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Integrating Domains of Physics: Learning Strategies and the Role of Teachers

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INTRODUCTION

Traditionally, physics is taught in high schools according to domains: mechanics, electricity, magnetism, optics, etc. A survey of 30 textbooks from all over the world indicates that 20 of the textbooks present each domain as a completely isolated unit. As a result, students studying from such textbooks are exposed to domains in physics serially, i.e., one after the other.

Our studies and those of others (Bagno, Eylon & Ganiel, 1993; Van Heuvelen, 1991; Iran-Nejad, McKeachie & Berliner, 1990; Bicak & Bicak, 1990; Anderson & Botticelli, 1990; Burkhard, 1987; Perry & Miller, 1970) have shown that knowledge acquired by students studying in this manner is fragmented. Students lack a knowledge structure containing the relationships between the central concepts of physics and between the various studied topics. In addition, it is known that students encounter various difficulties both in comprehending basic concepts and also in applying acquired knowledge to problem solving (e.g., de Jong & Ferguson-Hessler, 1986; Eylon & Reif, 1984; Heller & Reif, 1984). In the long term, the knowledge of many of the students deteriorates into a number of partial equations and the concepts are represented by meaningless labels.

It has been shown in the past (e.g., Meyer, 1975; Kintsch, 1975) that fragmented knowledge is one of the possible sources of difficulty in comprehending concepts and in problem solving. Furthermore, it has been shown (Eylon & Ganiel, 1990) that the same concept can have various meanings in different domains. For example, the meaning students attribute to the concept of "potential" in the context of electrostatics is different from the meaning of "potential" in DC circuits.

In light of the above, it is important to guide students to construct for themselves a central knowledge structure in which the details are firmly anchored. Such a knowledge structure will enable the students gain an in-depth understanding of concepts and implement this understanding in solving complicated problems. In the long term, the structure will help them memorize central concepts which will make more detailed concepts accessible. A useful knowledge structure can be achieved by organizing the material around physical principles and central concepts while, at the same time, treating the specific learning difficulties associated with the domain under study (Eylon & Reif, 1984; Bagno, 1986).

The organization of physics concepts and principles is characterized by two types of relationships:

1. *Intradomain relationships* - Physics principles or relationships between concepts belonging to one domain. For example, the relationship between a magnetic field and an electric field, or the relationship between power and energy. The instructional unit "Organization of Concepts in Electromagnetism" is an example of intradomain organization of knowledge (Bagno, 1986). Within the framework of this unit, the material in electromagnetism is organized around key concepts of the domain and the relationships summarize in a qualitative way Maxwell's equations. The results of an evaluation study of this unit clearly show the utility of the organization. After studying the unit, students are able to memorize central concepts and apply acquired knowledge for problem solving.
2. *Interdomain relationships* - Relationships between central concepts in different domains. For example, in the course "Electricity and Conservation Laws", a high school physics program developed in the 1960's at the Weizmann Institute, the topics studied are organized around the laws of conservation of momentum and conservation of energy.

Interdomain organization has several advantages:

1. It reduces the load on memory.
2. It enables the student to get accustomed to difficult concepts by illuminating them from various points of view. For example, the concept of "potential energy" is transferred via such organization from an intuitive domain, such as mechanics, to a less intuitive domain, such as electricity.
3. It enables the student to use methods of one domain to solve unfamiliar problems in another domain. For example, analysis of the potential energy curve, often used in mechanics, is used to explain the behavior of diatomic molecules which is a less familiar context.

Describing a general concept and its examples

In a discipline like physics, in which most of the concepts are difficult and non intuitive, it is essential that the examples studied in "distinct" domains will be related to the general concept. The relationship between a general concept and its specific examples can be described as follows:

A general concept is defined by "critical attributes" (Hershkowitz, 1989; Rosch & Mervis, 1975), namely those properties that characterize the concept through its relationships to other concepts. For example, a critical attribute of the concept "potential energy" is defined through its relationship to the concept "reference point". Specific examples of a general concept must have the critical attributes of the concept, and additional "non-critical attributes" that distinguish the particular example from other examples. For instance, the concept "gravitational potential energy" is an example of the general concept "potential energy". This example has all the critical attributes of the general concept and additional attributes, such as relationship to the concept of "mass".

In our study, we investigated several aspects of high shool students' interdomain knowledge. The main finding of the diagnostic study was that students fail to discriminate between the general concept and its specific examples. More specifically:

1. The general concept:
    - Does not include some of the critical attributes
    - May include some of the non critical attributes of specific examples encountered by the students.
2. There is no clear discrimination between critical and non critical attributes of examples.

These results suggested that there was a need either to redesign existing courses of high school physics or to design auxiliary instructional materials that would guide students in creating a useful interdomain organization of the knowledge. The next section describes an example of interdomain organization for the concepts of “fields” and “potential” in mechanics and electromagnetism. Instructional units were developed to promote this organization in learning these concepts. The following sections describe a study that examined the utility of these instructional units.

INTERDOMAIN-ORGANIZATION: THE SEVEN "MAOF" UNITS

(MAOF - Overview in Hebrew)

"The prime aim of all science is to reduce it to the smallest number possible of principles". This statement, attributed to Maxwell, describes the outlook of a person whose famous equations (Maxwell's Equations) concisely sum up the whole of the Electromagnetism. Following Maxwell's lead, we designed the MAOF units that focus on the general concepts of vector fields and potentials in the domains of mechanics and electromagnetism. The examples of these general concepts discussed in the MAOF units are electrostatic field, gravitational field, the induced electric field and the magnetic field.

The Didactic Approach

Ausubel's learning theory (Ausubel, 1968) suggests that hierarchical structures should be useful in promoting understanding and recall. More recently, Novak and co-workers (Novak, 1981) have developed the idea of "concept maps" as an exemplary learning/teaching strategy. Many studies (Novak, 1987) have shown the utility of such maps in the diagnosis of conceptual difficulties and instruction. Figure 1 describes the vector field classification chart and notes and relevant MAOF units which deal with them.

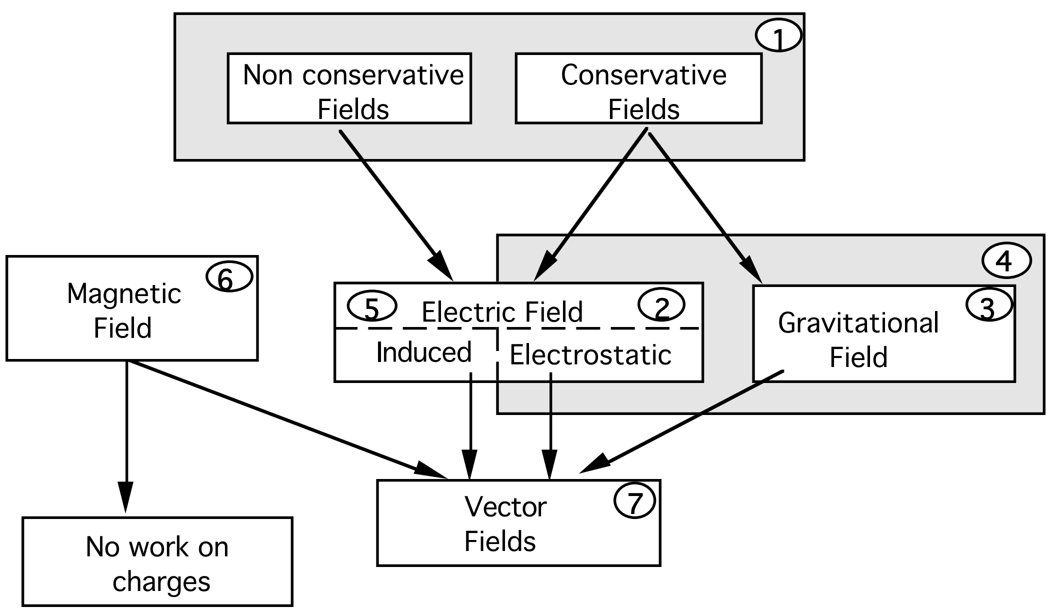


Figure 1: Vector Field classification chart.

As can be seen, the first four units are devoted to conservative fields. Figure 2 describes in greater detail the learning sequence in these units.

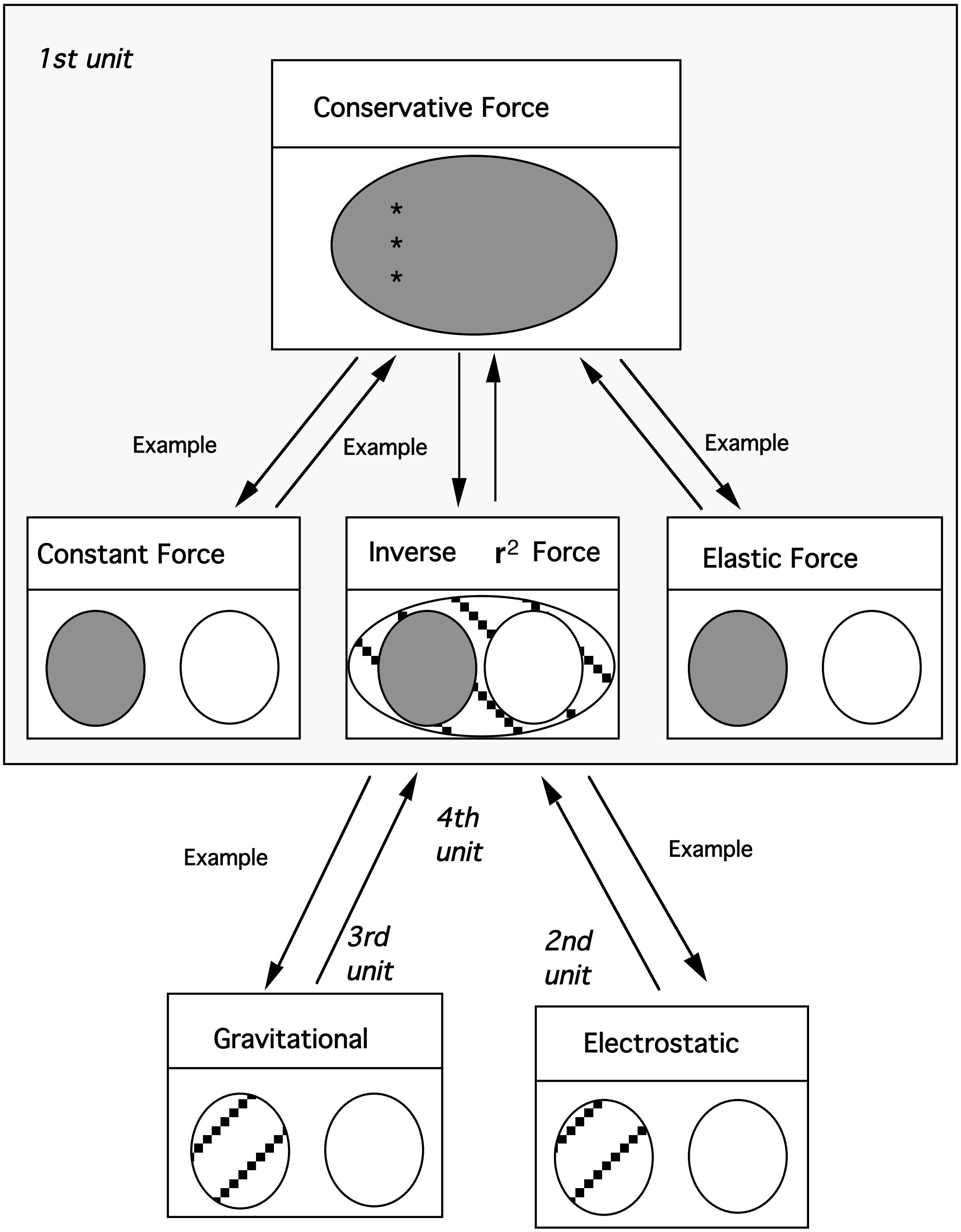


Figure 2: The learning sequence in MAOF units 1-4.

The first unit deals with the general concept of conservative force and three examples of it: Constant force, $\frac{1}{r^2}$ force and elastic force. In learning about the general concept - critical attributes are highlighted. In learning about the examples the focus is on the distinction between critical and non-critical attributes.

Units 2 and 3 deal with the electrostatic and gravitational forces (fields). In this context, the general concept is the $\frac{1}{r^2}$ force discussed in the first unit and the electrostatic and gravitaional forces (fields) are examples of it. Once again, the focus is on the distinction between critical and non-critical attributes.

Units 5 and 6 deal with other vector fields. Unit 5 discusses an example of a non-conservative field - the induced electric field. Unit 6 discusses the magnetic field. This field cannot be classified as a conservative or non-conservative field.

Unit 7 summarizes the characteristics of vector fields. The laws which relate the central concepts are formulated again in a more qualitative way. For example, this unit contains a discussion of the physical significance of Maxwell's equations.

To summarize, the MAOF units:

1. Deal with central concepts and principles studied in high school physics.
2. Discriminate between critical and non critical attributes of examples.
3. Integrate critical attributes of examples to support the construction of general concepts.

The MAOF units include activities for the student as well as materials to be used in the classroom. The instructional approach is integrative. The activities guide the student to clarify the meaning of each concept and to construct relationships between concepts. These goals are achieved through active problem-solving.

Figure 3 shows a representative sequence of learning events in which the understanding of two concepts is improved, while at the same time they are being related to central structures represented by concepts maps.

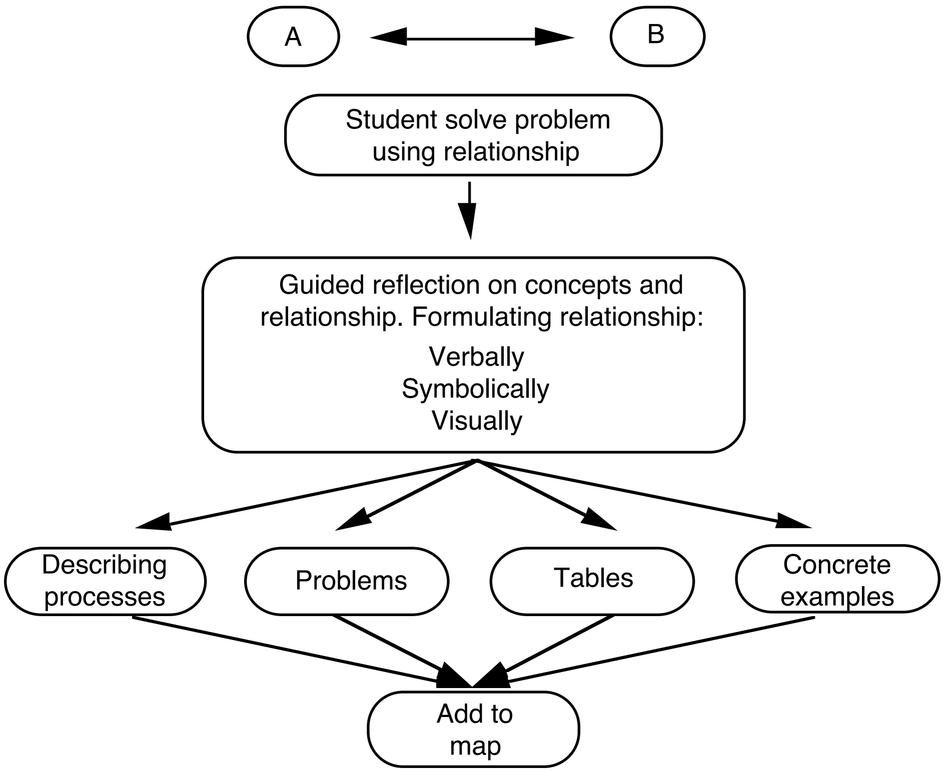


Figure 3: A representative sequence of learning events in which the relationship between two concepts is constructed.

As can be seen from the figure, the learning sequence consists of several stages:

Stage 1: The student is asked to solve a problem (or problems) in which the relevant relationship between A and B plays a central role. These problems can be chosen from standard problems that are used in regular instruction.

It is important to note that the central problems are, by and large, simple problems in which the student is required to perform minimal mathematical manipulations. This is so as not to disguise the message of the problem, which is the construction of relationships between concepts.

Stage 2: A written discussion follows in which the relationship is identified and compared to other relevant relationships. Differences and similarities are pointed out, and finally the relationship is formulated verbally, symbolically and visually. For example, in the case of electromagnetism a bi-directional arrow between the electric field and potential difference is used E < - - > V in order to emphasize that the first concept can be defined by the second one and vice versa. In addition to the relationship, the characteristic properties of the concepts involved are illuminated and the concepts are developed and elaborated.

This is the stage in which common misconceptions are pointed out. (For example, students tend to mix up the concepts of potential and potential difference, and therefore the treatment can clarify the meaning of these two concepts).

Stage 3: In this stage the following means are used to help students create an improved knowledge structure:

1. Concrete examples including non-routine situations illustrate the relationship.

2. Compact tables are provided to facilitate retention and retrieval.

3. Students are asked to apply the already defined relationships in non-standard problem solving.

4. Students are asked to use the concept map to describe various physical processes. Special attention is given to misconceptions. Non-routine problems which create conflict are used in each chapter in order to highlight inconsistencies.

Stage 4: The new part of the concept map including A and B and the relevant relationship is added to the previously existing concept map. For example, the following interdomain concept map summarizes the first unit.

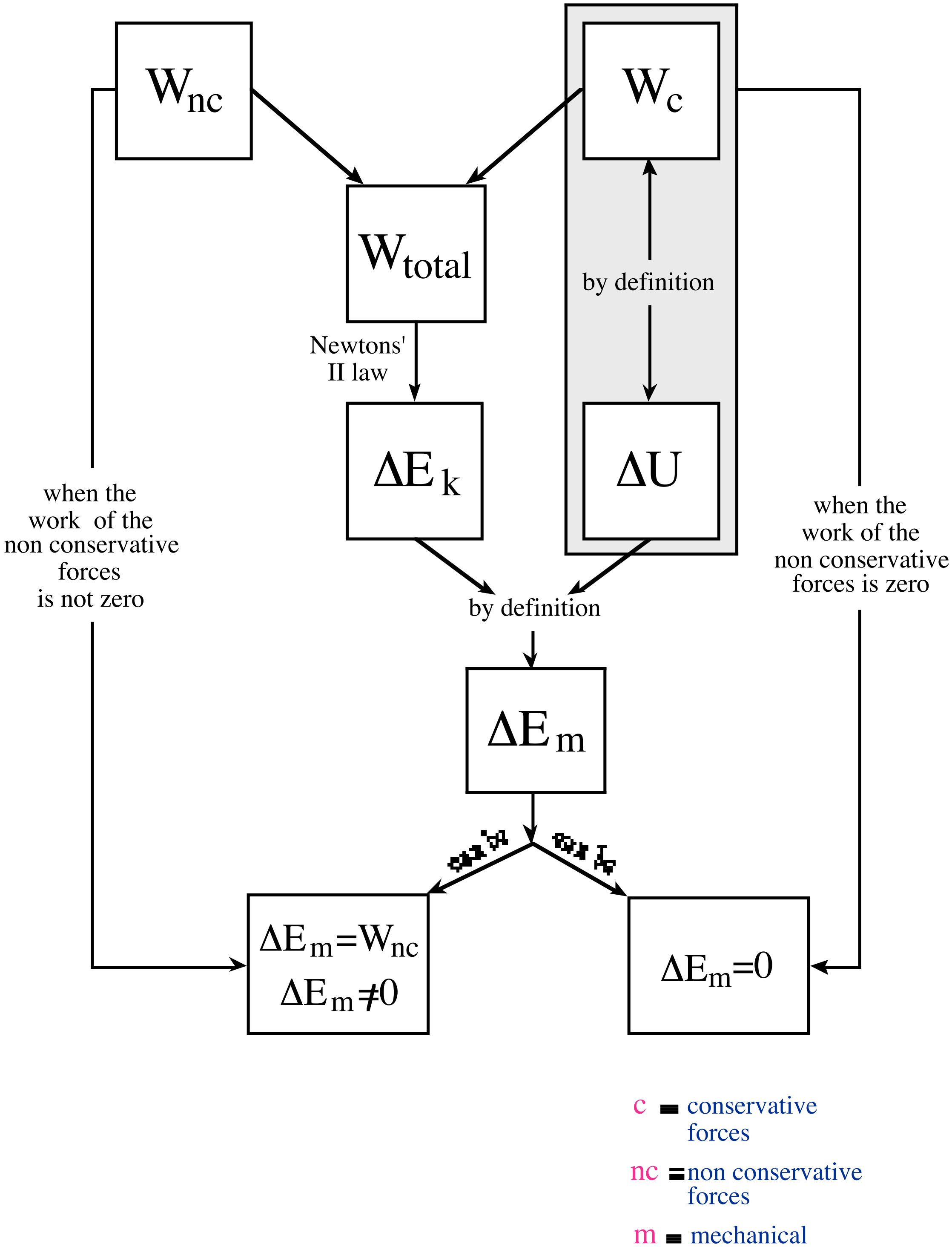


Figure 4: An interdomain organizational concept map summarizes the first unit.

THE STUDY

Rationale and Method

As was mentioned earlier, the results of a diagnostic study about students' interdomain organization of knowledge motivated this study. It was found that students fail to discriminate between the general concept and its specific examples. Hence, a method for enhancing the development of a useful interdomain organization was developed. Originally the units were designed as self-study units to be minimally supported by teachers. It was hoped that this approach would allow maximum flexibility. Therefore, the natural next step should have been the implementation of the instructional units in the manner described above.

As part of the effort to involve the teachers in the process of implementation, we examined the relevant interdomain knowledge of experienced physics teachers. Surprising similarities were found between the knowledge structures of the students and their teachers. This finding led us to the idea that we must relate to the teacher as a "learner", and therefore, try and offer the teachers a course similar to that being offered to the students. The teachers were also guided to construct a knowledge structure surrounding the central principles of physics, so as to bring about a better understanding of the concepts and the relationships between them. The teachers were very enthusiastic about the approach and decided to take a much more active role in the implementation process than we had originally planned.

The study reported below refers to this new approach that evolved from our interaction with teachers. The study was carried out with several teachers and their students who used the MAOF units. As was mentioned previously, these units deal with two central general concepts and their examples.

Sample

Sample of students: The sample consisted of 200 students (ages 17-18) from eight different classes. All students studied physics at the advanced level offered in Israeli high schools (5 credit-points). The classes were divided into two matched groups of four classes, where the general level of the students and informal information about their teachers were taken into account. The four groups were randomly assigned to the experimental group E (N=100) and comparison group C (N = 100).

Sample of teachers: The teachers who took part in this project were chosen from a group of twenty experienced physics teachers who teach this subject at the highest level. All had at least a B.Sc. degree in physics. They were all given the pretest. Four of them participated in the experiment.

<u>Treatment</u>

The treatment was implemented in an in-service teacher training program and after that in the participants classes. The teachers were instructed in the same way as they were requested to instruct their students. The complete course consists of seven parts, corresponding to, and designed around, the seven MAOF units.

The first part takes place after completing the study of mechanics and electricity. The remaining six parts of the treatment are provided, in a similar fashion, after studying each of the topics in the classroom. Each of the seven parts of the course is splited into three major stages:

Stage 1: Takes place at home. The learners solve all the central problems in the MAOF unit. They are not required at this stage to read through the entire unit.

Stage 2: Takes place in the classroom. The learners, under guidance of the teacher, formulate the relationships which lead to the construction of a concept map (for example, the concept map described in Figure 4).

Stage 3: Takes place at home. The learners study the entire unit and complete all the required tasks.

<u>The Pretest: Analysis and Results</u>

The pretest and posttest were administered in the classrooms and lasted about 45 minutes each. Both the pretest and the posttest examined the general concepts and their examples. A-priori, seven general relationships which are the critical attributes of those two concepts were identified:

- The concept of "potential energy". Potential energy is related to: conservative force (x_1), to reference point (x_2), to conservation of mechanical energy (x_3) and to work (x_4).
- The concept of "central forces which are proportional to $\frac{1}{r^2}$ ". They are conservative (x_5), their functional behavior is $\frac{1}{r^2}$ (x_6) and obey Gauss' law.

The pretest consisted of three parts:

Part 1 - The attributes of the general concept: For example, the task about potential energy was phrased in the following manner:

Next to the concept "Potential Energy" write meaningful relationships in physics that include this concept. The more you can think of the better.

The answers to this recall task can shed light on the relative importance that is attached to different ideas in the domain and thus can reveal omisssions of ideas that are considered to be important by physicists, or overemphasis of less important ideas. Furthermore, this kind of recall task can predict what information is likely to be remembered by the students after a long period of time. Previous research (Kintsch, 1975, Meyer, 1975) has shown that in studying new information, people extract a hierarchy of ideas, where the "important" information (as grasped by the learner), is placed at the top of the hierarchy. As time passes, lower levels of the hierarchy will be forgotten and people will remember the top level - "important" information. The critical attributes of a general concept are essential for its understanding, they should be at the top level of the hierarchy.

Three measures were examined in the recall task for each of the seven attributes identified a-priori:

a. The presence of critical attributes $x_1 \ldots\ldots x_7$.
b. The presence of non-critical attributes that belong to prototypical examples. As mentioned above, the highest level of the hierarchy should include critical attributes exclusively.
c. The number of general statements.

a. Figures 5 and 6 summarize, for each critical attribute, the percentages of students and teachers who mentioned it. (The figures include also student percentages for the posttest that will be discussed later. The posttest was not given to the teachers). As can be seen from the figures, none of the critical attributes of the two general concepts was retrieved by more than 40% of the students or teachers. The actual percentages were even lower, since we included in our counting also vague statements.
b. More than half of the students or teachers retrieved the attributes of gravitational potential energy as well. For example, the relationship "potential energy is related to mass" which is correct for this example only was commonly mentioned.
c. The third measure, i.e., the number of general statements, is described later in conjunction with the posttest.

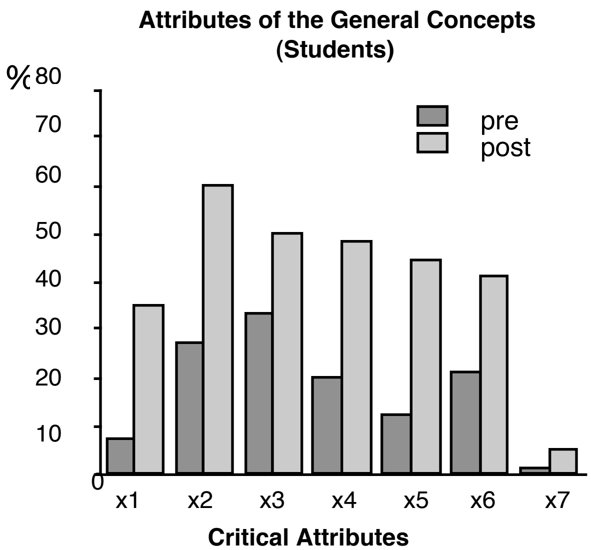


Figure 5: Retrieval - students

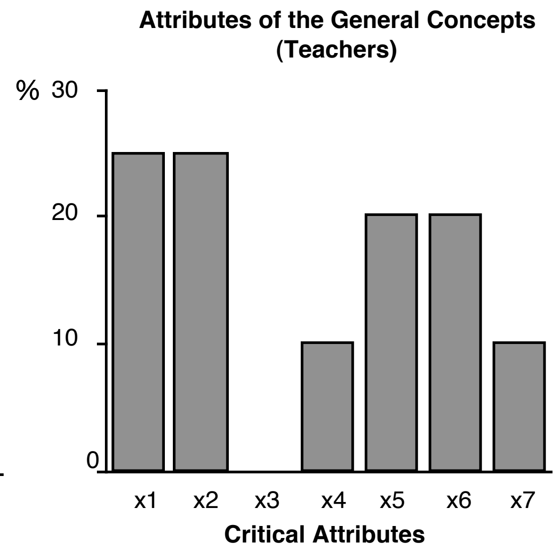


Figure 6: Retrieval in pretest - teachers

Part 2 -The Attributes of the examples: Tasks were given in order to examine whether students and teachers discriminate between critical and non-critical attributes of an example. Students were asked to judge the correctness of several statements and explain their answers. The critical attributes x_1, x_2, x_3, and x_7 of the previously mentioned general concepts, were examined through four examples.

For instance, in the following statement, the critical attribute x_2, which is the relationship between potential energy and reference point, was examined in the context of elastic potential energy (an example of potential energy).

The statement was the following:

You may use the formula $\frac{1}{2}kx^2 + 5$ to calculate the elastic potential energy of a spring with force constant k stretched x meters.

1. Yes, you may ___________________
2. No, you may not _________________

The idea that the choice of a reference point is arbitrary has to be grasped in order to judge this statement correctly.

Figures 7 and 8 show the percentages of students and teachers who succeeded to discriminate between critical and non-critical attributes of the four examples. As can be seen, a low level of discrimination was found.

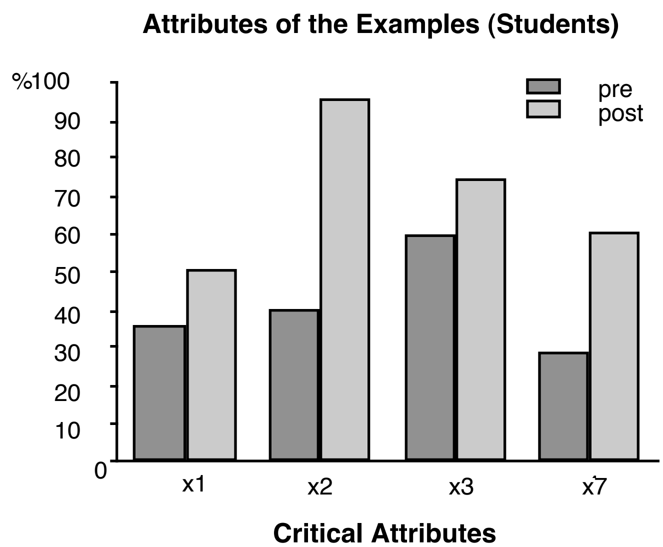


Figure 7: Discrimination - students

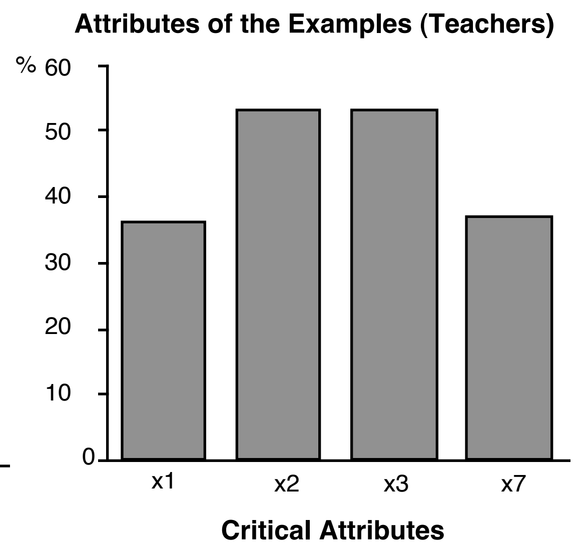


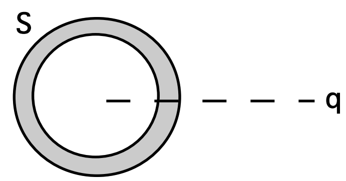
Figure 8: Discrimination in pretest - teachers

Part 3 - Judgment of unfamiliar cases:: In order to judge whether an unfamiliar case is an example of a general concept, one should be able to identify whether the case possesses all the critical attributes. Furthermore, one should not be misguided by non-critical attributes of the case. To examine this aspect, x7, the relationship between "central forces proportional to $\frac{1}{r^2}$" and "Gauss' law" was used. Both electrostatic and gravitational forces are examples of inverse square forces, therefore they both obey Gauss' law. The electrostatic case is a prototypical example of Gauss' law represented in textbooks and taught in the classroom. Apparently two similar statements were given.

a. The prototypical case with the critical attribute: $F \alpha \frac{1}{r^2}$

A charge q is placed as shown in the figure. S is a charged conducting sperical shell. If the shell shrinks uniformly, (it remains spherical and the distance of its center from q does not change, the force the shell exerts on q decreases.

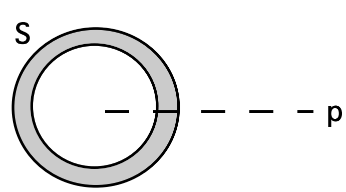
1. correct _______ 2. false__________



b. An unfamiliar case follows, which does not share the same critical attribute. The force is not expressed by an inverse square law, but it does share the same non-critical attributes, namely, a shell and a point outside. Thus, the second situation is a <u>non-example of Gauss' law.</u>

Unknown particles were found in one of the galaxies. The force between two particles is attractive and its magnitude is $F = \frac{A}{x}$ where **x** is the distance between the centers of the particles and **A** is a positive constant. A bulk of these particles is uniformly distributed and forms a spherical shell **S**. A particle **p** is placed as shown in the figure. If the shell shrinks uniformly (it remains spherical and the distance of its center from **p** does not change) the force the shell exerts on **p** will not change.

1. correct _______ 2. false______



Figures 9 and 10 show the percentages of students and teachers who seemed to judge familiar and unfamiliar cases correctly.

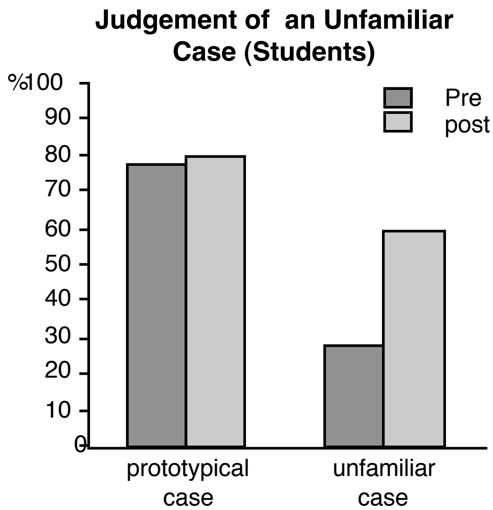


Figure 9: Judgement of cases - students

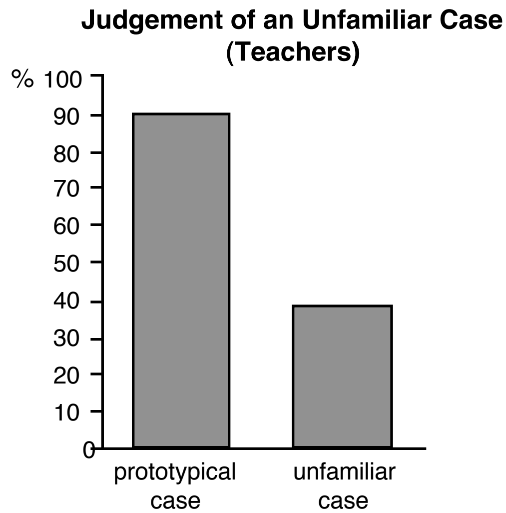


Figure 10: Judgement of cases in pretest- teachers

The fact that Gauss' law in electricity is a prototypical example of Gauss' law explains the high proportion of students and teachers who succeeded in this task. Their failure in the unfamiliar case was probably caused by the over emphasis of the non-critical attributes of the prototype.

Posttest: Analysis and Results

The tasks included in the posttest were given to examine whether the treatment actually improves the learners' ability to:

1. Include at the general concepts' level critical attributes exclusively.
2. Discriminate between critical and non-critical attributes of an example.
3. Judge unfamiliar cases on the basis of critical attributes.

The examination of the attributes of the general concept was similar to the one used in the pretest. The examination of the attributes of the examples and judgment of unfamiliar cases was different. Learners were asked to judge the correctness of a new set of statements and explain their answers.

Out of consideration for the teachers' status, they were not given the posttest. Instead, we interviewed each teacher.

The analysis of students answers attempted to assess whether there were differences between the experimental group's performance in the pretests and the posttests.

Part 1 - The atributes of the general concepts:

a. The number of critical attributes present:

A paired t-test was performed on students' scores in the pretests and the posttests for x_1, . . .x_7. Figure 5 presents the scores for the students.

As indicated in the figure, students recalled better important relationships in the posttest. Excluding x_3 and x_7, all the results are significant.

b. The number of the non critical attributes of prototypical examples.

A comparison of the pretest and the posttest shows a significant decrease in the retrieval of the non critical attributes of gravitational potential energy ($t=4.023$, $p<0.0001$).

c. Number of general statements: A comparison of the pretest and the posttest shows a significant increase in the number of general statements ($t=8.511$, $p<0.0001$).

Part 2 - The attributes of the examples: A paired t-test was performed on students scores in the pretest and posttest for x_1, x_2, x_3 and x_7. Figure 7 presents the data.

As indicated in the figure, students performed better in the posttest than in the pretest. They also discriminated better between the critical and non critical attributes of the four examples. All the results are significant.

Part 3 - Judgment of unfamiliar cases: In this test students were presented with a new set of familiar and unfamiliar situations. The unfamiliar situation had a strong resemblance to non critical attributes of a familiar situation. It was expected that the treatment actually facilitates students ability to judge unfamiliar situations on the basis of critical attributes. A t-test comparing pretest and posttest scores for the experimental group shows a significant improvement ($t=4.108$, $p<0.0001$).

DISCUSSION

It is often assumed that the strong resemblance between several examples of a general concept is readily identified by learners. Furthermore, it is also assumed that in comparing examples of a general concept, learners would easily differentiate between the critical attributes that characterize the general concept and the non-critical attributes special to each example. The results of this study show that these assumptions are unwarranted not only for high-school students, but also for their teachers. The fact that even teachers do not differentiate clearly between critical and non-critical attributes of examples, shows that experience does not lead automatically to the formation of general concepts as generalizations of examples learnt in different domains.

The present study describes an instructional approach that facilitates the formation of interdomain organization of concepts learnt in different domains of physics. In this approach students' acquisition of useful knowledge structures is driven by problem-solving activities augmented with treatment of specific conceptual difficulties. The relationships acquired are represented by concept maps at different levels of detail. After constructing the maps students use them for further problem-solving.

Students using the MAOF units, after completing the study of mechanics and electromagnetism, improved considerably their ability to identify the critical attributes of the general concepts discussed in these units. They also improved their ability to distinguish between critical and non-critical attributes of the examples and to analyze unfamiliar examples and non-examples of the general concepts.

Teachers found the approach very useful for enhancing their own understanding of the presented material. This includes a better understanding of the individual examples that were included (e.g. the conservation of mechanical energy), and also the relationship between examples of the same general concept in mechanics and electricity. The following are some examples of their reactions:

* I enjoy it . . . My students like it.
* That's the way things have to be presented in the first place . . .
* I am convinced.
* That's the way I present things now.
* I am going to convince my colleagues.

Thus in the process of conducting our experiments, the teachers found it useful to integrate the ideas more fully into their teaching and not only as summary units providing an overview of what has been learnt. Based on this study we plan to follow the lead of the teachers and integrate this didactic approach into the curriculum.

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