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Exploring the reasons for the seasons using Google Earth, 3D models, and plots

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ABSTRACT

Public understanding of climate and climate change is of broad societal importance. However, misconceptions regarding reasons for the seasons abound amongst students, teachers, and the public, many of whom believe that seasonality is caused by large variations in Earth's distance from the Sun. Misconceptions may be reinforced by textbook illustrations that exaggerate eccentricity or show an inclined view of Earth's near-circular orbit. Textbook explanations that omit multiple factors influencing seasons, that do not mesh with students' experiences, or that are erroneous, hinder scientifically valid reasoning. Studies show that many teachers share their students' misconceptions, and even when they understand basic concepts, teachers may fail to appreciate the range of factors contributing to seasonal change, or their relative importance. We have therefore developed a learning resource using Google Earth, a virtual globe with other useful, weather- and climate-related visualizations. A classroom test of 27 undergraduates in a public research university showed that 15 improved their test scores after the Google Earth-based laboratory class, whereas 5 disimproved. Mean correct answers rose from 4.7/10 to 6/10, giving a paired *t*-test value of 0.21. After using Google Earth, students are helped to segue to a heliocentric view.

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1. Introduction

There is a substantial body of discipline-based education research demonstrating the depth and breadth of astronomy misconceptions that are held by students, their teachers, and the general public (e.g. Sadler 1998; Bailey and Slater 2003; Lindgren 2003; Danaia and McKinnon 2007, Küçüközer 2007). The seminal study entitled *A Private Universe* (Schneps et al. 1989) dramatically showed how pervasive and persistent are people's – even highly educated people's – misconceptions regarding basic concepts in planetary science. When interviewed at a commencement ceremony, 21 of 23 Harvard students, alumni, and faculty could not correctly explain the phases of the Moon nor the causes of seasons. Seasonal change was most commonly ascribed to large variations in Earth's distance from the Sun (as also found by Trumper 2000 and numerous other studies). Interviewees

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included students who had taken physics and astronomy courses at Harvard, one of the world's top-ranked universities.

In an associated presentation, Wandersee (1989) asserted that students must be challenged to deconstruct misconceptions before they can construct valid mental models. A college student, he argued, is not a *tabula rasa* (cf Pinker 2003), but rather a carrier of misconceptions that are deeply rooted since early childhood. He used an analogy to home construction: teachers may think of students as constructing new houses and may see their own role as the supplier of raw materials and tools, whereas in fact students are remodeling their existing mental homes and will construct new walls only when convinced of the need to tear down old ones (see also Nussbaum and Sharoni-Dagan 1983). Working with preservice teachers, Frede (2008) designed a refutation approach to conceptual change and found that teachers improved significantly when they had to refute misconceptions in small-group laboratory activities. Tsai and Chang (2005) found that introducing discrepant and critical events to generate dissatisfaction with misconceptions was effective in promoting learning. Van Loon et al. (2015) found that misconceptions held with high confidence were most effectively corrected by a combination of refutation text and correct text. In the words of Carsten-Conner et al. (2015),

In order to change preconceptions to be consistent with scientifically accepted concepts, learners must be provided with experiences that can aid student comprehension, rather than simply being given new factual explanations. (cf Posner et al. 1982; Bransford, Brown, and Cocking 1999; Hsu 2008; Vosniadou 2012)

Introductory college science courses that are commonly taken as a distribution requirement by non-science majors and preservice teachers can inadvertently reinforce or even worsen misconceptions about seasonality that students bring from their schools and homes. Bisard et al. (1994) tested 700 students with Earth and Planetary Science topics, including seasons, and found that scores increased with school grade level but then dropped in general education college courses. They and Zeilik, Schau, and Mattern (1998) found that preservice teachers scored roughly the same as the school students they were destined to instruct in their future inservice careers. There seems to be a cycle of misconception being passed on through the generations (Ojala 1997; Türk, Sener, and Kalkan 2015). Atwood and Atwood (1996) and Frede (2006) reported prevalent misconceptions among preservice elementary school teachers, whilst Mant and Summers (1993) found that only 4 out of 20 inservice teachers held scientifically valid mental models of the Earth's movement in space.

In response to the clear need to promote conceptual change amongst both students and instructors, we here offer a set of learning resources, using the Google Earth virtual globe to display 3D COLLADA models that allow students and their teachers to actively explore, visualize, deconstruct misconceptions, and discover the multiple reasons for seasonality. These are suitable for school, 2- and 4-year college, and informal education. Unlike previous models, ours permit the separate visualization of Earth's daily rotation and the Sun's annual migration around the ecliptic.

Google Earth has been widely used in education, including weather, climate, and a range of other geoscience topics (Bodzin et al. 2013; Richard 2014). Barab et al. (2000), Mintz, Litvak, and Yair (2001), Bakas and Mikropoulos (2003), and Küçüközer (2008) all found that 3D computer modeling was effective in challenging misconceptions in this domain, and Covitt et al. (2015) recommend a teaching sequence involving testing and falsification of students' misconceptions which can be facilitated by interactive models.

In addition to use on desktop and laptop computers, Google Earth is suited to projection in digital planetariums¹ which Plummer and Krajcik (2010), Carsten-Conner et al. (2015), Türk and Kalkan (2015), and Yu et al. (2015) all found to be beneficial to student learning outcomes. De Paor and Oakley (2010) described how virtual globes projected onto the concave planetarium dome mentally pop into an immersive, convex, 3D visualization. However, planetarium projections should be offered in addition to, not in place of, student-centered active inquiry using personal computers during laboratory classes. Hudgins et al. (2006) and Ashcraft and Courson (2003) found significant improvement in preservice teacher scores linked to inquiry-based lab activities.

2. Planetary orbits, spin axes, and reasons for the seasons

To aid in understanding the working of our models, we begin with a brief review of orbital mechanics. All planets orbit the Sun (strictly the Solar System's barycenter) close to the ecliptic plane and spin about axes of rotation that precess (wobble) on long timescales but are essentially fixed in spatial orientation during a single year. Early in an Earth Science 101 or Planetary Science 101 course, students are told about Johann Kepler's (1609) discovery that the orbits of the planets are ellipses with the Sun at one focus. Students also learn that planetary spin axes are variously tilted with respect to the ecliptic plane. The challenge for teachers is to help students evaluate why seasons on Earth are caused overwhelmingly by Earth's tilt and not significantly by variation in the distance from the Sun. We suggest that introducing elliptical orbits *before* seasonality on Earth is pedagogically bad practice, especially at primary and secondary level.

2.1. Exaggerated orbits

Figures such as [Figure 1\(a\)](#) are commonly used to illustrate a planet's orbit. A google image search for 'Kepler's First Law' reveals an overwhelming preponderance of highly elliptical illustrations, with eccentricities resembling those of Earth-crossing asteroids or short-period comets. The correct eccentricity for Earth is undetectable to the naked eye, as illustrated in [Figure 1\(b\)](#), where Earth's orbit is 300 pixels wide and 299 pixels tall, and the Sun is 3 pixels left of center corresponding to Earth's aphelion of ~ 153 million km and perihelion of ~ 147 million km. Even this illustration exaggerates eccentricity by an order of magnitude because pixels cannot be subdivided. The correct axial ratio for Earth's orbital eccentricity of 0.016723 would be 300:299.958. It is more accurate to describe Earth's orbit as circular for all intents and purposes.

Based on the lead author's years of experience as a planetarium director, school teachers commonly misinterpret Kepler's First Law as requiring elliptical *as opposed to circular*, orbits. A perfect circular orbit is a special case of an ellipse with equal axes and coincident foci, and is in accordance with Kepler's First Law. Geostationary satellites must have circular orbits to avoid drifting, for example. By emphasizing elliptical orbits at the outset, we send students off-track. We should introduce seasons *before* we tell students about the very slightly elliptical orbits of most planets, and then go on to the more significant eccentricities of Mercury and Mars.

2.2. Neglecting Copernicus's explanation of seasons

Students are not generally told that Nicolas Copernicus first attributed seasons to Earth's tilt, at least not in most introductory astronomy textbooks. Of the 16 we checked, only one (Chaisson and McMillan 2014) mentions Copernicus specifically in the context of tilt and seasons. Copernicus did not discover tilt. The angle between the celestial equator and ecliptic (or equivalently between the Earth's pole and the ecliptic pole) was first measured as 24° by Oenopides circa 450 BCE using a gnomon (Bulmer-Thomas 1974). Circa 200 BCE, Eratosthenes measured the difference between the midday altitude of the Sun on the summer and winter solstices and, dividing by half, calculated today's figure of approximately 23.5° . However it was Copernicus (1543) who first associated tilt with seasonal change. Serendipitously, Copernicus avoided the misconception that distance from the Sun significantly affected Earth's seasons because he mistakenly believed all planetary orbits to be circular.

There is thus an asymmetry in the authoritative underpinning of competing concepts. Elliptical orbits are required by 'law' and are associated with one of the great names of astronomy. Seasonal change due to tilt is, for most students and teachers, a concept without an authoritative source.

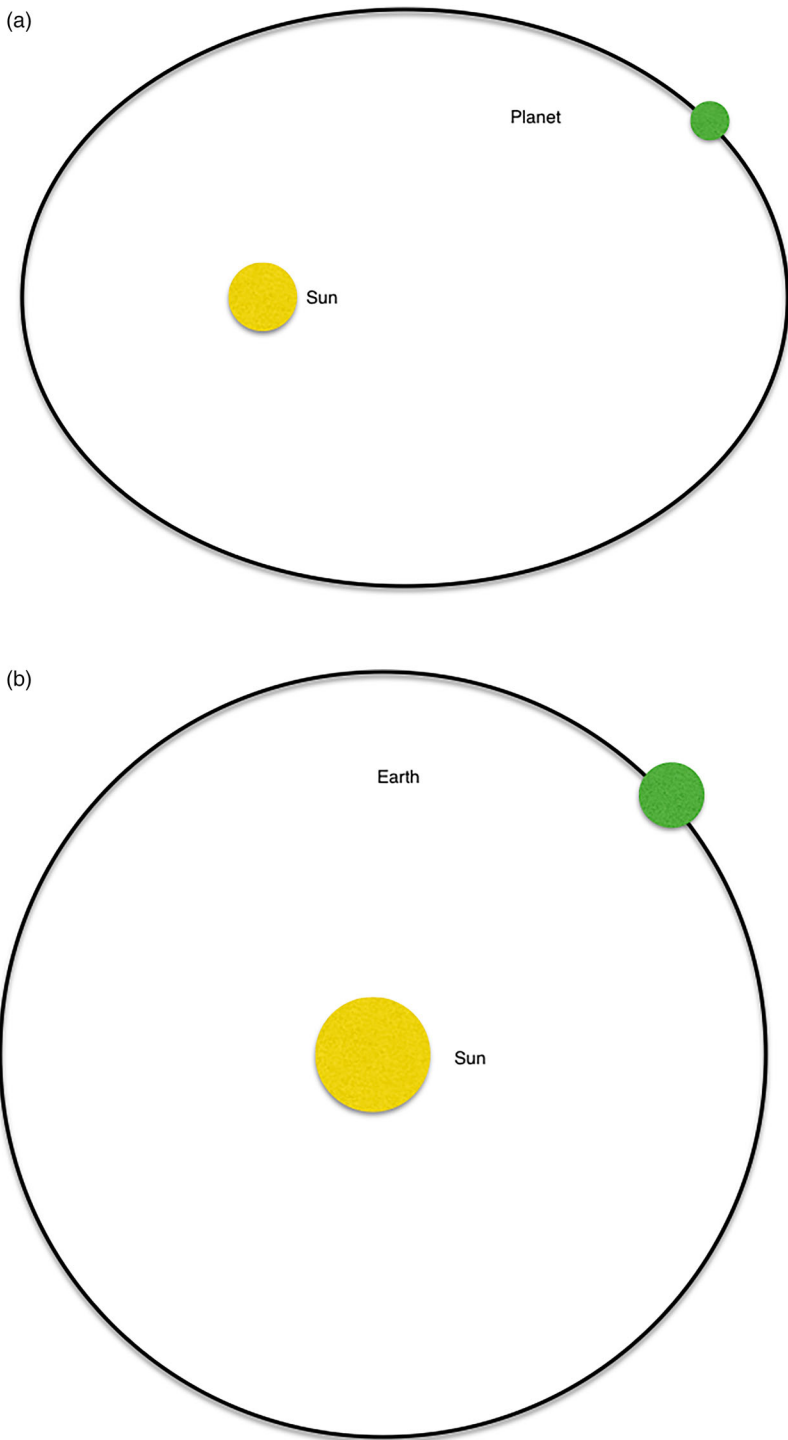


Figure 1. (a) Typical textbook illustration of a planet's orbit and (b) Earth's actual orbital.

2.3. Compounding misconceptions

To explain how tilt affects seasons, textbooks often use illustrations such as [Figure 2](#) (a). Here the apparent eccentricity of the orbit is due to the inclined perspective view, as is clear to an expert because the Sun is near the center, not at a focus of the ellipse as drawn on the page. But this subtle cue may be lost on students. Yu, Sahami, and Denn (2010) found that three quarters of non-major undergraduates in general education astronomy classes believed in highly elliptical orbits. Teachers may point to the alternate occurrence of seasons in the northern and southern hemispheres as evidence that distance cannot be the main cause of seasons, but affirming that concept requires high-level thinking and does not relate to the lives of most students who live in one hemisphere and experience seasonal change in time, not space. Students yearn for summer to arrive, they do not often drive or fly from their winter home to summer in the opposite hemisphere. In the planetary science classroom, lab, or planetarium, the instructor's argument regarding opposite seasons in opposite hemispheres may simply fall on deaf ears as students stare at what looks like a highly elliptical orbit that reinforces their beliefs. Ascribing seasonal change to variations in the Sun's midday altitude also faces an uphill battle because many people believe that the Sun is overhead everyday at noon (Trumper 2001; Plummer 2009), including one-fifth of pre-service and inservice teachers in a test by Kanli (2014). The two common terms for the Sun's angular 'height' in the sky – altitude and elevation – are potentially confusing because they are also used to describe height above sea level, which students may associate with moving closer to the Sun.

Instructor gestures (Kastens, Agrawal, and Liben 2008) can make matters worse. When describing the orbit of the Earth around the Sun, it is easy to wave one's index finger in a conical gesture ([Figure 3](#)(a)) instead of a skewed cylindrical one that would keep the Earth's axis pointing to Polaris ([Figure 3](#) (b)). The lead author has seen several school teachers perform the conical gesture during question time at planetarium field trips. Unless students understand that Earth's axis points in a constant direction on a short timescale, they have no chance of successfully relating tilt to seasonality. If Earth's axis precessed once a year instead of every 26,000 years, tilt would have no climatic effect. The height of the midday Sun would be a function only of latitude, not time of year.

Plummer and Agan (2010) found that only a quarter of their eighth grade students gave scientific responses to seasonality questions after 10 days of learning activities and concluded that many students have a poor understanding of Earth's rotation which made the use of the tilt model for instruction (their word) 'meaningless.'

A further potential source of confusion is instructor insistence that the Sun does not orbit the Earth. The real error in Ptolemy's geocentric model (Toomer 1984) was the belief that the Sun orbited the Earth every day, not just once a year. It is perfectly valid to say that relative to an origin at the center of the Earth, the Sun revolves annually, as illustrated by the sunbeam in our model, below (See the Supplemental Documents for further discussion).

Whatever the combination of reasons, the facts are clear – students learn far less from planetary science instruction than their teachers expect them to learn. In a survey, Lightman and Sadler (1993)

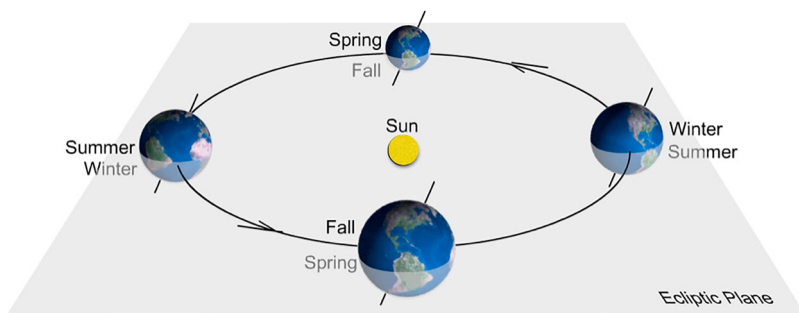


Figure 2. Perspective view of Earth's orbit creates illusion of ellipse with Sun at center.

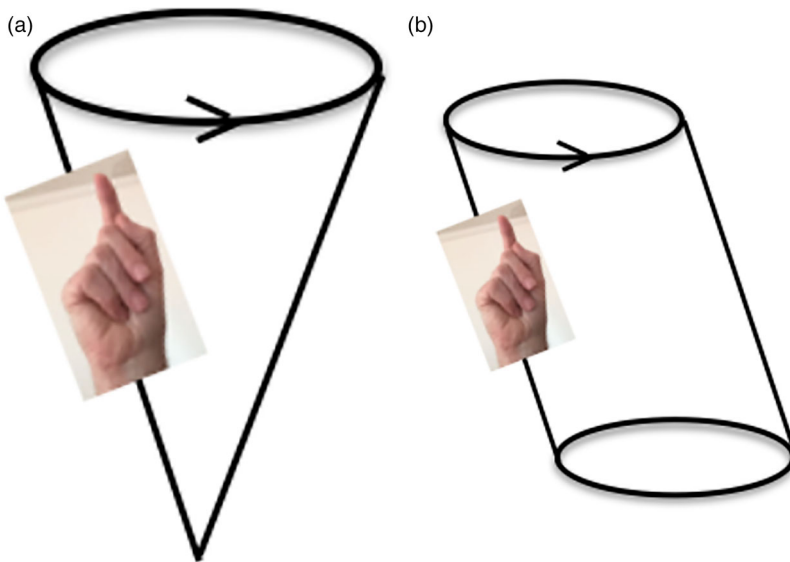


Figure 3. (a) Confusing conical gesture and (b) Inclined cylindrical gesture, which is correct.

found that teachers predict a post-instruction test gain in their students' scores that is twice the observed gain. We argue that learning-by-doing and student-centered learning (Lo Presto and Slater 2016) using our models may help instructors to avoid compounding misconceptions.

3. The models

We created COLLADA models using the free version of SketchUp (Chopra, Town, and Pichereau 2012) and exported them in digital asset exchange (.dae) format (Arnaud and Barnes 2006). There are COLLADA plug-ins available for high-end modeling applications such as 3D Studio Max and Maya, but they are very expensive and do not provide a direct interface with Google Earth. Some may prefer the free applications Blender or Renderman.

Critical features of our Google Earth-based models include: (i) a representation of the ecliptic plane at a fixed angle of 23.5° to the Earth's axis; (ii) the display of a fixed right ascension/declination (r.a./dec) grid under which the Earth spins; (iii) a clear separation of Earth's daily spin on its axis from the annual migration of the midday Sun's central ray along the ecliptic; (iv) tools that enable students to measure variations in the azimuth of sunrise and sunset, the altitude of the midday Sun, and the length of the day; (v) rotational interactivity that removes the ellipse-generating effect of oblique viewing; (vi) access to Google Earth's 3D terrain, historical imagery, and weather layer, which can help students appreciate geographic contributions to seasonal effects, bearing witness to the lag between solstices and climate maxima; (vii) the Google Earth search box that allows students to zoom in on their home location – a virtual 'parallel globe' (Rossi, Giordano, and Lanciano 2015); and (viii) a teaching sequence from geocentric Google Earth models to heliocentric plots and digital astronomy applications such as Stellarium, Celestia, and Starry Night Pro.

The main feature that supports student learning about the seasons is the separation of the daily spin of the Earth and annual migration of the Sun. To our knowledge, no other kinematic model permits such differentiation. Student learning is also supported by use of the built-in Google Earth ruler (set to degrees) which places the student in the center of the learning process.

Presenting students with new visualizations, however, is insufficient in itself. Instructors must have a deep understanding of the multiple factors impacting seasons if they are to guide students

constructively away from misconceptions toward scientifically normative views. We address these factors in a Supplemental Document.

3.1. The fixed r.a./dec grid

Astronomy students learn to locate objects in the night sky using local polar coordinates of azimuth and altitude. Because humans lack depth perception of the stars the ‘r’ in (r, theta, phi) polar coordinates is ignored on the ‘celestial sphere.’ Since these coordinates change with the passage of time as the Earth spins, they must be converted to right ascension (r.a.) and declination (dec) to have time-independent significance. Declination is equivalent to latitude and right ascension is related to longitude with the essential difference that the r.a./dec grid does not spin with the Earth – it is fixed in space on sub-millennial times scales. So as the night passes, the r.a./dec grid appears to spin counterclockwise about Polaris, the North Star, when viewed by a person standing on the northern hemisphere of the spinning Earth, and as the year progresses, different parts of the r.a./dec grid lie in Earth’s shadow. Also, right ascension is measured in hours, minutes, and seconds of arc, with one hour corresponding to 15 degrees of arc.

It is an understatement to say that students struggle with these concepts. They have to visualize a stationary r.a./dec grid and understand that because the Earth spins counterclockwise when you look down from space on the northern hemisphere, therefore the r.a./dec grid appears to spin counterclockwise when you look up in the northern hemisphere.

We have developed an interactive visualization that allows students to visualize the r.a./dec grid whilst looking down on the globe. Our grid shows students the r.a./dec coordinates of their zenith at a given place and time.

3.2. The spinning blue marble

Google Earth’s companion program SketchUp was designed to enable users to make 3D buildings and other COLLADA models that can be added to Google Earth. De Paor (2007) found that COLLADA models could be made much larger than buildings or bridges, and thus could be used very effectively to represent geological and geophysical concepts (see, for example, De Paor 2008; De Paor and Whitmeyer 2011). The size limit on COLLADA models is about twice the Earth’s diameter.

Our Google Earth-based COLLADA models (Figure 4) are global in scale and unapologetically geocentric. Earth is, after all, where our students’ lives are centered. Plummer and Krajcik (2010) and Plummer and Maynard (2014) stress the need for a learning progression that starts with Earth-based observations. We delay exposing students to misconception-reinforcing, highly elliptical-looking orbits such as Figure 1(a), rather we depict the ecliptic plane as an annulus inclined at 23.5° to Earth’s equator which it intersects along the vernal equinox (VE) and autumnal equinox (AE), and marked with the months and the constellations of the Zodiac. A central yellow ray of sunshine beams down on the Earth along the ecliptic plane and the night side is shaded with a semi-transparent dark hemisphere. These are animated in steps of hours, days, and months, with minor adjustments of the increments to account for the Analemma.

The critical innovation was to allow the Earth to spin under stationary models of the ecliptic plane and r.a./dec grid. To achieve this effect, we draped the NASA Blue Marble image (Stöckli et al. 2007) over the Google Earth terrain as a Keyhole Markup Language (KML) ‘ground overlay’ with initial north-east-south-west coordinates of 90°, 180°, -90°, and -180°. This image, not the Google Earth terrain, is what is seen to spin when the Google Earth time-lapse tool is clicked. In place of the built-in Google Earth grid of longitude and latitude lines (which must be turned off in the View menu), we constructed an r.a./dec graticule demarcated in hour- or 10-minute intervals of right ascension (blue) and ten- or two-degree intervals of declination (cyan). This r.a./dec graticule never moves relative to the hidden virtual globe and so the Blue Marble is seen to move under it. Consequently students can click and drag the virtual globe to change their viewpoint without

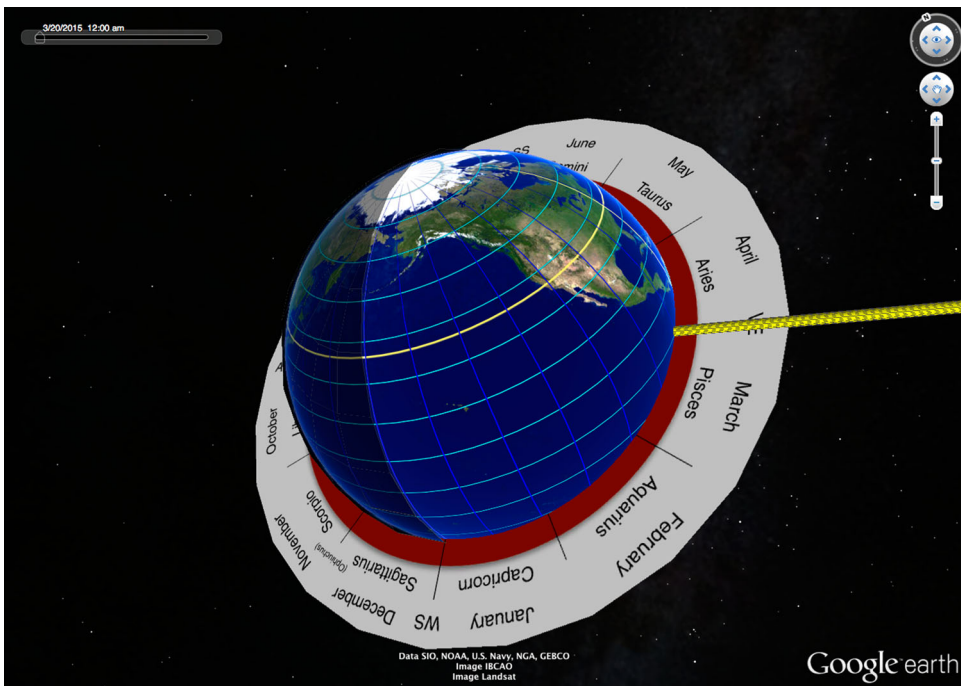


Figure 4. Giant COLLADA models in Google Earth. Image source: NASA.

interrupting the spin of the Blue Marble image. There are options to show the north celestial pole, ecliptic pole, tropical circles, and polar circles, to which the ecliptic and its poles are tangential at different points over the year. Note that the terminator (day–night line) always passes through the pole to the ecliptic. It passes through the geographic poles on the equinoxes and is asymptotic to the polar circles on the solstices.

4. Implementation

The home page of *Reasons for the Seasons* may be accessed at De Paor et al. (2016). There are two versions – a KML file that can be downloaded for use with the Google Earth desktop application and a version that employs the Google Earth web browser plug-in and its Application Program Interface (API). Browser plug-ins in general are being phased out for security reasons, thus the API will work only on certain web browsers and in the short-term, however we will port to a promised plugin-free API as soon as Google releases same, or failing such release, to the Cesium virtual globe (Pinkos 2016). See the Supplemental Documents for a full description of the desktop versus API versions.

The API enables students to interact with the model via JavaScript controls. The control panel (an API feature developed by Dordevic 2012), permits students to animate Earth's daily rotation on its axis throughout the year and follow the Sun's annual migration along the ecliptic in steps of hours, days, or months (Figure 5). Students are often intrigued to discover the slow motion of the central sunbeam around the ecliptic after prolonged staring when the increment is in hours. 'Look, it's moving!' they exclaim. The slow change in declination of the Sun on the r.a./dec grid is, of course, the fundamental concept we struggle to convey on our frenetically spinning Earth (Riddle 2011).

The desktop version of Google Earth has certain advantages. For example, to help students obtain a comprehensive understand of the seasons, instructors can at any time ask them to turn off our model and examine the current weather or switch to Google Sky. They can also turn on the Sun or run historical imagery in time-lapse to examine the lag of the seasons. Our Supplemental

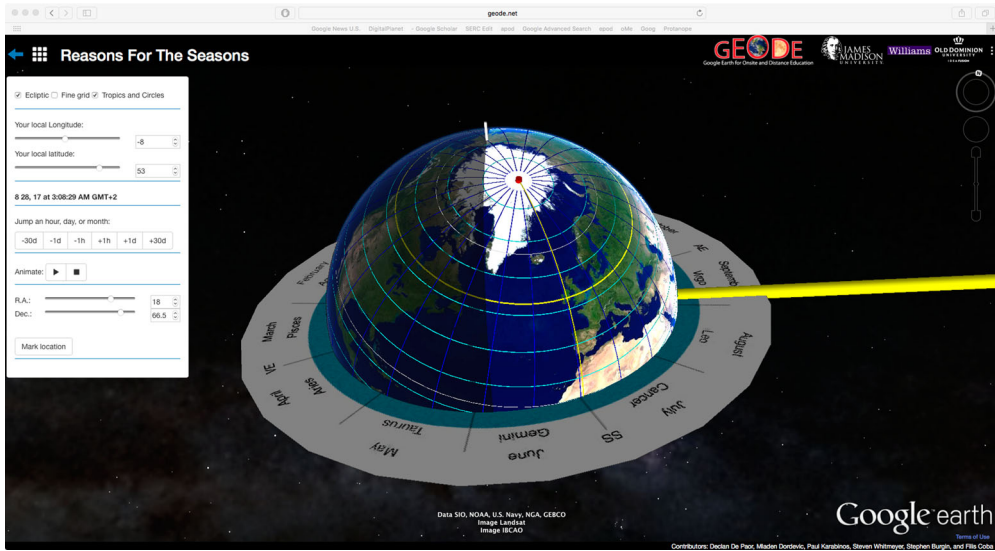


Figure 5. The API version interface. Image source: NASA.

Documents include a KML file centered on Grimsey Island, offshore northern Iceland, which lies precisely on the Arctic Circle. Students can turn on the Google Earth Sun and use the time slider to watch it kiss the horizon on the solstice (Figure 6). And of course students can use the search box to zoom in on their own home (Figure 7).

The KML document that we distribute consists of a simple 'NetworkLink' to the main KML document on our server. Thus updates are automatic whenever the file is loaded into Google Earth. Instructors should run the animations in the desktop version once through before class to cache the images and thus avoid the white flashes that occur on the first loading.

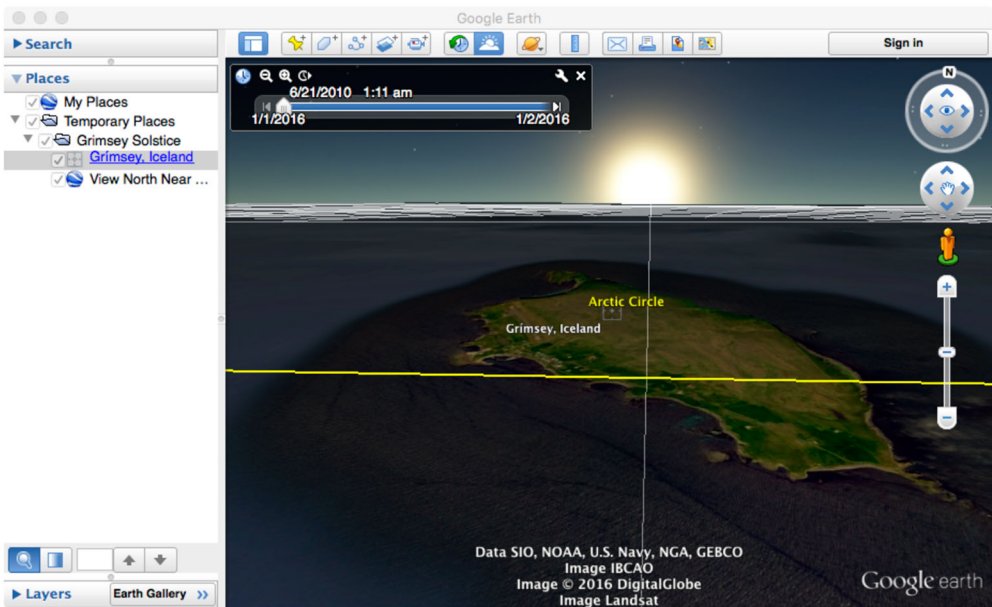


Figure 6. View of southernmost midnight Sun on the northern summer solstice in Google Earth. The location is Grimsey Island, Iceland through which the Arctic Circle passes. ©2016, Google Inc. Image sources: SIO, NOAA, US Navy, NGA, GEBCO, IBCAO, DigitalGlobe, Landsat.

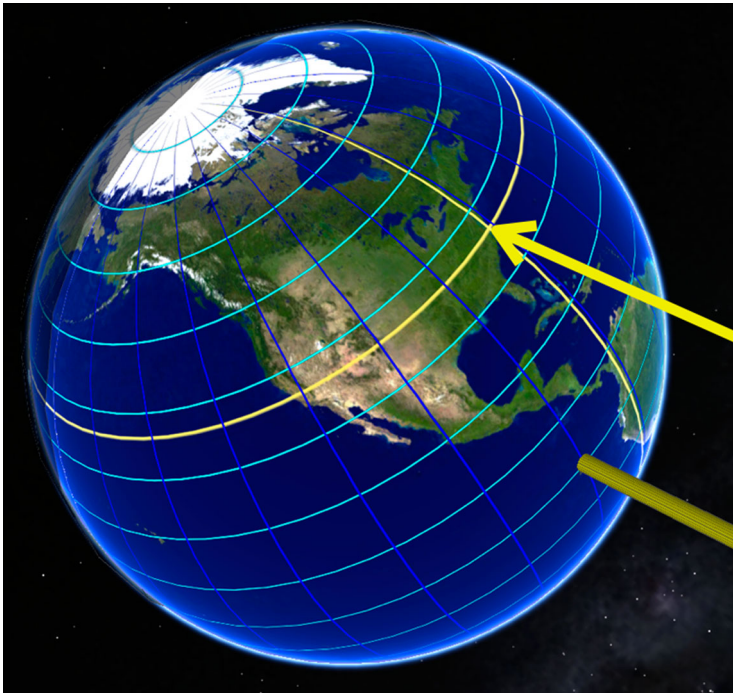


Figure 7. Students can zoom in on home. Yellow lines marking our university can be easily changed to reader's location in the API version and with KML code in the desktop version. ©2016, Google Inc. Image source: NASA.

5. Classroom testing

With Institutional Review Board (IRB) approval, we tested the KML version on 27 general education introductory astronomy students in a large U.S. research university and planetarium. Students had prior exposure to lectures and labs discussing stars and galaxies but had no prior classes involving the Solar System. We administer a pre-test consisting of 10 questions (see Supplemental Documents), delivered the 2-hour lab using Google Earth, and followed immediately with an identical post-test. Students worked in collaborative groups of three at a set of desktop computers and were challenged to describe how their location changed relative to the Sun's central ray on both a daily and annual basis, and thence to discuss implications for the seasons. They used the Google Earth ruler set to degrees to measure this change as an arc length and used the r.a./dec grid to measure length of day at different times of year and the height of the midday Sun above their local horizon. To do this, students counted the number of lines of r.a. intersecting their latitude on the bright/dark side of the terminator and they measured the Sun's zenith angle as it passed their longitude and subtracted from 90° to determine midday solar altitude. They were encouraged to click and drag the globe to change viewpoint.

Results are presented in Figure 8 where blue triangles represent improved scores, magenta diamonds are unchanged, and orange triangles are worse post-tests (identical points were separated slightly on the grid for clarity). The raw data are presented in Table 1.

The numbers represent number of correct answers out of 10 questions. The mean number of correct answers rose from 4.77 in the pre-test to 6 in the post-test. Interestingly, the standard deviation increased significantly, from 1.61 to 2.11, reflecting an increased spread of scores across the class. The paired t -test value of 0.021 implies a small but statistically significant learning gain. The gain was small because whereas 15 students improved their score by at least one quiz question, 7 remained unchanged, and 5 got worse. Remarkably, one student went from 1/10 to 10/10 correct answers – he or she obviously 'got it!' On the other hand, one student went from 5/10 to 1/10 correct answers.

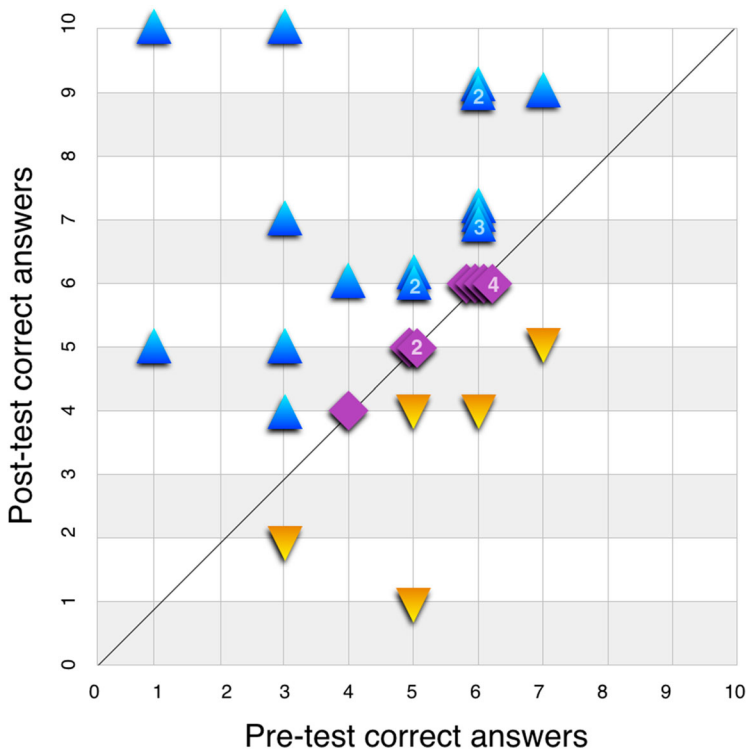


Figure 8. Correct answers in pre-test (horizontal) and post-test (vertical). Blue triangles represent students who improved, magenta diamonds unchanged, yellow triangles worsened. Identical scores numbered and nudged for visibility.

Nevertheless, the preponderance of blue and magenta data gives us confidence that this curricular resource is of general value.

6. Seasons on Mars

After students have used the Blue Marble model, they may be introduced to the effect of elliptical orbits using the example of Mars. On Mars, the axial tilt is about 25° , very close to Earth's value, but distance from the Sun varies from 1.64 to 1.36 AU², an eccentricity of almost 1%. As with Earth, Mars is further from the Sun during northern hemisphere summers, but the difference is much more significant on Mars, resulting in southern hemisphere summers being strikingly warmer than northern hemisphere ones (Figure 9a,b – also see the COLLADA model in our Supplemental Documents). A future human colony on Mars will have to teach children differently. Eccentricity also changes with time. Were we tasked with teaching students a million years ago, we would have had to discuss Earth's orbital eccentricity which was then five times greater than now.

7. Extensibility

Our Google Earth models can be used to teach aspects of positional astronomy beyond the reasons for the seasons. They have the potential to aid reasoning about the Earth's relation to the Sun and the stars, promoting spatial thinking (Kerski 2008) – which Goodchild (2006) called 'The Fourth R.' Students can add their own stars and asterisms to the sky using the Google Earth placemark and polyline tools with 'extend to ground' selected (Figure 10(a)) and they can measure angles with the Google Earth ruler set to degrees (Figure 11). Star placemark altitude

Table 1. Raw data from Figure 8.

Student ID #	Pre-test	Post-test
0543	4	6
9340	5	5
4988	5	6
7498	3	2
0142	6	9
2804	6	6
8070	5	2
2480	6	9
8664	1	10
8717	6	6
6120	6	7
7696	7	9
2825	6	7
4261	5	5
8331	6	7
2816	5	4
3735	3	5
4304	6	4
9138	6	6
7773	7	5
4389	1	5
6313	3	7
6790	4	4
5787	3	4
5737	5	6
0168	6	6
8457	3	10
Mean	4.77	6
Standard deviation	1.61	2.11
Paired t-test		0.021

can be scaled to distance in light years, effectively demonstrating that stars in a single asterism such as the Big Dipper are not necessarily equidistant from Earth. Placemarks are fixed to the hidden virtual globe and so they do not rotate with the Blue Marble, but rather maintain fixed r.a./dec values. The r.a./dec coordinates of the point directly above the observer (the zenith) can be read off the grid and tracked with time.

After placemarking their current location, students can blank out the Blue Marble in order to concentrate on the celestial sphere. They can imagine the Earth shrunk to a tiny point at the center of the celestial sphere and visualize the outward view. To determine which stars are visible, they can use the Google Earth ruler extended to 90° or Google Earth Pro's circle ruler set to 10,000 km (approximately one quarter of Earth's circumference). In contrast to r.a./dec, stars' azimuths and altitudes change with time. These can be measured using the ruler's heading and map length (purple arc in Figure 10(b)).

In the case of the Sun, the midday zenith angle ($90^\circ - \text{altitude}$) is easily measured along the students meridian (Figure 11(a)). At other times, the ruler's 'heading' value gives the azimuth and the length of the ruler arc gives the zenith angle (Figure 11(b)). The time slider thumbs can be separated to show a time series and changes in azimuth and altitude can be studied (Figure 11(c)).

8. Progressing to a heliocentric view

Lab and planetarium exercises can also be used to emphasize the theory-laden nature of scientific knowledge. Preservice and inservice teachers could explore the applicability and use of models and visualizations as a practice within science (Gilbert, Reiner, and Nakhleh 2007; Whitmeyer et al. 2012; Frigg and Hartmann 2013). They would be able to see first hand some of the strengths and weaknesses of modeling and simulation while at the same time understanding how the utility of the model justifies its application in spite of its potential drawbacks.

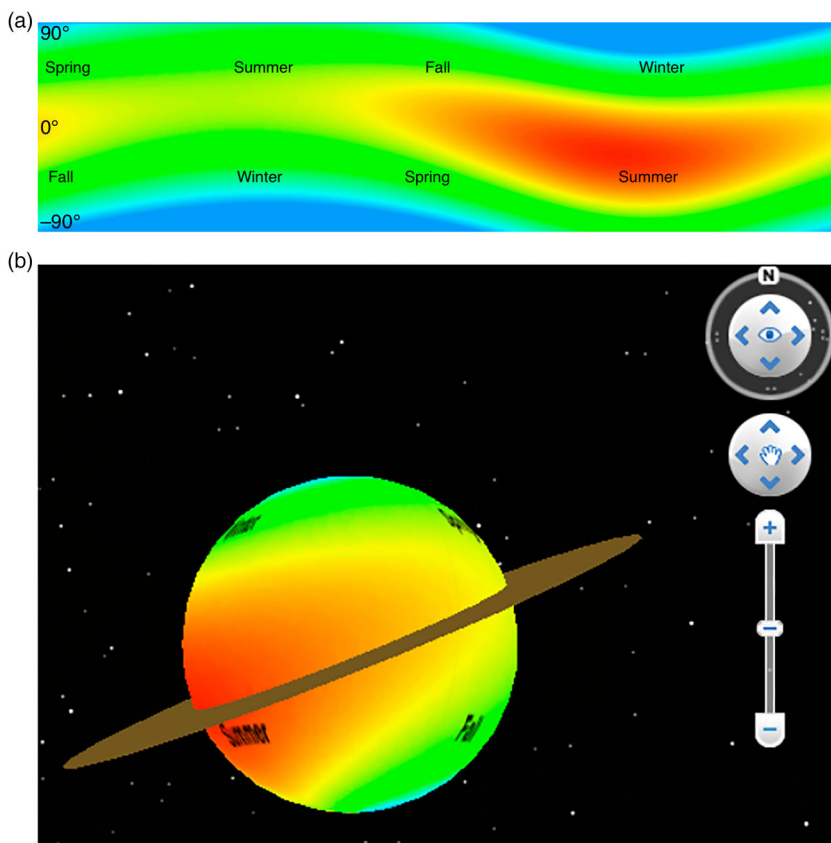


Figure 9. (a) Seasonal variations of noon insolation on Mars. Blue=least insolation, red=most. (b) image wrapped around Google Mars. Beige plane is the ecliptic. ©2016, Google Inc. Image source: Caplinger (1994).

For example, our Google Earth model leverages the geocentric view but a progression to a heliocentric view is difficult to convey with only our small screen overlay. In fact, in our courses, a pencil-and-paper exercise (borrowing stereographic projection techniques from structural geology) was used to relate the geocentric and heliocentric views (Figures 12 and 13). This conveys the important and challenging concept that times of year such as solstices, equinoxes, and birthdays correspond to locations on Earth's orbit in space. We point out to students that they were not just born in a state such as Massachusetts or Hawaii, but in a 'place' on Earth's orbit such as November or May (Figure 13). The custom stereographic net required for this exercise is included as a Supplemental Document. Future plans include digitization of this exercise, although students anecdotally report that they enjoy the tactile nature of hand plotting and the exercise challenges students to port their 3D visualization gained from Google Earth and develop it into a 3D mental model.

8.1. A scale model of the solar system on Google Earth

There is obviously a risk that students will think that traveling over the Earth's surface toward the central sunbeam brings them closer to the Sun in space, as previously discussed (Trumper 2001; Plummer 2009; Kanli 2014), just as they are known to often believe that telescopes are placed on mountaintops to get closer to the stars. Kalkan and Kiroglu (2007) found that dimension and distance misconceptions were particularly difficult to shift. We can help counter the distance issue using a separate Google Earth model – De Paor (1984), De Paor, Coba, and

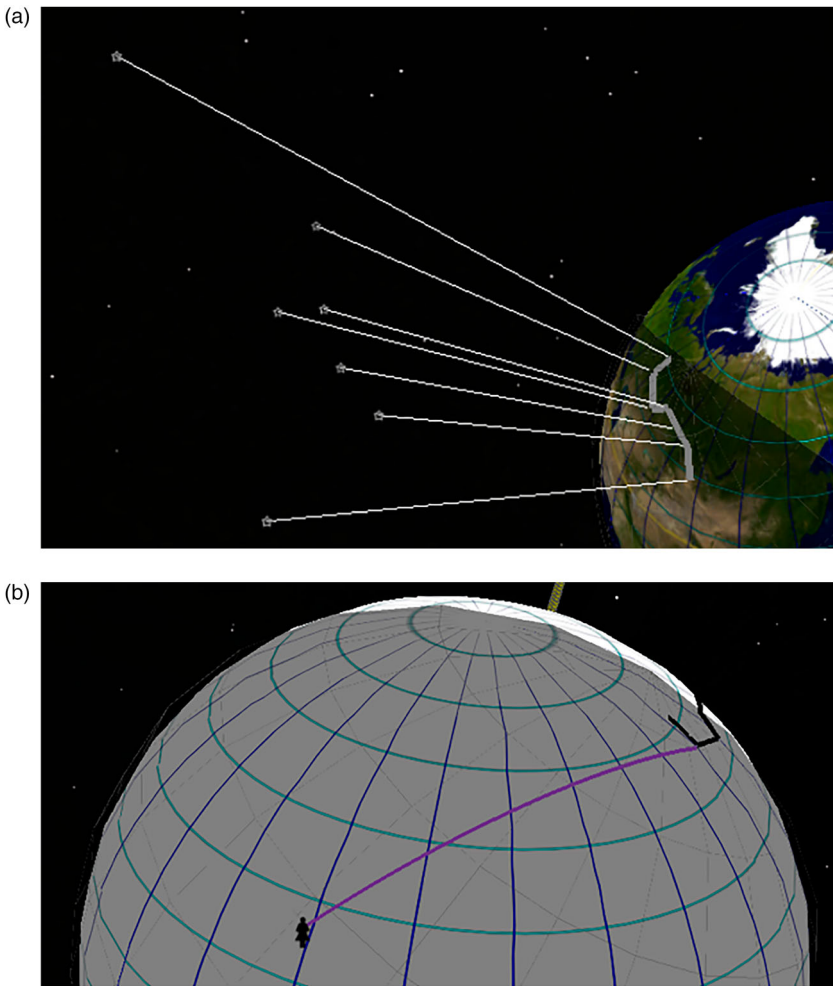


Figure 10. (a) Elevated Google Earth placemarks represent varying distances to stars in asterism such as Big Dipper. (b) Blue Marble can be blanked out to concentrate attention on r.a./dec grid. Google Earth style elements can be varied (black). Current azimuth and zenith angle (90° -altitude) of a star may be determined from the heading and map length of the Google Earth ruler set to degrees (purple arc). ©2016, Google Inc. Image source: NASA.

Burgin (forthcoming), and Figure 14. Unlike 1:1 billion physical models of the Solar System (Bennett et al. 2012), we are not constrained by engineering or finances, and so can represent the Sun by a 1.391 km diameter sphere centered on our planetarium and the Earth by a 12.756 m diameter sphere on Pea Island in the Outer Banks of North Carolina. This 1:1 million model can help deconstruct misconceptions about the effect of tilt on distance from the Sun since the whole Earth fits in a carpark that students know is a two hour drive away from their campus. The Supplemental Document's KML code can be editing to move the Sun and planets to center on reader's locations.

9. Discussion and conclusions

Despite the best efforts of our best teachers and authors (e.g. Schatz and Frankoi 2016), misconceptions about seasons are proving immensely resistant to conceptual change. Perhaps we need to

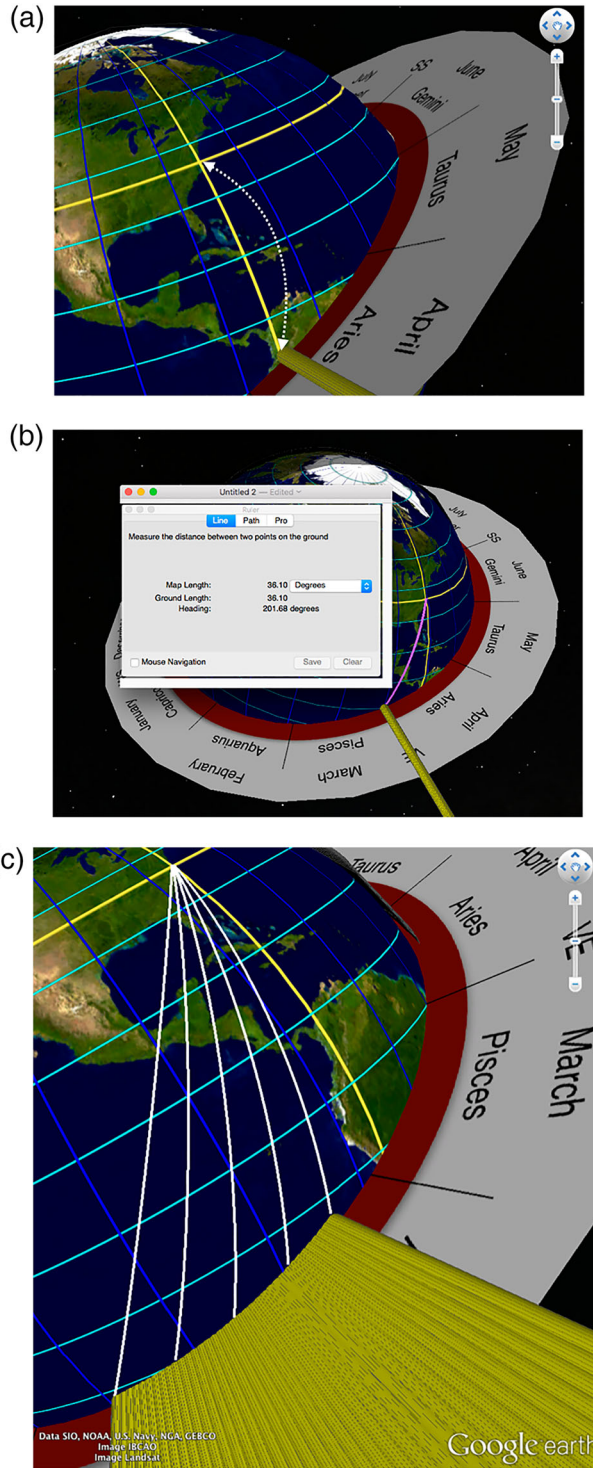


Figure 11. (a) Altitude of the midday Sun is 90° - zenith angle which is measured along the meridian (yellow) from the student's location to the sunbeam. (b) Measuring azimuth and altitude with Google Earth ruler tool. (c) Spreading the time slider's thumbs reveals the change in az/alt with time. Blue arcs are sequential solar zenith angles. ©2016, Google Inc. Image sources: SIO, NOAA, US Navy, NGA, GEBCO, Landsat.

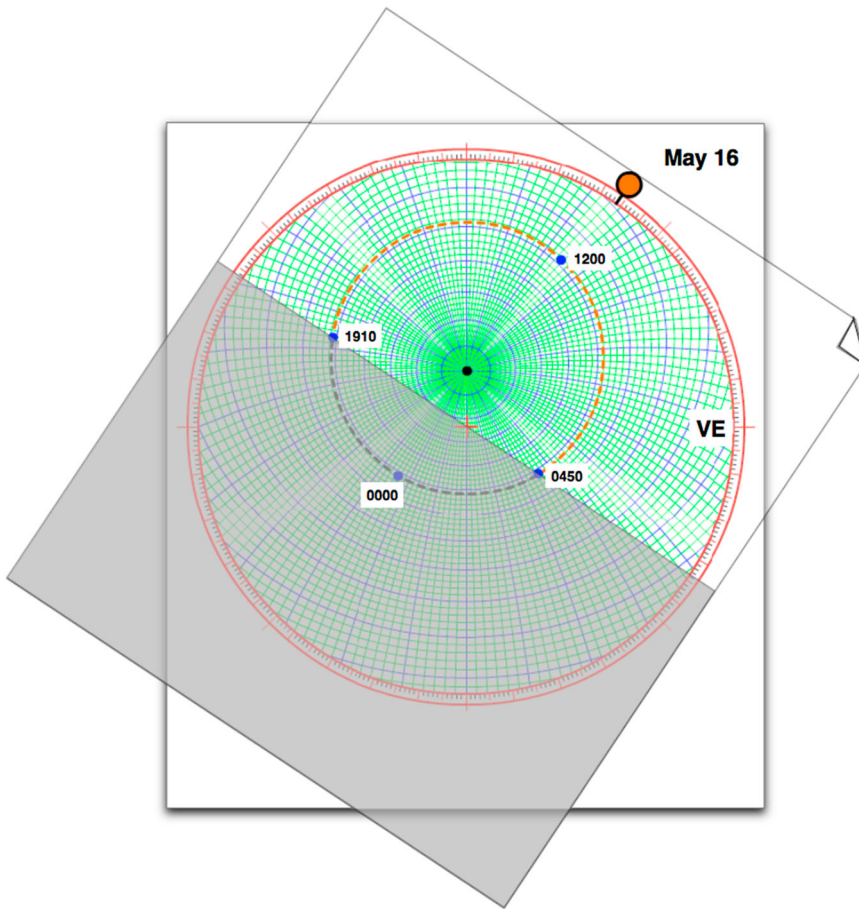


Figure 12. Paper plot exercise. Inclined stereographic net centered on ecliptic pole. Latitude of Norfolk is dashed. VE = Vernal Equinox. Tracing overlay rotates about a central thumbtack. Orange dot represents direction of Sun, gray = nighttime. Sunrise mid-day, sunset, and midnight on May 16 are marked.

consider whether a radical change in approach is required. Teaching elementary school students about Kepler's First Law before or whilst teaching them about seasons is a pedagogical booby trap that invites students to develop the misconception that distance from the Sun matters. There are not many areas of science education where we tell students 'This is a fundamental principle but actually it doesn't matter.' It would make more sense to tackle seasons first and introduce elliptical orbits later. We should tell our students that for all practical purposes, the Earth's orbit is circular. We can later add that a circle is just a special type of ellipse and that on other planets such as Mars, seasons are significantly impacted by slight eccentricity as well as tilt. The Google Earth model presented here does not show the elliptical orbit but defers that to a later stereographic projection exercise.

We certainly do not propose that students be given only a geocentric view, rather that they start with the home-planet view and progress from there via our stereographic plotting exercises to a heliocentric view supported by digital astronomy applications – we use Stellarium and Celestia on the planetarium dome, and Starry Night Pro on the desktop computers (the latter is available under license for full dome projection). Starry Night Pro contains a favorite menu devoted to seasons (Figure 15). It grossly exaggerates the size of the Earth versus the Sun and shows the Earth's orbit in an inclined view that suggests a highly elliptical orbit.

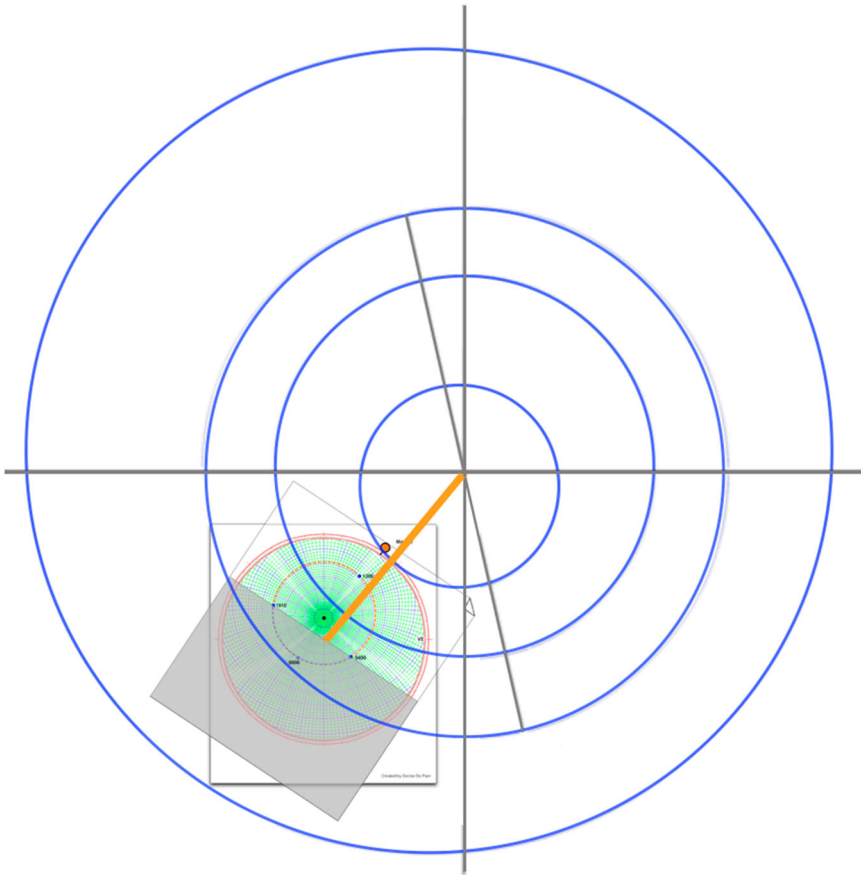


Figure 13. Relating geocentric stereographic projection to heliocentric terrestrial orbits drawn on a sheet of poster paper. Gray line joins Earth's perihelion to aphelion.

Our model permits students, and their teachers, to clearly distinguish the sidereal day that is due to Earth's 360° spin on its axis from the solar day that also includes the Sun's $\sim 1^\circ$ migration along the ecliptic. The model emphasizes multiple contributions to summer heat and winter cold that are not evident in Figure 2, namely: the closest daily angular distance from a student's location to the central sunbeam, a student-friendly proxy for the altitude of the Sun on their meridian (Figure 11(a)); the amount of time that location spends at a given distance from the central beam; the integral thereof over the hours of daylight; and local geographic features that are evident on Google Earth.

By pointing to the location of the Sun's central ray on the Earth's surface, we aim to nudge students' misconception regarding distance. Instead of distance to the Sun, which is not shown, what matters is *angular* distance over the surface of the Earth to the Sun's central ray. This aligns with conceptual change theory, which calls upon educators to build constructively on existing misconceptions rather than just present new information (Orley 2016). It is summer when you are closer to the yellow sunbeam at midday but that beam is never overhead in temperate latitudes. Measuring angles between surface and sunlight can follow.

The proven effective methods of learning we advocate are distributed practice and learning through doing (Dede 1996; Roediger III 2013). Most courses and textbooks lump practice. Students may learn about, say, velocity by solving several end-of-chapter problems in one homework assignment. The more effective distributed learning approach has students return to a topic repeatedly over



Figure 14. Google Earth model of Solar System with both orbits and globe sizes to a scale of 1: 1 million.
(a) Orbits of the terrestrial planets, (b) Sun centered on ODU Planetarium and (c) Earth model on Outer Banks NC.

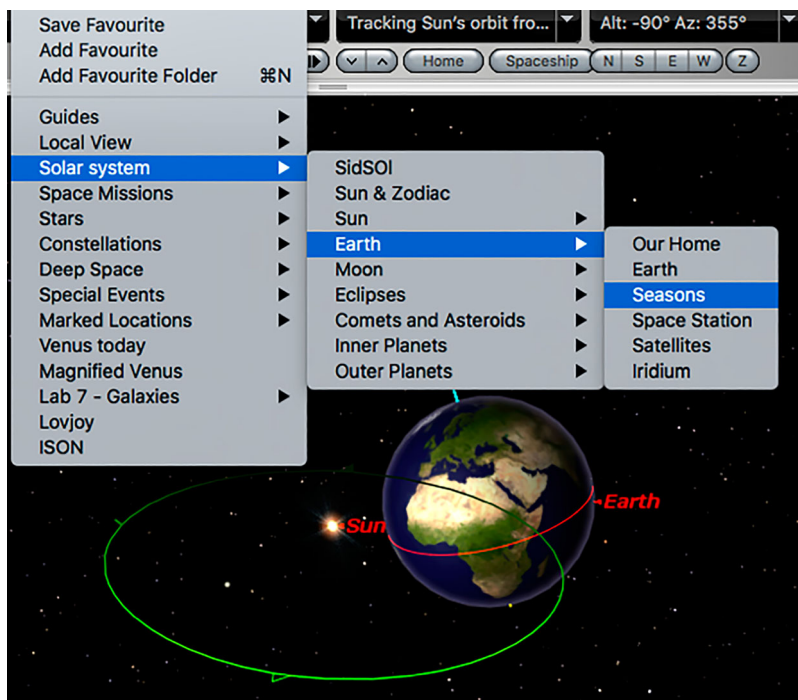


Figure 15. Starry Night Pro has a favorite menu item dealing with the seasons.

a long period. In the case of the seasons, it makes sense to have students study the Sun's location on the ecliptic at several times of the year. They can measure the arc between their location and the spring Sun in spring and the fall Sun in fall, and can view the summer and winter geometries during vacations, finally reaching the scientifically normative explanations of seasons. Being based on Google Earth, our model is suited to both in-person and distance education.

We are under no illusion that our model will effect a miracle cure for misconceptions about the real reasons for the seasons. University students have already been exposed to images of highly elliptical orbits in elementary and middle school and regardless of instructor effort, they may decide that hotter means closer, based on common experience. However, if our initial classroom test results are reproduced by others, as we hope they will be by readers, then it does have the potential to nudge students, their teachers, and the general population in the right direction, away from their *Private Universe*, toward an improved understanding of how the Earth moves in space and how multiple factors influence seasonality.

Notes

1. Some planetarium staff may not realize that their expensive, custom, full-dome projectors commonly have VGA and DVI ports for projecting from a computer, iPad, or Android tablet.
2. 1 AU (astronomical unit) is the mean distance from Earth to the Sun.

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