

Learning Critical Thinking Through Astronomy:
Eratosthenes And Scientific Models

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2017-09-13

STUDENT NOTE

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Questions

How can observing sticks' shadows lead to an understanding of Earth's size and shape?

Materials Needed

For this activity, you will need the following materials:

- a darkened room, the darker the better but total darkness is not necessary
- a light source to represent the nearby Sun (bright incandescent light bulb)
- a light source to represent the faraway Sun (use the real thing or a spotlight)
- a yoga ball to represent a non-flat Earth
- a whiteboard to represent a flat Earth
- four Nerf darts to represent sticks
- a ruler
- a pencil (preferable to ink)
- the ability to read and follow directions
- you must have previously completed either one of Activity0201 or Activity0202, and Activity0203 and Activity0204.

Points To Remember

This is the most difficult activity you have had so far in the course.

1 Four Models

In this activity, you are going to use the behavior of shadows to determine whether Sun is nearby or far away and to determine whether Earth's surface is flat or curved. The four models you will consider are the following:

- flat Earth, nearby Sun
- flat Earth, faraway Sun
- curved Earth, nearby Sun
- curved Earth, faraway Sun

At this point, you should have a framework that governs the behavior of a stick's shadow for all locations on Earth (or at least for locations in the other shadow activities you have completed).

1. From this framework, what can you infer about Earth's shape and size? There is no certain number of inferences you must have here, but show how each one you include follows from your framework.

2 Light Paths

If you place a light bulb in the center of a darkened room and turn it on, you can see almost all parts of the room. You can't see the floor directly underneath the table on which the light bulb rests, but you could if the table weren't actually there to support the light bulb. Similarly, Sun illuminates space in all directions but there isn't necessarily anything there to catch the illumination in every direction. We want to consider the geometry for two particular light paths coming from a point source of light to two observers at different places on Earth. The source is not actually shown. Imagine the two observers simultaneously raising their arms and pointing to Sun in the sky. Their arms help visualize the lines of sight along the two incoming light paths. If Sun is nearby, it is obvious from the diagram that the two observers will point in vastly different directions.



2. Look at the point where the extensions of the observers' arms intersect. What happens to the distance between Earth's center and the intersection point as the source (Sun) is pulled farther and farther from Earth?
3. As the source (Sun) is pulled farther and farther from Earth, what happens to the two directions specified by the observers' arms? Your answer should refer to something about the geometrical properties of these two directions. The diagram may not directly show the answer to this question, so you may need to either modify it or create your own more suitable diagram.
4. Would it be possible to put the source (Sun) at any **finite** distance from Earth and the directions of the observers' arms be **parallel**?
5. How would you describe where we would need to place the source (Sun) relative to Earth to make the directions of the observers' arms so nearly parallel that it wouldn't matter to us that they are not actually parallel? **Make sure you completely understand this question before you attempt to answer it!**

6. Do you think there would be any difference between the two observers being on a flat Earth versus a curved Earth when making their observations? There is no right or wrong answer to this question yet because you're basically being asked to make a prediction. We'll investigate the prediction later.

3 Where is Sun?

3.1 Flat Earth, Nearby Sun

Now we'll see if we can learn anything about Sun's distance from Earth. Place the light bulb at the center of a darkened room and turn it on. Place two Nerf darts on the whiteboard 1 cm-2 cm apart, making sure they are **both perpendicular** to the whiteboard.

7. Stand very close (no more than 1 m) to the light bulb and attempt to hold the "flat Earth" in whatever orientation is necessary to make **only one of the shadows vanish**. **Hold the "flat Earth" as close to the bulb as you can without burning yourself, the board, or the darts. Be careful! It may not actually be possible to make one shadow vanish, so don't be alarmed if you find it isn't possible.** If you can make **only one of the shadows vanish**, state what condition(s) is(are) necessary. If you are not able to make **only one** of the shadows vanish, explicitly state that.

8. Now attempt to hold the “flat Earth” in whatever orientation is necessary to make **both shadows simultaneously vanish**. **It may not actually be possible to make both shadows vanish, so don’t be alarmed if you find it isn’t possible**. If you can make **both shadows simultaneously vanish**, state what condition(s) is(are) necessary. If you were not able to make **both shadows simultaneously vanish**, explicitly state that.

9. Now hold the “flat Earth” in some new and arbitrary orientation with both shadows visible. Make sure neither shadow extends off the edge of your “flat Earth.” Devise a procedure for determining whether or not the two shadows are parallel. Two lines are either parallel or they are not; there is no such thing as “half parallel” or other such nonsense. Describe your procedure and resulting conclusion here.

10. Investigate the effect of changing the sticks’ lengths (always keeping them equal) on the above measurements, and describe both your investigation method and conclusions.

3.2 Flat Earth, Faraway Sun

11. Now, using either actual Sun or another light source to model faraway Sun, stand as far away from the source as the room will permit (obviously the room isn't a constraint if you're outside) and attempt to hold "flat Earth" in whatever orientation is necessary to make **both shadows simultaneously vanish**. If you can make **both shadows simultaneously vanish**, state what condition(s) is(are) necessary. If you were not able to make **both shadows simultaneously vanish**, explicitly state that.

12. Now hold "flat Earth" in **the same** arbitrary orientation you used above with both shadows visible. Make sure neither shadow extends off the edge of your "flat Earth." Devise a procedure for determining whether or not the two shadows are parallel. Two lines are either parallel or they are not; there is no such thing as "half parallel" or other such nonsense. Describe your procedure and resulting conclusion here.

13. Are the shadows closer to being parallel than with nearby Sun?

14. Are the shadows closer to being identical than with nearby Sun?

15. Investigate the effect of changing the sticks' lengths (always keeping them equal) on the above measurements, and describe both your investigation method and conclusions.

3.3 Curved Earth, Nearby Sun

Switch back to nearby Sun. Place two Nerf darts on a yoga ball 1 cm-2 cm apart as measured along the ball's surface. Make sure each dart is perpendicular to the ground. Stand very close (within 1 m) to nearby Sun and hold "curved Earth" in whatever orientation is necessary to make **only one of the shadows vanish**. Hold "curved Earth" as close to nearby Sun as you can without burning yourself or anything else. Be careful! It may not actually be possible to make one shadow vanish, so don't be alarmed if you find it isn't possible.

16. If you can make **only one of the shadows vanish**, state what condition(s) is(are) necessary. If you are not able to make **only one** of the shadows vanish, explicitly state that.

17. Now hold "curved Earth" in some new and arbitrary orientation with both shadows visible. Make sure neither shadow extends off the surface. Devise a procedure for determining whether or not the two shadows are parallel. Two lines are either parallel or they are not; there is no such thing as "half parallel" or other such nonsense. Describe your procedure and resulting conclusion here.

18. Investigate the effect of changing the sticks' lengths (always keeping them equal) on the above measurements, and describe both your investigation method and conclusions.

3.4 Curved Earth, Faraway Sun

19. Switch to faraway Sun. Now try to hold "curved Earth" in whatever orientation is necessary to make **both shadows simultaneously vanish**. If you can make both shadows simultaneously vanish, state what condition(s) is(are) necessary. If you were not able to make **both shadows simultaneously vanish**, explicitly state that.
20. Now hold "curved Earth" in **the same** arbitrary orientation you used above with both shadows visible. Make sure neither shadow extends off the surface. Devise a procedure for determining whether or not the two shadows are parallel. Two lines are either parallel or they are not; there is no such thing as "half parallel" or other such nonsense. Describe your procedure and resulting conclusion here.

21. Are the shadows closer to being parallel than with nearby Sun?

22. Are the shadows closer to being identical than with nearby Sun?

23. Investigate the effect of changing the sticks' lengths (always keeping them equal) on the above measurements, and describe both your investigation method and conclusions.

3.5 Can we tell the difference?

Okay here's where you currently stand. You have four models, each one of which tell you how two sticks' shadows should behave both close to and far away from Sun. Earth can't be both flat and not flat, and Sun can't be both nearby and far away. Therefore, some of the models have to be discarded, but how do we decide which ones to discard and which ones to keep? The answer is that we have to compare each model to what Nature actually shows us.

Now we need to look at some actual stick shadows. This part of the activity may need to be done outside of class depending on time constraints and sky conditions.

24. If both class time and weather conditions permit, get two identical sticks, take them outside, and observe their shadows. Understand that you're using Earth and not some Yoga ball or whiteboard representation of Earth. If conditions do not permit going outside during class, do this part at home. Based on your observations, what can we now say about Sun's distance and why?

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You already know the answer to this from the very first part of the activity. You're looking at how the results of testing the four models is consistent with what you already know.

25. From the comparison of all these observations, can we tell anything at all about Earth's shape? If so, what? Defend your answer.

26. Compared to the size of the simulated Earth in each case, were the two simulated sticks relatively close together or relatively far apart? Defend your answer.

27. Do you think two observers with identical sticks would observe identical shadows from northeast Hickory and southeast Hickory? Defend your answer.

28. Do you think two observers with identical sticks would observe identical shadows from Hickory and Statesville? Defend your answer.

29. Do you think two observers with identical sticks would observe identical shadows from Hickory and Los Angeles? Defend your answer.

30. Can we now discard any of our proposed models? If so, which ones?

4 Flat or Curved?

4.1 Flat Earth, Faraway Sun

Once again, use faraway Sun and “flat Earth” and try to make **both shadows look as identical as possible**. This means that if one vanishes, the other one must also vanish.

31. If you can make both shadows look identical (which includes making them simultaneously vanish), state what condition(s) is(are) necessary for that to happen. If you were not able to make the shadows look identical, explicitly state that and state what you could do, without changing anything about the sticks, to make it easier for you to make the shadows look identical.

4.2 Curved Earth, Faraway Sun

Now, once again use faraway Sun and “curved Earth” and try to make **both shadows look as identical as possible**. This means that if one vanishes, the other one must also vanish.

32. If you can make both shadows look identical (which includes making them simultaneously vanish), state what condition(s) is(are) necessary for that to happen. If you were not able to make the shadows look identical, explicitly state that and state what you could do, without changing anything about the sticks, to make it easier for you to make the shadows look identical.
33. Now we see it all comes down to whether or not two identical but widely separated sticks cast identical shadows or different shadows. Which situation corresponds to what Eratosthenes observed?
34. Which of our four initial models best accounts for actual observations?
35. There are simpler observations that can be made that indicate Earth's surface must be curved. See how many you can come up with from your own experiences and list them here.

5 Quantitative: How big is Earth?

Your instructor will now show you how Eratosthenes deduced Earth's size based on the **assumption** that Earth is spherical. You are responsible for understanding this process and for being able to articulate it orally and in writing.

6 Inquiry

6.1 Application

Put two Nerf darts on the yoga ball 4 cm-5 cm apart as measured along the ball's surface. Make sure each dart is perpendicular to the "ground". Use faraway Sun and hold "curved Earth" in whatever orientation is necessary to make one shadow vanish. **You must be able to clearly see the other stick's entire shadow.**

6.2 Some Measurements

With your ruler, measure the height of the stick (in millimeters) whose shadow is visible and then measure the length (in millimeters) of its shadow along the ball's surface. From these two lengths determine the angle that incoming light paths make with the top of the stick. There are several ways to do this, but the best is probably to create an enlarged scale drawing of the stick and its shadow. From this drawing, you can simply measure the angle in question with your protractor.

36. Record your measurements below. **YOU MUST HOLD YOUR YOGA BALL SO THAT ONE SHADOW VANISHES WHILE YOU MAKE YOUR MEASUREMENTS!**

Length of stick: _____ Length of visible shadow: _____
Angle between incoming light paths and top of stick: _____
Separation between the two sticks, measured along ball's surface: _____

6.3 Final Results

37. Use Eratosthenes' reasoning to deduce your yoga ball's circumference and radius. **YOU MUST SHOW ALL OF YOUR WORK!**

38. Earlier, we **assumed** Earth is spherical. Cite evidence that this is probably true. You may not include anything that could not be done in Eratosthenes' time. Rather than cite observational evidence, you may argue from symmetry or form.

39. How can observing sticks' shadows lead to an understanding of Earth's size and shape?

———— CHECKPOINT ————

40. Map this activity into as many of the elements of thought as you can.

Sample Student Version Activity

41. Every activity will have at least one standard associated with it.

STANDARD

I can distinguish among two or more scientific models of a natural phenomenon and decide which one is most likely correct.

STANDARD

I can articulate Eratosthenes' method for deducing whether Earth's surface is flat or not flat.

7 Feedback

What could be done to make this activity more interesting? Please be honest.