Squishy Science Sunday

APS

Activities Cookbook

Thank you to the APS Division of Soft Matter (DSOFT) Student Affairs Committee, Jack-William Barotta, Rae Robertson-Anderson, Shubha Tewari, and the 2026 Squishy Science Sunday planning committee for compiling this resource.

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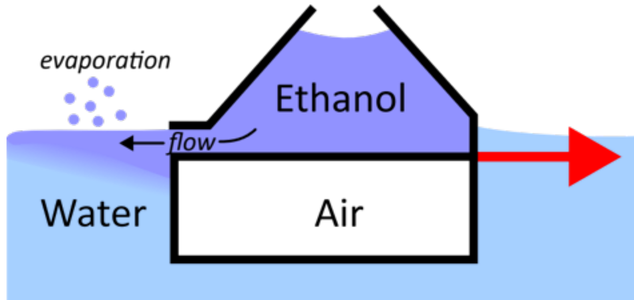
1: Marangoni Boats and Active Cheerios

Gaëlle Audéoud and Jared Popowski



Objective: To learn about Marangoni flows and the Cheerios effect through play with 3d-printed, alcohol-fueled boats.

Key Terms: Surface tension, Marangoni flow, Active particles, Collective motion, Cheerios effect

Materials:

- 3D-printed boats (several types exist: straight moving boats and spinning boats), designs available at https://github.com/FluidLab/Active_Cheerio_3Dprinting/tree/main
- A tank of water. This does not need to be very deep, but the wider it is, the more space the boats will have to travel.
- Alcohol or alcohol-based disinfectant (dilute in water if too thick), for boat fuel
- Pipettes

Estimated total time: 20-40 min

Targeted Age range: 6+ years old

Credit: https://www.fluidlab.nl/

Introduction

Play with self-propelled boats and see them interact with each other on the water surface! Their self-propulsion will teach you about the Marangoni effect, while their clear attraction to each other emerges from the Cheerios effect.

Protocol

1. Fill the tank with water.
2. Place a boat on the water surface.
3. Take some fuel (the alcohol-based disinfectant) into a pipette and carefully fill the boat's fuel reserve from the top with it. → The boat will immediately start moving!
4. If several boats are racing across the water at the same time, you will see them influence each other's trajectory!
5. (Optional): Have students try to design and race their own boats by cutting shapes out of a water-resistant paper (plastic coated), and dropping ethanol on the end of the boat!

Discussion

This entertaining experiment relies on two interesting physics effects. One of them explains how the boats move, the other how they interact with each other.

Principle behind the boat's self-propulsion: surface tension and the Marangoni effect

As represented in Figure 1, at the interface between a liquid and air, the liquid molecules have air molecules as neighbors. Fluid molecules don't really like interfaces, they would prefer to be around other fluid molecules of the same type (more concretely, it's an imbalance of the chemical bonds at the interface compared to in bulk, see red and blue arrows vs purple arrows in Figure 1). Therefore, the molecules at the interface tend to pull the other molecules around them to minimize the surface of liquid in contact with air. This force per unit length along an interface is called surface tension, and it's the reason that water forms spherical droplets in air - for a given volume, a sphere is the shape with the smallest surface area.

Different liquids have different surface tensions. For example, water "pulls" around 3.5 times harder than pure ethanol. Figure 2 shows a schematic of the inside of our Marangoni boats. The boat is designed such that when you fill it with ethanol, the output port on its side sits right at the water's surface, putting the two fluids in contact. This forms a fluid interface, just like in Figure 1. As we learned, fluids don't like interfaces, and pull on each other to minimize this interface. Water pulls harder than ethanol, so ethanol from the boat will be pulled outside of the output port, propelling the boat in the opposite direction by momentum conservation. This is similar to how a rocket shoots fuel down but flies up!

A fluid flow induced by a difference in surface tension is called a Marangoni flow, and is the principle behind how our boats move. The fact that our boats are self-propelling objects makes them active particles in the language of physicists: the boats are in the same category as groups of people, birds, or fish which consume fuel (such as food) to move, as opposed to passive systems like molecules of air or collections of beads.

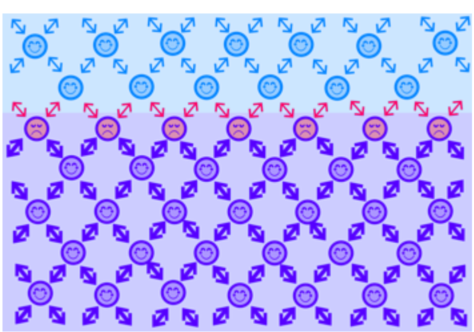


Figure 1: Surface tension. The thickness of the arrows indicate the strength of the chemical bonding : they are stronger between water molecules than between air molecules and air/water molecules.

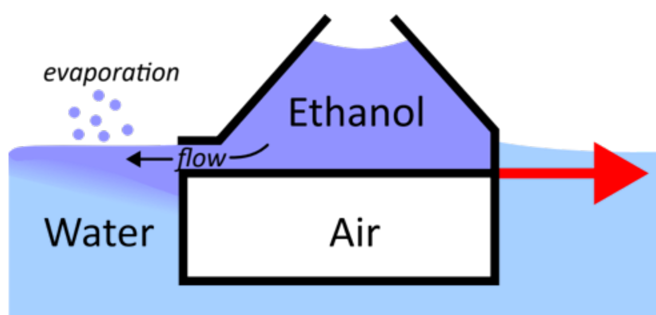


Figure 2: Marangoni boats operation.

Principle behind how they interact with each other: Collective motion

When an object floats on water, it slightly deforms the water interface. The way the interface deforms depends on the object's weight, how strongly the water holds itself together (cohesive forces), and the wetting properties of the object's surface (adhesive forces). There are two possibilities for the shape of an interface made by a single object: either a convex "U"-shaped interface or a concave "hill"-shaped interface, represented in Figure 3. If two objects are placed close enough, they can start feeling each other's deformed interfaces. Objects with the same interface shape will attract one another, while opposite shapes repel. This is called the Cheerios effect (inspired from the cereal of the same name, which you may have noticed always ends up clumping together in your bowl!).

The attractive behavior comes from the buoyancy of the objects. The interface between two objects with "U"-shaped interfaces is deeper than everywhere else around them, therefore to keep their center of mass at a constant distance from the water surface, they will "slide" into the "U" hole. In the same way, the interface between two objects with "hill"-shaped interfaces gets higher so they will "climb" it. When two objects with opposite-shaped interfaces meet, the interface between them flattens, and for the same buoyancy reason they will be repelled from each other.

In the case of the Marangoni boats, they all make "U"-shaped interfaces. Hence as they move close to each other, they attract and influence each other's trajectories. The same is true for the shape of fluid against the wall for most tanks that you will do the experiment in (unless they have a strong hydrophobic coating) - if you look closely, the interface is "U"-shaped on the wall. Hence, the boats without fuel are also gradually attracted to the wall itself.

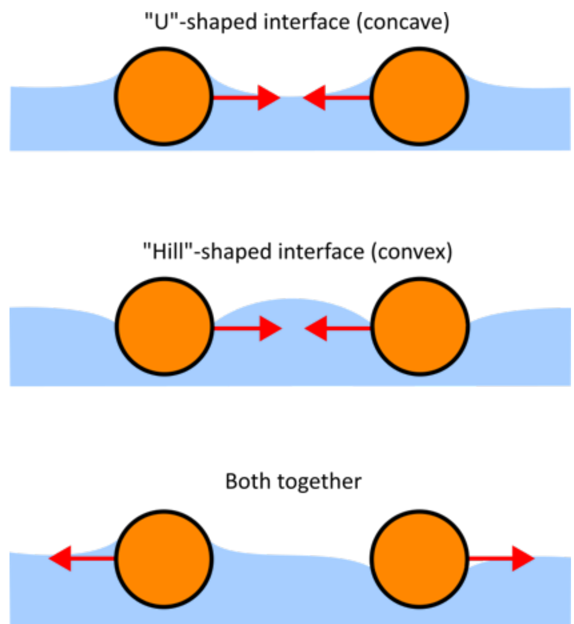
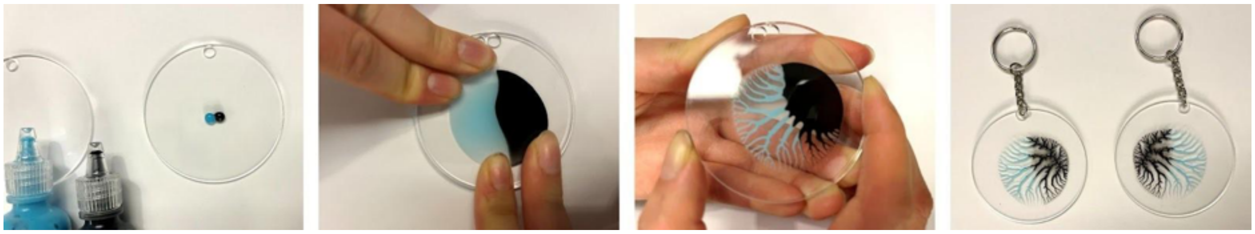


Figure 3: Cheerio effect

2: Make your own keychain with fluid instabilities!

Chloe Lindeman and Irmgard Bischofberger



Objective: We can learn a lot about fluids from how they flow. Often, slow-moving fluids have a steady, simple flow (think of oil spreading out in a pot). But when two or more different fluids are involved, the interface between them can form beautiful patterns due to an **instability**: the initial shape of that interface evolves, developing complex patterns. Using a few everyday items, we can watch these instabilities form and even put them to use making a colorful pattern for a keychain or desk trinket.

Key Terms: Viscosity, Surface tension, Interface, Fluid instability, Viscous fingering

Materials:

- One to three colors of paint (ideally bottles with thin nozzles). Fabric paint works very well
- Pairs of small (~1.5'' across) pieces of plastic, like flat acrylic blank keychains
- Optional: hair dryer or heat gun, to speed up paint drying

Estimated total time: 5-10 min

Targeted Age range: 3+ years old

Protocol

1. Put a very small amount of paint on one of the plastic pieces. The dot should be about two millimeters across; can be a single color or made of two or three
2. Sandwich the paint by pushing a second acrylic piece on top. The paint will spread out like a pancake; push until the paint has spread to a circle just smaller than the size of the plastic
3. Carefully pull the two acrylic pieces directly away from each other — avoid sliding them as this will smear the pattern. As you pull them apart, you should see the paint stick to both sides in an intricate network
4. Leave the pieces to dry fully or speed up the process with a hair dryer

Discussion

What just happened? There are two fluids involved here, air and paint. You have probably noticed that they behave very differently: air has little resistance to flow, while paint is thick and flows slowly. We call this resistance to flow “viscosity” and say that air has low viscosity while paint is more viscous. The experiment you just did shows two examples of how the interface between air and paint can behave.

In the first case, as you pushed the two plates together, the paint displaced the air around it in order to spread. As you might have noticed, this produced a nice circular outline — an example of a “stable” interface. In the second case, as you pulled the plates apart, air had to move back in to replace the paint being pulled outward. In other words, a low-viscosity fluid (air) was pushing into a high-viscosity fluid (paint) in the thin gap between the plates. This is a scenario that leads to an instability known as “Saffman-Taylor fingers.”

Although we used it here to create nice patterns, in industrial contexts like sugar refinement and oil extraction, these fingers cause problems because they make it harder to separate the two fluids involved. That’s one reason scientists have been studying these patterns, trying to understand what controls the features of the pattern (for example, the width of individual fingers and the rate at which the pattern grows) and find ways to stabilize the interface so that the two fluids remain nicely separated.

Want to try some additional experiments?

Play around with the amount of paint, how hard you squeeze the plates together, and how quickly you pull the plates apart.

How do these affect the pattern?

The width of the fingers is set by the ratio between the viscous forces and the surface tension forces, and by the amount of confinement. Mathematically, we can express the width w as

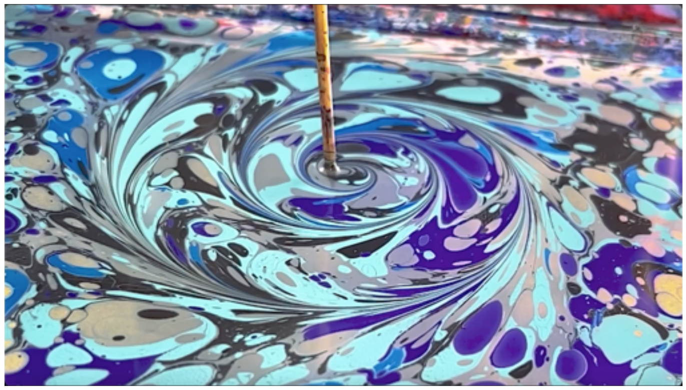
$$w = b\left(\frac{\sigma}{\Delta\eta * V}\right)^{1/2}$$

where b is the thickness of the paint layer set by the confinement between the two plates, σ is the surface tension of the paint, $\Delta\eta$ is the difference in the viscosity between the paint and air, and V is the velocity of the paint/air interface.

This equation provides several ways to tune the finger width: If students press down on the two plates more strongly, they can make the thickness of the paint layer smaller which leads to thinner and many more fingers. If they open the plates very slowly, they get thicker fingers than if they open the plates rapidly.

3: Paper marbling with acrylic paints

Yue Sun



Objective: Learn how to do paper marbling and investigate how interfacial tension keeps acrylic paint droplets afloat, how Marangoni stress and surface tension affect their spreading, and how viscosity helps create stable, delicate patterns on the bath.

Key Terms: Surface tension, interfacial tension, Marangoni stress, viscosity

Materials:

- Marbling bath: carrageenan powder (must be for marbling not food), distilled water, tray (baking tray/clear photo box/any box with at least 1.5 in depth)
- Marbling paints: heavy-body acrylic paints, distilled water, eyedroppers, cups, Photo-Flo
- Papers: alum, papers (recommend masa paper, wet-strength professional marbling paper for better outcome, but other papers should also work), newsprint paper for cleaning
- Tools: stylus (or stick/chopsticks), combs and rakes (you can make them with pins or nails)

(Note: You can NOT wash marbling tools with soap!!! Hot water is good.)

Estimated total time: Preparation time 12–24 hours, activity time 10 mins

Targeted Age range: 12–18

Credit: Activity by Yue Sun (University of Wisconsin–Madison). Adapted from: Yue Sun, John W. M. Bush, Saverio E. Spagnolie, and Chris H. Rycroft, "Hydrodynamics of marbling art", 10.1103/PhysRevFluids.9.110506 (2024). Multiple marblers also have online sources to show how to do acrylic marbling (examples, non-exhaustive): Chena River Marblers, The Soft Asylum, Clouds on Water. Yue Sun also keeps her marbling work on her website and Instagram account.

Introduction

In this activity, we explore how droplets of acrylic paint behave when placed on the surface of a viscous marbling bath. Because of the balance between interfacial tension and gravity, the droplets remain on the surface of the bath and spread rather than sink. Differences in surface tension between droplets, along with Marangoni stresses—introduced by adding surfactants or placing new droplets nearby—drive the evolution of the color patterns. The viscosity of the bath helps stabilize these flows so that fine, delicate patterns can be created. You will investigate how droplet size, the order in which colors are added, and the amount of surfactant influence the spreading dynamics and the resulting patterns. And have fun marbling!

Protocol

A. Preparation

1. *Bath:* Mix 3 tablespoons of carrageenan powder with 1 gallon of distilled water. Let it sit at room temperature for at least 12 hours, until the powder is fully dissolved. When prepared properly, the bath should still flow like water but feel slightly sticky and appear yellowish. Carrageenan is derived from seaweed and is safe to handle, but it should not be eaten. The bath can last for about 2 days before it begins to spoil. You may mix it with a blender (recommended) or whisk it by hand. Start with distilled water, and later test whether tap water also works.
2. *Pain*t: Mix 1 part heavy-body acrylic paint with 4 or 5 parts distilled water. Mix well until the consistency is similar to 2% milk. If the paint is too dense, add more distilled water. Always use distilled water for mixing paint, not tap water.
3. *Paper:* Dissolve 3 teaspoons of alum in 500 mL of warm water to make an alum solution. Spray the solution onto the paper and use a sponge to coat it evenly. Let the paper dry under a heavy weight.

B. Marbling

1. Clean the bath surface with newsprint paper.
2. Using a dropper, add one droplet of acrylic paint onto the bath surface at a time.
3. Continue adding droplets of acrylic paint with the dropper. Feel free to vary the location, arrangement, and colors.
4. Add one drop of Photo-Flo to the color you are working with and observe how the spreading changes. (You can also substitute Photo-Flo with diluted soap water.)
5. Once the droplets stop spreading, use tools (such as a stylus or combs) to create patterns.
6. When you are satisfied with the pattern, carefully lay the alum-coated paper onto the surface of the bath to transfer the design—this will be your marbled paper.
7. Rinse the paper gently with water (a sprayer works better), then hang it to dry. To flatten the paper, place the dried paper under a heavy weight.

Discussion

This experiment illustrates how surface tension and viscosity enable acrylic paint to float and spread on a marbling bath. Three interfaces are present: paint–air, paint–bath, and air–bath. Although the paint is slightly denser than the bath, interfacial tension prevents it from sinking. Instead, the paint spreads across the surface, and adding surfactant reduces its surface tension, increasing the spreading rate. The high viscosity of the bath makes inertia negligible. As a result, the motion of a stylus or comb produces controlled, detailed patterns in the paint layer rather than inducing turbulent mixing.

4: Magnetic Slime
Amy Graves

Objective: To investigate the ferromagnetism of iron oxide powder in a viscous slime.

Key Terms: Magnetism, Ferromagnetism, Viscoelasticity, Non-Newtonian fluids

Materials: Water, borax powder, school glue, iron oxide powder, strong magnet (i.e. neodymium), measuring cup, mixing bowl

Estimated total time: 20-30 min

Targeted Age range: 5-15 years

Credit: Activity by Amy Graves. Multiple versions of manuals for magnetic slime can be found online, including https://www.sciencebuddies.org/stem-activities/magnetic-slime-recipe .

Introduction

In this activity, we will make and explore some behaviors of magnetic slime.

Protocol

1. Dissolve ½ tbsp borax powder in ¼ cup water in a bowl. (Note: If safety of borax is a concern, contact lens solution containing boric acid may be used instead)
2. Mix ¼ cup school glue (white or clear) with ¼ cup water.
3. Add the borate solution sparingly, stirring, until the mixture becomes gooey. At this point it is just slime, specifically it is a non-Newtonian viscoelastic fluid.
4. Add iron oxide powder, enough so that the mixture becomes a uniform, dark grey. Stir and then knead with your hands. You now have magnetic slime!
5. Try balancing a small object (i.e. a penny) on it and observe how it stays on top without sinking through. If you replace the object with a small neodymium magnet, you can observe how the flowing slime slowly engulfs the magnet.
6. To manipulate the slime with a magnet (Recommendation: Use a long neodymium magnet or else place a small neodymium magnet at the end of a longer magnetized wand.) slowly bring the magnet near the slime - the slime will react quickly if you approach too fast. See how close you can get the magnet to the slime without the slime catching the magnet.

7. Try to deform the slime by moving the magnet around. If you place the slime on a thin surface such as a paper plate or shoebox top, you can move the magnet underneath to guide the slime without it getting covered with slime. You can try to move the slime along a track you draw, engulfing even non-magnetic objects such as an aluminum screw or plastic bead along the way.

Discussion

The mix of water, school glue, and borax powder creates a non-Newtonian, viscoelastic fluid. This means the slime displays both solid and liquid-like properties; like a solid, you can balance an object on it without it sinking through, and it can recover from small deformations. Like a liquid, it will flow over long time-scales.

When you add iron oxide powder to the slime, the slime becomes magnetic. The magnetism of the slime is different from the magnetism of the neodymium magnet, which is a permanent magnet. Both the magnetic slime and the neodymium magnet are examples of ferromagnets. Permanent magnets such as neodymium magnets are referred to as ‘hard’ ferromagnetic materials, while ‘soft’ ferromagnetic materials such as the slime tend not to stay magnetized. The tendency of a ferromagnet to remain permanently magnetized is typically measured by its coercivity.

The magnetic slime can be manipulated by magnetic fields like a soft robot, and can slither through complicated spaces and grip objects.

5: Squid divers

Haibei Zhang

Objective: This is a creative form of 'Cartesian divers" which is a small object that floats in water but sinks/"dives" when the pressure is applied to the bottle it's in. This experiment demonstrates the principle of buoyancy and the ideal gas law. Besides, the biology behind this demo is fascinating - glowing squids found in Hawaii have symbiotic partners (i.e., bacteria) to provide light for them.

Key Terms: Basic fluid dynamics, Archemede's principle of buoyancy, ideal gas law

Materials:

For the demo:

- Eyedropper (glass or plastic)
- Washer (for a plastic eyedropper)
- Squid fishing lure
- 2L plastic bottle
- Squid cardboard box (optional)
- Blacklight flashlight (optional).

For the take-home kits:

- Plastic bag
- Eyedropper
- Squid fishing lure
- Washer
- Small piece of paper with a QR code linked to this document.

Estimated total time: 20-30 min for set-up and the demo can go on for a whole day!

Targeted Age range: 5-12 (kindergarten and primary school)

Credit: Haibei Zhang, University of Chicago; "Make a Cartesian Diving Squid in a Bottle" by Danica https://www.instructables.com/make-a-cartesian-diving-squid-in-a-bottle/#ible-comments

Introduction

Hey, future scientists! *Want to check out our squid divers?* Squeeze the bottle and watch what happens! The squid is diving down when you squeeze the bottle, right? *But…Why?* Could you take a guess?

Here, when you squeeze the bottle, you apply the pressure to the water and it enters the squid because there is a tube inside to hold the water. And you can see the water level gets higher as you keep squeezing. This causes the density of the squid to increase and it sinks down to the bottom as it gets denser and denser! When you release the pressure, some water comes out of the squid and it floats back up again.

Protocol

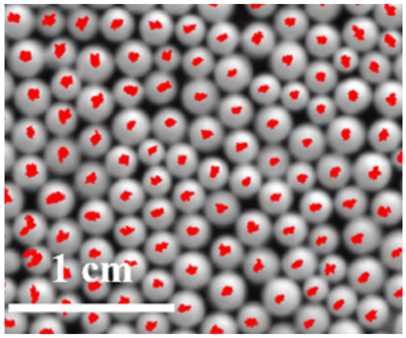
1. Gather the materials listed above
2. Fill the plastic bottle with water completely
3. Use the eyedropper to suck the water to approximately half
4. Pull the squid over the top of the eyedropper
5. Drop the squid eyedropper into the bottle and it should be neutrally buoyant
6. Tighten the lid. Prepare for awesome when you squeeze the bottle.
7. Optional: place the bottle in the cardboard box and turn on the blacklight flashlight inside the box. One can squeeze the bottle while watching the squid glow.

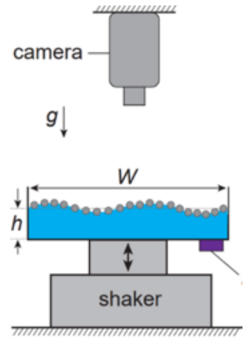
Discussion

This is an adapted version of a classic Cartesian diver. It is an ideal demo due to its easy setup. The timing depends on how familiar you are with the system. Filling the right amount of the water in the eyedropper can be a bit tricky but it takes no more than 30 minutes to set up everything. You also need to assemble the take-home kits ahead of time. Kids would love this demo so much – go squiddies!

6: Excited Raft of Particles

Hongyi Xiao, Tabitha Watson, and Wan-Jung Lin





Objective: To observe the various types of patterns and dynamics exhibited by a monolayer of floating particles on water. Understand the differences between solid-like and liquid-like behaviors via observing particle motion.

Key Terms: Pattern formation, Faraday waves, fluid dynamics, granular matter

Materials:

- Shaker (mechanical driver)
- Function generator
- Amplifier
- Shallow dish
- Styrofoam beads
- Camera
- Tweezers

Estimated total time: 20 min

Targeted Age range: 10-18

Credit: Activity by Hongyi Xiao, Tabitha Watson, and Wan-Jung Lin. Adapted from “Yan, Xiuhe, Tabitha C. Watson, and Hongyi Xiao. "Densely-packed particle raft at vertically vibrated air-water interface." arXiv preprint arXiv:2602.17539 (2026).”

Introduction

We vertically shake a dense layer of Styrofoam spheres at various frequencies and amplitudes.

At low frequencies and high amplitudes, we see the classical Faraday instabilities with standing waves decorated by particles.

At higher frequencies and lower amplitudes, we see that the particles collectively behave like atoms in either a liquid or a solid, depending on the packing fraction, i.e., number of particles in the dish.

Protocol

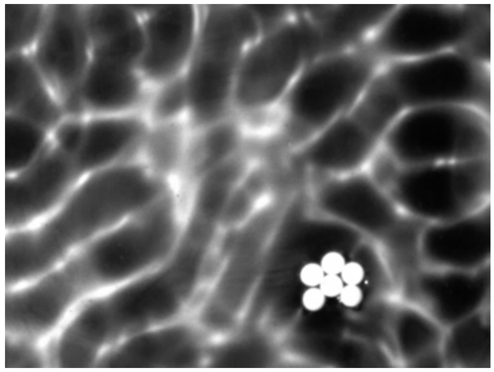
1. Connect the shaker to the function generator via an amplifier (optional). Add particles to the dish until they fully cover the water surface. The frequency range of interests is 20-100 Hz, adjust the amplitude to establish an effective range, in which we see interesting particle motion, yet no water sputters out of the dish.
2. Slowly adjust the frequency and amplitude to explore different regimes of patterns and particle dynamics.
3. Add a camera to provide a top-down view of the particle motion and compare that to videos of atomic systems and classical Brownian systems.

Discussion

Aside from classical Faraday-wave related topics, the discussion can be orientated on when a system of particles can be considered as a liquid, and when it can be considered a solid. The size dispersity of the particles can be controlled to show either crystalline solid-like behavior or an amorphous solid-like behavior.

7: Small Clusters in Faraday Waves

Jack-William Barotta and Caroline M. Barotta



Objective: To explore how multiple particles interact and self-organize on a vibrating fluid interface, and to relate these observations to concepts of energy, temperature, and particle binding in systems of sticky spheres.

Key Terms: Capillarity, Faraday Waves, Self-Assembly, Brownian Motion, Free Energy

Materials:

- Loudspeaker with petri dish glued onto it
- 3D-printed disks or small spheres that float
- Gloves
- Tweezers

Estimated total time: 40 minutes

Targeted Age range: 16-18

Credit: Activity by Jack-William Barotta and Caroline M. Barotta. Adapted from: Thomson, Stuart J., Jack-William Barotta, and Daniel M. Harris. "Non-equilibrium capillary self-assembly." arXiv:2309.01668 (2023). Github with a recent variation of this project (including build instructions): https://arxiv.org/abs/2512.15917

Introduction

In this activity, we explore the behavior of multiple small spheres or disks placed on a fluid interface being vibrated amidst Faraday waves on the interface. These waves generate random-like fluctuations that can mimic thermal motion (like Brownian motion). When multiple particles are placed on the surface, their capillary interactions and the motion of the surface can drive them to self-assemble into different shapes.

You'll investigate how the number of particles and the effective "temperature" (controlled by the vibration parameters) influence the types and stability of structures that form.

Protocol

1. Gently place a few spheres (2–6) on the vibrating water surface. Observe how they move and what shapes they form (e.g., lines, triangles, clusters). Repeat with different numbers of particles and record the types of arrangements you see. How does the geometry change as you add more particles?
2. *Varying Effective Temperature.* Keep the number of particles fixed. Increase the speaker volume to increase the "temperature" (i.e., agitation level). What happens to the stability of the structures? Now lower the volume and observe if the structures become more stable or rearrange.
3. Place 3, then 4, then 6 spheres on the surface and observe the patterns. Try to identify distinct stable configurations in each case. Record the shapes that emerge most often or seem the most stable. Consider which shapes might be lowest in energy or most entropically favored.

Discussion

This experiment offers a macroscopic analog of how microscopic particles interact through attractive forces. On the fluid interface, the spheres interact through capillary forces and the fluctuations in the surface act like thermal agitation. Different numbers of particles lead to different possible geometries.

When multiple configurations have similar energy, the deciding factor for which one is more commonly observed is free energy, which includes both energy and entropy. Structures that are slightly higher in energy but can form in many more ways (i.e., have higher entropy) may be more likely to appear in fluctuating systems.

8. Slimy Spaghetti and Meatballs

Konane Bay

Objective: Participants will learn about polymers and chemical bonding while creating a squishy and slimy version of spaghetti and meatballs.

Key Terms: Polymer, monomer, crosslinking, hydrophilic

Materials:

- 3 g Sodium Alginate*
- 10 g Calcium Lactate (Calcium Chloride can also be used but is very salty tasting)*
- Cups or containers
- Stirring utensils
- Pipettes or any kind of squeeze bottle
- Water
- Food coloring (optional)

**These chemicals can easily be purchased online, often as a kit. We don't recommend telling students to eat the products to limit the transfer of germs.*

Demonstration final product

Estimated Total Time: 5-10 mins

Targeted Age Range: Elementary (ages 5-10)

Credit: This demonstration was made in collaboration with the 2019 SOCK intern, Noura Ibrahim

Protocol:

1. Dissolve 3g of sodium alginate in 197g water to make a 1.5 % by weight solution. It is recommended to use warm water to speed the mixing process along. You will likely need to stir or shake the mixture; be patient as this may be take a while. Add food coloring if desired.
2. Dissolve 10g of calcium lactate in 190g water to make a 5% by weight solution. Add food coloring if desired.
3. Once both mixtures are properly dissolved, pour the calcium lactate solution in a bowl or a similar container.
4. Fill a few pipettes with some of the sodium alginate solution. For several students, multiple bowl setups can be helpful.

demonstration setup

Presenter Brief:

Be familiar with what a chemical bond is, specifically be comfortable explaining broadly what a polymer is and how they are formed through being cross-linked. Know how to explain chemical reactions, molecule chains, and how polymers build up. Understand the basic chemical properties of sodium alginate and why a sodium alginate solution takes on a gel form when combined with a calcium lactate solution.

Vocabulary:

- *Monomer*: a type of molecule that can be reacted with other identical molecules to form a polymer.
- *Polymer*: a large molecule consisting of many repeating chains of monomers.
- *Polymerization*: the process of turning monomers into polymers via a chemical reaction.
- *Cross-link*: a bond that links one polymer chain to another
- *Hydrophilic*: when the molecules of a substance are attracted to water molecules.
- *Sodium Alginate*: extracted from seaweed and used as a thickening and stabilizing agent for various foods (e.g. ice cream, yogurt, salad dressing).
- *Calcium Lactate*: commonly used with sodium alginate in the spherification process.
- *Spherification*: a culinary process of combining sodium alginate with calcium lactate to transform a liquid to a gel.

Physics & Explanation:

Elementary (ages 5-10):

Start by introducing both solutions and invite the students to touch the Sodium Alginate solution. Get them to acknowledge that the Sodium Alginate and the calcium lactate solutions are liquids. **Take a survey of what the students think will happen when the sodium alginate filled pipette is emptied in the calcium lactate filled bowl.** Pass a few pipettes to a few students. Instruct them to try creating a spaghetti strand by squeezing a constant stream of material. To create the meatballs, instruct students to squeeze a few small droplets of the solution into the bowl. Help students pick up their creations from inside the bowl and let them examine the gel.

Leave some spaghetti and meatballs in the calcium lactate solution to sit for a few minutes and compare them to the ones the students took out earlier. Ask the students to squeeze some of the meatballs and compare how soft they are as opposed to the ones that were left in the calcium lactate solution for a longer amount of time.

Popping Boba (image from Fanaledrinks.com)

Ask: What is the difference between the two?

Sodium alginate is a substance known as a polymer that is often extracted from seaweed. Polymers are long molecules that consist of chains of smaller molecules, often called monomers. These chains can chemically bond to each other in what is known as a cross-linked network to form a gel, as seen in figure 4.

This demonstration uses sodium alginate as the polymer. When it is added to the calcium lactate solution, the dissolved calcium ions cause the chains in the sodium alginate to cross link and form a soft and squishy gel. Alginate is specific type of polymer that likes water, so as it meets the calcium solution, the alginate can store a large amount of water inside the network. The longer the sodium alginate stays in the calcium lactate, the firmer the gel will become. One of the most common uses of this process can be found in popping boba as seen in figure 3. Juice mixed with sodium alginate is dropped in a solution containing chloride to make this delicious and fun treat.

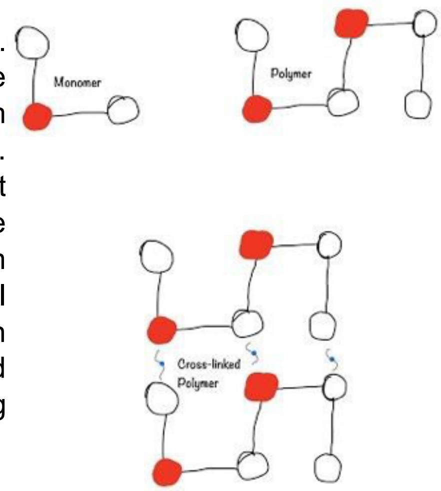


Diagram of Monomer, Polymer and Cross-linked Polymer Structures. From 'Risha's Science Notebook – 8th'

Alginate is a type of polymer that gels when it comes in contact with calcium ions by forming a cross-linked network.

Middle (ages 11-13) and general public:

Start by introducing both solutions and invite the students to touch the sodium alginate mix. **Take a survey of what the students think will happen when the sodium alginate filled pipette is emptied in the calcium lactate filled bowl.** Pass out a few pipettes to students and invite them to squeeze the material out inside the bowl. Instruct them to try creating a spaghetti strand by squeezing a constant stream of material. To createthe meatballs, instruct students to squeeze droplets of the solution into the bowl. Help students pick up their creations from inside the bowl and let them examine the gel. Leave some spaghetti and meatballs in the calcium lactate solution to sit for a few minutes and compare them to the ones the students took out earlier. Ask the students to squeeze some of the meatballs and compare how soft they are as opposed to the ones that were left in the calcium lactate solution for a longer time. **Ask: What is the difference between the two? How can a solid be formed from two liquids? Challenge students to answer why the material left in the water longer feels more solid?**

Sodium alginate is a polymer. A polymer is a substance made of long repeating chains of molecules called monomers can have thousands, or millions of carbon molecules connected. Polymers have different properties depending on the types of molecules being bonded and the types of bonds. For instance, some polymers such as rubber can bend and stretch while glass and epoxy are hard and tough. In the case of gels, the polymers are connected in a way that forms what is known as a cross-link network. Physical cross-links, as seen in figure 4, are formed by weak interactions that allow chains to bond and create bridges between them.

When sodium alginate is dissolved in water, the negatively charged parts of the alginate become able to associate with other ions. Sodium is a singly charged positive ion and can only bind to one negative charge on alginate at a time. However, calcium, another positive ion, associates with two negative charges on alginate at the same time. This causes cross-links to form, creating a gel. Cross-linked polymers can be compared to Velcro pieces. If you only have pieces from the smooth side, the pieces do not stick together. When you add in the hook side, though, they can catch onto multiple smooth pieces, creating a polymer.

Sodium alginate is hydrophilic, which means its molecules are attracted to water molecules. This property allows the polymer to effectively store water inside the network, so the resulting gel becomes soft and squishy. Sodium alginate is widely used in food for its great thickening, stabilizing, and gel forming properties. Examples include popping boba as seen in figure 3, ice cream, salad dressings, pudding and fruit-filled snacks. Other common food items have polymer gels that are not necessarily like sodium alginate. Egg whites for example are composed of mainly protein and water.

Protein is a natural polymer and it can be cross-linked when exposed to heat. When egg whites are cooked, the heat disturbs the bonds that hold the protein molecules, causing them to break certain bonds and cross-link with each other to form a firmer gel.

Alginate is a type of polymer that gels when it comes in contact with calcium ion by forming a cross-linked network. Sodium Alginate is commonly found in popular foods because of its gel forming properties. There are other types of natural polymer gels found in foods, like egg whites.

Additional Resources:

1. Slimy Spaghetti and meatballs, The Society of Rheology, http://www.ecs.umass.edu/mie/faculty/rothstein/Outreach/Demo3.pdf
2. More info on Polymers: https://www.livescience.com/60682-polymers.html
3. Polymerization Process: https://www.rsc.org/education/teachers/Resources/inspirational/resources/3.1.9.p df
4. Spherification example: https://www.youtube.com/watch?v=6kp6qhxchdg

References:

1. Slimy Spaghetti and meatballs, The Society of Rheology, http://www.ecs.umass.edu/mie/faculty/rothstein/Outreach/Demo3.pdf
2. How popping boba is made: https://fanaledrinks.com/blogs/blog/18322291-how-is-popping-boba-made
3. Physics of Fluids 31, 072102 (2019); https://doi.org/10.1063/1.5100243
4. Zumdahl, Steven S., and Donald J. DeCoste. Introductory Chemistry. Cengage Learning, 2019.

9: Marangoni Milk Stars

Justyn M. Friedler, Harrison W. Toll, Sarah Dané Taïwé, Jingyi Yuan, June Han, Caroline D. Tally, Charlotte G. Jones, Mariem Sayahi, Benjamin Tobin, Peter Fischer, Katharine E. Jensen

Objective: Explore and understand the Marangoni Effect, and visualize the presence of protein film on the surface of milk.

Key Terms: Marangoni Effect, surface tension, protein, thin film fracture

Materials:

- Milk
- Water
- Liquid soap
- Food coloring
- Wire or toothpick
- Small dish such as disposable bowl or petri dish

Estimated total time: 15 min

Targeted Age range: 5-18 years old

Credit: Justyn Friedler, Harrison Toll, Sarah Dané Taïwé, Jingyi Yuan, June Han, Caroline Tally, Charlotte Jones, Mariem Sayahi, Benjamin Tobin, Peter Fischer, Katharine E Jensen (PI).

Introduction

In this activity you will explore the effects of surface tension on thin protein films. Milk naturally forms a thin protein film adsorbed to its surface that can be fractured by the addition of soap to the interface. Because the soap has a lower surface tension than the milk, a spreading pressure is created that fractures the film into star-like patterns. This spreading phenomenon is known as the Marangoni Effect. You'll investigate how the presence of the protein film influences the patterns made by the Marangoni Effect.

Protocol

1. Make the soap solution by combining water, food dye, and soap in a proportion of roughly 69% - 30% - 1% by weight. (We have used water + water-based food coloring + Dawn dish soap, or water + gel-based food coloring + bubble bath soap. You can customize how colorful your stars will be by adding more or less food coloring or water.)

2. Pour water and milk into separate bowls and let the ripples settle. The milk needs to sit undisturbed for about 30 seconds for the proteins to rise to the surface and create a thin film.
3. Dip a thin wire or toothpick into the soap solution. You will see a drop of soap solution hanging on the tip of your poking apparatus. Dip this into the bowl of water and observe the soap spread in a circular shape.
4. Repeat the process for milk and observe the soap spread in a “star” shape. Sometimes the stars will look asymmetrical or jagged, which can be explained by minor disturbances to the protein film during its creation or various environmental factors that cannot be controlled.

Discussion

Ask students to observe the difference in the two liquids while keeping the soap solution and wire or toothpick the same. Ask questions such as:

Why does the soap spread out in both water and milk?

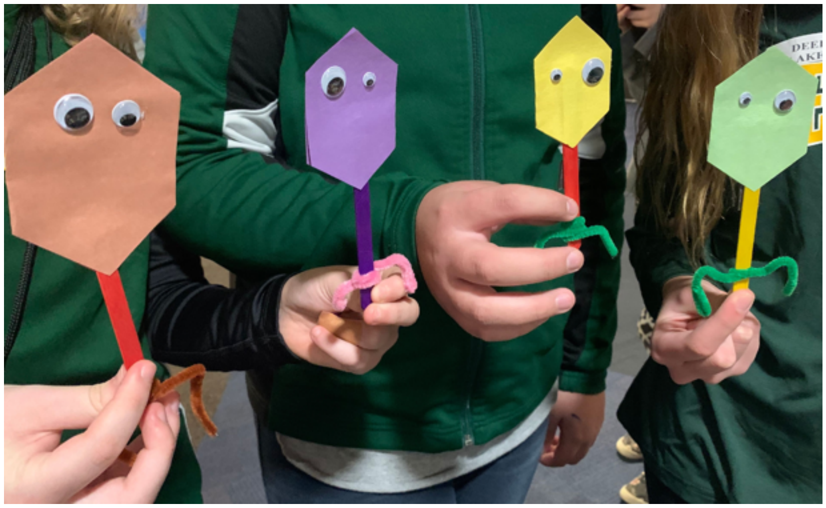
- *What is surface tension?* A: Affinity for liquid to “round” itself, which depends on the kind of liquid. You can imagine tension as what happens when you pull on a string. Liquid surfaces do this all the time naturally and thus wrap tightly around small drops of water or bubbles.
- *Why does a difference in surface tension create outward pressure?* A: Again using the string analogy, you can think of a surface tension difference as a “tug of war.” The region with higher surface tension pulls harder, leading to the outward expansion. From a more fundamental perspective, lower surface tension interfaces are energetically favorable, so the system rearranges and expands the area with lower surface tension to minimize its energy.
- *Why does the soap spread out in a circular shape in water?* A: The water has a uniform surface tension that is higher than that of the soap. Because this difference is uniform, the soap expands in a near-perfect circle. More precisely, the water is a homogeneous medium, so the Marangoni Effect has no preferred direction and the interface spreads evenly.

Why does the soap create a star / pointy shape in milk?

- *How does this show or suggest that there is a thin solid on the surface of the milk, as opposed to liquid?* A: Due to the “tugging” caused by surface tension, liquids will always round themselves, so you cannot create “pointy” pockets of liquid. Solids, on the other hand, can of course be sharp!
- *Why does the solid change the pattern?* A: The “tug of war” between the soap and water is now interrupted by the solid protein film. Instead of spreading evenly, the soap must now push against the solid film. When pushed hard enough, the film fractures, creating the sharp points and starbursts that appear. Physically, instead of minimizing just the interfacial energy, the system must now also minimize the energy contributed by the protein film. The film can either compress like a spring or fracture, and the competition between these two mechanisms gives rise to the star-like patterns. Whether the film “chooses” to compress or fracture is governed by the strength of the protein film and the magnitude of the Marangoni pressure.

10: Build your own bacteriophage

Krista G. Freeman



Objective: To learn what bacteriophages (viruses that infect bacteria) look like, how they are put together, and how their structure influences their function.

Key Terms: bacteriophage, virus, bacteria, structure

Materials:

- Construction paper (quartered and folded in half)
- Cardboard stencils of hexagons with different sizes and shapes
- Pencils
- Safety scissors
- Glue sticks
- Colorful popsicle sticks
- Pipe cleaners
- Markers
- Googly eyes
- Magnetic tape

Estimated total time: 5-15 minutes

Targeted Age range: 5-13

Introduction

Bacteriophages are viruses that infect bacteria. We can use bacteriophages to kill bacteria that make us sick! In this activity we will learn what bacteriophages look like, name their important parts (capsid, tail, tail fibers), and understand how those parts work together to let bacteriophage infect bacteria.

Protocol

1. Choose a piece of construction paper and a cardboard stencil.
2. Align the stencil against the folded edge of the paper and use a pencil to trace around the stencil everywhere except the edge along the fold.
3. Using scissors, carefully cut around the pencil lines – do not cut the folded edge! This is your paper bacteriophage capsid.
4. Unfold the paper so you have two identical halves connected at the fold. Spread glue all over the top surface of the paper.
5. Choose a popsicle stick and lay it the middle of the right half of the paper. You should have about 2 inches of the popsicle stick on the glue-covered paper, with the rest of the stick hanging off bottom of the paper.
6. Fold the paper back in half along the fold so you seal the popsicle stick inside between the two glued surfaces. This is the tail of your bacteriophage.
7. Wrap pipe cleaners around the bottom of the popsicle stick and bend them so they look like legs or lunar landing gear. These are the tail fibers of your bacteriophage.
8. Now give it some personality! Decorate your artistic phage with markers and give it some googly eyes if you like.
9. Finishing touch: stick a piece of magnetic tape on the back of your phage so you can display it on your refrigerator.

Discussion

The capsid of a bacteriophage is represented here by a hexagon shape cut from construction paper. In real life, it is a three-dimensional shape called an icosahedron. This shape is super strong, which is needed for the bacteriophage to hold its pressurized DNA (the genetic instruction manual for the bacteriophage) inside!

The tail of a bacteriophage is represented here by a popsicle stick. In real life, the tail is a hollow tube that helps DNA move from the capsid to the bacteria that the bacteriophage is trying to infect.

The tail fibers of a bacteriophage are represented here by pipe cleaners attached to the bottom of the tail. In real life, tail fibers do appear as "legs" at the bottom of the tail of a bacteriophage – these are important for a bacteriophage to find and attach itself to the bacteria it is trying to infect.

The googly eyes and other decorations are just for fun ☺

11: Bristolbot Bacteria: Modeling Run-and-Tumble Motion

Danielle Germann, Jay X. Tang

Objective: Participants will build small vibrating robots ("Bristle Bots") that mimic the run-and-tumble motion of swimming bacteria. Using pipe cleaners to represent bacterial flagella, students will explore how simple physical forces can produce complex biological motion. This activity introduces concepts from soft matter physics and microbiology, including active motion and random walks.

Key Terms: Bacteria, Flagella, Active Matter, Random Walk, Vibration Motor

Materials:

- Button cell batteries
- 3V mini vibration motors
- Disposable toothbrushes (hard bristle)
- Tape/glue dots
- Pipe cleaners
- Self-adhesive googly eyes

Estimated total time: 15-20 min

Targeted Age range: 6-14

Credit: Danielle Germann, Jay X. Tang, Brown University

Introduction

Bacteria are microscopic organisms that live almost everywhere on Earth. Many bacteria can move using long rotating tails called flagella. Rather than moving smoothly in one direction, many bacteria swim using a pattern called run-and-tumble motion**.**

During a run, the bacterium swims roughly straight. During a tumble**,** it quickly changes direction before starting another run. This process allows bacteria to explore their environment and find food.

In this activity, participants build a small vibrating robot called a "Bristle Bot" that behaves in a similar way. The vibration motor causes the toothbrush bristles to push against the surface, creating motion. Pipe cleaners act as model flagella**,** helping visualize bacterial swimming.

Although these robots are much larger than bacteria, they demonstrate how simple physical forces can produce complex motion, a key idea in physics and biology.

Protocol

1. Break/cut the toothbrush handle so that only the bristle head remains
2. Place the toothbrush flat on the table with the bristles downward
3. Place the vibration motor on top of the toothbrush head. Secure it using tape or glue dots if needed

4. Hold the battery against the motor terminals
5. When both terminals touch the battery, the motor will start vibrating
6. Secure the battery in place with tape if needed
7. Attached one or more pipe cleaners to the back or sides of the bot
8. Twist or curl the pipe cleaners to resemble flagella
9. Experiment with different numbers and shapes of flagella
10. Add googly eyes
11. Give your bacterium a name!
12. Place the bot on a flat surface and observe how it moves

Discussion

Real bacteria are powered by tiny molecular motors that rotate their flagella. When the flagella rotate in one direction, the bacterium moves forward in a run. When the rotation changes, the bacterium tumbles and reorients.

The Bristol Bots move differently from real bacteria, but the vibration causes irregular motion that resembles a random walk, similar to bacterial run-and-tumble motion.

Participants can explore questions such as:

- *Does adding more flagella change the motion?*
- *Does flagella length matter?*
- *Does the bot move in straight lines or random paths?*
- *Which design moves the fastest?*

This activity demonstrates how simple mechanical systems can model biological motion, connecting physics, engineering, and microbiology.

12: Auxetic metamaterials

Tyler Engstrom, Indigo Peppard, Ryan Otten-Reimer, Troy Singletary

Objective: To make a two-dimensional (2D) auxetic metamaterial and to demonstrate some of its remarkable properties

Key Terms:

- Poisson's ratio: roughly, the ratio of necking to stretching when a material is stretched
- Auxetic: having a negative Poisson's ratio
- Metamaterial: a material engineered to have exotic properties that don't usually occur in Nature

Materials:

- Glowforge Aura craft laser printer
- Glowforge craft laser filter
- Laptop
- Mobile hotspot or other means of a 2.4 GHz wi-fi connection
- Copy paper
- Clear plastic sleeves
- PDF file of auxetic pattern that can be obtained from tyler.engstrom@gmail.com upon request
- Beach ball
- Exercise band

Estimated total time: 5 min

Targeted Age range: 2-99

Credit: Tyler Engstrom, Indigo Peppard, Ryan Otten-Reimer, Troy Singletary (all from the University of Northern Colorado)

Introduction

This hands-on demonstration introduces the concept of a mechanical metamaterial. Participants will create their own metamaterial by laser cutting a specific pattern of slits into a piece of paper from a provided digital template. They will then experiment with the metamaterial and compare it to ordinary materials (uncut paper and an exercise band) to uncover some of its remarkable mechanical properties. One of these properties is called "auxetic" behavior, which means that when the metamaterial is stretched, it gets fatter instead of skinnier, unlike almost all naturally occurring materials.

Protocol

1. In the Glowforge web-based app, create a new design from file = auxetic_for_glowforge.pdf
2. Position paper and scale image so it cuts nearly all the way to the edges
3. Laser settings optimized for a single sheet of paper:
    a. Choose uncertified material and use thickness = 0.009 in
    b. Power = 10
    c. Speed = 150
    d. Print time is about 2 minutes

4. Remove paper and finish trimming with scissors or by tearing if it did not cut all the way to the edges of the sheet
5. Carefully insert the metamaterial into a clear plastic sleeve and watch what happens when you gently stretch it. It should get fatter instead of skinnier. Compare this to the behavior of the stretched exercise band.
6. Wrap the metamaterial around a ball and compare its behavior to a regular sheet of paper wrapped around a ball.

Discussion

Mechanical metamaterials such as this one are not only interesting from a fundamental physics perspective, they also have practical applications. For example, the wrapping ability of the auxetic design you made is put to use in certain clothing articles and shoe soles. And its ability to soak up stresses and deformations into the thin hinge structures makes it potentially useful as a sample support for cryogenic electron microscopy. Can you think of other applications? Can you come up with other slit patterns that might generate auxetic behavior?

For further reading on this topic, check out:

J. N. Grima and K. E. Evans, *Auxetic behavior from rotating squares*, Journal of Materials Science Letters 19, 1563-1565 (2000).

W. van Saarloos, V. Vitelli, & A. Zeravcic, *Soft Matter: Concepts, Phenomena, and Applications*, Princeton University Press (2024).

R. E. Thorne, T. A. Engstrom, & R. Jayne, *Sample supports for cryo-electron microscopy*, U.S. Patent Pending No. US20240242926A1 (2024).

13: Grains: Solid or Liquid?

Karen Daniels

Objective: In this activity we explore the conditions which cause sand to behave either like a solid or like a liquid.

Key Terms: Granular materials, States of matter, Sand

Materials for each group of 2-3 people

- 2 tall cups (like Red Solo cups)
- 1 paper towel tube
- 2/3 of a cupful of dry aquarium or sandbox sand (alternatives: sugar or rice)

Estimated total time: 5-20 minutes

Targeted Age range: 5 to 100

Credit: Karen Daniels, Department of Physics and Astronomy, North Carolina State University

Introduction

You may have noticed that sand can behave like a liquid (you can pour it out of a container, it takes the shape of the container) or like a solid (you can walk on it, and not fall in). This is true even though each *grain* of sand is itself a small solid. The behavior of a collection of grains is not the same as the behavior of a single grain. In this activity, we will explore how the way in which the sand is prepared controls which behavior is observed. Unlike water, we can change its behavior from liquid-like to solid-like without putting it into a freezer! Instead, the changes come from how the grains pack together, collectively.

Protocol

1. One person should hold a paper towel tube upright in the center of a cup, as if it were a giant straw to drink from.
2. The other person should slowly pour the sand into the cup (not into the paper towel tube itself) so that the material is reasonably well-distributed.
3. If you leave the cup where it is, and try to lift the paper towel tube, it will lift up in your hand and leave the sand behind in the cup. This means the sand is acting like a liquid: it flows into the gaps as the tube is pulled out.
4. Next, repeat steps 1 and 2.
5. This time, hold the outer part of the cup firmly, and give it a few strong taps on the table (not so hard that the sand leaps out!)
6. This time, if you try to lift the paper towel tube, the cup and sand will lift off the table alongside it. It may take a few tries to master the firmess of the Step 5 taps so that this step works well.
7. Other experiments to try: tapping more or less hard, using different grains, filling the inside of the tube as well.

Discussion

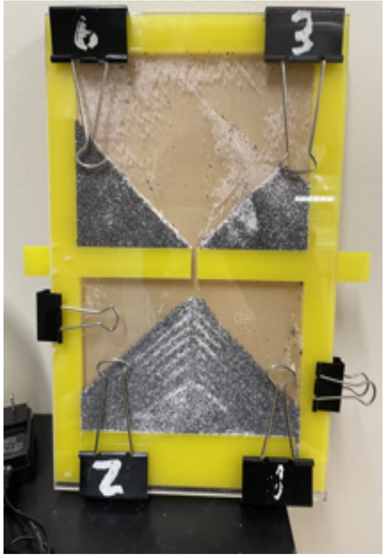
1. What do you observe about the level of sand when you do the Step 5 taps? What about when you tap harder or softer?
2. How does the experiment change (or not!) if you pick a different grain, like sugar or rice?
3. Compare and contrast: how is sand like or unlike ordinary liquids? Ordinary solids?
4. Why do you think long-jumpers and high-jumpers land in a sand pit at track and field competitions?
5. How do you think this matters for workers constructing the foundations of buildings? Have you ever seen equipment that acts like our Step 5 tapping?
6. How do you think this matters for engineering designing equipment to move drink mix or cereals through their factories?

Further Reading

Randall Munroe. “What Makes Sand Soft?” *The New York Times.* Nov. 9, 2020. https://www.nytimes.com/2020/11/09/science/what-makes-sand-soft.html

14: Grains: Self-Sorting

Carmen Lee and Karen Daniels



Objective: In this activity we explore how small particles (like sand or seeds) can self-sort themselves. Wouldn't it be nice if our socks knew how to do this when they came out of the laundry?

Key Terms: Granular materials, Sand, Sorting, Pattern formation

Materials:

- 1 cup each of common kitchen grains such popcorn, lentils, long or short grain rice, quinoa, mustard seeds, etc.
- Tape
- Cardstock
- Flow box built following these instructions: https://github.com/carmlingling/OutreachHopper. *If you can make one hopper for each type of grain, this is convenient (but not necessary).*
- Protractor (*optional, but useful if the students are studying angles*).
- Sheets of clear acrylic
- Laser cutter
- Acetone or acrylic cement (to bond the acrylic together). *Larger binder clips can replace the glue, but tend to fall off when participants are not gentle.*

Spacers between the flat sheets will need to be thick enough (or make them double-thickness) so that the grains don't get stuck between the plates. A gap of ~2-3 grain diameters is safest.

Estimated total time: 5 – 20 minutes

Targeted Age range: 5 – 100 (but middle school and higher will let you measure the angles)

Credit: Carmen Lee and Karen Daniels, Department of Physics and Astronomy, North Carolina State University

Introduction

Have you ever noticed a streambed or beach where the sand and pebbles seem to have sorted themselves into bands or piles which have different types of grains? The chances of this happening by accident are very small, but when *flow* is involved, the direction of the flow can bias which particles end up where. In this activity, we will watch this happen for poppy seeds (round, no pointy corners!) and sugar crystals (cube-like, with corners!).

Protocol

1. Make a flexible funnel using the cardstock and tape, so that the funnel fits into the fill-hole on the hopper.
2. With the central dividing wall closed, half-fill one side of the hopper cell with a mixture that is 50% poppy seeds and 50% sugar, and then seal the fill-hole with tape or a binder clip.
3. Slide the dividing wall to close the gap between the two sides of the hopper. Shake to mix the two types of particles somewhat evenly.
4. Stand the hopper upright so that grains could flow through the gap when you open it just a little. Keep opening until the grains just flow without clogging, but don't fall too fast. This step takes some practice, but you can do it over multiple times.
5. You should be able to get grains to flow into a stripe-like pattern as shown in the example at the top of this instruction sheet.
6. To restart the experiment, open the diving wall to move all the particles to one side, and then start again from Step 3.

Discussion

1. What do you see if you watch the surface of the bottom heap while the mixture is flowing onto it? Can you see that some particles roll more than others?
2. What happens to the pattern at the bottom if you let the grains flow faster or slower, by changing the size of the gap in the dividing wall?
3. What about this process do you think would be annoying for helpful in designing a factory for cake mix? What do you think the chocolate chips and flour would do as they moved through the factory?
4. Have you ever seen patterns like this out in nature, made from sand and pebbles?

15: Grains: Angle of Repose

Carmen Lee and Karen Daniels

Objective: We will use some common grains from our kitchens (rice, popcorn, lentils, etc.) to explore what sets the steepness of a pile of a grains (known as the angle of repose)

Key Terms: Granular materials, Grains, Angle of repose

Materials:

- 1 cup each of common kitchen grains such popcorn, lentils, long or short grain rice, quinoa, mustard seeds, etc.
- Tape
- Cardstock
- Flow box built following these instructions: https://github.com/carmlingling/OutreachHopper. *If you can make one hopper for each type of grain, this is convenient (but not necessary).*
- Protractor (*optional, but useful if the students are studying angles*).
- Sheets of clear acrylic
- Laser cutter
- Acetone or acrylic cement (to bond the acrylic together). *Larger binder clips can replace the glue, but tend to fall off when participants are not gentle.*

Spacers between the flat sheets will need to be thick enough (or make them double-thickness) so that the grains don't get stuck between the plates. A gap of ~2-3 grain diameters is safest.

Estimated total time: 5 – 20 minutes

Targeted Age range: 5 – 100 (but middle school and higher will let you measure the angles)

Credit: Carmen Lee and Karen Daniels, Department of Physics and Astronomy, North Carolina State University

Introduction

Sand dunes and piles of highway salt and embankments often have an interesting shape:

a straight slope that seems to have made itself. When landslides happen, it can be because a slope is too steep to hold itself in place. In this activity, we will predict which shapes of grains can make the steepest piles, and then test our predictions. Start by taking a look at the materials you have available, and put them in order from which one you will think will make the steepest pile, on down to the flattest. You can also think about why you put them in this order.

Protocol

1. Make a flexible funnel using the cardstock and tape, so that the funnel fits into the fill-hole on the hopper.
2. With the central dividing wall closed, half-fill one side of the hopper cell with a particular type of grain, and then seal the fill-hole with tape or a binder clip.
3. Slide the dividing wall to close the gap between the two sides of the hopper and set aside. Repeat Step 1-3 for each hopper you have, filling each one with a different type of grain.
4. Stand the hopper upright so that grains could flow through the gap when you open it just a little. Keep opening until the grains just flow without clogging, but don't fall too fast. This step takes some practice, but you can do it over multiple times.
5. The grains should form a nice triangle-shape heap at the bottom
6. If you want to measure the angle of your slope, do so now. This is called the *angle of repose.*
7. Try each type of grain, either by refilling one hopper each time (with a new type of grain) or by repeating the experiments with different filled hoppers.
8. To restart the experiment, open the diving wall to move all the particles to one side, and then start again from Step 4.

Discussion

1. What do you notice about how steep each triangular pile is, at the bottom of the box? Does the steepness depend on which particles you use? Which grains make the steepest pile? The flattest?
2. Does the steepness depend on how fast you let the grains flow (for instance,by changing the size of the gap in the dividing wall?
3. Have you ever seen embankments along the side of the road, where the soil was so steep that it was rolling down onto the road sometimes?
4. Have you ever see piles of sand or salt that road workers use during the winter, to let us drive safely in the snow? Are they also triangular when viewed from the side?

16: Grains: Clogging

Carmen Lee & Karen Daniels

Objective: Have you ever noticed that your cereal sometimes get stuck when you try to pour it out of the box? We will explore what happens when different shape grains try to flow through different size gaps.

Key Terms: granular materials, grains, clogging and flow

Materials:

- 1 cup each of common kitchen grains such popcorn, lentils, long or short grain rice, quinoa, mustard seeds, etc.
- Tape
- Cardstock
- Flow box built following these instructions: https://github.com/carmlingling/OutreachHopper. *If you can make one hopper for each type of grain, this is convenient (but not necessary).*
- Protractor (*optional, but useful if the students are studying angles*).
- Sheets of clear acrylic
- Laser cutter
- Acetone or acrylic cement (to bond the acrylic together). *Larger binder clips can replace the glue, but tend to fall off when participants are not gentle.*

Spacers between the flat sheets will need to be thick enough (or make them double-thickness) so that the grains don't get stuck between the plates. A gap of ~2-3 grain diameters is safest.

Estimated total time: 5 – 20 minutes

Targeted Age range: 5 – 100 (but middle school and higher will let you measure the angles)

Credit: Carmen Lee and Karen Daniels, Department of Physics and Astronomy, North Carolina State University

Introduction

Have you ever had the experience that people get stuck when they all try to exit through the same door? Or that your breakfast cereal gets stuck when you try to empty the box or use a cereal dispenser? In this activity, we will investigate what makes these traffic jams and clogs more or less likely. Start by taking a look at the materials you have available, and put them in order from which one you will think will be the easiest to hardest to clog a small opening. You can also think about why you put them in this order.

Protocol

1. Make a flexible funnel using the cardstock and tape, so that the funnel fits into the fill-hole on the hopper.
2. With the central dividing wall closed, half-fill one side of the hopper cell with a particular type of grain, and then seal the fill-hole with tape or a binder clip.
3. Slide the dividing wall to close the gap between the two sides of the hopper and set aside. Repeat Step 1-3 for each hopper you have, filling each one with a different type of grain.
4. Stand the hopper upright so that grains could flow through the gap when you open it just a little. If it clogs, you can give it a tap and see if it flows again, or you can open the gap a little wider.
5. Keep trying until you find the narrowest gap where the grains can flow without clogging. You can measure this gap size with a ruler if you're keeping track.
6. The grains should form a nice triangle-shape heap at the bottom.
7. Try each type of grain, either by refilling one hopper each time (with a new type of grain) or by repeating the experiments with different filled hoppers.
8. To restart the experiment, open the diving wall to move all the particles to one side, and then start again from Step 4.

Discussion

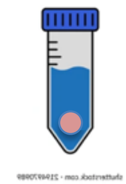
1. What do you notice about how likely the gap is to clog or not? Which grains are the easiest to clog? The hardest?
2. Does the likelihood of clogging depend on how fast you let the grains flow (for instance,by changing the size of the gap in the dividing wall?
3. Have you ever suffered a gumball clog when trying to get your gumballs from a gumball machine? What would you advise the designers of gumball machines they might do better?
4. Does this experiment give you any ideas about the design of doors where lots of people want to leave at once, like at schools and stadiums and concerts?

17. Grains: The Brazil Nut Effect

Shubha Tewari

Objective: In this activity, we investigate how a collection of grains respond to being shaken, and how grains of different sizes can be separated when shaken.

Key Terms: Segregation, Granular materials



Materials (for each setup):

- 1 Falcon tube or any narrow tube with a cap
- 2 transparent plastic cups (250 ml)
- 1 cup of sand or dry grains such as lentils, rice, glass beads, etc
- 1 marble
- marker pens

Estimated total time: 15 min

Credit: Shubha Tewari & Nalini Easwar, Department of Physics, University of Massachusetts, Amherst and Smith College

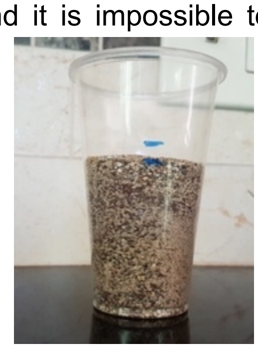
Introduction

Does a collection of grains of sand form a solid? You can walk on sand, even if you sink in a bit as you walk. But you can also pour sand into a container, as you might with water, and it takes the shape of the container. Is sand then a liquid? There are two ideas at play here. First, though each grain of sand is solid, a collection of grains does not display the properties of an ordinary solid or of an ordinary liquid. Second, the properties of the collection of grains are indifferent to the material properties of the individual grain, whether the grain is made of silicon dioxide (as sand or glass), or plastic, or organic matter.

Here we explore two activities that highlight the unusual properties of granular materials.

Activity A: Compaction

Pour sand into a container, and mark its volume, then tap the container and find the occupied volume decreases – sand is compressible. Try the same with water, and it is impossible to compress water into a smaller volume.



Protocol

1. Pour grains into a cup. Gently rotate the cup till the top is level.
2. Mark the level with a marker pen
3. Tap the base of the cup steadily and not too violently on the table. Then mark the level again. It should have decreased. See image on right.

Activity B: Brazil Nut effect

In this activity, you explore how vibrations can cause grains of different sizes to separate. You might imagine that shaking causes things to mix well. Counter-intuitively, it can promote the opposite effect. This is why you often find the largest nuts on top of a can of mixed nuts, or the largest clusters at the top of a box of cereal.

Protocol

1. Put marble into falcon tube.
2. Pour in smaller grains till tube is about two-thirds full.
3. Cap the tube.
4. The challenge is now to move the marble from the bottom of the column of grains to the top. (This should be presented as a challenge to those trying it out)
5. You can accomplish this by shaking the tube up and down vertically, and the marble will slowly make its way to the top of the column.

Discussion

1. *Is sand a solid or liquid?* Both solids and liquids usually have fixed volume, but sand appears not to – it can occupy smaller and smaller volumes.
2. Shaking a column of grains is like heating – it injects energy into the system, and grains move up the container and down the side walls in a fashion that resembles convection in a heated fluid. Everything moves up in a thick stream through the middle of the container, and a thin stream down the sides of the walls. Thus large grains move up with the small ones, but get marooned at the top.

References:

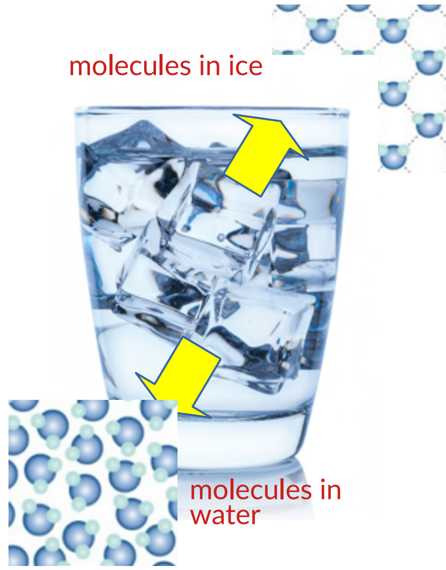
https://doi.org/10.1103/PhysRevLett.70.3728

https://doi.org/10.1103/PhysRevE.54.5726

Youtube video: https://youtu.be/ktA9CjbvDRo?si=05bvXAVmiQFGj7NI

18. Maxwell Counting and Rigidity

Jayson Paulose



Objective: To explore how the balance between degrees of freedom and constraints determines mechanical stability, and to show that simple counting provides physical principles underlying rigidity in structures ranging from crystals to bridges.

Key Terms: Rigidity, Degrees of Freedom, Constraints

Materials:

- ~15 LEGO Technic beams of various lengths
- ~6 axles with stops

Estimated total time: 10 min

Targeted Age range: 6-12

Credit: Activity by Jayson Paulose, developed with support from NSF CAREER award DMR-2145766

Introduction

In this activity, we explore the principle of Maxwell counting (named after JC Maxwell of electromagnetism fame) that explains how mechanical rigidity and stability arises from a balance between degrees of freedom and constraints. You are given some hinges (Technic axles) and beams and have to build structures that maintain their shape using as few beams as possible. You'll find that the number of beams needed to build a rigid structure grows in a systematic way. Variations of this simple count help us understand the mechanical stability of bridges, piles of sand, and blocks of ice!

Protocol

1. Start with two hinges. Your goal is to make a rigid structure (an assembly whose shape cannot be changed) incorporating both hinges, with the following **rules:**
   - Hinges can only go on the **ends** of beams
   - A hinge can be connected to any number of beams, but each beam can only connect two hinges (one on each end)
2. When you have made a rigid structure using as few beams as possible, add a hinge to the structure and add the smallest number of beams needed to rigidly connect the new hinge to the existing structure while following the rules. Record the number of beams you need for a rigid structure as you increase the number of hinges:

Two hinges : __________ beams

Three hinges : __________ beams

Four hinges : __________ beams

Five hinges : __________ beams

3. What pattern do you see in the beam count?
4. Whenever we add one more hinge, we must add ____________ more beams to build a rigid structure.
5. Does the size of the beams affect your answers?

Discussion

Each hinge adds two independent degrees of freedom (independent directions to move in) and each beam adds a constraint between the two hinges that it connects. For rigidity, degrees of freedom must balance constraints, leading to the pattern you observe. Similar counts are responsible for the rigidity of any structures made out of objects connected to other objects by beams or bonds. Engineers use the degree of freedom ↔ constraint balance to ensure that a building, bridge, or tower will be stable. Physicists use it to figure out when materials melt, or a pile of sand loses its rigidity and begins to flow.

For higher grades:

- Relate degrees of freedom and constraints to the mathematical problem of solving a system of equations in many variables
- Derive a mathematical formula connecting the number of beams to the number of hinges
- Ponder what might be different if your ‘hinges’ are atoms and ‘beams’ are bonds between them. Will the Maxwell count be the same? (You can build a similar activity using magnetic bar-steel ball construction kits such as Geomags for middle schoolers to explore this further.)

19: Good Vibrations: Rubber-band guitars

Lachlan H. W. Hamilton

Objective: To explore how the shape and size of an object affect the sounds it makes.

Key Terms: Vibration, Resonance, Frequency, Harmonics

Materials:

- Plastic container (takeaway tub or lunchbox)
- Rubber bands (different sizes and thickness)
- Phone/laptop with free spectrogram app (e.g. https://spectrogram.sciencemusic.org/)
- (optional) musical instruments, tuning fork

Estimated total time: 10 - 30 min

Targeted Age range: 5 – Adult

Credit: Lachlan H. W. Hamilton, 2026; QIMR Berghofer, Queensland, Australia

Introduction

All sounds come from vibrations. When something shakes back and forth, it moves the air, and we hear that movement as sound. The shape and size of an object change how it vibrates. That's why a tiny bell sounds different from a large drum. Today, we're going to build a simple instrument and *see* the vibrations using a sound visualiser.

Protocol

1. Turn on the spectrogram and allow microphone access.
2. Explore the sound made when hitting/tapping different objects in the room (desk, pencil, water bottle, wall). Watch the spectrogram. *What changes on the spectrogram when objects are hit? Can you find the lowest and highest frequency in the room?*

3. Hum a note and observe the spectrum.
   - *Can we hum at the same frequency as an object in the room?*
   - *Can you observe the different harmonics when humming (base frequency, and upper harmonics)?*
4. (Optional) Find a musical instrument, and explore how it affects the spectrogram. Play around with the instrument (place a hand to dampen different parts).
5. Stretch rubber band between fingers and pluck it, and observe the spectrogram.
6. Place a rubber band around the plastic container and pluck again (horizontal to avoid hitting the lid). *Does the container vibrate with the rubber band? This is resonance.*
7. Change the rubber band or add more rubber bands to the container.
   - *Thicker vs. thinner, longer vs. shorter stretch, and different angles.*
   - *Short and tight is a higher frequency.*
   - *Explore the note and harmonics.*
8. (Optional) Observe what happens if two rubber bands are placed to make a similar sound, and if one is strummed. (sympathetic resonance)
9. (Optional) Use a tuning fork. Excite the fork, then touch the base of the cylinder on the plastic container. Explore how the vibration transfers to objects that can resonate at the same frequency. *Do all objects vibrate with the fork?*

Discussion

This activity shows that:

- *All sound comes from vibration.*
- *Changing shape, size, or tightness changes vibration speed.*
- *When two objects share the same vibration speed, they can vibrate together (resonance).*
- *Most real objects produce more than one vibration pattern at once (harmonics).*

Musical instruments are designed to amplify useful resonances.

In buildings and bridges, engineers try to avoid dangerous resonances, because strong vibrations can cause damage (for example, the Tacoma Narrows Bridge collapse in 1940).

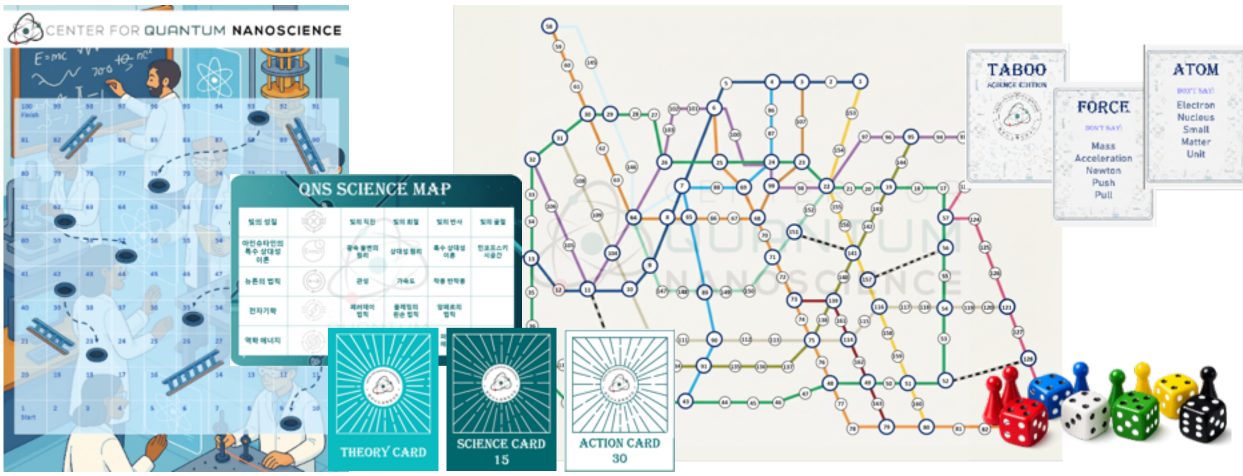
In the human brain, scientists measure electrical rhythms instead of sound. Different regions produce different patterns, and researchers study how these rhythms interact and respond to stimulation. Recent work has explored if stimulating the brain with magnets, electricity, or sound can change these rhythms.

2. Hold, bounce, and shake the intact soccer ball (Ball 1). *What is the ball made of so that we can kick and bounce it without it popping? What keeps the ball dry in the rain?*
3. Take a few minutes to touch and feel the air bladder (Ball 2) and the different layers of Ball 3. *How are the layers different? What do you think will happen when each layer is stretched or when they get wet?*
4. Gently stretch each layer from Ball 3. *What happens? How well do the materials return to their shapes?* This is called a tensile test. Pay attention to how the bladder behaves. *Why is this important for a soccer ball?*
5. Add 1-2 drops of water to the shiny exterior layer. *Does the water bead up or spread out?*
6. Add 1-2 drops of water to the other side of the exterior layer. *What differences do you notice?*
7. Answer the following questions based on your tests:
    - *What problems would happen if the whole ball was made of just the stretchy material?*
    - *What about if the whole ball was just from the shiny, stiff material?*
    - *Why are there so many layers in a soccer ball?*

Discussion

This activity demonstrates how materials scientists might test and evaluate different materials. It also shows the purpose of using different materials to make one object. The shiny exterior of the soccer ball is good for repelling water, as you saw with the wettability test. The soft foam cushions the ball when it hits the ground, and the tough fabric holds the exterior layer together. The entire exterior layer is not as stretchy as the bladder, as you saw from the tensile test. This helps with durability, and lets soccer players have better control and "feel" of the ball. The stretchable rubber bladder on the inside is the best material for retaining air tightly and bouncing back to its round shape when you kick it.

20: Quantum Arcade
Seokyong Choi



Objective: Through various game-based activities such as dice games and board games, students explore quantum computers, the lives of scientists, and scientific concepts in an engaging and enjoyable way.

Key Terms: Scientific concepts, Lives of Scientists, Quantum Computer, Superposition, Entanglement

Materials: In house developed games

- *Taboo game*: Scientific concepts
- *Element stepping game*: Periodic Table of Elements
- *Warm up games*: Superposition Bingo, Entangled Snakes and Ladders,
- *Board games*: The first Lab (Quantum Computer), Science map (Lives of scientists)

Estimated total time: 5 min each

Targeted Age range: 10-15

Credit: All games were developed by Seokyong Choi with the support of the IBS Center for Quantum Nanoscience.

Introduction

Taboo game: By explaining a target word without using taboo words, students can develop a deeper understanding of its concept.

Element stepping game: Students explore the various properties of atoms and identify their shared characteristics with other atoms.

Superposition Bingo: By applying the concept of superposition, the bingo game was upgraded into an advanced version. Through the game, students can intuitively understand the concept of superposition.

Entangled Snakes and Ladders: What happens if my game piece and my opponent's dice are entangled? Through this game, students can understand the concept of quantum entanglement.

The first Lab: Step into the role of a quantum scientist. Learn how qubits are developed and experience the challenges of building a real quantum computer.

Science map: Professors, PhD researchers, and students form a team and set off on an adventure to discover scientific laws. Using a map designed based on the Seoul subway system, they explore hidden scientific principles, experience the challenges scientists face, and build their own scientific laws through gameplay.

Protocol

Taboo game

1. Pick a card at random.
2. The player describes the target word without using the taboo words.
3. The team succeeds if they guess the word correctly.
4. Players who succeed in explained the word under the game rules can take the card home as a souvenir.

Element stepping game

1. Check the *Element Stepping Stones* card.
2. Read the atomic properties on the instruction card and color the atom that matches the description.
3. The player succeeds if the correct atom is colored.

Discussion

This game was created in collaboration with practicing scientists, making it more authentic and effective in conveying real scientific practices and quantum concepts. By presenting complex ideas through an engaging game format, it helps challenge students' prior misconceptions that science is difficult and boring.

The original was developed in Korea, an English version is available, and the rules have been simplified to ensure accessibility for both adults and students. As mentioned in the Introduction, each game is designed to help students naturally and engagingly experience quantum concepts and the lives of scientists. In addition, the games are structured so that participants can understand and develop interest in quantum science even without prior knowledge of classical physics.

21. Kitty Q Turns Quantum Physics into Child's Play

Nora Turner and Katja Lesser

Objectives: To spark enthusiasm for physics; to introduce school students to quantum physics and its origins; and to help them understand that scientific research leads to new technologies such as quantum computing. Using the interactive game Kitty Q, students explore the crazy quantum world in the company of Kitty Q, a cute, half-dead cat, and Anna, the great-granddaughter of Nobel laureate Erwin Schrödinger.

Key Terms: Mobile game; Schrödinger's cat; quantum physics; quantum technology; quantum computers; Einstein & Schrödinger; double-slit experiment; complex numbers; interference; temperature; magnetism; atomic models; topology; physics in everyday life; mathematics

Materials:

- Smartphone or tablet (iOS or Android)
- Mobile game *Kitty Q – A Quantum Adventure* (free in the App Store and Google Play)
- Printed cloze text or crossword puzzle

App Store:

https://kittyq.app/download/appstore

Cloze text:

https://school.kittyq.app/cloze-text

Google Play:

https://kittyq.app/download/googleplay

Crossword:

https://school.kittyq.app/crossword-puzzle

Estimated Total Time: Approximately 60 minutes of gameplay, including completion of the cloze text or crossword puzzle.

Targeted Age Range: Grades 7–8 and above

Credits: The game was developed by award-winning German app designer Philipp Stollenmayer in collaboration with the Cluster of Excellence ctd.qmat Complexity, Topology and Dynamics in Quantum Matter at Universities of Würzburg and Dresden, Germany. Cloze text is based on Matthias Melzer (workshoppen.de, 2022), and crossword puzzle is adapted from materials by Sandra Schneider and further developed by Carsten Albert, both from TUD Dresden University of Technology (2023).

Introduction

Kitty Q is an escape-style game for mobile devices centered on the story of Schrödinger's cat—the most famous thought experiment in quantum physics. In a series of more than 20 puzzles, children learn interactively about the strange nature of the quantum world. All the brain-teasers are grounded in established scientific concepts from quantum physics. Students who wish to explore the underlying ideas further can access user-friendly background information in Kittypedia. Each article becomes available once the corresponding puzzle has been solved.

Protocol

1. Students divide into small groups (preferably pairs). Each student receives a cloze text or crossword puzzle. Each group is handed a smartphone or tablet with the *Kitty Q* app installed.
2. The task is explained: Students play the game together and complete the cloze text or crossword puzzle as they progress.
3. Students tap through the opening dialogue and can already begin filling in the first blanks or solving the first clues.
4. Students continue playing and working on their cloze text or crossword puzzle. Once a puzzle has been solved, the corresponding Kittypedia article can be accessed. Completion of the written tasks may be assigned as homework at any point.
5. Students watch the video "#1 Schrödinger's Cat" from the YouTube playlist *QUANTube – Science Break.*
   - The video provides a clear explanation of the famous thought experiment.
   - The video series is connected to the mobile game *Kitty Q – a Quantum Adventure.*
6. Finally, students' understanding of these complex aspects of quantum physics is assessed. Students may ask questions, or the teacher may pose discussion questions to the class.

QUANTube#1: Schrödinger's Cat:
https://youtu.be/mbdKZWsonNA

QUANTube playlist
https://www.youtube.com/playlist?list=PL6tHzM5ttFrxydfPcYHf776tH8Sy125kC

Discussion

For many students, starting physics is challenging. Physics classes often begins with everyday phenomena that can be explained using physical principles, making the subject relatable and relevant. This approach works more easily in classical physics than in modern quantum physics.

Kitty Q helps bridge this gap. Through well-chosen examples, the game demonstrates how quantum physics works and why it matters in both everyday life and cutting-edge research. Its reference to quantum computers also opens the door to highly current topics that can connect, for example, to computer science classes.

The primary focus in class should be playing through the *Kitty Q* app. Alternatively, teachers may begin the game in class and assign the remaining sections as homework. The app is especially suitable for substitute lessons or project weeks, particularly for students who have only recently begun studying physics.

Because quantum physics is often not part of the physics curriculum at this level, the unit broadens students' horizons. The app connects naturally to physics topics such as temperature, magnetism, forces, atomic models, topology, and the work of Einstein and Schrödinger.

For students, the app fosters curiosity and interest in physics. This lesson unit is designed to guide students toward productive and independent learning.

22: Let's move an atom

Seokyong Choi and Jihee Min

Objective: Participants learn the principles of STM (Scanning Tunneling Microscope). They conduct hands-on experiments using an STM tip model to directly manipulate atoms on a clean surface. They also watch real scientific videos to see how researchers control atoms in practice and compare them with videos created by other students.

Key Terms: STM (Scanning Tunneling Microscope). Atom

Materials:

- STM Tip Model
- Movies: A boy and his atom, Nanokomik stop-motion videos

Estimated total time: 5-10 min

Targeted Age range: 10-18

Credit: This activity was planned by Seokyong Choi and Jihee Min from the IBS Center for Quantum Nanoscience. The tip model was created by artist Haeno Cho. The stop-motion video is part of the Nanokomik activities at the IBS Center for Quantum Nanoscience.

Introduction

STM is a cutting-edge technology widely used in modern quantum research that makes use of the quantum tunneling effect. It uses an atomically sharp tip to scan and manipulate individual atoms with extremely high precision. This technique allows scientists to observe and control matter at the atomic scale.

Using an STM Tip Model, students learn how the tip operates to move and observe single atoms. They can use the tip model to move colored balls representing atoms on small silver balls that simulate a clean metal surface. (In this STM Tip Model, magnetism is used instead of the actual tunneling effect.)

Protocol

1. Place two different atoms on a clean surface with an appropriate distance between them.
2. Use the STM Tip Model to carefully move one atom next to the other. *If the tip comes into contact with the atom during the process, the trial is unsuccessful.*
3. Students who successfully manipulate an atom will receive an “I Moved an Atom” badge as a prize.
4. Watch *A Boy and His Atom*, a movie created using real STM technology, and imagine how scientists made this movie.
5. Watch Nanokomik stop-motion movies made by other students using Aqua Beads and compare them with *A Boy and His Atom*.
6. Imagine what kind of movie you would create using atoms.

Discussion

Through this activity, students can experience and discuss cutting-edge technologies used by real quantum scientists.

In a real STM, the tip approaches the sample surface to within atomic-scale distances (about 1 nm). When a voltage is applied between the tip and the surface, a quantum tunneling current is generated. Because the tunneling current is exponentially sensitive to changes in distance, measuring it allows scientists to extract the height of individual atoms and this current can even be used to manipulate single atoms.

Quantum tunneling is a phenomenon in which particles can probabilistically pass through energy barriers that would be impossible to overcome in classical mechanics and this activity also provides an opportunity to expand students’ understanding of this tunneling effect used in real STM systems. (In this educational STM Tip Model, magnetism is used instead of actual tunneling.)

Nanokomik is a nanoscience education program for middle school students developed based on the comic series “Nano-fiction comic”, published by CIC nanoGUNE and Donostia International Physics Center (DIPC) in Spain.

The program includes various hands-on activities that can be applied in real classroom settings, and the stop-motion movie is one of the outcomes of these learning activities.

23: Materials Science of Soccer

Center for the Chemistry of Molecularly Optimized Networks (MONET)

Objective: Participants will investigate the materials science principles (how the properties of different materials determine their placement and function within the ball's layered structure) underlying soccer ball design by conducting hands-on tensile and wettability tests.

Key Terms: Surface tension, Wettability, Tensile test, Elasticity

Materials:

- Water
- Cups or beakers
- Pipettes
- Soccer balls and pumps
- Gloves
- Trays for water spills
- Paper towels
- Scissors (for facilitators)

Estimated total time: 40 min including prep

Targeted Age range: 9 - 12

Credit: Center for the Chemistry of Molecularly Optimized Networks (MONET)

Online instructions are here:
https://www.canva.com/design/DAG7x2SHqT4/ZsBF8Jz_KsMah-mCgCn1Ww/edit
You can request this kit (and others) from MONET here:
https://www.monetcci.org/bi-initiatives/outreach-kits

Introduction

What is inside a soccer ball? What is the purpose of each layer within a soccer ball and how do they work together to improve how it plays? In this activity, you will use two materials science techniques to see what each layer does best. In the tensile test, you will stretch the layers and see how well materials return to their original shapes to explore “elasticity”. In the wettability test, you will see how the layers interact with water.

Protocol

1. Prepare three soccer balls as follows. This can either be done in advance of the activity by facilitators, or by participants themselves (depending on age and context)
   - **Ball 1**: Fully intact and inflated
   - **Ball 2**: Carefully cut the seams around the hexagon that contains the pump opening to reveal the inflated interior bladder.
   - **Ball 3**: Fully deconstructed with separated layers and bladder cut into strips.

2. Hold, bounce, and shake the intact soccer ball (Ball 1). *What is the ball made of so that we can kick and bounce it without it popping? What keeps the ball dry in the rain?*
3. Take a few minutes to touch and feel the air bladder (Ball 2) and the different layers of Ball 3. *How are the layers different? What do you think will happen when each layer is stretched or when they get wet?*
4. Gently stretch each layer from Ball 3. *What happens? How well do the materials return to their shapes?* This is called a tensile test. Pay attention to how the bladder behaves. *Why is this important for a soccer ball?*
5. Add 1-2 drops of water to the shiny exterior layer. *Does the water bead up or spread out?*
6. Add 1-2 drops of water to the other side of the exterior layer. *What differences do you notice?*
7. Answer the following questions based on your tests:
    - *What problems would happen if the whole ball was made of just the stretchy material?*
    - *What about if the whole ball was just from the shiny, stiff material?*
    - *Why are there so many layers in a soccer ball?*

Discussion

This activity demonstrates how materials scientists might test and evaluate different materials. It also shows the purpose of using different materials to make one object. The shiny exterior of the soccer ball is good for repelling water, as you saw with the wettability test. The soft foam cushions the ball when it hits the ground, and the tough fabric holds the exterior layer together. The entire exterior layer is not as stretchy as the bladder, as you saw from the tensile test. This helps with durability, and lets soccer players have better control and “feel” of the ball. The stretchable rubber bladder on the inside is the best material for retaining air tightly and bouncing back to its round shape when you kick it.

Appendix 1: Particles on a Vibrating Liquid Interface

Harris Lab at Brown University (https://sites.brown.edu/harrislab/)

To help explore some of the Squishy Science Sunday Cookbook entries related to objects on a vibrating liquid interface, here are some instructables and Github pages that may be of interest for bringing these projects to life in the classroom.

Credit: Harris Lab at Brown University (https://sites.brown.edu/harrislab/)

Surferbot:

https://www.instructables.com/SurferBot/

Inspired by a survival mechanism initiated by the honeybee trapped on the surface of the water, the SurferBot is a small robot that self-propels on the fluid surface. This low-cost and easily assembled devices is created by combining a coin cell battery with a vibrating pager motor. The SurferBot is able to move thanks to forces arising from a wave-generated, unbalanced momentum flux.

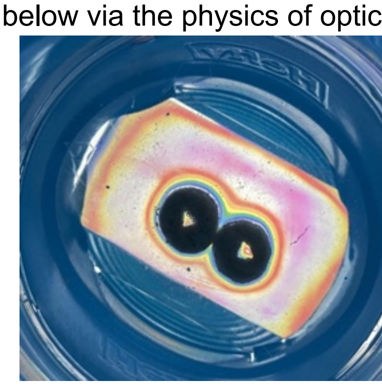
Meniscope: Fluid Interface Visualizer

https://www.instructables.com/Fluid-Interface-Visualizer/

The concept behind this demonstration device is based off of the idea presented in the article "Measuring the two-dimensional structure of a wavy water surface optically: A surface gradient detector" by Zhang and Cox, Experiments in Fluids, 1994.

A simple schematic of the working principle is provided above, adapted from the original publication. When the setup is viewed from directly above, the water slope is mapped to a particular color on the target pattern below via the physics of optical refraction.

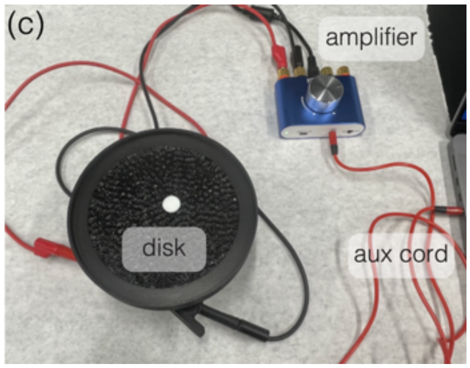
The goal here is to reproduce the striking qualitative effect with a low-cost setup, although the technique can be used for quantitative measurements of the shape of a fluid interface with a more refined experimental setup and post-processing software.



Github on making a shaker from a small speaker (3D-printer files included!)

https://arxiv.org/abs/2512.15917

We observe the trajectory of a millimetric disk driven by a field of chaotic Faraday waves excited by a shaker. The crossover from ballistic to diffusive motion occurs at time and length scales experimentally accessible through particle tracking of a video recorded with a standard phone camera. Along with representative data, we provide a complete assembly guide, and operating procedure for students so that the experiment can be readily applied in the classroom. The tabletop setup can also be adapted for other student projects and active research topics relating to particle motion on a vibrating fluid interface.



Appendix 2: Accessing DPOLY Instructional Resources

Thomas O'Connor and Kōnane Bay

Prof. Jon Rothstein has developed a comprehensive library of videos and documentation for a variety of Squishy Science demos that you can also check out!. These materials are specifically designed to make complex physical phenomena accessible and engaging for students and researchers alike. Prof. Jon Rothstein developed these materials through the Society of Rheology and the American Institute of Physics. Examples range from making Oobleck to capillary origami.

You can access the full suite of instructional guides and "video how-to" demonstrations at the following link:

https://people.umass.edu/jpr/links.htm