Revisiting the ‘Rate’ and ‘Direction’ of Technical Change:

Scenarios and Counterfactuals in the Information Technology Revolution

Thomas J. Misa

Charles Babbage Institute

University of Minnesota

<www.umn.edu/~tmisa>

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Over the years, there have been numerous attempts by economists and other quantitatively oriented analysts to assess the impacts of public subsidy on the ‘rate’ of technical change, and most studies have found that public R&D funding has had a strong and generally positive role on technology development and economic growth. The earliest studies to examine this problem systematically occurred in the 1960s. The NSF-funded TRACES project, “Technology in Retrospect and Critical Events in Science,” examined a carefully selected set of technological breakthroughs, in a programmatic attempt to find compelling evidence that earlier R&D “events” were key inputs to the five major selected technologies. TRACES found that 70 percent of the selected technologies could be traced to R&D “events” in non-mission-oriented research, 20 percent to mission-oriented research, and 10 percent to development and application work. The study was plagued by selection bias. One of the contract researchers in this study told me, years later, that cases of technologies that "fit" the science-driven thesis were added to the study population while cases that did not show sufficient dependence on science were simply dropped. There was no pretense of a representative sample. Using somewhat different methods, the DOD-funded Hindsight study started with a sample of twenty successful military systems and again looked backward to identify critical points labeled as "Research or Exploratory Development (RXD) Events." Looking backward from complex technology systems, Hindsight found rather weak linkages between R&D and successful systems with the linkages taking up to 20 years to come to fruition.[1] (Indeed, the release of preliminary Hindsight findings in 1966 so worried NSF managers that they were prompted to commission the TRACES project in rebuttal.) Despite the obvious problems in such retrospective studies, for a time historians of technology too attempted retrospective technology assessments.

In the mid-1990s, SRI International conducted a four-year study of the relations between NSF's engineering research support and commercial technology developments with a serious attempt to identify and

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[1] IITRI, *Technology in Retrospect and Critical Events in Science* (Illinois Institute of Technology Research Institute Report, December 1968); Department of Defense, *Project Hindsight* (Washington, DC: Office of the Director of Defense Research and Engineering; 1969; DTIC No. AD495905). The final TRACES technologies were magnetic ferrites, video tape recorder, oral contraceptives, electron microscope, and matrix isolation in chemistry. In an *Isis* Review, John Heilbron termed the TRACES findings "puerile." A favorable analysis of Hindsight was Karl Kreilkamp, "*Hindsight* and the Real World of Science Policy," *Science Studies* 1 (1971): 43-66.

overcome the more obvious analytical problems in such retrospective studies. Among the problems that SRI identified with these earlier studies were these: [a] case selection bias, with cases chosen for their fit with the aims of the study leading to serious questions concerning their being representative of any larger population; [b] reliability problems, since most studies attempted to identify "critical events" after the fact; [c] inadequate recognition of the uncertainty in the innovation process, with little attention paid to failures or dead ends, even though these might have resulted in research findings later deemed significant (or might just have been a waste); [d] a distinct "hardware bias" with too little attention to managerial and organizational issues.[2]

Studies of the government's impact on computing by Kenneth Flamm (1988), the Institute for Defense Analysis study of ARPA's first three decades (1990-91), and the National Research Council's *Funding a Revolution* (1999) similarly found positive results from public subsidies.[3] Flamm found that no less than 17 of 25 major developments in computer technology from the 1940s through the 1960s—including hardware components like transistors and integrated circuits as well as design elements like stored program code, index registers, interrupt mechanisms, graphics displays, and virtual memory—both received government research and development funding and also found early sustaining markets in the military services, the National Security Agency, or the AEC's Livermore weapons lab. In addition, such significant developments

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[2] See <www.sri.com/policy/csted/reports/techin/intro.html>

[3] Institute for Defense Analysis (IDA), "DARPA Technical Accomplishments," Volume 1, IDA Paper P-2 192 (February 1990); Volume II, IDA Paper P-2429 (April 1991); Volume III, IDA Paper P-2538 (July 1991).

as microprogramming, floating-point hardware, and data channels benefited from one or the other mode of government support. These findings have been given additional support and detail by Norberg and O'Neill, Donald MacKenzie, Bill Leslie, and other scholars.

Strangely enough, for all the attention to the 'rate' of technical change, it is far less common to assess the influence of public subsidy on the 'direction' of technical change. The analytical studies mentioned above (Traces, Hindsight, SRI) tended to assume that there was a single more-or-less linear technological path to the present and consequently to have ignored the multiple branching paths and alternate technical designs that typically exist while technologies are under development—but that are difficult to see once development is complete. Historians of technology, with our acute awareness of the indeterminacy of technological development paths, have many incisive case studies of the "roads not taken" that might help establish a broader understanding that technologies do not progress along a single line of development. After all, the dominant "contextual method" in history of technology assumes axiomatically that there have been multiple contingent forces or influences operating on technical change (we each have our preferences for cultural, political, organizational, social, economic, ideological and others) that variously inspire, guide, shape and condition the invention, development, innovation, and use of technologies. Attention to concepts such as technological style and also to comparative studies are additional ways to see that technological change is complex, contingent, and contested.

Military research and development has played a central role in the literature, and narrative history has been alive to the multiple technical paths and branchings. "The concentration of research on particular tasks greatly accelerated their achievement," writes Alan Milward of the second world war, "but this was always at the expense of other lines of development." During the Cold War "the increasing predominance of one patron, the military," writes Stuart Leslie, "indelibly imprint[ed] academic and industrial science with a distinct set of priorities" that set the agenda for decades. There were certainly winners in this processes—and losers. For example, solar power, analog computers, and machinist-controlled computer machine tools languished when (for various reasons) the military services backed rival technical options—nuclear power, digital computers, and computer controlled machine tools.[4] These state-backed successes, then, were at the same time <u>selections</u> of certain technological options over others.

What is more, the essentially open-ended nature of technological change has received explicit attention in evolutionary economics; my title for this paper comes from the classic National Bureau of Economic Research volume, *The <u>Rate</u> and <u>Direction</u> of Inventive Activity: Economic*

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[4] Alan Milward, *War, Economy and Society, 1939-1945* (Berkeley: University Of California Press, 1977), quote p. 180. Stuart W. Leslie, *The Cold War and American Science* (New York: Columbia University Press, 1993), quote p. 8. See Frank N. Laird, "Constructing the Future: Advocating Energy Technologies in the Cold War," *Technology and Culture* 44 (2003): 27-49. On rival digital and analog computers in Project SAGE, see Thomas P. Hughes, *Rescuing Prometheus* (New York: Pantheon, 1998), 40-47. On the military's role in shaping computer-controlled machine tools, see David F. Noble, *Forces of Production* (New York: Knopf, 1984).

and Social Factors (1962).[5] There are numerous pertinent concepts in the literature: variation and selection (see the cases in George Basalla's *Evolution of Technology* [1989] and the analysis in John Ziman's *Technological Innovation as an Evolutionary Process* [2000]) as well as Brian Arthur's well known 'path dependence' and 'lock in'. In the final section of this paper, I suggest how an evolutionary perspective can yield a richer approach to technology assessment and to a deeper appreciation for the 'rate' and 'direction' questions.

***Ruttan's* Is War Necessary?**

A recent book got me thinking more deeply about these problems including the generally positive but curiously linear assessment of the military's role in promoting technical changes. In his recent book, *Is War Necessary for Economic Growth?* (Oxford 2006), Vernon Ruttan examines six general-purpose technologies; here, I focus on his treatment of the computer and semiconductor industries. Briefly, his argument is that massive military support resulted in technical innovations and productivity growth that would not have occurred—or at least not at the same rate—given only private-sector actors and initiatives. While his analysis is informed and historically attentive, equaling that of the best writings of Nathan Rosenberg on the history of technology, Ruttan implicitly focuses on the 'rate' dimension while the 'direction' of technical change entirely slips out of focus.

With his focus on the substantial agency and impact of the military services, Ruttan has not provided a balanced evaluation that

[5] (Princeton: Princeton University Press, 1962).

acknowledges the substantial private-sector actors and initiatives. After all, solid-state electronics and computing emerged not only from the mythical garages of California but also from some of the leading actors of corporate America: AT&T's Bell Laboratories, RCA, and the four "office machine giants" including of course IBM. In two soon-to-be-published chapters on IBM, Steve Usselman makes (as he puts it) a "moderate adjustment" to the current scholarly understanding that modern computing is the product of massive government investments, especially by the military. In essence, Steve critically scrutinizes the oft-quoted comment by Thomas Watson Jr. that "I knew if you got the SAGE contract . . . you got the computer business" and shows that IBM needed substantial investment and a wide-ranging learning process, quite apart from the immensely valuable SAGE contract itself, for IBM to 'get' the computer business as it did with System/360. He concludes, "far more was involved in the establishment of solid-state electronic digital computing than the linear transfer of military-sponsored research to commercial products."[6]

While I deeply admire Ruttan's advocating narrative analysis over quantitative analysis, I believe he has imported into his narrative analysis a number of consequential historiographic oversights. Here I closely examine his evident assumption that there was little or no civilian market for transistors in the 1950s until the military came along. In his "counterfactual" appendix, "Computers, Microprocessors, and the Internet: A Counterfactual History," he states explicitly that while the

[6] Steven Usselman, "Learning the Hard Way: IBM and the Sources of Innovation in Early Computing" and "Unbundling IBM: Antitrust and the Incentives to Innovation in American Computing."

transistor would still have been invented in 1947, the "first commercial application" of transistors would have been delayed until 1965.[7] I believe this estimate is seriously in error, and hope to show why. (A similar correction should be made in his discussion that "a cautious IBM"[8] entered the computer field only when assured of a large military market; that the civilian airline reservation system "SABRE was a direct spin-off from the [military] SAGE project";[9] and implicitly that computer networking was

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[7] Ruttan, p. 195.

[8] Ruttan, p. 110. "Without the impetus of the SAGE project, for example, a cautious IBM and a financially constrained Remington Rand would have substantially delayed the investment necessary for the emergence of the technology that enabled the development of mainframe computers." IBM, as Usselman shows, was making active investments to develop computer technology beginning in the early 1950s.

[9] Ruttan, p. 108n26. I myself have perhaps erred in attributing too much to the obvious similarities in the names SAGE and SABRE. "IBM incorporated the computer-networking concepts of SAGE [Semi-Automatic Ground Environment] into its SABRE airline reservation system (the name is revealing: Semiautomatic Business-Research Environment) which became operational in 1964," *Leonardo to the Internet* (2004), 222. A careful study of SABRE notes that "many SAGE concepts were applicable to Sabre requirements for unprecedented reliability and human interaction" (p. 37). But the exact naming of SABRE was somewhat more elusive: "After rejecting about 100 suggestions, [Roger] Burkhardt still had a nameless system on the day a decision was needed for inclusion in the official press release. Cliff Taylor was leafing through a magazine that day when he noticed an advertisement for a 1960 Buick LeSabre. 'Let's call it Sabre,' offered Taylor, figuring that reversing the order of the last two letters in IBM's project code name [SABER for Semi-Automatic Business Environment Research, set up originally in 1953-54 to find business applications for a set of technologies IBM had under development including interactive remote terminals, teleprocessing, and disk files] would result in a less acronymic title. Burkhardt agreed and the name stuck." Duncan G. Copeland, Richard O. Mason, and James L. McKenney, "Sabre: The Development of Information-Based Competence and Execution

solely a government creation.) My chief point is this: by underemphasizing the non-military influences and dynamics Ruttan consequently overestimates the counterfactual "impact" of the hypothetical absence of the military.

So, was there an active commercial market for transistors prior to the massive military procurement of transistors in the latter 1950s? The answer is yes and the place to look is Bell Laboratories, whose scientists invented several different types of transistors beginning in 1947 and whose engineers conducted a large-scale development of these devices across the next decade. For years Bell had been working on alternatives to the electromechanical relays in its telephone system. In 1936 Bell's director of research, Mervin Kelly (formerly director of Bell's vacuum tube department from 1928 to 1934), was fully aware of the limitations of tubes in terms of the power they consumed, the heat they generated, and their expense, especially for the far-flung phone system. He spoke movingly about his desire to replace the metal switches in the telephone system with electronic ones to a recently hired Ph.D. physicist. "His interest in this goal was very great," recalled William Shockley. "He stressed its importance to me so vividly that it made an indelible impression."[10] In 1939 Shockley and Walter Brattain designed a solid-state amplifier based on copper oxide although when built it displayed only weak amplification. During the war, Bell devoted three-quarters of

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of Information-Based Competition," *Annals of the History of Computing* 17:3 (1995): 30-57, quote p. 35-36)

[10] William Shockley, "The Path to the Conception of the Junction Transistor," *IEEE Transactions on Electron Devices* ED-23 (July 1976): 597-620, quote 602.

its staff and facilities to military work, including a large effort in radar where the semiconductor research figured prominently.[11]

In July 1945, Bell launched a far-reaching research effort in solid-state physics. Kelly created a new Solid State Department to obtain "new knowledge that can be used in the development of completely new and improved components and apparatus elements of communications systems."[12] By January 1946, the establishment of a semiconductor subgroup in this department brought together the three co-inventors of the transistor—physicists William Shockley, Walter Brattain, and John Bardeen. Not only did they invent "the" transistor in December 1947, they also invented three of the most important types of transistors: a "point-contact" device (1947) that used poorly understood surface phenomena; the widely used junction transistor (1949-51) that exploited better understood electronic interactions internal to the device; and a "field-effect" transistor sketched in a laboratory notebook in April 1945, which two decades later became the dominant transistor type (MOS or FET) in integrated circuits of many sorts.[13]

After a flurry of early military support, Bell in the mid-1950s was planning a vibrant commercial market for its transistors. In March 1954, development engineering head Jack Morton noted in an internal report that "over the last year Bell Laboratories systems applications have

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[11] Lillian Hoddeson, "Research on Crystal Rectifiers During World War II and the Invention of the Transistor," *History and Technology* 11 (1994): 121-30.

[12] Lillian Hoddeson, "The Discovery of the Point-Contact Transistor," *Historical Studies in the Physical Sciences* 12 #1 (1981): 41-76, quote p. 53.

[13] See Ross Knox Bassett, *To the Digital Age: Research Labs, Start-Up Companies, and the Rise of MOS Technology* (Baltimore: Johns Hopkins University Press, 2002).

grown at an almost explosive pace." While acknowledging that a year earlier the military market had loomed large, Morton stated "this year's forecast can be seen to depend almost entirely on Bell applications" with the Bell commercial applications outpacing the military ones by ten to one. In 1954 Bell had transistor projects underway in the telephone system—each one already in manufacturing and most all entering field trials—for a toll card translator, amplifier for deaf subscribers, magnetic drum scanner, crossbar tone generator, and repeater (amplifier). Two large telephone projects, code named Rural Carrier and Line Concentrator, were to require 500,000 transistors in 1955 and more than a million in 1956. By contrast, Bell's military transistor sales were forecast at just 60,000 and 175,000 in those same years.[14] It seems inescapable that Bell knew what it wanted to do with transistors, and that was to use them in the telephone system.

In the event, however, beginning in February 1955 Bell's transistor effort was largely redirected away from Bell's telephone projects and toward a set of high-profile military projects, including the Army's Nike antiballistic missile system. This twenty-year project was described as "the largest and most extensive program in depth and breadth of technology carried out by the Bell System for the military services."[15] The missile mobilization certainly caused internal problems for Bell, even though it gained favorable publicity helpful for a regulated monopoly

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[14] Bell Telephone Laboratories, "Semiconductor Devices: Research and Development Report—March 5, 1954," copy in binder Semiconductor Devices, Box 67, Bell Laboratories Archives.

[15] M.D. Fagan, *History of Engineering and Science in the Bell System: National Service in War and Peace*, (Murray Hill: Bell Laboratories, 1978) 2: 394; quoted in Misa, p. 279.

perennially under the cloud of antitrust proceedings. Morton had already identified a "lack of device manpower" and a "lack of fundamental analytical technology development." "For any given specific device there may be a number of alternative technologies which might be used," he explained, neatly expressing the basic insight of evolutionary economics. "Lack of fundamental analytical technology development forces the project engineer to choose a technology purely on an expediency basis." Problems coordinating the high-profile military work mounted up so that Bell was forced to outright cancel one of the two large telephone projects. With this turn of events, Bell did not experience significant use of transistors in the telephone system until the early 1960s.

Moreover, Bell's military transistor effort, as I argued elsewhere, strongly favored diffused transistors owning to their high-frequency characteristics that were required in the military's high-speed data transmission and high-frequency transmission. At TI and Bell work on silicon transistors found military favor owing to their ability to withstand the high temperatures, up to 150°C, characteristic of jet aircraft and guided missiles, far better than germanium ones which topped out at around 75°C. (It is difficult to treat seriously the Air Force's billion-dollar scheme for the nuclear plane [1946-61], but the Air Force in an advisory group conference in 1956 stated its requirements for transistors able to withstand high radiation environments and its distinct preference for silicon devices.[16])

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[16] Palmer Koenig, "Transistor Reliability and Air Force Requirements," in *Proceedings of the Transistor Reliability Symposium*, sponsored by the Working Group on Semiconductor Devices of the Advisory Group on Electron Tubes, Office of the Assistant Secretary of

And Bell was not the only actor with commercial applications of transistors. By March 1953, Raytheon was manufacturing 10,000 junction transistors each month, mostly for hearing aids. Also in 1953 Texas Instruments established its research laboratory, headed by a former Bell researcher, Gordon Teal, and made two major process innovations in silicon transistors, which were heavily favored in the military market. Another TI project resulted in the first pocket-sized, mass-market transistor radio, the Regency TR-1, which was rushed from design to production and onto the market by Christmas 1954 for $49.95.[17]

By contrast, military-centered applications and assumptions are clearly in view with Ruttan's appendix on "Computers, Microprocessors, and the Internet: a Counterfactual History." There Ruttan hypothesizes an 8-year delay in the introduction of the commercial electronic digital computer; a 10-year delay in the planar process for making integrated circuits; approximately a 20-year delay in the federal government's initiation of sponsorship in computer networking; a 23-year delay in inventing the small IMP computers that formed the ARPANET nodes; a decade-long delay in inventing an internet browser; and a decade and a half delay in measurable economic growth attributable to computers.

Defense Research and Engineering, 17-18 September 1956 (New York: New York University Press, 1958).

[17] The story of the crash program to build Texas Instrument's first all-transistor radio is told by its designer in Paul D. Davis, "The Breakthrough Breadboard Feasibility Model: The Development of the First All-Transistor Radio," *Southwestern Historical Quarterly* 97 (July 1993): 57-80.

Ruttan Appendix on Counterfactual History

Actual year	Event	Absent military
1940	First electronic digital computer (Atanasoff)	1940
1947	Point-contact transistor invented (Bell)	1947
1952 *(IBM 701)*	Commercial electronic digital computer introduced	1960
1958	Planar process integrated circuit invented	1968
	Integrated circuits begin to replace vacuum tubes in telephone switchboards and computers	1975
	Minicomputer is introduced	1980
	Microcomputer is introduced	1985
	NSF initiates software development for computer networking	1985
1969 *(BBN)*	Computer interface message processor invented	1992
1990-94 *(TBL+MA)*	Internet browser invented	2002
	Rapid diffusion of personal microcomputers	2004-6
Early 1990s	Measurable impact of computer on total factor productivity detected	2010

Source: Ruttan, *Is War Necessary for Economic Growth?* (Oxford 2006) pp. 192-96.

Toward Evolutionary Technology Assessment

A key shortcoming to the retrospective approaches as well as Ruttan's suggestive counterfactual approach is an implicit yet fundamental assumption that technological change can be described as a linear process. The early retrospective studies sought to draw conceptual and temporal lineages—sometimes literally termed "traces"—from early research "events" to latter technology-system "results" and then to weigh the relative importance of different types of research and development activities. There is not really room in this analysis for addressing "what if" or counterfactual questions. This broader evaluative stance, however, is exactly the point of Ruttan's counterfactual timeline concerning semiconductor and computer developments. He asks, in effect, what computer technology would have looked like if such significant military research and development had not occurred. Not surprisingly, he finds a significant delay—but the shape of the latter-day results is almost exactly the same. It's as if military sponsorship had no effect at all on 'direction' but only had a strong positive effect on the 'rate' of technical change.

Recall, too, that the effect of any directed sponsorship might not be wholly positive, even focusing narrowly on the 'rate' of technical change. There are numerous instances of strong but negative effects of military sponsorship on technology developments. Archival evidence suggests that the press of military work upended Bell Laboratories' ambitions plans for commercial-sector transistor applications, in part by diverting scarce material and human resources away from commercial-sector applications of transistors and toward military applications in the mid-1950s. Ross Bassett has detailed the negative impact of military sponsored research on RCA's semiconductor efforts as well, with a focus on the internal coordination problems that firm experienced. "Military projects frequently drew IBM down highly specialized cul-de-sacs whose arcane lessons did not transfer readily to the commercial line," notes Steve Usselman.[18] In *Forces of Production* David Noble, too, found pronounced but largely negative consequences for military sponsorship of digital approaches to numerically controlled machine tools. These examples might be expanded, and they might certainly each be scrutinized. But we should be extremely cautious if our analytical scheme

[18] Usselman, "Learning the Hard Way," p. 3.

for analyzing technology has an implicit assumption that 'influence' from whatever actor is always 'positive'.

From an evolutionary perspective, we can expand the qualitative richness of our assessments. Evolutionary theory posits that at each historical moment there will be variation processes, generating new technological options, as well as selection processes that work to select which options are taken up and realized in practice. (Note that a variety of users as well as inventors, engineers, research managers and many others can play a role in these processes.) Instead of assuming a linear path to the present, then, evolutionary theory gives us tools to draw a multidimensional map of the technological options at each moment of time. Then, for each moment, we can identify the forces and influences that might be operating; these might be short-term "random events" or longer-term structural features, inputs of knowledge from allied fields, personal and institutional experiences with the options, expectations about the future. Then, we can make a reasonable analysis about which forces or influences were operative.

We might begin with identifying certain branching events or turning-points, where we can identify when major selections in technology were made, but there is no fundamental assumption that any key "event" is indeed a crucial or privileged one, as the early NSF or DOD studies tended to do. Let's take one example. We might investigate the several years in the early 1950s when germanium and silicon were both considered to be promising materials for solid-state devices like diodes and transistors, asking what persons, professions, laboratories and companies had accumulated experience with each material; which privateand public-sector research sponsors supported silicon, germanium, or other variants; and make a preliminary assessment about what set of influences, or forces, or possibly even non-planned accidents led to the result that silicon transistors gained ascendancy by the late 1950s.

This particular temporal scale of analysis is of course not the only one. Historians are increasingly aware that historical processes operate on different time scales and may even have distinct properties at different scales.[19] We might as it were zoom "outward" to a longer time scale—not 5 but say 20 years—and ask a similar set of questions about vacuum-tube circuit elements compared with solid-state ones. We might equally zoom "inward" and do an evolutionary technology assessment of the consequences of the germanium-silicon question for distinct types of transistors (point contact, junction, diffused, field effect).

In summary, this paper has outlined several reasons why historians of technology should be dissatisfied with schemes for assessing technologies that presume a linear model of technical change. Despite our field's central findings, many technology assessment efforts still do not recognize that technology is complex, contingent, and contested. The history of the IT revolution, curiously enough, is frequently understood as a linear unfolding of a preordained path, even by otherwise historically attentive authors. Using the language of evolutionary economics, I have suggested the outlines of what might be called "evolutionary technology

[19] Paul N. Edwards, "Infrastructure and Modernity: Force, Time, and Social Organization in the History of Sociotechnical Systems." Pp. 185-225 in Thomas Misa, et al. eds. *Modernity and Technology* (Cambridge: MIT Press, 2003).

assessment." This form of technology assessment, which might operate at many different time scales and for a variety of questions, might connect our qualitative findings with the more quantitatively oriented analysis. One hopes that we find a conceptual or analytical vehicle to place findings from the history of technology more centrally into public discussions on technology. The "rate" as well as the "direction" of technical change is the key point.