Lesson Plan	
Lesson Title	# Making Craters K.D. Denney[1] [1]Department of Astronomy, The Ohio State University
Nominal Grade Level	Versatile throughout K-12 based on content included in the lesson. Can be as elementary as K-1 with basic idea of craters are made by space rock hitting the surface of a terrestrial planet or a moon, or much more math-centric for upper grade levels through high school or even college if including the full lesson provided here.
Ohio's New Learning Science Standards Addressed	2(ES), 2(PS), 4(ESS), 4(PS), 4(LS, if an meteor impact killed the dinosaurs…), 5(ESS), 5(PS), 6(ES), 6(PS), 7(PS), 8(ESS), 8(PS), HS(PS), HS(Physics), HS(EnvironSci – maybe), HS(PhysGeo – maybe)
Goals and Objectives for Student Learning	Students will simulate how craters are made to investigate ways that we can learn about the surface of planets and moons and properties of the loose material in the solar system that creates such craters (e.g., mass, velocity, density). Students will also utilize math skills such as graphing and algebra and experimental design.
Teaching Method(s)	Guided Inquiry to Open Inquiry, depending on how much background information and structured materials/instruction students are given.
Materials	1.) Various sizes/masses of balls (metal work best for advance, math-centric form of lesson, such as ball bearings, etc., although other types can be used); must have at least 2 sizes/masses of the same type of ball for each group (i.e., you need to be able to vary the mass). Otherwise, anything goes (bouncy balls, actual rocks, golf balls, even gum balls, etc.). 2.) Sand, dirt, all-purpose flour, and cocoa mixture for making cratering material: mixture of sand and dirt for thicker 'bottom' layer, flour or mixture of sand and flour for thinner 'mid to upper' layer, and then cocoa for very top layer (e.g., like regolith on the moon; also makes it easier to see the crater ejecta). Open Inquiry option: provide many materials, e.g., sand, dirt (potting soil and/or top soil or anything you dug out of your yard…), flour, Nesquick or cocoa powder, any other material you can think to use, and make students do an open inquiry activity to determine the best combination of materials. 3.) Plastic tubs (cafeteria bussing trays work well too) to hold cratering material. Open Inquiry option: also need small test container, such as empty tissue or shoe box, or really anything to hold material. 4.) Meter sticks/rulers/tape measures 5.) Scale (for measuring masses of balls) 6.) Graph paper or Graphing software such as Excel.

Science Content Background	**The Moon's Surface:** The Moon's surface is far from smooth. With a small telescope, or even with binoculars, it's easily observable that the surface of the moon is pitted with **craters** – a generally circular, bowl-shaped cavity in the surface of a planet or moon, typically caused by the impact of a meteorite or other celestial body. These celestial bodies, or "space rocks" (aka meteoroids, asteroids, or cometary material) bombard the surface of the moon and leave evidence of their presence, and even size and mass by the crater they create on impact. The Moon is covered with so many craters because it doesn't have an atmosphere, which would help both to break and/or burn up the meteoroids above the surface and also to lead to weathering at the surface. As a result craters stay visible on the moon's surface for a very long time, even billions of years. Nearly the only process to disrupt the craters is the impact of more meteoroids that leave behind more craters and meteorites. One exception to this is the cause for the darker patches seen on the surface of the Moon. These areas, called "maria" (plural; Latin for seas), have fewer craters than the light colored patches of the Moon. These are areas believed to be solidified lava, from flows occurring early in the history of the Moon, likely also from impacts of meteoroids large enough to break through the Moon's crust. This released lava from the Moon's previously molten core. The significantly smaller number of craters on the maria suggest that these dark areas of the surface are relatively younger than the light-colored lunar terrain. In fact, the maria must have been formed relatively late in the geologic history of the Moon and Solar System because there are so many fewer impact craters on these portions of the lunar surface. **What we can learn from impact craters**: Impact cratering can be a dominant resurfacing process on terrestrial planets (i.e., Mercury, Venus, Earth, and Mars) and moons. Studying the size and shapes of craters can provide scientists with information about the properties of both the surface and the object that hit the surface to make the crater. On objects such as the moon with no atmosphere, weather, volcanic activity, or other natural resurfacing process, the impact craters allow scientists unique access to one aspect of the history of solar system, in particular, the relative number and sizes of meteoroids near the earth's orbit. From making many observations of craters on other planets and moons, astronomers have found a rough empirical relation (i.e., one determined by experiment) between the size of an impact crater and the kinetic energy of the object that made the crater. This relationship is a power-law relationship (simply meaning that one quantity is related to the other quantity raised to some power) of the form: $K = aD^n$ Where $K = \frac{1}{2} mv^2$ is the kinetic energy of the object that made the crater, D is diameter of the impact crater, n is an exponent, and a is a constant. In the

activity described below, students will create craters of their own by dropping balls of the same material, but different masses and sizes into a box containing a mixture of sand, dirt, and flour, to simulate the surface of the moon. By measuring the kinetic energy of the ball when it drops (See Energy Conservation below) and the diameter of the crater that results, younger students can make a plot of energy versus diameter to see that there is a correlation between the two: the more energy an object has, the larger the crater it produces (this idea should be highly intuitive as well). Older students can actually make fits to their data to determine the variables *n* and *a* in the above relation (See Supplement below).

Energy Conservation Considerations:

Because this relation involves the object's kinetic energy, but kinetic energy is often difficult to measure because the velocity of a projectile is difficult to measure without special equipment. This lesson is best executed by taking advantage of the conservation of energy, which simply states that energy is neither created nor destroyed, but can only be transferred from one form to another. Therefore, we will take advantage of the conversion of gravitational potential energy to kinetic energy in a falling object. The gravitational potential energy (PE_{grav}) can be expressed as:

$$PE_{\text{grav}} = mgh$$

Where m is the mass of the object, $g = 9.81\ \text{m/s}^2$ is the gravitational acceleration on the earth, and h is the height from which the object is dropped. Because of the conservation of energy, if you drop an object from some height with initially no velocity, the energy of the object at that stationary point above the ground is all gravitational potential energy, but when the object hits the ground, $PE_{\text{grav}} = 0$ because $h = 0$, and so all the previous gravitational potential energy has been converted into kinetic energy just before impact. So, you can determine the kinetic energy an object will have when it hits the cratering surface by simply dropping it from a fixed height with an initial velocity of 0.0 (i.e., students should not 'throw' the objects into the box of cratering material, but rather drop them from an initial stationary position and let gravity do the rest). With this information, the empirical crater relation becomes:

$$mgh = aD^n$$

Comparisons with the Earth's Surface:

Earth's surface is not covered with craters like the Moon, or e.g., Mercury. This is because most meteoroids break up and/or burn up in our atmosphere, resulting in something called a meteor (or shooting star). There are usually not any pieces remaining that are large enough to hit the earth's surface to create craters. However, not all meteoroids get destroyed by the earth's surface, and we do find meteorites on earth, but they're not often found in craters because earth's surface processes that cause weathering (like wind and rain) destroy the crater.

**Note the distinction above between meteoroid (a "rock" - or small solar

	system body - still in space or impacting the surface), meteor (the light show, also known as a shooting star, produced when a meteoroid enters our atmosphere), and meteorite (any part of a meteoroid remaining intact after impacting the planetary/moon surface).
Learning Activities	**Most Basic Procedure for youngest students**: 1.) Start out with an instructor led discussion including lots of questions to the students about how much they know about the moon, why the moon looks the way it does, if the surface looks smooth or not, why or why not, how could this have happened, etc. 2.) Provide students with pre-made boxes of "lunar surface" (layers of sand+dirt mix, then flour, then cocoa) and a variety of "meteorites" to use for making craters. 3.) Encourage students to make craters by dropping/throwing their meteorites to make impacts with the lunar surface. 4.) Have students compare and contrast different craters based on (1) meteorite size and mass (or weight), (2) how fast the meteorite impacted the surface (was it dropped or thrown), and (3) the angle at which it entered (straight up and down or at an angle). 5.) Follow up the activity time with additional discussion, e.g., if "space rocks" (aka meteoroids) are in space and hit the moon to make so many craters on the moon, why doesn't the Earth's surface look this way? **School Lesson Procedure**: **Before the day of the lesson: Have students – or groups – bring their own "test box" to school, e.g., empty shoe box or tissue box. Open Inquiry Starter: 1.) Investigate different possible materials to be used for making "lunar surface". 2.) Collect small amounts of each type of material to be used in your test box, as well as a single ball to be used as a test meteorite. 3.) Test different combinations of surface materials to find the combination which you feel makes the best craters, using some criteria you develop for what is a "good" crater. (Teachers may also put limits on the amount of each material you may have – you may have to compromise; too much cocoa becomes cost prohibitive). Main Procedure: 1.) First collect the two different sizes/masses of balls that you will be dropping, your box of sand, and a metric ruler. 2.) Use a scale to measure the mass of your two balls and record these values. 3.) Formulate a plan for the number of and the exact different heights

from which to drop the balls (A range of 0.5 meters to 3 meters is suggested, if climbing on furniture is acceptable).

4.) Calculate the kinetic energy that each of your balls will have after being dropped from each of the different heights you chose (i.e., this is actually the gravitational potential energy at the different heights chosen, because of the law of conservation of energy).
5.) Drop the balls from each of the heights that you have chosen. Measure the diameter of the craters formed (i.e., in metric units too!). ****Between each drop, it is important to “Fluff the sand” so that it doesn’t get packed down by the impacts, adversely affecting subsequent drops. To fluff the sand, simply grab one edge of the box, lift it slightly off the ground and drop is back down. Then shake it a bit from side to side to level the sand. This can be repeated a couple of times from different sides of the box.
6.) ** If time is available, you can have the students drop the balls from each of the heights multiple times and calculate the average crater diameter, which gives them more math practice, and reduces the chances that unknown effects (called systematics) will influence the crater size.
7.) Once all of the data is recorded (energy and crater diameter), plot the data either by hand or in a spreadsheet program like excel: energy on y-axis and diameter on x-axis.
8.) Take results as far as you’d like for your classroom, such as make students simply note the general trend between energy and diameter: the diameter of the crater gets larger for larger energies, called a “direct correlation”. Or you can go further, as described in the supplement below and have students actually determine the value of the exponent and proportionality constant.
9.) Ask other questions and have students think about other issues not directly covered. Examples include:
    a.) effect size has
    b.) effect angle of impact has
    c.) If they’ve learned about density, how does that relate
    d.) What effect does the atmosphere play (i.e., why we see so many craters on the moon but not on earth).

What is changed if you do this experiment on other planets or the Moon (i.e., think about the gravitational constant)? Do you think that changes the relation?

Supplements

Older students with more algebra and graphing experience can easily determine the actual power law exponent, *n*, and constant of proportionality, *a*, by graphing their data and fitting a line to the data (e.g., with Microsoft Excel).

The easiest way to execute this is to first make the power-law equation above look like a linear equation using the rules that come along with exponents and

	logs, by first taking the log of both sides: $\log(mgh) = \log(aD^n)$ Next, use the rules associated with logarithms to separate the terms you want: log(mgh) = log(a) + n*log(D) If you rearrange this equation, it looks like the simple equation for a line (y = mx + b): log(mgh) = n*log(D) + log(a) where y = log(mgh) (i.e., what to plot on the y axis) m = n (i.e., the slope of the line that you will fit to your data) x = log(D) (i.e., what to plot on the x axis) b = log(a) (i.e., the y intercept of the line fit to the data) In this way, you can plot log(mgh) vs. log(D) – the two things you measure in your experiment. Then using a graphing program like Excel make a scatter plot of your data and then fit a linear trend to the data, and have Excel display the equation of the fit. From this you can get m = n, and b, which you can then take 10^b to get the constant of proportionality, a. With this information, you can do a lot of math-related follow-up, giving them some of the information, and making them do algebra to solve for the answer using their derived relation. A few examples include: a.) Give an energy and make them solve for the resulting diameter. b.) Give them a crater diameter and a mass and have them come up with a velocity. c.) Change the location of the crater to another planet, forcing them to solve for the gravitational acceleration on that planet
Inter-Disciplinary Connection Ideas	**Reading and Literature Connections**: 1.) *Exploring Dangers in Space: Asteroids, Space Junk, and More* by Buffy Silverman 2.) *Night Comes to the Cretaceous: Comets, Craters, Controversy, and the Last Days of the Dinosaurs* by James Lawrence Powell 3.) Science Fiction: The Helium-3 Trilogy (*Crater, Crescent,* and *Crater Trueblood and the Lunar Rescue Company*) by Homer Hickam **Geology, Earth, and Space Science Connections**: 1.) Research the different types of meteorites commonly found on Earth. What are the differences? What are they made of? Which kind are most common? Why? 2.) Research types of weathering and surface processes responsible for erasing the evidence of craters on earth. Which process is the fastest? Which is the most efficient? What types of places on Earth is one most/least likely to find craters and meteorites? Why? (can do also in conjunction with finding craters on Earth with Google Earth.). 3.) Find out when the next meteor shower will be. What causes a meteor shower? Stay up to watch the meteor show and count how many meteors you see.

	4.) Explore the website hosted by NASA's Jet Propulsion Laboratory (http://neo.jpl.nasa.gov/neo/) to learn about Near Earth Objects (NEOs). How many are there? What is their range of sizes? How did they get there? Why do scientists study them? Etc. **Math and Computer Connections**: 1.) Use Google Earth to find, measure, and analyze impact craters on Earth, the Moon, and Mars: http://lcogt.net/book/exploring-impact-craters-google-earth (supported by Las Cumbres Observatory Global Telescope Network). 2.) Use a small telescope or just an image of the Moon and count the number of craters, sorted by some size criteria that you come up with. Graph the number of craters (even as crudely as small, medium, large). How many of each type did you count? Why do you think this is?
References	Adapted from a Boston University astronomy lab written by Melissa N. Hayes-Gehrke and Valerie Maher.