THE LINC WAS EARLY AND SMALL

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SUMMARY

The LINC represents one of the earliest attempts to put the stored program computer into the form of a general instrument for laboratory use. In a deliberate departure from the technology of Timesharing then just beginning nearly two decades of development, the LINC was designed for use by individual experimenters and thus anticipated features of the modern personal computer and personal workstation. Built at M.I.T. in 1962, its immediate forebears were the TX-0, ARC-1, and L-1 computers, in turn direct descendents of the M.I.T. Whirlwind and MTC computers. Of course the LINC in its day was neither personal computer nor personal workstation but simply the LINC.

The LINC was an outgrowth of interactions between two M.I.T. groups of scientists and engineers: the Communications Biophysics Laboratory interested in the quantification of neuroelectric activity, and the Lincoln Laboratory Digital Computer Group engaged in the development of advanced computers. Twelve LINCs were placed initially in biomedical research laboratories across the country under a unique NIH/NASA-sponsored evaluation program. Ultimately more than 1200 LINC or LINC variants were manufactured commercially for worldwide use. The basic system design went on to influence the design of the DEC PDP-4 and PDP-5 computers, which in turn helped to pave the way to the PDP-8.

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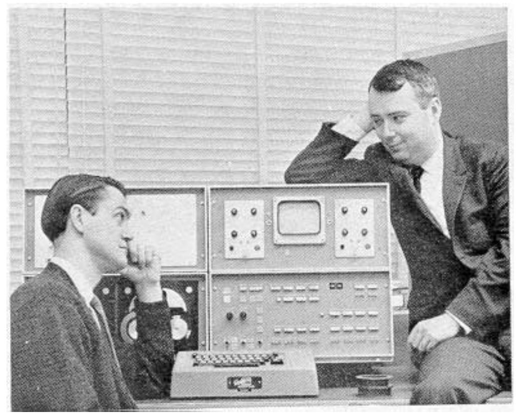
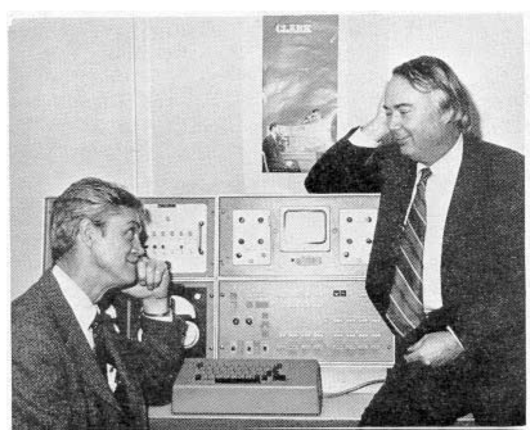


1963: The author and Mr. Charles E. Molnar with a LINC. The photograph was taken in Cambridge following the first phase of LINC Evaluation Program activities in which groups of scientists were given special training at a one-month summer course at M.I.T.



1981: The author and Dr. Charles E. Molnar with a LINC in a recreation of the above scene following a Digital Museum Lecture (see wall poster). Eighteen years grayed us both. Several of the original LINCs, also graying, were still in use in various parts of the world. (Photo courtesy of Digital Equipment Corporation)

INTRODUCTION

Twenty-two-plus years ago — in September, 1963 — the last of about twelve freshly assembled LINCs was safely delivered by moving van from M.I.T. to its new home in California. By itself, perhaps, this would not have been considered particularly noteworthy. But the event marked the successful completion of Phase I of a remarkable and unprecedented program. The twelve or so LINCs assembled during the very hot Cambridge summer of '63 had been put together by their new owners themselves. Each of these pioneers would take full responsibility for trial operation of the instrument as a workstation in his own biomedical research laboratory, and was expected to use it in the mode we have come to call, in Alan Kay's powerful paradigm, personal computing.

The participants in this innovative NIH/NASA-supported program had been selected on the basis of how suitable such a laboratory instrument would be in their ongoing or planned research activities. Each participant had agreed to assume individual responsibility for using and maintaining the machine throughout a subsequent eighteen-month period that defined Phase II of the program. The LINC Evaluation Program, as it was called, had been announced in *Science* and in descriptive brochures sent to academic and research institutions around the country. Candidates had been invited to submit proposals responsive to the scientific and technical objectives of the program. Computer programming or hardware experience was not required; the necessary fundamentals were to be learned in a one-month intensive training and kit assembly program to be conducted at M.I.T. by the LINC design team. Ultimate disposition of the assembled instruments was to be determined upon completion of Phase II.

More than seventy proposals had been received and studied by a specially created LINC Evaluation Board composed of distinguished scientists and engineers from research institutions across the country. After careful review the Board had finally accepted just twelve. These represented the fields of psychology, physiology, genetics, pharmacology, biophysics, and neurology. The selected participants had been divided into two groups to be convened in July and August respectively, with each principal investigator to be accompanied by one associate or colleague.

By mid-spring of 1963, all of the personal commitments had been made and much of the LINC hardware was in manufacture. But apart from one operating system/assembly program that had been developed and tested by simulation on a larger machine, the Lincoln Laboratory TX-2, the only LINC software in existence consisted of a few programs that had been written for an earlier demonstration prototype. With only two months to go, the final design of the LINC itself had not yet been completed.

How had all this come about? What was the LINC and what were its design objectives? Why did the field of biomedical research play such an important role in its development? I will try to recount something of the early history in answer to these questions. Like all such accounts of the introduction of a complex new instrument, the story is one of people, ideas, machines, and institutions and spans many years. As a principal instigator and designer of the LINC my perspective is limited to the events and circumstances that shaped only the earliest chapters. The full story must be left to others.

In what follows I will try to underscore and develop the title's assertion that the LINC, as personal workstations go, was early and small [1]. Early is evident; small, on the other hand, must be understood in the context of the memory capacity and the physical size of computers of the period. Since the machine's characteristics have been well documented (though not in the computer literature) I have indulged an urge to reminisce mostly about the people and events that really made the LINC experience such a rich and rewarding one. Some parts of the historical background may seem to be unnecessary embellishments, but I have included them in the hope that they will help in tracing the development of ideas and themes. The *dramatis personae* comprise extensive lists in both the computer and biomedical disciplines, and for the sake of simplicity I have kept professorial titles to a minimum and have arbitrarily 'Dr.'ed only those players who appear in character from the biomedical side of the stage. I hope that my friends will forgive me for this, as well as for any miscrediting of ideas and any errors or omissions of fact that may have settled into my own memory over the years.

BACKGROUND

Interacting with Whirlwind and MTC

Al Perlis and Doug Ross and I fondly remember the M.I.T. Digital Computer Laboratory Whirlwind computer, the machine on which I learned what little anyone knew about programming in 1952. One walked into it. What now sits comfortably on a small desktop, in those days required an entire room for the control consolery alone. Programming for its small electrostatic memory (1024 16-bit words on a good day) was a primitive affair carried out with the aid of heavily ruled coding forms on which to write out absolute-address instructions and octal numbers. [Confronted by the prospect of having to program in such a manner, Al immediately designed a new improved form that consisted of a large sheet of blank paper.] But its early users did indeed walk into the control room and for their assigned block of time, typically fifteen minutes or so depending on the time of day, the entire machine was theirs. In this regard the use of Whirlwind as a workstation of sorts was no different from that of many other early computers, especially in the universities. What makes the Whirlwind computer important in the history of the personal workstation is the fact that it was the first really high-speed machine with powerful interactive display capabilities [2].

But it was MTC that really drove the point home. MTC, the Memory Test Computer, was designed and built by Harlan Andersen and Ken Olsen to provide a working computer system in which to try out the first ferrite core memory, a vacuum-tube driven 1K 16-bit unit engineered by Bill Papian then a graduate student under Jay Forrester [3]. Blocks of time measured in hours were available and the entire machine, quite similar in architecture to Whirlwind, now occupied only a single large room. Bristling with toggle-switches, pushbuttons, and indicator lights and provided with audio output as well as versatile CRT displays, it made interactive use a quite lively and memorable experience.

I suppose the idea of using even a very large computer such as the 1953 MTC just as one would use any laboratory tool was introduced to me by Belmont Farley, my teacher and collaborator in early computer simulation studies of neuron-like networks [4]. Belmont, a physicist by training and a man of considerable vision and strongly held convictions, joined the Digital Computer Laboratory shortly after my own move to M.I.T. to learn computerology. [I had almost become a physicist myself at one time, in what I now consider a close call; but that's another story.]

Belmont and I spent enormous numbers of hours interacting with MTC and with one another (he talked, I listened) as we tried out ideas, modified parameters, and studied displays of the simulated behavior of our strange little networks, grateful for such extensive access to such a powerful if not yet completely reliable machine. [A self-restarting test program was left running on MTC whenever the machine was otherwise unoccupied. In those pre-regulation days you could tune a radio to the frequencies being broadcast by MTC's long open-wire bus and hear the test program running, or trying to run, from several city blocks away. Sometimes when approaching by automobile for an extra-long simulation run in the dead of night the signal was clear enough for a decision to turn back home if things weren't going well.]

It was in these sessions that I began to learn from Belmont many of the basic attitudes toward computers that I hold firmly to this day: *Computers are tools; convenience of use is the most important single design factor — Big computers are for big jobs; small computers, for small jobs — Separate personal files are safer than files held in a common shared space — Digital computers should handle analog signals as well* — and so on.

In what would become a very important liaison, Belmont and I began to attend the seminars of the Communications Biophysics Laboratory, CBL, under Prof. Walter Rosenblith, later Provost of M.I.T. and presently Foreign Secretary of the National Academy of Sciences. Walter's group was concerned with the problem of quantifying neuroelectric phenomena. It was quite interdisciplinary in its approach and attracted students, post-doctoral fellows, and visiting scientists from many parts of the world. CBL had been developing various signal processing techniques. Much of CBL's work involved auto- and cross-correlation analyses based on data recorded on FM tape and then processed by analog devices. Work was just beginning on the analysis of the electrical signals from single neurons.

Our interaction with CBL started slowly. The Digital Computer Laboratory was absorbed into the recently established Lincoln Laboratory to become a component of Lincoln's massive program in air defense. Our base of operations shifted fifteen miles west to Lexington and we were assigned to a new group charged with advanced computer development together with Ken Olsen, Bill Papian, Dick Best, Jim Forgie, John Francovich, Ben Gurley, and many other members of the former Digital Computer Laboratory staff. Belmont and I somehow managed to keep up our pilot studies in network simulation with much travel back and forth to CBL and to the MTC in Cambridge.

Bill Papian and others, bolstered by the immediate success of the 1K MTC memory (shortly thereafter replaced by a 4K unit) now began to build the largest core-memory array thought feasible, a 64K 36-bit unit. This array would be thirty-six times the storage capacity of the 4K MTC array and would certainly constitute a big step in computer memory technology. In my new capacity as leader of a small sub-group in logic design I made sure that its potential for further simulation and modeling work was kept in mind.

The Lincoln TX-0 Computer

It was a time of transistors. Ken Olsen, in charge of the sub-group in advanced engineering development, joined me in proposing the construction of a vacuum-tube machine of considerable size, the TX-1, as a suitable vehicle for testing the large memory array [5]. When this idea was turned down by Laboratory management (wisely enough) Ken and others began to develop transistor circuits in earnest. I began the logic design of a new machine, the TX-2, which would have about the same architecture as that of the rejected machine but would take advantage of the new circuits. It is interesting to note that one of the main architectural features of the TX-1/TX-2 design — multiple program counters used in what I badly termed multi-sequence programming [6,7] — was later employed to great advantage by Chuck Thacker in the design of the Alto workstation [8].

I proposed that we first build a much smaller, primitively simple computer that I had designed and named the TX-0 [3,9]. [We had already used up "1"; later Ken and I would say that we didn't build the TX-1 because we didn't like its color scheme.] The 18-bit TX-0 would use only half of the large memory array and would be quite simple in logical structure, maximally RISCy, one might say today. When the second half of the array was completed the full array would then be installed in the TX-2 on which design and construction would have been proceeding. The TX-0 would then be retrofitted with a new memory unit of some kind and serve as a front end processor to the TX-2, or perhaps simply be dismantled. In the meantime it would have served in early evaluation of the new memory and transistor circuits and would have been more than adequate to the task of network simulation as well as to other tasks more directly relevant to the Lincoln effort. Not a bad plan for an R&D program. It was adopted. The TX-0 was built and a three-year effort to design and build the TX-2 was begun [10]. In addition to powerful CRT display units designed by Ben Gurley, the consoles of both machines would ultimately bristle in the best M.I.T. tradition.

The simulation work Belmont and I were carrying out had long had the interest and support of Bill Papian. Appointed Leader of the Advanced Development Group, Bill actively encouraged further strengthening of the interaction with the CBL group. Students and scientists from Rosenblith's laboratory began to try their hand at digital processing of neuroelectric data on the TX-0 and later on the TX-2. One of these students was Charles Molnar, who was to become a primary catalytic agent in promoting sound relationships within and between the two groups. Charlie, I soon learned, was extraordinarily competent and talented both as an electrical engineer and as a student of biophysics. He shared the conviction that computer tools would play an important part in what was beginning to be called "the biomedical sciences" and proceeded to master the operational and technical details of both the TX-0 and the unfinished TX-2. Charlie and I began to develop a basis of collaboration that would lead to the LINC and to many other developments over the years.

As the second half of the large memory array neared completion it became time to decide what to do with the TX-0. Bill Papian suggested replacing its memory with the group's new transistor-driven 4K memory unit (about the same capacity as that of the earlier vacuum-tube-driven MTC unit) and then moving the entire machine to the M.I.T. campus. This would give a wider group of students and faculty an opportunity to experience the kind of hands-on interactive computer use that characterized our work at Lincoln Laboratory in the tradition we were carrying forward from Whirlwind and MTC.

By that time both of the Cambridge machines, Whirlwind and MTC, had been completely committed to the air defense effort and were no longer available for general use. The only surviving computing system paradigm seen by M.I.T. students and faculty was that of a very large International Business Machine in a tightly sealed Computation Center: the computer not as *tool*, but as *demigod*. Although we were not happy about giving up the TX-0, it was clear that making this small part of Lincoln's advanced technology available to a larger M.I.T. community would be an important corrective step. The machine was then being used in some very exciting work in interactive programming by Jack Gilmore (unfortunately never published) that anticipated much of what we do today, but Bill's argument that the group's attention would be shifting to the TX-2 prevailed. Arrangements were made to replace the memory, enrich the instruction repertoire, and move the modified TX-0 to the campus in Cambridge.

But where exactly should it go? The logical place, it seemed to me, was Walter Rosenblith's laboratory. After all, CBL was then using the TX-0 computer more actively than any other group of visitors from the campus and expanded use by George Gerstein, Charlie, and other members of CBL was expected. To my surprise Walter declined to accept the responsibility. I therewith gained an important insight about what would work in a small laboratory setting and what would not. It seems in retrospect that the TX-0, small as it was for its time and demonstrably useful in CBL research, was still too much "the computer" and not sufficiently "an instrument". Its care and feeding and the constant need for justification might well have compromised CBL's research objectives. Walter's technical judgement, as usual, was correct.

The modified TX-0 eventually found a home under the larger umbrella of the Electrical Engineering Department, where it was used heavily by CBL and other groups and helped to train several generations of students in the interactive use of computers on-line. Somewhat later it was joined and largely upstaged by a PDP-1 computer (in some sense a production version of the modified TX-0) that had been donated to M.I.T. by the Digital Equipment Corporation and would later be used in some of the earliest experiments in Timesharing [3].

Timesharing had by then captured the imagination of much of the M.I.T. computer science community (not yet a science, of course; it would not be so until a few years later, when Al Newell, Al Perlis, and Herb Simon said, *Let there be Computer Science*, and there was). This seemed to me a bad idea and still does, the captive imagination aspect no less than the underlying premise itself. Improved access, yes; thrashing competition and waste, no. This is not to deny that Timesharing resulted in a huge and productive impetus to computer science at a critical time. Certainly it has given much gainful employment to computer scientists and manufacturers and salesmen over the past twenty years or so. But it seems to me that we could have done better than to divert so much of our attention and resources to trying to make good the promise of a patently unattainable "sensible simultaneity" for all. [I may not always be right, but at least I am consistent. When working out the multi-sequence programming idea some years earlier I had considered and rejected the notion of competitive time-sharing by independent human users as grossly inefficient; much later at the dawn of the Timesharing Era I had no qualms about turning down a suggestion of Ed Fredkin's to set up such a system for the multi-sequence TX-2 (much to his disappointment and, as I recall, disgust); in meetings of the M.I.T. Long Range Study Committee in 1961 I objected (to no effect) that campus-wide Timesharing so enthusiastically being rationalized as a panacea would not be able to deal with real-time work such as CBL's and moreover would inhibit the development of any interactive computing that involved complex displays. The M.I.T. Study Committee Chairman and I both declined to sign an otherwise unanimous final report. He thought it didn't promise nearly enough. Walter urged me to write a minority report, but I knew a steam roller when I saw one and went on to other matters.]

The ARC and the L-1

Not long after the decision to move TX-0 was made, Charlie and I met with Moise Goldstein and Robert Brown of CBL. The subject of discussion was the possibility of building a digital device to extract stimulus-evoked neuroelectric potentials from a background of unrelated electrical activity by means of a summation technique then being tried at CBL on analog equipment. Aha! A digital instrument for Walter! I immediately agreed to take on the design task.

The logic design of the instrument fell into place readily enough. I simply used many of the transistor logic plug-in modules already designed by Ken Olsen and Dick Best for the TX-2, and my colleague Henry Zieman neatly solved the problem of memory by working out the details of a very small 256-word core array. An 18-bit structure seemed about right for the job and nicely matched that of the TX-0 with which the instrument might later be in communication. I designed two simple operating modes to provide response averaging and amplitude histogram compilation, both modes to be wired into the control circuits. With electronics, control switches, lights, CRT, plotter, and paper-tape punch, the whole thing — even without an analog-to-digital converter — required a cabinet about the size of two refrigerators turned on their sides. Today we would think it a machine of rare ugliness (as an unkind journalist once said of my automobile). We named it the ARC, an acronym for Average Response Computer [11].

The ARC was completed in early 1958. Though not all that much smaller than the TX-0, at least it was portable and rolled through doorways. I rode it in triumph into the Communications Biophysics Laboratory and it was almost immediately put into service. After about a year of operating experience the CBL staff decided that a third mode for compilation of time histograms of single neuron activity would be useful, and this was duly wired into the ARC control. Over the next several years the ARC served in a wide variety of studies, teaching researchers many new aspects of the neuroelectric behavior of the brain. It also confirmed my belief that there were indeed useful things that small digital computers could do in the laboratory.

But wouldn't it have been better to program these operating modes rather than wire them into the control circuits? I had since taken just that approach in designing an extremely simple stored-program computer of very limited capability, the 256 10-bit word L-1, for use in a special project [12]. There was no doubt in my mind that the far greater flexibility of the stored-program approach was of enormous value even in computers small enough to be considered "instruments" for laboratory use.

At the first symposium of the Brain Research Institute held at UCLA in 1960, Belmont and I joined with Walter and several members of CBL and Dr. M. A. B. Brazier (of both CBL and the BRI) in discussing some of the viewpoints and accomplishments of the M.I.T. work [13]. In my presentation I contrasted the stored-program and wired-logic approaches:

> The TX-0 is a relatively small but powerful stored-program computer. A rough comparison of the ARC and the TX-0 computers is illuminating. Both machines operate on 18-bit binary numbers, control analog-to-digital converters, have cathode ray tube displays, can be controlled by the experimenter, and hold about the same number of circuits derived from the same body of electronic technology. The TX-0, however, has about 8000 registers of digital storage and is organized as a general-purpose device.
>
> It is quite simple to program the TX-0 to act very much like the ARC; in fact this has been done, requiring an investment of effort measured only in hours. The TX-0 can in addition generate quite varied displays of the data and of results of analysis, and can be programmed to carry out exceedingly lengthy and complex operations if desired. This flexibility of behavior is characteristic of the stored-program computer and is obviously of great value.
>
> It is extremely important, of course, to provide for procedural flexibility and easy access to machines of this type in order to realize their full potential. Ideally the researcher would have the general-purpose computer in his laboratory for use "on-line", enabling him to observe and act on the basis of the calculated results while the experiment is in progress.
>
> Stored-program computers like the TX-0 are beginning to appear in commercial form and there is reason to hope that these machines, or perhaps other general-purpose machines with a capability somewhere between that of the ARC and the TX-0, will find their way into the laboratory.

Well, there it was. Clearly, the thing to do was to go off and design a machine that would fill the niche I had just defined.

DESIGNING THE LINC

It has been both pleasurable and dismaying to look over my design notebooks after a lapse of nearly twenty-five years. I can easily relive the exhilaration and sense of discovery in the pages detailing those rare ideas that "worked" and survived and were good. But there are other pages, too, some of them recording in distressing detail my false starts, muddled thinking, and irredeemably bad ideas. The design process is like that, of course; yet one always hopes that the overall record will reveal a higher order of thought and development. It is embarrassing to report, therefore, that the LINC design notebooks do not, on balance, document the workings of an orderly mind.

Following the October symposium at UCLA I increasingly began to sketch and doodle on various handy surfaces. It seemed to me that I now had most of the keys to the design process: a firm belief in the soundness of the goals and a good sense of the functional requirements, the general technology to be used, and the bounds of acceptable size, complexity, and cost. What I was trying to find was some gimmick, some architectural idea to start the process off in any promising direction. Taking the principal constraint to be the factor of acceptable cost I arbitrarily set a target of

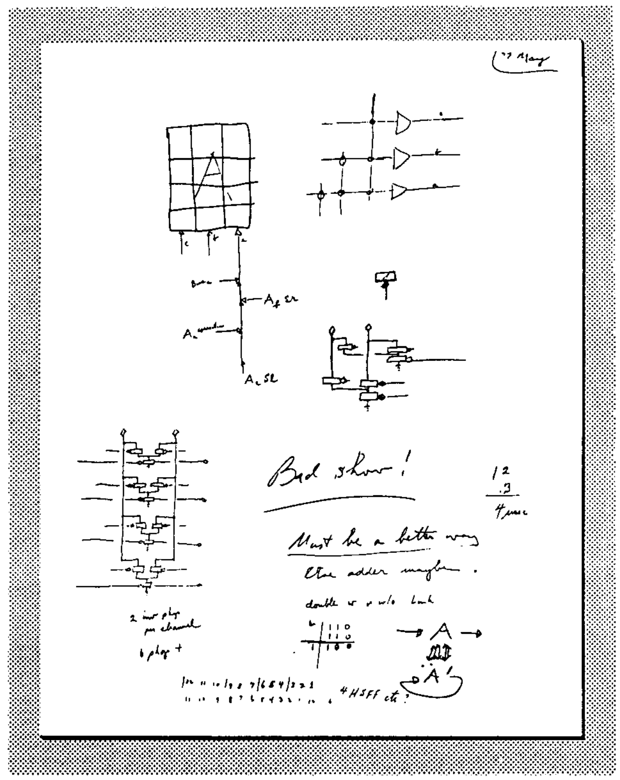
$25,000. This figure, relatively small for computers as we then knew them, seemed about right. It was about the size of one staff salary, for example, or about what a department head could authorize for equipment without the approval of higher management, and so on. Remarkably enough it was little more than twice the cost of the a-to-d converter used with the ARC. Was there some architectural scheme that might yield a useful laboratory-size computer subject to this cost constraint, something that would propel me out of the back-of-an-envelope phase and into the discipline of the engineering notebook?

First Attempts

Volume I of my three LINC notebooks carries the dates May 24 to July 4, 1961 — roughly Mother's Day to the Fourth of July. I had found a starting gimmick in the form of a serial-parallel scheme that appeared to reduce cost without seriously compromising speed. I would take advantage of a new family of plug-in circuit modules then being produced by the Digital Equipment Corporation. Ken Olsen and Harlan Andersen had left Lincoln Laboratory to found DEC in 1957 and were followed shortly thereafter by Dick Best, Ben Gurley (who later engineered the PDP-1), and others from the Lincoln group [3]. The circuit modules DEC was now manufacturing, forerunners of the integrated circuit chips that were not to appear for several more years, seemed quite suitable.

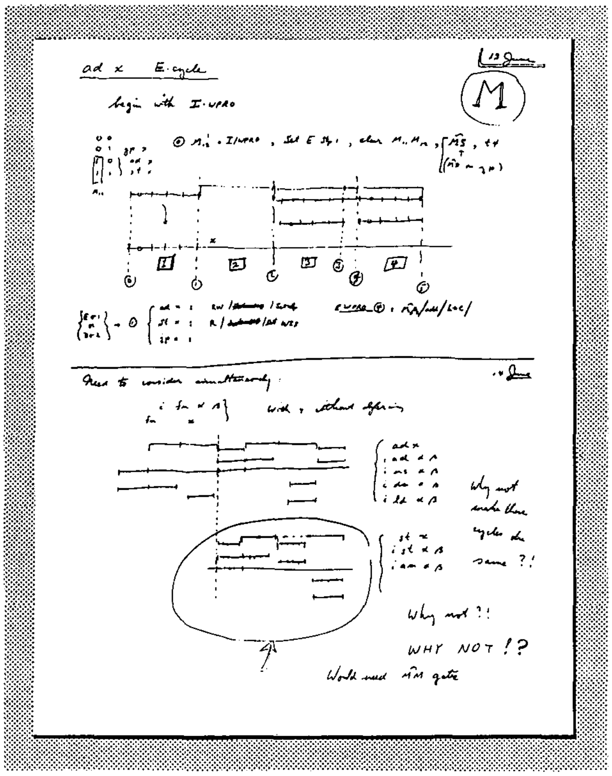
I knew that the machine would need two small tape units about the size of the "snapshot" unit I had proposed earlier for use with the TX-2 as a personal file input-output device and that my colleague Tom Stockebrand had tried to make. These units would have pocketably small reels for programs and data and would use block addressable magnetic tape like that of the TX-2's huge and frightening device for on-line files [14]. [The TX-2 tape unit used 14 inch reels of 3/4 inch tape, a very large inertial load. Its design was based on an observation of mine that the TX-2's multi-sequence capability made it possible to eliminate the usual requirement for finely controlled tape speeds, and I further proposed that the positions of all bit-cells on the tape be fixed by prerecording timing and blockmark tracks. In programming use, the resulting unit's tape speed varied markedly with wrap diameters, as did inertias and vibrational resonances. At top speed in block searching mode the tape's linear velocity reached 60 miles per hour! The whole room shook.]

Most of the work over these first two months went into thinking through the details of the serial-parallel architecture and an appropriate set of machine instructions. I knew that I had to build in a-to-d conversion channels and devote some of them to console potentiometers for convenient knob control of continuous variables (a good idea contributed by Belmont). I knew that CRT display would have to be inexpensive and would therefore use the same point-display technology that appeared in all of the M.I.T. machines. A more difficult task, however, would be thinking through the control for the tape units and developing the right set of block transfer modes for their use. The 1K or 2K 12-bit words of memory that seemed feasible under the cost constraint would not permit lengthy program routines for tape operation. These routines would therefore have to be wired into the central control circuits (of course there were no ROM chips in those early days). Block addressability of the tapes would help in running useful programs in the very small memory, the sort of thing we now do with disk systems.



The 27 May (1961) page from the LINC design notebooks. Early design was based on a serial-parallel logic using 4-bit shift register circuit modules made by DEC. Design progress was variably good.

I worked at home. Early in the design work I returned to the Laboratory briefly for an informal exposure of ideas to Charlie and Belmont and other members of the group, among whom were Severo Ornstein and a newcomer, Mary Allen Wilkes. There was a lively interest in what I presented as a "Linc". [I had thought that a generic name for this kind of computer would be useful and had decided on one that suggested the instrument's Lincoln Laboratory origins; Linc would be promoted to LINC by later events.] Following the meeting Severo and Mary Allen began to try programming with the proposed instruction set and I returned to the task of filling in design details. Charlie began to communicate his enthusiasm for the Linc scheme to CBL. Walter himself was later reported to be envisioning a relationship between a scientist and a computer similar to that between a scientist and a microscope. All was going well.



The 13 June (1961) page from the LINC design notebooks. Timing diagrams still appeared to support the serial-parallel scheme and new ideas were still emerging.

Alas, the serial-parallel approach turned out to be a false start. One month after its first exposure I had put enough of the design in place to establish the cost of the modules required by the central logic alone. Even without input-output devices or the core memory I had already used up my $25,000. Gad. The final entry in volume I is the single line: "Crisis in River City!"

The Prototype Linc

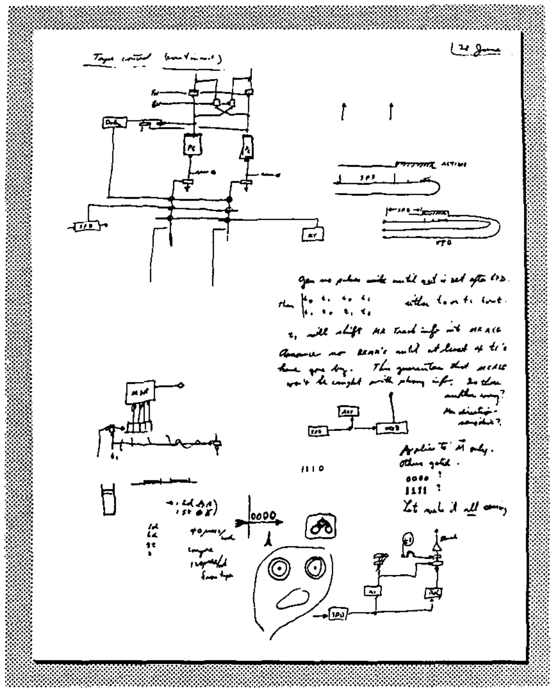
For the next several months I concentrated on simplifying the design and detailing the tape unit and its control, the most complex part of the machine and the largest single unknown. Much of my earlier work translated readily enough into a more straightforward 12-bit parallel form. Somewhat to my surprise this yielded a substantially lower cost. So much for gimmicks. Notebooks II and III record a great deal of work over the remainder of the year in refining the instruction set and developing simple operating modes for the tape units. Sketches for the tape transport mechanism and console appear here and there.

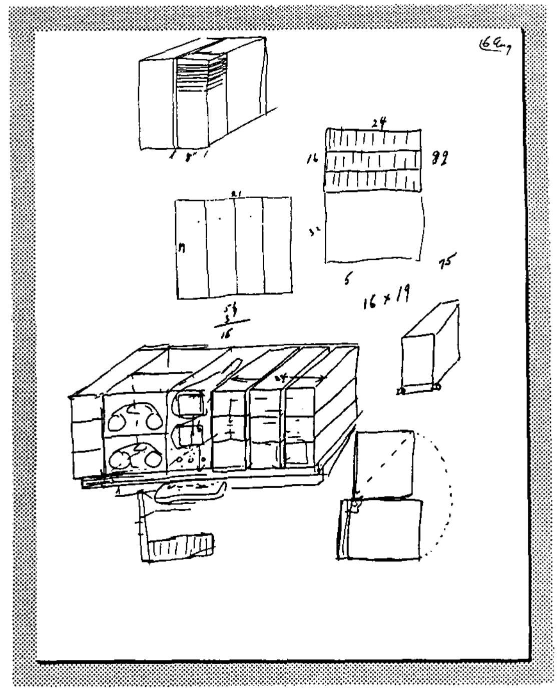
The need to build up a project effort at Lincoln began to demand more and more of my time as other members of the group joined in. Tom Stockebrand and I built a working model of the new tape unit, with Charlie contributing helpful insights from his experience with its fearsome progenitor, the giant tape unit of the TX-2. Severo designed and built a special subsystem to pre-mark tapes with the required fixed backbone of block addresses, timing signals, and control code patterns. Hershel Loomis and I assembled a tape unit exerciser/tester using DEC building block logic modules and established that the Linc tape equipment would indeed function as I had hoped. We were on the right track.

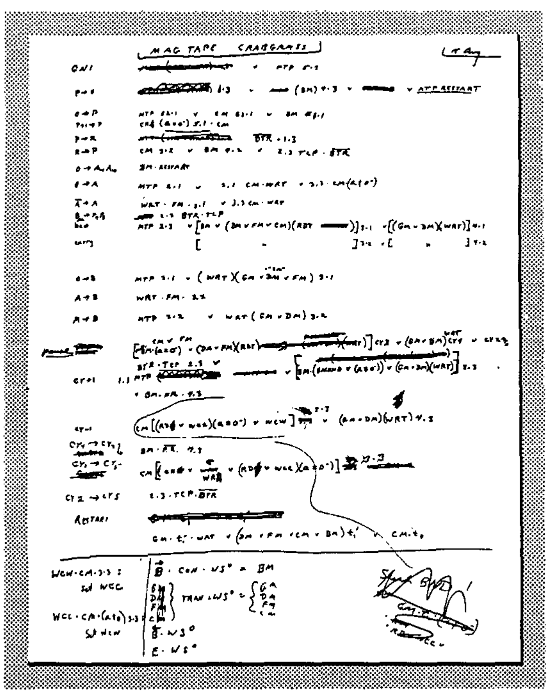
By early September the instruction timing diagrams had been completed in enough detail to enable Mary Allen to write a Linc system simulation program for the TX-2 and begin to develop a compact machine-code assembler for the proposed machine. Bill Simon, another newcomer and a remarkably creative scientist and engineer, designed a dual-scope alternative to the single-scope unit we eventually settled on, and began to write a number of test and demonstration programs. Norm Kinch, my right arm in matters of making things happen, began to produce large working drawings of system logic based on my notebook sketches and placed orders for parts as they emerged from the design. Severo and others helped with details of package layout and wiring lists. Charlie reviewed the design of the proposed 1K 12-bit memory system and watched over general engineering specifications. The final entry in Volume III was dated Christmas, 1961. Construction of the prototype Linc was already underway.

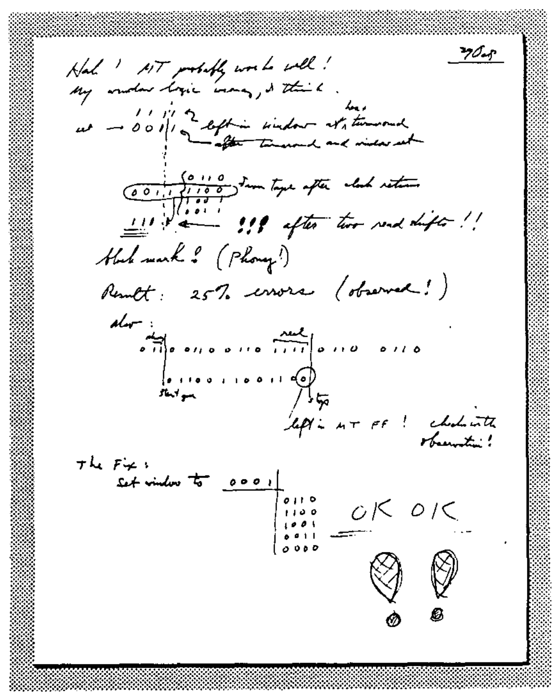
We hoped to complete the Linc prototype in time to take it to Washington for a demonstration in April at the forthcoming National Academy of Sciences Conference on Engineering and the Life Sciences. This had been urged by Walter and by Bill Papian as an excellent way to introduce the machine to a broad scientific and technical audience. Under this time schedule pressure but with tireless support from an enthusiastic technical staff, the Linc began to take shape. Hand-wiring of the electronics cabinet took its toll in anxiety and time over the ensuing weeks, as did the slow accumulation of special equipment and parts. But Norm kept the construction pretty much on schedule and the machine was completed in late February. It was working well enough for a Laboratory-wide demonstration at the end of March, 1962. The entire Linc group was justifiably proud of its accomplishment.

The demonstration prototype consisted of a set of four box-enclosed console modules, each connected by 20-ft long cables to a common electronics cabinet now the size of only *one* refrigerator; this general configuration would be used in all subsequent "academic" versions. One module, its box mostly empty, held a control panel that provided switches and register indicator lights (remember those?) together with speed and audio control knobs and so forth. A second module held a 5" CRT display adapted from a laboratory oscilloscope. A third module held the dual tape transport mechanics, while the fourth held a set of potentiometer knobs and jacks for analog input together with connectors for future input-output equipment. As an option for crowded laboratories, all modules could be removed from their boxes and mounted in standard equipment racks if desired. [Somewhat embarrassed



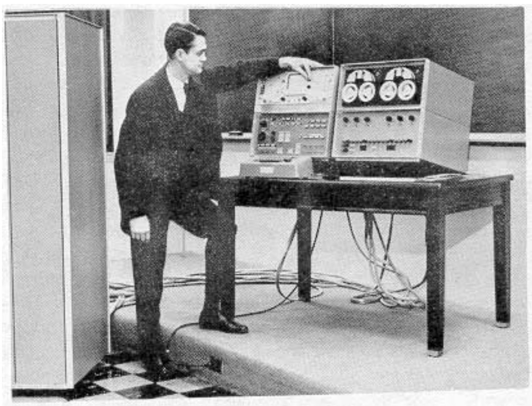






An abbreviated history of the LINC tape unit design. Upper left: June 28th sketches of parts of the tape turn-around control, including a picture of my foreboding of difficulties yet to come. Upper right: August 6th sketches of a possible arrangement of parts. Lower left: August 15th list of control logic expressions. Lower right: October 27th report of my realization that observed misbehavior of the prototype tape unit was caused by my design mistake. The unit worked well shortly thereafter. (From the 1961 LINC design notebooks).

by the size of the electronics cabinet, we adopted the point of view that it was only the console modules, taken together, that constituted the instrument itself; the rest was merely the electronics that made it all go and would be tucked out of sight in any convenient closet. We expected the cabinet eventually to disappear with advances in electronic packaging. It did, of course; but then so, eventually, did consoles.]



The Linc system demonstrated at the Lincoln Laboratory auditorium in March, 1962. Four console modules are connected by 20-foot cables to a cabinet holding the required digital electronics. The demonstration consisted of running a few simple programs toggled in by hand in advance.

The National Academy of Sciences Demonstration

Charlie, Norm, Bill Simon, and I took the Linc to Washington as planned and the National Academy demonstration was well if somewhat uncomprehendingly received [15]. Bill had arranged for closed circuit TV equipment and had set up several monitors about the meeting room. Charlie and I had spent the night before — *all* night — trying to fix some unexpected problem in the arithmetic element, crawling around the floor of our suite at the conference hotel with test equipment and soldering irons and discovering only by the dawn's early light that just outside our room there was a huge broadcast antenna tower that had been flooding everything with electromagnetic noise.

Norm commandeered one or two people from the hotel staff and moved the Linc to the meeting room for the presentation while Charlie and I dressed, Charlie in his Air Force uniform since at that time he was completing his military service at the Air Force Cambridge Research Laboratories and had to appear in offical garb. I stepped to the podium not knowing whether the machine was going to work or not, Charlie still frantically toggling in program parameters and trying out the demos. But at the last possible moment he slipped me a scrap of paper that said, "The following programs have my confidence: ... ". The Linc performed perfectly. Whew! The only question asked, Charlie recalls, came from an older gentleman who seemed to be quite interested in the durability of the wiring insulation. He was from the Smithsonian.

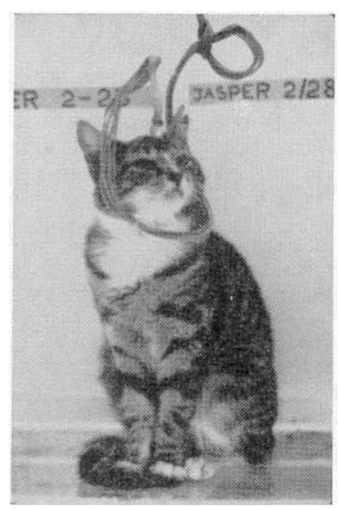
NIH Interest

After the Academy meeting Norm moved the Linc to one of the laboratories of Dr. Robert Livingston, Scientific Director of both the Institute of Neurological Diseases and Blindness and the Institute of Mental Health. There Charlie connected the analog-to-digital input channels to a multiple electrode array implanted in the brain of one of the lab's mascots, a cat whose name, I believe, was Jasper. In short order he wrote a small program that displayed on the CRT the average neuroelectric responses of the behaving animal. The Linc was successfully performing its first scientific task.

The writer Sam Rosenfeld, in a background paper prepared for a seminar held at NIH in celebration of the twentieth anniversary of the LINC, quotes Dr. Livingston's recollection of the event [16]:

> 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 opportunity to ski down a virgin snow field of a previously undiscovered mountain.

[Jasper merely purred and looked pleased.]



Jasper, one of several animals used in experimental work at a National Institutes of Health laboratory. The other end of the cable leading from the cat's head was connected to the Linc in a 1962 trial, the Linc's first scientific assignment.

It must be reported, however, that we did not have much success the next day when the Linc was moved to the laboratory of Dr. Mones Berman to see what it could do to isolate a very fast fluorescence transient produced in a particular biochemical reaction. Severo and Mary Allen answered an emergency call and came to Washington to help, but to no avail. Bill Simon would later write a superb program for the general problem of exponential decomposition but the limits of Linc speed had been reached.

Nonetheless, the interest of NIH had clearly been engaged. The National Academy of Sciences had already made the suggestion to Dr. James Shannon, Director of NIH, that he set up a committee to monitor and encourage the development of computer technology relevant to biomedical research. In response, Dr. Shannon had established the Advisory Committee on Computers in Research. This committee, among whose members were both Dr. Brazier and Bill Papian, had been following the M.I.T. activities closely. The Linc demonstrations at NIH had in fact been arranged by the committee's executive secretary, Dr. Bruce Waxman, who would shortly take further initiatives leading to the funding of a Linc evaluation program.

Linc Becomes LINC

The group at Lincoln had been joined by Dr. Thomas Sandel, a neurophysiological psychologist who had been conducting auditory research at CBL. Tom had organized and hosted an NSF-sponsored workshop the previous summer in which some of the M.I.T. computing techniques were shown to an invited group of biomedical researchers. He now proposed to use the Linc in a repeat of the workshop to be held in the summer of 1962. Plans were approved and a well-attended workshop was held during which several new Linc programs were written and new applications were investigated. [An amusing side benefit: In programming one of the data recording tasks we discovered that we had neglected to wire in a pathway for the signal specifying the initial direction of tape motion. Since the tape units were designed to search for designated blocks in either direction (now at a sedate though still uncontrolled speed of about 3 miles per hour), the occasional misbehavior had been self-correcting and had largely gone unnoticed.]

We began to think in terms of expanding the work. Bill Papian had been given to believe that under the right circumstances funds for support of a larger program in biomedical computing would be forthcoming from NIH. Charlie and Bill Simon and I were already beginning to modify and improve the design of the Linc so that a number of soundly engineered replicas could be made, and Tom Sandel was proposing to set up a small lab in space adjacent to the TX-2 for relevant biologically oriented work. But it was not to be. Lincoln Laboratory management, sensing that there would be serious organizational difficulties in administering such a program within its established framework, firmly rejected both the expansion and "wet" lab proposals. Instead, we were invited to find a more suitable home for any further work. In reporting to a stunned Linc design team the management's decision and my own decision to leave, I announced that "Linc" had just become "LINC", an acronym for Laboratory INstrument Computer.

The principals subsequently spent several disheartening months trying without success to find a "suitable home" for the continuation and extension of the work to which they were now deeply committed.

THE LINC EVALUATION PROGRAM

Toward the end of 1962, Walter Rosenblith put forth an imaginative proposal: M.I.T. would act as host institution in a multi-institutional, multidisciplinary endeavor to be called The Center for Computer Technology and Research in the Biomedical Sciences; faculty and staff from several New England universities would join in providing the scientific and technical substance of a long-range program; a Center Development Office would immediately be set up to work out details, secure multi-institutional blessing, and formalize a proposal to NIH; and finally, to avoid loss of momentum the LINC team would immediately be taken in under the CDO wing to complete the redesign effort and mount a program for the dissemination of LINC technology.

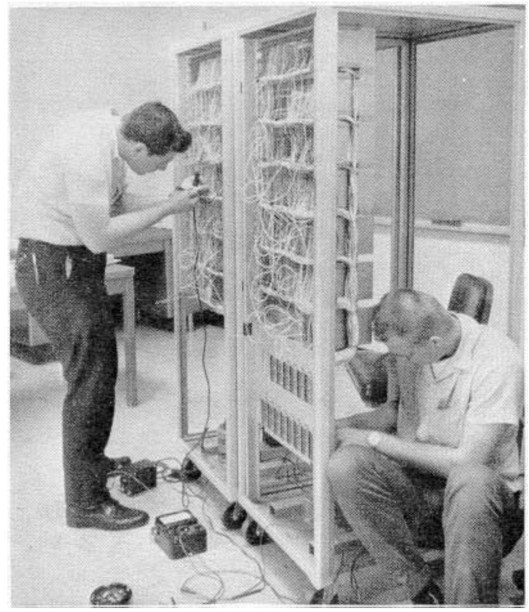
This proposal was widely accepted almost at once. Funds for the establishment of the CDO, with Walter as Director and Bill Papian as Associate Director, magically appeared. Arrangements were made with Lincoln for the transfer of staff and equipment, and the entire biomedical research computer effort at Lincoln Laboratory, together with several members of CBL, moved to new quarters next to the campus in Cambridge in January, 1963.

Redesign of the LINC

The next several months were ones of intense activity as we worked hard to complete the redesign in time for what was now formally known as the LINC Evaluation Program. Construction of 16 LINCs was authorized under the formal program. Twelve of these machines were to be assigned to biomedical research scientists selected by a nationally constituted LINC Evaluation Board for trial use in their own laboratories following a special Phase I training program at M.I.T. Four machines were to remain with the design team for coordination of Phase II evaluation activities and further refinement of the instrument itself. Given the new CDO framework Dr. Waxman of the NIH Committee, in a dazzling display of civil service at its best, had been able to earmark about half of the needed funds from NIH and had persuaded Dr. Orr Reynolds of NASA to put up the remainder from NASA's recently established Bioscience Program. In parallel with this activity NIH assembled the necessary committees to review the much larger proposal for the Center itself, and with amazing smoothness and speed authorized a huge M.I.T. research grant of an unprecedented scale sufficient to warrant announcement on the front page of the New York Times.

The idea of providing replicas of the LINC to individual researchers seemed quite natural. Tom Sandel had outlined just such a plan following the summer workshop the previous year and the idea had taken hold immediately. Charlie had then suggested, only partly in jest, that the computers be put together by the workshop participants themselves and I had promptly taken the idea quite seriously as an excellent way to teach the inner workings of the LINC. After all, it would be up to the participants to keep their machines running, wouldn't it? What better way to ease these good people into the discipline of digital systems? We would gather the parts and subassemblies together in the form of a kit and provide assembly instructions and any necessary documentation. This would not only keep the costs down but would also encourage later participation by other interested individuals.

William Simon with an interim version of the LINC. The dual-display module provided both long- and short-persistence phosphor CRTs. Six potentiometer knobs supplied input parameters.

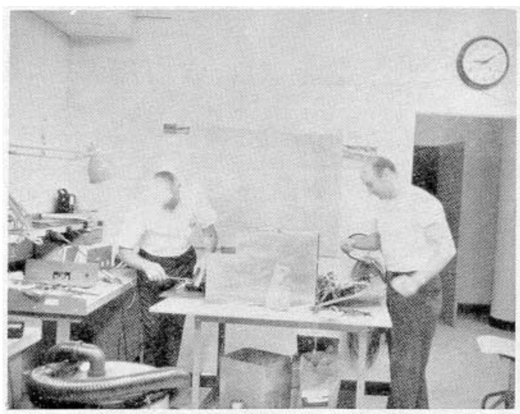


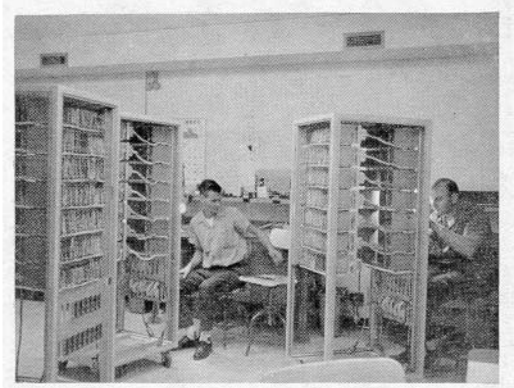
Technicians assembling wired frames for the LINC electronics cabinet. About twenty of these cabinets were required for the summer program.

Again the projected time schedule was extremely tight, especially for a development group in an academic setting. But morale was very high as it always is under such circumstances and every member of the now somewhat expanded design team proceeded to put in a magnificent performance. Charlie designed new circuits for the memory (now modularized in two 1K units with only one to be included initially) and completely reworked the magnetic tape unit read/write amplifiers and motor control circuits. Bill Simon redesigned the a-to-d circuitry and worked out a new single-scope system for the display module. Severo expertly refined the tape control logic and incorporated the tape pre-marking subsystem. Mary Allen traveled back and forth to the TX-2 at Lincoln Laboratory to update the LINC simulator and complete the new LINC Assembly Program, LAP3. Don Malpass joined us temporarily from Lincoln and did an outstanding job of designing the power supply and the interconnection system, the high-speed computer's Achilles' heel if not very skillfully handled. Norm Kinch prepared and endlessly updated the necessary drawings, and supervised our support staff as well as the beginning manufacture of subassemblies by local vendors. I concentrated on the surprisingly difficult job of working out the details of console control and the proper arrangement of indicators and switches, and generally tried to keep the overall program on target.

Charlie debugging a prototype of the final LINC system. Modifications to the frame wiring were few but had to be made to all frames being assembled by a local vendor.

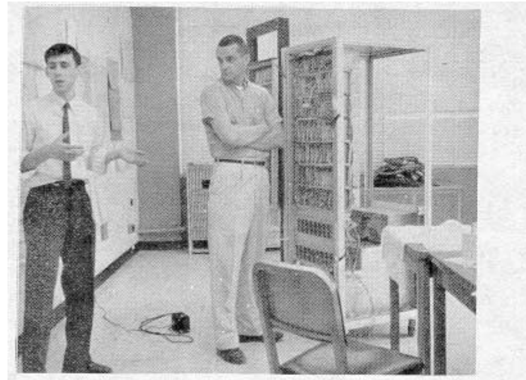
One month to go. Parts and subassemblies were continuing to arrive and the final LINC prototype neared completion. Mary Allen finished off the layout of the central control logic. Mishell Stucki, a man without peer in attention to detail, organized the wiring lists in a form suitable for the electronics frame checkout so critical to the success of the kit concept. Mort Ruderman of DEC took personal responsibility for assuring that sets of DEC modules, about 90% of the required electronics, would arrive on time. Howard Lewis and Dan Calileo and others stepped up the pace of special parts assembly under Norm and Charlie's supervision. Don O'Brien saw to it that the extensive and growing documentation was kept in good shape and had the assistance of Henry Littleboy of Massachusetts General Hospital. Severo was everywhere. One could not have hoped for a more dedicated and competent team.

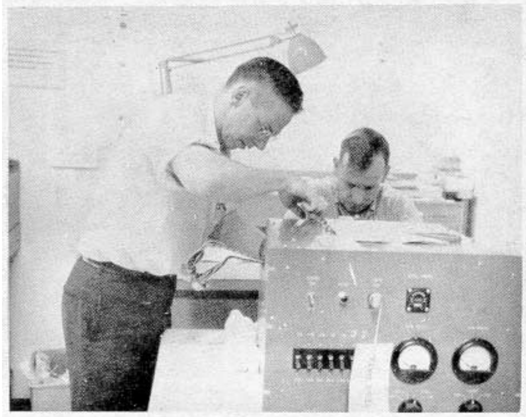


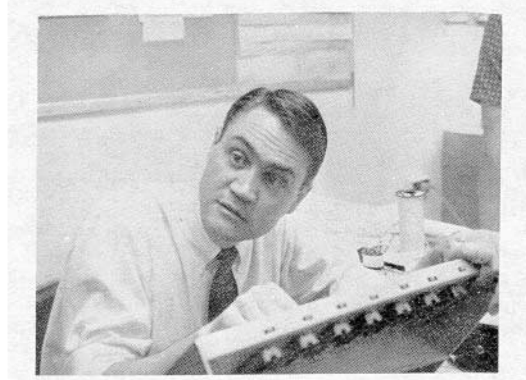


(Upper) Norm Kinch (left) and Dan Calileo repairing prototype power supply; (lower) Howard Lewis and Dan making "final" wiring changes to the electronics frames. Several additional modifications were later found to be necessary and were added, using white wires to avoid confusion with color-coded frame wiring already documented.

[Phase I photographs taken by Bill Simon.]





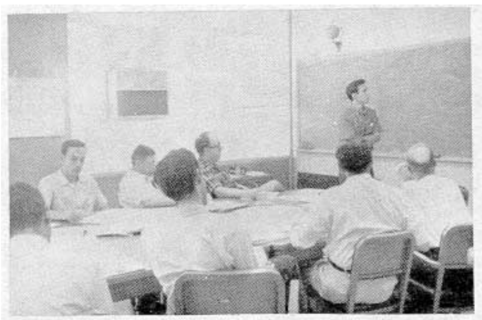


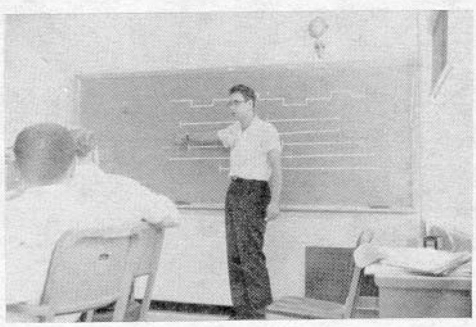
(Top to bottom) Severo Ornstein (left) and Prof. Jerome R. Cox of Washington University review last-minute problem; Bob Brown (left) and Tom Sandel examine incoming power-supply; I check the wiring of a control panel module.

One week to go. One or two frames had been completely wired but there was still difficulty in obtaining the necessary test equipment to verify wiring accuracy. A last minute circuit problem that Charlie had discovered was overwhelmed with the help of Maynard Engebretson and Prof. Jerome R. Cox (a member of the Evaluation Board), who made a special trip from Washington University in St. Louis. Tom Sandel, Chairman of the LINC Evaluation Board, monitored progress with increasing anxiety. Charlie and I maintained a facade of manifest confidence that masked serious concern.

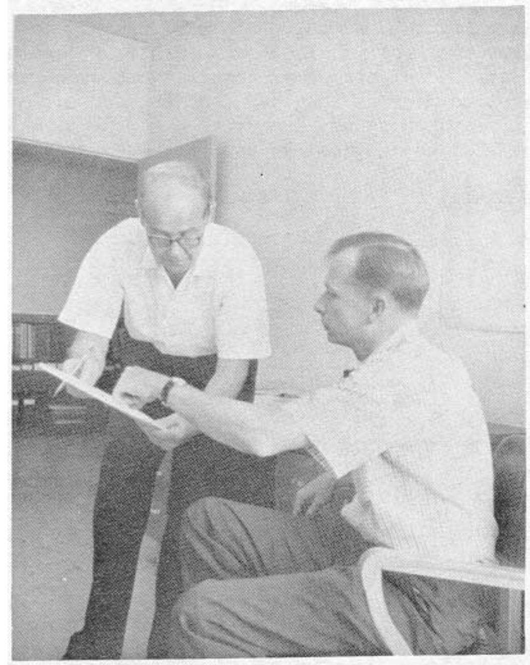
Phase I: The LINC Summer of '63

On July 1 the first group of visitors arrived, some of them with golf clubs they would never use. We immediately put them into a crash course on the theory and use of computers, a holding action managed by Mary Allen and Irving Thomae and Severo for the two more weeks it would be until the kits were ready.





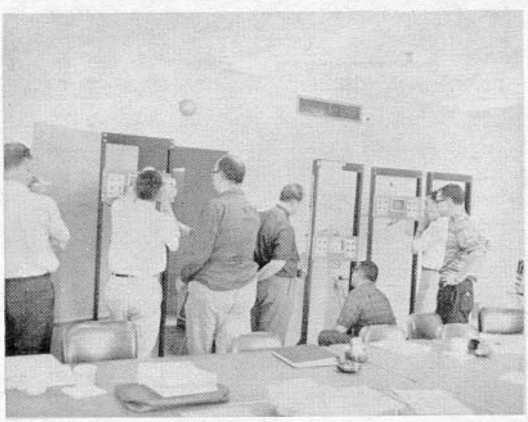
(Top to bottom) Severo explains LINC logic to the first group of visiting scientists; Irving Thomae reviews timing diagrams; Mary Allen Wilkes shows LINC programming.



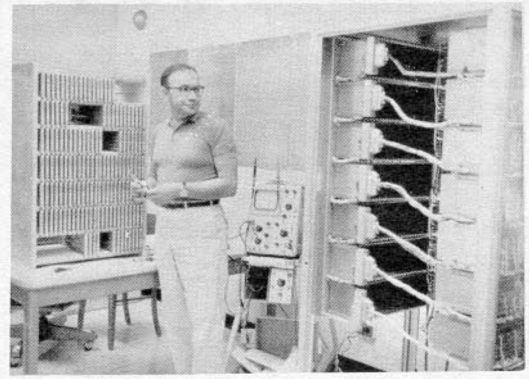
(Upper) Tom Sandel (right) in discussion with Dr. Gerhardt Werner of Johns Hopkins University; (lower) Mary Allen works on a program using rack-mounted equipment.

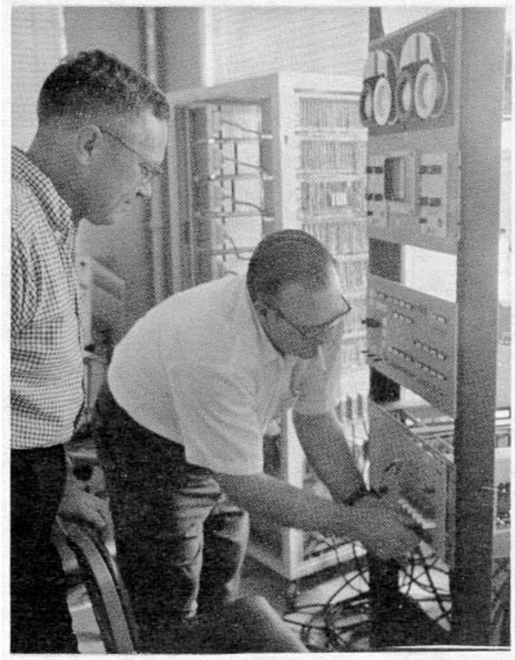
While classes were proceeding, the rest of us worked over the electronics frames and completed the job of checking the wiring, using Mishell's well-organized lists. The only part of this miserable and boring task we found rewarding was a sparkling Christmas-tree light effect produced by the test equipment. We found only a few wiring errors and fixed them.

Finally the assembly process began. To our delight and relief all went smoothly, though many long days and nights of exhausting work were still required to make up the lost time and correct minor design mistakes as we found them. The visiting scientists energetically and with much spirit and enormous dedication to the task proceeded quite successfully to bring all six or so LINCs to life.

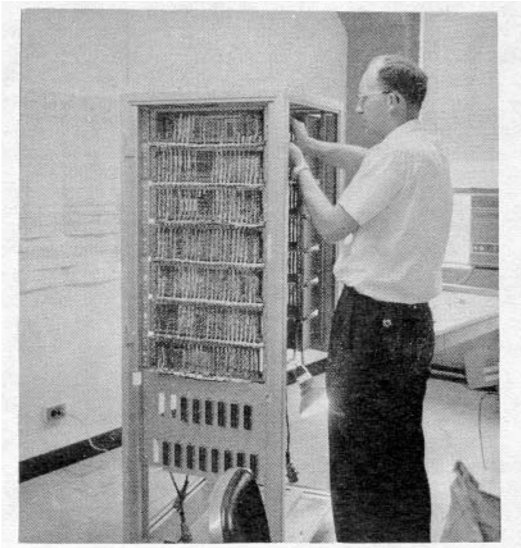


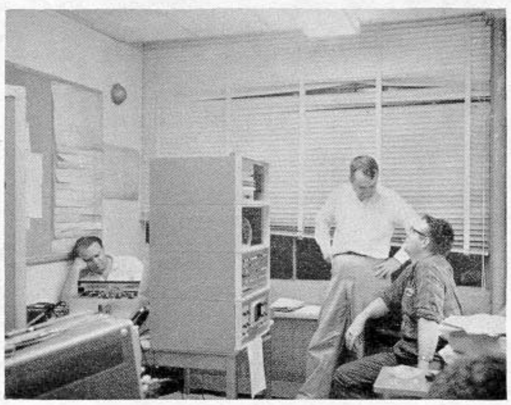
(Upper) Dr. A. J. Hance examines his tape unit module. Tape unit modules were almost entirely electromechanical; one critical component was a rubber-band. (Lower) A group of visiting scientists mount display units in staging racks.

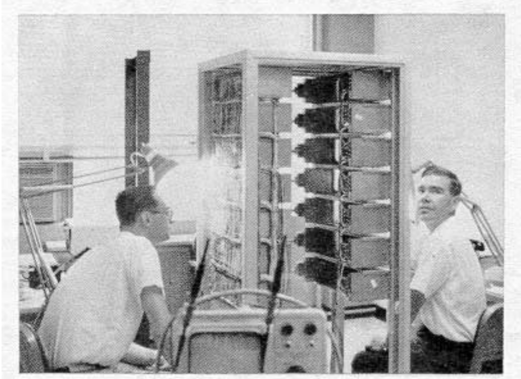




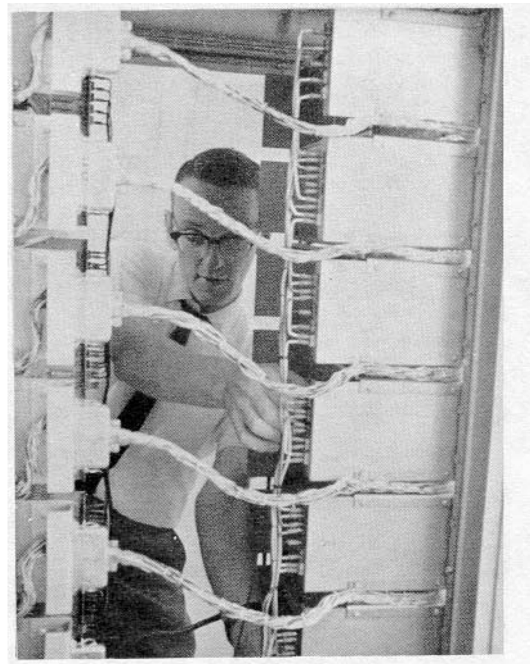
(Top to bottom) Dr. G. F. Poggio contemplates the plug-in unit installation task; Drs. N. Bell (left) and R. Stacy with staging rack; Dr. J. C. Lilly installs a modification while Mishell Stucki (rear right) ponders a problem.

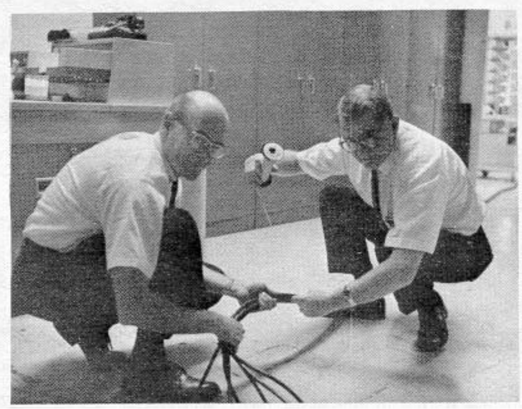






(Top to Bottom) Dr. J. W. Woodbury installs a plug-in unit; Charlie discusses a point with Dr. K. Killam (right) while Dr. Hance nods (it is 2 a.m.); Drs. C. D. Geisler (left) and J. E. Hind examine wiring.





(Upper) Dr. C. A. Boneau reaches into his cabinet to make an adjustment. (Lower) Drs. F. S. Grodins (left) and J. E. Randall wrap interconnection cables.

Each of the visiting teams was required to write and demonstrate a small program representative of the work of its home laboratory. With the completion of these final assignments, the machines were packed up for shipment and the entire group of hosts and visitors, now fast friends, celebrated with great exuberance at a farewell banquet.

The M.I.T. hosts had only three days to recover before the second group of visitors arrived. This final session of Phase I went more smoothly than the first, with less pressured teaching and more time for thoughtful assembly. Once again the visitors carried out all of their assignments with flair and great good humor, and again — on time — the LINCs were packed up for shipment. Our final banquet this time was an occasion for sober reflection on the magnitude and importance of what we had all achieved.

Moving day. Although some parts were crated for transportation, the electronics cabinets were simply taped up and carried in moving vans as furniture. Most of the machines were moved in this manner and all arrived safely at their new homes in laboratories across the country.

The LINC was now well and safely launched and in good hands. Charlie and I had little doubt of its ultimate success.

For the most part the participants had all taken to the unfamiliar fairly well. For those few who had already worked with computers, the general acceptance of machine-level programming as the price of dealing with such a small memory had been cheerful enough. Productive software, however, would not begin to accumulate in the various laboratories until the following year; the first published version of the programming manual, the year after that; and the first edition of the final assembly program, LAP6, not until 1967.

We had had to formulate both teaching and assembly procedures as we went along, but this resulted in only a few bruised knuckles and egos and a few inefficient hours (one of the visitors, a neurosurgeon, did have difficulty adjusting a tiny slotted-screwhead potentiometer deep within the recesses of the electronics frame, as I recall). Fixing design mistakes and modifying the circuits and wiring to reduce system noise meant repairing all machines in parallel. Each machine, by the way, had required a budget outlay of about $32,000, or so the accountants told us. Not too bad a miss.

Throughout it all we had been sustained in our endeavors not only by our boundless energy and enthusiasm, our spirited sense of adventure, and our deep reserves of unshakeable conviction and commitment, but also by the Fox & Tishman Restaurant of Kendall Square, Cambridge. The F&T's sympathetic management and colorful staff fed and otherwise refreshed us at all hours of the day and night. [Following a suggestion of Charlie's, any member of the team who was responsible for a design goof agreed to buy one martini for all other members of the team at the end of the effort — one martini per goof, non-cancelling. On the day of reckoning we all repaired, of course, to the F&T. I can't remember how it all turned out.]

The Move to Washington University

The weeks immediately following our intensive summer effort did not go well. We were not only exhausted but were also confronted with an unanticipated organizational problem. The nascent M.I.T. Center, prospectively multi-institutional and multi-disciplinary, turned out to be irremediably multi-problematical as well and de-materialized. The result was that once again the peripatetic LINC team found itself in need of a more suitable home for its work. We were ...um... disappointed.

I suppose that these days it is natural to expect a group in such circumstances to form a commercial company. The LINC team, however, had always been more academically than entrepreneurially inclined. In many subsequent months of searching, the principals traveled about the country and met with many university presidents and trustees, examining several propositions quite seriously. But it was an unscheduled meeting in Cambridge with George Pake that convinced us that the best choice for the continuation of the program was Washington University in St. Louis, where Dr. Pake was Provost in the years before he left the academic world to set up XEROX PARC. He had heard about our situation from Professor Cox, he said, and had "just happened" to be visiting Cambridge on his way to Woods Hole (he never got there). He had stopped by so that we could, in his words, look him over. We were already well acquainted with Jerry Cox, an old friend even then, especially since those final hectic days before summer, and had a high regard for his innovative work in biomedical computing at Washington University. For many of us, then, this extraordinary meeting with George Pake made an already very promising possibility irresistible.

And so it was that the Washington University Computer Research Laboratory was established in 1964 under the direction of William N. Papian, Associate Dean of Engineering. CRL set up shop in newly renovated space made available by its new-found "sister laboratory", the Biomedical Computer Laboratory under Jerry Cox. Tom Sandel accepted an appointment as Professor of Psychology, and I became Research Professor of Computer Science and Associate Director of CRL. Many from the Cambridge team, including Severo, Mishell, Howard and Ken Lewis, and Constance and Joe Towler uprooted and moved to St. Louis, followed by others from M.I.T. over the next few years. Charlie remained in Cambridge to complete both his military service and his doctorate at M.I.T. and rejoined the group a year later as Associate Professor of Physiology and Biophysics. Norm Kinch rejoined us after an assignment at an experimental radar site operated by Lincoln Laboratory in the Southwest. Mary Allen received her appointment letter from George Pake midway in a one-year trip around the world (she was then in Calcutta), but before coming to St. Louis spent another year as an extramural member of CRL working on a new assembly-program/operating system, LAP4, using a LINC set up in the living room of her family home in Baltimore — surely a first in personal computing. But the original team never entirely regrouped. To our great regret, George Gerstein and Belmont decided that their immediate scientific interests were better served by accepting appointments at the University of Pennsylvania in the Laboratory of Dr. Britton Chance, and Bill Simon elected to accept an appointment at the Harvard Medical School.

Phase II Activities

Four main tasks faced us in carrying out our Phase II responsibilities under the formal evaluation program.

1) We had to assure that the LINC equipment itself had been transplanted successfully into each of the participants' laboratories and was kept up-to-date.

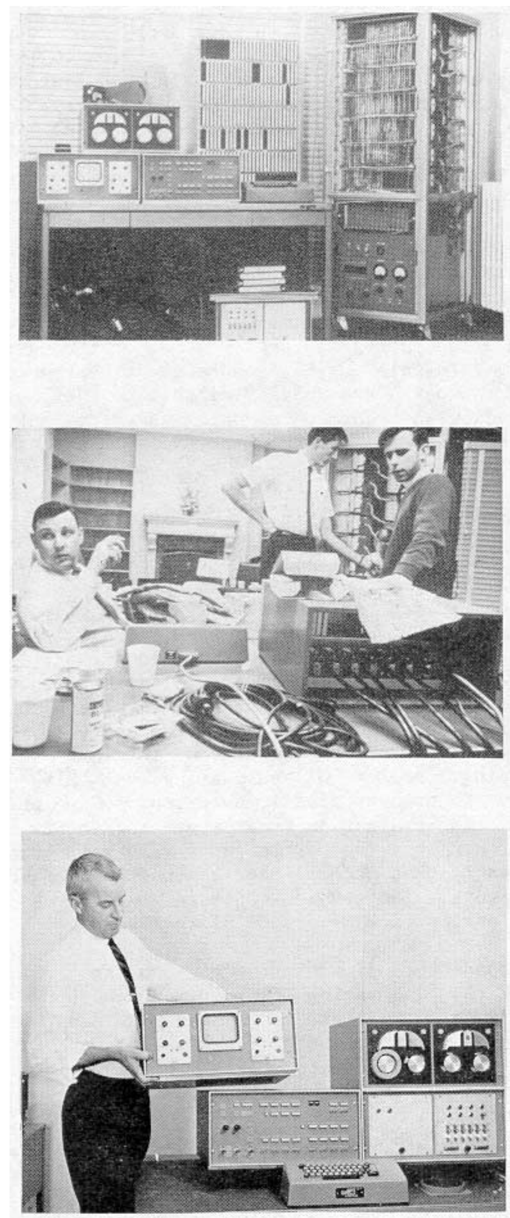
2) We had to complete and distribute further documentation on the machine and its use.

3) We had to improve LINC software, starting with an enhanced version of the basic assembly program that provided automatic filing capabilities and improved editing and operational features.

4) Finally, we had to accumulate operating experience with the LINC in our own work in biomedical research and in other application areas.

Assuring ourselves and our sponsors that the LINC was taking root required considerable use of the telephone and post office as well as visits to each site. A few faulty switches and parts needed to be replaced, a few adjustments made, and a few circuit improvements installed as we verified their need. We adhered to the principle that any modification to one machine meant a modification to all machines. By and large, however, machine reliability was excellent, thanks to sound engineering by Charlie, Bill Simon, and Don Malpass as well as to the robustness of DEC circuit packages when carefully used. [From one of the sites, the only call for hardware help we ever got dealt with what to do about the fact that the elapsed-time meter on the power supply had just jammed at 99999.]

Completing a set of finished documents on LINC hardware and operation was more difficult (the evaluation program participants had been able to take away from Cambridge only the roughest of descriptive material and operating notes). Among other things, it meant that a full production version of a LINC kit and its accompanying assembly and test procedure documentation had to be checked out and certified. Not long after CRL had been set up, Mort Ruderman brought the first complete DEC-produced kit to St. Louis. Mishell and Severo then put it together and verified the accuracy of the documents and test procedures, making a few necessary corrections. Final documents were prepared with the help of newcomers Dave Stewart (who had worked with Charlie during his Air Force days), Gerald Johns, Robert Ellis, and Maurice Pepper. After printing and distributing revised final documents to all evaluation program participants, we sold document sets at cost to anyone who wanted them.



(Top to bottom) The LINC kit produced by DEC; Mort Ruderman of DEC (left), Mishell (rear) and Severo assembling the kit; Norm Kinch stacks console modules.

Building up a base of operating software was accelerated with the help of the Biomedical Computer Laboratory. A variety of utility programs were written by our BCL colleagues Jerry Cox, Mike MacDonald, Sharon Davisson, and others. BCL incorporated these into LAP4 (an interim modification of the LINC Assembly Program, LAP3), and many of its operating features were later incorporated by Mary Allen in the ultimate version, LAP6. Software was generally distributed on LINC tape reels via the mails. Since direct exchange of programs among the participants was rare, we did what we could to certify and distribute copies of application software that was submitted to CRL or written at CRL or its sister laboratory BCL.

Use of the LINC in our own work was supplemented by work at BCL, where a few kits were assembled and used in connection with collaborative programs with the Washington University School of Medicine and its associated hospitals. Later we acquired several of the LINC variant machines made by DEC and others and began to use them in our developing research program in macromodular systems (which soon took over as the major focus of CRL activities). [BCL went on to design the Programmed Console, the result of a design seminar that Jerry and I taught in 1965 [17]. Known as the PC, it provided both autonomous and remote-connnection modes of operation and thus was one of the earliest "smart terminals". It was subsequently produced in small numbers and made available to radiologists for radiation treatment planning under a national program modeled after the LINC Evaluation Program.]

The Final Evaluation Program Meeting

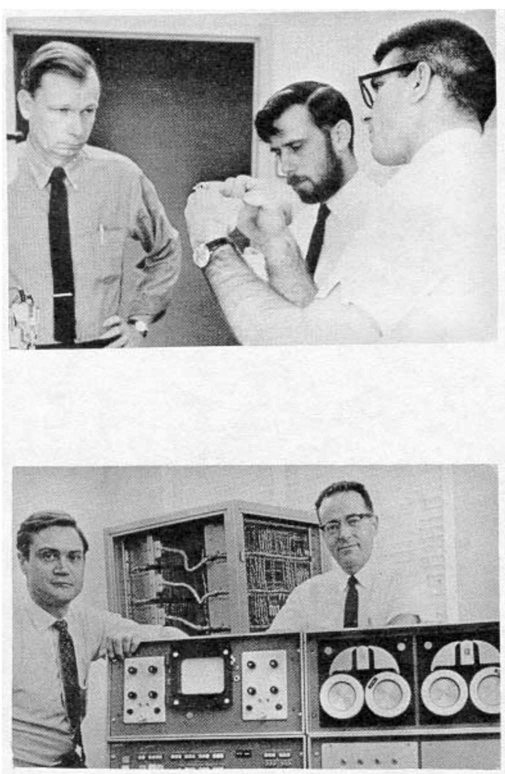
The program participants began to use and then gradually depend on the LINC in their research. It had not seemed so, however, at our first regathering in June, 1964, when we all met for a show-and-tell at a distinguished old resort hotel in New Hampshire. Just short of a year since the Cambridge Summer, there hadn't yet been enough experience gained in the use of the new tool, especially in view of the scarcity of software and the upsetting problem of relocating the LINC core group. No one was greatly surprised. But at the final LINC Evaluation Program meeting in St. Louis in March, 1965, the participants were well prepared and had by then accomplished a great deal of scientific work. The studies reported covered a wide range of topics [18]. Some of them were:

> Operant conditioning of pigeons and monkeys. [One series of experiments made use of a wonderful Lazy Susan holding a pigeon at each of four stations around its circumference, with indexing into data-collecting position, stimulus generation, and data analysis all provided by the LINC.]
>
> Spontaneous activity in thalamic and cortical neurons, behavior of single cochlear neurons, and somatosensory responses evoked in intracranial stimulation of cortex.
>
> Pulsatile blood flow, cardiac muscle behavior, hydrodynamics of the mammalian arterial system, and human finger tremor.
>
> Genetics at the bacterial and molecular level using mass spectrometers and other instruments.
>
> Communication between man and dolphin. [An unanticipated equipment hazard: the dolphin, one Elvar, could accurately spit a stream of seawater a distance of twenty feet.]

Preparation for the Final LINC Evaluation Program Meeting, March, 1965. (Top to bottom) I talk with Joseph Foley of Spear, Inc. while a LINC is being set up on stage; Prof. Harold Shipton (left) in discussion with Mort Ruderman and Winn Hindle of DEC; Drs. L. Wienckowski (left) and Bruce Waxman of NIH.

In addition to their scientific accomplishments the participants reported several other technical and software development activities. These included the connection of the LINC to computation center machines, the development of a system for remote control of the LINC, the design of interface circuits for control of a blue-format tape transport and other laboratory equipment, and the development of several experimental operating system programs and floating-point routines.

By the end of Phase II the Evaluation Program participants had an accumulated experience of about 50,000 hours of LINC use with remarkably little trouble, and at least that many hours had also been accumulated at other LINC sites with similar results. For the most part the original participants were awarded permanent custody of their machines following their reports of this strikingly successful operation in laboratories across the country.



(Upper) Tom Sandel and a now bearded Severo in a visit to the laboratory of Dr. G. S. Malindzak; visits were made by various members of the Washington University group to each of the participating Evaluation Program laboratories. (Lower) The author and William N. Papian with the final version of the LINC [Photo courtesy of the Saint Louis Post-Dispatch].

IN LATER YEARS

Although our formal responsibilities under the LINC Evaluation Program had been discharged, there was still work to be done that would take some of us a few more years.

Final LINC Modifications

Following the recommendation of the growing band of LINC users as reported at the final Evaluation Program meeting in St. Louis, a decision was made to undertake a number of hardware modifications. A new register and an arithmetic overflow circuit were provided to extend the range of arithmetic and to facilitate running a certified floating-point software package for which a considerable consensus had developed among the mathematically inclined. These changes were seasoned, documented, and distributed (with a few installation visits) to all of the original LINC sites, as was the floating-point package itself. Similarly, data and program interrupt features were incorporated to improve performance in several high rate applications. Altogether six new instructions dealing with these new features were wired into all machines.

The Final LINC Operating System

The final assembler/operating system, LAP6, was put together by Mary Allen with great care. Discussion of its specification had begun early in 1965 during her visits to several of the participating laboratories to develop a consensus regarding users' needs. A decision to double the initial 1K memory size had already been made; but as Mary Allen put it, doubling a 1K memory produces another small memory. Despite this limitation she was able to define a remarkably efficient operating system based on a LINC tape scrolling algorithm developed by Mishell and Severo. LAP6 included a line-by-line editor, an assembler, automatic management of files, user-defined metacommands, and runtime debugging aids [19]. It was thoroughly tested before being distributed in 1967 and the accompanying LAP6 Handbook still stands as a model of simplicity, accuracy, and usability [20]. A student of philosophy (today a lawyer in Massachusetts), Mary Allen quoted Kierkegaard in the foreword to the handbook:

To promise the System is a serious thing.

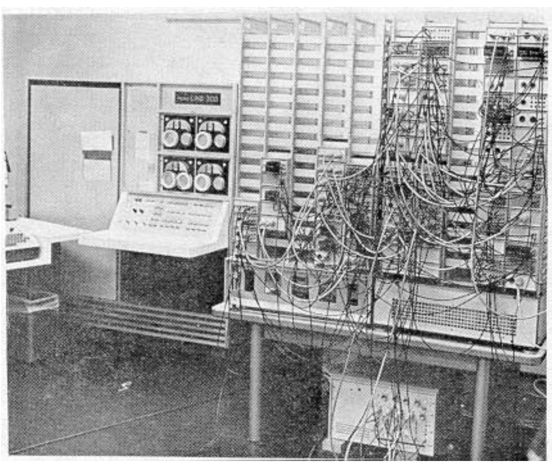
The handbook and the second edition of its companion programming tutorial document published in 1969 reflect the final form of what is now referred to as the "classic" LINC [21].

Manufacture of the LINC and LINC Variants

DEC went on to manufacture altogether fifty or sixty classic LINCs, only a few of these in kit form — an idea whose time never quite came. [Some of the kits were assembled for others by Prof. Harold Shipton of the State University of Iowa, previously a member of the LINC Evaluation Board. "Shippy", one of the most charming people ever to walk the face of the planet and well known to the biomedical community for his perceptive and imaginative engineering, later joined the faculty of Washington University.]

In 1965 I joined forces with Dick Clayton of DEC to design the LINC-8, a 32K dual-machine combination of the LINC and Gordon Bell's PDP-8, in which the complex LINC tape control logic was relegated to a concurrently executable program on the PDP-8 side using software written by Severo. While the nearly 150 LINC-8s were being made, Dick designed a new version of the machine, the PDP-12, of which about 1000 were manufactured [3].

In 1965 a new Massachusetts start-up company, Spear Inc., made its appearance. It began to manufacture a 4K integrated circuit version of the LINC, called the micro-LINC 1. Spear went on to produce the micro-LINC 300, a higher-performance 32K variant. [Spear, Inc. subsequently became a division of Becton Dickinson and Company. I have no doubt that the transaction helped Spear's former president farther along toward his life-long goal of retiring to some small South Sea Island that had an 18-hole golf course and a native monarch.]



A Spear Inc. micro-LINC 300 (left) providing operational support to an experimental macromodular system at Washington University.

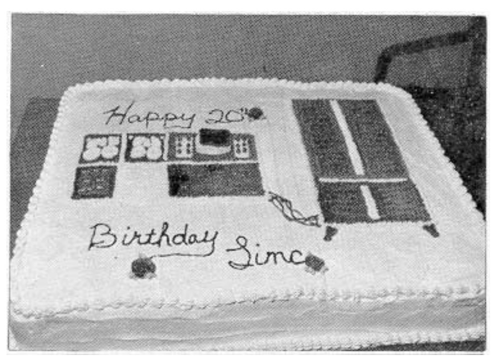
DENOUEMENT

With more than 1200 LINC or LINC variants at work around the world, research over the ensuing years began to result in very substantial contributions to the body of scientific literature. An effort was made to maintain a bibliography of LINC-related publications for the first few years, but the task soon got out of hand. The July, 1969 edition lists more than 150 scientific papers, journal articles, and published books [22]. By then the growth rate of bibliographic references was already doubling each year, and the number of LINC programs and application notes alone soon became so large that responsibility for handling them had to be turned over to the DECUS Program Library.

The careers and lives of those associated with the LINC development continued to grow and change in many ways, as new academic appointments were assumed and new professional challenges undertaken. Many early students of these scientists and engineers, and their students in turn, went forth to seek their fortunes after training in the LINC and its ways.

Washington University's program in the medical and biological research uses of computer science and technology grew in prominence and soon came to be regarded among the foremost in the country. In the course of years Prof. Jerome R. Cox became Chairman of the Department of Computer Science, and Prof. Charles E. Molnar, Director of the Institute of Biomedical Computing. Dean William N. Papian retired from the University to private consulting practice, as did I. In a very saddening turn of the historical wheel Prof. Thomas T. Sandel, after many years as Chairman of the Washington University Department of Psychology, died just weeks before the LINC's twentieth anniversary gathering of old friends of the Summer of '63 was to take place.

The LINC design went on to influence the design of DEC machines that further reinforced the concept of the small computer as a tool for personal work and very soon took over center stage. Yet over the years the LINC and its variants continued to serve the needs of biomedical research. A few of them were still on the job productively in 1985, and one of these — perhaps the last of the "classics" — could be found at the Massachusetts General Hospital, not yet retired after more than two decades of continuous use.



The birthday cake that made its appearance at the LINC Twentieth Anniversary Celebration held on November 30, 1983 at NIH.

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APPENDIX

The LINC Evaluation Program Participants

Without any doubt whatsoever, as Tom Sandel would have said, the success of the LINC is due in incalculably large part to the pioneering work of the evaluation program participants. Its formal members were: Drs. E. O. Attinger and A. Anne, Research Institute, Philadelphia Presbyterian Hospital; Dr. D. S. Blough, Dept. of Psychology, Brown University; Drs. S. Goldring and J. L. O'Leary, Dept. of Neurology, Washington University; Drs. F. S. Grodins and J. E. Randall, Dept. of Physiology, Northwestern University; Drs. J. E. Hind and C. D. Geisler, Laboratory of Neurophysiology, University of Wisconsin; Dr. J. Lederberg and Lee Hundley, Dept. of Genetics, Stanford University; Dr. C. A. Boneau, Dept. of Psychology, Duke University; Dr. J. C. Lilly, Communication Research Institute; Drs. G. S. Malindzak and F. S. Thurstone, Dept. of Physiology, Bowman-Gray School of Medicine; Drs. G. F. Poggio, G. Werner, and V. B. Mountcastle, Dept. of Physiology, and Dr. B. Weiss, Dept. of Pharmacology and Experimental Therapeutics, Johns Hopkins University; and Drs. J. W. Woodbury and A. M. Gordon, Dept. of Physiology, University of Washington.

The number of LINCs actually built in the summer of 1963 was about twenty. Several other investigators had been invited to participate on an informal basis. These informal participants assembled their computers alongside the others, using their own funds but taking advantage of whatever batch orders were placed for parts and subassemblies. They were: Drs. K. Killam and A. J. Hance, Dept. of Pharmacology, Stanford University; Dr. H. E. Tompkins and Mr. J. S. Bryan, National Institutes of Health; Dr. J. B. Lewis, M.I.T. Lincoln Laboratory; and Drs. R. Stacy and N. Bell, Institute of Statistics, North Carolina State College.

Under the chairmanship of Dr. T. T. Sandel of

M.I.T., the LINC Evaluation Board included Dr. M. A. B. Brazier of the University of California at Los Angeles, Dr. J. R. Cox of Washington University, Dr. E. R. Dempster of the University of California, Dr. J. Macy, Jr., of the Albert Einstein School of Medicine, Dr. H. V. Pipberger of the Veterans Administration, Dr. M. D. Rosenberg of the Rockefeller Institute, and Prof. H. W. Shipton of the State University of Iowa.

THE EVALUATION PROGRAM LINC INSTRUCTION SET

FULL ADDRESS CLASS | ADD | X |

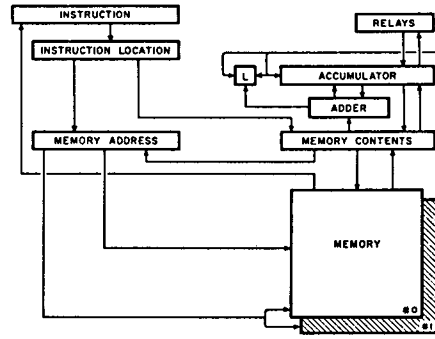
The right-most ten bits of the instruction word specify one of the memory registers 0–1777 (octal).

ADD X	Add the contents of memory register X to the Accumulator.
STC X	Store the contents of the Accumulator in memory register X, and clear the Accumulator.
JMP X	Take the next instruction from memory register X, and save the subroutine return point in memory register 0.

INDEX CLASS | LDA | i | β | | LDA | i | 0 | → | OPERAND OR ADDRESS |

If $\beta \neq 0$, the instruction is single word length and the address of the memory operand is located in index register β ($1 \leq \beta \leq 17$ octal). If $\beta = 0$, the instruction is double word length and the second word is either the operand (case $i = 1$) or the address of operand (case $i = 0$). The specified index register is incremented by ONE before use if $i = 1$.

LDA i β	Load the Accumulator with the memory operand.
STA i β	Store the contents of the Accumulator in the specified memory location.
ADA i β	Add the memory operand to the contents of the Accumulator.
ADM i β	Add the memory operand to the contents of the Accumulator and leave the sum in the Accumulator and in the memory operand location.
LAM i β	Add the memory operand to the contents of the Accumulator, together with any previous overflow held in the Link Bit. Leave the sum in the Accumulator and the memory operand location, and retain any new overflow in the Link Bit.
MUL i β	Multiply the contents of the Accumulator by the memory operand, and retain either high-order half or low-order half of the double-length product in the Accumulator.
SAE i β	Compare the contents of the Accumulator with the memory operand, and skip the next instruction if they are identical.
SRO i β	Rotate the memory operand to the right one place and skip the next instruction if the sign bit of the operand is ZERO.
BCL i β	Clear each bit in the Accumulator which corresponds to a ONE in the memory operand.
BSE i β	Set to ONE each bit in the Accumulator which corresponds to a ONE in the memory operand.
BCO i β	Complement each bit in the Accumulator which corresponds to a ONE in the memory operand.
DSC i β	Display character intensifying points on the scope in a 2 by 6 array according to the bit pattern of the memory operand.



HALF-WORD CLASS | LDH | i | β | | LDH | i | 0 | → | OPERAND OR ADDRESS |

Addressing is similar to that of the INDEX CLASS, except that the left-most bit of the address specifies which half of the memory operand is used. When $i = 1$ and $1 \leq \beta \leq 17$ (octal), the address word in index register β is incremented before use, in such a way as to step through consecutive half-words, the address of the operand increasing by one on every second reference.

LDH i β	Load the Accumulator with the specified half of the memory operand.
STH i β	Replace the specified half of the memory operand with the contents of the right half of the Accumulator.
SHD i β	If the contents of the right half of the Accumulator are not identical to the specified half of the memory operand, skip the following instruction.

TAPE CLASS | (MTP) | i | u | RDC | → | SECTOR | BLOCK NUMBER |

These are double word length instructions in which the first word specifies the tape unit (u-bit), the motion state following execution (if $i = 0$, the selected unit is stopped), and in which the second word specifies one of eight sectors of memory and one of 512 tape blocks between which transfers are to be made. All required searching operations and checking are performed automatically, and are repeated if checks indicate improper transfer.

RDC i u Q, N	Read tape block N into memory sector Q, and check the transfer.
RCG i u Q, N	Read from one to eight consecutive tape blocks, beginning with block N, into memory and check all transfers.
RDE i u Q, N	Read tape block N into memory sector Q.
MTB i u Q, N	Move toward tape block N on specified unit.
WRC i u Q, N	Write contents of memory sector Q in tape block N and check the transfer.
WCG i u Q, N	Write from one to eight consecutive memory sectors on tape, beginning with block N, and check all transfers.
WRI i u Q, N	Write contents of memory sector Q in tape block N.
CHK i u Q, N	Find tape block N and leave the check sum for this block N in the Accumulator.

SHIFT CLASS	ROL | i | n
If $i = 1$, the Link Bit is coupled into the shift path. $0 \leq n \leq 17$ (octal)	
ROL i n	Rotate the contents of the Accumulator n places to the left.
ROR i n	Rotate the contents of the Accumulator n places to the right.
SCR i n	Multiply the contents of the Accumulator by 2^{-n}.

SKIP CLASS	SNS | i | n
Skip the next instruction if the specified conditions are met. If $i = 1$, the skip conditions are reversed.	
SNS i n	Check whether Sense Switch n is up, $0 \leq n \leq 5$.
AZE i	Check whether the Accumulator contains ZERO.
APO i	Check whether the contents of the Accumulator are positive.
IBZ i	Check whether either tape unit is reading an interblock zone mark.
SXL i n	Check whether External Level input line n is negative, $0 \leq n \leq 14$ (octal).
KST i	Check whether a key has been struck on the keyboard.
LZE i	Check whether the Link Bit contains ZERO.

SET	SET | i | β ; OPERAND OR ADDRESS
SET i β	Set register β, $0 \leq \beta \leq 17$ (octal), to the value of the second word (case $i = 1$) or to the value of the operand whose address is located in the second word (case $i = 0$).

DISPLAY	DIS | i | β
DIS i β	Intensify a point on the scope whose vertical position is given by the right-most nine bits of the Accumulator and whose horizontal position by the right-most nine bits of memory register β, $0 \leq \beta \leq 17$ (octal). If $i = 1$, increment contents of register β before use.

INDEX AND SKIP	XSK | i | β
XSK i β	Increment by 1 the contents of memory register β (if $i = 1$) and skip the next instruction if the new contents of this register equal 1777, 3777, 5777, or 7777 (octal).

SAMPLE	SAM | i | n
SAM i n	Convert the analog signal appearing on channel n, $0 \leq n \leq 17$ (octal), to an eight-bit binary number in the Accumulator. If $i = 0$, this instruction takes 24 microseconds; if $i = 1$, the instruction is completed in 8 microseconds although the conversion process continues for an additional 16 microseconds.

MISCELLANEOUS	HLT
HLT	Halt the computer and sound a gong.
CLR	Clear the Accumulator and Link Bit.
ATR	Load the six Relay flip flops from the right half of the Accumulator.
RTA	Load the Accumulator from the six Relay flip flops.
NOP	Do nothing for 8 microseconds.
COM	Complement the Accumulator.

OPERATE CLASS — OPR | i | n

These instructions form a general input-output command set whose execution is partially controlled by externally generated signals. Some functions of this instruction set are summarized below.

1. *Pausing,* with conditional restarting.
2. *Generating outputs* on any one of sixteen control output lines.
3. *Reading into the Accumulator* from either of two twelve-bit parallel sets of gates.
4. *Reading into the Memory Buffer* from either of two twelve-bit sets of gates.
5. *Clearing of A* conditional upon externally generated signals.
6. *Gating outputs* from the Accumulator to external equipment.
7. *Transferring information* from the Memory Buffer to the Accumulator under the control of external signals.
8. *Controlling high-rate inputs and outputs* between internal core memory and external equipment.
9. *Reading of keyboard.*
10. *Reading of console switches.*