INQUIRY & INVESTIGATION

How to Use Taxonomic Principles in a Non-Scientific Setting to Teach Hierarchical Thinking

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Abstract

Science education as it is taught in the twenty-first century primarily focuses on scientific literacy, specifically on the process of science and how it can be applied. Most process-driven pedagogical tools are based on hypothesis-driven science, in which the hypothesis is the focal point. In descriptive science, the focal point is the organization of data, leading ultimately to the formation of questions and hypotheses. This technique helps students through the process of data collection, organization, and application without the use of scientific terminology. The students are led through the process using common objects, and then required, as a homework assignment, to collect, organize, and apply their own data. By using this simple, repetitive technique, students will see how a classical scientific field (taxonomy) can be applied to modern life situations.

Key Words: *dichotomous key; descriptive science; scientific literacy.*

○ Introduction

Identifying organisms using a dichotomous key is a valuable skill for budding biologists, but one not easily mastered and frequently challenging to teach. One obstacle students face is the presence of scientific terminology based on Latin and Greek. This is especially true for keys to flowering plants, which are replete with anatomical terms students are unlikely to have ever encountered. A more fundamental impediment is that students often fail to grasp the hierarchical thinking underlying the dichotomous key. This may result, at least in part, from an unfamiliarity with the word "dichotomous," which is not a part of most people's lexicon. To dichotomize is nothing more than to divide one group into two smaller groups (from the Greek *dicho-*, in two, and *-tomo*, to cut). An effective strategy for teaching dichotomous keys, therefore, would be (1) to avoid the use of off-putting technical jargon by using everyday items, and (2) to emphasize the heirarchical organization behind dichotomizing.

The Role of Scientific Literacy in the Classroom

Broadly speaking, the goal of science teaching is to instill scientific literacy. Scientific literacy is a multifaceted topic around which a sizable literature has grown. Miller (1983) was the first to identify three pillars of scientific literacy: (1) an understanding of the scientific approach, (2) knowledge of basic science concepts, and (3) an appreciation of public policy issues relating to science. Subsequent authors have expanded upon these three pillars, providing more detail about understanding and recognizing good science (e.g., Hurd, 1998; McFarlane, 2013) and expanding scientific attitude to include both civic and cultural subdivisions (Hurd, 1998; Laugksch, 2000). Recent authors have downgraded the importance of factual knowledge, focusing instead on the scientific process (e.g., Laugksch, 2000).

Types of Science and How They Are Approached

Science is usually taught through the experiment, that is, experimental or hypothesis-driven science. Here the emphasis lies with the hypothesis and the experiment (Casadevall & Fang, 2008). Students are instructed to make observations, articulate a question, and then formulate a hypothesis. With the hypothesis in hand, they can then construct and run an experimental test (with controls), and finally present their results in the form of a paper or an oral presentation. There are numerous publications describing how such an approach has been used to teach science, including, for example, photosynthesis (Collins et al., 1990) and cardiac physiology (Oates, 2002). As a result, students often learn about scientific methodology and the roles of predictions, hypotheses, tests, and theories, without necessarily understanding the concept of organizing facts prior to conceiving the experiment.

In contrast to experimental science, the practice of descriptive science involves the hierarchical organization of facts. It is first about making detailed observations of characters of given specimens (Casadevall & Fang, 2008), second about logically arranging these observations to find patterns (Ridley, 1985), and third about

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comparing these data to other observations (Grimaldi & Engel, 2007). This process should lead ultimately to questions and the formation of hypotheses (Rehorek, 2004). One example would be identifying a suite of characters from bones of different animals and deriving a taxonomic key from those features (e.g., Gobalet, 2003). Such a key not only aids in the identification of newly found bones, but its construction also allows patterns in the characteristics to be detected. It is from these patterns that questions may be formulated and hypotheses proposed. A case in point: a scientist may use multiple physical characters to derive a cladogram, which is a phylogenetic tree showing possible genealogical relationships among organisms (Ridley, 1985). A cladogram can then serve as a functional hypothesis about how organisms are evolutionarily related.

The Role of Classification

Classification involves the hierarchical organization of observations into groups that share multiple characteristics (Carrillo & Vicente, 2015). These classifications schemes, in the form of taxonomic keys, can be either single-access keys (i.e., the familiar keys with paired, dichotomous questions that the investigator must answer) or multi-access keys (i.e., where the investigator can choose any combination of characters; Tilling, 1984). Either way, heirarchical thinking is involved and the identification keys force the user of the key to think in terms of answering questions (Knight & Davies, 2016). This methodological process of answering questions is a useful introduction to scientific investigation and experimentation (Tilling, 1984).

Classification may be practiced in three ways (Marradi, 1990): (1) as an intellectual operation whereby a general concept is subdivided into more specific concepts, as when one genus is separated into several species; (2) a mechanism to assign objects to previously established groups (i.e., supporting a previously determined pattern); (3) a means of grouping objects into subsets based upon perceived similarities (i.e., forming artificial patterns).

These three types of classification may be challenging to teach to students below the university level. The first operation can involve multiple subdivisions at any given level, and thus is difficult to explain in a short period of time. The other two have been readily incorporated into the biological sciences as phylogenetic and phenetic classifications, respectively (Ridley, 1985). Phylogenetic classification revolves around preformed taxonomic keys, which are often complex and replete with terminology (Carrillo & Vicente, 2015). Such taxonomic keys often confound students, who obsess over the unfamiliar words (Tilling, 1987) and lose sight of the overarching idea. This classification system is also based on evolutionary theory, as members of each group are assumed to have descended from a common ancestor. Thus, full comprehension of this system requires both a basic understanding of evolutionary thought as well as a thorough knowledge of vocabulary for that specific field.

This leaves phenetic classification, termed "classing" by Marradi (1990), which is based only on similarities of defined traits (characteristics), and is thus the simplest and the most practical to use as an example of how the process (hierarchical organization) works. Students generally find it difficult to apply such knowledge (e.g., classification) outside of their learning environment, especially if more theoretical knowledge is required (Hwang et al., 2010). Phenetic classification does not rely upon evolutionary thought nor an extensive vocabulary, as it distills classification into its most fundamental basis—hierarchical thinking. Thus, this is the least complex way that students can be introduced to this form of thinking.

Heirarchical organization (in the form of phenetic classification), scientific literacy, and descriptive science can all be taught easily using simple dichotomous keys. Several authors have discussed how to teach science using dichotomous keys, but none managed to touch upon all three key points. Specifically, collecting characters to form either a dichotomous key (Gobalet, 2003; Beeber et al., 2004; Watson & Miller, 2009) or a flow chart (aka, a decision tree; Šorgo, 2006; Hwang et al., 2010), does not show how this type of thinking could be useful to the general public (i.e., it does not show, in terms of scientific literacy, how this is applicable to public policy issues). Using a previously generated dichotomous key to identify non-biological items (Watson & Miller, 2009) does not teach the hierarchical thinking beyond key construction. In this paper, we show how all three of these aspects—hierarchical organizations, scientific literacy, and descriptive science—can be taught in one module.

○ Objectives

The objectives of this assignment are as follows:

- Objective 1: Describe a simple way to collect characteristics (descriptive science).
- Objective 2: Explain how these characteristics are based on observations of non-biological items so that students will be undeterred by unfamiliar terminology, which they may be learning concurrently in another class (e.g., an aspect of scientific literacy and its application to the general populace).
- Objective 3: Show how to derive both a flow chart and ultimately a dichotomous key (heirarchical thinking) from the data.

This type of exercise is ideally suited for an introductory class for college undergraduate non-science majors, and can be easily completed within an hour. It can also be used in an advanced high school biology class.

○ Step 1: Collect Observations

Purpose

Students learn how to make observations.

Objectives

Students learn about the two types of characterstics: quantitative characteristics are those measurable on a quantitative scale (length, mass, volume, etc.), whereas qualitative characteristics are general features not measurable on a quantitative scale (color, texture, shape, etc.). In this assignment, students are specifically told to focus on qualitative data, which must be collected in an objective manner. This means that students must be able to reliably see these characteristics; they cannot use characteristics not directly observable. (They cannot, for example, use the function of the object as a characteristic, but only its observable properties.) This is when students learn about descriptive science (Objective 1).

Table 1. Table used to collect characteristics for office supplies. Number of rows is determined by the number of groups present. Students would be given the table containing only the two column headings, and the words "Specimen X: Name = ."

Specimen	Characteristics
Specimen A: Name = Stapler	gray, metallic, hinged, rectangular
Specimen B: Name = Ruler	red, plastic, rectangular
Specimen C: Name = Eraser	green, rubber, rectangle
Specimen D: Name = Paperclip	gray, metallic, oblong
Specimen E: Name = Pen	gray, plastic, oblong
Specimen F: Name = Tape dispenser	black, plastic, rectangular, sharp edge

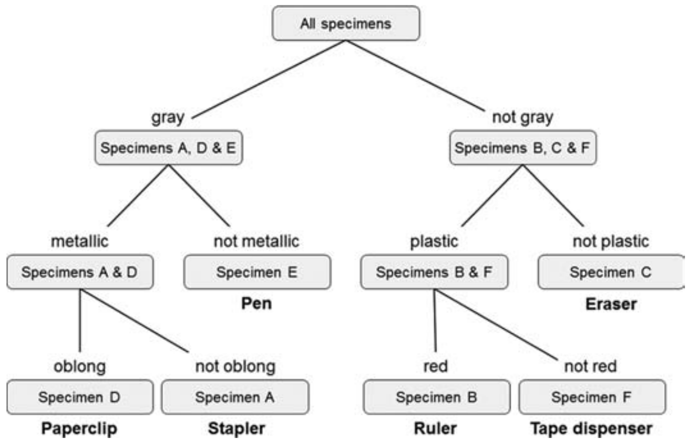

Figure 1. Example of a how a completed flow chart would look. Students would get a flow chart with just the boxes and lines. It is up to them to fill it out with the words.

Methods

A collection of related items, such as office supplies (stapler, ruler, eraser, etc.), is assembled. Students are arranged in groups of two to four, and each group is given a different item to describe; e.g., one group gets a stapler, another a ruler, and so on. Each group then fills out a specified row in a table (e.g., Specimen A = stapler, Specimen B = ruler, and so on), listing three to six qualitative characteristics of their item (see Table 1). These characteristics are then written on a board so that all students can then fill out the table with all the specimens and characteristics.

○ Step 2: Creating a flow chart

Purpose

Students learn how to arrange data into groups and how to find patterns in their observations.

Objectives

To make a flow chart, students must be able to examine a collection of specimens and divide them into groups based on shared characteristics. Students are taught that (a) not every characteristic must be used, and (b) not all flow charts are going to be the same (i.e., there is no one correct flow chart). This is when students learn about hierarchical thinking (Objective 3).

Methods

Students are told that they must split the specimens into two groups based on a characteristic that one group has and the other does not. In so doing, they begin to understand the concept of dichotomy.

For example: based on the data in Table 1, they can divide the specimens into two groups based on color. They then begin to fill out the flow chart. At each juncture, they must clearly state the defining character that is or is not present for each group. They continue until each specimen is in its own box and every specimen has been identified (see Figure 1). This is done with the class as a whole, with the students participating, so that they can see how this process works. The result is then written on the board, so all the students see the same chart. It must therefore be emphasized that there is no single correct chart.

○ Step 3: Creating a dichotomous key

Purpose

Students learn how to transform a flow chart into a dichotomous key.

Objectives

If students had seen a dichotomous key before, it would have been in a biological or geological context. (Keys to various animals and minerals are usually in the form of dichotomous keys.) Flow charts are more common and can be seen in a variety of contexts, not only scientific. This is when students learn about scientific literacy (Objective 2). In addition, students learn that these are two different, but interconvertible, ways of organizing and showing qualitative characteristics (Objective 3).

Methods

Students take their flow chart and transform it into a series of paired questions. The questions are based upon the features used to distinguish between the groups and must be written in a sequential and logical manner. The dichotomy of the questions must be emphasized. Once again, this is done on the board, with student input, as they fill out their sheet appropriately (see Table 2).

Observe the following guidelines when constructing a dichotomous key:

1. Make sure the paired statements reflect contrasting characteristics.

   For example:

   1a. The specimen is gray. 1b. The specimen is NOT gray.

   Not:

   1a. The specimen is gray. 1b. The specimen is plastic.
2. Start with a characteristic that will allow you to divide the specimens into two roughly even groups (e.g., the gray color of

Table 2. This is the dichotomous key based upon the characteristics from the flow chart in Figure 1. Note the dichotomous nature of the statements. The students are given a lined table with only the numbers 1a through 6b. Not all lines need to be filled out, as there are some keys that may be shorter than others.

1a. The specimen is gray	go to 2
1b. The specimen is NOT gray	go the 4
2a. The specimens is metallic	go the 3
2b. The specimen is NOT metallic	Pen
3a. The specimen is oblong	Paperclip
3b. The specimen is NOT oblong	Stapler
4a. The specimen is plastic	go to 5
4b. The specimen is NOT plastic	Eraser
5a. The specimen is red	Ruler
5b. The specimen is NOT red	Tape dispenser

three of the items), and not with minor differences (e.g., the presence of a sharp edge). The final paired statements would center on the minor differences.

3. Use only the physical characteristics of the specimens, those directly observable, and not differences in function.
   For example: The specimen is red.
   Not: The specimen is used to measure the length of objects.

A common stumbling block is how to proceed from Statement 1b. Students often do not have the foresight or experience to see where the instructions should go next. For the purposes of this assignment, they are told to complete one set first (i.e., items that are gray), and then go back to write out the lineage of Question 1b. Once again, this must be emphasized.

A final guideline: the number of paired statements should be equal to the number of specimens being identified minus one. In the above example, it took five pairs of statements to key out six specimens.

○ Step 4: The homework assignment

Purpose

Students use this newly gained knowledge and to derive their own keys from their surroundings.

Objectives

The keys to any successful assignment are repetition and application. The students are given a blank worksheet: this the same worksheet they had just filled out in class, including a blank table for observations, a blank flow chart, and blank lines for the dichotomous key. They are required to fill it out using a different set of observations (this is Objective 1). If they do not remember the steps, they can use the sheet filled out in class, as it was not collected at the end of class. This will test to see whether they are able to complete the task in a coherent, step-wise manner. By using a set of data of their own choosing, they learn how to look at and categorize their surroundings (Objective 3), and therefore learn how this technique can be used in their everyday lives (Objective 2). Thus, all three objectives are revisited.

Methods

Students are given a blank sheet, with only the barest of instructions (the boxes for the specimen character identification, the empty flow chart, and the lines for the dichotomous key). They are instructed to find a set of specimens, and to fill out the sheet, ultimately deriving a dichotomous key. They are told specifically to be objective, and not to describe people (to avoid potential subjectivity). Over the years this has been taught, some of keys returned have included cars in a parking lot, shoes in a closet, pets in a pet store, and contents of a pencil case, a medicine cabinet, and a refrigerator!

○ Conclusions

Descriptive science is often overlooked in science classes, as most tools for teaching science focus on the experiment and experimental science. However, using descriptive science creates the opportunity to emphasize heirarchical thinking and teach basic organizational skills at many levels in science education. By going through the process with the students in the classroom environment, and then requiring them to complete another taxonomic key using their own objective observations, students learn to see how scientific principles work and how they can be applied in their daily lives.

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