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LINC: biology's revolutionary little computer

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The 1963 LINC (Laboratory INstrument Computer) stands at the center of two stories: the computerization of the biologist's laboratory and the advent of small-scale computing. The brainchild of Wesley Clark, 'the most brilliant computer designer of his generation', LINC was developed specifically to address the failure of biologists to adopt computer technology. To meet their unique needs, Clark built a machine the radical design of which defied and subverted the then dominant conventions of computer architecture.

> While probing electrodialysis,
> a man suffered mental paralysis.
> His friend, the LINC-8
> alarmed by his state,
> revived him with real-time analysis. [1] (Figure 1).

Of the countless scientists who have harnessed small-scale computers to further their research, neurologist Arnold Starr was arguably the first. In 1962, Robert Livingston, Starr's boss at the National Institutes of Health (NIH) (http://www.nih.gov), invited two young Massachusetts Institute of Technology (MIT) (http://web.mit.edu) computer developers, Wesley Clark and Charles Molnar (Figure 2), to demonstrate a new general-purpose digital computer that they had designed especially for biologists. The machine, nicknamed Linc after MIT's Lincoln Laboratory, was not as powerful as other transistorized computers then available to researchers, but it was smaller and simpler to use – so small that the whole apparatus could be hauled right into Starr's laboratory and so simple that scientists themselves could program it without the aid of a computer technician.

The demonstration was a success. In a single afternoon, Linc helped solve a problem that had dogged Starr for months. Before Clark and Molnar arrived, Starr had struggled unsuccessfully to record the neuroelectric signals that cats generated in their brains when they heard sounds. Despite much tinkering with the electrodes that were implanted in the brains of his cats, Starr could not distinguish neuroelectric signals from the electrical noise that the ear membranes created when a sound entered the auditory system. However, this was just the sort of problem that Linc was designed to overcome.

After connecting Linc directly to an electrode array implanted in the audio cortex of one cat, Molnar wrote a short program that commanded Linc to: (i) send a pulse to a device that would generate a click stimulus; (ii) record the reaction of the audio cortex to the click; (iii) repeat steps (i) and (ii) as many times as desired; and (iv) display – in real time – the average neuroelectric response of the cat to the multiple stimuli [2]. The program and the hardware could be adjusted on the spot to focus on the exact signal that interested Starr. After a couple of hours, he had the data that had eluded him for so long. Livingston recalled the breakthrough: 'It was such a triumph that we danced a jig right there around the equipment. No human being had ever been able to see what we had just witnessed. It was as if we had an

Figure 1. Advertisement for the LINC in *Scientific American*, May 1966. The Digital Equipment Corporation hoped their LINC variants would appeal to biomedical workers frustrated with sharing centralized computers.

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opportunity to ski down a virgin snow field of a previously undiscovered mountain.' [3].

The coup caused by the Linc in Starr's laboratory catalyzed more than just insight into the nature of hearing. By proving that their little machine could facilitate research, Clark and Molnar demonstrated to biologists who wanted to use computers that they no longer needed to choose between either stretching their experimental agendas, research budgets and sleep cycles to meet the needs of a large, centralized computer or not using computers at all. The NIH soon funded a dozen more Lincs and, throughout the 1960s, Digital Equipment Corporation (DEC) and other companies manufactured hundreds more. Although the Linc did not proliferate beyond the confines of the biologist's laboratory, the rewards that its neophyte users reaped from its rebellious, yet elegantly engineered, departure from the entrenched norm of mainframes inspired a generation of computer architects to 'think small'.

Biology: a niche for small computing

In recent years, some of the prominent admirers of Linc have crowned it 'the first personal computer' [4], whereas others believe that its place in the genealogy of computers is as a precursor to the minicomputer [e.g. the Programmable Data Processor (PDP)]. However, both groups agree that the Linc, a small computer designed to serve single users rather than whole communities, represented a fundamental shift in computer design philosophy. Those who use modern computers on a daily basis will recognize many elements of the individual-oriented mode of computing that were introduced by the advent of Linc. For instance, Linc was the first small, programmable computer to combine visual presentation with the ability to manipulate images in real-time (via analog knobs). Furthermore, the Linc tape unit is the earliest example of a small, pocketable storage medium akin to contemporary diskettes and CD-ROMs. This personal style of computer use that Linc helped to propagate initially found fertile ground in an area that the computing revolution had hitherto bypassed: the typical American biology laboratory of the early 1960s.

Throughout the postwar decades, biologists commonly used electronic instruments, including analog computers, for sensing and recording experimental data. But compared with physical scientists, biologists had been slow to adopt digital computers. When breakthroughs in biological problems were enabled by computers, the researchers responsible were usually not biologists. For instance, X-ray crystallographers John Kendrew and Max Perutz used one of the earliest electronic computers, the Electronic Delay Storage Automatic Calculator (EDSAC), in their efforts to determine the structures of hemoglobin and myoglobin during the late 1940s and early 1950s, but neither man was a biologist [5].

In the rare cases where life scientists did use digital computers, they usually shared time on a large machine that served an entire university. These mainframes proved particularly unsuitable for use by biologists because using them entailed surrendering real-time control of experiments [6]. Scientists who depended on being able to modify the parameters of their experiments based on accumulating results – a necessity for almost anyone investigating notoriously unpredictable living processes – were unable to extract much utility from programs that had to be prepared by outsiders long before the experiment commenced.

As the 1950s progressed, the US Government entities then funding the lion's share of life sciences research worldwide grew alarmed about biologists' reluctance to use computers [7]. Looking to the example set by physicists, who had used computers to help develop

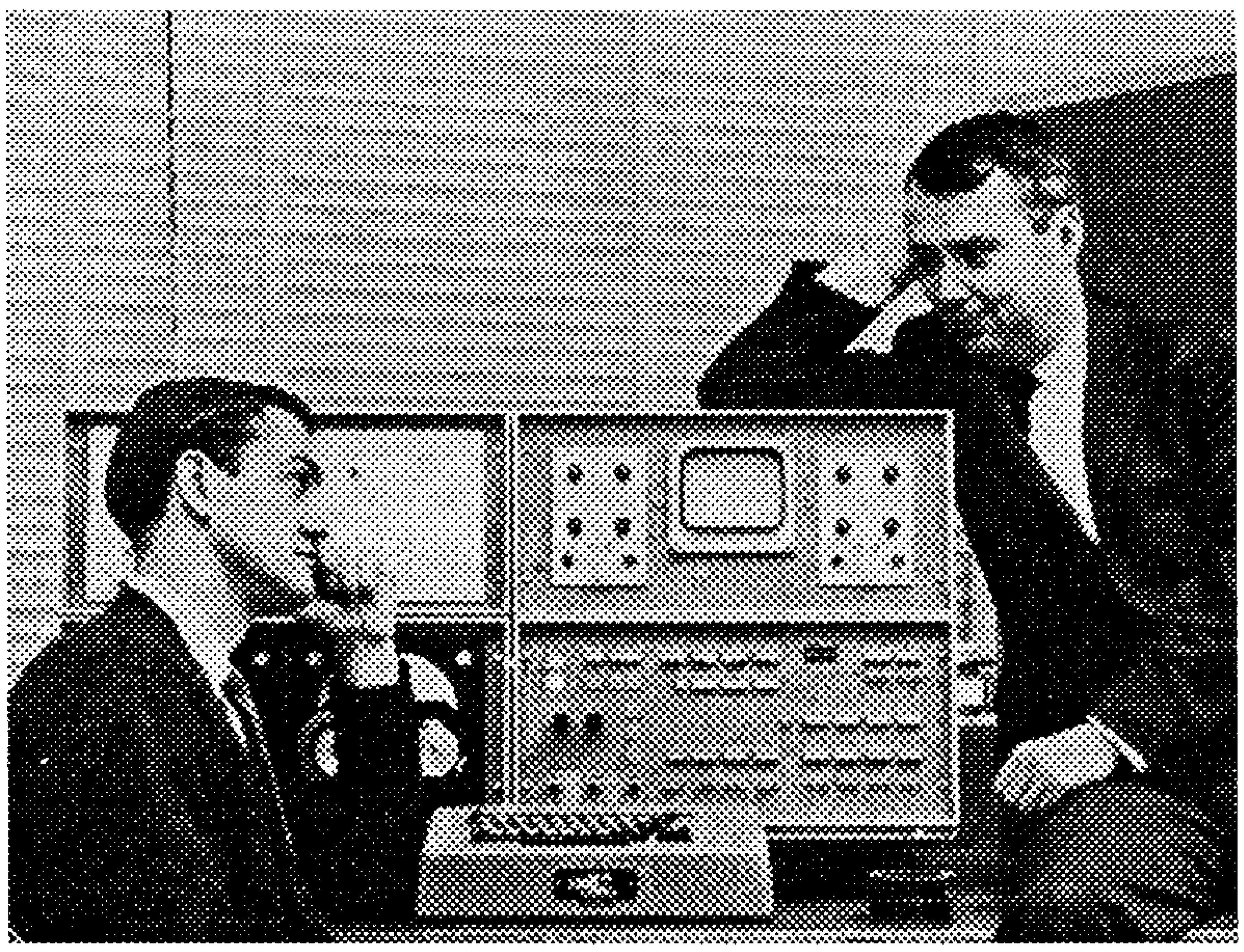

Figure 2. Wesley Clark and Charles Molnar with the Linc. Wesley Clark (left) and Charles Molnar (right) pose with a Linc in 1963. Image supplied by, and reproduced with permission from, the Computer History Museum.

nuclear weapons and spaceflight, sponsors of biological research asked why biologists could not exploit computer technology to generate medical and agricultural breakthroughs. To address this concern, dentist-turned-computer expert Robert S. Ledley and radiologist Lee B. Lusted propelled a National Academy of Sciences (http://www4.nationalacademies.org/nas/nashome.nsf) program to catalog, and then surmount, the obstacles that stood between biologists and computers. Ultimately, Ledley and Lusted met with only limited success in their attempts to computerize biology, but their efforts shed much light on the problems that the Linc would be designed to overcome.

In 1959, after touring dozens of biology laboratories that were trying, or hoped, to use computers, Ledley wrote a widely read article in *Science* outlining the steps he believed were necessary to bring together biologists and computers. For biologists who wanted to use computers, he prescribed a 'severe and formidable course of study' of the mathematical methods and techniques that formed the analytical basis for the statement of problems in computer programming languages. He also insisted that, instead of relying on programming specialists, biologists themselves must learn how to translate and delimit the data that they were gathering into information that the computer could process [8].

While Ledley outlined his plan to train biologists as 'computerniks', Lusted called for biologists and biomedical researchers to consolidate their many small laboratories to the point where they could afford their own multimillion dollar computers. Noting that 'precedents for such large-scale cooperative efforts have already been set in basic physics', Lusted urged the US Government and philanthropists to establish 'biomedical computer research centers' at national research laboratories or in association with academic institutions [9].

By the early 1960s, Ledley and Lusted's vision proved impossible to implement in the near-term: biologists had neither the time nor resources to pursue Ledley's training regimen, and nobody was willing to pay for Lusted's proposed transformation of biology into a 'big' science [10]. Nevertheless, they had whetted many a biologist's appetite for computing, sending them and their bureaucratic patrons scrambling for new means to computerize biology.

Clark thinks 'small'

While efforts to train biologists as computer programmers stalled, the chief architect of the Linc, Wesley Clark, was spending his spare time at MIT devising ways to turn the problem of biologists' apparent incompatibility with digital computers on its head. Instead of transforming biologists into 'computerniks', Clark hoped to transform computers to meet the specific needs of biologists. To understand how he came to be interested in designing a computer for biologists, and how the Linc emerged from that interest, we must delve into Clark's (and the Linc's) crucible – the jumble of engineers, physicists, mathematicians, biologists and polymaths who flocked to MIT after World War II to become computer pioneers.

Clark's journey to MIT began in 1949, when the young Californian was struggling to find new direction during a leave of absence from the physics department at Berkeley (http://www.berkeley.edu) after 'a bruising experience in a seminar with Oppenheimer' [11]. While studying nuclear reactors that produced weapons-grade plutonium for the Atomic Energy Commission, Clark read of Edmund Berkeley's Simon, a simple computer that performed binary additions using magnetic relays [12]. Inspired by Simon, he resolved to learn 'computerology' and, less than 2 years later, found himself in Cambridge, MA programming Whirlwind, the first real-time general-purpose digital computer.

Clark later described the thrill of having all of Whirlwind's components at his disposal as tantamount to a religious experience [13]. The more he became involved in the design of new computer systems, the more he became convinced that placing the power of a system such as Whirlwind in the hands of non-expert users was primarily a matter of architecture. While helping to develop Whirlwind's successor, the Memory Test Computer (MTC), Clark began a lengthy collaboration with neural network pioneer Belmont Farley. As the two men coaxed the 'powerful if not yet completely reliable' MTC into running the first simulations of neural networks, they spent many hours ruminating over how to bend computers to the scientific user's will. Clark cites these conversations as the source of his basic attitudes towards computer design. In essence, Farley and Clark concluded that computers were used most effectively when treated not as demigods, but as tools; convenience of use, rather than absolute processing power, was paramount [14].

Clark's work with neural nets also brought him into contact with Walter Rosenblith's Communications Biophysics Laboratory (CBL), where he became familiar with the frustration experienced by those who wanted to apply computer technology to the study of living processes. Years of watching CBL neurophysiologists struggle unsuccessfully to interface existing computers with scientific instruments convinced Clark that, if it were to be used by biologists, a computer would need to be able to handle analog as well as digital signals. Finally, it was through the CBL that Clark met Charles Molnar, a graduate student of Rosenblith's who had come to MIT to find an outlet for his exceptional talents in both electrical engineering and neurophysiology.

By the beginning of the 1960s, Clark had gained a reputation as a brilliant computer architect and also as something of a maverick. While most of his colleagues devoted their energy to devising schemes to create powerful computers that would be shared by hundreds, or even thousands, of users, Clark sought to design a system that would give absolute control to a single user. He argued that sharing file space and processing cycles prevented users from tailoring machines to suit their specific needs [15]. The most common criticism of Clark's lonely position was that a computer sufficiently powerful to process data quickly would still be too large and complicated for a small group of casual users to run effectively [16].

Critics of Clark's emphasis on accessibility seemed vindicated when Rosenblith's laboratory rejected the Lincoln Test-Experimental Computer Model 0 (TX-0), Clark's first attempt to deliver a small general-purpose computer to scientists. Although the TX-0 was small and powerful, the biologists found that it was neither small nor simple enough to be integrated into their confined laboratories without severe disruption. As Clark later reflected, the TX-0 was still 'too much a "computer" and not sufficiently an "instrument".' Nonetheless, he sensed that strong demand for a computer that was capable of helping biologists remained, and he began to look for ways to rearrange existing technology into a form that would enable biologists to use the machine in real time. To concentrate on the structure of this new computer Clark withdrew to his home for about six weeks, emerging in July 1961 with a general plan for building the Linc [17].

Linc takes form

Clark's priorities are evident in Linc's overall design, as well as the design of the individual components. His chief aim was for scientists to regard Linc as being no different from their common instruments, such as microscopes and centrifuges. He hoped to realize this vision by providing biologists with a computer that they could access directly, which, in turn, would 'maximize the degree of control over the instrument by the individual researcher. Only in this way...can the power of the computer be usefully employed without compromising scientific objectives' [18].

Clark believed Linc could only become regarded as another laboratory tool if it met five conditions that he had set. In each of these conditions, there is a move away from the then-dominant mode of centralized computing. First, Clark wanted Linc to be small enough that individual researchers or small laboratory groups could assume complete responsibility for its administration, operation, programming and maintenance. Second, Linc would have to be easy to program and operate. His hope was to provide the experimenter with direct control of the machine from a console located near or on the laboratory bench. The third goal in Linc's design was for it to be fast enough to provide immediate displays of data and results from experiments currently in progress, but also logically powerful enough to enable researchers to pursue more complex calculations offline. Fourth, Clark envisioned a machine that could be connected easily to a variety of laboratory equipment – both analog and digital – so that its users could process biotechnical signals with ease. Finally, Linc would have to be accessible to researchers new to digital computing [19]. Clark hoped that the whole system would cost less than US$25 000 (~US$150 000 today), typically the largest sum a laboratory director could spend without higher-level approval [20].

Working with Clark's initial specifications, Molnar spearheaded an effort that, in a matter of months, produced a prototype that met most of Clark's conditions, except for cost. The finished product cost about twice as much as had been hoped. Physically, the Linc was amenable to storage in ordinary laboratories. It consisted of four suitcase-sized independent modules: a console, display scope, magnetic tape unit and terminal. All of these were connected through 30-foot cables to a cabinet containing the electronics and power supply. The modules could be arranged in any configuration within the limits of the cable length and, moreover, they could be mounted on standard 19-inch laboratory racks. When the modules were stacked, their base was less than 2 ft^2.

The 512×512 point array display and keyboard-operated console of the Linc enabled users to write or edit programs, organize data and generate results without leaving the room (Figure 3). Among the other feedback mechanisms of Linc was a set of knobs that let users manually control program parameters, such as how Linc interpreted analog signals. The machine also included a small speaker that was a hit among users because it enabled them to eavesdrop on the machine's processor to

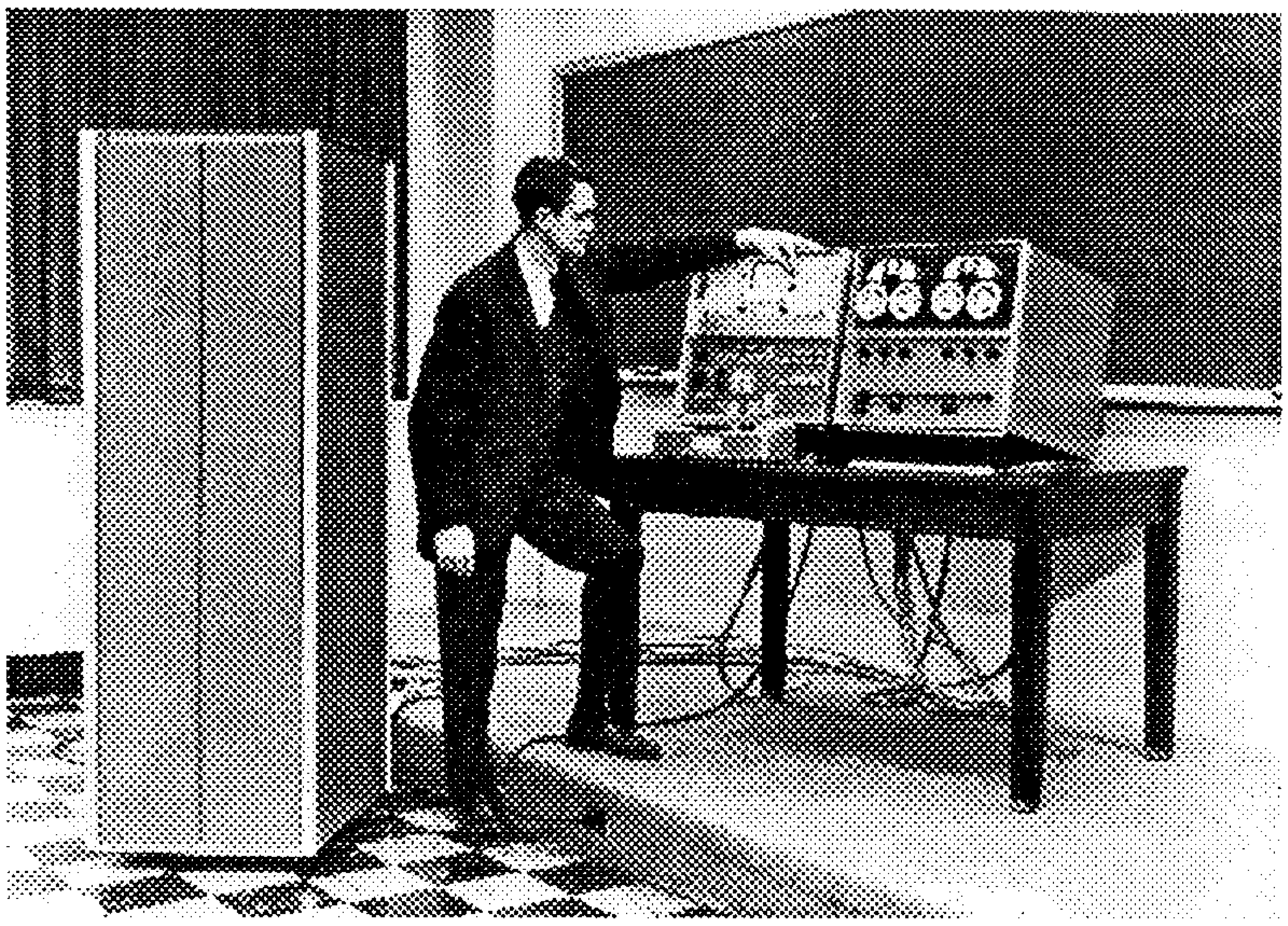

Figure 3. Wesley Clark at the Lincoln Laboratory demonstration. Wesley Clark's first demonstration of the Linc was at the Lincoln Laboratory in March 1962. The electronic cabinet to Clark's right was intended to be 'tucked out of sight in any convenient closet'. Image supplied by, and reproduced with permission of, the Computer History Museum.

get a gross idea of whether their program was behaving as expected or perhaps looping [21]. Meanwhile, for users who wanted to customize the Linc to perform specialized tasks, such as coordinating clocks or managing apparatuses that controlled the feeding of animals, the terminal module made installation and removal of plug-in units easy.

Clark and Molnar relied almost exclusively on well established components to manufacture a machine that was inexpensive and reliable, prompting Molnar to recall that 'technologically the Linc was no great shakes' [22]. Indeed, the only new hardware designed specifically for the Linc was its tape unit (Figure 4). Even though the tapes did not contain much information by today's standards – just 512 blocks each containing 256 12-bit words – they were much more durable and reliable than other tapes then available and, most significantly, they were easily removable. Although the computer users of today often take for granted the ability to tote small, removable storage media, such as diskettes or CD-ROMs, carefree portability was unheard of before the Linc tape.

The task of uniting all of these components into a single, usable package fell to the Linc Assembly Program (LAP), which served as both an operating system and a code assembler for Linc. Working to fulfil Clark's vision, the LAP was designed so that it combined a screen editor, a file management system and an assembler into a single package. Although the LAP was user friendly for its time, mastering it still represented a significant hurdle for the biologists who were using the Linc. To that end, the Linc operating manual, *Programming the LINC*, was among the first manuals written to introduce complete neophytes to computer operations and programming [23].

Linc becomes LINC

Linc came together physically as institutional support for its development fell apart. Immediately following Clark and Molnar's successful demonstration at Starr's laboratory in 1962, the future had looked bright for Linc. Bruce Waxman, Secretary of the NIH Advisory Committee on Computers in Research, enthusiastically recommended funding to test a dozen machines, while his colleagues expressed interest in making Linc the centerpiece of a planned formal program in biomedical computing. However, Lincoln Laboratory's management strongly opposed plans to construct an in-house biology laboratory in which the Linc prototype would be tested to prepare it for further production. The management of the laboratory argued that the integration of biologists would introduce insurmountable financial, spatial and administrative difficulties into a defense research-oriented environment. Faced with the choice of abandoning Linc or Lincoln Laboratory, Clark resigned and changed Linc's name to the acronym LINC (Laboratory INstrument Computer) [24]. Most of the original development team chose to follow their computer wherever it went. As Severo Ornstein recounts: 'Each of us had poured a lot of blood into the LINC development and we weren't inclined to let it go. Moreover, we had developed a conviction that we were on an exciting trail and that our futures lay ahead in biomedical computing' [25].

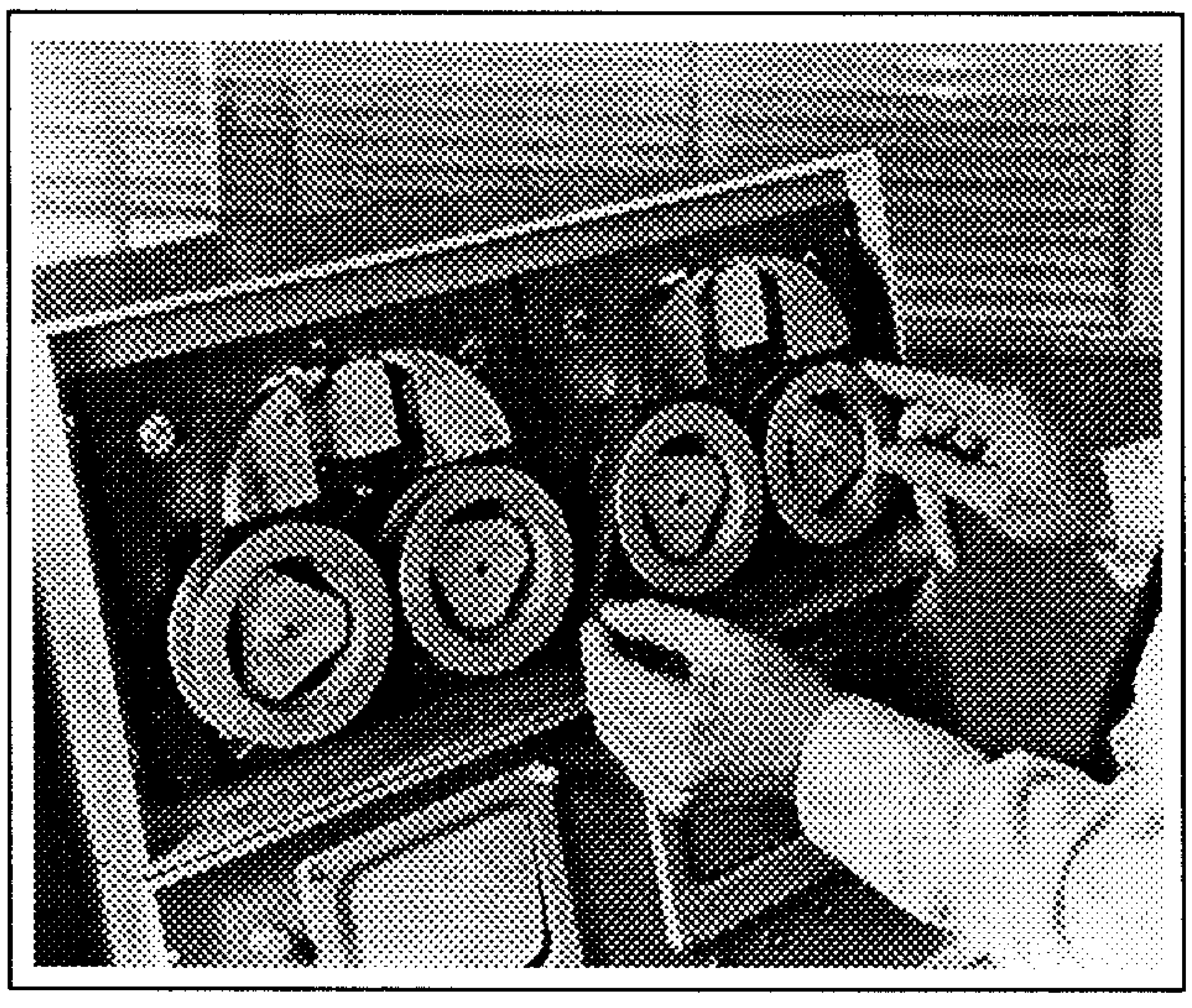

Figure 4. The LINC tape unit. The tape unit was the only component of the LINC that did not rely on existing technology. LINC tapes were hailed for being unpredentedly small and durable, but their greatest admirers were left-handed computer users! To load a LINC tape, the operator snaps a reel of tape on to the right hub and then draws the tape across the guide and head, before attaching it to the take up reel. Image courtesy of the Massachusetts Institute of Technology Museum.

After a few months of searching for local sources of institutional support, the individuals behind the LINC found a home at Walter Rosenblith and William Papian's short-lived Center for Computer Technology and Research in the Biomedical Sciences, where they began to prepare the dozen NIH LINCs for their first meeting with the biologists who were its potential users. In April 1963, NIH announced the LINC Evaluation Program, through which they would offer a LINC to biomedical researchers who were willing to spend several weeks during the coming summer near Boston learning how to operate it [26]. The response to NIH's call was overwhelming: 72 groups applied for the 12 machines.

Those selected to attend the LINC 'summer camp' hailed from a variety of biological disciplines, including molecular biology, physiology, genetics and biochemistry. The camp began with 12-hour days of lectures, mainly because the computers were not ready to be used, but also because the biologists had to be taught the basics of programming and computer maintenance from scratch. When Molnar joked that running the camp would be easier if the attendees assembled the LINCs themselves, Clark put them to work, deciding that assembly was the best way to become familiar with the hardware (Figure 5). A great deal of knowledge flowed from the attendees to the LINC design team as well. Weeks in close quarters with biologists taught the creators of LINC what researchers expected from computers and revealed the dynamics of the process through which neophytes approached computing. Not only did the lessons learned from the biologists' experience become manifest in final design of the LINC, but they were also passed down to its descendents [27].

LINC in the lab and beyond

The LINC summer camp of 1963 ended when the biologists packed their assembled LINCs into vans for

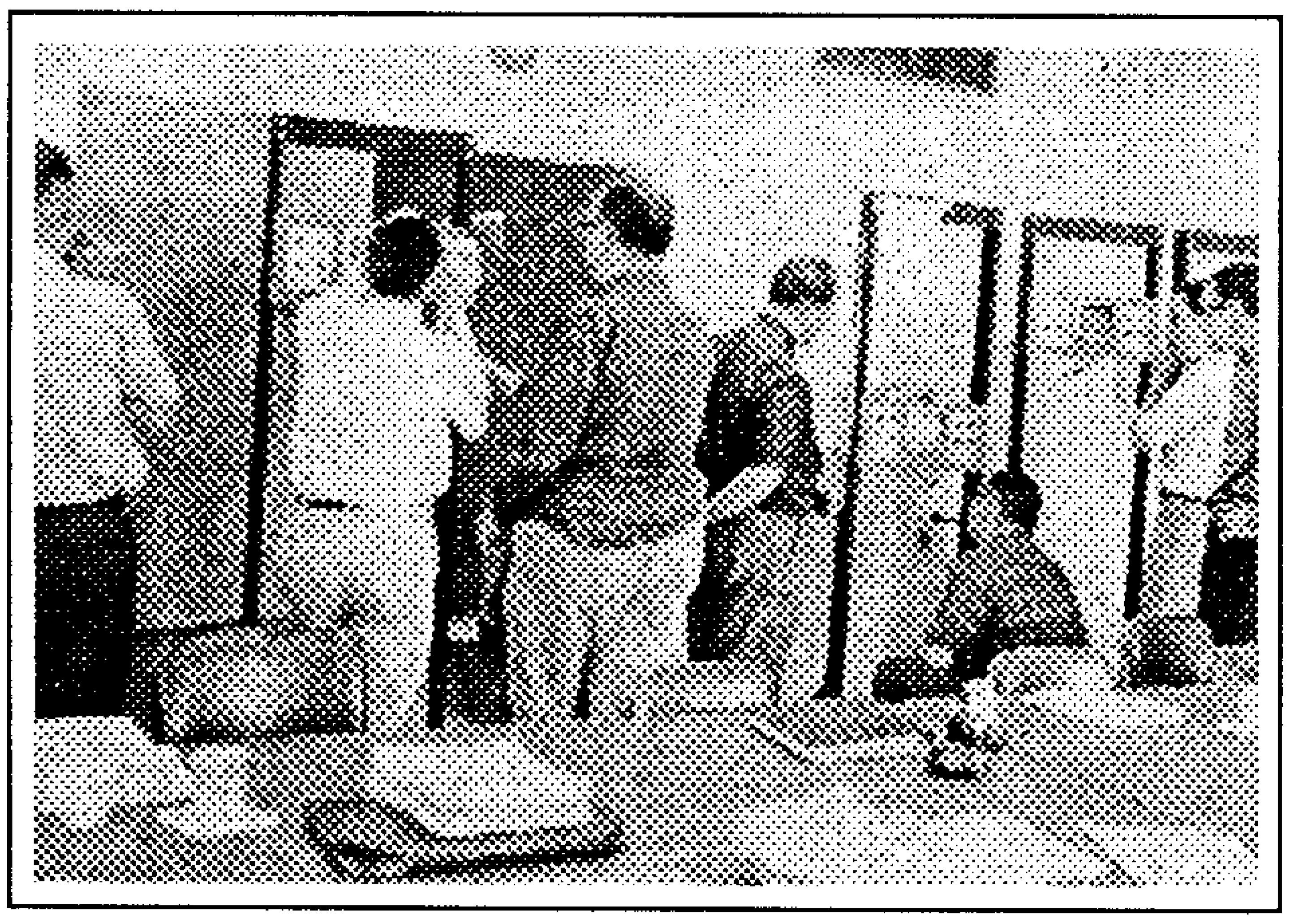

Figure 5. The LINC 'summer camp' of 1963. Here, biologists assembling LINCs are attempting to install display units during the 1963 LINC Evaluation Program. Image supplied by, and reproduced with permission of, the Computer History Museum.

shipment to their home laboratories. The first year during which LINC was present in laboratories did not yield many published studies, but by 1965 it was clear that a great deal of scientific work in diverse biological disciplines depended on LINC. For example, physiologists used LINCs to record and analyze the hydrodynamics of blood flowing through mammalian arterial systems, while geneticists rigged the computers to mass spectrometers to study bacterial genetics at the molecular level and cognitive psychologists used them as mediators in human–dolphin communication.

The most numerous and persistent users of LINC were biomedical researchers, who often used the machines in conjunction with physicians and engineers. Seeing a potentially lucrative market in laboratory computers, DEC began to offer clones of Clark's 'classic' LINC as well as the LINC-8 – a PDP-8/LINC hybrid – to biomedical researchers starting in the mid-1960s (Figure 6). Although DEC only managed to sell about 50 LINC classics and 150 LINC-8s, its later minicomputer models incorporated many aspects of the design of the original LINC. For instance, the popular PDP-12 (initially called the LINC-8/I) enabled users to emulate most of the functions of the original LINC on a platform that also provided a general-purpose computer much more powerful than LINC. The LINCtapes too were reincarnated as DECtapes, which were used with most DEC machines during the mid-1970s.

Counting the LINC-8 and the PDP-12, more than 1200 LINCs and their variants could, by the mid-1970s, be found in laboratories around the world. In each year of the 1970s, LINC-related scientific publications numbered in the hundreds, a rate sustained until the early 1980s, when the microcomputer began to supplant minicomputers as the biologist's laboratory computer of choice. Even after the advent of the PC, dozens of laboratories continued to use LINCs because the new generation of computers could not match its seamless interface with analog laboratory equipment. The last regularly active LINC, operated by Nelson Y.S. Kiang's team at the

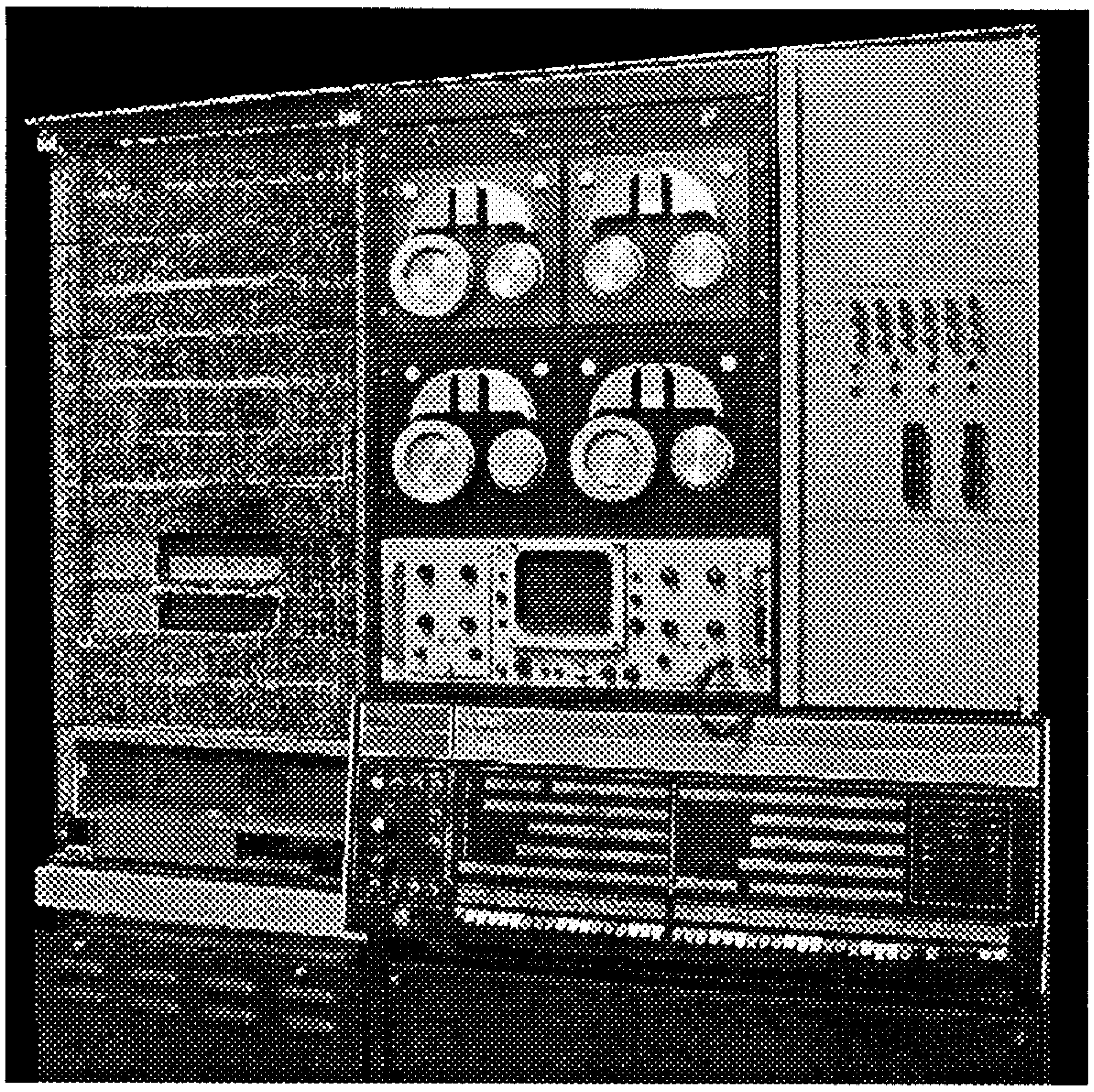

Figure 6. The LINC-8. During the 1960s, Digital Equipment Corporation manufactured hundreds of LINC variants, such as this LINC-8. The wiring visible in the left side of the image was normally covered by a panel.

Eaton-Peabody Laboratory (EPL, http://web.mit.edu/epl/index.html) of Auditory Physiology of the Massachusetts Eye and Ear Infirmary (http://www.meei.harvard.edu), shut down for the final time in 1992. For 28 years, the EPL LINC so reliably helped researchers record and analyze data 'that there was little need to modernize its functions' [28].

References

1 Digital Equipment Corporation advertisement for the LINC-8 in Scientific American 213 (5) May (1966), p. 20

2 Clark, W.A. and Molnar, C.E. (1965) A description of the LINC. In *Computers in Biomedical Research* (Vol. 2) (Stacy, R.W. and Waxman, B.D., eds), pp. 35–66, Academic Press

3 Rosenfeld, S.A. (1983) Laboratory Instrument Computer (LINC): The genesis of a technological revolution. In the proceedings of the *Seminar in Celebration of the Twentieth Anniversary of the LINC Computer*, p. 7 (http://history.cit.nih.gov/exhibits/linc/full-text.html)

4 In 1996, Alan C. Kay, establisher of the 'paradigm of personal computing', declared LINC the first PC. Kay, A.C. (1996) The early history of small talk. In *History of Programming Languages* (Vol. 2) (Bergin, T.J. and Gibsons R.G., eds), pp. 511–536, Addison–Wesley

5 For more on the early use of computers in x-ray crystallography, see de Chadarevian, S. (2002) *Designs for Life: Molecular Biology after World War II*, Cambridge University Press

6 Clark attributed computer scientists' lack of interest in developing real-time computers to curricula that ignored user interaction: 'Generation after generation of computer science students were taught that time was not important; only sequence and "functionality" were important. How fast things worked overall was important, but interaction with users in real time was not. So, we had generation after generation of machines in which interactive, real-time work was not possible.' Molnar, C.E. and Clark, W.A. (1990) Development of the LINC. In *A History of Medical Informatics* (Blum, B.I. and Duncan, K. eds), pp. 119–140, ACM Press (New York, NY, USA)

7 Bradley. T. (1957) National Academy of Sciences memorandum: On the application of computers to biology and medicine, 6 September

8 Ledley, R.S. (1960) Digital electronic computers in biomedical science. *Science* 130, 1230

9 Lusted, L.B. (1960) Foreword by the committee. In *Report on Use of Computers in Biology and Medicine* (Ledley, R.S. ed.), pp. vii–viii, NASNRC (Washington, DC, USA)

10 Robert G. Hoffman's letter to *Science* in 1960 provides an example of resistance to Ledley's initiative. Hoffman complained that computer represented a threat to the 'interpersonal relationship between the physician and patient.' Hoffman, R.G. (1960) Computers in medicine. *Science* 131, 472, 474, 564

11 Clark, W.A. (1988) The LINC was early and small. In *A History of Personal Workstations* (Goldberg, A. ed.), pp. 347–400, ACM Press (New York, NY, USA)

12 For a general description of Berkeley's Simon see Berkeley, E.C. (1949) *Giant Brains, or Machines That Think*, John Wiley & Sons

13 Young, J.S. (1998) *Forbes Greatest Technology Stories: Inspiring Tales of the Entrepreneurs and Inventors who Revolutionized Modern Business*, John Wiley & Sons, p. 88

14 Clark held similarly speculative conversations with MIT colleague Ken Olsen, who went on to found Digital Equipment Corporation. Clark, W.A. (1988) pp. 350–355

15 Clark, W.A. (1988) p. 354

16 Morse, P.M. and Teager, H.M. (1961) Real-time, time-shared computer: progress report. In *Laboratory for Computer Science Technical Report*, Lincoln Laboratory document Nonr-1841 (69), pp. 4–5

17 Clark, W.A. (1988) p. 362

18 Clark, W.A. and Molnar, C.E. (1965) p. 38

19 Ibid, p. 38

20 Rosenfeld notes that Clark was adamant that LINC's console should not be physically taller than its operators. He explains that Clark held the 'belief that a machine should not intimidate its owner' and that a computer should not be regarded as an 'awe-inspiring Golem'. Rosenfeld, S.A. (1983) Laboratory Instrument Computer (LINC): The genesis of a technological revolution. In the proceedings of the *Seminar in Celebration of the Twentieth Anniversary of the LINC Computer*, p. 3 (http://history.cit.nih.gov/exhibits/linc/full-text.html)

21 Clark, W.A. and Molnar, C.E. (1964) The LINC: a description of the Laboratory Instrument Computer. *Annals of the New York Academy of Sciences* 115, 653–668

22 Molnar, C.E. and Clark, W.A. (1990) Development of the LINC. In *A History of Medical Informatics* (Blum, B.I. and Duncan, K. eds), pp. 119–140, ACM Press (New York, NY, USA)

23 Wilkes, M.A. and Clark, W.A. (1969) *Programming the LINC*, Washington University Press

24 Clark, W.A. (1988) p. 369

25 Ornstein, S.M. (2002) *Computing in the Middle ages: A View From the Trenches 1955–1983*, 1st books Library (Bloomington, IN, USA), p. 114

26 NIH. (1963) Announcement. *Science* 139, 743

27 Weeks after the 'LINC camp' ended, the MIT Center collapsed, forcing the LINC team to again look for a new base. In 1964 most of the team resettled at Washington University (St Louis, MO, USA) where they continued to update the hardware and software of the LINC before branching out into other realms of biomedical computing. For further details see Cox, J.R. (1990) Recollections on the processing of biomedical signals. In *A History of Medical Informatics* (Blum, B.I. and Duncan, K. eds), pp. 197–221, ACM Press (New York, NY, USA)

28 Stefanov-Wagner, I.J. (1993), *Lights out for the Last Linc*, MIT bulletin