Where Are We Going, Phil Morse? Changing Agendas and the Rhetoric of Obviousness in the Transformation of Computing at MIT, 1939–1957

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This paper discusses the failure of the attempt to establish a computational center at MIT in the 1930s and the effect it had on the subsequent shift from analog to digital computing during the 1950s.

Introduction

In 1957, the Massachusetts Institute of Technology (MIT) threw the switches on a newly installed IBM 704 that signaled both the inauguration of its new Computation Center under the leadership of Philip Morse and a commitment to leadership in the dynamic field of computing. Yet this was not the first time MIT had made such a commitment. In the 1930s, MIT had embarked on a similar effort, one that seemed on the verge of fulfillment when the Carnegie Corporation agreed to fund the Department of Electrical Engineering's pioneering Center of Analysis. With $45,000 for two years, the center had planned

- to capitalize on MIT's growing reputation in machine computation, based on Vannevar Bush's 1931 differential analyzer,
- to take advantage of an updated, electronicized replacement then being built with Rockefeller money, and
- to make MIT a world center for the study of mathematical machines, digital as well as analog.[1,40]

This earlier effort collapsed shortly after World War II and has remained in the shadows, virtually forgotten, ever since. We need to understand that failure. both to appreciate the real character of Morse's later success and to gain insight into the oftentimes complicated causes of traumatic technological change. The story, I will suggest, pits an older against a younger generation in a period of profound disciplinary and institutional change at MIT. It also pits the analog against the digital computer, but in such a way as to suggest that the "victory" of the one over the other was due as much to cultural change and shifting interests as to inherent and unproblematic mechanical superiority.

A Tale of Two Centers

The timing for the center was inauspicious. Bush's creativity and dynamic drive were lost to the institute when he left MIT to go to Washington to become the Carnegie Institution's president. Shortly after that, the outbreak of World War II preoccupied both the center's staff and its new machine, which was quickly put to work computing ballistics tables behind the veils of wartime secrecy. Nevertheless, with the war's end, the effort was back on track with plans for an expanded stable of machinery to complement the Bush analyzers and revitalized ambitions to become a world center for the study of computation. While the center faced new and aggressive rivals both within and without MIT (notably in the Whirlwind project in the Servomechanisms Laboratory and in the ENIAC development at the University of Pennsylvania), it was still the key player, a "going concern," as James Killian reported to MIT President Compton in the fall of 1945, that had "contacts, reserve funds, prestige, and staff."[34] With the backing of the administration, Sam Caldwell, the center's director and Bush's right-hand man in the early development of the analyzers, easily arranged with the Rockefeller Foundation a two-year, $100,000 study of electronic digital computation

> aimed not at producing a machine nor even a specific design, but rather at an appraisal and development of fundamental methods, both mathematical and instrumental, that would provide a well-founded basis for the subsequent design and construction of a machine.[28]

But surprisingly quickly, the center collapsed as a vital enterprise, disappointing administrators who hoped that it would facilitate efforts to put MIT's computational house in order. Indeed, midway through its Rockefeller study, Compton terminated the project and, somewhat chagrined, returned the foundation's unexpended funds.[28] While computer development continued apace at various sites throughout the institute, by 1950 Provost Julius Stratton confessed to then-President Killian that MIT had muffed its chances to establish leadership in computing.

> There was a time not so long ago when the Institute held unchallenged leadership. It was Van Bush's imagination and drive that contributed to the nationwide interest in analogue computers from which the digital computer was but a natural step.[45]

But after World War II, "the Center of Analysis began visibly to crumble," lost the confidence of other departments, and, in the years after 1950, simply faded from sight.[45] The Rockefeller analyzer itself was granted a stay of execution when it was adopted by Stark Draper and put to doing yeoman work in the

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design of computing gun sights during the Korean War.[48] But by 1954 it had reached the end of its life and, in a feeding-frenzy during October, the massive machine was picked entirely apart, and the 2,500 square feet it had occupied for years was reallocated to the Department of Architecture. For $923, Purdue got the biggest chunk of the machine, six of its 18 integrators. Other large pieces went to the University of Connecticut, the Boston Museum of Science, and the Franklin Institute. Counters, motors, switches. and large numbers of telephone switching relays disappeared into engineering labs. Servos, tape-punch units, and control panels of various sorts were reincarnated by the Acoustic Lab, the Dynamic Analysis and Control Lab, and the Instrumentation Lab into other, newer computers. The Tech Model Railroad Club and the Rocket Research Society scavenged components, as did MIT's Physical Plant, where salvaged parts presumably helped make more comfortable the lives of a newer generation of computer builders. Not least, and true to the pedagogical spirit of the analyzer, large numbers of vacuum tubes and resistors were donated to Belmont High School to aid in vocational training.[48]

The task of restoring MIT's fortunes and "knitting together" its scattered, proliferating efforts in computing fell to physicist Philip Morse, recently back from service at Brookhaven and with the Defense Department's Weapons System Evaluation Group.[44] Deeply impressed by the new Whirlwind digital computer masterminded by Jay Forrester but also by Forrester's lack of inclination "to take charge of the missionary work," Morse agreed to head a new Center for Machine Computation.' With the aid of an interdepartmental Committee on Machine Methods of Computation and with support for graduate assistants from the Office of Naval Research, Morse set out to educate the MIT community in the ways of computing: Seminars were held, courses revamped, research assistants put to work, and dissertations supervised-all in the pursuit of digital evangelism.[3]

Morse became convinced that both the center and his mission to teach the community "to think digitally," as Bush" once put it, required a battery of machines devoted primarily to education. Such machines as the IBM 605, a Card Program Calculator, and a large, high-speed machine like the Whirlwind or the IBM 701 would do the trick.[4] The turn to IBM was inspired.

> We had contributed a lot to IBM's progress: Forrester's core memory and some of the Whirlwind team had helped develop the Fortran compiler. Besides, I suggested, if students learn about computers on an IBM machine, they will be more likely to prefer IBM later."

The appeal to self-interest worked, and IBM donated the most powerful of its new machines to the new Computation Center inaugurated in 1957. Looking back on events from 1977, Morse took pride in bringing order to the chaos of MIT's postwar efforts and also in presiding over the replacement of one computational regime with another. As he put it, by 1955:

> Digital computation had won out over the older analogue computation, represented by the Bush differential analyzer. An electronic version had been built during the war [which] took up an inordinate amount of space and electric power. Although Whirlwind was overcrowded, almost no one wanted to use the much slower and less accurate differential analyzer, so it was scrapped.'"

Times were a changin', and it was out with the old, in with the new.

Morse's Selective Memory

While none would deny that computing underwent profound changes after World War 11, Morse's account short-circuited history in interesting ways. First, it ignored the substantial achievements on which the Center of Analysis had been predicated and that first attracted international attention to MIT's efforts in computing. Admittedly, the center was dominated by the Bush differential analyzers; nevertheless, its mission and often imaginative efforts embraced the whole field of computational strategies, digital as well as analog. Among the more interesting studies Caldwell and his staff initiated, for example, was the design of a mixed-analog/digital electronic calculator whose architecture could be configured to suit the task at hand.[46] Second, Morse's account both abbreviated and homogenized a contentious period in which his so-called victory of digital over analog was neither clear-cut nor simple. And third, it implied that the changes that remade computing between 1939 and 1957 were the straightforward consequences of technical superiority.

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In fact, the computational landscape even as late as 1954 was quite varied, as was indicated by a survey conducted in that year by Morse's own committee: Altogether. MIT was spending some $856,000 a year and employing a staff of 163 to maintain and operate a battery of seven major and hundreds of lesser machines, among which the digital was by no means dominant. Ranked by the cost of upkeep and operation, at the top was the Dynamic Analysis and Control Laboratory's analog, analyzer-derived flight simulator; at the bottom was the electrical engineering department's REAC; in between were IBM calculators, simulators, analyzers, the Rockefeller differential analyzer, Forrester's Whirlwind, and batteries of desktop calculators. A quick inspection of Morse's survey suggests that of the 488 machine hours/week performed by the various devices, approximately 37% was digital, a figure that rose to 45% with the rendering of the Rockefeller analyzer. Military work accounted for 76% of the 488 hours; academic, 17%; administrative, 3%; and industrial, 4%.[5,49]

This computational diversity reflected, of course, a similar expansiveness of definition. In the 1930s, if someone had pointed out a room filled with "computers," we wouldn't have been surprised to find a group of young, single women toting up figures with the help of pencil, paper, and adding machine. Move to the early 1950s: Seeking a "computer" for help with a problem in optics would probably have led us to the Barta Building at MIT, where Whirlwind was housed. Yet an equally possible destination could have been the office of the mathematician from whom we first sought advice. By the time Morse's new Computation Center was dedicated, the word "computer" had come to denote, more often than not, that IBM mainframe that filled the available space.[6]

What all this means is that Morse's digital victory—remembered so clearly in his 1977 memoir-was no fait accompli in 1955. That does not mean that the claim was ill-conceived, ungrounded, irrelevant, or unimportant; after all, it was those who believed that such was the case who ended up making it so. It does suggest, however, that the revolution in computing involved, even more than the disassembly of old machines and the construction of new ones, the deconstruction of one frame of mind and its replacement with another. When the differential analyzer was disassembled, so too was its world-the frame of mind, the intellectual and institutional interests, the sites, the pedagogy, the values, and the curricula that made it work and resonate, a symbol as well as a tool. And when Morse declared the victory of digital over analog, he was proclaiming not just the superiority of one technique over another, but even more his commitment to that new configuration of interests that was in the ascendant at MIT ever since World War 11 and in which it was obvious that the "digital way of thinking" made more sense.

Obvious to Whom?

We should be skeptical of Morse's straightforward claim of digital victory. History is always tidied up after the fact, inevitably in self-interested ways and frequently, even by those who are not historians of technology, by invoking the indisputable logic of technical superiority. But the obviousness of Morse's account can be turned on its head, so to speak, laying bare the vested interests, embedded agendas, and disciplinary conflicts that shaped developmental possibilities at MIT after World War II. A story might help us unpack that postwar "black box" in which the new digital computer was being packaged and on which the obviousness of Morse's history depends.

Imagine it is the year 2094 and that the National Aeronautics and Space Administration, inspired by the President's Council on Fitness, has launched an expedition to Alpha Centauri under the command of Arnold and Ursula Schwarzenegger. In their zeal to spread the culture of fitness, it is easy to imagine our colonists making life difficult in their new world. As their simpler dwellings were replaced with structures that rose higher, they would enthuse about the virtue of climbing from floor to floor by rope, either with or, better, without knots. But as the years go by and industry develops, inventors would inevitably seek to mechanize an older handicraft. Some particularly ingenious inventor would note that his world's many health clubs were filling up with a variety of ingenious devices with implications for an ascending cityscape and would eventually design an automated system that linked one floor and another with appropriately arranged stair-master-type exercise machines. In no time at all, the delighted colonists would be keeping fit-and getting around in their new high-rise world-by going up the down escalator.

The Schwarzeneggerian escalator disturbs our sense of the obviousness of machines. Surely, the up escalator is a superior means of getting from the second to the third floor-except on the planet Arnold, where those who shared our sense of the obvious would appear to be rude social misfits or, worse, criminally lazy. The point is, of course, that it is simply not possible for mechanical superiority-whatever that might be-to be nothing but an objective and intrinsic property. Machines emerge from-and make sense within-particular cultures; and what seems obvious about them also depends on culture. Make that culture idiosyncratic enough-for the sake of a telling example, for instance-and what is obvious within one culture can seem from the outside to be bizarre indeed. I think the history of computing could use a dose of Schwarzeneggerian fitness; so in that spirit, let us search Morse's account of a pivotal moment for those elements of the obvious-both explicit and implicit—that will allow us to ask, "What sort of people could possibly have come to take such things for granted in the machines they were building?" Two points stand out: first, that digital was better, obviously, because it was faster; and second, and implicitly, that digital machines like Whirlwind were general-purpose devices and therefore, obviously, better than the "specialized" machines like the differential analyzers.

About the matter of speed: Is it enough to claim that electronic digital computers superseded analog devices because they were so much faster? Anyone who deals with benchmarks knows that measuring and comparing speeds is a slippery and contentious task. For that matter, the current textbook of computer science I recently consulted spent many pages trying to come to grips with what one meant by speed in any event. Several things seem clear: It is absolutely essential to know what it is that is claimed to be fast and for whom that sort of speed is important. At the end of World War II, the most facile comparisons were between electronic digital machines like ENIAC and relay machines like Harvard's Mark I. But what did it really mean in practical terms to conclude that ENIAC's tubes were 10,000 times faster than the Mark I's relays if it was not the tube but the slower pulse time or the even slower multiplication time or the slower time yet to get data in and out of the machine by means of punched cards that was the real rate-determining step?[29] The same machine could be extraordinarily fast or slow indeed, depending on where one drew the boundary between core-and definitive-and peripheral components. And if one includes the time it took to "arrange" the machine so it could go about computing its answers, things were worse yet. Morse once confessed that at MIT we

> adopted the rule of thumb that any computation which can be completed by hand with an expenditure of less than about three man-months of time, and which won't be repeated sooner than a year, should not be programmed for Whirlwind. We have found by experience that the answers to such problems can usually be obtained quicker by hand.'*

How fast was Whirlwind? Anywhere from three milliseconds to three months, depending on where one placed the starting and finishing lines! We should keep this in mind when Morse tells us that the differential analyzer was so much slower.

The surest way of demonstrating the superior speed of newer digital over older analog machines meant ignoring real-world solution times and fudging the comparison of "arithmetic elements," even though, as one observer cautioned at the time: "This comparison is more difficult than the comparison between digital machines because there is no possibility of comparing times required for *elementary operations*."[35]

That analog computers did not have comparable arithmetic elements was beside the point. Thus, when one computer pioneer tells us that ENIAC could do a multiplication in three milliseconds while it took the differential analyzers two seconds, the comparison is doubly artificial: first, in pegging the real speed of ENIAC at the speed of its quickest element and, second, in using (presumably) a real-world solution time for the analyzer to estimate the speed of its fictional elementary operation.[22] My point is not to deny that digital computing became impressively speedy as the years went by, especially as programming became, as Morse put it, a less "timeconsuming piece of drudgery,"[39] but merely to point out that at the moment of Morse's so-called victory, speed was as much a rallying cry as an accomplished fact. Indeed, speed is somewhat of a red herring in the computing story: It might be that it is not simply speed that is the real issue, but the different sort of speed made possible by the new digital computer that highlighted the skills and ambitions of a new generation of experts-and that leads to the matter of "general-purpose" machines.

Why second-guess the advantages of general-purpose machines whose flexibility could be exploited in a variety of ways? Again, I would not argue that flexibility is not a useful quality, merely that circa 1954 the matter was not nearly as straightforward as retrospective accounts like Morse's would have it. In fact, there are good reasons for believing that the appeal of "generality" was rooted in matters much broader than mere machine design.

In 1952, Gordon Brown, who had nurtured Forrester's development of Whirlwind, became head of MIT's electrical engineering department and began remaking electrical engineering into an applied science. Over several years he became confident enough to remove the 10-ton traveling crane and discard most of the electrical machinery from the Dynamo Lab, where generations of students, by working with standard rotating machinery, had acquired the practical skills they would need in industry.[52] The machinery lab did not disappear altogether, although one gets the idea that postwar reformers found engineering labs and workshops slightly distasteful, especially those that emphasized the practical work believed to displace more theoretical, science-based courses from the engineering curriculum.[7] But, where possible, Brown replaced dedicated machinery with multipurpose devices like the new "generalized rotating energy converter" that could be "programmed" to mimic a variety of particular motors and generators and that came to represent, within the reformed curriculum, the new dominance of theory and basic science over practice and hands-on experience. Along with these "generalized" machines went new sets of lectures that reconceived the problems of industrial machinery as more stylish examples of energy conversion. From this approach came White and Woodson's new text," *Electromechanical Energy Conversion,* in which the behavior of the "generalized rotating energy converter" was derived from first principles and the "equations of motion of electromechanical systems"-a ghostly sort of text with no illustrations of real machinery and virtually no depictions of real-life situations even as diagrams.

Another example can be found in the following: While Brown was busily remaking the curriculum, Morse remembers feeling proud that, faced by wartime pressure to get things done, physicists "beat the engineers at their own game."[39] They did so, as he made clear to his audience, because their mastery of basic science and method allowed them to transcend the limited eye-level view of engineers. "In a number of cases," he told the MIT community at the end of the war, "the scientist did the engineering work on the development of new weapons because it was quicker for him to apply the principles of science than it was for the engineers to learn the principles of a new branch of science."[37] What these examples present, of course, is a set of analogies all touching on the theme of generality: i.e., just as the physicist was "better" than the engineer, and the generalized rotating energy converter "better" than the standard dynamo, so the general-purpose Whirlwind was "better" than the special-purpose analyzer.

The element of "speed" and the quality of being "general purpose," which play such a large part in histories of computing, were not in any simple way merely objective properties. In the crucial postwar years out of which the new computer emerged, they were even more rallying cries of self-interested participants, gambits in a new rhetoric of the obvious that took for granted as accomplished fact things still unresolved, and signs of a new configuration of interests that shaped the emerging machine as much as it was shaped by them. It is within that new configuration—wherein a new academic culture was being built as quickly as old machines were disassembled-that the electronic digital computer came to "make sense" and acquired its 'obvious" superiority.

Any computation which can be completed by hand with an expenditure of less than about three man-months of time, . . . should not be programmed.... We have found by experience that the answers to such problems can usually be obtained quicker by hand.

Generational Change

Among the most important elements in this new configuration of interests that shaped the fate of the two centers and conditioned the emergence of the new computer were generational change, new devices and techniques, new sponsors, the shifting balance of professional status, and different pedagogical expectations. As for devices and generations, Maurice Wilkes, the creator of EDSAC, remembered how disconcerting it was when he and most of the others who had congregated to work on early radar and who had become used to working with pulses and short time intervals had to cooperate with an older generation who thought in terms of recurrent wave forms and phase differences.[53] The path Wilkes followed, which carried him from physics through wartime work on radar into the new world of the electronic digital computer, was not unusual, as recent work has pointed out.[26] For physicists and like-minded engineers who saw in the vacuum tube a high-speed counting machine and logic element, the analog analyzers and their mechanical dance, embodying the wave motions of 19th-century physics and the cycles of radio, telephony, and electrical power transmission, seemed a foreign world indeed.

To many of these younger scientists and engineers, that older world of experience was not just foreign but increasingly obsolete. Morse and his crew could beat the engineers at their own game not simply because science was general and engineering was not, but because science, especially physics, was modern and engineering was not." So much had the successes of the war raised the relative status of physicists that even an engineer like Brown, who successfully remade himself in the new image of the applied scientist, remembered how much his earlier training had made him feel like "a displaced person."[21] This status revolution is partly responsible for caricatures of earlier engineering education that "taught manual dexterity, the use of simple mathematics and elementary physics in solving not very complicated engineering problems," and, when combined with a drastic drop in undergraduate electrical engineering enrollments (see Fig. 1) after the war (which contrasted sharply with stable enrollments in math and physics), fueled the drive of men like Brown to redefine the curriculum: thus the creation of machines like the generalized rotating energy converter, which seem to exist more as intellectual abstractions in textbooks than as real fixtures in the oil and grime of the engineering laboratory. And thus also the reluctance to give center stage to analog computers like the differential analyzers, the product of an engineering culture around which one could still detect, as one observer put it, "the odor of the workshop." It is no wonder, as Paul Ceruzzi's work on the evolution of computer science suggests, that the new field shied away from the environment of electrical engineering and veered toward physics.[26]

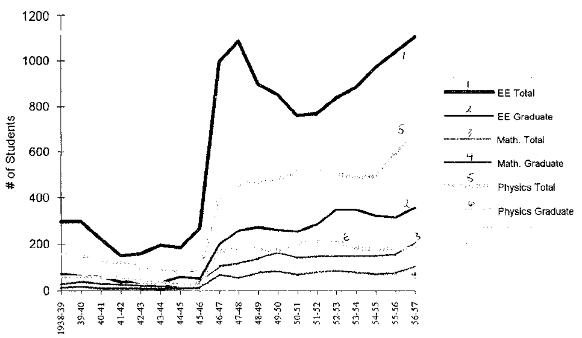

Fig. 1. Electrical engineering, math, and physics enrollments at MIT from 1938 to 1957.

These ambitions of physicists and their supporters to "modernize" the engineering curriculum, redesign' the engineer himself, and co-opt the machineries of computation were fueled by new sponsors with new agendas that left older groups like Caldwell's Center of Analysis out in the cold. During the last summer of World War II, for example, the Navy, which was sponsoring Forrester's work on a simulator that had not yet metamorphosed into Whirlwind, invited Caldwell and the Center of Analysis to submit a proposal for "an electronic computer of greater versatility and speed." Encouraged by the Rockefeller Foundation's Warren Weaver, who believed that "the Navy would not be a good sponsor for the development which involved a major and basic scientific program," Caldwell rebuffed the Navy's offer.[25] Private philanthropy had funded MIT's earlier efforts in computing, and it could continue to do so.

When, some months later, the foundation did begin to sponsor Caldwell's electronic computer study with obvious duplication of what had become the Whirlwind development, Caldwell argued that if such duplication was "the price which must be paid for independence of thought and action," then so be it.[10] Qualms about military sponsorship surely did not slow movers of the younger generation like Brown, Morse, and Forrester, and it was not long before the Navy's generosity overwhelmed private support, and MIT was embarrassed into returning the foundation's money. By 1957, the burdens of support had shifted to business and the military, and the existence of an earlier, philanthropically funded computing center had been entirely forgotten.

New Agendas and Cold War Fears

The shift from philanthropic to military and corporate sponsorship eased the introduction of new interests and agendas into the development of the computer. While it is hard to be entirely definite, one can detect an uneasiness about the era that insinuates itself into these agendas-an uneasiness that centers on the military insecurities of the early Cold War, corporate fears about industrial turmoil and postwar economic change, and the driving determination displayed by academics to bolster U.S. scientific superiority through curricular modernization. It is an uneasiness evident, for instance, in Brown's 1955 "displaced person" talk on the significance of automation when he speaks of living in "a humpty-dumpty world."" Cold War worries about unrest, uncertainty, and unpredictability fed a countervailing emphasis on management and control evident in the spread of operations research and also, I think, evident in the shaping of a new sort of computer-a computer that had to be digital rather than analog.

Why? The key, I suspect, lies in the complexity of analog versus digital elements. It is a mistake to think of analog as primitive and digital as sophisticated. Indeed it is the other way around: Analog elements like the disk integrators of the differential analyzer were sophisticated indeed, performing a complex mathematical operation by means of a simple but highly precise physical motion. Moreover, these computers were haunted, so to speak, by the ghosts of those who made and used them-the skilled machinists and artisans needed to build and maintain their high-precision components as well as the engineers who felt at home with their elegant mathematical motions.

Digital elements, on the other hand, were dumb. But that's just the point. While the analog element was richly symbolic, the digital element did little (but turn on and off) and signified less: The physical form the device assumed was largely irrelevant to its function. Neither metaphor nor physical model, it also did not demand the craftsmanship of the machinist or the interpretive skills of an engineer at home in the shop. And that, significantly, maximized the need for control-a digital computer does nothing without instruction. It is unformed computational clay, lacking identity, function, or significance until given shape by the codes, instruction sets, and programs of a new sort of expert. In this stripping down, the digital computer was like that generalized electrical machine that could be given any identity Brown's theory found pertinent or even like the new draftees soon to fill up Cold War boot camps who needed to be stripped down and relieved of prior dependencies to make them properly malleable. The digital computer, the generalized converter, the new draftee, not to mention the workers in postwar factories and offices-all could be promoted as advertisements and opportunities for operations research and cybernetics, whose prophets found in management and manipulation antidotes to Cold War chaos and uncertainty.[11]

The very formlessness of the digital computer thus presented opportunities for self-promotion to groups newly powerful (or attempting to consolidate power) after the war. In shaping a machine, they shaped themselves-employing computational strategies and designing architectures that necessitated new forms of expertise and control. They built a "black box" that embodied a new disciplinary balance of power and radically altered relationships between the machine and its public and between teacher and student.

First, there was the matter of institutional power. The new computer fed the growing prominence of those with a predilection for, and in command of, the esoteric and abstract languages needed to give the computer form, to make it work and manage it-prominent among them physicists like Morse, engineers like Forrester and Brown, and mathematicians who, in taking up the banner of numerical analysis, found the new machine a means of liberating their discipline from its accustomed service role within the traditional engineering curriculum.[12] When Princeton's John Tukey surveyed the employment opportunities for mathematicians in 1953, he noted particularly the arrival of the first batch of new IBM defense calculators: Each required a substantial investment in staff: 30 per machine, some 500 altogether. But what sort of staff? "Today the man with a 701 seeks out A.B.'s or M.A.'s in mathematics for his coders and lower level problem analysts, who will form 90% or more of his staff."[47] Given Bush's uneven track record with mathematicians during the war, as well as the intriguing digital logic of the new machine, new developments must have seemed a godsend.

Second, the new computer redrew paths of accessibility. As the digital computer became less immediately understandable but more useful, there developed a growing need for mediators—students, consultants, and office staff-who could stand between the machine and the general end user, who had no need to understand its inner workings but knew it could do useful work. In the earlier generation, one might have called on engineers and machinists of traditional sorts to get help with computational machinery like the differential analyzers and the other devices that filled the Center of Analysis. By 1957, this help was found in the offices of physicists and mathematicians (disciplines newly powerful since the war) and, increasingly, in specially created layers of clerks, permanent computer consultants, and graduate research assistants acquiring on-the-job training on their way to advanced degrees in computer science-all helping to keep the end user and the machine itself (at least its operation) comfortably separate. Not the least of these mediators were the graduate students who formed the next generation of computer experts, a limited resource essential to dreams of helping MIT think digitally. For example, during the academic years 195441956, when Morse and his Committee on Machine Methods of Computation assembled 33 graduate research assistants to help with computers, especially Whirlwind, 22 of them came from the mathematics and physics departments but only nine from the engineering departments, and of those nine only one was an electrical engineer despite Caldwell's apparent desire for research assistants.[13]

Third, this altered access helped establish very different relationships among machine, user, and the understanding and skill the computer demanded. Analog computers were, in certain ways, "transparent." Weaver had remarked in 1950 that there was

> a vividness and directness of meaning of the electrical and mechanical processes involved which can hardly fail, I would think, to have a very considerable educational value. A Digital Electronic computer is hound to he a somewhat abstract affair, in which the actual computational processes are fairly deeply submerged.[50]

Early analog computers (and especially the differential analyzers at MIT) were compendia of the tools, instruments, and devices that formed the working world of the early 20th-century engineer and were demonstrations of the nature of the physical world for which these machines were appropriate. Echoing Henry Ford's dictum that there was "an immense amount to be learned simply by tinkering with things,"[36] Bush was fond of telling how the differential analyzer had transformed an untutored draftsman into a mathematical consultant:

> I never consciously taught this man any part of the subject of differential equations; but in building that machine [the differential analyzer], managing it, he learned what differential equations were.[24]

Digital elements, on the other hand, were *dumb.* But that's just the point. While the analog element was richly symbolic, the digital element did little (but turn on and off).

These were machines with little distinction between inside and outside, between hardware and software; the machinery itself and its operation were invested with an intuitive significance that impressed immediate lessons about mathematics and the nature of that world in which the engineer worked his craft.[14]

If the analyzers and other analog devices, as expressions of shared skills, training, and curricula, were transparent, the new digital computer became for most a black box.[15] Forrester captured this difference during an early discussion in Morse's committee of the need for new courses on computers when he remarked that "a certain small amount of material on what is inside 'black boxes' is needed, but the primary emphasis should be on the operating characteristics and the use of the machine."[16] E.B. Wilson, Jr., in a book written for newcomers to scientific research, echoed Forrester when, after detailing the analog computer as a model of a physical system, he passed up the chance to describe the digital machine with the comment that "since few investigators are in a position to build such machines, their inner workings will not be discussed here."[54]

But the new computer was "black-boxed" in the corporate workplace as well. As General Electric put it in 1952: "A virtue of the analog computer is that its basic design concepts are usually easy to recognize. What goes on inside is understandable since it is an analog of the real thing" whereas "the digital type computer is a product of pure logic. It cannot be described as similar to something with which we are familiar and, hence, it will be difficult to describe." Continuing in a vein that echoed Fred Taylor's early 20th-century Scientific Management, the report noted that the digital computer could be actuated only by the use of a highly specialized but flexible language that was complete, rigorous, and correct, free of emotion, ambiguity, and loose talk.[30]

When expert cultures change, so do the machines with which they resonate and by which they reproduce themselves.

A Versatile Icon for Postwar America

One way to explain the emergence of digital computing focuses on the invention of electronic, digital elements and circuits whose technical superiority in speed and fleribility made inevitable the obsolescence of older, slower, more limited analog machines. In this view, just as these older machines were superseded by newer and faster devices, so institutional sites like the early Center of Analysis were supplanted by newer and better sites created by those whose freedom from the intellectual constraints of outdated paradigms allowed them to quickly appreciate and adopt the newer computer. But there is an alternative way, I have suggested, to tell the story. In this latter version, speed and flexibility were not so much, if at all objective properties of machines but elements in a rhetoric of the obvious, and the victory of digital over analog was as much a persuasive achievement as the foregone consequence of superior devices. Likewise, the Center of Analysis gave way to Morse's Computation Center not simply because the newer machinery was obviously better but because the Center of Analysis no longer convinced enough people in the high-stakes postwar period that it embodied the best in engineering.

In an earlier account[40] of MIT's initial foray into computing, I concluded that the analyzers had been "texts" in which students could read lessons on the nature of mathematics, the world, and even the profession of engineering. I ended with the conclusion that when engineers and others "turned to the problems of computation at the end of the Second World War, they discovered the need for new texts in a more modern idiom." In the light of the present account, however, what seems most striking about the new computer is not any univocal textuality but a veritable glossolalia of symbolisms provoked by its opportune formlessness, demonstrating how well the digital computer played up the interests and played to the strengths of a multitude of postwar experts. Fond though he was of the differential analyzer, Weaver sensed that the digital character of the newer computer echoed the quantum discontinuities of up-to-date science. Data General's Tom West had peered inside the VAX and seen a diagram of DEC's corporate organization, a perception that reminds one of the General Electric report of 1952.[33] Warren McCulloch, Walter Pitts, and Norbert Wiener found in the tubes and circuits of the digital computer the neural structure of the human brain.[17,32] Morse undoubtedly envisioned an operations research schematic; Claude Shannon, I suspect, an information processor; Alan Turing and John von Neumann, a logic machine; and Forrester surely the block diagrams and flow charts he began propagating when he moved from the Whirlwind project to MIT's Sloan School of Management. This useful malleability allowed rising powers at MIT and elsewhere to shape computational clay into an icon of new interests, a token of disciplinary fortunes, and a powerful manifesto of new analytical agendas.

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[1] For an interesting comparison of American with the much less successful British efforts to develop differential analyzers-as well as the digital computer after the war-see M. Bowles, "Theory and Practice: Obstacles and Opportunities in the Development of the British and American Differential Analyzers," *Annals of the History of Computing*, vol. 18, no. 4, 1996.

[2] The quotes are from Morse on his appointment as head of the Center; see MIT Archives, AC 62 (MIT Computation Center), Box 1, "Project Proposal-Contract Material," material dated 2-20-51.

[3] The minutes of the committee are in MIT Archives, MC 75 (Morse Papers), Box 2, "Committee on Machine Methods of Computation."

[4] "Requirements for Electronic Computing Equipment for Training and for Educational Res. at the Institute," 5-l-54, MIT Archives, MC 75, Box 21, "Committee on Machine Methods of Computation." For more on the Center of Analysis and Bush's prewar exploration of computing technologies, as well as acute insights into Bush's character and intellectual predilections as an inventor, see the intriguing book by Colin Burke, *Information and Secrecy: Vannevar Bush, Ultra, and the Other Memex*. Metuchen, N.J.: Scarecrow Press, 1994.

[5] REAC is mentioned in (Rees, 1950) "The Federal Computing Machine Program," *Science, vol.* 112, pp. 731-736, Dec. 1950.

[6] Ceruzzi's 1991 paper is an interesting overview of the period when "computer" could mean both person and machine; Phil Morse in his autobiography sometimes mixes references to human and machine "computers" in the space of a few pages. P. Ceruzzi, "When Computers Were Human," *Annals of the History of Computing*, vol. 13, pp. 237–244, 1991.

[7] "Report of the Committee on Evaluation of Engineering Education," *J. Eng. Education*, vol. *46*, p. *38, 1955;* best for the changing curriculum for electrical engineering at MIT are Wildes and Lindgren, 1985 and Ceruzzi, 1989.

[8] For more on engineers, education, and professional self-identity especially in relation to basic and applied science in the years after the war, see Reingold in Goldberg and Steuwer, 1988.

[9] See, for instance, "The Role of Physics in Engineering Education—the Report of a Committee of the American Institute of Physics," *J. Eng. Education*, vol. 46, p. 593, 1956, that speaks of the "engineers that are needed in the complex civilization in which we find ourselves."

[10] Wildes and Lindgren, 1985 p. 233, citing a Caldwell memo of 3-46 to Forrester.

[11] For the professionalizing self-promotion of cyberneticists after World War II, see Bowker, 1993

[12] On numerical analysis and early computing, see Aspray in McCleary and Rowe, 1989.

[13] The figures for research assistants are drawn from the minutes of the Morse committee, MIT Archives, MC 75, Box 2, "Committee on Machine Methods of Computation." Sponsorship for the assistantships shifted from the Office of Naval Research to IBM in 1955.

[14] Bush once wrote about the mathematics of circuits that "every formula, every step should have for him a real and vital meaning in terms of copper and iron, the flow of water, or whatever he may treat" (Bush, 1929, pp. 6-7). Bush's computers-and analog devices generally-were interpretations of mathematics and computation in terms of "copper and iron."

[15] Even when digital computers were designed and constructed to display their internal components and operation, as was Paul Morton's CALDIC at Berkeley, they did not bear the same pedagogical burdens as the analog analyzers, for they were never intended to reflect the nature of the world or the tools appropriate to its study. See Rees, 1982, p. 117.

[16] See notes of the meeting of 1 l-5-52, "Committee on Machine Methods of Computation," MIT Archives, MC 75, Box 2.

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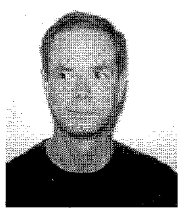

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