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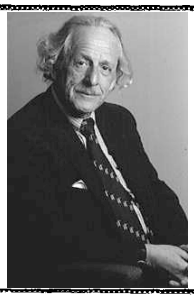

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Theory of Technology's Role in Economic Growth Brings MIT's Robert M. Solow the 1987 Nobel Prize in Economic Sciences

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For his contributions to the theory of economic growth, Robert M. Solow, Department of Economics, Massachusetts Institute of Technology (MIT), Cambridge, was awarded the 1987 Nobel Prize in economics. In two articles, published in 1956 and 1957, Solow proved that technical change (both improved technology and improved education in the work force) was chiefly responsible for long-term growth, much more so than increases in labor or capital. Solow's 10 most-cited publications are reviewed, as well as the 1986 research fronts that include core publications by him. A biographical sketch highlights Solow's long career at MIT and his professional partnership with colleague Paul A. Samuelson.

Scientists probably do not realize it, but as a group they may owe a greater debt of gratitude to Robert M. Solow, the 1987 Nobel laureate in economics, than to any one or all of last year's prizewinners in the sciences.

In the late 1950s Solow formulated a theory of economic growth that emphasized the importance of technology. He stated that technology—broadly defined as the application of new knowledge to the production process—is chiefly responsible for expanding an economy over the long term, even more so than increases in capital or labor. And since basic and applied research is often the prelude to the birth of new technologies, the work of researchers has increasingly been perceived to have economic—not merely intellectual and cultural—significance.

"Research = investment" is a constantly quoted equation nowadays. That intellectual formulation has brought and will likely continue to bring a higher level of public and private support to scientists than was available long before. For that increased support scientists can thank, at least in part, Solow.

The Royal Swedish Academy of Sciences chose to honor Solow for "his contributions to the theory of economic growth" and his analytical demonstration of that theory. The statement of the academy notes that "Solow's growth model constitutes a framework within which modern macroeconomic theory can be structured."[1]

What Fuels the Economic Engine?

What makes for steady growth in a nation's economy? Before Solow's work it was thought that sustained growth required a precise coordination of the rate of savings, the rate of growth in the labor force, and the capital-output ratio. These three had to be balanced within very narrow and unforgiving parameters—on a "knife-edge"—or else the economic engine, like a combustion engine given the wrong mixture of fuel, would begin to sputter and cough.

Solow rejected the theory of knife-edge equilibrium growth, which he found too inflexible and remote from reality. Under such a scenario, he noted in his Nobel lecture, "most economies, most of the time, would have no equilibrium growth path.... The history of capitalist economies should be an alternation of long periods of worsening unemployment with long periods of worsening labor shortage,"[2] which it plainly is not.

Another implication of the then accepted theory of growth seemed unsound to Solow. The theory suggested that "a recipe for

Table 1: Robert M. Solow's publications most cited in the *SCI®*, 1955-1987, and the *SSCI®*, 1966-1987. A = number of citations. B = bibliographic citation.

A	B
421	**Arrow K J, Chenery H B, Minhas B S & Solow R M.** Capital-labor substitution and economic efficiency. *Rev. Econ. Statist.* 43:225-50, 1961.
390	**Solow R M.** Technical change and the aggregate production function. *Rev. Econ. Statist.* 39:312-20, 1957.
341	**Dorfman R, Samuelson P A & Solow R M.** *Linear programming and economic analysis.* New York: McGraw-Hill, 1958. 527 p.
253	**Solow R M.** A contribution to the theory of economic growth. *Quart. J. Econ.* 70:65-94, 1956.
143	**Solow R M.** The economics of resources or the resources of economics. *Amer. Econ. Rev.* 64(2):1-14, May 1974.
98	**McDonald I M & Solow R M.** Wage bargaining and employment. *Amer. Econ. Rev.* 71(5):896-908, December 1981.
84	**Solow R M.** Intergenerational equity and exhaustible resources. *Rev. Econ. Stud.* (Symp.):29-45, 1974.
74	**Samuelson P A & Solow R M.** Analytical aspects of anti-inflation policy. *Amer. Econ. Rev.* 50(2):177-94, May 1960.
72	**Solow R M.** On theories of unemployment. *Amer. Econ. Rev.* 70(1):1-11, March 1980.
71	**Solow R M.** *Growth theory: an exposition.* New York: Oxford University Press, 1970. 109 p.

doubling the rate of growth in a labor-surplus economy was simply to double the savings rate...."[2] This implied that nations that saved more could grow faster and that poorer countries, because they saved so little, could not attain high growth rates. The recipe sounded implausible to him, especially in light of the rapid economic expansion of some developing nations and the clear differences in rates of growth among developed nations.

In 1956 Solow proposed a more flexible theoretical explanation of economic growth,[3] and in the next year he showed how the various components of growth—including technical change—could be sorted out and measured.[4] In these two articles Solow proved that steady growth could be achieved despite variations in the recipe.

The Role of Technical Change

But most remarkable, and startling even to the discoverer, was the finding, reported in the 1957 article ("Technical change and the aggregate production function"), that seven-eighths of the doubling in gross output per hour of work in the US economy between 1909 and 1949 was due to "technical change in the broadest sense" (which includes improvements in education of the labor force). Only one-eighth was due to increased injections of capital. In fact Solow observed that after a certain point capital infusions yield diminishing returns in output.[4]

Karl-Goran Maler, Stockholm School of Economics, Sweden, a member of the Nobel committee, noted, "Solow showed us that in the long run it is not increase in quantity that is important. It is the increase in quality through better technology and increased efficiency."[5]

The finding that technical change is most responsible for growth "has held up surprisingly well in the 30 years since [its publication]," Solow observed in his Nobel lecture. "It stimulated hundreds of theoretical and empirical articles by other economists. It very quickly found its way into textbooks and into the fund of common knowledge of the profession."[2] From that finding there emerged an entire specialty, growth accounting.

Solow's 1957 and 1956 articles rank second and fourth, respectively, among his most-cited publications, according to data from the *Science Citation Index®*, 1955-1987, and the *Social Sciences Citation Index®* (*SSCI®*), 1966-1987. (See Table 1.) Any attempt to judge the influence and impact of this pair of papers by raw citation scores should, however, heed Solow's warning that his findings quickly entered into "the fund of common knowledge of the profession."

That is very nearly a description of the obliteration-by-incorporation (OBI) phenomenon, whereby publications do not get cited because their substance has been in-

corporated in current knowledge.[6-8] Impressive as his counts are for these two articles, they are undoubtedly depressed by the OBI effect. Moreover, since the *SSCI* begins only in 1966, many citations to these two papers from social-sciences journals of the late 1950s and early to mid-1960s are missing entirely from our counts.

The 1957 article is a core publication in the 1986 research front "Long-run productivity models and capital inputs" (#86-0289). (A research front consists of current-year articles and publications from previous years that, after co-citation analysis, cluster together into intellectually coherent, closely related units, each representing an active area of current research.) This research front contains 231 articles indexed in 1986 and 34 core publications that those current-year papers consistently co-cite.

The cluster #86-0289 is linked to three other C1-level clusters: "Regional growth models" (#86-4777), "Productive efficiency and fuel choices" (#86-1322), and "Dynamic demand systems and nonlinear equations" (#86-4674). The group of four fronts, and a fifth ("Monte Carlo tests and demand systems," #86-1788), are aggregated in the C2-level research front "Demand systems and productivity models" (#86-0160), and the whole appears in the multidimensional scaling map in Figure 1. (A Monte Carlo test is a computer simulation program used widely in economics and other sciences.)

Solow's most-cited publication, "Capital-labor substitution and economic efficiency," has collected over 400 citations since its publication in 1961.[9] Coauthor Kenneth J. Arrow, Harvard University, Cambridge, Massachusetts, the 1972 Nobel laureate in economics, wrote about this work in a *Citation Classic*® commentary published in *Current Contents*® in 1979.[10] The paper, Arrow recollected, showed that the Cobb-Douglas production function's linear logarithmic formulation was too simple. "The elasticity of substitution between capital and labor was [shown to be] no longer restricted to one, but could be any constant," Arrow wrote. He also mentioned Solow's 1956 paper in which "Solow had in fact suggested just such a production function" in theory.[10]

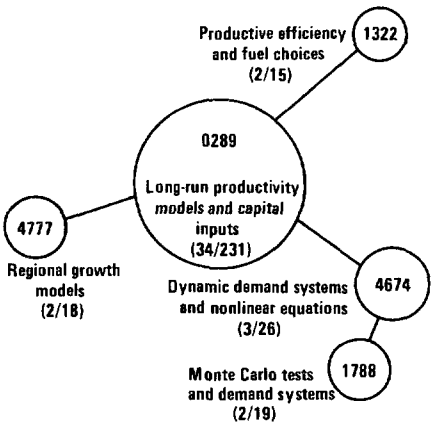

Figure 1: DEMAND SYSTEMS AND PRODUCTIVITY MODELS. Multidimensional scaling map for C2-level research front #86-0160. Numbers in parentheses indicate the numbers of core/citing papers in each research front. The size of the circles is determined by the total number of cites received by the core papers in the research front.

Solow's third most-cited publication is a book cowritten with Paul A. Samuelson, the 1970 Nobel laureate in economics and his colleague at the Massachusetts Institute of Technology (MIT), Cambridge, and Robert Dorfman, Harvard.[11] This volume, published in 1958, is an introductory text, written especially for economists without high-level mathematical skills, on the theory of linear programming, an important tool for economic and econometric analyses.

Natural Resource Economics

His fifth and seventh most-cited papers represent a more recent research interest, but one related to the theory of economic growth.[12,13] The Nobel committee, although singling out Solow's 1956 and 1957 articles, made mention of his "important contributions in the area of natural resource economics." Their statement continues with a question: "Is it possible to imagine continued economic growth when we know that natural resources are finite? Solow studied this question from a theoretical perspective...and found that the key to this problem lay in assumptions made about the substitution elasticity for capital and natural resource inputs."[1]

The ninth most-cited publication of Solow's is also his presidential address to the American Economic Association, delivered in 1979, in which he examined macroeconomic questions about unemployment.[14] This paper is core to the 1986 research front "Equilibrium unemployment" (#86-7984), a small cluster composed of 22 current-year citing articles and two core documents.

Solow's tenth most-cited publication is the elegant little book *Growth Theory: An Exposition*,[15] which contains six lectures on the aggregative theory of growth that he delivered at the University of Warwick, Coventry, UK, in December 1968 and January 1969.

Embodiment, or the Vintage Approach

Not listed in Table 1, but worthy of notice since the Nobel committee explicitly mentioned it, is Solow's article "Investment and technical progress," published in 1960.[16] In this paper Solow introduced the concept of "embodiment," sometimes called the vintage approach, which attempts to account for the technology that is built into a capital good. That good, say a machine, retains its level of technology throughout its life. In projecting growth in which technology is a key element, machines of different vintages, embodying different technologies, must be kept separate in the growth accountant's ledger. Aside from making the work of accountants more complex, the vintage approach revealed the reality that investment in today's technology ties up future technology to some extent. "Nowadays, the vintage capital concept has many other applications and is no longer solely employed in analyses of the factors underlying economic growth," noted the Nobel committee. "The vintage approach has proved invaluable, both from the theoretical point of view and in applications such as the analysis of the development of industrial structures."[1]

Early Years

Robert Merton Solow was born in Brooklyn, New York, on August 23, 1924. He began his undergraduate studies at Harvard College in 1940, intending at first to study biology, botany, or genetics. "I discovered very quickly that I was not good at those things, so I stopped," Solow recalled in an interview in 1983. "I was interested in social questions because the Depression was just over or not quite. I remembered from my childhood what an unpleasant time the Depression had been for my family and more so for others."[17] Focusing on the social sciences, Solow studied sociology with Talcott Parsons, anthropology with Clyde Kluckhohn, and economics with Paul Sweezy. Soon, however, his course work was interrupted by the war and he left college for service in the US Army. In 1945, after completing his tour of duty, he returned to Harvard to finish his baccalaureate.

Solow decided to major in economics and had the great fortune to have as his chief instructor Wassily Leontief, the 1973 Nobel laureate in economics.[18] "Wassily was my tutor; he taught me most of the economics I learned," Solow has said.[17] In 1947 Solow was graduated from Harvard College.

He continued at Harvard for advanced study in economics, concentrating on mathematical economics and statistics. He received a master's degree in 1949 and a PhD in 1951. His dissertation examined how random processes affect the distribution of income by size among families. It won for Solow Harvard's David A. Wells Prize, given annually for the best PhD thesis in economics.

Solow Joins MIT

In 1950 Solow joined MIT as an assistant professor of statistics in the economics department. Again Solow was blessed with good fortune, as he himself observed: "You take a 25-year-old economist, a theorist at that, and you give him an office next to Paul Samuelson...that's a great experience."[19]

Solow has been at MIT ever since. He became associate professor in 1954, full professor in 1957, and Institute Professor in 1973. In fact, his only extended time away from MIT came in 1961-1962, when he served as a staff economist on President Kennedy's White House Council of Economic Advisors. Although he returned to MIT in 1962, his government service was not yet over: in 1964 President Johnson named Solow to the National Commission

on Technology, Automation and Economic Progress and in 1968 to the President's Commission on Income Maintenance Programs. Solow also served as a member of the board of directors of the Federal Reserve Bank of Boston from 1974 to 1980 and was its chairman during 1979-1980.

Solow's list of visiting professorships, honorary degrees, society memberships, and awards is, as one would expect, quite extensive. Especially notable are his 10 honorary degrees from highly distinguished universities worldwide and his membership in the American Philosophical Society and in the National Academy of Sciences, among others. He was also elected president of the Econometric Society in 1964 and of the American Economic Association in 1979.

One honor of special significance to Solow is the James R. Killian, Jr., Faculty Achievement Award, which he received in 1977-1978. Given by an MIT faculty committee for "extraordinary professional accomplishment," the award recognized the excellence of his teaching, as well as the more widely recognized impact of his research. The citation accompanying the award specifically mentioned that he has "accorded equal time and attention" to undergraduates as to graduate students and his own research.[20]

While it is plain that Solow has given much to MIT and its students, he would say that the institute and his colleagues there have given much more to him. In particular, his long-standing personal and professional association with Samuelson, now Institute Professor Emeritus, has been extremely fruitful. The citation of the Killian prize contains the following observation:

> The intellectual partnership of Solow and Samuelson must rank among the most productive of such relationships in the history of economics, extending far beyond the occasional explicitly collaborative work. Each served as a testing ground for the ideas of all of his colleagues, but most of all for each other. The gain to each, and to the discipline of economics, from the interaction has been immeasurable.[20]

Solow has frequently been the target of recruiters from other universities but has steadfastly refused their offers. About that he has said, "A man would have to be a fool to go somewhere just for money when instead he could sit and talk with Paul Samuelson every day."[19]

It is not merely his association with Samuelson that has kept Solow in one place for 38 years but also the excellence of the Department of Economics at MIT, which for the past decade has been rated the best in the nation.

MIT: A National Treasure

Last August—two months before Solow's prize was announced—I received a letter from my friend Robert K. Merton of Columbia University, New York, in which he drew my attention to "the vastly talented array of economists at MIT."[21] He was suggesting that I might conduct a citation-based study on the research activities and impact of this department. He noted that among the faculty were two Nobel laureates—Samuelson and Franco Modigliani, who won the prize in 1985.[22] He also noted "an overdue prospect, Bob Solow." About this extraordinary group of economists he continued,

> I don't think one has seen their equivalent anywhere else—and for such a sustained period. Initiated years ago by Paul Samuelson, they have recruited and developed exceptional talents. What's striking, they are all great talents AND actually like one another. I have the well-based impression that this is one of the more unusual academic departments in any field anywhere.[21]

In the near future I hope to undertake the intriguing study he proposes. But I can predict what it would reveal in general terms: an influence throughout the scholarly literature that is disproportionate to the size of its faculty or the number of their contributions. And that goes as well for the entire research community at MIT, which is no less than a national treasure. MIT now counts eight Nobel laureates on its faculty, the most recent of whom, besides Solow, is immunologist Susumu Tonegawa, who won the 1987 prize for physiology or medicine and about whose life and work I have also recently written.[23]

Wealth from Knowledge

I stated at the beginning of this essay that perhaps not many scientists have realized the impact of Solow's work and its importance to public and private support for scientific research. However, in the late 1960s a group of researchers on the science faculty of the Victoria University of Manchester, UK, were inspired by Solow's classic paper of 1957[4] to investigate closely the role of science in creating wealth by underpinning technology and industry. Using the case study method on some 84 technical innovations they found that

> Scientific discoveries occasionally lead to applications in the form of new technology; this is rare, but the effects may be multiplied indefinitely as technology builds on technology. Science also provides techniques which make it possible or easier to tackle industrial problems successfully. Finally, basic research is an element contributing to the output of highly qualified men and women educated in science and its methods. Of these three factors, the manpower benefit may be the most important when the justifications for basic science are considered in the national context, partly because discoveries and techniques cross international boundaries more easily than men.[24]

That work of some 20 years ago invites renewed investigation of the relationship between science, technology, and economic advance. But for opening up this whole field and for placing such investigations on a firm scientific footing, we have Solow to thank.

* * * * *

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