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Teaching Scientific Logic: Theories and Observations

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Abstract

We present a type of assignment designed to teach scientific thinking in introductory astronomy. Students are presented with a list of ideas that have been studied earlier in the course. The students must first classify each idea as being either an observation or a theory. Then the students must match them up in pairs: in each pair, the theory explains the observation, and the observation is evidence supporting the theory.

1. INTRODUCTION

The reason that most undergraduate students take introductory astronomy is to fulfill their requirement for a course in the natural sciences, and often it is the only science course they ever take. Thus, astronomy has a special responsibility to emphasize scientific methods, processes, and logic; indeed, these are prominently featured in the goals presented by Partridge and Greenstein (2004), and considerable work has been done on teaching the nature of science at the college level (see, e.g., Shipman 2004). Astronomy is a particularly good subject for an introduction to the natural sciences because there are so many exciting examples of scientific thinking in the history of astronomy, from the geocentric/heliocentric models of the Solar System to the discovery of the cosmic microwave background that substantiated the big bang theory. In many astronomy classes, the scientific method is given a lot of play toward the beginning and then is presented regularly as a recurring theme, as discussed in LoPresto (2003).

While it may be easy to describe examples of the scientific process in a lecture or a textbook, creating good *assignments* that require students to demonstrate an understanding of scientific logic can be a considerable challenge. Ultimately, students learn and retain most strongly information from activities that they do themselves, while they retain less of what they hear and what they read about. Thus, the tasks that we give to our students, the assignments that they complete throughout the term, are perhaps the most important facet of any course. To develop a solid understanding of scientific logic, our students must not only hear about it and read about it, but they also must complete a series of assignments that center on this topic.

2. THEORIES AND OBSERVATIONS: CLASSIFY AND MATCH

To deal with this challenge, I have developed a series of very simple assignments that present students with a list of ideas that they must classify as being either an observation or a theory. Then the students must match them up in pairs: in each pair, the theory explains the observation, and the observation is evidence supporting the theory. An example of one pair follows:

- In atoms, electrons are only allowed in certain orbits (which correspond to energy levels), and photons of light are produced when electrons move between these orbits.
- When heated until it glows, a gas of each element produces a unique pattern of spectral lines.

A typical assignment has 12 such ideas, 6 theories, and 6 observations. (See the appendix for two examples of these assignments that I have class-tested, one dealing with Solar System astronomy, one dealing with stars and galaxies.)

The first time I gave my students an assignment like this, I was surprised to see how difficult it was for them just to classify ideas as either observation or theory. Most of my students really did not have a clear idea of what exactly we are seeing and what is being theoretically inferred. Students asked very basic questions, like "How am I supposed to know the difference between a theory and an observation?" Some students did not realize that we cannot actually see fusion taking place in stars. This assignment really emphasizes the difference between the use of the word "theory" in the sciences as compared with normal conversation, where "theory" is often used to refer to speculation and conjecture. Ultimately, if we want the scientific method to be the lens through which students view the subject of astronomy, knowing the difference between ideas that are empirical observations and others that are theoretical constructs is absolutely essential.

These assignments are particularly useful because much of the scientific method material is built into the first part of a typical astronomy course, when we discuss the Solar System models of Ptolemy, Copernicus, and Kepler. These classify-and-match assignments are an easy way for a busy astronomy instructor to keep the most basic ideas of scientific logic in front of the students throughout the course, and they can be used with even very large classes. They are especially valuable as review assignments, after we have finished a unit of material, because they help students organize and consolidate a set of topics that we have covered. Further, these assignments are very easy to calibrate in terms of difficulty: the more ideas that students are presented with, the more challenging the assignment will be. At this point, I have only my own anecdotal experience as evidence of the effectiveness of these assignments, and further validation would require pre- and posttest studies.

One misconception that students might get from these assignments is the idea that every theory is supported by exactly one observation, and vice versa. In reality, theories and observations form a complex web of interrelated ideas. A logical extension of these assignments would be to give the students a list in which the ideas do not match up in pairs, but instead might have several observations to support a single theory. For example, the expansion of the universe, the cosmic microwave background radiation, and the abundances of the light elements could be listed as three observations, and all of them support the big bang theory.

3. CONCLUSIONS

Developing an understanding of scientific thinking is perhaps the most important theme of an introductory astronomy course. While it may be easy to describe the scientific process in lecture, I have found it to be a substantial challenge to develop assignments that teach scientific logic and keep these ideas in forefront of the students' minds throughout the course. These theory/observation classify-and-match assignments have been useful in my introductory astronomy classes. Give them a try and see how they work for you.

References

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APPENDIX: SAMPLE ASSIGNMENTS

The Logic of Science: Theories and Observations in the Solar System

Below we have listed a series of scientific ideas. Half of these are theories and half are observations. Every theory has a set of observations that supports it, and every set of observations has a theory to explain it. For each one you must do two things: (1) Identify it as theory or observation. (2) Write down the number of its pair.

1. In atoms, electrons are only allowed in certain orbits (which correspond to energy levels), and photons of light are produced when electrons move between these orbits.
2. There are many craters on the Moon and Mercury, fewer on Mars, and not very many on the Earth and Venus.
3. When heated until it glows, a gas of each element produces a unique pattern of spectral lines.
4. All the objects in our Solar System formed out of one disk of material that orbited our Sun as it formed 4.6 billion years ago.
5. There is a force called gravity, which attracts every object in the universe to every other object, and this force gets weaker with distance.
6. Near the Sun, only rocks and metals are in solid form, while far from the Sun, the ice materials become solid too. As a result, when the Solar System formed, planets far from the Sun could grow much larger.
7. All the planets in our Solar System orbit the Sun going in the same direction, in a flat disk. Most planets also rotate in this direction, and most moons do too.
8. Inside very large Jovian planets, there is enough pressure to turn hydrogen into a liquid form that conducts electricity.

9. All terrestrial planets formed with molten interiors, but smaller planets cooled more quickly, causing their volcanoes to go dormant. The interiors of larger terrestrial planets cooled more slowly, so their volcanoes could remain active for a much longer period of time.
10. The planet Jupiter has an extremely powerful magnetic field.
11. Terrestrial planets are found nearest the Sun, while Jovian planets are found farther away.
12. All orbits of moons around planets, planets around stars, and stars around each other are in the shape of ellipses.

The Logic of Science: Theories and Observations about Stars and Galaxies

Below we have listed a series of scientific ideas. Half of these are theories and half are observations. Every theory has a set of observations that supports it, and every set of observations has a theory to explain it. For each one you must do two things: (1) Identify it as theory or observation. (2) Write down the number of its pair.

1. When gas is caught by the gravity of a black hole, it forms an accretion disk, where friction makes the gas very hot, and slows it down, allowing it to spiral into the black hole.
2. A minority of stars called red giants are very luminous and reddish in color.
3. There are hundreds of X-ray binaries in our galaxy: systems with two stars that have very hot objects that give off large quantities of X-rays.
4. Occasionally a star will disappear in a supernova, becoming brighter than a billion normal stars for a few weeks.
5. When a star builds up a core of iron, this causes the core to collapse, making the star explode.
6. Most of the mass in our galaxy is a mysterious unseen "dark matter."
7. When a star runs out of hydrogen in its core, it burns hydrogen in a shell around this core. The star’s fusion runs very fast, and the outer layers of the star expand and cool.
8. Spiral galaxies are currently forming new stars, while star formation in elliptical galaxies ended long ago.
9. The oldest stars are made almost completely of just hydrogen and helium. Young stars have more of the other elements, up to 2% of their mass.
10. Very massive stars do many types of nuclear fusion in their interiors, creating many different chemical elements. When they explode as supernovae, they increase the quantity of heavy elements out in space. As a result, the amount of heavy elements in the universe has grown over time.
11. Spiral galaxies tend to look blue in color, while elliptical galaxies tend to be orange or red.
12. Stars in our galaxy move faster than we would expect if they were just being pulled by the gravity of other stars.

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