Module 9: Analysis of Physics Concepts

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Introduction

Most physics teachers think about their courses in terms of topics covered, concepts explained, and principles applied. Our effort in this workshop has been to call your attention to another important dimension of physics teaching, your students' patterns of reasoning. By this time, you have probably concluded that most physics courses are addressed primarily to students who can use formal reasoning patterns with ease, and we would agree with that. Yet there are also the students who use formal reasoning patterns only with difficulty and in limited areas. To help you analyze course content and present it in a way that will be understandable to more of your students, we suggest that you classify physics concepts according to the reasoning patterns necessary to understand the meaning you wish to communicate. Concepts may then be called "concrete" or "formal," in analogy to the stages of reasoning. This module presents examples and explanations of "concrete" and "formal" concepts.

Objectives

To assist you in classifying physics concepts on the basis of the patterns of reasoning needed to understand them.

Procedure

We have arranged this module in the form of a learning cycle built around the distinction between concrete and formal concepts. Please find a partner with whom you can join in the activities. Then undertake the designated exploration, invention, and discovery activities described in the attached instructional materials. An audiotape to supplement the invention phase is available; we suggest you listen to it at a certain time as indicated in the text, but you may wish instead to proceed to some of the discovery activities before listening.
Module 9 Instructional Materials

1. Exploration

Four concepts commonly introduced in an introductory physics course are listed below. Determine from your teaching experience whether a student could develop an initial understanding by the use of concrete reasoning patterns together with actual experience using suitable materials. Begin by discussing each of the topics listed below with your partner and briefly outlining to one another the instructional experiences you would provide for students at your institution. Then identify in writing the reasoning patterns necessary and laboratory experiences that could be used. If you believe that a concept could be introduced at various levels, use the simplest one here.

Interaction:

Electrical Conductor:

Ideal Gas:

Light Wave:

Please come to an agreement with your partner on each item before continuing to read.
2. Invention

In our opinion, "interaction" and "electrical conductor" can readily be understood in terms of familiar actions, observations, and examples. In other words, these concepts can be derived from using concrete reasoning patterns. Such concepts are called concrete concepts. The concepts of "ideal gas" and "light wave" must be understood in terms of other concepts (pressure, volume, electric field, etc.), functional relationships (ideal gas law, wave function), inferences, and/or idealizations. Those understandings are not the direct result of concrete experiences but are theoretical elaborations that require application of formal reasoning patterns. Such concepts are called formal concepts. Many concepts, of course, have more than one meaning and may therefore be concrete or formal, depending on their treatment. Thus, temperature as read on a thermometer is a concrete concept; temperature as a measure of the average molecular kinetic energy is a formal concept.

It may be good to mention at this time that the concrete vs. formal distinction is not equivalent to the familiar concrete vs. abstract distinction. All concepts are abstract, abstracted from many specific instances and concrete examples. Interaction is abstract in that it is very general, applicable to all objects that influence one another, regardless of whether they exchange energy or momentum, modify the chemical composition, or (if living) infect with a disease. The abstraction process involved in the interaction concept, however, depends on reasoning patterns appropriate to the concrete stage, and the concept has been taught successfully to second and third grade children in the framework of everyday objects and their interactions.

The light wave concept is also abstract, though more restricted in applicability than interaction. Yet the meaning of light wave depends essentially on Maxwell's electromagnetic theory, which can be understood only through the use of propositional reasoning, functional relationships, abstract variables, idealized models, and other formal reasoning patterns. We might add that the concept of electrical conductivity is a formal concept, even though we considered electrical conductor concrete because it could be identified by direct empirical criteria.

Please listen to the audiotape on Self-Regulation and Physics Concepts now. For your convenience, the script is included at the end of these instructional materials.

3. Discovery

To allow you to apply your present understanding of the distinction between concrete and formal concepts, we have constructed a list of items we should like you to classify. Discuss each item with your partner to help you clarify your ideas, but record your own views if the two of you disagree. To help you justify your classifications, we have included here a slightly edited version of the concrete and formal reasoning patterns originally given in Module 2.
The formal reasoning patterns most frequently required for the understanding of physics concepts are:

F1. understands concepts defined in terms of other concepts or through abstract relationships such as mathematical limits.

F2. imagines all possible combinations of conditions even though not all may be realized in nature.

F3. separates the effects of several variables by holding all but one constant.

F4. uses theories or idealized models.

F5. recognizes and applies functional relationships, such as direct and inverse proportion.

The concrete reasoning patterns most frequently required for the understanding of physics concepts are:

C1. understands concepts defined in terms of familiar actions and examples.

C2. applies conservation reasoning.

C3. establishes one-to-one correspondences and arranges data in increasing or decreasing sequence.

C4. makes simple classifications and successfully relates systems to subsystems, classes to subclasses.

The differences between these reasoning patterns might be summarized as follows: the concrete patterns employ simple operations applied to real objects and experiences, but not to relationships, hypothesized objects, or postulated properties. A concept can usually be considered concrete, therefore, if one can grasp its meaning through direct experience. If a concept derives its meaning principally from its position within a theoretical system, it has to be classified as formal.

Here are the concepts for your exercise. We have included answers for the first two items to illustrate how you might refer to the above lists of reasoning patterns when you give your reasons.

<table>
<thead>
<tr>
<th>Concept</th>
<th>C or F</th>
<th>Reasons</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Pressure</td>
<td>C</td>
<td>Defined operationally through a barometer reading, with pressure differences defined by a manometer (C1). Pressures can be compared (C3) but not used to calculate gas volumes or forces exerted on container surfaces.</td>
</tr>
<tr>
<td>Pressure</td>
<td>F</td>
<td>The usual definition, force per unit area, depends on the force concept (F1) and on proportions (F5).</td>
</tr>
</tbody>
</table>
Pressure \( F^+ \)  

Pressure is the time-average effect of molecular bombardment of the containing surface (F1, F4, F5). This concept derives its meaning from the kinetic-molecular theory, a theoretical system in modern physics.

2. Shadow \( C \)  

Can be observed easily and is familiar (C1). Correspondence of obstacle shape and shadow shape can be established (C3), as can qualitative size relationships.

Shadow \( F \)  

Ratio and proportions are used to describe size relations of obstacle and shadow in terms of light source, obstacle, and shadow positions (F3, F5).

Shadow \( F^+ \)  

The concept of shadow is qualified by the diffraction of light according to the wave theory (F4). This concept's meaning is affected by the theoretical system of the electromagnetic theory of light. (Note: introduction of the quantum theory would escalate the conceptual level another step.)

3. Temperature

4. Vertical

5. Latent heat

6. Wave interference
If you have reached the conclusion that many physics concepts, though not necessarily all, can be interpreted on either the concrete or formal level, then you will be able to relate this activity to teaching through self-regulation. As was explained on the audiotape, learning that begins with a concrete version of a concept is likely to make a more secure connection with the student's previous understandings and preconceptions. After he encounters some limitations of this concept — for instance, the difficulty of making quantitative predictions from pressure defined concretely in terms of a barometer reading — he can extend its significance to that of a formal concept through self-regulation.

Please look back at the above concept list now, and do the following together with your partner: for each item that you classified on two or more levels, think of an activity that would bring out the shortcomings of the concrete version and thereby initiate self-regulation.
Module 9 Review Questions

Please work on these items together with your partner.

1. Name two physics concepts that can only be understood by use of formal reasoning patterns (i.e., they have no "concrete" version).

2. Name two physics concepts for which you can identify three or more levels of meaning. Briefly define each level.

3. Select one of the concepts you have named in #1 or 2, or a concept mentioned earlier in this module, and briefly work out a learning cycle of exploration, invention, and discovery that might be built around it.

4. Compare the learning activities that might be used for a formal concept with those that might be appropriate for a concrete concept (or the concrete version of the same physical quantity).
Robert Karplus: This is the audio tape accompanying Module 9 in the Workshop on Physics Teaching and the Development of Reasoning. The workshop was prepared under the auspices of the American Association of Physics Teachers with partial support from the National Science Foundation. The speakers are Bob Fuller, who is a little confused, and Jack Renner, who helps to explain.

Jack Renner: How are you doing?

Bob Fuller: Well, I'm a bit confused. These last two modules had something to do with the concept of self-regulation and I'm not sure I understand it. Think you could help me a little bit?

Jack Renner: Well, that is a confusing concept, and you know, it is so important for any teaching activities that are based on the intellectual development theory of Piaget that maybe I should take a few minutes to run over its meaning with you. Think of it like this. Whenever a student encounters an unfamiliar object, unfamiliar situation, or new event—in short, has a new experience—he interprets that new experience in terms of his existing patterns of reasoning, which form a system of understandings and operations called mental structures. Assimilation is Piaget's term. If the new experience is sufficiently complex and unfamiliar to the student, he will only understand it in terms of what he already knows and will not develop an appreciation of the entire meaning the teacher had intended. Development of a greater depth of understanding requires a change in the student's mental structures, a change Piaget calls accommodation. To change the structures, the student must have extensive exploratory experiences as was explained in Module 8. After an appropriate mental reorganization or accommodation, the intended impact of the new experience can be more fully felt. The process leading from assimilation to accommodation is self-regulation. After accommodation the student is in the position of re-interpreting his other knowledge in terms of the new mental structures.

Bob Fuller: Oh, I see. You start by assimilating into your present structures, then through self-regulation, you can accommodate to the new experiences. Sounds like some kind of new jargon to me. I wonder if you could give me some more specific example, maybe taken from physics.

Jack Renner: All right. The first physics course I ever had was in college. I remember the instructor very well, Dr. Tom Bedwell, who was a superior instructor, and he really drove home the concept of velocity. Velocity is the change of distance with respect to time. Thought I, "Big deal! That's speed. Just exactly
what you read from a speedometer. Vectors are not important to the speedometer of my Model A." (That kind of dates me, doesn't it?) I promptly forgot all about the direction aspect of velocity.

Next, we encountered acceleration through an experience in the laboratory with a spark-gap device. That apparatus was, as I remember it, a free-fall apparatus and it delivered to me a nice tape that I could use to see that the carriage fell farther each successive unit of time. Therefore the carriage had to be traveling faster and the velocity had to increase during each interval of time. I could then appreciate the concept of acceleration, that is, a change of velocity with respect to time. I know my reasoning was, at best, early formal operational and that ratio of a ratio gave me some trouble; but in a short time I was saying centimeters per second per second just like everyone else. The holes in the tape made by the spark provided the concrete experience that led me to change my mental structures. Notice, Bob, that once again I did not pay any attention to the vector aspect of acceleration. Nor did the experience require this to be done! I had achieved self-regulation without it, I thought, and to a degree, I had.

Then the roof fell in. Uniform circular motion! Speed is constant and the object is accelerating. Impossible, said I. When the speedometer on my Model A reads constant, I am not accelerating. The patient instructor then reinforced the idea of velocity to a thoroughly confused physics student. I discovered that velocity and acceleration were completely different than I had thought them to be. My entire mental structure regarding velocity and acceleration had to be changed, I had to undergo a completely new self-regulation.

Now, when the instructor drew arrows over the V and A symbols, those arrows really meant something to me and led me to an entirely new set of understandings about Newtonian mechanics. I had finally changed my mental structures, the ultimate outcome of self-regulation (it was a lengthy and uncomfortable process, yet essential for my understanding).

Oh, yes, I think I've had similar experiences with self-regulation as a physics student myself. Now let me ask you a question that's really got me confused. I picked up this module that says something about analyzing physics concepts for formal and concrete concepts and now I find at the beginning all of this introduction to the idea of self-regulation. What has that got to do with it?

That's a very good question. The basic answer to that question is that, in order to initiate self-regulation, you, the physics teacher, must do something with the physics subject matter. Think back to what I said earlier about how self-regulation starts. The student assimilates the outcome of a new experience to his present mental structures. If these mental structures are based on concrete reasoning
Renner (cont'd): patterns, and the student is presented with content that requires formal thought, he is in trouble. Without the aid of concrete experience and the opportunity for self-regulation, he will resort to rote memorization and learn a recipe. So you must begin with concrete concepts. Learners with concrete mental structures need exploration experiences that will lead them to comprehend concrete concepts. Data from such exploration plus the introduction of new concepts may then initiate self-regulation that will ultimately make the student think about the world in a formal way.

Bob Fuller: Oh, I see; so ability to be able to analyze physics concepts into concrete and formal categories might be very helpful for me as a physics teacher. What then is a concrete concept or a formal concept in physics?

Jack Renner: Well, Bob, a concrete concept is one about which the student can develop understanding through exploring concrete objects, concrete events, and/or concrete situations. Those explorations must produce concrete information that can be used to introduce the concept. In other words, for a concept to be concrete, the learner has to be able to develop understanding of it through actual experience. Consider the series circuit. A student can actually observe the fact that the elements in the series circuit are connected each one to the next, and that if you follow from one element to the next, you will come back to where you started. An aspect of the series circuit is that anything moving in the circuit, moves through or over every element. Furthermore, if you define an ammeter as a black box that measures what is moving in the circuit the student can insert the ammeter in the circuit at any one of several places and observe the same reading throughout. Thus a series circuit can actually be experienced. Many concrete discoveries can be made with the series circuit concept.

Temperature, Bob, is another concrete concept if it is related to hot and cold, which can be experienced, and can be measured with a thermometer. So, a concrete concept is one of which the student can develop an understanding through direct experience.

Bob Fuller: Oh, I get it, Jack, that seems fairly easy. Then just about anything I cover in the introductory physics course is probably a concrete concept.

Jack Renner: I wish that were true, but it isn't. Consider the idea of pressure. Now that's a common concept that we always have in physics courses. Pressure is normally defined as a ratio, force per unit area. To understand pressure, the student must understand force and area. While a single force can be experienced, generalizing the idea so force can be thought of as acting on one unit of area requires the student to use a formal reasoning pattern. Hence pressure viewed in
Renner (cont'd): this way is a formal concept. Pressure viewed as the reading of a barometer, however, is a concrete concept, just as temperature defined as a thermometer reading was a concrete concept.

Bob, the nuclear atom is another formal concept. For it to have meaning, the student must grasp the theoretical constructs of plus charge, minus charge, electron, proton, and neutron. None of those can be experienced; none is based upon experience.

Bob Fuller: Oh, I see, Jack; so that really means that a lot of the concepts we use in the basic models we use in physics are formal concepts.

Jack Renner: That's right. A formal concept is one that has meaning because of its position within a hypothetical deductive system. The concept of light polarization, for example, has meaning only in terms of the wave theory. Temperature viewed as mean molecular kinetic energy is a formal concept deriving its meaning from the kinetic molecular theory. Often teachers try to make formal concepts concrete by introducing a tangible model, such as styrofoam balls for atoms, ball bearings for molecules, water waves for light waves. Yet many students only learn about the model from such an experience. They do not construct the related system of postulates and deductions, and do not recognize the relationship of the theory to the concrete materials used to represent the idealized entities of the theory. Examples and careful explanations do help to clarify concepts, but models and examples do not of themselves turn formal concepts into concrete concepts.

Bob Fuller: Now you've got me scared, Jack. What am I going to do with a course in which I have students who are still using concrete operational mental processes?

Jack Renner: Well, students with concrete mental structures cannot properly assimilate formal concepts. Therefore, and this we believe to be the primary message of this module, these students can initiate self-regulation only if they have concrete experiences and the opportunity to begin with an understanding of concrete concepts in the topic to be mastered. After they reflect on the meaning of their experiences, self-regulation will lead them to build the formal mental structures with which they can then assimilate the necessary formal concepts.

Bob Fuller: Oh, I see. Well, thank you very much, Jack. I am eager to go home and try these ideas out in my physics classroom.

Jack Renner: Glad to help.

Robert Karplus: This is the end of the Module 9 audio tape. Thank you very much for listening. Please rewind the tape back to the beginning so another workshop participant can use it. Goodbye.