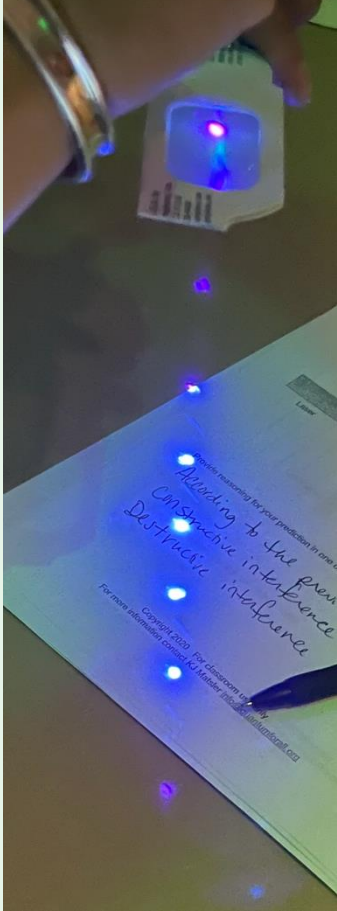
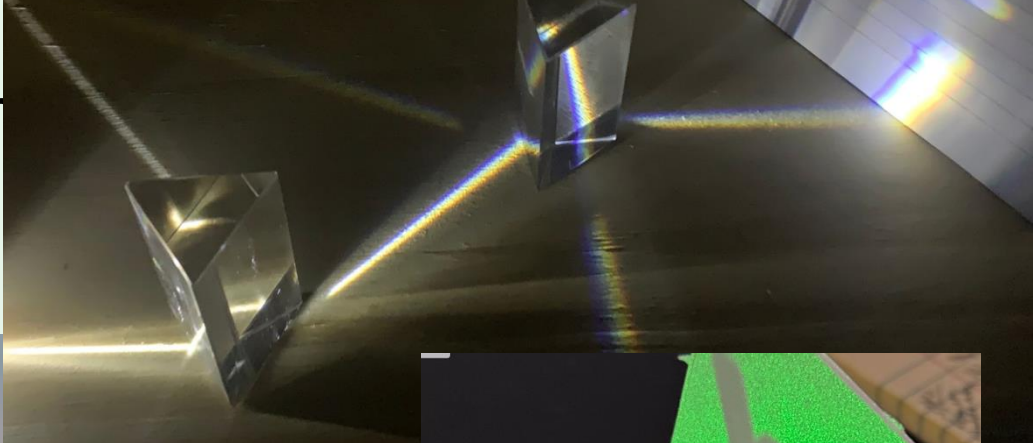


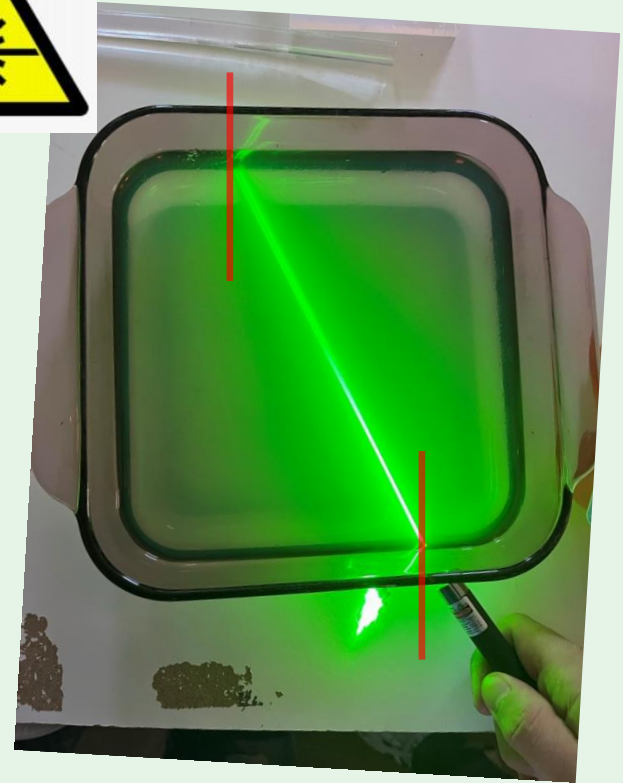
Refraction

Phenomen



EXPLORE: Refraction

- Use a clear glass block or gelatin as the medium to be explored.
- Lay the laser on the table and shine at an angle into the gelatin from the outside. Mark the point of entry into the gelatin. Align a ruler with the beam as it enters the gelatin and draw this as the incident ray.
- Observe how the beam bends (refracts) as it hits the barrier and again as it leaves the barrier (lens). Align the ruler with the exiting refracted ray (opposite side of the lens when the beam exits) and again draw.
- Remove the lens, mark the normal line at the point of incidence and then mark the “different” normal line at the point where the beam exits the lens. Note: A normal line is perpendicular to the barrier surface.
- Change the angle of incidence and notice how the angle of refraction changes.



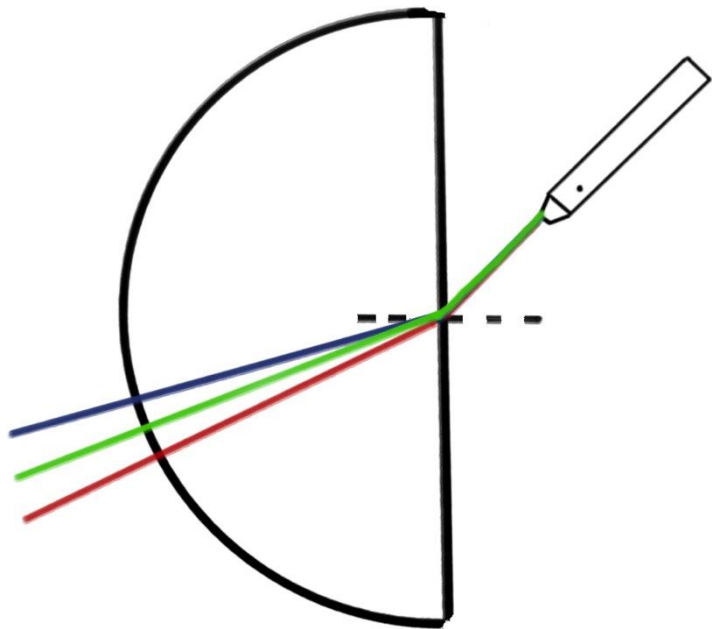
Red line = normal

EXPLORE

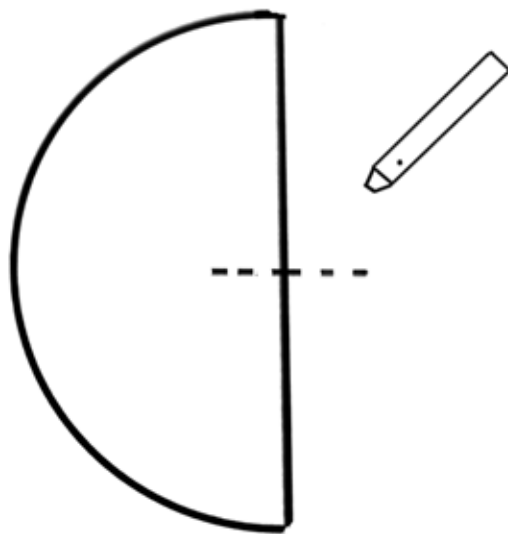
Repeat the activity with different colored lasers. Record observations and then compare to another group.

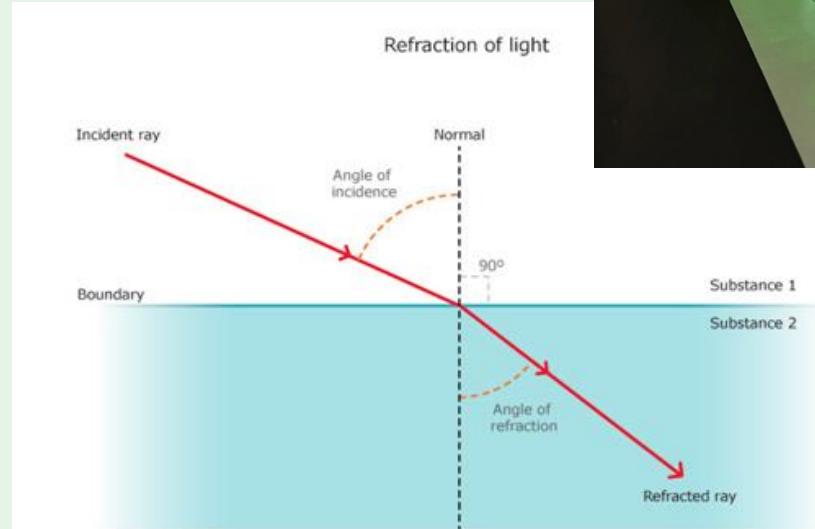
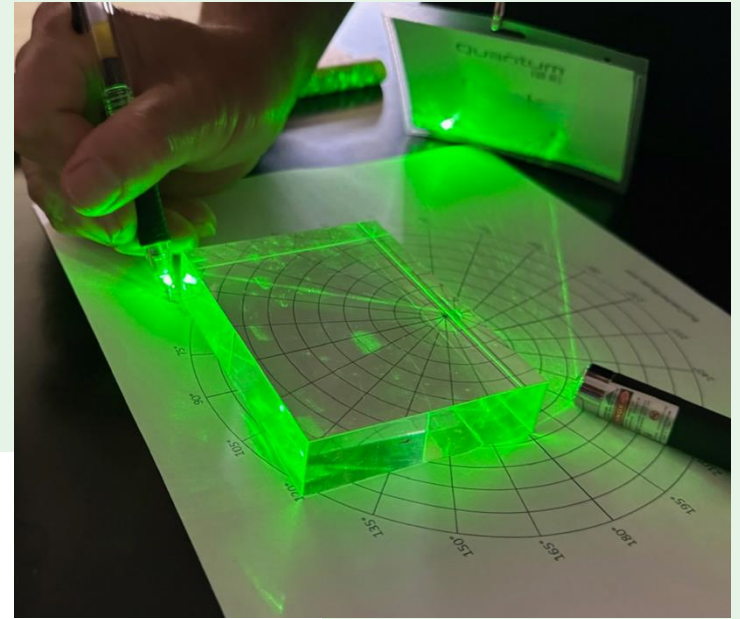
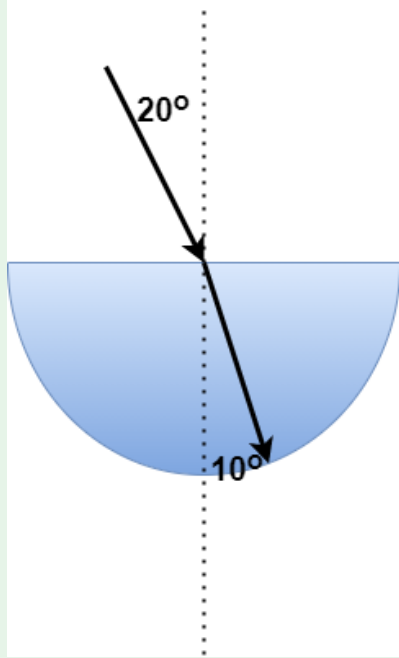
If materials are available, use refraction cups with different liquids and repeat. Identify materials that bent the light the most by comparing your results to classmates.





Credit: KJ Matsler





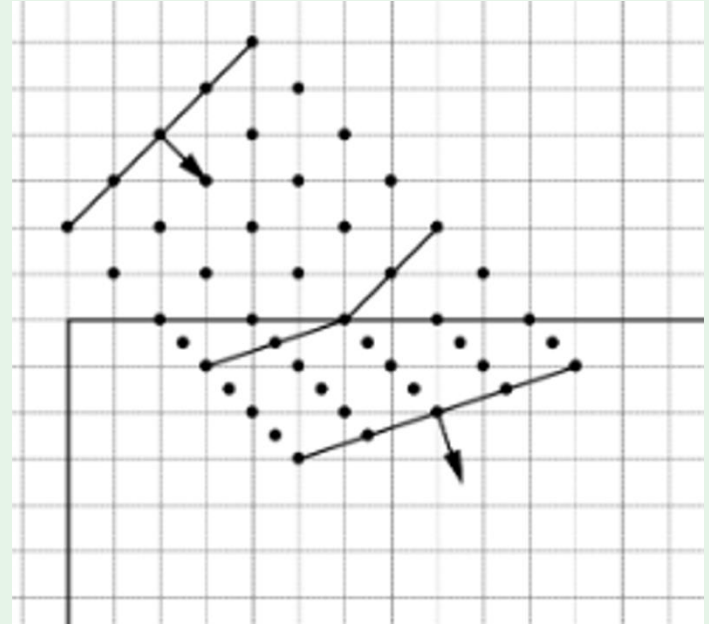
TN

It may help students understand conceptually what is happening by to use a graph to plot points similar to what is shown.

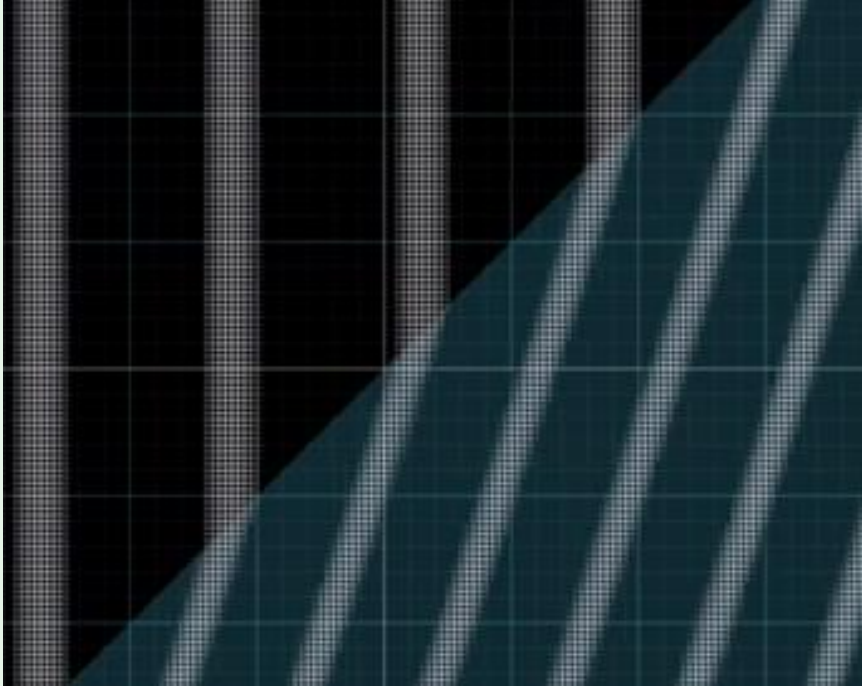
Start with a plane wave front and progress through time as it passes through a medium of greater density.

As the right side of the wave touches the boundary it will begin to interact with the particles in the medium and the result is a slowing down for the portion of the front that is now in the medium.

The wave front that is still in air (or outside the medium) will continue at the same speed until it hits the medium.



TN: Speed of Light



The speed of light is always constant in a vacuum.

However, in materials (acrylic, glass, gelatin) light appears to travel slower. This is NOT because photons slow down, but because of how they interact with the material as they pass through.

When light enters a material, it interacts with the electrons in the atoms. Photons travel between the atoms at the speed of light, (c), but as they hit atoms, they get absorbed and re-emitted, or they induce oscillations in the electrons which then radiate new waves. This repeated interaction causes a delay in the forward progress of the wave. Therefore, the overall effective speed of light through the medium is reduced. This is called the group velocity or phase velocity.

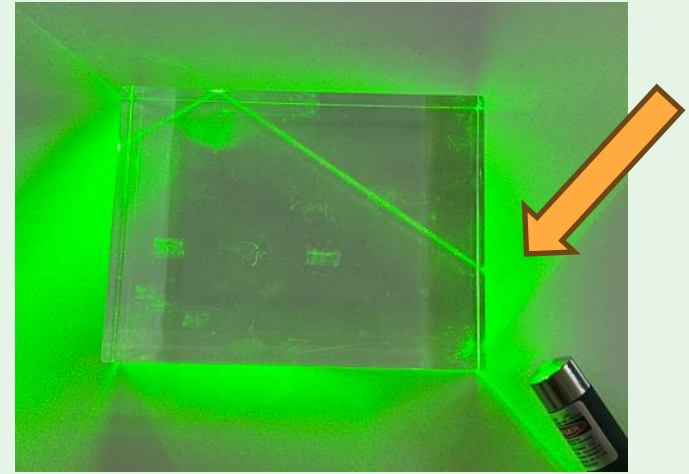
EXPLAIN: Refraction

- Veritasium
- Go to 6 min



Internal Reflection

- Shine the laser inside the medium, aiming toward the inner surface at a shallow (i.e. close to the medium) angle.
- Gradually increase the angle until you see the beam reflect completely inside the gelatin without escaping. This is total internal reflection.
- Observe that at some angles, very little light escapes. However, past a certain angle it reflects fully. Compare results of the different angles.

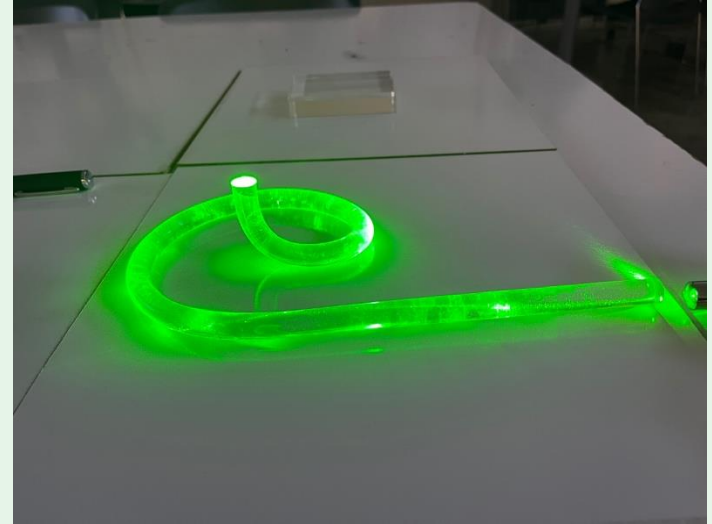


Fiber Optics

Shine a laser into the end of a fiber optic cable.

Adjust the angles of the laser and observe what happens in the medium.

Identify possible uses for this phenomena.



Quantum Connections

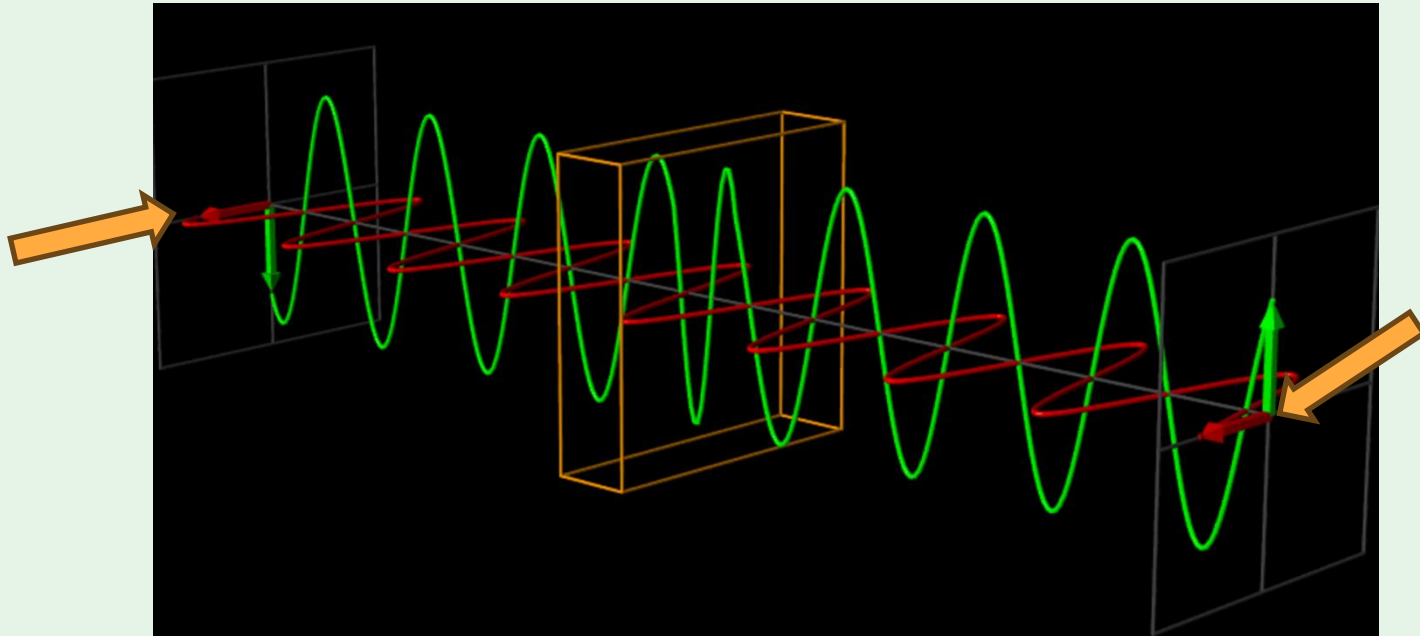
- Photons are information carriers and fiber optics allow photons to be transmitted without disturbing their quantum states.
- Entangled photon pairs can be created and sent through fiber optic cables for quantum networks.
- Biosensors, chemical sensors, and environmental detectors use optical fibers for transmission of information.
- Light refraction is explained at the quantum level by Quantum Electrodynamics (QED). Instead of light physically "slowing down", photons continuously interact with the electrons of the medium. This creates secondary waves that interfere with the original photon, generating a phase shift that appears as a bent trajectory and a reduced effective speed.

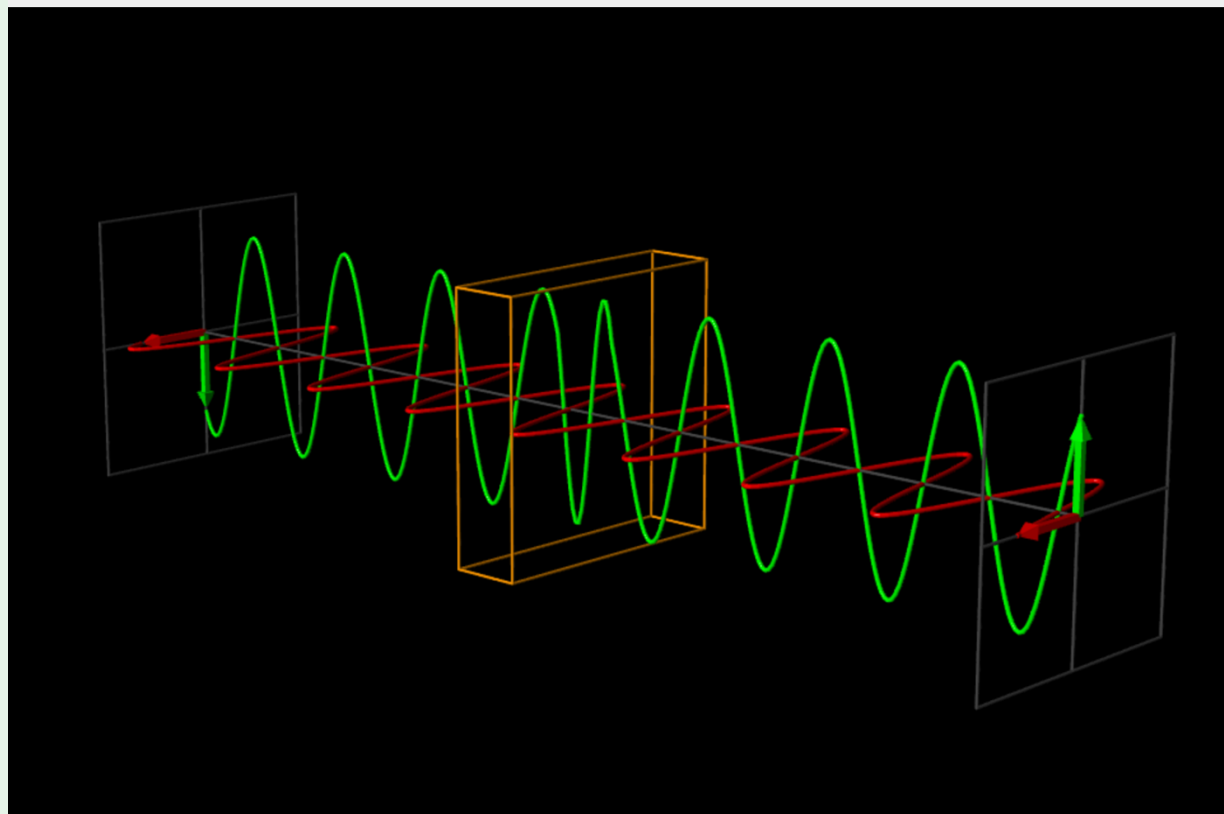
Oscillators (deeper look at refraction)

- On a microscopic scale, a refractive medium acts as an array of quantum oscillators. When the oscillating electric field of an incoming photon strikes the atoms, it displaces the electrons, forcing them to oscillate. These vibrating electrons emit their own secondary electromagnetic waves. The total optical wave propagating through the material is a superposition (interference) of the original photon wave and these secondary waves. This causes the resulting wavefront's phase to lag, forcing a directional change (Snell's Law) to maintain continuity at the boundary.
- Higher-frequency photons (like blue or violet) have greater energy and interact more strongly with the electrons. They experience a larger phase shift and greater bending, causing a higher index of refraction. Because the momentum of the photon changes inside the medium where $p=h/f$, (h is Planck's constant and λ is wavelength), the wavelength is compressed while the frequency remains constant.
- Modern quantum optics allows physicists to design artificial media where the rules of refraction are dynamically controlled through quantum coherence. In fact, physicists can make an opaque medium completely transparent within a narrow frequency which is where the refractive index changes dramatically. This manipulation allows researchers to slow, trap, or store light pulses in the medium using quantum coherence. <https://journals.aps.org/rmp/abstract/10.1103/RevModPhys.82.1041>

EMANIUM simulation

- Orange box = material
- Compare direction of red line at peak of green line





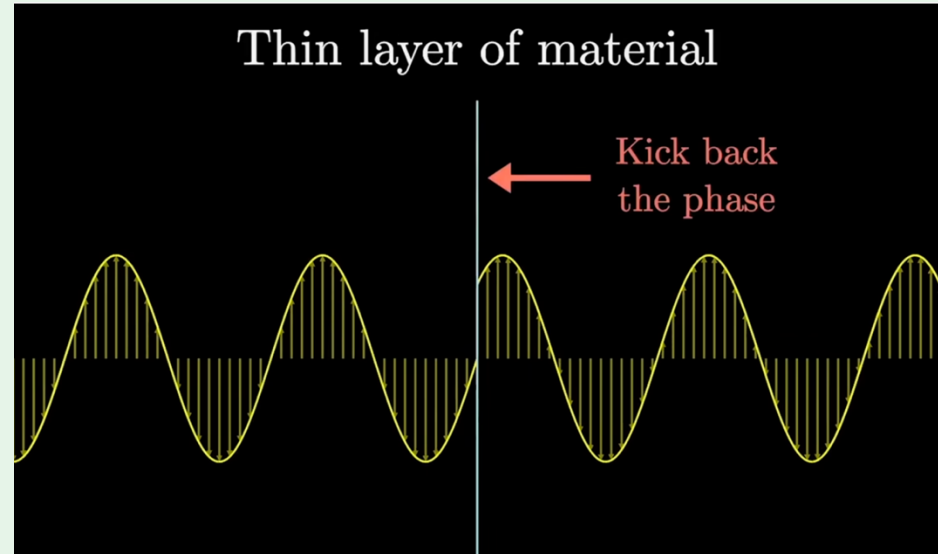
Welcome to EMANIM!

Wave 1	Wave 2
Polarization: Horizontal	Polarization: Vertical
Amplitude: 5	Amplitude: 5
Wavelength: 4	Wavelength: 4
☐ Reverse direction	Phase difference: 0
☐ Wave 1 + Wave 2	
Material	
Length: 2	
For Wave 1	For Wave 2
Extinction coefficient: 0.00	Extinction coefficient: 0.00
Refraction index: 1.00	Refraction index: 2.00
	☐ Same as Wave 1
Hide curves: ☐ Components ☐ Superposition	Animation rate: 6

EXPLAIN: Refraction

- v = speed of light in the medium
- f = frequency
- Wavelength within the medium is determined by the frequency and refractive index of the medium.
- Wavelength decreases (phase shift) in the medium and frequency stays the same so velocity is less.
- When light travels between different media, its speed and wavelength change, but its frequency remains constant.

$$v = \frac{c}{n}$$

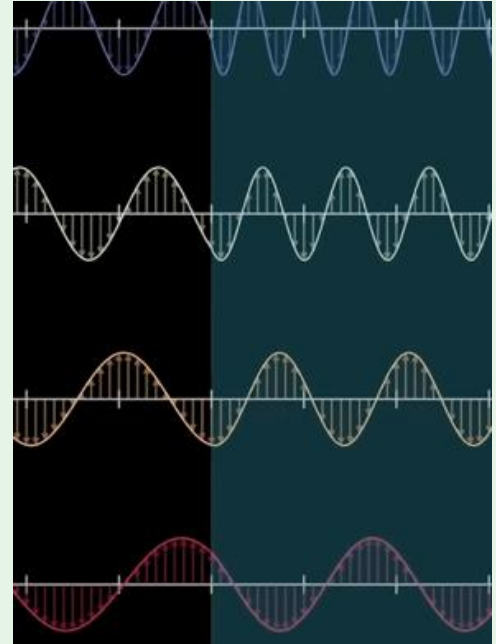


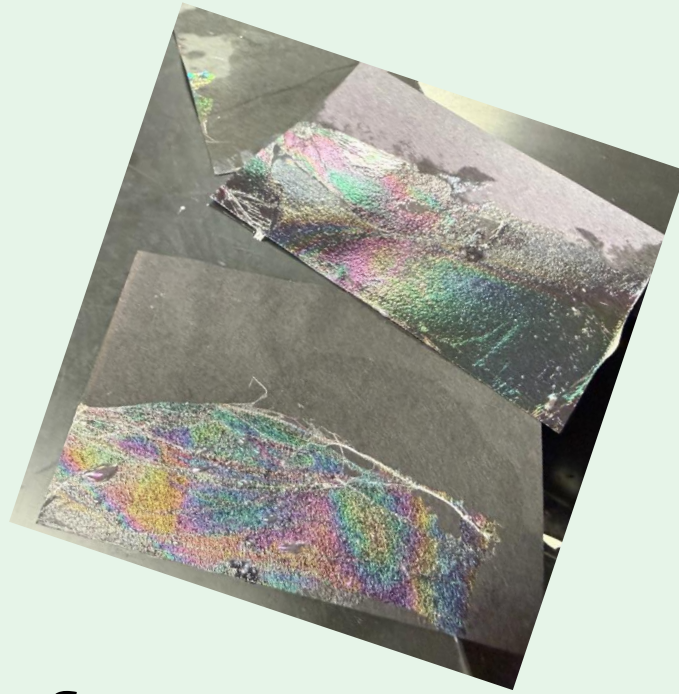
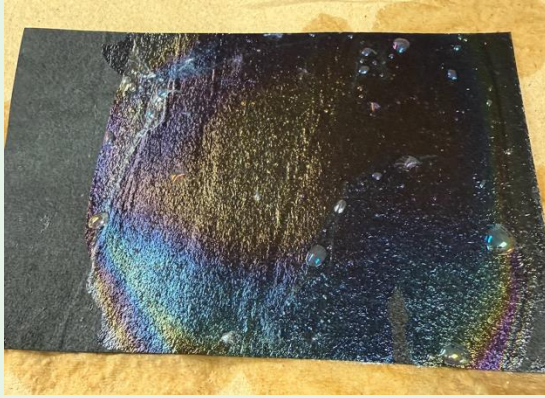
$$v = f\lambda$$

Summary

Light causes the charges to wiggle, so they create their own EM wave which gives the light a phase kick shortening its wavelength slowing it down. Refraction separates colors because different colors bend differently as they pass through materials.

This spreads the white light out into components, called the spectrum. These are the colors seen in a rainbow.





Thin Film Interference

Anodization

EXTEND: Thin Film Interference and Anodization

The colors seen from oil slicks on the road or water are a result of interference (i.e. thin film interference). This type of interference can be duplicated by placing a small drop of clear nail polish on water and then carefully sliding a piece of black construction paper underneath to remove it. This is sometimes called water marbling or making rainbow paper.

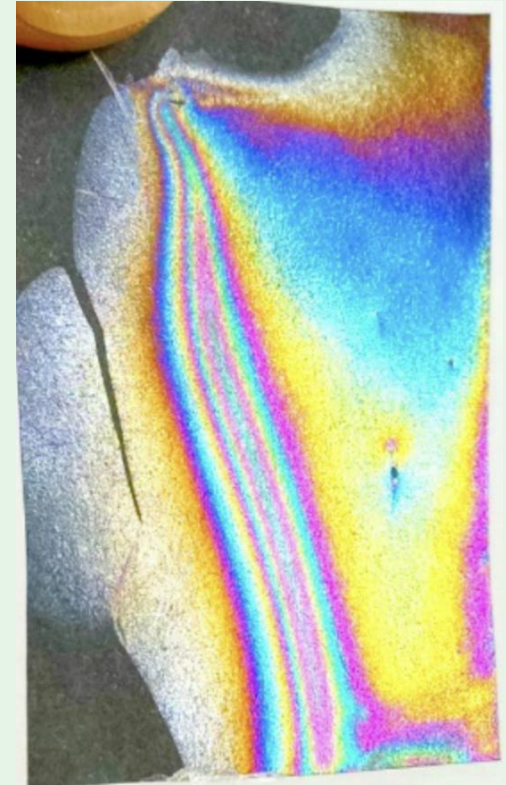
Since nail polish and water do not mix, the polish will spread into an ultra-thin layer on top of the water. The thin film is only a few hundred nanometers thick. When white light hits this layer, it reflects off both the top of the polish and the bottom of the polish. This is called thin-film interference.

As the paper is rotated, students will notice the colors change. This is due to the light hitting the paper at different angles as it moves and the colors of the rainbow vary with the thickness of the nail polish on the paper. Different thicknesses in the film emphasize different wavelengths of light, breaking them into brilliant, iridescent rainbow colors.

Having students do this after discussing light will allow for a discussion of thin film interference or other applications such as anodization and scanning electron microscopes. Some students may have used a similar process to create unique patterns on their fingernails.

Rainbow Paper

- Use a shallow bowl or container filled with about 1-2" of water. It is advisable to place the container on a towel or surface that will not be harmed when getting wet as there are usually extra drips of water as the card is removed.
- Place a single drop of clear nail polish (colored polish will produce more marbling, clear give the rainbow effect) carefully on the surface of the water. Do not use a gel polish. If students want to experiment with more colors the drops should be added quickly.
- Use a half sheet of construction paper (black usually works best but white can be used) and slide it into the water at an angle being sure to fully submerge under the film. Slowly lift the paper straight up through the film catching the film on the surface of the paper.
- Gently pat any excess water off the paper and lay flat on towel to dry.



EXPLAIN

Review of wave properties.

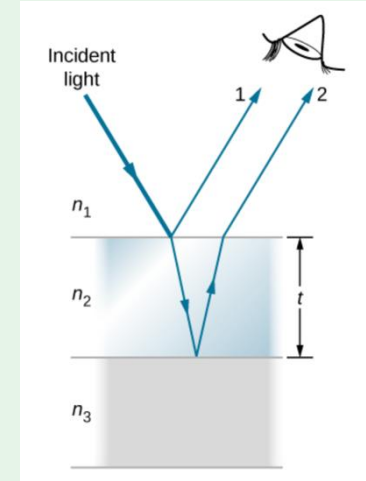
Thin film interference is around
4:30



https://www.youtube.com/watch?v=-ob7foUzXaY&list=PL8dPuuaLjXtN0ge7yDk_UA0ldZJdhwkoV&index=41

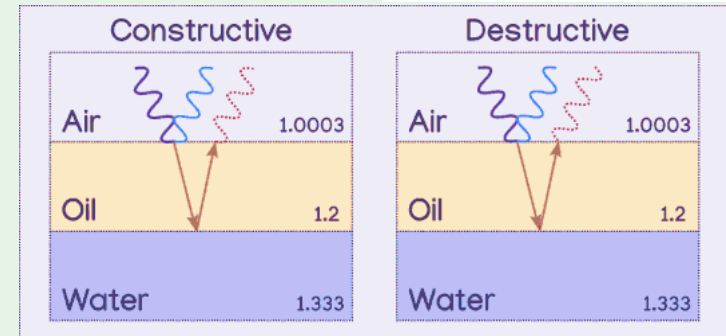
EXPLAIN

- When the paper is dipped into the water-nail polish solution, the paper is coated in a thin layer.
- As light hits the surface of the coating, some passes through and some reflects off the surface.
- The light that passes through refracts, then reflects off the paper.



As the waves interact, both constructive and destructive interference occurs.

- Low n to high n : 180° phase change (Destructive)
- High n to low n : no phase change (Constructive)



EXTEND: Anodization Applications

- Anodization is an electrochemical process used in many industrial applications to transform a metal's surface into a corrosion-resistant finish.
- The process thickens the naturally occurring oxide layer of a metal that results in a permanent structural alteration to the surface and can last over 50 years.
- Phone cases and laptop bodies (i.e. MacBooks) use anodized aluminum to give a sleek scratch-resistant finish.
- Many portable speakers and headphone components use anodized surfaces for vibrant, fade-resistant color.
- Window frames, storefronts, and roofing systems use anodized aluminum to protect against weather exposure.
- Bathroom accessories and mailboxes use the process to prevent rusting.
- Cookware uses anodization to give durable, non-stick pans that will not react with acidic foods.
- Pistons and hydraulic valves use a heavy-duty anodized coating to reduce friction and prevent wear.
- Aircraft wings use thin anodized layers to protect from extreme weather without heavy weight.
- Camping gear, bike frames, and car wheel rims use anodized finishes to resist rusting.
- Titanium surgical tools and medical implants are anodized to create an inert surface that the human body accepts.

Ryan Behurin

Connections to Research

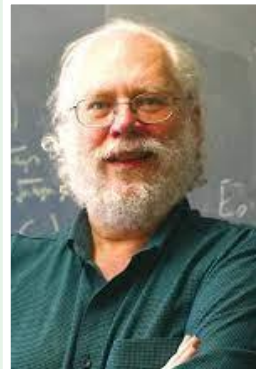
The potential of quantum physics

Potential of quantum science

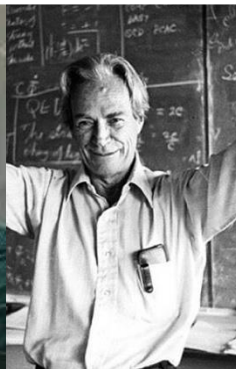
- Exponential speedup
- Simulations of complex quantum systems
- Superb sensors

Challenge “decoherence”

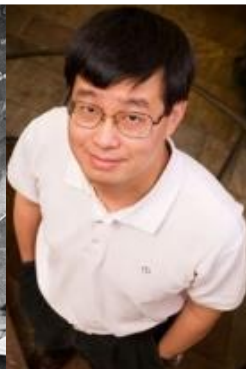
Shor



Feynman



Ye



P. W. Shor, *Proc. 35th Ann. Symp. on F. of Comp. Sci.* 124 (1994).

R. Feynman, *Int. Journal of Theoretical Physics* **21**, 467 (1982).

B. J. Bloom, *et al.* *Nature* **506**, 72 (2014).

H. Yu, *et al.*, *Nature* **583**, 43 (2020).

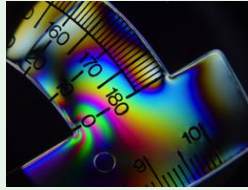
H. -D. Zeh, *Foundations of Physics* **1**, 69–76 (1970).

Phonons are a promising candidate to solve this problem

Elements of phonon-photon (Brillouin) interactions

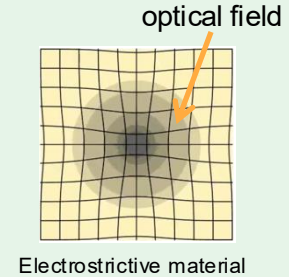
1. Photoelasticity

- Refractive index change under stress



2. Electrostriction

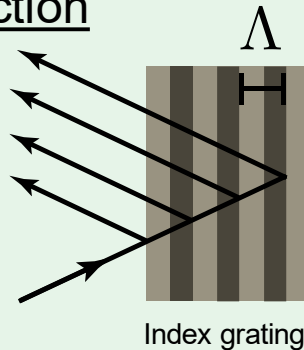
- mechanical stress induced by electric fields



3. Bragg Reflection

Index grating = narrow-band mirror

Reflected wavelength
 $\lambda_{\text{inc}} = 2n\Lambda$

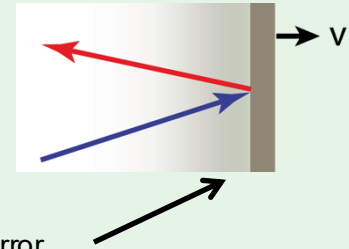


4. Doppler Shift

Reflected rays

Incident ray

Moving mirror



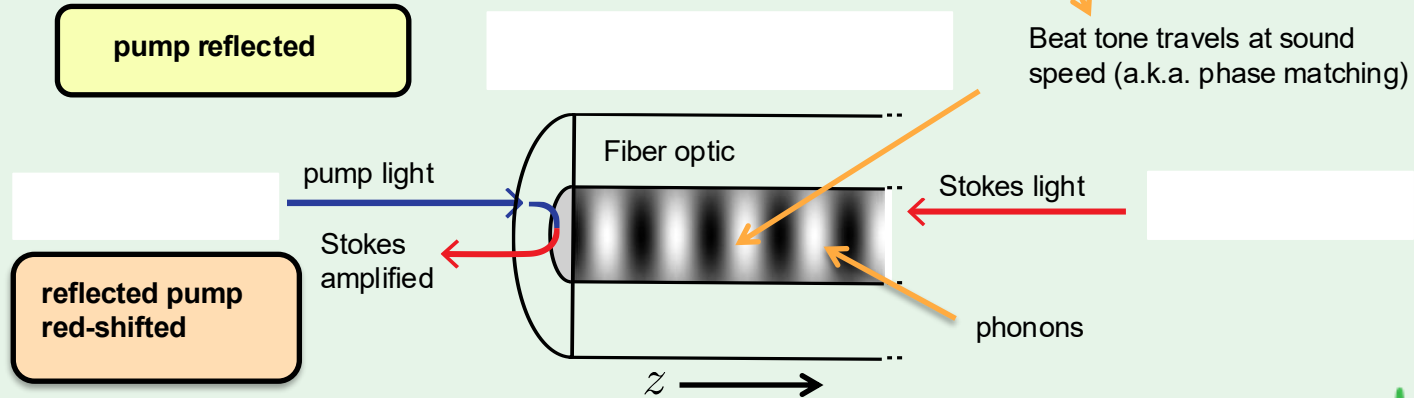
Putting this all together...

Brillouin scattering

Electrostriction: beat tone from two optical beams drives travelling strain wave

Phonons generated resonantly when $\omega_p - \omega_S = v(k_p + k_S)$

Photoelasticity, Bragg, and Doppler: phonons act as moving mirror



Imagine a transparent medium in which two optical beams counter-propagate

Phonons for quantum information science

- Motivation: phonons as an untapped quantum resource
 - Long lifetime

Lifetime → 10s of hours

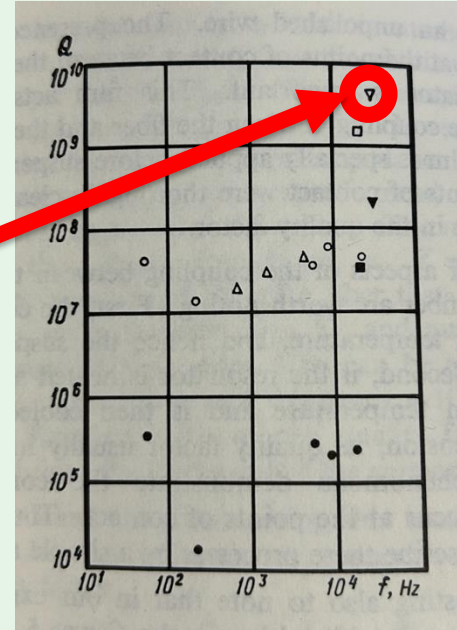
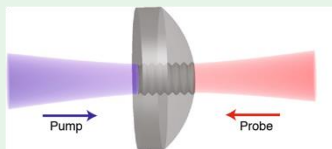


Fig. 6 Maximum quality factors for mechanical resonators made from different materials. ○ = Al-5056 (Oide, Tsubono, and Hirakawa 1980), △ = Nb (Blair *et al.* 1980b), □ = Si (McGuigan *et al.* 1978), ▽ = Al₂O₃ (Bagdasarov *et al.* 1977). Solid symbols correspond to $T = 300$ K, open symbols to $T = 4.2$ K. Note added in press: Recently Veitch *et al.* (1985) have reported a Q of 2×10^8 at 4 K in a niobium bar.

Phonons for quantum information science

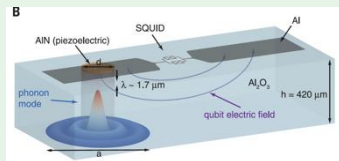
- **Motivation: phonons as an untapped quantum resource**

- Long lifetime
- Telecom control + readout



ntum systems

Renninger, *et al.* Nature Physics (2018).



Y. Chu *et al.*, Science **358**, 199 (2017).

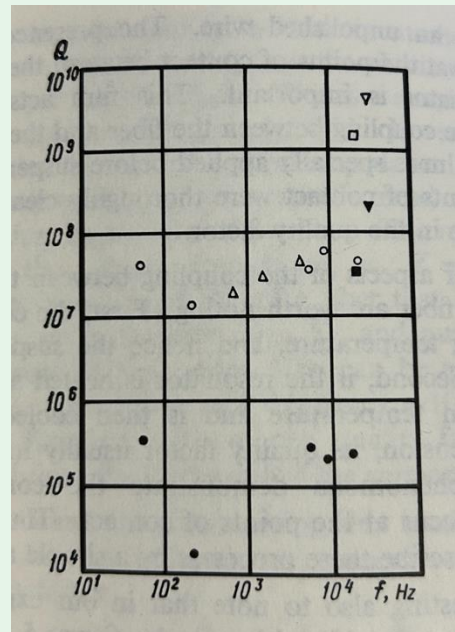


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Phonons for quantum information science

- **Motivation: phonons as an untapped quantum resource**
 - Long lifetime
 - Telecom control + readout
 - Coupling to quantum systems

Can these extraordinary phonon lifetimes be useful for quantum technology?

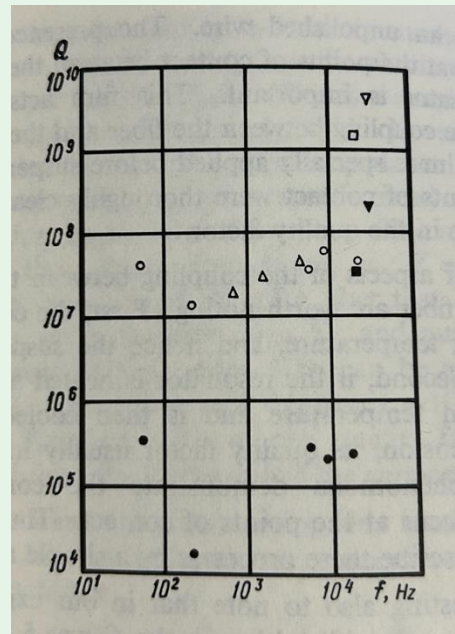
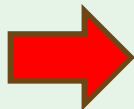


Fig. 6 Maximum quality factors for mechanical resonators made from different materials. $\circ$ = Al-5056 (Oide, Tsubono, and Hirakawa 1980), Δ = Nb (Blair *et al.* 1980b), $\square$ = Si (McGuigan *et al.* 1978), ∇ = Al₂O₃ (Bagdasarov *et al.* 1977). Solid symbols correspond to $T = 300\text{K}$, open symbols to $T = 4.2\text{K}$. Note added in press: Recently Veitch *et al.* (1985) have reported a Q of 2×10^8 at 4K in a niobium bar.

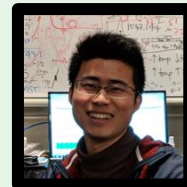
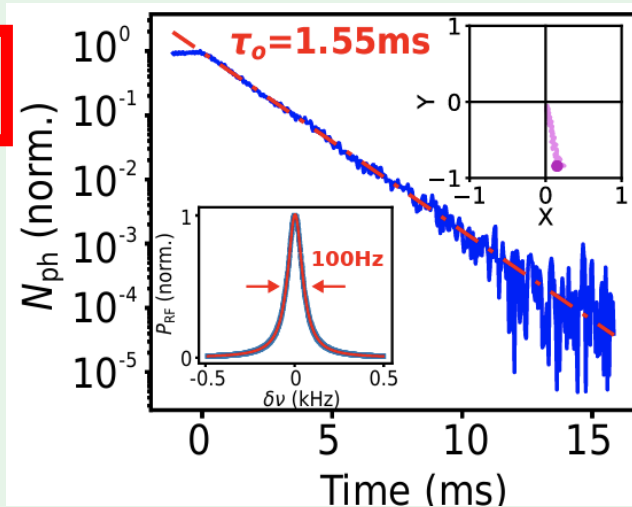
Phonons for quantum information science

Can these extraordinary
phonon lifetimes be useful
for quantum technology?



YES

***Long quantum
state lifetime
demonstrated***



Dr. Royce Liu

Luo, et al. *Nature Physics* 1-7, (2026).

Key scientific objective: utilize these phonons for quantum technology