Using the learning cycle to teach biology concepts and reasoning patterns

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The learning cycle method of teaching is introduced in the context of biology instruction. The learning cycle is a three-phase inquiry approach consisting of exploration, term introduction, and concept application. The approach has proven effective at helping students construct concepts and conceptual systems as well as develop more effective reasoning patterns, primarily because it allows students to use if/then/therefore reasoning to test their own ideas and to participate in the knowledge construction process. Three types of learning cycles exist (i.e., descriptive, empirical-abductive, and hypothetical-predictive) that represent points along a continuum from descriptive to hypothetico-predictive science.

Key words: Learning cycle, Conceptual change, Reasoning, Declarative and procedural knowledge.

Introduction

Suppose you plan to teach a lesson on the metabolic rate of water fleas (*Daphnia*). Which of the following procedures do you think would be most effective?

(a) Provide students with live *Daphnia*, thermometers, slides, and microscopes. Have them count the number of *Daphnia* heartbeats per minute at 5, 20, and 35°C, and then graph the number of heartbeats versus temperature.

(b) Provide students with live *Daphnia*, thermometers, slides, and microscopes. Ask them to find out if different temperatures influence heart rate and to graph their results.

(c) Explain that temperature has a general effect on the metabolism of invertebrates. A cold-blooded animal like *Daphnia* is directly influenced by temperature. Higher temperature means higher metabolic rate. One rule states that metabolic rate doubles for every 10 degrees increase in temperature. Now have students use live *Daphnia* to verify and graph this relationship using the steps outlined in (a).

(d) Provide students with live *Daphnia*, a hot plate, dexedrin solution, 5% alcohol solution, a light source, rulers, thermometers, slides, pH paper, balances, graph paper, microscopes, a stirring device, and ice cubes. Ask them to investigate the influence of environmental factors on *Daphnia* heart rate, to search for quantitative relationships, and then attempt to explain what they find.

Certainly your resources and as well as your students' preparation will influence your choice. Compare your selection with the following comments:

(a) This approach may be effective for students who are inexperienced in scientific inquiry as it is fairly directive yet does not spoil motivation by telling students what they will discover. However, for experienced students, it may be too directive as it limits inquiry to only one variable (temperature) and fails to justify the selection of three specific temperatures.

(b) This approach also focuses on the effect of a single variable, but does so without specifying temperatures. This increased openness is a strength as it is more likely to cause students to think about what they are doing and make their own decisions. If improved reasoning is a goal, then some openness is essential.

(c) This approach has little to recommend it as it tells students what they will find. This has two unfortunate consequences. First, it shifts motivation away from satisfying one's curiosity to satisfying the teacher. Secondly, it shifts authority about the correctness/incorrectness of ideas from its natural place in data to an authority figure, namely the teacher.

(d) This is the most open-ended approach. It does what (a) and (b) do and more so. For the inexperienced student, this increased openness would be difficult to cope with without helpful procedural hints. If frustration is a problem, hints can be provided to small working groups. Or, if necessary, the entire class can be stopped to discuss ways of getting started. For experienced students, this approach is highly recommended as it allows for a variety of investigations. This variety allows considerable opportunity to think and make decisions about what and how to investigate.

The recommended approach in (d) and the somewhat more directive approaches in (a) and (b) are examples of *exploration* activities upon which later conceptual understandings can be built. *Exploration* is the first phase of a three-phase learning cycle. The three phases were initially called *exploration, invention*
tation, and discovery (Karplus and Thier, 1967). More recently, they have been referred to as explore, explain, and expand (Trowbridge and Bybee, 1990) and to exploration, term introduction, and concept application (e.g., Lawson, 1995).

During exploration, students learn through their own actions and reactions as they explore new materials and ideas. Exploration should raise questions, complexities, or contradictions. Explorations may also lead to the identification of a pattern of regularity (e.g., heart rate increases with temperature). Approaches (a) and (b) are also explorations, although for many students they are not as likely to encourage reflective thought as (d).

The second phase includes the introduction of a new term or terms such as metabolism, cold-blooded, or poikilotherm, which refer directly to the issues raised and patterns discovered during exploration. The term(s) may be introduced by the teacher, the textbook, a video, or another medium. The lecture in alternative (c) could be part of a term introduction session following an exploration like (d). Students should be encouraged to identify as much of a new pattern as possible before it is introduced, but expecting students to discover all of the complex patterns of modern biology is unrealistic.

During concept application, students apply the new terms and/or reasoning patterns to additional contexts. After the introduction of cold-bloodedness, for instance, concept application might involve determining the metabolic type of other invertebrates or vertebrates. Concept application is necessary to extend the range of applicability of new concepts and reasoning patterns. Without such applications, meanings may remain restricted to examples used in their initial introduction. In addition, applications aid students whose conceptual reorganization takes place more slowly than average, or who do not adequately relate the teacher’s original explanation to their experiences.

**Why use the learning cycle?**

Cognitive science distinguishes two types of knowledge, declarative and procedural, also referred to as figurative and operative (e.g., Piaget, 1970). The distinction is essentially between knowing that (e.g., I know that London is the capital of the United Kingdom, and animals inhale oxygen and expel carbon dioxide) and knowing how (e.g., I know how to ride a bicycle, to count, to conduct a controlled experiment). According to Anderson (1980), ‘Declarative knowledge comprises the facts that we know; procedural knowledge comprises the skills we know how to perform.’ Declarative knowledge is explicit in the sense that we generally know that we have it and when it was acquired. On the other hand, procedural knowledge is generally implicit in the sense that we often are not conscious that we have it and when it was acquired.

Importantly, learning new concepts is not a purely abstractive process. Rather, concept learning depends in part on one’s ability to generate and test ideas and reject those that lead to contradictions. In this sense, concept learning can be characterized as ‘constructive’, as new conceptual knowledge (an aspect of declarative knowledge) depends in part upon skill in generating and testing ideas (an aspect of procedural knowledge). As one gains skill in generating and testing ideas, concept ‘construction’ becomes easier. This view is consistent with Piaget’s when he claimed that ‘learning is subordinated to development’ (Piaget, 1964), a view supported by numerous studies that have found that, following instruction, students who lack reasoning skills do more poorly on measures of conceptual understanding than their more skilled peers (e.g., Cavallo, 1996; Lawson et al., 2000; Shayer and Adey, 1993).

**Using reasoning to construct a concept**

To see how reasoning (i.e., procedural knowledge) is used during concept construction, consider the ‘creatures’ shown in Figure 1. The top row shows several creatures called Mellinars (Elementary Science Study, 1974). Notice that none of the creatures in the second row are Mellinars. Your job is to figure out which creatures in the third row are Mellinars. Take a few minutes to see what you come up with.

Did you conclude that creatures one, two, and six of row three are Mellinars? If so, how did you arrive at that conclusion? This question is difficult because it requires reflecting on one’s reasoning. Nevertheless, consider the following reasoning, which previous research indicates successful students use (Lawson, 1993).

Suppose we glance at the Mellinars in the first row and see that they all contain one large dot. Could one large dot be the key feature? We can test this idea as follows: If... Mellinars are creatures with one large dot (descriptive hypothesis), and... we look at the non-Mellinars in row two (planned test), then... none of them should contain a large dot (prediction). But... creatures one, two, and four in row two each contain a large dot (observed result). Therefore... Mellinars are not creatures defined solely by the presence of one large dot. We need to generate and test another idea (conclusion).

Recycling this If/then/Therefore reasoning pattern to test and reject additional possibilities eventually allows the reasoner to conclude that Mellinars are defined by the presence of one

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**Figure 1 The Mellinar Task (from Elementary Science Study, 1974).**

1. All of these are Mellinars.
2. None of these is a Mellinar.
3. Which of these are Mellinars?
4. 1 2 3 4 5 6
large dot, a curly tail, and shading. Hence, creatures one, two, and six in row three are Mellinarks. The instructional point is this: if students are simply told answers (e.g., using procedure (c) above), they will not engage in the knowledge construction process, thus will not employ and improve their present reasoning skills. On the other hand, if instruction is more open-ended (e.g., using procedure (d) above), then considerable opportunity exists for students to use and improve their reasoning skills while exploring nature and using if/then/Therefore reasoning to test their ideas and those of others.

**How are theoretical concepts constructed?**

In the Mellinark example, the concept constructed was descriptive as its defining attributes were perceptible. How does one construct concepts when their defining attributes are not perceptible, that is when the concepts are theoretical? Further, when does one assist in a theoretical concept to be constructed or contradicts a previously held belief?

Again let's consider an example. In this case, the example is that of Charles Darwin from 1832 to 1838 as he underwent a conceptual change from a belief in special creation to evolution. Figure 2 highlights the major changes in Darwin's conceptual system during this time as described by Gruber and Barrett (1974).

In 1832, Darwin believed that the creator made an unchanging organic world (O) and an unchanging physical world (P), which were perfectly adapted to each other (Figure 2(a)). But during the voyage of the Beagle, Darwin read a book by Charles Lyell containing persuasive ideas about change of the physical environment through time. At each place Darwin visited, he noted examples and important extensions of Lyell's ideas and was becoming convinced that the physical world was not static. This view in opposition to his earlier belief and created a contradiction, i.e., if...the organic and physical world are perfectly adapted to each other, and...the physical world changes, then...the organic world should also change. But...according to special creation, the organic world does not change. Therefore...a contradiction exists.

This contradiction put Darwin into a state of mental disequilibrium. Piaget (1971) refers to the process of moving from a state of disequilibrium back to equilibrium as equilibration. For Darwin, the equilibration process took until 1838 when he finally resolved the contradiction by converting to evolution. Precisely how and why Darwin changed his mind is, of course, not known. However, Smith and Millman (1987) characterize Darwin's thinking as 'exploratory', meaning that rather than accepting any particular theory, Darwin was considering alternatives and the accumulating evidence, e.g.:

If...God created life forms 'each according to its own kind' (causal hypothesis), and...life forms in several places are compared (planned test), then...intermediate life forms should not be found (prediction).

On the other hand, If...life forms evolve through time (alternative causal hypothesis), then...intermediate life forms should be found (alternative prediction). And...intermediate life forms are found; varieties are the rule (observed result).

Therefore...it seems that life forms evolve (conclusion).

If we assume that internal arguments such as these, and the weight of accumulating evidence (e.g., physical change, intermediate life forms, untold diversity of life forms = more than could be held on Noah's ark), forced a rejection of special creation, then Darwin's exploratory thinking was aimed primarily at making a decision about which theory to accept. Thus, Figure 2(e) represents the partial restoration of mental equilibrium as it eliminates the contradiction implied in Figure 2(b).

Therefore, an initial answer to the question how does conceptual change occur is through equilibration, which is provoked by contradiction. The necessary conditions for conceptual change to take place appear to be: (1) data inconsistent with prior concepts, (2) the availability of alternative conceptions/hypotheses/theories, and (3) sufficient time, motivation, and reasoning skill to compare the alternatives and their predicted consequences with the evidence (e.g., Poser et al., 1982; Hewson and Hewson, 1984).

**The use of analogy**

Once Darwin accepted evolution, the question of how evolution occurs immediately arose. Of course Darwin's answer was through natural selection. Thus, the phrase natural selection represents a theoretical concept constructed by Darwin. Further, unlike the descriptive Mellinark concept, the defining attributes of the natural selection concept are not visible. What cognitive processes did Darwin use to construct the natural selection concept? How, in general, are theoretical concepts constructed?

According to the record, Darwin's search for an explanation involved a number of trials and a good deal of grasping until
September 1838 when Darwin read Thomas Malthus’ Essay on Population. Darwin wrote, ‘I came to the conclusion that selection was the principle of change from the study of domesticated productions; and then reading Malthus, I saw at once how to apply this principle’ (Green, 1959). Apparently, Darwin saw in Malthus a key idea that he could borrow and use to explain evolution. The key idea was that artificial selection of domesticated plants and animals was analogous to what presumably occurs in nature. Of course, once an analogy occurs, it must be tested.

This example suggests that analogy plays a central role in theoretical concept construction. The concept or ‘pattern’ that Darwin borrowed to make sense of his data was inherent in the process of artificial selection. Hanson refers to this process of idea borrowing as abduction (Hanson, 1947). Others have referred to it as analogical reasoning (Karpplus, 1979) or analogical transfer (e.g., Boden, 1994; Holland et al., 1986).

Examples of analogy use are numerous in the history of science. Kepler borrowed the idea of the ellipse from Apollonius to describe planetary orbits. Mendel borrowed patterns of algebra to help understand hereditary patterns. Kekulé borrowed the vision of snakes eating their tails (in a dream?) to propose a molecular structure for benzene; and Coulomb borrowed Newton’s ideas of gravitational attraction to help understand the electrical forces within atoms.

Thus, the answer to the question of how are theoretical concepts constructed is by identifying a previously constructed pattern from the world of familiar objects and events and borrowing it to explain unfamiliar objects and events. The scientist must invent the analogy, while students can be assisted when the teacher introduces the relevant analogy.

**Essential elements of instruction**

The main thesis is that lessons that allow students to examine the adequacy of prior beliefs (conceptions) forces them to argue about and test those beliefs. This in turn leads to disequilibrium when preferences based on their prior beliefs are contradicted and provides the opportunity to construct more appropriate concepts and become increasingly skilled in the reasoning patterns used in concept construction. The central instructional claim is that correct use of the learning cycle accomplishes this end. The following elements are included in learning cycles designed to improve both declarative and procedural knowledge:

- Questions should be raised, or problems posed, that require students to generate predictions based on prior beliefs (concepts and conceptual systems) and/or prior procedures.
- Those predictions or procedures then lead to results that are ambiguous and/or contradicted. This forces students to argue and to reflect on the prior beliefs and/or procedures.
- Alternative beliefs and/or more effective procedures can now be suggested.
- Alternative beliefs and/or the more effective procedures should now be utilized to generate new predictions and new data that allow either the change of old beliefs and/or the construction of new beliefs (concepts).

**Three types of learning cycles**

Learning cycles can be classified as one of three types, descriptive, empirical-abductive, and hypothetical-predictive. The essential difference among the three is the degree to which students either gather data in a descriptive fashion, or initially set out to test alternative causal hypotheses. The three types represent points along a continuum from descriptive to hypothetico-predictive science. They place differing demands on student initiative, knowledge, and reasoning skills. In terms of student reasoning, descriptive learning cycles generally require only descriptive patterns (e.g., seriation, classification, conservation) while hypothetico-predictive learning cycles demand higher-order patterns (e.g., the identification and control of variables, proportional, combinatorial, probabilistic, and correlational reasoning). Empirical-abductive learning cycles are intermediate and require descriptive reasoning patterns, but generally involve some higher-order patterns as well.

During descriptive learning cycles, students discover and describe an empirical pattern within a specific context (exploration). The teacher gives it a name (term introduction), and the pattern is then identified in additional contexts (concept application). This type of learning cycle is called descriptive because students describe what they observe without explaining their observations. Descriptive learning cycles answer the ‘What?’ question, but do not raise the causal ‘Why?’ question.

During empirical-abductive learning cycles, students again discover and describe an empirical pattern (exploration), but they proceed further by generating possible causes (alternative causal hypotheses) for the pattern (term introduction). This type of learning cycle is called empirical-abductive because students describe what they observe without explaining their observations. Descriptive learning cycles answer the ‘What?’ question, but do not raise the causal ‘Why?’ question.

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**Effectiveness of the learning cycle**

Since its inception in the 1960s, the learning cycle has been the focus of hundreds of studies designed to assess its effectiveness. A comprehensive review as of the late 1980s can be found in Lawson (1995). The interested reader may consult either source for details. It suffices to say that the learning cycle has proven very effective at teaching science concepts and improving generalizable reasoning skills in students from first grade to college. For example, in an early study, Renner et al. (1973) assessed basic skills developed by a first-grade, learning cycle based unit called Material Objects. Control students experienced a commercial reading readiness program. The reading readiness of both groups was evaluated by the Metropolitan Reading Readiness Test. Over a six week period, in spite of the fact that the learning-cycle students were not engaged in a reading readiness program, they showed significantly greater gains in word meaning, listening, matching, alphabet, and numbers. Renner
al. (1973) also compared students who had engaged in learning cycle based science instruction for at least four years to students who had been taught science using a textbook for the same length of time. They found that 5th grade, learning cycle students were superior to the textbook students on measures of several process skills (i.e., observing, classifying, measuring, experimenting, interpreting, and predicting). Perhaps more importantly, when general achievement was assessed by the Stanford Achievement Test, the learning cycle students scored significantly higher on mathematics applications, social studies skills, and paragraph meaning. These results are particularly important as they indicate that learning cycle based instruction promotes generalizable intellectual gains.

Three large scale studies conducted in the 1980s with high school chemistry and physics students investigated the role played by each phase of the learning cycle by systematically eliminating a phase and by varying the phase sequence (Abraham and Renner, 1986; Renner et al., 1985; Renner et al., 1988). Five key conclusions were drawn:

- All three phases are necessary for the optimum concept learning.
- Students prefer learning cycles with all three phases.
- Students dislike learning cycles with long and/or complex application phases.
- The combination of exploration and term introduction phases is more effective than term introduction alone.
- The application phrase may substitute for term introduction if the application includes the use of the term(s) used to refer to the concept(s).

More recently, the learning cycle has been found to be effective at helping students eliminate scientific misconceptions. For example, Guzzetti et al. (1993) conducted a meta-analysis of 47 learning cycle based studies and found effect sizes in favour of the learning cycle students that varied from 0.3 to 0.5 standard deviations. Still more recently, Benford (2001) found that the extent of college student’s reasoning improvements was significantly related to the instructors’ skill at engaging students in the learning cycle based inquiries.

In conclusion, becoming a skilled learning cycle teacher takes time and effort. But for those who become skilled, the experience is very rewarding for both the students and the teacher. Once teachers ‘go there’, they never ‘go back’.

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