

Quantum Technician Bootcamp

Brian Rashap

September 2025

Introduction



Instructional team

A physicist, an engineer, and a technician walk into a classroom...



The Engineer: Brian Rashap, Ph.D.

- Proud husband of Krista and father of Shelby (27) and Ethan (23)
- Electrical Engineer (Michigan) with 23 years industrial experience (Intel)
- Created and taught IoT Bootcamp for 5 years (and going)
- Hobbies: painting, cycling, swimming, reading, spending time with family





The Physicist: Megan Ivory

- Foster mom to two cats, Joey and Tessa; auntie to two humans, Liana and Azeria
- PhD in atomic physics (William and Mary), startup ColdQuanta (now Infleqtion), Univ of Washington, Sandia since 2019 working on atomic clocks, quantum computers, and quantum programs like QuLL!
- Outside hobbies: trail running, hiking, gardening, backpacking, trad climbing, canyoneering, and skiing
- Inside hobbies: cooperative board games, reading trashy fantasy series, acting/writing



I've never taken a quantum information science class. . .



The Technician: Shawn Morales

- Blessed husband of Joy and proud father of Katelyn (29) and Kimber (28)
- Intel Manufacturing Technician of 32 years
- Worked on 26 different tools within Intel
- Adore my time with family, mountain biking, and the great outdoors





Student Introductions

- Your name
- What were you up to before starting the bootcamp
- Any prior experience with math, science, machining, etc.
- What do you hope to get out of the bootcamp



Drinks, Lunch and Snacks

- There is a kitchenette down the hall with coffee/tea, snacks, frig, microwave
 - The rest of the room is the TSL Lab - please don't disturb it
 - Please clean up the area every time you use it.
 - Don't leave leftovers overnight in the frig
- Drink are allowed in the QuLL, but not near the optical tables or vacuum systems
- You can eat lunch in the QuLL,
 - There will be a mid-day 1 hour lunch break
 - Again, no food/drink near optical tables or vacuum systems
 - Tables wiped down at the end of lunch
- No food trash in QuLL garbage can (use the kitchenette trash)



Class Rules

- Respect each other. Help each other.
- Ask questions.
- Be on time (let us know via Slack if you won't be here)
- Keep your workspace and the classroom neat and tidy.
- If you are struggling, let us know. We are here to HELP!
- Class hours
 - Mon-Th: 8am to 5pm ¹ and Friday: 8am to 3pm ²
 - Lunch Break: 1 hour near noon. Maybe combined with work time.
 - Please respect the instructors' lunch break as well.
- Phone Policy: phones should not be out or used during class
 - No gaming, no surfing social media
 - If you need to take/make a call, please set out of the classroom
 - Exceptions: two-factor authentication, pictures of projects, class videos

¹Doors open at 7:50, please be in your seats ready to learn by 8:00

²Occasionally on Friday there will be optional activities from 3 to 5



Credit for Prior Learning (CPL)

If students enroll in an academic program at CNM, they are eligible for up to 24 credits through CPL:

- Current CPL (will be finalized before December)
 - MATH 1220 College Algebra
 - BCIS 1110 Fundamentals of Information Literacy and Systems
 - BUSA Business Professionalism
- CPL that can be claimed starting in Fall 2026
 - ENGT 10xx Optics
 - ENGT 20xx Laser and Photonics
 - CSCI 10xx Survey of Quantum Computing
 - CSCI 20xx Quantum Hardware



Professional Development and Guest Speakers

- Clifton Strength Finder
- CNM Workforce and Community Success
- LinkedIn / Online Job Search
- Resume Workshop
- Interview Skills
- Effective Influencing
- Constructive Confrontation
- Presentation/Pitch Pitch
- City of ABQ
- Elevate Quantum
- Quantum NM Institute / UNM
- Quantinuum
- Qunnect
- Vescent
- 3D Glass Solutions
- Infleqtion

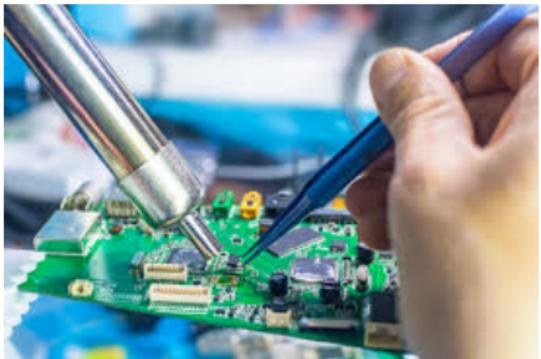


Foundation of Lean Certificate





IPC Solder Certification

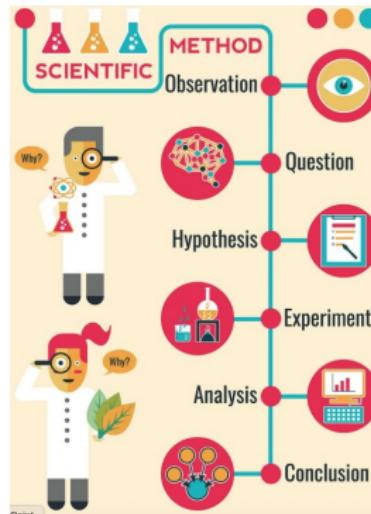


**IPC-J-STD-001 Rev.
H, Certification**



Important Attribute in an Employee

- Tolerance of Ambiguity
- Attention to Detail
- Reliability
- Curiosity
- Structured Problem Solving



Note: employers regularly ask the instructional team for references, it is these attributes that we will be the basis of our recommendation.

Overview: QIS in NM



Introduction

NM will be tomorrow's quantum hotbed

The collage includes:

- A screenshot of a news article from "THE QUANTUM INSIDER" titled "Tomorrow's quantum hotbeds? 7 U.S. cities that could incubate the next great quantum technology ecosystem". It features a photograph of a city skyline at sunset with a glowing quantum symbol overlaid.
- A photograph of a laboratory or research facility with the text "QUANTUM NEW MEXICO INSTITUTE (QNM-I)" and "RESEARCH".
- A graphic for "Elevate Quantum" with a triangle icon.
- A timeline of events:
 - JANUARY, 2024: "The University of New Mexico launches the Quantum New Mexico Institute"
 - MARCH, 2024: "Governor Polis and Governor Lujan Grisham urge the Department Of Commerce to fund the Regional Quantum Partnership"
 - MAY, 2024: "Central New Mexico Community College" (CNM) receives funding to launch a quantum learning lab and training program.
 - July, 2024: "EDA announces \$504 million in funding to 12 designated tech hubs across America"
- A photograph of a person working at a computer in a lab setting, with the text "National Nuclear Security Laboratories" visible.

Why?

- World Class Research Institutions
- Entrepreneurial Ecosystems
- Pro-Innovation Government
- Quantum Solutions for NM priorities



Introduction

What is Quantum Information Science (QIS)?

- Emerging technology that will revolutionize computing, communication and sensing:
 - Quantum computers to **solve previously unsolvable problems**
 - Break **unbreakable** cryptography and enable **provably** secure communications
 - Dramatically improve **sensing** and **detection**

The convergence two of the great scientific pillars of the 20th Century

Quantum Mechanics:
The physics of the microscopic world

atom electron photon

Albert Einstein

Information Science:
Computers & communications

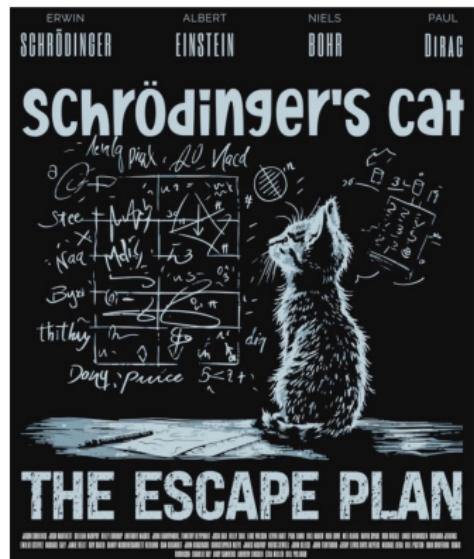
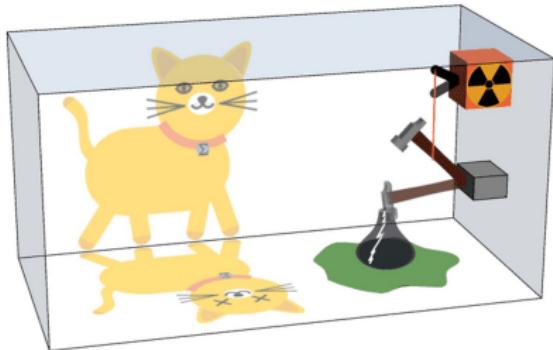
Claude Shannon



Introduction

Superposition

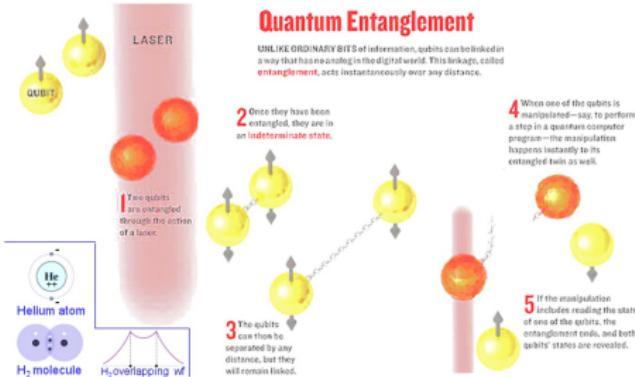
- Superposition describes a particle's ability to exist across many possible states at the same time.
- The superposition collapses into one specific state when a measurement/observation is made.





Introduction

Spooky Action at a Distance (Entanglement)



In 1964 John Bell discovered that quantum theory conflicts with any local theories involving hidden variables. He found a way to test whether local hidden variables could explain the apparent "spooky action."



The **Bell test**: Two observers would make separate measurements of two supposedly entangled particles. Bell calculated the maximum amount of correlation that could arise between the two observers' findings if local hidden variables limited by the speed of light were at work.



For the first time, a loophole-free Bell test



At Delft, scientists ran 245 trials in which a pair of electrons 1,280 meters apart were entangled. They measured the particles in every case and found 80 percent were correlated—significantly more than would be possible with local hidden variables.

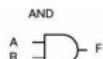
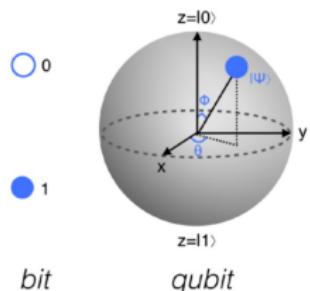
Experiments in the U.S., Austria and Germany found similar results.





Introduction

Classical vs Quantum Logic



Input	Output
A	F
0	1
1	0

Inputs		Output
A	B	F
0	0	0
1	0	0
0	1	0
1	1	1

Inputs		Output
A	B	F
0	0	0
1	0	1
0	1	1
1	1	1

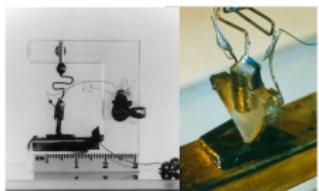
Operator	Gate(s)	Matrix
Pauli-X (X)	$\begin{array}{ c }\hline \text{X} \\ \hline \end{array}$	$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$
Pauli-Y (Y)	$\begin{array}{ c }\hline \text{Y} \\ \hline \end{array}$	$\begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}$
Pauli-Z (Z)	$\begin{array}{ c }\hline \text{Z} \\ \hline \end{array}$	$\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$
Hadamard (H)	$\begin{array}{ c }\hline \text{H} \\ \hline \end{array}$	$\frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$
Phase (S, P)	$\begin{array}{ c }\hline \text{S} \\ \hline \end{array}$	$\begin{bmatrix} 1 & 0 \\ 0 & i \end{bmatrix}$
$\pi/8$ (T)	$\begin{array}{ c }\hline \text{T} \\ \hline \end{array}$	$\begin{bmatrix} 1 & 0 \\ 0 & e^{i\pi/4} \end{bmatrix}$
Controlled Not (CNOT, CX)	$\begin{array}{ c }\hline \bullet \\ \hline \oplus \\ \hline \end{array}$	$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$
Controlled Z (CZ)	$\begin{array}{ c }\hline \bullet \\ \hline \text{Z} \\ \hline \end{array}$	$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix}$
SWAP	$\begin{array}{ c }\hline \times \\ \hline \times \\ \hline \end{array}$	$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$
Toffoli (CCNOT, CCX, TOFF)	$\begin{array}{ c }\hline \bullet \\ \hline \bullet \\ \hline \oplus \\ \hline \end{array}$	$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$



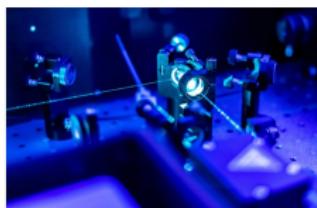
Introduction

Quantum Has Been With Us

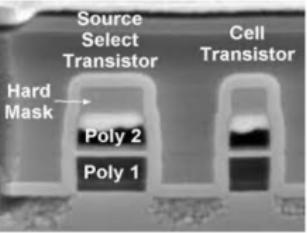
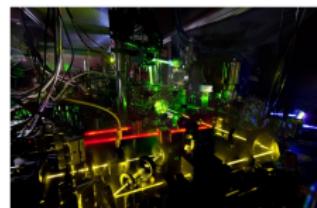
Transistors / Semiconductors



Lasers



Atomic Clocks / GPS





Introduction

Advances in Quantum (Quantum 2.0) will supercharge the information economy

Quantum Computing

A new computing paradigm that will help us solve problems in completely new ways



BREAK SECRET CODES OR CRYPTOGRAPHY

DRUG DESIGN

OPTIMIZE THE ENERGY GRID

FRAUD DETECTION IN FINANCIAL MARKETS

Quantum Sensing

Atomic level sensors that will greatly enhance sensing capabilities



GPS DENIED NAVIGATION

ENHANCED BIOLOGICAL SENSORS

MINERAL AND OIL EXPLORATION

Quantum Communication

Provable secure communication and new communication protocols



THE QUANTUM INTERNET

ULTRA-SECURE COMMUNICATIONS

ENERGY EFFICIENT COMMUNICATIONS

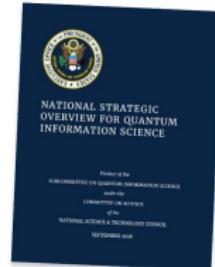


Introduction

Quantum is one of the top emerging technologies in the world

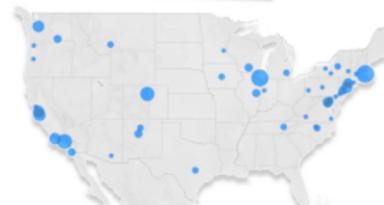
Federal legislation

- **National Quantum Initiative (NQI):** Passed in 2018, authorized \$1.15B in funding to support an all of government approach to sustain national and economic security in quantum.
- **National Defense Authorization Act (NDAA):** Passed in 2019 and 2020, legislate DOD to carry out and support quantum R&D
- **CHIPS and Science Act:** Passed in 2021, authorized additional funding for quantum infrastructure, R&D, and workforce development programs



Federally supported quantum programs

- **National Science Foundation**
 - Quantum-Leap Challenge Institutes*
 - Technology, Innovation and Partnerships
- **Department of Energy**
 - NQI Science and Research Centers*
 - Office of Science - Reaching a New Energy Sciences Workforce
- **Department of Defense**
 - NDAA QIS Research Centers*
 - Defense Advanced Research Projects Agency
 - Office of the Undersecretary of Defense for Research and Engineering

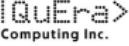


The 13 major NQI research centers and their affiliates (quantum.gov)

*Blue dots on the map correspond to "Federal Quantum Programs"



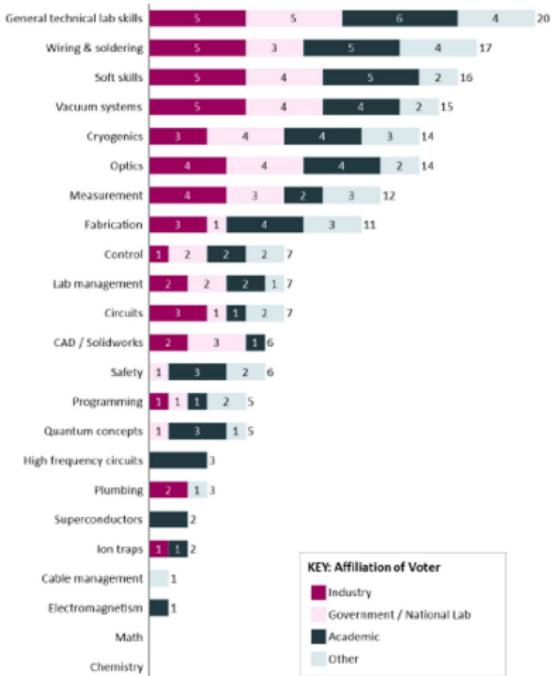
Introduction

Neutral Atom	Trapped Ion	Photonics	Superconducting	Silicon Spin / Quantum Dots
<p>Neutral atoms are cooled using tuned laser and store qubits within electron states. Interactions through excitation to Rydberg states.</p> 	<p>Trapped ion technology uses charged atomic particles, which can be confined and suspended in free space using electromagnetic fields. Qubits are stored in the stable electronic states of each ion. Lasers are used to induce coupling</p> 	<p>Photonic-based technology consists of superpositions of multiple photons in a light pulse. Qubits consist of so-called "squeeze states" consisting of superpositions of multiple photons in a light pulse</p> 	<p>Resistance-free current oscillations back and forth around a circuit loop. An injected microwave signal excites the current into superposition states.</p> 	<p>"Artificial atoms" are made by adding an electron to a small piece of pure silicon. Microwaves control the electron's quantum state.</p> 
<p>Pros: Long coherence times. Strong connectivity including more than 2Q. External cryogenics not required.</p> <p>Cons: Requires ultra-high vacuum. Laser scaling challenges.</p>	<p>Pros: Extremely high gate fidelities and long coherence. No External cryogenics.</p> <p>Cons: Slow gate times / operations. Low connectivity between qubits. Requires ultra-high vacuum. Laser scaling challenges.</p>	<p>Pros: Extremely fast gate speeds and promising fidelities. No cryogenics or vacuum. Leverage existing CMOS fabs.</p> <p>Cons: Noise from photon loss. Each program requires custom chip. Photons don't naturally interact so 2Q gate challenges.</p>	<p>Pros: High gate speeds and fidelities. Leverage existing lithographic processes.</p> <p>Cons: Requires cryogenic cooling. Short coherence times. Microwave interaction not well understood.</p>	<p>Pros: Leverage existing semiconductor technologies. Strong gate fidelities and speeds.</p> <p>Cons: Requires cryogenics. Only a few entangled gates with low coherence times. Interference and cross-talk challenges.</p>
    	   	   	    	     



Introduction

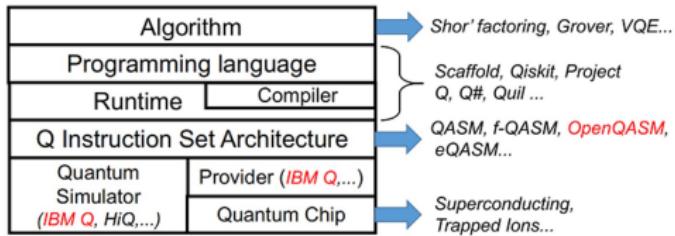
Quantum Technician Skills





Introduction

Quantum Programming Languages



12



Introduction

CNM Partnerships



Elevate
Quantum

Elevate Quantum's mission is to unite Colorado, New Mexico, and Wyoming to secure the Mountain West's position as the global epicenter for Quantum development and enhance US economic and national security.



Catalyzing national leadership in quantum information science to co-design the algorithms, quantum devices, and engineering solutions needed to deliver certified quantum advantage in Department of Energy Office of Science scientific applications.



Berkeley

Caltech

HARVARD UNIVERSITY





Introduction

Quantum Learning Lab (QuLL)

- Sandia National Labs and CNM Partnership
- Training lab for Quantum Workforce Development located at the FUSE Makerspace in downtown ABQ
- Provide hands-on quantum experience for University and Community College students across the state
- Enhance knowledge of early-stage researchers and entrepreneurs



- Immersive Hands-On Workforce Training (10-weeks)
 - Built on the success of CNM Ingenuity's Deep Dive Bootcamps
 - No prior math/science needed

- Focus on:

- Optics and Photonics
- Ultra-High Vacuum Systems
- Quantum Phenomenon
- Problem Solving, Documentation, Math, Statistics

- Skills applicable to adjacent industries
 - Semiconductor, Solar Cell, Opto-Electronic Manufacturing

- CPL opportunities with Engineering Technician (and more)

Quantum Technician Bootcamp





Introduction

Carpe Diem

- Quantum Information Systems industry is poised to revolutionize computing, sensing, and communications
 - > Solve complex optimization problems, provide ultra secure communications, radical new sensing capabilities
- National Priority: Quantum is the next technology “Space Race”
- New Mexico is positioned to attract Quantum employers and grow a Quantum economy
 - > Quantum capabilities at the SNL, LANL, AFRL, and Research Universities
 - > Elevate Quantum Tech Hub: CNM Ingenuity is the workforce co-lead
 - > Strong support from the Governor and State Legislature
- Today, 95% of Quantum jobs require advanced degrees; however, in 5-10 years 75% of the Quantum jobs will be certificates, associate, or bachelor degrees.
 - > The Quantum Technician Bootcamp is one of the first/only programs in the country focused on the technician workforce
- We need to build a workforce by training quantum-ready technicians for adjacent industries
 - > Jobs exist today in semiconductor, solar cell, opto-electronics and space.
 - > A quantum-ready workforce is an enabler to NM to attract Quantum companies
- Quantum Technician Bootcamp is part of a portfolio of CNM offerings for an advanced manufacturing workforce

STA - Mechatronics

Industrial Technician
Industrial Automation Technician

Ingenuity

Internet of Things
Quantum Technician

Math Science Engineering

Engineering AS degree
Engineering Technician

BHT – CS/CIS

Internet of Things
Industrial Automation



What you will learn

- Optics
- Lasers / Photonics
- Ultra-High Vacuum Systems
- Quantum Phenomenon
- Applied Mathematics
- Structured Problem Solving



Brightspace

cnm.edu

Email myCNM CNM Brightspace

En Espanol MAP



Students ▾ Programs Workforce & Community About CNM ▾ Help ▾

mycourses.cnm.edu/d2l/home/214794

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oPhysics CNMI Deep Dive -... CNM Ingenuity - H... Instances | Brev.dev Quality Assurance... EC Markdown Live Pr... Orders - Bambu L... Login

Deep Dive Quantum Technician Bootcamp S...

Course Home Course Work ▾ Communication ▾ My Grades ▾ Resources ▾ Course Admin Course Tools ▾

Deep Dive Quantum Technician Bootcamp September 2025



Solidworks - Windows Users

To install Solidworks (Windows only), go to

<http://www.SolidWorks.com/SEK>

- Enter your contact information.
- Check the radio button “Yes” under ”I already have a Serial Number that starts with 9020”.
- Select the version: 2024 SP5.0 and click Request Download.
- On the next page, Accept the agreement and continue.
- On the final page, click the Download button to download the SolidWorks Installation Manager.
- Unzip the files to launch the Installation.
- Select the option for Individual/On this machine.
- Install using the following serial number provided by your instructor.



Other Software

① Bambu Studio

- <https://bambulab.com/en/download/studio>

② Microsoft Excel

- <https://office365.com>
- Log in with your CNM credentials
- Download excel (and any other office programs)

③ Adobe Illustrator

- <https://adobe.com/creativecloud>
- Log in with your CNM credentials
- Select Work/School account

④ Octave

- <https://octave.org/download>

⑤ Bookmark the following:

- <https://www.desmos.com>
- <https://quantum.cloud.ibm.com/composer>
- <https://colab.research.google.com>

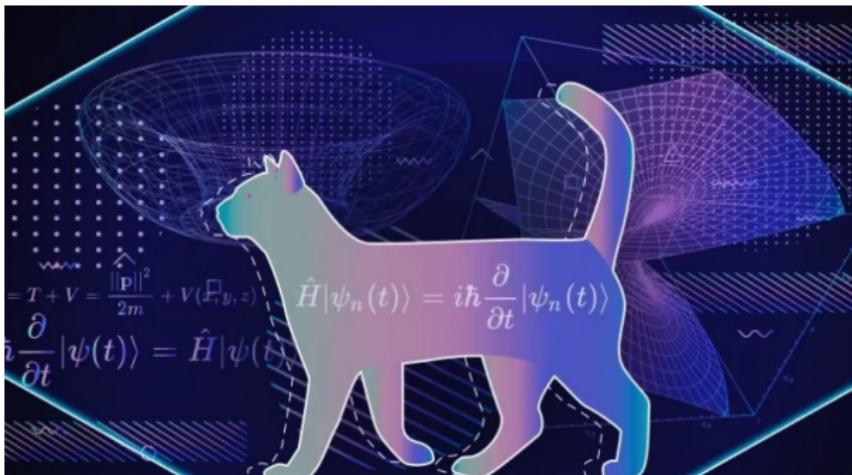


Inaugural Cohort





Pre Knowledge Check



- We are assuming no prior knowledge
- Pre and Post check will be used to help instructional team for future cohorts
- D) I am not familiar with this concept is an option on every question

Safety



Safety Walk

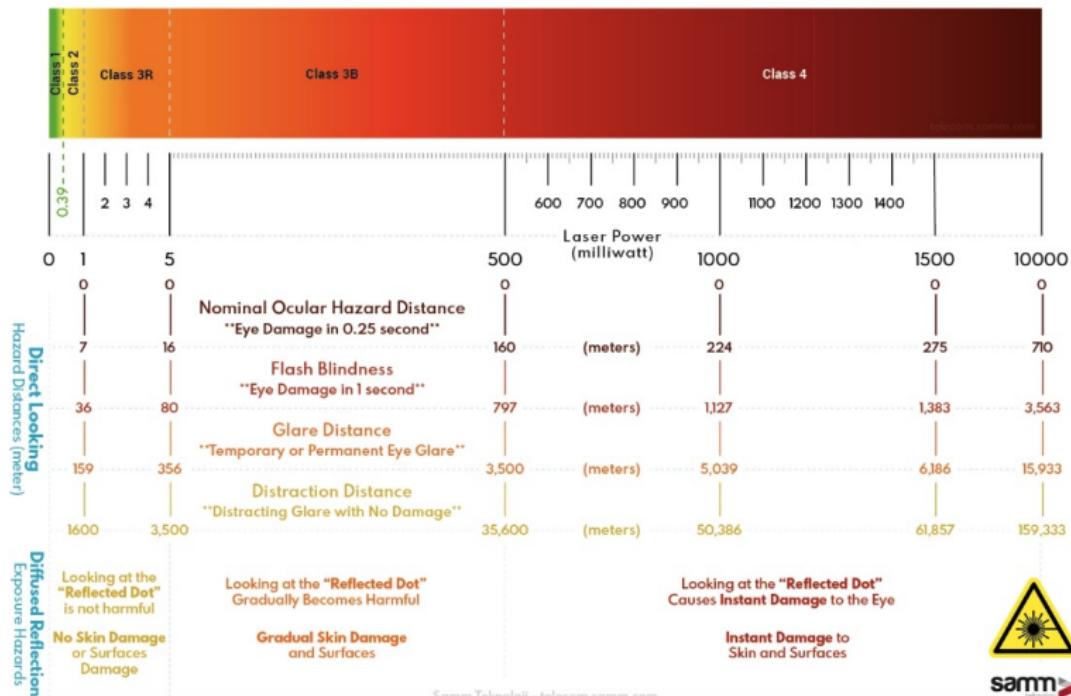




Laser Safety - Laser Classes

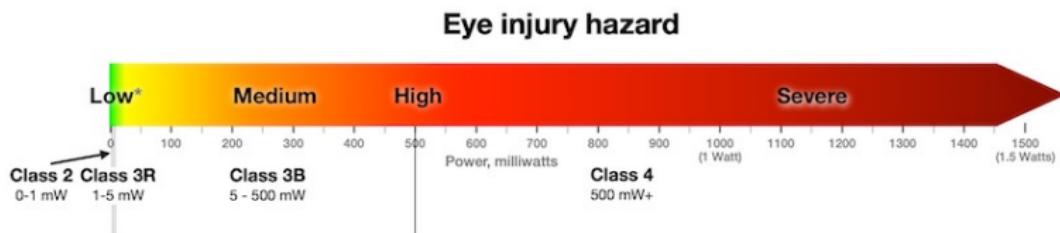
Laser Hazard Classes

*** Avoid eye exposure to direct or reflected laser beams,
especially within the “Nominal Ocular Hazard Distance”
The closer you are to the beam the greater the risk of injury.





Laser Safety - Class 2



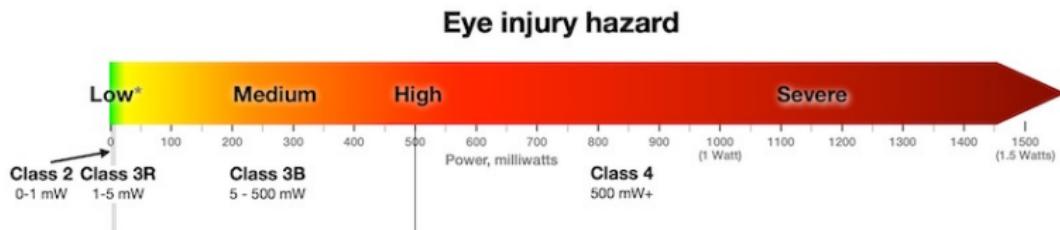
*Eye injury hazard descriptions above are valid for exposures relatively close to the laser. Because the beam spreads, less light will enter the pupil at greater distances. The hazard decreases the farther a person is from the laser, and the shorter the exposure time (e.g., do not deliberately look or stare into the beam). For example, a 1mW Class 2 laser beam is eye safe for unintentional exposures after about 23 ft (7 m), a 5mW Class 3R beam is eye safe after about 52 ft (16 m), a 500 mW Class 3B beam is eye safe after about 520 ft (160 m), and a 1500 mW Class 4 beam is eye safe after about 900 ft (275 m).

(Calculations are for visible light, a 1 milliradian beam, and a 1/4 second Maximum Permissible Exposure limit.)

- Class 2 lasers, which are limited to 1 mW of visible continuous-wave radiation, are safe because the blink reflex will limit the exposure in the eye to 0.25 seconds. This category only applies to visible radiation (400 - 700 nm).



Laser Safety - Class 3R

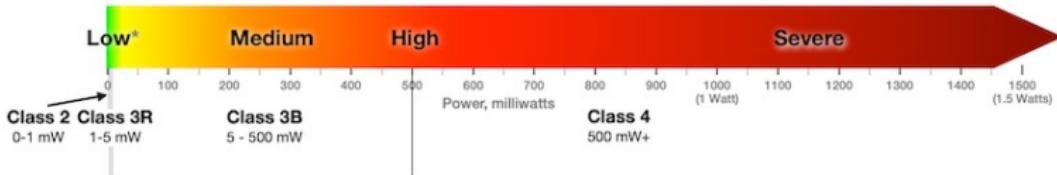


- Class 3R lasers produce visible and invisible light that is hazardous under direct and specular-reflection viewing conditions. Eye injuries may occur if you directly view the beam, especially when using optical instruments. Lasers in this class are considered safe as long as they are handled with restricted beam viewing. Visible, continuous-wave lasers in this class are limited to 5 mW of output power.



Laser Safety - Class 3R

Eye injury hazard



- Class 3B lasers are hazardous to the eye if exposed directly. Diffuse reflections are usually not harmful. Safe handling of devices in this class includes wearing protective eyewear where direct viewing of the laser beam may occur. Lasers of this class must be equipped with a key switch, laser safety signs should be used. Laser products with power output near the upper range of Class 3B may also cause skin burns.



Lock Out Tag Out



- Electrical Energy
- Mechanical Energy
- Mechanical Energy - Pneumatics



Sharps





High Voltage



Python



Google Colab and Jupyter³ Notebooks



- Colab is a hosted Jupyter Notebook service that requires no setup to use and provides free access to computing resources, including GPUs and TPUs. Colab is especially well suited to machine learning, data science, and education.
- Jupyter Notebook is an interactive web application for creating and sharing computational documents. It supports more than 40 languages including Python, R, and Scala.

³formerly ipython or interactive python



Python



- Easy to understand: Python's readability, non-complexity and ability for fast prototyping contribute to its popularity.
- Libraries: Python comes with numerous built-in libraries that are well suited for data mining, machine learning and AI.
- Easier, more powerful implementation: With Python, programmers spend less time writing code and debugging errors compared with other languages.
- Syntax: Python uses modern scripting and friendly syntax.



Python Libraries

Python libraries are collections of pre-written code, including modules and routines, that provide specific functionality to developers.

- Numpy: fundamental package for scientific computing in Python. It is a Python library that provides a multidimensional array objects. It contains routines for operations on arrays, including mathematical, logical, shape manipulation, basic linear algebra, basic statistical operations, random simulation, etc.
- Scipy: algorithms for optimization, integration, interpolation, eigenvalue problems, algebraic equations, differential equations, statistics and many other classes of problems.
- Matplotlib: Matplotlib is a comprehensive library for creating static, animated, and interactive visualizations in Python.

Getting Started:

https://colab.research.google.com/github/data-psl/lectures2020/blob/master/notebooks/01_python_basics.ipynb

Atomic Quantum Systems

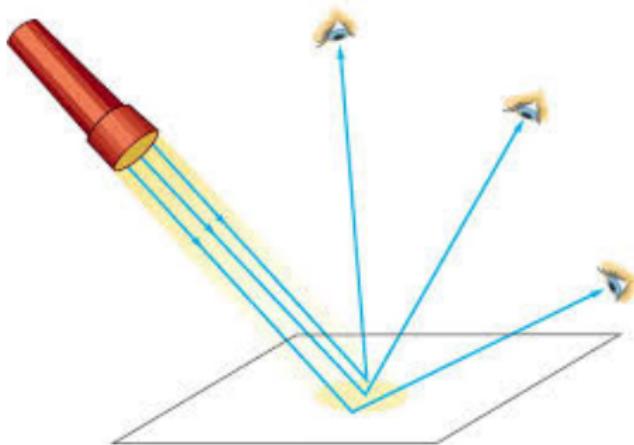
Vacuum Systems

Geometric Optics



Ray Nature of Light

The word "ray" means a straight line that originates at some point.

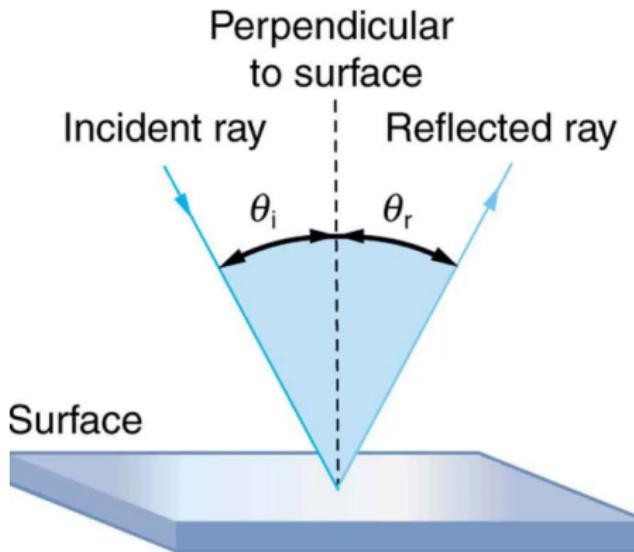


The part of optics dealing with the ray aspect of light is called "geometric optics."



Reflection

The angle of reflection equals the angle of incidence



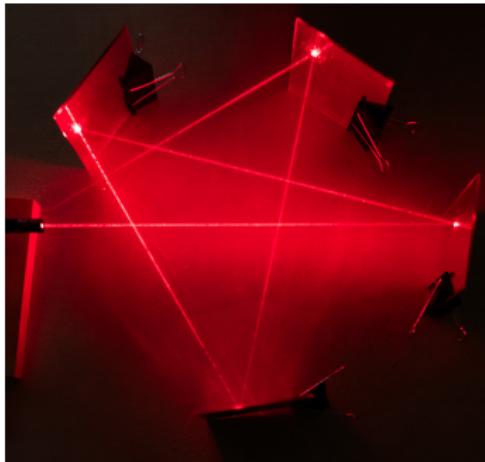


Demonstration: Handling Optics





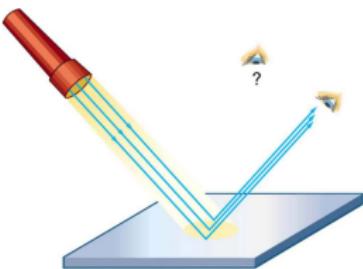
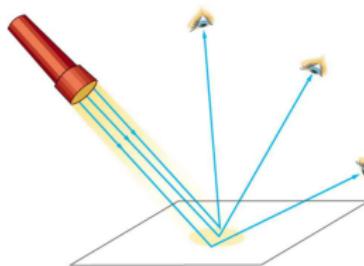
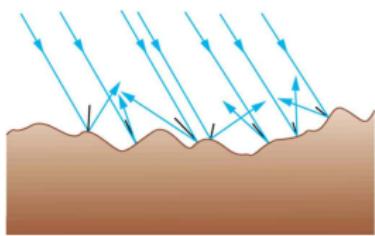
Assignment: Laser Tag



- Align a Laser and a target at opposite ends of the table.
- When obstacles are placed in the path, without adjusting laser, add mirrors to get the beam to the target.



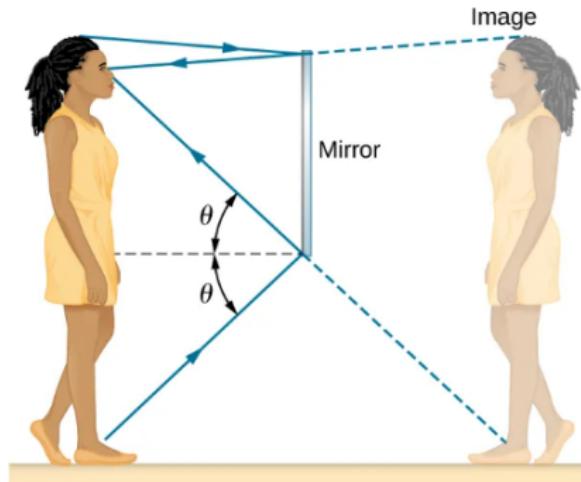
Rough vs Smooth Surfaces





Mirrors and Virtual Images

When we see ourselves in a mirror, it appears that our image is actually behind the mirror.

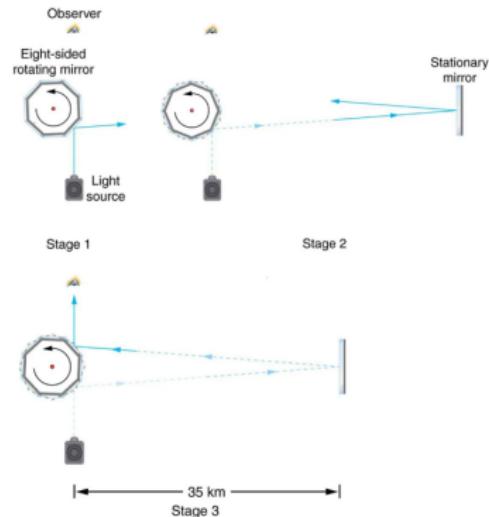




Speed of Light

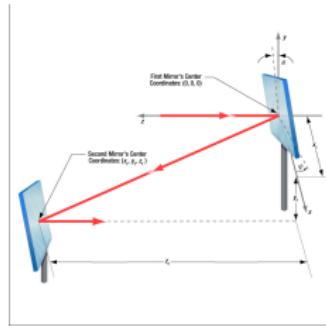
- In 1676, Danish astronomer Ole Roemer noted the change in orbital period of Jupiter's moons depending on if the earth was moving towards or away from Jupiter. He was able to calculate speed of light to be $2.26 \times 10^8 (\frac{m}{s})$.
- In 1887, American physicist Albert Michelson used a rotating mirror to get a more precise measurement of the speed of light.
- Today, the speed of light is known as:

$$c = 2.9979245810^8 (\frac{m}{s}).$$

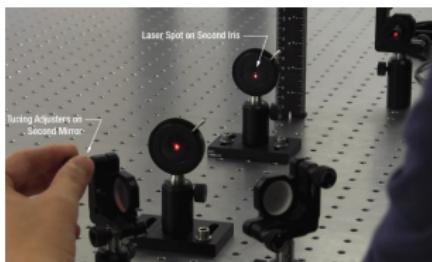




Assignment: Two Mirror Walk



- ➊ Setup: Laser, 45° mirror, second 45° mirror, two irises, target.
- ➋ Adjust first mirror to center beam on center iris 1
- ➌ Open iris 1, adjust second mirror to center beam on iris 2
- ➍ Iterate steps 2 and 3 until the beam passes through the center of both iris and hits target.



Math Interlude: Trigonometry

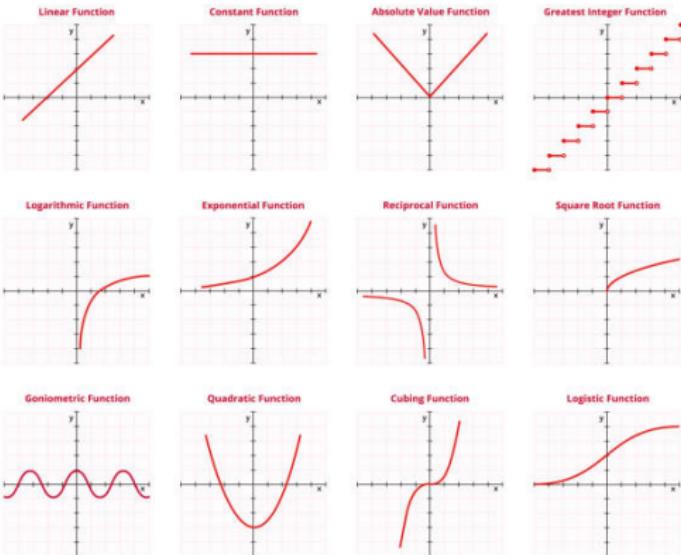


Algebraic Functions

An algebraic function provides a "y-value" for every "x-value"

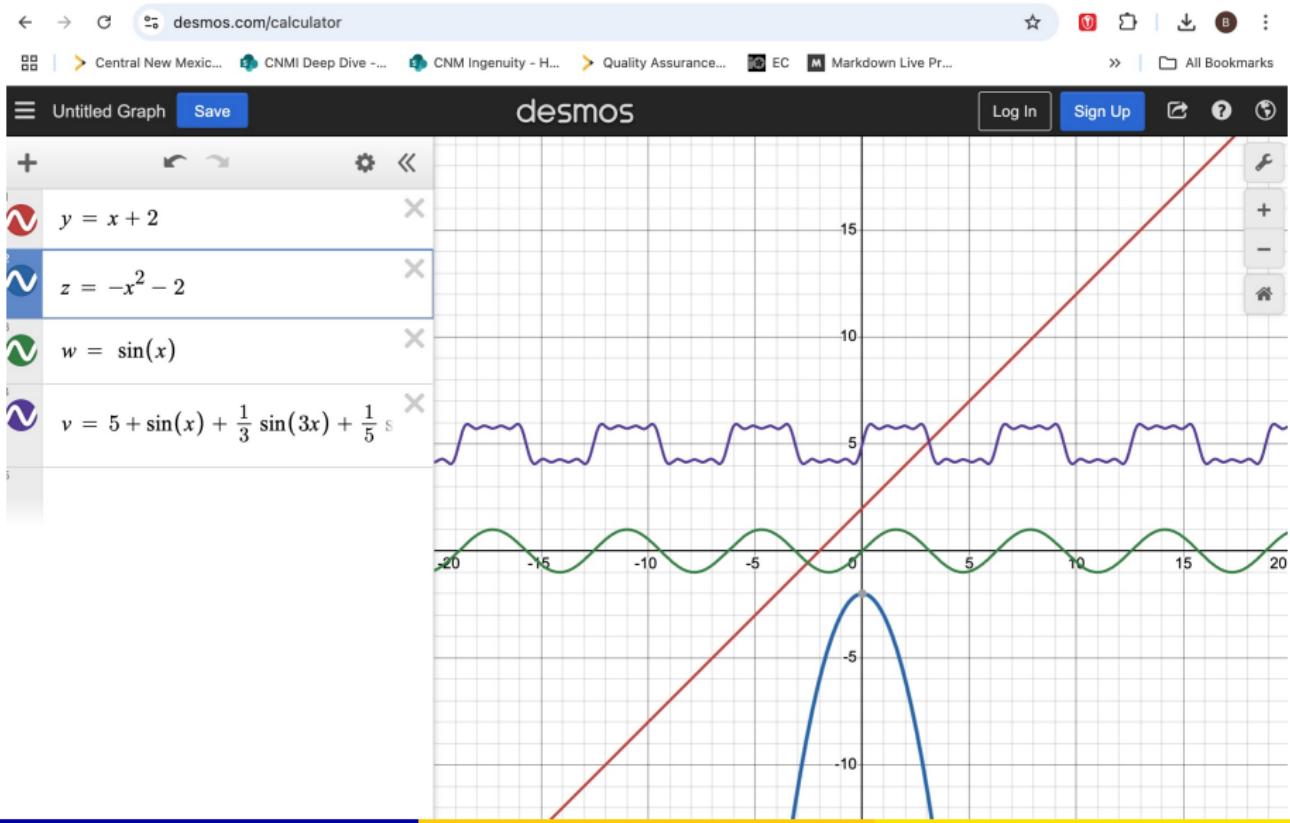
- Linear: $y = x + 2$
- Quadratic: $y = x^2$
- Periodic: $y = \sin(x)$

12 BASIC FUNCTIONS



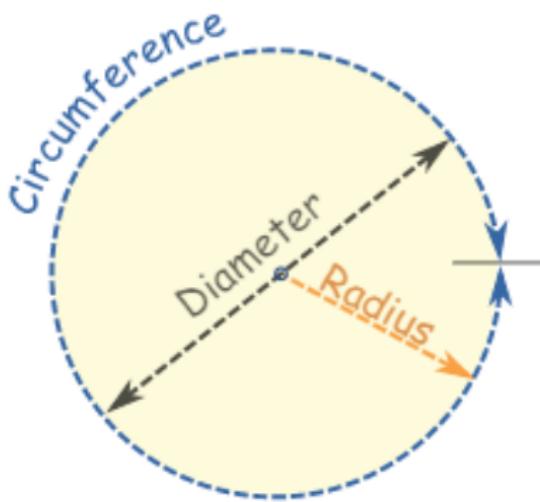


More Desmos Fun





Pi (π)

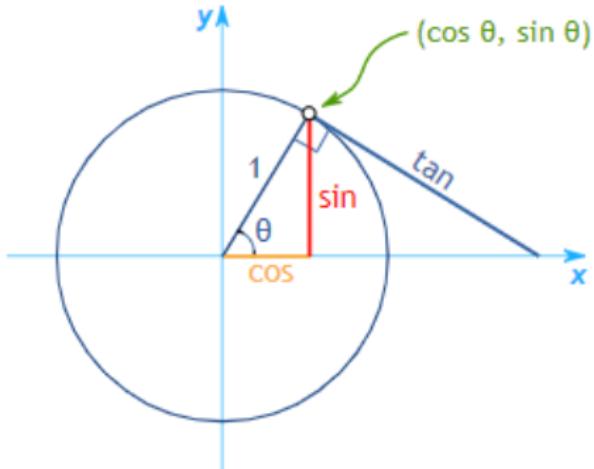
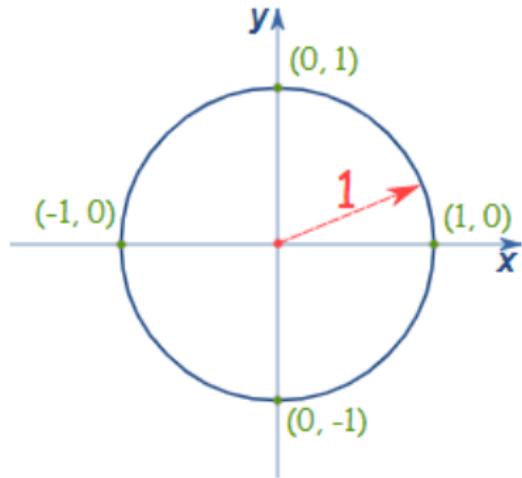


$$\frac{\text{Circumference}}{\text{Diameter}} = \pi = 3.14159\dots$$



Unit Circle and Trigonometric Functions

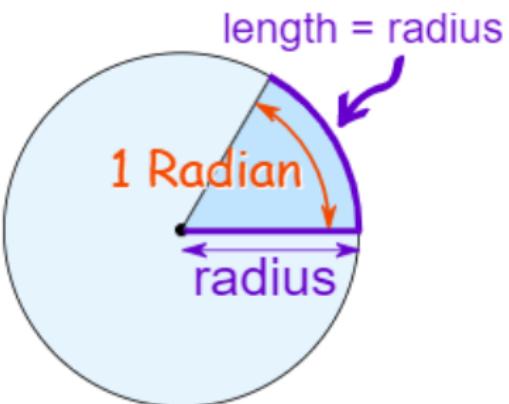
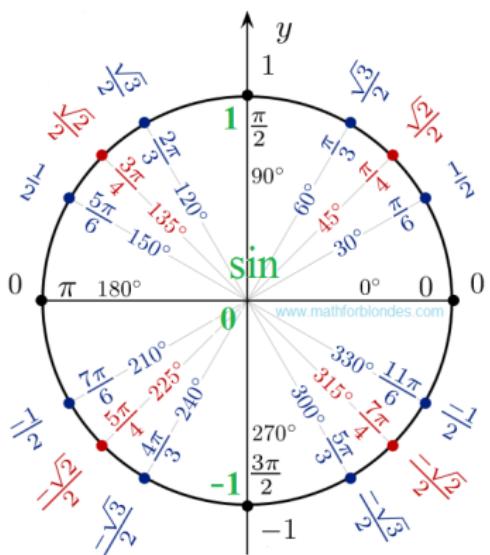
The Unit Circle is a circle with a radius of 1.



The Unit Circle can be used to map out the trigonometric values of sine, cosine, and tangent.



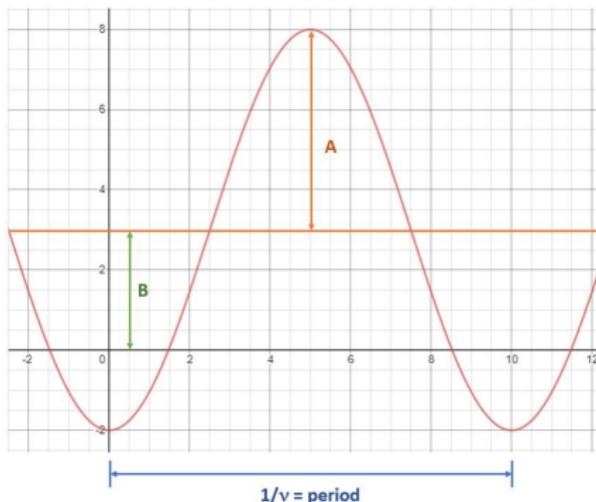
Unit Circle and the Value of $\sin(\theta)$



- $\sin(\theta)$ is the y-value of the point on the Unit Circle at angle θ .
- In our trig functions, θ is measured in radians (rad), not degrees.
- 360 degrees = 2π radians.



Sine Waves

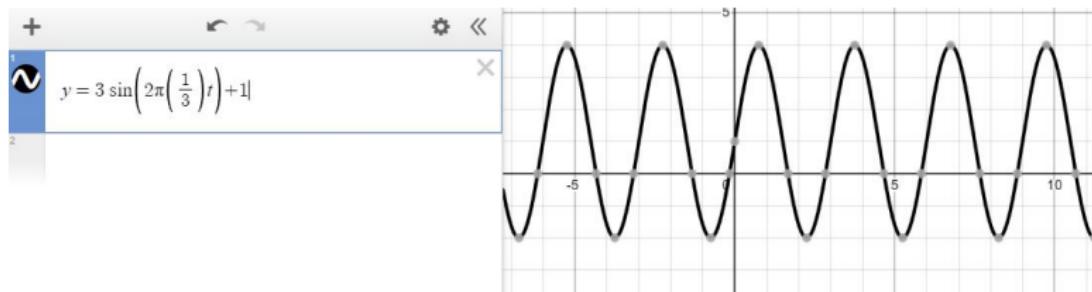
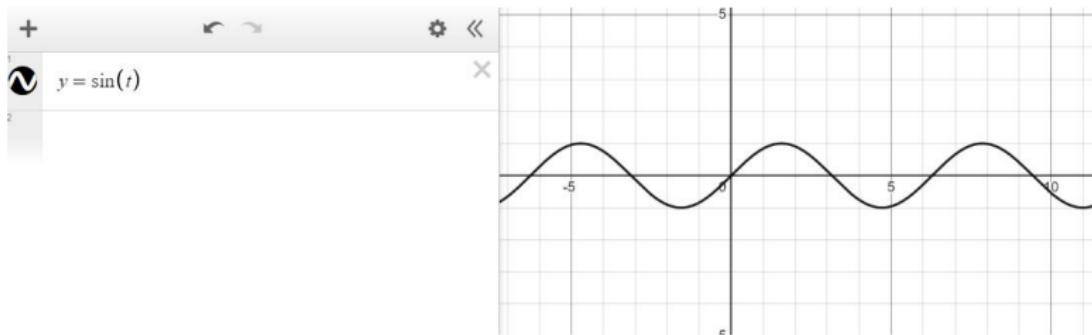


$$y = A * \sin(2 * \pi * \nu * t) + B$$

where A = amplitude, B = offset, ν = frequency = $\frac{1}{\text{period}}$,
and t = time in seconds.



Using Desmos (desmos.com/calculator)

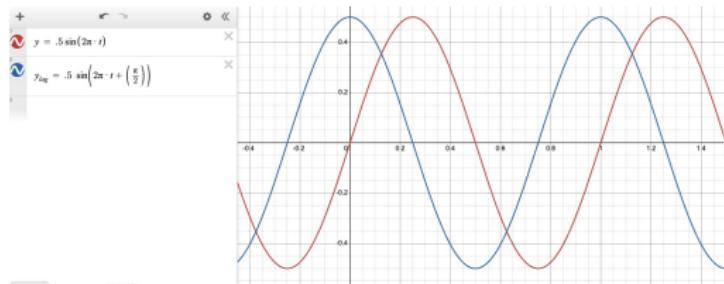




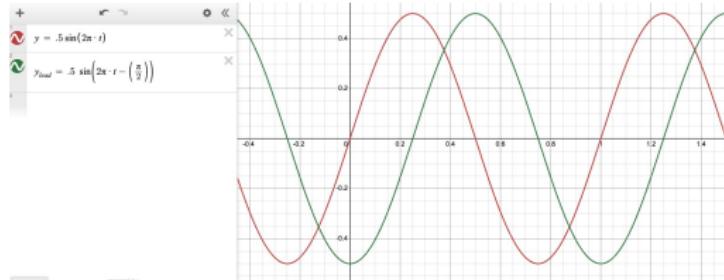
Phase Shift

The sine wave can be shifted relative to each other by adding in a phase shift (ϕ), which will shift the wave to the left or right.

Blue lags Red:



Green leads Red:





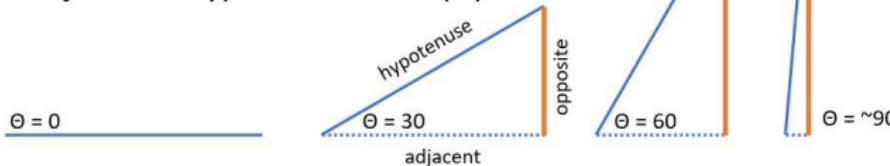
SOH CAH TOA

- $\sin = \text{opposite over hypotenuse}$
- $\cos = \text{adjacent over hypotenuse}$
- $\tan = \text{opposite over adjacent}$

$$\cos(\Theta) = \text{adjacent} / \text{hypotenuse}$$

or

$$\text{Adjacent} = \text{hypotenuse} * \cos(\Theta)$$



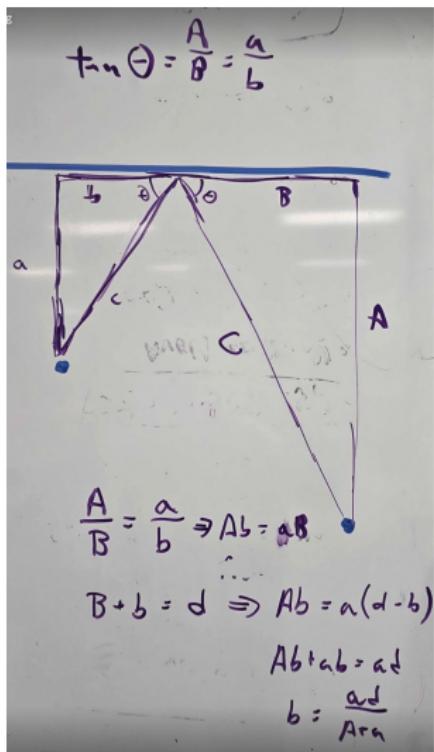
$$\sin(\Theta) = \text{opposite} / \text{hypotenuse}$$

or

$$\text{opposite} = \text{hypotenuse} * \sin(\Theta)$$



Assignment: Calculating Angles: Laser Billiards



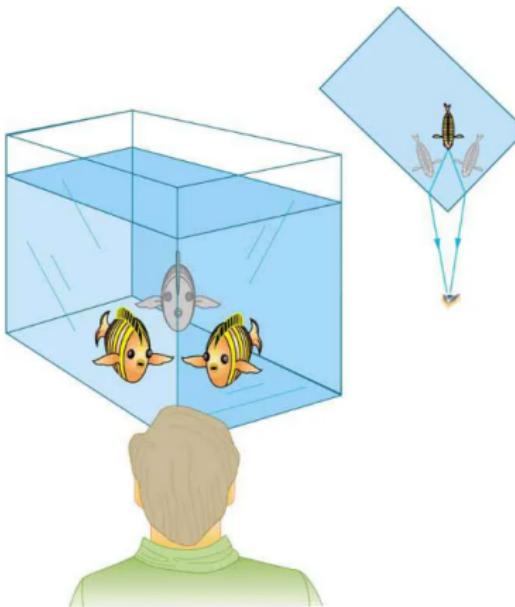
- Setup a mirror line on the optical table.
- Place the laser and target two different distances from the line.
- Calculate the location of the mirror, place the mirror there.
- Calculate the angle of the laser, adjust laser angle.
- Turn on laser and see how close on target the calculations are.

Return to Geometric Optics



Refraction

The changing of a light ray's direction (loosely called bending) when it passes through variations in matter is called refraction.





Index of Refraction

The speed of light depends strongly on the type of material. We define the index of refraction (n) as

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

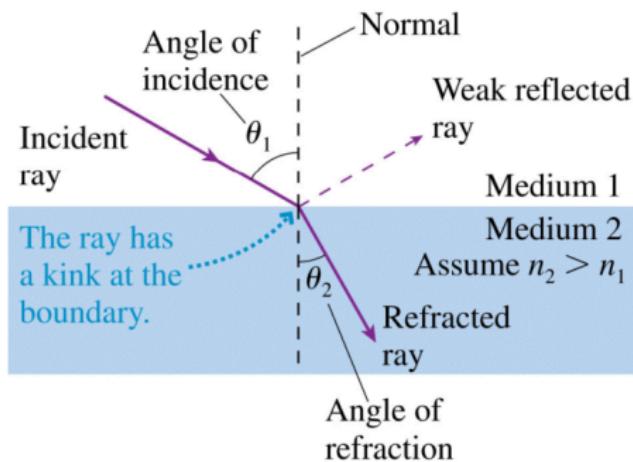
where v is the speed of light in the material and c is the speed of light in a vacuum.

Medium	n
Vacuum	1.00 exactly
Air (actual)	1.0003
Air (accepted)	1.00
Water	1.33
Ethyl alcohol	1.36
Oil	1.46
Glass (typical)	1.50
Polystyrene plastic	1.59
Cubic zirconia	2.18
Diamond	2.41
Silicon (infrared)	3.50



Law of Refraction - Snell's Law

The law of refraction is also called Snell's law after the Dutch mathematician Willebrord Snell (1591–1626).



$$\text{Snell's Law: } n_1 \sin \theta_1 = n_2 \sin \theta_2$$



Finding Index of Refraction

Snells Law:

$$n_1 \sin \theta_1 = n_2 \sin \theta_2 \quad (1)$$

Rearranging to isolate n_2 :

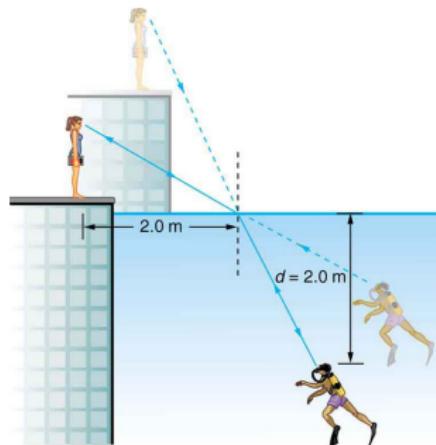
$$n_2 = n_1 \frac{\sin \theta_1}{\sin \theta_2} \quad (2)$$

For example, if the initial medium is air, $\theta_1 = 30^\circ$ and $\theta_2 = 22^\circ$

$$n_2 = (1.00) \cdot \frac{\sin 30^\circ}{\sin 22^\circ} = \frac{0.500}{0.375} = 1.33 \quad (3)$$



Assignment: Measuring Refraction



- Some assignment on refraction
- Acrylic, water, what else?
- Different color lasers (red, green, and if we get blue in time)



Total Internal Reflection

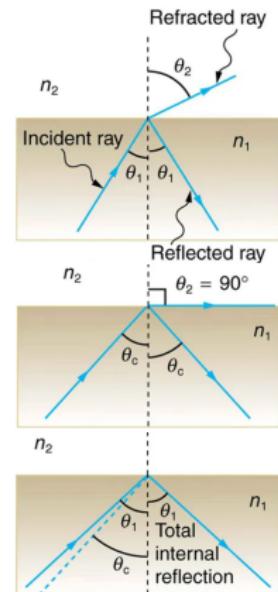
Good mirrors reflect > 90% of the light; however, total reflection can be produced via refraction.

If the index of refraction of the second medium is less than that of the first medium, the rays are refracted away from the perpendicular.

- Since $n_1 > n_2$, the angle of refraction is greater than the angle of incidence: $\theta_2 > \theta_1$.
- Increasing θ_1 causes θ_2 to increase.
- The critical angle (θ_c) is defined to be the incident angle (θ_1) that produces a $\theta_2 = 90^\circ$

The critical angle is given by:

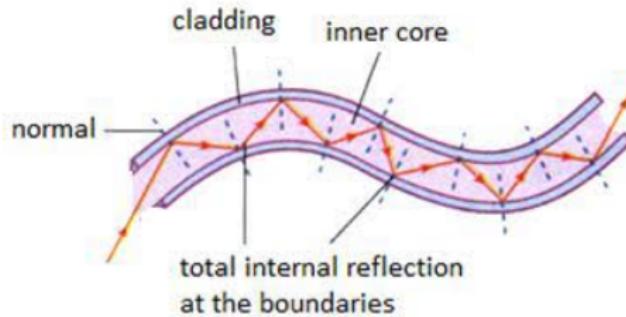
$$\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right), \quad \text{for } n_1 > n_2 \quad (4)$$





Fiber Optic Cable

The fiber optic cable takes advantage of the core having a high index of refraction than the cladding.





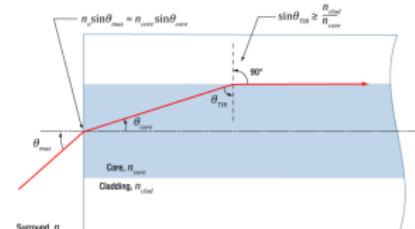
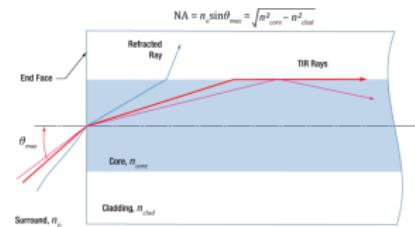
Fiber: Acceptance Angle

For multi-mode fibers, the numerical aperture (NA) provides a good estimate of the maximum acceptance angle.

- The cutoff angle is the maximum acceptance angle (θ_{max}), which is related to NA:

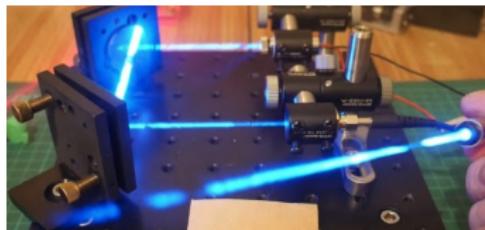
$$NA = n_0 \sin(\theta_{max}) = \sqrt{n_{core}^2 + n_{clad}^2}$$

- Rays with an angle of incidence $\leq \theta_{max}$ are totally internally reflected (TIR) at the fiber core/cladding boundary.
- Rays with an angle of incidence $> \theta_{max}$ refract at and pass through the boundary.





Assignment: Fiber Coupling

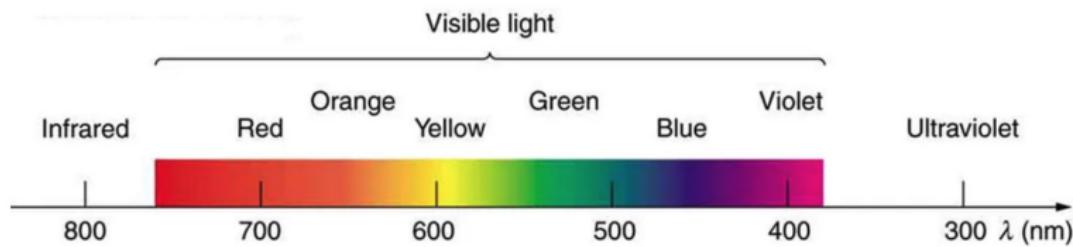


- Use the two mirror walk to align a HeNe laser beam to a fiber.
- Improve the quality of the coupling by maximizin the power meter reading.
- How can you improve the coupling?



Dispersion

Dispersion is defined to be the spreading of white light into its full spectrum of wavelengths.



- The angle of refraction depends on the index of refraction.
- The index of refraction (n) depends on the properties of the medium.
- However, for a given medium, n also depends on the optical wavelength.



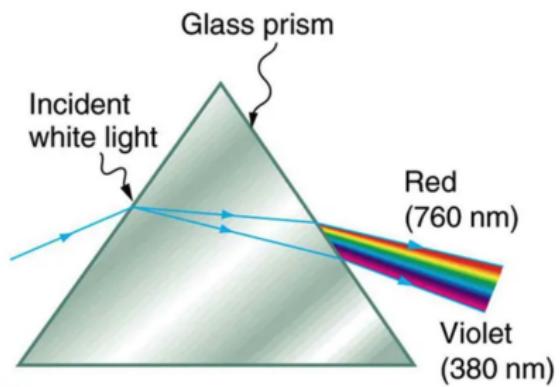
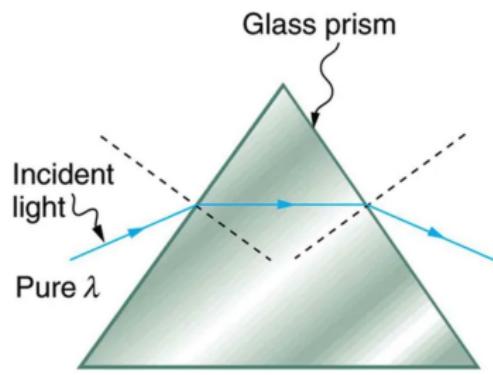
Index of Refraction by Wavelength

Index of refraction (n) by wavelength (λ):

Medium	Red (660 nm)	Orange (610 nm)	Yellow (580 nm)	Green (550 nm)	Blue (470 nm)	Violet (410 nm)
Water	1.331	1.332	1.333	1.335	1.338	1.342
Diamond	2.410	2.415	2.417	2.426	2.444	2.458
Glass, crown	1.512	1.514	1.518	1.519	1.524	1.530
Glass, flint	1.662	1.665	1.667	1.674	1.684	1.698
Polystyrene	1.488	1.490	1.492	1.493	1.499	1.506
Quartz, fused	1.455	1.456	1.458	1.459	1.462	1.468

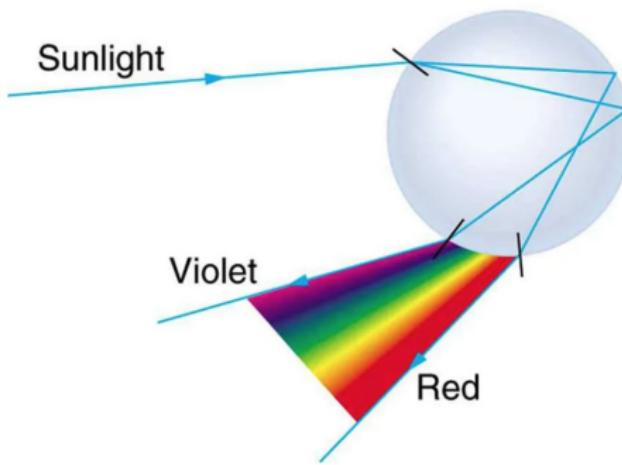


Glass Prism





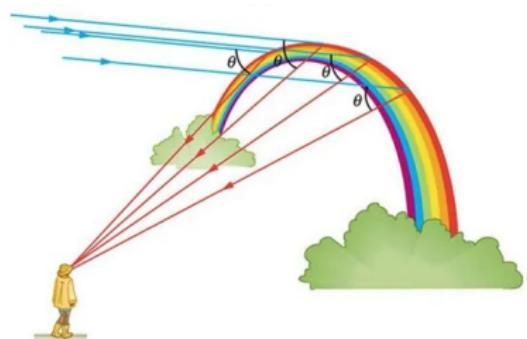
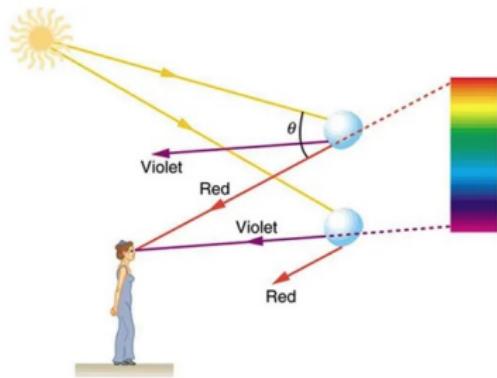
Rainbow



Rainbows are produced by a combination of refraction and reflection. You may have noticed that you see a rainbow only when you look away from the sun. Light enters a drop of water and is reflected from the back of the drop. The light is refracted both as it enters and as it leaves the drop. Since the index of refraction of water varies with wavelength, the light is dispersed, and a rainbow is observed.



Rainbow as an Arc



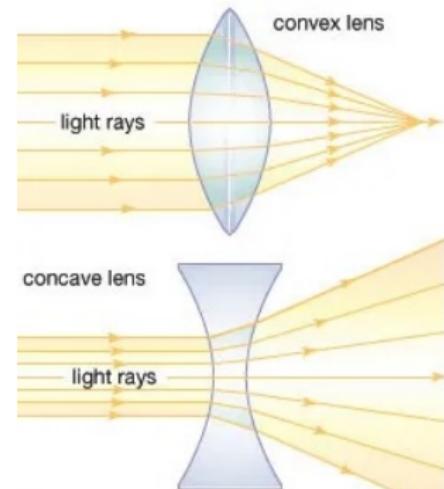
Lens



Lens

With the Law of Refraction, we can explore the properties of lens and how images are formed.

- The word lens comes from the Latin word for lentil bean, the shape of which is similar to a convex lens.
- Convex Lens: all light rays that enter parallel to the axis cross one another at a single point on the opposite side of the lens, i.e., they converge.
- Concave Lens: all light rays that enter parallel to the axis diverge (bend away) from the lens axis.

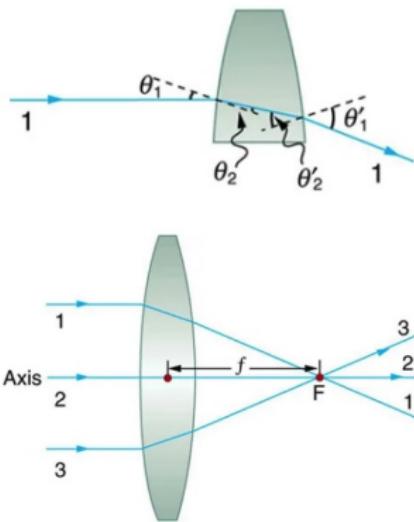




Convex Lens

With the Law of Refraction, we can explore the properties of lens and how images are formed.

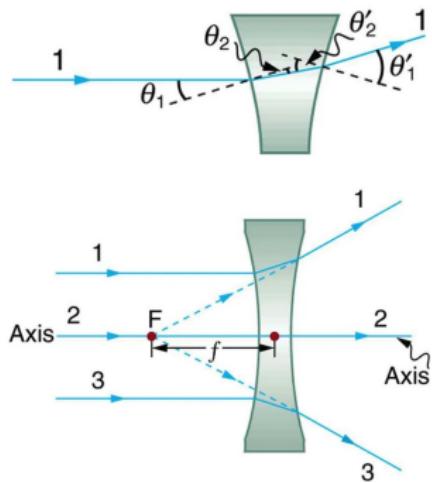
- A ray of light bends (refracts) at both interface, and for convex lens converge.
- The point at which the rays crossed is defined as the Focal point (F) of the lens.
- The distance from the center of the lens to its focal point is called the focal length (f).
- The Power of the lens, measuring in Diopters ($P = \frac{1}{f}$) where f is measured in meters.





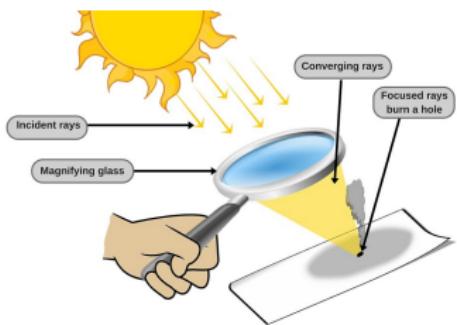
Concave Lens

- A concave lens is a diverging lens, it causes light rays to bend away from the axis.
- In the case of all rays entering parallel to its axis, the light appears to originate at the same point F .
- The distance from the center of the lens to its focal point is called the focal length (f) and is defined to be negative.





Assignment: Find the Focal Length



- Using some random lens, use the overhead lighting to find the focal length
- Repeat on optical table using laser
- Clean lens before putting away



Thin Lens

A thin lens is defined to be one whose thickness allows rays to refract but does not allow properties such as dispersion and aberrations.



Ray Tracing

- ① A ray entering a converging lens parallel to its axis passes through the focal point F of the lens on the other side.
- ② A ray entering a diverging lens parallel to its axis seems to come from the focal point F.
- ③ A ray passing through the center of either a converging or a diverging lens does not change direction.
- ④ A ray entering a converging lens through its focal point exits parallel to its axis.
- ⑤ A ray that enters a diverging lens by heading toward the focal point on the opposite side exits parallel to the axis.

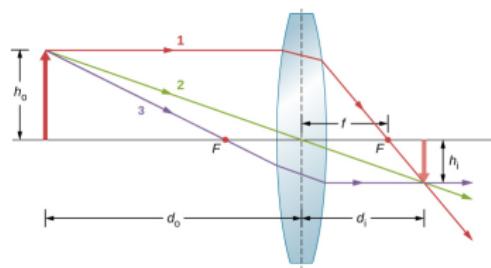
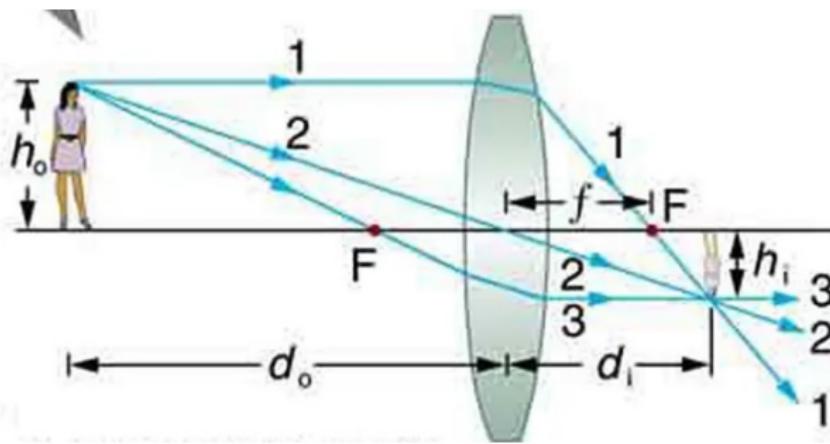




Image Formation



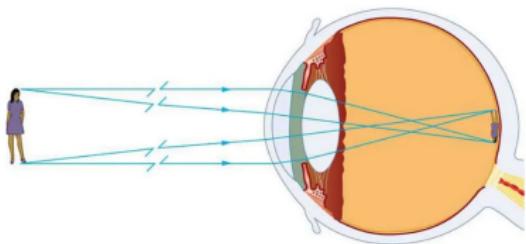
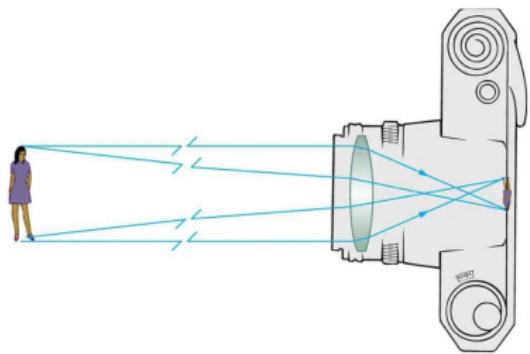
Thin Lens equations:

$$\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}$$

$$\frac{h_i}{h_o} = -\frac{d_i}{d_o} = m$$



Image Formation - Real Image



The image in which light rays from one point on the object actually cross at the location of the image and can be projected onto a screen, a piece of film, or the retina of an eye is called a real image.



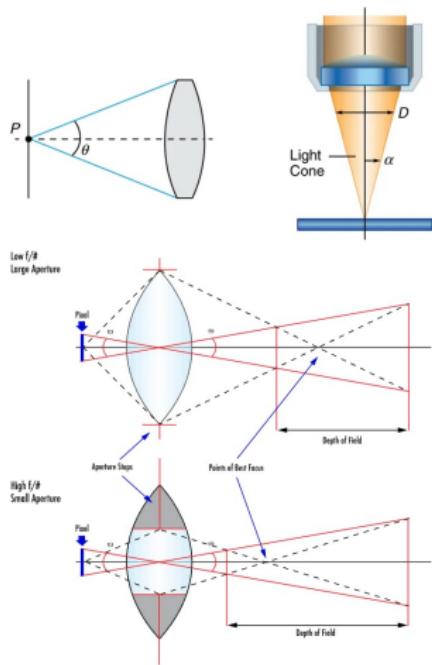
Assignment - Focus CCD Camera



- Get a Thor CCD camera from the Optical Tweezer kit
- Select lens tube, adjustable lens tube, and lens
- Assemble and mount on table.
- Connect to ThorCam software
- Using adjustable lens tube, focus on various objects



Optical System Parameters



- Numerical Aperture (NA):

$$NA = n \cdot \sin(\alpha) \text{ where } \alpha = \frac{\theta}{2}$$

- f -number - light per unit area reaching image plane:

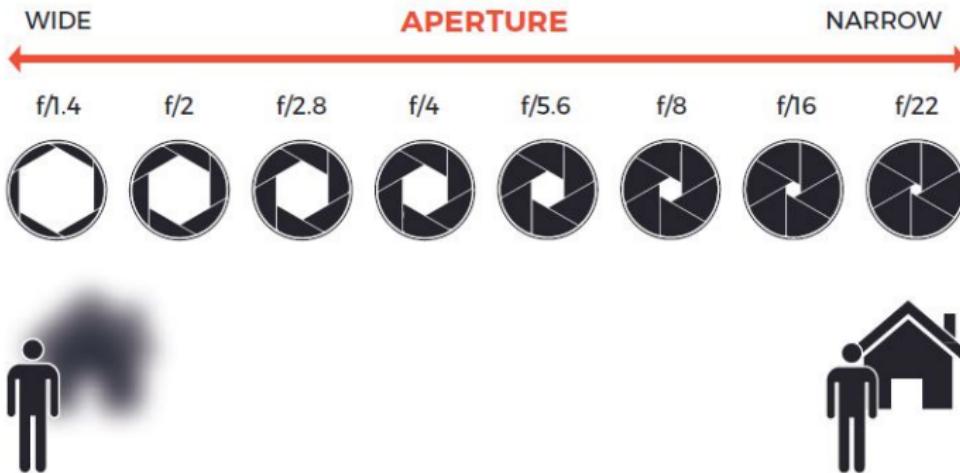
$$f/\# = \frac{f}{D} \approx \frac{1}{2NA}$$

- Resolution and Depth of Focus:

$$R = \frac{1.22\lambda}{2NA} \text{ and } DOF = \frac{\lambda n}{NA^2}$$



Aside: Camera f -stop



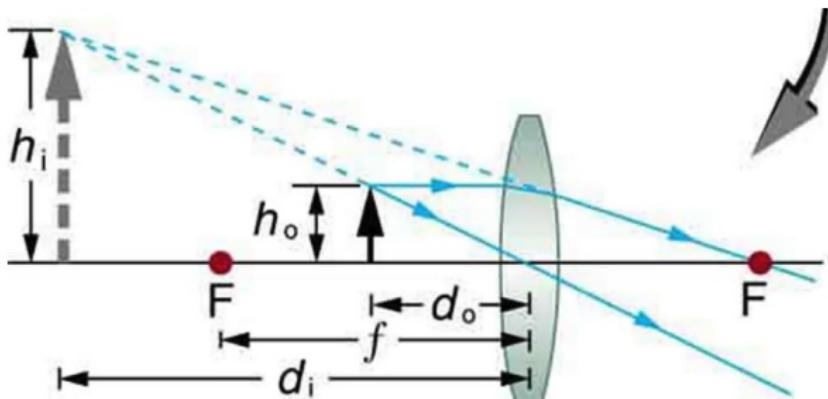
Light floods in and less is in focus.
Shallow depth of field occurs.

Light funnels in and more is in focus.
Deeper depth of field occurs.

$$f/1 = \frac{f}{(\sqrt{2})^0}, f/1.4 = \frac{f}{(\sqrt{2})^1}, f/2 = \frac{f}{(\sqrt{2})^2}, f/2.8 = \frac{f}{(\sqrt{2})^3}, \dots$$



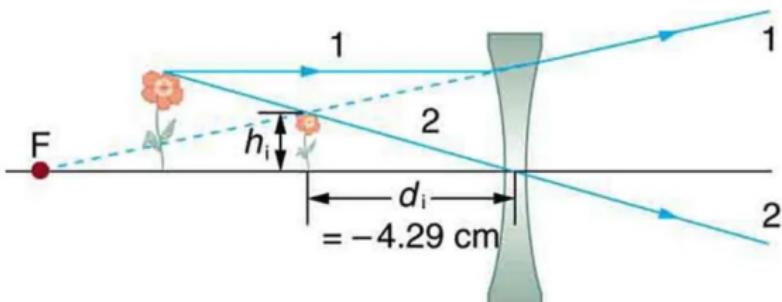
Image Formation - Virtual Image



If an object is held closer to the converging lens than its focal length (f), then the rays from a common point continue to diverge after passing through the lens. They all appear to originate from a point at the location of the image, on the same side of the lens as the object. This is a virtual image.

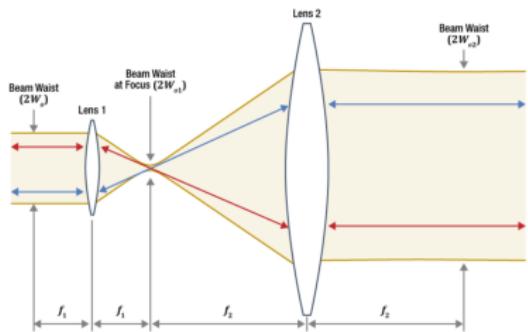


Image Formation - Concave Lens

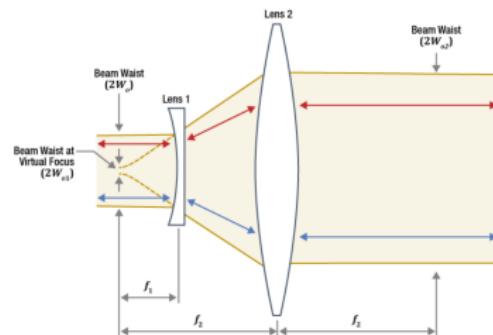




Beam Expander/Reducer - Telescope



Keplerian Design



Galilean Design

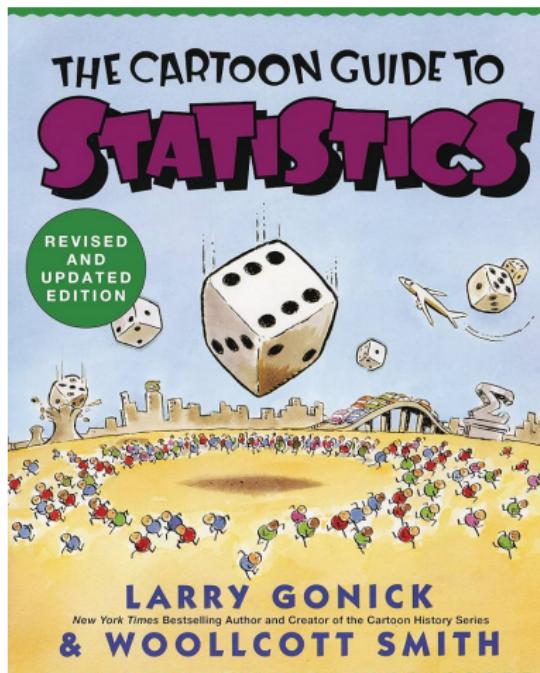
Both the beam's waist ($2W_0$) and the divergence angle (θ) are affected by the beam expanders and reducers. If Lens 2 is the output lens, then the beam expansion ratio (m_{12}) is:

$$m_{12} = \frac{f_2}{f_1} \quad (5)$$

Math Interlude: Probability



Probability and Statistics



- Data Analysis: The gathering, display, and summary of data
- Probability: The laws of chance (inside and outside of a casino)
- Statistical Inference: the science of drawing statistical conclusions from specific data using the laws of probability



A Tale as Old as Time



Gambling is as old as mankind, so it seems that probability should be almost as old. But, the realization that one could predict an outcome to a certain degree of accuracy was unconceivable until the 16th century. In order to make a profit, underwriters were in need of dependable guidelines by which a profit could be expected, while the gambler was interested in predicting the possibility of gain.



Rich Guys Gambling



Known as the “Father of Probability”, Gerolamo Cardano was an Italian mathematician, physician, and gambler who first talked about probability. Cardano’s fascination with games of chance led him to write the first book dedicated to probability, “Liber de Ludo Aleae” (Book on Games of Chance), published in 1564. Cardano introduced concepts like odds and probabilities in this work, providing a framework for analyzing the likelihood of different outcomes in dice rolls and other games.



Probability

The probability of an event expresses the likelihood of the event outcome

$$P(\text{event}) = \frac{\# \text{ of favorable outcomes}}{\# \text{ of all possibly outcomes}}$$

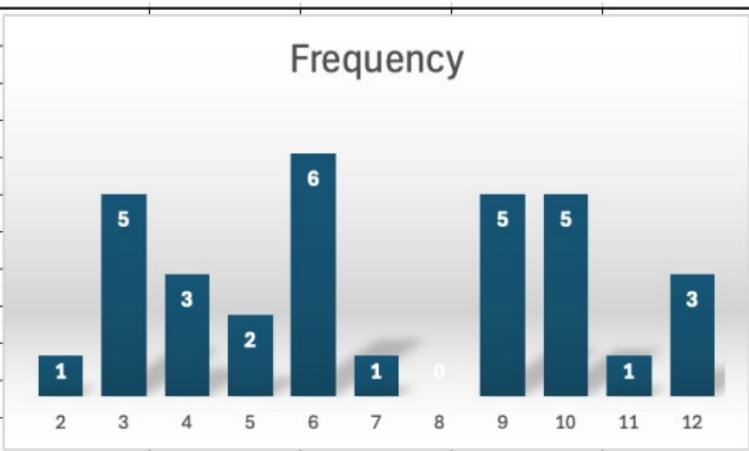




Frequency Tables and Histograms

Roll two dice and add them together, repeat.

Dice Roll	Frequency
2	1
3	5
4	3
5	2
6	6
7	1
8	0
9	5
10	5
11	1
12	3





Assignment: Tenzi



Role two dice 12 times, after each role:

- Record the sum
- Record the running average (total up to this point divided by number of roles)

After the twelfth role:

- Create a histogram of the sums
- Create a line chart of the running averages



Summary Statistics

- Mean (or average): add the totals and divide by number of samples

$$\bar{x} = \frac{x_1 + x_2 + x_3 + \dots + x_n}{n}$$

or

$$\bar{x} = \frac{\sum_{i=1}^n (x_i)}{n}$$

- Median: middle sample in the ordered distribution
 - Odd: median is the value of middle sample
 - Even: median is the average of the two middle samples
- Mode: the value that appears most often

Dice Roll	Frequency	Total
2	1	2
3	5	15
4	3	12
5	2	10
6	6	36
7	1	7
8	0	0
9	5	45
10	5	50
11	1	11
12	3	36
SUM	32	224

$$\text{average} = \bar{x} = 7$$

$$\text{median} = 6$$

$$\text{mode} = 6$$



Summary Statistics: Variation

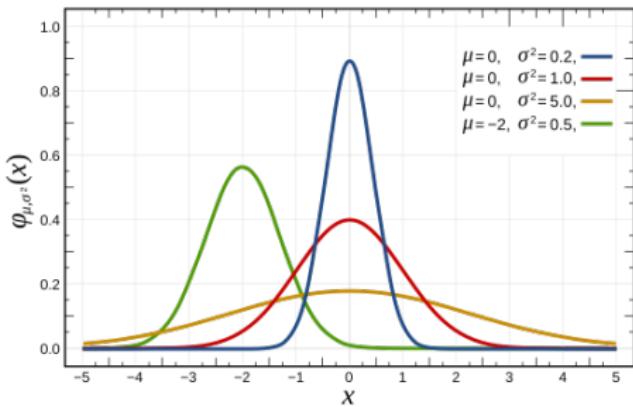
1-8	9-16	17-24	25-32
2 3 3 3 3 4 4	4 5 5 6 6 6 6	6 7 9 9 9 9 10	10 10 10 10 11 12 12 12

- Interquartile Range (IRQ): Spread of the middle 50% of the data
 - Find the median
 - Find the first quartile (Q1): median of the lower half.
 - Find the third quartile (Q3): median of the upper half.
 - $\text{IRQ} = \text{Q3} - \text{Q1} = 6$
- Standard Deviations (σ):

$$\sigma = \sqrt{\frac{\sum_{i=0}^n (x_i - \bar{x})^2}{n}} = 3.06$$



Gaussian Distribution

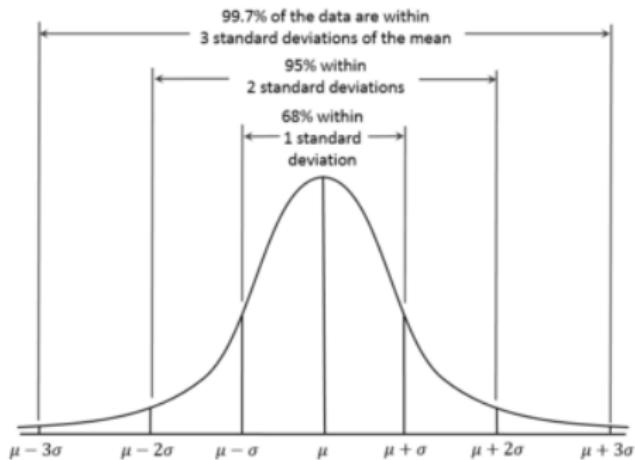


Probability Distribution Function $f(x)$:

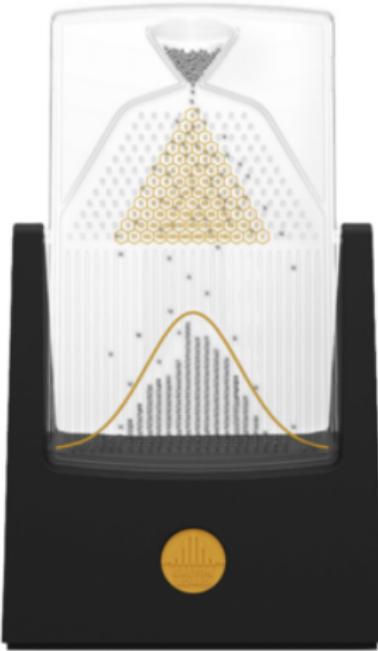
$$f(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-\bar{x})^2}{2\sigma^2}}$$



Gaussian Distribution: 3σ

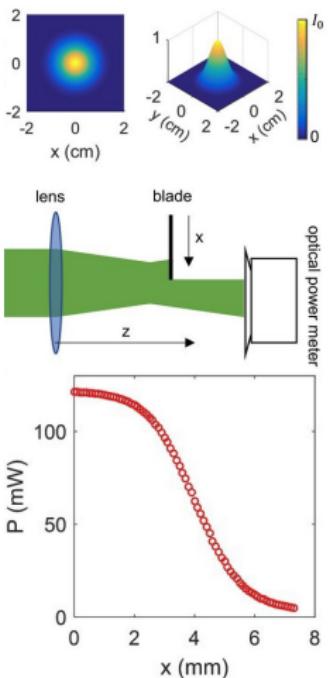


Galton Baord





Assignment: Measuring Bean Profile



The laser beam has a Gaussian profile.

- ① Direct a laser beam at a power meter, setting the correct wavelength
- ② Moving the knife edge across the beam path, record the drop in power vs distance.
- ③ Setup a telescope to expand the beam size by 2-5 times.
- ④ Repeat the knife edge process.
- ⑤ Plot the results of both sets of measurements on paper and in excel.



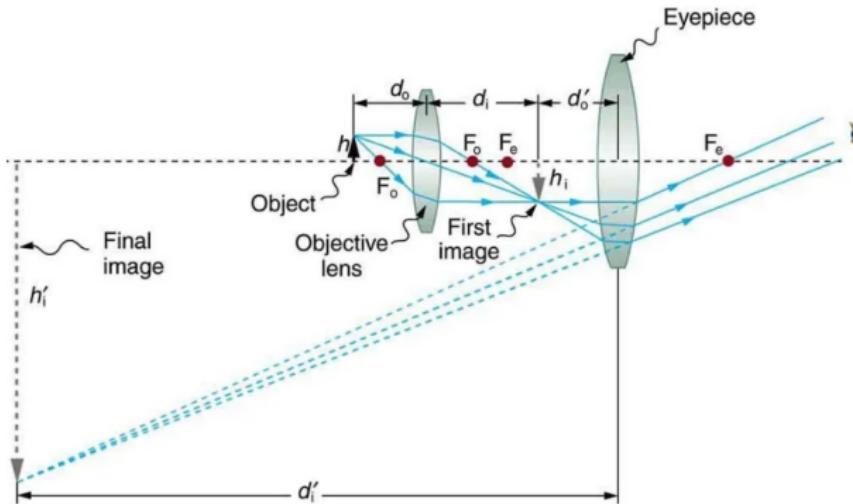
Python Excursion



Optical Tweezers



Microscope

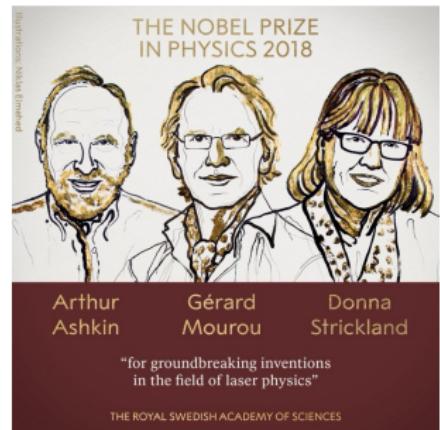


$$m = m_o \cdot m_e = \left(-\frac{d_i}{d_o}\right) \cdot \left(-\frac{d'_i}{d'_o}\right)$$



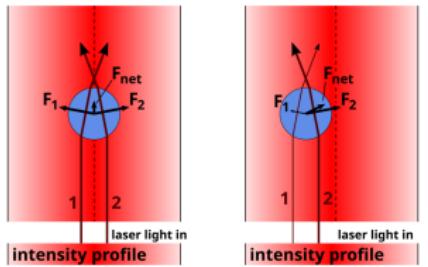
Optical Tweezers - Collimated Laser

- Ashkin's award was being given for his ability to "realize an old dream of science fiction – using the radiation pressure of light to move physical objects" aka the Tractor Beam.
- In 1987 Ashkin and his team were able to send a laser through a microscope's objective lens and trapping particles varying in size from a tens of nanometres up to tens of micrometres





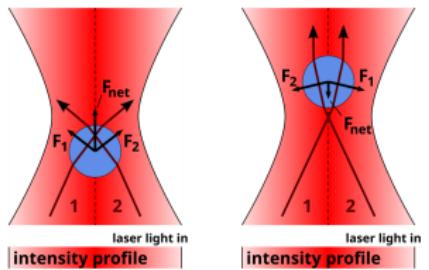
Optical Tweezers - Collimated Laser



When the bead is displaced from the beam center (right image), the larger momentum change of the more intense rays cause a net force to be applied back toward the center of the laser. When the bead is laterally centered on the beam (left image), the resulting lateral force is zero. But an unfocused laser still causes a force pointing away from the laser.



Optical Tweezers - Focused Laser



In addition to keeping the bead in the center of the laser, a focused laser also keeps the bead in a fixed axial position: The momentum change of the focused rays causes a force towards the laser focus, both when the bead is in front (left image) or behind (right image) the laser focus. So, the bead will stay slightly behind the focus, where this force compensates the scattering force.



Assignment: Optical Tweezers



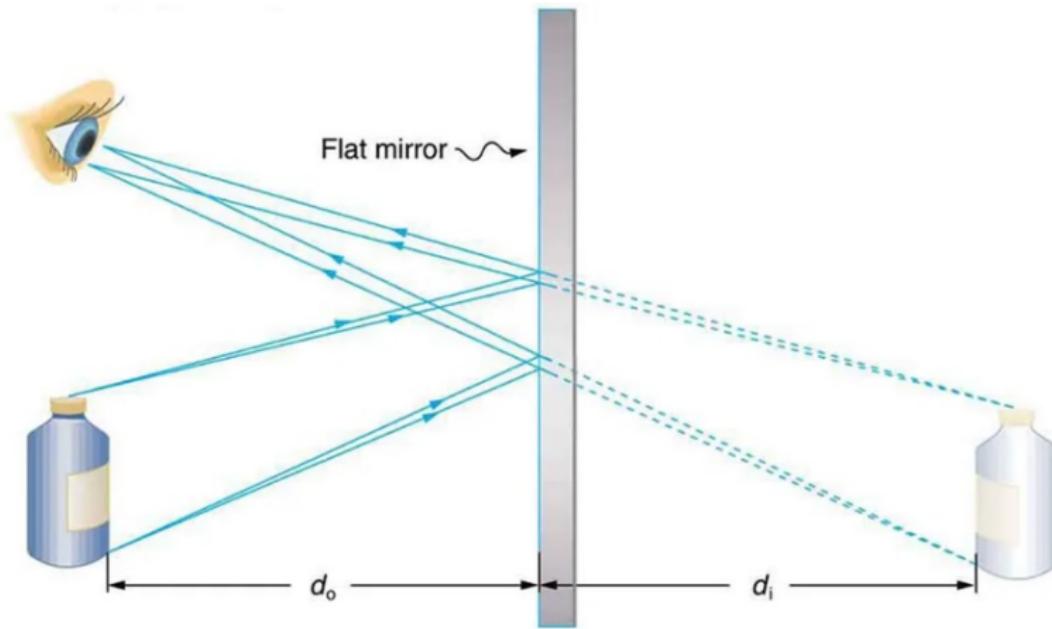
Over the next few days, we will take a few hours at a time to work on EDU-OT3

- Carefully get the parts for the Optical Tweezers from the cabinets
- Please don't write in the lab manuals, document progress in your notebooks.
- Follow assembly instructions
 - Take your time, alignment is critical
 - Take notes on the handouts on any documentation changes you feel are needed
- Once constructed, follow the experiment instructions.

Mirrors

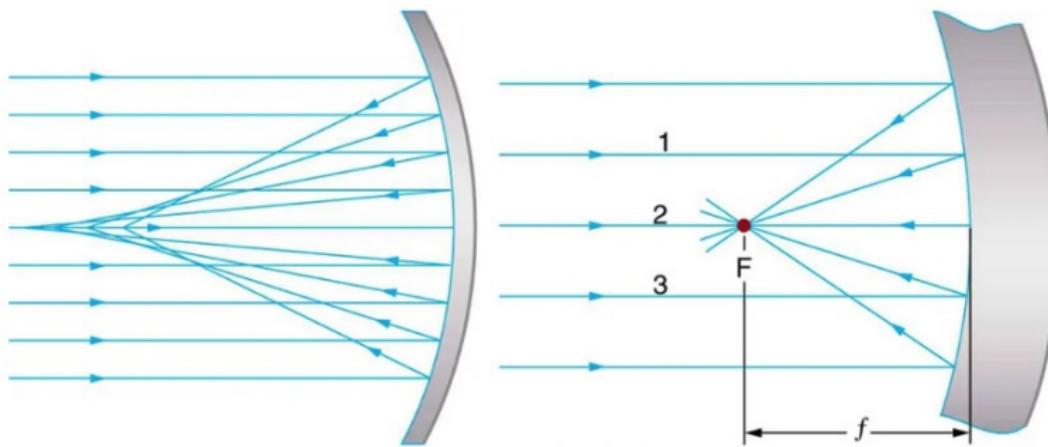


Flat Mirror





Concave Spherical Mirrors - Thin Lens Equivalent



For a mirror that is large compared to the radius of curvature, the reflected rays do not cross at the same point. A parabolic mirror, the rays would indeed cross at a single point. However, parabolic mirrors are expensive. So, using a mirror that is small compared to the radius of curvature, leads to a well-defined focal point F , with $f = \frac{R}{2}$.



Convex Mirrors

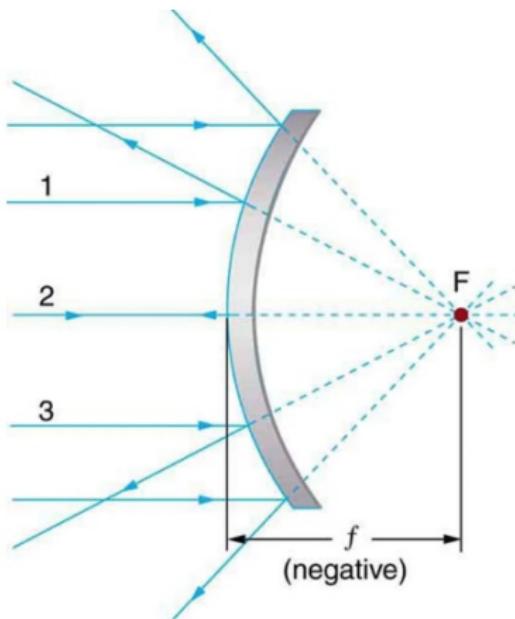




Image Formation - Concave Mirrors

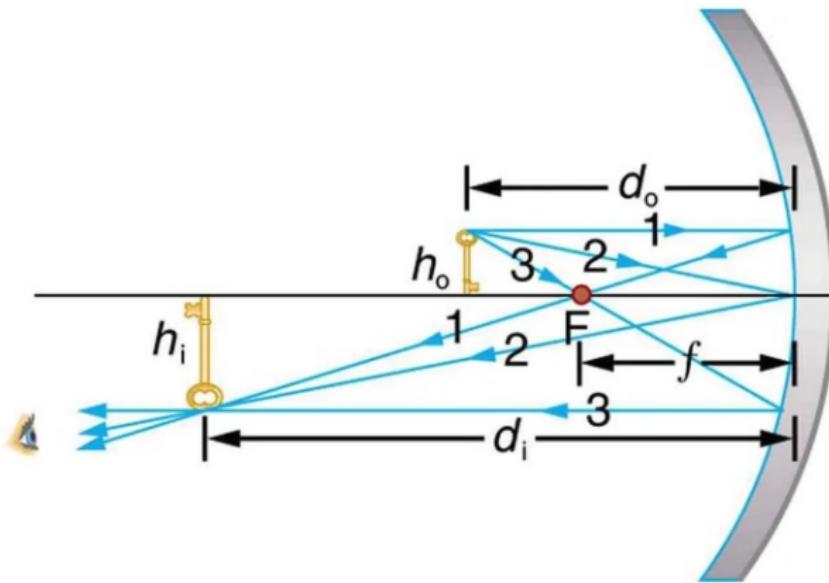




Image Formation - Concave Mirrors

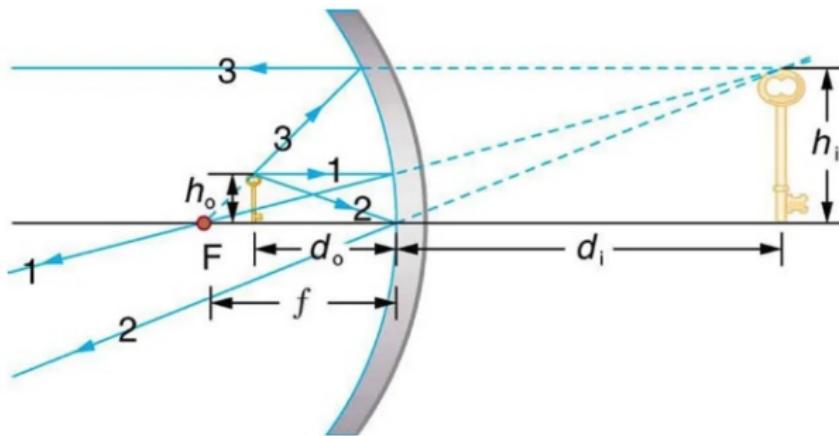
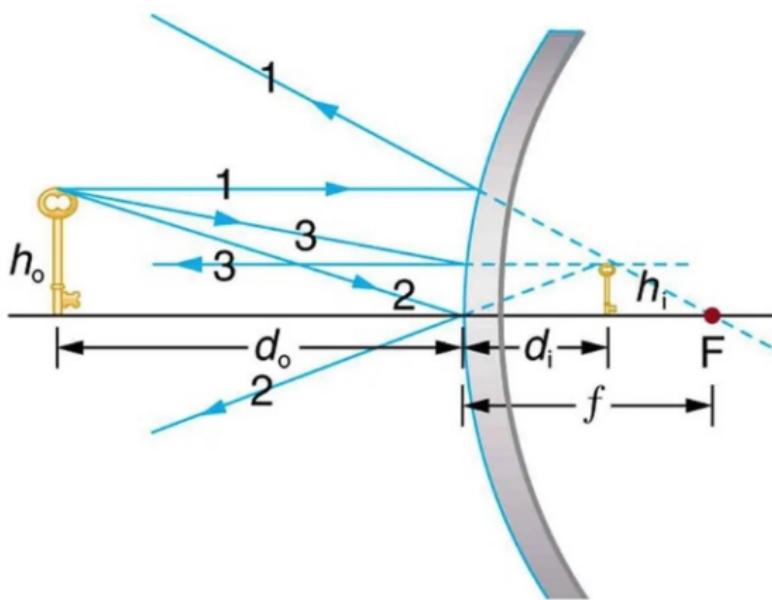




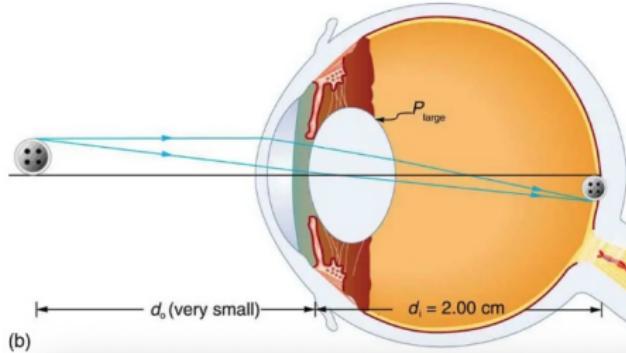
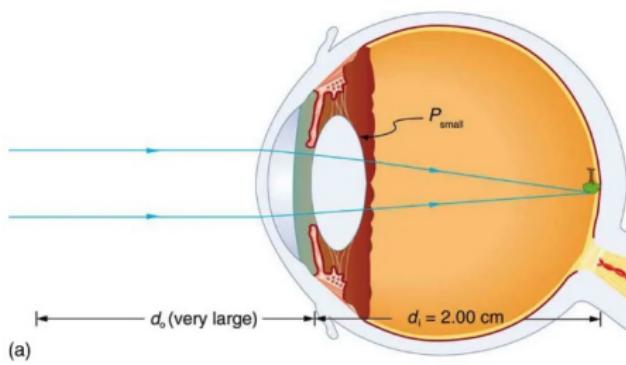
Image Formation - Convex Mirrors



Vision

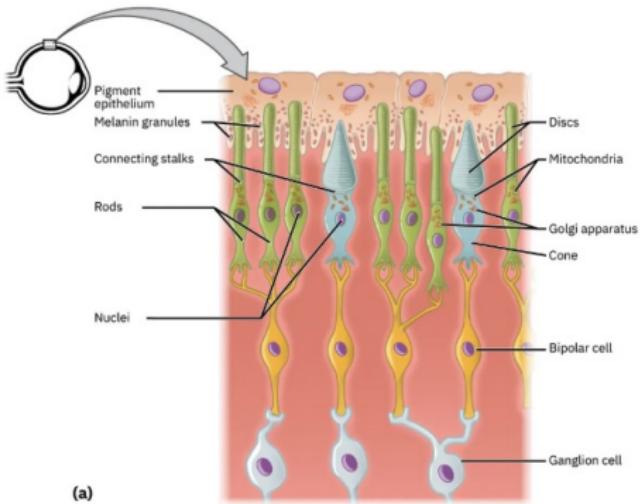


The Eye





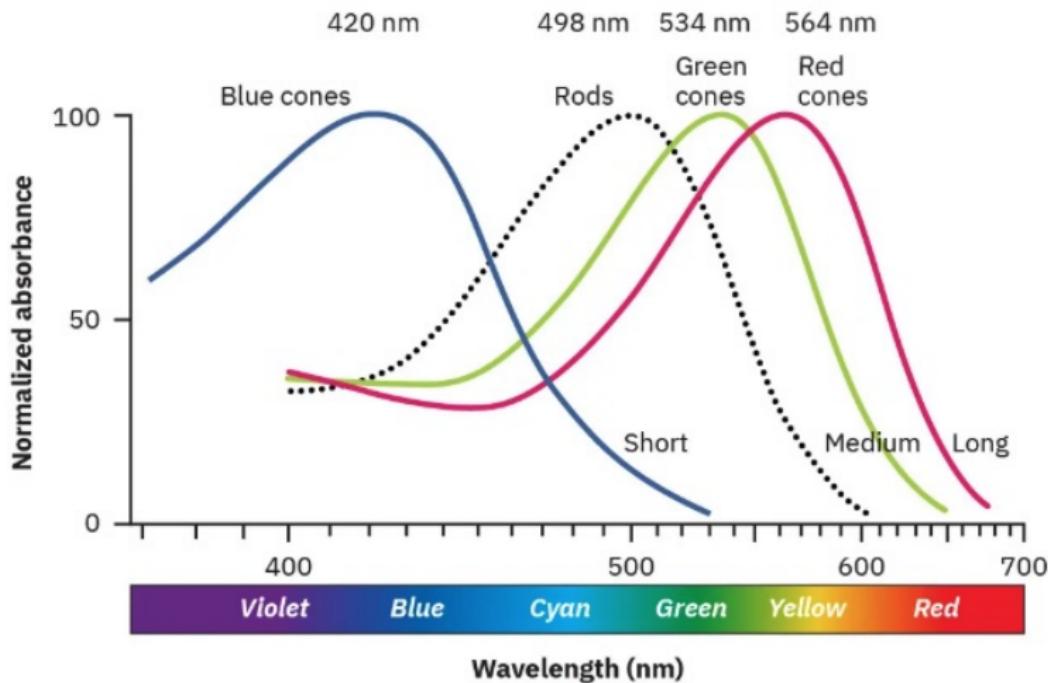
Rods and Cones and Color



(a)

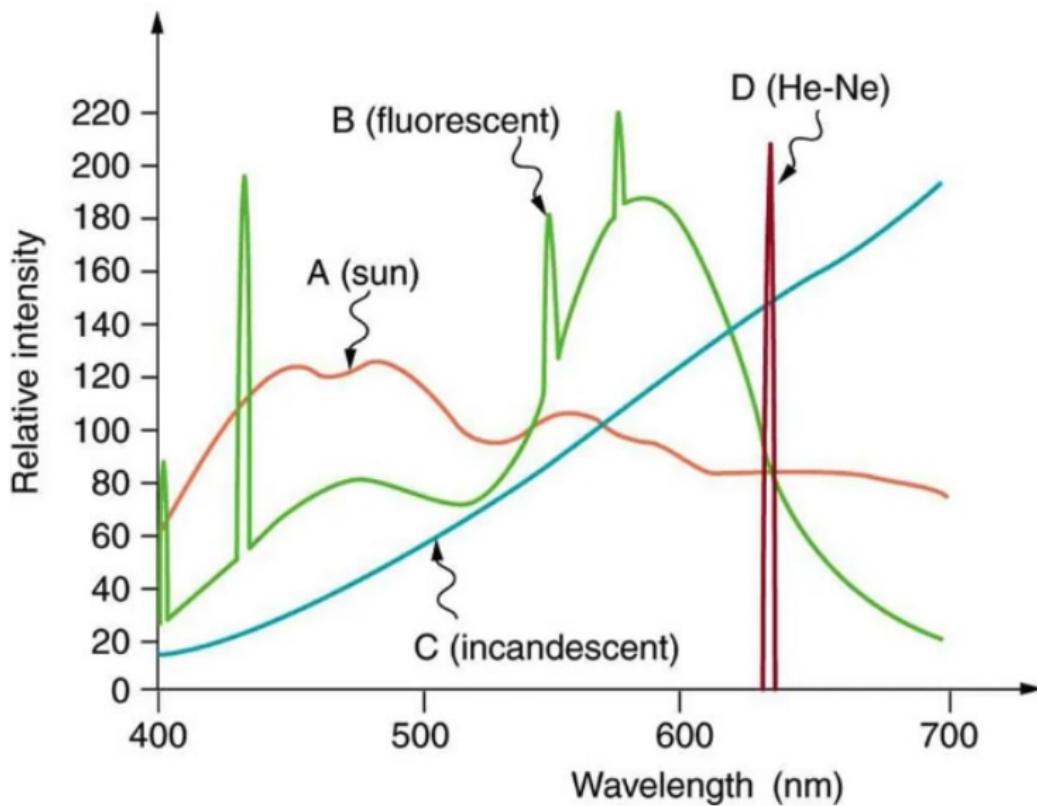


Visible Spectrum



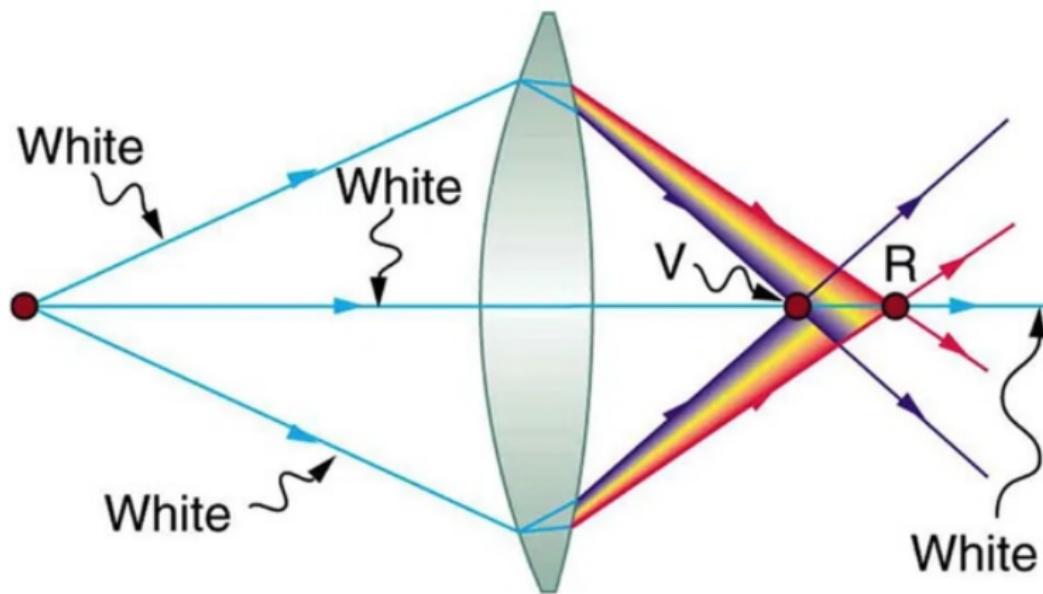


Spectrum of Light Sources



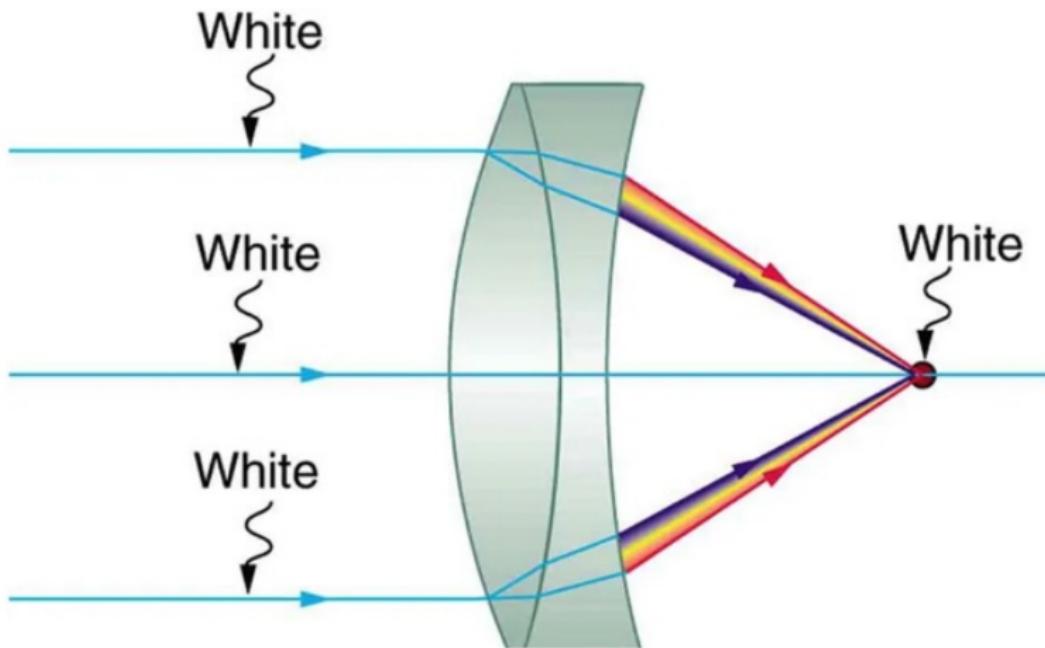


Chromatic Aberrations



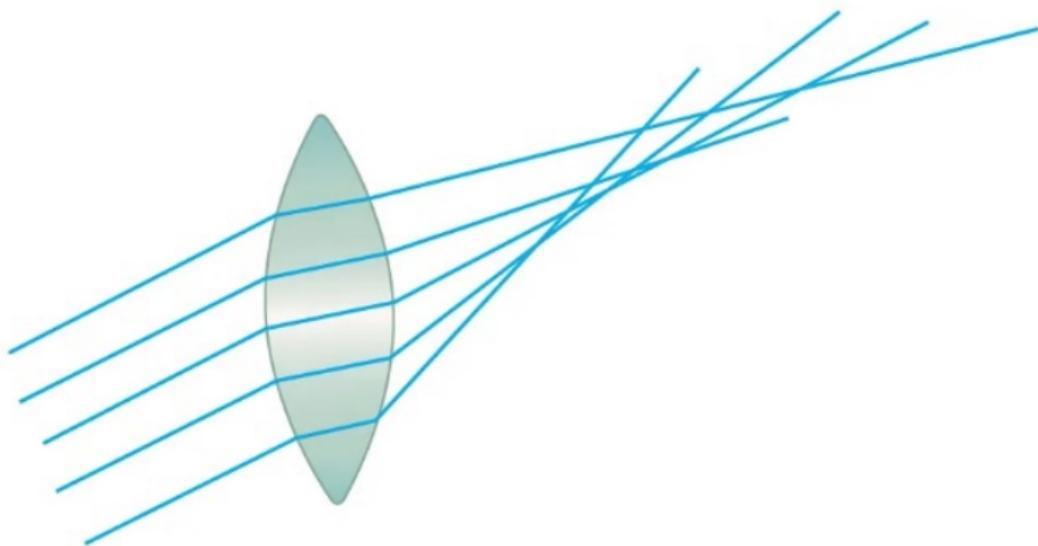


Correcting Chromatic Aberrations



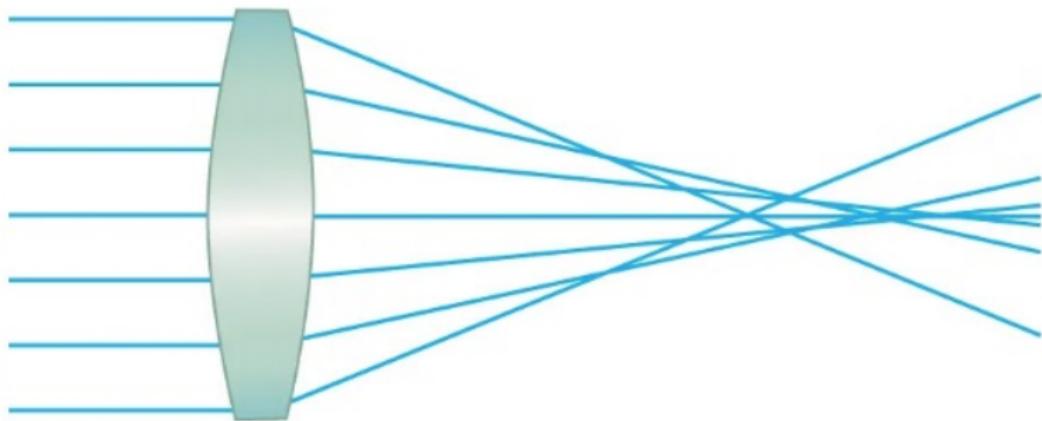


Coma - Off Axis Abberation





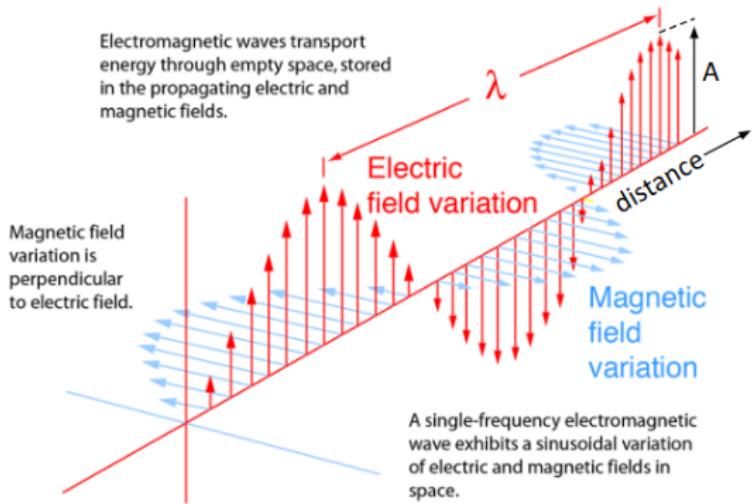
Spherical Aberrations



Wave Optics



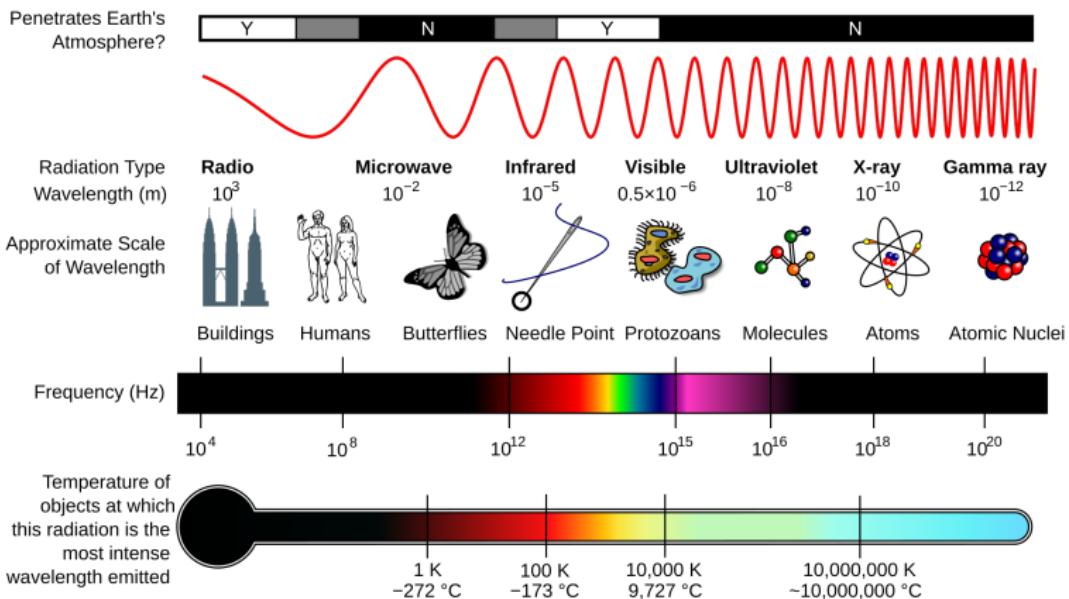
Light as an Electromagnetic Wave



- Wavelength (λ) is the distance between peaks.
- Amplitude (A) is the value between 0 and peak. Or half the distance between peak and trough.

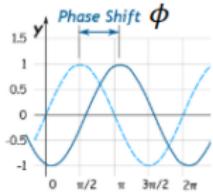
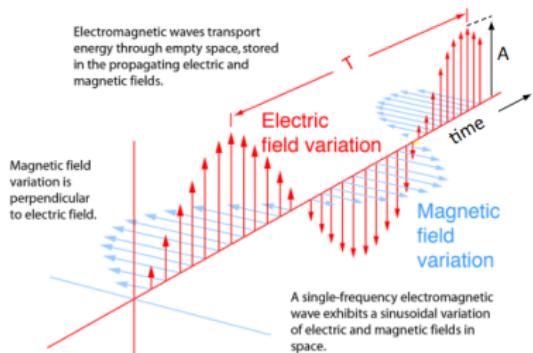


Electro-Magnetic Spectrum





Light as Wave (Wave Equation)



- Period (T) - time between peaks
- Frequency (f) - oscillations per second
- Basic wave equation

$$c \cdot T = \lambda = \frac{c}{f}$$

- Waves in time

$$y(t) = A \cdot \sin(2\pi ft + \phi)$$



Documentation/Lab Notes

Name:	Date:	
Title:		
Hypothesis or Goal:		
Equipment and Procedures:		
Observations / Raw Data:		
Data Analysis:		
Key Findings / Reflections:		
Future Explorations:		

Regular Feedback on Employers:
Documentation, Documentation,
Documentation

- Use the labnotes.doc (template on Teams) or hardcopy to record lab experiments.
- List hypothesis or goal with experiment
- Can reference manual, where applicable, for procedures
- Reflections and Future Explanations are important steps, don't skip



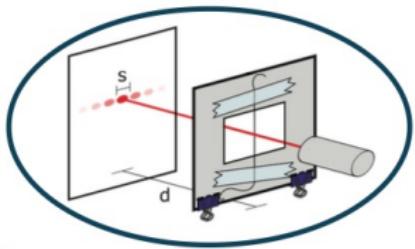
Assignment: Width of Human Hair

Educator's Guide

INTERFERENCE & MEASUREMENT:
MEASURING THE WIDTH OF YOUR HAIR



- Mount a hair and shine laser (of wavelength λ) through it at a screen
- Measure distance to the screen (d)
- Measure the distance between dark spots (s)
- Calculate the width of the hair (w)



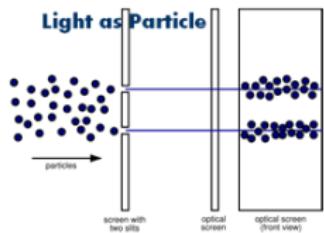
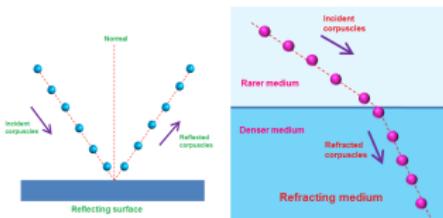
$$w = \frac{2d\lambda}{s}$$

- Try someone else's hair or a different color laser.

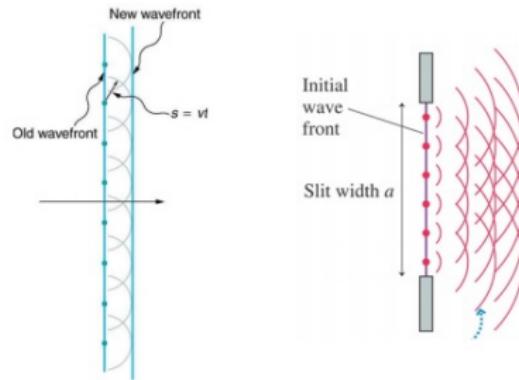


Corpuscular or Waves

In 1675, Sir Isaac Newton hypothesized that light was made up corpuscles (small particles) with the size/mass of the corresponding to different colors.

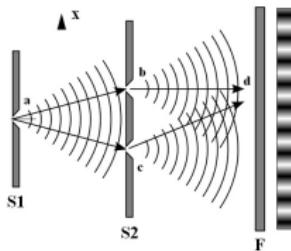


In 1678, Christian Huygens, in order to explain the diffraction of light, proposed that every point on a wavefront is a source of wavelets that spread out in the forward direction at the same speed as the wave itself. The new wavefront is a line tangent to all of the wavelets.





On the theory of light and color



Thomas Young, who had read Newton's Opticks at age 17 saw some problems with Newton's corpuscular theory.

- At interfaces (air/water) some light is reflected and some is refracted.
- Different colors refracted to different degrees

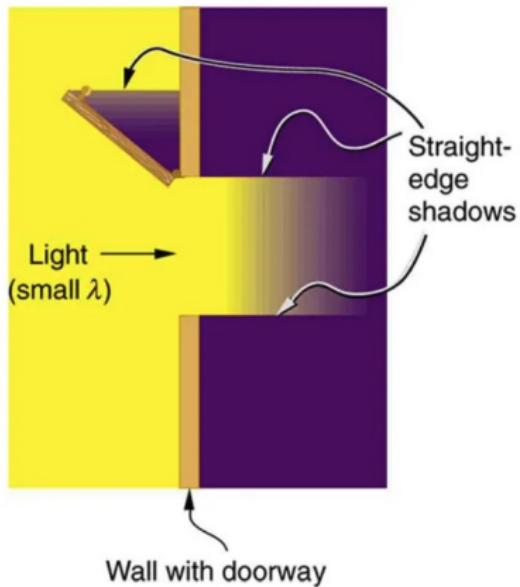
Observing sound (a compression wave in air):

- When two waves of sound cross, they interfere with each other
- Light might exhibit interference phenomena as well
- Developed basic idea for the double-slit experiment, which demonstrated the interference of light waves.



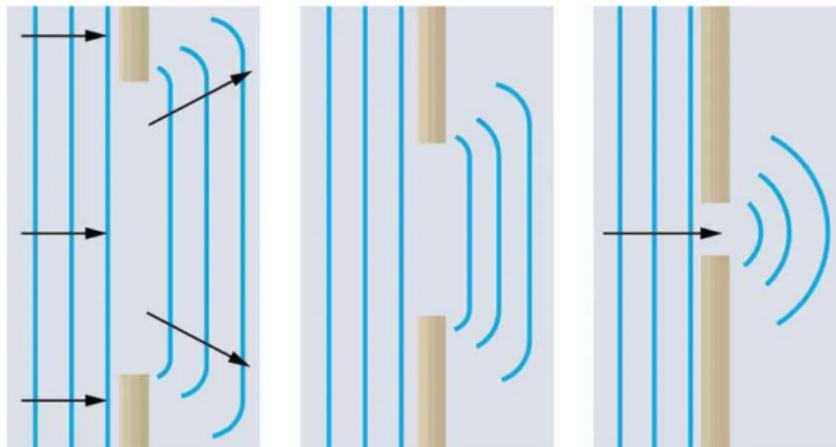
Diffraction

While the ray optics method is useful, if light indeed traveled in straight rays then there would be a pitch black shadow where the light is blocked by the wall.





Diffraction

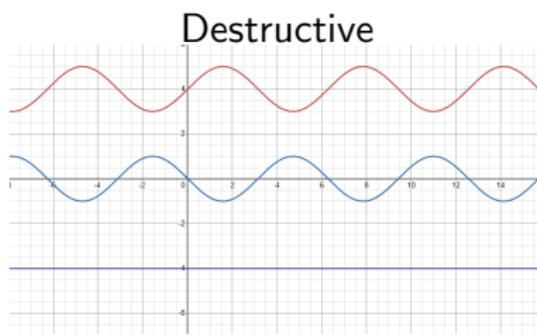
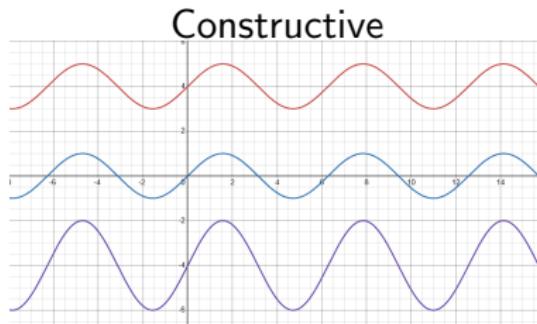
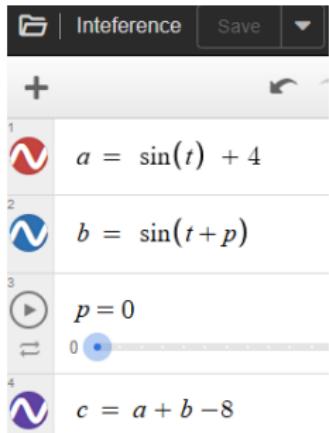


If we pass light through smaller openings, often called slits, we can use Huygens's principle to see that light bends. The bending of a wave around the edges of an opening or an obstacle is called diffraction. Diffraction is a wave characteristic and occurs for all types of waves.



Interference

<https://www.desmos.com/calculator>





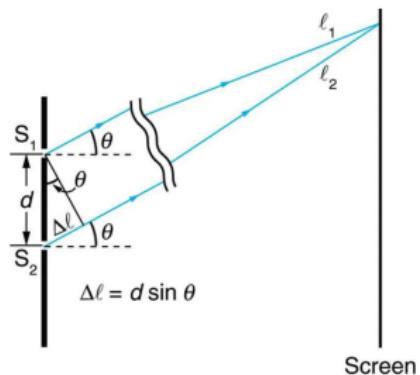
Path Length Difference

- Constructive Interference - peaks are in phase

$$d \sin(\theta) = m\lambda, m = 0, 1, -1, 2, -2, \dots$$

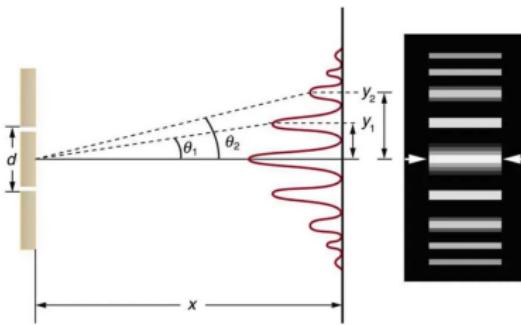
- Destructive Interference - peaks are perfectly out of phase

$$d \sin(\theta) = \left(m + \frac{1}{2}\right)\lambda, m = 0, 1, -1, 2, -2, \dots$$





Double Slit - Constructive Interference



$$\tan(\theta_1) = \frac{y_1}{x}$$

Using small angle assumption⁴:

$$dy_1 = x\lambda \text{ for } m = 1$$

$$d = \frac{x}{y_1} \lambda$$

⁴for small angles (θ) measured in radians, $\tan(\theta) = \sin(\theta) = \theta$.



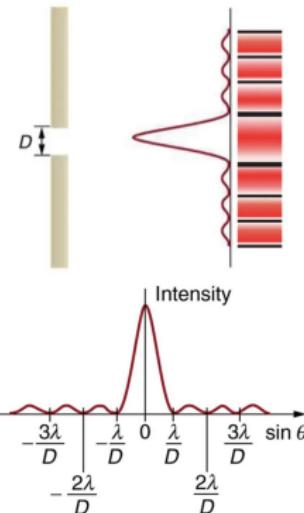
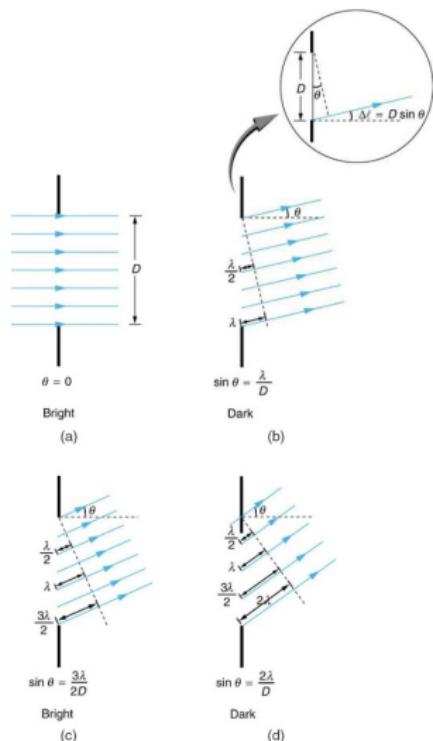
Assignment: Double Slit



- Calculate the slit distance and slit width for three different double slits.



Single Slit



$$D = \frac{2x\lambda}{y_{dark}}$$

Double slit is actually the double slit result times the single slit.



Assignment: Single Slits and Pinholes



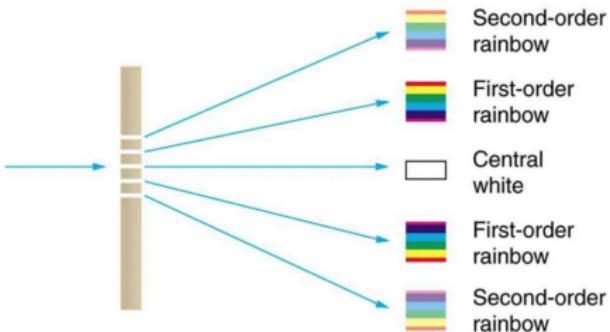
- Calculate the size of the various slits and pinholes using the distance between dark bands



Diffraction Grating

If light is passed through a large number of evenly spaced parallel slits, called a diffraction grating, the interference pattern is created that is very similar to the one formed by a double slit.

Diffraction gratings can be made to work with the transmission or reflection of light.



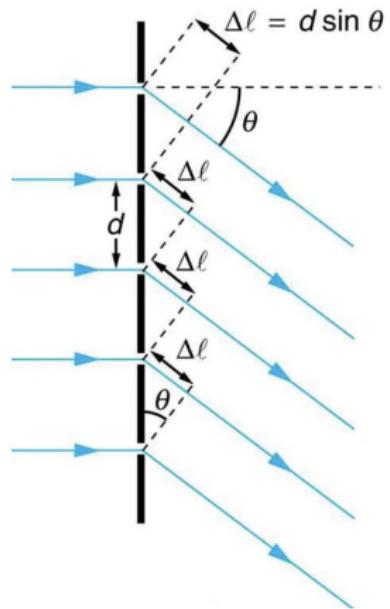


Diffraction Grating - Constructive Interference

Similar to a double slit, the constructive interference happens on integral number of wavelengths:

$$d \cdot \sin(\theta) = m\lambda$$

for, $m = 0, 1, -1, 2, -2, \dots$



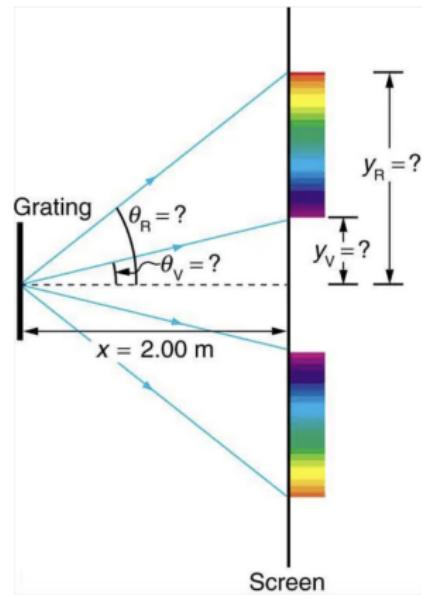


Diffraction Grating - Spread of Wavelength

We can find θ_R , y_R , θ_V , and y_V by using:

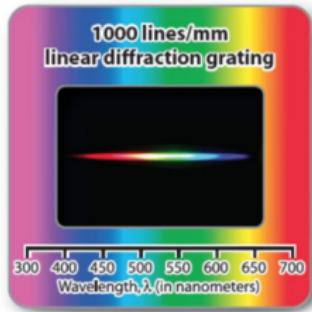
$$d \cdot \sin(\theta) = m\lambda$$

for, $m = 1$.





Assignment: Diffraction Grating

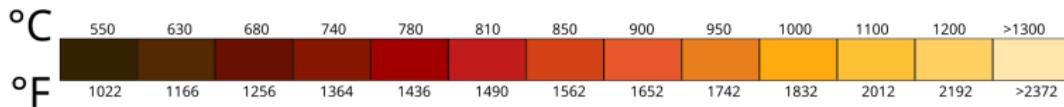


- Setup: Red Laser, Diffraction Slide, Mount, Screen
- Place diffraction slide approximately 3 inches from screen
- Calculate wavelength of laser using diffraction equation
- Repeat for Green and Blue/UV laser



Black Body Radiation

The EM spectrum radiated by a hot solid is linked directly to the solid's temperature. An ideal radiator is one that has an emissivity of 1 at all wavelengths and, thus, is jet black. Ideal radiators are therefore called blackbodies, and their EM radiation is called blackbody radiation.





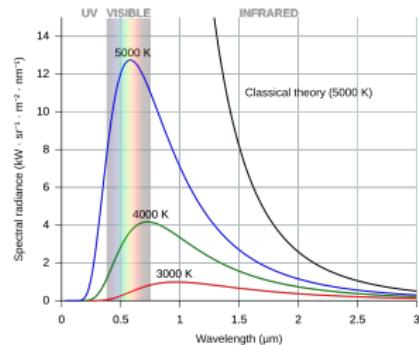
Ultraviolet Catastrophe

The ultraviolet catastrophe was the prediction of classical physics that an ideal black body at thermal equilibrium would emit an unbounded quantity of energy as wavelength decreased into the ultraviolet range.

$$B_f(T) = \frac{2f^2 k_B T}{c^2}, f = \frac{c}{\lambda}$$

where $B_f(T)$ is radiance or intensity at a given frequency

$$B_f(T) \rightarrow \infty, \text{ as } f \rightarrow \infty$$





Quanta

Max Planck assumed that electromagnetic radiation can be emitted or absorbed only in discrete packets, call quanta⁵, of energy:

$$E_{quanta} = hf = h\frac{c}{\lambda}$$

where

- h is Planck's Constant
- f is the frequency of light
- c is the speed of light
- λ is the wavelength of light

Applying the quantification to statistical mechanics:

$$B_\lambda(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{(\frac{hc}{\lambda k_B T})} - 1}$$

⁵Planck considered this a mathematical trick, not reality



Electron Energy



- Charge of an electron ($-q$):

$$q = 1.602 \cdot 10^{-19}$$

- Energy of light or energy loss of electron that has passed through the LED potential

Voltage is **electric potential energy per unit charge** ($V = J/C$)

$$E_{quanta} = V \cdot q$$

- Plank's constant

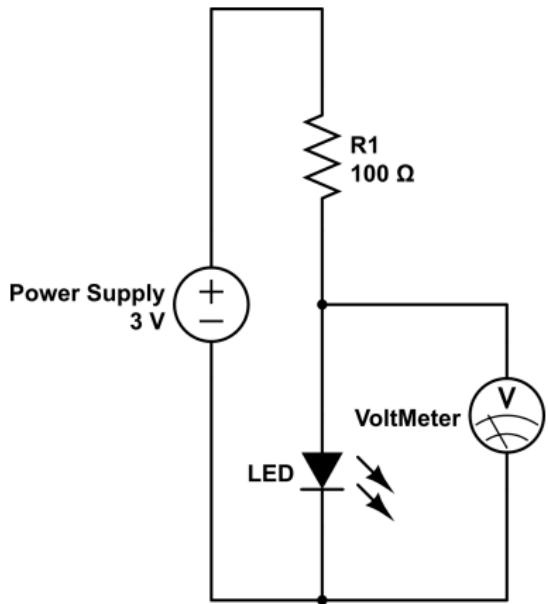
$$E_{quanta} = hf = h\frac{c}{\lambda}$$

$$h = E_{quanta}\left(\frac{\lambda}{c}\right) = \frac{Vq\lambda}{c}$$

where $c = 3 \cdot 10^8(m/s)$



Assignment: Plank and Colors



Using "Determine the Wavelength of an LED" lab sheet:

- Build the circuit to measure voltage across Red LED
- Also use Diffraction slide and ruler to calculate wavelength
- Repeat for Yellow, Green, and Blue LEDs
- Plot voltage vs wavelength in your notebook, excel, or python



The story of the Blue LED



<https://youtu.be/AF8d72mA41M?si=dGNIvEEUrIV7rAS0>



Assignment: Spectrometer



(1. SMA905 connector, 2. Slit, 3. Optional filter, 4. Collimating mirror, 5. Diffraction grating, 6. Focusing mirror, 7. L4 detector collecting lens, 8. CCD detector, 9. Optional OFLV filters, 10. Optional UV4 detector upgrade)

A spectrometer:

- Fiber input and aperture
- Columnating mirror
- Diffraction grating
- Focusing mirror
- CCD detector

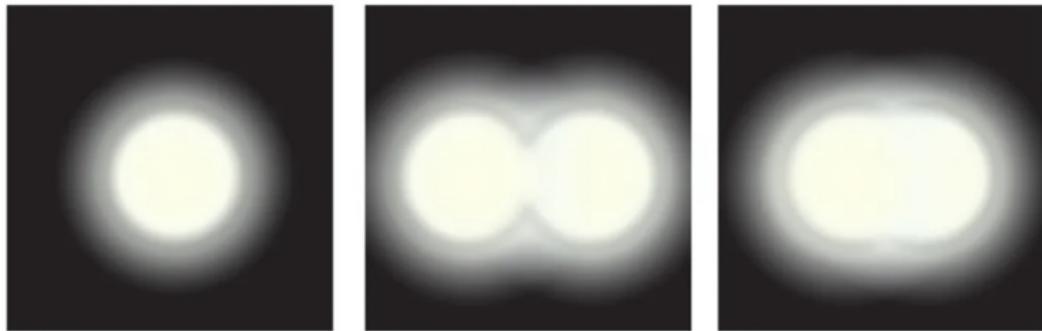
Assignment:

- Measure RED LED wavelength with spectrometer
- Compare to your values from Plank assignment
- Repeat for other colors.



Limits of Resolution

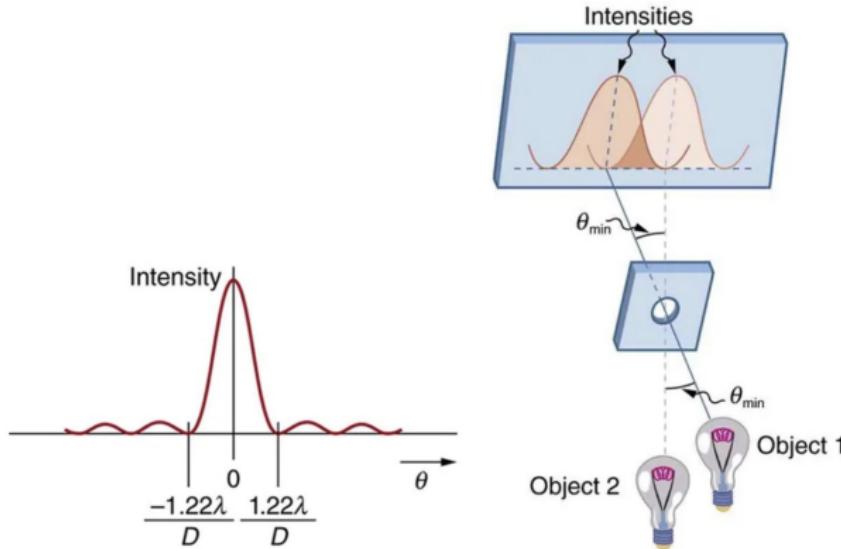
Diffraction affects the detail that can be observed when light passes through an aperture.





Rayleigh Criterion

Two points are just resolved if they are separated by an angle of $\theta = 1.22 \frac{\lambda}{D}$



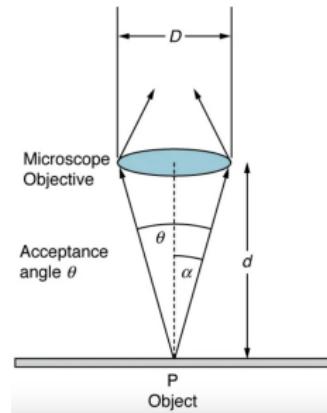


Resolving Power

The resolving power of a system is the smallest distance of separation (x) where two objects can be seen as distinct. It is given by the Rayleigh Criterion:

$$\theta = 1.22 \cdot \frac{\lambda}{D} = \frac{x}{d}$$

where d is the distance between the lens objective and the object.





Numerical Aperture (NA)

The Numerical Aperture (*NA*) is the maximum acceptance angle of a fiber or lens. The *NA* is a measure of the ability to gather light and resolve detail.

Using the $\alpha = \frac{\theta}{2}$ and the small angle approximation:

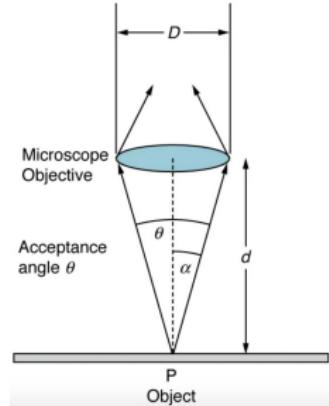
$$\sin(\alpha) = \frac{D/2}{d} = \frac{D}{2d}$$

The *NA* is defined as $NA = n \cdot \sin\alpha$ where *n* is the index of refraction of the medium between the objective and point P.

$$x = 1.22 \frac{\lambda d}{D} = 1.22 \frac{\lambda}{2\sin(\alpha)} = 0.61 \frac{\lambda n}{NA}$$

6

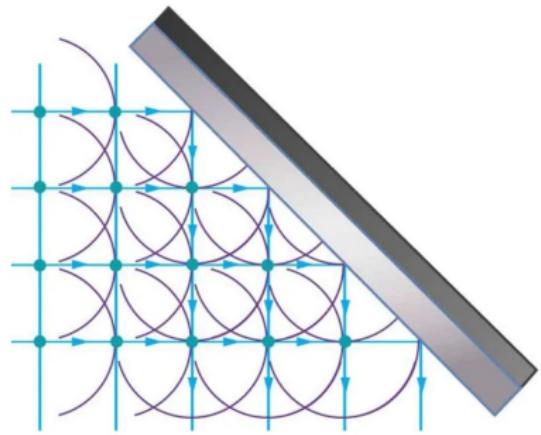
⁶Small angle approximation: $\sin(\theta) = \theta$ where θ is measured in radians.





Huygens's Mirror

A mirror reflects an incoming wave at an angle equal to the incident angle, verifying the law of reflection. As the wavefront strikes the mirror, wavelets are first emitted from the left part of the mirror and then the right. The wavelets closer to the left have had time to travel farther, producing a wavefront traveling in the direction shown.





Speed of Light in a Medium

The speed of a wave is the frequency ($\frac{1}{s}$) times the wavelength (m):

$$c = f\lambda \quad (6)$$

where in a vacuum, $c = 2.99 * 10^8 (\frac{m}{s})$.

Light has wave characteristics in a medium other than a vacuum, as well. In this case, the speed and wavelength change, but the frequency stays the same. The speed of light in a medium is governed by its index of refraction (n), where $v = \frac{c}{n}$.

Divide both sides of the above equation by n yields:

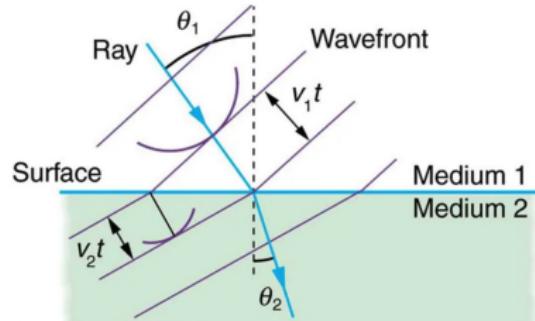
$$v = \frac{c}{n} = \frac{f\lambda}{n} = f\lambda_n \quad (7)$$

where λ_n is the wavelength in the medium.



Huygens's Refraction

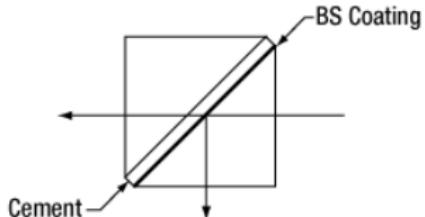
Each wavelet to the right was emitted when the wavefront crossed the interface between the media. Since the speed of light is slower in the second medium, the waves do not travel as far in a given time, and the new wavefront changes direction as shown. This explains why a ray changes direction to become closer to the perpendicular when light slows down and can be used to derive Snell's Law.



Interferometry



Optical Component: Beam Splitter

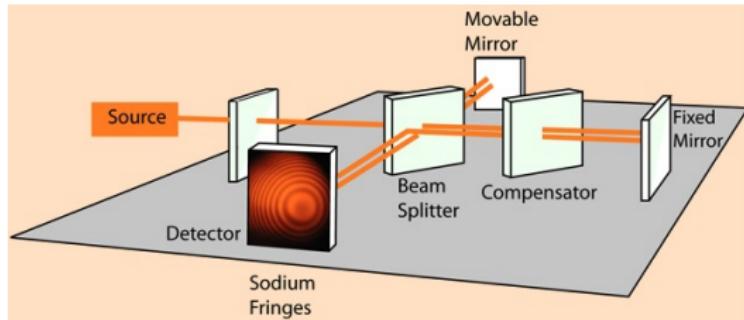


- ① Beamsplitter allows half of the light to pass through the diagonal interface and half to reflect
- ② Light can enter at any of the four faces and 1/2 reflected, 1/2 transmitted.
- ③ The arrows indicate the path where the specs are guaranteed.



Michelson Interferometer

Invented by the American physicist Albert Abraham Michelson in 1887.

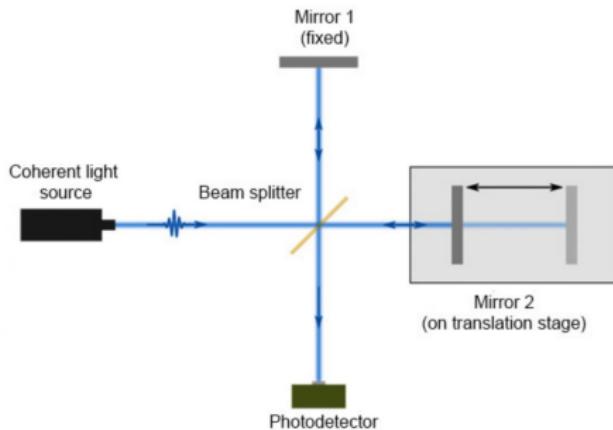


- ① Laser
- ② Beam Splitter
- ③ Mirror
- ④ Screen

- Laser light is divided by the beamsplitter, the partial beams are reflected by the mirrors and overlap again at the beamsplitter.
- The light intensity on the screen is dependent on the path length difference (Δs) between the two paths s_1 and s_2 .



Interferometer Math



- Path 1 (s_1): Laser reflects off of Beamsplitter to Mirror 1 through Beamsplitter to Detector
- Path 2 (s_2): Laser through of Beamsplitter to Mirror 2 reflects off Beamsplitter to Detector
- $\Delta s = s_1 - s_2$: Constructive: $\Delta s = m\lambda$, Destructive: $\Delta s = (m + \frac{1}{2})\lambda$



Interferometer Math - More Detailed

- The Electric Field (E_i) is given by

$$|E_i| = \sqrt{R \cdot T} \cos(\omega t + \phi_i) \quad (8)$$

where T is the transmission capacity of the beamsplitter, R is the reflection capacity, and ϕ_i is the phase which value is defined by the actual optical path.

- Intensity (I) on the screen is given by

$$I = c\epsilon_0 |E_1 + E_2|^2 \quad (9)$$

- If we assume that the transmission and reflection capacity are 0.5 then the average intensity (\bar{I}) is given by

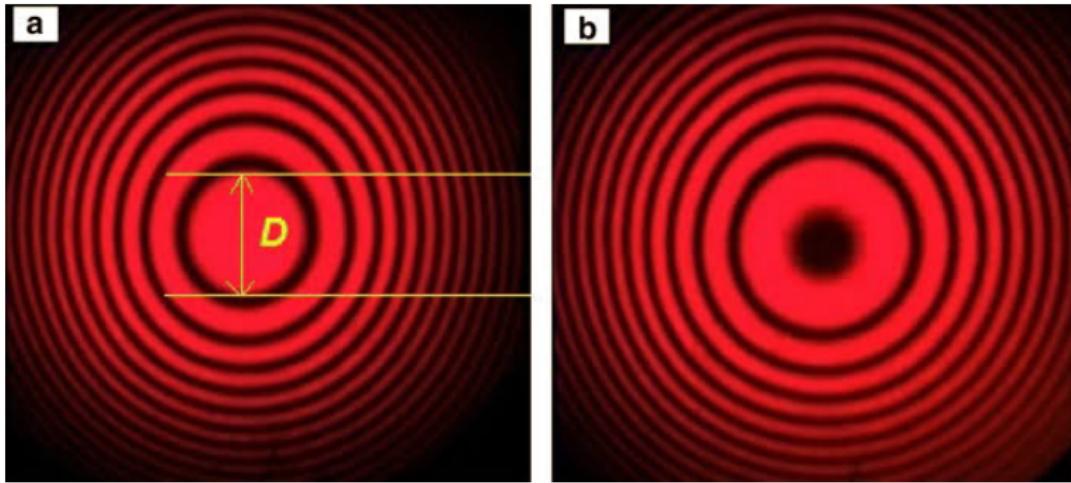
$$\bar{I} = \frac{1}{4} c\epsilon_0 E_0^2 (1 + \cos(\Delta\phi)) \quad (10)$$

where $\Delta\phi = \frac{2\pi}{\lambda} \Delta s$ and λ is the wavelength



Interferometer Math - what does it mean

Compare the centers:



Why are there alternating concentric circles?



Assignment: Michelson Interferometer

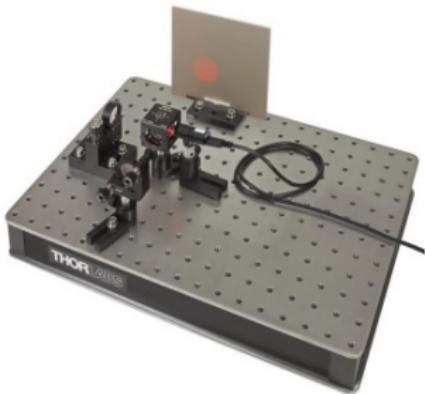


Using the ThorLabs Michelson Interferometer Kit:

- Setup per Chapter 4
- Complete Preliminary Test (Chapter 6.1)
- Determine Laser Wavelength (Chapter 6.2), document using the Labnotes worksheet.
- Draw a diagram of the Laser Wavelength setup.
- When told: teardown setup, but keep optics in mounts



Assignment: Michelson Interferometer 2



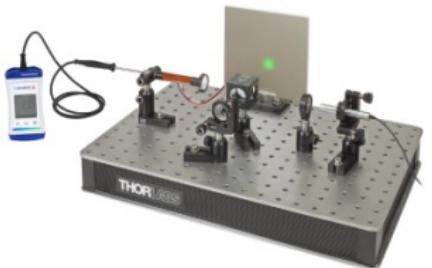
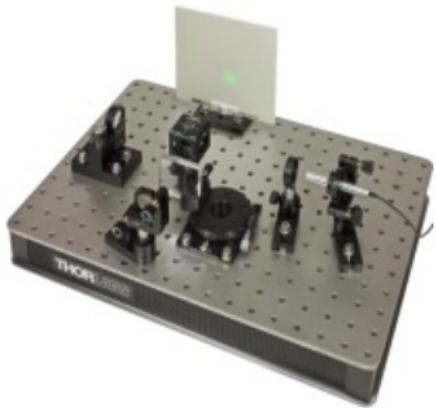
Using the ThorLabs Michelson Interferometer Kit and documenting your experiment on the Labnotes worksheet:

- Setup per Chapter 4
- Use as spectrometer (Chapter 6.3)
- Explore coherence (Chapter 6.4)
- When told: teardown setup, but keep optics in mounts

Optional: if instructed, repeat Chapter 6.3 Spectrometer experiment using the laser from the Optical Tweezers at above and below the lasing threshold.



Assignment: Michelson Interferometer 3



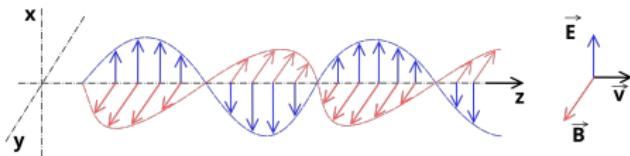
Using the ThorLabs Michelson Interferometer Kit and documenting your experiment on the Labnotes worksheet:

- Setup per Chapter 4
- Measure index of refraction (Chapter 6.5)
- Measure thermal expansion (Chapter 6.6)
- When told: teardown setup completely, clean optics, and store
- As a group, answer the questions in Chapter 8.

Polarization



Electromagnetic Wave



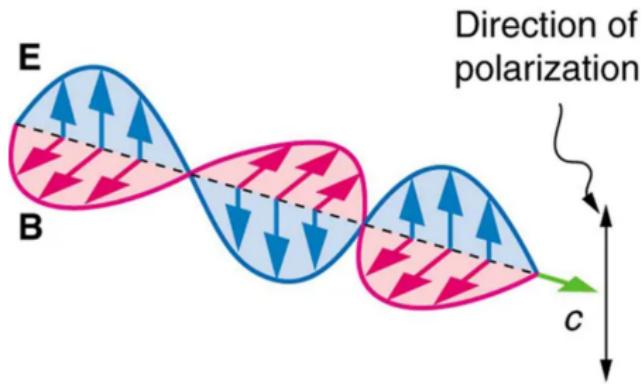
An Electromagnetic (EM) wave is a transverse wave where the electric and magnetic fields are perpendicular to each other and to the direction of propagation.

- Light is called unpolarized if the direction of this electric field fluctuates randomly in time.
- If the direction of the electric field of light is well defined, it is called polarized light.



Linear Polarization

We define the direction of polarization to be the direction parallel to the electric field.





Linear Polarizer

Natural light has polarizations in random directions, it is unpolarized.

Light Passing Through Crossed Polarizers

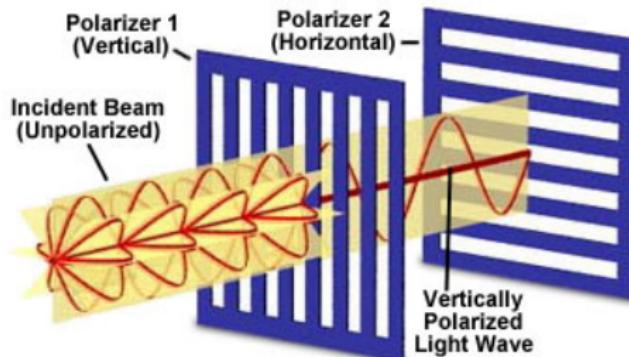


Figure 1



Assignment: Malus' Polarization

Documenting your work with the Labnotes worksheet:

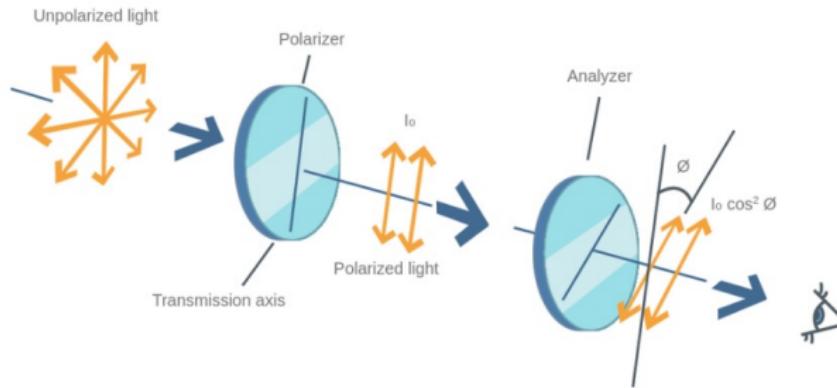


- Mount a linear polarizer slide horizontally
- Mount a cutout of the linear polarizer film to a RSP1 mount
- Shine a laser through both polarizers on a power meter, setting the maximum power to a rotation of 0°
- Take power measurements at every 15° of rotation
- Plot the results



Malus's Law

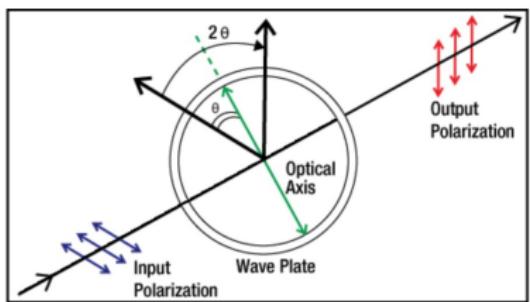
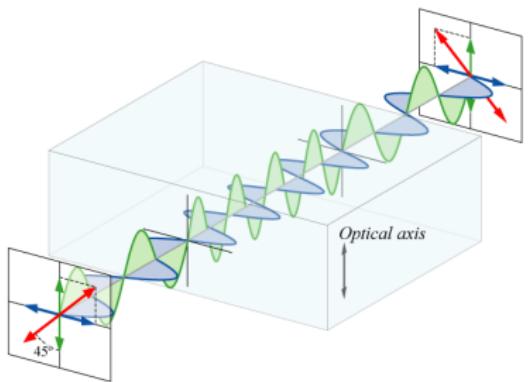
In 1810, French engineer Étienne-Louis Malus studied polarization after casually examining a doubly refracting prism of quartz the sunlight reflected from the windows of the Luxembourg palace.



$$I = I_0 \cos^2(\phi)$$



Rotating Linear Polarization with Half Wave Plate

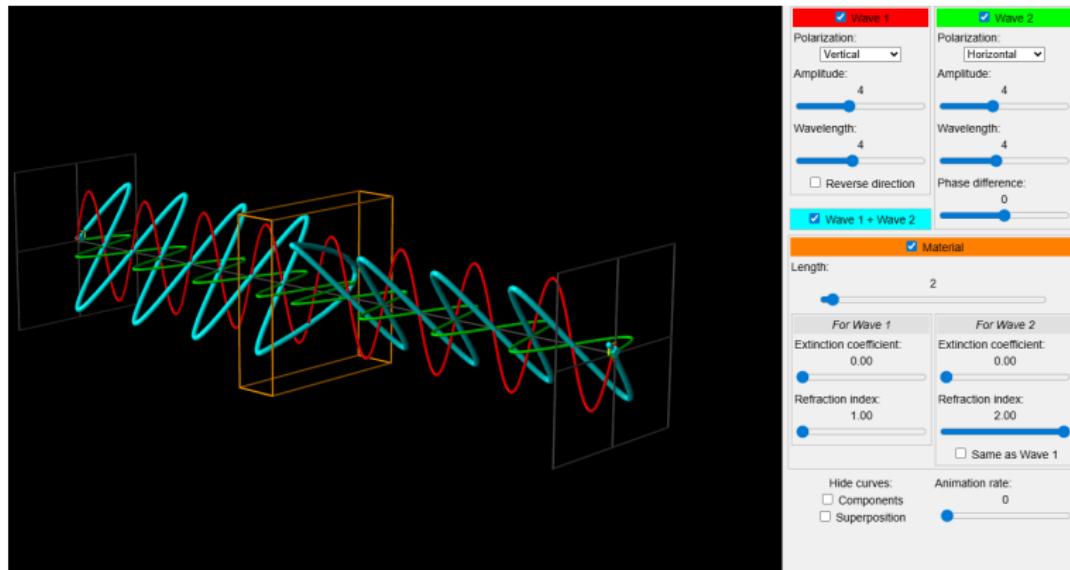


- Half-wave plates rotate the axis of polarization for linearly polarized light
- The plate is made of Birefringence material where the index of refraction is different along two perpendicular crystal axes
- The thickness is set so that light polarized along one axis is retarded a half-wavelength from the other axis.



Incoming 45° with Half-Wave Plate

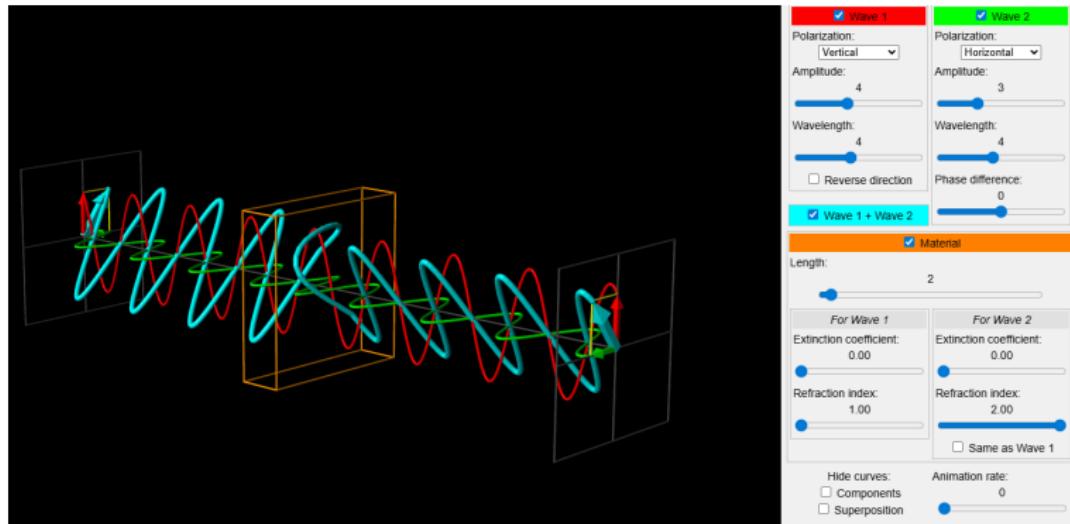
From <https://emanim.szialab.org/>





Incoming 37° with Half-Wave Plate

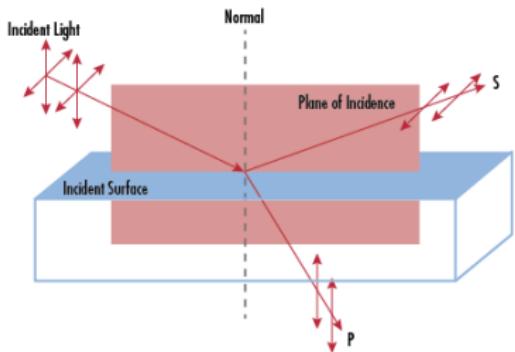
From <https://emanim.szialab.org/>





Reflection vs Polarization

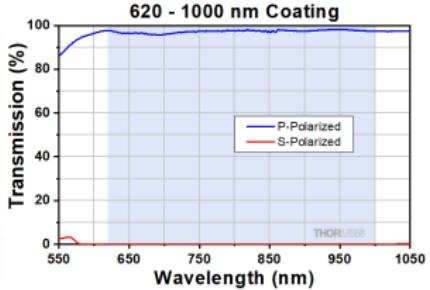
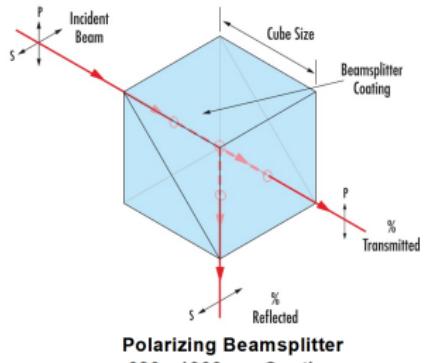
When light is incident on the interface of materials with different indices of refraction:



- Polarized light that is parallel to the plane of incidence (P-Polarization) is reflected
- Polarized light that is perpendicular (senkrecht in German) to the plane (S-Polarization) is refracted.
- The angle where the reflected and refracted angles are at 90° to each other, the angle of incidence is called the Brewster's Angle.



Polarizing Beam Splitter



- Similar to a non-polarized beam splitter, it splits the light path.
- P-polarization is transmitted, S-polarization is reflected by interface
- By changing the polarization direction, the amount of light transmitted vs reflected can be adjusted.



Assignment: More Polarization

Documenting your work with the Labnotes:

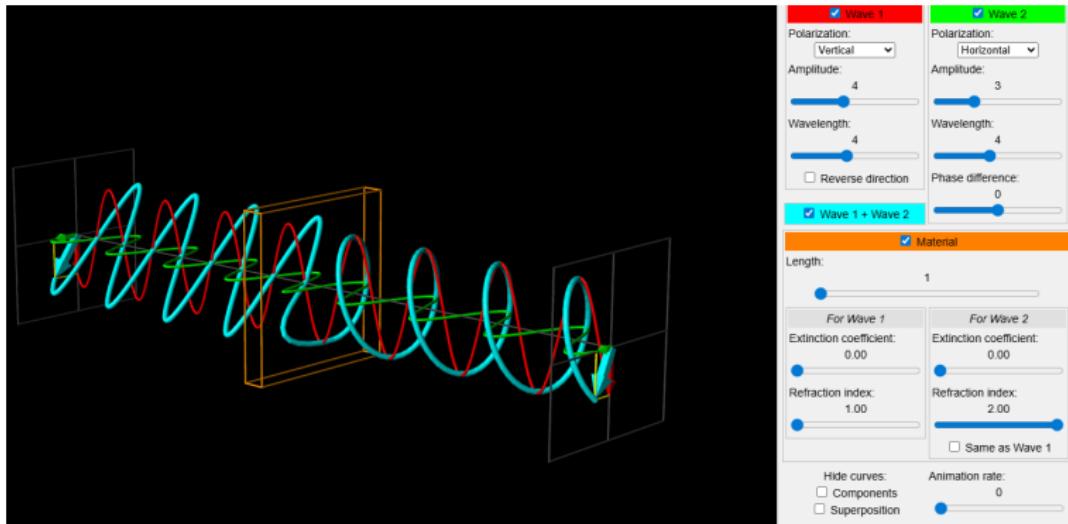


- Mount the half-wave plate on a rotating mount.
- Shine the laser through the linear polarizer slide, the half-wave plate, the beamsplitter
- Rotate the half-wave plate so all the light transmits through the beamsplitter
- Measure the power with the power meter and then the detector connected to an oscilloscope. Find the scaling factor between volts and power.
- Rotate the half-wave plate 45 degrees and measure the reflected beam power. (Don't move the detector attached to the o-scope)
- Rotate the half-wave plate recording both measurements. Convert between volts and power.



Incoming 37° with Quarter-Wave Plate

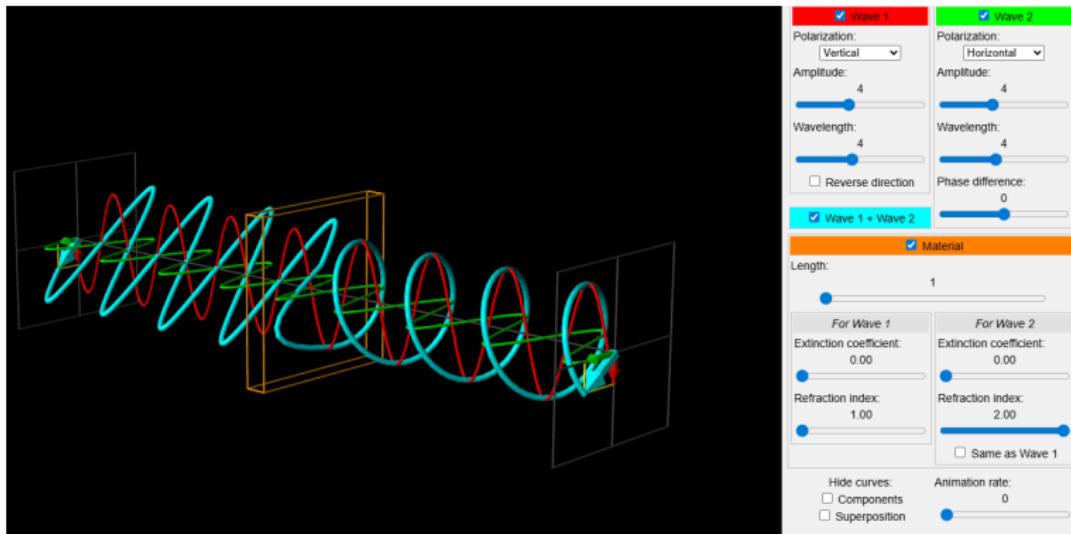
From <https://emanim.szialab.org/>





Incoming 45° with Quarter-Wave Plate

From <https://emanim.szialab.org/>

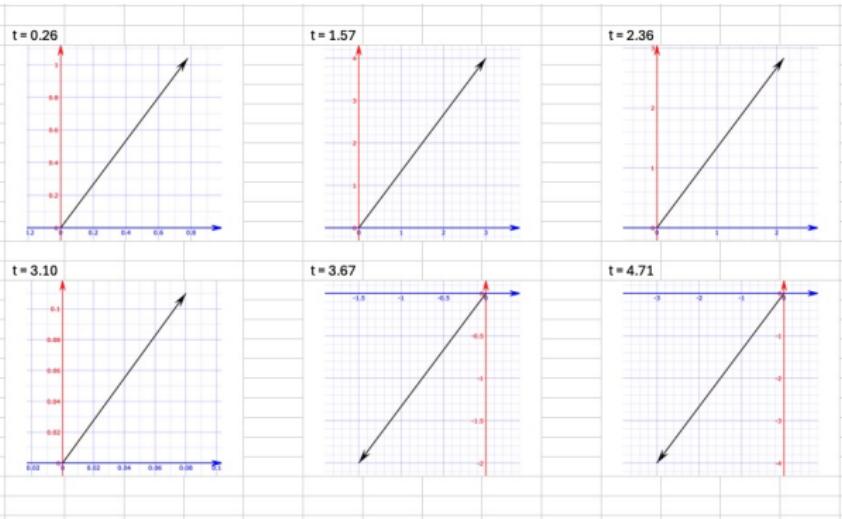




Linear Polarization - Off Axis

<https://www.mathsisfun.com/algebra/vector-calculator.html>

time	v	h	length	angle
0.00	0.00	0.00	0.00	53
0.26	1.04	0.78	1.29	53
0.52	2.00	1.50	2.50	53
0.79	2.83	2.12	3.54	53
1.05	3.46	2.60	4.33	53
1.31	3.86	2.90	4.83	53
1.57	4.00	3.00	5.00	53
1.83	3.86	2.90	4.83	53
2.09	3.46	2.60	4.33	53
2.36	2.83	2.12	3.54	53
2.62	2.00	1.50	2.50	53
2.88	1.04	0.78	1.29	53
3.14	0.00	0.00	0.00	53
3.40	-1.04	-0.78	1.29	-127
3.67	-2.00	-1.50	2.50	-127
3.93	-2.83	-2.12	3.54	-127
4.19	-3.46	-2.60	4.33	-127
4.45	-3.86	-2.90	4.83	-127
4.71	-4.00	-3.00	5.00	-127
4.97	-3.86	-2.90	4.83	-127
5.24	-3.46	-2.60	4.33	-127
5.50	-2.83	-2.12	3.54	-127
5.76	-2.00	-1.50	2.50	-127
6.02	-1.04	-0.78	1.29	-127
6.28	0.00	0.00	0.00	-127



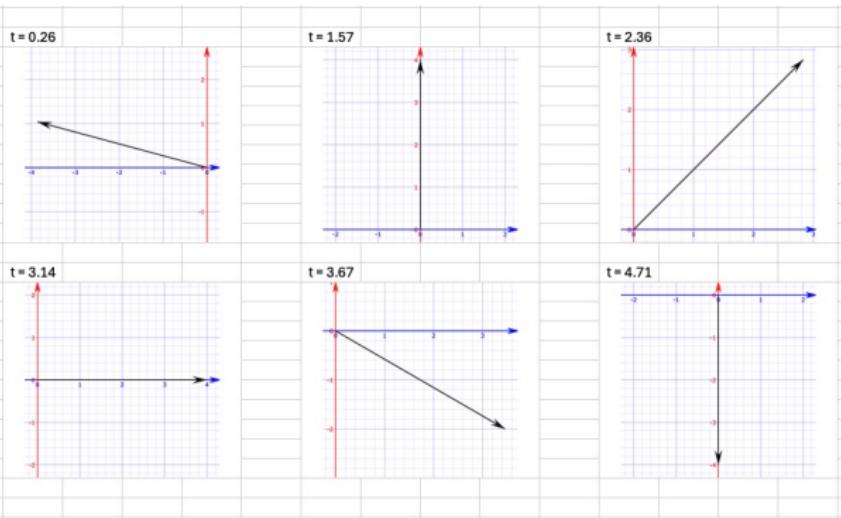
$$\vec{E} = 3 \sin(t) \vec{i} + 4 \sin(t) \vec{j} \quad (11)$$



Circular Polarization

<https://www.mathsisfun.com/algebra/vector-calculator.html>

time	v	h	length	angle
0.00	0.00	-4.00	4.00	180
0.26	1.04	-3.86	4.00	165
0.52	2.00	-3.46	4.00	150
0.79	2.83	-2.83	4.00	135
1.05	3.46	-2.00	4.00	120
1.31	3.86	-1.04	4.00	105
1.57	4.00	0.00	4.00	90
1.83	3.86	1.04	4.00	75
2.09	3.46	2.00	4.00	60
2.36	2.83	2.83	4.00	45
2.62	2.00	3.46	4.00	30
2.88	1.04	3.86	4.00	15
3.14	0.00	4.00	4.00	0
3.40	-1.04	3.86	4.00	-15
3.67	-2.00	3.46	4.00	-30
3.93	-2.83	2.83	4.00	-45
4.19	-3.46	2.00	4.00	-60
4.45	-3.86	1.04	4.00	-75
4.71	-4.00	0.00	4.00	-90
4.97	-3.86	-1.04	4.00	-105
5.24	-3.46	-2.00	4.00	-120
5.50	-2.83	-2.83	4.00	-135
5.76	-2.00	-3.46	4.00	-150
6.02	-1.04	-3.86	4.00	-165
6.28	0.00	-4.00	4.00	-180



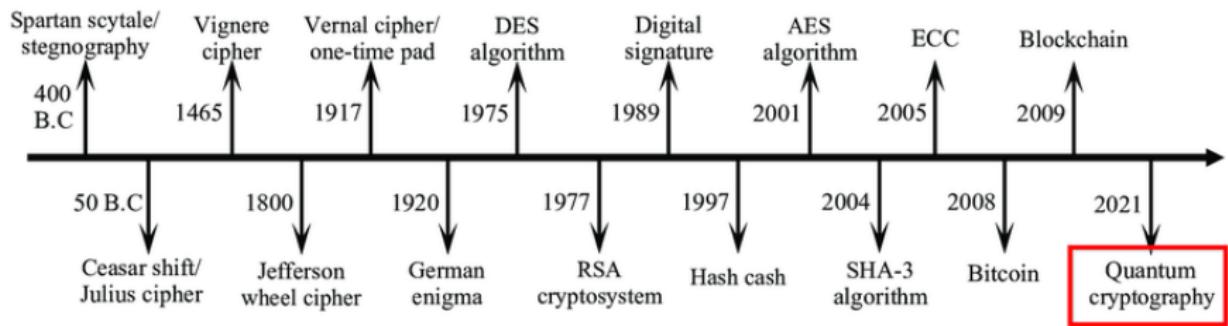
X lags Y by $\frac{\pi}{2}$:

$$\vec{E} = 4 \sin(t + \frac{\pi}{2}) \vec{i} + 4 \sin(t) \vec{j} \quad (12)$$

Quantum Cryptography - Quantum Key Distribution



Crypt





Cesear Cypher



Caesar cipher or the shift cipher is one of the simplest and most widely known encryption techniques. It is a type of substitution cipher in which each letter in the plaintext is replaced by a letter some fixed number of positions down the alphabet. For example, with a left shift of 3, D would be replaced by A, E would become B, and so on. The method is named after Julius Caesar, who used it in his private correspondence.



Vernam Cypher

Encrypt:

h	e	l	l	o	message
7 (h)	4 (e)	11 (l)	11 (l)	14 (o)	message
+ 23 (X)	12 (M)	2 (C)	10 (K)	11 (L)	key
= 30	16	13	21	25	message + key
= 4 (E)	16 (Q)	13 (N)	21 (V)	25 (Z)	(message + key) mod 26
E	Q	N	V	Z	→ ciphertext

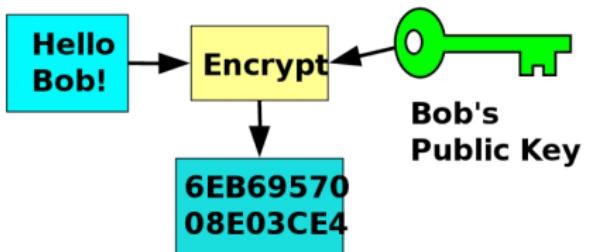
Decrypt:

E	Q	N	V	Z	ciphertext
4 (E)	16 (Q)	13 (N)	21 (V)	25 (Z)	ciphertext
- 23 (X)	12 (M)	2 (C)	10 (K)	11 (L)	key
= -19	4	11	11	14	ciphertext - key
= 7 (h)	4 (e)	11 (l)	11 (l)	14 (o)	ciphertext - key (mod 26)
h	e	l	l	o	→ message

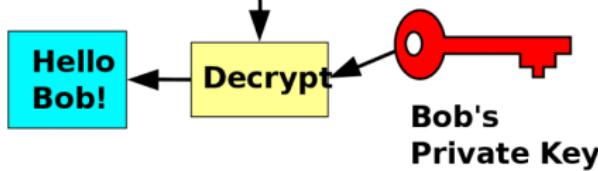


Crypt

Alice



Bob



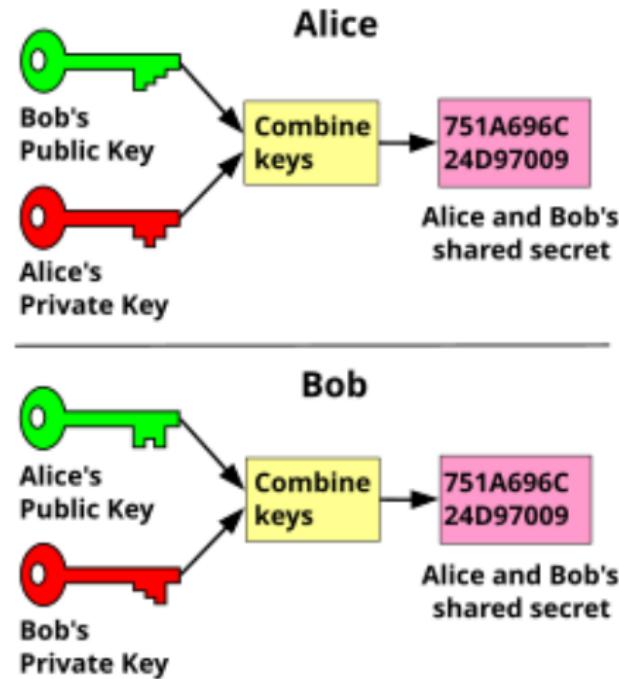


Advanced Encryption Standard (AES)

AES is a symmetric key encryption method developed by a pair of Belgian cryptographers named Joan Daemen and Vincent Rijmen. The AES was published by NIST in 2001. Rijndael protects the critical information of communication networks, financial dealings, and file storage. AES supports 128-bit data blocks using 128, 192, or 256-bit keys. Substitutions, permutations, and mixing are used to secure encryption. The transmitter and receiver share a key for symmetric encryption. Alice and Bob must securely exchange a secret key before sending an AES-encrypted message. Bob can decrypt the message using the same secret key.



Crypt





Rivest-Shamir-Adleman (RSA)

Ron Rivest, Adi Shamir, and Leonard Adleman invented RSA in 1977. This encryption uses huge prime numbers and the difficulty of factoring large composite numbers. RSA encrypts and decrypts using public and private keys. The public key is disclosed, but the secret key is concealed. This enables keyless secure communication. Bob's public key lets Alice send Bob an RSA-encrypted message. Bob's private key decrypts the message. Digital signatures and key exchange use RSA. RSA is slower than AES and unsuitable for big data encryption owing to its computational complexity.



Assignment: Quantum Key Distribution



- Some Items
- Another Item

The Atom and Quantum Mechanics



The Electron

The English physicist, J.J. Thompson experimented with Cathode-Ray Tubes passing the "ray" through both electric and magnetic fields.

- E-field used to deflect beam:

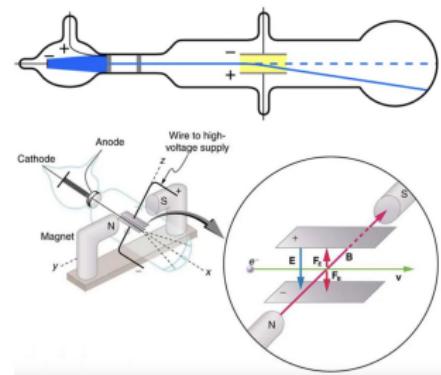
$$F = q_e E$$

- The vertical deflection was given by:

$$a = \frac{F}{m_e} = \frac{q_e E}{m_e}$$

- Leading to:

$$\frac{q_e}{m_e} = \frac{a}{E} = -1.76 \times 10^{11} (C/kg)$$



- CRT w/Hydrogen Ion:

$$\frac{q_p}{m_p} = 9.58 \times 10^7 (C/kg)$$



The Electron

American physicist, Robert Millikan improved on the experiment:

- Drop of oil in E-field

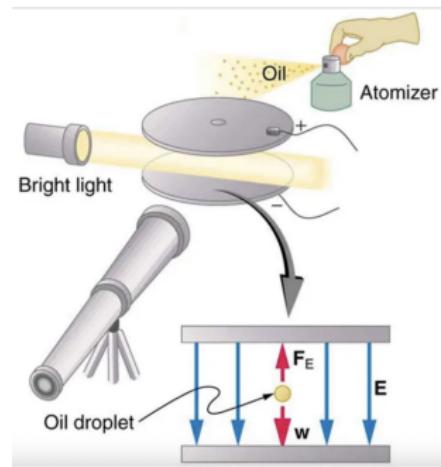
$$m_{drop}g = q_e E$$

- where, the E-field created by voltage

$$E = \frac{V}{d}$$

- This lead to the mass of an electron:

$$q = \frac{m_{drop}g}{E} = \frac{m_{drop}gd}{V} = -1.6 \times 10^{-19} (C)$$





Mass of Electron and Proton

With the charge of the electron known (and thus the proton), that allowed the mass of the electron and proton to be calculated:

$$m_e = \frac{q_e}{\left(\frac{q_e}{m_e}\right)} = \frac{-1.6 \times 10^{-19} - 1.76 \times 10^{-11}}{= 9.11 \times 10^{-31}} (kg)$$

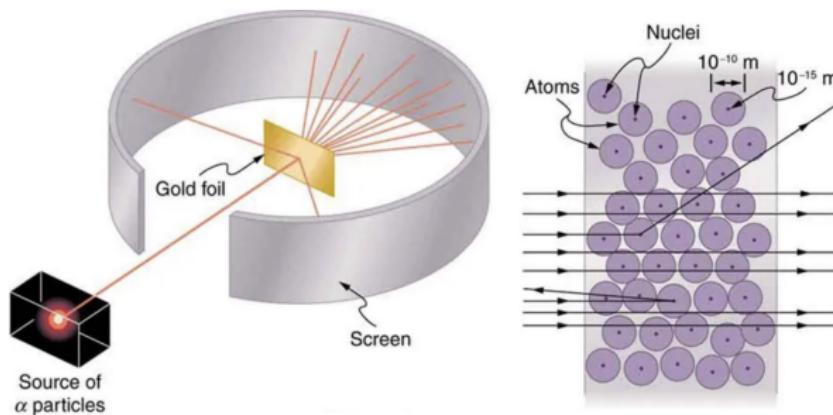
And, the mass the proton:

$$m_p = 1.67 \times 10^{-27} (kg)$$



The Nucleus

Australian physicist, Lord Ernest Rutherford conducted scattering experiments where a thin gold foil was placed in a beam of alpha particles (a double charged helium atom) and the resulting scattering was observed. Based on scattering angles, Rutherford estimated the size of the nucleus to be 10^{-15} m , or 100,000 smaller than the radius of an atom.

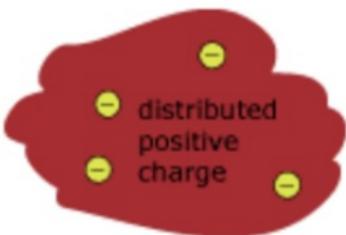




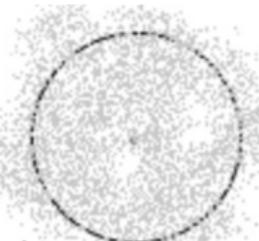
Models of the Atom



**Indivisible
Atom
(hard sphere)**



**'Plum-pudding'
Atom**

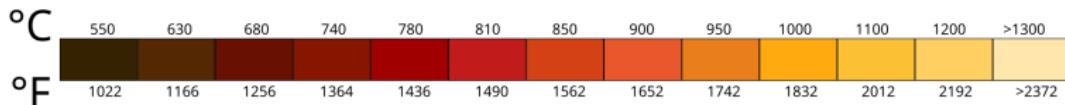


**Rutherford
Atom**



Black Body Radiation

The EM spectrum radiated by a hot solid is linked directly to the solid's temperature. An ideal radiator is one that has an emissivity of 1 at all wavelengths and, thus, is jet black. Ideal radiators are therefore called blackbodies, and their EM radiation is called blackbody radiation.



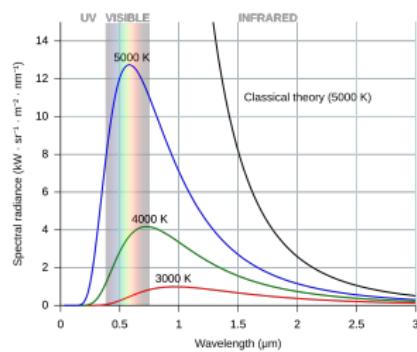


Ultraviolet Catastrophe

The ultraviolet catastrophe was the prediction of classical physics that an ideal black body at thermal equilibrium would emit an unbounded quantity of energy as wavelength decreased into the ultraviolet range.

$$B_\nu(T) = \frac{2\nu^2 k_B T}{c^2}, \nu = \frac{c}{\lambda}$$

$$B_\nu(T) \rightarrow \infty, \text{ as } \nu \rightarrow \infty$$





Quanta

Max Planck assumed that electromagnetic radiation can be emitted or absorbed only in discrete packets, call quanta⁷, of energy:

$$E_{quanta} = h\nu = h\frac{c}{\lambda}$$

where

- h is Planck's Constant
- ν is the frequency of light
- c is the speed of light
- λ is the wavelength of light

Applying the quantification to statistical mechanics:

$$B_\lambda(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{(\frac{hc}{\lambda k_B T})} - 1}$$

⁷Planck considered this a mathematical trick, not reality

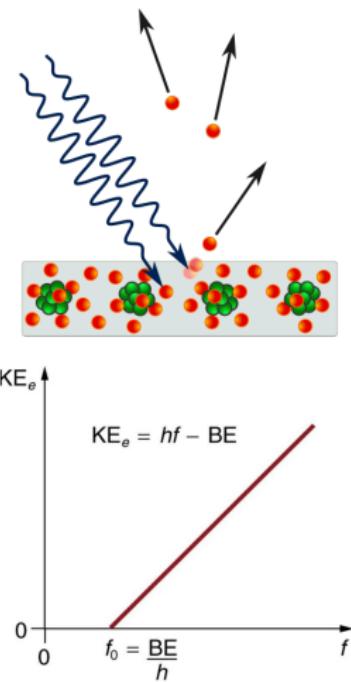


Photoelectric Effect

Albert Einstein realized the photoelectric effect could be explained only if EM radiation is itself quantized $E = hf$

- There is a minimum energy (f_0) before any electrons are ejected.
- Electrons are ejected without delay.
- The number of electrons ejected is proportional to intensity of EM.
- The maximum kinetic energy of the electrons is independent of intensity.
- The maximum kinetic energy is given by $KE_e = hf - BE$.

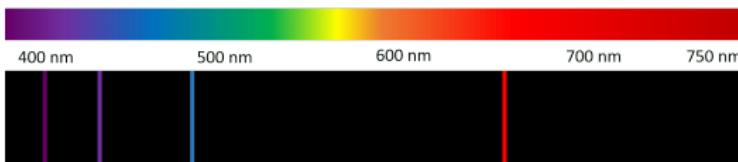
A quantum of light is called a photon.





Bohr's Atom

Atomic Spectrum of Hydrogen



The observed hydrogen-spectrum wavelengths can be calculated using the following formula:

$$\frac{1}{\lambda} = R \left(\frac{1}{n_f^2} - \frac{1}{n_i^2} \right)$$

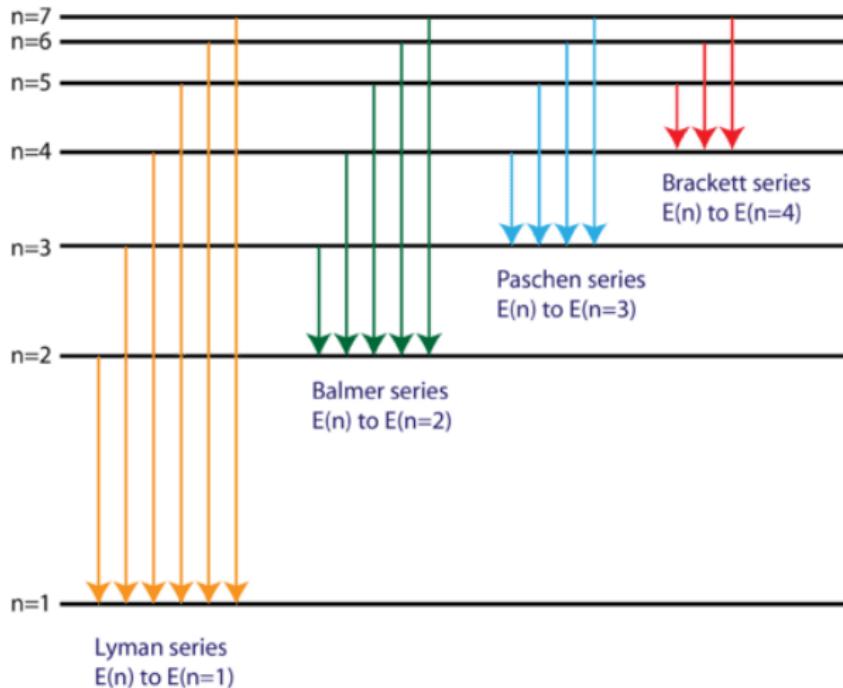
where the Rydberg constant (R): $R = 1.097 \times 10^7 (m^{-1})$.

- Lyman Series: $n_f = 1$.
- Balmer Series: $n_f = 2$.
- Paschen Series: $n_f = 3$.



Bohr's Atom

Electron transitions for the Hydrogen atom

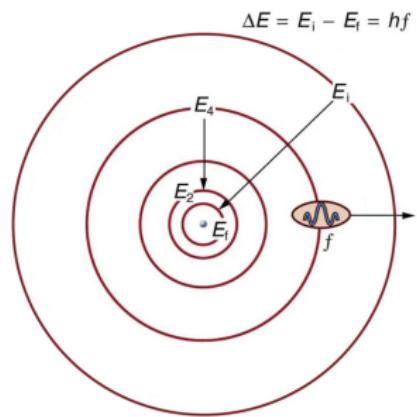




Bohr's Atom

Neils Bohr, Dutch physicist, derived the spectrum from the planetary model and:

- Only certain orbits area allowed (orbits of electrons in atoms are quantized)
- Each orbit has different energy: absorb to move to a higher orbit, drop to lower orbit by emitting.
- Energy absorbed/emitted is also quantized, producing discrete spectra.
- Energy to move from one orbit to another

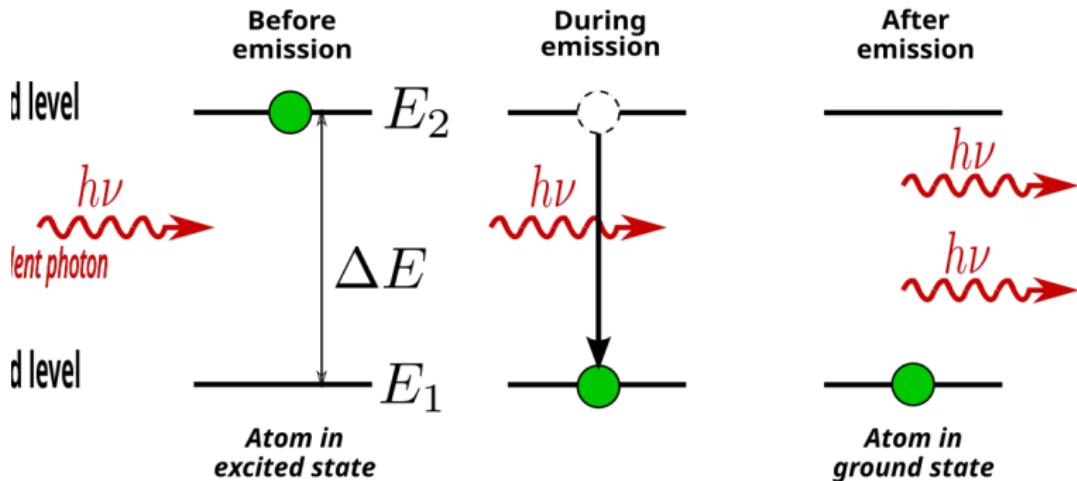


$$\Delta E = hf = E_i - E_f$$

The Laser



Stimulated Emission

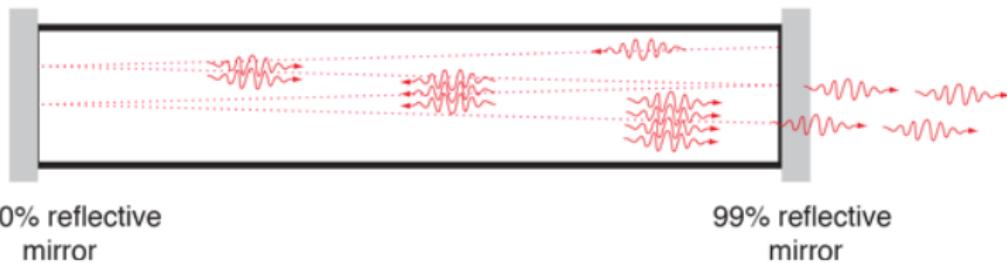


$$E_2 - E_1 = \Delta E = h\nu$$



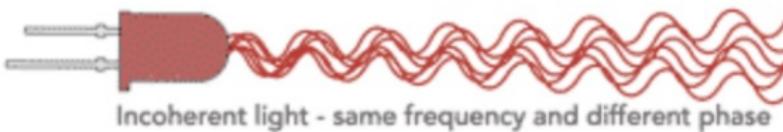
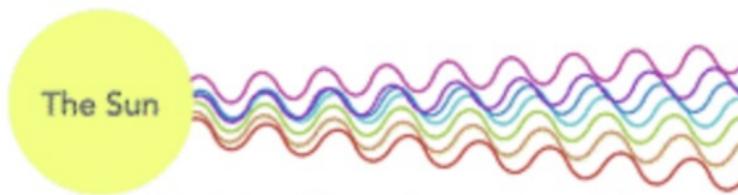
Light Amplification → LASER

Light Amplification by Stimulated Emmission of Radiation



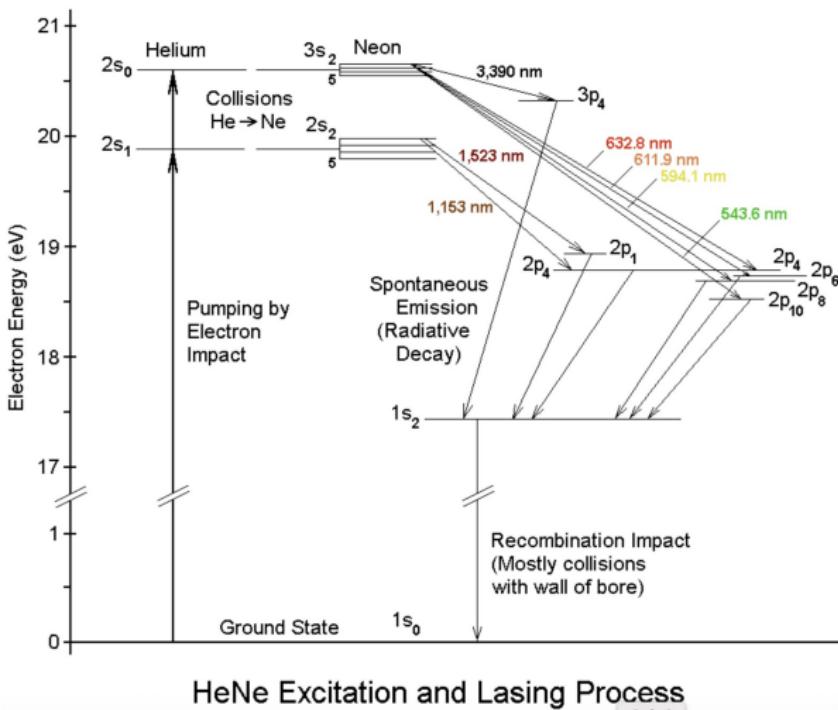


Coherence





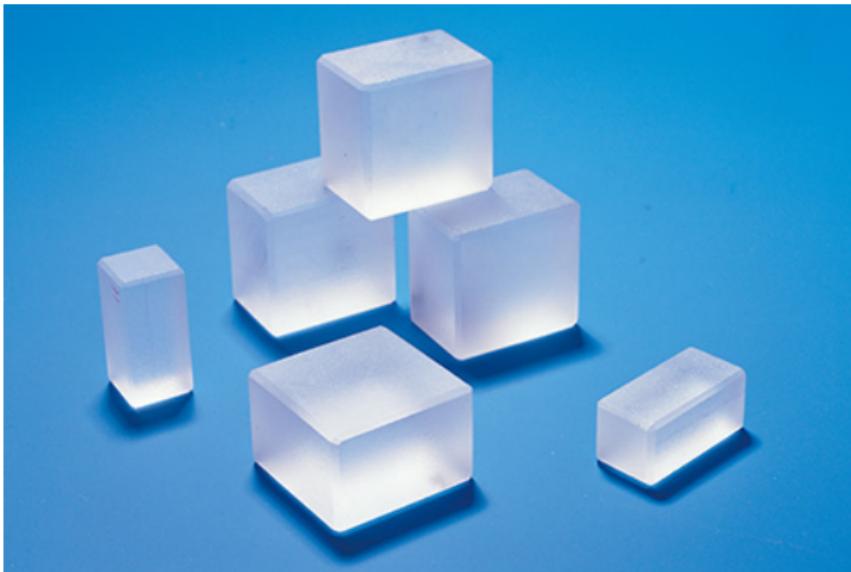
HeNe Laser



Entanglement

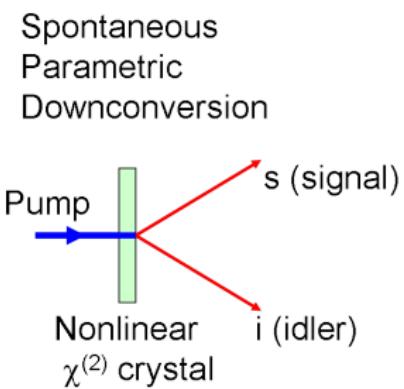


BBO Crystals

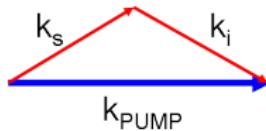




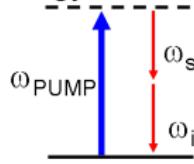
Spontaneous Parametric Down Conversion



Momentum Conservation



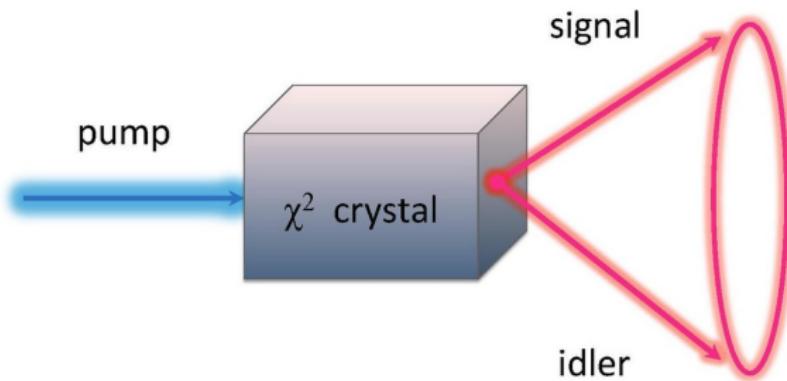
Energy conservation



$$\phi_{\text{PUMP}} = \phi_s + \phi_i$$



Spontaneous Parametric Down Conversion





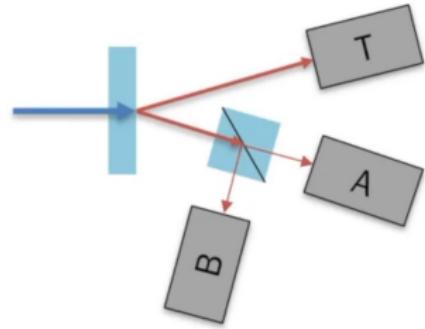
Single Photon?

Grangier-Roger-Aspect experiment

- Introduce beamsplitter
- Single photon transmitted or reflected, but not both
- Autocorrelations:

$$g^{(2)}(0) = \frac{N_{TAB} \cdot N_T}{N_{TA} \cdot N_{TB}}$$

- Coherent (Laser): $g^{(2)}(0) = 1$
- Classical Light: $g^{(2)}(0) > 1$
- Non-Classical Light: $g^{(2)}(0) < 1$



Schrodenger's Atom



Waves and Quantization

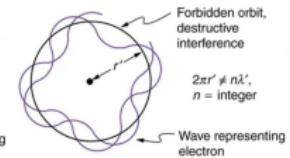
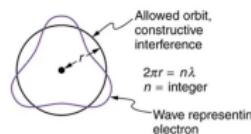
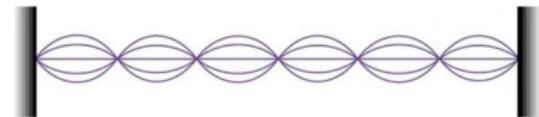
- Per de Broglie proposed matter has wave-like properties ($\lambda = \frac{h}{p}$)
- Electrons can only exist in locations where they interfere constructively.
- Not all orbits produce constructive interference, so not all allowed

$$n\lambda_n = 2\pi r_n, \text{ for } n = 1, 2, 3, \dots$$

$$\frac{nh}{m_e v} = 2\pi r_n$$

Angular Momentum (L):

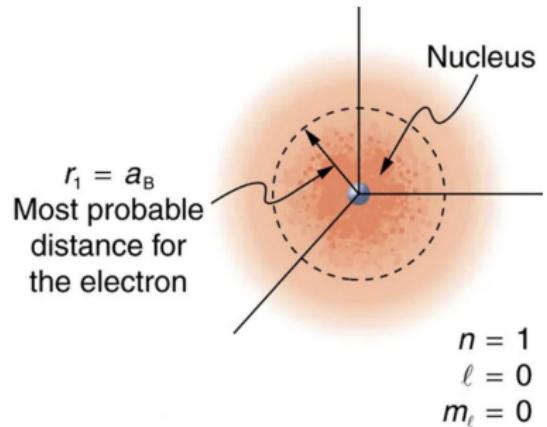
$$L = m_e v r_n = n \frac{h}{2\pi}, \text{ for } n = 1, 2, 3, \dots$$





Probability Cloud

Due to the wave nature of matter, the idea of well-defined orbits gives way to a model in which there is a cloud of probability, consistent with the Heisenberg uncertainty principle.

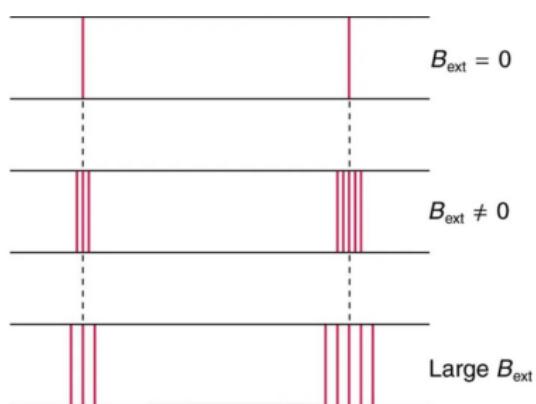




Patterns in Spectra - Zeeman Effect

Dutch physics student Pieter Zeeman investigated how spectra are affected by magnetic fields. In the presence of an external^a magnetic fields, the spectral lines split into two or more separate lines.

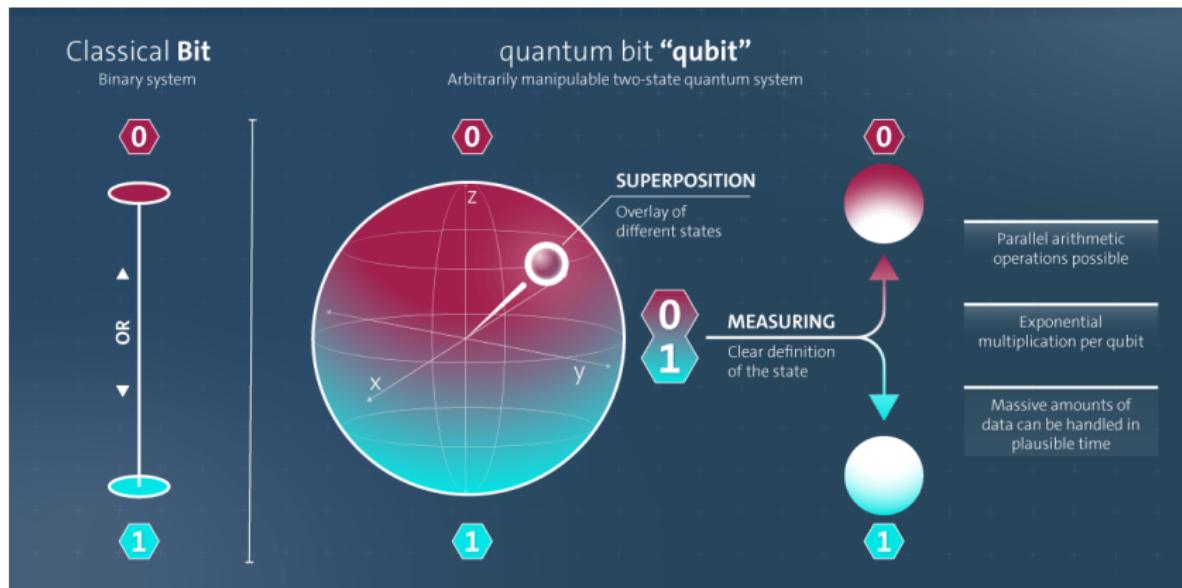
^aVery precise measurements have shown that spectral lines are doublets (split in two) apparently by the magnetic fields within the atom itself.



What is a Qubit



Bit vs Qubit



Quantum Computing



Types of Quantum Computers

- Superconducting
- Photonic
- Neutral Atom
- Trapped Ion
- Quantum Dots
- Diamond Nitrogen Vacancies



Quantum Computing: Superconducting

One of the most popular types of quantum computers is a superconducting qubit quantum computer. Usually made from superconducting materials, these quantum computers utilize tiny electrical circuits to produce and manipulate qubits. When using superconducting qubits, gate operations can be performed quickly.

Companies actively researching and manufacturing superconducting quantum computers include Google, IBM, IQM and Rigetti Computing to name just a few.



Quantum Computing: Photonics

These types of quantum computers use photons (particles of light) to carry and process quantum information. For large-scale quantum computers, photonic qubits are a promising alternative to trapped ions and neutral atoms that require cryogenic or laser cooling.



Quantum Computing: Neutral Atom

Quantum computing based on neutral atoms involves atoms suspended in an ultrahigh vacuum by arrays of tightly focused laser beams called optical tweezers, though not all neutral atom companies use optical tweezers. Neutral atom quantum computers are less sensitive to stray electric fields, which makes them a good option for quantum processors.



Trapped Ions



A trapped ion quantum computer involves using atoms or molecules with a net electrical charge known as “ions” that are trapped and manipulated using electric and magnetic fields to store and process quantum information. As trapped ions can be isolated from their environment, they are useful for precision measurements and other applications requiring high levels of stability and control. Also, the qubits can remain in a superposition state for a long time before becoming decoherent. Representing the trapped ions community of companies in the quantum space, we have Quantinuum (a company that came out of the merger between Cambridge Quantum Computing and Honeywell Quantum.



Quantum Computing: Quantum Dots

A quantum dot quantum computer uses silicon qubits made up of pairs of quantum dots. In theory for quantum computers, such 'coupled' quantum dots could be used as robust quantum bits, or qubits.

Companies focused on this area include Diraq, Siquance and Quantum Motion.



Quantum Computing: NV Diamond