

In Grace J. Kelleher (Ed.), The Challenge to Systems Analysis. New York: Wiley, 1970.

Chapter 11

SYSTEMS ANALYSIS OF COMPUTER-ASSISTED INSTRUCTION¹

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On the basis of several years' experience in computer-assisted instruction, I think we can now make a fairly accurate analysis of the major components of the total system, and the implications of these components for education, government, and industry. For proper perspective it undoubtedly will be helpful to the reader to provide some background on the development and status of computer-assisted instruction in this country.

In our present society, printed matter dominates a large part of personal and mass communication and is essential to regular school instruction. The place of books in our society is widespread and accepted by everyone. This gradual adoption of books in formal education during several centuries prior to 1800 marks probably the first great technological revolution in education.

There is good reason to think that a comparable revolution has already

¹This paper is a product of research in computer-assisted instruction over the last several years. Research has been supported by the Carnegie Corporation of New York, the National Science Foundation, and the U.S. Office of Education.

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begun in the use of computers as instructional aids. It is also reasonable to forecast that with the pace of current technological development, computer-based devices will be widely adopted much more quickly than books were. There are at least four major reasons for believing that computers will come to be of great importance as instructional devices in schools. The first and most important is that the great speed of a computer makes it possible to offer individualized instruction to a large number of students simultaneously. This individualization has at least two major aspects: (a) the student's own response can be corrected and evaluated immediately, and (b) the type, the level of difficulty, and even the character of the curriculum material being presented to the student can be varied according to the student's level of ability and achievement. Very elementary considerations establish that both these aspects of individualization are very difficult for a classroom teacher to carry out as part of a daily program of instruction. The second main reason for holding that computers will assume an important place in instruction is their capacity to relieve teachers of routine work. Ways of accomplishing this goal range from the presentation of individualized drill-and-practice work to the performance of many kinds of record keeping now expected of teachers. The third important aspect of computer-assisted instruction is the ability of the computer system to provide administrators and supervisors with detailed information about the progress and achievement of students. Finally, the fourth major advantage is to provide data, and data analysis, for those concerned with research in the learning of children and the specific development of curriculum to maximize that learning. Because of the advent of computers, the opportunities for educational research are unparalleled and have no clear previous precedent in the history of education. Perhaps the deepest long-term gain to be obtained from computer-assisted instruction is the vastly increased understanding we shall be able to obtain of students' learning difficulties.

I think it is characteristic in making a systems analysis of any complex phenomena that absolutely crystal-clear or logically tight components of the system cannot be identified. What can be identified is a division of the system into components that begin at natural breaking points, or at natural points of differentiation of function and responsibility. In the case of computer-assisted instruction, it has seemed to me that we can easily identify 11 major components that should be considered in any analysis of the total system. Putting the hardware first, we identify these 11 components as follows: the main computer or central processing unit, file storage, communication lines, visual devices, audio devices, response devices, programming language, curriculum materials, teacher training, administrative organization, and evaluation. Plans for installing computer-

assisted instructional systems in schools must consider each of these 11 components. It is important to realize that in the present state of the technology, decisions about many components are difficult and complex, especially when problems of cost must be carefully considered. Moreover, in a tightly organized activity like computer-assisted instruction, failure to take account of the problems and costs associated with any one of these components can lead to difficulties that are not easily remedied after the fact.

In order to give the discussion some definiteness, I have pursued the systems analysis under the supposition that we are dealing with a school system that has 20 elementary schools. We suppose also that each school has approximately four classes at each grade level, for a total of 24 classes in grades 1 through 6. The population of each school we take to be

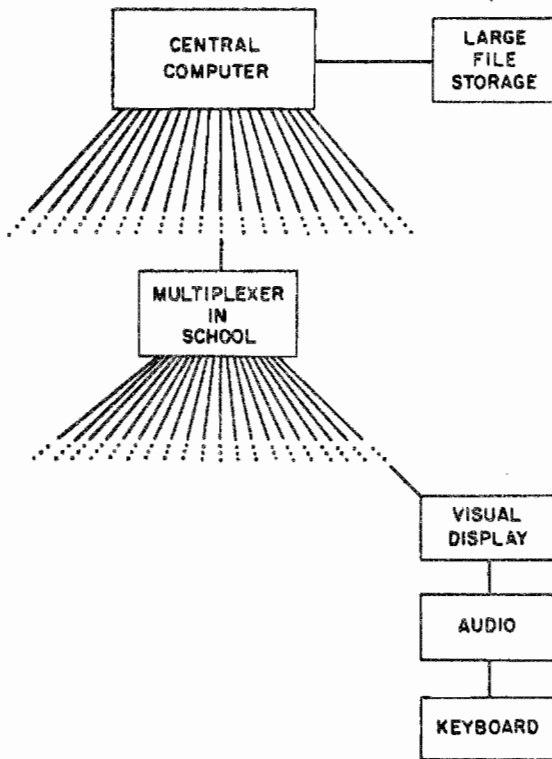


Figure 1

Diagram of system for the 20 schools with 20 terminals for each school.

somewhere between 600 and 700 students. In actual practice the variation will be somewhat greater than I have hypothesized, but a faithful representation of possible distribution of students and classes in the schools will not be of major importance. This school system, we shall suppose, is considering the adoption of a computer-assisted instructional system to teach elementary mathematics and language arts in its elementary schools. I have picked language arts and mathematics because of their central importance to the elementary-school curriculum and because they are subjects that are particularly amenable to handling by computer-based instructional devices.

My analysis of the 11 components of a computer-assisted instructional system will be very much directed toward the needs of the school system. Figure 1 shows a highly simplified diagram of the system layout. The main point of the diagram is to show the one-many relation between the central computer and the 20 schools, as well as the one-many relation between the multiplexer in each school and the 20 terminals or student stations. The three most important components of the student station are shown in the diagram, namely, the visual display, audio capacity to address the student, and keyboard for student response.

It will be apparent that fairly definite changes would be needed to accommodate a very large school system or a very small one, but what I am saying is of practical import for large school systems that may wish to consider a demonstration of computer-assisted instruction operating in 20 elementary schools. For example, the system analyzed and configured in this paper would provide a very meaningful demonstration for a city like Chicago, which has 500 elementary schools.

CENTRAL PROCESSING UNIT

The first and most essential feature that the central computer must have for applications to computer-assisted instruction (CAI) is reliability. The requirements of reliability are higher than in a batch-processing computation center, where a shutdown is inconvenient but not disastrous. The requirements of reliability for computer-assisted instruction are similar to those for process-control computers used in industry for control of manufacturing processes. The requirements of reliability are high but not quite as high as those required of computers used for landing aircrafts, managing guidance systems, and others. A second essential feature of the system is modularity. In a standard batch-process mode when a computer or any part of the system is in malfunction, the entire system is dead. It is essential that a computer running a large number of instructional

terminals not be rendered inoperative by failure of a single terminal or other component at a remote location, or by transmission of an inappropriate message.

In terms of functional specifications, the central processing unit should have a high channel capacity for the handling of large numbers of communication lines, and also a high capacity for data transfer to and from file storage. A large computation capacity as such is usually not required. For this reason, most computers now on the market are not ideally designed for large-scale use in computer-assisted instruction. If we have a classroom of 20 terminals in each of our 20 schools, then the central computer would be required to handle 400 terminals simultaneously on the assumption that all of the computer functions will be centralized. It should be emphasized that the decision to centralize the computer facilities is itself a major decision. An alternative is to place some of the computer power in each of the 20 schools and to have small computers placed in the school to call upon the central computer as required. For simplicity of analysis here, I shall restrict attention to the centralized system in which all of the computer power is located in the central computer. In the individual schools we would have at most a very small computer for purposes of multiplexing the data signals coming over a telephone line from the central computer to each school. The requirement of handling simultaneously 400 terminals, even if these terminals are only teletypes or typewriters, is a demanding one; consequently our central processing unit, in terms of current computer design, must be a medium-to-large-sized computer.

FILE STORAGE

In order to have adequate individualized curriculum on-line and available to students, substantial file storage is required. Above all, this file storage must be available under fast access. As an example, let us consider the 400-terminal system just described and let us suppose that we are running elementary-school mathematics on these terminals. Each student will complete a problem approximately every 5 seconds. This means, on the assumption of a uniform distribution, that in a 5-second period we will need to access file storage 400 times to obtain the problems required for the student at each terminal. This requires an accessing rate of 80 times per second or approximately every 12 milliseconds. These numbers are somewhat pessimistic, but they are the correct order of magnitude and they give an idea of accessing speed required. Most bulk-storage devices now on the market do not provide an accessing speed in this range, and many of them are off by a factor of 10. In our own experience,

we have also found that there is no difficulty at all in filling up a 100-million-byte bulk file if programs of any diversity and depth are being run in an instructional mode. Probably the most desirable kind of file storage for our 400-terminal system is a disk-pack system permitting us to change curriculum material during the day in terms of what is on-line and to expand the total file storage indefinitely at relatively low cost.

COMMUNICATION LINES

In our 400-terminal system involving 20 schools a central component of the system consists of the communication lines between the central processing unit and the 20 schools. The simplest implementation in present technology is simply to lease telephone lines, one conditioned line between the central processing unit and each school. Data sets at both ends are required, and, in addition, a multiplexer which may well be a small computer would be needed at each school to sort out the digitized signals and send them to each of the 20 terminals in that school. In the past, for various reasons we have often run individual lines to each terminal from the central processing unit, but when the number of terminals in a school in one location is 20, it is not economical to do so. Once the number in a given location rises above 10 or so, it is almost always more economical to lease a single line and to add the cost of a multiplexing device at the terminal end.

Other technological approaches to communication lines are possible. The cost of microwave equipment is now within range of leased phone lines. It requires close study to determine which is more economical. In addition, there are some other features of microwave systems that need to be emphasized. The school system we are discussing could also use a microwave system to install closed-circuit television. At the present time, I do not think anyone in the country has a system of closed-circuit television that is also using the same communication network for computer-assisted instruction. However, technically it is certainly feasible, and it would be surprising if examples of this technological approach did not appear in the near future.

VISUAL DEVICES

In selecting a terminal at which instructional material will be delivered to the student, a first and central decision is what sort of visual displays will be offered to the student. As is apparent from earlier remarks, the simplest and cheapest device that would both deliver a satisfactory visual

display and provide an adequate general response mechanism is a standard teletype, which retails for about \$500. It is a challenge to other manufacturers to devise a technology in the same price range that is at least as good as the Model-33 teletype.² We have used Model-33 teletypes extensively and have great respect for them as rugged and economical devices in comparison with almost everything else now on the market.

In terms of devices already being used and being planned for the future the most important decision is to move away from the print-wheel to a faster and more flexible mode of visual display as exemplified in cathode-ray tubes. Cathode-ray tubes (CRTs) have many advantages that are evident to all of us. They are very fast; they permit the display of graphics as well as alphanumeric. As the technology is developed further, it is also feasible and practical to display the full range of TV pictures on the same tube. There is no doubt that a cathode-ray-tube device with television and alphanumeric capacities will be widely used. What we need at present is a cathode-ray tube with television capacity and a keyboard, offered at a retail price comparable to Model-33 teletypes, that is, at about \$500.

AUDIO DEVICES

From a technological standpoint, at the present time the selection and installation of appropriate audio devices is by far more difficult in our 400-terminal system than the selection and installation of visual display devices. It is true that we can go far in providing instruction programs that do not require audio, but, on the other hand, it is also true that almost all forms of complex instruction, particularly to children and younger adults, require an auditory input. In my own experience, I have practically never met anyone who learned mathematics in the elementary stages entirely by eye. Though I do not think we have yet available the appropriate fundamental research, it seems fairly evident that learning by ear, beginning with early childhood, is important and fundamental. Only for a very small class of human beings is it possible to learn vast amounts of new material purely by eye. Granted then that we need audio devices for extensive teaching by means of computer, the problem is how to obtain satisfactory results. At least three features need to be satisfied. The speech should be of high quality, particularly of high intelligibility; large quantities need to be available, with the messages selected on the basis of the student's own behavior and responses; and fast access is needed to the messages, in order not to delay the pace of the teaching.

² Manufactured by Western Electric.

These three requirements of high intelligibility, large quantities of storage, and fast random access are not easily met. In our own laboratories at Stanford University, we have used four different audio systems. One consists of regular tape recorders under computer control. These tape recorders satisfy the first two requirements but provide very unsatisfactory random access. A second system consists of modified tape devices that have a high-speed search mechanism. These devices are more satisfactory, but they are extremely difficult to work with in terms of programming, recording, and debugging. They are also very expensive. A third system consists of very broad tape loops. Messages of 8 to 16 seconds in length, depending on the size of the tape loop, are played in any one of 128 tracks, and these tracks themselves are searched in a direction orthogonal to the direction of play. These devices unfortunately are not yet in really satisfactory condition for large-scale operational efforts. They require an extensive amount of care, and preparation of material for use on them is not simple. The fourth approach we now have operating is the most radical, and from our standpoint, the most promising. In this case we are using the computer itself as an audio device. Words are recorded in digitized form and the computer then puts together sentences from these words under programmed command. (Of course, a digital-to-analog converter is needed for playback.) For example, we currently have running a simple review program in exercises in elementary mathematics. With a vocabulary of 60 words we are able to compose thousands of sentences and thousands of exercises. There are a number of technical problems that still must be solved for satisfactory large-scale use of this type of audio. We believe that it is the most promising, because it will permit the deepest developments in connection with contingent speech as required for establishing a genuine dialogue between the student and the computer program.

RESPONSE DEVICES

The main response device that we would probably use in our 400-terminal system has already been mentioned, namely, a standard keyboard. The selection of a standard keyboard as the central response device seems advisable because of its great flexibility and generality. Almost all instructional material can be handled by making available to the student this response device, but in our own laboratories we also have experience in other response devices. The most important in terms of our past practice has been the use of a light pen on a cathode-ray-tube screen. The light pen can be used to point to, and to select, answers or objects on the cathode-ray-tube screen. Our experience has shown this method of re-

sponse to be particularly useful for young children in primary school at the beginning of their work in computer-assisted instruction. Our tutorial programs in reading and elementary mathematics both lean heavily upon this response device during the beginning phases of instruction.

The response device that we are particularly anxious to see developed for the future and that I would like to have available for our 400-terminal system in another 20 or 30 years is a standard speech-recognition device—a device that would permit the student to speak at least a limited vocabulary and to have what he says recognized by the computer system. Work on speech recognition is underway in many parts of this country at an intensive level. For 10 or 15 years now it has been customary to say that we are just 5 years away from a real solution to the problems. I think we are all aware of the depth and difficulty of these problems. However, it does not seem feasible to plan on such devices in the initial installation of our 400-terminal system, but I would hope to have such devices available for the first round of major revisions and change in technology.

PROGRAMMING LANGUAGE

It seems fairly certain that the most satisfactory programming language for computer-assisted instruction has yet to be developed. I would predict that we will move increasingly toward higher-level languages and that neither the curriculum builder nor the student will be aware that anything but a natural language is being used. However, we are still some distance away from having developed a language of this power. Minimum requirements of a programming language for our 400-terminal system or any related sort of system are that it have a real-time, terminal-interaction capacity, at least restricted time-sharing of the central processing unit, and timing requirements that enable us to keep records of student responses and to reconstruct these records for data analysis.

It is not appropriate here to go into the technical discussion of programming languages for computer-assisted instruction. One point, however, that I would like to emphasize strongly is the necessity of developing languages that permit rapid input of large amounts of instructional material in a fashion that is not tedious and does not require elaborate debugging. In other words, we need languages that permit curriculum personnel to input material in a form very close to that in which they expect the material to be presented to the student. The languages should permit them to debug the material in a very similar format. Most available languages still have not gone far enough in this direction. I would hope

that for our 400-terminal system a language aimed at great efficiency in this respect would be available.

CURRICULUM MATERIALS

In some romantic discussions of computer-assisted instruction, it is suggested that the teachers will prepare curriculum materials, and the lengthy and tedious procedures of publication now prevalent will not be required. In my own judgment, this is strictly a romantic myth. Teachers will be no better prepared to write curriculum materials, once computer-assisted instruction is the mode, than they now are to write them for regular textbook publication. In fact, I would predict that they will be even less able to construct appropriate curriculum materials once individualization of materials becomes the major theme of computer-assisted instruction. The more complex logic of organization and the deeper analysis of student requirements will make the construction of curriculum material an even less suitable job for the broad mass of teachers than it now is.

It also seems clear to me that the preparation of an adequate body of instructional materials may turn out to be the major stumbling block to the widespread use of computer-assisted instruction. There are various kinds of estimates around. Conservatively, it does seem to take a minimum of 10 to 20 man-years to prepare a 1-year course. Major curriculum efforts will be needed over the next decade if we are to have an adequate range of curriculum offerings for our 400-terminal system.

In discussing our 400-terminal system, I have ignored some of the distinctions that are critical for the preparation of curriculum materials and for use of the system in the schools. If we are to use the system primarily as a supplement to ordinary teaching, in what I have in the past termed a drill-and-practice mode, then the preparation of curriculum materials will be less onerous and less difficult than if we plan to use the system for tutorial instruction. In tutorial instruction, the computer system introduces concepts and presents new material, as, for example, in elementary mathematics or in such subjects as spelling and grammar. In this mode of instruction the teacher is a backup to the computer, providing trouble-shooting and individual attention to those students who need help. The preparation of curriculum materials for presentation in tutorial mode has turned out to be a time-consuming and difficult task. It will be some time before an adequate body of material is available in this mode. In the meantime, it will be possible rapidly to prepare large bodies of drill-and-practice material. The economics of computer-assisted instruction lead me to predict that drill-and-practice materials

will be the ones adopted by our school system in the initial years and will find widespread adoption in other schools. However, over the years an increasing body of tutorial material will be prepared, and as the economics of tutorial instruction become more feasible, a more extensive use of them may be anticipated.

TEACHER TRAINING

Over the last decade, I have directed a wide variety of teacher-training institutes and other activities to prepare teachers for handling the new mathematics curriculum in the schools. During the last 5 years, we have been concerned with the particular problem of training teachers to handle computer-assisted instruction. From a technological standpoint, we are increasingly aiming to make the instructional programs and devices relatively self-contained and extremely simple to operate. However, it does not follow that we will thereby be able to eliminate teacher training. Our experience has been that one of the most sensitive indices to the success of computer-assisted instruction in elementary schools is the depth of training of the teachers and the degree to which the program is accepted by the teachers. In our system for 20 schools, it would be a major mistake not to plan an extensive and well-coordinated teacher-training program that would brief teachers thoroughly in all aspects of the program. From our experience at Stanford, I would say that our most successful work has been a 4-week training course we gave teachers from Mississippi in the summer of 1967 in preparation for our current program in the McComb City School System in McComb, Mississippi. We gave these teachers a training program that covered everything from the actual curriculum content, to the operation of terminals in the classroom, to the selection of weekly data reports available to them. We found that a training program that lasted for 4 weeks and ran for 8 hours a day was not too long for the purpose.

ADMINISTRATIVE ORGANIZATION

A successful program in computer-assisted instruction also requires effective administrative organization of the program in the schools. This involves operational problems of classroom scheduling and the less direct problems of organization in the administration of the school district. A thorough briefing of administrative personnel on the purpose and function of the program is necessary for a successful venture. Of the greatest importance is the explicit organization of the operation of the program in the schools. There is not time here to review the various scheduling practices

and arrangements we have experimented with over the last 5 years. I do emphasize, however, that this is not a minor matter and does need careful attention. There is one aspect of our experience that has been sufficiently sharply defined and is of enough importance that it should be mentioned. One organizational decision that must be made in the initial plans for our 20 school system is whether the terminals will be placed in a single room in the school and classes come in groups to that room or whether individual terminals will be placed in each classroom. Our experience thus far very much argues for the former alternative. It also appears advisable to have a paraprofessional, for example, a teacher's aide, in charge of this single room during the day. Our experience so far shows that the problems generated by placing a single terminal in each classroom far outweigh the conveniences of this placement. The difficulty is that the program is running all day. It continues to interrupt the teacher's work. She must be concerned about students at the terminal the entire day. On the other hand, when the class goes as a whole to a single place in the school, the work in computer-assisted instruction is accomplished in a set period or several set periods during the day. Thus the teacher is free of any responsibility in this direction during the remainder of the day.

EVALUATION

Administrators, parents, and school board members will want an evaluation of our 400-terminal system. They will want to know what educational gains and losses have resulted from instituting this system in their schools. Any system of computer-assisted instruction that neglects this important and fundamental final component of evaluation will soon be in trouble. It is not appropriate here to review the many complex problems of evaluation that exist for any curriculum innovation, whether it be computer-based or not. We should emphasize, however, the necessity of instituting a well-conceived and well-organized program of evaluation. It may be a standard conservative program of offering the new material to a given percentage of the students on a random basis. We would conceive of a classical experiment with an experimental group and a control group receiving the same standard tests before and after the intervention of computer-assisted instruction. In this case we are interested in making an inference to the relative rate of achievement of the experimental group as compared with the control group. We would hope to show that the use of additional instructional devices in the schools differentially increases the rate of learning and achievement in a given subject matter, for example, in mathematics or language arts. From classically designed evaluation plans of this sort,

we may move to the other extreme: a loosely conceived program in which we seek the evaluation of teachers, students, and parents on the basis of anecdotal evidence. In most practical situations a broad spectrum of evaluation procedures will be followed, ranging from rigorous statistical evidence to the collection of a variety of anecdotal evidence.

In this paper I have tried to indicate what I consider to be the 11 essential components of a systems analysis of computer-assisted instruction. I would claim that any attempt to institute a computer-assisted instructional program in schools would almost certainly fail if careful attention were not given to each of these 11 components. I have not had space here to discuss the enormously important problems of costs and of cost benefits, but it should be apparent that each of these 11 components must enter into cost analysis. Ideally, in making decisions about what kind of program to institute, we would cast the analysis of each of the 11 components into mathematical form and then solve a constrained maximization problem in terms of the budget available. Realistically, we are still far from being able to formulate our systems analysis in a form amenable to mathematical methods of optimization, but this is a direction in which we shall all want to move in another decade. In the reasonably near future, something serious of a quantitative sort may feasibly be said.