure Science to Industrial Research, *op. cit*.

benefits, though certain, are usually indirect, intangible or remote" (p. 8), Carty thought the "natural home of pure science and of pure scientific research is to be found in the university" (p. 9), where each master scientist "should be provided with all of the resources and facilities and assistants that he can effectively employ, so that the range of his genius will in no way be restricted for the want of anything which money can provide. Every reasonable and even generous provision should be made for all workers in pure science" (p. 12). But "where are the universities to obtain the money necessary for the carrying out of a grand scheme of scientific research? It should come from those generous and public-spirited men" [philanthropists and, much later, the State] and "from the industries" (pp. 14-15). This rationale is not very far from that offered by W. von Humboldt, founder of the modern university, in his memorandum of 1809. [22]

V. Bush followed in this rhetoric with his blueprint for science policy, titled *Science: The Endless Frontier*. [23] He suggested the creation of a National Research Foundation that would publicly support basic research on a regular basis. The rhetoric behind the Bush report was entirely focused on the socioeconomic benefits of science: "Advances in science when put to practical use mean more jobs, higher wages, shorter hours, more abundant crops, more leisure for recreation, for study, for learning how to live the deadening drudgery which has been the burden of the common man for past ages. Advances in science will also bring higher standards of living, will lead to the prevention or cure of diseases, will promote conservation of our limited resources, and will assure means of defense against aggression" (p. 10). "Without scientific progress no amount of achievement in other directions can insure our health, prosperity, and security as a nation in the modern world" (p. 11).

But what is the mechanism by which science translates into socio-economic progress? Bush distinguished between basic research, or research "performed without thought of practical ends" and resulting "in general knowledge and an understanding of nature and its laws", and applied research (p. 18). To Bush, however, the two types of research were

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[22] W. von Humboldt (1809), On the Spirit and the Organizational Framework of Intellectual Institutions in Berlin, *Minerva*, 8, 1970, pp. 242-250.

or should be seen in relation to each other: “the further progress of industrial development would eventually stagnate if basic research were long neglected” (p. 18). Basic research is the “means of answering a large number of important practical problems” (p. 18). But how?

> Basic research (…) creates the fund from which the practical applications of knowledge must be drawn. New products and new processes do not appear full-grown. They are founded on new principles and new conceptions, which in turn are painstakingly develop by research in the purest realms of science. Today, it is truer than ever that basic research is the pacemaker of technological progress (p. 19).

This was the furthest Bush went in explaining the links between science and society. It is clear that Bush was, at the very best, dealing with the Basic research → Development (technology) part of the linear model of innovation. Certainly, in the appendix to the Bush report, the Bowman committee used a taxonomy of research composed of pure research/background research/applied research and development, and argued that “the development of important new industries depends primarily on a continuing vigorous progress of pure science” (p. 81). But the taxonomy was never used as a sequential model for explaining socio-economic progress. It served only to estimate the discrepancy between the funds spent on pure research and those spent on applied research.

Bush succeeded in putting the ideal of pure science on officials’ lips and influencing the emerging science policy. [24] But he suggested no more than a causal link between basic research and its applications, and the rhetoric had been developed and discussed at length before him. Nowhere has Bush suggested a model, unless one calls a one-way relationship between two variables a model. Rather, we owe the development of such a model to industrialists, consultants and business schools.

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[23] V. Bush (1945), *Science: The Endless Frontier*, North Stratford: Ayer Co., 1995.

[24] B. Godin (2003), Measuring Science: Is There Basic Research without Statistics?, *Social Science Information*, 42 (1), pp. 57-90.

An Industrial Perspective

The early public discourses of industrialists on science, among them US National Research Council members, were aimed at persuading firms to get involved in research. For this reason, they talked mainly of science or research, without always discussing the particulars of science in industry. But within firms, the reality was different: there was little basic research, some applied research, and a lot of development. It was not long before the organization of research reflected this fact.

Development is a term that came from industry. [25] In the early 1920s, many large firms had "departments of applied science, or, as they are sometimes called, departments of development and research". [26] It was not long before every manager was using the expression "research and development", recognizing the fact that the development of new products and processes was as important as research, if not the primary task of industrial laboratories. In the 1930s, several annual reports of companies brought both terms together. [27]

To industrialists, in fact, development was more often than not an integral part of (applied) research or engineering. [28] "Many laboratories are engaged in both industrial research and industrial development. These two classes of investigation commonly merge so that no sharp boundary can be traced between them. Indeed, the term research is frequently applied to work which is nothing else than development of industrial processes, methods, equipments, production or by-products". [29] And the organization of research in firms reflected this interpretation. Until World War II, there were very few separate departments for research on the one hand, and (product) development on the

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[25] B. Godin (2005), Research and Development: How the "D" got into R&D, *Science and Public Policy*, forthcoming.

[26] J. J. Carty (1924), Science and Business, *op. cit.* p. 4.

[27] For examples, see M. Holland and W. Spraragen (1933), *Research in Hard Times*, Division of Engineering and Industrial Research, National Research Council, Washington pp. 9-11.

[28] For an excellent discussion of the "confusion" between research and other activities in firms, see: F. R. Bichowsky (1942), *Industrial Research*, New York: Chemical Publishing, chapters 3 and 7.

[29] National Research Council (1920), *Research Laboratories in Industrial Establishments of the United States of America*, Bulletin of the NRC, vol. 1, part 2, March, pp. 1-2.

other.[30] Both activities were carried out in the same department, and it was the same kind of people (engineers) that carried out both types of tasks.[31] As noted by J. D. Bernal, the British scientist well known for his early social analysis of science and his advocacy for science planning as opposed to the freedom of science: there is a "difficulty of distinguishing between scientists and technicians in industrial service. Many mechanical engineers, and still more electrical and chemical engineers, are necessarily in part scientists, but their work on the whole cannot be classified as scientific research as it mostly consists of translating into practical and economic terms already established scientific results".[32]

Development as an activity got more recognition and visibility when industrialists, consultants and academics in business schools started studying industrial research. In the 1940s and 1950s, these individuals began developing "models" of innovation. The models, usually illustrated with diagrams, portrayed research as a linear sequence or process starting with basic research, then moving on to applied research, and then development.

Already in 1920, in a book that would remain a classic for decades, C. E. K. Mees, director of the research laboratory at Eastman Kodak, described the development laboratory as a small-scale manufacturing department devoted to developing "a new process or product to the stage where it is ready for manufacture on a large scale".[33] The work of this department was portrayed as a sequential process: development work is "founded upon pure research done in the scientific department, which undertakes the necessary practical research on new products or processes as long as they are on the

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[30] After 1945, several large laboratories began having separate divisions for the two functions. See: F. R. Bichowsky (1942), Industrial Research, *op. cit.*; W. E. Zieber (1948), Organization Charts in Theory and Practice, in C. C. Furnas (ed.), *Research in Industry: Its Organization and Management*, Princeton: D. Van Nostrand, pp. 71-89; C. E. K. Mees and J. A. Leermakers (1950), The Organization of Industrial Scientific Research, *op. cit.* pp. 175-202.

[31] G. Wise (1980), A New Role for Professional Scientists in Industry: Industrial Research at General Electric, 1900-1916, *Technology and Culture*, 21, pp. 408-429; L. S. Reich (1983), Irving Langmuir and the Pursuit of Science and Technology in the Corporate Environment, *Technology and Culture*, 24, pp. 199-221.

[32] J. D. Bernal (1939*), The Social Function of Science*, Cambridge (Mass.): MIT Press, 1973, p. 55.

laboratory scale, and then transfers the work to special development departments which form an intermediate stage between the laboratory and the manufacturing department" (p. 79).[34] To the best of my knowledge, however, the first discussion of such a model in the literature came in 1928 from Maurice Holland, Director of the Engineering and Industrial Research Division at the National Research Council.[35] To Holland, research is "the prime mover of industry", because it accelerates the development of industries by reducing what he called the "time lag" between discovery and production. As n argument to convince industries to invest in research, Holland portrayed the development of industries as a series of successive stages. He called his sequence the "research cycle". It consists of the following seven steps:

- pure science research
- applied research
- invention
- industrial research [development]
- industrial application
- standardization
- mass production

More than ten years later, R. Stevens, vice-president at Arthur D. Little, in a paper appearing in the US National Research Council report to the Resources Planning Board titled *Research: A National Resource*, made his own attempt "to classify the stages through which research travels on its way towards adoption of results by industry".[36] By then, such sequences were the common understanding of the relations between research and industry, and would proliferate among industrialists' writings in the 1940s. For

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[33] C. E. K. Mees (1920), *The Organization of Industrial Scientific Research*, New York: McGraw Hill, p. 79.

[34] In the 1950 edition, the process of "technological advance" included the following steps: research, then development, the latter composed of three steps (establishment of small-scale use, pilot plant and models, adoption in manufacturing). C. E. K. Mees and J. A. Leermakers (1950), *The Organization of Industrial Scientific Research*, New York: McGraw-Hill, p. 4-5.

[35] M. Holland (1928), Research, Science and Invention, in F.W. Wile, *A Century of Industrial Progress*, American Institute of the City of New York, New York: Doubleday, Doran and Co., pp. 312-334.

[36] R. Stevens (1941), A Report on Industrial Research as a National Resource: Introduction, in National Research Council: A National Resource (II): Industrial Research, *op. cit.* p. 6-7.

example, F. R. Bichowsky, in a lucid analysis of industrial research, distinguished several industrial activities and organized them into a "flow sheet chart": research, engineering (or development), and factory (or production). [37] C. C. Furnas, in a classical analysis conducted for the Industrial Research Institute, proposed five activities and presented them as a flow diagram: exploratory research and fundamental research activities at a first level, followed by applied research, then development, then production. [38]

These efforts would soon culminate in the well-known three-stage model: Basic research → Applied research → Development. It is to official (i.e.: government) statistics that we owe this simpler (and now standardized) model.

A Statistical Classification [39]

Over the period 1920-1950, official statisticians developed a definition and a classification of research made up of three components – basic research/applied research/development. The story of these statistical categories is the key to understanding the crystallization of the linear model of innovation and its coming into widespread use: statistics solidified a model in progress into one taken for granted, a "social fact".

Although research had been measured since the early 1920s, the question "what is research?" was often left to the questionnaire respondent to decide. The first edition of the US National Research Council directory of industrial research laboratories, for example, reported using a "liberal interpretation" that let each firm decide which activities counted as research: "all laboratories have been included which have supplied information and which by a liberal interpretation do any research work". [40] Consequently, any studies that used National Research Council numbers, like those by Holland and Spraragen [41] and by the US Works Projects Administration [42] were of questionable

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[37] F. R. Bichowsky (1942), Industrial Research, *op. cit.* p. 81.

[38] C. C. Furnas (1948), Research in Industry: Its Organization and Management, *op. cit.* p. 4.

[39] This section draws on B. Godin (2005), Research and Development: How the D got into R&D, *op. cit.*

[40] National Research Council (NRC) (1920), *Research Laboratories in Industrial Establishments of the United States of America*, Bulletin of the NRC, vol. 1, part 2, March, p. 45.

[41] M. Holland and W. Spraragen (1933), Research in Hard Times, *op. cit.*

quality: "the use of this information [National Research Council data] for statistical analysis has therefore presented several difficult problems and has necessarily placed some limitations on the accuracy of the tabulated material". [43] Again in 1941, in its study on industrial research conducted for the US National Resources Planning Board, the National Research Council used a similar practice: the task of defining the scope of activities to be included under research was left to the respondent. [44] In Canada as well, the first study by the Dominion Bureau of Statistics contained no definition of research. [45]

The situation improved in the 1950s and 1960s thanks wholly to the US National Science Foundation (NSF) and the OECD and their methodological conventions. In 1951, the NSF was mandated by law to measure scientific and technological activities in the country. [46] To that end, the organization developed a series of surveys on R&D based on precise definitions and categories. Research then came to be defined as "systematic, intensive study directed toward fuller knowledge of the subject studied and the systematic use of that knowledge for the production of useful materials, systems, methods, or processes". [47] Industrialized countries followed the NSF definition when they adopted the OECD Frascati manual in 1963. The manual was designed to help countries in their measurement efforts, offering methodological conventions that allowed international comparisons. In line with the NSF definition, the manual defined research as "creative work undertaken on a systematic basis to increase the stock of scientific and technical knowledge and to use this stock of knowledge to devise new applications". [48]

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[42] G. Perazich and P. M. Field (1940), *Industrial Research and Changing Technology*, Work Projects Administration, National Research Project, report no. M-4, Pennsylvania: Philadelphia.

[43] *Ibid*. p. 52.

[44] National Research Council (1941), Research: A National Resource (II): Industrial Research, *op. cit*. p. 173.

[45] Dominion Bureau of Statistics (1941), *Survey of Scientific and Industrial Laboratories in Canada*, Ottawa.

[46] B. Godin (2003), The Emergence of S&T Indicators: Why Did Governments Supplement Statistics with Indicators, *Research Policy*, 32 (4), pp. 679-691.

[47] National Science Foundation (1953), *Federal Funds for Science*, Washington, p. 3.

[48] OECD (1970), *The Measurement of Scientific and Technical Activities: Proposed Standard Practice for Surveys of Research and Experimental Development*, Paris, p. 8. The first edition contained no definition of research.

Before such definitions were arrived at, however, two practices prevailed. First, research was “defined” either by simply excluding routine activities or by supplying a list of activities designed solely to help respondents decide what to include in their responses to the questionnaires. Among these activities were basic and applied research, but also engineering, testing, prototypes, and design, which would later collectively come to be called development. No disaggregated data were available for calculating statistical breakdowns, however. In fact, “in these early efforts, the primary interest was not so much in the magnitude of the dollars going into scientific research and development, either in total or for particular agencies and programs, but in identifying the many places where research and development of some sort or other was going on (…)”. [49]

Although no definition of research *per se* existed, people soon started “defining” research by way of categories. This was the second practice. The most basic taxonomy relied on the age-old dichotomy: pure vs. applied research. Three typical cases prevailed with regard to the measurement of these two categories. The first was an absence of statistics because of the difficulty of producing any numbers that met the terms of the taxonomy. Bernal, for example, was one of the first academics to conduct measurements of research in a western country, although he used available statistics and did not conduct his own survey. In *The Social Function of Science* (1939), Bernal did not break the research budget down by type of research or “character of work” — such statistics were not available. “The real difficulty (…) in economic assessment of science is to draw the line between expenditures on pure and on applied science”, Bernal said. [50] He could only present total numbers, sometimes broken down by economic sector according to the System of National Accounts, but he could not figure out how much was allocated to basic research and how much to applied research.

The second case with regard to the pure vs. applied taxonomy was the use of proxies. In his well-known report, *Science: The Endless Frontier* (1945), Bush elected to use the term “basic research”, and defined it as “research performed without thought of practical

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[49] W. H. Shapley (1959), Problems of Definition, Concept, and Interpretation of Research and Development Statistics, in NSF, *The Methodology of Statistics on R&D*, NSF 59-36, Washington.

ends".[51] He estimated that the nation invested nearly six times as much in applied research as in basic research.[52] The numbers were derived by equating college and university research with basic research, and equating industrial and government research with applied research. More precise numbers appeared in appendices, such as ratios of pure research in different sectors – 5% in industry, 15% in government, and 70% in colleges and universities[53] – but the sources and methodology behind these figures were totally absent from the report.

The third case was skepticism about the utility of the taxonomy, to the point that authors rejected it outright. For example, *Research: A National Resource* (1938), one of the first measurement of science in government in America, explicitly refused to use any categories but research: "There is a disposition in many quarters to draw a distinction between pure, or fundamental, research and practical research (…). It did not seem wise in making this survey to draw this distinction".[54] The reasons offered were that fundamental and applied research interact, and that both lead to practical and fundamental results. This was just the beginning of a long series of debates on the classification of research according to whether it is categorized as pure or applied.[55]

We owe to the British scientist J. S. Huxley, a colleague of Bernal and a member of the "visible college" of socialist scientists, as G. Werskey called them,[56] the introduction of new terms and the first formal taxonomy of research (see Table 1). The taxonomy had four categories: background, basic, ad hoc and development.[57] The first two categories defined pure research: background research is research "with no practical objective consciously in view", while basic research is "quite fundamental, but has some distant practical objective (…). Those two categories make up what is usually called pure

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[50] J. D. Bernal (1939), The Social Function of Science, *op. cit.* p. 62.
[51] V. Bush (1945), Science: The Endless Frontier, *op. cit.* p. 18.
[52] *Ibid*. p. 20.
[53] *Ibid*. p. 85.
[54] National Resources Committee (1938), *Research: A National Resource*, Washington: USGPO, p. 6.
[55] B. Godin (2003), Measuring Science: Is There Basic Research Without Statistics?, *op. cit.*
[56] G. Werskey (1978), *The Visible College: The Collective Biography of British Scientific Socialists of the 1930s*, New York: Holt, Rinehart and Winston.
[57] J. S. Huxley (1934), *Scientific Research and Social Needs*, London: Watts and Co.

science”. [58] To Huxley, ad hoc meant applied research, and development meant more or less what we still mean by the term today: “work needed to translate laboratory findings into full-scale commercial practice”.

Despite having these definitions in mind, however, Huxley did not conduct any measurements. Nevertheless, Huxley’s taxonomy had several influences. Bush borrowed the term “basic” from Huxley when talking of pure research. The concept of “oriented basic research”, later adopted by the OECD, comes from Huxley’s definition of basic research. [59] Above all, the taxonomy soon came to be widely used for measurement. We owe to the US President’s Scientific Research Board the first such use.

Table 1.
Taxonomies of Research

J. Huxley (1934)	background, basic, ad hoc, development
J. D. Bernal (1939)	pure (and fundamental), applied
V. Bush (1945)	basic, applied
Bowman (in Bush, 1945)	pure, background, applied and development
US PSRB (1947)	fundamental, background, applied, development
Canadian DRS (1947)	pure, background, applied, development, analysis & testing
R. N. Anthony	uncommitted, applied, development
US NSF (1953)	basic, applied, development
British DSIR (1958)	basic, applied and development, prototype
OECD (1962)	fundamental, applied, development

Adapting Huxley’s taxonomy, the President’s Scientific Research Board conducted the first real survey of resources devoted to “R&D” in 1947, the first time that term appeared in a statistical report, using precise categories, although these did not make it “possible to arrive at precisely accurate research expenditures” because of the different definitions

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[58] *Ibid*. p. 253.
[59] OECD (1970), The Measurement of Scientific and Technical Activities: Proposed Standard Practice for Surveys of Research and Experimental Development, *op. cit*. p. 10.

and accounting practices employed by institutions. [60] In the questionnaire it sent to government departments (other sectors like industry were estimated using existing sources of data), it included a taxonomy of research that was inspired directly by Huxley's four categories: fundamental, background, applied and development. [61] Using these definitions, the Board estimated that basic research accounted for about 4% of total research expenditure in the United States, [62] and showed that university research expenditures were far lower than government or industry expenditures, that is, lower than applied research expenditures, which amounted to 90% of total research. [63] Despite the Board's precise definitions, however, development was not measured separately, but was rather included in applied research.

We owe to the Canadian Department of Reconstruction and Supply the first measurement of development *per se*. [64] In the survey it conducted in 1947 on government research, it distinguished research, defined as being composed of pure, background [65] and applied research (but without separating the three items "because of the close inter-relationships of the various types of research"), from development and analysis and testing. Development was defined as "all work required, after the initial research on laboratory (or comparable) level has been completed, in order to develop new methods and products to the point of practical application or commercial production".

The inclusion of development was (probably) motivated by the importance of military procurement in the government's budget for science (contracts to industry for developing war technologies). Indeed, most of the data in the report were broken down into military and non-military expenditures. Overall, the Department estimated that 40% of the $34

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[60] President's Scientific Research Board (PSRB) (1947), *Science and Public Policy*, Washington: USGPO, p. 73.

[61] *Ibid*. pp. 299-314.

[62] *Ibid*. p. 12.

[63] *Ibid*. p. 21.

[64] Department of Reconstruction and Supply (DRS) (1947), *Research and Scientific Activity: Canadian Federal Expenditures 1938-1946*, Ottawa; DRS (1947), *Research and Scientific Activity: Canadian Federal Expenditures, 1946 and 1947*, Ottawa; DRS (1947), *Research and Scientific Activity: Provincial Government Expenditures: 1946-1947*, Ottawa.

[65] Here, the term background has changed meaning, as in Bush, and means collection and analysis of data.

million spent on federal scientific activities went to research, 48% to development, and 12% into analysis and testing.

Although innovative with regard to the measurement of development in government research, [66] Canada would not repeat such measurements for years, and never did measure development in industry before the advent of the OECD statistical recommendations in the Frascati manual (1962). It is rather to R. N. Anthony from Harvard Business School that we owe the first, and influential, of a series of systematic measurements of all of the terms in the taxonomy. By that time, however, the taxonomy was reduced to three terms, as it continues to this day: basic research, applied research, and development.

An important measurement issue before the 1950s concerned the demarcation of research and non-research activities. Anthony *et al*. identified two problems: there were too many variations on what constituted research, and too many differences among firms concerning which expenses to include in research. [67] Although routine work was almost always excluded, there were wide discrepancies at the frontier between development and production, and between scientific and non-scientific activities: testing, pilot plants, design, and market studies were sometimes included in research and at other times not. To Anthony, the main purpose of a survey was to propose a definition of research and then to measure it.

In the early 1950s, the US Department of Defense's Research and Development Board asked Anthony to conduct a survey of industrial research to enable the government to locate available resources in the event of war, that is, to "assist the military departments in locating possible contractors for research and development projects". [68] Anthony had just conducted a survey of management controls in industrial research laboratories for the

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[66] The report of the US National Resources Committee on government research published in 1938 made no use of the category development. See National Resources Committee (1938), Research: A National Resource, *op. cit*.

[67] D. C. Dearborn, R. W. Kneznek and R. N. Anthony (1953), *Spending for Industrial Research, 1951-1952*, Division of Research, Graduate School of Business Administration, Harvard University, p. 91.

Office of Naval Research in collaboration with the corporate associates of the Harvard Business School, [69] and was about to begin another survey to estimate the amounts spent on research. The Research and Development Board asked both the Harvard Business School and the Bureau of Labor Statistics to conduct a joint survey of industrial research. The two institutions coordinated their efforts and conducted three surveys. The results were published in 1953. [70]

The Bureau of Labor Statistics report does not have detailed statistics on categories of research, but Anthony's report does. The survey included precise definitions that would have a major influence on the NSF, the official producer of statistics on science in the United States, and on the OECD. Anthony's taxonomy contained three items: [71]

- Uncommitted research: pursue a planned search for new knowledge whether or not the search has reference to a specific application.
- Applied research: apply existing knowledge to problems involved in the creation of a new product or process, including work required to evaluate possible uses.
- Development: apply existing knowledge to problems involved in the improvement of a present product or process.

Along with the definitions, Anthony specified precisely the activities that should be included in development (scale activity, pilot plants and design) and those that should be excluded (market research, legal work, technical services, and production). The survey revealed that industry spent 8% of its research budget on basic research (or uncommitted research), 42% on new products (applied research) and 50% on product improvement

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[68] Bureau of Labor Statistics (1953), *Scientific R&D in American Industry: A Study of Manpower and Costs*, Bulletin no. 1148, Washington, pp. 1, 51-52.

[69] R. N. Anthony and J. S. Day (1952), *Management Controls in Industrial Research Organizations*, Boston: Harvard University.

[70] D. C. Dearborn, R. W. Kneznek and R. N. Anthony (1953), Spending for Industrial Research, 1951-1952, *op. cit*; US Department of Labor, Bureau of Labor Statistics, Department of Defense (1953), Scientific R&D in American Industry: A Study of Manpower and Costs, *op. cit*.

[71] D. C. Dearborn, R. W. Kneznek and R. N. Anthony (1953), Spending for Industrial Research, 1951-1952, *op. cit*. p. 92.

(development). [72] This was the first of a regular series of measurements of the three categories in the history of science statistics. It soon became the norm.

In the 1950s, the NSF started measuring research in the United States, as part of its mandate requesting the regular evaluation of national scientific activities. The NSF extended Anthony's definitions to all sectors of the economy – industry, government, and university – and produced the first national numbers on research so broken down. It took about a decade, however, for standards to appear at the NSF. Until 1957, for example, development was merged with applied research in the case of government research, with no breakdown. Similarly, until 1959, statistics on development were neither presented nor discussed at all in reports on industrial research. [73] But thereafter, the three components of research were separated, and a national total was calculated for each based on the following definitions:

- Basic or fundamental research: research projects which represent original investigation for the advancement of scientific knowledge and which do not have specific commercial objectives, although they may be in the fields of present or potential interest to the reporting company. [74]
- Applied research: research projects which represent investigation directed to discovery of new scientific knowledge and which have specific commercial objectives with respect to either products or processes.
- Development: technical activity concerned with non-routine problems which are encountered in translating research findings or other general scientific knowledge into products or processes.

As Anthony had done, the NSF suggested three categories – with different labels. The main, and important, difference has to do with the fact that Anthony's definitions center on output, while the NSF's emphasized aims or objectives. Nevertheless, the two

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[72] *Ibid*. p. 47.

[73] The situation was similar in other countries. See, for example: DSIR (1958), *Estimates of Resources Devoted to Scientific and Engineering R&D in British Manufacturing Industry, 1955*, London.

[74] The last part of the definition was, and still is, used for the industrial survey only.

taxonomies produced approximately the same statistical results. The NSF surveys showed once more the importance of development in the research budget: over 60% in the case of government research, [75] and 76.9% for industrial research. [76] For the nation as a whole, the numbers were 9.1% of the research budget for basic research, 22.6% for applied research and 68.3% for development. [77]

Anthony's and the NSF's categories were developed for statistical purposes. However, the three categories also served to describe components or stages in the process of innovation, a description that culminated in the three-stage linear model: Basic research → Applied research → Development. Anthony talked of "a spectrum, with basic research at one end, with development activities closely related to production or sale of existing products at the other end, and with other types of research and development spread between these two extremes". [78] The NSF, for its part, suggested that: "the technological sequence consists of basic research, applied research, and development", where "each of the successive stages depends upon the preceding". [79]

Economists Appropriate the Model

By the early 1960s, most countries had more or less similar definitions of research and its components. [80] Research had now come to be defined as R&D, composed of three types of activities. [81] The OECD gave itself the task of conventionalizing and standardizing the definition. In 1963, OECD member countries adopted a methodological manual for conducting R&D surveys and producing statistics for indicators and policy targets, like

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[75] National Science Foundation (1957), *Federal Funds for Science: The Federal Research and Development Budget, Fiscal Years 1956, 1957, and 1958*, NSF 57-24, Washington, p. 10.

[76] National Science Foundation (1959), *Science and Engineering in American Industry: Report on a 1956 Survey*, NSF 59-50, Washington, p. 49.

[77] National Science Foundation (1962), Trends in Funds and Personnel for Research and Development, 1953-61, *Reviews of Data on R&D*, 33, April, NSF 62-9, p. 5.

[78] R. N. Anthony and J.S. Day (1952), Management Controls in Industrial Research Organizations, *op. cit.* pp. 58-59.

[79] National Science Foundation (1952), *Second Annual Report of the NSF: Fiscal Year 1952*, Washington: USGPO, pp. 11-12.

[80] J. C. Gerritsen (1961), *Government Expenditures on R&D in France and the United Kingdom*, EPA/AR/4209, Paris: OEEC; J. C. Gerritsen (1963), *Government Expenditures on R&D in the United States of America and Canada*, DAS/PD/63.23, Paris: OECD.

the GERD/GDP ratio. The Frascati manual included precise instructions for separating research from related scientific activities [82] and non-research activities [83] and development from production. The manual, in line with the NSF definitions, also recommended collecting and tabulating data according to the three components of research defined as follows: [84]

- Fundamental research: work undertaken primarily for the advancement of scientific knowledge, without a specific practical application in view.
- Applied research: work undertaken primarily for the advancement of scientific knowledge, with a specific practical aim in view.
- Development: the use of the results of fundamental and applied research directed to the introduction of useful materials, devices, products, systems, and processes, or the improvement of existing ones.

Economists came into the field quite late. In the early 1960s, when the three components of R&D were already in place in official circles, economists were still debating terms like development and its inclusion in R&D – because it was seen as not inventive in character [85] – and looking for their own definitions and taxonomy of research. [86] They finally settled on the conventional taxonomy, using the standard three categories to analyze industrial research, [87] and using numbers on R&D for measuring the contribution of

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[81] B. Godin (2005), Research and Development: How the "D" got into R&D, *op. cit.*

[82] Scientific information, training and education, data collection, testing and standardization.

[83] Legal administrative work for patents, routine testing and analysis, technical services.

[84] OECD (1962), *The Measurement of Scientific and Technical Activities: Proposed Standard Practice for Surveys of Research and Development*, DAS/PD/62.47, p. 12.

[85] S. Kuznets (1962), Inventive Activity: Problems of Definition and Measurement, in National Bureau of Economic Research (NBER), The Rate and Direction of Inventive Activity: Economic and Social Factors, *op. cit*, p. 35; J. Schmookler (1962), Comment on S. Kuznets' paper, in NBER, The Rate and Direction of Inventive Activity: Economic and Social Factors, *op. cit.* p. 45.

[86] E. Ames (1961), Research, Invention, Development and Innovation, *American Economic Review*, 51 (3), pp. 370-381; S. Kuznets (1962), Inventive Activity: Problems of Definition, in NBER, The Rate and Direction of Inventive Activity, *op. cit.* pp. 19-43; J. Schmookler (1962), Comment on S. Kuznets' paper, in NBER, The Rate and Direction of Inventive Activity: Economic and Social Factors, *op. cit.* pp. 43-51; J. Schmookler (1966), *Invention and Economic Growth*, Cambridge: Harvard University Press, pp. 5-9.

[87] For early uses of these categories and construction of tables of categories by economists, see: C. F. Carter and B. R. Williams (1957), *Industry and Technical Progress: Factors Governing the Speed of Application of Science*, London: Oxford University Press; F. M. Scherer (1959), The Investment Decision Phases in Modern Invention and Innovation, in F. M. Scherer et al. (eds.), *Patents and the Corporation*, Boston: J. J. Galvin; E. Ames (1961), Invention, Development and Innovation, *op. cit.* p. 373; F. Machlup (1962), *The*

science to economic progress. [88] In fact, as R. R. Nelson reported in 1962, "the establishment of the NSF has been very important in focusing the attention of economists on R&D (organized inventive activity), and the statistical series the NSF has collected and published have given social scientists something to work with". [89]

Where some economists innovated was in extending the model to one more dimension: the steps necessary to bring the technology to commercial production, namely innovation. Some authors often refer back to J. Schumpeter to model the process of innovation. Certainly, we owe to Schumpeter the distinction between invention, (initial) innovation, and (innovation by) imitation (or diffusion). [90] While invention is an act of intellectual creativity – and "is without importance to economic analysis" [91] – innovation and diffusion are defined as economic decisions, because of their "closeness to economic use": a firm applying an invention or adopting it for the first time. [92]

Despite having brought forth the concept of innovation in economic theory, however, Schumpeter professed little dependence of innovation on invention, as several authors commented: [93] "Innovation is possible without anything we should identify as invention and invention does not necessarily induce innovation". [94] The formalization of Schumpeter's ideas into a sequential model arose due to interpreters of Schumpeter, particularly in the context of the technology-push/demand-pull debate. [95]

Production and Distribution of Knowledge in the United States, Princeton: Princeton University Press, pp. 178s.

[88] B. Godin (2004), The New Economy: What the Concept Owes to the OECD, *Research Policy*, 33 (5), pp. 579-690.

[89] R. R. Nelson (1962), Introduction, in NBER, The Rate and Direction of Inventive Activity, *op. cit.* p. 4.

[90] J. Schumpeter (1912), *The Theory of Economic Development: An Inquiry into Profits, Capital, Credit, Interest, and the Business Cycle*, Cambridge: Harvard University Press, 1934; J. Schumpeter (1939), *Business Cycles: A Theoretical, Historical, and Statistical Analysis of the Capitalist Process*, New York: McGraw-Hill.

[91] J. Schumpeter (1939), Business Cycles, *op. cit.* p. 85.

[92] J. Schmookler (1962), Comment on S. Kuznets' paper, *op. cit.* p. 51.

[93] C. S. Solo (1951), Innovation in the Capitalist Process: A Critique of the Schumpeterian Theory, *Quarterly Journal of Economics*, LXV, August, pp. 417-428; V. W. Ruttan (1959), Usher and Schumpeter on Invention, Innovation, and Technological Change, *Quarterly Journal of Economics*, 73, pp. 596-606.

[94] J. Schumpeter (1939), Business Cycles, *op. cit.* p., 84.

[95] For schematic representations of the views in this debate, see: C. Freeman (1982), *The Economics of Industrial Innovation*, Cambridge: MIT Press, 1986, pp. 211-214; R. Rothwell and W. Zegveld (1985), *Reindustrialization and Technology*, New York: Sharpe, pp. 60-66.

The first sequential interpretations came from two American economists who used and improved on Schumpeter's categories in the early 1950s. Y. Brozen, from Northwestern University, suggested two models, one that used Schumpeter's three categories, [96] and another that explained the factors necessary "to capitalize on the discoveries of science": research, engineering development, production, service. [97] W. P. Maclaurin, an economist from MIT interested in science and technology studies early on, was another academic who developed a sequential analysis of innovation. Maclaurin served as secretary of the committee on Science and Public Welfare, which assisted V. Bush in the preparation of *Science: the Endless Frontier*. In 1947, he published a paper in *The Harvard Business Review* in which he defended Bush's proposal for a National Research Foundation. [98] He discussed the importance of fundamental research and its funding with the aid of a model broken down into "four distinct stages": fundamental research, applied research, engineering development, production engineering. Then, in 1953, Maclaurin devoted an entire paper on the process of technological change. Suggesting that "Schumpeter regarded the process of innovation as central to an understanding of economic growth", but that he "did not devote much attention to the role of science", Maclaurin "broke down the process of technological advance into elements that may eventually be more measurable". He identified five steps: pure science, invention, innovation, finance, acceptance (or diffusion). [99]

We had to wait several years, however, to see these propositions coalesce into a series of linear models of innovation. Certainly, in their pioneering work on innovation in the late 1950s, C. F. Carter and B. R. Williams from Britain would examine investment in technology, as a "component in the *circuit* which links the pure scientist in his laboratory

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[96] Y. Brozen (1951), Invention, Innovation, and Imitation, *American Economic Journal*, May, pp. 239-257.

[97] Y. Brozen (1951), Research, Technology and Productivity, in L. R. Tripp (ed.), *Industrial Productivity*, Industrial Relations Research Association, Champaign: Illinois, pp. 25-49.

[98] W.R. Maclaurin (1947), Federal Support for Scientific Research, *Harvard Business Review*, Spring, pp. 385-396.

[99] W. R. Maclaurin (1953), The Sequence from Invention to Innovation and its Relation to Economic Growth, *Quarterly Journal of Economics*, 67 (1), pp. 97-111. A few years before, Maclaurin suggested another model composed of five stages: fundamental research, applied research, engineering development, production engineering, service engineering. See: W. R. Maclaurin (1949), *Invention and Innovation in the Radio Industry*, New York: Macmillan, p. xvii-xx.

to the consumer seeking a better satisfaction of his needs”. [100] But the authors neither discussed nor suggested a formalized model of innovation until 1967. [101] Similarly, the influential conference on the rate and direction of inventive activity, organized in 1960 by the National Bureau of Economic Research (NBER) and the Social Science Research Council (SSRC), was concerned with another model than that of innovation *per se*: the production function, or input-output model. [102] If there is one study that deserves mention before the 1960s, it is that of V. W. Ruttan. Ruttan gave himself the task of clarifying the terms used up to the present to discuss innovation, and suggested a synthesis of A. P. Usher’s steps in the invention process [103] and Schumpeter’s concept of innovation. From his analysis, Ruttan suggested the following sequence: Invention → Innovation → Technological Change. [104]

Then a series of models of innovation appeared in the 1960s. E. Ames, although critical of the term innovation (“innovation has come to mean all things to all men, and the careful student should perhaps avoid it wherever possible, using instead some other term”), suggested a model composed of four stages that he discussed in terms of a “sequence of markets”: research, invention (applied research), development, innovation. [105] This model came from F. Machlup’s early measurement of the knowledge society. [106] A few years later, economist J. Schmookler, well-known for his analyses on the role of demand in invention, looked at what he called technology-producing activities as being composed of three concepts: research, development, and inventive activity. [107] In light of other economists’ definitions, Schmookler was definitively dealing with invention rather than innovation, although he was concerned with the role of market forces (wants) in invention. At about the same time, F. M. Scherer, in a historical analysis of the Watt-

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[100] C. F. Carter and B. R. Williams (1957), Industry and Technical Progress, *op. cit.*; C. F. Carter and B. R. Williams (1958), *Investment in Innovation*, London: Oxford University Press.

[101] B. R. Williams (1967), *Technology, Investment and Growth*, London: Chapman and Hill.

[102] NBER (1962), The Rate and Direction of Inventive Activity, *op. cit.*

[103] A. P. Usher (1954), *A History of Mechanical Inventions*, Cambridge: Harvard University Press.

[104] V. W. Ruttan (1959), *Usher and Schumpeter on Invention, Innovation, and Technological Change*, op. cit.

[105] E. Ames (1961), Research, Invention, Development and Innovation, *op. cit.*

[106] F. Machlup (1962), *The Production and Distribution of Knowledge in the United States*, Princeton: Princeton University Press, p. 178s.

[107] J. Schmookler (1966), Invention and Economic Growth, *op. cit.*, p. 7.

Boulton engine, identified four ingredients or steps that define innovation: invention, entrepreneurship, investment, and development. [108] E. Mansfield, for his part, distinguished invention from innovation and diffusion, and defined innovation as the (first) application of an invention and diffusion as its (first) use. [109]

All of these individuals were developing models that defined innovation as a sequence from research or invention to commercialization and diffusion. Academics from management schools followed, and have been very influential in popularizing such models. [110] S. Myers and D. G. Marquis, in a study conducted for the NSF, defined the process of innovation as composed of five stages: recognition (of both technical feasibility and demand), idea formulation, problem solving, solution, utilization and diffusion. [111] J. M. Utterback is another author often cited in the literature for his model of innovation, composed of the following three steps: generation of an idea, problem-solving or development, and implementation and diffusion. [112]

It was these efforts from both economists and researchers in management schools that led to the addition of diffusion in the much-quoted linear model of innovation: Basic research → Applied research → Development → (Production and) Diffusion (Table 2). Yet, it is important to mention two areas of research that contributed to the focus on diffusion and its integration into theoretical models of innovation. The first was the sociological literature, particularly on the diffusion of invention. This tradition goes back to W.F. Ogburn and S.C. Gilfillan and their contributions to the US National Resources Committee's report on technology and its social impacts (1937). The "model" they suggested was one of the first description of innovation as a social process, and was

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[108] F. M. Scherer (1965), Invention and Innovation in the Watt-Boulton Steam Engine Venture, *Technology and Culture*, 6, pp. 165-187.

[109] E. Mansfield (1968), *The Economics of Technological Change*, New York: W. E. Norton, chapters 3 and 4.

[110] For reviews, see: R. E. Roberts and C. A. Romine (1974), *Investment in Innovation*, Washington: National Science Foundation, pp. 20-29; M. A. Saren (1984), A Classification and Review of Models of the Intra-Firm Innovation Process, *R&D Management*, 14 (1), pp. 11-24; J. E. Forrest (1991), Models of the Process of Technological Innovation, *Technology Analysis and Strategic Management*, 3 (4), pp. 439-452.

[111] S. Myers and D. G. Marquis (1969), *Successful Industrial Innovations: A Study of Factors Underlying Innovation in Selected Firms*, NSF 69-17, Washington: National Science Foundation, pp. 3-6.

[112] J. M. Utterback (1974), Innovation in Industry and the Diffusion of Technology, *Science*, 183, p. 621.

motivated by the authors' interest in social consequences of technology and diffusion lags. It included diffusion as a phase in the process, but also the social impacts of invention, an ultimate phase. [113] It was E. M. Rogers' classic book, however, that would be most influential on the literature. In *Diffusion of Innovations* (1962), Rogers depicted innovation as composed of four elements: innovation, communication (or diffusion), consequences on the social system, and consequences over time. [114] By the third edition (1983) of his book, however, Rogers had assimilated the economic understanding of innovation. The process of innovation was now portrayed as composed of six main phases or sequential steps: needs/problems, research, development, commercialization, diffusion and adoption, consequences (p. 136).

The second influence with regard to diffusion was the theory of the product life cycle. Authors portrayed the life cycle of new products or technologies as having an S-shaped curve, and the process of technological development as consisting of three phases: innovation (product), maturation (process), and standardization. [115]

By the early 1960s, then, the distinctions between and the sequence of invention, [116] innovation and diffusion were already in place – and even qualified as "conventional" [117] or "common". [118] Invention was defined as the development of a new idea for a product or process and its reduction to practice; innovation as the process of bringing invention

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[113] The Subcommittee on Technology of the National Resources Committee, presided by W.F. Ogburn, defined invention as a process composed of four phases "occurring in sequence": beginnings, development, diffusion, social influences. See *Technological Trends and National Policy* (1937), Subcommittee on Technology, National Resources Committee, Washington, p. vii. See also pp. 6 and 10. Few years before, in the President's report on social trends, Ogburn and Gilfillan defined invention as a series of stages as follows: idea, trial device (model or plan), demonstration, regular use, adoption. See W.F. Ogburn and S.C. Gilfillan (1933), The Influence of Invention and Discovery, in *Recent Social Trends in the United States*, Report of the President's Research Committee on Social Trends, New York: McGraw-Hill, Volume 1, p. 132. In the 1950 edition of *Social Change*, first published in 1922, Ogburn developed another classification: invention, accumulation, diffusion, adjustment (p. 377).

[114] E. M. Rogers (1962), *Diffusion of Innovations*, New York: Free Press, p. 12-20.

[115] R. Vernon (1966), International Investment and International Trade in the Product Cycle, *Quarterly Journal of Economics*, 80, pp. 190-207; J. M. Utterback and W. J. Abernathy (1975), A Dynamic Model of Process and Product Innovation, *Omega*, 3 (6), pp. 639-656.

[116] Invention as a short-cut for Basic research → Applied research → Development.

[117] A. D. Little (1963), *Patterns and Problems of Technical Innovation in American Industry*, Washington: NSF, p. 6.

[118] US Department of Commerce (1967), *Technological Innovation: Its Environment and Management*, Washington: USGPO, p. 9.

into commercial use or an invention brought into commercial use; and diffusion as the spread of innovation in industry. The sequence became a taken for granted "fact" in the OECD literature, [119] and a classical proposition or "lesson" for managers of research. [120]

Table 2.
Taxonomies of Innovation

Mees (1920)	Pure science, development, manufacturing
Holland (1928)	Pure science research, applied research, invention, industrial research [development], industrial application, standardization, mass production
Stevens (1941)	Fundamental research, applied research, test-tube or bench research, pilot plant, production (improvement, trouble shooting, technical control of process and quality)
Bichowsky (1942)	Research, engineering (or development), factory (or production)
Furnas (1948)	Exploratory and fundamental research, applied research, development, production
Maclaurin (1949)	Fundamental research, applied research, engineering development, production engineering, service engineering
Mees and Leermakers	research, development (establishment of small-scale use, pilot (1950) plant and models, adoption in manufacturing)
Brozen (1951a)	Invention, innovation, imitation
Brozen (1951b)	Research, engineering development, production, service
Rostow (1952)	Fundamental science, application of science, acceptance of innovations
Maclaurin (1953)	Pure science, invention, innovation, finance, acceptance
Carter and Williams (1957)	Basic research, applied research, pilot plant, development, production
Ruttan (1959)	Invention, innovation, technological change
Ames (1961)	Research, invention, development, innovation
Scherer (1965)	Invention, entrepreneurship, investment, development
Hollomon (1965)	perceived need, invention, innovation, diffusion or adaptation
Hollomon (1967)	invention, innovation diffusion
Schmookler (1966)	research, development, invention
Shepard (1967)	Idea generation, adoption, implementation
Allen (1967)	Research, Development, Investment, Construction, Production, Distribution
Mansfield (1968)	Invention, innovation, diffusion
Gruber (1969)	invention and discovery, innovation, adoption and diffusion
Myers and Marquis (1969)	Problem solving, solution, utilization, diffusion
Goldsmith (1970)	pure science, applied science, development, design, production, marketing, sales and profits
Utterback (1974)	Generation of an idea, problem-solving or development, implementation and diffusion
Rowe and Boise (1974)	Knowledge accumulation, formulation, decision, implementation and diffusion

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[119] OECD (1966), *Government and Technical Innovation*, Paris: OECD, p. 9.

[120] J.R. Bright (1969), Some Management Lessons from Innovation Research, *Long Range Planning*, 2 (1), pp. 36-41. For an example of the use of the model in project evaluation, see: A. Albala (1975), Stage Approach for the Evaluation and Selection of R&D Projects, *IEEE Transactions on Engineering Management*, EM-22 (4), pp. 153-164.

Conclusion

The linear model of innovation was not a spontaneous invention arising from the mind of one individual (V. Bush). Rather, it developed over time in three steps. The first linked applied research to basic research, the second added experimental development, and the third added production and diffusion. These three steps correspond in fact to three scientific communities and their successive entries into the field of science studies and/or science policy, each with their own concepts. First were natural scientists (academic as well as industrial), developing a rhetoric on basic research as the source for applied research or technology; second were researchers from business schools, having been interested in science studies long before economists, and studying the industrial management of research and the development of technologies; third were economists, bringing forth the concept of innovation into the discipline. All three communities got into the field by adding a term (their stamp) to the most primitive term – pure or basic research –and its sequence. The three steps also correspond to three policy preoccupations or priorities: the public support to university research (basic research), the strategic importance of technology for industry (development), and the impact of research on the economy and society (diffusion).

Despite its widespread use, the linear model of innovation was not without its opponents. In 1967, the Charpie report, an influential study by the US Department of Commerce on measuring the costs of innovation, estimated that research amounts to 10% of the costs of innovation only. Briefly stated, innovation does not depend on either research or basic research specifically. Other "steps" are more important. [121] The US Department of Defense also challenged the linear sequence. As we have seen with Anthony's study conducted for the Defense's Research and Development Board, the Department of Defense was a pioneer in the use of the R&D categories, even developing its own

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[121] The numbers were based on a "rule of thumb", and were widely criticized. See: E. Mansfield et al. (1971), *Research and Innovation in the Modern Corporation*, New York: Norton; H. Stead (1976), The Costs of Technological Innovation, *Research Policy*, 5: 2-9.

classification of R&D activities and using the linear model to manage its programs. [122] In the mid-1960s, however, the Department began to defect from its previous optimism regarding investments in basic research as a factor for innovation. The Department was, in a sense, beginning to question aspects of the linear model. It therefore conducted an eight-year analysis of twenty major weapon technologies and concluded that only 0.3% of innovations "events" came from "undirected science". [123] The NSF replied with its own study, and came to opposite conclusions. The organization found that 70% of the key events in the development of five recent technological innovations stemmed from basic research. [124] These two studies, each carrying the message of its respective community (industrialists in the case of Defense, scientists for the NSF) were among the first of a long series of debates on aspects of the linear model of innovation.

In the 1960s, academics also leveled criticisms concerning the linearity of the model. [125] It was historians and histories of technology that proved the most productive and convincing: the literature documented the complex interrelationships between science and technology, [126] and developed the idea of technology as knowledge as a "substitute" for basic research in engineering. [127] Despite these efforts, the linear model continued to feed public discourses and academic analyses – despite the widespread mention, in the same documents that used the model, that linearity was a fiction.

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[122] See: A. C. Lazure (1957), Why Research and Development Contracts are Distinctive, in A. C. Lazure and A. P. Murphy (eds.), *Research and Development Procurement Law*, Washington: Federal Bar Journal, pp. 255-264.

[123] US Department of Defense (1969), *Project Hindsight Final Report*, Office of the Director of Defense Research and Engineering, Washington.

[124] IIT Research Institute (1968), *Technology in Retrospect and Critical Events in Science (TRACES)*, Washington: NSF; Battelle Columbus Labs. (1973), *Interactions of Science and Technology in the Innovative Process: Some Case Studies*, Washington: NSF

[125] J. Schmookler (1966), Invention and Economic Growth, *op. cit.*; W. J. Price and L. W. Bass (1969), Scientific Research and the Innovative Process, *Science*, 164, 16 May, pp. 802-806; S. Myers and D. G. Marquis (1969), Successful Industrial Innovation: A Study of Factors Underlying Innovation in Selected Firms, *op. cit.*

[126] The journal *Technology and Culture* published several issues and articles on the topic from 1959. For early representatives of the discussions on the non-causality between science and technology, see: D.J.D. Price (1965), Is Technology Historically Independent of Science? A Study in Historiography, *Technology and Culture*, 6 (4), pp. 553-568; M. Kranzberg (1968), The Disunity of Science-Technology, *American Scientist*, 56 (1), pp. 21-34.

[127] E.T. Layton (1974), Technology as Knowledge, *Technology and Culture*, 15 (1), pp. 31-41. See also the collected papers of Vincenti in W.G. Vincenti (1990), *What Engineers Know and How They Know It*, Baltimore: Johns Hopkins University Press.

In a sense, we owe this continuity to the very simplicity of the model. The model is a rhetorical entity. It is a thought figure that simplifies and affords administrators and agencies a sense of orientation when it comes to thinking about allocation of funding to R&D. However, official statistics are in fact more important in explaining the continued use of the linear model. By collecting numbers on research as defined by three components, and presenting and discussing them one after the other within a linear framework, official statistics helped crystallize the model as early as the 1950s. In fact, statistics on the three components of research were for a long time (and still are for many), the only available statistics allowing one to "understand" the internal organization of research, particularly in firms. Furthermore, as innovation came to define the science-policy agenda, statistics on R&D were seen as a legitimate proxy for measuring technological innovation because they included development (of new products and processes). Having become entrenched in discourses and policies with the help of statistics and methodological rules, the model became a "social fact".

Recent efforts to modify or replace the model have been limited with regard to their impact. First, alternative models, with their multiple feedback loops, [128] look more like modern artwork or a "plate of spaghetti and meatballs" [129] than a useful analytical framework. Second, efforts to measure the new interactive models have not yet been fruitful, at least in the official literature: statistics and indicators on flows of knowledge between economic sectors, performers and users of research, and types of activities are still in the making. [130] Equally, very few accurate numbers on the costs of innovation have come from the official innovation surveys, at least not robust enough numbers to

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[128] S. J. Kline (1985), Innovation is not a Linear Process, *Research Management*, July-August, pp. 36-45; R. Rothwell (1992), Successful Industrial Innovation: Critical Factors for the 1990s, *R&D Management*, 22, pp. 221-239.

[129] This is how Kelly et al. contrasted their "ecological" model to the linear model. See: P. Kelly, M. Kranzberg, F. A. Rossini, N. R. Baker, F. A. Tarpley and M. Mitzner (1975), *Technological Innovation: A Critical Review of Current Knowledge*, volume 1, Advanced Technology and Science Studies Group, Georgia Tech, Atlanta, Georgia, Report submitted to the NSF, p. 33.

[130] B. Godin (2004), The Knowledge-Based Economy: Conceptual Framework or Buzzword, *Journal of Technology Transfer*, forthcoming.

supplement R&D figures. [131] All in all, the success of the linear model suggests how statistics are often required to give (long) life to concepts, but also how their absence is a limitation in changing analytical models and frameworks.

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[131] B. Godin (2005),The Rise of Innovation Surveys: Measuring a Fuzzy Concept, in Measurement and Statistics on Science and Technology, *op. cit.*, Chapter 8.