THERMEX: An Educational Expert System for Thermodynamics Students

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Abstract: This article describes the phases involved in the development of an educationol expert-system called THERMEX. THERMEX is designed to assist low-achieving engineering students in the solution of thermodynamic problems. The underlylng instructional strategy of THERMEX is a Socratic dialogue based on an "on-task" diagnosis of the students misconception(s).
Based on 50 final examinations, observations and student intervlews, misconceptions were identified and classified to create the student model and to develop the tutor model. Knowledge is represented according to experts' paths when solving complex thermodynamic tasks. THERMEX is written in Turbo-Prolog which lends itself well to rule-based heuristics.
Validation procedures and results are communicated. as well as a discussion of future plans and research needs, mainly dealing with ideas of how to increase diagnostic capabilites by restructuring of the student model.

Résumé: Cet article décrit les différents phases de développement d'un systéme-expert pédagogique appelé THERMEX. Le but de THERMEX est d'assister les étudiants d'ingénierie qui ont des notes publes dans la solution de problèmes thermodynamiques. La stratégie d'apprentissage sur lequel est fondé THERMEX est un dialogue socratique basé sur un diagnostique des tâches des erreurs d'interprétention de étudiants. Les erreurs d'interprétention, identifés et classlfiés pour créér le modéle d'étudiant et pour développer le modèle de tuteur, étaient fondées sur 50 examens finaux, observations et entrevues d'étudiants. La connaissance est représentée selon les tâches complexes de thermodynamie résolues par les voles de spécialistes. THERMEX est écrit en Turbo-Prolog, ce qui respecte les réglements d'heuristiques. Les résultats et les procédures de validation sont communiqués, en regard des besoins généraux de recherche et des modèles de recherche futurs. Ces derniers étants caracterisés par l'augmentation des capacités diagnostiques par la restructuration du modèle d'étudiant.

INTRODUCTION

An Educational Expert-System can be described as a software programme including specific domain knowledge and a tutor capable of solving a learner's task. The ultimate goal of such a system can be defined as rendering the computer "capable of entirely autonomous pedagogical reasoning", that is claiming domain as well as instructional expertise (Wenger, 1987, p. 5). thermex is an attempt towards the realization of this goal, where the domain expertise is Thermodynamics and the instructional expertise follows a Socratic method. In this method the tutor leads a student through a sequence of questions intending to make the student formulate correct general principles by examination of the validity of hypotheses, by discovering contradictions (diagnostic phase) and extracting correct inferences from known facts (correcting phase) (Collins, 1977; Wenger, 1987). It can be seen as a rule-based decision-making procedure in which the individual learner is confronted with and allowed to correct misconceptions. In THEBMEX, the diagnostic phase is guided by the explicit task questions and the correction phase refers to the heuristics following the identification of errors. The justification for applying a Socratic approach lies in the nature of Thermodynamics which requires an explicit conceptualization or at least formulation of general principles, here labelled qualitative reasoning, before tackling the quantitative procedures of a task.

Smith (1987), in his meta-analysis of current instructional strategies for engineering education, states that learning effectiveness can be facilitated by providing the student with learning strategies which stress; the use of simple heuristics closely related to the studied subject-matter, visual and verbal mapping, computer programming and reasoning sessions with peers and domain experts. In much engineering education, these aspects have been neglected and it is suggested that engineering departments change their approach from stand-up lectures to active learning environments (Smith, 1987).

THERMEX is a software program written in Turbo-Prolog II, which lends itself well to questioning and answering processes. It runs on IBM-PC compatible computers. The following features can be considered as particular to THEBMEX:

- the structuring of the subject matter is based upon principles and axioms including specific heuristics leading to an appropriate choice of hypotheses
- student errors are classified as either procedural or conceptual
- the expert model and the student model represent knowledge in the same manner
- the student model uses a combined approach, applying theories from both the “buggy” and the “overlay” model
- the tutor model is built according to teaching strategies used by professors in thermodynamics. It forms the bases for both the diagnosis and any attempt to provide the student with an adequate problem-solving strategy of learning.

This article describes the different steps, problems, and findings involved in the development of the THEBMEX. A short review of supporting literature is presented in order to illustrate the underlying instructional and modeling methods applied in THEBMEX. The main components of THERMEX and their interrelationships are described. Finally, the formative validation procedure and outcomes are discussed. These will constitute our foundation for future research and development.

AN OVERVIEW OF EDUCATIONAL EXPERT SYSTEMS

Recent studies in Artificial Intelligence have advanced knowledge about how people learn and how experts solve problems. It is widely accepted that intelligence is the capability of formulating and solving problems and that solving problems is best attained through a heuristically guided search among alternatives (Lenat, 1988; Haugeland, 1985). Expert systems, considered as a branch of artificial intelligence, are domain specific problem-solving systems containing a knowledge-base from which correct decisions within the specified field can be made. Intelligent Tutoring Systems (ITS) can be seen as an educational domain specific tutor expert and must therefore include an instructional knowledge base as well as a domain specific knowledge base (Dede & Swigger, 1988). Dede and Swigger (1988) argue that an ITS should be able to adapt itself to different student learning styles and that this can best be attained by using a flexible student model built on "on-task" and continuous diagnosis of the student's misconceptions.

The past ten years show an increasing number of articles dealing with the development and implementation of educational expert systems in science teaching:

1) Brown, Burton and de Kleer (1982) developed an interactive learning environment, SOPHIE, in an advanced electronic trouble-shooting course. They convincingly argue the benefits of first employing a qualitative reasoning about general principles of the domain before trying a quantitative solution of the task to be resolved.
2) Bottino, Forcheri, and Molfino (1986) constructed ESCORT, that teaches group theory which demands not only knowledge of modern algebra, but also the ability to abstract reasoning leading to an acceptable solution. They contend that abstract or qualitative reasoning will help a student to a better conceptual understanding of the subject matter.
3) Slater and Ahuja (1987) produced MACAVITY, an expert tutor for rigid-body mechanics, focussing on the expert's knowledge representation and explanatory facilities for the student. MACAVITY is competent in answering questions through an automatic generation of a code system, which includes the required action. They argue the importance of including the option for the student to get help in the form of, for example, definitions of expressions, concepts, principles, laws, etc.

In summary, expert systems have enclosed a structure where four necessary components can be distinguished (Kearsley, 1987; Becker, 1988):

- an Expert Model;
- a Student Model;
- a Tutor Model; and
- an Interface

The following sections will treat the context for the intended use of THERMEX., and descriptions of the Expert Model, the Student model, the Tutoring model and the Interface.

Architecture of THERMEX

At Sherbrooke University Thermodynamics is an obligatory undergraduate course for engineering students. About 350 students enroll per year and the course consists of a conceptual part (39 hrs), an applied part (12 two-hour exercise sessions), held by T.A.'s, and three exams. Classical Thermodynamics deals with the relation of heat and work in different states of a dynamic system and is defined as the "Science of Energy and Entropy" (Van Wylen, 1978). The general objective of the course is "to acquire and to apply thermodynamic concepts relative to systems and substances". It appears to be a subject-matter difficult to grasp and therefore, emphasis has always been put on providing the students with adequate heuristic strategies to facilitate their conceptual and procedural understanding. However, the current oversized classes and the insufficient time allotted put unreasonable pressure on the teachers and the T.A.'s, consequently provision of individualized instruction is inadequate.

THERMEX is designed to assist student in their attempts to learn the basic concepts and to use appropriate procedures to solve thermodynamics problems. It can thus be likened to a teaching assistant. THERMEX is based on exercises from the French version of the course book "Fundamentals of Classical Thermodynamics" by G.J. Van Wylen (1978), widely used in North America.

A second source of thermodynamic problems, used in THERMEX, is selected final exam problems from the past ten years.

THERMEX provides a learning environment in which the locations of the students' errors are diagnosed through heuristic techniques, that is, the learner has to answer sequential questions pertinent to the chosen exercises. THERMEX assumes that the student has previously attempted a solution and failed. The goal of the diagnostic procedure is to lead the student to an appropriate method of solving a thermodynamic task. When the student fails, THERMEX assists by giving hints in form of pertinent questions.

Figure 1 (a & b) (see page 221) shows the context of THERMEX and the relationships between the learner and the software.

Expert Module

As a first step in the construction of the expert model, an analysis of the subject-matter in thermodynamics was carried out, using an approach proposed by Clancey (1986), which includes the representation of a formal domain knowledge (e.g. algebraic and/or geometrical expressions) and a natural domain knowledge (diagnostic and/or strategic). Formal domain knowledge can be considered to be of algorithmic nature, whereas the natural domain knowledge is seen as heuristic: "the expert's rule of thumb". Several content specialists were involved to insure a more accurate knowledge representation.

Figure 1.a.
Context of THERMEX.

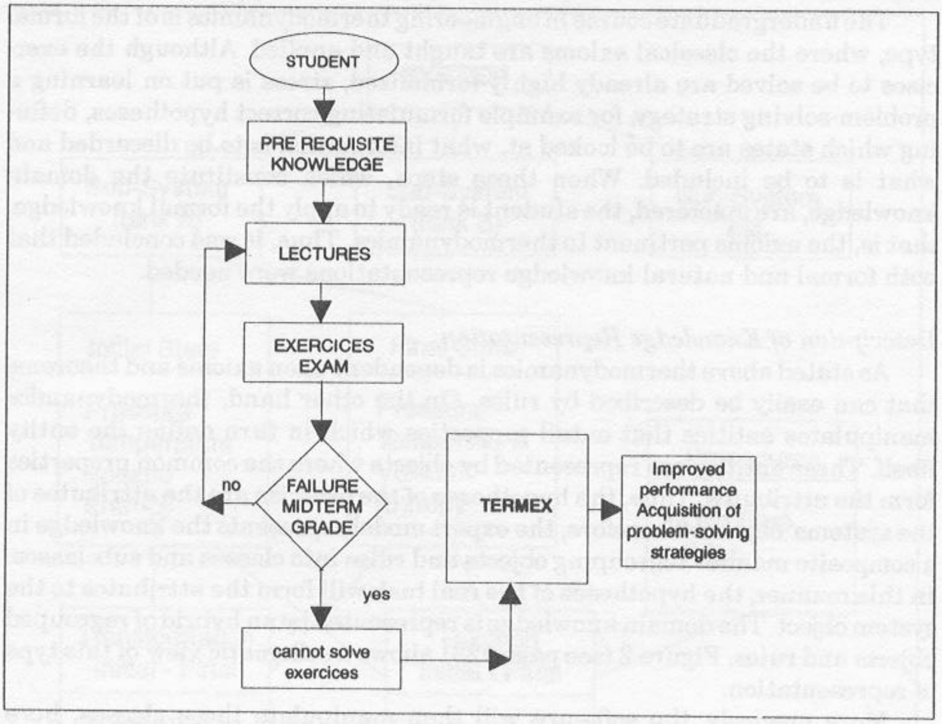
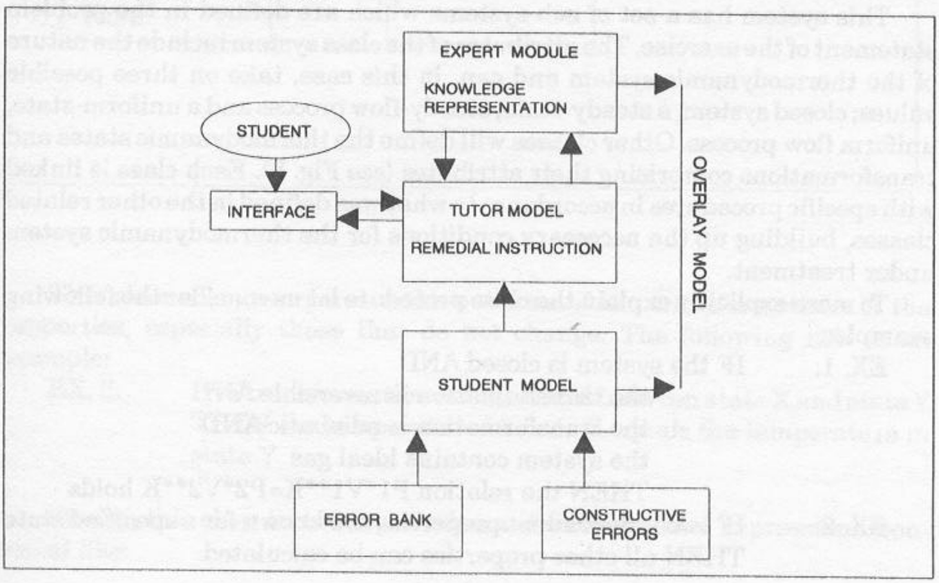


Figure 1.b.
Relationships in THERMEX.



Once the expert model was formally planned, the same "experts" verified and commented on the rule-like representation that was suggested.

The undergraduate course in engineering thermodynamics is of the formal type, where the classical axioms are taught and applied. Although the exercises to be solved are already highly formalized, stress is put on learning a problem-solving strategy, for example formulating correct hypotheses, defining which states are to be looked at, what information is to be discarded and what is to be included. When these steps, which constitute the domain knowledge, are mastered, the student is ready to apply the.formal knowledge, that is, the axioms pertinent to thermodynamics. Thus, it was concluded that both formal and natural knowledge representations were needed.

Description of Knowledge Representation

As stated above thermodynamics is dependent upon axioms and theorems that can easily be described by rules. On the other hand, thermodynamics manipulates entities that entail properties which in turn define the entity itself. These entities are represented by objects where the common properties form the attributes. Thus, the hypotheses of the exercise are the attributes of the systems' objects. Therefore, the expert model represents the knowledge in a composite manner regrouping objects and rules into classes and subclasses. In this manner, the hypotheses of the real task will form the attributes to the system object. The domain knowledge is represented by an hybrid of regrouped objects and rules. Figure 2 (see page 223) shows a schematic view of this type of representation.

More precisely, the software will then manipulate these classes, here transformations, states, and procedures. The first class is related to the thermodynamic system in question.

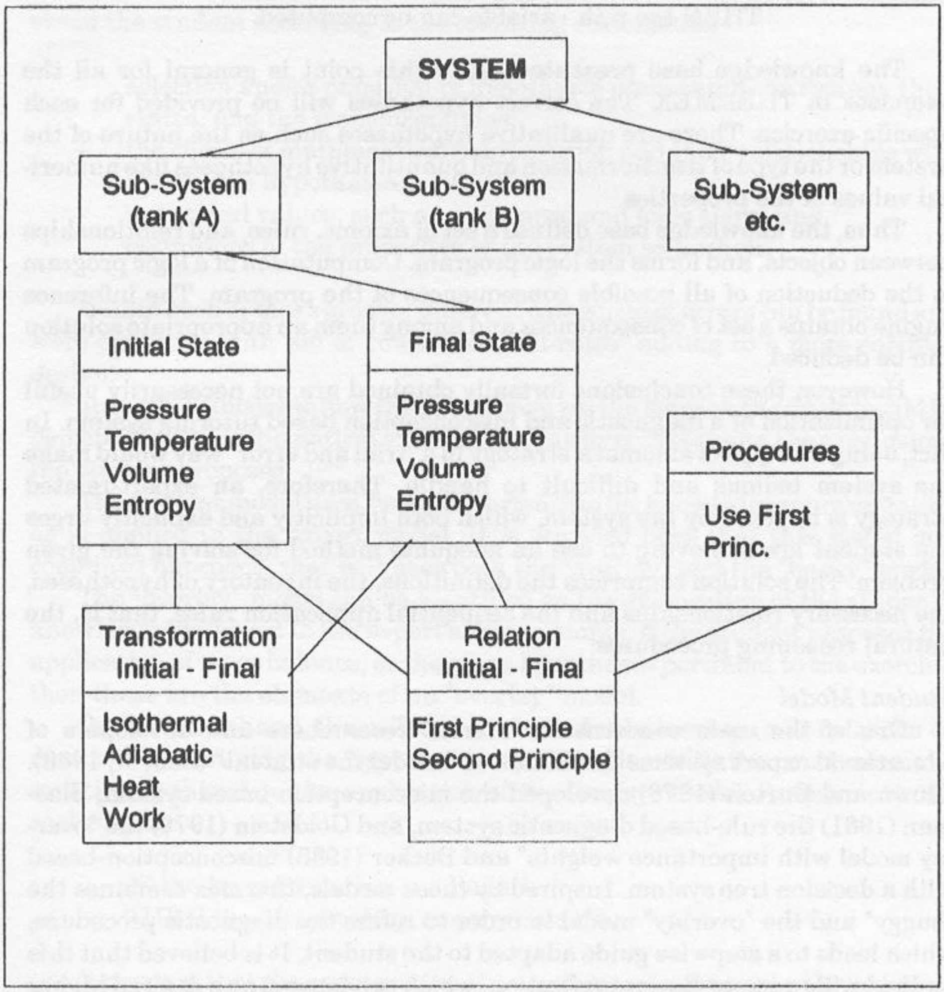
This system has a set of sub-systems which are defined in the problem statement of the exercise. The attributes of the class system include the nature of the thermodynamic system and can, in this case, take on three possible values; closed system, a steady-state, steady-flow process and a uniform-state, uniform flow process. Other classes will define the thermodynamic states and transformations comprising their attributes (see Fig. 2). Each class is linked with specific procedures in accordance to what was defined in the other related classes, building up the necessary conditions for the thermodynamic system under treatment.

lb more explicitly explain the class procedure let us consider the following examples:

EX. 1: IF the system is closed AND
the transformation is reversible AND
the transformation is adiabatic AND
the system contains ideal gas
THEN the relation Pl*Vl**K=P2*V2**K holds

EX. 2: IF two independent properties are known for a specified state
THEN all other properties can be calculated.

Figure 2.
Knowledge Representation.



This class also incorporates the outcome of the transformations of the properties, especially those that do not change. The following rule is an example:

EX. 3: IF a transformation is isothermal between state X and state Y THEN the temperature in state X equals the temperature in state Y

Finally, this class includes procedures of mathematical expressions (concepts) like:

EX. 4: IF a relation includes n variables AND (n - 1) variables are known the knowledge base
THEN the n:th variable can be computed.

The knowledge base presented up to this point is general for all the exercises in THERMEX. The correct hypotheses will be provided for each specific exercise. There are qualitative hypotheses such as the nature of the system or the type of transformation andquantitative hypotheses like numerical values of the properties.

Thus, the knowledge base defines a set of axioms, rules, and relationships between objects, and forms the logic program. Computation of a logic program is the deduction of all possible consequences of the program. The inference engine obtains a set of consequences and among them an appropriate solution can be deduced.

However, these conclusions formally obtained are not necessarily useful for optimization of a diagnostic and misconception based tutoring system. In fact, using this type of axiomatic strategy in a “trial and error” way would make the system tedious and difficult to handle. Therefore, an expert-related strategy is imposed by the system, which both implicitly and explicitly urges the student low-achieving to use an adequate method for solving the given problem. The solution comprises the definitions, the inventory of hypotheses, the necessary relationships and the sequential application rules, that is, the natural reasoning procedures.

Student Model

One of the main concerns for current researchers and developers of educational expert systems lies in how to “model the student” (Self, J., 1988). Brown and Burton (19’78) developed the misconception-based system, Sleeman (1981) the rule-based diagnostic system, and Goldstein (1979) the “overlay model with importance weights” and Becker (1988) misconception-based with a decision tree system. Inspired by these models, thermex combines the “buggy” and the “overlay” model in order to refine the diagnostic procedure, which leads to a stepwise guide adapted to the student. It is believed that this method will promote student reflection, which can be seen as a desired higher order learning function.

To ensure a more accurate model of the student, a group of students were individually videotaped during four two-hour sessions. The students were asked to do their weekly thermodynamic exercises and to verbalize every step they took to solve the task. These videotapes were analyzed and resulted in a list of errors, These were classified into strategic, conceptual and computational procedural errors. In this study, emphasis was put on how students went about solving their problem and why they would block. This analysis resulted in valuable information for the creation of both the student and tutor model.

Another source of useful information for the construction of the student came from the analysis of 50 student exams where errors were categorized in the same manner.

Description and Examples

The student model was developed on these observations. Thus, THERMEX views the student according to the following statements:

- selection and/or omission of hypotheses concerning the system, the states, and the transformations;
- the choice of mathematical expression(s) and their relationships with the chosen hypotheses;
- numerical values, such as units used and logic signs; and
- definitions of the properties of the system as a whole.

Within each of these groups, different categories of errors can be found and were classified with aid of rules and “mal-rules” adding to a more complex design.

To further illustrate how thermex perceives the learner, the model could be depicted by its mathematical expressions, the hypotheses and the conclusions the student proposes.

The student model uses the same formalism for knowledge representation as is applied in the expert model. It is stressed here that this model is a combined approach, that is it uses both the “overlay” and the “buggy” model.

The “overlay” model can be identified as the verification of the student’s knowledge compared to the expert’s. For example, if the student proposes the application of mass balance, or the given hypotheses pertinent to the exercise, then these are the elements of an “overlay” model.

On the other hand, the utilization of a bad relationship (mal-rule) can be detected by verifying the hypotheses in connection with the conclusion and constitutes therefore the application of the “buggy” model. An example of a mal-rule is:

IF the transformation is adiabatic
THEN the temperature stays constant

It appears that the construction of a pie-determined error bank, including known mal-rules, does accelerate the diagnostic procedure. In THERMEX a certain number of mal-rules are defined and it would be interesting to find a way of progressively increasing this bank, whenever new mal-rules are detected. Becker (1988) proposes to make this error bank individual in order to create a student “on-task” history, thus increasing the individualistic capacities of the ITS and thereby rendering the system more adaptive.

Tutor Model

Smith (1987), as earlier mentioned, argues that especially low-achievers benefit from learning a qualitative reasoning strategy before attempts are made to do quantitative solutions. The target learners for THERMEX are low-achievers; that is, they received a grade lower than 45% on the first midterm exam. The main goal is to provide the student with efficient learning strategies appropriate to the subject-matter (in the present case thermodynamics). Thus, the instructional strategy adopted in THERMEX includes an individualized diagnosis in form of questions tailored to each problem and depending on the errors committed by the learner. Once this initial diagnosis is carried out, the "tutor" selects the appropriate remedial strategy, The selected strategy then leads the student through the different steps of the solution again by questions. This approach attempts to fulfill the assumptions of Socratic tutoring (Wenger, 1987, p. 39).

The diagnosis is divided into three parts. First, THERMEX asks the student which parts of exercise have been attempted; secondly, it asks the student to give numerical values of given and computed data, thirdly it asks to define the physical properties (the hypotheses) of the thermodynamic system. This information forms the outer limits within which a stepwise heuristic guide takes over. The purpose of this guide is to point out to the student where he goes wrong. It tells him to verify the problem statement, given data, his computations, the hypotheses (a built-in dictionary of definitions and explanations of expressions are available on command to assist the student in verifying his solution), etc. By doing all this in a carefully structured manner, it is hoped that the student will identify, and correct the errors. If the student fails more than twice, then correct answers are provided stepwise, until the exercise is fully solved. This method was adopted in order to increase the learning efficiency of THERMEX. However, a chance is left for the student to continue whenever the misconception(s) seem(s) to be cleared up as far as the "tutor" can judge.

Description and Examples

Once the exercise is chosen, THERMEX determines by questioning the student on which part of the exercise the learner needs help. Each exercise is divided into 3-6 main questions, which are displayed in a menu (Fig. 3), where the student can easily mark which questions the learner has attempted. For this reason, the task of finding out precisely where aid is desired is also facilitated. These exercises are displayed using the same indications as in the course book, so that the student can immediately recognize which exercise is assigned for whatever week the learner is in.

The next step is to compare the main numerical values, both those given in the problem statement and computed by the student, as well as to identify which formulas he has proposed. The formulas are numbered in the same way as in the coursebook, for example, if "3.4" is displayed in the menu the student knows that it means "PV=nRT" or "PV=mT", which are alternative ways of finding "PV". Further, a comparison of the proposed hypotheses and the physical properties pertinent to the exercise takes place. These types of errors are classified as conceptual and stem from the course objectives, experience of the professors and the analyses of the student exams. Hence, if the results are correct, the next question is considered until the blockage point is found. This technique provides the diagnosis, then the tutoring takes over. The information gathered from the diagnosis serves in briefing the student what type of errors the learner has committed.

If none of the important concepts are absent or omitted, the programme lets the student continue, but stores whatever mistakes are committed. These mistakes are, for example superfluous hypotheses, unnecessarily proposed relationships, small computational errors, etc. If a numerical error is detected the expert-system highlights the wrong number, and comments on how the error appears to be classified, for example as a copy/typing error, as a wrong unit, as a miscalculation, and prompts the student to verify these, but lets the learner go on. THERMEX does not consider these types of errors important enough to force a stop. However, a summary of them is given at the end to further make the student aware of diagnosed errors. The program does not furnish the exact numerical value(s), but rather leaves it up to the student to calculate these outside the program.

Qualitative reasoning, that is, knowing the concept of the thermodynamic system in terms of characteristics such as open-closed, adiabatic, etc. (see Figure 3 on page 228), is to be understood before attempting a quantitative solution. This strategy is supported by the analyses of the videotapes where students erroneously tried to put numerical values "into any old formula" before defining the thermodynamic system and thus missed out on understanding the problem altogether.

Since THERMEX is directed towards students having difficulties, stress is put on learning an adequate strategy to solve thermodynamic tasks. To help thestudent in this task, the "tutor" analyzes steps taken by thestudent to solve the tasks. Thus, if, for example, the student proposes the correct hypotheses, but does not know how to use them, the expert-system first reminds the learner that the hypotheses are correct and then points out what relationships are compatible with these hypotheses. If the learner omits information, then the THERMEX "tutor" suggests: "read the problem statement again". If this procedure does not clarify the concepts to be used, then THERMEX indicates a correct procedure.

In the case where the student blocks from the start, the "tutor" suggests a convenient content-related strategy for solving thermodynamic problems. This strategy is used by professors and teaching assistants and is also fundamental to the tutoring system, but not explicit until the blockage point is found. This strategy can be outlined in a few statements:

- to define the thermodynamic system(s) of the problem;
- to identify the principal hypotheses concerning this system;
- to name the essential relationships according to the chosen hypotheses which are appropriate to the exercise; and
- to correctly apply these relations.

Here again, as indicated above, the assumed instructional strategy

Figure 3.
Menu of Questions and Hypothesis.

Système Expert THERMEX

Quelle(s) sont la ou les questions pour lesquelles tu veux de l'aide. ?
Tu peux choisir une ou plusieurs questions, quand tu as FINI
TOUS TES choix, appuie sur F10 pour les enregistrer.

Questions	
1	Quels sont le travail et la chaleur (T = Cte) ?
2	Quelle est la variation d'entropie ?
3	Quels sont le travail et la chaleur (poly.) ?
4	Quelle est la variation d'entropie ?
5	Quels sont le travail et la chaleur (adia.) ?
6	Quelle est la variation d'entropie ?

Choisis ta ou tes questions avec RETURN, puis appuie sur F10 pour terminer.

Système Expert THERMEX

Hypothèses de la question 1

- Système fermé
- Système ouvert
- Système ouvert permanent
- Système ouvert uniforme
- Réversible
- Irréversible
- Adiabatique
- Frontière mobile
- Travail d'arbre
- Isotherme
- Isobare
- Isochore
- Polytrope (P*V**n = Cte)
- Equilibre thermodynamique
- Gas parfait
- Mélange
- Air humide

POUR LE SYSTEM ---> Air
Quelles hypothèses as-tu faites pour cette question ?
Tu peux utiliser la touche F1 pour voir l'hypothèse où est le curseur avant de la sélectionner.
Tu peux choisir une ou plusieurs hypothèses,quand tu as FINI TOUS TES choix, appuie sur F10 pur les enregistrer.

F1 VOIR RETURN POUR TON OU TES CHOIX F10 CONTINUE stresses that answers are not given directly but instead thermex tries helping the student to find them through heuristically formulated feedback.

Interface

All computer assisted systems include an interface allowing communication between the system and the user. Constructing an interface based on natural language is a very difficult process. The biggest problem appears to lie in foreseeing and dealing with the individual learner's way of thinking and phraseology, In order to reduce these types of problems a menu driven interface is adopted in thermex.

For example, when defining the physical properties of a thermodynamic system, the learner can choose from a menu of keywords, including all possible hypotheses, by moving down or up with the help of the arrow keys. Different function keys are assigned to either get help, a definition of a certain concept, or to get the problem statement on screen. The return key is used to confirm whatever the user proposes. These features are consistently applied throughout the program and shown in a status line at the bottom of the screen.

Numerical values are verified through a process whereby the answer to a specific question is compared to the exact value within a 10% miscalculation limit.

Dialogues and comments are always shown in the bottom area of the screen, in a window with a different color (see Figures 4 and 5 on page 230). Dialogues and comments are continued by a "yes", "no" or <RETURN> statement.

FORMATIVE EVALUATION

The goal of this formative evaluation was to obtain initial reactions to the instructional strategy used in THERMEX directly from the target learners.

One third of the low-achievers (midterm grade < 45%), that is students volunteered for this formative evaluation, that lasted for 8 weeks consecutive, 3 hours at a time. Like the rest of the class, these students were assigned a certain number of thermodynamic exercises each week. They were told to attempt a solution on paper and to use THERMEX as a "teaching assistant" who could help answer questions and verify steps. An average of two exercises per session was solved this way. The students were directly observed using a checklist concerning THERMEX technical, instructional and conceptual qualities.

Findings

Observations brought into light the following points:

The students tended to use concepts at random, without complete understanding. Since THERMEX forced the learner to explicitly state the concepts

Figure 4.
Dialogues.

Eq5.51 : m * (hf - hi) + Ecf - Eci + Epf - Epi = Q - W

Variables	Valeurs	Unités	Diagnostic
m	1	kg/s	OK
h2 - h1	2	kJ/kg	revoir l'expression intermédiaire.
Ec2 - Ec1	0	kW	OK
Ep2 - Ep1	0	kW	OK
Q	1	kW	à calculer
W		kW	revoir l'expression intermédiare.

Conclusion

Ques	Système	Etat
1	Air	début compression
		fin compression

Figure 5.
Comments.

Vérification des expressions et des valeurs numériques

Formules	
3.4	Question 1
Table	Entre les ou le numéro des principales formules que
4.3	tu as utilisées pour résoudre la question.
5.11	Tu peux utiliser F1 pour voir la formule où est le
5.18	le curseur avant de la sélectionner.
5.21	Tu peux choisir une ou plusieurs formules et quand
5.22	tu as FINI TOUS TES CHOIX appuie sur F10 pour les
5.24	enregistrer.
5.51	
5.55	
5.56	
6.1	
6.3	
6.8	
7.2	
7.4	
7.21	
7.32	
7.36	
7.66	
7.67	

F1 VOIR   RETURN POUR TON OU TES CHOIX   F10 CONTINUE to be used, the learners were able to identify and correct their omitted or misunderstood concepts. For example when an open system was assumed, confusion was observed when the student had to distinguish between input and exit states versus initial and final states. THERMEX benefitted from these findings since new explanations could be added to the software.

· The students also tended to use mathematical expressions (thermodynamic formulas) at random without verifying the specific conditions under which these formulas could be applied. THERMEX detected these types of errors through the use of the "mal-rules" in the student model. In this case, THERMEX forced a justification procedure, whereby the student stepwise had to identify all the necessary operational conditions for the suggested relationships. Most of these "mal-rules" were represented in the error bank, which in turn was used to help the student clarify the misconception(s) that were employed. Through this formative evaluation it was possible to identify more of the common "ml-rules", and the error bank was expanded.

· It was encouraging to note that students did indeed take care in choosing between options of the different menus. Most of them read carefully and reflected on what would be the mos tappropriate choice. This type of continuous reflection was perceived to implicitly reinforce strategic steps as well as the subject-matter, because it involved them in verifying definitions and meanings of the concepts presented.

· The fact that THERMEX was capable of indicating numerical errors related to signs or magnitude showed that students often do not question the results obtained; e.g., 1.234 instead of 12.34. The students appreciated this feature, sincethey, when it was pointed out to them, usually could immediately distinguish and correct the error. This was seen as a time saving feature and they thought THERMEX was more effective in this sense than a human T.A, they also believed that the use of THERMEX increased their efficiency of learning, that is, they perceived it as a time-saving aid. These points raise questions that can hopefully be answered by the summative evaluation. The fact that it is computer-mediated does not inspire any fear at all in these students. It should be noted here that the thermodynamics course is preceded by a course in computer programming, thus possibly explaining this fact.

· The students consistently attempted to solve their exercises completely, and appreciated the comments and encouragements displayed by THERMEX. Even when it was a question of a simple calculation error, they returned to the beginning until obtaining the correct answer(s).

Discussion

In summary, this formative evaluation supported the hope that students appreciated the instructional strategy applied in THERMEX. They perceived it as a time-saving which provided them with adequate information about the subject-matter and related methods to solve problems when compared to help given by a teaching assistant or a copy of a solution of the thermodynamic exercise.

The student also valued the capacity of THERMEX to give specific feedback to each class of errors. In this sense. it appears that THERMEX could provide an individualized learning environment where a problem-solving strategy might be developed.

The observations provided valuable information on where more dialogues, extensions of the error bank, and the mal-rules are needed to refine the diagnosis and to increase the effectiveness, efficiency and adaptability of the expert-system. With these modifications it is believed that THERMEX can be submitted to a true experimental situation, where changes in student performance can be quantitatively as well as qualitatively compared and measured.

All through the construction of THERMEX, the main concern was to find out whether the proposed student model would be sufficiently precise to display a helpful diagnosis of the learners' misconceptions and to provide an appropriate remedial strategy The validation procedures confirmed that most of the students' erroneous behavior were, in fact, correctly identified by the student model. One of the recognition difficulties encountered is the case where a student suggests a resolution that will actually lead to a correct answer, but goes about it in a slightly different way than the expert, that is, than the way it is represented in the knowledge base. These differences refer especially to unexpected intermediary expressions utilized by the student.

It was observed, several times, that the learner can precisely understand some of the important relationships but did not declare one or two intermediary equations, although he employed them, hence confusing the "tutor" into believing that the learner did not know the intermediary equations. This problem was overcome by delaying the error comments of important steps until the whole question was treated. Therefore, if the end computational results are correct, the "tutor" will assume that the student did understand and correctly used these omitted intermediary expressions. This technique permits alternative strategies in obtaining results and focuses on the important conceptual and procedural steps.

However, it is difficult to foresee and categorize all of these different types of student models; for examples when a student "invents" given numerical information, THERMEX has difficulties understanding the behavior of the student. An example of these types of "inventions" was when two fluids with different temperatures was mixed together and the sum of the temperatures are put as the value of the temperature of the mixture. These error models are not random, since they correspond to a mental representation of the student which is a conceptual error. Another error was the creation of new equations or formulas. Since these expressions are entered only by menus, the system cannot detect what the misconception is because the menu is a correct expression. If the numerical value entered by the student is wrong, it is pointed out to him that a calculation error is committed, but in reality it is a conceptual error, which is not detectable.

CONCLUSION AND FUTURE RESEARCH PARADIGMS

This article has presented the different steps that were taken to develop a particular educational expert-system in which efforts have been put on diagnostic and remedial strategies related to the learning of fundamental concepts and problem-solving methods of classical thermodynamics. It appears that the methodology used in thermex could easily be transfered to other academic subject-matters that display approximately the same characteristics as thermodynamics.

THERMEX is conceived for students who have difficulties in conceptualizing thermodynamics, after using THERMEX and it was exciting to observe that these students tried to employ the "expert's' strategy of solving a thermodynamic task. The utility of THERMEX will be twofold, acquiring a transferable method of solving scientific problems and filling the void concerning the concepts and objectives of the subject-matter.

However encouraging these first trials with THERMEX were, further research and development are needed, especially in the area of tutor decision-making and student modelling. It is believed that the knowledge representation problem is adequately solved by using rules and objects. The formative evaluation also appears to confirm the adequacy of the basic instructional strategy, although efforts will be put on finding out what, where, and when the student will benefit more from further interventions of the system. As mentioned earlier, it sometimes appeared to be more adequate to delay comments and, in other instances, it seemed better to display corrective comments immediately. These features need to be further researched.

For the time being, the student models consist of a mixed approach including features from both the "overlay" (Goldstein, 1979) and the "buggy" (Brown & Burton, 1978) model. It is planned to investigate the possibility of incorporating a "decision tree model" (Becker, 1988) in order to increase and refine the diagnostic capabilities of thermex. A "decision tree model" would expand the error bank and restructure related errors in a way that might overcome problems with the student's "invented" information.

Our next step is to carry out a formal summative evaluation where student performance will be quantitatively, as well as qualitatively, measured. It is planned for the winter term of 1990, using the low-achieving students of two groups of about 80 students each, taking the obligatory course in thermodynamics at the University of Sherbrooke.

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