Understanding Concepts: Implications for Science Teaching

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Many teachers who teach science in grades 3 – 8 have neither majored nor minored in science while in college. Current science teaching methods and materials tend to gloss over this fact, and do not provide adequate instructional support for teachers. While an emphasis on teaching science process is very important, science content must also be learned. To compound matters, research into science education by the American Association for the Advancement of Science (the country’s leading scientific organization, and the publisher of the prestigious Science magazine) has found that learners often emerge from science instruction with troubling misconceptions. It is not easy to fully teach science concepts. But what does it really mean to teach a science concept? First, let’s define what we mean by concept.

WHAT IS A CONCEPT?

Many years of learning-sciences research, involving hundreds of studies, have pretty clearly identified what learning scientists mean when they use the word “concept.” A concept is defined by a set of shared features found in each example of the concept. That is, every example of a concept shares certain must have features with all other examples of the concept. In addition to these must have features, the examples have other can have features, which other examples of the concept may or may not have. The can have features describe the many ways examples of a concept can be different: think of the concept “dog,” for example. Thus, the shared must have features are what define something as an example of a concept and do not change from example to example. The other non-defining features are those the example can have, often changing from example to example, but that don’t define the example as an instance of the concept.

WHAT DOES IT MEAN TO UNDERSTAND A CONCEPT?

Understanding a concept means that for each concept learned (or taught), the learner is guided by the must have properties of each instance of the concept and ignores the varying, can have properties. Further, examples that do not have all the defining properties must be rejected as instances of the concept. Accordingly, concept teaching requires that each concept be thoroughly analyzed and the must have features of each instance identified. The set of features that can vary are also described, so that they do not get erroneously paired with the examples used in instruction. Further, these non-defining features need to be systematically varied so that learners will have experience responding to the critical (defining) features among a vast array of different-looking instances.

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1 Thanks to Sara Pendergast for suggesting the “must have,” “can have” terminology.

2 Technically, a concept is a class of stimuli, each instance of which shares a set of features or properties with other instances of the class, with the instances also varying across many other features or properties (Tiemann & Markle, 1990).

3 During assessment, a learner must identify all instances of a concept that include the critical or defining set of properties across a specified, wide-range of examples, and must distinguish these from matched instances that do not have the full set of critical properties.
To say learners understand a concept, they must be able to do the following:

- Distinguish examples of the concept from close-in (very similar) non-examples that lack one or more of the defining *must have* features (see illustration below).
- Identify examples of the concept across a wide range of varying, non-defining *can have* features.
- Demonstrate this with examples and non-examples not presented during instruction or while learning the concept (Bruner, Goodnow, & Austin, 1956; Clark, 1971; Merrill, Tennyson, & Posey, 1992; Sota, Leon, & Layng, 2011; Tiemann & Markle, 1990).

However, it is not necessary for learners to be able to describe the *must have* or *can have* features or properties.

Unfortunately, very few, if any, science textbooks, digital interactive texts, online science movies and activities, interactive whiteboard lessons, or computer programs on the market today provide this type of instruction for learners. Few instructional activities are so systematically designed as to allow for challenging, guided, authentic discovery, which leads to meeting the Next Generation Science Standards (NGSS.) In addition, little instruction provides for built-in concept assessment and correction, which ensure that each learner can identify or use concepts taught in the program but not encountered during instruction.

THE CHALLENGE OF CONCEPT TEACHING

Most of the time we respond to concepts correctly, without being able to state the features that are guiding our behavior. Take the concept “chair,” for example. If asked to locate a chair and bring it into the room, most people can do this with little trouble. They don't bring in desks, or bicycles, or even couches. They can do this even if the type of chair they find is of a kind they have never encountered. It is the *must have* features that define the concept. The shared properties define the class − the concept.

Perhaps they locate a chair like the one pictured here. Something about the instance brought into the room is shared with the class of objects we call “chair” and allows us to respond correctly to an instance we have never seen before.

Ask a room full of people to define a chair and one gets a range of definitions. Some definitions will be pretty close, others way off, but few will actually describe the features that result in something being classified a chair. We see two things in this demonstration: 1) our definitions do not necessarily guide our classifications, and 2) we do not necessarily consciously understand what guides our classifications. These are two really big reasons why
good teachers can get bad results. We can teach learners definitions or classification rules that are not accurate and that lead to wrong classifications or, worse, misconceptions. We can “know” the concept, but cannot adequately describe what is guiding our behavior in such a way as to provide that knowledge to our learners. It doesn’t matter if the learners are being directly taught, discovering, working on big problems, etc. Unless we fully understand what we are trying to accomplish, creating the right learning environment is very difficult, and becomes a hit-or-miss affair.

HOW CAN CONCEPTS SUCCESSFULLY BE TAUGHT?

For concept teaching to be successful, we first must identify which (must have) features of each instance or example of the concept are completely shared with other instances, and what (can have) features are not shared by each instance. In the case of our chair, one instance may have four legs, another none (as in the picture above). Some may be made out of wood, others out of plastic or metal. Some may be black; others may be any other color. Some may have arms, others may not, and so on. Yet even though there is all this variation from instance to instance, we still recognize a chair as a chair.

How do we find those instances shared by all examples? We can begin by comparing our chair to instances of other concepts that are very close to our example. We can compare a chair to a love seat, for example. What is the difference? The love seat is designed to have room for two, the chair for only one. A chair seats only one person (critical, must have attribute 1 – CA 1). Are there things that seat one person that are not called chairs? We locate a stool that seats someone at the same height as our chair. What is the difference? A stool has no back. A chair has a back (CA 2). Are there things that have a back and seat only one person, that are not called chairs? We find a barstool. What’s the difference? When a person is seated on a barstool, the legs are often left to dangle. When a person is seated on a chair, the legs are supported at about a 90-degree angle (CA 3). This critical attribute (CA 3) is also missing in a chaise lounge.
What we see is that when those three *must have* features occur together in an object, we call that object a chair, and not a stool, a couch, a bench, etc. And because we have seen these features together across a wide range of chairs differing in many other features, we won’t be tricked by color or material or number of legs.

We can use a concept analysis to design high-quality, guided-inquiry-based activities. Let’s consider our chair vs. love seat example: we can provide an example of a chair and juxtapose it with a love seat. We can ask the learners to form small groups and work together to identify the differences, with the goal being to identify each of the defining features one at a time.

Learners will pretty quickly come to see that the chair seats one person, the love seat two. Notice that the two examples differ only in the number of people each seats. By matching the variable features, we can direct learner attention to the defining features. Compare this to what is likely to happen if, instead, we used the example of the love seat to the right.
It is quite likely that one of the variable features would be mistaken for a defining feature.

Sometimes, however, we may want to add more variability and have the features tested against one another over a series of examples and non-examples. Other times we may want to guide the experience a bit more, as learners develop their inquiry skills. With the concepts analyzed and the varying properties identified, we can build highly successful, scaffolded discovery activities that teach content and process at the same time. For example, telling the difference between this “high chair” and “stool” (and acting on that difference) is a challenge, especially when the variable features are very similar.

As a result of this analysis, we can build more effective applications and creative exercises in which learners make full use of the concepts and principles learned. What is more, we can leverage this outcome to quickly extend the concepts and build upon them in such a way as to provide a basis for quickly adding new concepts and principles with little additional teaching, a form of generative learning (Alessi, 1987; Johnson & Layng, 1992 and 1994; Leon et al, 2011; Sota, Leon, & Layng, 2011; Sota, 2012).

WHAT DOES THIS MEAN FOR TEACHING SCIENCE CONCEPTS?

The successful teaching of science concepts requires the very same approach. Each concept should be analyzed and rational sets of examples and non-examples produced that allow for the design of sequences that ensure students will learn the concept. A similar approach is taken to teaching principles (a principle describes a relation between concepts that can typically be stated, “If..., then...”).

For example, the science concepts of solid, liquid, and gas may begin with observed differences between these states of matter. The states of matter can be distinguished by the features of shape (Does the shape of the matter change or not change?) and volume (Does the amount of space the matter occupies change or not change in an unenclosed environment?). For a solid, the must have features are: shape, no change; volume, no change. For a liquid, the must have features are: shape, changes; volume, no change. And for a gas, the must have features are: shape, changes; volume, changes. Each of these two features, shape and volume, is critical to the definition of each state of matter. And since a change in a feature of one concept makes it an example of another concept, we teach these at the same time as coordinate concepts. We need to juxtapose the coordinate concepts so as to highlight the critical (must have) features, while holding the varying (can have) features constant.
The varying (can have) features are many. For solids, these would include objects that are hard and soft (e.g., an anvil and a pillow), inorganic and organic, alive and not alive, etc. The range would be similarly described for liquids and gasses. Learners would be asked to identify examples of each (and, in so doing, correctly reject the coordinate non-example).

If taught correctly, a young learner will be able to identify new examples of solids, liquids, and gasses not encountered during instruction, no matter what they are or where they are found. Once these concepts are learned, we can add another defining feature at the molecular level. That is, why do these states of matter have these properties? We can now link the movement of the atoms and molecules to a single example of each (solid: atoms vibrate in place, not much movement; liquid: more movement, atoms slip past each other; gas: rapid movement, with atoms moving away from each other).
As a result of the earlier concept teaching, when we have the learner match the molecular movement depicted to the state of matter depicted (such as when the coordinate concepts were introduced), we will find that the learner can often go on to match those molecular movements to the entire range of solid, liquid, and gas examples, including examples never before presented – an example of simple generative learning (Sidman, 1994).

We can next look at what it takes to change the motion of atoms (heat and pressure), and thereby change one state of matter into another. We can even provide rather sophisticated simulated experiments that learners can conduct to solve problems involving changing states of matter based on these features. And just as before, by linking the changes caused by heat and pressure to molecular movement, we will find that learners will link them to observed states of matter, with little or no direct teaching required – another example of generative learning.
Learners can now be presented with interesting thought questions about real world events that may occur around the house, thereby increasing the likelihood of science-oriented discussions around the dinner table or elsewhere. In this way, learners are encouraged to extend their knowledge in ways in which their families and peers will notice.

Why can we pour juice into a cup?

There are other benefits to this type of concept analysis. Once the concepts are analyzed, one can more readily specify an optimal learning environment for acquiring the concept. We can target popular misconceptions and prevent them or correct them. Given different classes of student errors, we can precisely diagnose and provide the specific examples or non-examples required to ensure full understanding.

Further, interactive lessons that focus on inquiry can be designed to make it likely that nearly all learners will come to really understand the concepts. We want learners to explore,
ask questions, change variables, and discover the concepts (and principles) we think are important, so they can meet the NGSS and other standards. Often, interactive activities are designed that may engage students but produce little real learning or understanding, and little real concept learning. With the concepts fully analyzed, we can design more effective instruction.

As Susan Markle and Philip Tiemann (1970) observed,

A person who understands physics behaves like a physicist under the same conditions as a physicist. Given a novel slice of reality, he sees it as a physicist would and takes the same actions as a physicist would. Some part of the action may be verbalizing—naming or giving a formula, or such. But the understanding shown by this verbal repertoire is a strong function of the situation in which it occurs. Rarely in the physicist’s world is this situation a verbal stimulus, such as “Define subatomic particle.” Given a complex mixture of manipulations, machinery and observations, the key response is deciding whether or not the observed slice of reality is a member of the class which leads him to say “subatomic particle,” or to flick a particular switch, or to take any other action relevant to subatomic particles.

Each subject matter is a way of looking at reality in terms of certain classes (concepts) and hierarchies of classes (conceptual structures) and stated relations between classes (principles)...
References


