

1.6. Resources and Environment

RESOURCES AND ENVIRONMENT

FACILITIES: Mark the facilities to be used at the applicant organization and briefly indicate their capacities, pertinent capabilities, relative proximity and extent of availability to the project. Use "other" to describe the facilities at any other performance sites listed in Item 9, page 1, and at sites for field studies. Using continuation pages if necessary, include an explanation of any consortium arrangements with other organizations.

Laboratory:

Clinical:

Animal:

Computer: See Major Equipment paragraph below.

Office:

Other (_____):

MAJOR EQUIPMENT: List the most important equipment items already available for this project, noting the location and pertinent capabilities of each. SUMEX-AIM develops and operates a heterogeneous networked system of computing resources, including mainframe host computers, Lisp workstations, and network utility servers. Host machines include a DEC 2060 and 2020 running TOPS-20 and a VAX 11/780 running UNIX (these are the current core of the nationally available resource). Our Lisp workstations include more than 25 Xerox 11xx's, a Symbolics LM-2, eight Symbolics 36xx's, and five Hewlett-Packard 9836's. Network printing, file storage, gateway, and terminal interface services are provided by dedicated VAX 11/750's through an extensive Ethernet and to external resources through the ARPANET and TYMNET.

ADDITIONAL INFORMATION: Provide any other information describing the environment for the project. Identify support services such as consultants, secretarial, machine shop, and electronics shop, and the extent to which they will be available to the project.

2. Resource Plan

Before launching into the technical details of our proposal, we want to explain two matters relating to its scope and organization:

Combined SUMEX-AIM and ONCOCIN renewal

This is an application for the 5-year merged renewal of two on-going Biomedical Research Technology Resource efforts: 1) the Stanford University Medical *EX*perimental computer research resource for applications of Artificial Intelligence in *Medicine* (SUMEX-AIM, RR-00785) and 2) the resource-related research project for Studies in the Dissemination of Consultation Systems (ONCOCIN, RR-01631). We propose that the combined research activities of these projects be funded under a continuation of the SUMEX-AIM grant and that the core research aspects of the resource-related ONCOCIN work not be continued separately. The reasons for merging these renewals are both technical and administrative.

On the technical side, the goals for the two projects are inextricably mingled in the development and exploitation of AI techniques and Lisp workstation technology for experimental applications in medical decision-making systems. The recent ONCOCIN experiments in developing and disseminating a cancer chemotherapy protocol advisor (built on joint SUMEX/ONCOCIN system technology) have effectively demonstrated the viability of this applied technology. They have accordingly helped define important future directions for the longer term thrust of the SUMEX-AIM resource toward distributed workstations as the computing model for the next generation of biomedical AI systems.

On the administrative side, the current award periods for both grants end in mid-summer of 1986. Also, Professor Shortliffe is now Principal Investigator of both projects and there is no logical way to separate the management of such closely linked research efforts.

Length of this proposal

We have attempted to keep this proposal as brief as possible. However, we felt obliged to exceed some of the page limitations stipulated in the NIH guidelines for a several reasons.

First, the computer science discipline of artificial intelligence is relatively new and its intersection with and significance to medicine requires more explanation than more traditional areas of biomedical research. Second, the SUMEX-AIM resource encompasses a national community of more than 12 core research projects and 13 collaborative research projects pursuing diverse applications areas. In order to illustrate the scope of the community and provide the scientific basis for continued support of SUMEX as a resource, the objectives of these projects must be presented with enough detail to give reviewers unfamiliar with some aspects of the work a proper perspective. We also include a brief description of the important operational base of the resource. And finally, this application is for a 5-year renewal term. Many of the core and collaborative research efforts are aimed at long term goals to assist biomedical researchers and clinicians in information management, analysis, and decision making. In order to provide a more efficient research environment, avoiding the overhead of additional proposal preparations and reviews on time scales shorter than expected result horizons, we hope to describe our goals in sufficient detail to justify the 5-year award period.

2.1. Introduction and Background

2.1.1. Principal Investigators' Executive Summary

In the almost twelve years since the SUMEX-AIM resource was established, computing technology and biomedical artificial intelligence research have undergone a remarkable evolution. As we prepare this proposal to renew the resource through the remainder of the 1980's, we take pride in the realization that SUMEX has both influenced and responded to those changing technologies. It is widely recognized that our resource has fostered highly influential work in medical AI -- work from which it is generally acknowledged that the expert systems field emerged -- and that it has simultaneously helped define the technological base of applied AI research. The LISP machines to which we directed our attention in 1980 have now demonstrated their practicality as research tools and, increasingly, as potential mechanisms for disseminating AI systems as cost-effective decision aids in clinical settings such as private offices. We look forward to another half decade during which the era of centralized machines for AI research will come to an end, having been supplanted by networks of distributed and heterogeneous single-user machines sharing common resources such as file servers, printers, and gateways to other local and long-distance networks.

Although we reflect on the past with pride and satisfaction, and continue to be motivated by the goals that led to the initiation of SUMEX over a decade ago, our present momentum and on-going accomplishments inevitably direct us to the future. We are delighted that our sense of excitement about this field and its evolution has been sustained and that the future holds both challenges and promise that continue to carry our research community forward. The "spirit of SUMEX" that was fostered by our past efforts and goals provides an on-going stimulus to innovation and accomplishment. However, the contributing parts of that spirit do not come across well in the dry recitations of a voluminous proposal document such as the one that follows. Thus we begin with this prelude that provides an overview of our accomplishments and our proposed future directions. As in the past, we continue to be motivated by three main goals:

1. to develop and provide impeccable computing resources and human assistance to scientists working on applications of artificial intelligence research in medicine and biology;
2. to demonstrate that it is feasible to provide resources and assistance to a national community of researchers from a central site, integrating distributed and centralized computing technology, local and national computer communication networks, and a staff oriented toward the special problems of individuals participating in AIM research at other institutions;
3. to develop the community of scientists interested in working on applications of AI to the biomedical sciences; facilitating the growth, health, and vigor of the community by providing electronic communications that link its members and by assisting with the dissemination of systems software and applications programs that are of use to the wider community of AIM researchers. One question we have been asking is, "Is there a new style of science that will emerge in a communications-enhanced setting of national, rather than institutional, scope?" Within a decade it was clear that the answer to this question was (and is) "yes"!

SUMEX's Success as a National Research Resource

The SUMEX Project has demonstrated that it is possible to operate a computing research resource with a national charter and that the services providable over networks were those that facilitate the growth of AI-in-Medicine. Many NIH computer RR's have been mostly institutional in scope, occasionally regional (like the UCLA resource). SUMEX now has the reputation of a model national resource, pulling together the best available interactive computing technology, software, and computer communications in the service of a national scientific community. Planning groups for national facilities in cognitive science, computer science, and biomathematical modeling have discussed and studied the SUMEX model and new resources, like the recently instituted BIONET resource for molecular biologists, are closely patterned after the SUMEX example.

A decade ago, when machines up to the task of supporting AI research cost \$1M, some of the most notable projects in the history of Artificial Intelligence were done with terminal-and-network, without a computer on site. In human terms, this meant, of course, not having the headaches and energy drains of proposing a machine, installing it, maintaining it and its software, hiring its system programmers and operators, dealing with communication vendors, etc. The famous INTERNIST program was developed from Pittsburgh in this way. And the ACT computer model was begun at Michigan, continued at Yale, and later at Carnegie-Mellon, all without moving the program or losing a day's work because of machine transition problems. The GENET community of over 300 molecular biologists grew up in a year around SUMEX programs for analyzing DNA sequences. Their demand for these centralized capabilities ultimately swamped our machine and led to the initiation of a separate resource (BIONET) to meet their needs.

The projects SUMEX supports have generally required substantial computing resources with excellent interaction. Even today though, with the growing availability of Lisp workstations, this computing power is still hard to obtain in all but a few universities. SUMEX is, in a sense, a "great equalizer". A scientist gains access by virtue of the quality of his/her research ideas, not by the accident of where s/he happens to be situated. In other words, the resource follows the ethic of the scientific journal.

SUMEX has demonstrated that a computer resource is a useful "linking mechanism" for bringing together and holding together teams of experts from different disciplines who share a common problem focus. For example, computer scientists have been collaborating fruitfully with physical chemists, molecular biochemists, geneticists, crystallographers, internists, ophthalmologists, infectious disease specialists, intensive care specialists, oncologists, psychologists, biomedical engineers, and other expert practitioners. And in some of these cases, the interdisciplinary collaboration, usually so difficult to achieve in the best of circumstances, was achieved in spite of geographical distance between the participants, using the computer networks.

SUMEX has also achieved successes as a community builder. AI concepts and software are among the most complex products of computer science. Historically it has not been easy for scientists in other fields to gain access to and mastery of them. Yet the collaborative outreach and dissemination efforts of SUMEX have been able to bridge the gap in numerous cases. Over 36 biomedical AI application projects have developed in our national community and have been supported by SUMEX over the years. And 9 of these have matured to the point of now continuing their research on facilities outside of SUMEX. For example, the BIONET resource (named GENET while at SUMEX) is being operated by IntelliCorp; the Rutgers Computers in Biomedicine resource is centered at Rutgers University; the CADUCEUS project splits their research work between their own VAX computer and the SUMEX resource; and the Chemical Synthesis project now operates entirely on a VAX at U.C. Santa Cruz.

The SUMEX mission has been able to capture the contributions of some of the finest

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computers-in-medicine specialists and computer scientists in the country. For example, Professor Joshua Lederberg (SUMEX's first PI, now President of The Rockefeller University) is a member of SUMEX's Executive Committee; and Dr. Donald Lindberg, former Director of the University of Missouri's Medical Information Science group, and now Head of the National Library of Medicine, was until recently the Chairman of the AIM Advisory Group. Professor Herbert Simon of Carnegie-Mellon University, Professor Marvin Minsky of MIT, and many other distinguished scientists serve on that peer review committee.

SUMEX and Artificial Intelligence Research

The SUMEX Project is a relative latecomer to AI research. Yet its scope has given strong impetus to this historic development in applied computer science. AI research is that part of computer science that investigates symbolic reasoning processes, and the representation of symbolic knowledge for use in inference. It views heuristic or judgmental knowledge to be of equal importance with "factual" knowledge, indeed to be the essence of what we call "expertise". In its "Expert Systems" work, it seeks to capture the expertise of a field, and translate it into programs that will offer intelligent assistance to a practitioner in that field.

For computer applications in medicine and biology, this research path is crucial, indeed ineluctable. Medicine and biology are not presently mathematically-based sciences; unlike physics and engineering, they are seldom capable of exploiting the mathematical characteristics of computation. They are essentially inferential, not calculational, sciences. If the computer revolution is to affect biomedical scientists, computers will be used as inferential aids.

Perhaps the larger impact on medicine and biology will be the exposure and refinement of the hitherto largely private heuristic knowledge of the experts of the various fields studied. The ethic of science that calls for the public exposure and criticism of knowledge has traditionally been flawed for want of a methodology to evoke and give form to the heuristic knowledge of scientists. The AI methodology is beginning to fill that need. Heuristic knowledge can be elicited, studied, critiqued by peers, and taught to students.

The tide of AI research and application is rising. AI is one of the principal fronts along which university computer science groups are expanding. Federal and industrial support for AI research is vigorous and growing, although support specifically for biomedical applications continues to be limited. The pressure from student career-line choices is great: to cite an admittedly special case, approximately 80% of the students applying to Stanford's computer science Ph.D. program cite AI as a possible field of specialization (up from 30% 4 years ago). At Stanford, we have vigorous special programs for student training and research in AI -- a new graduate program in Medical Information Sciences and the two-year Masters Degree in AI program. All of these have many more applicants than available slots. Demand for our graduates, in both academic and industrial settings, is so high that students typically begin to receive solicitations one or two years before completing their degrees.

There is an explosion of interest in medical AI. The American Association for Artificial Intelligence (AAAI), the principal scientific membership organization for the AI field, has 7000 members, over 1000 of whom are members of the medical special interest group known as the AAAI-M. Speakers on medical AI are prominently featured at professional medical meetings, such as the American College of Pathology and American College of Physicians meetings; a decade ago, the words "artificial intelligence" were never heard at such conferences. And at medical computing meetings, such as the annual Symposium on Computer Applications in Medical Care and the international MEDINFO conferences, the growing interest in AI and the rapid

increase in papers on AI and expert systems are further testimony to the impact that the field is having.

AI is beginning to have a similar effect on medical education. Such diverse organizations as the National Library of Medicine, the American College of Physicians, the Association of American Medical Colleges, and the Medical Library Association have all called for sweeping changes in medical education, increased educational use of computing technology, enhanced research in medical computer science, and career development for people working at the interface between medicine and computing. They all cite evolving computing technology and (SUMEX-AIM) AI research as key motivators.

In industry, AI is on an exponential growth path as well. In the USA alone, over 30 AI start-up companies have been formed in the past four years and many groups have been established in large companies as well. The list of names is long and includes Hewlett-Packard, Schlumberger (including Fairchild), Texas Instruments, Xerox, IBM, DEC, General Motors, General Electric, Boeing, Rockwell, FMC Corp, Ford-Aerospace, Apple Computer, Teknowledge, IntelliCorp, Syntelligence, Lucid, Inference Corp, Symbolics, LMI, and so on... Many of these firms are marketing hardware and software tools for expert system development, as well as custom system services. And Japan has mounted a long-term, well-funded "Fifth Generation" computing effort to broadly develop knowledge-based systems technology as part of their national economic base of the 1990's.

The AI tide is rising largely because of the development in the 1970's and early 1980's of methods and tools for the application of AI concepts to difficult professional-level problem solving. Their impact was heightened because of the demonstration in various areas of medicine and other life sciences that these methods and tools really work. Here SUMEX has played a key role, so much so that it is regarded as "the home of applied AI."

SUMEX has been the nursery, as well as the home, of such well-known AI systems as DENDRAL (chemical structure elucidation), MYCIN (infectious disease diagnosis and therapy), INTERNIST (differential diagnosis), ACT (human memory organization), ONCOCIN (cancer chemotherapy protocol advice), SECS (chemical synthesis), EMYCIN (rule-based expert system tool), and AGE (blackboard-based expert system tool). In the past four years, our community has published a dozen books that give a scholarly perspective on the scientific experiments we have been performing. These volumes, and other work done at SUMEX, have played a seminal role in structuring modern AI paradigms and methodology. First among these scientific directions has been a switch in AI's focus from inference procedures to knowledge representation and use. There is now a recognition that the power of problem solvers derives primarily from the knowledge that they contain -- of the elements of the problem domain, of the strategies for solving problems in that domain, and of the forms in which the knowledge is to be acquired. In 1977, Goldstein and Papert of MIT, writing in the journal *Cognitive Science*, described the change of focus as a "paradigm shift" in AI. This shift was induced largely (though, of course, not exclusively) by the work at SUMEX, beginning with the DENDRAL development in 1965.

Toward the '90s: the Future of SUMEX

Given this setting of success and vitality, what is the future need and course for SUMEX as a resource -- especially in view of the on-going revolution in computer technology and costs, with the emergence of powerful single-user workstations and local area networking? The answers remain clear.

At the deepest research level, despite our considerable success in working on medical

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and biological applications, the problems we can attack are still sharply limited. Our current ideas fall short in many ways against today's important health care and biomedical research problems brought on by the explosion in medical knowledge and for which AI should be of assistance. Just as the research work of the 70's and 80's in the SUMEX-AIM community fuels the current practical and commercial applications, our work of the late 80's will be the basis for the next decade's systems. Our growing knowledge is clearly attained in an incremental fashion; we build today on the results of the past decade, and we will build in the 1990's on the work we undertake today.

At the resource level, there is a growing, diverse, and active AIM research community with intense needs for computing resources to continue its work. Many of these groups still are dependent on the SUMEX-AIM resources. For those who have been able to take advantage of newly developed local computing facilities, SUMEX-AIM provides a central cross-roads for communications and the sharing of programs and knowledge. In its core research and development role, SUMEX-AIM has its sights set on the hardware and software systems of the next decade. We expect major changes in the distributed computing environments that are just now emerging in order to make effective use of their power and to adapt them to the development and dissemination of biomedical AI systems for professional user communities. In its training role, SUMEX is a crucial resource for the education of badly needed new researchers and professionals to continue the development of the biomedical AI field. The "critical mass" of the existing physical SUMEX resource, its development staff, and its intellectual ties with the Stanford Knowledge Systems Laboratory (previously called the Heuristic Programming Project), make this an ideal setting to integrate, experiment with, and export these methodologies for the rest of the AIM community.

At the beginning, the SUMEX community was small and idea-limited, and the central SUMEX computer facility was an ideal vehicle for the research. Now the community is large, and the momentum of the science is such that its progress is limited by computing power and research manpower. The size and scientific maturity of the SUMEX community has fully consumed the computing resource in every critical dimension -- CPU power, main memory size, address space, and file space -- and has overflowed to decentralized machines of many types. Our projection about the central role of Lisp workstations in AI research and applications has come true dramatically. As we were writing our application five years ago, a few experimental workstations existed in research laboratories and Xerox was laboring over bringing out the first commercial Dolphin. In that short time, Xerox has significantly increased its product line and Symbolics, Lisp Machines Inc., Texas Instruments, and Hewlett Packard have introduced extensive Lisp machine product lines -- at both the low-cost and high-performance extremes of the spectrum. As indicated in the body of this proposal, with NIH and DARPA funding and industrial gifts we have been able to purchase a substantial number of Lisp machines of various types. And much of our work has already been focussed on developing and experimenting with workstation environments for biomedical AI applications. We are fully committed to continuing this line of research for the future hardware thrust of the resource. We will continue our "experimental" approach to these systems, eschewing articles of faith for real experience. We must learn to build and exploit distributed networks of these machines and to build and manage graceful software for these systems. Since decentralization is central to our future, we must learn its technical characteristics.

Our planning axiom for the next period continues to be: the need to accommodate and exploit a *heterogeneity* of computers and peripheral devices. We must maintain a flexible posture with respect to the introduction of new capabilities and changing costs during this continuing revolution. Yet we must choose, while avoiding precipitous decisions. Our plan is conservative, recognizing that there is still a community of national users -- particularly young projects needing seed support prior to obtaining major funding -- who will depend for several years on a central shared resource like

the SUMEX mainframe. Since the trend is clear, however, we intend to phase out the role of the central SUMEX machine over the next five years. The existing 2060, with its superb software, will be frozen except for possible minor upgrades (such as in memory) to minimize maintenance costs. It will continue to serve the AIM community during the period of transition, but the costs to SUMEX for its maintenance will decrease linearly until, at the end of the five years, it will no longer be part of the resource. During the phase out period, the 2060 will continue to provide a start-up environment for new projects and will facilitate communication among members of the AIM community. It will also provide us with a "link to the past" -- access to software that is still needed by the community and can be transferred only gradually to the totally distributed computing environment which we anticipate will exist in 1990. The 2060 (plus its satellite 2020 and local VAX's) have been amiable workhorses and, although we do not propose to have SUMEX maintain the smaller mainframe machines into the renewal period, we can not (indeed dare not) do without the 2060 during this period of turbulence. It will have a continuing important role in serving national and local users until an adequate number of workstations gradually become available to all collaborative projects.

On the workstation front, we propose buying a few additional Lisp machines each year to allow our core efforts to stay abreast of the advancing technology. For example, in the first year we plan to buy four of the newly-announced Xerox 6085 machines (these do not even have an 11xx designation yet for the Lisp versions) as the basis for our virtual system development work and the ONCOCIN dissemination research. By the second year, we expect VLSI versions of machines from several companies to choose from and so on through the 5-year term.

These machines will be integrated into the SUMEX local area network and software developed to allow these machines to be more broadly available to local and remote researchers and to cooperate on complex problems. We will enhance the computing environments of these systems to allow users to move off of mainframe systems into increasingly intelligent and supportive surroundings for their work. To facilitate the transfer of software and access to valuable common facilities, the SUMEX complement of equipment will be linked by local digital networks to other major centers of computing at Stanford, the most important of which is the Computer Science Department.

The success of SUMEX is the success of its dedicated and extraordinarily competent faculty and staff. This human resource of SUMEX should not, and will not, be decentralized. In the world of computer systems talent and user-assistance expertise, there are indeed continuing large "economies of scale".

The smoothly operating management structure of SUMEX is one of its joys and victories. We do not plan to fix something that is not broken. We plan that the Executive Committee and the AIM Advisory Committee will continue to function as they now do.

To summarize our goals for the five years that lie ahead:

- Maintain the clear thread through SUMEX core system development, core AI research, our experimental efforts at disseminating clinical decision-making aids, and new applications efforts.
- Continue to serve the national AIM research community while gradually phasing out the existing DEC-20 machine and focussing new computing resource developments on more effective exploitation of distributed workstations through communication and cooperative computing over transparent digital networking schemes.

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- Enhance the computing environments of workstations so that no dependency on central hosts remains and the general mainframe time-sharing systems can be phased out eventually.
- Continue the central staff and management structure, essentially unchanged in size and function, except for the merging of the core part of the ONCOCIN research with the SUMEX resource.

As we add up the budget (flinchingly, we hasten to say), we note that the cost will not be cheap, despite the much-touted fall in the cost of computing. Part of the expense is related to merging the budgets of ONCOCIN and SUMEX, each of which have been separately funded by the Division of Research Resources and are now to be combined in a unified effort. Despite the costs, we believe that we have been conservative; that the scientific community we serve needs these resources; and that by its science and its applications orientation, it has earned them. The scientific work of the SUMEX-AIM community is the quintessence of experimental computer science. It is advancing, and gaining acceptance, beyond expectations. SUMEX serves the nation, not one university or department. We believe that its budget accords well with the national interest and with the scientific interest.

2.1.2. Objectives

2.1.2.1. Resource Goals and Definitions

SUMEX-AIM is a national computer resource with a multiple mission: a) promoting experimental applications of computer science research in artificial intelligence (AI) to biological and medical problems, b) studying methodologies for the dissemination of biomedical AI systems into target user communities, c) supporting the basic AI research that underlies applications, and d) facilitating network-based computer resource sharing, collaboration, and communication among a national scientific community of health research projects. The SUMEX-AIM resource is located physically in the Stanford University Medical School and serves as a nucleus for a community of medical AI projects at universities around the country. SUMEX provides computing facilities tuned to the needs of AI research and communication tools to facilitate remote access, inter- and intra-group contacts, and the demonstration of developing computer programs to biomedical research collaborators.

In the succeeding sections of this proposal, we offer descriptions 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 definition of AI and a summary of the aims, background, and present status of our research relative to the requested term of the renewal, the five years beginning August 1, 1986.

What is Artificial Intelligence?

Artificial Intelligence research is that part of Computer Science concerned with symbol manipulation processes that produce intelligent action [1, 56, 61, 69]. Here *intelligent action* means an act or decision that is goal-oriented, is arrived at by an understandable chain of symbolic analysis and reasoning steps, and utilizes knowledge of the world to inform and guide the reasoning.

Placing AI in Computer Science

A simplified view relates AI research with the rest of computer science. The manner of use of computers by people to accomplish tasks can be thought of as a one-dimensional spectrum representing the nature of the instructions that must be given the computer to do its job. At one extreme of the spectrum, representing early computer science, the user supplies his intelligence to instruct the machine precisely *how* to do the job, step-by-step.

At the other extreme of the spectrum, the user describes *what* he wishes the computer to do for him to solve a problem. He wants to communicate what is to be done without having to lay out in detail all necessary subgoals for adequate performance, yet with a reasonable assurance that he is addressing an intelligent agent that is using knowledge of his world to understand his intent, complain or fill in his vagueness, make specific his abstractions, correct his errors, discover appropriate subgoals, and ultimately translate what he wants done into detailed processing steps that define how it should be done by a real computer. The user wants to provide this specification of what to do in a language that is comfortable to him and the problem domain (perhaps English) and via communication modes that are convenient for him (including perhaps speech or pictures).

Progress in computer science may be seen as steps away from that extreme *how* point on the spectrum: the familiar panoply of assembly languages, subroutine libraries, compilers, extensible languages, etc. illustrate this trend. The research activity aimed at

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creating computer programs that act as *intelligent agents* near the *what* end of the spectrum can be viewed as a long-range goal of AI research.

Expert Systems and Applications

The national SUMEX-AIM resource has in large part made possible a long, interdisciplinary line of artificial intelligence research at Stanford concerned with the development of concepts and techniques for building expert systems [31]. An *expert system* is an intelligent computer program that uses knowledge and inference procedures to solve problems that are difficult enough to require significant human expertise for their solution. For some fields of work, the knowledge necessary to perform at such a level, plus the inference procedures used, can be thought of as a model of the expertise of the expert practitioners of that field.

The knowledge of an expert system consists of facts and heuristics. The *facts* constitute a body of information that is widely shared, publicly available, and generally agreed upon by experts in a field. The *heuristics* are the mostly-private, little-discussed rules of good judgment (rules of plausible reasoning, rules of good guessing) that characterize expert-level decision making in the field. The performance level of an expert system is primarily a function of the size and quality of the knowledge base that it possesses.

Projects in the SUMEX-AIM community are concerned in some way with the application of AI to biomedical research. Brief abstracts of the various projects currently using the SUMEX resource can be found in Appendix D on page 311 and more detailed progress summaries in Section 6 on page 191. The most tangible objective of this approach is the development of computer programs that will be more general and effective consultative tools for the clinician and medical scientist. There have already been promising results in areas such as chemical structure elucidation and synthesis, diagnostic consultation, molecular biology, and modeling of psychological processes.

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 comprising artificial intelligence research. 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 structure problems in organic chemistry or in the rigorous consideration of a large diagnostic knowledge base.

Resource Sharing

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 engaged in biomedical computer science research and for the dissemination of AI technology. 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 [41, 11]. And, as projected in our previous application, we are seeing a growing decentralization of computing resources with the emerging technology in microelectronics and a correspondingly greater role for digital communications to facilitate scientific exchange.

Our community building effort is based upon the developing state of distributed computing and communications technology. While far from perfected, these capabilities offer highly desirable latitude for collaborative linkages, both within a given research

project and among them. A number of the active projects on SUMEX are based upon the collaboration of computer and medical scientists at geographically separate institutions, separate both from each other and from the computer resource (see for example, the MENTOR and PathFinder projects). Many other projects, once begun using the facilities of the SUMEX-AIM resource, have developed and matured to the point of justifying their own computing resources and now operate independent of, but linked through electronic communications to, the SUMEX-AIM resource. Our network connections and common facilities for user terminals have been indispensable for effective interchanges between community members, workshop coordinations, and software sharing.

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2.1.2.2. Specific Aims

The goals of the SUMEX-AIM resource are long term in supporting basic research in artificial intelligence, applying these techniques to a broad range of biomedical problems, developing the methodologies for disseminating AI systems into the biomedical community, experimenting with communication technologies to promote scientific interchange, and developing better tools and facilities to carry on this research.

Toward a More Distributed Resource

In the early 1970's, the initial model for SUMEX-AIM as a centralized resource was based on the high cost of powerful computing facilities and the infeasibility of being able to duplicate them readily. As planned, this central role has already evolved significantly and continues to evolve with the introduction of more compact and inexpensive computing technology now available at many more research sites. At the same time, the number of active groups working on biomedical AI problems has grown and the established ones have increased in size. This has led to a growth in the demand for computing resources far beyond what SUMEX-AIM could reasonably and effectively provide on a national scale. We have actively supported efforts by the more mature AIM projects to develop or adapt additional computing facilities tailored to their particular needs and designed to free the main SUMEX resource for new, developing applications projects. To date, over 10 of the national projects have moved some or all of their work to local sites and several have begun resource communities of their own (see page 116). Thus, as more remotely available resources have become established, the balance of the use of the SUMEX-AIM resource has shifted toward supporting start-up pilot projects and the growing AI research community at Stanford.

Summary of Specific Objectives

Our future goals for the central SUMEX-AIM resource are then guided by:

- The increasingly decentralized character of the resource and community and the need to find ways to maintain the scientific communication and sharing that has characterized SUMEX-AIM work
- The continuing exploration of important new areas of biomedical research in which AI techniques can be effectively applied
- The need for a strong basic research effort to investigate methodologies to attack the many problems still beyond our current AI systems and to develop improved tools to build more complex and effective expert systems
- The growing impact of biomedical AI and the need to find and evaluate ways for effectively disseminating biomedical AI technology into real-world settings.
- The need for computing environments for our research and dissemination work that anticipate the needs of AI applications systems over the next 5-10 years, based on the rapidly changing computing hardware and software technology base

SUMEX-AIM will retain its role as a national experimental laboratory for biomedical AI research with a double thrust -- on the one hand, pursuing the basic research for, experimentation on, and trial dissemination of interesting applications and on the other, anticipating and developing the model computing and community environment in which

this work can take place. We will nurture existing and new projects and serve as a communications cross-roads for the now diverse AIM community. We will provide the computing resources and some manpower support for long-term basic AI research activities that promise to illuminate issues relevant to future selected collaborative application areas in biology and medicine. For example, as our detailed plans are presented, you will find threads between our basic research in general patient treatment protocol acquisition, representation, and decision-making tools and our collaborative applications in cancer chemotherapy or hypertension trials. Or between our basic research in blackboard problem-solving frameworks and system architectures and our collaborative application in NMR protein conformation determination. Other basic research areas have even longer term goals for problems we hope to be able to address in the future. Underlying all this work will be the development of the Lisp workstation system and network environment that will facilitate these research results and that we feel will become the routine computing environment of the next decade.

In all of this, SUMEX will be both a working laboratory for selected projects within our computing and manpower capacity limits and a source and repository for software and ideas for a broader remote community. We will become an increasingly distributed community resource with heterogeneous computing facilities tethered to each other through various communications media. Many of these machines will be located physically near the projects or biomedical scientists using them. We retain our sincere commitment to our national community of projects. But, inevitably their needs will be met more and more by local facilities and our plans as a resource for the next term place greater emphasis than in the past on supporting the growing Stanford community of AIM collaborations and projects and on developing and integrating model systems at Stanford that can be emulated elsewhere for AIM community needs.

Even with more distributed computing resources, the central resource will continue to play an important role for the next term as a communication crossroads and as a focus for our active dissemination efforts. A key challenge will be to maintain the scientific community ties that grew naturally out of the previous co-location within a central facility.

The following outlines the specific objectives of the SUMEX-AIM resource during the follow-on five year period. Note that these objectives cover only the resource nucleus; objectives for individual collaborating projects are discussed in their respective reports in Section 6. Specific aims are broken into five categories: 1) Core Research and Development, 2) Collaborative Research, 3) Service and Resource Operations, 4) Training and Education, and 5) Dissemination.

1) Core Research and Development

SUMEX funding and computational support for core research is complementary to similar funding from other agencies (see page 105) and contributes to the long-standing interdisciplinary effort at Stanford in basic AI research and expert system design. We expect this work to provide the underpinnings for increasingly effective consultative programs in medicine and for more practical adaptations of this work within emerging microelectronic technologies. Specific aims include:

- Basic research on AI techniques applicable to biomedical problems. Over the next term we will emphasize work on blackboard problem-solving frameworks and architectures, knowledge acquisition or learning, constraint satisfaction, and qualitative simulation.
- Investigate methodologies for disseminating application systems such as clinical decision-making advisors into user groups. This will include generalized systems for acquiring, representing and reasoning about complex

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treatment protocols such as are used in cancer chemotherapy and which might be used for clinical trials.

- Support community efforts to organize and generalize AI tools and architectures that have been developed in the context of individual application projects. This will include retrospective evaluations of systems like the AGE blackboard experiment and work on new systems such as BB1, MRS, SOAR, EONCOCIN, EOPAL, Meta-ONYX, and architectures for concurrent symbolic computing. The objective is to evolve a body of software tools that can be used to more efficaciously build future knowledge-based systems and explore other biomedical AI applications.
- Develop more effective workstation systems to serve as the basis for research, biomedical application development, and dissemination. We seek to coordinate basic research, application work, and system development so that the AI software we develop for the next 5-10 years will be appropriate to the hardware and system software environments we expect to be practical by then. Our purchases of new hardware will be limited to experimentation with state-of-the-art workstations as they become available for our system developments.

2) Collaborative Research

- Encourage the exploration of new applications of AI to biomedical research and improve mechanisms for inter- and intra-group collaborations and communications. While AI is our defining theme, we may consider exceptional applications justified by some other unique feature of SUMEX-AIM essential for important biomedical research. We will continue to exploit community expertise and sharing in software development.
- Minimize administrative barriers to the community-oriented goals of SUMEX-AIM and direct our resources toward purely scientific goals. We will retain the current user funding arrangements for projects working on SUMEX facilities. User projects will fund their own manpower and local needs; actively contribute their special expertise to the SUMEX-AIM community; and receive an allocation of computing resources under the control of the AIM management committees. There will be no "fee for service" charges for community members.
- Provide effective and geographically accessible communication facilities to the SUMEX-AIM community for remote collaborations, communications among distributed computing nodes, and experimental testing of AI programs. We will retain the current ARPANET and TYMNET connections for at least the near term and will actively explore other advantageous connections to new communications networks and to dedicated links.

3) Service and Resource Operations

SUMEX-AIM does not have the computing or manpower capacity to provide routine service to the large community of mature projects that has developed over the years. Rather, their computing needs are better met by the appropriate development of their own computing resources when justified. Thus, SUMEX-AIM has the primary focus of assisting new start-up or pilot projects in biomedical AI applications in addition to its core research in the setting of a sizable number of collaborative projects. We do offer continuing support for projects through the lengthy process of obtaining funding to establish their own computing base.

Training and Education

- Provide documentation and assistance to interface users to resource facilities and systems.
- Exploit particular areas of expertise within the community for assisting in the development of pilot efforts in new application areas.
- Accept visitors in Stanford research groups within limits of manpower, space, and computing resources.
- Support the Medical Information Science and MS/AI student programs at Stanford to increase the number of research personnel available to work on biomedical AI applications.
- Support workshop activities including collaboration with other community groups on the AIM community workshop and with individual projects for more specialized workshops covering specific research, application, or system dissemination topics.

5) Dissemination

While collaborating projects are responsible for the development and dissemination of their own AI systems and results, the SUMEX resource will work to provide community-wide support for dissemination efforts in areas such as:

- Encourage and support the on-going export of software systems and tools within the AIM community and for commercial development.
- Assist in the production of video tapes and films depicting aspects of AIM community research.
- Promote the publication of books, review papers, and basic research articles on all aspects of SUMEX-AIM research.

2.1.2.3. Resource Scope

The SUMEX-AIM resource has been from its inception a national experimental resource for biomedical AI with a scope that is carefully defined. Within its limited manpower and computational resources, its focus has been on experiments in new and varied biomedical applications of AI, assisting new research groups in biomedical AI get started, exploring ways to disseminate AI systems into biomedical user communities, supporting relevant basic AI research, and facilitating scientific communications and community sharing. The SUMEX-AIM user community comprises projects from many biological and medical disciplines, ranging from chemistry to molecular biology to clinical medicine to cognitive psychology, and represents collaborations between computer and biomedical scientists from many parts of Stanford University and other universities around the country. The development of this diverse community of projects has both justified the cost of and made effective use of SUMEX-AIM computational and communication facilities at Stanford and elsewhere in our resource community. In its resource role, SUMEX has intentionally limited its production computational capacity to meet the needs of national start-up projects and Stanford research groups, while encouraging self-sufficient community members to develop resources to meet their own computing needs. This has allowed us to provide a level of support for on-going projects and to concentrate most of our efforts on experiments with integrating emerging hardware and software technologies that will be the vehicles of future biomedical AI systems. The results of these experiments are widely disseminated and help other groups through example and direct export of software and ideas.

2.1.2.4. Significance to Biomedicine

Artificial intelligence is the computer science of representations of symbolic knowledge and its use in symbolic inference and problem-solving processes. There is a certain inevitability to this branch of computer science and its applications, in particular, to medicine and biosciences. The cost of computers will continue to fall drastically during the coming two decades. As it does, many more of the practitioners of the world's professions will be persuaded to turn to economical automatic information processing for assistance in managing the increasing complexity of their daily tasks. They will find, from most of computer science, help only for those problems that have a mathematical or statistical core, or are of a routine data-processing nature. But such problems will be relatively rare, except in engineering and physical science. In medicine, biology, management, indeed in most of the world's work, the daily tasks are those requiring symbolic reasoning with detailed professional knowledge. The computers that will act as *intelligent assistants* for these professionals must be endowed with symbolic reasoning capabilities and knowledge.

The growth in medical knowledge has far surpassed the ability of a single practitioner to master it all, and the computer's superior information processing capacity thereby offers a natural appeal. Furthermore, the reasoning processes of medical experts are poorly understood; attempts to model expert decision-making necessarily require a degree of introspection and a structured experimentation that may, in turn, improve the quality of the physician's own clinical decisions, making them more reproducible and defensible. New insights that result may also allow us more adequately to teach medical students and house staff the techniques for reaching good decisions, rather than merely to offer a collection of facts which they must independently learn to utilize coherently.

The knowledge that must be used is a combination of factual knowledge and heuristic knowledge. The latter is especially hard to obtain and represent since the experts providing it are mostly unaware of the heuristic knowledge they are using. Medical and scientific communities currently face many widely-recognized problems relating to the rapid accumulation of knowledge, for example:

- codifying theoretical and heuristic knowledge
- effectively using the wealth of information implicitly available from textbooks, journal articles and other practitioners
- disseminating that knowledge beyond the intellectual centers where it is collected
- customizing the presentation of that knowledge to individual practitioners as well as customizing the application of the information to individual cases

We believe that computers are an inevitable technology for helping to overcome these problems. While recognizing the value of mathematical modeling, statistical classification, decision theory and other techniques, we believe that effective use of such methods depends on using them in conjunction with less formal knowledge, including contextual and strategic knowledge.

Artificial intelligence offers advantages for representing and using information that will allow physicians and scientists to use computers as intelligent assistants. In this way we envision a significant extension to the decision-making powers of specific practitioners without reducing the importance of those individuals in that process.

Knowledge is power, in the profession and in the intelligent agent. As we proceed to model expertise in medicine and its related sciences, we find that the power of our

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programs derives mainly from the knowledge that we are able to obtain from our collaborating practitioners, not from the sophistication of the inference processes we observe them using. Crucially, the knowledge that gives power is not merely the knowledge of the textbook, the lecture and the journal, but the knowledge of *good practice*--the experiential knowledge of *good judgment* and *good guessing*, the knowledge of the practitioner's art that is often used in lieu of facts and rigor. This heuristic knowledge is mostly private, even in the very public practice of science. It is almost never taught explicitly, is almost never discussed and critiqued among peers, and most often is not even in the moment-by-moment awareness of the practitioner.

Perhaps the the most expansive view of the significance of the work of the SUMEX-AIM community is that a methodology is emerging for the systematic explication, testing, dissemination, and teaching of the heuristic knowledge of medical practice and scientific performance. Perhaps it is less important that computer programs can be organized to use this knowledge than that the knowledge itself can be organized for the use of the human practitioners of today and tomorrow.

Evidence of the impact of SUMEX-AIM in promoting ideas such as these, and developing the pertinent specific techniques, has been the explosion of interest in medical artificial intelligence and the specific research efforts of the SUMEX community. In SUMEX's second decade, we have found that the small community of researchers that characterized the AIM field in the early 1970's has now grown to a large, accomplished, and respected research community. The American Association for Artificial Intelligence (AAAI), the principal scientific membership organization for the AI field, has 7000 members, over 1000 of whom are members of the medical special interest group known as the AAAI-M. This subgroup was founded by members of the SUMEX-AIM community who were active in AAAI and is the only active subgroup in the Association. The organization distributes semiannual newsletters on medical AI and provides a focus for cosponsoring relevant medical computing meetings with other societies (such as the American Association for Medical Systems and Informatics -- AAMSI). Medical AI papers are prominently featured at both medical computing and artificial intelligence meetings, and artificial intelligence is now routinely featured as a specific subtopic for specialized sessions at medical computing and other medical professional meetings. For example, members of the AIM community have represented the field to physicians at the American College of Pathology and American College of Physicians meetings for the last several years. A mere decade ago, the words "artificial intelligence" were never uttered at such conferences. The growing interest and recognition are largely due to the activities of the SUMEX-AIM community.

Another indication of the growing impact of the SUMEX-AIM community is its effect on medical education. For reasons such as those outlined above, there is an increasing recognition of the need for a revolution in the way medicine is taught and medical students organize and access information. Computing technology is routinely cited as part of this revolution, and artificial intelligence (and SUMEX-AIM research) generally figures prominently in such discussions. Such diverse organizations as the National Library of Medicine, the American College of Physicians, the Association of American Medical Colleges, and the Medical Library Association have all called for sweeping changes in medical education, increased educational use of computing technology, enhanced research in medical computer science, and career development for people working at the interface between medicine and computing; reports of all four organizations have specifically cited the role of artificial intelligence techniques in future medical practice and have used SUMEX-AIM programs as examples of where the technology is gradually heading.

In summary, the logic which mandates that artificial intelligence play a key role in enhancing knowledge management and access for biomedicine -- a logic in which we have long believed -- has gradually become evident to much of the biomedical

community. We are encouraged by this increased recognition, but humbled by the realization of the significant research challenges that remain. Our goals are accordingly both scientific and educational. We continue to pursue the research objectives that have always guided SUMEX-AIM, but must also undertake educational efforts designed to inform the biomedical community of our results while cautioning it about the challenges remaining.

2.1.3. Background

Beginning in the mid-1960's with DENDRAL, a project focused on applications of artificial intelligence to experiments in modeling scientific inference in biomolecular structure characterization problems [43], the Stanford Knowledge Systems Laboratory (formerly named the Heuristic Programming Project, see Appendix A) has pioneered in expert systems research with funding support from NIH, ARPA, NSF, and NASA and other government and private sources. Much of the early DENDRAL computation work was done on the ACME IBM 360/50 interactive computing resource at Stanford, which was funded by the NIH Biotechnology Resources Program between 1965 and 1973. This system, while an excellent experiment in interactive medical computing, could not provide the symbolic computing resources needed for AI research. Such resources were not available from other sources either since the system hardware and software requirements for AI research (for example, address space, memory size, languages and debugging support, and interactive facilities) surpass the services customarily offered in academic or commercial computing facilities. With the success of DENDRAL by the early 1970's and the start of experiments in other application areas such as clinical medicine, chemical synthesis, learning, and cognitive psychology, a general need for state-of-the-art AI computing resources became manifest. Because no single project could justify funding for its own computing facility of the needed magnitude, we were led to formulate a shared community solution that was to have far-reaching impact, both in the support of biomedical AI research and as an experiment in electronic collaboration among scientists. Since 1973, SUMEX-AIM has developed as a national resource for applying AI techniques to a broad range of biomedical research problems.

Funding of the SUMEX-AIM resource from the NIH Biomedical Research Technology Program (formerly Biotechnology Resources Program) began in December 1973 for a five year period. Prof. Joshua Lederberg was Principal Investigator and Prof. Edward A. Feigenbaum was co-Principal Investigator. The major hardware, a DEC KI-10 system running the experimental TENEX operating system, was delivered and accepted in April 1974, and the system became operational for users during the summer of 1974. In 1977, we applied for a five-year renewal grant to continue our national research effort. We received a recommendation for approval of the five year period from the study section but this was reduced to three years following Professor Lederberg's decision in early 1978 to accept the presidency of The Rockefeller University. The principal investigator role passed easily to Prof. Feigenbaum, then Chairman of the Stanford Computer Science Department, based upon his long-time involvement with the project and close collaboration with Prof. Lederberg. The highly interdisciplinary spirit of SUMEX was retained with very close ties to the Stanford Medical School through Drs. E. H. Shortliffe (then co-Principal Investigator of SUMEX) and S. N. Cohen. At the end of that 3-year term, we applied for and were awarded a third renewal for the SUMEX-AIM resource for 5 years starting in August 1981, under Professors Feigenbaum and Shortliffe. This winter, with his appointment to a tenured faculty position at Stanford and with his physical and administrative proximity to the SUMEX resource in the Department of Medicine, Dr. Shortliffe took over as Principal Investigator of SUMEX and Professor Feigenbaum again became co-Principal Investigator

Although the 12 years of support the SUMEX-AIM resource has received is long by some standards, it is short in terms of the time needed to develop the discipline of artificial intelligence and to realize the potential of its applications in biomedicine. The existence of SUMEX-AIM and its support by NIH has been crucial to the substantial progress made to date. It is hardly long enough for a conclusive determination of the long term impact of this work but we can fairly take pride in the scientific success of SUMEX-AIM as a community and in the success of the SUMEX-

AIM model as a resource. Beginning with 5 projects in 1973, over 35 research projects have started within the SUMEX-AIM community and, after initial nurturing, 9 have developed independent computing resources of their own and now operate as autonomous projects. More than a dozen books describing the results of community work have been published since 1980. And as indicated earlier, increased training and the use of computing in general, including programs centered on symbolic computation, are being advocated for medical education and research. Finally, significant progress has been made in starting the commercialization of AI technology, based to a significant extent on the success of early research in the SUMEX-AIM community.

On the resource management side, we take pride in the diligence and technical competence with which we have responded to the community responsibilities mandated by the terms of our grants [51]. Good will and common purpose are of course the indispensable ingredients for an effective community resource, 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. The character of the SUMEX resource has changed with the evolving computer and communications technology on which it is based. Starting with fully centralized hardware and distributed research groups in 1974, the community (research groups and computing resources) is now highly distributed. This change is essential to the technical vitality of the on-going work and to ensuring the availability of computing resources that will be the means for disseminating AI programs to biomedical researchers and practitioners.

The present renewal application is therefore written from a perspective of having built a significant community of active biomedical AI research projects and of entering a new phase of our research to integrate and exploit exciting computer technologies that will have a profound effect on the development and export of practical medical AI programs. As discussed in the sections describing the individual projects (see Section 6), many of the computer programs under development by these groups are maturing into tools increasingly useful to the respective research communities. The demands from innovative new core research work and for production-level use of these programs has long ago surpassed the capacity of the present SUMEX facility and has raised important issues of how such software systems can be developed in effective research environments and then optimized for production environments, exported, and maintained.

2.1.4. Resource Progress

This progress summary covers only the resource nucleus. Objectives and progress for individual collaborating projects are discussed in their respective reports in Section 6. In particular, progress in the current ONCOCIN resource-related research project for Studies in the Dissemination of Consultation Systems, which will be merged with SUMEX in the renewal period, is reported there. Longer term goals for the ONCOCIN core research work over the period of this renewal application are discussed under the *Planned Resource Activities* section of this proposal. These collaborative projects collectively provide much of the scientific basis for SUMEX as a resource and our role in assisting them has been a continuation of that evolved in the past. Collaborating projects are autonomous in their management and provide their own manpower and expertise for the development and dissemination of their AI programs.

2.1.4.1. Summary of Prior Goals

The following summarizes SUMEX-AIM resource objectives as stated in the proposal for the on-going five-year grant, begun on August 1, 1981, and provides the backdrop against which specific progress is reported. These project goals are presented in the three categories used in the previous proposal: 1) resource operations, 2) training and education, and 3) core research.

1) Resource Operations

- Maintain the vitality of the AIM community by continuing to encourage and explore new applications of AI to biomedical research and improving mechanisms for inter- and intra-group collaborations and communications. User projects will fund their own manpower and local needs; will actively contribute their special expertise to the SUMEX-AIM community; and will receive an allocation of computing resources under the control of the AIM management committees. There will be no "fee for service" charges for community members.
- Provide effective computational support for AIM community goals, including efforts to improve the support for artificial intelligence research and new applications work; to develop new computational tools to support more mature projects; and to facilitate testing and research dissemination of nearly operational programs. We will continue to operate and develop the existing KI-10/2020 facility as the nucleus of the resource. We will acquire additional equipment to meet developing community needs for more capacity, larger program address spaces, and improved interactive facilities. New computing hardware technologies becoming available now and in the next few years will play a key role in these developments and we expect to take the lead in this community for adapting these new tools to biomedical AI needs. We planned the phased purchase of two VAX computers to provide increased computing capacity and to support large address space LISP development, a 2 GByte file server to meet file storage needs, and a number of single-user "professional workstations" to experiment with improved human interfaces and AI program dissemination.
- Provide effective and geographically accessible communication facilities to the SUMEX-AIM community for remote collaborations, communications among distributed computing nodes, and experimental testing of AI programs. We will retain the current ARPANET and TYMNET connections for at least the near term and will actively explore other advantageous connections to new communications networks and to dedicated links.

2) Training and Education

- Provide community-wide support and work to make resource goals and AI programs known and available to appropriate medical scientists. Collaborating projects are responsible for the development and dissemination of their own AI programs.
- Provide documentation and assistance to interface users to resource facilities and programs and continue to exploit particular areas of expertise within the community for developing pilot efforts in new application areas.
- Allocate "collaborative linkage" funds to qualifying new and pilot projects to provide for communications and terminal support pending formal approval and funding of their projects. These funds are allocated in cooperation with the AIM Executive Committee reviews of prospective user projects.
- Support workshop activities, including collaboration with the Rutgers Computers in Biomedicine resource on the AIM community workshop and with individual projects for more specialized workshops covering specific application areas or program dissemination.

3) Core Research

- Explore basic artificial intelligence research issues and techniques, including knowledge acquisition, representation, and utilization; reasoning in the presence of uncertainty; strategy planning; and explanations of reasoning pathways, with particular emphasis on biomedical applications.
- Support community efforts to organize and generalize AI tools that have been developed in the context of individual application projects. This will include work to organize the present state-of-the-art in AI techniques through the AI Handbook effort and the development of practical software packages (e.g., AGE, EMYCIN, UNITS, and EXPERT) for the acquisition, representation, and utilization of knowledge in AI programs.