THE USE OF LEARNING THEORY IN THE APPLICATION OF ARTIFICIAL INTELLIGENCE TO COMPUTER-ASSISTED INSTRUCTION OF PHYSICS

DISSERTATION

Presented to the Graduate Council of the North Texas State University in Partial Fulfillment of the Requirements

For the Degree of

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BY

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It was the purpose of this research, to develop and test an artificially intelligent, learner-based, computer-assisted physics tutor. The resulting expert system is named ARPHY, an acronym for ARtificially intelligent PHYsics tutor. The research was conducted in two phases.

In the first phase of the research, the system was constructed using Ausubel's advance organizer as a guiding learning theory. The content of accelerated motion was encoded into this organizer after sub-classification according to the learning types identified by Gagné. The measurement of the student's level of learning was accomplished through the development of questioning strategies based upon Bloom's taxonomy of educational objectives.

The second phase of this research consisted of the testing of ARPHY. Volunteers from four levels of first-semester physics classes at North Texas State University were instructed that their goal was to solve three complex physics problems related to accelerated motion. The only students initially instructed by ARPHY were from the class of physics majors. When the threshold values of the pedagogical parameters stabilized, indicating the fact that ARPHY's
instructional technique had adapted to the class' learning style, students from other classes were tutored.

Nine of the ten students correctly solved the three problems after being tutored for an average of 116 minutes. ARPHY's pedagogical parameters stabilized after 6.3 students. The remaining students, each from a different class, were tutored, allowing ARPHY to self-improve, resulting in a new tutorial strategy after each session.

It is recommended that future research into intelligent tutoring systems for science incorporate the principles and theories of learning which this research was based upon. An authoring system based upon the control structure of ARPHY should be developed, since the modular design of this system will allow any field which can be organized into a net-archy of problems, principles, and concepts, to be tutored.
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CHAPTER I

INTRODUCTION

Background

The instruction of introductory, non-calculus physics in the higher education environment has been centered around straight lecture format with occasional demonstrations (11). One glaring deficiency in this method is the lack of conformity to the basic principles of learner-based instruction (7). For example, the rate at which students learn concepts of physics is variable, ranging from little or no understanding to a sudden "AHA" phenomenon, occurring possibly days after the first exposure to the subject. Obviously some students will be bored while others are lost. It can therefore be determined that for any given class of physics students, only certain students will be able to be taught at their optimum rate of learning (10).

The self-paced learning environment required for learner-based instruction has been augmented by recent advances in computer-assisted instruction (CAI) (10). Freshman physics courses have been designed, using various versions of CAI. Some of the successful CAI modules for physics include programmed simulation of physical phenomena, computer-assisted
testing, and aids for numerical analysis (1). However, most of these systems fail to emulate the unique experience that occurs between a student and human tutor. Traditional CAI, for example, will not perform personalized instruction, experiment with instructional strategy modifications, or make intelligent estimates as to what the student understands. In other words, traditional CAI uses the same teaching strategy for all students and does not generate responses to general or specific questions raised by students at unanticipated times.

Artificial intelligence theory and techniques provide a means for enhancing and extending the capabilities of CAI. Artificial intelligence allows the computer to reason, thereby making expert decisions based on the instructional conditions specific to a student. The use of artificial intelligence in CAI is termed intelligent computer-assisted instruction, or ICAI. ICAI can provide individualization of instruction, self-paced learning, appropriate remedial instruction, and other favorable aspects of one-on-one tutoring which are not realistic in the typical classroom environment.

In order to perform like a human tutor, the ICAI system must also know how to best teach the subject in a manner easily learned by the student. Much research was carried out during the 1960's and early 1970's involving programmed instruction and theories of learning. Due to the unavailability of an affordable computer system for research during
this period, programmed instruction and theories of learning remained largely on paper. Their complete incorporation into the educational environment would have involved the expensive task of re-writing textbooks. As microcomputers become more available to the educational environment, a doorway to a more personalized system of learning will open wider. Since certain CAI programs will become accepted as models, it appears to be wise to investigate the feasibility and viability of the pre-microcomputer learning theories and instructional techniques as a basis for future development. In this way, a model for ICAI with a foundation in educational theory may be established.

The incorporation of learning theories into an ICAI system should enable the students' learning experience to be personalized. The qualities which this system should possess include the following:

1. Self-paced instruction for each student;
2. The ability of the system to hypothesize the student's current state of knowledge;
3. The ability to carry on a reactive dialogue with the student during the tutorial session;
4. The development of an improved overall teaching strategy by experimentation during the tutorial session; and
5. The construction of a student profile containing parameters unique to each student so that the system
can familiarize itself with the student to facilitate learner-based instruction. In this way, the computer will more closely approach the desired one-on-one tutorial atmosphere.

Because of the popularity of CAI and the perceived possibilities of artificial intelligence, it may seem curious that the field of ICAI has not developed any further than it has. One reason is that much of the development of programmed learning modules took place at a time when CAI was neither widely accepted nor economically feasible (8). Another problem is that microcomputers capable of handling the tremendous random access memory (RAM) requirements (> 640,000 bytes) of artificial intelligence were rarely found in the educational environment. In addition, the languages of artificial intelligence (LISP and PROLOG) could not be implemented on the memory-deficient microcomputers, those with 128,000 bytes of RAM or less, commonly found in classrooms.

One intriguing explanation of the lack of ICAI development proceeds as follows. No matter how easy the subject matter, a good CAI package must be programmed by a CAI designer, one of a finite but growing number available, who is a competent computer programmer. Due to the law of supply and demand, these competent computer programmers are sought by non-academic institutions, and will only continue writing CAI software if the profit margin is high. The profit margin is high if the software is written for computers already well
established in the educational environment. This situation tends to promote a proliferation of courseware which may not be effective in the transmission of knowledge.

There are approximately 7000 educational software packages on the market. Of the 125 new packages released each month, 1 or 2 are judged by the Education Product Information Exchange (EPIE), a non-profit organization, to be effective teaching tools (5). EPIE notes that much of the software duplicates the workbook drill-and-practice environment. One of the more discouraging aspects of the CAI products market is the fact that, even with the poor quality products, many schools still purchase the products solely for the status of having CAI facilities.

Purpose

The purposes of this research are both developmental and experimental in nature. Specifically, the purposes are to describe, construct, and test a learner-based, artificially intelligent, computer-assisted physics tutor that teaches students the basic content of accelerated motion.

Learner-based instruction will be accomplished through the incorporation of the learning theories and principles of Ausubel, Gagné, and Bloom. The system will be artificially intelligent, allowing expert decisions to be made based upon each student's unique learning style, topic preferences, and previous misconceptions.
Statement of the Problem

The problem of this research is the incorporation of learning theories of Ausubel, Bloom, and Gagné into an artificially intelligent physics tutor.

Method

The artificially intelligent physics tutor will teach the basic content of accelerated motion as addressed in a first-semester non-calculus physics course. It is hypothesized that ARPHY would be able to estimate the state of knowledge of the student, experiment with instructional strategies, and improve overall performance based on an evaluation of the results of its experimentation. The system will also be tested to determine the performance of its self-improvement procedures.

Significance

At this stage in the development of ICAI, the development of ARPHY will lay a framework and theory for future ICAI development. One of the major problems facing ICAI researchers is that there is no pool of AI modules which may be incorporated into their software to serve as, for example, pedagogical parameter improvers, topic selectors, or progress monitors. The learning theory expert resident in ARPHY works independently of the subject matter, therefore allowing the eventual adaptation to other subjects.
Another promising feature of ARPHY is the incorporation of the pedagogical theories of Ausubel, Bloom, and Gagné into an ICAI system. As will be shown, the above theories, although developed between 1955 and 1965, not only fit easily into an ICAI atmosphere, they allow ICAI to fit within them. Interestingly, the original language used in describing the above theories bears a striking similarity to many concepts of artificial intelligence. The expert system resulting from this research will be a major step in the use of ICAI not only in physics but in science education in general.

This dissertation will focus on the integration of ICAI physics instruction, and the pedagogical theories of Ausubel, Gagné, and Bloom. The resulting tutor (ARPHY) will also, after interaction with the students it tutors, have become an improved tutor. The control structure and methodology by which an ICAI system may self-improve will serve as a possible guideline for future work.

Perhaps the most significant result of this research is the production of a learner-based system for computer-assisted instruction of physics. One feature of ARPHY, representative of the tremendous advantages offered by AI, is the ability to understand a physics problem and be able to answer questions beginning with "why" and "how." Contrasted to present systems consisting of drill-and-practice exercises, test administration, and plotters for graphical data, the incorporation of ARPHY into the science educational environment could certainly
provide the long-awaited qualities of personal tutoring in situations where this would not be feasible for one teacher.

**Definition of Terms**

**Accelerated motion** is the motion of an object undergoing a change in velocity during an interval of time. This velocity change arises due to either a change in speed or direction and is therefore the result of a net external force acting upon the object. The understanding of accelerated motion requires the learning of many prerequisite principles and concepts.

**Artificial intelligence (AI)** is the area of study or discipline which seeks the development of computer software which will allow the computer to perform tasks which, at the time, humans are better at performing (9). Some fields or specializations which are developing artificial intelligence include speech recognition, pattern recognition, interplanetary probes, advanced chess programs, numerical integration programs, and other applications where human reasoning is the goal of the program.

**Computer-assisted instruction (CAI)** is the use of a computer to deliver a programmed course of instruction to a student through the use of pre-determined branching strategies.

**Expert (in field)**, as used here, applies to the knowledge, actions, and rules resident in the brain of a human which are
transferred to ARPHY through the use of a branch of AI known as knowledge-based, or expert systems.

Intelligent computer-assisted instruction (ICAI) is instruction through the use of computer software which has elements of artificial intelligence incorporated within the controlling structure. True ICAI systems differ from conventional CAI systems in that they are able to:

1. self-improve;
2. analyze student errors;
3. know students on an individual basis; and
4. allow the student the freedom to control (or feel in control of) the learning environment.

Node is a term used frequently in AI literature to refer to a connecting point in a tree structure.

LISP is an acronym for LIST Programming. LISP is the premier language for AI programming due to its ability to adapt to concept and symbolic manipulation. The specific version of LISP used here is COMMON LISP. This version is the most universally used of all LISP dialects, and will therefore be the most likely candidate to be found in mass-produced ICAI systems of the future.

Newton's laws are the foundation of all basic physical concepts of accelerated motion. These laws govern the principles of inertia, acceleration, and reaction.
**Pedagogical parameters** are the dynamic set of thresholds used by ARPHY to make certain pedagogical decisions. The decisions governed by the pedagogical parameters include whether to allow the student to attempt a more difficult topic, how many knowledge-type questions to ask, and how many application questions to ask.

**Software** is the intangible portion of a computer system which includes the logic guiding the control of the operation of the system.

**Tutorial strategy** is the basic methodology the computer follows to deliver its instruction. Examples of tutorial strategy include the Socratic method, the inductive method, and in this case, Ausubel's advance organizer.

**Limitations**

Research and development, by nature, seeks to challenge any limitations set forth by previous work in the same area. The innovations of this research have certain boundaries. First of all, since the emphasis is on innovation, the amount of physics taught by ARPHY will be less than the content found in a first semester physics course. When the proper foundation is laid, further content will be added to ARPHY. Secondly, not all students tutored by ARPHY will have much prior experience with computer interaction. Some responses interpreted by ARPHY to be incorrect may be due to typing errors or
confusion arising from unfamiliar screen design. Finally, the ability of ARPHY to self-improve is proportional to the number of times that the student allows ARPHY to choose the path of instruction. Several, but not all, of the pedagogical parameters are altered only if ARPHY made the last instructional decision. It is possible that ARPHY may never be allowed to improve certain parameters.

Assumptions

A basic assumption made as to the nature of the student is that the student will not attempt to put "bugs" into ARPHY. These bugs can be introduced by the student purposely entering incorrect answers, extraneous dialogue, or abnormal learning patterns. Perhaps a human tutor can determine when a student is trying to answer incorrectly, but ARPHY is quite naive in this respect. Another assumption made is that the student is motivated to learn. Perhaps the novelty of CAI is what has motivated learning so far, but just as the novelty of any new system will eventually wear off, straight CAI is in danger of becoming a relic. The application of AI is probably the best hope for insuring that a session at a computer will motivate a student. The feature which may make an ARPHY-type system well accepted by students is the feeling it produces among its tutees that they are a unique individual, known personally by their tutor.
Summary

This document consists of six chapters. The second chapter contains a review of the literature related to intelligent computer-assisted instruction (ICA1), CAI in physics, and an overview of the learning theories, principles, and concepts on which this work is based. The third chapter describes the technical details of the construction and operation of ARPHY in enough detail for future expert systems developers to be able to follow the guidelines and construct a similar system. The fourth chapter contains the procedures for the student-in-the-loop test of ARPHY, whereas the fifth chapter reports the test results. The final chapter contains a summary of the research, conclusions, and recommendations for future research.


7. Gale, Fred L., Determining the Requirements for the Design of Learner-Based Instruction, Columbus, Ohio, Charles E. Merrill Publishing Co., 1975.


CHAPTER II

OVERVIEW OF THE BASIC PRINCIPLES OF INTELLIGENT
COMPUTER-ASSISTED INSTRUCTION AND PERTINENT
FOUNDATIONS FOR EFFECTIVE PEDAGOGY

A search of the literature related to intelligent computer-assisted instruction of physics revealed only research in conventional computer-assisted instruction in physics and intelligent computer-assisted instruction of other subjects. Aside from verbal remarks as to the tremendous possibilities of ICAI in physics, such as those of Bork (6), research in ICAI of physics has not been a priority of ICAI researchers for a several reasons. First, ICAI researchers tend to choose a domain with which they are familiar. Secondly, ICAI researchers seek a domain which will fit easily into their tutorial strategies. Many subjects, such as algebra, circuit design, geography, and rainfall fit nicely into the framework of these researchers' systems.

To provide the best background of literature related to ICAI of physics, the related fields will be investigated. The following fields will be discussed, paying particular attention to work which, directly or indirectly, points to the subject of this research:
1. traditional (same method every time) computer-assisted instruction;
2. artificial intelligence, including expert systems and knowledge-based systems;
3. computer-assisted instruction of physics;
4. intelligent computer-assisted instruction; and
5. learning theory.

A major emphasis will be placed on learning theory and the theory and development of ICAI.

**Traditional Computer-Assisted Instruction**

Essentially an electronic page-turner in the 1960's and early 1970's, computer-assisted instruction is still developing in its use as an aid to the learning process. Unfortunately, many of the same methodologies used in CAI in the past two decades still govern many of today's CAI courses. Drill and practice, computer-based testing, and video-games are usually found in educational settings under the name of computer-based education. The above functions are quite helpful to the teacher, but still don't even closely approximate a personal tutoring environment. This problem has been recognized and addressed by educators. Tsai and Pohl (40) mention that modern educational theory suggests that the optimum teaching/learning environments are those that involve personalized systems of instruction (PSI), with straight CAI being but one method of PSI. According to Kulik, Kulik, and
Smith (22), the three basic concepts in PSI are that the students:

1. move through the materials step-by-step;
2. receive feedback at every step; and,
3. continue to work on a single unit until mastery is demonstrated.

Regarding concept number one, Goldstein (15) asserts that students should not be forced into a pre-programmed sequence of topics. Concept number two is a remnant of the days of programmed instruction. In programmed instruction, a student advances when an answer is correct and branches to a remedial section if his/her answer is wrong. Since the programmed texts were not able to diagnose the misconceptions of students, it was felt that reiteration would correct the misconceptions.

Tsai and Pohl (40), in their study, determined that, although students experiencing a CAI environment performed no differently on achievement or retention tests than students experiencing a traditional lecture/discussion environment, students experiencing an "enriched" CAI environment (CAI plus teacher/student contacts) performed significantly better on achievement tests than students experiencing any of several other environments. The environments included in this study were:
1. lecture/discussion;
2. lecture/discussion supplemented with planned teacher/student contacts;
3. programmed instructional texts;
4. programmed instructional texts supplemented with planned teacher/student contacts; and,
5. straight CAI.

One conclusion that can be drawn from the above results is that CAI may tend to be non-personal where students may need a human touch to their instruction. Another related conclusion is that the benefits of straight CAI are over-shadowed by the fact that CAI systems lack the ability to respond to the misconceptions of the students, thereby being an inferior teacher compared to a human.

Hall (17) has constructed a decision table of types of instructional questions covering the range of Bloom's taxonomy. The table emphasizes the importance of recognizing learner differences and developing better questioning techniques which would serve to determine the level of learning scaled to Bloom's taxonomy. This points to a need for a system of storing student knowledge in CAI systems. As will be discussed later, this need for knowledge representation is effectively addressed by a computer language suitable to knowledge representation (LISP) and a technique adaptable to the manipulation and understanding of knowledge (artificial intelligence).
In an effort to make CAI more effective, Watson (43) has, over a period of ten years, developed a model for the production of computer-assisted learning (CAL) material. He reports that good educational software is a rare commodity and certain factors should be present in order to assure a quality CAI system. Some of these factors are

1. creative and energetic teachers should be actively involved in the design stage;
2. software needs to be prepared by programmers who are able to write software that will run and be effective on today's computers while leaving open the options for the future generation of hardware; and,
3. educational software should fit into some form of accepted curriculum framework, without simply replacing existing methods without good reason.

According to Contes (12), when analyzing good examples of computer-based learning (CBL) programs, three basic properties need to be evaluated. They are

1. creative design of the curriculum element;
2. creative design of the teaching strategy; and,
3. creative computer programming.

The necessity of these components dictates that CAI programs need to be the products of several diverse minds. The best resources for these minds are found, in the case of physics,
in an expert physics teacher, an expert learning theorist, and an expert computer programmer. These three experts, when consolidated, should form an effective intelligent tutor for physics. Codifying the knowledge, experience, strategy, and behavior of these experts points again to the need for artificial intelligence techniques.

Computer-Assisted Instruction of Physics

Since so much of the language of physics is mathematical in nature, the usage of computers in the field of physics instruction has mainly been restricted to solving rigorous mathematically-intensive problems. Yu (47) mentions that a PDP-11/20 computer has been successfully incorporated into a non-calculus general physics course. The areas of use of the computer included

1. canned programs including games such as lunar landing programs;
2. using the computer to assist in problem solving;
3. computerized testing and storage of results; and,
4. graphics generator.

These uses were implemented within the Physics Department at Seattle Pacific College in a non-calculus physics course designed for chemistry, pre-med, and engineering majors.

Simulation programs gave the students a chance to supplement their lecture instruction by interacting with the computer in a simulation of a concept of physics. For example,
LUNA is the popular simulation where the student tries to land his lunar lander softly on the surface of the moon without running out of fuel. The student is never directly taught, but the principles governing this activity are those of potential energy and momentum.

As for the problem solving approach to CAI, the students, after one week of instruction in basic computer programming, write a program to solve basic physics problems. This process forces the students to break down seemingly difficult problems into simpler components. Weekly quizzes were given to the students via tests stored in the system. Some of the advantages of CAI in test-giving over conventional in-class tests include immediate feedback, a chance to re-work problems without penalty, and less pressure due to time.

Yu (47) noted that the instructor saw an increased enthusiasm among the students toward the simulation programs. This supports the idea of teaching mathematical concepts of physics through an initial interactive simulation of the phenomenon. Kiestler (21) has developed a program at the University of California at Irvine in which students in a non-science major physics class spend an average of two hours per week at one of 25 graphic terminals learning physical concepts through the use of a friendly interactive graphics terminal.

Although these uses of the computer to teach physics were reported to be highly successful, a truly interactive
computer physics tutor would allow students to receive personalized instruction. The physics tutor should be capable of knowing the pattern of learning specific to each student in order to maximize its effectiveness. One possible method to personalize the learning process for students is through the use of ICAI.

Intelligent Computer-Assisted Instruction

Up to this point, many shortcomings in traditional, or straight CAI have been pointed out, along with hints as to how an intelligent system can either alleviate the problem or bring it under manageable control. A look will now be taken at the differences between CAI and ICAI, followed by an overview of the components of an ICAI system.

Contrast Between CAI and ICAI

In traditional CAI, the system is programmed with the information that there is a certain answer the student is supposed to input, and can only relate to the student certain facts such as whether or not the answer was too high, or what the correct answer was. Most of the systems cannot rework a problem at the student's request, explain why a principle was used, or give an answer to an unanticipated verbal question. A more traditional CAI environment does not possess any knowledge of physics itself nor does it possess knowledge of the student it tutors. To the conventional CAI system, all students are essentially the same, except for their names and
which topics they have passed. CAI systems are programmed not only to teach the same way to all students, they teach the same way every time they tutor. A mistake in pedagogy remains as a possible source of reduced effectiveness. To an ICAI system, each student is known to the extent of, and usually surpassing, topics completed, misconceptions, deficiencies, and learning styles.

**ICAI Systems--Components and Operation**

The four modules of an ICAI system are the expert module, the student module, the tutorial strategy module, and the communications module. Developers of ICAI have concentrated their effort in these and other areas so as to produce a tutor which knows its subject, knows the student, knows how to become a better teacher, and knows how to communicate with the student. Most literature on ICAI refers to these domains as separate modules to allow for ease of discussion and explanation (28). In practice, however, the modules may not be well-defined. Following is a summary of these modules.

**Expert module.**--This module contains the domain of knowledge the system is trying to impart to the student. This knowledge includes the facts to be taught and procedural knowledge, which is the set of procedures used by experts in solving a particular problem. Within the field of artificial intelligence there is a large concentration of research in knowledge engineering. There are methods for expert retrieval
of facts, methods for storing procedural knowledge based on a set of condition-action rules, and as a result, ways to allow a machine to reason through a problem.

The least complex task for the designer of an ICAI expert module is to construct a system for the storage of facts. A common method of information storage is through the use of frames. Winston and Horn (45) describe frames as fancy databases, whereby pieces of knowledge are tied to other pieces through the use of property lists. However, a system needs more than just static facts.

The expertise module should ideally think like a human expert if the students it tutors are to acquire the expertise of their role-model (13). The expert in a field must be able to recognize a situation and act accordingly. This procedural knowledge, or inference capability, may be a covert solution to a mathematical problem so that the procedure of solution may be explained to the student, as Blaine and Smith have shown (4). Miller (24) has worked with machine grammar to allow the expert to be able to relate to the student its knowledge of strategies for solving a problem. The procedural knowledge may be similar to the procedure used by a doctor to recognize an infectious disease (11). The system may also call upon its procedural knowledge to explain the steps used in an algorithm, as per Sleeman (30).

Thus being equipped with procedural knowledge, the expert module, due to its base in AI can intelligently generate
answers concerning why a particular action was taken or how a rule was used in the solution of a problem. Swartout's (37) XPLAIN is an excellent example of the application of an expert system to facilitate an explanation capability.

The expert module may also be required to possess knowledge of how a system works with particular attention paid to causal reasoning. One system accomplishing this type of reasoning was SOPHIE (7). Another was the STEAMER system (35). As its name implies, STEAMER was a program which simulated the workings of a network of steam generators, steam engines, and the related plumbing. The student could set up a network and STEAMER could detect faults in the design.

The expert module is also able to store a syllabus of topics within the domain of the subject to allow an expert-recommended sequencing of topics. The syllabus approach was used in WHY (33) to allow the proper flow of instruction through a tutorial concerning the causes of rainfall. In many of these systems such as WHY, the student's knowledge is internally represented as a subset of the expert's knowledge. This subset could be comprised of both knowledge of facts stored in frames or procedural knowledge. The expert module, therefore, seeks to equate the student's knowledge with its own.

**Student Module.**—This module represents the student's understanding of the material being taught. When an ICAI
system is spoken of as "knowing the student," it is due to developments in this module that the "knowing" is possible. The student module, through the incorporation of AI techniques, models the behavior of each student through processes ranging from simple storage of topics completed through analysis of possible misconceptions. The model may contain a storage of facts the student knows related to the topic, rules the student has used, or even teaching strategies which have produced favorable results in past tutorial sessions.

According to Carr and Goldstein (10), ICAI systems have four methods of supplying information about the student to the student module. The first method is through direct conversation with the student. The second method is through an observation of learner behavior during situations requiring the application of learned rules. The third method is termed structural, which is a rough measure of how the student relates one "chunk" of knowledge to another "chunk." The fourth method is through an overall evaluation of the student's past performance which provides a filtered predictor of future behavior.

Some modules construct the student model by searching for differences between the student's knowledge base and that of the expert. In brief, discrepancy models (31) infer a student weakness from observed behavior. Another method of constructing a student model is by modeling the student as having a subset of the expert's knowledge. This method is also called
an overlay method by Goldstein (16), as the tutor concentrates its teaching in the areas the student lacks compared to the expert.

When the student performs poorly, it is the responsibility of the student module to diagnose the underlying cause(s) of the errors. O'Shea's introductory algebra tutor attempted to determine incorrect rules used by the student (25). One problem arising from this process is that some students may be plagued by so many "mal-rules" that isolation may be difficult to achieve (32). An active area of interest within ICAI involves this detection and correction of "buggy", or faulty strategies used by the student. Van Lehn's (41) work with a theory of repairing these buggy strategies is based on the theory that the student may have a good basic knowledge of rules, but has problems in applying the rules.

**Tutorial Strategy Module.**—Also called the teaching module, this portion of the ICAI system is responsible for changing the student into an expert in the most efficient and effective manner possible. This module, through communicating with the expert module and the student module, chooses an initial instructional strategy based on either the student's past performance or on an evaluation of other students' past performances. After choosing the instructional strategy, this module communicates with the expert module to select the appropriate portion of the expert's knowledge for teaching.
Pedagogical principles are located within this module, guiding the instructional sequence according to a sound theory of learning.

The tutorial strategy module is usually responsible for analyzing the student module so that strategic decisions can be partially based upon the students' proficiencies and weaknesses. The tutorial strategy module makes the final decision of remedial action when the probable weakness is identified. O'Shea (25) used a set of means-end guidance rules to select an appropriate action. One of the condition-action rules used in O'Shea's algebra tutor, for example, read:

$$(\text{LASTOP1}, *, \text{SCORE1}, \text{NUMOP1}) \rightarrow T(2)$$

Each of the four positions in the left-hand set of parentheses corresponds to a variable set as a result of interaction with the student. This rule translates as: "If the last teaching operation was T(1), no matter what the previous state of knowledge was (*), and the student's score was less than five out of ten (SCORE1), and the total number of teaching operations performed was less than four (NUMOP1), then attempt teaching method T(2). This method could be translated into an expert system's rule base in COMMON LISP as:

```
(if ((last teaching operation was T1)
     (last score was score1)
     (number of teaching operations is numop1))
  (then ((attempt teaching method T2)))
```

When teaching operation T(2) is then implemented, the variable LASTOP2 replaces LASTOP1 in the state vector. The system
then tutors the student with this teaching operation and, after either a certain number of questions asked or correct answers given, evaluates the conditions again to analyze whether or not a change in strategy should be performed.

The method of delivery of the information could be selected according to student preferences. One student may prefer graphics while another may prefer verbal information. Of course, the more delivery methods available, the greater the amount of programming time and expertise required in the expert module.

Since students like to receive explanations of complex phenomena in a variety of ways, the ICAI system has the capacity of presenting many possible modes of explanation. STEAMER (34) was able to shift into nine different modes of explanation, such as explaining how the parts of the power plant fit together, demonstrating cause-effect relationships, and straight didactic exposition.

Although it seems as if the incorporation of nine methods of explanation would require nine times the amount of programming of the expert module, the explanation facility can be designed in such a way that all methods of explanation draw on the same base knowledge. NEOMYCIN (11), the infectious disease diagnosis tutorial system, has the ability to generate explanations through the use of a domain-independent explanation-generator.
The tutorial strategy module should also be capable of improving its instructional ability with time. The previously mentioned algebra tutor of O'Shea made experimental changes in tutorial strategy and analyzed the results of the changes so that successful strategy changes could be made a permanent part of the module.

Woolf and McDonald (46) have developed a LISP program called Meno-tutor which makes context-dependent transitions in its tutoring discourse. Its responses are dependent upon the level of understanding of the student.

As has been shown, there are many approaches to the solution of the problem of making the tutorial strategy module behave more like a teacher than a repeater of information contained in a book. The wide variety of approaches taken assures ICAI researchers that a uniform methodology for the module is still in a nascent state of development. It is for this reason that it is quite important to incorporate the best background of learning theory possible during the formative years of the module's development rather than add the learning theory later.

Communication module.--Ideally, the ICAI system would work best if the student could wear a helmet fitted with an electro-magnetic induction device capable of rearranging the existing structure of the neurons into the same structure of the expert's brain. Basically, the fewer interruptions in the
expert-to-student path, the more likely the information will be transferred without distortion. The student possesses at least five senses capable of sending the expert information to the brain. Currently, the eyes provide the main communication channel. Until speech synthesis and recognition research produces an acceptable alternative, ICAI will be faced with developing the best possible module for the actual interface between the expert and the student.

Winograd (44) notes that ICAI systems need a communications module capable of complex interaction between the expert, student, and tutorial strategy modules. This communication must include the ability to understand the student's responses and respond to the student in a way that the student will understand what is said. GUIDON (11), the intelligent tutor for diagnosing infectious diseases, has a communications module with the ability to refer to three types of knowledge to assist in an explanation. GUIDON can access data and explain why an expert decision was made, make an abstraction from highly specific knowledge to explain patterns, and of course, supply purely factual information.

In order to understand student input, be it a question or an answer, the communications module is the vital link between human and some type of data storage. Ideally, the communications module should be able to understand the utterance of the student. This involves a process known as parsing, whereby the student's sentence is analyzed according to
its structure. The system looks for the pronoun, adverb, modifier, and all the possible meanings that can be inferred from the parsed structure. SOPHIE (9) used such a system of parsing the student's responses to infer a meaning.

Since parsing involves such a great amount of computer time and memory, another method of understanding the student's response is used. This method, known loosely as pattern matching, preceded the development of parsing. Pattern matching involves the communications module priming itself from one of the other modules so as to search the response for a keyword or words located in a specific pattern. The system does not really "understand" the student's response, but clever programming of the other three modules as to what patterns are acceptable produces a "simulated understanding." For example, if the expert module is looking for the student to say something like "higher velocity," the communications module may be primed with (in COMMON LISP):

\[\text{(match? '}(+L) (RESTRICT ? INCREASING-WORD?) velocity)\]
response nil)

Acceptable words indicating an increase are defined:

\[\text{(defun INCREASING-WORD? (word)}\]
\[\quad (\text{member word '}(\text{greater increased higher}))\]
\[\text{)}\]
The "(+L)" is a wild card which will record the portion of the student's response up to a match with a member of the INCREASING-WORD? list. Acceptable student responses would include the following:
"The object will have a higher velocity."
"I bet greater velocity."
"increased velocity"

The "(+L)" portion can be recalled to give a personal response to the student, such as (for the first student response):

"YES, THAT'S RIGHT! THE OBJECT CERTAINLY WILL HAVE A HIGHER VELOCITY!"

The student may feel as if the system understood his response, but all that has happened is that the programmer anticipated three possible correct responses. Obviously this method is just a patch to hold over communications modules until a universal front-end parser is available to interface with the other three modules. Perhaps this unit could have its own microprocessor and large memory space so that it could be more beneficial to ICAI systems.

Pedagogical Base for an ICAI System in a Science

An ICAI system must base its teaching ability on a sound foundation of pedagogical theory if it is to function effectively as a transmitter of knowledge. Following is an overview of three promising pedagogical components which can be incorporated into an ICAI system. These components include a theory of learning, a method of applying the theory to a hierarchical subject, and a method of measuring the amount of learning.
Learning Theory for an ICAI System in a Science

Since the goal of any ICAI system is the development of the best possible mechanism for allowing a machine to transfer information into the cognitive structure of a student, the system should incorporate the best findings, strategies, and theories that educational technology has to offer. One problem is determining which theory is best.

Below are several possible models for transmitting information to a student, as identified by Joyce (19) as information processing models (major theorists in parentheses):

1. inductive thinking (Taba);
2. inquiry training (Suchman);
3. biological science inquiry mode (Schwab);
4. concept attainment (Bruner);
5. advance organizer (Ausubel); and,
6. developmental (Piaget).

Not only does each one of these models have its own following, many educators favor more than one of these. Since each model was developed with a certain purpose in mind, different situations may be able to be best handled by different models.

The inductive thinking approach of Taba (38), the inquiry training of Suchman (36), and science inquiry of Schwab (29) (models 1, 2, and 3), while being quite favorable from both the points of view of the educational theorist and the science educator, rely far too heavily on understanding the natural
language responses of students to be considered for incorporation within the environment of the personal computer. While much research is being carried out in the areas of parsing sentences and inferring meanings, the software required to accomplish this task, using present technology, would impose a detrimental time delay at critical periods of the instructional process. Furthermore, natural language understanding is not yet able to be packaged into the "front-end" of a personal computer system. One of the most significant accomplishments of recent natural language systems was the system of Waltz and Pollack (42) which successfully parsed the sentence: "The astronomer married a star," by eventually associating the word "star" with "movie-star," then proceeding to identify "movie-star" as a possible spouse. If this is the limit of the technology of natural language understanding, then present systems would be hard-pressed to parse the following hypothetical response from a student:

"I think that those two forces over there which pushed on that flying thing on the right probably caused it to have velocity in a constant direction."

Present systems would probably detect the proximity of "velocity" and "constant," thereby inferring that the student was thinking about constant velocity.

Bruner's model (8) for concept attainment would be acceptable if the domain of the expertise to be tutored was limited to concepts. As with most sciences --particularly
physics-- concepts are only a starting point for the eventual understanding of principles and the solution of problems.

The developmental model of Piaget (26) could be appropriate for a long-term study, but would not be appropriate for the rapid transfer of knowledge involved in a science tutorial. Piaget's work is designed for mental development, especially social and moral development.

The structure and theory of the advance organizer, developed before the microcomputer during the early years of programmed instruction (27), have a striking similarity to the architecture of the expert and knowledge-based systems of the artificial intelligence community. Ausubel's theory (1) of meaningful learning can briefly be described as a subsumption theory of meaningful learning. The associated advance organizer model is designed to facilitate information-processing capacities to meaningfully absorb and relate bodies of knowledge. The key hypotheses are

1. In the learning of potentially meaningful information, meaningful learning is superior to rote learning in terms of amount learned in a given amount of time, retention of what is learned, and the learner's ability to apply what was learned.

2. In the learning of potentially meaningful information, the potential meaningfulness of the material is related to its relative generality or specificity as follows:

   The more general the material, the greater the potential meaningfulness.

   The more specific the material, the less the potential meaningfulness. (1), p. 142.
The common approach taken by standard CAI authors in presenting material to be learned is to follow the sequence of material in a textbook. Unfortunately, Ausubel's organizer is not able to be incorporated into the structure of a textbook due to the fact that the organizer does not sequence topics linearly. One explanation is that textbooks may not be able to follow Ausubel's model. Physics textbooks commonly introduce new information to the student in such an order that it has little, if any, meaning to some students. For example, in his introductory physics textbook, Beuche (3) introduces standard international (SI) units, scientific notation, dimensional analysis, and vector subtraction in the first chapter. The student is immediately thrust into a position of rote learning since any general subsuming knowledge which may have helped the student to learn the material is at that time unfamiliar.

Another example of non-meaningful learning is the situation on page four of the same text, where the student is informed: "A meter is equal to the length of 1,650,763.73 wavelengths (in a vacuum) of the orange-red line of krypton 86." The student, at this point, probably has no knowledge of the nature of isotopes, spectroscopy, or the reason for measuring wavelengths in a vacuum. Again, new information needs to have meaning with respect to existing knowledge. Following are the three major concepts of Ausubel's theory (1) of learning:
**Subsumption.**--As used in the context of the advance organizer, subsumption refers to the classification of information within or under a more inclusive category or level of organization. For example, distance is classified under (among others) speed, speed under velocity, and velocity under acceleration.

**Meaningful Learning.**--When a student learns new material which is presented only if it can be related to the learner's current knowledge of a related topic, then meaningful learning has occurred. For example, if the learner's present knowledge is:

- A scalar quantity has magnitude but not direction.

New meaningful information could be:

- Mass is a scalar quantity.

**Reception Learning.**--Reception learning is the learning process by which new specific information is presented to the learner in its final form from the tutor. Hempel (18) favors this method as the basis for all scientific explanation and points out that this is the antithesis of discovery learning. For example, the student, after learning the more inclusive category of "gravity as an accelerator," may then be informed that the acceleration due to gravity at sea level is 9.8 m/s/s.
It must be emphasized that the subsumption theory of meaningful learning is not only designed for the presentation of material that is less general than topics already in the students' cognitive structure. This form of information transferral, sub-ordinate subsumption, would be a one-way path toward highly specific information, starting with the student's initial knowledge, as shown in Figure 1. Here, topic B has just been completed. Instruction may proceed to topic G because topic G has meaning relative to topic B. In reality, the completion of B indicates with fair certainty that the student understands topic G. This movement and probable subsequent completion of topic G will provide a means for the student to meaningfully learn topics B or C. In contrast, the branching method used by traditional CAI is fixed in its ability to allow the learner control over the direction of instruction.

According to the above definition of meaningful learning, new learning need only to be related to existing knowledge. Consequently, there are two other forms of subsumption. The second form of subsumption is super-ordinate subsumption, as shown in Figure 2. Here, the current topic is B. Due to the fact that topic A requires B as a prerequisite, A could be meaningfully learned. Note, however, that the student's understanding of A will be limited due to the lack of knowledge of topics C and D.
With super-ordinate subsumption, new information which is related to, but more general than the learner's present knowledge is presented. As shown in Figure 3 a, the advance organizer also facilitates co-ordinate subsumption, which is the subsumption of new information at the same level of
generality as a relevant category in the learner's cognitive structure. In the situation shown, the current topic is shown as box B. If the student has already demonstrated proficiency with topic A, instruction may proceed to topics C or D due to their being prerequisites for topic A.

This form assumes the existence of either a "parent cell" of information which is related to, but more general than both subsumed categories, or as shown in Figure 3 b, a common "child cell" which is related to, but more specific than both subsumed categories. In this situation, the current topic is B. The instruction may proceed to C or D because topic G, having been meaningfully related to B, is a prerequisite of C and D.
The use of the terms "parent" and "child" is in keeping with the terminology used by the artificial intelligence community when addressing a search space with properties of a family tree (45). In this system of terminology, the parent is the cell which has more connections to cells in the child direction than in the parent direction. By a simple reversal of convention, the family tree could be inverted, however.

Even though the advance organizer was designed for a discipline that is purely hierarchical in structure, it can easily be modified to adapt to a subject such as physics which has a basic hierarchical, yet intricately networked structure. The structure resembling an intricately-networked hierarchy will be termed a net-archy. This system for organizing knowledge is in keeping with the both past thinking,
such as Thorndike (39), and current biophysical thinking that new learning is built through connections with existing memory.

One observation that can be made about the net-archy is that it appears that the model would deny any entry point for anyone unfamiliar with the subject domain. Simply put, there must be some initial knowledge the entering student must possess that can be used by the system as a starting point for future instruction. It must therefore be assumed that the student has some prerequisite knowledge which matches at least one area of the organizer. This assumption is easily realized in most all sciences. For example, in physics, three areas of prerequisite knowledge the student will bring to a session are

1. The student is aware of the concepts of "heavy" and "light;"
2. The student can judge obvious velocity differences; and,
3. The student can work with the direction labels that some of the projected objects will have.

The adaptability of the advance organizer in helping students learn by approaching the goal knowledge from various directions is obviously learner-oriented. In the interest of learner-based instruction, the student should always be able to refer to a "map" of the organizer to be made aware of his progress. Depending on where the student is in the
instructional process, the student should also be allowed to basically chose the general path of instruction through the net-archy to insure the maximum starting motivation. This structure also allows for lesser-achieving students to advance, while allowing higher-achieving students to be challenged.

**Gagné's Levels of Learning**

Up to this point, the categories within the organizer have not been defined. In order to determine what "bit of the domain" needs to be assigned to each category, it is necessary to examine both the structure of the organizer and the student's cognitive structure. At each topic level, called a node by artificial intelligence, the system will attempt to cause the student to progress toward an instructional objective. The objective, according to Mager (23), must be both observable and measurable. The measurement must be made by evaluating the student's learning (20). In this study, the objective is the solution of three problems related to accelerated motion. An understanding of a science such as physics requires more than just the assimilation of pieces of information, so the nodes can't all be packed with facts.

Gagné (14) has identified eight basic types of learning. The levels of learning appropriate for an ICAI system (those above stimulus-response and verbal association) are, from most to least complex:
Problem solving
Principles
   Inferences, Communication, Space-time relationships
   Measuring, Classification
Concepts
   Abstract, Concrete, Defined
Multiple discriminations

Gagné also identifies the need for a cognitive strategy and sets this apart because it is the learner's internal method of handling knowledge--sort of an internal scheduler of thought. Since a certain strategy can be applied to many problems, cognitive strategies will be included with the learning types between principles and problem solving. Some students may never acquire a cognitive strategy, and will need to be cued through the problem; otherwise, they will perform only by rote.

Measuring Learning--Bloom's Taxonomy
Since the amount of learning of any topic is dependent upon factors such as previous misconceptions and paths taken, Bloom's taxonomy for assessing cognitive behaviors provides a method of assessing how well a student understands a topic (5). The classes, from highest to lowest cognitive understanding are (6.00) evaluation; (5.00) synthesis; (4.00) analysis; (3.00) application; (2.00) comprehension; and, (1.00) knowledge.
There are 23 sub-classes within these major classifications. This allows the levels of learning to become even more defined, as rankings such as 2.20 (interpretation) and 1.23 (knowledge of categories) can be attached to certain learning levels. Questions posed to the student can be geared to determine the student's learning level for a specific topic. As demonstrated in Figure 4, the student's level of learning of the concept of force may be determined by gearing the questions to correspond with the behavior taxonomy.

<table>
<thead>
<tr>
<th></th>
<th>Synthesis—The student is able to modify existing misconceptions of the nature of forces.</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Analysis-- The student checks the consistency of graphical depictions of applied forces</td>
</tr>
<tr>
<td>3</td>
<td>Application-- The student predicts the probable effects of various forces acting on objects in specified situations.</td>
</tr>
<tr>
<td>2</td>
<td>Comprehension-- The student translates verbal descriptions of applied forces into a mathematical expression.</td>
</tr>
<tr>
<td>1</td>
<td>Knowledge-- The student recalls the definitions of force and net force.</td>
</tr>
</tbody>
</table>

Fig. 4--Designing questions according to Bloom's taxonomy for cognitive behaviors.

Although any two educators may disagree as to the classification of a certain question, this taxonomy nevertheless provides a solid foundation from which learning may be assessed. For example, a student should not be considered to
have mastered a principle of physics if he/she recognizes a correct formula but can not apply it successfully in the solution of a problem.

Summary

The theories of learning, types of learning, and the assessment of learning presented in this chapter are only a small fraction of the great amount of literature existing which could be applied to ICAI. It is necessary, however, to go forth from this investigation and observe the result of the application of the theories, principles, and concepts which have been presented. The following chapter describes the method of construction and operation of ARPHY, the intelligent computer-assisted physics tutor.
CHAPTER BIBLIOGRAPHY


CHAPTER III

CONSTRUCTION AND OPERATION OF THE ARTIFICIALLY INTELLIGENT PHYSICS TUTOR (ARPHY)

Overview

The artificially intelligent physics tutor is named ARPHY, an acronym for ARTificially intelligent PHYsics tutor. The control system structure, expert system rules, and flow of logic involved in ARPHY's thinking process is discussed in the first portion of this chapter. The procedure used to test ARPHY is discussed in the second portion. The actual software which produces the actions and thoughts of ARPHY will not be disclosed due to the fact that the code is approximately 500,000 characters in length and is quite esoteric.

Since modularity of ICAI systems is a major goal of research and development, the structure of ARPHY is discussed in four sections corresponding to the expert, student, tutorial strategy, and communications modules. Although the modules can be defined as individualized units, they often function as an integrated whole. For instance, the tutorial strategy module is not one, but dozens of procedures which call upon each other at various times, depending upon the nature of the current problem. Although it is not one
physical unit, the tutorial strategy module, nevertheless, operates as a single entity as the other modules do.

**Expert module**

**Integration of the Learning Theory**

The following criteria were used to select a learning theory which could be used to drive the ICAI system:

1. ability to be incorporated with the equipment used for the research;
2. appropriateness as a learning theory for science education; and,
3. acceptance as a valid educational theory of learning.

The major learning theory which was used as the basis of the system of the artificially intelligent physics tutoring developed for this study was Ausubel's advance organizer. This decision was based on an analysis of five theories of learning as noted in Chapter II. This selection of Ausubel's advance organizer was not the result of the elimination of the other theories; rather this theory was considered to be most adaptable to both the practical and theoretical nature of the AI research.

The organizer is constructed so that each of the nodes of the networked hierarchy (net-archy) represents an area of physics corresponding to one of the Gagné learning types. The learning types parallel the structure of the advance organizer. The expert module for physics is constructed by
recursively asking the question "What prerequisite learning is necessary to learn this node"? The major instructional objective or goal for the system is for the student to solve three basic types of accelerated motion problems.

Problem 1.--In the first problem, the student is presented a situation where an object, with a given initial horizontal velocity, is projected off a cliff which is a known height above the ground. He/she is then asked to calculate the amount of time required for the object to hit the ground. Several principles are involved here, but due to the depth-first manner of construction, only one principle is initially placed in the net-archy. This necessary prerequisite principle is:

* For projectile motion, the projectile's vertical and horizontal velocities are independent of each other.

The constructor of the net-archy must then decide which prerequisites are necessary for full understanding of the principle. Four concepts are required for full understanding. One of these concepts is an understanding of gravity as a force. This concept, in turn, requires the student to learn three other concepts, including the concept of gravity as cause of acceleration.

After achieving the most basic concept, acceleration, the recursive function returns to the next-highest level that
has not had all its prerequisites fully defined, as shown in Figure 5.

Figure 5.—Initial depth-first pass in recursion for building the physics net-archy.

This process finally recurses through the prerequisites for each of the principles, thus completing the net-archy for one problem, as shown in Figure 6.
Figure 6--Networked hierarchy (net-archy) for one physics problem involving an object projected horizontally off a cliff.

Although there is a limited amount of networking within the learning net-archy for one problem, the fact that most, if not all, concepts and principles of physics are prerequisites to at least two problems causes the complexity of the
linkages to increase as the number of problems increases. On the other hand, as the number of problems increases, the number of new prerequisites decreases due to this same effect. The other two problems whose net-archy recursions are incorporated within ARPHY are both related to accelerated motion and share many common prerequisite principles and concepts.

Problem 2.—An object of known mass rests on a frictionless horizontal surface and is subjected to multiple forces of known magnitudes and directions simultaneously. The student is asked to determine the acceleration of the object. The solution to this problem rests on the student's recognition and application of the principle of net force and Newton's second law \( f = m a \).

Problem 3.—An object is projected upwards with an initial vertical component to its velocity. The student is asked to calculate the total length of time the object is airborne, neglecting air resistance. One principle required for the solution of this problem is the re-arrangement of the formula for acceleration \( v = a t \rightarrow t = v/a \) which yields the length of time required for the object to reach its maximum altitude. Another principle states that the length of time required for the object to reach its peak is equal to the length of time for the object to fall back to the ground.
The student also needs to understand the concept of weight before he can solve this problem.

**ARPHY** represents all the prerequisite information for each problem in the form of parent-child relationships. Each problem has its associated children, or first-generation prerequisites. These children, in turn, have their children, second-generation prerequisites. Table I shows the first generation of three families--one family for each problem.

**TABLE I**

FIRST GENERATION PREREQUISITES OF THE THREE PHYSICS PROBLEMS RELATED TO ACCELERATED MOTION

<table>
<thead>
<tr>
<th>Parent</th>
<th>Children (prerequisites)</th>
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<tbody>
<tr>
<td>Problem 1</td>
<td>* formula for constant velocity (principle)</td>
</tr>
<tr>
<td></td>
<td>* d=(1/2) a t^2 (principle)</td>
</tr>
<tr>
<td></td>
<td>* horizontal independent of vertical velocity (principle)</td>
</tr>
<tr>
<td>Problem 2</td>
<td>* f = m a (principle)</td>
</tr>
<tr>
<td></td>
<td>* net force (principle)</td>
</tr>
<tr>
<td>Problem 3</td>
<td>* v = a t (principle)</td>
</tr>
<tr>
<td></td>
<td>* time up equals time down (principle)</td>
</tr>
<tr>
<td></td>
<td>* weight (concept)</td>
</tr>
</tbody>
</table>

It is apparent that, in general, each physics problem calls immediately upon a principle. While the prior learning of many concepts is required for the solution of the problems, the concepts are prerequisites for the principles, and will, therefore, appear in later generations of the family tree. The decision as to how large a "chunk" of knowledge should be represented at each node is made by the human expert of
physics. This decision is based upon the following two factors: how "self-contained" the chunk is, and how potentially meaningful the chunk is.

The second generation of the family tree is shown in Table II.

<table>
<thead>
<tr>
<th>Parent</th>
<th>Children (prerequisites)</th>
</tr>
</thead>
<tbody>
<tr>
<td>constant velocity * formula</td>
<td>constant velocity idea (concept) speed (concept)</td>
</tr>
<tr>
<td>horiz. vel. indep.* of vertical vel. *</td>
<td>constant velocity idea (concept) gravity as a force (concept) horizontal velocity idea (concept) vertical velocity idea (concept)</td>
</tr>
<tr>
<td>$d = (1/2) a t^2$ *</td>
<td>formula for acceleration (principle) gravity as a force (concept)</td>
</tr>
<tr>
<td>$f = ma$ *</td>
<td>force (concept) mass (concept) formula for acceleration (principle)</td>
</tr>
<tr>
<td>net force *</td>
<td>force (concept)</td>
</tr>
<tr>
<td>$v = at$ *</td>
<td>vertical velocity idea (concept) constant change in vel. (concept) formula for acceleration (principle)</td>
</tr>
<tr>
<td>time up equals time down *</td>
<td>gravity as a force (concept) free-fall idea (concept)</td>
</tr>
<tr>
<td>weight *</td>
<td>mass (concept) free-fall idea (concept)</td>
</tr>
</tbody>
</table>

It is clear that most principles for accelerated motion require only concepts as prerequisites, although high-level
principles such as Newton's second law \( f = m a \) require prior learning of a lower-level principle, the formula for acceleration.

The third generation of the family tree for the three accelerated motion problems contains the prerequisites for second generation children and is shown in Table III.

### Table III

**Third Generation of the Net-Archy for the Three Accelerated Motion Problems**

<table>
<thead>
<tr>
<th>Parent</th>
<th>Children (prerequisites)</th>
</tr>
</thead>
<tbody>
<tr>
<td>speed</td>
<td>distance (concept)</td>
</tr>
<tr>
<td></td>
<td>horizontal velocity idea (concept)</td>
</tr>
<tr>
<td></td>
<td>vertical velocity idea (concept)</td>
</tr>
<tr>
<td>formula for acceleration</td>
<td>constant velocity idea (concept)</td>
</tr>
<tr>
<td>constant change in velocity</td>
<td>constant change in vel. (concept)</td>
</tr>
<tr>
<td>gravity as force</td>
<td>force (concept)</td>
</tr>
<tr>
<td></td>
<td>direction of gravity (concept)</td>
</tr>
<tr>
<td></td>
<td>gravity as an accelerator (concept)</td>
</tr>
</tbody>
</table>

Since many of these children are already part of the family, only two new children appear in the fourth generation. All the other children above call on concepts found within the first three generations. The principle called upon, constant
velocity formula, appears in the second generation shown in Table II. The two remaining parents form the fourth generation and are shown with their children in Table IV.

**TABLE IV**

FOURTH GENERATION OF THE NET-ARCHY FOR THE THREE ACCELERATED MOTION PROBLEMS

<table>
<thead>
<tr>
<th>Parent</th>
<th>Children (prerequisites)</th>
</tr>
</thead>
<tbody>
<tr>
<td>direction of gravity</td>
<td>directions</td>
</tr>
<tr>
<td>gravity as an <em>accelerator</em></td>
<td>acceleration idea</td>
</tr>
<tr>
<td></td>
<td>free-fall idea</td>
</tr>
</tbody>
</table>

Obviously, the parallel between the AI notation of parents and children and the human relationships is limited to the context of prerequisites only. Some children which appear in the fourth generation above, such as the idea of free-fall, are prerequisites (children) for the second generation.

So far, the ARPHY only knows which nodes of the net-archy connect to which nodes. ARPHY thus knows, at best, possibilities for the direction of future meaningful instruction. The next step is to load ARPHY with some facts related to the content of accelerated motion.

**Loading ARPHY with Accelerated Motion Facts**

In order to handle questions from the student and also to be able to interact with the student intelligently about accelerated motion, facts are stored in frames. Some of the
facts which are stored by ARPHY as frames, are the following:

(English translation follows the LISP notation)

(setf (get 'vector 'characteristics) '(magnitude direction))
* Magnitude and direction are characteristics of vectors.
(setf (get 'mass 'units) '(kilograms grams slugs))
* The possible units of mass are kilograms, grams, and slugs.
(setf (get 'acceleration 'examples)
     '(change-in-speed change-in-direction))
* Examples of acceleration include either a change in speed
  or a change in direction.

Students can obtain the above information by asking questions of the system. The system matches students' responses and retrieves the appropriate information.

Loading ARPHY with Accelerated Motion Rules

Since the knowledge of facts has been shown to be rather low level learning according to Bloom's taxonomy, ARPHY is equipped with higher-level problem solving abilities in the form of rules. These rules consist of condition-action pairs and are also called IF-THEN rules (3). The expert in any field acts after an evaluation of a situation, making sure that any action taken follows logically from a set of guidelines or pre-conditions (3). It is hoped that the student will also be able to adapt the same guidelines to his
problems. The initial conditions for problem 1 are transformed into a set of assertions, written in COMMON LISP as:

```
(setf assertions
  '((situation is free-fall)
   (object is moving initially)
   (initial-motion is constant-vel)
   (initial-direction is horizontal)
   (air-resistance is zero)))
```

All subsequent actions taken by ARPHY in solving problem 1 are based on these initial assertions.

ARPHY proceeds to solve the problem by looking through its internal representation of the rules it knows regarding accelerated motion. Each rule is an IF-THEN pair consisting of conditions and actions. If the IF portion of any rule is satisfied by the assertions, the THEN portion becomes a new assertion. Following, is the first rule ARPHY sees which is satisfied by the assertions.

```
(rule free-fall-1
  (if (situation is free-fall))
  (then (there is initial-acc)
        (situation involves acc)
        (acc-rate maybe nominal)
        (acting-force is gravity)
        (object-acted-on is falling-body)
        (acc-dir is toward-earth)))
```

The assertions are supplemented with the six assertions found in the THEN portion of the rule after ARPHY checks the remaining rules for a match. Before reaching the end of the rule list, ARPHY finds the IF's of the following rule matching the assertions:
(rule free-fall-24
  (if (situation is free-fall)
      (air-resistance is zero)
      (object is moving initially)
      (initial-direction is horizontal))
  (then (motion-graph is parabola)
      (problem-solving method is
       keep-hor-indep-of-vert-vel)))

After searching the remaining rules and finding no more matches, the THEN's of the previous two rules are appended to the list of assertions. The rules are searched again for a match between the new assertion list and an IF portion of a rule. One of the problems of expert systems involving multiple rule firings is avoided by careful construction of the rule base. On the next pass, the following rule is satisfied by the new assertions:

(rule free-fall-32
  (if (acting-force is gravity))
  (then (dir-of-force-acting is downward)))

Likewise, the THEN becomes the new assertion and is added to the assertion list. On the next pass, a new rule is fired due to the addition of this new assertion:

(rule free-fall-37
  (if (initial-direction is horizontal)
      (dir-of-force-acting is downward))
  (then (dir-of-force-acting perp-to init-dir)))

This process, known as forward-chaining, proceeds until no new rule can be fired during a pass through the rules. The resulting set of THEN's forms ARPHY's inferences.

Questions beginning with "Why" and "How" can be answered by pattern matching the question with either an IF or a THEN of a rule. For instance, if the student asks:
S: "Why is the direction of the acting force downward?"

ARPHY checks the rule-base to see if a rule with a THEN portion matching the question has been fired. If it has, ARPHY answers with the IF portion:

A: "The direction of the acting force is downward because the acting force is gravity."

If the rule has not been fired, ARPHY responds:

A: "Sorry, (name), that fact has not been deduced."

This process of backward-chaining to explain why certain inferences were made can be used recursively to explain the complete solution to a problem. If the student asks the question:

S: "Why is gravity the acting force?"

the rules which were fired are searched, resulting in rule free-fall-1 being found, and the answer:

A: "Gravity is the acting force because the situation is free-fall."

The "How?" questions are handled by forward-chaining from an IF portion of a fired rule which matches the question. This allows the student to inquire as to the consequence of a particular condition, as follows:

S: "How do I use the fact that I know that there's free-fall?"
The rule which was fired earlier is:

\[
\text{rule free-fall-1} \\
\quad (\text{if (situation is free-fall)}) \\
\quad (\text{then (there is initial-acc)} \\
\quad \quad (\text{situation involves acc)}) \\
\quad \quad (\text{acc-rate maybe nominal}) \\
\quad \quad (\text{acting-force is gravity}) \\
\quad \quad (\text{object-acted-on is falling-body}) \\
\quad \quad (\text{acc-dir is toward-earth}))
\]

ARPHY forward-chains from the IF and replies:

A: "Since the situation is free-fall, you can infer that acceleration is involved, there is initial acceleration, the acceleration rate may be normal gravity, the force acting is gravity, the object acted upon is the falling body, and the direction of acceleration is toward the earth."

The greatest limiting factor with this intelligent question-handler is the ability of the communications module to match the students' questions with an anticipated pattern. The communications module must be able to pass the decoded question to the expert module in such a way that all the expert receives is an assertion and the request keyword which will either be "how" or "why."

**Setting up ARPHY to Instruct**

In order to teach students to solve three accelerated motion problems, ARPHY must have knowledge about 9 principles and 14 concepts. The method by which the knowledge is transferred to the student is through an interactive session at the terminal of an IBM PC-XT equipped with a color monitor.
Resident within the hard disk is the software which drives the 23 routines. Each routine occupies approximately 10 Kilobytes of static memory. When loaded, the routine occupies more RAM (random access memory) than 10 Kilobytes due to the fact that LISP must bind variables and define functions, thus using cons cells (equivalent to a high-level memory). This requires each routine to be developed so that any new routine loaded into memory completely replaces the former routine, thus minimizing the loss of RAM.

The routines, therefore, follow a standard outline. The topic is introduced (introduce function), followed by an initial overview of the domain of the topic and its possible uses (present1). Specific instructions then relate the topic to the other connected topics nearby in the organizer (present2, present3, and present4). The COMMON LISP implementation is shown in Figure 7, below.

```
(defun presentation () ; function is defined
  (progn (introduce) ; topic is introduced
    (present1) ; overview of domain
    (present2) ; early instruction
    (present3) ; other necessary instruction
    (present4) ; tying the loose ends
    (alpha)) ; resume alpha-numeric mode
```

Figure 7.—High-level structure of the presentation routine used for each topic.

When a topic is loaded into RAM, it will have routines defined with the same names as the routines called by the presentation
function. This modularity will allow future development of the tutorial strategy module which may then select specific styles or levels of presentation.

Whenever the controller determines the presentation of a specific topic, a routine associated with the presentation of the topic is called and the instruction of the topic commences. The instructional sequence for concepts generally consists of positive and negative examples of the concept, whereas the sequence for principles involves demonstrations of the applications of concepts. Following are four graphical representations of the screen as seen by a student during the presentation of the principle that teaches that horizontal velocity is independent of vertical velocity. While the actual presentation consists of more than these four screens, these specific four have been selected to demonstrate the usefulness of real-time computer-generated graphics to simulate physical phenomena. Each screen is shown in Figures 8 through 11.

The system introduces the student to ballistic motion. Figure 8 shows the initial introduction to the principle that horizontal velocity is independent of vertical velocity. The student becomes aware that some of the previously learned concepts are necessary to explain the complicated motion. The screen shown in Figure 9 represents the first time the student sees the decomposition of a projectile's motion into a component part.
When an object is projected horizontally, it appears difficult to analyze the path.

Figure 6.--Initial introduction to the principle that horizontal velocity is independent of vertical velocity.
OK—watch this again, but this time watch the top box and observe that it has constant velocity. Watch again !!

Figure 9.—The student's first view of the decomposition of a principle into component concepts.

The above screen decomposes the principle that horizontal velocity is independent of vertical velocity. The concept which is emphasized is constant velocity. The student is then instructed that the concept was only seen in the
horizontal direction. The student is then able to meaningfully learn that the vertical motion has its underlying concept, as shown in Figure 10.

Here it comes!

Note that the downward acceleration acts the same as if the object were dropped (it's freefall!)

Figure 10.—Student's first view of the concept of freefall being one source of the object's parabolic motion.

The student is then presented further examples of the separation of the components of the object's motion. The immediate educational objective of this routine is for the student to be able to think of two separate motions when
presented a situation where an object is projected horizontally from a certain height.

Assessing Student Competency

The expert module must not only be the source of expert knowledge and behavior, it must also be able to determine how well the student has learned the information it transmits. When the student has not learned a topic well, the expert module (EM) must also provide the tutorial strategy module with information about which misconceptions the student may have. The modularization of ARPHY results in the TSM actually performing the questioning process, but only after communication with the EM.

Assessing the level of learning.—Bloom's taxonomy of educational objectives in the cognitive domain, as discussed in Chapter II, forms the basis for determining the student's level of learning. There are two general classifications of questions which ARPHY poses to the student. The first classification, called BLOOM-1, includes questions which test behaviors falling in the 1.00-2.30 range. This includes the knowledge domains of terminology, facts, classifications, categories, criteria, methodology, principles, and structures. The comprehension domain includes translation, interpretation, and extrapolation. The other classification, called BLOOM-2, includes questions which test behaviors in the 3.00-6.2 range. The domains included are application,
analysis (of elements, relationships, and organizational principles), synthesis, and evaluation. The most common BLOOM-2 questions are those at the application and analysis levels.

When the tutorial strategy module passes to the expert module the need for an assessment of competency for a certain topic, the expert module executes the function EXPLORE-COMP which is a function defined specifically for each topic. Within the tutorial strategy-to-expert module instruction is a qualification concerning which level of learning the expert module should test (BLOOM-1 or BLOOM-2).

For example, if the current topic is mass and the tutorial strategy module passes the message (EXPLORE-COMP BLOOM-1), the expert module proceeds to test the student to determine if a BLOOM-1 (knowledge, comprehension) level has been attained for the topic. A BLOOM-1 question for mass is shown in Figure 11. If the student answers this question correctly, the expert passes to the tutorial strategy module the message: "(BLOOM-1 CORRECT)"

Then, depending upon the decision of the tutorial strategy module, the expert may be asked to question the student at the same level (BLOOM-1), a higher level (BLOOM-2), or terminate the competency-exploring procedure and pass along all intermediate assertions.
Let me get an idea of how well you understand the concept of mass, Rodney.

What do you call the unit of mass equivalent to one cubic centimeter of water???

(I'm looking for a word:

Just type in your answer, then press [return] ______

Figure 11.—BLOOM-1 question assessing the student's understanding of the concept MASS.

If the expert module is asked to, say, explore competency at the higher levels (BLOOM-2) for the topic (HORIZONTAL VELOCITY INDEPENDENT OF VERTICAL VELOCITY), a corresponding question is asked, as shown in Figure 12.

The decision as to whether or not the student responded correctly is made by the TSM which has been informed of the correct answer by the EM. Decisions are not made by the communications module since, by definition, the communications module does not actually know the subject. If the student answers a BLOOM-2 question correctly, the message "(BLOOM-2 CORRECT IN HOR-INDEP-OF-VERT-VEL)" is sent to the tutorial strategy module, which again makes a decision whether to continue with BLOOM-2 questions or terminate the explore-competency procedure.
What force(s) is (are) acting on it?

A. none.
B. gravity.
C. force of motion.
D. both B & C.

Figure 12.--BLOOM-2 question for the topic (HORIZONTAL VELOCITY INDEPENDENT OF VERTICAL VELOCITY).

At this level of competency assessment, errors are more frequent and less the result of improper reiteration of stored facts. In fact, errors occurring at the BLOOM-2 level may be due not only to the mis- or non-learning of material within the topic itself, but may be due to misconceptions of
prerequisite material. This is another vital role played by the expert module, as discussed below.

**Misconception Detection.**—When a student answers a BLOOM-2 question incorrectly, ARPHY passes control to the SAY-WRONG function located within the communications module. SAY-WRONG communicates the incorrectness of the response to the student and then passes control over to the misconception-detector function MISCONDET located within the expert module. MISCONDET calls on the expert system rules, discussed previously regarding forward- and backward-chaining, and searches the THEN sections for a match with the current topic addressed by the question. This process is called the determination of the applicable rule, or AP-RULE. Backward-chaining is recursively performed, once for each child of the current topic, until a match occurs between the physical parameters of the child and the IFS of the AP-RULE. This results in a rule search-space which places a boundary on the logic of the student's misconception. The boundary runs from all the IFS just located by backward-chaining, forward to the THEN of the current problem. Clearly, multiple IFS from different rules won't all forward-chain to the same THEN of the current topic, so the excess rules are discarded after recursively forward-chaining from each of the boundary IFS. This leaves a precise location in the thought process where the student's misconception has occurred. The child whose
parameters matched the remaining IF is identified as the probable source of the misconception and attached to the variable PICK-ON. The following message is sent to the tutorial strategy module:

'(BLOOM-2-WRONG IN ,pick-on
   DISCOVERED BY ,current-topic)

In COMMON LISP, any expression inside of a backquoted '() has all variables preceded by a comma evaluated. So, if the current topic is the formula for acceleration and the student just missed a question at the analysis level (BLOOM-2) in an area identified by MISCONDET as being the concept of "constant change in velocity", the tutorial strategy module actually receives the following message:

( B2-WRONG IN
   CONST-CHANGE-IN-VEL
   DISCOVERED BY
   ACCELERATION-FORM )

This information is used by the tutorial strategy module to guide the direction of future instruction.

Student Module

The student module within ARPHY has the responsibility of keeping all the records specific to each student which are accessed by the other three modules. This module is
responsible for the individualization of the learning experience. Information kept by the student module includes the student's reading speed, topics completed, probable areas of misconceptions, and the path instruction has taken through the topics. This information is stored as a set of dynamic variables which can be updated when necessary. Before the student exits the system, the current status of these variables is stored on disk so that they may be invoked during the next session. Following is a discussion of each feature of the student module.

**Assessment of Reading Speed**

Ideally, when presenting information to the student, the screen should refresh itself immediately after the student has finished reading the information on the screen. This is usually accomplished by instructing the student during the orientation period that new information will be presented whenever a key such as the space bar is pressed. A more desirable situation in terms of learner-based instruction is one where the tutor knows the student's reading speed. The reading speed is measured in an introductory session whereby a lengthy piece of text is presented and the student is asked to respond when the text has been read. ARPHY accomplishes this by presenting the student with the text shown in Figure 13.
During the course of working through this physics tutorial, you may desire at some point to hold the information on the screen so that you may either think about it or make a note in your notebook.

If you want to HOLD the screen, then press the [+] key which is over on the right side of your key-board. Any key pushed thereafter will allow me to proceed.

If you want me to hurry up, then just press the [space bar].

When you're done reading this, press the [space bar].

Figure 13.—Text used by the student module of ARPHY in the determination of the student's reading rate.

When the space bar is pressed, an internal timer begun when the text was first presented is stopped, and a reading is taken of the number of 1/25 second intervals required for the student to read the text. This number becomes the reading delay for the student and is stored by the student module.

In the presentation of information to the student, the information appears on the screen for a length of time equal to the product of two numbers. The first of these numbers is a suggested number of "hold" units corresponding roughly to the number of seconds required by the average reader to read the material. The second of the two numbers is the reading delay. Every time the machine holds information, the length of time the information is held is equal to:

\[(\text{number of "hold" units}) \times (\text{delay factor of student})\.

When this time period is reached, the screen is refreshed with new information, thus reducing the number of times the
When this time period is reached, the screen is refreshed with new information, thus reducing the number of times the student needs to press the space bar. As a stand-by, the screen is immediately refreshed upon the pressing of the space bar. The screen is held indefinitely when the [+] key is pressed. This allows the student the chance to take a break or write down a formula.

Topics Completed

As each topic is successfully completed by the student, the student module is updated by adding the topic to a list associated with the variable *topics-completed*. When LISP adds elements to a list, the most recent addition is located at the front of the list, thus allowing the student module to keep a simultaneous record of the order of topics completed. This facilitates communication between the student module and the tutorial strategy module, should the latter ever attempt to assess preferred paths through the topics.

Record of Performance

Each time the expert module evaluates the student's response to a question, an assertion is placed on a fictitious blackboard located within ARPHY's memory. Blackboarding techniques are used extensively in the HEARSAY-II speech recognition system (2) to facilitate ideas or partial solutions generated by one section of an AI system to be communicated to another portion of the system. With ARPHY, the
blackboard is available for inspection by all modules. The student module is responsible for recording all the expert module's assertions on the blackboard. Since any module may permanently erase any portion of the blackboard at any time, the student module becomes a necessary permanent record of the student's performance and can be accessed days or months later by another module.

For example, if the student has just answered four questions while learning the topic of "gravity as a force," the portion of the blackboard transferred to the student module may include:

(BLOOM-1 CORRECT IN GRAV-AS-FORCE)
(BLOOM-2 WRONG IN DIRECTION-OF-GRAV DISCOVERED BY GRAV-AS-FORCE)
(BLOOM-2 CORRECT IN FORCE DISCOVERED BY GRAV-AS-FORCE)
(BLOOM-2 WRONG IN GRAV-AS-ACCELERATOR DISCOVERED BY GRAV-AS-FORCE)

In addition, the specific topics identified by MISCONDET as areas of possible misconceptions and appended to the list associated with the variable *warn-list* are permanently stored by the student module. This list may be modified if the expert module strongly believes that a misconception has been corrected.

Tutorial Strategy Module

The pedagogical decisions are made by the tutorial strategy module (TSM). The TSM consists of a dual expert system in a nested configuration. The top-level expert
system is the controller of the actions taken by ARPHY. The nested (inner) expert system is responsible for determining the sequence of topics to be instructed. At the highest-level of control, the TSM is continuously looping through a list of possible procedures, waiting for the appropriate command to activate one of the procedures. The commands originate from the expert system rules as an assertion or assertions which resulted from some pre-condition. When a procedure recognizes its triggering assertion, the procedure takes control and performs its task, be it a calculation, student interface, or a decision. When the procedure finishes, it erases the assertion that triggered itself into action and returns another assertion indicating its final results or thoughts.

After the entire list of possible procedures has been shown the activating assertions and the appropriate actions have been taken, the TSM high-level expert system forward-chains through a list of high-level rules, or metarules. New assertions result from this forward-chaining and the loop is repeated, with each procedure waiting for its activating assertion. Due to the recursive nature of LISP, each procedure may call upon other procedures to accomplish its immediate tasks. The high-level control structure is shown in Figure 14.
Figure 14.—High-level structure of the tutorial strategy module (TSM). Procedures are activated ONLY by an appropriate assertion. Usually, only ONE procedure is activated during each pass through the loop.

The metarules which guide the decisions of the TSM are usually simple multiple condition-single action rules such as the following rule guiding the initiation of competency exploration:

(RULE STRATEGY-17
 (IF (TOPIC-PRESENTED)
    (STRATEGY IS DEFAULT))
 (THEN (EXPLORE-COMPETENCY BLOOM-1)))

Thus, when a topic has been presented and the current strategy is at its normal, or default status, then the TSM asserts that the student's competency at the BLOOM-1 level should be assessed.
In the remainder of this section, each high-level procedure within the TSM is discussed. The actual code for the procedures will not be shown explicitly so that attention may be given to the overall function and theory of operation of each procedure. It should be emphasized again, that the procedures written in LISP are independent units but may call on any number of other procedures to accomplish a specific task.

**OPEN-SESSION**

This procedure is activated when the assertion (SESSION NOT OPEN) exists. An introductory message is presented to the student who is then prompted for his name. If ARPHY has not met the student, the procedure (OPEN-NEW-STUDENT) is called. This procedure first transfers control to the student module to assess the student's reading speed, then gives an introduction to the structure and operation of ARPHY. Regardless of whether or not ARPHY has met the student, ARPHY then introduces the student to the other students in the class. If the student has been tutored prior to the session, ARPHY summarizes the student's previous progress and areas of possible misconceptions.

**CHOOSE-A-TOPIC**

This procedure is the most complex within ARPHY. The easiest method of choosing a topic would be for the system to be primed with an order of topics for the student to follow.
To facilitate learner-based instruction, however, the student should have a degree of control over the path of instruction. The (CHOOSE-A-TOPIC) procedure is dynamic in its approach to topic selection. It can also be passive and allow the student to have total control over the instructional process, but if the student has exhibited poor performance due to diagnosed misconceptions, (CHOOSE-A-TOPIC) can take control and steer the student through a period of remedial instruction. The student also has the option of allowing ARPHY to select the next topic.

Regardless of who selects the subsequent topic, ARPHY ranks the available topics based on a combination of three factors. These factors are: (1) if the topic has enough prerequisites completed to be meaningfully learned, (2) how well the topic's prerequisites have been meaningfully learned, and (3) if any of the prerequisites have been identified as areas of possible misconceptions. Each of these factors is based upon a dynamic pedagogical parameter. For each of the three possible motions through the net-archy (super-, sub-, and co-ordinate subsumption), there are two parameters which the ranking is based upon. Therefore, six variables, which can be reset by ARPHY, constitute the modus operandi of ARPHY's TSM. The variables are actually thresholds used during the ranking process to determine if a criterion has been met. The thresholds will hereafter be
referred to as threshold C (for children) and threshold B (for Bloom level).

The modus operandi is rigorous when the two super-ordinate thresholds are high. In this situation, ARPHY ranks a topic very low if the topic has either not had enough of its prerequisites completed, or the prerequisites were completed at a low level of learning. ARPHY will most likely not select this topic. This is a desirable situation when the student has a weak background in the sciences and requires all necessary prerequisites before any topic can be learned. The modus operandi is permissive when thresholds B and C are low. In this situation, ARPHY will rank a super-ordinate topic high even if the fraction of prerequisites completed is low. The super-ordinate topic has a good chance of being selected. This is a desirable situation when the student has some background knowledge in the subject area and may become bored if not continuously challenged.

In keeping with Ausubel's (1) theory of meaningful learning, as discussed in Chapter II, the highest priority is given to topics which can be reached from the most recent topic through one of the three allowed motions through the net-archy. There must be an additional ranking, however, to accommodate the following two situations.

In the first situation, the most recent topic completed may be effectively "land-locked" by previously-completed topics. For example, if the student has completed, among
others, net force, \( f = m a \), and then problem 2, there is no legal "escape" to reach another topic. This is why a remote ranking is performed, regardless of whether or not this situation actually arises. In a remote ranking, all completed topics become possible starting points for movements through the net-archy. This procedure is within Ausubel's theory that meaningful learning will still occur, although the starting point will not be the most recent topic completed. Perhaps this insures a better transfer of short- to long-term memory.

The second reason a remote ranking is performed is to allow the student to have the greatest possible degree of control over his own learning environment. A motivated student may try to cross the net-archy laterally at the principle level and avoid the concept level. This also allows the easily-distracted student the chance to quickly change the nature of the subject matter.

If the student is new, no ranking is performed, rather, the student is allowed to choose between three basic concepts which are easily learned. In any other situation, ARPHY ranks both the immediate-access and the remote-access topics, then presents the student with the message:

A: "Want me to choose the next topic? (Y or N)"

If the student allows ARPHY to choose the next topic, ARPHY selects the highest-ranked topic. The ranking scale ranges from -100 to 100. Rankings with negative numbers indicate that ARPHY is not ambivalent about the topic--ARPHY has
determined that some reason exists why the topic should not be chosen. Negative numbers arise when the thresholds (B or C) for a certain movement are not satisfied. This effectively gives the six thresholds greater power in the decision-making process. An example of the situation where the ARPHY is allowed to choose the next topic is shown in Figure 15.

<table>
<thead>
<tr>
<th>#</th>
<th>ARPHY's Ranking</th>
<th>Topic</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>35.25</td>
<td>* Direction of gravity</td>
</tr>
<tr>
<td>2</td>
<td>25.5</td>
<td>Idea of constant velocity</td>
</tr>
<tr>
<td>3</td>
<td>12.5</td>
<td>Idea of vertical velocity</td>
</tr>
<tr>
<td>4</td>
<td>-40.5</td>
<td>Horizontal velocity being independent of vertical velocity</td>
</tr>
</tbody>
</table>

I choose topic # 1 --- direction of gravity !!!

Figure 15.--ARPHY selects the next topic

ARPHY was able to locate a topic reachable through one of the three net-archy movements. As previously mentioned, the path of instruction could lead to an isolation of a topic. Ties are broken and direction of movement in case of landlocking is determined by an inherent bias on the part of ARPHY toward concepts and principles closest to the lowest-numbered problem. Figure 16 shows how the remote ranking is used in the event of a "landlock".
Ok, Tracy, here are your topics that are immediately available from DIRECTIONS. I have ranked them according how likely you will be able to meaningfully learn them:

# ARPHY's Ranking: Topic:

!!!!!!!!??????????--------> Well........!!!!!!

You've completed all the topics normally reachable from this one.
I'll go and find a topic which will meaningfully relate to one of the other topics you have completed.
Here's the remote listing:

<table>
<thead>
<tr>
<th>#</th>
<th>ARPHY's Ranking</th>
<th>Topic</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>47.25</td>
<td>Direction of gravity</td>
</tr>
<tr>
<td>2</td>
<td>47.25</td>
<td>Idea of vertical velocity</td>
</tr>
<tr>
<td>3</td>
<td>- 5.25</td>
<td>Force</td>
</tr>
<tr>
<td>4</td>
<td>- 5.25</td>
<td>Constant change in velocity</td>
</tr>
<tr>
<td>5</td>
<td>- 5.25</td>
<td>Formula for constant velocity</td>
</tr>
<tr>
<td>6</td>
<td>-18.75</td>
<td>Idea of constant velocity</td>
</tr>
<tr>
<td>7</td>
<td>-18.75</td>
<td>Horizontal velocity being independent of vertical velocity</td>
</tr>
<tr>
<td>8</td>
<td>-18.75</td>
<td>Problem 1</td>
</tr>
</tbody>
</table>

I choose topic # 1 - Direction of gravity !!!!!

Figure 16.--ARPHY detects the landlock of the previous topic and makes a selection based on the remote topics.

In this situation, the student has just completed the topic concerning directions and has previously completed all topics that could be reached via a net-archy movement.

If the student elects to choose the next topic, the rankings are shown to the student so that the student may be aware of how ARPHY would approach the situation. At the bottom of the screen, the student is reminded that the remote
ranking may also be obtained. This situation is shown in Figure 17.

Ok, Francis, here are your topics that are immediately available from FORGE. I have ranked them according to how likely you will be able to meaningfully learn them.

<table>
<thead>
<tr>
<th>#</th>
<th>ARPHY's Ranking</th>
<th>Topic</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>38.25</td>
<td>Direction of gravity</td>
</tr>
<tr>
<td>2</td>
<td>-5.25</td>
<td>Idea of constant velocity</td>
</tr>
<tr>
<td>3</td>
<td>-5.25</td>
<td>Idea of horizontal velocity</td>
</tr>
<tr>
<td>4</td>
<td>-5.75</td>
<td>Idea of vertical velocity</td>
</tr>
<tr>
<td>5</td>
<td>-40.5</td>
<td>Horizontal velocity being independent of vertical velocity</td>
</tr>
</tbody>
</table>

Type in either the number of your choice, then [return] or type in [r] for a list of topics remote from your present topic: __________

Figure 17.—Student wishes to choose the next topic

Another situation could arise in which the student was denied completion because the required level of learning was not exhibited. The MISCONDET procedure located within the expert module will have located some areas where possible misconceptions exist. These "warned" topics may be considered by ARPHY to be so vital to the full understanding of the affected region of the net-archy that "mandates" are written ordering immediate remedial instruction. When remedial instruction is mandated, the student is not even given the chance to determine who selects the next topic. The student
receives the message shown in Figure 18 and instruction commences.

Well, Misty, since you didn't do so well with CONSTANT CHANGE IN VELOCITY, I'm going to choose a topic for you!

(you can thank me later !!!)

...  
...
Ah !! There we go!

Let's try (IDEA OF CONSTANT VELOCITY)

Figure 18.--ARPHY takes control when sure of the nature of a misconception.

Although the student may think that ARPHY has just selected a topic from a large pool of alternatives, there is probably one topic which the expert module had diagnosed as a misconception that is tagged by ARPHY for remedial instruction.

When the topic is chosen, the TSM decides what type of presentation should be used for the topic. Presentation modes are available for introducing, laying foundations, and relating topics to existing knowledge. For purposes of this research, the TSM used the default approach for all students and allowed the complete presentation of each topic in the normal order of (1) introduction, (2) background, (3) theory, and (4) relating to existing knowledge.
Presentation

A topic is presented to the student as a sequence consisting of an introduction, a general overview of the topic domain, and a section which meaningfully relates the topic to existing knowledge. This modularity of the presentation sequence is to facilitate the implementation of future expert system rules which may infer that the student may not need an introduction or general overview of the topic. For this study, however, the subsections within the presentation routine will all occur in a pre-determined default sequence.

The PRESENT-TOPIC procedure transfers control to the expert module to commence the presentation of the topic. During the course of the presentation, the expert may question the student as to whether or not he remembers a certain principle or formula. If the student voluntarily admits a deficiency in a topic, a soft warning is issued on that topic and ARPHY will rank that topic highly in future rankings. After the presentation is completed, the expert system sends the TSM the assertion: (TOPIC PRESENTED). The expert system then forward-chains to decide the next action. Since the strategy is default, the expert will decide to explore the student's competency at the BLOOM-1 level.

Competency Determination

The control of the EXPLORE-COMPETENCY procedure rests within the expert module. There is a constant communication
between the expert module and the TSM during this procedure, however. Two other pedagogical parameters play a role in the behavior of ARPHY during competency assessment. These are, like the other six, thresholds. Both the maximum number of BLOOM-1 questions and the maximum number of BLOOM-2 questions asked by ARPHY are determined by these two dynamic thresholds. Each topic routine within the expert system has the capability of asking up to two BLOOM-1 questions and eight BLOOM-2 questions. The goal ARPHY tries to meet with regard to these two thresholds is to achieve the best compromise between asking an appropriate number of questions to assess the student's competency, while not making the student impatient with possibly unchallenging questions. At one extreme, ARPHY should be able to detect a student who is an exceptionally fast learner and reduce the number of questions accordingly. At the other extreme, ARPHY should be able to detect exceptionally slow learners and increase the number of questions both to provide a more accurate assessment of misconceptions and to allow the student more opportunities to receive remedial instruction after incorrect answers.

When the question limit is reached for BLOOM-1 questions, as determined by a comparison with the current threshold value for the variable *num-BLOOM1-questions*, BLOOM-2 level questions are asked until the other threshold (*num-BLOOM2-questions*) is reached. These thresholds are two of the eight dynamic pedagogical parameters and will therefore have
values determined by past student performance. The expert system transfers control back to the TSM while adding the assertion: (COMPETENCY EXPLORED BLOOM-2). The TSM then (in the default setting) invokes the WRAP-UP procedure.

WRAP-UP

The WRAP-UP procedure is essentially a final set of "house-cleaning" procedures designed to take care of all necessary tasks relating to the previous topic prior to a possible closing of the tutorial session which may subsequently be invoked. First, all misconceptions detected by MISCONDET are removed from the blackboard and placed in the student module. Secondly, the thresholds are modified by the previously-mentioned nested expert system. Finally, a decision is made by the TSM concerning whether the student has completed the topic satisfactorily. Following is a summary of these three routines.

MISCONDET Transfer.--The first activity merely involves a transfer of data from temporary memory to permanent (disk) memory. A copy of the list of misconceptions remains within the TSM to facilitate the operation of the CHOOSE-TOpic routine.

Threshold transfer.--The modification of the eight dynamic pedagogical parameters' threshold values is based upon the actions of a nested expert system whose only function
is to decide what modifications to the parameters need to be made. The six parameters governing the CHOOSE-TOPIC procedure and the two parameters governing the number of questions to ask during the EXPLORE-COMPETENCY procedure are only modified when the topic is chosen by ARPHY. In other words, ARPHY only evaluates its performance when it actually performs. Assuming ARPHY chose the last topic, the INSPECT-THRESHOLDS routine computes four numbers. These numbers are: (1) number of BLOOM-1 correct, (2) number of BLOOM-1 wrong, (3) number of BLOOM-2 correct, and (4) number of BLOOM-2 wrong. The basic rationale behind the forthcoming expert decision is that if ARPHY chose a topic in which the student performed poorly, then some threshold was not at the correct level. Conversely, if ARPHY chose a topic involving, say, a coordinate move through the net-archy, and the student performed well, then ARPHY will modify the threshold so that the coordinate movement will more likely be chosen during the next cycle.

Consider the following situation. Assume the initial values of the two thresholds for super-ordinate movement to be .30 for prerequisite children and .30 for prerequisite Bloom level. ARPHY evaluates all possible movements through the net-archy. One topic in the super-ordinate direction has three prerequisites. One of the prerequisites (the current topic) has been passed with three BLOOM-2 correct. ARPHY will note that the thresholds for children and Bloom have
been exceeded by the fraction of prerequisite children passed (.33) and proceed to calculate a ranking for the topic. The ranking will have a positive value since both thresholds have been exceeded. The greater the differential between the actual status of the parameter C or B and the threshold, the higher the ranking of the topic.

Assume that the super-ordinate topic is ranked the highest of all the possible topics. ARPHY chooses the topic and proceeds with the instruction. Assuming the student performs poorly, the following assertions may result.

(MULTIPLE BLOOM-2 WRONG)
(MULTIPLE BLOOM-2 CORRECT)

The specialized expert system which is devoted only to making threshold value decisions forward-chains to determine if any threshold values need to be changed. In the above case, the following rule is activated.

(RULE THRESHOLD-SET-17
 IF (LAST MOVEMENT WAS SUPER-ORDINATE)
 (LAST CHOICE MADE BY ARPHY)
 (MULTIPLE BLOOM-2 CORRECT)
 (MULTIPLE BLOOM-2 WRONG))
 (SITUATION IS DEFAULT)
 (THEN (RAISE THRESHOLD *SUPER-C*)))

The assertion (RAISE THRESHOLD *SUPER-C*) is acted upon and the threshold for the percentage of completed prerequisite children for super-ordinate movement is increased. The size of the increase may be dynamic, but for this research was set at .1. Threshold *SUPER-C* becomes .4. If ARPHY again encounters the above situation where one-third (.33) of the
children are completed, the threshold value will not be exceeded, and ARPHY assigns a negative value to the ranking with the magnitude of the ranking proportional to the differential between the percentage of children completed and the threshold value. This will result in super-ordinate movements becoming less likely as students perform more poorly after super-ordinate movements.

The self-improving capabilities of the TSM with regard to selection of topics allows weaker students to receive a complete foundation of prerequisites prior to any super-ordinate movement. More learned students will continuously be challenged by more and more difficult material until they reach their optimum level of learning according to the Gagné learning types. Should one of the latter students reach a topic which must have a complete foundation of prerequisite learning, the student will probably not pass the topic, then ARPHY will diagnose the misconceptions, and remedial instruction will occur with little significant change to the pedagogical parameters.

The pedagogical parameters will have limits on the thresholds. ARPHY will always consider super-ordinate to be more difficult than sub-ordinate movement. The lower limit of the threshold values for co-ordinate movement is ranked between sub-ordinate and super-ordinate movement. The following lower limits are used by the TSM:
*SUPER-C* .3    *SUPER-B* .35
*CO-C*    .2    *CO-B*    .15
*SUB-C*    .1    *SUB-B*    .05

The upper limits are 1.00 for all parameters. If the nested expert requests a threshold to be changed to a value outside of its allowable boundary, the threshold will remain at its present status.

The other two parameters constitute the threshold values for the number of BLOOM-1 or BLOOM-2 questions to ask. If the student is performing well, ARPHY will self-improve by lowering the threshold values for these parameters so that less questions are asked. If the student is performing poorly, ARPHY resets these parameters so that more questions are asked during the next session. The effect of the modifications is delayed until the next session to filter out short-term trends.

Topic completion.--The decision as to whether or not a topic has been actually learned by the student is not as much of a YES-NO choice for ARPHY as it is a two-fold series of actions. First, the actual learning has been recorded as Bloom level measurements which are placed on the blackboard along with any misconceptions which may have been detected. Secondly, ARPHY must draw an imaginary line somewhere as to what is or is not acceptable. During this research, the line was fixed so that a student was not be considered to have completed a topic when either of the following two situations
occurred: (1) multiple BLOOM-2 wrong, or (2) single BLOOM-1 wrong and single BLOOM-2 wrong. The rules governing this decision are located in the main bank of expert system rules. If completion is allowed, the topic name is added to the list stored as *TOPICS-COMPLETED* and transferred to the student module. If completion is disallowed, the topic is recorded in the student module as having been attempted and remains available to be completed after remedial work is completed.

Quitting or Continuing

After wrapping-up the topic, ARPHY asks the student:

"WANT TO CONTINUE  ????  (Y OR N)"

The student may choose to proceed with another topic, take a break (by not responding), or terminate the session. If the student chooses to continue, the TSM begins at the top of the high-level loop under expert system control. If the student wishes to terminate the session, ARPHY invokes the procedure CLOSE-UP which essentially calls a conference with each module and allows all final messages to be passed and data to be stored.

During CLOSE-UP, ARPHY presents the student with a report detailing the information contained in the current student module. This information includes a list of the problems completed and the prerequisite topics which have been learned. The misconceptions identified by MISCONDET which remain to be corrected are listed. ARPHY then informs the
student that the misconceptions are targeted for correction
during the next session. A sample CLOSE-UP screen is shown
is Figure 19.

OK, Twyla, Let's summarize your over-all progress:

<table>
<thead>
<tr>
<th>Task Complete Status</th>
<th>Problems Completed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not completed</td>
<td>1</td>
</tr>
<tr>
<td>Completed</td>
<td>2, 3, 4, 5, 6</td>
</tr>
<tr>
<td></td>
<td>7, 8, 9, 10, 11, 12</td>
</tr>
</tbody>
</table>

Here are the topics you have completed:

1. GRAVITY AS A FORCE
2. TIME
3. V = A * T
4. NET FORCE
5. F = M * A
6. D = (1/2)*A*T^2
7. FORMULA FOR ACCELERATION
8. GRAVITY AS ACCELERATOR
9. IDEA OF ACCELERATION
10. IDEA OF FREE-FALL
11. WEIGHT
12. MASS

The word is out on you in the following topics. We'll probably work on these next time!

1. HORIZONTAL BEING INDEPENDENT OF VERTICAL VELOCITY
2. DIRECTIONS

Your reading speed is 178.7 wpm

I'll be looking forward to our next session!!!
BYE BYE !!

Figure 19.--CLOSE-UP routine as observed by student

The student is then provided with a hard copy (print-out) of
the CLOSE-UP report. This print-out allows the student to retain a reminder of his progress through the tutorial.

Communications Module

Two basic types of communication are used by the communications module: direct and indirect. Direct communication is used when the message is intended only for one module. Indirect communication is used when the message is either of general interest to more than one module or may need to be accessed at some later time.

Direct Communication

Whenever one module needs to communicate with another, LISP facilitates the communication by direct entry through a function call. Whenever, say, the TSM needs the expert module to perform a task and return a value, the appropriate function within the expert module is called either by the TSM or by a high-level function within the expert module. When the called procedure has completed its task, one or more values is passed back to the original calling procedure within the TSM.

The other form of direct communication is that between the student and ARPHY. The communications module functions as a translator. In one mode of the translator, input from the student is received and translated into a form acceptable to the module requesting the input. In the other mode, the translator receives non-humanly intelligible information from
a module and translates it into a form which the student will understand. One example of the student-to-module translator is the GET-RESPONSE procedure. GET-RESPONSE is called by the expert module, the latter of which passes the type of input which is expected of the student, i.e., letter, word, sentence, or function key. The student is then informed by the communications module that ARPHY is waiting for the appropriate response. If the student response deviates from expected the translator works with the student until the correct type of response is received. This process enables ARPHY to control the number of errors which could occur and limits confusion.

Two related procedures which involve the communications module are the SAY-RIGHT and the SAY-WRONG procedures. The expert module calls upon these two procedures during the EXPLORE-COMPETENCY PROCEDURE by passing them the correct answer, the student's answer, and its evaluation of the student's response. These procedures then convert the expert module's utterance into an intelligible communication to the student.

Indirect Communications

As mentioned earlier, information which either is intended for more than one module or is not ready for use by a module passes through one of two types of indirect communication links. The first link is the blackboard. Messages can be placed on the blackboard by one module and be read by more
than one other. For example, the expert module places evaluations of the student's performance on BLOOM-1 and BLOOM-2 questions on the blackboard. The blackboard is then read by the tutorial strategy module while in the INSPECT-THRESHOLDS procedure. The student module also inspects this blackboard information when storing a permanent record of the student's performance. The blackboard can be modified by any procedure within any module. The two procedures called for handling blackboard modification are the ADD-BB and the REMOVE-BB procedures located within the communications module.

The other method of indirect communications is the assertion list used by the main and nested (threshold inspector) expert systems. Whenever an assertion is produced by one of the experts during a forward-chaining procedure, the assertion is recorded on the assertion list. This assertion is an IF of a rule which may be fired during a subsequent inferencing procedure. The assertion list is modifiable through the REMOVE-ASSERTION and ADD-ASSERTION procedures located within the communications module. Other modules may call these procedures to alter the assertion list.

Description of the Hardware and the Software

Hardware

The hardware, or the physically tangible equipment to be used in the construction of ARPHY is an IBM PC-XT with color
graphics and monitor equipped with the following non-standard modifications to facilitate the complex software:

* 655,000 bytes of internal random-access memory (RAM).
* two 10-megabyte Winchester-type (hard, or fixed) disk drives (one used only for back-up).
* an Intel 8087 math co-processor interfaced with the main CPU (8088) to facilitate numerical processing.

An IBM PC graphics printer is used to provide the student with both a hard copy of his progress and a print-out of any interesting or important graphics display from the screen.

The fixed disk drive will hold all resident COMMON LISP software, the student, expert, and tutorial strategy software, and the controlling software. This way, the student will never need to exchange any disks, as is usually the case when running complex software on a dual disk drive system.

Software

The software which is used by ARPHY is based in GOLDEN COMMON LISP, a version of COMMON LISP marketed by Gold Hill Computers, Cambridge, Mass. Designed to be run on IBM PC or PC-compatible computers with at least 256 K of RAM, or 512 K for developing applications, the complete GCLISP software occupies 1.8 Megabytes of hard disk space. The top-level control software occupies 128 K, as does the GMACS editor. Following are the memory requirements of the remaining components of ARPHY:
* Student module 3 K-bytes
* Expert module 195 K-bytes
* Tutorial module 155 K-bytes
* Auxiliary routines 60 K-bytes

Garbage collection, a process for which LISP is well-known, whereby old thoughts (useless bound variables) are cleaned out of RAM, will be forced at the beginning of each instructional routine to alleviate the possibility of a disturbing garbage collection occurring during a projectile's flight.

Summary

This chapter has presented the structure of ARPHY as a collection of modules, each of which is a collection of procedures. In the actual LISP implementation, there is no distinct boundary between the modules. Procedures call other procedures without regard for the parent module. The reason for discussing the procedures as sub-structures of modules is to facilitate future work in ICAI development. All ICAI systems will have some set of procedures devoted to, say, storing knowledge. In this way, all developers of machine knowledge may be able to discuss the problem in terms of how one researcher's expert module approached the problem.

The structure which has been discussed in this chapter has yet to be analyzed during an actual tutorial session. In the following chapter the procedures through which ARPHY was tested are discussed.


CHAPTER IV

STUDENT-IN-LOOP TESTING PROCEDURE

In deciding the proper conditions under which ARPHY should be tested, it was necessary to evaluate the optimum conditions under which ARPHY would be operating. The possible implementations of a tutor such as ARPHY with self-improving capabilities include both single-course and multiple-course settings. A physics course with strong mathematical emphasis and a conceptual course with little mathematical emphasis could both use ARPHY since the pedagogical parameters could be (and should be) made course-dependent. In both course settings, ARPHY was designed to self-improve a set of pedagogical parameters unique to each student.

Since only three problems were being addressed in this research, testing ARPHY's performance for a complete physics course was not possible. However, both the multiple-course and the multiple student-type conditions were simulated. The ability of ARPHY to self-improve and provide learner-based instruction was rigorously tested by subjecting ARPHY to various types of learners from four physics courses, each of
which required different backgrounds and foundations in science.

Student Population

The students used in the testing of ARPHY were volunteers from four first-semester courses offered by the Physics Department at North Texas State University. The courses, ranked by difficulty according to the 1985 NTSU classification scheme are: (1) physics for majors, (2) conceptual physics for physical education and industrial arts majors, (3) conceptual physics and physical science for elementary education and liberal arts majors, and (4) descriptive astronomy. The students were classified according to the physics class they were taking. Group I consisted of those students in physics for majors class. Group II included the students from the conceptual physics class for physical education and industrial arts majors. Group III included the students from the conceptual physics class for elementary education majors. Group IV included students from the astronomy class. The first ten volunteers from each group comprised the pool from which a total of ten were selected to participate according to the conditions set forth below.

Sequencing of the Students

The students were scheduled according to their group membership. When ARPHY's pedagogical parameters reached an arbitrarily established level indicating relative stability
for this particular classification of students, another group was scheduled. This initial single-class tutoring had a two-fold purpose. First, the selective sequencing facilitated an analysis of ARPHY's rate of self-improvement for students within the same type of physics class. The measurement provided by this process was termed the new learner stabilization factor, or NLSF. An NLSF of 1.00 signifies that ARPHY's pedagogical parameters reached relative stability (filtered) after one student completed three problems of the tutorial. An NLSF of 2.00 signifies that ARPHY reached stability after two complete three-problem sessions (two students). Secondly, ARPHY's stability for tutoring within the class-type can be observed. The interval of each threshold change could be too large to have a stable system during ambient, or non-significant, changes. The INSPECT-THRESHOLDS procedure was programmed to effectively give ARPHY a tutorial modus operandi ranging from overly-reactive to quite complacent.

The first group of students studied were in a first-semester calculus-based physics class (Group I). When ARPHY stabilized after n students, the remaining sessions (10 - n) were filled with a rotation of the first students that could be scheduled.
Conditions of the Test

The students were informed that the amount of time necessary for completing the tutorial would be from 45 minutes to 4 hours. They were also informed that their goal was to correctly solve three basic physics problems. The students were allowed to schedule the tutorial as either a series of short sessions or one visit. To provide additional motivation for students in Groups II, III, and IV, it was emphasized that they were under no obligation to complete the tutorial.

Student Preparation

The students were advised that ARPHY was an intelligent tutor which tries to help them solve physics problems by building upon simple concepts. They were told that ARPHY does not mind if they miss any questions and actually does equally well when the student makes a mistake. The students were shown a diagram of the net-archy, shown their three goals, and told that their objective was to achieve the three goals in any order and through any path. Finally, the fact that they or ARPHY can choose each topic was explained.

Initial Pedagogical Parameters

The initial values for the threshold levels were selected to cause ARPHY to adapt to a student with a weak background in physics. For the weak student, ARPHY is most likely to choose sub-ordinate movement through the net-archy and least likely to choose super-ordinate movement. The values of
these pedagogical parameters used by ARPHY at the start of the test were as follows:

- Super-ordinate threshold C (*SUPER-C*) = 0.9
- Super-ordinate threshold B (*SUPER-B*) = 0.95
- Co-ordinate threshold C (*CO-C*) = 0.8
- Co-ordinate threshold B (*CO-C*) = 0.85
- Sub-ordinate threshold C (*SUB-C*) = 0.1
- Sub-ordinate threshold B (*SUB-C*) = 0.15

The questioning strategy used by ARPHY was selected to allow ARPHY enough questions to reasonably assess student competency, but neither cause the first student too much boredom with easy questions, nor to risk mis-assessing the competency of the student by not asking enough questions. The starting threshold values for the questioning strategy were:

- Number of BLOOM-1 questions: 2
- Number of BLOOM-2 questions: 4

To insure the misconception-detection ability of ARPHY, a minimum threshold value of BLOOM-1 questions was established at 1 and the minimum for BLOOM-2 questions was established at 2. When a student exited ARPHY, new pedagogical parameters were stored both within the tutorial strategy module (TSM) and the student module (SM). These values determined the teaching strategy of ARPHY for the next student.

Completion of the Testing of ARPHY

When each of the ten students finished the tutorial, the testing of ARPHY was completed. A student was judged to have finished when one of the following conditions existed:
(1) all three problems had been successfully completed; (2) the student, after attempting to solve each problem at least once, did not solve all the problems and decided not to attempt the unsolved problems again; or (3) the student was tutored at least a total of one hour and decided not to complete the tutorial.

Summary of the Test

The answer to the question as to whether or not ARPHY actually improved its performance depends on how the term "improve" is defined. For purposes of this study, improvement occurred any time a modification was made in the tutorial strategy module so as to reduce the difference between the learning-type of the student and the model student the TSM was ideally prepared to tutor, as determined by the threshold values of the pedagogical parameters.
CHAPTER V

RESULTS AND DISCUSSION OF THE STUDENT-IN-LOOP TEST

The results of the student-in-loop testing of ARPHY are discussed as ten sets of data, one for each student. Each set of data consists of two tables and a brief discussion. The first table presented for each of the ten sets of data contains a brief student profile, the sequence of instruction, who chose each topic (student or ARPHY), the performance of the student for each topic, and the actions taken by ARPHY at the completion of the topic. The second table contains the system changes within the Tutorial Strategy Module (TSM) and the Student Module (SM) after each student has completed the tutorial. The TSM modifications include a new list of students encountered, and the new threshold values for each of the eight pedagogical parameters. Information stored in the SM includes the student's reading speed, remaining misconceptions, order of topics completed, blackboard data, and verbal comments relating to the tutorial session. The data shown for the student module will neither include the order of topics completed since the previous table covered these data, nor will it contain the blackboard data. Some of the instructional sequence tables are divided into two portions due to a
student choosing to quit for the day and return at a later time.

The initial modus operandi of ARPHY was determined by the threshold values of the pedagogical parameters. As discussed in Chapter IV, these values were arbitrarily chosen so as to give ARPHY rather conservative parameters, as shown in Table V below.

### Table V

**INITIAL PEDAGOGICAL PARAMETERS**

Tutorial Strategy Module

<table>
<thead>
<tr>
<th>Students encountered: none</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of BLOOM-1 questions to ask: 2</td>
</tr>
<tr>
<td>Number of BLOOM-2 questions to ask: 4</td>
</tr>
<tr>
<td>Threshold value (C) for super-ord child-ok .9</td>
</tr>
<tr>
<td>Threshold value (B) for super-ord Bloom-ok .95</td>
</tr>
<tr>
<td>Threshold value (C) for co-ord child-ok .8</td>
</tr>
<tr>
<td>Threshold value (B) for co-ord Bloom-ok .85</td>
</tr>
<tr>
<td>Threshold value (C) for sub-ord child-ok .1</td>
</tr>
<tr>
<td>Threshold value (B) for sub-ord Bloom-ok .15</td>
</tr>
</tbody>
</table>

Although it is obvious that a more dramatic change in the threshold values of the parameters would have been realized by initially reversing the values for sub- and super-ordinate movement, ARPHY would have made unreasonable strategic decisions. In brief, these unreasonable decisions would have included choosing topics for the student which were
super-ordinate to the present topic, and did not have all the prerequisites completed.

The first student to be tutored was Rahul. As a member of the first group of mathematically proficient students, Rahul represented an obvious mis-match between tutorial strategy and learning-type. This mis-match is apparent upon an inspection of the following two sequences of instruction: (1) the instructional sequence ARPHY would most likely follow; and (2) a reasonable sequence for the student based upon principles of learner-based instruction. ARPHY was prepared for a student who had a weak background in physics. Rahul was therefore going to be bored with ARPHY's instructional sequence due to his strong background in the sciences. The instructional sequence of topics for Rahul is shown below in Table VI.

The topics were either chosen by the student or by ARPHY. There were two methods by which ARPHY chose the next topic. With the first method, the student, having just successfully completed a topic, elected to allow ARPHY to choose the next topic. The second method by which ARPHY chose the following topic was due to the student not completing a topic, resulting in a mandated topic selection, governed by the MANDATE procedure. Completion was disallowed whenever either at least Bloom-2 questions were answered incorrectly or one Bloom-1 and one Bloom-2 question was answered incorrectly.
### TABLE VI

**INSTRUCTIONAL SEQUENCE FOR STUDENT 1**

<table>
<thead>
<tr>
<th>Topic</th>
<th>Chosen by</th>
<th>Student</th>
<th>Performance</th>
<th>ARPHY</th>
</tr>
</thead>
<tbody>
<tr>
<td>distance</td>
<td>student</td>
<td>all correct</td>
<td></td>
<td>[nc]</td>
</tr>
<tr>
<td>speed</td>
<td>student</td>
<td>all correct</td>
<td></td>
<td>[nc]</td>
</tr>
<tr>
<td>constant vel. formula</td>
<td>ARPHY</td>
<td>all correct</td>
<td></td>
<td>lower co-ord thresholds B &amp; C</td>
</tr>
<tr>
<td>problem 1</td>
<td>student</td>
<td>single BLOOM-2 wrong</td>
<td></td>
<td>MISCONDET at hor-indep-vert</td>
</tr>
<tr>
<td>hor-indep-vert</td>
<td>student</td>
<td>multiple BLOOM-2 wrong</td>
<td></td>
<td>mandate sub-ordinate, MISCONDET at const vel idea</td>
</tr>
<tr>
<td>const vel idea</td>
<td>MANDATED</td>
<td>all correct</td>
<td></td>
<td>[nc]</td>
</tr>
<tr>
<td>( d = \frac{1}{2} a t^2 )</td>
<td>student</td>
<td>all correct</td>
<td></td>
<td>[nc]</td>
</tr>
<tr>
<td>problem 1</td>
<td>student</td>
<td>all correct</td>
<td></td>
<td>[nc]</td>
</tr>
<tr>
<td>( f = ma )</td>
<td>student</td>
<td>all correct</td>
<td></td>
<td>[nc]</td>
</tr>
<tr>
<td>problem 2</td>
<td>student</td>
<td>all correct</td>
<td></td>
<td>[nc]</td>
</tr>
<tr>
<td>time up = down</td>
<td>student</td>
<td>all correct</td>
<td></td>
<td>[nc]</td>
</tr>
<tr>
<td>problem 3</td>
<td>student</td>
<td>all correct</td>
<td></td>
<td>[nc]</td>
</tr>
</tbody>
</table>

Performance was determined through an analysis of the student performance, and the actions taken by ARPHY. The student could have gotten all questions correct, had a single BLOOM-1 wrong, a single BLOOM-2 wrong, multiple BLOOM-2
wrong, or a combination of the BLOOM-1 and BLOOM-2 wrong. As for the ARPHY's performance, there could have been no change in status, denoted by [nc], or ARPHY could have taken one of three major actions. One of the possible actions included the alteration of threshold values for the pedagogical parameters. Recalling the discussion in Chapter III concerning the various pedagogical parameters, there were two thresholds for each of the three types of net-archy movement, labeled B and C. These abbreviations stood for prerequisite Bloom level and prerequisite children for the topic under consideration. Another action which could have been taken by the TSM was the detection of misconceptions by the expert module (EM). The third action occurred when the student did not pass a topic and ARPHY mandated tutoring in a topic.

Whenever the student chose the topic, no threshold values were altered. This situation occurred for Rahul's first two topics (distance and speed). While allowing the student to take the initiative, ARPHY's capacity for self-improvement is decreased since the decisions are the student's instead of ARPHY's.

Rahul allowed ARPHY to choose the third topic (constant velocity formula). Because of the initial values of the pedagogical parameters, the topic chosen was the most cautious topic available. Since the topic was chosen by ARPHY and the topic was reached through a co-ordinate movement, the threshold values B and C for the co-ordinate subsumption were
decreased, as shown in Table VII. Rahul sought more challenging material and chose his next topic at a higher level, which resulted in a wrong response.

**TABLE VII**

**SYSTEM STATUS AFTER STUDENT 1**

**Tutorial Strategy Module**

<table>
<thead>
<tr>
<th>Students encountered: Rahul</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of BLOOM-1 questions to ask:</td>
</tr>
<tr>
<td>Number of BLOOM-2 questions to ask:</td>
</tr>
<tr>
<td>Threshold value (C) for super-ord child-ok</td>
</tr>
<tr>
<td>Threshold value (B) for super-ord Bloom-ok</td>
</tr>
<tr>
<td>Threshold value (C) for co-ord child-ok</td>
</tr>
<tr>
<td>Threshold value (B) for co-ord Bloom-ok</td>
</tr>
<tr>
<td>Threshold value (C) for sub-ord child-ok</td>
</tr>
<tr>
<td>Threshold value (B) for sub-ord Bloom-ok</td>
</tr>
</tbody>
</table>

* indicates lowest limit allowed

**Student Module**

Name: Rahul

Reading speed: 210 wpm

Remaining misconceptions detected by MISCONDET: none

Duration of tutorial: 1 h 48 m

Comments: -previously had trouble visualizing principles
- appreciated seeing principles animated

Since Rahul chose most of his topics, ARPHY did not have the opportunity to alter many of its threshold values. Consequently, the next student to be tutored was slightly more likely to have ARPHY access a topic through co-ordinate
movement due to the lowered thresholds. The next student was only asked three BLOOM-2 questions since Rahul had such a high percentage of his topics completed with no incorrect answers.

Since the pedagogical parameters were far from being stabilized, the next student selected was from the same group as Rahul. As shown in Table VIII, this student also had little problem completing the tutorial.

TABLE VIII
INSTRUCTIONAL SEQUENCE FOR STUDENT 2

<table>
<thead>
<tr>
<th>Topic</th>
<th>chosen by</th>
<th>Performance</th>
<th>ARPHY</th>
</tr>
</thead>
<tbody>
<tr>
<td>const vel idea</td>
<td>student</td>
<td>all correct</td>
<td>[nc]</td>
</tr>
<tr>
<td>constant vel. formula</td>
<td>ARPHY</td>
<td>all correct</td>
<td>lower super-ord thresholds B &amp; C</td>
</tr>
<tr>
<td>const change in velocity</td>
<td>ARPHY</td>
<td>all correct</td>
<td>lower co-ord thresholds B &amp; C</td>
</tr>
<tr>
<td>v = at</td>
<td>student</td>
<td>single BLOOM-1 wrong</td>
<td>[nc]</td>
</tr>
<tr>
<td>horiz indep of vert velocity</td>
<td>ARPHY (remote)</td>
<td>single BLOOM-1 wrong</td>
<td>lower co-ord thresholds B &amp; C</td>
</tr>
<tr>
<td>problem 1</td>
<td>student</td>
<td>all correct</td>
<td>[nc]</td>
</tr>
<tr>
<td>problem 3 (rem)</td>
<td>student</td>
<td>all correct</td>
<td>[nc]</td>
</tr>
<tr>
<td>f = ma</td>
<td>student</td>
<td>all correct</td>
<td>[nc]</td>
</tr>
<tr>
<td>problem 2</td>
<td>student</td>
<td>all correct</td>
<td>[nc]</td>
</tr>
</tbody>
</table>
Since Frank allowed ARPHY to select the second topic, the only movement possible was super-ordinate. The subsequent successful completion of this topic caused the two super-ordinate threshold values to be decreased. The system changes after Frank completed his tutorial are shown in Table IX.

**TABLE IX**

**SYSTEM STATUS AFTER STUDENT 2**

**Tutorial Strategy Module**

<table>
<thead>
<tr>
<th>Students encountered: Frank, Rahul</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of BLOOM-1 questions to ask: 1 *</td>
</tr>
<tr>
<td>Number of BLOOM-2 questions to ask: 2 *</td>
</tr>
<tr>
<td>Threshold value (C) for super-ord child-ok .8</td>
</tr>
<tr>
<td>Threshold value (B) for super-ord Bloom-ok .85</td>
</tr>
<tr>
<td>Threshold value (C) for co-ord child-ok .5</td>
</tr>
<tr>
<td>Threshold value (B) for co-ord Bloom-ok .55</td>
</tr>
<tr>
<td>Threshold value (C) for sub-ord child-ok .1 *</td>
</tr>
<tr>
<td>Threshold value (B) for sub-ord Bloom-ok .15</td>
</tr>
</tbody>
</table>

* indicates lowest limit allowed

**Student Module**

<table>
<thead>
<tr>
<th>Name: Frank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reading speed: 182 wpm</td>
</tr>
<tr>
<td>Remaining misconceptions detected by MISCONDET: acceleration idea</td>
</tr>
<tr>
<td>Duration of tutorial: 1 h 16 m</td>
</tr>
</tbody>
</table>

Comments: English was not his native language, so he appreciated graphical depictions of principles
The fact that Frank was a physics major is reflected in the brief duration of the tutorial and the absence of any incorrect answers for BLOOM-2 questions. Frank was from Taiwan and had trouble reading English. This is a possible explanation for the incorrect answers to BLOOM-1 questions. The BLOOM-1 questions were designed in part to test the students' abilities to recall verbal information.

The following student was from the same class. She had a strong mathematical background, but little experience with any physical science. As shown in Table X, students may carry misconceptions into the most basic entry-level topics.

**TABLE X**

**INSTRUCTIONAL SEQUENCE FOR STUDENT 3**

<table>
<thead>
<tr>
<th>Name:</th>
<th>Major: Secondary Education (math)</th>
<th>Math level: pre-calculus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dona</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Topic chosen by</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Student</td>
<td>ARPHY</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Topic</th>
<th>Student</th>
<th>BLOOM-2 wrong</th>
<th>MISCONDET at mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>mass</td>
<td>single</td>
<td></td>
<td></td>
</tr>
<tr>
<td>weight</td>
<td>ARPHY</td>
<td>all correct</td>
<td>raise super-ord thresholds B &amp; C</td>
</tr>
<tr>
<td>free-fall idea</td>
<td>ARPHY</td>
<td>all correct</td>
<td>lower sub-ord thresholds B &amp; C</td>
</tr>
<tr>
<td>acceleration idea</td>
<td>ARPHY</td>
<td>all correct</td>
<td>lower co-ord thresholds B &amp; C</td>
</tr>
</tbody>
</table>

(Continued on next page)
Dona admitted to being quite afraid of physics. She blamed her fear on her lack of coursework in the physical sciences, but said that she was determined to solve at least one problem. Possibly due to time constraints or a phobia, Dona never returned to complete her tutorial. The resulting system changes are shown in Table XI.

An indicator which, at least in Dona's case, was correlated with ability in this subset of physics was the performance on one of the entry-level topics. Dona expressed pleasure that ARPHY was able to guide her through as much territory as it did in an hour. She noted that the session helped her much more than an hour of lecture, but wished that she could enjoy physics more than she did.
TABLE XI
SYSTEM STATUS AFTER STUDENT 3

Tutorial Strategy Module

Students encountered: Dona, Frank, Rahul

| Number of BLOOM-1 questions to ask | 2 |
| Number of BLOOM-2 questions to ask | 3 |
| Threshold value (C) for super-ord child-ok | 0.9 |
| Threshold value (B) for super-ord Bloom-ok | 0.85 |
| Threshold value (C) for co-ord child-ok | 0.4 |
| Threshold value (B) for co-ord Bloom-ok | 0.45 |
| Threshold value (C) for sub-ord child-ok | 0.1 * |
| Threshold value (B) for sub-ord Bloom-ok | 0.05 * |

* indicates lowest limit allowed

Student Module

Name: Dona
Reading speed: 329 wpm
Remaining misconceptions detected by MISCONDET: constant change in velocity
Duration of tutorial: 1 h 16 m
Comments: Dona did not return to complete the tutorial.

The pedagogical parameters had not yet stabilized, however, and the number of BLOOM-2 questions to be asked was the first parameter to reverse its direction of change. The instructional sequence for the following student, also from the same class, is shown in Table XII below.
## TABLE XII

**INSTRUCTIONAL SEQUENCE FOR STUDENT 4**

<table>
<thead>
<tr>
<th>Topic</th>
<th>Student</th>
<th>ARPHY</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>distance</td>
<td>student</td>
<td>all correct</td>
<td>[nc]</td>
</tr>
<tr>
<td>speed</td>
<td>student</td>
<td>all correct</td>
<td>[nc]</td>
</tr>
<tr>
<td>constant vel ideas</td>
<td>ARPHY</td>
<td>all correct</td>
<td>lower sub-ord thresholds B &amp; C</td>
</tr>
<tr>
<td>hor indep of vertical vel</td>
<td>student</td>
<td>all correct</td>
<td>[nc]</td>
</tr>
<tr>
<td>problem 1</td>
<td>student</td>
<td>all correct</td>
<td>[nc]</td>
</tr>
<tr>
<td>acceleration formula</td>
<td>student</td>
<td>all correct</td>
<td>[nc]</td>
</tr>
<tr>
<td>( f = ma )</td>
<td>student</td>
<td>all correct</td>
<td>[nc]</td>
</tr>
<tr>
<td>( d = \frac{1}{2} a t^2 )</td>
<td>ARPHY</td>
<td>all correct</td>
<td>lower co-ord thresholds B &amp; C</td>
</tr>
<tr>
<td>const velocity formula</td>
<td>ARPHY</td>
<td>all correct</td>
<td>lower co-ord thresholds B &amp; C</td>
</tr>
<tr>
<td>problem 2</td>
<td>student</td>
<td>all correct</td>
<td>[nc]</td>
</tr>
<tr>
<td>weight (remote)</td>
<td>student</td>
<td>all correct</td>
<td>[nc]</td>
</tr>
<tr>
<td>problem 3</td>
<td>student</td>
<td>problem WRONG</td>
<td>MISCONDET in time up = down, ( v = a \times t ) MANDATE sub-ord</td>
</tr>
<tr>
<td>time up = down</td>
<td>student</td>
<td>all correct</td>
<td>[nc]</td>
</tr>
<tr>
<td>problem 3</td>
<td>student</td>
<td>all correct</td>
<td>remove MISCONDET</td>
</tr>
</tbody>
</table>
The first choice made by ARPHY was sub-ordinate movement. Trevor then chose the next four topics to be more challenged. After problems 1 and 2 were successfully completed, Trevor chose problem 3 with only one out of three of the prerequisites successfully completed. Trevor worked the problem incorrectly, so ARPHY proposed possible misconceptions in the principle that time up is equal to time down and v=at. ARPHY guessed at which possible misconception to remediate. This guess was probably correct since Trevor correctly solved problem 3 after learning the principle. The resulting student module and TSM are shown in Table XIII below.

| TABLE XIII |

**SYSTEM STATUS AFTER STUDENT 4**

**Tutorial Strategy Module**

<table>
<thead>
<tr>
<th>Students encountered: Trevor, Dona, Frank, Rahul</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of BLOOM-1 questions to ask: 1 *</td>
</tr>
<tr>
<td>Number of BLOOM-2 questions to ask: 2 *</td>
</tr>
<tr>
<td>Threshold value (C) for super-ord child-ok .8</td>
</tr>
<tr>
<td>Threshold value (B) for super-ord Bloom-ok .85</td>
</tr>
<tr>
<td>Threshold value (C) for co-ord child-ok .3</td>
</tr>
<tr>
<td>Threshold value (B) for co-ord Bloom-ok .35</td>
</tr>
<tr>
<td>Threshold value (C) for sub-ord child-ok .1 *</td>
</tr>
<tr>
<td>Threshold value (B) for sub-ord Bloom-ok .05 *</td>
</tr>
</tbody>
</table>

* indicates lowest limit allowed

(Continued on next page)
### TABLE XIII—Continued

**SYSTEM STATUS AFTER STUDENT 4**

<table>
<thead>
<tr>
<th>Student Module</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Name:</strong></td>
<td>Trevor</td>
</tr>
<tr>
<td><strong>Reading speed:</strong></td>
<td>115 wpm</td>
</tr>
<tr>
<td><strong>Remaining misconceptions detected by MISCONDET:</strong></td>
<td>v = a t</td>
</tr>
<tr>
<td><strong>Duration of tutorial:</strong></td>
<td>1 h 48 m</td>
</tr>
</tbody>
</table>

**Comments:** English is second language. Had no trouble with understanding text. --- enjoyed graphics.

Since Trevor chose eleven out of fifteen topics, the six movement thresholds only had four opportunities to change. The two other thresholds (number of BLOOM-1 and BLOOM-2 questions) are independent of who chose the topics and have both their minimum values. The next student was from the same class as Trevor. His instructional sequence is shown in Table XIV.

Henry obviously had a solid foundation of accelerated motion principles. He worked his way quickly to the level of principles and solved the problems in a time-efficient manner. The system status is shown in Table XV.
Despite the ease with which Henry completed the tutorial, he noted that he was never bored because he was quite interested in the graphic representations of the physics principles and concepts which were more interesting than his textbook. While Henry took advantage of the ability to select his own topics, the next student allowed ARPHY to choose many of the topics, as shown in Table XVI.
TABLE XV

SYSTEM STATUS AFTER STUDENT 5

Tutorial Strategy Module

<table>
<thead>
<tr>
<th>Students encountered: Henry, Trevor, Dona, Frank, Rahul</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of BLOOM-1 questions to ask: 1 *</td>
</tr>
<tr>
<td>Number of BLOOM-2 questions to ask: 2 *</td>
</tr>
<tr>
<td>Threshold value (C) for super-ord child-ok .8</td>
</tr>
<tr>
<td>Threshold value (B) for super-ord Bloom-ok .85</td>
</tr>
<tr>
<td>Threshold value (C) for co-ord child-ok .2</td>
</tr>
<tr>
<td>Threshold value (B) for co-ord Bloom-ok .25</td>
</tr>
<tr>
<td>Threshold value (C) for sub-ord child-ok .1 *</td>
</tr>
<tr>
<td>Threshold value (B) for sub-ord Bloom-ok .05 *</td>
</tr>
</tbody>
</table>

* indicates lowest limit allowed

Student Module

| Name: Henry |
| Reading speed: 203 wpm |
| Remaining misconceptions detected by MISCONDET: none |
| Duration of tutorial: 1 h 5 m |
| Comments: Regular class instructor indicated that Henry, a student from Thailand, was near the top of his class. |

During her tutorial, Vicky commented that she never had understood the difference between constant velocity and constant acceleration, but she was finally getting a clearer understanding. It is noteworthy that the two thresholds (C and B) related to co-ordinate movement were raised for the first time.
<table>
<thead>
<tr>
<th>Topic</th>
<th>Performance</th>
<th>Student</th>
<th>ARPHY</th>
</tr>
</thead>
<tbody>
<tr>
<td>const vel idea</td>
<td>student</td>
<td>single</td>
<td>MISCONDET at const vel idea</td>
</tr>
<tr>
<td>constant vel. formula</td>
<td>ARPHY</td>
<td>all correct</td>
<td>lower super-ord thresholds B &amp; C</td>
</tr>
<tr>
<td>constant change in velocity</td>
<td>ARPHY</td>
<td>multiple</td>
<td>raise co-ord thresholds B &amp; C</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>MISCONDET at accel. idea</td>
</tr>
<tr>
<td>const vel idea</td>
<td>MANDATED</td>
<td>all correct</td>
<td>[nc]</td>
</tr>
<tr>
<td>constant change in velocity</td>
<td>ARPHY</td>
<td>all correct</td>
<td>[nc] (after MANDATE)</td>
</tr>
<tr>
<td>v = a t</td>
<td>student</td>
<td>single</td>
<td>[nc]</td>
</tr>
<tr>
<td>horiz indep of vertical vel (remote)</td>
<td>ARPHY</td>
<td>single</td>
<td>MISCONDET at gravity as accel</td>
</tr>
<tr>
<td>time up = down</td>
<td>student</td>
<td>all correct</td>
<td>[nc]</td>
</tr>
<tr>
<td>gravity as force</td>
<td>ARPHY</td>
<td>all correct</td>
<td>lower sub-ord thresholds B &amp; C</td>
</tr>
<tr>
<td>weight</td>
<td>student</td>
<td>all correct</td>
<td>[nc]</td>
</tr>
<tr>
<td>problem 3</td>
<td>student</td>
<td>all correct</td>
<td>[nc]</td>
</tr>
<tr>
<td>BREAK after 1 h 20 m</td>
<td>student</td>
<td>all correct</td>
<td>[nc]</td>
</tr>
</tbody>
</table>

(Continued on next page)
TABLE XVI
INSTRUCTIONAL SEQUENCE FOR STUDENT 6—Continued

<table>
<thead>
<tr>
<th>Topic</th>
<th>Topic chosen by</th>
<th>Performance</th>
<th>ARPHY</th>
</tr>
</thead>
<tbody>
<tr>
<td>mass</td>
<td>ARPHY</td>
<td>all correct</td>
<td>[nc]</td>
</tr>
<tr>
<td>( f = ma )</td>
<td>student</td>
<td>all correct</td>
<td>[nc]</td>
</tr>
<tr>
<td>problem 2</td>
<td>student</td>
<td>all correct</td>
<td>[nc]</td>
</tr>
<tr>
<td>( d = (1/2) a t^2 )</td>
<td>student</td>
<td>all correct</td>
<td>[nc]</td>
</tr>
<tr>
<td>problem 1</td>
<td>student</td>
<td>all correct</td>
<td>[nc]</td>
</tr>
</tbody>
</table>

The resulting student module and TSM are shown in Table XVII.

TABLE XVII
SYSTEM STATUS AFTER STUDENT 6

Tutorial Strategy Module

<table>
<thead>
<tr>
<th>Students encountered: Vicky, Henry, Trevor, Dona, Frank, Rahul.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of BLOOM-1 questions to ask: 1 *</td>
</tr>
<tr>
<td>Number of BLOOM-2 questions to ask: 2 *</td>
</tr>
<tr>
<td>Threshold value (C) for super-ord child-ok 0.7</td>
</tr>
<tr>
<td>Threshold value (B) for super-ord Bloom-ok 0.75</td>
</tr>
<tr>
<td>Threshold value (C) for co-ord child-ok 0.3</td>
</tr>
<tr>
<td>Threshold value (B) for co-ord Bloom-ok 0.35</td>
</tr>
<tr>
<td>Threshold value (C) for sub-ord child-ok 0.1 *</td>
</tr>
<tr>
<td>Threshold value (B) for sub-ord Bloom-ok 0.05 *</td>
</tr>
</tbody>
</table>

* indicates lowest limit allowed

(Continued on following page)
### TABLE XVII—Continued

**SYSTEM STATUS AFTER STUDENT 6**

<table>
<thead>
<tr>
<th>Student Module</th>
<th>Name:</th>
<th>Vicky</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reading speed:</td>
<td>192 wpm</td>
<td></td>
</tr>
<tr>
<td>Remaining misconceptions detected by MISCONDET:</td>
<td>gravity as accelerator acceleration idea</td>
<td></td>
</tr>
<tr>
<td>Duration of tutorial:</td>
<td>2 h 10 m</td>
<td></td>
</tr>
<tr>
<td>Comments:</td>
<td>Continuously had trouble with principles involving acceleration due to a prior misconception.</td>
<td></td>
</tr>
</tbody>
</table>

All thresholds except the two related to super-ordinate motion either reached their minimum values (such as subordinate) or stabilized as judged by their reversal in the direction of change. The system was not yet deemed to be completely stable since ARPHY had limited chances to alter the super-ordinate thresholds. Again, the next student was from the same class. This student's instructional sequence is shown below in Table XVIII.

Bryan said that he enjoyed allowing ARPHY to choose the topics since each topic picked by ARPHY resulted in an interesting demonstration of certain physics principles. Since Bryan did allow ARPHY much control over the learning environment, ARPHY was able to modify its super-ordinate thresholds significantly, as shown in Table XIX.
### TABLE XVIII

**INSTRUCTIONAL SEQUENCE FOR STUDENT 7**

<table>
<thead>
<tr>
<th>Name:</th>
<th>Major:</th>
<th>Math level:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bryan</td>
<td>comp. science</td>
<td>trigonometry</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Topic</th>
<th>chosen by</th>
<th>Student</th>
<th>ARPHY</th>
</tr>
</thead>
<tbody>
<tr>
<td>const vel idea</td>
<td>student</td>
<td>all correct</td>
<td>[nc]</td>
</tr>
<tr>
<td>constant vel. formula</td>
<td>ARPHY</td>
<td>all correct</td>
<td>lower super-ord thresholds B &amp; C</td>
</tr>
<tr>
<td>const change in velocity</td>
<td>ARPHY</td>
<td>multiple</td>
<td>raise co-ord thresholds B &amp; C</td>
</tr>
<tr>
<td>horiz indep of vertical vel</td>
<td>ARPHY</td>
<td>BLOOM-2 wrong</td>
<td>MISCONDET at const vel idea</td>
</tr>
<tr>
<td>problem 1</td>
<td>ARPHY</td>
<td>all correct</td>
<td>MANDATE sub-ord</td>
</tr>
<tr>
<td>d = (1/2) a t^2</td>
<td>ARPHY</td>
<td>all correct</td>
<td>lower super-ord thresholds B &amp; C</td>
</tr>
<tr>
<td>acceleration formula</td>
<td>ARPHY</td>
<td>all correct</td>
<td>lower sub-ord thresholds B &amp; C</td>
</tr>
<tr>
<td>acceleration idea</td>
<td>ARPHY</td>
<td>all correct</td>
<td>lower sub-ord thresholds B &amp; C</td>
</tr>
<tr>
<td>f = ma</td>
<td>student</td>
<td>all correct</td>
<td>[nc]</td>
</tr>
<tr>
<td>force</td>
<td>ARPHY</td>
<td>all correct</td>
<td>lower sub-ord thresholds B &amp; C</td>
</tr>
</tbody>
</table>

(Continued on next page)
### TABLE XVIII--Continued

**INSTRUCTIONAL SEQUENCE FOR STUDENT 7**

<table>
<thead>
<tr>
<th>Topic</th>
<th>Topic chosen by</th>
<th>Performance Student</th>
<th>ARPHY</th>
</tr>
</thead>
<tbody>
<tr>
<td>net force</td>
<td>student</td>
<td>all correct</td>
<td>[nc]</td>
</tr>
<tr>
<td>problem 2</td>
<td>ARPHY</td>
<td>all correct</td>
<td>lower super-ord thresholds B &amp; C</td>
</tr>
<tr>
<td>weight</td>
<td>student</td>
<td>all correct</td>
<td>[nc]</td>
</tr>
<tr>
<td>gravity as accelerator</td>
<td>ARPHY</td>
<td>all correct</td>
<td>lower co-ord thresholds B &amp; C</td>
</tr>
<tr>
<td>( v = a t )</td>
<td>student</td>
<td>all correct</td>
<td>[nc]</td>
</tr>
<tr>
<td>problem 3</td>
<td>student</td>
<td>all correct</td>
<td>[nc]</td>
</tr>
</tbody>
</table>

### TABLE XIX

**SYSTEM STATUS AFTER STUDENT 7**

**Tutorial Strategy Module**

---

Students encountered: Bryan, Vicky, Henry, Trevor, Dona, Frank, Rahul.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of BLOOM-1 questions to ask:</td>
<td>1 *</td>
</tr>
<tr>
<td>Number of BLOOM-2 questions to ask:</td>
<td>4</td>
</tr>
<tr>
<td>Threshold value (C) for super-ord child-ok</td>
<td>.3 *</td>
</tr>
<tr>
<td>Threshold value (B) for super-ord Bloom-ok</td>
<td>.35 *</td>
</tr>
<tr>
<td>Threshold value (C) for co-ord child-ok</td>
<td>.2</td>
</tr>
<tr>
<td>Threshold value (B) for co-ord Bloom-ok</td>
<td>.25</td>
</tr>
<tr>
<td>Threshold value (C) for sub-ord child-ok</td>
<td>.1 *</td>
</tr>
<tr>
<td>Threshold value (B) for sub-ord Bloom-ok</td>
<td>.05 *</td>
</tr>
</tbody>
</table>

* indicates lowest limit allowed

(Continued on next page)
TABLE XIX--Continued
SYSTEM STATUS AFTER STUDENT 7

<table>
<thead>
<tr>
<th>Student Module</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name:</td>
</tr>
<tr>
<td>Reading speed:</td>
</tr>
<tr>
<td>Remaining misconceptions detected by MISCONDET:</td>
</tr>
<tr>
<td>Duration of tutorial:</td>
</tr>
<tr>
<td>Comments:</td>
</tr>
</tbody>
</table>

The two super-ordinate thresholds reached their lowest limit allowable according to the initial strategy. Therefore, ARPHY was essentially stabilized after 7 students. The next student was from a low-level conceptual physics class. Her instructional sequence is shown in Table XX.

Mary's rate of information processing was slower than the previous students. She was weak in mathematics and struggled with each topic which was more difficult than the three entry-level topics.
### TABLE XX

**INSTRUCTIONAL SEQUENCE FOR STUDENT 8**

<table>
<thead>
<tr>
<th>Topic</th>
<th>Performance</th>
<th>Student</th>
<th>ARPHY</th>
</tr>
</thead>
<tbody>
<tr>
<td>mass</td>
<td>student</td>
<td>all correct</td>
<td>[nc]</td>
</tr>
<tr>
<td>weight</td>
<td>ARPHY</td>
<td>single BLOOM-1 wrong</td>
<td>lower super-ord thresholds B &amp; C</td>
</tr>
<tr>
<td>free-fall idea</td>
<td>ARPHY</td>
<td>all correct</td>
<td>lower sub-ord thresholds B &amp; C</td>
</tr>
<tr>
<td>acceleration idea</td>
<td>ARPHY</td>
<td>single BLOOM-2 wrong</td>
<td>maintain threshold level</td>
</tr>
<tr>
<td>gravity as accelerator</td>
<td>ARPHY</td>
<td>all correct</td>
<td>lower super-ord thresholds B &amp; C</td>
</tr>
<tr>
<td>acceleration formula</td>
<td>student</td>
<td>all correct</td>
<td>[nc]</td>
</tr>
<tr>
<td>( d = \frac{1}{2} a t^2 )</td>
<td>ARPHY</td>
<td>all correct</td>
<td>lower super-ord thresholds B &amp; C</td>
</tr>
<tr>
<td>BREAK for the day</td>
<td>student</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

She did, however, take her time and accomplished the above topics during one session. Her next session is shown below.

Although Mary had initially felt that she would never understand physics, her perseverance helped her in more fully understanding many of the principles and concepts of accelerated motion which were previously beyond her comprehension.
Mary never returned to work on the prerequisite principle for problem 1. The resulting system status follows in Table XXI. Had Mary returned, the data in the student module would have caused ARPHY to work on the principle that horizontal velocity is independent of vertical velocity.
### TABLE XXI

**SYSTEM STATUS AFTER STUDENT 8**

#### Tutorial Strategy Module

| Students encountered: Mary, Bryan, Vicky, Henry, Trevor, Dona, Frank, Rahul. |
| Number of BLOOM-1 questions to ask: | 1 * |
| Number of BLOOM-2 questions to ask: | 4 |
| Threshold value (C) for super-ord child-ok | .3 * |
| Threshold value (B) for super-ord Bloom-ok | .35 * |
| Threshold value (C) for co-ord child-ok | .2 |
| Threshold value (B) for co-ord Bloom-ok | .25 |
| Threshold value (C) for sub-ord child-ok | .1 * |
| Threshold value (B) for sub-ord Bloom-ok | .05 * |

* indicates lowest limit allowed

#### Student Module

| Name: Mary |
| Reading speed: 179 wpm |
| Remaining misconceptions detected by MISCONDET: general directions, horizontal independent of vertical velocity |
| Duration of tutorial: 2 h 5 min |
| Comments: Due to Mary's weak mathematical ability, she had to struggle to understand most of the principles. Mary did not return to pass problem 1 |

The next student was from an astronomy class. Since astronomy is commonly taken as a laboratory science by students with varying backgrounds, the ability level of this
student was unknown. The instructional sequence is shown in Table XXII below.

### TABLE XXII

**INSTRUCTIONAL SEQUENCE FOR STUDENT 9**

<table>
<thead>
<tr>
<th>Topic</th>
<th>Topic chosen by</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>mass</td>
<td>student</td>
<td>all correct</td>
</tr>
<tr>
<td>weight</td>
<td>student</td>
<td>all correct</td>
</tr>
<tr>
<td>free-fall idea</td>
<td>ARPHY</td>
<td>all correct</td>
</tr>
<tr>
<td>time up = down</td>
<td>student</td>
<td>single</td>
</tr>
<tr>
<td>gravity as a force</td>
<td>student</td>
<td>all correct</td>
</tr>
<tr>
<td>$f = ma$</td>
<td>student</td>
<td>single</td>
</tr>
<tr>
<td>force</td>
<td>student</td>
<td>all correct</td>
</tr>
<tr>
<td>problem 2</td>
<td>student</td>
<td>problem wrong</td>
</tr>
<tr>
<td>BREAK</td>
<td>student</td>
<td></td>
</tr>
<tr>
<td>problem 3</td>
<td>student</td>
<td>problem wrong</td>
</tr>
<tr>
<td>$v = at$</td>
<td>ARPHY</td>
<td>single</td>
</tr>
</tbody>
</table>

(Continued on next page)
TABLE XXII--Continued

INSTRUCTIONAL SEQUENCE FOR STUDENT 9

<table>
<thead>
<tr>
<th>Topic</th>
<th>topic chosen by</th>
<th>Performance Student</th>
<th>ARPHY</th>
</tr>
</thead>
<tbody>
<tr>
<td>problem 3</td>
<td>student</td>
<td>all correct</td>
<td>[nc]</td>
</tr>
<tr>
<td>problem 2</td>
<td>student</td>
<td>problem wrong</td>
<td>MISCONDET at net force</td>
</tr>
<tr>
<td>net force</td>
<td>ARPHY</td>
<td>single</td>
<td>lower sub-ord threshold B</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>MISCONDET at directions</td>
</tr>
<tr>
<td>problem 2</td>
<td>ARPHY</td>
<td>all correct</td>
<td>[nc]</td>
</tr>
<tr>
<td>horiz indep of vertical vel</td>
<td>ARPHY</td>
<td>single</td>
<td>[nc]</td>
</tr>
<tr>
<td>(remote)</td>
<td></td>
<td></td>
<td>(repeated prob.)</td>
</tr>
<tr>
<td>constant vel. formula</td>
<td>ARPHY</td>
<td>all correct</td>
<td>lower co-ord thresholds B &amp; C</td>
</tr>
<tr>
<td>acceleration formula</td>
<td>student</td>
<td>single</td>
<td>[nc]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>BLOOM-1 wrong</td>
</tr>
<tr>
<td>d = (1/2) a t^2</td>
<td>student</td>
<td>single</td>
<td>MISCONDET at accel. idea</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>BLOOM-2 wrong</td>
</tr>
<tr>
<td>problem 1</td>
<td>ARPHY</td>
<td>problem wrong</td>
<td>MISCONDET at speed</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>STUD, may choose raise super-ord</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>threshold C</td>
</tr>
<tr>
<td>problem 1</td>
<td>student</td>
<td>all correct</td>
<td>[nc]</td>
</tr>
</tbody>
</table>

Rich entered the tutorial with many misconceptions which were easily corrected possibly due to the fact that he had not
applied the misconceptions to many situations prior to his tutorial. Although being embarrassed by his wrong answers, he liked the fact that he could still achieve his goals knowing that ARPHY would help him if he did miss any questions. The system status after Rich's sessions is shown below in Table XXIII.

### TABLE XXIII

**SYSTEM STATUS AFTER STUDENT 9**

**Tutorial Strategy Module**

<table>
<thead>
<tr>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of BLOOM-1 questions to ask: 1 *</td>
</tr>
<tr>
<td>Number of BLOOM-2 questions to ask: 5</td>
</tr>
<tr>
<td>Threshold value (C) for super-ord child-ok: .6</td>
</tr>
<tr>
<td>Threshold value (B) for super-ord Bloom-ok: .35 *</td>
</tr>
<tr>
<td>Threshold value (C) for co-ord child-ok: .1 *</td>
</tr>
<tr>
<td>Threshold value (B) for co-ord Bloom-ok: .15 *</td>
</tr>
<tr>
<td>Threshold value (C) for sub-ord child-ok: .1 *</td>
</tr>
<tr>
<td>Threshold value (B) for sub-ord Bloom-ok: .05 *</td>
</tr>
</tbody>
</table>

* indicates lowest limit allowed

**Student Module**

| Name: Rich                                                      |
| Reading speed: 355 wpm                                         |
| Remaining misconceptions detected by MISCONDET: acceleration idea, directions, speed problem 1 |
| Duration of tutorial: 2 h 50 min                                |
| Comments: Rich had been analyzed as having severe test anxiety. He appreciated ARPHY's patience and remedial actions. |
An inspection of co-ordinate threshold C makes it apparent that ARPHY became more rigid with respect to the percentage of completed prerequisites necessary before choosing coordinate movement. ARPHY, therefore, asked the next student 5 BLOOM-2 questions since the last two students had their misconceptions discovered through BLOOM-2 questioning.

The final student was an industrial technology major with many misconceptions. His instructional sequence is shown in Table XXIV below.

**TABLE XXIV**

INSTRUCTIONAL SEQUENCE FOR STUDENT 10

<table>
<thead>
<tr>
<th>Name:</th>
<th>Gary</th>
<th>Major:</th>
<th>Industrial Tech.</th>
<th>Math level:</th>
<th>high school algebra</th>
</tr>
</thead>
<tbody>
<tr>
<td>Topic</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>distance</td>
<td>student</td>
<td>all correct</td>
<td>[nc]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>speed</td>
<td>student</td>
<td>all correct</td>
<td>[nc]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>constant vel. formula</td>
<td>student</td>
<td>all correct</td>
<td>[nc]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>problem 1</td>
<td>ARPHY</td>
<td>problem wrong</td>
<td></td>
<td>MISCONDET at horiz indep of vertical vel, MANDATE sub-ord, raise super-ord thresholds B &amp; C</td>
<td></td>
</tr>
<tr>
<td>horiz indep of vertical vel</td>
<td>MANDATE</td>
<td>multiple BLOOM-2 wrong</td>
<td>MISCONDET's at vert vel idea, const vel idea</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(Continued on next page)
TABLE XXIV—Continued

INSTRUCTIONAL SEQUENCE FOR STUDENT 10

<table>
<thead>
<tr>
<th>vert vel idea</th>
<th>MANDATE</th>
<th>all correct</th>
<th>continue MANDATE</th>
</tr>
</thead>
<tbody>
<tr>
<td>const vel idea</td>
<td>MANDATE</td>
<td>all correct</td>
<td>[nc]</td>
</tr>
<tr>
<td>horiz indep of vertical vel</td>
<td>ARPHY</td>
<td>multiple</td>
<td>MISCONDET's at</td>
</tr>
<tr>
<td>gravity as force</td>
<td>MANDATE</td>
<td>all correct</td>
<td>gravity as force</td>
</tr>
<tr>
<td>time up = down</td>
<td>ARPHY</td>
<td>all correct</td>
<td>and gravity as</td>
</tr>
<tr>
<td>v = a * t</td>
<td>ARPHY</td>
<td>single</td>
<td>an accelerator,</td>
</tr>
<tr>
<td>problem 3</td>
<td>student</td>
<td>all correct</td>
<td>raise super-ord</td>
</tr>
<tr>
<td>f = m a</td>
<td>student</td>
<td>single</td>
<td>thresholds B &amp; C</td>
</tr>
<tr>
<td>net force</td>
<td>ARPHY</td>
<td>all correct</td>
<td>[nc]</td>
</tr>
<tr>
<td>problem 2</td>
<td>student</td>
<td>all correct</td>
<td>MISCONDET at</td>
</tr>
<tr>
<td>constant change in velocity</td>
<td>ARPHY</td>
<td>all correct</td>
<td>accel. formula</td>
</tr>
<tr>
<td>horiz indep of vertical vel</td>
<td>ARPHY</td>
<td>all correct</td>
<td>lower co-ord</td>
</tr>
<tr>
<td>accel. formula</td>
<td>ARPHY</td>
<td>all correct</td>
<td>thresholds B &amp; C</td>
</tr>
<tr>
<td>d = (1/2) a t^2</td>
<td>ARPHY</td>
<td>all correct</td>
<td>[nc]</td>
</tr>
<tr>
<td>problem 1</td>
<td>ARPHY</td>
<td>all correct</td>
<td>(repeat problem)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>[nc]</td>
</tr>
</tbody>
</table>
Gary's extensive set of misconceptions caused more activity within the TSM than any other student for two reasons. First, Gary incorrectly answered many BLOOM-2 questions, and secondly, Gary allowed ARPHY to choose a higher percentage of topics than any other student. Tracing the sequence beginning with Gary's incorrect response to problem 1, ARPHY mandated the principle that horizontal velocity is independent of vertical velocity. After Gary's poor performance on this topic, ARPHY, thanks to good questioning from the expert module, was able to detect a double misconception and mandated two topics for remedial instruction. The final system status is shown in Table XXV.

**TABLE XXV**

**SYSTEM STATUS AFTER STUDENT 10**

**Tutorial Strategy Module**

<table>
<thead>
<tr>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of BLOOM-1 questions to ask: 1 *</td>
</tr>
<tr>
<td>Number of BLOOM-2 questions to ask: 6</td>
</tr>
<tr>
<td>Threshold value (C) for super-ord child-ok: .6</td>
</tr>
<tr>
<td>Threshold value (B) for super-ord Bloom-ok: .35 *</td>
</tr>
<tr>
<td>Threshold value (C) for co-ord child-ok: .1 *</td>
</tr>
<tr>
<td>Threshold value (B) for co-ord Bloom-ok: .15 *</td>
</tr>
<tr>
<td>Threshold value (C) for sub-ord child-ok: .1 *</td>
</tr>
<tr>
<td>Threshold value (B) for sub-ord Bloom-ok: .05 *</td>
</tr>
</tbody>
</table>

* indicates lowest limit allowed
TABLE XXV--Continued

SYSTEM STATUS AFTER STUDENT 10

<table>
<thead>
<tr>
<th>Student Module</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name:</td>
</tr>
<tr>
<td>Reading speed:</td>
</tr>
<tr>
<td>Remaining misconceptions detected by MISCONDET:</td>
</tr>
<tr>
<td>Duration of tutorial:</td>
</tr>
<tr>
<td>Comments:</td>
</tr>
</tbody>
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Gary required the greatest amount of time to complete the tutorial due in part to the large number of misconceptions which needed correction. He nevertheless was very patient with the tutorial and verbalized his thought processes while solving the problems. In every case where he worked a problem incorrectly, the misconception identified through his verbalization was the same as that detected by ARPHY.

Obviously, the final values of the pedagogical parameters was dependent upon the types of students tutored. The values which remained essentially unchanged were the thresholds for sub-ordinate movement. ARPHY almost always found that students were able to learn topics which were prerequisites for the previous topic, so would always allow sub-ordinate
movement. Due to the misconceptions brought to the tutorial by the last three students, ARPHY would have asked the next student six BLOOM-2 questions. ARPHY was programmed to be very reactive to students who perform poorly, so it did not require very many mistakes on the students’ part to cause this variable to increase.

With the results of the student-in-loop testing of ARPHY having been presented and discussed, the following chapter will summarize the research. Problems occurring during the research will be discussed along with suggestions for future innovations.
CHAPTER VI

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Summary

An analysis of the literature related to the use of the computer in physics education, as discussed in Chapter II, revealed that the computer is being used as an instructional tool. The physics instructor is still responsible for the organization of the subject in such a way that the student learns physics within the tutorial structure determined by the instructor for the whole class. The computer is not in control of the learning process. It was emphasized that the computer in the physics classroom was not able to think like a teacher, did not know its subject matter well enough to answer questions, and did not know its students.

An overview of the field of intelligent computer-assisted instruction was given, with special attention being paid to the structure of the component modules and the need for an innovative design which would incorporate learning theory. Ausubel's (1) advance organizer was selected as the basic theory of learning and a method was developed by which the organizer would be incorporated within the tutorial strategy module (TSM). Further incorporation of the types of learning
identified by Gagné (3) and the taxonomy of cognitive educational objectives identified by Bloom (2) yielded an ICAI system which was based upon respected theories of learning.

The resulting system (ARPHY) was set up with the goal of tutoring students in the basic physical concepts and principles related to accelerated motion. The system's tutorial modus operandi was based upon a set of eight pedagogical parameters which were dynamic so the system could self-improve. ARPHY was tested by ten students from various levels of first semester physics classes at North Texas State University during the spring semester of 1985. The sequence of student-types was chosen so the response rate of self-improvement to a certain type of student could be observed. The new learner stabilization factor, or NLSF, was measured as 6.3, meaning that ARPHY's set of pedagogical parameters reached stability for the first ability level of students after six students had each solved three problems and one student had solved one problem. The NLSF was dependent upon the degree to which the student allowed the system to select the topics for instruction. The threshold values of the pedagogical parameters, modified after the completion of a topic which was selected by ARPHY, always indicated self-improvement of the system. Self-improvement was defined as any adjustment in the system performance so as to allow the discrepancy between the actual student-type and the imaginary
type of student the system would be set to tutor to be reduced.

The average length of time required by each student to complete the tutorial was 116.2 minutes. Five of the ten students elected to break their tutorial into two sessions. One student did not complete the tutorial.

The average number of topics covered by each student in order to meaningfully learn the subject well enough to solve the three problems was 13.2 out of a maximum possible of 23. One facet of learner-based instruction which was provided by the system is observed by calculating the average number of topics required for completion of the topics for different classes of students. It was found that the high-level group required 11.7 prerequisites to solve the three problems. The other students, however, required an average of 16.3 prerequisites for solution of the three problems.

The performance of the system in regard to working on misconceptions when necessary (thus increasing the number of topics covered) was in the same pattern as would have been the case with a human tutor.

As with any expert system, a set of rules was used to describe the expert module's domain of knowledge. By no means is there a master set of rules published for physicists, however, the rules used reflect perfectly valid guidelines implemented by physicists in solving Newtonian mechanics problems. The rules relating to Newtonian
mechanics, particularly accelerated motion, are much more rigid than, say, those governing the creation of a piece of art. Part of the beauty of an expert system is the ability to incorporate newly-formulated rules. Pioneering work in the field of physics involves this reformation of rules. A question may be raised as to whether or not this system could teach creativity. It is probable that brilliant minds from Einstein to Picasso knew the rules of their respective fields. It was, however, probably an in-born characteristic of their minds that allowed them to challenge the rules.

Conclusions

The first conclusion is that the ability of ARPHY to provide learner-based instruction was evidenced by the fact that the students took advantage of the opportunity to select their own topics, unless a particular strategic decision on the part of ARPHY prevented their doing so. The distribution of initial topics chosen by the students, out of a choice of three, was evenly distributed (3 distance, 4 mass, 3 constant velocity idea). None of the three non-calculus-based physics students chose to begin with the constant velocity concept, however. Four of the seven calculus-based physics students worked toward solving problem 1 first despite the simplicity of problem 2 which could have been ascertained from an inspection of the prerequisites for the latter problem. Two of the three students from the other groups chose to work toward
problem 2 first. The group 1 students may have attacked the tutorial by goal-setting and efficient selection of topics so as to reach the goal in the shortest amount of time. This is supported by the fact that this group selected their topic 65.7 percent of the time (when they had a decision) versus 53.1 percent for the non-calculus-based physics students.

With the students utilizing about half of the available expert system knowledge during the tutorial, yet still able to meaningfully learn the necessary topics to solve the desired problems, a second conclusion is that ARPHY was able to provide effective learner-based instruction by selecting the instructional sequence based upon learner strengths and weaknesses. The remaining topics, while not being covered with the same frequency by all students, were all valuable to some student at some time. The principle of \( f=ma \) was used by all ten students as a springboard to problem 2. The probability of a principle becoming a "universal" topic is proportional to the number of prerequisites necessary for solution of the problem, in this case, two.

A third conclusion is that an understanding of principles proved to be extremely important for solution of the problems, in keeping with the ideas of Gagné (3). In every situation where a problem was worked incorrectly, the mandated remedial work with the unlearned principle allowed the successful solution of the problem. Since students entered the tutorial with varying degrees of knowledge of the prerequisite
concepts, no concept was investigated by more than four students. In fact, three concepts were not investigated at all. These concepts, horizontal velocity idea, direction of gravity, and direction, were all prerequisites for problem 1. It is probable that all students had prior knowledge of these concepts. It is possible that these concepts, if not previously learned, were able to be learned through the other concepts and principles.

A fourth conclusion is that the concepts were most important for the students who had the weakest foundation in physics. The three non-calculus-based physics students (30 percent) were responsible for 46 percent of the activity at the concept level.

A fifth conclusion is that some principles, such as net force, which was only covered by one out of the seven high-level students, were of varying importance to the solution of the problems depending upon which type of student was being tutored. This points to the tremendous advantage of this ICAI system over conventional physics tutoring. Since a physics textbook only presents information sequentially, the need of students to receive information meaningfully is better met through a system with ARPHY's design.

A final conclusion is that ARPHY's adaptability to the various types of learners faced during the test showed that individualization of instruction was indeed facilitated through the self-improvement as manifested in the altering of
the pedagogical parameters. Thus ARPHY could effectively tutor any level of student from the physics major to the non-science major with little background in physical science.

Recommendations

Due to the advances in computer architecture and artificial intelligence, ICAI will likely play a more important role in education in the future. There exists a great need for designers of CAI material to learn more about the learning process. Obviously, this would require foresight on the part of the software companies responsible for the courseware, but the long-term benefits for ICAI would be substantial. Further innovations in AI and microcomputer technology will allow profits to be more easily realized for large-scale ICAI implementation. It is imperative that a sound integration of learning theory, AI, and cognitive science, occur prior to the time when possible profits bring in CAI designers with no regard for the learning process.

It is recommended that any future work in the area of ICAI for science education be done after consideration of the basic design of ARPHY. The learning theory resident in the system fits extremely well into the artificially intelligent structure. The variety of abilities of students is accommodated by the adaptation of the system to the students.

With further testing of the system, a set of initial threshold values for the pedagogical parameters may be
recommended for various types of physics classes. The system
could then self-improve to adapt to the particular class
while in the environment.

When a complete course is developed, the threshold
values for the pedagogical parameters should be established
in two ways. First, a set of parameters should be kept
which represents an average of all the students within a
class. This will allow ARPHY to have a higher probability of
matching its tutorial strategy with the ability of the stu-
dent. Secondly, the system should develop a set of values
unique to each student in the course. This would be accomp-
lished by starting the student with the initial system values,
then at the end of each session, saving the new values in the
student module. Thus, the tutor would remember the most
effective teaching strategy for each student.

Developing a complete course will be a most difficult
task. Each one of the 26 instructional routines required
approximately eight hours of programming time, using an
intelligent GMACS editor resident in the GCLISP environment.
There is presently no authoring system for intelligent physics
tutoring. The development of an authoring system will allow
rapid development of each one of the routines for the expert
module. Physics teachers with no LISP programming experience
could work with an ARPHY authoring system, if developed, to
write certain modules within their specialty.
The authoring system would not need to be limited to physics education. Due to the modularity of ARPHY, any science which is based upon problems, principles, and concepts could be taught via an ARPHY-based system. Once the expert module is developed, the system would only need to be programmed with the structure of the networked hierarchy. The other modules of the tutor would retain their identity.

Finally, with the development of a complete first-semester physics course and the implementation of personal computers in the educational environment which are capable of running a program of ARPHY's complexity, students of physics would be assured of a firm foundation. The large-scale implementation will also free the regular instructors to spend more time with individual instruction, class and laboratory preparation, and course development.
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