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The American Biology Teacher; Nov/Dec 2003; 65, 9; Education Module
pg. 679

The Great Clade Race

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Cladistics is one of the most commonly used methods today for reconstructing evolutionary ancestries. Developed by Willi Hennig in 1966, cladistics uses patterns of shared derived characters called synapomorphies to infer the order of lineage divergences within a group of organisms. Unfortunately, while this methodology forms the foundation of many biological investigations, its principles, goals, and methods are often perceived by students as absolute gibberish.

For many students, an introductory lecture on cladistics comes across as an onslaught of strange new terms and opaque jargon. By the time they have even begun to learn the meaning of words like "synapomorphy," "homologous," and "parsimony," many of them have already reached the conclusion that cladistics is something so complex that they simply cannot understand it. Once a student arrives at this conclusion, it is particularly difficult to lead him or her past it. I have developed a simple puzzle to begin my introductory cladistics lessons that allows students to use cladistic thinking without first bogging them down with terminology. In classes where I have used this exercise, which I call the *Great Clade Race*, students not only begin their approach to cladistics with a more positive attitude, they also seem to have a better comprehension of what cladistics does and why cladistics is used.

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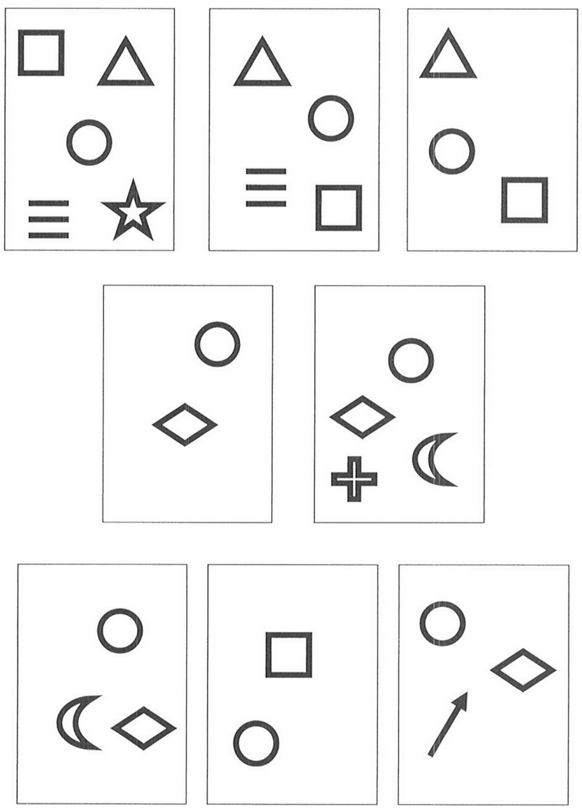
The Challenge

For this exercise, the class works in groups of three to five students. I give each group a set of eight index cards (shown in Figure 1) and start them with a simple task: Organize these cards into distinct groups using any criteria they wish. They can make as few or as many groups as they want, but each card must be put into exactly one group.

After each group has had a few minutes to think about the problem and discuss it among themselves, they invariably use one of two different grouping schemes. Some students will group the cards together based on the number of shapes each card has. Other students will group the cards based on whether they have squares or diamonds. I will then go around the room and ask if anyone would like to defend their classification scheme as being demonstrably superior to the alternative.

Following this brief discussion, I give them some new information and a new challenge. I tell the students to imagine a race through the woods. All participants in the race start at the same starting line at one end of the woods. As the race continues, the path through the woods repeatedly splits, and runners are free to take either fork. Each series of forks leads to a separate finish line at the other end of the forest. As the runners make their way through the woods, each carries a card that he/she must have stamped at check-in stations along the way. I tell the students that the cards that they have been working with are the cards carried by eight runners in this imaginary race.

Figure 1. The eight index cards used in the first steps of the *Great Clade Race*. At first, each group of students only needs to devise a way to organize these cards into groups. Typical organization schemes include squares versus diamonds, and number of shapes per card.



The students' next challenge is to work with their groups to draw a map of the racecourse, complete with check-in stations. While doing so, they must follow a few simple rules:

1. All runners must complete the race. They cannot stop part of the way down a path.
2. When the path branches, it only branches into two new paths, never three or more.
3. Once two paths have branched off from one another, they can never reunite.
4. Check-in stations are located along straightaways between the branching points.

Preliminary Results: Synapomorphy & Tree Topology

Initially, many students believe that their task is too difficult given the paucity of information provided. Eventually, however, they get down to work and realize that they can reconstruct the map rather easily. After about ten minutes, each group has completed the task. They then elect a representative to draw their completed map on the board. Each map looks slightly different from the others, but I ask them to ignore that fact for the moment.

After the class reviews the maps on the board, we then re-evaluate the groups' initial sorting of the cards. At this point, students almost always prefer the division of cards into square versus diamond, and will tell me that it makes more sense, since these cards have a shared history to them. All of the cards with a square on them passed through the square check-in station. Likewise, the presence of a diamond on the other cards indicates a separate history passing by a different check-in station. It is only now, when the students have broached the subject of shared accumulated history, that we begin to incorporate terms like synapomorphy, clade, and cladogram into the exercise.

It is also now that I point out to them that, while their maps all look slightly different, the branching orders are the same (see Figure 2 for an example). The differences between the maps are differences in the directions that the branches travel, not in the order of the branches themselves. If I wanted to divide the cards into nested groups (clades and subclades), we could follow any of their maps and get the same results.

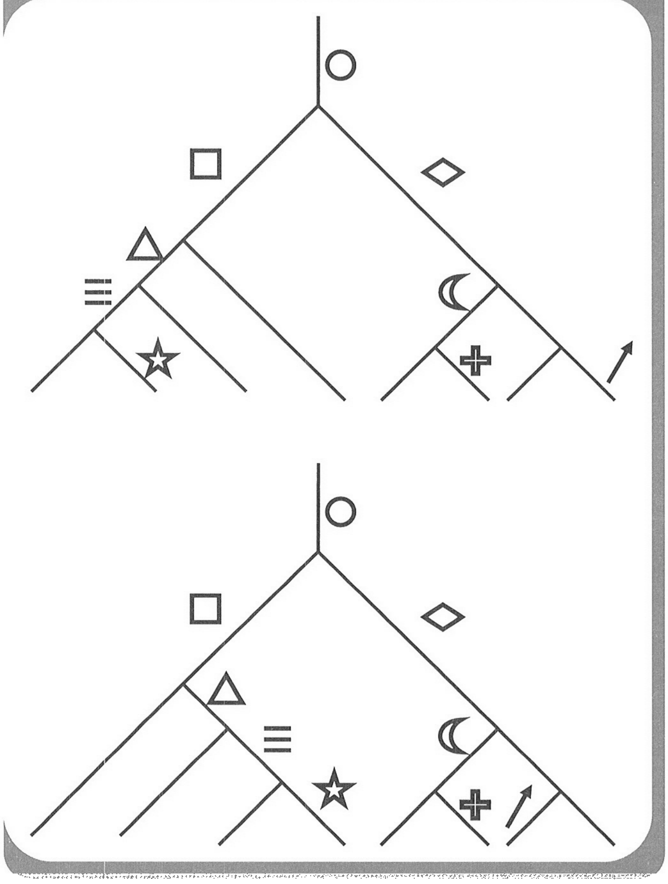
I use this exercise in two different courses – a mid-level evolution course for biology majors, and a team-taught scientific methods course for nonscience majors. This exercise is easy to adapt to either type of course. In the class for nonmajors, we typically stop with the simple eight-card exercise and discuss the utility of cladistic methodology in biology, linguistics, and even economics. In the course for biology majors, the exercise continues to look at deeper evolutionary issues.

Digging Deeper: Homoplasy, Homology & Parsimony

At this point I give my biology majors a ninth card to think about, and I ask them to put this new card into their cladogram. This ninth card (shown in Figure 3) complicates matters because it requires students to infer the possibility of homoplasy, the evolution of the same character multiple times. The only way for them to include this ninth card in the cladogram is if they have two square check-in stations.

This typically takes them a while. In their minds, they have created a set of rules for this game. One of these rules is that there is only one of each check-in station. In biological terms, they have assumed that having a square is a "homologous" character across all cards –

Figure 2. Two different correct answers for Part Two of the *Great Clade Race*. Each answer appears to have a different topology, but in actuality the branching orders are the same.



one that has only evolved once. They typically resist the idea of adding the second square check-in station because, in their minds, that violates the rules of the game. It is at this point that I typically introduce the concepts of homology and homoplasy. I ask them if they can think of any physical features of animals that are probably homoplastic rather than homologous. Wings and eyes are good examples of features that have independently evolved multiple times in animal history.

One last important issue to address is the principle of parsimony. If the rules of this game allow students to posit multiple copies of the same check-in station, then anything goes. You can draw any map you want as long as it has nine finish lines, and then add as many check-in stations as you need to satisfy the requirements of the game at the end of each path. There is no longer any single correct branching order.

In principle, this is true. However, when biologists use cladistics, they typically employ the principle of parsimony as their guide. The principle of parsimony is really an extension of one of the primary tenets of science: actualism, or Occam's Razor. Begin to solve each problem by invoking as few new causal elements as possible. When you need to multiply causal agents (as they needed to in order to fit the ninth card into the game), minimize the extent to which you do so. The simplest answer is not always correct, but it is typically the best starting point for exploration.

Going Further: Tailoring the Exercise to Class Needs

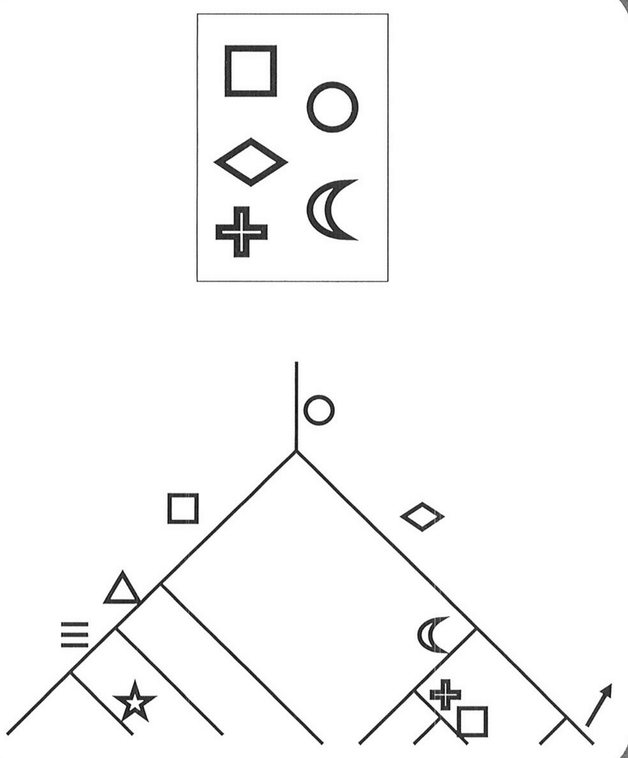
In the course for biology majors, I include the ninth card and use this exercise as an introduction to cladistics, a topic that will be repeatedly visited throughout the term. In this class, I move into the applications of cladistics beyond just classification. Topics that we cover that require cladistic thinking include hierarchical selection, determining rates of evolution, and exploring patterns of biogeography.

In the course for nonmajors, the emphasis is on the commonalities of science. Students learn that although each branch of science has a particular field of inquiry on which it concentrates, all of the sciences share some unifying characteristics. These commonalities include observation, modeling, and classification. For this class, the point of cladistics is to illustrate alternative methods of classification. Students see that when objects share a common history they fall into natural, hierarchical groups based on that history.

Student Response

The scientific methods class has been offered each term for several years. This past year has been the first

Figure 3. The ninth card and its resulting map. Incorporating this card into the exercise requires students to infer the action of homoplasy. The only way they can complete this portion of the exercise is to realize that the square stamp has "evolved" twice.



time that we have incorporated cladistics into the curriculum. In the fall term, I introduced cladistics with a traditional lecture on its methods and theoretical basis. In the spring term, I used the *Great Clade Race* exercise to introduce the concepts, and began using the more technical terminology in the discussion at the end of the activity.

As a way to help tie course concepts together, students in this class compose daily reflective writings. In the fall term, students' reflective writings concentrated primarily on questions about definitions and methodology. In the spring term, however, the questions that most students asked themselves had more to do with applications and reflected an honest curiosity about what cladistics can do. For example:

> *Looking at the history of a [clade] could tell us more about the animals than just grouping them by characteristics ... like why do they have those characteristics.*

One student, who noted that he didn't know how long to draw the different paths in his map, included in his reflection:

> *Did they ever have big evolutionary changes? Or have they changed very little over time, and if so why?*

The students' improved understanding of cladistics was also reflected in their exam performance. In the fall term, we gave students an exam question asking them to read a cladogram and interpret what it said about common ancestries. Only about half of the students in the class were able to answer the question correctly. In the spring term, we gave students a midterm question not only requiring them to read a cladogram, but also asking them to evaluate alternative methods of classification and decide whether or not cladistics was an appropriate tool to use for various systems. Nearly all of the students were able to answer the question correctly.

Regardless of the type of class in which this exercise is used, student response has been positive. Perhaps one of the most important things that this exercise illustrates is that cladistics makes sense. In fact, when given the right way to approach a problem, the basic model of cladistics (grouping by shared, accumulated history) is something that students can derive by themselves. Finally, and perhaps equally important, since this exercise is framed as a puzzle, it takes a concept that is traditionally approached through rote memorization and adds an element of fun. A little bit of fun, particularly in a required course for nonmajors, can make a world of difference.

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