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AUTHOR Pilot, A.; And Others
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ABSTRACT

Gal'perin's instructional theory of problem solving is described. This theory of stage-by-stage formation of mental actions was chosen as a theoretical basis for the construction and evaluation of courses in higher education, particularly in science and technology. A Programme of Actions and Methods (PAM) for problem solving in science, particularly in thermodynamics, was developed, and a system of heuristics was derived from it. Details on the instructional theory, PAM, the systems of heuristics, teaching plans, as well as the main data on the process and product evaluation of the experimental courses are presented. (Author/JN)

Learning and Instruction of Problem solving in Science

A.Pilot, C.T.C.W. Mettes, H.J. Roossink and J.M.Donders
Centre for Educational Research and Development,
Twente University of Technology, P.O. Box 217, 7500 AE Enschede,
The Netherlands.

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Many students have difficulties in solving problems in science. They use trial and error methods and hope this will build up sufficient routine to enable them to pass the exam by sheer recognition of sets of problems. To change this situation some teachers and the authors in 1975 started to remake two conventional first year courses in Thermodynamics in the Department of Chemical Technology at Twente University of Technology. Later on, a remake of courses in Electromagnetism and Mechanics was started. In this project we specifically focussed our attention on finding procedures for the development and evaluation of instruction in problem solving in higher education, particularly in science and engineering.
In all these courses students should learn heuristic problem solving, which requires both a factual knowledge base and a strategic knowledge base (Greeno, 1980). In order to improve the achievement of this instructional objective we developed a system of heuristics for students and an instructional plan to teach this problem solving in each of the courses.
In our research we iterated between psychological laboratory research (thinking aloud and small scale learning and teaching experiments) and research on the classroom situation in the courses. So we did meet the areas of difficulty, Larkin described recently as well (Larkin, 1980).

The main issues of this article can be split up in three parts:
1. Which actions and methods should be learned to promote the effectiveness of the problem solving process?
2. How should students learn these actions and methods? Which instructional procedures and materials should be applied to get an optimal learning process?
3. How should the results of the experimental course be evaluated? What kind of criteria should be applied on what kind of data for judging the worth of the new instructional programme?

Each of these parts is represented in our project and produced an intermediate product in the development and evaluation of the experimental course.
The products of phase 1 were firstly the principles of instructional learning to be used in course development (Chapter 1), and secondly the Programme of Actions and Methods (PAM) for solving problems in Thermodynamics that was developed on the basis of these instructional principles and from which a system of heuristics was derived (Chapter 2).
The instructional plan consisting of the instructional procedures, materials and teaching activities is summarized in Chapter 3. Chapter 4 reviews the evaluation: the data on the processes and the results of teaching and learning.

1. PRINCIPLES OF INSTRUCTIONAL LEARNING

Before developing the new course we looked for a suitable theory of instructional learning. In our opinion such a theory should contain directives which relate instructional objectives to learning processes, and also learning processes to instructional procedures.

The instructional objectives of the thermodynamics course involve, as mentioned before, skills in solving problems found rather difficult by the students. Because of this, only a small number of theories of learning were relevant, among which those of Ausubel (1968), Gagné (1977) and Gal'perin (Talyzina, 1973). In this project we eventually chose Gal'perin's theory of instructional learning supplemented with contributions of Talyzina (1973) and Landa (1975).

Our main reasons for choosing this theory are :

a. Gal'perin's theory is the only one explicitly instructional in the sense that Gal'perin gives a definition of an optimal learning result and prescribes the microbehaviour desired of both the teacher and the student;

b. The learning result is consistently defined in terms of (mental) operations or actions. Acquisition of knowledge requires the formation of adequate systems of actions, that specify what a student should do to solve problems properly, in terms of particular algorithms and heuristics.

1.1. Gal'perin's theory of stage by stage formation of mental actions

According to the theory of Gal'perin (Talyzina, 1973) there are four characteristics or parameters in the performance of an action:

1. Form. An action can be executed by:

a. Manipulating actual objects (material form) or overtly manipulating representations such as symbols (materialized form).

An example of an action in material form is counting with the help of an abacus, an example of an action in materialized form is counting by manipulating figures on paper.

b. Stating in words or formulating how the action is executed (verbal form).

c. Speaking silently or thinking without speaking. The action is executed by performing mental operations (mental form).

2. Generalization. An action can be directed to one or more different (sets of) objects.

3. Completeness of action links. An action can be executed in its full extension (all action links are carried out successively) or in a more abbreviated form (certain links are carried out at the same time).

4. Mastery. The execution of an action can be more or less well mastered and as a consequence the rate of performance may be high or low.

Learning is the acquisition of new (mental) actions, and instructional learning is a process of planned progressive internalization of external actions. This transformation in the form of the action is accompanied by changes in the other three parameters. The performance of the action resembles more and more that of an expert i.e. becomes more transferable, abbreviated and automatized. According to this theory of learning the student has to exercise in a stage by stage procedure.

In the beginning of this procedure the student should perform a complete action in material or materialized form. By observing the completely externalized performance both student and teacher can detect incorrect or incomplete actions and administer feedback. Also they get knowledge of the results on the other parameters of the performance. This knowledge has to be used to achieve that the performance becomes more transferable, abbreviated and automatized.

When the action is mastered in material or materialized form the teacher allows the student to exercise at the next form and so on, until the student reaches mastery in the mental form.
Gal'perin points out, that before starting this stage by stage exercising of new actions, the student must have an orienting basis to be able to perform the action for the first time. He must have information to orientate himself about what to do in what circumstances. This orienting basis should be complete i.e. contain all information necessary for a perfect performance: such as the goal of the action, the composition of all action links, the conditions in which the action can and cannot be performed. The best orienting basis is both complete and presented to the student in a generalized form i.e. a form that covers a whole class of problems. The quality of the orienting basis is emphasized in this theory, because it outlines the conditions which are objectively necessary for the student to perform the action successfully i.e. to solve the relevant problems.

1.2. Emphasis on systems of actions and knowledge

We want to emphasize the importance of systems of actions. By thinking aloud techniques and in depth analysis of mistakes made in exams (Mettes and Pilot, 1980), we analysed difficulties students have and discovered strong deficiencies in the coherence of the factual and procedural knowledge of our students.
In his research on problem solving Landa (1975) pays much attention to forming systems of actions. One way to form such a system is the so called "through" systematization of knowledge.
"Through" systematization of knowledge means combining in a single system all knowledge relevant for problem solving that is contained in separate sections of a book, a course etc. In this way the subject matter should be reorganized in an operational form.

Talyzina (1973) developed on the basis of Gal'perin's theory a procedure for the development of instruction. In this procedure systems of actions, subprogrammes in her terminology, occupy an important place. These subprogrammes are:
1. The bulk of knowledge in a particular subject matter.
2. The rational actions and methods of thinking adequate to learning to apply this knowledge. This subprogramme is called a Programme of Actions and Methods. It is divided in two parts:
   a. actions and methods constituting specific types of thinking (specific for this subject matter) and
   b. logical actions and methods of thinking (not dependent on a concrete subject).

Summarizing: because we are dealing with heuristic problem solving the orienting basis cannot be complete, but should be as complete and generally applicable as possible. Such an orienting basis consists of :
a. subject matter (knowledge) in operational form, and
b. heuristics and general methods of thinking , which should be derived from a Programme of Actions and Methods (PAM).

2. THE DEVELOPMENT OF A PROGRAMME OF ACTIONS AND METHODS

The teachers in the course in Thermodynamics and other specialists in this field could not give us an adequate description of problem solving in this subject matter. The literature on Thermodynamics does not contain any adequate system of heuristics. The situation for most subject matter at this moment may, in our opinion, well be similar. Our first attempt at producing a PAM for Thermodynamics was based on the well known and widely used set of heuristics Polya (1957) developed for problem solving in mathematics. Unfortunately Polya's heuristics for the analysis of problems were too incomplete or gave hints in the wrong direction. For the transformation of the problem no adequate heuristics were found and reasoning by analogy is not successful in this type of problems (Mettes and Pilot, 1980).

So we decided to do some research on a descriptive model of problem solving behaviour. The problems in our courses are called specification problems (Mettes and Pilot, 1980). In typical problems of this type of well-specified problems a situation, certain relations, variables, magnitudes etc. are given, the problem is to find or calculate etc. one or more unknowns, other relations, variables, magnitudes and such-like. If the unknown is found the situation is more specified. This type of problems is very frequently used in science and technology curricula. We carried out experiments in which students as well as teachers tried to solve problems relevant for the course objectives. They were requested to think aloud, and protocols of their problem solving behaviour were recorded and transcribed. These protocols were interpreted in terms of a model derived from theories on problem solving of Duncker (1945), De Groot (1965), Newell and Simon (1972), in an iterative process (for details see Mettes and Pilot, 1980). The result of this process was a model (called Transformation to Standard Problem, TSP model). Although we derived this model from studying Thermodynamics protocols, it can be used to describe problem solving behaviour in more subject matter areas in science and technology, with few or no adaptions. Recently the TSP model was used successfully to describe protocols of problem solving in Electromagnetism (Van Weeren et al., 1980).
In the following phase we tried to develop from this descriptive model a prescriptive one: a Programme of Actions and Methods to be used in the training of problem solving in Thermodynamics.

When designing this PAM from the TSP model we looked for actions and methods to ensure a systematic and effective problem solving process, irrespective of whether these actions and methods were found in the protocols or not. We used a number of indications and criteria for desirable actions and methods, such as:

- indications from the protocols, e.g. differences in problem solving behaviour between students and teachers,
- indications from the literature on special heuristics (Marples, 1974),
- indications from the literature on research on PAM's for other subject matter (Talyzina, 1973; Dubovskaja, 1967; Obuchowa, 1968),
- research on frequently made mistakes and difficulties in exercises and exams in this course.

The programme has four principal phases:

Phase 1: Reading the problem thoroughly; careful analysis of the data and the unknown by making a scheme.

Phase 2: Establishing whether or not it is a standard problem, i.e. a problem that can be solved by mere routine operations; if not:
Looking for relations between the data and the unknown that can be of use in the transformation of the problem to a standard problem; conversion of the problem to a standard problem.

Phase 3: Execution of routine operations.

Phase 4: Checking the answer; interpretation of the results.

Phase 1 will be presented in more detail here (for other phases see Mettes et al., 1980b). We first mention its purpose and then list a number of desired actions. We only list the actions that can be expressed in general terms. For different fields, different specifications of the actions are needed.
An example of a problem in Thermodynamics that has been worked out according to the PAM (specified for Thermodynamics) is given in figure 1 (see also par. 3.2).

Phase 1 : Analysis of the problem

Purpose : Getting an overall picture of the data and the unknown. The problem-solver should first understand the problem well before he starts solving it.

Desired actions:

1.1. Reading the problem carefully, e.g. by putting a slant line after every datum.
1.2. Transformation of the text of the problem into a scheme, using paper and pencil to develop an image of the problem situation and to get a schematic survey of the data and unknown.
All data should be mentioned in the scheme, in correct symbols and units.
In some cases, plotting or sketching a graph; this may help to get a better image of the problem situation.
1.3. Writing down the unknown if possible in symbols.
1.4. Estimation of the answer: probable sign, magnitude, dimension, special cases. An estimation facilitates checking the answer later on.

The Programme as such contained information that was not suitable to be presented to the students. So, the next step was the transformation of this Programme into a system of heuristics that students can use to orientate themselves in problem solving. (The teachers can use it also when giving feedback to students). A survey of this system is condensed to one page, usually referred to as the SAP chart for Thermodynamics, where SAP means Systematic Approach to Problem solving (figure 2).

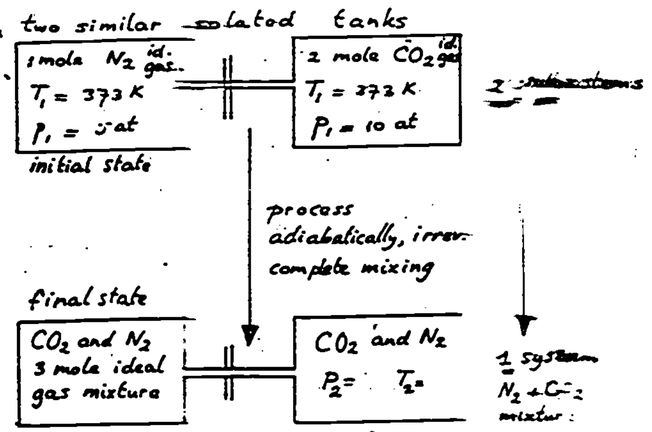
Figure 1: An example of a problem in Thermodynamics (TC2), worked out according to the PAM.

An isolated tank, containing 1 mole of nitrogen at 100 °C and 5 at is connected with a similar tank with 2 moles of carbondioxide at 100 °C and 10 at. The gases in the two tanks mix up adiabatically and complete. Nitrogen and carbondioxide can be considered to be ideal gases in these circumstances. What is the change in entropy in this process ? R = 8. . . J.mol^{-1}.K^{-1}

Worksheet for the systematic approach to solving problems:

ANALYSIS

1. read
2. scheme
   a. system
   b. boundaries
   c. content
   d. states
   e. processes
   f. other data
   g. graph
   h. unknown
   i. estimation



unknown: ΔS_m

estimation: > 0 (J.K^{-1})

~~R = … J … K~~

PLAN

4. select relations
   a. KR-chart
   b. general relations
   c. from data

$[Y = \sum n_i y_i]_{p,T}$ ~~...~~ $S = \sum n_i s_i]_{p,T}$

$\left(\frac{\partial \mu_i}{\partial T}\right)_{p,n_i,n_j} = -s_i$

$\mu_i(p,T,x_i) = \mu_i^{\circ}(p,T,x_i=1) + RT \ln \gamma_i x_i$

$\mu_i^{\circ}(p,T) = \mu_i^{+}(p=1,T) + RT \ln p$ (ideal gas)

$pV = nRT$

$p_i = x_i p$

5. check validity

6. Transformation to standard problem
   a. unknown
   b. relation in which unknown occurs
   c. specification
   d. new unknowns
   e. new start
   f. substitution

7. if not soluble
   a. other (key) relation
   b. alternate processes
   c. assumptions

Unknown: $\Delta S_m = S_{final} - S_{initial}$ → two new unknowns : S_2 and S_1

S_1 ← $[S = \sum n_i s_i]_{p,T}$ ← $S_1 = s_{1,N_2}^{\circ}(373\,K, 5\,at) + 2 s_{1,CO_2}^{\circ}(373\,K, 10\,at)$ } four new unknowns

S_2 ← $S_2 = s_{2,N_2}(p_2, T_2, x_{N_2}) + 2 s_{2,CO_2}(p_2, T_2, x_{CO_2})$

→ search a relation for $s_i(p,T,x_i)$; ← $\left(\frac{\partial \mu_i}{\partial T}\right)_{p,n_i,n_j} = -s_i$; this relation can be transformed by specifying and differentiating $\mu_i(p,T,x_i)$: therefore we need p_2 and T_2.

T_2 ← ideal gas → mixing gives no temperature change → $T_2 = T_1 = 373$ K.

p_2 ← $pV = nRT$ and $p_i = x_i p$ → $p_i V = n_i RT$; for both components applies: $V_2 = 2V_1$ } $p_2 = p_{2,N_2} + p_{2,CO_2} = 5/2 + 10/2 = 7.5$ at

$$\left(\frac{\partial \mu_i(p,T,x_i)}{\partial T}\right)_{p,n_i,n_j} = \left(\frac{\partial \mu_i^{+}(p=1,T,x_i=1) + RT \ln x_i + RT \ln p}{\partial T}\right)_{p,n_i,n_j} \longrightarrow$$

$$-s_i(p,T,x_i) = -s_i^{+}(p=1,T,x_i=1) + R \ln x_i + R \ln p \rightarrow s_i(p,T,x_i) = s_i^{+}(p=1,T) - R \ln x_i p$$

→ specify further →

$$S_2 = s_{N_2}(p_2,T_2,x_{N_2}) + 2 s_{CO_2}(p_2,T_2,x_{CO_2}) = s_{N_2}^{+}(p=1,T_1) - R \ln \tfrac{1}{3} \cdot 7.5 + 2 s_{CO_2}^{+}(p=1,T_1) - 2R \ln \tfrac{2}{3} \cdot 7.5$$

and $S_1 =$ (pure substances!) $= s_{N_2}^{+}(p=1,T_1) - R \ln 5 + 2 s_{CO_2}^{+}(p=1,T) - 2R \ln 10$

$$\rightarrow S_2 - S_1 = -R \ln \frac{7.5}{3} - 2R \ln \frac{2 \cdot 7.5}{3} + R \ln 5 + 2R \ln 10 \rightarrow \text{standard problem!}$$

3. standard problem

$$\Delta S_m = R \ln \frac{5 \cdot 10^2}{25 \cdot 5^2} = R \ln 8$$

8. calculation and answer

EXECUTION OF ROUTINE OPERATIONS

$\Delta S_m = 17.3$ J.K^{-1}

9. check
   a.
   b. OK
   c.

if necessary:

10. tracking down mistakes

Figure 2a:

Scheme of the Method of Systematic Approach to Problem Solving (SAP-chart)

(see also page 8)

1. Read the problem carefully

2. Make a scheme
- a. Draw the system, draw system-boundaries
- b. Write down characteristics of system-boundaries (w,q,dn=0)
- c. " " " " contents of system (phase, ideal behavior)
- d. " " " " the states (P,V,T, other state-variables)
- e. " " " " processes (reversible, state-variables constant? process variables zero? chem. reaction?)
- f. " " " " other data (use correct symbols)
- g. If necessary plot a graph (to obtain a better picture of the process)
- h. Write down characteristics of the unknown (math. formulation)
- i. Estimate answer (probable sign, magnitude, dimensions)

3. Is it a standard problem? (+ → 8; – → 4)

4. Write down possibly useful key relations + conditions for validity, by looking from the unknown and/or data, at
- a. charts with key relations (equations of state, process equations)
- b. charts with non-thermo relations
- relations which follow directly from data

5. Check relations for their validity in this problem situation

6. Conversion to standard problem
- a. Write down the unknown using the right symbols
- b. Write down a valid key relation in which the unknown occurs (from list at 4)
- c. Replace general quantities by specific quantities in this relation
- d. Check which specific quantities are still unknown
- e. Write them down as new unknowns
- f. When all specific quantities are known, substitute them by numerical values and dimensions

7. If not soluble:
- a. Check whether there are still key relations lacking, or
- b. introduce alternate processes, or
- c. separate variables, or
- d. make assumptions in connection with validity

8. Execute routine operations, have computation and answer well-ordered

9. Check answer against estimation of the unknown
- a. sign
- b. magnitude
- c. dimension

10. Check whether you made mistakes on the
- a. estimation
- b. setting up the scheme
- c. writing down key relations
- d. conversion to standard problem
- e. executing routine operations

Correct, then proceed to 9

11. All problems solved?

yes → READY

no:
- a. fill in answer in the scheme
- b. see whether same procedure is again appli-

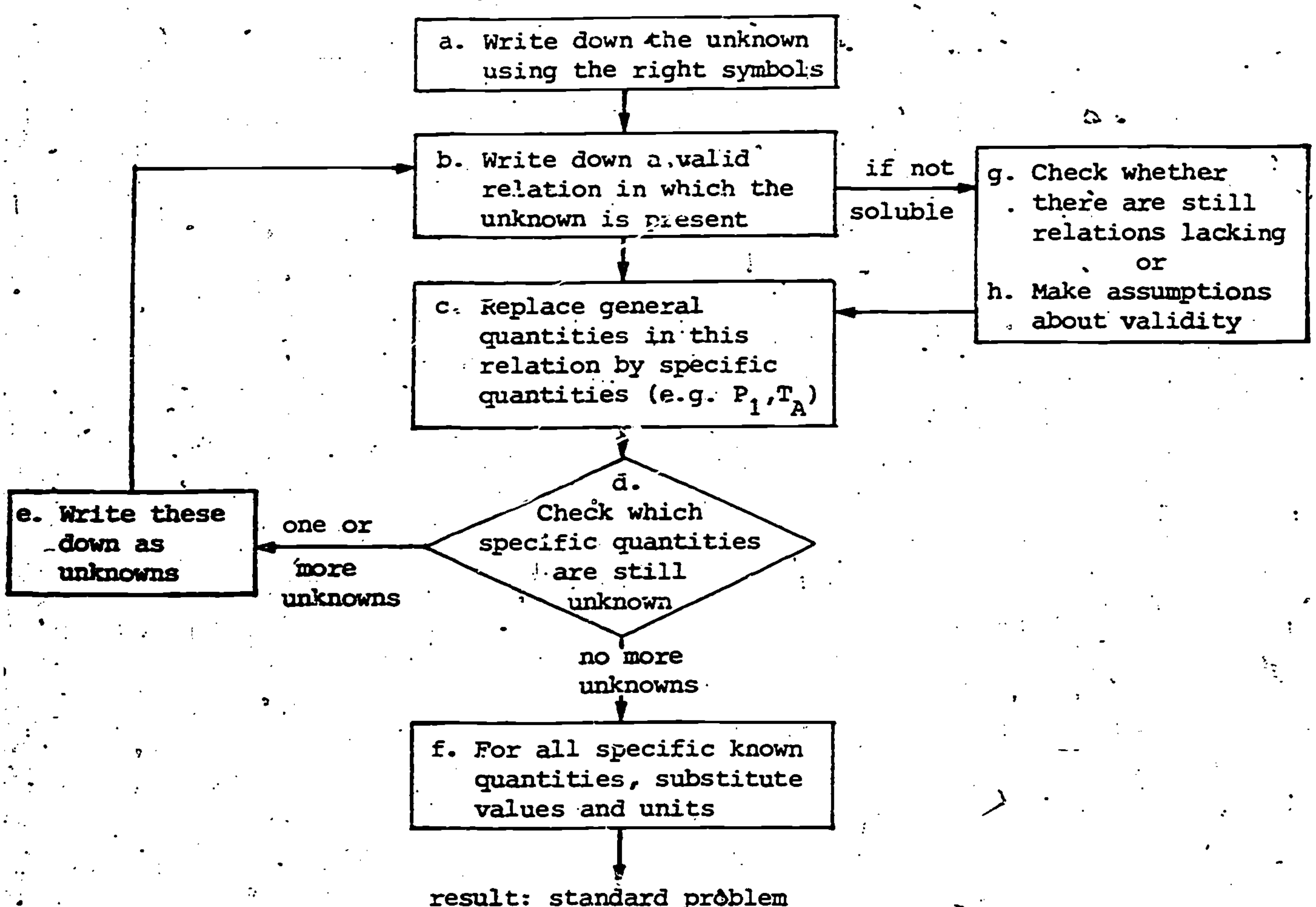


Figure 2b:
Diagram of strategy: transformation, using the unknown as starting point.
(see also page 7)

The content of the heuristics is essentially similar to the PAM, but there may be considerable functional differences in form and wording of the actions and methods. The SAP chart was drawn up by the following principles :

1. Only those heuristics were included that refer to actions unknown to the students and are strictly necessary for solving the most important problems.
2. The heuristics had to be worded in such a way that the students could readily understand them.
3. The text had to be as complete as possible, to enable the students to perform a complete action in materialized form.
4. The heuristics had to be worded in such a way as to insure the appropriateness throughout the course, even if the subject matter varies. From this general wording, more specific applications - related to specific subject matter - had to be deducible.
5. The imperative mood had to be used to show clearly that the heuristics are directions for desired actions.

The first design of the SAP chart was checked and corrected in small scale experiments with students. On the basis of these experiments a more definitive version of the SAP chart - and consequently of the PAM from which it was deduced - was designed and used in two experimental courses. Based on the evaluation data of these courses the definitive version of both this PAM and the chart was developed.

A general procedure for the construction of a PAM consists of ten steps that are summarized in figure 3. Until now we have the impression that the validity of this procedure is limited by two conditions:

1. The problem solving to be learned must concern specification problems.
2. For solving these problems it is among others necessary to use as transformations a limited set of quantitative relations.

Within these limitations the procedure can be used generally because of the great analogy between specification problems in Thermodynamics and other science subject matter areas. Empirical evidence has been shown by Van Weeren et al. (1980) and Kramers et al. (1980 ,1981).

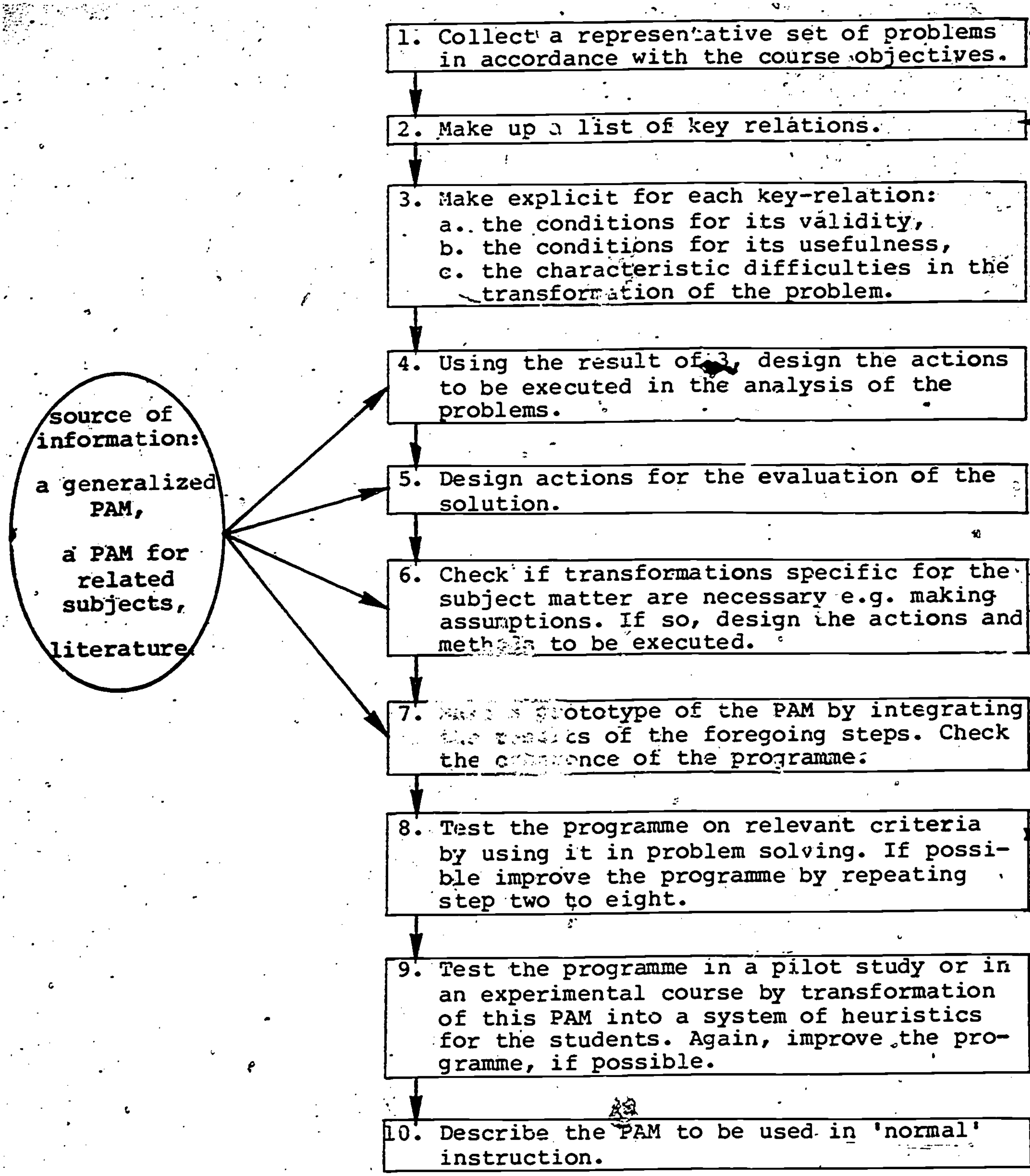


Figure 3 :
Summary of the ten steps for the construction of a PAM.

3. THE CONSTRUCTION OF AN INSTRUCTIONAL PLAN

3.1. Instructional functions.

In our opinion learning theories should bridge the gap between objectives and procedures. We therefore restated the phases of the learning process in terms of instructional functions. In analogy with the concept 'function' used in engineering design instructional functions are defined as general operations or actions that have to be performed in instruction to realize the necessary phases of the learning process. Figure 4 gives a survey of the phases of the learning process in accordance with the theory of Gal'perin, the instructional functions derived from them, and the instructional procedures and materials for the realization of each function. Details of the phases of the learning process were described in Chapter 1. Here we only describe how they were utilized to develop an instructional plan.

The best way to realize an instructional function does very much depend on the specifics and context of the course. We think that achieving realization of a function is more important than the specific way it is realized. Since the experience of the teachers is very important for the realization of functions, we selected procedures that differed as little as possible from the procedures teachers were used to in our university.

The instructional plan was constructed by matching procedures and materials with instructional functions and integrating them into a consistent programme. One condition was made beforehand: once devised, the experimental course should not take more time from the teachers and students than the existing course.

Before the course started, we organized some training sessions for the three teachers to get used to the new procedures and materials. During the course, we observed all lectures and small group activities to gather data for the evaluation of the instructional process. If there were discrepancies between the planned and the actual procedures the observer consulted the teacher about the causes for this, immediately after the session. Deviations from the plan that endangered the realization of a function were as far as possible remedied and steps taken to prevent their re-occurence.

We will now discuss the most characteristic elements of the experimental instruction: SAP chart, SAP worksheet, Key Relations, and tests.

3.2. SAP chart and SAP worksheet

The Systematic Approach to Problem solving is presented to the students in several ways. The most important explanation is done by the SAP chart. On this chart a survey of all heuristics is condensed to one page (figure 2). In the lectures, these heuristics are illustrated by problems used as examples. The teacher uses the heuristics regularly when explaining concepts and laws in the lectures.

In the classes after the lectures, the students exercise by solving problems in accordance with the heuristics as far as possible. In the first phases of the learning process they exercise performing the new actions and methods with completeness of all action links on paper. The paper is a special worksheet with a lay-out reflecting SAP. The heuristics are represented on this sheet by catchwords. Figure 1 shows such a worksheet, with a worked problem on it.

Phases of the learning process	Functions of the instruction	lecture	lecture notes	SAP chart* (group of 20 students)	KR chart** (group of 20 students)	problems for work in groups (group of 20 students)	problems for selfstudy	tests and feedback	remedial instruction	exam
		1	2	3	4	5	6	7	8	9
1. Learning the conditions of the program of actions and methods.	**Orientation**									
	1. Presentation of the essential elements of knowledge and actions specific for this subject	●	●							
	2. Making these elements of knowledge and actions operational	●			●		●			
	3. Giving a system of heuristics for problem solving			●						
	4. Realizing the connection with the entering behavior				●	●				
	5. Giving the student insight in the objectives of instruction					●		●		
2. Learning to perform the program of actions and methods.	**Stage by stage exercising**									
	6. Exercising the actions and methods of problem solving (PAM)					●	●			
	7. Giving feedback during exercises					●				
3. Getting knowledge of the learning results.	**Testing PAM**									
	8. Checking what learning outcome is reached and establishing whether this satisfies the standard							●		●
4. Improving the execution of PAM.	**Feedback after a test**									
	9. If it is below standard: eliminating the cause of the mistakes							●	●	

Figure 4: Survey of relations between phases of the learning process, instructional functions, and the instructional procedures and means used in the Thermodynamic courses

* SAP = systematic approach to problem solving

** KR = key relation

● means: this procedure or means should give a main contribution to realization of this function.

The students in a class work individually or in small subgroups of 2 or 3 students. The teacher makes his rounds, checks their work, gives directions and explanation in accordance with the procedure of stage by stage exercising (see par.1.1). This means e.g. that he avoids showing the students how to do the problem, because the students have to get exercise in doing the problems by themselves. Only as a last resort should he actually solve a problem for a student. In general students can work reasonably well on their own, because they are guided by the heuristics.

The use of the worksheets allows the teacher to closely observe the work of each student. Consequently, the teacher is able to give precise feedback at an early phase. Besides correcting mistakes, the teacher also comments on the learning process of the students, e.g. when a part of the systematic approach is abbreviated too early in the stage by stage exercising (see par.1.1).

As the course proceeds, students execute parts of SAP faster and more automatically. This is infact the intention, but every time new subject matter is introduced, the pace is slowed down in order to enable new elements to be carefully integrated: e.g. other aspects in the analysis and new Key Relations.

3.3. Key Relations

The core of the problem solving process is phase 2 of the Programme of Actions and Methods:linking up unknown and data, using relationships between quantities. These relationships in science and technology usually result from laws, formulas, diagrams etc. Such quantitative relationships are referred to as 'relations'. An important part of all instruction is the derivation and explanation of such relations. In order to be able to use these relations in solving problems, the student must have at his disposal a structured survey of the most important relations.

To be more exact: he must select and hold at his disposal the relations that are particularly suitable as starting point in solving problems. These relations are called Key Relations. The number of Key Relations has to be kept as small as possible, because then it is easier to remember the relations and the conditions for their validity (Mettes et al.,1981) Key Relations must be formulated in a way to insure their usefulness in the transformation of the problem.

The Key Relations for a topic, and the conditions for their validity, are written out on KR charts. An example of a KR chart is given in figure 5.

After a few lectures on a given topic the students are asked to design a KR chart for that topic. Before they start working on problems in the class, the teacher discusses these designs. He then hands out his own KR chart and, if necessary, comments on differences between the two. Students use the KR charts continuously during the problem solving exercise and the teacher refers to these charts regularly when giving feedback. In this way, the students survey the core of the subject matter, use this survey to begin to master it. They also learn to obtain an important study skill.

3.4. Tests

During the course students do problems under examination conditions, i.e. without the help of the teacher, another student or study materials and under pressure of time (about 30 minutes). The teacher checks the work and writes comments concerning both the way the problem has been solved and, if necessary, mistakes that have been made. In the classmeeting after the test, these remarks are briefly discussed, if necessary. Then, under close supervision, the students who have shown insufficient mastery of the preceding subject matter to be able to grasp the next topic are assigned additional exercises relating to that subject. In the meantime

Figure 5:

Key Relations for open systems ($dn \neq 0$), consisting of ~~one~~ component, and for equilibria with one component.

$$dU = TdS - PdV + \mu dn$$

$$\downarrow$$

$$dG = -SdT + VdP + \mu dn$$

$$\mu = \left(\frac{\partial G}{\partial n}\right)_{P,T} = \frac{G}{n} = g = h - T.s$$

① Pressure dependence

$$\left(\frac{\partial \mu}{\partial P}\right)_{T,n} = \left(\frac{\partial V}{\partial n}\right)_{P,T} = v$$

$$\mu(P,T) = \mu(P=1,T) + \int_{P=1}^{P} \left(\frac{\partial \mu}{\partial P}\right)_{T,n} dP$$

$$\mu(P,T) = \mu(P=1,T) + \int_{P=1}^{P} v\,dP$$

For ideal gases

$$\mu(P,T) = \mu^{+}(P=1,T) + RT\ln P$$

For non-ideal gases

$$\mu(P,T) = \mu^{+}(P=1,T) + RT\ln f$$

For liquid and solid phases (approximately)

$$\mu(P,T) = \mu^{\circ}(P=1,T) + v\Delta P$$

② Temperature dependence

$$\left(\frac{\partial \mu}{\partial T}\right)_{P,n} = -\left(\frac{\partial S}{\partial n}\right)_{P,T} = -s$$

$$\mu(P,T) = \mu(P,T=298K) + \int_{298}^{T} \left(\frac{\partial \mu}{\partial T}\right)_{P,n} dT$$

$$\mu(P,T) = \mu(P,T=298) - \int_{298}^{T} s\,dT$$

More usual is: $\mu(P,T)$ first transforming to $\mu(P=1,T)$

and then by

$$\mu(P=1,T) = h(P=1,T) - T.s(P=1,T)$$

transforming by

$$h(P=1,T) = h(P=1,298) + \int_{298}^{T} C_p\,dT$$

and

$$s(P=1,T) = s(P=1,298) + \int_{298}^{T} \frac{C_p}{T}\,dT$$

$$\left(\frac{\partial \mu/T}{\partial T}\right)_{P,n} = \frac{-h}{T^2}$$

EQUILIBRIUM : P, T and μ equal in the whole system

SPONTENEOUS PROCESS :

$$dG_{P,T} < 0$$

$$dS_{adiab,V} > 0$$

molar quantity : $x = \left(\frac{\partial X}{\partial n}\right)_{P,T}$

fugacity : $f = \gamma P$; γ = fugacity coefficient

$\gamma - P_R/T_R$ diagram (generalized fugacity diagram)

$Z = P_R/T_R$ diagram

o (e.g. μ°) means pure substance of

+ (e.g. μ^{+}) ,, : ~~at~~ 1 at, pure zuivere substance (gases) the other students work almost independently on problems in the next topic. With this test feedback system, we try to check and improve mastery of a subject before proceeding to the next one. The tests are taken on SAP worksheets and are not graded.

For the construction of an instructional plan also a general procedure was developed. This procedure is based on the results of the courses in Thermodynamics (Mettes et al.,1980a). Evidence of the usefulness of this procedure has been shown in course development on Electromagnetism (Van Weeren et al.,1980) and more recently on Mechanics. Our research and development is now directed to test the effectivity of this procedure for a quite different type of course: problem solving in political administration.

4. SUMMATIVE EVALUATION.

This chapter summarizes the results of the experimental course. The most important criteria for judging the worth of the instructional plan were:
1. The feasibility of the instructional plan: was it possible in the experimental course to teach according to this plan (the feasibility criterion).
2. The functionality of the instructional plan: was it possible in the experimental course to fulfill sufficiently the instructional functions (the functionality criterion).
3. In judging the success of the experimental course we hoped above all that the teachers and students would prefer to teach and learn in the way that is recommended in the instructional plan (satisfaction criterion).

In assessing the quality of the PAM and the heuristics on the SAP chart the following six criteria are used:
1. the extent to which it contains all all necessary action links and conditions;
2. the appropriateness for all relevant problems of the course;
3. the fitness for promoting the abbreviation and automatization of the performance of the actions;
4. the comprehensibility of the heuristics,
5. the suitability of the design of the charts,
6. the acceptance by teachers and students.

Our criterion variables for judging the results of the course were:
1. the learning outcomes of the students,
2. the time teachers and students spent on the course,
3. the satisfaction of teachers and students.

The original course ran for two years (1975 and 1976) without modification and was replaced by the new course in 1977 - 1979. We took the first two years as our 'control' groups of students. So the summative evaluation involved two control groups (1975, 1976) and three experimental groups (1977,1978, 1979).
The lectures and classes of all courses were observed to gather data for the evaluation of the instructional process, except for the last experimental course in 1979. Because of this the results of this last course are considered to be representative for the results of a course in 'normal' circumstances. The control courses were observed intensively to gather data for the construction of the experimental instructional plan and also to minimize differences which would arise from observing just the experimental group. Other methodological aspects were described elsewhere (Mettes and Pilot, 1980).

4.1. Summative evaluation of the PAM

In the formative evaluation the general conclusion was that the PAM and the heuristics derived from it were usefull instructional means. Only minor changes were proposed (Mettes and Pilot, 1980a). The data in the summative evaluation (including thinking aloud techniques after the experimental course in 1979) showed that these changes were improvements indeed. These data also indicated that still more explicitness on the SAP chart might be relevant on some minor points:

- the relation between analysis of the problem and the action of replacing general by specific quantities in the Key Relations;
- "hidden" Key Relations. Hidden Key Relations are general relations students know very well but do not think of in solving a problem, e.g. the relation: the sum of all fractions is one.

We concluded that the PAM and SAP chart meet the criteria of quality.

4.2. Summative evaluation of the instructional plan

In the first try-out of the experimental course, there were some deviations from the planned process so that both the functionality and the feasibility of the instructional plan needed improvement. The feasibility of the plan had to be improved by training the teachers in supervising the exercising. To reach easier adaptation of the exercising procedure by the students PAM and the instructional plan were implemented in the Introductory Course in Thermodynamics in the first trimester of the first year. We were convinced students then would more easily accept and use the PAM and the exercising procedure because in this way the introduction of PAM and exercising procedure was integrated in the introduction of the subject matter.
As a consequence of this the students had no possibility to develop a (less suitable) way of problem solving before the Thermodynamics course started.
The changes suggested in the formative evaluation (Mettes et al., 1980a) appeared to be improvements. Especially the implementation of the experimental instruction into the first trimester was successfull and gave more time to exercise problem solving in the Thermodynamics course in the third trimester. All instructional procedures and materials were carried out respectively handled sufficiently conform the instructional plan. As a consequence of this all functions were sufficiently realized. It appeared however that the extent of the subject matter to be mastered limited the time available for exercising in the materialized form. Also the teachers had hardly enough time for diagnosing the mistakes made by the students.
From the data of the summative evaluation we concluded that the instructional plan met the criteria of feasibility and functionality.

4.3. Summative evaluation of the results

Exam scores

Tabel I shows the mean exam scores and the percentage sufficient marks of the experimental and control courses. The scores in the courses 1976, 1977 and 1979 are equated by the equipercentile conversion (Angoff 1971, page 564). The level of difficulty of the other examinations are not comparable because they may vary in difficulty.

The percentages sufficient marks of the experimental courses in 1977 and 1979 meet our standard of 70-75%, those of the control course in 1976 do not.
Because the entrance qualifications of the students in the courses differed to some extent, we used ANCOVA (analysis of covariance) to

	control courses		experimental courses		
	1975	1976	1977	1978	1979
mean	5.8	5.7	6.9	6.1	7.3
s.d.	1.6	1.9	1.7	1.9	1.8
n	19	43	32	52	51
% s.m.	54	61	85	69	79
n	22	49	33	52	53

Tabel I:
Mean exam scores, standard deviations, numbers of students and percentages sufficient marks.

assess a treatment or course effect. The covariates in this analysis were the scores for the high school examinations in mathematics, physics and chemistry, which in The Netherlands are controlled by a central examination board. The assumptions involved in analysis of covariance: homogeneity of variance, normality of distribution and homogeneity of regression were met (Mettes and Pilot 1980).
The course effect is significant, but much more variance is explained by the sum of the covariates. The variance explained by course effect and covariates together is less than the error variance (Mettes et al., 1980a).

Scores on the problem solving process

The problem solving process of the students is an important criterion in examining the learning outcomes. The exam consisted of 13 problems . All mistakes students made were placed in categories that are summarized in table II. In this paper we only look at the scores of two courses (1976 and 1979). Half of the group of students in 1979 got the same examination as the students in 1976 so we consider identical sets of problems. Details of the scoring system, reliability etc. were described in the final report of the project (Mettes and Pilot, 1980).
From this it appeared that the percentage of students that did not even solve a problem in part (i.e. did not write down anything) dropped from 18% in 1976 to 5 % in the experimental course in 1979 (chi square = 29.7; s=.001 two tailed).
Because the problem solving process contains several successive phases, one can mark up to a certain phase. As can be seen in table II scores are given up to:
. selection of relations,
. transformation to standard problem, and
. routine operations.
We had the intention also to mark the analysis of the problem but could not do this because most students wrote down in the examination too small a part of their actions in the analysis. In tabel II only the first mistake a student made in each of the 13 problems is included, because mistakes tend to cause further mistakes.

Phases of the problem solving process, and categories of mistakes	fraction of processes executed without mistake up to indicated phase		distribution of the mistakes in each phase in percentages of mistakes in that phase	
	control course 1976 n = 42	experimental course 1979 A n = 26	control course 1976 n = 42	experimental course 1979 n = 26
1. analysis	-	-	-	-
2. selection of relations	.64	.78		
a. relation not valid			12	19
b. relation formulated incorrect			22	29
c. relation derived incorrect from data			4	11
d. relation is lacking			63	40
3. transformation to standard problem	.49	.65		
a. wrong specification			67	51
b. wrong substitution			33	49
c. wrong alternative process			0	0
d. mistake in separating variables			0	0
d. routine operations	.39	.59		
a. wrong calculation			94	78
b. wrong differentiation or integration			3	3
c. mistake in units			3	17

Tabel II: Mistakes in exams of two courses in Thermodynamics (control course, 1976 and experimental course, 1979). Only the first mistake a student made in each of the 13 problems of the exam is included.

In this table the fraction is shown of problem-solving processes that were executed without any mistake in one of the three phases. In the experimental course 59% of all problems are solved without any mistake at all. We consider this a very good result for the course on Thermodynamics, because students, as we mentioned before, found it one of the most difficult courses in the first year.
To assess the effect of the mean scores of the experimental course up to each phase and the final solution, again ANCOVA was used with the same covariates as above.
In comparison with the results in the exam scores, the course effect explains much more variance. The amount of explained variance remains less than the error variance.(Mettes and Pilot, 1980).
Table II also shows the distribution of the mistakes in each phase, given in percentages of the total number of mistakes in that particular phase. The difference in category 2d ('One or more relations lacking) is significantly less (chi-square=7.55 ; s=.02 twotailed). The other differences are relatively small, which indicates that all categories of mistakes have become less in about an even rate. In the 'Introductory Course' about the same results were found (Mettes and Pilot, 1980).

4.4. Time spent on the course and satisfaction

The students voluntarily wrote down each day the time spent on the course on computer cards. Only the mean time the students spent in the first experimental course in 1977 exceeds the nominal time. This difference is however far too small to be of any significance. The mean time in the experimental and control courses also does not differ significantly.

Both students and teachers were satisfied with the lectures, classes and new instructional materials (charts and worksheet). In the questionnaire after the course 85% of the students answered that the experimental treatment should be introduced by teachers of similar courses.

4.5. Conclusion

The examination scores of two experimental courses came up to the absolute standard of 70 to 75% sufficient marks, in one course this norm was almost met.
The means of the exam scores of the experimental courses were significantly higher than those of the control courses. Scores on the problem solving process showed also sinificantly better results. There is no indication that students spent more time in the experimental courses.
Both teachers and students prefer with the experimental treatment.
The results of the evaluation of the experimental course 'Introduction in Thermodynamics' in the first trimester are the same or even better. We will not describe those results here (see Mettes and Pilot 1980).
According to the criteria for the evaluation we conclude that the experimental treatment is superior to the control treatment.

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