ESSAY

Moore's Law and Technological Determinism

Reflections on the History of Technology

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Just over a year ago, the arrival in my mailbox of a book I had agreed to review triggered some thoughts about technology I had been meaning to articulate. The book was Ross Bassett's *To the Digital Age: Research Labs, Start-up Companies, and the Rise of MOS Technology* (Baltimore, 2002).[1] In it, Bassett describes the development of metal-oxide semiconductor (MOS) technology, which enabled semiconductor firms to place more and more transistors on a single silicon chip.[2] This became the basis for what is now known as Moore's law, after Gordon E. Moore. In April 1965, Moore, then the director of research and development at the semiconductor division of Fairchild Camera and Instrument Corporation, published a paper in which he observed that the number of transistors that could be placed on an integrated circuit had doubled every year since integrated circuits had been invented and predicted that that trend would continue.[3] Shortly afterward, Moore left Fairchild to cofound Intel—a company, Bassett notes, that staked its future on MOS technology.

It is important to note at the outset that Moore's law was an empirical observation; it is not analogous to, say, Ohm's law, which relates resistance to current. Moore simply looked at the circuits being produced, plotted their density on a piece of semi-log graph paper, and found a straight line. Furthermore, he made this observation in 1965, when the integrated circuit was only six years old and had barely found its way out of the laboratory.

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1. My review appeared in the October 2004 issue of this journal, *Technology and Culture* 45 (2004): 892–93.

2. A variant, in which PNP-type transistors alternate with NPN types, is called "complementary MOS," or CMOS, and has the advantage of requiring very little power.

3. Gordon E. Moore, "Cramming More Components onto Integrated Circuits," *Electronics*, 19 April 1965, 114–17.

The name "Silicon Valley" did not even exist; it would be coined at the end of that decade. Nonetheless, Moore's prediction that the number of transistors that could be placed on an integrated circuit would continue to double at short, regular intervals has held true ever since, although the interval soon stretched from twelve to eighteen months.[4]

Moore's law has been intensively studied, mainly by those wondering when, if ever, fundamental physical constraints (such as the diameter of a hydrogen atom) will interrupt the straight line that Moore observed. These studies note the lengthening of the interval mentioned already: chip densities now double about every eighteen to twenty months, although no one is sure why.[5] Analysts have been predicting the failure of Moore's law for years. Interestingly, the moment of its demise seems always to be about ten years from whenever the prediction is made; that is, those writing in 1994 anticipated that it would fail in 2004, while some today put the likely date at about 2015. Obviously one of these predictions will pan out someday, but for now Moore's law is very much in force, as it has been for over forty-five years—a fact from which the lengthening of the doubling interval should not distract us. Over the same period, computer-disk memory capacity and fiber-optic cable bandwidth have also increased at exponential rates. Thus, in 2005 we see memory chips approaching a billion (10^9) bits of storage, Apple iPods with forty-gigabyte (3×10^{11} bits) disks, and local networks capable of transmitting a full-length Hollywood feature film in seconds.

But while industry analysts, engineers, and marketing people have studied Moore's law intensively, historians of science and technology have shown less interest. That is surprising, since it cuts to the heart of an issue that they have debated over the years: technological determinism.

Mel Kranzberg and his colleagues organized the Society for the History of Technology in part to foster a view of technology running counter to the notion that technology is an impersonal force with its own internal logic and a trajectory that human beings must follow. The society's founders spoke of a "contextual" approach to technology, in which the linear narrative of events from invention to application was accompanied by an understanding of the context in which those events occurred.[6] They named the

4. The mathematical relationship described by Moore is $n = 2^{((y - 1959) \div d)}$, where n is the number of circuits on a chip, y is the current year, and d is the doubling time, in years. For a doubling time of eighteen months, or $d = 1.5$, this equation predicts chip densities of about one billion in 2005. Chips with that density are not yet available commercially as far as I know, but are being developed in laboratories.

5. For early discussions on this topic among the principals, see Gordon E. Moore, "Progress in Digital Integrated Electronics" (paper presented at the International Electronic Devices Meeting, Washington, D.C., 1–3 December 1975, technical digest 11–13); Robert N. Noyce, "Microelectronics," *Scientific American* 237 (September 1977): 65.

6. See, for example, Stephen H. Cutcliffe and Robert C. Post, eds., *In Context: History and the History of Technology—Essays in Honor of Melvin Kranzberg* (Bethlehem, Pa., 1989).

society's journal *Technology and Culture* to emphasize the importance of all three words. Of course, the founding of SHOT and the establishment of *T&C* did not settle the framework for studying technology once and for all, and periodically the concept of determinism is revisited.[7] Nor did the contextual approach remain static. Led by a second generation of scholars including Thomas Parke Hughes, Wiebe Bijker, and Donald MacKenzie, it evolved into the notion (borrowed from elsewhere) of the "social construction" of technology.[8] At the risk of telescoping a complex and rich story, recall that part of the context of the founding of the Society for the History of Technology in 1957 was the Soviets' launch of *Sputnik* and its effect on the perception of U.S. and British technology.[9] The idea of free peoples choosing their destiny freely was very much on the minds of Americans and Britons, then engaged in a cold war with a nation whose citizens lacked such freedom.

I agree with and support this approach to the history of technology. But it must confront a serious challenge: the steady and unstoppable march of semiconductor density, which has led to the rapid introduction of an enormous number of new products, services, and ways of working and living. Think of all the cultural, political, and social events that have occurred in the West since 1965. Think of our understanding of the history of science and technology today compared to then. Now consider that throughout all of these years, the exponential growth of chip density has hardly deviated from its slope. Can anything other than the limit implied by Planck's constant have an effect on Moore's law?

That Moore's law plays a significant role in determining the current place of technology in society is not in dispute. Is it a determinant of our society? The public and our political leaders believe so. In the popular press, the term "technology" itself is today synonymous with "computers." Historians of technology find that conflation exasperating, as it excludes a vast array of technology-driven processes, such as textiles or food production.

The public acceptance of technological determinism is evident among the many visitors where I work, at the National Air and Space Museum, and a recent essay in this journal indicates that determinism is again very much on the minds of historians of technology as well. In "All that Is Solid Melts into Air: Historians of Technology in the Information Revolution," Rosalind Williams recounts her experiences as dean of students at the Massachusetts Institute of Technology during that institution's transition from a

7. See, for example, Merritt Roe Smith and Leo Marx, eds., *Does Technology Drive History? The Dilemma of Technological Determinism* (Cambridge, Mass., 1994).

8. For example, Donald MacKenzie and Judy Wajcman, eds., *The Social Shaping of Technology*, 2nd ed. (Buckingham, 1999); Wiebe Bijker, Thomas P. Hughes, and Trevor Pinch, eds., *The Social Construction of Technological Systems* (Cambridge, Mass., 1987).

9. Mel Kranzberg, "The Newest History: Science and Technology," *Science*, 11 May 1962, 463–68.

set of internally generated, ad hoc administrative computing systems to one supplied by a commercial vendor, SAP.[10] Williams noted that MIT faculty and administrators felt powerless to shape, much less resist, the administrative model embodied in the new software. Such feelings of powerlessness might be understandable elsewhere, but MIT faculty are supposed to be the masters of new technology—they are the ones who create the science and engineering that underpin SAP's products. How could *they* be powerless?

A close reading of Williams's essay reveals that MIT faculty and staff were not exactly passive consumers of SAP R/3. They may have conformed to the software's rigid structure, but not without a fight. The final implementation of this "reengineering," as it was called, was much more than a simple top-down process. Is that not a refutation of the notion that increases in semiconductor density drive society? If one looked instead at a liberal arts college, less technologically savvy than MIT, would the deterministic nature of computing assert itself more strongly?

Williams used her own institution and her own role as a dean as data points (although she did exclaim "There must be an easier way to do research").[11] I propose that we do the same: look not at other people and institutions but rather at ourselves, historians of technology who live and work in a digital environment and who assert the right to criticize the blind acceptance of the products of the information age. How do we, as individuals, handle the consequences of Moore's law?

I begin with the ground on which we stand—or, more accurately, the chairs in which we sit. We spend our days in offices, staring into computer screens, using software provided by corporations such as Microsoft, Adobe, AOL, Novell, Lotus. We do not design or build the hardware or write the software, nor do we have more than a rudimentary notion of how to repair either when something breaks. "Wizards" install new applications for us; we insert a disk and press "Enter." The computer recognizes when a new device is attached, a process called "plug and play." How far removed this is from the days when many of us used jacks, wrenches, screwdrivers, and other tools to replace broken or worn parts on our cars, reinstalled everything, tested it, and then drove off![12]

We are trying to have it both ways. We pass critical and moral judgment on Harry Truman for his decision to use atomic bombs against Japan, we criticize a museum for showing, out of context, the aircraft that carried the

10. Rosalind Williams, "All that Is Solid Melts into Air: Historians of Technology in the Information Revolution," *Technology and Culture* 41 (2000): 641–68. See also her more recent book, *Retooling: A Historian Confronts Technological Change* (Cambridge, Mass., 2002).

11. Williams, "All that Is Solid," 641.

12. I can no longer make such repairs, as the engine and basic components of the car I now drive are inaccessible. Its ignition, fuel, brake, and other systems are all heavily computerized.

first bomb, yet we ignore our inability to exert more than a smidgen of control over technologies that affect—determine—our daily lives.[13] In her recent book *User Error*, Ellen Rose, a professor of education and multimedia at the University of New Brunswick, writes that when it comes to software people uncritically accept technology without regard to its context or social dimension.[14] This time the villains are not Harry Truman, the Air Force Association, or senior management at the Smithsonian. We are responsible. Historians of technology find determinism distasteful. Yet we validate it every day.

Consider the tools that I and my colleagues used when I began my career as a historian of technology and a teacher:

16 mm movies
Triplicate 3″ × 5″ library cards (author, title, subject)
5″ × 8″ note cards, some with edge notches sorted by a knitting needle
35 mm film camera, producing color slides or 8″ × 10″ black-and-white prints
Blackboard and chalk
Cassette tape recorder
Drafting table, for producing hand-drawn maps and charts
Hewlett-Packard pocket calculator
Microfilm
Mimeograph machine
Overhead transparencies, hand drawn on the fly during a lecture
Photocopier
Preprints or offprints of published papers
Telephone, rotary dial, leased from AT&T
Typed letters, sent through U.S. mail
Typewriter, manual

Now consider the tool set we use today in our daily work of teaching, researching, and writing. This list is based on an informal look around my own office and at nearby universities in Maryland and Virginia where I have taught or lectured. For convenience I divide it into software and hardware. Strictly speaking only hardware obeys Moore's law, but in practice the advances in semiconductor technology allow for more and more complex software products, so both lists are appropriate.

13. Robert C. Post, "A Narrative for Our Time: The *Enola Gay* 'and after that, period,'" *Technology and Culture* 45 (2004): 373–95. But see also his "No Mere Technicalities: How Things Work and Why It Matters," *Technology and Culture* 40 (1999): 607–22, which expresses Post's concerns about the way historians of technology react to claims that "life without technology isn't an option."

14. Ellen Rose, *User Error: Resisting Computer Culture* (Toronto, 2003).

HARDWARE	SOFTWARE
Blackberry or PDA	JPEG image files
Compact disks	PDF files (plus Adobe Reader)
Cell phone	Electronic mail
Digital camera	Instant messaging or chat
DSL or cable modem	Groupware (Lotus Notes or Microsoft Outlook)
DVD player	Adobe Photoshop
GPS receiver	Microsoft Excel
MP3 player	Microsoft PowerPoint
Laptop computer	Microsoft Word
Desktop personal computer	Worldwide Web browser
Scanner, with digitizing software	Amazon.com
Sony MiniDisc recorder	Blackboard.com
VoIP telephone	Blogs
Wireless ethernet (Wi-Fi) networking device	Google
	HTML documents
	JSTOR
	Listservs, Usenet, or similar discussion groups
	ProQuest on-line newspaper retrieval
	QuickTime Virtual Reality
	Turnitin.com

I have probably left some out. Few readers will be enthusiastic users of every device or program or service listed above (though some will be). But I have made my point: Moore's law is at work.

Every three years, as chip capacity quadruples, a new generation of electronic products appears, along with new versions of existing software or new software products. Six years from now probably half the devices in my list of current hardware will be superseded. We see Moore's law at work in the progression of personal computer system software from CP/M to MS-DOS to Windows in its numerous versions, each integrating more and more functions (and triggering antitrust actions, to little avail). We see it, too, in the progression of personal computers, laptops, cell phones, digital cameras, MP3 players, and other devices far more powerful than the computer that accompanied Neil Armstrong, Michael Collins, and Buzz Aldrin to the Moon in 1969.[15]

15. The Apollo Guidance Computer had a read-write memory capacity of two thousand sixteen-bit words, or four thousand bytes. See the History of Recent Science and Technology project web pages for the Apollo Guidance Computer, http://hrst.mit.edu/hrs/apollo/public/, accessed July 2005.

JULY
2005
VOL. 46

It is this progression that drives the current relationship between culture and technology. Right now, many of us are abandoning film for digital photography. For those of us who took pleasure in working in a darkroom, this transition is painful. Do we have a choice? I vividly remember getting a pocket calculator and putting away my beloved slide rule.[16] It was a conscious decision that I made with an appreciation of its cultural implications. But who thinks about the wholesale transition to digital technology? Ellen Rose argues that we adopt these things en masse, without questioning them. And if we do not question them, we are at the mercy of those who produce and sell them to us. How can we espouse theories of the social shaping of technology when our daily interaction with technology is driven to such a great extent by the push of engineering?

This phenomenon seems, furthermore, without regard for the themes of gender, race, and class to which historians of technology have devoted so much attention. This journal, for example, has published an excellent study of women's involvement with programming early computers.[17] The popular press carries almost daily reports on, for example, how technologies such as the cell phone are used in less-developed countries lacking extensive wired phone infrastructure, how such technologies are differently adopted in various developed countries, how such devices are manufactured in Asia, or the outsourcing of software production to countries like India.

These are second-order examples of social construction. Silicon Valley firms frequently introduce products that fail in the marketplace, and the consumer plays a role in that process. Race, class, and gender factor into consumers' decisions. But transistor density and memory capacity never stop growing. The MIT faculty may balk at implementing a particular database product, but not at the doubling of chip capacity every eighteen months. It is a prerequisite for employment at MIT, Microsoft, or in Silicon Valley that one buy into the perpetuation of Moore's law. People who do not believe it must find work elsewhere.

Is this belief, then, an indication of the social construction of computing? I think not. Rather, it is an indication of the reality of technological determinism. Computing power must increase because it can.

PowerPoint

In an earlier version of this essay I examined the debate over Microsoft PowerPoint as a possible refutation of the thesis of determinism. Many

16. The calculator was a Hewlett-Packard HP-25C. The letter "C" meant that it used CMOS chips, novel at that time.

17. Jennifer S. Light, "When Computers Were Women," *Technology and Culture* 40 (1999): 455–83.

scholars have criticized this program. Edward Tufte, the well-known author of books on the visual presentation of information, is especially harsh, arguing that PowerPoint "elevates format over content, betraying an attitude of commercialism that turns everything into a sales pitch."[18] Vint Cerf, coinventor of the Internet protocols, prefers old-fashioned overhead transparencies and typically begins his public talks with the admonition, "Power corrupts; PowerPoint corrupts absolutely." For Cerf it is more of an apology; at most conferences he is the only speaker who does not use the program.[19] Originally I intended to add my own critique, but in the interval between early draft and later revision the debate was flattened by the steamroller of Moore's law. Neither Tufte nor Cerf has made the slightest dent in the adoption of PowerPoint. And if they could not, who can? Two years ago it was still possible to warn scholars not to use PowerPoint. Now that sounds like a crusty old newspaper reporter waxing nostalgic about his old Underwood (and the bottle of bourbon in the top desk drawer).

Comparing PowerPoint to Stalin, as Tufte does, does not advance the debate over technological determinism. Nor will it do to deny determinism because one uses only a fraction of the electronic devices listed above—or even none of them. In a famous and now fairly old essay titled "Why I Am Not Going to Buy a Computer," Wendell Berry raised many of the objections found in more recent critiques, albeit with a succinct eloquence that few can match.[20] One objection not found in many later commentaries that Berry nonetheless advanced was that his wife did the typing for him. That brought him a lot of criticism, of course, but no argument he could have raised would have made a difference. As Ellen Rose points out, even if one writes an essay in longhand, someone else will have to scan or key it into a computer before it can be published.[21] Who is kidding whom? All of these critiques wither before Moore's law. When I was preparing these remarks I found Berry's famous essay not by going to the library and looking for a print copy but by typing the title into Google. The full text came up in seconds. Whether Berry knows or cares that his writings can be found that way, I cannot say. Nor do I know if whoever put the essay onto the World-wide Web did so with a sense of irony. It does not matter. That is how one retrieves information nowadays.

18. Edward Tufte, "Power Corrupts: PowerPoint Corrupts Absolutely," *Wired*, September 2003, 118–19; also Ian Parker, "Absolute PowerPoint," *New Yorker*, 28 May 2001, 86–87.

19. This is the title of Tufte's article cited above, of course, but I heard Cerf use the phrase on the two occasions when we were on the same program as speakers; we were the only two who did not use PowerPoint.

20. The essay was published in print in various places, but I found it on the World-wide Web at http://www.tipiglen.dircon.co.uk/berrynot.html (accessed July 2005).

21. Rose (n. 14 above), 175. She is referring to Neil Postman, who proudly claimed that he wrote all his work by hand.

JULY
2005
VOL. 46

A common method by which scholars communicate today is via Microsoft Word files attached to e-mail messages. Most publishers and publications (including this journal) ask that manuscripts be submitted as e-mail attachments. Microsoft Word has its flaws; most of us who use it, for example, have encountered instances where the font suddenly changes, randomly, for no apparent reason.[22] Word is also a voracious consumer of memory, but thanks to Moore's law that does not matter. Attaching Word files to e-mail is simple and it works, and so the practice is ubiquitous. I compare it to the 4′8½″ railroad gauge, which experts say is slightly narrower than the optimum, in terms of engineering efficiency. That drawback is overshadowed by the virtue of being a standard.[23] But remember that the encoding of text in Word is controlled by Microsoft, and Microsoft has the right to change the code according to its needs—not ours. Indeed, Microsoft has done so in the past, and we may assume that it will do so again.[24] The same holds true of another "standard" now taking hold, Adobe's Portable Document Format (PDF). PDF files also take up a lot of memory, but that is not the problem. The coding of these files is owned by Adobe, not by the person who wrote the words or created the document. Before reading such a file, we have to look at a page of dense legalese that states that we "accept" whatever terms of use Adobe wants us to accept (I have never read it).

One response to these concerns is to adopt "open source" programs that do what Word and Acrobat do but run under some other operating system, such as Linux, and adhere to the GNU general public license. Such programs are available and their numbers are increasing. By definition, their source code is available publicly, without charge, and cannot ever come under the control of a private entity.[25] Users are encouraged to modify the software to fit their needs. The historian who learns how to write open-source code would be the present-day counterpart to one who could repair and modify his own automobile in the dim past.

But can open-source software refute the thesis that historians have no ability to control the pace of digital technology? Thus far, the number of historians of technology who use these programs is miniscule. Perhaps open source will prevail, but the movement is mature and yet has not had much effect on us.

22. This happened to me as I was preparing this essay.

23. George W. Hilton, *American Narrow Gauge Railroads* (Stanford, Calif., 1990).

24. And this does not address the question whether one can still read the disk on which a document was stored.

25. Paul Ceruzzi, "A War on Two Fronts: The U.S. Justice Department, Open Source, and Microsoft, 1995–2000," *Iterations*, an on-line journal, http://www.cbi.umn.edu/iterations/ceruzzi.html (accessed July 2005). Among colleagues in SHOT, I note that Bryan Pffafenberger, of the University of Virginia, uses open source software. At home I use several open-source programs, but my employer in general does not allow them at work. GNU, a recursive acronym for "GNU's Not UNIX," is, among other things, an open-source operating system.

An Internal Logic at Work

Historians need to be cautious when predicting the future—or, for that matter, assessing the present. Using ourselves as data points, as I (like Rosalind Williams) have done, is also dangerous. Yet the data are there, and it would be foolish to ignore our own actions. Readers interested in critiques of the pace of digital technology besides the ones cited here can find a range of studies.[26] I have not dwelled more on them because, like everything else, they have had no effect on Moore's law. For the same reason, I do not offer this essay as yet another critique of digitization. My goal is more modest: to ask that we step back from a social constructionist view of technology and consider that, in at least one instance, raw technological determinism is at work. Only then can we begin to make intelligent observations about the details of this process. Ross Bassett's *To the Digital Age* is one such study. There ought to be many more, and they ought to address the question of why the exponential advance of computer power is so impervious to social, economic, or political contexts.

I do not deny that the digital world we inhabit is socially constructed. I am reminded of it every time I observe the celebrity status afforded to Steve Jobs—who, by the way, is not an engineer. Biographies of individuals like Jobs tell how they willed the future into being through the strength of their personalities. One must read these biographies with care, but their arguments are valid. Studying the history of computing in the context of social, political, and economic forces makes sense. It identifies us as like-minded thinkers who do not embrace every new gadget. But if we assert the right to look at technology that way, we must also recognize that in at least one case, Moore's law, an internal logic is at work, and that it is based on old-fashioned hardware engineering that an earlier generation of historians once celebrated.

26. The best are written by computer-industry insiders. See, for example, Clifford Stoll, *Silicon Snake Oil: Second Thoughts on the Information Superhighway* (New York, 1996); Ben Shneiderman, *Leonardo's Laptop: Human Needs and the New Computing Technologies* (Cambridge, Mass., 2003); Steve Talbott, *The Future Does Not Compute* (Sebastopol, Calif., 1995); Thomas K. Landauer, *The Trouble with Computers: Usefulness, Usability, and Productivity* (Cambridge, Mass., 1995); Donald A. Norman, *The Invisible Computer: Why Good Products Fail, the Personal Computer Is so Complex, and Information Appliances Are the Solution* (Cambridge, Mass., 1998).