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

-

The Technician: Shawn Morales

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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

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

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

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

Important Attribute in an Employee

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

Overview: QIS in NM

Introduction

NM will be tomorrow's quantum hotbed

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

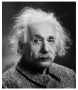
Quantum Mechanics:

The physics of the microscopic world

atom

electron

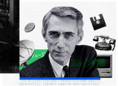
photon



Albert Einstein

Information Science:

Computers & communications

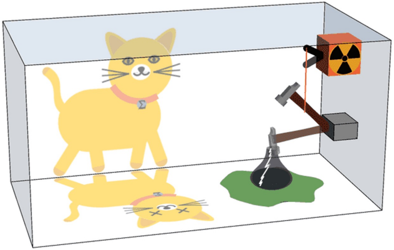


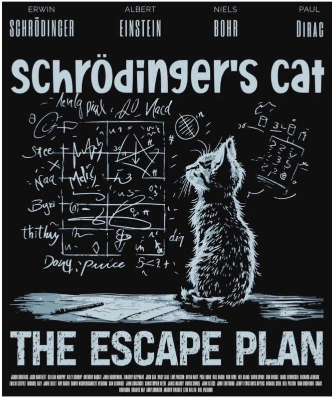
Claude Shannon

Introduction

Superposition

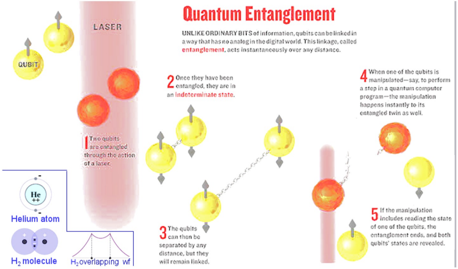
- Superposition describes a particle's ability to exist across many possible states at the same time.
- The superposition collapses into one specific state when a measurement/observation is made.

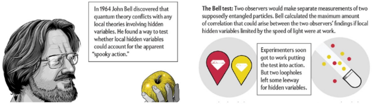




Introduction

Spooky Action at a Distance (Entanglement)





For the first time, a loophole-free Bell test

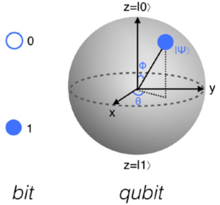
At Delft, scientists ran 245 trials in which a pair of electrons 1,280 meters apart were entangled. They measured the particles in every case and found 80 percent were correlated—significantly more than would be possible with local hidden variables.

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

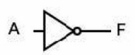
5

Introduction

Classical vs Quantum Logic

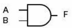


NOT



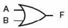
Input	Output
A	F
0	1
1	0

AND



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

OR

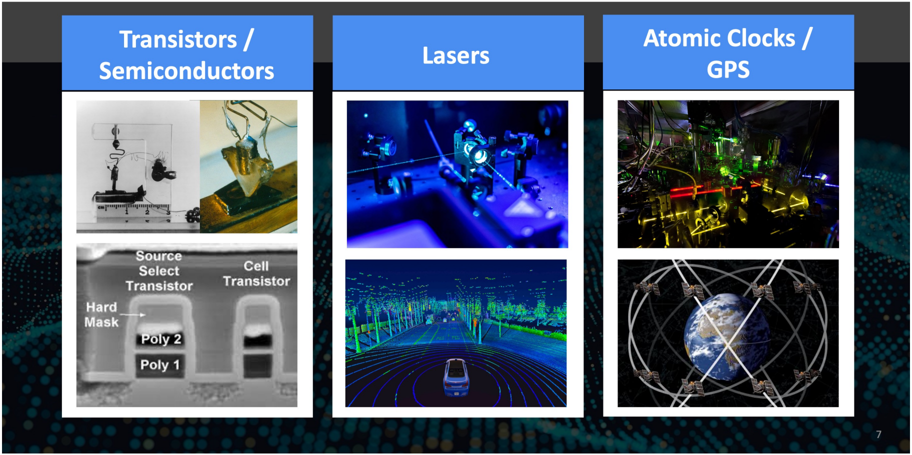


Inputs		Output
A	B	F
0	0	0
1	0	1
0	1	1
1	1	1

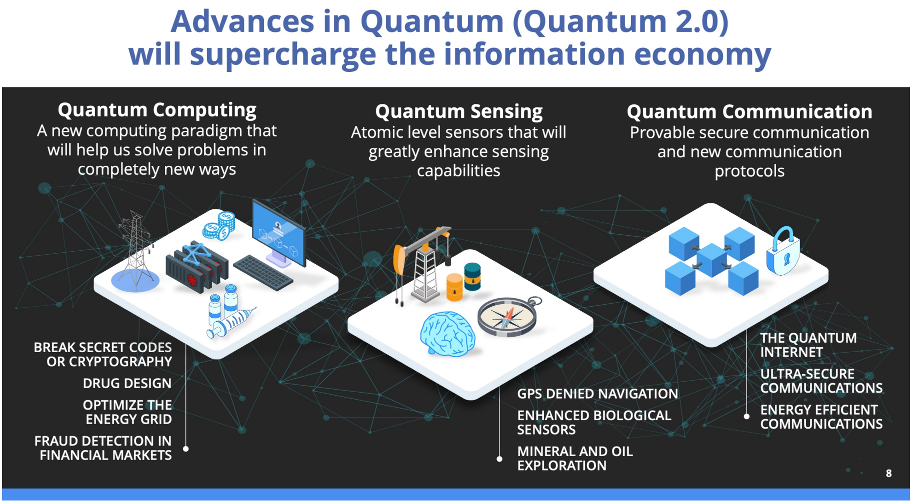
Operator	Gate(s)	Matrix
Pauli-X (X)	$\boxed{X}$ $\oplus$	$\begin{bmatrix}0 & 1\\1 & 0\end{bmatrix}$
Pauli-Y (Y)	$\boxed{Y}$	$\begin{bmatrix}0 & -i\\i & 0\end{bmatrix}$
Pauli-Z (Z)	$\boxed{Z}$	$\begin{bmatrix}1 & 0\\0 & -1\end{bmatrix}$
Hadamard (H)	$\boxed{H}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\1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

Introduction

Quantum Has Been With Us



Introduction



Introduction

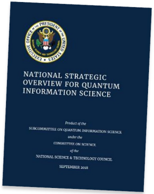
Quantum is one of the top emerging technologies in the world

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

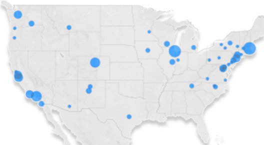
Federally supported quantum programs

- **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


NATIONAL STRATEGIC OVERVIEW FOR QUANTUM INFORMATION SCIENCE

Product of the
SUBCOMMITTEE ON QUANTUM INFORMATION SCIENCE
under the
COMMITTEE ON SCIENCE
of the
NATIONAL SCIENCE & TECHNOLOGY COUNCIL

SEPTEMBER 2018

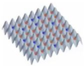
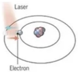
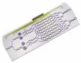
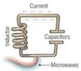


The 13 major NQI research centers and their affiliates (quantum.gov)

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

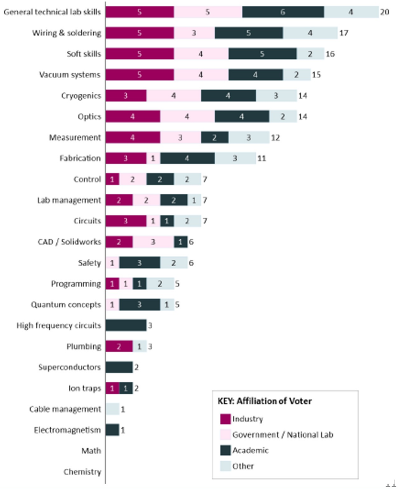
9

Introduction

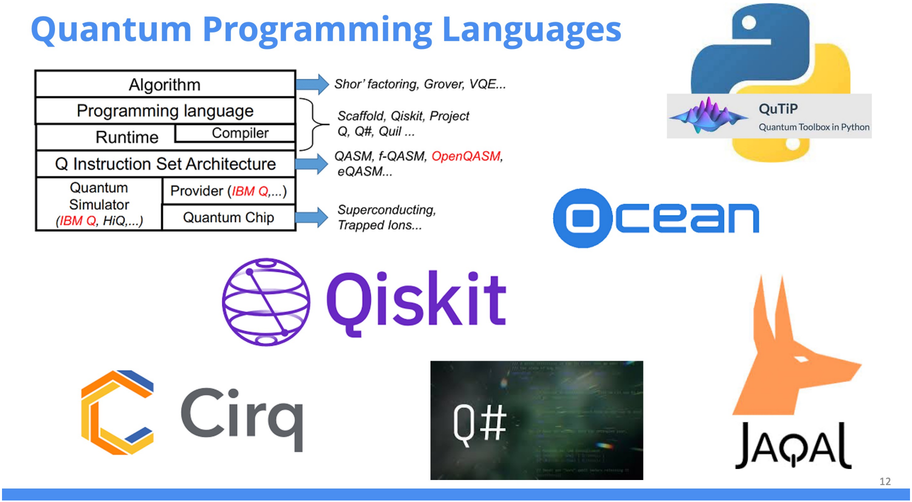
Neutral Atom	Trapped Ion	Photonics	Superconducting	Silicon Spin / Quantum Dots
Neutral atoms are cooled using tuned laser and store qubits within electron states. Interactions through excitation to Rydberg states. 	Trapped Ion technology uses charged atomic particles, which can be confined and suspended in free space using electromagnetic fields. Qubits are stored in the stable electronic states of each ion. Lasers are used to induce coupling 	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 	Resistance-free current oscillations back and forth around a circuit loop. An injected microwave signal excites the current into superposition states. 	”Artificial atoms” are made by adding an electron to a small piece of pure silicon. Microwaves control the electron’s quantum state. 
Pros: Long coherence times. Strong connectivity including more than 2Q. External cryogenics not required. **Cons**: Requires ultra-high vacuum. Laser scaling challenges.	**Pros**: Extremely high gate fidelities and long coherence. No External cryogenics. **Cons**: Slow gate times / operations. Lowe connectivity between qubits. Requires ultra-high vacuum. Laser scaling challenges.	**Pros**: Extremely fast gate speeds and promising fidelities. No cryogenics or vacuum. Leverage existing CMOS fabs. **Cons**: Noise from photon loss. Each program requires custom chip. Photons don’t naturally interact so 2Q gate challenges.	**Pros**: High gate speeds and fidelities, Leverage existing lithographic processes. **Cons**: Requires cryogenic cooling. Short coherence times. Microwave interaction not well understood.	**Pros**: Leverage existing semiconductor technologies. Strong gate fidelities and speeds. **Cons**: Requires cryogenics. Only a few entangled gates with low coherence times. Interference and cross-talk challenges.
atom computing PASQAL Infleqtion QuEra Computing Inc. planqc	QUANTINUUM IONQ QUANTUM FACTORY AQT eleQtron engage quantum	XANADU QuiX THE FASTEST WAY TO A QUANTUM FUTURE QUANDELA ORCA Computing PsiQuantum	IBM OQC ATLANTIC QUANTUM IQM Google AI	intel diraq QUANTUM MOTION QUANTUM BRILLIANCE Silicon Quantum Computing

Introduction

Quantum Technician Skills

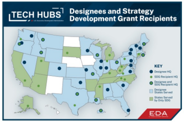


Introduction



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.

Quantum Systems Accelerator

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.

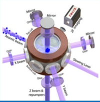
Berkeley Lab, Sandia National Laboratories, MIT Lincoln Laboratory, Berkeley, Caltech, Harvard University, University of Colorado Boulder, Duke, MIT, Tufts University, University of Maryland, Université de Sherbrooke, UNM, USC, Texas

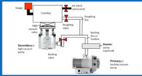
13

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)

DEEP DIVE powered by CNM Ingenuity

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	**Ingenuity**	**Math Science Engineering**	**BHT – CS/CIS**
Industrial Technician	Internet of Things	Engineering AS degree	Internet of Things
Industrial Automation Technician	Quantum Technician	Engineering Technician	Industrial Automation

What you will learn

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

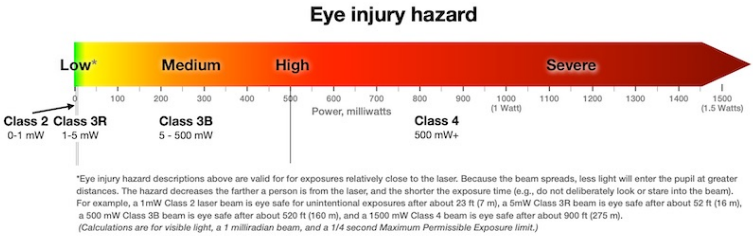
Atomic Quantum Systems

Safety

Safety Walk


現場
GEMBA
WALK
Observation · Recognition · Cooperation
Communication · Problem Solving

Laser Safety



- 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 - Continued

- 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. The MPE can be exceeded with this class of laser; however, this presents a low risk level to injury. Visible, continuous-wave lasers in this class are limited to 5 mW of output power.
- Class 3B lasers are hazardous to the eye if exposed directly. Diffuse reflections are usually not harmful, but may be when using higher-power Class 3B lasers. 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 and a safety interlock; moreover, laser safety signs should be used, such that the laser cannot be used without the safety light turning on. Laser products with power output near the upper range of

Lock Out Tag Out

- Electrical Energy
- Mechanical Energy
- Mechanical Energy - Pneumatics

Sharps

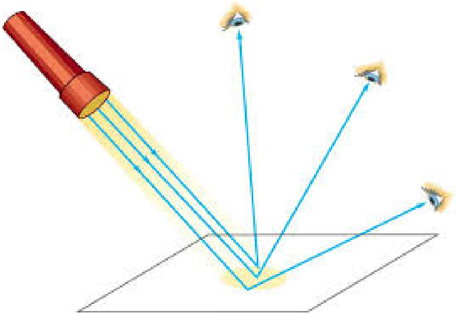

FILL LINE
Sharps Container
dynarex
Reorder No. 4622
CAUTION: FORCING OR OVERFILLING SHARPS INTO COLLECTOR MAY CAUSE SERIOUS INJURY
This collector is puncture-resistant, but not puncture proof. To avoid injury, examine the collector carefully before you fill, carry or dispose of it.
CLOSE COVER AND SECURE WHEN LEVEL IS REACHED
BIOHAZARD
WARNING
BIO-PELIGROSO
Warning: Used sharps are contaminated. Disease may occur from injury. Handle carefully. Refer to OSHA, AORN, CDC, or other local standards setting organization guidelines.
Regulated Medical Waste
One time use only
Manufactured for:
Dynarex Corporation
10 Glenshaw Street
Orangeburg, NY 10962
USA • www.dynarex.com
Made in China R190111
1 Quart (946 mL) LOT 53237

High Voltage

Geometric Optics

Ray Nature of Light

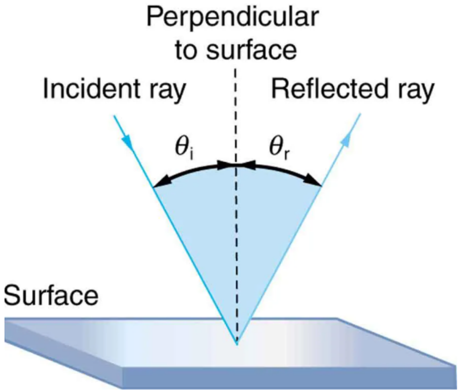
The word "ray" means a straight line that originates at some point.



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

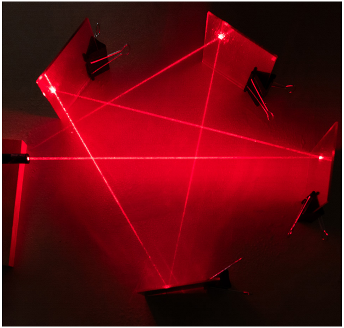
Reflection

The angle of reflection equals the angle of incidences



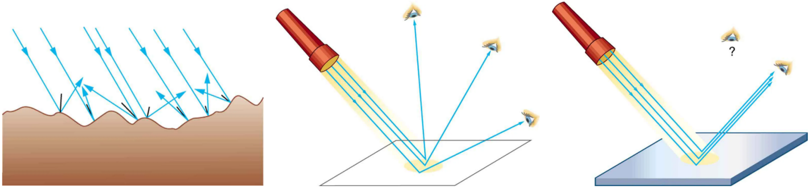
Demonstration: Handling Optics

Assignment: Laser Tag



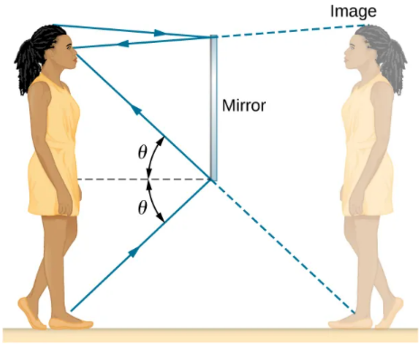
- Align a Laser and a target at opposite ends of the table.
- When obstacles are placed in the path, without adjusting laser, add mirrors to get the beam to the target.

Rough vs Smooth Surfaces



Mirrors and Virtual Images

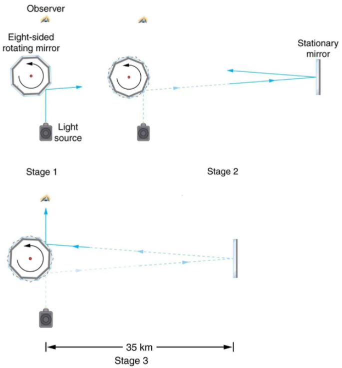
When we see ourselves in a mirror, it appears that our image is actually behind the mirror.



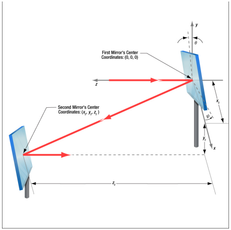
Speed of Light

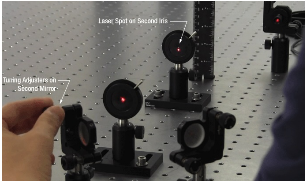
- In 1676, Danish astronomer Ole Roemer noted the change in orbital period of Jupiter's moons depending of if the earth was moving towards or away from Jupiter. He as able to calculate speed of light to be $2.26x10^8(\frac{m}{s})$.
- In 1887, American physicist Albert Michelson used a rotating mirror 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





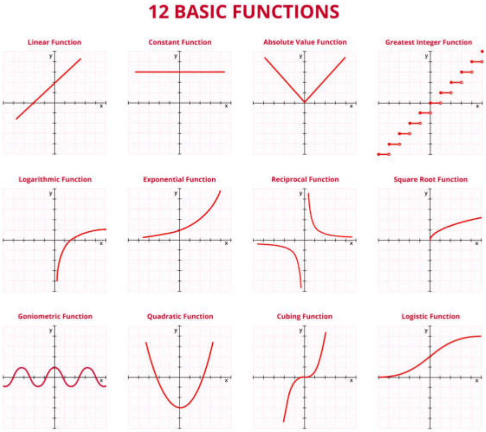
1. Setup: Laser, 45° mirror, second 45° mirror, two irises, target.
2. Adjust first mirror to center beam on center iris 1
3. Open iris 1, adjust second mirror to center beam on iris 2
4. Iterate steps 2 and 3 until the beam passes through the center of both iris and hits target.

Trigonometry

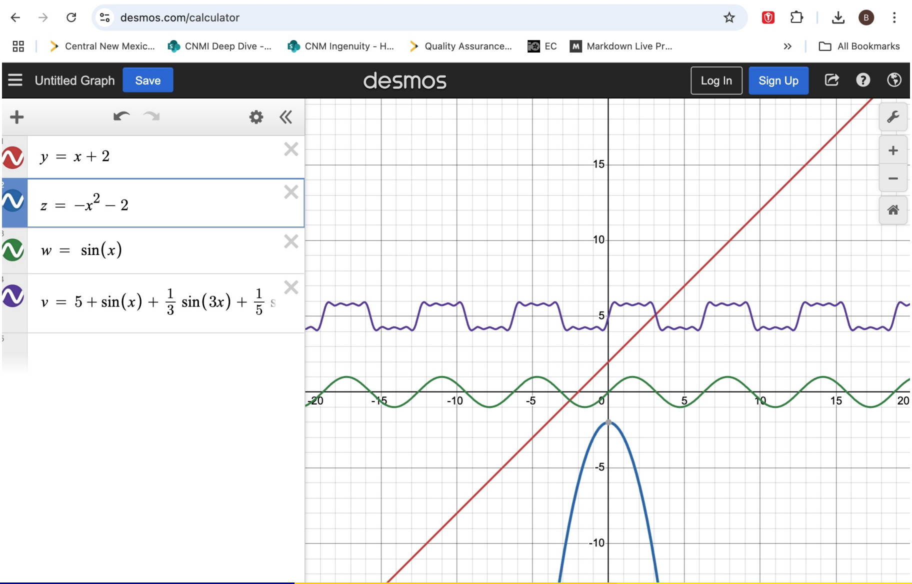
Algebraic Functions

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

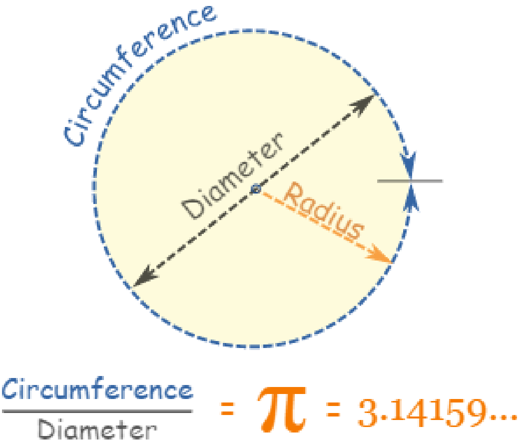
- Linear: $y = x + 2$
- Quadratic: $y = x^2$
- Periodic: $y = sin(x)$



More Desmos Fun

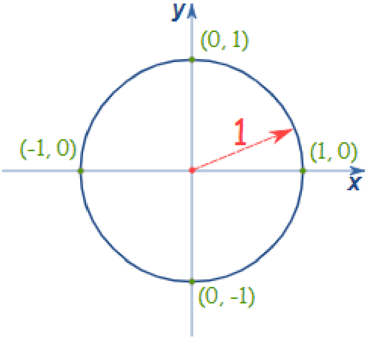


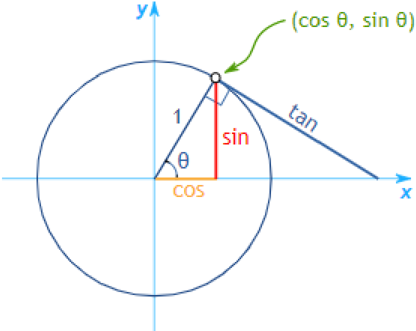
Pi (π)


Circumference
Diameter
Radius
Circumference
Diameter
= π = 3.14159...

Unit Circle and Trigonometric Functions

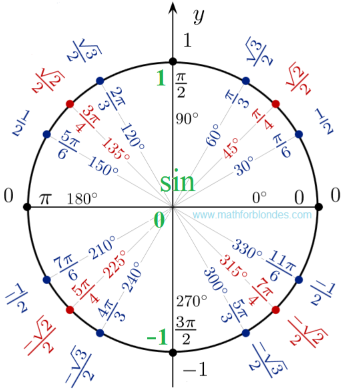
The Unit Circle is a circle with a radius of 1.

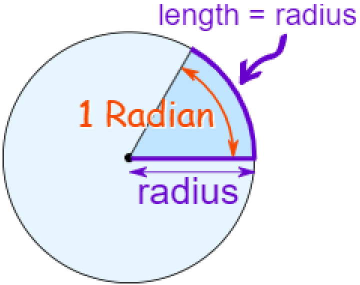




The Unit Circle can be used to map out the trigonometric values of sine, cosine, and tangent.

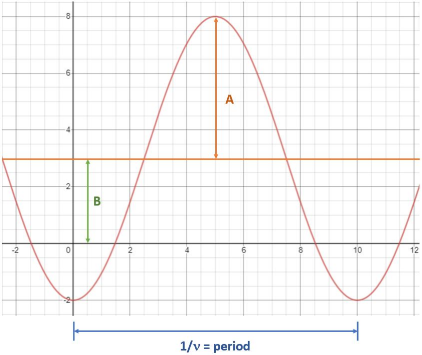
Unit Circle and the Value of $sin(\theta)$





- $sin(\theta)$ 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 $= 2\pi$ radians.

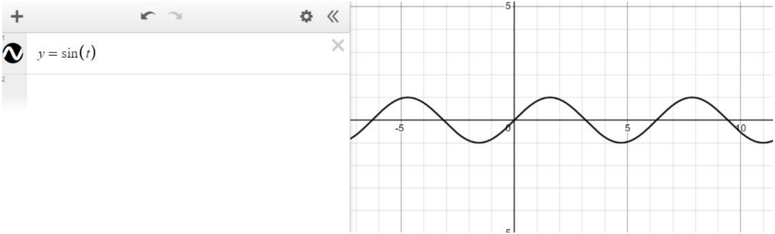
Sine Waves

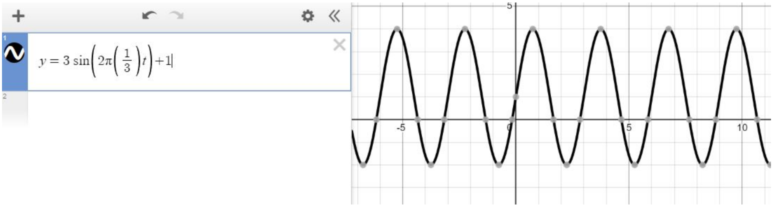


$$y = A * sin(2 * \pi * \nu * t) + B$$

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

Using Desmos (desmos.com/calculator)

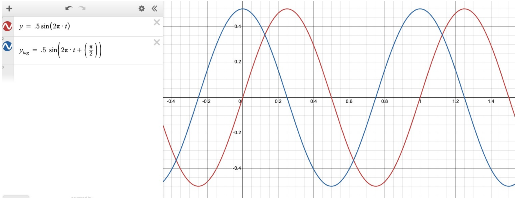




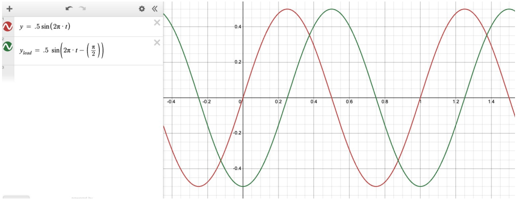
Phase Shift

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:



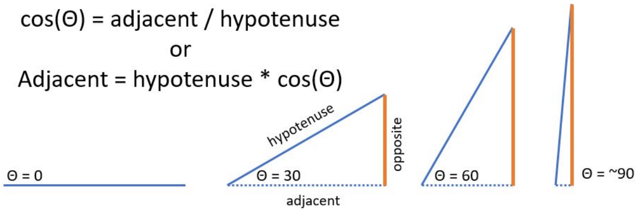
Green leads Red:



SOH CAH TOA

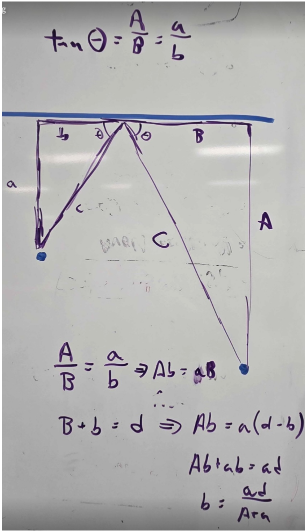
- sin = opposite over hypotenuse
- cos = adjacent over hypotenuse
- tan = opposite over adjacent

cos(Θ) = adjacent / hypotenuse
or
Adjacent = hypotenuse * cos(Θ)



sin(Θ) = opposite / hypotenuse
or
opposite = hypotenuse * sin(Θ)

Assignment: Calculating Angles: Laser Billards

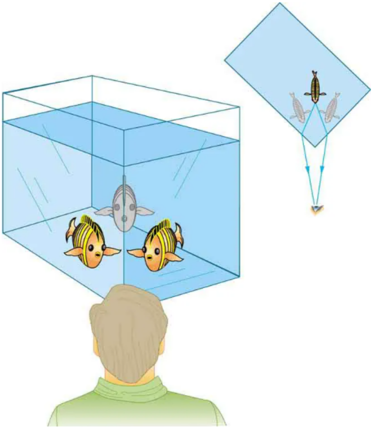


- Setup a mirror line on the optical table.
- Place the laser and target two different distances from the line.
- Calculate the location of the mirror, place the mirror there.
- Calculate the angle of the laser, adjust laser angle.
- Turn on laser and see how close on target the calculations are.

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

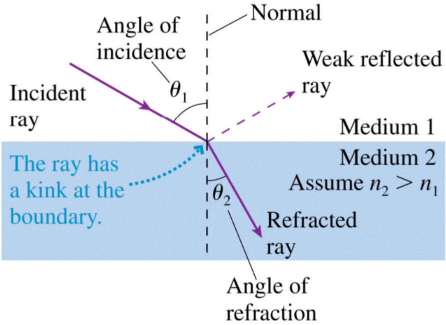
$$n = \frac{c}{v}$$

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).



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

Finding Index of Refraction

Snells Law:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \tag{1}$$

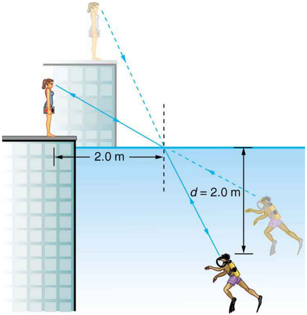
Rearranging to isolate n_2:

$$n_2 = n_1 \frac{\sin\theta_1}{\sin\theta_2} \tag{2}$$

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

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

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

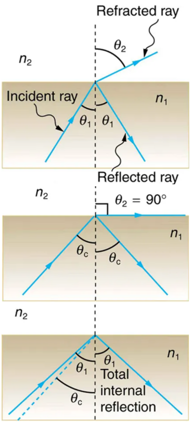
Good mirrors reflect $> 90\%$ of the light; however, total reflection can be produced via refraction.

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 angel 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 $\theta_2 = 90^\circ$

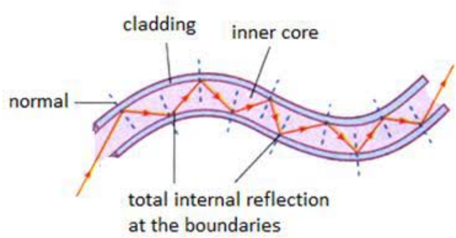
The critical angle is given by:

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



Fiber Optic Cable

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



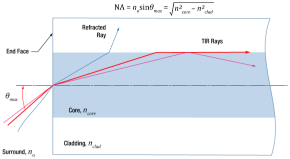
Fiber: Acceptance Angle

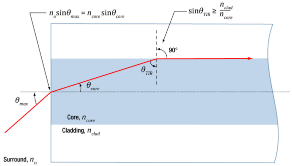
For multi-mode fibers, the numerical appeture (NA) provides a good estimate of the maximum acceptance angle.

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

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

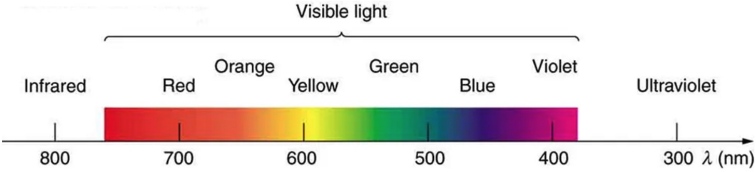
- Rays with an angle of incidence $\leq \theta_{max}$ are totally internally reflected (TIR) at the fiber core/cladding boundary.
- Rays with an angle of incidence $> \theta_{max}$ refract at and pass through the boundary.





Dispersion

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



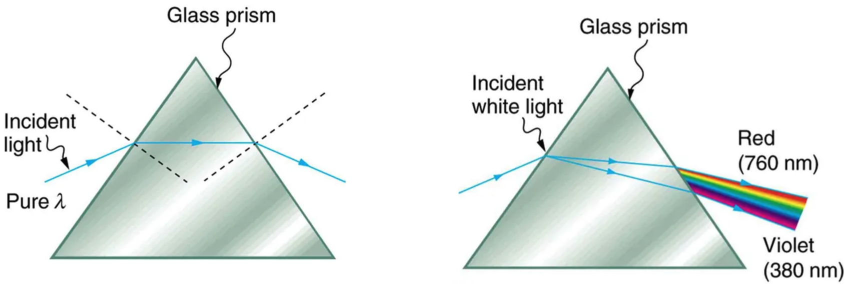
- The angle of refraction depends on the index of refraction.
- The index of refraction (n) depends on the properties of the medium.
- However, for a given medium, n also depends on the optical wavelength.

Index of Refraction by Wavelength

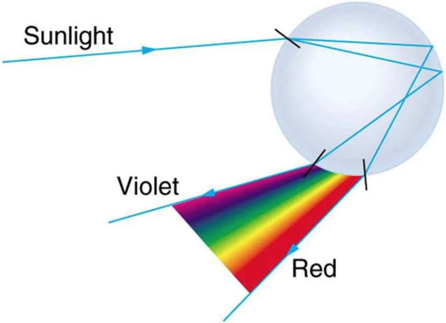
Index of refraction (n) by wavelength (λ):

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

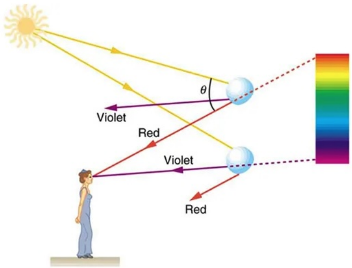

Glass prism
Incident light
Pure λ
Glass prism
Incident white light
Red (760 nm)
Violet (380 nm)

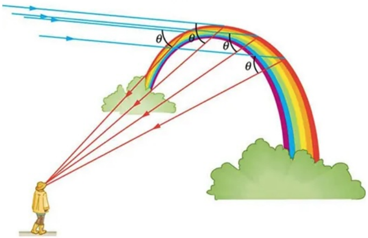
Rainbow



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



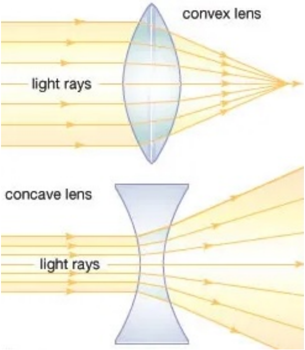


Lens

Lens

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

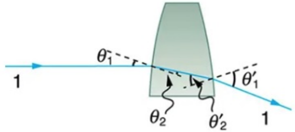
- The word lens comes from the Latin word for lentil bean, the shape of which is similar to a convex lens.
- Convex Lens: all light rays that enter parallel to the axis cross one another at a single point on the opposite side of the lens, i.e., they converge.
- Concave Lens: all light rays that enter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

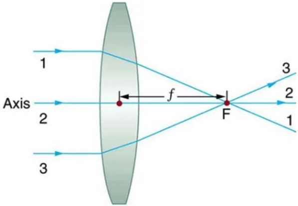


Convex Lens

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

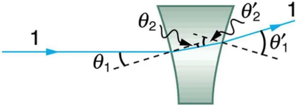
- A ray of light bends (refracts) at both interface, and for convex lens converge.
- The point at which the rays crossed is defined as the Focal point (F) of the lens.
- The distance from the center of the lens to its focal point is called the focal length (f).
- The Power of the lens, measuring in Diopters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

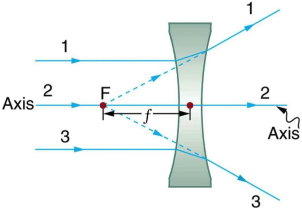




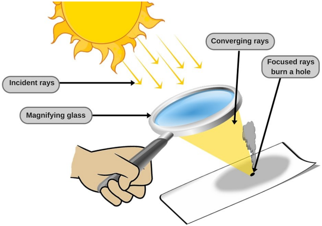
Concave Lens

- 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.





Assigment: 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.

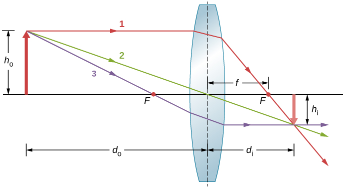
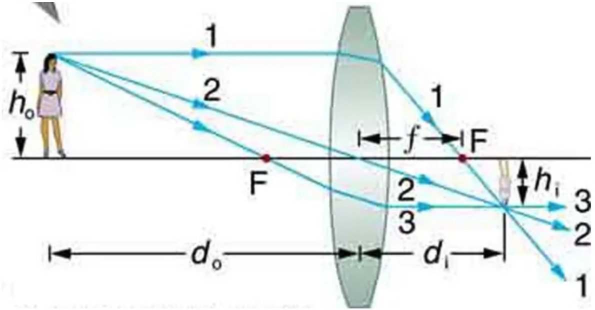


Image Formation

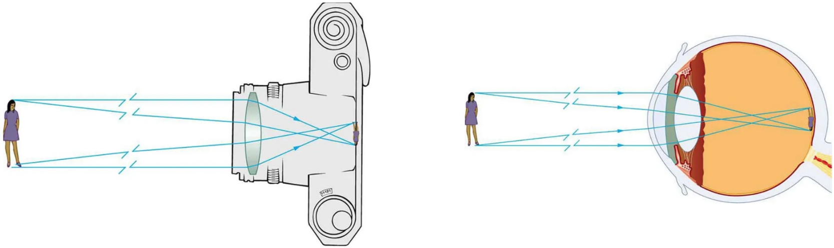


Thin Lens equations:

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

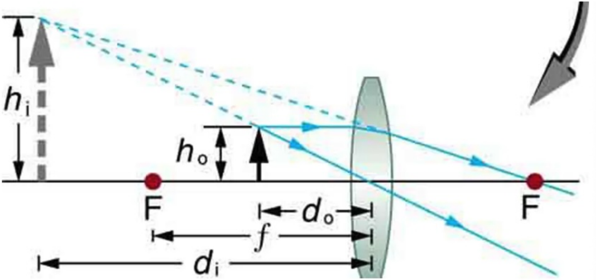
$$\frac{h_i}{h_o} = -\frac{d_i}{d_o} = m$$

Image Formation - Real Image



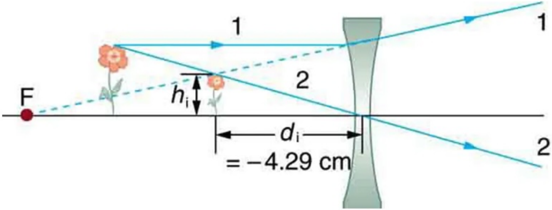
The image in which light rays from one point on the object actually cross at the location of the image and can be projected onto a screen, a piece of film, or the retina of an eye is called a real image.

Image Formation - Virtual Image

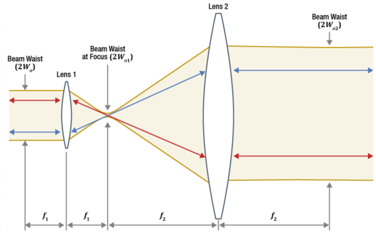


If an object is held closer to the converging lens than its focal length (f), then the rays from a common point continue to diverge after passing through the lens. They all appear to originate from a point at the location of the image, on the same side of the lens as the object. This is a virtual image.

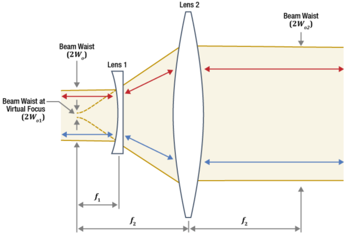
Image Formation - Concave Lens



Beam Expander/Reducer - Telescope



Galilean Design



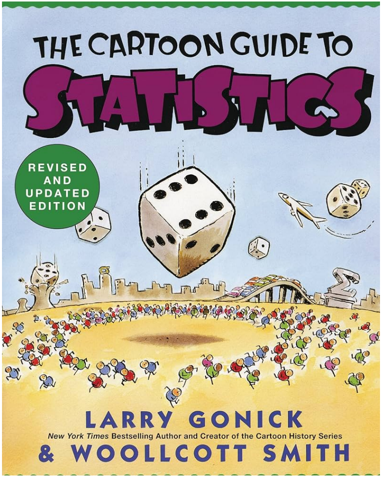
Galilean Design

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

$$m_{12} = \frac{f_2}{f_1} \tag{5}$$

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 16^{th} 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

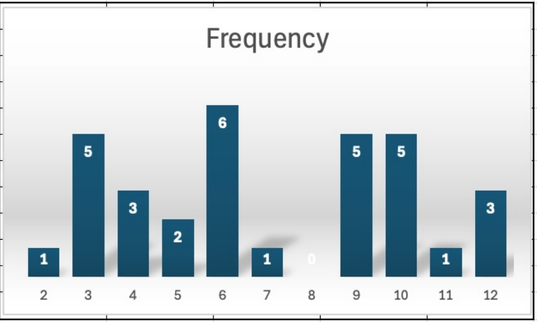
The probability of an event expresses the likelihood of the event outcome

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

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

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

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 the 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**

$$\text{average} = \bar{x} = 7$$
$$\text{median} = 6$$
$$\text{mode} = 6$$

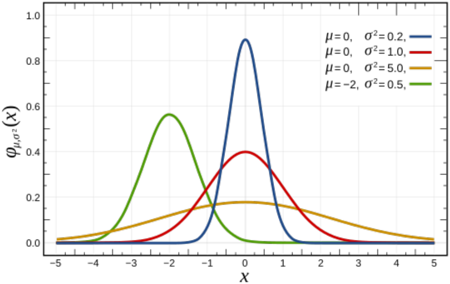
Summary Statistics: Variation

1-8								9-16								17-24								25-32							
2	3	3	3	3	3	4	4	4	5	5	6	6	6	6	6	6	7	9	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.
  - IRQ = Q3 - Q1 = 6
- Standard Deviations (σ):

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

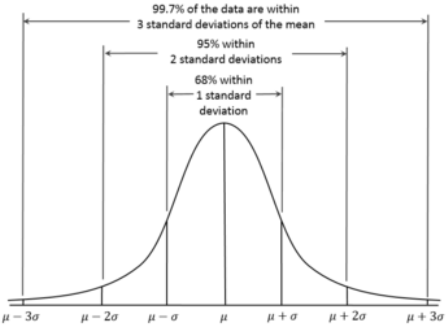
Gaussian Distribution



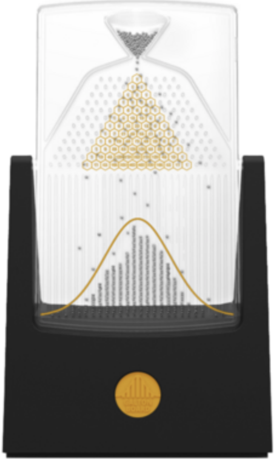
Probability Distribution Function $f(x)$:

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

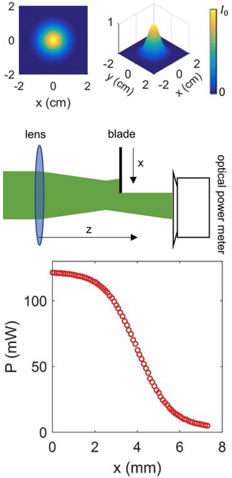
Gaussian Distribution: 3σ



Galton Baord



Assignment: Measuring Bean Profile

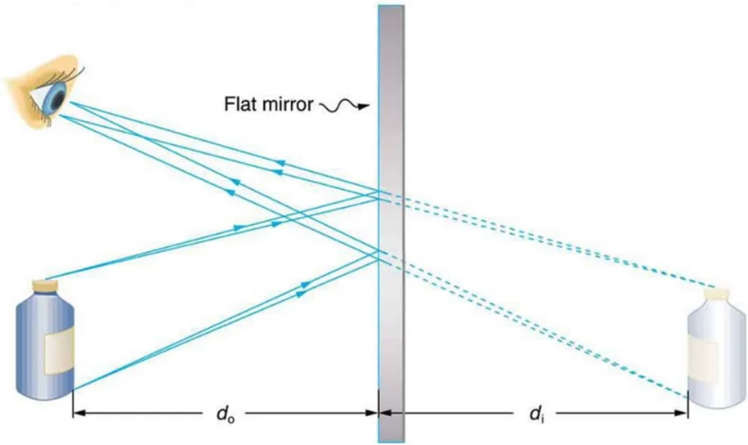


The laser beam has a Gaussian profile.

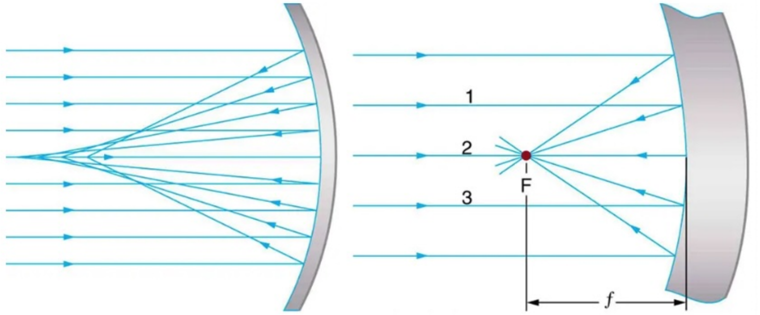
1. Direct a laser beam at a power meter, setting the correct wavelength
2. Moving the knife edge across the beam path, record the drop in power vs distance.
3. Setup a telescope to expand the beam size by 2-5 times.
4. Repeat the knife edge process.
5. Plot the results of both sets of measurements on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

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

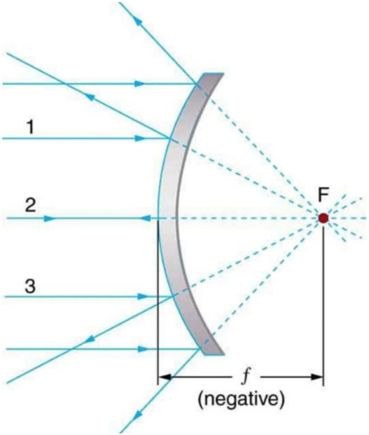


Image Formation - Concave Mirrors

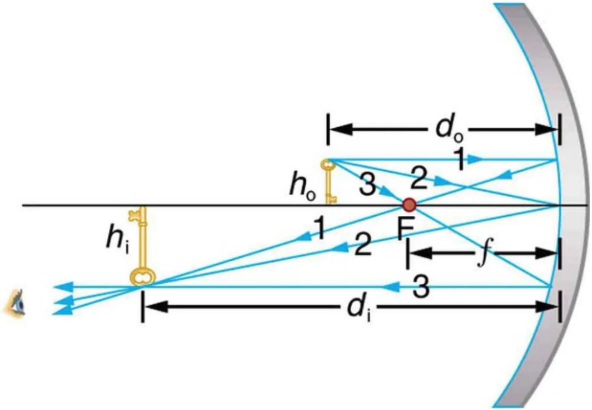


Image Formation - Concave Mirrors

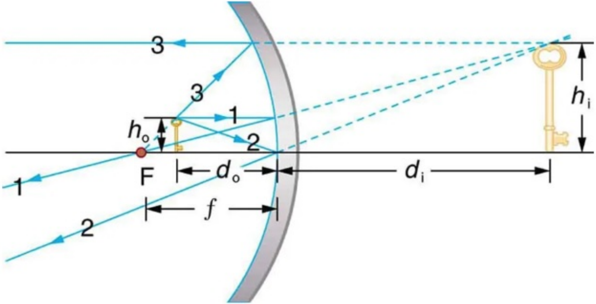
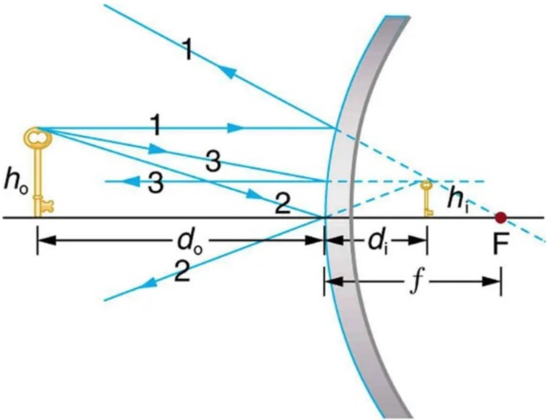
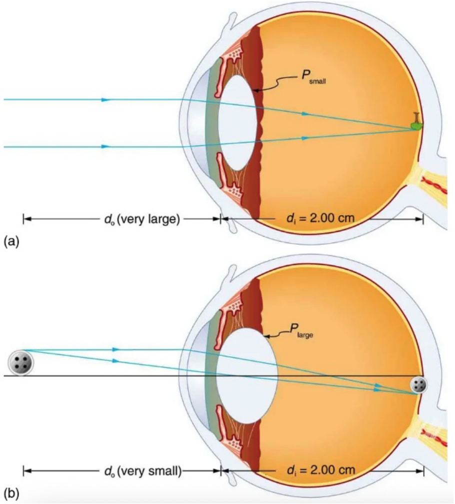


Image Formation - Convex Mirrors



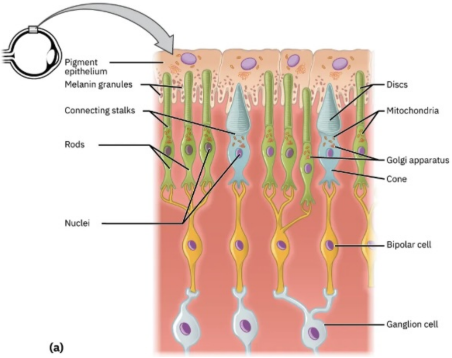
Vision

The Eye

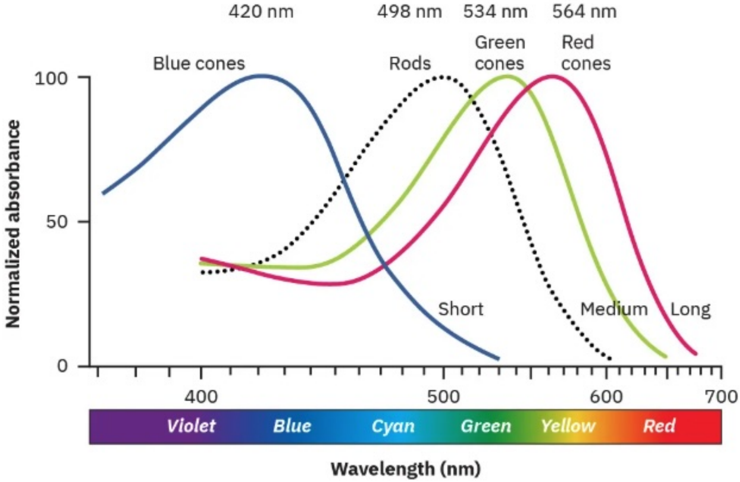


P_{small}
d_o (very large)
d_i = 2.00 cm
(a)
P_{large}
d_o (very small)
d_i = 2.00 cm
(b)

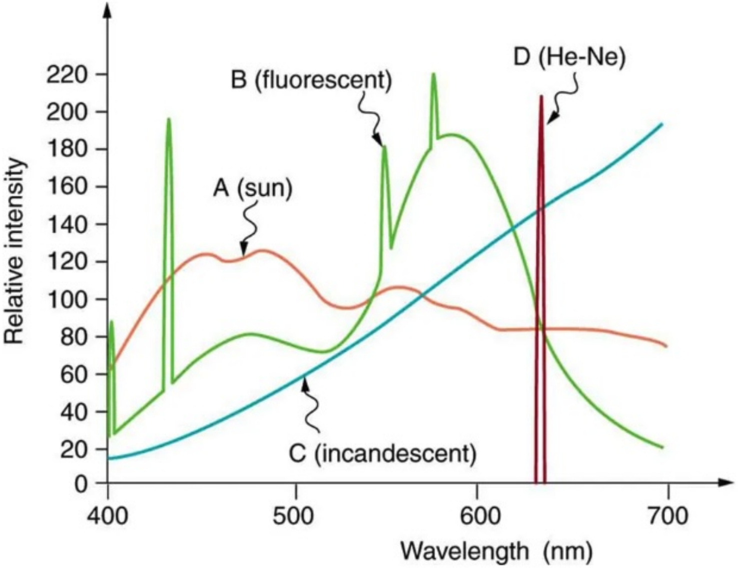
Rods and Cones and Color



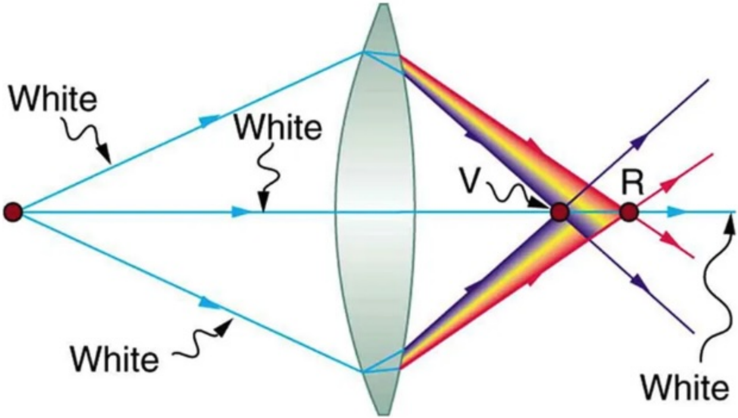
Visible Spectrum



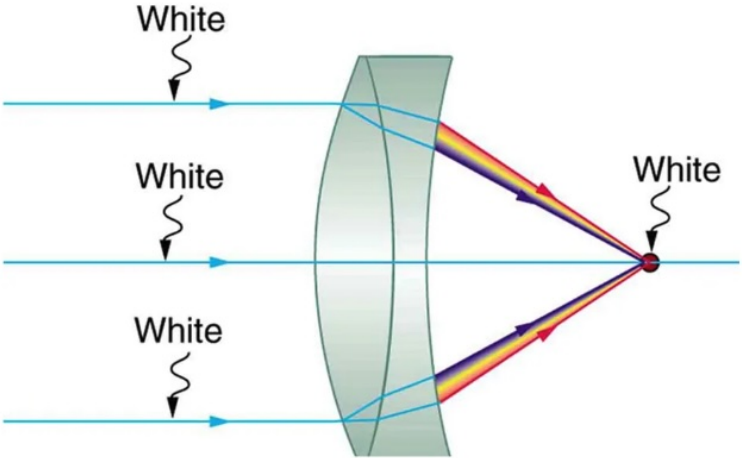
Spectrum of Light Sources



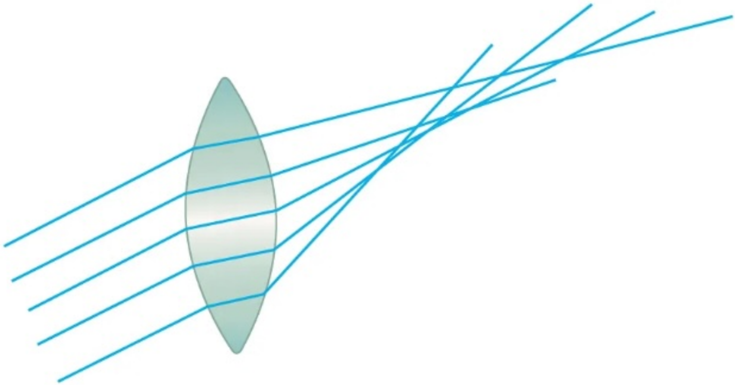
Chromatic Aberrations



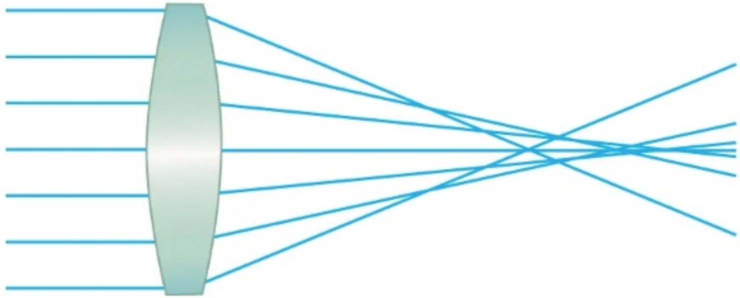
Correcting Chromatic Aberrations



Coma - Off Axis Abberation



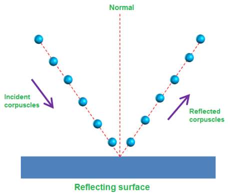
Spherical Aberrations

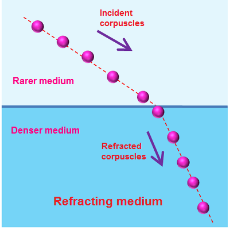


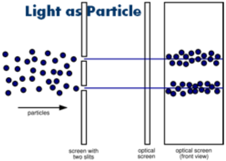
Interlude: Light - a particle or a wave?

Corpuscular Theory of Light

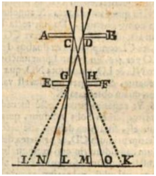
In 1675, Sir Isaac Newton hypothesized that light was made up corpuscules (small particles) with the size/mass of the corresponding to different colors.

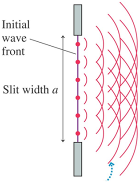






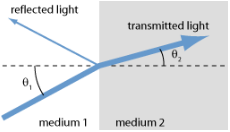
Huygens Principle

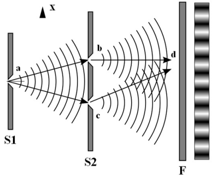




- Francesco Maria Grimaldi (mid-1600's) made accurate observations of the diffraction of light.
- In 1678, Christian Huygens, in order to explain the diffraction of light, proposed that every point on a wavefront (of light) is a wavelet that spreads.

Fresnel and Young





- In 1815, Augistine Jean Fresnel devleoped the laws of reflection and refraction.
- And, in 1817, Thomas Young calculated the wavelength of light

Maxwell's Equations: Electric $\vec{E}$ and Magnetic $\vec{B}$ Fields

In 1864, James Clerk Maxwell predicted electromagnetic waves

- Gauss's Law: $\nabla \cdot \vec{E} = \frac{\rho}{\epsilon_0}$, where ρ is enclosed charge
- Guass's Law for Magnets: $\nabla \cdot \vec{B} = 0$
- Farday's Law: $\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$
- Ampere's Law: $\nabla \times \vec{B} = \mu_0 \vec{J} + \mu_0 \epsilon_0 \frac{\partial \vec{E}}{\partial t}$

where
$\mu_0 = 4\pi * 10^{-7} \frac{F}{m}$ and $\epsilon_0 = 8.85 * 10^{-12} \frac{Nm^2}{C}$

Maxwell noted that the speed of the electromagnetic wave is equal to the speed of light:
$\frac{1}{\sqrt{\mu_0 \epsilon_0}} = \frac{1}{\sqrt{4\pi * 10^{-7} \cdot 8.85 * 10^{-12}}} = 2.99 * 10^8 \frac{m}{s} = c$

Wave Optics

Speed of Light in a Medium

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

$$c = f\lambda \tag{6}$$

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

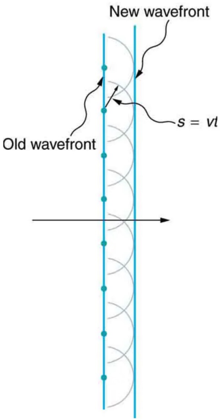
Divide both sides of the above equation by n yields:

$$v = \frac{c}{n} = \frac{f\lambda}{n} = f\lambda_n \tag{7}$$

where λ_n is the wavelength in the medium.

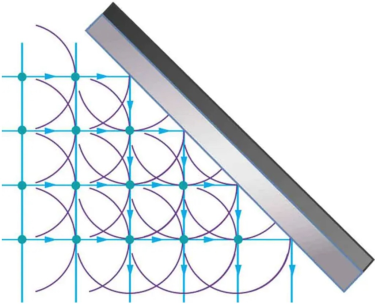
Huygens's Principle: Diffraction

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.



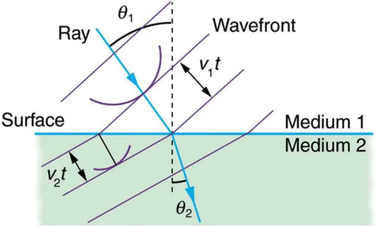
Huygens's Mirror

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.



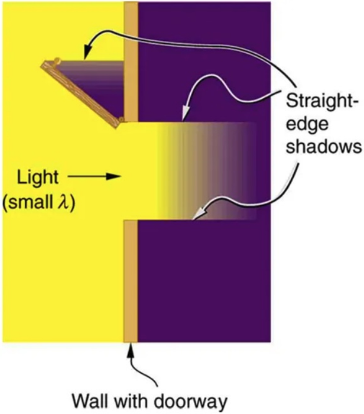
Huygens's Refraction

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.

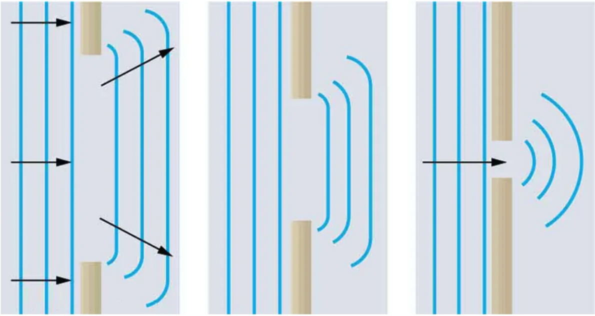


Diffraction

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.

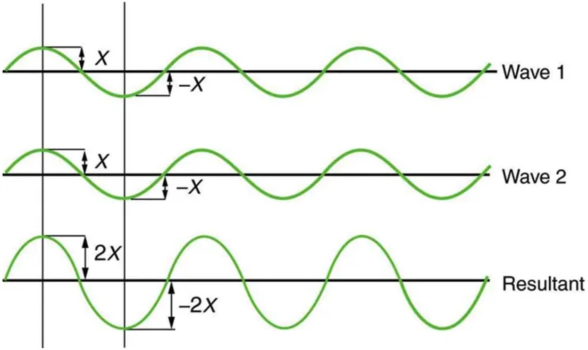


Diffraction

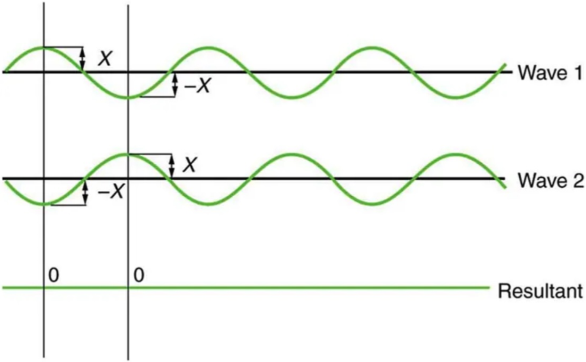


If we pass light through smaller openings, often called slits, we can use Huygens's principle to see that light bends. The bending of a wave around the edges of an opening or an obstacle is called diffraction. Diffraction is a wave characteristic and occurs for all types of waves.

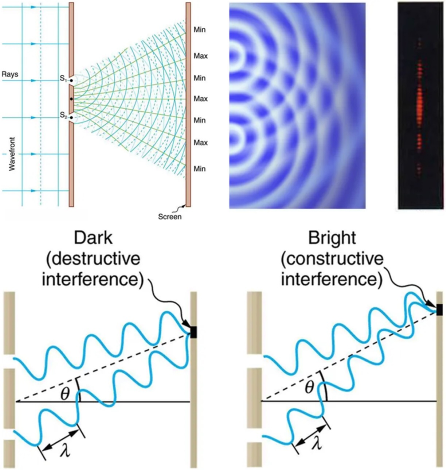
Constructive Interference



Destructive Interference



Double Slit


Rays
Wavefront
S_1
S_2
Min
Max
Min
Max
Min
Max
Min
Screen
Dark
(destructive
interference)
Bright
(constructive
interference)
θ
λ
θ
λ

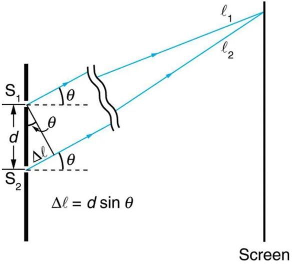
Path Length Difference

- Constructive Interference - peaks are in phase

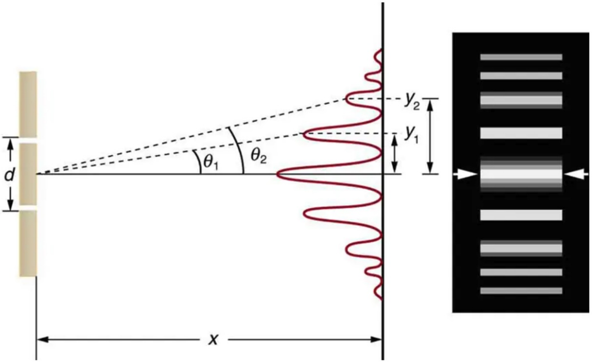
$$d \sin(\theta) = m\lambda, m = 0, 1, -1, 2, -2, ...$$

- Destructive Interference - peaks are perfectly out of phase

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



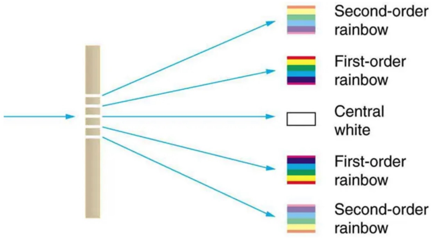
Double Slit - Constructive Interference



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.

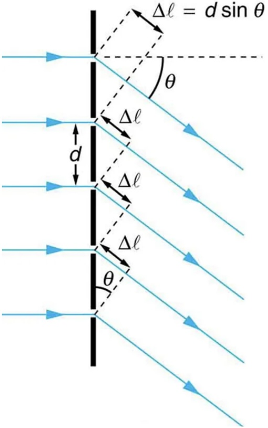


Diffraction Grating - Constructive Interference

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

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

for, $m = 0, 1, -1, 2, -2, ...$

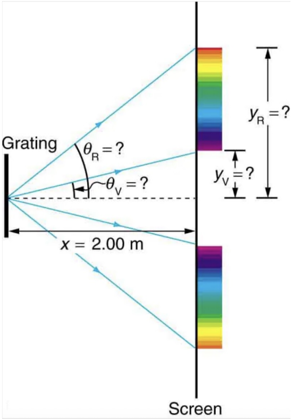


Diffraction Grating - Spread of Wavelength

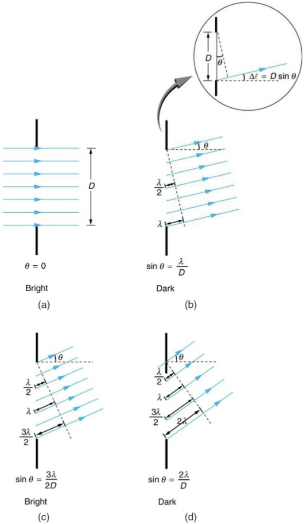
We can find θ_R, y_R, θ_V, and y_V by using:

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

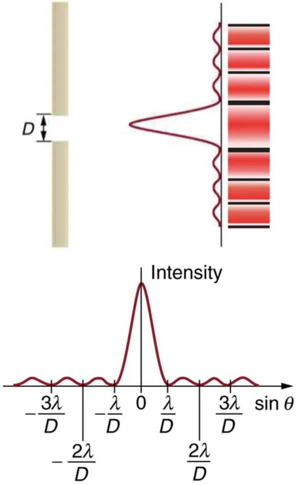
for, $m = 1$.



Single Slit



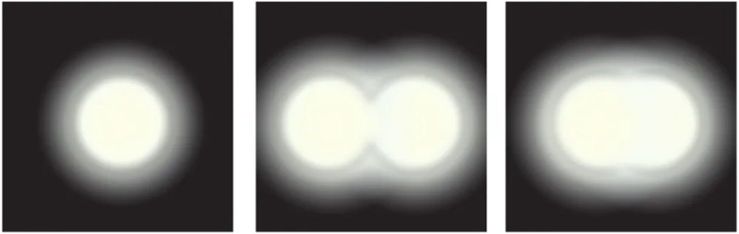
D
$\theta = 0$
Bright
(a)
θ
$\frac{\lambda}{2}$
λ
$\Delta\ell = D\sin\theta$
$\sin\theta = \frac{\lambda}{D}$
Dark
(b)
$\frac{3\lambda}{2}$
$\sin\theta = \frac{3\lambda}{2D}$
Bright
(c)
2λ
$\sin\theta = \frac{2\lambda}{D}$
Dark
(d)



D
Intensity
$-\frac{3\lambda}{D}$
$-\frac{2\lambda}{D}$
$-\frac{\lambda}{D}$
0
$\frac{\lambda}{D}$
$\frac{2\lambda}{D}$
$\frac{3\lambda}{D}$
$\sin\theta$

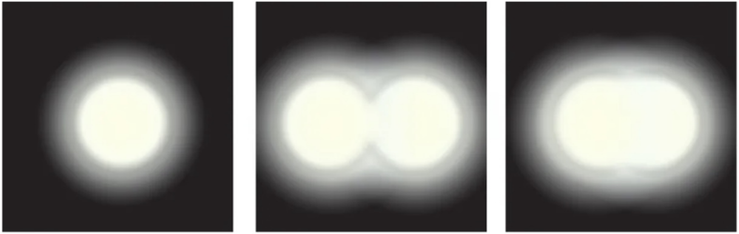
Limits of Resolution

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



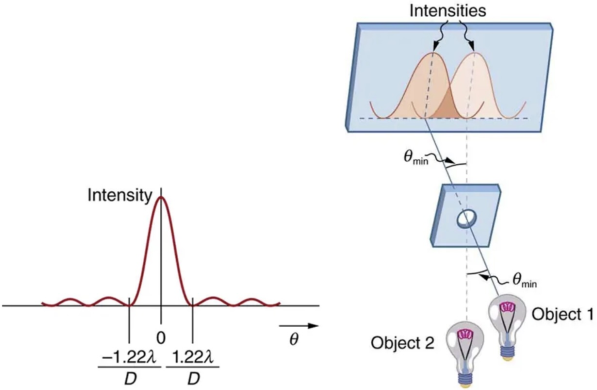
Limits of Resolution

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 $\theta = 1.22\frac{\lambda}{D}$

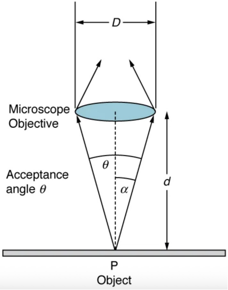


Resolving Power

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 between the lens objective and the object.



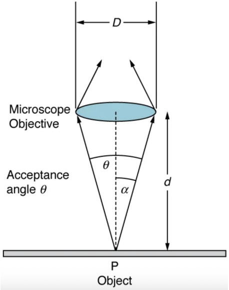
Numerical Aperture (NA)

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.



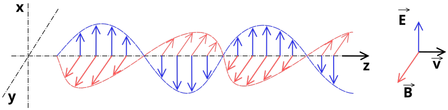
$$x = 1.22\frac{\lambda d}{D} = 1.22\frac{\lambda}{2sin(\alpha)} = 0.61\frac{\lambda n}{NA}$$

[3]

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

Polarization

Electromagnetic Wave

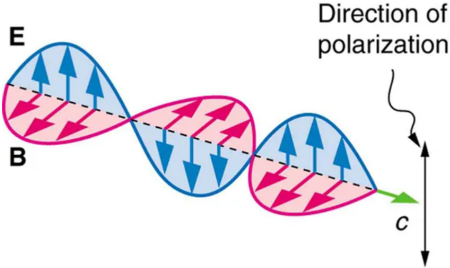


An Electromagnetic (EM) wave is a transverse wave where the electric and magnetic fields are perpendicular to each other and to the direction of propagation.

- 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.

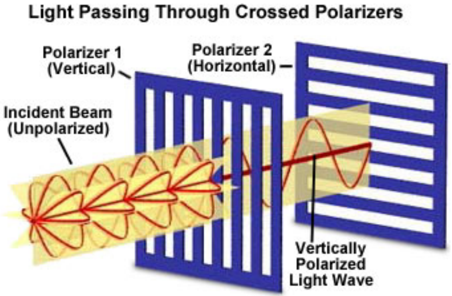
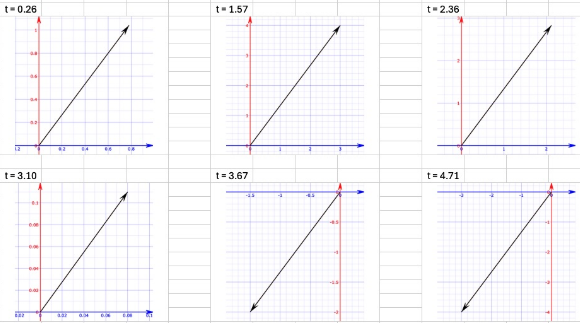


Figure 1

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

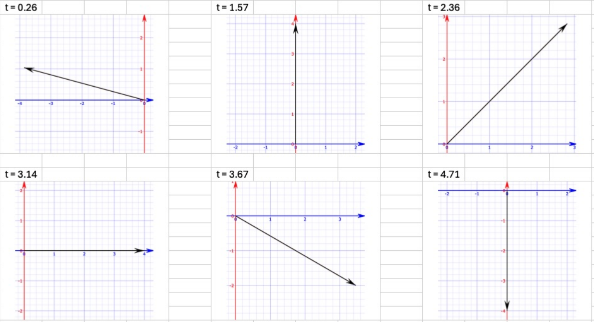


$$\vec{E} = 3\sin(t)\vec{i} + 4\sin(t)\vec{j} \tag{8}$$

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

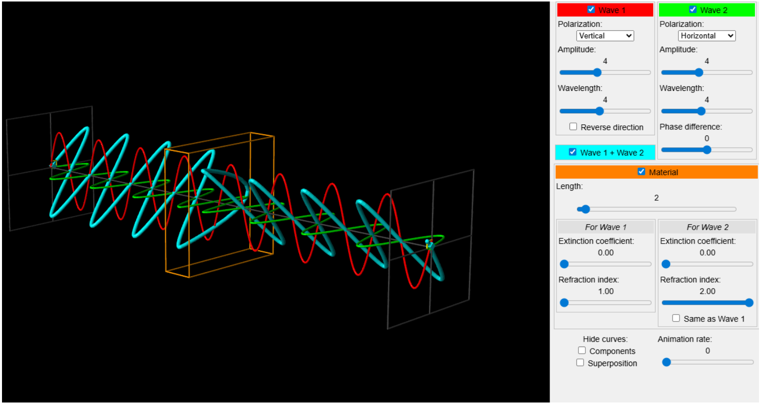


X lags Y by $\frac{\pi}{2}$:

$$\vec{E} = 4\sin\left(t + \frac{\pi}{2}\right)\vec{i} + 4\sin(t)\vec{j} \tag{9}$$

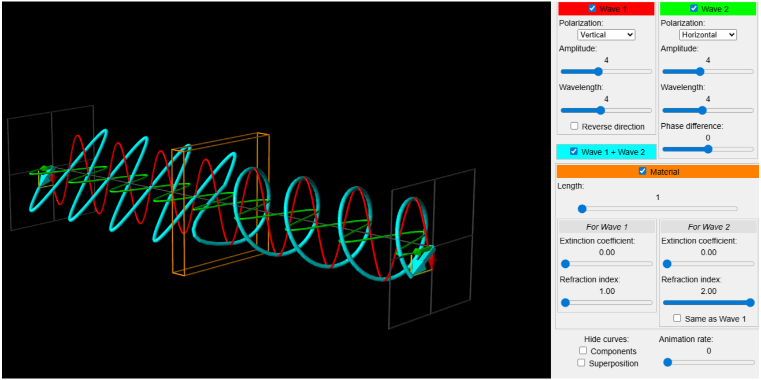
Incoming 45° with Half-Wave Plate

From https://emanim.szialab.org/



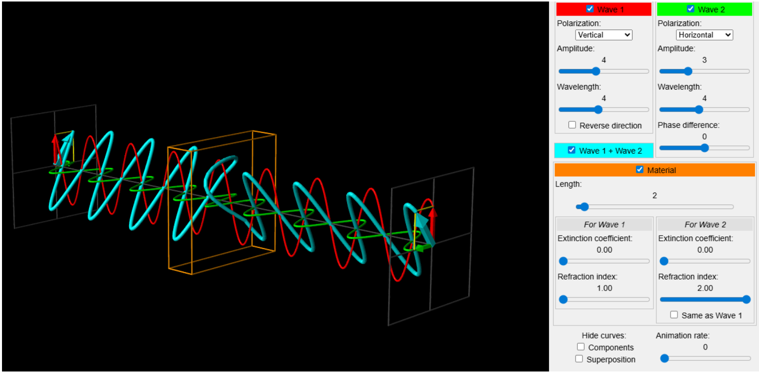
Incoming 45° with Quarter-Wave Plate

From https://emanim.szialab.org/



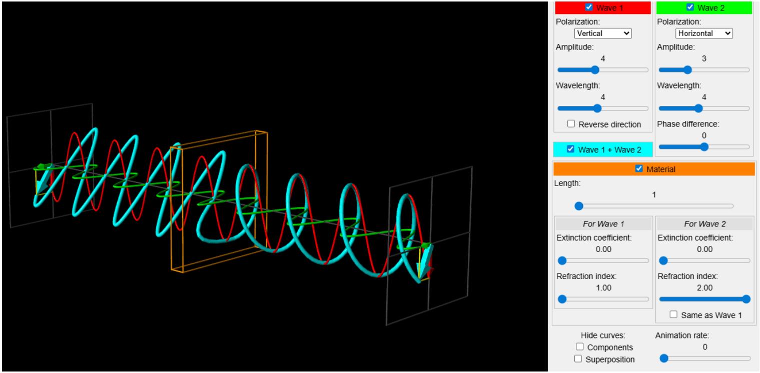
Incoming 37° with Half-Wave Plate

From https://emanim.szialab.org/



Incoming 37° with Quarter-Wave Plate

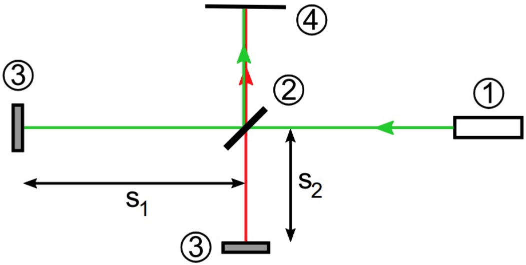
From https://emanim.szialab.org/



Interferometry

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

- The Electric Field (E_i) is given by

$$|E_i| = \sqrt{R \cdot T} \cos(\omega t + \phi_i) \tag{10}$$

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

- Intensity (I) on the screen is given by

$$I = c\epsilon_0 |E_1 + E_2|^2 \tag{11}$$

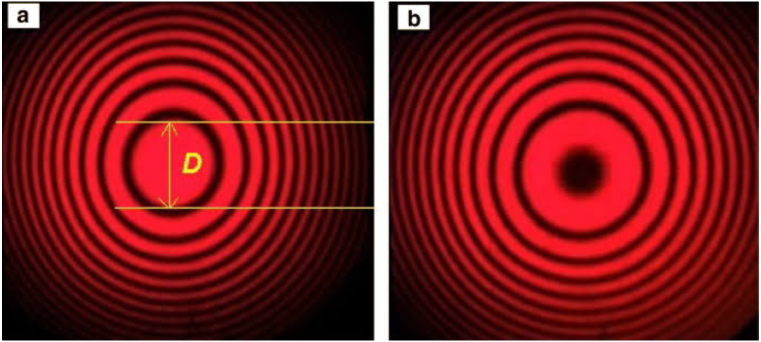
- If we assume that the transmission and reflection capacity are 0.5 then the average intensity ($\bar{I}$) is given by

$$\bar{I} = \frac{1}{4} c\epsilon_0 E_0^2 (1 + \cos(\Delta\phi)) \tag{12}$$

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?

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:

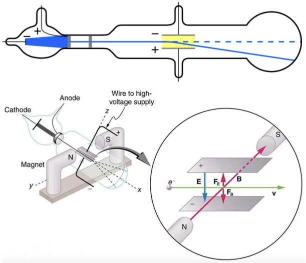
$$F = q_e E$$

- 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

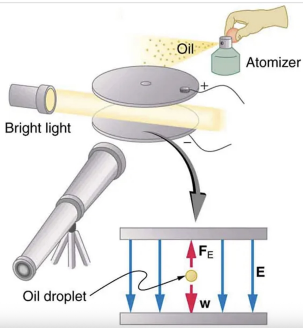
American physicist, Robert Millikan improved on the experiment:

- 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:

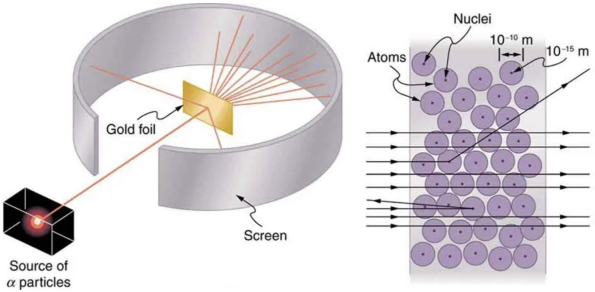
$$m_e = \frac{q_e}{\left(\frac{q_e}{m_e}\right)} = \frac{-1.6 \times 10^{-19} - 1.76 \times 10^{-11}}{=} 9.11 \times 10^{-31}(kg)$$

And, the mass the proton:

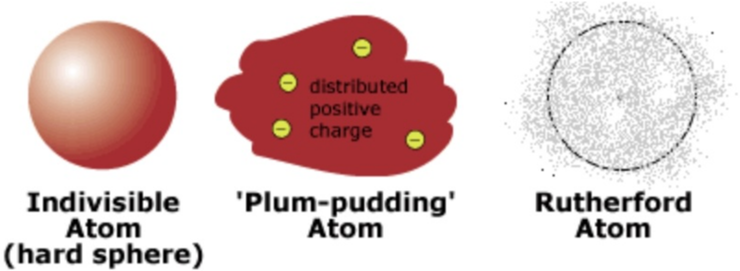
$$m_p = 1.67 \times 10^{-27}(kg)$$

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



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.

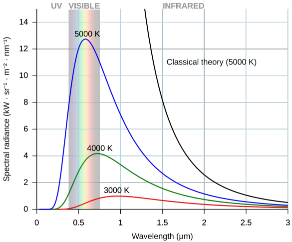
°C	550	630	680	740	780	810	850	900	950	1000	1100	1200	>1300
°F	1022	1166	1256	1364	1436	1490	1562	1652	1742	1832	2012	2192	>2372

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.

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

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



Quanta

Max Planck assumed that electromagnetic radiation can be emitted or absorbed only in discrete packets, call quanta[4], 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:

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

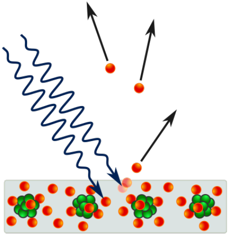
[4] Planck considered this a mathematical trick, not reality

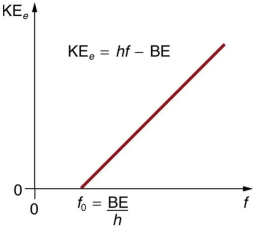
Photoelectric Effect

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

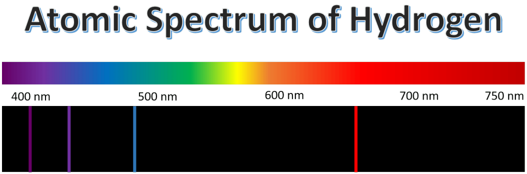
- There is a minimum energy (f_0) before any electrons are ejected.
- Electrons are ejected without delay.
- The number of electrons ejected is proportional to intensity of EM.
- The maximum kinetic energy of the electrons is independent of intensity.
- The maximum kinetic energy is given by $KE_e =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

A quantum of light is called a photon.





Bohr's Atom



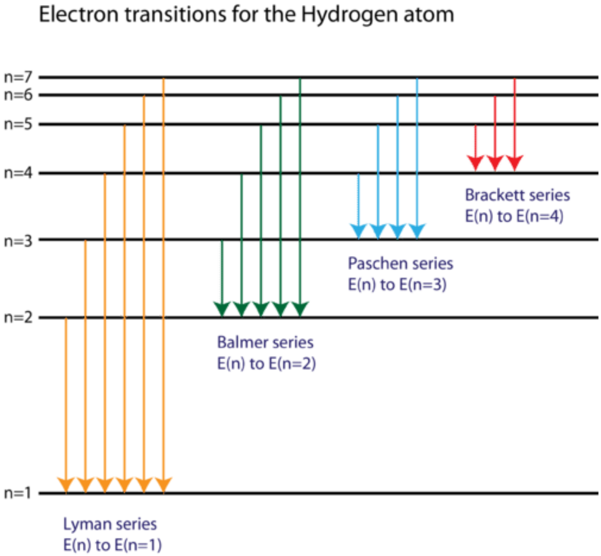
The observed hydrogen-spectrum wavelengths can be calculated using the following formula:

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

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

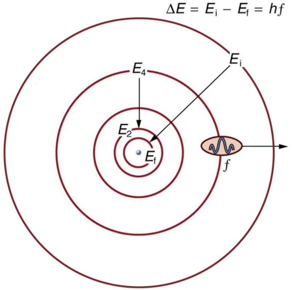

Electron transitions for the Hydrogen atom
n=7
n=6
n=5
n=4
n=3
n=2
n=1
Brackett series
E(n) to E(n=4)
Paschen series
E(n) to E(n=3)
Balmer series
E(n) to E(n=2)
Lyman series
E(n) to E(n=1)

Bohr's Atom

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

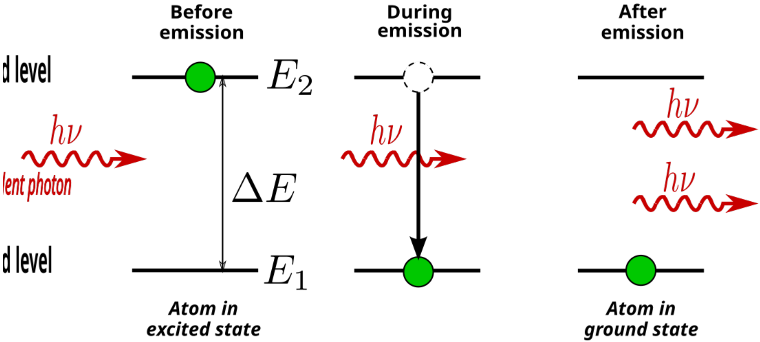
- Only certain orbits area allowed (orbits of electrons in atoms are quantized)
- Each orbit has different energy: absorb to move to a higher orbit, drop to lower orbit by emitting.
- Energy absorbed/emitted is also quantized, producing discrete spectra.
- Energy to move from one orbit to another

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



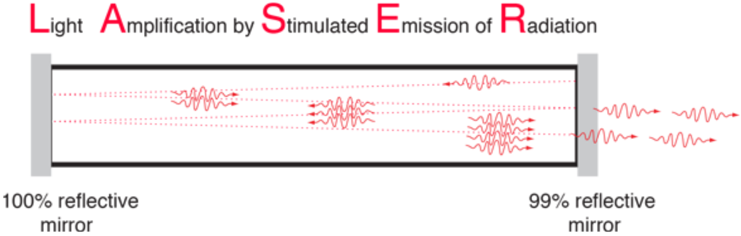
The Laser

Stimulated Emission

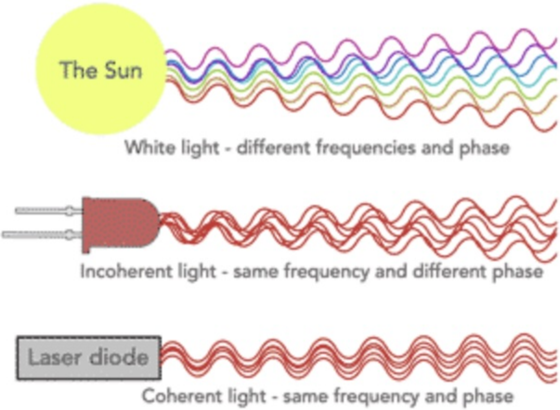


$$E_2 - E_1 = \Delta E = h\nu$$

Light Amplification → LASER



Coherence


The Sun
White light - different frequencies and phase
Incoherent light - same frequency and different phase
Laser diode
Coherent light - same frequency and phase

Schrodenger's Atom

Waves and Quantization

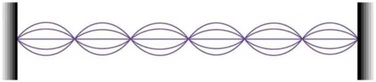
- Per de Broglie proposed matter has wave-like properties ($\lambda = \frac{h}{p}$)
- Electrons can only exist in locations where they interfere constructively.
- Not all orbits produce constructive interference, so not all allowed

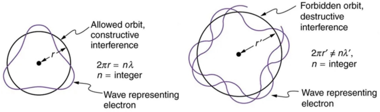
$$n\lambda_n = 2\pi r_n, \text{ for n} = 1, 2, 3, \ldots$$

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

Angular Momentum (L):

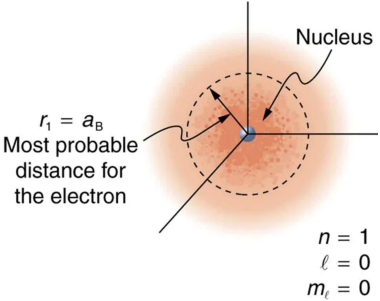
$$L = m_e v r_n = n\frac{h}{2\pi}, \text{ for n} = 1, 2, 3, \ldots$$





Probability Cloud

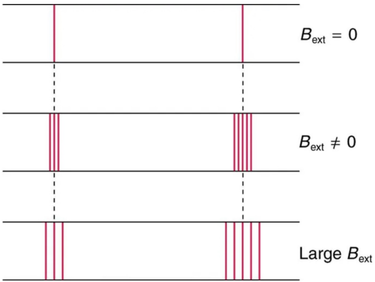
Due to the wave nature of matter, the idea of well-defined orbits gives way to a model in which there is a cloud of probability, consistent with the Heisenberg uncertainty principle.



Patterns in Spectra - Zeeman Effect

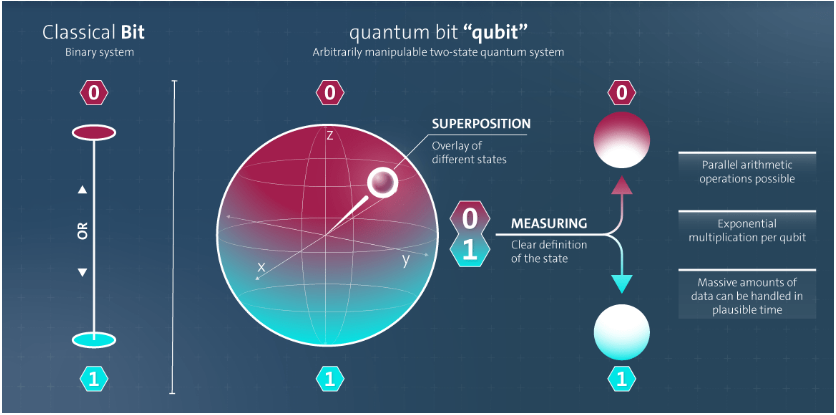
Dutch physics student Pieter Zeeman investigated how spectra are affected by magnetic fields. In the presence of an external[a] magnetic fields, the spectral lines split into two or more separate lines.

[a] Very percise measurements have shown that spectrail lines are doublets (split in two) apparently by the magnetic fields within the atom itself.



What is a Qubit

Bit vs Qubit


Classical Bit
Binary system
0
OR
1
quantum bit "qubit"
Arbitrarily manipulable two-state quantum system
0
z
x
y
1
SUPERPOSITION
Overlay of different states
0
1
MEASURING
Clear definition of the state
0
1
Parallel arithmetic operations possible
Exponential multiplication per qubit
Massive amounts of data can be handled in plausible time

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.

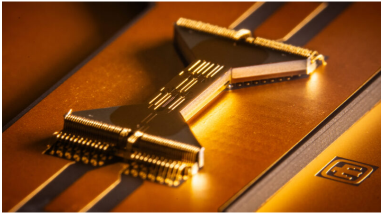
Quantum Computing: Photonics

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