A panel session—Computer-assisted instruction: 
Current status—Future problems

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CAI problems and prospects

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The expression “computer-assisted instruction” (CAI) is generally used to describe situations in which the computer is used as a teaching surrogate in some sense—whether as drill instructor, tester, or specialized tutor. Most applications of this kind have had specific, limited, and modest educational goals. When used to administer drills or branching tests, a computer is not called upon to be intelligent—only useful. Yet it is interesting and important to ask whether the computer can become an intelligent artificial teacher, and more generally, whether there are valuable ways of using computers for teaching and learning.

In artificial teaching, the computer controls the interaction with the student. There are applications of the opposite kind, where the student controls the machine. The most common one is the teaching of computer programming itself. Another is the use of a computer to simulate a “real” laboratory. And, there is a potentially rich spectrum of intermediate arrangements—strong instructional interactions—in which the student and the computer share control and direct each other. As an example, student programming and artificial teaching might be coupled by having the computer monitor a student’s work as he uses a programming language to perform a simulated experiment or to solve a problem. No significant experiments in this direction can be done without a great deal of work; but we do know, in principle, how to make a program follow the steps of a student who is not constrained by a stereotyped pattern and how to diagnose his difficulties on the way.

We shall argue that computers will make deep contributions to education in all three areas:

1. first, and with capabilities already well established, through the teaching of programming languages;
2. ultimately, and to an extent largely dependent on progress in artificial intelligence research, as an artificial teacher;
3. intermediately, as an instructional monitor or assistant, in a number of different subjects as diverse as music, language, and physics.

Along the way, we shall elaborate on specific educational contributions including the following.
1. The teaching of programming can provide a conceptual and operational framework for the teaching of mathematics.

2. Using an appropriate language, programming can be introduced routinely to third-graders for its special value in teaching the skills of clear and precise thinking and expression.

3. The computer can enhance the teaching of "practical" subjects (such as navigation or speaking a foreign language) whose mastery requires the integration of mechanical and intellectual skills.

Finally, we shall contrast the present lack of depth and perspective characterizing much of the work in this field with its rich prospects. In particular, we shall discuss our view that a serious investigation of the problems involved in developing an intelligent teaching system will yield rich results in the fields of computers, education, and psychology.

CAI: Research requirements for instructional strategies

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The current developments of computer-assisted instruction (CAI) can be characterized as a phased transition from the creation of hardware and language systems for implementation into the more fundamental examination of the features of optimal instructional strategies for CAI applications. Instructional strategies are the plans by which informational presentations are matched with the current requirements of a learner in order to optimize on a set of criterion objectives. The research approaches into the nature and process of instructional strategies has been twofold, namely, naturalistic and systematic.

The naturalistic approach consists of three applicational types that developed concurrently with the hardware and language CAI systems. First, the complementary CAI type provides instruction that is adjusted to the stage of progress that a student has acquired in the conventional educational classroom; this approach is best exemplified by the Stanford Drill and Practice Mathematics Project. Secondly, the autonomous CAI type provides instruction that is the full corpus of an accredited course; the physics course at Florida State University and the library science course at the University of Illinois best represent the autonomous type. Lastly, the enriched CAI type provides instruction on content considered as extensions of the conventional classroom curriculum; the simulation games at BOCES are excellent examples of the enrichment type. An analysis and comparison of the instructional strategies of these three naturalistic CAI applicational types will be discussed.

The systematic approach to CAI research on instructional strategies resolve into six areas. First, what is the appropriate media for the presentation of a given concept? Second, what are the desirable time parameters for the CAI system to respond to the learner's answer? Third, what are the characteristics of the answer analysis routines that promote the specified learning objectives? Fourth, what is the decision logic of the presentation plan that specifies the sequence, amount of practice, and termination of the instruction? Fifth, what are the payoffs to the instructional process within CAI? And lastly, what kinds and types of reports should be part of CAI application? Current research findings and implications for future investigations are discussed within the framework of the six aspects of instructional strategies for CAI.

Instructional uses of computers to grow gracefully and effectively

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INTRODUCTION

In this brief discussion, it is suggested that three principal functions be recognized and be performed in parallel in order to achieve a graceful and effective growth in the instructional uses of computers. These functions are described as:

1. the practice of teaching using computers as aids;
2. research and development directed toward the practical uses of computers in teaching and learning;
3. basic research in intelligent systems.

Function (1) is dependent on function (2) and (2) is dependent on (3). Computer hardware and software and
people are included in the discussion of each of the functions.

The practice of teaching using computers as aids

Computers in education today can be used most effectively to assist in the teaching of subjects that are mathematically disciplined, such as, programming, mathematics, engineering, physics, statistics, and bookkeeping. For courses of this type, much of the knowledge is contained in mathematical expressions and communication between student and computer can be more easily accomplished than in verbally oriented courses. Computers used in courses of this type can (1) assist individual students in a direct learning experience, (2) perform the calculations in solving assigned problems, and (3) aid the instructor in demonstrating the functional characteristics of the various types of mathematical equations, the effects of changes in the variables of computational models, and various physical phenomena through simulations.

Hardware and Software. The function should employ existing computer systems. The one selected must be a practical operating system with integrated hardware and software and with well-defined capabilities. Because rapid advances will continue to be made in systems, the policy should be that of leasing. Currently, the choice can be made between the leasing of terminals of a large utility type system and the leasing of a relatively small complete system. Small computer systems are available with complex man-machine interfaces which make them very capable in special types of applications, such as, graphics. The leased terminals of large utility systems are relatively simple man-machine interfaces, and the systems have limited capabilities in a conversational mode of operation. Since the fixed cost of leasing is low and the usage cost is variable, the number of students and the amount of time each uses a system can be small to accommodate a minimal budget. Because a leased complete system has a fixed total cost, it may be difficult to find enough student users to make the cost per student a reasonable value.

People. If current systems can be used effectively as aids in teaching mathematically disciplined subjects ranging from arithmetic in elementary schools to advanced college subjects, and if they can be cost justified for small numbers of students, then the only additional requirement is the training of teachers in the rules for communicating with the computers and in methods for using them. Usually, courses are offered for training in the rules of communication. Until similar courses exist for training in the new methods, teachers should be encouraged to experiment in developing simpler methods and techniques through the use of leased terminals of systems of limited capabilities. They will gain valuable experience which will prepare them for future systems of greater capabilities.

Research and development directed toward the practical uses of computers in teaching and learning

This function establishes teaching methods using computers as aids, determines the psychological factors related to these methods, and provides for the training of teachers in practical application of these methods, particularly those teachers in the lower levels of education.

Hardware and Software. An integrated hardware-software system for this function should be supplied as a practical result of research in intelligent systems, the third function, and should be replaced every three to five years with one of greater capabilities. The packaged system should provide for the maximum of flexibility and should be able to:

a. gather and analyze physiological information on a human subject
b. receive and analyze the various requested responses of the subject
c. provide flexibility in selection of the content and organization of learning materials and the interface devices
d. provide a variety of learning strategies through a choice of (b), (c), and an alternating sequence or an integration of the two
e. gather information on the environment of the subject
f. permit a higher level of control which coordinates the controlling actions for (a), (b), and (c)
g. permit a high level supervisory control with flexibility for coordinating and directing two or more subjects at different terminals in competitive learning experiments.

People. There should be a number of groups in different fields in a university performing this function, for example, the School of Education, Engineering, and Computer Sciences. The School of Education should place emphasis on the lower levels of education. Special training may be required in computational modeling, computers, and in the capabilities and the use of the man-machine interactive system to be used.

Basic research in intelligent systems

This research, in the broadest sense, should strive to use the human intelligence of a society better by improved ways of synthesizing intelligent systems and
by more effective ways of transferring knowledge from one generation to the next. It should also strive to increase the intelligent capabilities of a society by imparting intelligence to machines.

Hardware and Software. Current hardware should be selected and developed into a hardware system, and initial software design should be based on the principles determined from the previous research system. Basic research should then be applied to the current machine system to improve its performance as a component of an intelligent system. The improved system, in turn, should further basic research which is again applied to produce additional improvements in performance. A machine system with significant improvements should evolve every three to five years and then should replace the system in research and development directed toward the practical uses of computers in teaching and learning.

People. Since complete interactive systems contain both man and machine as components, the research must draw on select basic knowledges from a number of fields. Unifying disciplines must evolve relating the various knowledges, and a graduate program should be associated with the research effort. The students must be able to acquire the variety of existing knowledges, and through their active participation in research, they should have an opportunity to apply and associate these knowledges. The build-up of both the research effort and the graduate program must be gradual.
A picture is worth a thousand words—and it costs . . .* 

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INTRODUCTION

The present is a critical, frustrating, and exciting time in the history of computer graphics. A dozen significant trends are developing in the same field of view. Several much-needed trends are not developing. The technology is changing so rapidly that four generations of graphical systems are in operation at once. “Computer graphics” means different things to different people. This is therefore a difficult session to “introduce.”

Perhaps the most important introductory remark to make about the session is that the papers that follow this one do not attempt to cover the topic of computer graphics. They are in computer graphics, not on it. In this paper, I shall not try to cover the topic, either, but I shall take a brief look at the over-all field and try to sketch out enough of a map to provide an orientation and context for the papers that follow. In the process, I shall unburden myself of a few deep convictions.

There are three main efforts in computer graphics. The first is to improve the capability of graphical displays to represent things and processes. This capability extends into dimensionality, verisimilitude, complexity, and motion.

The second main effort is to improve the interaction between men and computers through graphics, to improve graphics as a medium of communication. It is important to distinguish between communication and representation. Both involve languages, but not in the same way.

The third main effort is to develop applications of computer graphics. Applications run the gamut from computer-aided composition of printed pages to computer-aided design and dynamic modeling.

All the foregoing pose problems of computer-system design and are energized and/or inhibited by economics.

This paper will deal, then, in an introductory—and necessarily sketchy—way with representational capability, communication and interaction, applications, computer-system design, and economics—all in the context of computer graphics. Because the art is long and the time fleeting, the paper will consist essentially of observations and assertions within those areas rather than reviews or analyses of them.

Representational capability

Although most computer graphics is limited to arrangements of points and line segments, together with perhaps a hundred elementary figures (characters), computers are of course capable of processing and displaying areal pictures replete with graded lightness (brightness) and varied hue (color). The work of Stockham¹ at the M.I.T. Lincoln Laboratory and the University of Utah illustrates the versatility of the computer in handling still pictures with gray scale. Stockham scans a low-contrast photograph into the computer memory, takes the logarithm of every lightness coefficient, applies a la Ernst Mach a second-spatial-derivative operator to each neighborhood of coefficients to yield a new coefficient for the central element of the neighborhood, then takes the antilogarithm and displays the resulting picture. Detail not visible in the original stands out clearly in the processed picture. But the processing requires many seconds for a picture with a million elements, and Stockham’s kind of picture processing is not kinematic or “on-line interactive” in the present state of the technology. Nor does the computer “understand” the

* The ideas described herein were derived mainly from research supported by Project MAC, an M.I.T. research program sponsored by the Advanced Research Projects Agency, Department of Defense, under Office of Naval Research Contract Nonr-4102(01).
picture in the sense of forming a structured model of the pictured scene in which the various objects and their parts are represented separately in a hierarchy. Thus in Stockham's application we see an emphasis of high precision in representation and processing at a sacrifice of speed and structuredness.

The work of Evans, Warnock, and their colleagues at Utah starts with a structured model in the memory of the computer, rather than a high-information-content photograph at the input scanner. They have developed methods of processing that yield a halftone-like picture, in color, with "hidden lines" suppressed—in a small fraction of the computer time that would have been required two years ago. At the present time, however, even with the Utah methods, one cannot process and display areal (e.g., halftone) pictures fast enough to produce moving pictures in real time. He can go to slow-time frame-by-frame generation of film, or he can schematize, or both.

The technology for handling schematized pictures and diagrams—made up of points, line segments, and characters—has advanced markedly during the last two years. Roberts described some of the basic ideas, involving homogeneous-matrix representation and perspective transformation. In the work that won them the prize at the Fall Joint Computer Conference, Robert Sproull and Ivan Sutherland developed hardware that very rapidly transforms selected parts of a model in the computer's memory to a line drawing on the cathode-ray screen. The hardware rejects all the parts of the model—a large two-dimensional drawing or a threedimensional scene—that would not be seen through a given window, and it produces the magnifications or perspective transformations and the clippings or trimmings at the window frame necessary to display just what would be seen through the window. It does all that fast enough to display 3000 lines flicker-free. The "3000 lines" refers to what is actually displayed; there can be many more lines that that in the model. The hardware handles curved lines and surfaces. It works hand-in-glove with the Warnock hidden-line algorithm, which works on schematized (linear) as well as areal displays, and the hardware is applicable to, and will decrease the processing time required for, areal displays.

The foregoing dealt with actually two-dimensional displays of two- and three-dimensional objects and scenes. There are interesting ways to make the displays perceptually, or even actually, three-dimensional. The method of calculating and presenting two slightly different "stereo" views is well known. So are methods based on the "kinetic depth effect," which present a single, changing view. When successive two-dimensional cross sectional images are projected in rapid sequence upon a moving screen, the eye, because of its persistence, sees the composite three-dimensional image. See Traub. The computer can control the settings of a matrix of push rods to make a three-dimensional surface, a histogram rising from a plane. And, of course, it can synthesize a hologram.

Of those and other approaches to 3-D, the most exotic appears to be one demonstrated by Ivan Sutherland and associates at Harvard last year. The computer has a model of a situation in its memory, and it receives signals from sensors that tell it where the observer is and in what direction his head is oriented. With the aid of hardware described earlier, the computer then displays the part of the modeled situation that the observer would see. The display is projected from a small cathode-ray tube on the observer's head through a semi-silvered mirror into one of the observer's eyes, and the observer sees the displayed part of the situation out in front of him. He can look around and walk around—and always see what he would see if he were in the modeled situation. When I saw the demonstration, the hardware was not finished, and the situation was just an outline room with windows, a door, and a geometrical piece of statuary. Even at that, it was quite an adventure. Given situations defined by thousands of line segments, one could surely create some exciting experiences—and probably some very significant ones.

As Sutherland has pointed out, the "physical" laws of the modeled world can be determined by the programmer. They can change with time. They can even depend upon the observer's behavior. Elsewhere, the possibility of creating a direct four-dimensional experience has been discussed. See Licklider. I shall not go through it again here, but let me say that it will be intellectually at least as exciting to perceive and explore a synthetic 4-D world as to perceive and explore a merely actual, merely 3-D moon.

Most of the capabilities of representation described in the foregoing are characteristic at present solely of expensive equipment and are regarded by many as esoteric. I shall say something about that under the heading, Economics, but for the moment let it direct our attention to the other end of the spectrum. Among the most significant developments as judged from a practical point of view, certainly, are computer setting of type, computer-aided preparation of diagrams and graphs for the printed page, computer-aided composition of advertisements, computer-aided generation of films, off-line production of graphics (as with curve plotters and as with the Stromberg-Carlson 4020), and fast on-line display of alphanumeric data and text.
Communication and interaction

It is of course very important in computer graphics to be able to represent things and processes accurately and in detail. I think it is more important to be able to represent them in proper structural organization. I think it is still more important for computer graphics to be an effective medium of communication. Good one-way communication is good, but good two-way communication—good graphical man-computer interaction—is better.

Now, as the history of art shows, and as Huggins and Entwisle will emphasize, and as I hoped Don Hatfield would develop in depth in this session, the representation with the greatest verisimilitude is not often the best means or medium of communication. Good graphical communication is more a matter of linguistic expression than it is of pictorial reproduction. Unfortunately, we in the computer world do not know much about the language, and unfortunately not many of us are trying hard to find out about it. Obviously, it does not have much to do with programming languages. It probably does have something to do with data structures. But mainly it is the art of expressing ideas through configurations and manipulations of signs and symbols. Let me call that art an essential extension of computer graphics and then leave the topic to Huggins and Entwisle. I like their approach to it, insofar as the one-way language—computer to man—is concerned.

In my assessment, however, communication is essentially a two-way process, and in my scale of values, interaction predominates over detail, gray scale, color, and even motion. In my judgment, the most important problem in computer graphics is that of establishing excellent interaction—excellent two-way man-computer communication—in a language that recognizes, not only points, lines, triangles, squares, circles, rings, plexes, and three-way associations, but also such ideas as force, flow, field, cause, effect, hierarchy, probability, transformation, and randomness. Nowhere, to the best of my knowledge, is such interaction approached in a broad problem area at the present time. The nearest things to exceptions are the graphical computer-programming interactions of Ellis and Sibley at RAND, the partly graphical, partly alphanumeric on-line augmentation of Engelbart's intellect at Stanford Research Institute, and the graphical explorations in architecture of Negroponte at M.I.T. It is very frustrating to me that five and a half years have elapsed since Sketchpad passed its milestone without bringing more progress in man-computer interaction at the level of ideas and concepts.

It seems unlikely that work in computer-aided design of devices and structures will lead to the advances I am hoping for. Computer-aided design of complex systems or processes might do it. I like the name, "interactive dynamic modeling," for the art. I want to see develop a kind of combination of computer-aided design à la Sketchpad and computer-program simulation à la on-line GPSS or OPS—in which the modeler and the computer engage in a high-level graphical interaction to formulate and test hypotheses for the solution of difficult problems that are not amenable to straightforward logico-mathematical formulation, that involve more synthesis than analysis, more discovery than proof. What, it is not much to have the name. I wish I had the method, the language, the software, and the hardware.

Man-computer interaction of course presupposes computer-input devices (as well as languages) to mediate the communication from man to computer. The man should be able to signal the computer in a natural and synergic way, as by pointing and marking with a stylus while enunciating control words or phrases. He should be able to write or draw on the same surface as the computer. I shall not develop this part of the discussion beyond saying that one can appreciate the problem after he has read the transcript of a good blackboard lecture and then later (and separately) seen photographs of the blackboard. "Chalk plus talk" is an excellent medium. Neither chalk nor talk alone carries much information. The communication must therefore lie in the coordination.

Applications

At present, it appears that three very different classes of application of computer graphics are successful: (1) routine applications in the field of publishing (e.g., Chemical Abstracts) that yield printed pages as primary output and at the same time retain the information in computer-processible form for updating or secondary exploitation; (2) routine applications throughout business and industry (e.g., airline ticketing, display of stock quotations) that involve fast online display of alphanumeric data or text from computers; and (3) "cream" (and often highly nonroutine) applications in government and industry (e.g., military command and control, space-mission control, seismic prospecting for oil) in which the premium on being first or best is very high or in which the required results cannot be achieved any other way. The first two do not require sophisticated graphic capability. The third requires and can afford very sophisticated capability.

If and when there exists and is available the kind of computer graphics I referred to as "interactive dynamic modeling," computer graphics will become a part of thinking and problem solving and decision making
wherever those functions are carried out. Design will of course be a major application area: design of all kinds of systems and processes—space, urban, transportation, manufacturing, military—as well as devices and structures. Management of government and business will use graphics in its “command and control.” Applications will abound in research and development and in medicine. But the application area par excellence will be education. Almost anything not involving muscular skill that needs to be explained and demonstrated can be explained and demonstrated best with the aid of interactive computer graphics. For the sake of brevity, I shall leave that as a simple assertion in need of proof by demonstration.

The trouble is, all those applications that depend upon a significant augmentation of the human intellect (to use Engelbart’s phrase) demand a level of computer graphics as sophisticated as that required for the “dream” applications mentioned earlier—or even more sophisticated.

The field is ready for and cultivating simpleminded applications in which computer graphics will do faster or less expensively things that can already be done without it, but the field is not yet ready to accept the challenge of “mind expansion.” That carries us to the economics again—which we shall examine very shortly.

System design

The prevailing idea in computer-system design for graphics is that graphical display places too heavy a demand for processing to be handled by the (or a) main, central processor and that there should, therefore, be a satellite graphical processor for each graphics console or cluster of graphics consoles. At present, the satellite processor is usually a small general-purpose computer augmented by a display processor.

The design of the satellite processor is itself an interesting problem. Is it to be programmed once and for all and viewed thereafter as just part of the hardware, or is it to be thought of as remaining a programmable computer? Is its display processor to do nothing but display, or should it be able to call display subroutines and perhaps handle the integer arithmetic of indexing? Sutherland and Myer11 have observed the tendency for the display processor to evolve into a general purpose computer and then to need a subordinate display processor, and they have determined how and where to stop the potentially infinite regress.

The aspect of system design that I think has not been thought through clearly concerns the division of tasks between the central computer and the satellite computers. There is a watershed: either all the satellites will be near the central computer, or at least one will be remote. If all are near, why should each satellite computer have a separate memory? That leads to a wasteful transferring of data from one memory to another. Why shouldn’t the satellite processor be precisely a display processor and address a block of the main memory?

If the satellite is remote, of course it cannot address the main memory directly; it must have a memory of its own. If one satellite is remote, all the satellites should have memories of their own, for it is most important to preserve homogeneity for the sake of simplicity.

Now we come to Bert Sutherland’s Dictum: “Think Network!” Even if you plan to have all the graphics consoles in the same room as the main computer, treat them as if remote—because one day soon it will be desirable to admit a remote satellite into the system—or you will want to share software with a system that has remote satellites.

The key problem then becomes the division of tasks and the specification of the interface between the central and the satellite computers. That problem must be solved in such a way that the satellite does not pester the central computer continually, yet the user should feel that he is interacting directly with the central machine. I doubt that there is a good solution.

Economics

There are of course two main kinds of cost: (1) the cost of the equipment; (2) the cost of developing the methods and preparing the programs. The bad thing is that for sophisticated computer graphics both are very great. The good things are that the hardware costs tend to drop rapidly, once they start dropping, and that, as soon as there is replication of hardware, the software costs increase much less rapidly than the number of hardware systems in which the software is used. That is elementary, but it is very important and evidently not well enough recognized.

During the 25-year history of digital computing, the costs of arithmetic units, control units, and processible memories have halved approximately every two years. On-line terminals have not had such a “long” history—at least not in significant quantity—but it appears that some of the simple keyboard-and-cathode-ray-tube consoles that are coming into use in time-sharing systems dropped from about $13,000 to about $6,500 in the year between the last two Fall Joint Computer Conferences. If some are priced at $5,000 in the exhibit area of this conference, it will suggest that, for a time, one class of equipment will be halving in cost each year. I do not want to make too much of such gross trend analysis, even though it does point to the source of
much of the magic of our field, and I certainly shall not
base anything on a halving of cost each year. However,
the question of optimal research lead time is a very im-
portant question, and it needs an answer. When should
we develop the kind of computer graphics that will
most strongly augment the intellect? When should we
start if we want to have it ready when it will be afford-
able? In their paper, Huggins and Entwisle will call
educational application of interactive computer graph-
ics, based on time sharing, an "economic absurdity" and
suggest that the facilities be used to generate edu-
cational films. Insofar as operations are concerned,
I agree with them. But what about research?
As basis for a rough calculation, let me take a system
that I think would make an excellent base for a com-
puter graphics laboratory. A few months ago I deter-
mined the cost of a graphics-oriented PDP-10 computer
with 256K words of 2.5-microsecond memory, 15 million
words of disk storage, 16 consoles with storage-tube dis-
plays, and quite an assortment of supporting equip-
ment. It was about $700,000. If it were used 8 years,
with an average of 10 consoles active over the 24-hour
day, the cost per console hour would be $1. Double that
to cover maintenance, operation, supplies, and over-
head, and you have $2 per console hour to use as an
argument that you could be within hailing distance of
economic operation now if you had the programs.
As I see it, the advances in methodology and soft-
ware required to achieve the kind of computer graphics
and the kind of interactive dynamic modeling I hope
for will require about as much research effort and time
as several laboratories have devoted to interactive
computing since 1961. If we look ahead to 1977, and
assume hard work in the interim, I think we can count
on a fairly good methodological and programming
capability. If the halving-every-two-years rule held,
the over-all equipment cost would be about 12 cents per
console hour in 1977. It need not be that low to support
all the educational and personal applications that it
should support. Other applications—in management,
research, medicine, etc.—would have become economic
earlier, of course.
My conclusion—which is of course as tentative and
open to bias as the foregoing estimates, and perhaps as
simpleminded—is that now is the time to push forward
with research in the areas of computer graphics that
people call expensive, sophisticated, esoteric, and exotic.
I think that they are the areas in which lie the real
promises of significant improvement in our intellectual
processes. If we do not push forward with research in
those areas now, we shall find ourselves with a magic
lantern that we don't know how to rub.

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