ESSAY

The Digital Construction of Technology

Rethinking the History of Computers in Society

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Envisioning Latour 2.0

When the young anthropologist Bruno Latour visited the laboratory at the Salk Institute for Biological Studies, he famously set aside all of his preconceptions about the goals and behaviors of its inhabitants. Rather than accept as reality the Salk researchers' self-interpretation of their collective enterprise, he carefully observed their day-to-day activities and material practices and came to his own somewhat startling conclusion. What the scientists and technicians at Salk spent the greatest part of their day doing, noticed Latour, was "coding, marking, altering, correcting, reading, and writing" various forms of documentary material. In this they resembled nothing so much as a "strange tribe" of "compulsive and manic writers" whose principal function seemed to be the manufacture of paper documents. Even their large and expensive experimental instruments acted primarily as "inscription devices," technologies designed specifically to "transform material substance into a figure or diagram."[1] It was through these various and repeated acts of inscription and transcription, argued Latour, that ordinary data was transmuted into scientific fact.

Whatever you might think about Latour's overall methods and analysis, his close attention to the material practices of scientific knowledge production inspired generations of historians and sociologists of science and technology to take seriously the notion that technique and technology are epistemologically significant. The tools we use to think with affect the char-

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1. Bruno Latour and Steve Woolgar, *Laboratory Life*, 48–51.

acter of our thoughts; to write something down is to transform it. The material culture of the laboratory is important because experimental instruments are agents in the production of scientific knowledge. It matters who built these instruments, and how, and for what purposes; it matters how these instruments are used, and by whom. These are no longer controversial assertions, even outside the narrow confines of the academic literature on science and technology studies.

Given that the close observation of material practices has proven such a productive methodology, it is curious how little attention has been paid within the historical community to the single most widespread and significant innovation that has occurred within the material culture of the laboratory—and indeed, almost every site of scientific or technoscientific activity in contemporary society.

Let us imagine, for a moment, that Latour were to return to the Salk Institute of the present to revisit his observations of four decades previous. There are many things about the institute that would be familiar: the stark modernism of the Louis Kahn–designed architecture; the academic credentials and distinctions of the research staff and their ambitious young postdoctoral fellows; the perpetual conversational obsession with publications, priority, and position. Latour might even recognize some old friends, or at least familiar faces. And yet there would be one striking and obvious difference that would be immediately evident: with the possible exception of the janitorial staff, every single employee of the Salk Institute would spend the majority of their time each day interacting with a computer screen. From scientist to secretary, their work would revolve around computer technology. Even those operating experimental instruments or other equipment would do so via a computer-based interface. In fact, to a naive observer, it might seem as if the designated role of most of the Salk researchers and technicians was simply to shuffle from one computer screen to another, with little perceptible differences among the activities engaged in at each location. Every room in the institute would contain at least one computer, and it would be difficult to distinguish between the computers in the rooms designated as "laboratories" and those labeled as "offices" (whether faculty or administrative). There would be entire rooms devoted to computers, some of which would only rarely be visited by human beings. All of the computers in the institute would be networked to every other, and computers would serve as the primary means of communication both within the institute and to the outer world. There would be nary a piece of actual paper in sight—with the possible exception of the Ph.D. diplomas hanging on the office walls, which would be as likely to reflect degrees in the fields of computer science and bioinformatics as in molecular biology.

It might be that our hypothetical Latour version 2.0 would explain away the pervasive presence of computers and other digital technologies in the laboratory as simply being the modern incarnation of the inscription device. After all, the majority of these technologies would be used, at least in part, for the creation of digital documents. In fact, the very essence of all of these machines could be described as being literary, their primary function being the reading and writing of codes—albeit codes intended to be read primarily by machines rather than people. Seen from this perspective, there would be no significant difference, at least in analytical terms, between the traditional version of a scientific "paper" and its electronic equivalent, or between the tracings on the paper tape of a 1960s-era gas chromatograph and the digital representation of the same produced by a more modern instrument. The larger interpretation of the laboratory would remain essentially the same, with the computer being merely the most convenient contemporary tool available to perform the more timeless and abstract tasks associated with scientific knowledge production.

To dismiss so easily this dramatic transformation of material practice would, however, run counter to the entire theoretical and methodological revolution in science studies that Latour himself played such a key role in enabling. It would also require him to ignore the visible evidence of another, perhaps even more profound incorporation of computer technology into the modern biological laboratory. Scattered across the Salk Institute are buildings whose very names—the Crick-Jacobs Center for Computational and Theoretical Biology, the Computational Neurobiology Laboratory, the Razavi Newman Center for Bioinformatics—bear witness to the centrality of the computer not just to the production, but to the content of scientific knowledge. Lily Kay, among others, has documented the ways in which concepts from computer science and information theory disseminated throughout the biological sciences in the late twentieth century. It is now commonplace, for example, to talk about the human genome as a code to be decrypted, the brain as a neural network, and disease as a "subspecies of information malfunction or communications pathology."[2] These are not mere metaphors, but statements about ontology. As the noted biologist Richard Dawkins described it, "genetics has become a branch of information technology. The genetic code is truly digital, in exactly the same way as computer codes. *This is not some vague analogy, it is the literal truth*."[3] For many working in the modern biological sciences, living cells are not *like* computers—they *are* computers. While the long-term utility and durability of this computational turn in biology might still be an open question, the existence of the phenomenon is undeniable. Without presuming to know the mind of Latour, it seems safe to assume that if he were to repeat his visit to the Salk Institute, he would both notice and take seriously the transformative power of the electronic digital computer and its kindred technologies.

2. Lily Kay, "Who Wrote the Book of Life?"; Hunter Crowther-Heyck, "George A. Miller, Language, and the Computer Metaphor of Mind"; Donna Haraway, "Cyborg Manifesto"; Cornelius Borck, "Toys Are Us."

3. Richard Dawkins, "Genetics" (emphasis added).

The pervasive ubiquity of the computer and the computational mindset are hardly confined to the Salk Institute or the biological sciences. In the past several decades, computational models and techniques have transformed the theory and practice of disciplines as diverse as physics, economics, psychology, linguistics, anthropology, psychology, meteorology, cognitive science, and ecology. The dominance of the computer in the practice of engineering has been especially dramatic: until the final stages of production, it is not unusual for a manufactured good to live an almost entirely virtual existence. Engineers use computer-aided design tools to construct digital models, evaluate those digital models using computational techniques like finite element analysis, and test their performance in virtual environments via virtual instruments before transmitting their designs in digital form over electronic networks to computer-controlled machine tools. Many of the products that these engineers design with computers contain their own computers embedded within them: microprocessor-based control systems are used as key components in everything from automobiles to elevators, from refrigerators to pacemakers, from electronic books to children's toys. In fact, there are few technologies, industries, or social practices that have not been significantly influenced, if not radically transformed, by the incorporation of computers and computer-based technologies.

Outside of the academic historical literature, the centrality of the computer to contemporary social, political, and economic life is widely recognized. No technological development of the past century is considered to be as profoundly influential as the invention of the electronic digital computer. Indeed, in most contemporary contexts, the word "technology" has come to mean computer technology. When educators advocate for more technology in the classroom, medical practitioners for more technology in the hospital, and economists for the development of a more technology-proficient workforce, they are not talking about filing cabinets, stethoscopes, or drill-press operators; what they are calling for is more computers, computer-based diagnostic systems, and computer-savvy technicians. There is a vast and growing popular literature on the impact of computerization on almost every aspect of modern society. And while historians of technology are right to be skeptical of the hyperbole and simplistic determinism that characterizes much of this literature, we also ignore it at our peril, as David Edgerton has recently suggested.[4] By not engaging more substantially with the technological phenomena that most of our contemporaries regard as one of the most consequential of all in human history, historians of technology run the risk of becoming increasingly irrelevant, losing our voice in a conversation to which we, of all disciplines, are uniquely prepared to contribute.

But what exactly does the history of technology have to say to the broad

4. David Edgerton, "Innovation, Technology, or History."

range of questions raised by the hegemonic technological, intellectual, and ideological dominance of computers, computing, and the computational mindset? Thus far our contributions have largely been confined to the history of the computer, which is a worthy topic and one that capitalizes on our traditional strengths of studying engineers, innovation, and industries. But this focus on the machinery of computation also limits our ability to speak to larger questions. Consider, for example, the many computers we noticed earlier in our imagined tour of the Salk Institute: in terms of their underlying physical architecture they would be essentially identical, commodity hardware such as could be purchased anywhere by anyone. But each of these generic machines would be transformed, depending on the software program it was running, into an almost infinite range of specific devices, from word processor to communications tool to simulation model to (no doubt surreptitiously) video game console. Historians of technology are only just beginning to come to terms with the history of software, a subject of even larger scope and complexity than the history of the hardware that runs it. And as for the larger history of computerization, as it transformed the ways in which the Salk biologists conceptualize and practice their discipline, or engineers and architects design and build things, or artists make music, movies, or photographs, or average citizens communicate, consume, and interact with their environment—these are obviously not just one history but many, all linked in fundamental and significant ways by their shared reliance on the vast sociotechnological network of computers, microprocessors, and other digital devices.

It may be that the story of the computerization or, as I will argue, the digitization of modern society is too massive, recent, or amorphous a topic for any one discipline to claim in its entirety. Communications departments, information schools, interdisciplinary programs in the digital humanities, and the emerging discipline of internet studies have all laid claim to some of this territory, and for legitimate reasons. But many of these approaches are frustratingly ahistorical, adopting unquestioningly the claims of computer enthusiasts and internet utopians that we are living through a technological revolution unprecedented in all of human history. There is a desperate need for historians of technology, with their long tradition of providing nuanced, theoretically sophisticated analyses of technological and cultural developments, to provide some historical context for understanding these phenomena.

In this essay I will explore the ways in which the history of science and technology has thus far engaged with the history of computers, computing, computerization, and other closely related technologies and practices. I will argue for a new approach toward integrating these histories and addressing more directly the broader questions being raised by academics in other disciplines, by policy makers and business leaders, and by the larger general public.

Whither the History of Computing?

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The conventional classification used within the history of technology discipline to designate works dealing with the topics outlined above is "history of computing." For most of the past few decades this has been a serviceable category, covering in theory both machines (computers) and processes (computing). In recent years, as our understanding of the relevant histories of modern-day ICTs (information and communications technologies) and other digital devices has expanded to include a whole host of developments and technologies for which no one term is a satisfactorily comprehensive descriptor—including, for example, the data-processing machines that predated the electronic digital computer, such as the mechanical tabulating machine, or the many communication devices whose histories are essential to understanding the social and technological architecture of the contemporary smart-phone—specialists in the history of computing have experimented with using other unifying concepts around which to organize their respective disciplines. For example, it is no coincidence that so many of these historians hold positions in schools of information, given that the seemingly universal desire to manage and control information is a common theme in much of their work. This said, "history of computing" remains the dominant, catchall term for describing all these subdisciplines.

Within the history of computing literature, the primary concern has been the development of the electronic digital computer. This represents both the popular understanding of what is the most significant innovation in the history of computing, as well as the background of many of the earliest historians working in this area. These included many computer professionals-turned-amateur historians who, like many non-academic historians of technology, were concerned primarily with the key moments of invention and questions of priority.[5] The academic historians who wrote about computing tended to have backgrounds in the history of science, mathematics, or technology, and although they produced much more sophisticated histories, they also tended to address questions of interest to their respective disciplines and focus on the contributions of the traditional academic, scientific, and engineering elites. As a result, these histories gravitated naturally toward the high-status activities associated with the design and theorization of computers, rather than toward the more mundane work of actual computation. To the degree that they dealt with computing, as opposed to the computer, they focused almost exclusively on scientific computing. In the popular literature, of course, the emphasis has always been on great men and important "firsts," on the massive early arti-

5. Herman Lukoff, *From Dits to Bits*; David E. Lundstrom, *A Few Good Men from Univac*; Michael Williams, *A History of Computing Technology*; Alice Rowe Burks, *Who Invented the Computer?*

facts that now look so impressive mounted in museums, and on the lineage of technological descent from past accomplishments that best explains the shape of things in the present.

It did not take long, however, for the academic historians at least to discover a history of computing that predated the invention of the electronic digital computer, and that challenged the very centrality of the computer in that history. Most obvious were the immediate precursors of the large-scale electronic-computing experiments of the World War II period, including mechanical calculating machines, human computing projects, and analog-electric cybernetic control systems.[6] It turned out that there were also entire industries devoted to information and data processing, such as the business machines industry, whose origins were distinct from those of scientific computing and pursued an entirely different technological trajectory, but which came to define during the immediate postwar period not only the technical architecture of the electronic computer, but also its cultural meaning and social significance.[7] In fact, the "Cambrian explosion" of innovation that occurred in the business machines industry during the last decades of the nineteenth century, which produced most of the firms, such as IBM, Burroughs, Honeywell, and Remington Rand, that would later play such formative roles in the early commercial computer industry, was at least as significant in the history of modern computing as the later innovations that would emerge from the wartime experiments with electronic calculating machines.[8] The fact that none of these companies viewed themselves as being primarily involved in "computing," at least for the first half-century or more of their existences, complicated our understanding of what the history of computing was really about. In their excellent (and extraordinarily durable) historical synthesis of this second generation of history-of-computing literature, Martin Campbell-Kelly and William Aspray characterized the computer as "the information machine," which aptly captured this new perspective on relevant history—or histories, as Michael Mahoney repeatedly argued is the more appropriate description.[9]

The expansion of the history of computing to include more information-processing technologies than just the electronic computer opened up the field to a broader range of participants as well. Historians looking beyond the manufacturing of computers began asking questions about how computers were used, by whom, and for what purposes. They uncovered the crucial contributions made by nonelite actors like technicians, opera-

6. Paul Ceruzzi, *Reckoners*; David Alan Grier, *When Computers Were Human*; David A. Mindell, *Between Human and Machine*.

7. James Beniger, *The Control Revolution*; JoAnne Yates, *Control through Communication*; Alfred Chandler and James Cortada, *A Nation Transformed by Information*.

8. James Cortada, *Before the Computer*; Lars Heide, *Punched-Card Systems and the Early Information Explosion*.

9. Martin Campbell-Kelly and William Aspray, *Computer*; Michael S. Mahoney, "The Histories of Computing(s)."

tors, and programmers, and in doing so rediscovered the significant presence of women in computing.[10] They also revealed the ideological dimensions of the computer revolution: far from being an inevitable consequence of economic rationality, the desire to computerize was often driven by the need for centralized administrative control, or to advance individual or professional agendas, or simply to appear cutting-edge and "shiny."[11] For a wide variety of efficiency experts, systems men, management consultants, and government officials, the novel and as yet inchoate technology of electronic computing represented the ideal tool with which to achieve goals that already had been decided on. In this case, computerization was a means to an end, not the end in itself. But although this new generation of historians of computing engaged explicitly with other historical literatures like those of business, labor, and social history, they continued to take seriously the centrality of technology in the larger structures of power and processes of social change. To borrow from a felicitous phrase from Jon Agar's history of computing initiatives in the British civil service, historians of computing were "putting the 'bureau' back into 'bureaucracy.'"[12] In doing so, they not only enriched the specialist history of computing literature, but reminded historians in other subdisciplines that any serious study of mid- to late-twentieth-century history would necessarily have to engage with innovations in computing and information technology.

The Protean Machine

Perhaps the most promising development in the recent literature on the history of computing has been the increasing focus on software. The history of software has long been recognized as a critical subject of historical inquiry, but it is only in the past decade that historians have developed the tools and methods to write about it effectively. While the significance of software is widely acknowledged, coming to terms with it from a historical perspective has proven extraordinarily difficult.[13]

First, a note on why software is so central to our modern understanding of what computers are and what they can be used for. The first electronic digital computers were designed as special-purpose machines understood primarily in terms of existing traditions of mechanical (or at least

10. Jennifer Light, "When Computers Were Women"; Marie Hicks, "Only the Clothes Changed"; Nathan Ensmenger, "Making Programming Masculine."

11. Thomas Haigh, "The Chromium-Plated Tabulator"; Nathan Ensmenger, "Letting the 'Computer Boys' Take Over"; Eden Medina, *Cybernetic Revolutionaries*; Joseph A. November, *Biomedical Computing*; Christopher D. McKenna, *The World's Newest Profession*.

12. Jon Agar, *The Government Machine*, 6.

13. Ulf Hashagen, Reinhard Keil-Slawik, and Arthur L. Norberg, eds., *History of Computing*; Martin Campbell-Kelly, "The History of the History of Software"; Michael S. Mahoney, "What Makes the History of Software Hard."

mechanically assisted) calculation. But it was soon realized that, by reengineering these devices to eliminate the distinction between the operating instructions of the device (its program) and the data on which it operated, the electronic digital computer could be reinvented—and reconceptualized—as a universal logic machine. It is this inherent flexibility, and its ability to be programmed via software to serve an almost infinite number of purposes, that makes the electronic digital computer such a powerful and compelling technology. Given the right software, an electronic digital computer can simulate, control, or even replicate almost any other complex technological, social, or even biological system. "What the gears cannot do the computer might," the pioneering computer scientist Seymour Papert famously suggested, "The computer is the Proteus of machines. Its essence is its universality, its power to simulate."[14] While the perceived universality of the computer has certainly been overstated, it is clear that it is software, as much as the computer itself, that makes such claims and predictions plausible.

Software is also what defines our relationship to the computer. It is what we experience when we interact with the machine. It turns the generic, commodity computer configuration—screen, keyboard, and the (quite literally) black boxes that contain all of its essential circuity—into a multipurpose collection of capabilities that reflects our particular requirements and desires, such as an email client, word processor, media player, simulated oscilloscope, or a collection of virtual Angry Birds, among many other things. We might not know what kind of computer we are using or who manufactured it, but we definitely know what software we are currently running. It is software that provides the computer with such an unusual degree of sustained interpretive flexibility, and software that provides the computer with much of its perceived economic, social, and cultural significance.[15]

The idea that it is the software that defines the computer is not some mere flight of fancy sprung from the fevered imagination of a postmodern theorist, but is rather the essence of all modern theories of computation. For present-day computer scientists, the computer is by definition a machine that runs a certain kind of software program; whether the machine is electronic, digital, biological, or even material is irrelevant. What matters is that it can run software. It is this notion of the abstract computer, the Platonic ideal known as the universal Turing machine, that renders the computational mindset so compelling—and indeed, so hegemonic. Any system that can be described in terms of a Turing machine is a type of computer and can be understood using computational terminology. This is what allows Dawkins to describe the genome as computer code, the physicist Stephen Wolfram to conclude that the universe is fundamentally digital, and

14. Seymour Papert, *Mindstorms*, viii.
15. Sherry Turkle, *The Second Self*.

the psychologist Steven Pinker to represent the human brain as the intersection of Darwin and a computer program.[16]

But we are running ahead of ourselves. From a historical perspective, this understanding of software as the essence of computing took some time to develop. The first electronic digital computers were simply programmable calculators. The pioneering ENIAC machine, for example, was not so much *programmed* as *configured*, with each new application requiring extensive preparation, because the machine needed to be rewired using plug cables and mechanical dials. The work involved in "setting up" the computer was considered to be low-skilled clerical work and was accordingly assigned to low-status, female machine operators. The assumption of the ENIAC project leaders and most other early hardware designers was that once scientists or engineers had decided what work the computer needed to do, "programming" it to actually complete the task would be a relatively mechanical process of translating from one language (English, for example) into another (machine language, or assembly code). As it turned out, neither step in this process was straightforward. Not only was the work of programming extraordinarily difficult, but it also became evident that even deciding *what* to program presented serious challenges. Indeed, by the end of the 1950s the critical "reverse salient" of the nascent computer industry had shifted from hardware design and construction (building the computers themselves) to software development ("software" was defined at the time as being everything about a computer installation that was not obviously "tubes, transistors, wires, tapes and the like").[17] It was this "everthing else" about computers that turned out to be the real complication.

What made software so difficult to develop is exactly what makes it so interesting to historians. Whereas the computer itself was a definite material artifact that could readily be identified and isolated for testing, evaluation, and improvement, software systems were inextricably intertwined with a larger system of computing that included not just machines, but also people and processes. The software that had to be developed to computerize an accounting operation, for example, included not only computer code, but also an analysis of existing operations, the reorganization of procedures and personnel, the training of users, the construction of peripheral support tools and technologies, and the production of new manuals and other documentary materials.[18] Of all of the aspects of software development, writing the actual application code generally involved no more than a third of the overall time and effort. And even after the accounting application had been designed, coded, tested, and debugged (and in the process often redesigned and reprogrammed), the system would have to be oper-

16. Dawkins, "Genetics"; Stephen Wolfram, *A New Kind of Science*; Steven Pinker, *How the Mind Works*.

17. John W. Tukey, "The Teaching of Concrete Mathematics."

18. Andrew Friedman and Dominic Cornford, *Computer Systems Development*.

ated and, unexpectedly, continuously maintained—not because the software application would "break," but rather the context in which it was used or the other systems it interacted with, including such nontechnical systems as corporate accounting policies and governmental regulations, would change over time. As much as two-thirds of the costs of a software system were incurred *after* the software was developed and operational.[19] For computer users, the vague boundary between the social and the technical aspects embodied by the software was an expensive nightmare; for historians of technology, it is a goldmine. A better example of the complexity of a sociotechnical system or a heterogeneous network can scarcely be imagined.[20] Software is where the technology of computing intersects with social relationships, organizational politics, and personal agendas.[21]

As I have argued extensively elsewhere, software is an extraordinarily heterogenous technology; it straddles the boundaries between science and technology, art and engineering, and the intellectual and the material.[22] Software is clearly a built object, designed and implemented by humans, yet it is also a mathematical formalism, an appropriate object of study for the scientist or theorist.[23] The people who develop software refer to themselves alternatively as programmers, computer scientists, or software engineers—as well as black artists, wizards, hackers, gurus, and cowboys.[24] They do not fit neatly into established academic or professional categories. The systems they construct are as much literary as technological productions, and are often referred to by practitioners as such.[25] Like a poem, a program exists in the mind of its creator, regardless of whether it is ever written or performed. Software might even be considered a form of incantation: words are spoken (or at least written) and the world changes.[26] A computer program is invisible, ethereal, and ephemeral. It exists simultaneously as an idea, as language, as technology, and as practice. Certain forms of software, such as a sorting algorithm, can be generalized and formalized as mathematical abstractions, while others remain inescapably local and specific, subject to the particular constraints imposed by corporate cultures, formal and informal industry standards, and/or government regulations.[27] In this sense, software sits ambiguously at the intersection of science, engineering,

19. Nathan Ensmenger, "Software as History Embodied."

20. John Law, "Notes on the Theory of Actor-Network"; Bruno Latour, "Social Theory and the Study of Computerized Work Sites."

21. Thomas Haigh, "Inventing Information Systems."

22. Nathan Ensmenger, *The Computer Boys Take Over*.

23. Michael S. Mahoney, "Software as Science"; Herbert Simon, *The Sciences of the Artificial*.

24. Maurice Black, "The Art of Code"; Paul Graham, *Hackers & Painters*; Ensmenger, *The Computer Boys Take Over*.

25. Frederick Brooks, *The Mythical Man-Month*.

26. Wendy Hui Kyong Chun, "On 'Sourcery,' or Code as Fetish."

27. JoAnne Yates, *Structuring the Information Age*.

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and business. As may be imagined, all this heterogeneity renders software extraordinarily difficult to isolate, understand, and write about.[28]

Because the heterogeneity of software inevitably shifts the eye of the historian from his traditional focus on the computer as artifact and toward the larger context in which computers function in society, the emerging scholarship in this area has opened up new questions, sources, and sites of historical analysis. Among other things, the study of software allows the historian of computing the opportunity to analyze failure. Whereas the story of computer hardware is dominated by triumphal and deterministic progress narratives driven by the seemingly inexorable march of Moore's law toward smaller, faster, and less expensive microelectronics, the history of software is characterized by conflict, tension, and disillusionment. More than three-quarters of all software development projects fail to be completed. The costs associated with software development continue to rise, and complaints about software projects being over-budget, behind-schedule, and bug-ridden remain a constant refrain within the industry literature.[29] For more than four decades key leaders in software development have been warning about a looming "software crisis" threatening the health and future of their industry. The Y2K and H1B crises and a whole host of other conflicts and debates provide ample opportunity to explore questions about technical expertise, professional identity, community dynamics, and race, ethnicity, and gender. In fact, most of the controversies attributed to various aspects of computerization, including concerns about technologically driven unemployment, government surveillance, breaches of privacy, cybercrime, and so on, are really, at their hearts, debates about software and/or software developers. While clearly, in the end, software is largely a success story—after all, without functioning software, there would have been no computer revolution—the prominent visibility of failure in the software story is an excellent lens through which to view the messiness and permeability of the computer/society continuum. As Rosalind Williams wrote about her experience as an MIT adminstrator attempting to implement a university-wide software system, "In a digital world, technological consciousness and cultural consciousness are simultaneously heightened. . . . The relationship between the two is one of constant and often painful tradeoffs."[30]

Another productive avenue of research opened up by the history of

28. The ephemeral nature of software also poses serious challenges to the archivist, museum curator, and historical researcher. Even when the actual source or machine code of a particular software package has been saved, the social and technological systems that allow it to function are generally not available. For good reason, archivists warn about this period in history degrading into a digital dark age.

29. Eloina Paleaz, "A Gift from Pandora's Box"; Ceruzzi, "Moore's Law and Technological Determinism"; David C. Brock and Christophe Lécuyer, "Digital Foundations."

30. Nathan Ensmenger, "The 'Question of Professionalism' in the Computer Fields"; Rosalind Williams, "Historians of Technology in the Information Age."

software has to do with the study of computer use and users. Historians of technology have long been interested in the ways in which artifacts and their users are co-constructed through use-practices. Given the inherent plasticity of the programmable digital computer, this process of co-construction is particularly visible. Obviously some users, such as operators, technicians, and programmers, have a great deal of control over the structure, function, and meaning of the technology. But all users have at least the perception of control over the computer as it is represented and made tangible by software. One of the defining features of software is its literary nature: the way the software works is determined, to a greater or lesser degree, by how the software is written. This implies, in theory at least, that software can also be rewritten, which means that all software is contingent, transitional, and subject to constant renegotiation and redesign. Whereas conventional engineers and architects plan carefully before committing their ideas to manufacturing, computer programmers face no such material constraints on their creativity. While this allowed programmers an unprecedented degree of freedom and creativity ("build first and draw up the specification afterwards" was a frequent mantra of the software industry), it also created unrealistic expectations on the part of the ultimate end-users of the software. Software applications were perpetually works in progress, with new features being requested and new bugs introduced.

As more of the programmability of the computer was made visible to the end-users (what is a spreadsheet, after all, but a specialized interface to a programming language?), the possibilities for users to reconfigure their software to their own preferences and requirements became even more apparent. This became even more true with the development of the personal computer, which created both new users and a new category of computer software: the mass-market, prepackaged consumer good that, as Campbell-Kelly suggests, has as much in common with the products of the entertainment industry as with the custom-made software systems of the earlier mainframe era.[31] The taxonomy of software types that Campbell-Kelly develops is an excellent reminder that although all software shares some essential characteristics, specific software systems, such as those developed for particular machines, industry standards, regulatory environments, corporate cultures, or technical ecosystems, are very different technologies indeed.[32] In any case, the software developed for personal computers, which is inexpensive, often amateurish, and, in the early years at least, extremely limited, nevertheless provided a kind of power to computer users that was previously nonexistent. Jon Lindsay, for example, in a recent issue of *Technology and Culture* describes the way in which individual air force pilots

31. Martin Campbell-Kelly, *From Airline Reservations to Sonic the Hedgehog.*

32. Jeanette Hofmann, "Writers, Texts and Writing Acts"; Jessica Johnston, *Technological Turf Wars.*

could circumvent the policies of the U.S. military simply by loading a piece of software smuggled on a floppy disk onto a personal computer.[33] And Steven Levy, among others, suggests that the development of spreadsheet software created the context for a fundamental change within U.S. financial markets.[34] There are few consumer-oriented software packages today that are not built around the idea that end-users will also act as programmers. The business models of most present-day video-game companies, for example, rely upon the players themselves to generate their games' core functionality and content.

Everything Is Digital

The incorporation of the history of software into the history of computing has greatly expanded its ability to address the questions outlined at the beginning of this essay: namely, how historians of science and technology can engage productively with the pervasive and powerful influence of computers and computational thinking in almost every intellectual, economic, and social activity of the previous half-century. Nevertheless, the rich possibilities suggested by the inclusive term "computing" have been limited by the narrow specificity implied by the word "computer." A key feature of the very phenomena that we are interested in studying has to do with the hegemony of computational discourse, the way in which an increasing number of complex physical and social systems are being redefined in terms of an abstract and universalizing understanding of the computer. Unless we, as historians, adopt this same broad conception of the computer as a timeless ontological entity (which is, of course, fundamentally ahistorical), it can be difficult both to acknowledge the computer as a significant and unifying presence in contemporary history and to find a useful language for talking about related though definitively distinct techniques and technologies.

One approach to solving this historiographic conundrum is to situate the electronic digital computer within a larger history of information technology. This has the distinct virtue of linking the computer to earlier or parallel technological developments without suggesting, for example, that a Hollerith tabulator is simply a primitive attempt at implementing a Turing machine. The term "information technology" also encompasses communications technologies, which in the era of the iPhone are revealed to be central to our overall understanding of what it means to be a "computerized" society. And for some scholars, the concept of "information" provides a more fundamental unit of analysis than even the abstract, timeless, uni-

33. Jon R. Lindsay, "War upon the Map."

34. Steven Levy, "A Spreadsheet Way of Knowledge"; Robert X. Cringely, *Accidental Empires*.

versal computer. According to information theory, for example, information is just another property of matter, a measure of its degree of organization and the negative of entropy. Almost everyone else uses the term in a more colloquial sense, but with the shared assumption that information, and the desire to organize and communicate it, is common across all periods and cultures. The study of how various societies and individuals engage in information-seeking behaviors, develop systems of information organization, management, and communication, and conceptualize the role of information in other processes of social and cultural change has proven to be an important complement to the history-of-computing approach.[35]

The problem with the term "information" is that it contains too many multitudes; outside of the technical literature, it is used almost indiscriminately. Once information is adopted as a fundamental unit of analysis, then almost everything becomes an information technology: cuneiform scratches, quipu knots, smoke signals, quill pens and parchment, church bells, newspapers, optical telegraphs, and so on. While there are some interesting commonalities among all of these technologies, it is not clear that lumping them together into a single conceptual category adds much to our understanding of information. Although there are important historical questions that, very broadly, can be asked about the history of information; the danger is that we lose sight of the specific character of the underlying technological changes that make some forms of information technology especially meaningful in specific historical contexts. In popular literature on information in particular, the role of technology is simultaneously taken too seriously (making it fundamentally determinist) and not seriously enough (in the sense that the particularities of any given technological system are rarely analyzed in any actual detail). There does seem to be something especially powerful, for example, about the digital representations of information made possible by the technology of the computer. These representations are not unprecedented and do not stand outside of history as some enthusiasts and theorists would have us believe, but their specific technical features are nonetheless highly significant. While the laboratories at the Salk Institute have always been deeply connected to the history of information, the remarkable changes in scientific practice and material culture that have occurred there in recent decades seem more fundamental than a mere change in scale or scope.

For these reasons and more, I am going to suggest that a productive strategy for addressing the questions raised by computers and information technology is to talk not in terms of "computerization," but rather "digitization." There are obvious similarities between the two processes, but focusing

35. Chandler and Cortada, *A Nation Transformed by Information*; Bruce Allen Bimber, *Information and American Democracy*; Daniel Headrick, *When Information Came of Age*; Reijo Savolainen, *Everyday Information Practices*; William Aspray and Barbara M. Hayes, *Everyday Information*.

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on the constellation of technologies and practices linked together by the common characteristic of being digital offers some significant advantages.

First, a few clarifications are necessary: not all computers are digital, and not all digital devices are computers. Not every digital device encodes information in exactly the same format, although most modern digital devices store and communicate data in a binary format. Digital devices are not necessarily electronic—consider, for example, the digital data stored in the ivory tablet of a Jacquard loom or the paper tapes that control a mechanical player piano—but the invention of the vacuum tube and the transistor made it possible to communicate and manipulate digital data as a series of electronic pulses. Subsequent innovations in chemistry, physics, and semiconductor manufacturing made possible the mass production of densely packed collections of transistors on a silicon wafer.[36] As a result, most modern digital devices contain their own tiny microprocessor computer and therefore share a collective family resemblance. Many of the same hardware and software technologies that can be found in the internals of your laptop computer can also be found in your cell phone, digital camera, and high-definition LED television. The skills required to design and program digital devices are therefore the same as those to design and program more conventional computers. Nevertheless, the concepts of "computer" and "digital" are not always interchangeable, and it is important to maintain this distinction.

So why digitization and not simply computerization? To begin with, of the two concepts, the former is broader and more inclusive, encompassing both conventional computing devices and novel hybrid technologies like smartphones and video game consoles, while still being coherent enough to remain analytically productive; the latter is limited by its close historical association with one particular technology. This association has long been problematic: many of the founders of the discipline of computer science soon regretted the conflation of "computing" with "computer," and within a decade of its founding, the discipline's principal professional society, the Association of Computing Machinery, proposed dropping "machinery" altogether. In any case, to computerize an organization or process still implies the adoption of certain types of machines; but what it means for that same organization or process to "go digital," on the other hand, involves a range of technologies and practices, some of which might require the incorporation of traditional computers although not necessarily so.

More significantly, the idea of digitization encompasses not only artifacts, but also data representations. Among the many commonalities found in digital devices—including the fact that most are constructed around a common core of components and formal and informal standards and design conventions—they all, by definition, operate on data stored in a dig-

36. Ross Knox Bassett, *To the Digital Age*; Christophe Lécuyer, *Making Silicon Valley*.

ital format. The formats built around binary data are particularly amenable to being stored and manipulated electronically. Digital data is not required to be either binary or electronic, but the shared infrastructure built around the data stored digitally in such a medium allows digital devices an extraordinary range of interconnectivity. Once data is in digital format, it can be replicated, transformed, and communicated by using an ever-increasing range of readily available technologies. The notion of being digital implies therefore both a specific type of technology and the structure of the underlying data. Unlike information, which lacks grounding in any particular medium, digital implies an underlying technological architecture. This is important because, as we well know, the construction of any technological architecture is never a value-neutral proposition. In the same way that to write something down is to transform it, to represent something in digital format is to fundamentally alter its nature.[37] This is an essential insight drawn from the history of technology that is too often neglected in most popular treatments of the computer and the information revolution.[38]

It is important to note that this process of digitization is not the same as quantification. Although digital data is essentially numeric data (binary data is typically represented as a series of "1"s and "0"s, for example), to digitize a phenomenon is not simply to translate it into numbers. The defining motivation of quantification is measurement; the principal goal of digitization, however, is manipulation. The representation of an acoustic wave as an MP3 file, for example, involves much more than another method of measuring and quantifying sound; in fact, as a means of capturing the information contained in the original sound wave, the MP3 format represents a regression from alternative, analog representations. Although the digital data in an MP3 file is numeric data, these numbers are not so much a *measurement* of sound as a *model* of sound. The value of that model is not so much that it is accurate as it is manipulable; MP3 data is valuable because it is easy to capture, store, communicate, analyze, and transform. It is only within a digital ecosystem of networks and devices that digital data becomes truly significant; but the rapidly increasing scale and scope of this ecosystem makes the imperative to digitize almost irresistable. There is, of course, a close relationship between the historical processes that encouraged and enabled quantification and those that currently drive digitization, but they are not identical.

It is the combination of data and the means of manipulating it that makes the concept of digitization so much more compelling than computerization. The common project of the scientists, technicians, and support staff at the present-day Salk Institute is not, after all, the wholesale adoption of computer technology, but rather the generation, manipulation, and pres-

37. Paul Edwards, *The Closed World*; Kathryn Henderson, *On Line and on Paper*.
38. James Gleick, *The Information*.

entation of digital data. To play once more on an observation of Latour, they are a strange tribe of compulsive and manic digitizers, not compulsive and manic computerizers. And the digital data generated by the instruments and researchers at the institute are not simply digital representations of the numeric data or paper documents previously recorded or inscribed in an earlier era; what makes this new kind of digital data so powerful is that it can be incorporated into a digital model represented in software on a digital computer. The integration of digital data and digital model allows for the digital simulation of the original physical system, which is what is so revolutionary about the presence of the computer in the scientific laboratory. New knowledge is produced not by observing and experimenting on the natural world, but by simulating the natural world within a virtual environment. This is a fundamental shift in the epistemological foundations of the scientific enterprise. Peter Galison writes about the origins of this shift in microphysics; Paul Edwards describes this process as it occured in meteorology; and Diane Bailey, Paul Leonardi, and Stephen Barley describe a similar process under way in automative engineering.[39] There is a small but growing literature on the philosophical implications of digital modeling in the sciences.[40] The influence of digital technology on the processes of scientific knowledge production and engineering design are nevertheless not yet thoroughly documented by historians and are therefore an area that begs for further work.

A vivid illustration of the difference between computerization and digitization can be found in the motion-picture industry. Almost all contemporary filmmaking (the word "film" here is a quaint reference to an earlier technological era) incorporates at least some degree of computer-generated graphics, if only to draw in a background or to erase unwanted elements. In fact, in most studios the production process, from start to finish, has become almost entirely digital and therefore computers are omnipresent and indispensable. But the computer is only one of the digital elements of a larger digital toolchain that, when taken together, have entirely transformed the modern film industry. Computer-generated images are more than simply the representations, in digital form, of the same visual information that in a previous generation would have been captured and stored using photochemistry. To be sure, there are some that are mere digital paintings or virtual backdrops, but for the most part, computer-generated images are two-dimensional snapshots of what is really a three-dimensional digital model or sculpture. Computer artists in the film industry do not use computers so much to draw digital images as to construct digital environments. Once a setting or character has been modeled in digital format it takes on an almost material reality. If a director wants to change the

39. Peter Galison, "Computer Simulations and the Trading Zone"; Paul Edwards, *A Vast Machine*; Diane Bailey, Paul Leonardi, and Stephen Barley, "The Lure of the Virtual."

40. Eric Winsberg, *Science in the Age of Computer Simulation*.

angle of the shot or the perspective of the camera, he or she does not need to have an artist or animator redraw the scene; instead, a virtual camera is simply rotated within the digital environment. In an epic production like the *Lord of the Rings* trilogy, entire armies of virtual actors were developed to populate the massive battle scenes.[41] These digital soldiers were not animations drawn on computers; they were simulated life forms whose broad patterns of behavior were preprogrammed into their software, but whose individual actions emerged only as the simulation played out in real time. The essential characteristic of this new mode of film production is that it is digital, not simply that it is computerized; the difference is that digital implies both a kind of tool and a model of data representation.

There are many questions that the history of technology might ask about the process of digitization as it has occurred in industries and activities as varied as science, filmmaking, musical performance, engineering design, and social interaction. Many of these involve the traditional concerns of the historian of computing. But there are also new insights to be gained from shifting our emphasis from the computer to the digital. At the moment, our treatment of these topics is too narrow, too focused on machines rather than data, representations, and processes. In the broader culture, talk of computerization and the computer age already sounds dated and irrelevant. Without chasing too closely the whims of the contemporary zeitgeist, historians of technology need to engage more directly with the popular conversation about the digital revolution. It is the activity of digitization, not computerization, that is occurring repeatedly throughout our laboratories, factories, studios, schools, shopping malls, and living rooms. Like the terms "computer," "computing," "information," and "information technology," "digital" can be a vague and elusive descriptor. Nevertheless, the idea of the digital captures better than its alternatives the distinctive features of the technological and conceptual phenomenon that we are interested in understanding. Stepping back and witnessing these acts of digital inscription with new eyes and a deliberately naive perspective, we will uncover new questions, challenge stale historiographical certainties, and produce better and more compelling histories.

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41. Thompson, "Scale, Spectacle and Vertiginous Movement."

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