Teaching and Learning Problem Solving in Science

Part II: Learning Problem Solving in a Thermodynamics Course

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In “Part I: A General Strategy,” which appeared in the previous issue of THIS JOURNAL, we described a systematic approach to problem solving. In this part, we will describe in brief the specifics of instruction using the proposed problem solving technique in a thermodynamics course. Our main point is that the student must do his/her own learning; the instructor is only there to facilitate this learning process. The theoretical background for the instructional design of this program has been described previously (1–3). In this paper, we will discuss only the most important new aspects and results as they relate to the experimental courses.

The System of Heuristics

The Program of Actions and Methods (PAM) for solving problems (described in Part I) describes desired actions. It is only an intermediate product in course construction that must be translated into a system of directions to be useful in solving problems. The content of these directions is essentially similar to PAM, but there may be considerable functional differences in form and wording.

Figure 1 contains a survey of such a system of directions for thermodynamics. Such a chart is usually referred to as SAP, a Systematic Approach to Solving Problems. The content criteria of this SAP chart are

1) Only those heuristics are included that are new and strictly necessary for solving the most important problems.
2) The heuristics must be worded in such a way that the students can readily understand them.
3) In regard to directions necessary for a correct execution of actions to be learned, the text must be as complete as possible.
4) The directions have to be worded in such a way to insure the appropriateness throughout the course, even if the subject matter varies. From this general wording, more specific applications related to a specific subject matter must be deducible.

The imperative mood is used throughout the construction of the SAP chart to clearly show that these are directions for desired actions.

SAP Chart and SAP Worksheet

SAP is explained 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. 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.

After the explanation of the subject matter and heuristics in the lectures, students divide into groups of about 20 and work on problems with the help of the teacher. Much of the instruction at our university follows such a pattern of large group lectures (about 8 or more students) and small group work.

As far as it is possible, students do the assigned problems in complete accordance with the heuristics. A special worksheet form is used which utilizes catchwords to key the student to a specific direction. Figure 2 shows such a completed worksheet.

The students in a group work individually or in smaller sub-groups of 2 or 3 students. The teacher makes his rounds, checks their work, gives directions and explanation as necessary. He avoids, however, showing the students how to do the problem. In general, students can work reasonably well on their own, because they are guided by the heuristics.

The use of such worksheets allows the teacher to observe closely the student work. 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 part of the systematic approach is omitted prior to total understanding. As the course proceeds, the students continually execute parts of SAP faster and more automatically. This is, in fact, the intention, but every time new subject matter is introduced, the pace is slowed in order to enable the new elements to be integrated carefully into the system.

Key Relations

As indicated in phase 2 of PAM, the core of the problem-solving process is linking up unknown and data using relationships between quantities. These relationships in science and technology usually result from laws, formulas, definitions, 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 such relations. Those relations that are particularly necessary as starting points are called key relations. The number of key relations are kept as small as possible. Key relations are formulated in a way to insure their usefulness in the transformation of the problem.

The key relations for a specific subject and the conditions for their validity are written on KR charts. By the continuous use of these charts, it is easier for the student to memorize the relations and recall them as he needs them in solving problem situations. An example of a KR chart is given in Figure 3.

After a few lectures on a given topic, the students are asked to design a KR chart for that topic. Before they start working problems in the small groups, the teacher discusses their proposed designs. He then hands out his own KR chart and, if necessary, comments on differences between the two.

Students use 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 and use this survey to begin to master it. They also learn to obtain an important study skill.

Tests

During the course, students also 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 min). The teacher checks the work and writes comments concerning both the way the problem has been solved and the student’s performance on the contents. A description of the tests and student performance is given in Part III.
solved and, if necessary, mistakes that have been made. In the group meeting 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, the other students work almost independently on problems on the next topic. With this test feedback system, we try to check and improve the mastery of a subject before proceeding to the next. The tests are taken on SAP worksheets and are not graded.

**Functions of Instructional Procedures**

Figure 4 gives a clear picture of the instructional system used; procedures are matched in this matrix with the instructional functions they impart. The functions described in Figure 4 are deduced from the phases of the learning process the student should complete. This is based on the theory of learning and instruction of Gal'perin (4).

The instructional functions can be realized in several ways. We believe that realization of a function (i.e., the guarantee that the learning process takes place as planned) is more important than the specific pathway used (procedures and materials). For the realization of functions, the experience of teachers is very important, so we selected procedures which differed as little as possible from the usual procedures used by the teachers in our university. The black dots in Figure 4 give a description of the experimental courses we developed and not necessarily the optimal general choice.

**Results**

The plan of instruction has been tried out in several courses of Thermodynamics I and II. The PAM described is applicable in both courses, with only minor changes. The learning results show important improvements, both in mean scores on exams and in the quality of problem-solving actions and methods.

The mean exam scores of the experimental courses Thermodynamics I and II are compared with the results of similar non-experimental classes (Fig. 5).

Because of the variation in entrance qualification for students of different years, we used analysis of covariance to assess the effect of the changes. It appears to be significant (at

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**Figure 1. Scheme of the Method of Systematic Approach to Problem Solving (SAP-chart).**

1. Read the problem carefully
2. Make a scheme
   a. Draw the system, draw characteristics of system-boundaries
   b. Write down characteristics of system-boundaries \( w, Q, d \)
   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?)
   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?
   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
4. Write down possibly useful key relations
   a. 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
      c. Relations which follow directly from data
   b. Write down key relations
   c. Write down key relations
   d. Conversions to standard problem
   e. Execute routine operations
   f. Check whether the unknown is known
   g. Substitute the unknowns by numerical values and dimensions
5. Check answers for their validity in this problem situation
   a. Estimation
   b. Magnitude
   c. Dimension
6. Conversion to standard problem
   a. Write down the unknown using the right symbols
   b. Write down the unknown using the right symbols
   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 solvable:
   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
    f. Correct, then proceed to 9
11. All problems solved?
    yes
    no:
       a. Fill in answer in the scheme
       b. See whether same procedure is again applicable

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`Figure 1. Scheme of the Method of Systematic Approach to Problem Solving (SAP-chart).`
An evacuated vessel with a volume of 67.8 dm³ is equipped with a valve. The vessel and valve are thermally isolated from the surrounding air. The surrounding air has a temperature of 22°C and a pressure of 1 atm (1013 Pa). The valve is opened. After some time the valve is closed again. 1.63 moles of air have entered the vessel then. It may be assumed that the vessel and valve are also thermally isolated from the stream of air, and that air behaves like an ideal gas.

What is the temperature of the air inside the vessel after the valve is closed again?

\[ C_V = 2.5R \quad R = 8.31 \text{ J mol}^{-1} \text{ K}^{-1} \]

Figure 2. (above) Text of the problem elaborated on the worksheet. (below) Worksheet with a worked problem on it.
also has been designed successfully using these instructional principles (6).

Acknowledgment

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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 relations

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

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<thead>
<tr>
<th>Functions of the instruction</th>
<th>Orientation</th>
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<tbody>
<tr>
<td></td>
<td>1. Presenting the essential elements of knowledge and actions specific for this subject</td>
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<td></td>
<td>2. Making these elements of knowledge and actions operational</td>
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<td>3. Giving a system of heuristics for problem solving</td>
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<td>4. Realizing the connection with the entering behavior</td>
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<td>5. Giving the student insight in the objectives of instruction</td>
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<td>6. Exercising the actions and methods of problem solving (PAM)</td>
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<td>7. Giving feedback during exercises</td>
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<td>8. Checking what learning outcome is reached and establishing whether this satisfies the standard</td>
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<td></td>
<td>9. If it is below standard: eliminating the cause of the mistakes</td>
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<tr>
<th>Phases of the learning process</th>
<th>THERMO I THermo I</th>
<th>THERMO II THERMO II</th>
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<tr>
<td>2. Learning to perform the program of actions and methods.</td>
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<tr>
<td>3. Getting knowledge of the learning results.</td>
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<td>4. Improving the execution of PAM.</td>
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Figure 5. Mean scores, standard deviation, and number of students in several thermodynamic courses.

\( \text{score}^* = 5.9 \) 7.5
\( \text{standard} \quad \text{deviation} = 1.96 \) 1.75
\( \text{number of students} = 50 \) 61

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Literature Cited