Why do we have the seasons?

Why is it hot during the summer and cold during the winter? Why does the season repeat itself? To answer these questions, we will consider other simpler questions first, then answer them. Why is it hot during the day, and during the night? This is an easy question. It's because the Sun is up during the day, and the Sun is not there during the night. The sunshine warms the ground. Another question. Why is it hotter at noon than in the morning or on the late afternoon? The sun is shining at noon as well as in the morning or on the late afternoon. A rough answer to this question is that the Sun is "higher" at noon than in the morning or on the late afternoon. So, what do I mean when I say that the Sun is high? And, why does the higher Sun make the weather hotter?

The distance to the Sun does not considerably change during the course of day. Therefore, we can safely ignore its distance change effect on the temperature. What is important is the "altitude" of the Sun. When the Sun is right above your head, the altitude of the Sun is 90°. In such a case, the angle that the sunray makes with the ground is 90°, as it is shown in Fig. 1. The solid line denotes the ground, and the dotted lines denote the sunrays. Now, consider the case that the altitude of the Sun is 30°, as depicted in Fig. 2.

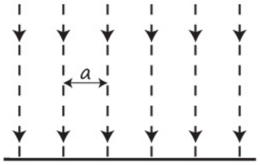

Figure 1: Sunrays' representation when the Sun's altitude is 90°.

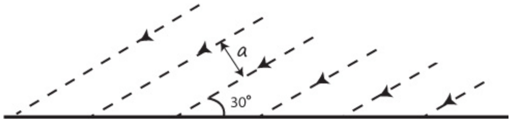

Figure 2: Same as Fig. 1 when the Sun's altitude is 30°.

You see that the sunrays hit the ground less densely than in Fig. 1. To be fair, the parallel distances between the adjacent sunray are equal in Fig. 1 and Fig. 2. They are denoted by a in the figures. Now, notice that the ground has to be much larger in Fig. 2 than in Fig. 1 to get the same amount of the sunrays (i.e., 6 sunrays in both Fig. 1 and Fig. 2). In other words, if the area of the ground is the same, the lower the altitude of the Sun, the less energy the ground receives from the Sun. In conclusion, at noon, the ground receives much more energy than in the morning or on the late afternoon, because the altitude of the Sun is higher. In reality, noon is not the hottest hour, because it takes time for the ground to get warm. So, the hottest hour is usually the early afternoon. Nevertheless, it remains true that the ground receives the most energy from the Sun when its altitude is highest, i.e., around the noon.

Now, let's move on to season. To understand season, you need to understand that the Earth orbits around the Sun once every 365 and a quarter days (see Fig. 3). The figure is not in scale. In reality, the diameter of the Sun is about 109 times the one of the Earth, and the distance between the Sun and the Earth is about 12,000 times the diameter of the Earth. If I drew the figure in scale, the Sun and the Earth would be hardly visible if the Earth's orbit needs to fit on this page. The dotted lines denote the path of the Earth around the Sun. The arrow denotes the Earth's rotation axis. It is the same axis as the orange one in Fig. 1. Here, what is important is the fact that the rotation axis is tilted. It is tilted by about 23.4°. As we will see shortly, this tilt makes seasons change. In other words, if the rotation axis were not tilted as you see in Fig. 4, seasons would never exist, and we would only have the same season all around the year.

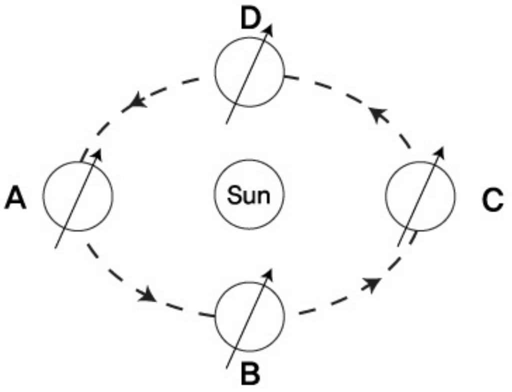

Figure 3: Schematization of the Earth's orbit around the Sun.

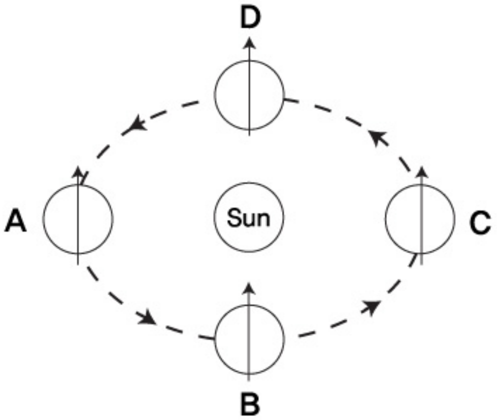

Figure 4: A *hypothetical* Earth's orbit in which there are no seasons.

Now, see Fig. 5. It is a close view of the Earth when it is at position A.

You see that the sunrays come from the right. At which latitude, would you find that the Sun is right above your head (i.e., the Sun's altitude is 90°) at noon? At point F. What is the altitude of the Sun at the equator at noon (denoted by E)? It is $90° - 23.4° = 66.6°$. What is the altitude of the Sun seen at the North Pole(denoted by N)? It is 23.4°. Notice also that at point I where the latitude is $-66.6°$, the altitude of the Sun is 0°. Notice also that the places between I and S do not get the sunshine at all, even at noon. At these locations, the Sun doesn't rise at all (when the position of the Earth is at A). On the other hand, consider the point G. Its latitude is $66.6° (= 90° - 23.4°)$. As the latitude of the point G is 23.4° lower than the North Pole by 23.4°, the altitude of the Sun at noon should be 23.4° greater than the one seen at the North Pole. So, it is 46.8°. Now, consider where the

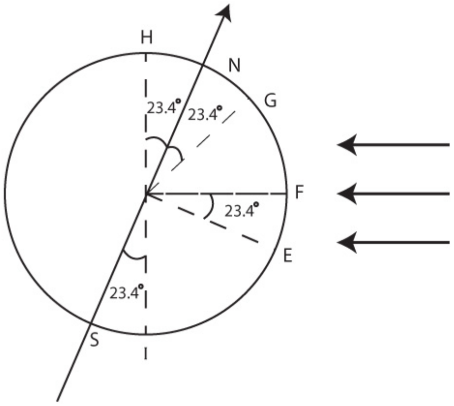

Figure 5: Representation of sunrays hitting the Earth it is at A in Fig. 1.

G move to at midnight. It will move to the point H. Notice that there, the Sun's altitude is 0°, so the Sun can be (almost) seen at the horizon. Notice that the locations between G and N move to the locations between H and N at midnight. Now, it is clear from the figure that the locations between H and N still get the sunshine! The Sun never sets (when the position of the Earth is A). We call it "white night". In Table 1, I made a chart for the relation between the latitude and the altitude of the Sun at noon, when the position of the Earth is at A.

Table 1: Latitude and Sun's altitude at noon for the summer solstice.

Latitude	Sun's altitude at noon
90°N	23.4°
66.6°N	46.8°
23.4°N	90°
0°	66.6°
23.4°S	43.2°
66.6°S	0°
90°S	below the horizon

Problem 1. In Fig. 5 (i.e., when the position of the Earth is at A), what is the altitude of the Sun at noon at the latitude 40° and at the latitude $-40°$?

If you correctly solve this problem, you will get that the altitude of the Sun at the latitude 40° is bigger than the one at the latitude $-40°$. In other words, a location at the Northern hemisphere is hotter than a comparable location at the Southern hemisphere. So, when the Earth is at position A, we have summer in the Northern hemisphere and winter in the Southern hemisphere. This is obvious from Fig. 5. The Northern hemisphere gets more sunlight than the Southern hemisphere.

Actually, when the Earth is at the position A, the date is around June 21st. Unless you live in the tropical region (i.e., the region where the latitude is between -23.4° and 23.4°), I am sure that you can make sense out of this. You know that it is relatively hot on June 21st in the Northern hemisphere (or it is relatively cold on June 21st in the Southern hemisphere). However, you may also know that July and August are hotter (or July and August are colder if you live in the Southern hemisphere), it's because it takes some time for the Earth to get warmed up (or to get cooled).

When the Earth is at the position A (i.e., when it is around June 21st), we say that it is the "summer solstice" or "midsummer" in the Northern hemisphere, and it is the "winter solstice" in the Southern hemisphere. Some countries in the Northern hemisphere, especially the most Northern ones, have a tradition of celebrating this day (the midsummer day), because the day is longest on this day, and they don't like the cold winter, when the days are so short. (We will see soon why the day is so short in winter.)

We can perform a very similar analysis when the Earth is at position C. See Fig. 6.

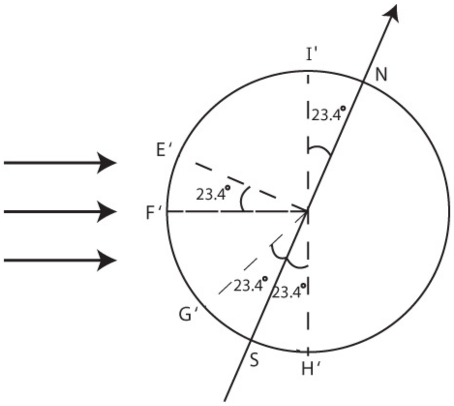

Figure 6: Same as Fig. 5 when the Earth is at C in Fig. 1.

The Sun has the highest altitude (i.e. 90°) at position F' where the latitude is $-23.4°$. The altitude of the Sun at the equator (denoted by E) at noon is 66.6°. We have the white night at places between S and H', and the Sun never rises at places between I' and N. Furthermore, we do have the Sun at places between E' and I' on this day, but the day is shortest. If we make another table that relates the latitude and the altitude of the Sun when the Earth is at position C (Table 2, everything is same as Table 1, if we exchange N and S. For example, in Table 1, the altitude of the Sun is 46.8°. at the position with the latitude 66.6°N. In Table 2, the altitude of the Sun is 46.8° at the position with the latitude 66.6°S.

So, we can see that the Northern hemisphere is winter and the Southern hemisphere is summer when the Earth is at position C. Actually, it's when the date is around December

Table 2: Latitude and Sun's altitude at noon for the winter solstice

Latitude	Sun's altitude at noon
90°N	below the horizon
66.6°N	0◦
23.4°N	43.2°
0°	66.6°
23.4°S	90°
66.6°S	46.8°
90°S	23.4°

21st. When the Earth is at the position C (i.e., when it is around December 21st), we say that it is the "winter solstice" in the Northern hemisphere, and it is the "summer solstice" in the Southern hemisphere.

When the Earth is at the position B, the date must be (roughly) half way between the two solstices. If it were exactly half way, it would be either September 20th or 21st. However, as the orbiting speed of the Earth slightly changes, it is either September 22nd or 23rd, when the Earth is at position B. In such a case, the Northern hemisphere is fall and the Southern hemisphere is spring. It's when the Sun is right above your head at the equator at noon (see Fig. 7).

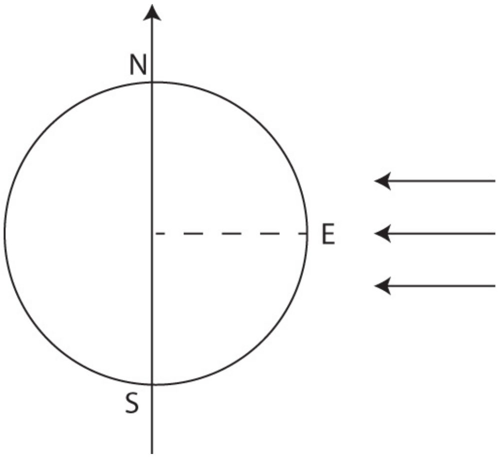

Figure 7: Same as Figs. 5 and 6 when the Earth is at D or B.

For convenience, I changed the perspective from the one in Fig. 1 and drew as if the Sun ray comes from the right. The length of the day and the length of the night are same on this day. It is called "fall equinox" in the Northern hemisphere. For the altitude of the Sun, see Table 3.

When the Earth is at the position D, the date must be (roughly) half way between the

Table 3: Same as Tables 1 and 2 for fall equinox and spring equinox.

Latitude	Sun's alt. at noon
90°N	0°
66.6°N	23.4°
23.4°N	66.6°
0°	90°
23.4°S	66.6°
66.6°S	23.4°
90°S	0°

two solstices. It is around March 20th. The Northern hemisphere is spring and the Southen hemisphere is fall. The Sun is right above your head at the equator at noon. The length of the day and the night are same on this day. It is called "spring equinox" in the Northern hemisphere. The altitude of the Sun is same as the one on fall equinox as seen in Table 3.

Now, some terminologies. "Arctic Circle" is the latitude line of 66.6°N$(= 90° - 23.4°)$, and "Arctic" is the region above the Arctic Circle. This is the region where they have a day or days the Sun never sets in summer. To understand this, remember that the day is longest during summer solstice. On summer solstice, a place with latitude 66.6° has the Sun for 24 hours. Below 66.6°, the Sun necessarily sets even on summer solstice. Of course, at Arctic, they have a day or days the Sun never. That happens in winter, which includes winter solstice. Similarly, "Antarctic Circle" is the latitude line of 66.6°S. In summer, they have white night, and in winter, they have a day or days when the Sun never rises. Arctic circle and Antarctic Circle are collectively called "Polar Circles".

The Northern Tropic is the latitude line of 23.4°N and the Southern Tropic is the latitude line of 23.4°S. Tropic is the region between the Northern Tropic and the Southern Tropic; the latitude there is between 23.4°N and 23.4°S. People there have at least one day that the Sun is right above their head at noon. For example, at the equator, the Sun is right above their head at noon on equinoxes. At the Northern Tropic (the latitude 23.4°N), the Sun is right above their head at noon around June 21st. At the Southen Tropic (the latitude 23.4°S), the Sun is right above their head at noon around December 21st.

So, what advantages or disadvantages do Muslims living in the Arctic? If Ramadan, the month of fasting, falls on summer solstice, they cannot eat at all for 24 hours on that day. (During Ramadan, Muslims cannot eat when the Sun is up. Ramadan month doesn't fall in the same season every year, because a year in Muslim calendar is 354 or 355 days, which is different from a true year, about 365 days, the period of the seasons.) On the other hand, if Ramadan falls on winter solstice, they do not need to fast at all on that day. So, what should you do, if you do not want to fast at all during Ramadan? If Ramadan falls between March 20th and September 22nd (or 23rd), move to the South Pole or enough Southern place. If Ramadan falls between September 22nd (or 23rd) and March 20th, move to the North Pole or enough Northern place. Nevertheless, avoiding fasting at all will be quite hard, if Ramadan includes March 20th or September 22nd (or 23rd).

A common misunderstanding of seasons is that the Earth is closest to the Sun when it is summer, and the Earth is farthest from the Sun when it is winter. This is not true, even though it is true that the distance between the Earth and the Sun changes. I want to note two things. First, the distance changes about 3 percents, so it is not significant enough to offset the effect of the tilt of the axis which causes the seasons. Second, the Earth is closest to the Sun in early January, when the Northern hemisphere is in the middle of winter!

Now, let me explain why only certain stars are visible in certain seasons. It's because the position of the Earth is different in a different season, and stars are visible only during night, because during day the Sun is so bright that other stars are invisible. See, for instance, Fig. 8, where we have drawn stars.

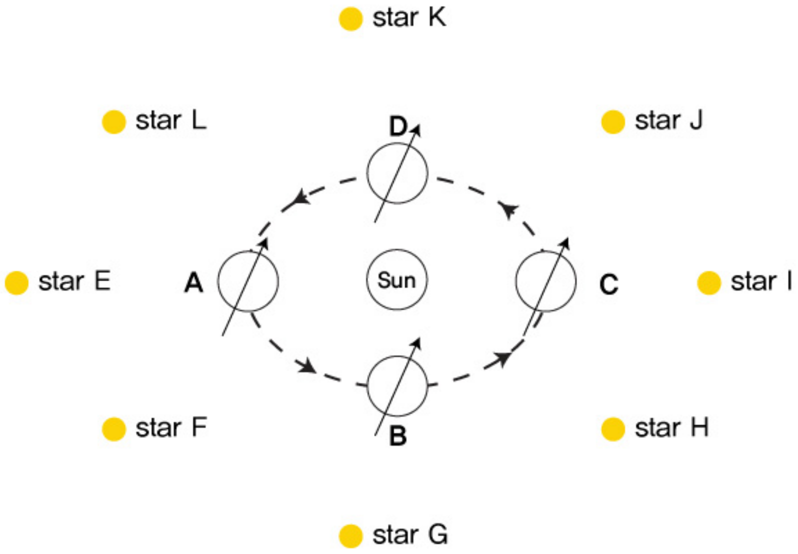

Figure 8: Schematization of different stars scattered on the sky and how we see them on different seasons.

In reality, stars are much farther than drawn here. Anyhow, when the Earth is at position A, stars H, I, J are not visible, because they are on the side of the Sun. But, stars E, F, L are visible at night, as they are on the opposite side of the Sun. Star G and star K are still visible, but are hard to see at midnight because they are near the horizon then. Similarly, when the Earth is at position B, stars J, K, L aren't visible, but star F, G, H are visible. Star I and star E are still visible, but are hard to see at midnight.

Problem 2. When the Earth is position at C, which of the following three stars are visible?

(1) stars E, F, L (2) stars H, I, J

From the point of view of an observer on the Earth, it's not the Earth that is moving, but the Sun that is moving. Let's visualize this by looking at Figs. 9 and 10. Figure 9 is essentially Fig. 3 with more descriptions, and Fig. 10 is Fig. 9 with a different perspective.

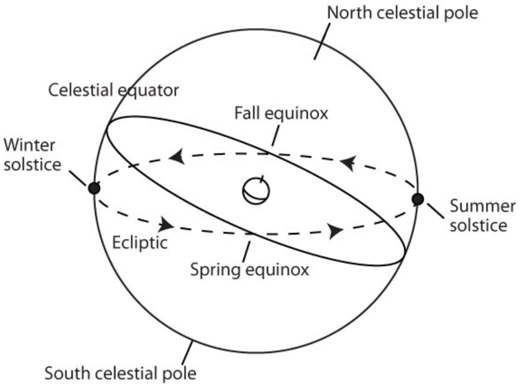

Figure 9: Representation of the ecliptic, the Sun's path seen from Earth.

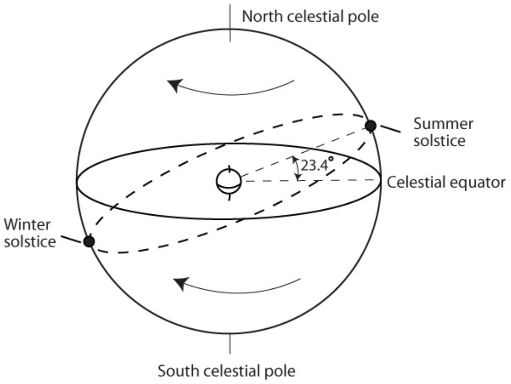

Figure 10: Same as Fig. 9, but with the daily motion and from a different perspective.

The two arrows in Fig. 10 denote the rotation of the Sun and the stars due to the daily rotation of the Earth. The dotted line is the path of the Sun called "ecliptic". The Earth rotates itself around the axis that connects two celestial poles drawn in the figure. You see that it is tilted. Thus, the ecliptic is inclined 23.4° with respect to the celestial equator. This is called "the obliquity of the ecliptic". You can also easily recognize the positions of the Sun at two solstices and two equinoxes. We could have also denoted the path of other stars than the Sun on this sphere, but we didn't. However, unlike the Sun, they are so far away that their apparent positions hardly change. As we will talk in "Parallax, how do we measure distances to stars?", their apparent position changes were so small that they have been first observed as late as in the 19th century. So, they can be regarded more or less as having fixed positions. Therefore, they are called "fixed stars". Thus, the ecliptic is the path of the Sun with this background of fixed stars. Of course, you cannot see the Sun with this background of fixed stars directly, because the Sun is so bright that the fixed stars near it are invisible. The ecliptic is just a path that the Sun is deduced to follow.

We also would like to mention that some stars are not visible at all on certain locations of the Earth for all seasons. For example, let's say that you are at the North Pole. Then, stars below the celestial equator drawn in Fig. 9 or Fig. 10 will be never visible. You can never see something beyond horizon, because you can never see something under the ground. To see a star, it has to be on the sky, not under the ground. Similarly, if you are at the South Pole, stars above the celestial equator will be never visible. If you are at a place that is not the North pole but somewhere in the Northern hemisphere, some stars below the celestial equator will be visible, but not all, including the stars near the South celestial pole. If your position in the Northern hemisphere is closer to the equator, you will be able to see more Southern stars. And, if you are at equator, you will be able to see both the stars near the

North celestial pole at the Northern horizon and stars near the South celestial pole at the Southern horizon.

Problem 3. Which of the following two places can you see more stars placed more northward than the celestial equator?

(a) Sydney, Australia (latitude: -33.9, longitude 151.2)

(b) Lima, Peru (latitude: -12.0, longitude -77.0)

Finally, let me talk about calendar. I have mentioned that it takes about 365.2422 days for the Earth to orbit around the Sun once (called "orbital period of the Earth"). This means that a year is 365.2422 days and it takes 365.2422 days from a summer solstice to the next summer solstice (or, from a winter solstice to the next winter solstice, or a spring equinox to the next spring equinox, or a fall equinox to the next fall equinox). It is important that a summer solstice falls around the same date every year. Otherwise, it's confusing. For example, if a summer solstice falls in October in a certain year, then, the summer months will be October, November, and December, instead of June, July, and August. Thus, it is important that a good calendar should have about 365.2422 days in a year on average. This means that a year has to be 365 days for most of the years, and 366 days for the other years. If the orbital period of the Earth were exactly 365.25 days, having 365 days for three quarters of the years and having 366 days for a quarter of the years will be most desirable. In such a case, we need to have a leap year (a year that has 366 days) every 4 year. Julius Caesar proposed such a calendar in 46 BC, and this is called the "Julian calendar". However, there is a difference between 365.2422 days and 365.25 days. To remedy this situation, in 1582, about 1600 years after the introduction of Julian calendar, Pope Gregory XIII introduced the Gregorian calendar, which is now used by most countries in the world. According to the Gregorian calendar, we have a leap year, if the year is divisible by 4. For example, 2016 and 2020 are leap years. However, there is an exception to this rule. If the year is divisible by 100, it is not a leap year. For example, 1900 and 2100 are not leap years, even though they are divisible by 4. However, there is an exception to this rule of the exception. If the year is divisible by 400, it is a leap year. For example, 1600, 2000 are leap years, even though they are divisible by 100. This makes an average year 365.2425 days, which is slightly different from 365.2422 days, but the difference is still quite bearable. It is 0.0003 days per year, which is only 3 days in 10,000 years.

Problem 4. Check that a year is on average 365.25 days in the Julian calendar and 365.2425 days in the Gregorian Calendar

Summary

- The higher the altitude of the Sun, the more energy per area the ground receives

- We have seasons because the rotation axis of the Earth is not perpendicular to its orbiting plane, but tilted. It is tilted by about 23°.
- We see different stars on different seasons, because we have different positions of the Earth on different seasons.
- Ecliptic is the apparent path of the Sun seen on the Earth.
- That the rotation axis is tilted by about 23° means that the ecliptic is inclined with respect to the celestial equator by about 23°.
- When it is summer in the Northern hemisphere, the apparent position of the Sun is located north compared to the celestial equator. Accordingly, it is winter in the Southern hemisphere.
- When it is winter in the Northern hemisphere, the apparent position of the Sun is located south compared to the celestial equator. Therefore, it is summer in the Southern hemisphere.
- At the summer solstice in the Northern hemisphere, the apparent position of the Sun is located most north, right at the Northern Tropic (i.e., the latitude line of 23.4°N). At the regions located further north than the Northern Tropic, the day is longest on this day. In the Arctic region, they have white nights, and in the Antarctic region, the Sun never rises on this day.
- At the winter solstice in the Northern hemisphere, the Sun is located most south, right at the Southern Tropic. At the regions situated further south than the Southern Tropic, the day is longest on this day. In the Antarctic region, they have white nights, and in the Arctic region, the Sun never rises on this day.
- Fixed stars located near the South celestial pole can't be seen at most places of the Northern hemisphere, and fixed stars located near the North celestial pole can't be seen at most places of the Southern hemisphere.