INTRODUCTION

Prerequisite Knowledge

- Basic familiarity of the changing rising and setting locations of the Sun throughout the year, as well as the Sun's changing elevation
- The definitions for solstices and equinoxes

Goals

- Develop a coherent model of the Sun's annual path through the observer's sky

Pre-activity Question

1) When does a vertical flagpole not cast a shadow at your current location?
   a) every day at noon
   b) every day at the time when the Sun is highest in the sky
   c) when the Sun is highest in the sky on the summer solstice
   d) when the Sun is highest in the sky on the winter solstice
   e) **none of the above**

   With the exception of equatorial regions, the correct answer will be choice **e**.

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Figure Discussion

The figure presents a view of the path of the Sun, from rising to setting, of the solstices.

1) **[South]**

   Many students believe that the Sun is overhead at noon, which is intentionally not provided as a possible answer. Many, of course, will answer this question without reference to the figure.

2) **[Increases]**

   Some students will confuse the quantity (the Sun's altitude is low in wintertime) with the way that the quantity is changing (the altitude is increasing). This difficulty is pervasive in introductory physics and astronomy and can be the source of the response "decreases" in this particular example. Although not formally defined as an angle, students' basic understanding of the concept of "altitude" is normally sufficient.

3) **[No]**

   This directly confronts a common misconception that the Sun is always directly overhead at noon in all locations.

4) a) **[March 22 through September 20]**

   It is also acceptable for students to answer "Spring/Verbal Equinox through Fall/Autumnal Equinox." Note: The Sun rides the celestial sphere high in the sky in spring and summer rising north of due east to do so. Students often provide an answer of summer solstice rather than a range of dates.

   b) **[September 22 through March 20]**

   It is also acceptable for students to answer "Fall/Autumnal Equinox through Spring/Verbal Equinox." Note: The Sun rides the celestial sphere low in the sky in fall and winter rising south of due east to do so. Students often provide an answer of winter solstice rather than a range of dates

   c) **[March 21 and September 21]**

   It is also acceptable for students to answer "Fall/Autumnal Equinox and Spring/Verbal Equinox." Note: Students immediately recognize that the date will fall between the two extremes. Simple answers of "March" and "September" are acceptable. Students sometimes fail to recognize that this question has two answers, or will just provide the answer of the equinoxes rather than a set of dates.

5) **[No]** As seen from the northern hemisphere, the Sun will set south of west in winter months, directly west on the equinoxes, and north of west in the summer months.

   Students extrapolate their results from Question 4 to answer this. Some will fail to recognize that they are now asked about setting rather than rising.

Figure 2

This is a diagram of a standard shadow plot. Students can fail to make the connection between the physical arrangement and the resulting figure and will, for instance, think of the shadow as pointing toward the Sun (which also means they have failed to recognize that the top of the poster board is north). This is easily identified in their resulting responses, which have north-south and east-west reversed.

6) **[The x's in the shadow plots represent where the end of each shadow was at the time the x was drawn.]**

7) **[About two hours went by between the time each x was drawn since the Sun would have been up approximately twelve hours.]**

8) **[It took about twelve hours (slightly more for Plot A and slightly less of Plot B) for each shadow plot to be created.]**

9) **[The Sun is on the opposite side of the stick from each x. For example, the x for the shadow shown in the northwest must have been made when the Sun was in the southeast.]**

10) **[Northwest]** No need to use Figure 1. The shadow is always on the opposite direction of the Sun.

This is very close to the case in Figure 2, which would be shortly after sunrise. This is a good check question, since an answer of "southeast" indicates a failure to understand how the Sun's position determines the resulting shadow.

11) **[Circle the x's on the north-south line in the diagram for both Path A and Path B.]**

12) **[Shadow Plot B]** When the Sun is higher in the sky, light rays from the Sun are more steeply inclined. As a result, the stick will cast a shorter shadow.

Students answering "A" are typically seeing that curve A is higher on the page and are not accounting for how the shadow is actually created.

13) **[B → summer path; A → winter path]** As answered in Question 12 above, the Sun is higher in the sky at noon for Path B than for Path A. A higher noontime Sun happens during the summertime.

14) **[Sun at right just north of east and label the x in the southwest, lower left]** The sun rises during the summer to the north of east, so I drew my Sun just above the "East" label. Since the Sun is rising in the northeast, the shadow of the stick would point to the southwest. Also, since at this time the Sun will be to furthest north it will be while in the east, the end of the x will be the one that is to furthest southwest. Therefore, I circled the x on Path B that is furthest to the left.

For students who are struggling, it is helpful to have them turn back to Figure 1, and ask "Point to the path that is the path for the Sun in winter, and tell me what direction the Sun is rising? Now point to the path that is the path of the Sun in summer, and tell me what direction the Sun is rising. Now turn back to Figure 2. Point to the northeast [this is the answer they should have given you to the previous question] somewhere on this page outside of the poster board." At this point, they should be pointing to a location that is outside of the gray area that is northeast. In addition, Questions 4, 12, and 13 suggest which shadow plot represents summer.

15) **[Winter]** From Question 13, Path A corresponds to the Sun's path during winter. As answered in Question 9, the shadow points opposite the direction of the Sun. For Path A, the shadow points northwest when the Sun rises, so the Sun must rise in the southeast.

16) **[No]** On the winter solstice the Sun is at its lowest path in the southern sky and so will cast the longest shadow at noon on that day of the year.

17) **[No]** Analogous to Question 16, on the summer solstice the Sun is at its highest path in the southern sky and so will cast the shortest shadow at noon on that day of the year.

18) *Answers will depend on the date.*

Note that Plots A and B are never defined as the solstice paths, although students typically assume this to be the case based on the previous two questions and place their x between the x's for Plots A and B. Points outside the boundaries of these two paths could be correct provided the student could articulate this reasoning.

19) **[No]** In the continental US the Sun is always in the southern sky at noon and so cannot cast a shadow to the south along the north-to-south line.

This question requires students to think carefully since the stick will cast shadows to the southwest and southeast but never directly south.

20) **[No]** As seen from the continental United States, the Sun never reaches the Zenith, which is the only place the could be for the stick to cast no shadow.

This is meant as a wrap-up question that most students answer correctly. Individual intervention will likely be required for any student answering this question incorrectly.

INTRODUCTION

Prerequisite Knowledge

- The rise and set times for stars are constantly changing
- Thorough understanding of the celestial sphere model
- The definition of ecliptic

Goals

- Describe how the Sun moves on the celestial sphere
- Distinguish between the Sun's annual motion and its diurnal motion, and demonstrate how these two motions can explain changes in the sky

Pre-activity Question

1) In the celestial sphere model, the Sun's position is constantly changing; the path that it follows is called the ecliptic. About how long does it take the Sun to complete one trip around the ecliptic?
   a) 23 hours 56 minutes
   b) 24 hours
   c) 27 days
   d) **365 days**

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Figure 1

It may be helpful for students to look at Figure 1 from the *Seasonal Stars* Lecture-Tutorial, which shows an observer and the Sun encircled by the zodiacal constellations. Note that Scorpius is quite a bit farther behind the Sun. For simplicity, the Sun is assumed to be on the meridian, due south, at exactly noon.

1) **[Scorpius]** Over short time periods, all celestial objects appear fixed in place on the celestial sphere and move with it.

   Many students are uncomfortable thinking that stars move across the sky during the daytime and many will claim the Sun moves over to Libra. This issue is re-visited in Question 2.

2) **[Student 2 is correct]** Student 1 incorrectly thinks that only the Sun appears to move across the sky while the constellations stay fixed where they are. Student 2 correctly understands that all objects that rise in the east will move to the southern sky and then to the west—this includes both the Sun and the constellations. So, the Sun will still be near the constellation Scorpius at 3:00 P.M.

Student 2's answer is intentionally written to sound more compelling to help those students inclined toward Student 1's incorrect reasoning.

3) **[Yes]** The Sun moves along the ecliptic just under 1° per day. This motion is small enough to neglect for any one 24-hour period. So it is appropriate to model the Sun as fixed on the celestial sphere.

   In Part II, students modify this idea to include the Sun's motion along the ecliptic.

4) **[On the dotted line, in Scorpius]**

   The shift in the position of Scorpius in one day is exaggerated for clarity.

5) **[On the dotted line, now in Sagittarius]**

   Students are drawn into conflict with their answer to Question 3 and must either now draw the Sun on the meridian but in the constellation Sagittarius or off the meridian in Scorpius. Also note that the changes in the Sun's altitude are irrelevant for this Lecture-Tutorial*.*

6) **[Student 1 is correct]** Student 2 incorrectly thinks that since we can describe the daily motion of the Sun by imagining that it is fixed in one position on the celestial sphere, that it will always be fixed in one position on the celestial sphere—which would mean the Sun would always be aligned with the same constellation. But Student 1 correctly understands that the idea of the Sun being "fixed in one position" only works for a small time period, like a day, otherwise the Sun's setting time would drastically change (like, setting at noon). Student 1 also correctly understands that the celestial sphere must be rotating enough over longer periods of time, like a month, so that the Sun keeps moving to the east causing the Sun to be aligned with different constellations, and keeping it in the correct part of the sky (like, in the south at noon).

   Student 1's answer is intentionally written to sound more compelling. The point of the discussion is to get students thinking about the connection between the daily and annual motions of the Sun.

7) The motion of the Sun along the ecliptic during one 24-hour period is negligible but becomes significant as this motion is observed over many days.

   Here, the students are asked to resolve the conflict by noting that the Sun does not shift very far (about 1°, in fact) during the course of a day. The answers to Questions 3, 5, and 6 are included in the question, letting students know if they are on the right track.

Figure 4

Figure 4 shows the celestial sphere with the Sun in Scorpius. The ecliptic lies in the horizontal plane and Earth's equator is tilted at 23.5° with respect to it. This figure is similar to those in earlier *Lecture-Tutorials*, but the observer's horizon is not shown. The observer in the diagram is drawn nearly vertically, but his precise latitude on Earth is not meant to be taken literally.

8) **[In Sagittarius]**

For students struggling to determine where they should draw the Sun, ask them to show you where they drew the Sun on Figure 3 based on Question 5.

9) *Students should have continued the pattern suggested in Question 8 by listing the 10 remaining months in a counterclockwise fashion around the ecliptic (note that Ophiuchus has been omitted to make this easier).*

10) *Students should have solid/dashed line that goes through the constellations in the ecliptic.*

11) **[About 30 times]**

12) **[365 days]**

This revisits the pre-activity question. It is designed to help students confront a common confusion that the ecliptic represents a daily path.

Figure 5

Figures 5a through 5d show three quarters of a revolution of the celestial sphere with 6 hours between successive figures. The positions of the Sun on June 1 and December 1 are both shown, but not labeled, as students are asked about this in Question 13. Note that in the celestial sphere model, the ecliptic wobbles daily, like a coin spinning on a desk.

13) **[The December path is the lower dashed line, the ecliptic is the central, solid line, and the June path is the top dashed line.]**

These are complicated figures and students should be encouraged to study them carefully and think about what they mean. In a closing class discussion it is worth emphasizing that the figures show how the ecliptic fixes the Sun's position on a given day, and that the daily motion does not follow the ecliptic.

14) **[5a]**

"At noon" for the observer shown.

15) **[5c]**

"At noon" for the observer shown.