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Exploring the universe: from very small to very large

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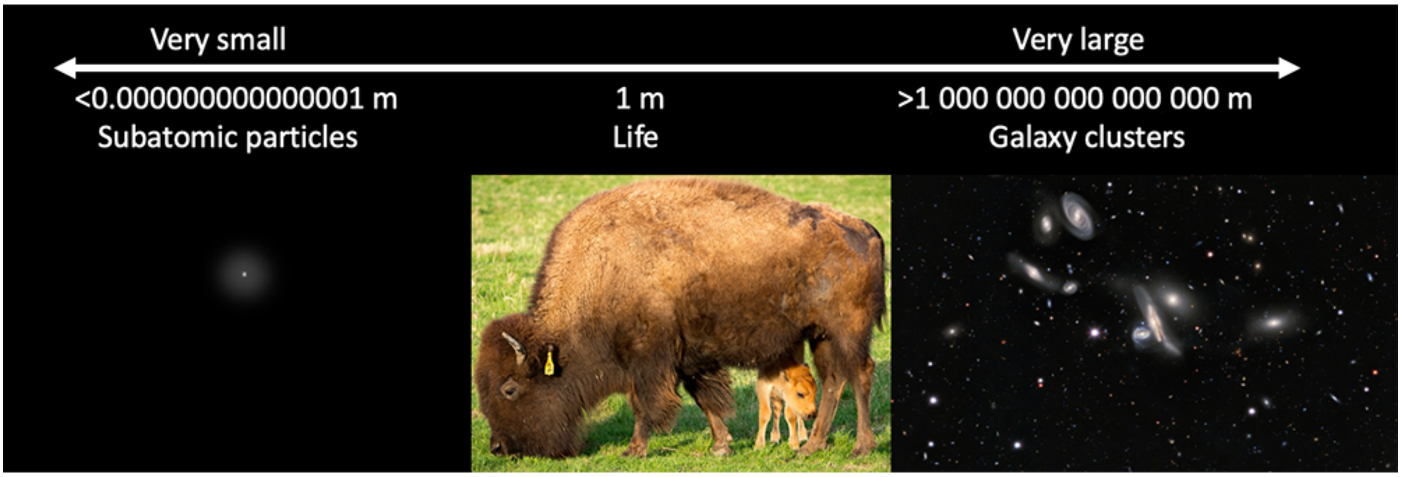
How do physicists study very small objects (like molecules, atoms, and subatomic particles) and very large objects (such as galaxies) that cannot be directly observed or measured?

Imagine a single grain of sand. Subatomic particles, such as protons or neutrons, are a trillion times smaller than this grain of sand. Particle physicists study these tiniest building blocks of matter. To explore the invisible subatomic world, scientists build particle accelerators, create particle collisions, and try to observe patterns. Scientists analyse millions of different particle interactions and gather information about the properties of particles.

Now imagine a bison. Our galaxy, the Milky Way, is 1 000 000 000 000 000 000 000 times larger than a bison. Astrophysicists study very large objects, such as galaxies and galaxy clusters. They use the profound result of Einstein's theory of general relativity – gravity bends the path of light – to explore and study astronomical bodies that are too far away to see, even with the most powerful telescopes.

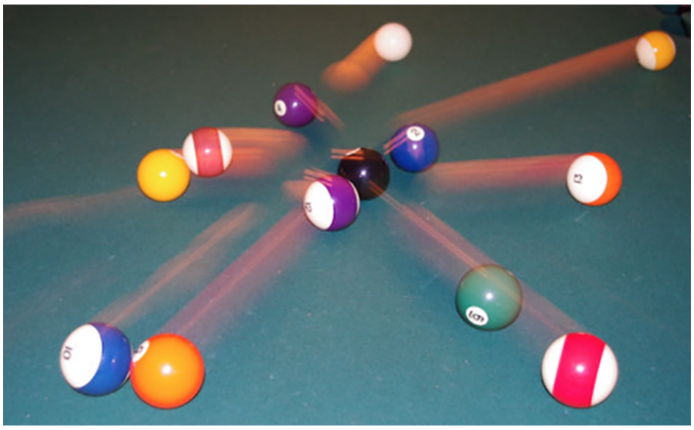


The scale of the Universe: subatomic particles are the smallest objects currently known to scientists and galaxy clusters are the largest. Pictures not to scale.
Fermilab Office of Education and Public Engagement

Activity 1: Collisions and scattering

Suggested age: 10 years and up (the activity should be done with adult supervision)
Estimated time for the activity: 20–30 minutes
Pre-lesson preparation time: 10–15 minutes

Most collisions in our world, from billiard balls to particles, can be described by one word: scattering. Physicists build particle accelerators to study particle collisions and their scattering patterns. They collect data, analyse particle interactions, find patterns, and learn about the basic building blocks of matter.



Billiard balls scatter after a collision.
Brian Demaio, CC BY 2.0

This activity demonstrates how scattering works. It introduces students to a method of identifying target shapes from characteristic scattering patterns.

Materials

- 6 mm steel ball bearings
- Small, flat objects with different geometric shapes (triangle, disc, square)
- Sturdy cover, such as a piece of cardboard
- A Hula Hoop
- Double-sided sticky tape

Procedure

1. Find a large, smooth surface (like a tabletop). Define an area on that surface where you can roll ball bearings. Use the Hula Hoop to set up a perimeter on the surface. Line the inner surface of the Hula Hoop with double-sided sticky tape.
2. Place a small, flat object in the centre of the Hula Hoop. You can use the double-sided tape to fix the object in the centre.
3. Roll a handful of ball bearings at the object and observe how they bounce off from it. Use a magnet to collect the ball bearings. Repeat the experiment several times until you find a pattern. Do this for every object.
4. Have an assistant place one of the objects in the centre of your experimental area and hide it under the cover. (The ball bearings need to pass under the cover, so you might need to elevate it slightly if the object is too flat). Can you guess the shape of the object based on how the ball bearings scatter from it?

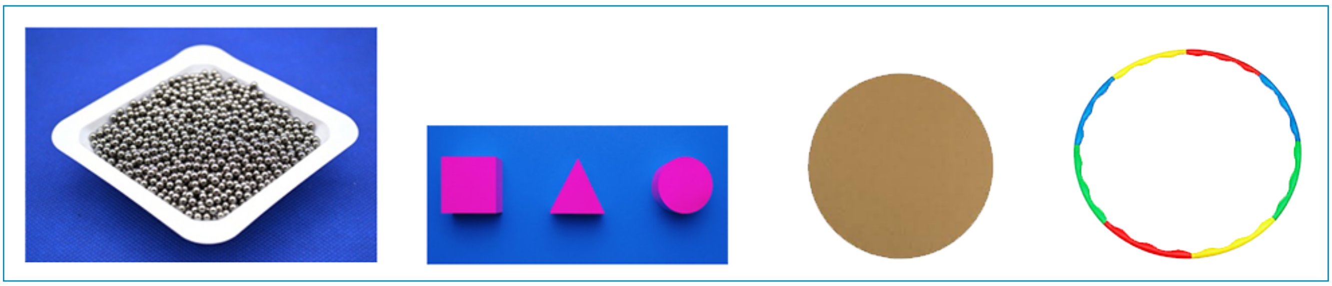
You can watch a video of the scattering experiment in action here.

Try this

Map how the ball bearings are scattered by different known surface types (curved, straight, slanted, etc.). Then ask your lab assistant to find a new object to hide under the cover. Roll the ball bearings at the new hidden object from multiple angles. Can you guess the shape and size of the new object based on the scattering patterns?

Real-life applications

In the early 1900s, a team of physicists led by Ernest Rutherford fired positively charged alpha particles at a thin leaf of gold foil. Most of the particles passed straight through, but a



Materials for the activity
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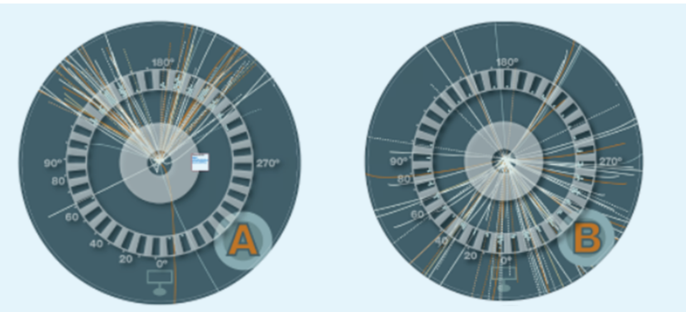
few rebounded in odd directions. This experiment led to the discovery of the atomic nucleus, the positively charged part of the gold atoms that sent the alpha particles ricocheting away. Since then, scientists and engineers have used particle scattering to determine the microscopic structures of everything, from subatomic particles to proteins. Multiangle laser-light scattering is also used to determine the molecular weights of proteins and protein complexes.[1]

Discussion

- What happens when ball bearings hit the target?
- Does the scattering pattern depend on the target's shape?
- Why do you need to repeat the experiment many times (and collect more data)?
- What scattering pattern is produced with a triangle? (Disc? Square?)

When ball bearings hit the target, they scatter in different directions. Different shapes produce different scattering patterns. Here are two examples: (A) is produced by an equilateral triangle, and (B) is produced by a disc. You will need to repeat your experiment for each shape several times before you see the scattering pattern. Then, based on the pattern, you can tell the shape of the hidden object.

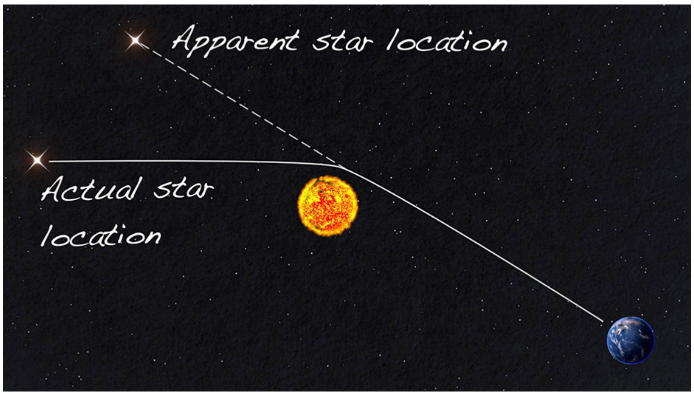


Examples of different scattering patterns
Fermilab Office of Education and Public Engagement

Activity 2: Can you bend light?

Suggested age: 10 years and up (the activity should be done with adult supervision)
Estimated time for the activity: 20–30 minutes
Pre-lesson preparation time: 10–15 minutes

In space, light rays bend when passing near very massive objects, such as stars and galaxies. The presence of matter curves space, and the path of a light ray will be deflected as a result. Just like lenses bend light, supermassive objects (such as galaxies) bend light due to their powerful gravitational pull; therefore, this effect is called 'gravitational lensing'.



Light rays bending in the presence of a large mass
NASA's Goddard Space Flight Center

Imagine a bowling ball sitting at the centre of a trampoline. The bowling ball acts as a massive object (like the sun or a galaxy) and the trampoline fabric acts as space-time. If you roll a small ball toward the bowling ball, it won't follow a straight path. Instead, it will follow the curve in the trampoline and its trajectory will become 'bent' by the presence of the bowling ball. That's what light does around very massive objects: the more massive the object, the more light will bend around it.

Materials

- 1 m of stretchy fabric, such as Lycra
- 1 large, open-top box (cardboard or wood)
- 1 stapler
- 2–3 weights of varying sizes
- 10–15 ball bearings

Materials for the activity.
Fermilab Office of Education and Public Engagement

Procedure

1. Stretch the fabric over the top of the open box.
2. Staple the fabric to the sides of the box. (It should form a suspended and taut surface.)
3. Place a weight on the fabric. What happens? The stretched fabric represents space-time, and each weight represents a massive object, such as a star or galaxy cluster.
4. Roll a ball bearing past the massive object (ball bearings represent particles of light). What happens to its trajectory?
5. Play with the speed of the ball bearing and weight of the massive object. Can you get the ball bearing to orbit the massive object?

You can watch a video of the light-bending experiment in action here.

Try this

Use safety pins and a net to hang a massive object underneath the space-time fabric. Can you guess the mass of the object based on the trajectory of the ball bearings?

Real-life applications

Physicists use gravitational lensing to determine the mass of galaxies and measure the amount of dark matter in the universe. Scientists think dark matter is plentiful and warps space-time, but it has so far evaded other forms of detection.[2–4]

Discussion

- What happens to the photon's path when it passes near a galaxy?
- How does bending depend on the mass of the galaxy?
- How do scientists determine masses of galaxies?
- Can light always escape the gravitational pull of a massive object?

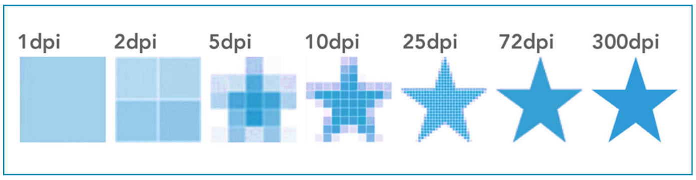
The path of photons is distorted when they pass near a galaxy due to gravitational lensing. As space is warped by massive objects, light from a distant object bends as it travels to us, and we see a distorted image of it. The heavier the massive object, the more it distorts the path of light, so the distortion of light gives us information on the object's mass.

Gravitational lenses provide an opportunity to study the properties of distant galaxies. An important consequence of lensing distortion is magnification, which allows us to observe objects that would otherwise be too far away and too faint to be seen. However, light can't always escape the gravitational pull of supermassive objects: black holes are regions in space-time where gravity's pull is so powerful that not even light can escape.

Activity 3: Can you probe shapes with pinheads?

Suggested age: 10 years and up (the activity should be done with adult supervision)
Estimated time for the activity: 20–30 minutes
Pre-lesson preparation time: 10–15 minutes

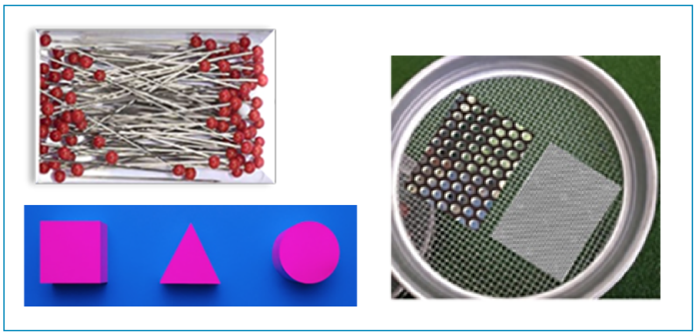
Particle physicists study nature by using particle collisions. A particle's energy is inversely proportional to its wavelength. High-energy particles have extremely small wavelengths and can probe nature at the subatomic level.[5] The higher the energy, the closer particles come to each other, revealing smaller details of their structure. Particle detectors are used to record the results of these high-energy collisions. Detectors can be thought of as giant digital cameras that are used to 'photograph' extremely small particles. This activity explains how one can probe shapes with different-sized pinheads and draws an analogy between particle energy/wavelength, resolution, and pinhead size.



In digital images, the higher the dots per inch (dpi), the higher the resolution, and the sharper the image.
Fermilab Office of Education and Public Engagement

Materials

- Two sets of different-sized spherical pinheads (or round-headed nails)
- One mesh sieve
- Small geometric shapes (triangle, disc, square, trapezoid)



Materials for the activity.
Fermilab Office of Education and Public Engagement

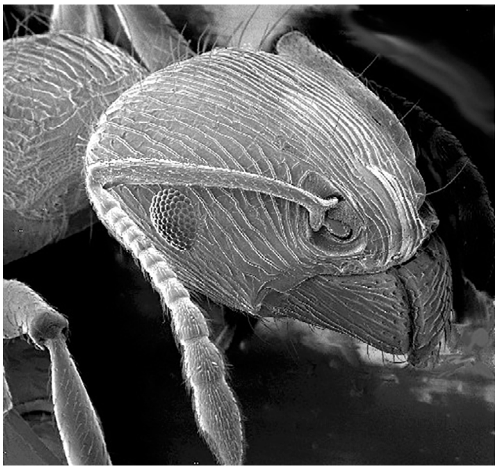
Procedure

1. Cover half of one mesh sieve with large pinheads.
2. Cover the other half of the mesh sieve with small pinheads, as shown in the image above.
3. Take a flat geometric shape and push the pinheads from underneath, so that they move up and reveal the shape of the object under them.
4. Now pick shapes without looking at them, repeat the experiment, and try to guess what shape is under the pins.

You can watch a video of the pinheads experiment in action here.

Real-life applications

Electron microscopes use a beam of electrons to examine objects on a very fine scale. In an optical microscope, the wavelength of light limits the maximum magnification that is possible. As electrons have a smaller wavelength, they can achieve a higher magnification, and can be used to see very small objects – typically around 1000 times smaller than those observed with an optical microscope. Scanning electron microscopes (SEMs) use an electron beam to image samples with a resolution down to the nanometre scale.



Scanning electron microscope (SEM) image of an ant

Discussion

- Does the resolution depend on pin size?
- What gives better resolution: smaller pins or larger pins?

This experiment shows that higher resolution can be achieved with smaller pins: the smaller the pin size, the higher the resolution. Similarly, in particle collisions, the higher the energy, the closer particles come to each other, revealing finer details of their structure. This is why we need accelerators with higher and higher energies, to probe the universe on the smallest scale possible and reveal the properties of subatomic particles.

References

[1] Mogridge J (2004) Using light scattering to determine the stoichiometry of protein complexes. *Methods Mol Biol.* **261**:113–118. doi: 10.1385/1-59259-762-9:113.

[2] An article on The Dark Energy Survey about the distribution of dark and visible matter with gravitational lensing: https://www.darkenergysurvey.org/darchive/a-new-method-to-measure-galaxy-bias-by-combining-the-density-and-weak-lensing-fields/

[3] Information and animations to illustrate how gravity warps light: https://nasa.tumblr.com/post/187009797389/how-gravity-warps-light

[4] Ford F, Stang J, Anderson C (2015) Simulating gravity: dark matter and gravitational lensing in the classroom. *The Physics Teacher* **53**:557. doi:10.1119/1.4935771

[5] A Wikipedia article introducing angular resolution: https://en.wikipedia.org/wiki/Angular_resolution

Resources

- The Lederman Science Center (LSC) houses many interactive exhibits and hands-on activities. While the center is currently closed to the public, Fermilab is excited to bring science to the public virtually. Find out more here.
- Fermilab activity sheets for all the activities in this article are provided as PDF attachments (see the Supporting Material).
- Read how X-ray free-electron lasers are used to investigate particles' structure: Wilson R (2021) Plant solar power: unlocking the secrets of photosynthesis with X-ray free-electron lasers. *Science in School* **54**.
- Investigate light spectra using a home-made spectrometer: Ribeiro CI, Ahlgren O (2016) What are stars made of? *Science in School* **37**:34–39.
- Read an introduction on the electromagnetic spectrum: Mignone C, Barnes R (2011) More than meets the eye: the

electromagnetic spectrum. *Science in School* **20**:51–59.

- Build a black-hole model in your class: Turner M (2013) Peering into the darkness: modelling black holes in primary school. *Science in School* **27**:32–37.
- This pair of videos explains how X-rays can be used to solve molecular structures. The first illustrates (literally) how X-ray diffraction works and the second provides more technical insight into how this technique can be used to solve protein structures.
- Download this useful ESA infographic of the electromagnetic (EM) spectrum.
- Read a short introduction to the EM spectrum by the ESA.
- Watch a video on the EM spectrum and the relationship between wavelength and frequency.
- Watch a video on electron microscopy to find out why smaller wavelengths give better resolution.

AUTHOR BIOGRAPHY

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