Foucault's Pendulum

A Study of Gravity and Earth's Rotation

More Lessons from the Sky
Satellite Educators Association
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Please see the Acknowledgements section for historical contributions to the development of this lesson plan. This form of “Foucault's Pendulum: A Study of Gravity and Earth’s Rotation” was published in October 2013 in “More Lessons from the Sky,” a regular feature of the SEA Newsletter, and archived in the SEA Lesson Plan Library. Both the Newsletter and the Library are freely available on-line from the Satellite Educators Association (SEA) at this address: http://SatEd.org.

Content, Internet links, and support material available from the online Resources page were revised and updated October 2019.

**SEA Lesson Plan Library Improvement Program**

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Foucault's Pendulum
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Invitation
On September 18, 2013, Google posted an animated doodle celebrating the life of Jean Bernard Léon Foucault, a French physicist born on that date in 1819. Foucault is remembered for several things including his experiment demonstrating the speed of light in water is slower than in a vacuum; his famous pendulum with which he demonstrated the rotation of the Earth on its axis; and his invention and naming of the gyroscope that behaved in much the same way as the pendulum. To follow Foucault's logic for the pendulum, one must possess an open mind free of misconception and be able to apply Newton's first law of motion to the observations and measurements before us. Starting with a video of a Foucault pendulum at the Chicago Museum of Science and Industry, does the arc swing of the pendulum move closer to the pins on the floor or is the floor moving closer to the arc swing of the pendulum? How does Foucault's pendulum really work? And what does this all have to do with satellites and remote sensing?

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Student Learning Outcomes
By the end of this lesson students should be able to do the following:
- Construct a simple pendulum
- Observe the properties of a simple pendulum
- Demonstrate how the mass of the bob, the length of the pendulum, and the starting angle of the first swing are related to the pendulum's period
- Measure the motion of a simple pendulum and calculate its period
- Compare and contrast your simple pendulum with Foucault’s pendulum in terms of gravity and momentum
- Interpret the motion of Foucault's pendulum in terms of Earth's rotation
- Describe and calculate the period of Foucault’s pendulum based on the latitude of its location

These may vary with the specific lesson plan selected or adapted by the teacher.

Lesson Description
The topics highlighted in this lesson presentation are gravity, the rotation of the Earth and, by extension, how these are related to launching a rocket, a satellite's orbit, and the ground path traced by remote sensors onboard Earth-looking satellites. The approach to these is a study of pendulums and especially Foucault’s pendulum. There are a number of appropriately constructed lesson plans available on the Internet already that can be used as is or adapted to a particular classroom or student need. The teacher is urged to try one of these or, better, synthesize one of your own based on these
suggestions.

Sample lesson plan #1 - Exploring Pendulums
✓ From Science Net Links
✓ Grades: 9-12 Physics

This lesson helps students understand concepts related to how gravitational forces act on objects by exploring the motion of pendula. Using an online simulator, students can vary the length of the pendulum and the amplitude (the starting angle for the bob) to gather, analyze and interpret data. Following this link:
takes students to a hands-on activity creating their own pendula and testing the length, amplitude, and mass to reach their own conclusions about the relationship between gravitational forces and the periodic motion.

Sample lesson plan #2 - Foucault's Pendulum
✓ From Science Net Links
✓ Grades 9-12 Physics

This is a lesson of guided research utilizing resources available on the Internet. Most included links connect to valid lesson resources on this and other AAAS Science Net Links pages and the California Academy of Sciences online. The lesson begins with background context including reference to AAAS Benchmarks for Science Literacy. See the Standards section of these Teaching Notes for Next Generation Science Standards addressed by this lesson. Learners are introduced to pendulums through a graphic pamphlet that is read online or from a downloaded pdf. Then they experiment using a simple pendulum online simulator by varying length, initial angle, gravity, and planetary rotation. There is a downloadable worksheet to guide learner thinking and development - answer key included. Learners are led to calculating the pendulum's period and the daily rate of rotation based on the pendulum’s latitudinal location. The suggested assessment involves constructing a written explanation of how Foucault’s pendulum proves that Earth rotates.

Sample lesson plan #3 - Pendulums on the Moon
✓ From SCRIBD.com and PhET Simulations
✓ [https://phet.colorado.edu/sims/pendulum-lab/pendulum-lab_en.html](https://phet.colorado.edu/sims/pendulum-lab/pendulum-lab_en.html)
✓ Grades 9-12 Physics

Using a different online simulator than that used in the previous lesson, learners experiment with a pendulum on Earth by varying the length of the pendulum and initial angle (must be a small angle) to calculate acceleration due to gravity. Then duplicate the experiment on the Moon. Measurements of period using a photogate timer are graphed as a function of pendulum length. The slope of the resulting line is used to
calculate acceleration due to gravity. The simulator also allows the procedure to be repeated on the Moon, Jupiter, and Planet X (a planet with unknown gravity). The lesson and calculations are explained in the document on the Scribd site. The full lesson plan, with sample data and explanation of calculations, is freely available for on-screen viewing but requires registration for download. The online simulator is offered by Phet Simulations, free simulations from the University of Colorado.

Sample lesson plan #4 – Galileo: A Different Thinker
✓ From PBS Learning Media
✓ https://www.pbslearningmedia.org/resource/phy03.sci.phys.mfw.lp_galileo/galileo-a-different-thinker/#.WyDA_CAnZpg
✓ Grades 6-12 physical science

Students examine four of the experiments that Galileo used to discover the effects of gravity and inertia on moving objects. Galileo challenged the thinking of the day by studying falling objects, projectiles, objects rolling down inclined planes, and swinging pendulums. His observations are the basis for much of current classical physics. Students use a combination of interactive activities, video segments, and reading to study Galileo’s ideas.

The Student Activity pages that follow these Teaching Notes contain only a suggested focus setting activity. It is a You Tube video of the Foucault pendulum at the Chicago Museum of Science and Industry. The photographer has captured six minutes of pendulum behavior prior to and concluding with the bob’s bottom spike knocking over a pin in the row of pins encircling the pendulum’s swing area - a demonstration of the rotation of the Earth under the pendulum. It is suggested that the class view the first minute or so allowing learners to observe the perceptible distance between the bob and the pin. Then fast forward to the last 30-60 seconds of the video to see the pin contacted by the bob and knocked down. The video can be found at this URL: https://www.youtube.com/watch?v=iqpV1236_Q0.
PE- MS-PS2-2 - Plan an investigation to provide evidence that the change in an object’s motion depends on the sum of the forces on the object and the mass of the object.

DCI- MS-PS2.A - The motion of an object is determined by the sum of the forces acting on it; if the total force on the object is not zero, its motion will change. The greater the mass of the object, the greater the force needed to achieve the same change in motion. For any given object, a larger force causes a larger change in motion.

SEP- Plan an investigation individually and collaboratively and in the design identify independent and dependent variables and controls, what tools are needed to do the gathering, how measurements will be recorded, and how many data are needed to support a claim.

CC- Explanations of stability and change in natural or designed systems can be constructed by examining the changes over time and forces at different scales.

Grades 6-8: Motion and Stability: Forces and Interactions

PE- MS-PS2-4 - Construct and present arguments using evidence to support the claim that gravitational interactions are attractive and depend on the masses of interacting objects.

DCI- MS-PS2.B - Gravitational forces are always attractive. There is a gravitational force between any two masses, but it is very small except when one or both of the objects have large mass.

SEP- Construct and present oral and written arguments supported by empirical evidence and scientific reasoning to support or refute an explanation or a model for a phenomenon or a solution to a problem.

CC- Models can be used to represent systems and their interactions—such as inputs, processes, and outputs—and energy and matter flows within systems.

Grades 9-12: Motion and Stability: Forces and Interactions

PE- HS-PS2-4 - Use mathematical representations of Newton's Law of Gravitation and Coulomb's Law to describe and predict the gravitational and electrostatic forces between objects.

DCI- HS-PS2.B - Newton's Law of Gravitation and Coulomb's Law provide the mathematical models to describe and predict the effects of gravitational and electrostatic forces between distant objects.

SEP- Use mathematical representations of phenomena to describe explanations.

CC- Different patterns may be observed at each of the scales at which a system is studied and can provide evidence for causality in explanations of phenomena.

Preparation

Preparation and set up for this lesson must be guided by the specific lesson chosen and adapted by the teacher. Please refer to the website listed for each lesson above for information about the specific materials for each lesson.

The teacher is strongly urged to download the video of the Foucault pendulum at the Chicago Museum of Science and Industry and show it by projecting it for the whole class or otherwise making it available to each student or student group for viewing locally. To avoid the advertisements and comments that may be inappropriate in an educational setting, the video is also available from this the online Resources page for this lesson at
Background
In 1851, French physicist Jean Bernard Léon Foucault built a pendulum with a large iron mass on a long wire. Once it started swinging, the pendulum’s plane of oscillation was observed to precess clockwise around the center of the swing. Foucault determined the change of the vertical plane of the swing at a rate and direction dependent on the geographic location of the pendulum. The experiment was repeated in several locations with successively longer pendulums. The most famous of these was a 28 kg (62 lb) brass coated lead bob suspended on a 67 meter (200 feet) piano wire from the dome of the Church of Saint Geneviève, also known as the Panthéon, in Paris. Each trial confirmed earlier results. Using his knowledge of Newton’s first law of Motion, Foucault concluded the Earth was rotating on its axis.

Newton’s first law of motion is also called the law of inertia.

An object at rest remains at rest and an object in motion will continue in motion with a constant velocity unless a net external force acts on the object. (Serway)

Aside from momentum, the only forces acting on the pendulum bob are gravity and the cord suspending it. Air resistance makes each swing slightly shorter than the previous. To counteract air resistance, Foucault pendulums today are energized with an electromagnetic ring arranged with a switching mechanism at the top of the suspending wire. This provides a very slight extra kick of energy to insure each swing is the same arc length. Considering Newton’s first law, the vertical plane of the pendulum’s swing will not change in space unless an outside force is applied to cause a change of direction. Consequently, the direction of the vertical plane of the pendulum swing remains consistently unchanged. If the pendulum seems to rotate with respect to the floor and there is no known force available to make the pendulum rotate, then it must be the floor that is rotating - that is, the Earth under the pendulum is rotating.

At the poles, the pendulum swing will appear to precess 360° in one sidereal day of approximately 24 hours. At the equator, the plane of oscillation remains fixed relative to the Earth. At all other latitudes between, pendulum’s vertical plane appears to precess relative to the Earth, but slower than at the pole. The rate of precession or angular speed, then, appears to depend on the latitude of pendulum’s location on the Earth. Some geometric knowledge leads the investigator to conclude this relationship:

$$\omega = 360 \sin \phi \arcmin /\text{day}$$

where $\omega$ is angular speed measured in clockwise degrees per sidereal day and $\phi$ is the latitude of the pendulum’s location. A common example is a Foucault pendulum located...
at latitude 30˚ north. The angular speed per day is 180˚. That is, it will take two days for the precessing plane of the pendulum’s oscillation to complete a single, full rotation.

A very clear and accurate description of this is given in *The Scientific American Book of Projects for the Amateur Scientist* published in 1960. The teacher is referred to this source for detailed information found at [http://SatEd.org/library/Resources.htm](http://SatEd.org/library/Resources.htm) or [http://www.sciencemadness.org/library/books/projects_for_the_amateur_scientist.pdf](http://www.sciencemadness.org/library/books/projects_for_the_amateur_scientist.pdf).

So, what does Foucault’s pendulum have to do with satellites, orbits, and rockets? Gravity is the natural force that must be acted against in order to lift a rocket and its payload off the surface of the Earth. Even in orbit at approximately 250 miles above the Earth, astronauts in the space shuttle are in a low gravity environment - not completely weightless. It is gravity that holds the low earth orbit satellites (approximately 250-600 mile altitude range) in their orbits, the geostationary satellites in their orbits at about 22,000 miles altitude, the Moon in its orbit around the Earth, and the Earth and all other planets, moons, comets, and asteroids in their orbits around the sun. The force of gravity between two bodies in space was defined by Newton’s law of gravitation:

Every particle in the Universe attracts every other particle with a force that is directly proportional to the product of their masses and inversely proportional to the square of the distance between them. (Serway)

The direction of the force is along a line joining the objects. The magnitude of the force ($F_g$) is expressed by the equation:

$$F_g = G \frac{m_1 m_2}{r^2}$$

where $m_1$ and $m_2$ are the masses of the bodies in space, $r$ is the distance between them, and $G$ is Newton’s constant of proportionality [$6.674 \times 10^{-11} \text{ N(m/kg)}^2$].

It is a common misconception that a "geostationary" satellite remains motionless over one surface location. In fact, it must be at an altitude of about 35,000 km (22,000 miles) and travel at a velocity of 3.07 km/s (1.91 mi/s) or about 6876 miles per hour. This speed at this distance from the Earth in an orbit around the equator allows the satellite to match the rotation rate of the Earth and appear to be stationary over one ground location at all times.

Polar orbiting satellites, such as weather satellites, travel in a vertical plane similar to the pendulum’s vertical plane of oscillation. As the Earth rotates beneath the satellite, the ground path of the satellite seems to precess around the globe. This can be seen in a scan of the Earth’s surface as seen by the satellite’s remote sensors during a 24 hour period. The scans appear to have gaps of missing data - areas of the surface not seen by the sensors during that time period.
Each day, the gaps of missing data will be in different positions. For this reason, remotely sensed data are sometimes averaged and interpolated over 8 days, a month, or even a year to provide a complete global coverage.

Acknowledgements
The idea for this lesson plan actually came from Google's doodle celebrating the September 18 birthday of French physicist Jean Bernard Léon Foucault (1819-1868), inventor of the famed Foucault pendulum with which he demonstrated the rotation of the Earth on its axis. Rather than develop an original lesson plan synthesized from many already available, More Lessons from the Sky spotlights the selection of lesson plans presented here. All are freely available on the Internet and each utilizes a unique pedagogical approach.

This lesson arrangement, supplemental materials, and this edition of Teaching Notes were developed by J.P. Arvedson for the Satellite Educators Association as part of More Lessons from the Sky published on-line each month in the Satellite Educators Association Newsletter. More information about the Satellite Educators Association, its annual Satellites & Education Conference, international student environmental research collaborative, and free access to the online Newsletter can be found at http://SatEd.org.


Please credit all contributors to the lesson when duplicating, distributing, or otherwise utilizing any part of this lesson plan or any of its supporting materials.

References
Note: All of these URLs were current and active as of this writing. If any are unreachable as printed, the use of on-line search engines such as DuckDuckGo, Ask, Google, or Bing is suggested to find current links.


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Introduction

On September 18, 2013, Google posted an animated doodle celebrating the life of Jean Bernard Léon Foucault, a French physicist born on that day in 1819. Foucault is remembered for several things including his experiment demonstrating the speed of light in water is slower than in a vacuum; his famous pendulum with which he demonstrated the rotation of the Earth on its axis; and his invention and naming of the gyroscope that behaved in much the same way as the pendulum. To follow Foucault's logic for the pendulum, one must possess an open mind free of misconception and be able to apply Newton's first law of motion to the observations and measurements before us. Starting with a video of a Foucault pendulum at the Chicago Museum of Science and Industry, does the arc swing of the pendulum move closer to the pins on the floor or is the floor moving closer to the arc swing of the pendulum? How does Foucault's pendulum really work? And what does this all have to do with satellites and remote sensing?

Preparation

Your teacher will show you a short video of the Foucault pendulum at the Chicago Museum of Science and Industry. Observe as much as you can about the behavior of the pendulum.

○ What do you suppose the mass of the bob to be?
○ How long do you think the pendulum wire might be?
○ What keeps it from slowing down due to the resistance of air in the room?
○ At the start of the video, how far is the needle on the bottom of the bob from the pins standing on the floor and encircling the pendulum's swing area?
○ How long is the video?
○ Did the pendulum strike any pins during the video? If so, when? (Hint: Note the time on the video.)
○ What questions arise about the behavior of the pins on the floor and the pendulum swinging above them?

Give particular attention to the distance between the pins on the floor and the pendulum at the start of the video compared to what you see at the end. Replay those portions of the video several times if needed.
Follow your teacher's directions to proceed with the assigned investigation of Foucault's pendulum, gravity, the rotation of the Earth and satellite remote sensing.
YOUR TURN

After completion of the assigned investigation, extend and apply your thinking to one or more of the following Your Turn activities.

Select and complete one or more of the activities below. Then create and deliver a report of the results. The report must be in a format you have discussed and agreed upon with your teacher. It could be audio visual in form using presentation software such as PowerPoint; it could be in printed format such as a poster presentation; or it could be in written or oral form similar to a letter, a printed report, or an oral report to the class. In each case, drawings, computer graphics, or other artwork should be included to clarify explanations.

- Research and collect photographs and/or drawings of ways pendula are used in our society today. How are these devices important? What would it be like if the pendula were not available?

- Pendula that swing in the air are slowed by resistance from the air. Investigate, describe and explain the operation of a device that will keep the pendulum swinging without slowing from air resistance.

- Design and construct a Foucault pendulum complete with a device for counteracting the effect of air resistance. Demonstrate the pendulum to an audience and explain how it works.

- Obtain remotely sensed images of the Earth (downloaded from NOAA and NASA web sites). How do these demonstrate the rotation of the Earth?

- The attraction of gravity on the surface of the Earth is 9.8 m/s². Investigate Newton’s Law of Gravitation and use it to calculate what gravitational attraction would be on a 180 lb. astronaut orbiting 400 km (about 250 miles) above the Earth in a space shuttle. Assuming an astronaut could travel to the Clarke Belt where geostationary satellites orbit around the equator, what would the gravitational attraction be on that same astronaut at that location?

- Research the rockets used to place satellites in polar-orbit. Today, Delta II rockets are often used, sometimes with several solid-fuel rocket boosters attached. Determine the mass of the rocket package including payload. How much thrust would be necessary to counteract gravitational attraction of the Earth and accelerate the satellite to the appropriate altitude? How is this value calculated?

- Devise a plan to investigate satellites in orbit. Describe the orbit in detail. It has been determined that low Earth orbiting satellites such as environmental satellites travel with a velocity of nearly 27,360 KM per hour (about 17,000 mph) while geostationary satellites travel with a velocity of about 11,000 km per hour (about 6800 mph). What causes the difference? What factors must be considered when determining the velocity of a satellite in orbit? Mathematically demonstrate how average velocity of each satellite type can be calculated?