

## II. RESEARCH PLAN - BOOK I

This is an application for renewal of a grant supporting the Stanford University Medical EXperimental computer (SUMEX) research resource for applications of Artificial Intelligence in Medicine (AIM). The research plan has been divided into several logical parts:

- 1) Book I - Resource research objectives and rationale, progress report, and detailed research plans.
- 2) Book II - Biographical sketches, collaborating project reports and plans, and supporting appendixes.
- 3) Budget - First year budget detail, five-year budget summary, and budget explanation and justification.

## 1 BACKGROUND AND PROPOSED WORK

### 1.1 OVERVIEW OF OBJECTIVES AND RATIONALE

The SUMEX-AIM project is a national computer resource with a dual mission: 1) the promotion of applications of artificial intelligence (AI) computer science research to biological and medical problems and 2) the demonstration of computer resource sharing within a national community of health research projects.

In the body of this proposal, we offer definitions and explanations of these efforts at several levels of detail to meet the needs of reviewers from various perspectives. For this overview, we give only a brief summary of our recent accomplishments, present status and expectations for the requested term of the renewal, the five years beginning August 1, 1978.

Definitive funding of the SUMEX-AIM resource was initiated in December 1973. The principal hardware was delivered and accepted in April 1974, and the system became operational for users during the summer of 1974. The present renewal is therefore written from a perspective of just short of three years of experience in attempting to develop and serve the user community for the resource.

The original SUMEX proposal was an outgrowth of two lines of endeavor at Stanford that had been supported by the Biotechnology Resources Program. The ACME project (Advanced Computer for MEDical Research), 1965-72, had introduced the innovation of interactive time-shared computing to the medical research community at the Stanford Medical Center. Based on an IBM 360/50 with mass core storage, this system was notable for the ease with which physicians and scientists, previously inexperienced with computers, were able to learn a variety of applications with minimal help from professional programmers. With the further development of the technology, and the rationalization of computer support functions at Stanford, this system was eventually integrated with the university-

wide time-sharing service. While ACME had some shortcomings as a production (contra development) tool many of our colleagues at the medical school still look back regretfully at having lost it as a medical-school-dedicated system tuned to their special needs. The second line, the DENDRAL project, is a resource-related project connected with applications of artificial intelligence to problems of molecular characterization by analytical instruments like mass-spectrometry, gas-chromatography, nuclear magnetic resonance, and so on.

In 1972 we applied to NIH for the establishment at Stanford of a next generation computer resource to supplant ACME for applications for which the university-wide facility was inadequate. The DENDRAL project was the central source of this initiative; several others entailing real-time instrumentation as much as AI needs were also specified. During the subsequent 18 months, we entered a phase of protracted review and negotiations with BRP and its advisory groups, from which emerged the policy determination that resources of this scope were best justified if they could be functionally specialized, but geographically generalized. The emerging technology of computer networking opened an opportunity to demonstrate this model in a way that could serve both local and national needs. With all of this in mind, we were happy to undertake the responsibility of such a demonstration, which seemed important as a step in community-building as well as in providing the computing resources so urgently needed for our own and others' research efforts. In many respects it would have been far more convenient to focus on our own requirements, but the satisfaction of these seemed both infeasible and too limited an aspiration in the face of the suggested opportunity.

Three years is hardly long enough for a conclusive determination of the success of such a model, though we can fairly take pride in the diligence and technical competence with which we have responded to the community responsibilities mandated by the terms of the award. An important element in satisfying those responsibilities was the establishment of a mutually satisfactory management structure, on which we report in further detail below. Good will and common purpose are of course the indispensable ingredients, and we are grateful to have been able to offer this service in a congenial framework, and at the same time to be able to support our local computing research needs.

Our technical task has been achieved: to collect and implement an effective set of hardware and software tools supporting the development of large and complex AI programs and to facilitate communications and interactions between user groups. In effect, users throughout the country can turn on their own teletype or CRT-display terminals, dial a local number, and logon to SUMEX-AIM with the same ease as if it were located on their own campus -- and have access to a specialized resource unlikely to be matched nearby. From the community viewpoint, we have substantially increased the roster of user projects (from an initial 5) to 11 current major projects plus a group of pilot efforts. Many of these projects are built around the communications network facilities we have assembled; bringing together medical and computer science collaborators from remote institutions and making their research programs available to still other remote users. As discussed in the sections describing the individual projects, a number of the computer programs under development by these groups are maturing into tools increasingly useful to the respective research communities. The demand for production-level use of these programs has surpassed the capacity of the present SUMEX facility and has raised the general issues of how such software systems can be optimized for production environments, exported, and maintained.

The principal thrust of this renewal proposal is to sustain the momentum of SUMEX-AIM, both as a facility and as a community, during a period of rapid change in the technology and economics of computers. For reasons that will be justified in more detail, we do not plan further major expansion of centralized hardware at SUMEX, believing that growing community needs should now be met as justified at distributed nodes. It is difficult to make firm predictions of the technological changes that will present themselves during the period of the grant, but it may be that some conversion of the system will be necessary if only to keep pace with the software exchanged with cognate communities.

More concretely, our objectives for this next grant term include:

- 1) Maintaining the vitality of the AIM community of projects. This will entail scrutiny of old and new projects in what is approaching a steady-state of maximum capacity, and improving the efficiency with which developmental programs can be furnished to medical research groups.
- 2) Continued computational support for the AIM community based initially on our existing KI-10 facility. We expect the computing hardware technology to change substantially in the next few years with the availability of both more powerful and smaller and cheaper machines. Additional large-machine resources may still be necessary to meet the growing needs of the community during this period. As already stated, this kind of growth should be implemented at sites other than Stanford, but can be embraced by the same management structure as governs SUMEX-AIM. We plan to study these new technological alternatives affecting our central facility and to attempt to maintain software compatibility for our dual KI-10 system. Only should this prove untenable or grossly inefficient will we consider a hardware conversion to a more directly compatible implementation.
- 3) Continued work to improve system software and communication facilities for community interactions and the dissemination of programs. This will include advantageous connections to emerging communications networks and administrative efforts to exploit community expertise and sharing in software development.
- 4) Core research work to explore ways of exporting complex AI programs including new language support (MAINSAIL), specialized satellite computer systems, the use of networks for software dissemination and maintenance, and examinations of more operationally efficient implementations of AI programs. We will continue to work closely with the XEROX-PARC group, which remains primarily responsible for maintaining INTERLISP.
- 5) Core research work to attempt to generalize and document AI tools that have been developed in the context of a number of individual application projects. This will include work to organize the present state-of-the-art in AI techniques and tools through the AI-Handbook effort and the development of generalized software packages for the acquisition, representation, and utilization of knowledge in AI programs. These packages will facilitate the exploration of new areas of application of these tools.

1.2 SIGNIFICANCE

Viewed in the narrowest definition of a biotechnology resource, SUMEX-AIM is justified by the technical capabilities it offers for the pursuit of research using advanced computer applications relevant to the NIH mission. The progress reports of the various user projects speak for themselves in the diversity and pertinence of the work accomplished. We do not underestimate (and share as a grave responsibility) the overall investment charged to the resource; but this is quite reasonable when apportioned over the whole range of projects. The shared resource is plainly far more economical than any alternative method of providing comparable facilities to such a range of users distributed over the country.

Similar considerations apply to a variety of other kinds of research hardware. Unique to the computer is the extent to which shared hardware contributes to methodological cooperation; what in this context we call software compatibility. This follows from the unparalleled complexity of computer programs as process-specifications. What other techniques are or can be formulated as recipes of 100,000 or more instructions, each of which must be faithfully executed or the whole system will collapse? Yet we know that a great deal of our knowledge, e.g., in medical diagnosis, may prove to be of similar complexity when explicitly and formally expressed. We infer that many fields of scientific inquiry will have to use similar methods of exchange of critical commentary; that the electronic communications of computer programs is a prototype for the maintenance of other knowledge bases essential for the fabric of a complex and demanding society. The computer is at one time the node of a knowledge-sharing network, and the device for verifying the consistency and pertinence of the updates and criticisms that the users remit. Thus we can view our resource as exemplifying a technology that induces a new social organization of scientific effort (we would not be the first to recall Gutenberg; and to view ourselves as analogs of some of the early experiments with the use of the print medium for journals and academies.) From this perspective, it is quite fitting that the initial grant that established SUMEX-AIM was attended by so much preoccupation with managerial design, not ordinarily the favorite occupation of scientific types.

Several concrete illustrations of the encouragement of dynamic criticism that enhances the robustness of shared knowledge can be elicited from current projects (see Section 6 on page 41 in Book II), apart from the most familiar instances of sharing of software over the computer networks. The MYCIN rule bases, and the text of the AIHANDBOOK are continuously updated by critical users and reviewers. In fact, the text of various parts of this proposal went through dozens of iterative revisions, with comments from many interested groups, within the several weeks that were dedicated to its preparation. Another, and one of the most interesting examples, was the experimental use of the CONGEN program (See the DENDRAL progress report on page 42 in Book II) in a graduate class in advanced organic chemistry taught by Professor Djerassi. Each of 25 students scanned the recent literature for claims of new structures whose proofs were deemed to be interesting or dubious or both. Five examples were selected for exhaustive reexamination by the students. In each case, the published proof was found to be defective when it was checked by CONGEN -- alternative structures having been overlooked by the authors that still gave good fits to the given data. These and several comparable examples of asserted scientific fact are being more carefully reexamined in the authors' laboratories in response to the

program's refutations. In due course, we believe this kind of mechanized checking of "proofs" of chemical structures will be a routine part of the peer-review critical function of the editorial staff of the journals. These advances are facilitated by the tight internal cohesion of argument in structural organic chemistry, compared to other scientific fields -- precisely why this scientific domain was the one chosen for our initial work on applied AI.

The technical and sociological implications of our program are in fact elaborated throughout this proposal. By contrast, this may be the place to digress with some more personal observations (in the voice of the principal investigator) about the need for scientists to attend more self-consciously to the process of science itself, and to the political questions of social choice that are part of the accountability of science, to offer due return for value received.

Although SUMEX-AIM is rooted in the sub-discipline of "Artificial Intelligence" we understand and share the discomfort that many bystanders have in trying to give it a precise definition. It might have been preferable to think of "knowledge-engineering" as the thread that links almost all of our projects. This has connotations that might recall "data-base-management"; and we should not disparage the role that efficient systems for retrieving complex data will have in our effort. But our task is not usually to maintain a telephone-directory with yellow pages, but instead to gather, test and validate a hierarchy of generalized rules that operate both on each other, and on data of the kind that are the province of the information-retrieval subdiscipline. The development of the computer programs to perform these operations is the software-science part of our effort. Behind it is necessarily a new level of focussed inquiry into the rules of scientific inference in detail that could only be cross-checked by interaction with the machine.

We are traversing a time when the very justification for basic research is under critical, often even hostile scrutiny. Many quarters are asking such questions as "How much of the health progress of the past 30 years can be attributed to advances in knowledge connected with NIH-supported research?" Are our institutional arrangements and patterns of funding really the most appropriate for the most efficient 'transfer of technology' from the basic laboratory 'to the bedside'?" Less often raised by external critics is, "To what extent does the present system support the most fundamental innovations within science itself; or does it inevitably focus overwhelming support on the most obvious, transparent questions and discourage more revolutionary kinds of inquiry?"

Within the NIH directorate, it has been stipulated that "Currently, within the research community, formal processes are lacking to assure systematic identification and evaluation of clinically relevant research information, and its effective transfer to the health care community...."

It is not always popular to insist that these questions must be faced up to -- that basic science cannot indefinitely subsist on unconfirmed faith as to its promise. Furthermore, it is easy to show that many short-term advances have arisen from the most pragmatic kinds of investigation: empirical screening for antibiotics or antidiuretics has undoubtedly generated more life-saving therapeutic products than the most sophisticated molecular biology, up to the

present moment. Indeed, salt-water, intelligently administered, has been one of the great life-savers of the recent era! On the other hand, I hold that it would be tragic to undermine the enormous long range potential of basic insight without a deeper analysis of the process by which knowledge and insight move from basic science into clinical problems; and we just might find some ways to improve the system without wrecking it!

These remarks should be taken as exposing a philosophical preoccupation rather than as the design of a research program. They do relate to efforts like the MOLGEN project, which include a great deal of focussed introspection on the intellectual substance of scientific inquiry. It would be premature to claim that computer programs per se will soon be delegated the major responsibility for "systematic identification of relevant knowledge", although they can already play a very helpful role in assisting human intelligence to correlate bibliographic data, and in other ways. However, the very process of implementing an "applied philosophy of science", which is the principal forework of developing a domain for the application of knowledge-based AI, is exactly the kind of formal systematization called for in these renewed efforts to facilitate technology transfer to health care. Longer range success in our AI research will be as important in helping us understand what we are doing as scientists and diagnosticians as in providing mechanical assistance to these ends.

Although our substantive efforts are mostly concerned with the "micro-problems" of scientific or clinical inference, there may be more important treasures in a macro-perspective on the integration of knowledge in medicine. My own most important laboratory accomplishments have all concerned the discovery of new problems, and the bringing together of previously disparate disciplines, rather than the solution of extant puzzles -- the discovery of sex in bacteria, better viewed as the marriage of genetics and bacteriology is perhaps the least controversial instance. I believe that it is reasonable to expect that the systematization of biomedical knowledge, to which computer AI will make an indispensable contribution, is an important side effect of these investigations in knowledge-engineering; and that this will lead in turn to the recognition of holes in the overall fabric that badly need patching.

We have too little theory of the practice of science to offer more than case studies at this time -- I have been spending some time in collaboration with a historian and sociologist in trying to achieve a better understanding of the dynamics of discovery of bacterial recombination, and found there is more to the context of that story than my own ingenuity. But it is also very difficult to reconstruct such events without critical recordings of the incidents as they occur -- recordings we are learning how to make in the MOLGEN work. [\*\* Copies of a working paper illustrating this are available on request. \*\*]

To turn to a more clinically urgent arena, it is somewhat dismaying to recall that it took 35 years from Beadle and Tatum's discovery of nutritional mutants in *Neurospora* to the beginnings of the biochemical genetics of such important situations in man as atherosclerosis. I do intend to initiate some inquiry as to the inevitability of delays of that kind, which seem retrospectively absurd. We will not get analytically persuasive or policywise sound determinations of such questions without more attention to the underlying process of scientific inquiry than unselfconscious scientists are customarily wont to indulge in.

This kind of speculation can also be translated into concrete research programs, which in turn may evoke some new principles. Kidney-stones are an unlikely arena of concern for someone of my particular scientific background; but a number of issues have emerged in consultations with some of my colleagues in the Stanford Division of Urology. There has been substantial evidence for some time of a significant genetic factor in chronic recurrence of stones. This does not seem to be correlated with overall rates of calcium oxalate excretion; indeed one must focus on the stone as a pathological form of crystal aggregation -- much larger quantities of calcium oxalate are passed as microcrystals by normal individuals. Several workers have identified mucopolysaccharides in the matrix of these stones, and some have speculated about their possible role as initiators or cements in stone formation. On the other hand, geneticists have long known that blood-group substances, (mucopolysaccharides!) appear in the secretions, including the urine, of the Se/se and Se/Se [Secretor] genotypes; although saliva is the preferred sample for diagnosis. Still another worker, a pathologist, has remarked on the occurrence of mucopolysaccharide concretions in the tubules near the renal papillae of Se/se subjects. To the best of my knowledge, these disciplinary nuggets have been privately and separately held, and there has been no effort to study their possible interconnection. A survey is now underway at Stanford to test a possible statistical association of Secretor and blood group type with stone recurrence.

These suggestions were arrived at through interpersonal discourse, experts from different disciplines being able to furnish provocative data points when prodded by a more general inquiry. Could one imagine a more general problem-generator that could arrive at similar conclusions? Perhaps so -- one could parse through the medical subspecialties, or through significant diseases, to ask more systematically if they had been scrutinized from the perspective of, say, biochemical genetics. And this raises many other hypothetical inputs to a combinatorial-generator of potential, new interdisciplines. One hastens to add, that most of the rotely drawn intersections will be meaningless or empty -- enough perhaps that the whole game may end up looking quite silly. However, the problematics of the game have not been explored, and to that extent, there is a pilot project here that I intend to pursue. Its practical feasibility will depend in part on the briskness with which relevant data can be fetched from the literature and from other experts, and I will be exploring possibilities of on-line access to bibliographic databases 1) to help support this effort, and 2) to suggest further research efforts in the use of AI techniques for bibliographic inquiry in ways that may be pertinent to macro-policy of research management.

### 1.3 BACKGROUND AND PROGRESS

#### 1.3.1 PROGRESS SUMMARY

This progress summary covers the period from December 1973, when the SUMEX-AIM resource was initially funded, through April 1977. During this period we have met all of the defined goals of the resource:

- i) We have established an effective computing facility to support a nation-wide community of medical AI research projects including connections to two computer communication networks to provide wide geographical access to the facility and research programs.
- ii) We have actively recruited a growing community of user projects and collaborations. The initial complement of collaborators included five projects. This roster has grown to eleven fully authorized projects currently plus a group of approximately six pilot efforts in various stages of formulation. Recruiting efforts have included a public dedication and announcement of the resource, NIH referrals from computer-based project reviews, direct contacts by resource personnel and on-going projects as well as contacts through the AIM workshop series coordinated by the Rutgers Computers in Biomedicine resource under Dr. Saul Amarel.
- iii) We have established an AIM community management structure based on an overseeing Executive Committee and an Advisory Group to assist in recruiting and assessing new project applications and in guiding the priorities for SUMEX-AIM developments and resource allocations. These committees also provide a formal mechanism for user projects to request adjustments in their allocated share of facility resources and to make known their desires for resource developments and priorities.
- iv) SUMEX user projects have made good progress in developing more effective consultative computer programs for medical research; one of the major goals toward which our AI applications are aimed. These performance programs provide expertise in analytical biochemical analyses and syntheses, medical diagnoses, and various kinds of cognitive and affective psychological modeling.
- v) We have worked hard to build system facilities to enable the inter- and intra- group communications and collaborations upon which SUMEX is based. We have a number of examples in which user projects combine medical and computer science expertise from geographically remote institutions and numerous examples of users from all over the United States and occasionally from Europe experimenting with the developing AI programs. The SUMEX staff itself has had good success in establishing such sharing relationships on a system level with other research groups and has many examples of complementary development and maintenance agreements for system programs.
- vi) We have made numerous improvements to the computing resource to extend its capacity, to improve its efficiency, to enhance its human interfaces, to improve its documentation, and to enhance the range of software facilities available to user projects.



- vii) We have begun a core research effort to investigate alternatives and programming tools to facilitate the exportability of user and system software. This is just now producing a "machine-independent" implementation of the ALGOL-like SAIL language which will run on a range of large and small machines and provide a language base for transferring programs.
- viii) We have supported community efforts in the more systematic documentation of AI concepts and techniques and in building more general software tools for the design and implementation of AI application programs. These have included a Stanford AI Handbook project comprising a compendium of short articles about the projects, ideas, problems, and techniques that make up the field of AI.

### 1.3.2 DETAILED PROGRESS REPORT

The following material covers in greater detail the SUMEX-AIM resource activities over the past 3.5 years. These sections attempt to define in more detail the technical objectives of our research community and include progress in the context of the resource staff and the resource management. Details of the progress and plans for our external collaborator projects are presented in Section 6 on page 41 (in Book II).

#### 1.3.2.1 DEFINITION OF TERMS AND OBJECTIVES

Artificial Intelligence is a branch of computer science which attempts to discern the underlying principles involved in the acquisition and utilization of knowledge in reasoning, deduction, and problem-solving activities (1). Currently authorized projects in the SUMEX community are concerned in some way with the application of these principles to biomedical research. The tangible objective of this approach is the development of computer programs which, using formal and informal knowledge bases together with mechanized hypothesis formation and problem solving procedures, will be more general and effective consultative tools for the clinician and medical scientist. The exhaustive search potential of computerized hypothesis formation and knowledge base utilization, constrained where appropriate by heuristic rules or interactions with the user, has already produced promising results in areas such as chemical structure elucidation and synthesis, diagnostic consultation, and mental function modeling. Needless to say, much is yet to be learned in the process of fashioning a coherent scientific discipline out of the assemblage of personal intuitions, mathematical procedures, and emerging theoretical structure of the "analysis of analysis" and of problem solving. State-of-the-art programs are far more narrowly specialized and inflexible than the corresponding aspects of human intelligence they emulate; however, in special domains they may be of comparable or greater power, e.g., in the solution of formal problems in organic chemistry or in the integral calculus.

An equally important function of the SUMEX-AIM resource is an exploration of the use of computer communications as a means for interactions and sharing between geographically remote research groups in the context of medical computer science research. This facet of scientific interaction is becoming increasingly important with the explosion of complex information sources and the regional specialization of groups and facilities that might be shared by remote researchers. Our community building role is based upon the current state of computer communications technology. While far from perfected, these new capabilities offer highly desirable latitude for collaborative linkages, both within a given research project and among them. Several of the active projects on SUMEX are based upon the collaboration of computer and medical scientists at

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(1) For recent reviews to give some perspective on the current state of AI, see: (i) Winston, P.H., "Artificial Intelligence", Addison-Wesley Publishing Co., 1977; (ii) Nilsson, N.J., "Artificial Intelligence", Information Processing 74, North-Holland Pub. Co. (1975); and (iii) a summary by Feigenbaum, E. A., attached as Appendix I, page 202 (see Book II). An additional overview of research areas in AI is provided by the outline for an "Artificial Intelligence Handbook" being prepared under Professor Feigenbaum by computer science students at Stanford (see Appendix II on page 225 in Book II).

geographically separate institutions; separate both from each other and from the computer resource. The network experiment also enables diverse projects to interact more directly and to facilitate selective demonstrations of available programs to physicians and medical students. Even in their current developing state, we have been able to demonstrate that such communication facilities allow access to the rather specialized SUMEX computing environment and programs from a great many areas of the United States (even to a limited extent from Europe) for potential new research projects and for research product dissemination and demonstration. In a similar way, the network connections have made possible close collaborations in the development and maintenance of system software with other facilities.

### 1.3.2.2 FACILITY HARDWARE

Based on the AI mission of SUMEX-AIM, we selected a Digital Equipment Corporation (DEC) model KI-10 computer system for our facility. This selection was based on 1) hardware architectural and performance features, 2) available software support relevant to AI applications, 3) price versus performance data for the system, and 4) the scope of the user community from which we might expect to draw collaborators and share software. This choice has proved highly effective.

The current system hardware configuration is diagrammed in Figure 1 on page 14. It is the result of a number of augmentations over the past 3 years to meet the capacity needs of the growing SUMEX-AIM project community. Our initial configuration consisted of a KI-10 processor, core memory (192K 36-bit words @ 1 microsecond), swapping storage (1.7M words @ 8 msec average rotational latency and 2 microsecond/word transfer rate), file storage (40M words), magnetic tapes, DEC tapes, terminal line scanner, and line printer. Our network connections are discussed in Section 1.3.2.4 on page 20.

This system reached prime-time saturation by fall of 1974. Since many of our medical and other professional collaborators cannot adjust their schedules to match light computer loading during the night-time hours, the prime-time responsiveness is crucial to being able to support medical experimentation with developing programs and to allow community growth. We have taken active steps to transfer as much prime-time loading as feasible to evening and night hours including shifting personnel schedules (particularly for Stanford-based projects), controlling the allocations of CPU resources between various user communities and projects, and encouraging jobs not requiring intimate user interaction to run during off hours by developing batch job facilities. Despite these efforts, prime-time loading has remained quite high, particularly with the growth of the number of user projects.

A similar congestion has persisted in the on-line file space we have been able to allocate to user projects. Again we have implemented controls to try to assure effective use of available space and to encourage use of external file storage facilities such as the ARPANET Data Computer and other computer sites. Nevertheless, the interactive character of SUMEX use, the large AI program files, and the extensive use of SUMEX for collaborator communications have continuously raised file space demands beyond those we could meet.

We have proposed a number of hardware configuration augmentation steps to the Executive Committee to cost-effectively provide additional capacity. These were based on analyses of predominant system bottlenecks and enhancement steps feasible within available budgets. The enhancements approved by the committee and implemented include:

- 1) Add 64K words of core memory and 20M words of file storage (11/74)
- 2) Add second KI-10 CPU for dual processor operation (5/76)
- 3) Add 256K words of core memory and upgrade file system to higher volume, lower cost technology (recently approved by NIH and the AIM Executive Committee with implementation in progress)

A plot of effective CPU capacity as a function of continuing investment is shown in Figure 2 on page 15 and displays the cost-effectiveness of our sequential augmentations. At the present time our hardware configuration has grown about as much as is cost-effective. Additional growth would entail significant redesigns of the system including upgrades of existing hardware. Contemplating such future expansion also raises the issues of compatibility with newer hardware technologies being announced. These provide advantages in speed, cost, size, and maintainability. Such a complete upgrade is not envisioned in the immediate future as a number of interesting new product announcements are expected over the next 1 or 2 years that could substantially affect such an upgrade strategy. Our plans in this direction are discussed in more detail under the proposed resource plans for the continuation period (see Section 3.1 on page 62).

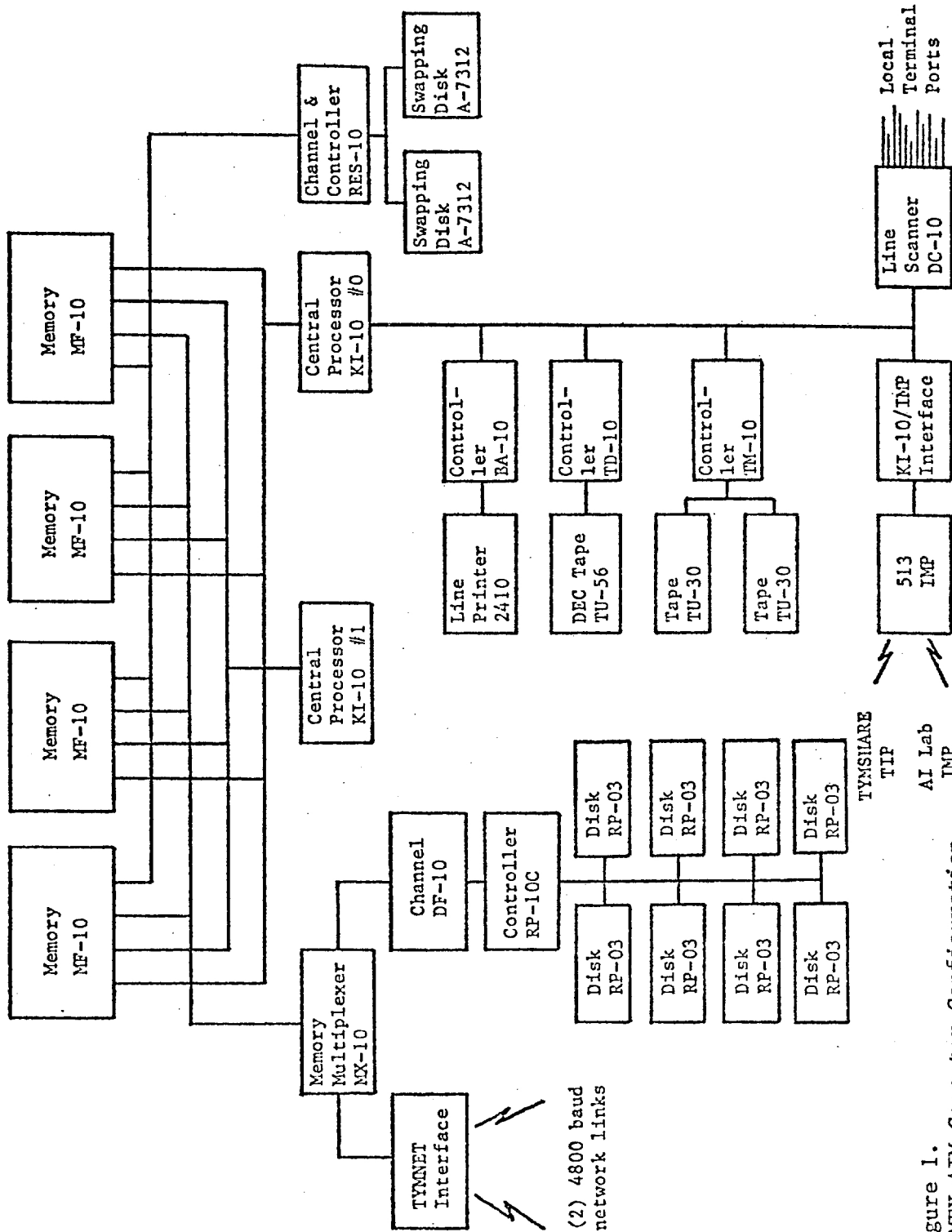
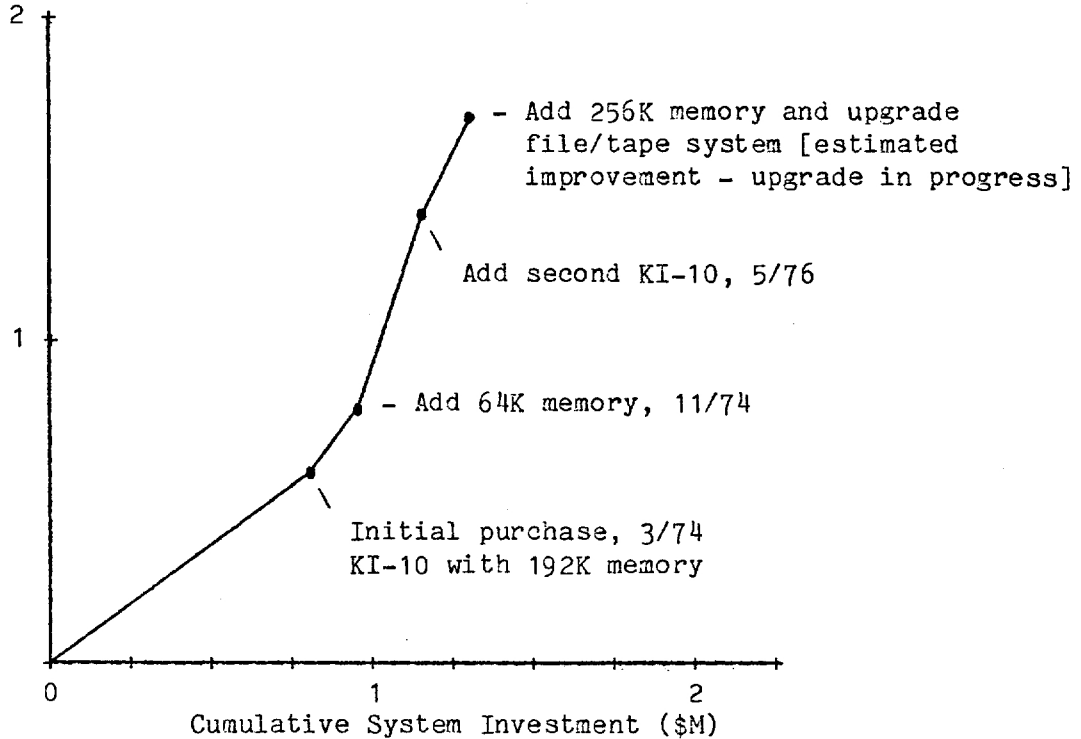


Figure 1. SUMEX-AIM Computer Configuration

Figure 2. Cost-effectiveness of SUMEX Augmentations

Estimated Capacity in Useful KI-10 Equivalents (Net of overhead)



This plot illustrates the incremental increases in computing capacity achieved as a function of cumulative investment in the SUMEX-AIM facility. The higher slope of the curve after the initial investment illustrates both the substantial investment in peripheral devices (file system, tapes, communications, etc.) and the trend toward lower memory prices. The largest impact in terms of PDP-10 memory price reductions occurred around the time of adding the 64K increment in November 1974. Since then processor prices have stayed relatively stable and memory prices have dropped less dramatically. It should be noted that semi-conductor memories have not yet made a big in-road in the PDP-10 market; this technology is where the more recent memory price reductions have occurred.

The original purchase of 1 KI-10 with 192K of memory for about \$800K performed with about 60% efficiency under peak load. Adding the 64K of memory for \$75K brought the efficiency up to about 85%. Then adding the second processor for \$200K increased throughput to about 1.3-1.4 KI-10 equivalents. This step represents about a 59% increase in throughput for a 20% increased investment. A proposal has been approved recently by the AIM Executive Committee and NIH to augment core memory by 256K words. This augmentation would increase throughput to about 1.7 KI-10 equivalents for another \$100K; this would be a 26%

throughput increase for 8% additional investment. As part of the proposed memory augmentation we plan to upgrade the file and tape systems as well to relieve file space congestion and increase system operations efficiency. Including the net cost of the file/tape upgrade in these figures (purchase price less resale of existing equipment) raises the proposed additional investment to \$160K and the fractional increase from 8% to 13%. Of course, the disk upgrade affects CPU throughput only indirectly in that the increased speed reduces contention, particularly when moving head swapping is necessary. It contributes primarily to supporting the growing on-line file needs of the projects.

Figure 3. Capacity and Loading Increase with Dual Processor Augmentation

	1-PROC OP'N 1/76 - 4/76 -----	2-PROC TRNS'N 5/76 - 8/76 -----	2-PROC OP'N 9/76 - 12/76 -----	2-PROC OP'N 1/77 - 3/77 -----
Peak Ld Ave	4.8	5.6	6.0	6.6
Peak Jobs	30.2	33.3	34.7	38.1
% Overhead/ Processor	18.1	31.1	33.2	31.9
Total CPU Hrs/Mo	304.4	384.9	534.0	520.1

This table presents system usage data averaged over several months preceding, during, and after installation of the SUMEX-AIM dual processor system in order to show real changes in peak loading capacity and computing resources delivered. The first three rows of data are derived from monthly diurnal loading data and reflect average prime-time peak loading conditions (daily peak usage figures are often considerably higher, but those shown better represent gross trends). The last row gives average total monthly CPU hours delivered during the various periods.

With the common criterion that users have pushed both the single and dual processor systems to the limits of useful work in terms of prime time responsiveness, it is clear that the second processor has substantially increased throughput ("tolerable" peak load average up 38%, number of jobs up 26%, and delivered CPU hours up 71%). At the same time the overhead burden per machine has risen from 18 to 32%, principally in the category of I/O wait (total scheduler time and time waiting for a runnable job to be loaded in core). An additional factor, not explicitly shown in these data (because we only have a 1 msec clock), is the added time spent at interrupt level servicing drum swapping. This adds another 10-15% estimated overhead.

We feel these increased overhead figures can be reduced roughly to the single processor levels by adding more memory, thereby effectively recovering about 40-50% of the capacity of a KI-10 processor. A proposal is now pending with the AIM Executive Committee for this augmentation and we expect it to be implemented within the funding ceiling of the current grant.



1.3.2.3 SYSTEM SOFTWARE

In parallel with the choice of DEC PDP-10 hardware for the SUMEX-AIM facility, we selected the TENEX operating system developed by Bolt, Baranek, and Newman (BBN) as the most effective for our medical AI applications work. TENEX was the only available demand-paged system to support simultaneous large address space users, offered the INTERLISP language for LISP-oriented program development, and was well integrated with the ARPANET facilities which provide an excellent base for our community sharing efforts. This choice has proven a very effective one in that the productivity of the TENEX community in AI research has been highly advantageous to us (2).

The original BBN TENEX was written for a hardware-modified KA-10 system. This version of the system required a substantial amount of work to accommodate the relatively limited paging facilities of the KI-10 to run effectively. These early phases also included substantial monitor work to incorporate the TYMNET memory-sharing interface which connects us to the TYMNET and to integrate the high speed swapping storage. We have made numerous enhancements to the monitor calls and corrections of bugs to develop a highly reliable and effective operating system for our community work.

We continue to work to improve the efficiency of the system and its effectiveness in allocating valuable resources. For example we have modified the handling of user page tables so that the expensive procedure of clearing page tables and setting them up to run time-shared users could be minimized. This involved creating a pool of page tables which could be allocated to currently running users and could be kept available without setup overhead. We also implemented a system for migrating dormant pages from our fast swapping storage to moving head disk. This preserves the use of this limited resource for the currently active jobs.

We have implemented a form of "soft" CPU allocation control in the monitor, assisted by a program which adjusts user percentages for the scheduler based on the dynamic loading of the system. The allocation control structure works based on the scheduler queue system and takes account of the a priori allocation of CPU time and that actually consumed. Our TENEX uses a hierarchy of five queues for jobs ranging from highly interactive jobs requiring only small amounts of CPU time between waits to more CPU intensive jobs which can run for long periods without user interaction. These interactive queues (text editing, etc.) are scheduled at highest priority without consideration of allocation percentages. If nothing is runnable from the high priority queues, the CPU-bound queues are scanned and jobs are selected for running based on how much of their allocated time has been received during a given allocation cycle time (currently 100 seconds). If no such jobs are runnable, then those that have received their allocation of CPU time already are scheduled based on how much they are over

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(2) It should be noted that DEC has recently adopted a form of TENEX (TOPS-20) as their choice for future system marketing. They have made improvements in a number of areas of the monitor and subsystem software but have also shown an increasing tendency to make changes to the TOPS-20 system that impair compatibility with older TENEX systems. The long-term impact of this trend toward incompatibilities with the coming DEC "standard" is discussed in more detail on page 62.

allocation and how long they have waited to be run again. This system is not a reservation system in that it does not guarantee a given user some percentage of the system. It allocates cycles preferentially, trading off a priori allocations with actual demand but does not waste cycles. This allocation control system is still in an experimental state and we are attempting to evolve the "best" policies with the AIM Executive Committee for dividing the system fairly and effectively among the various communities of users.

During the spring of 1976 we implemented a dual processor version of TENEX as the most cost-effective way to increase our processing capacity. In order to upgrade to the new KL-"n" technology, we would have had to replace most of the equipment that had been purchased initially. For the cost of an additional processor and 8 man-months of intensive software development we were able to increase our CPU capacity by 75%. We have an additional 40% equivalent of a KI-10 processor which can be made available by increasing memory to reduce our swapping contention. The dual processor system that has evolved is running quite reliably. It treats the two machines in an almost symmetric manner. The only difference is that one of the machines has all of the I/O equipment attached to it. They both schedule jobs independently and share the rest of the non-I/O-device monitor code. The areas of the monitor involving the management of resources and jobs which cannot be manipulated by both machines simultaneously are protected by a system of locks. We have made some measurements indicating that overhead for lock waits is less than 10%. The overall increase in capacity provided by the processor upgrade is illustrated in Figure 3 on page 17 which measures key loading parameters in the periods before and after the dual processor installation. Observing the delivery of DEC's high-performance KL-TENEX systems over the past 6 months, it seems clear that for the investment, we made the best choice for the community by implementing the dual processor upgrade. We hope to augment the memory soon to finish exploiting the capacity this extra machine provides and to remove some non-linearities remaining in system swapping performance.

Now that the dual processor system has stabilized, we are undertaking another assessment of system performance to be sure we have removed residual and correctable inefficiencies. This study is on-going now.

Finally, over the past year we made several substantial improvements in the "GTJFN" monitor call which interactively acquires handles on file names specified by the user. These extensions allow for more general "wild card" specifications and interactive help in deciding between and searching for existing file name alternatives. They also give the user much more flexibility in designating groups of files and therefore in structuring his data.

With a working dual processor system, the current implementation of allocation controls in our system, the diverging path of the DEC TOPS-20 system, the termination of active BBN TENEX development, and the unique complications of the KI-10 paging system, we have not made any concerted effort to upgrade our TENEX system to the latest BBN release (1.34). The advantages of such an upgrade are not overwhelming in face of the complicated conversion (KI paging, dual processor, special swapping device handler, TYMNET service routines, local JSYS's, etc.) and resulting system unreliability for some period.

Another area of software development is in the EXECutive program which is the basic user interface to manipulate files, directories, and devices; control job and terminal parameter settings; observe job and system status; and execute public and private programs. This work improves system accommodation to users and provides more convenient and useful information about system and job status. Through such features as login default files, directed file search path commands, mail notification, help facilities, better file archival and retrieval commands, and flexible status information, we have tried to make it easier for users to work on the SUMEX-AIM machine.

#### 1.3.2.4 NETWORK COMMUNICATION FACILITIES

A highly important aspect of the SUMEX system is effective communication with remote users. In addition to the economic arguments for terminal access, networking offers other advantages for shared computing such as uniform user access to multiple machines and special purpose resources, convenient file transfers for software sharing and multiple machine use, more effective backup, co-processing between remote machines, and improved inter-user communications. Over the past year we have been substantially aided in exporting the MAINSAIL system through our network connections. Because of the developmental nature of the language at present, it is important that we have close interactions with the user community and that we be able to effectively perform bug fixes and upgrades. Since MAINSAIL by its nature involves operations on a variety of machines and since our access to example systems cannot be entirely local, the network connections to Rutgers, the Stanford AI Lab, and Stanford Research Institute have been invaluable. It would be considerably more difficult to export MAINSAIL and communicate with users via tapes and mail.

We have based our remote communication services on two networks - TYMNET and ARPANET. These were the only networks existing at the start of the project which allowed foreign host access. Since then, other commercial network systems (notably TELENET) have come into existence and are growing in coverage and services. The two networks to which we are currently connected complement each other; the TYMNET providing primarily terminal service with very broad geographical coverage and unrestricted user access, and the ARPANET having more limited access but providing a broader range of communication services. Together, these networks give a good view of the current strengths and weaknesses of this approach.

Users asked to accept a remote computer as if it were next door will use a local telephone call to the computer as a standard of comparison. Current network terminal facilities do not quite accomplish the illusion of a local call. Data loss is not a problem in network communications - in fact with the more extensive error checking schemes, data integrity is much higher than for a long distance phone link. On the other hand, networking relies upon shared community use of telephone lines to procure widespread geographical coverage at substantially reduced cost. However, unless enough total line capacity is provided to meet peak loads, substantial queueing and traffic jams result in the loss of terminal responsiveness.

TYMNET:

Networks such as TYMNET are a complex interconnection of nodes and lines spanning the country (see Figure 4 on page 24). The primary cause of delay in passing a message through the network is the time to transfer a message from node to node and the scheduling of this traffic over multiplexed lines. This latter effect only becomes important in heavily loaded situations; the former is always present. Clearly from the user viewpoint, the best situation is to have as few nodes as possible between him and the host - this means many interconnecting lines through the network and correspondingly higher costs for the network manager. TENEX in some ways emphasizes this conflict more than other time-sharing systems because of the highly interactive nature of terminal handling (e.g., command and file name recognition and non-printing program commands as in text editors or INTERLISP). In such instances, individual characters must be seen by the host machine to determine the proper echo response in contrast to other systems where only "line at a time" commands are allowed. We have connected SUMEX to the TYMNET in two places as shown in Figure 4 so as to allow more direct access from different parts of the country. Based on delay time statistics collected during the previous year from our TYMSTAT program, the response times are scarcely acceptable. When delay times exceed 200-300 milliseconds, the character printing lag problems become noticeable with a full duplex, 30 char/sec terminal. In the past these times have been particularly bad in New York with peak delays approaching 3 seconds one way! Other nodes have shown uniformly high readings as well. These data were reflected in the subjective, but strongly articulated, comments of many of our user groups.

We have had numerous meetings with TYMNET personnel to try to ease these problems and have instituted reroutings of the lines connecting SUMEX-AIM to the network. Also local lines to more strategic terminal nodes have been considered for users in areas poorly served by the existing line layout. TYMNET has also made some upgrades in the internal connectivity and speeds with which data is switched within their node clusters. These changes seem to have had some beneficial effects in that delay times have improved and user complaints have subsided.

We will continue to pursue improvements in TYMNET response but user terminal interactions such as used in TENEX programs are not realized in the time-sharing systems offered by most other TYMNET users and hence are not supported well by TYMNET. TYMNET has implemented 1200 baud service in 7 major cities over the past year. Unfortunately many of our users are not in these cities so we have only limited experience with the 1200 baud support.

ARPANET:

The ARPANET, while designed for more general information transfer than purely terminal handling, has similar bottleneck problems in its topology (see the current geographical and logical maps of the ARPANET in Figure 5 and Figure 6 on page 25). These are reduced by the use of relatively higher speed interconnection lines (50 K baud instead of 2400 - 9600 baud lines as in TYMNET) but response delays through many nodes become objectionable eventually as well.

Consistent with the agreements with ARPA when we were granted network access initially, we are enforcing a policy to restrict the use of the ARPANET to users who have affiliations with ARPA-supported contractors and system/software interchange with cooperating TENEX sites. The administration of the network passed from the ARPA Information Processing Techniques Office to the Defense Communications Agency as of July 1975. At that time policies were announced restricting access to DoD-affiliated users. We have restricted the facilities for calling from SUMEX out to other sites on the ARPANET to authorized users. This also protects the SUMEX-AIM machine from acting as an expensive terminal handler for other machines - this function is better fulfilled by dedicated terminal handling machines (TIPS). In general, we have developed excellent working relationships with other sites on the ARPANET for system backup and software interchange - such day-to-day working interactions with remote facilities would not be possible without the integrated file transfer, communication, and terminal handling capabilities unique to the ARPANET.

We take very seriously the responsibility to provide effective communication capabilities to SUMEX-AIM users and are continuously looking for ways to improve our existing facilities as well as investigate alternatives becoming available. We have done preliminary investigations of the TELENET facilities that have been rapidly expanding this past year. BB&N has hooked one of their TENEX systems up to TELENET and whereas we did not have the same quantitative tools we have for measuring response on the TYMNET, we observed TELENET delays at least as long as those encountered on TYMNET. We did the reverse experiment by using long distance telephone to connect from the TELENET node in Washington, D.C. to the SUMEX machine in California and observed the same sort of delays reaching several seconds per character. The TELENET has many attractive features in terms of a symmetry analogous to that of the ARPANET for terminal traffic and file transfers and being commercial would not have the access restrictions of the ARPANET. However, until the network throughput improves we would not get substantial benefits from connecting to it.

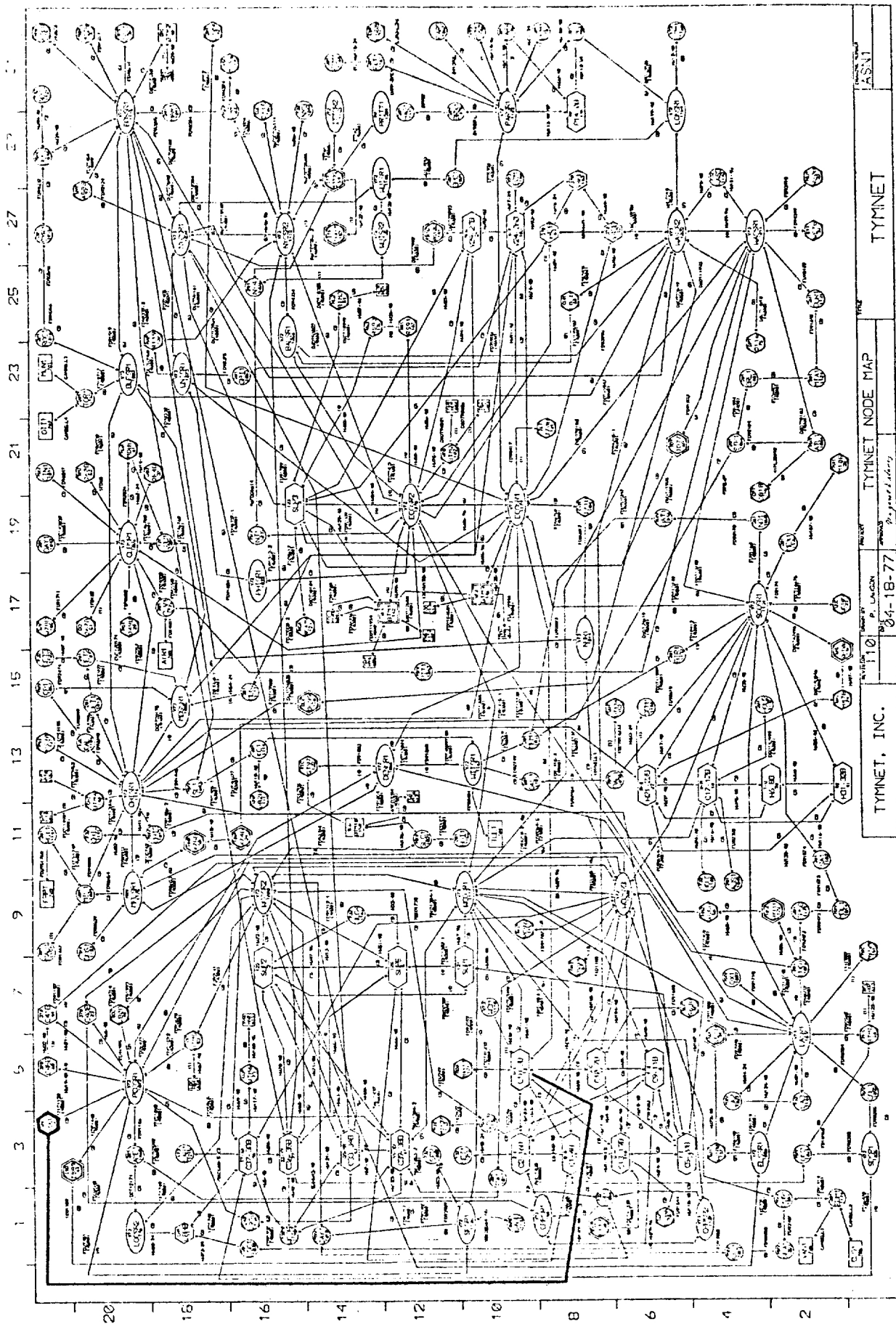


Figure 4. TYMNET Network Map

Figure 5.  
 ARPANET GEOGRAPHIC MAP, APRIL 1977

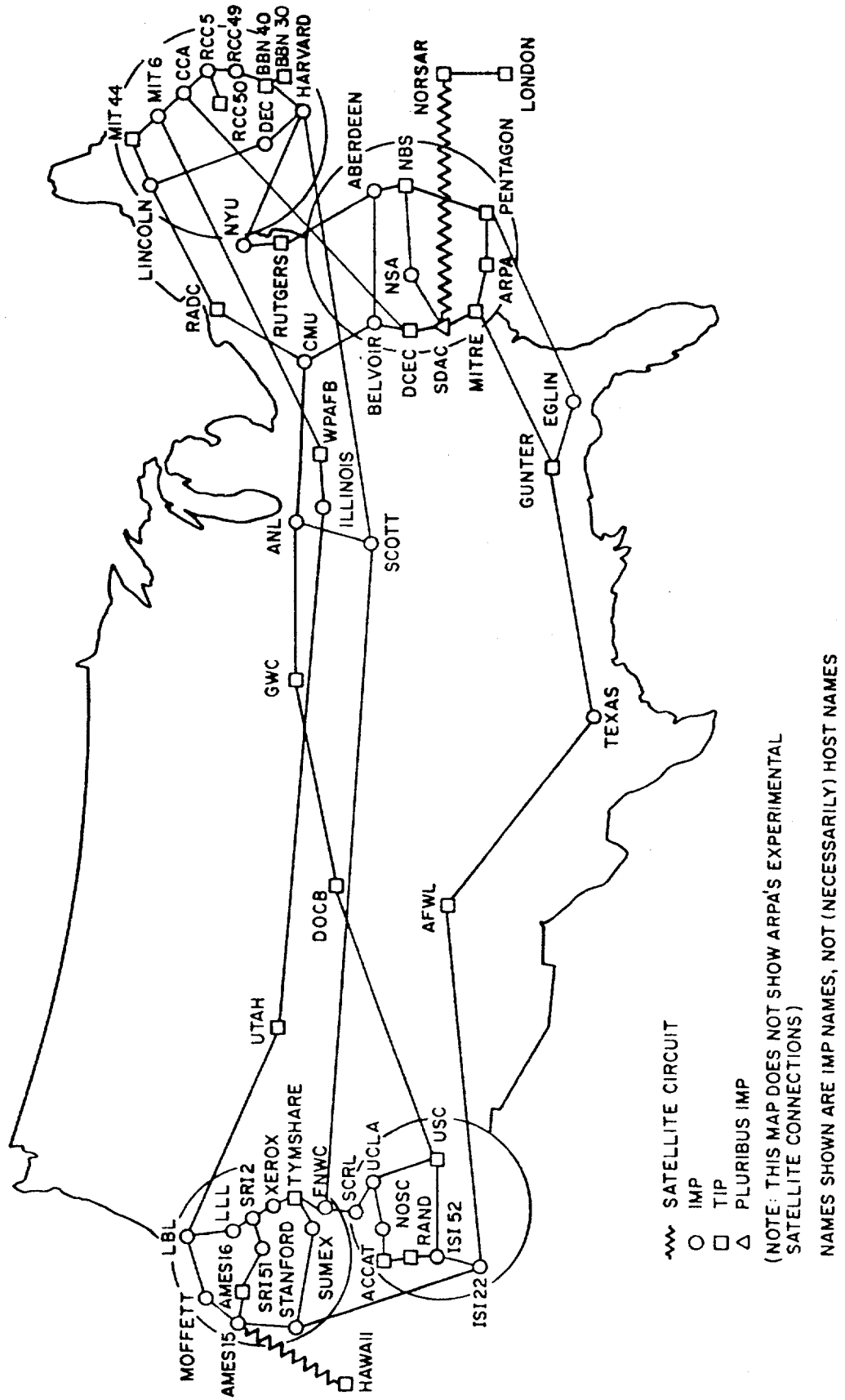
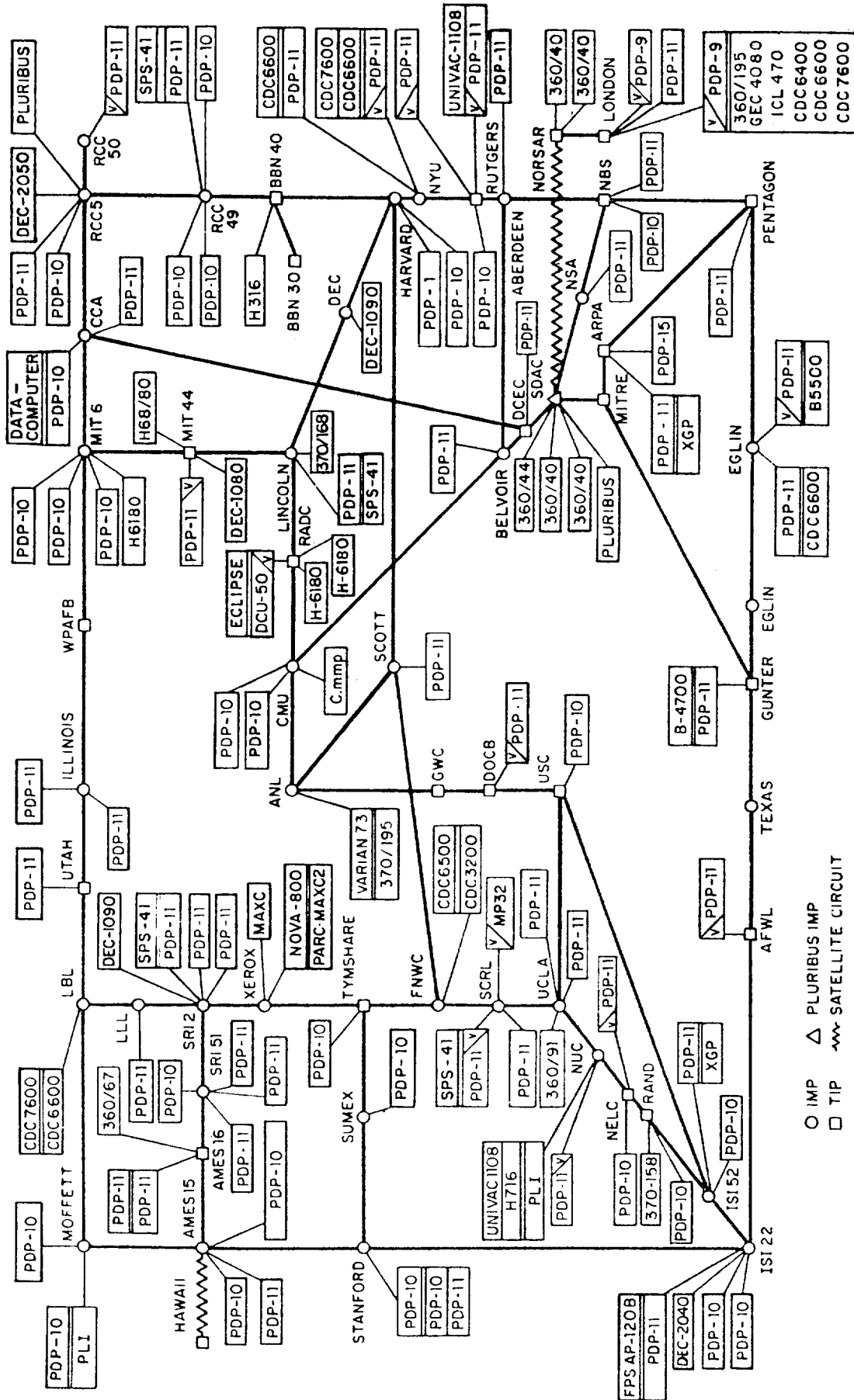


Figure 6.  
ARPANET LOGICAL MAP, MARCH 1977



(PLEASE NOTE THAT WHILE THIS MAP SHOWS THE HOST POPULATION OF THE NETWORK ACCORDING TO THE BEST INFORMATION OBTAINABLE, NO CLAIM CAN BE MADE FOR ITS ACCURACY)  
 NAMES SHOWN ARE IMP NAMES, NOT (NECESSARILY) HOST NAMES