Quantum Technician Bootcamp

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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

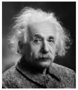
Quantum Mechanics:

The physics of the microscopic world

atom

electron

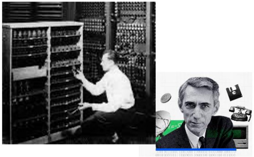
photon



Albert Einstein

Information Science:

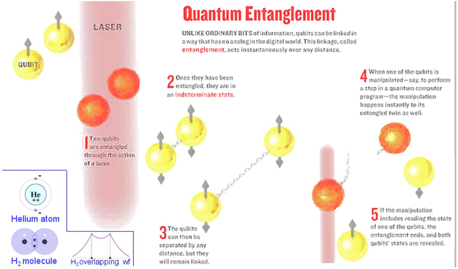
Computers & communications

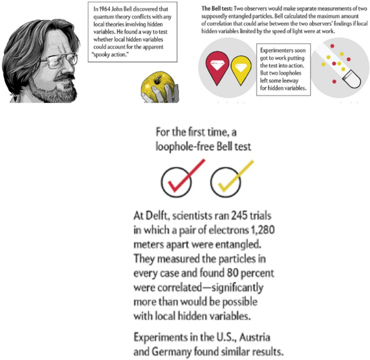


Claude Shannon

Introduction

Spooky Action at a Distance (Entanglement)





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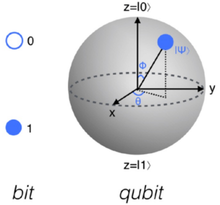
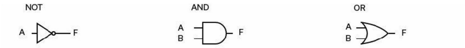
Introduction

Classical vs Quantum Logic





Input	Output
A	F
0	1
1	0

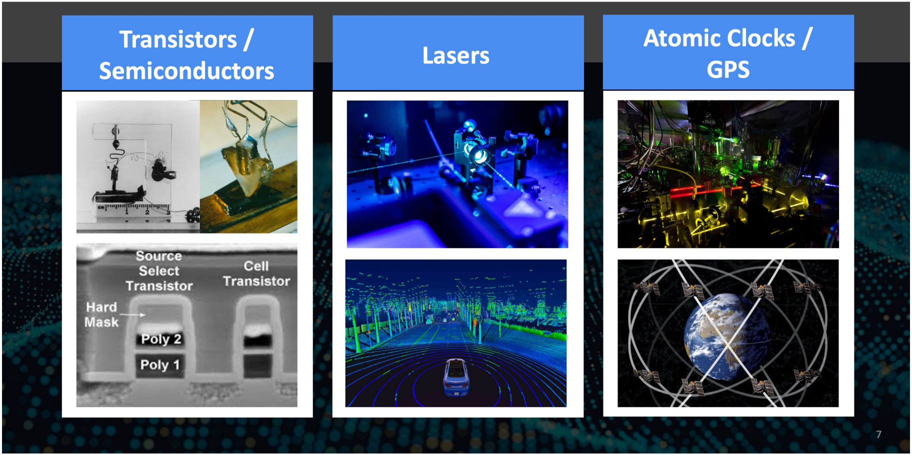
Inputs		Output
A	B	F
0	0	0
1	0	0
0	1	0
1	1	1

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

Operator	Gate(s)	Matrix
Pauli-X (X)	X	$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$
Pauli-Y (Y)	Y	$\begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}$
Pauli-Z (Z)	Z	$\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$
Hadamard (H)	H	$\frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$
Phase (S, P)	S	$\begin{bmatrix} 1 & 0 \\ 0 & i \end{bmatrix}$
$\pi/8$ (T)	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)	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)		$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}$

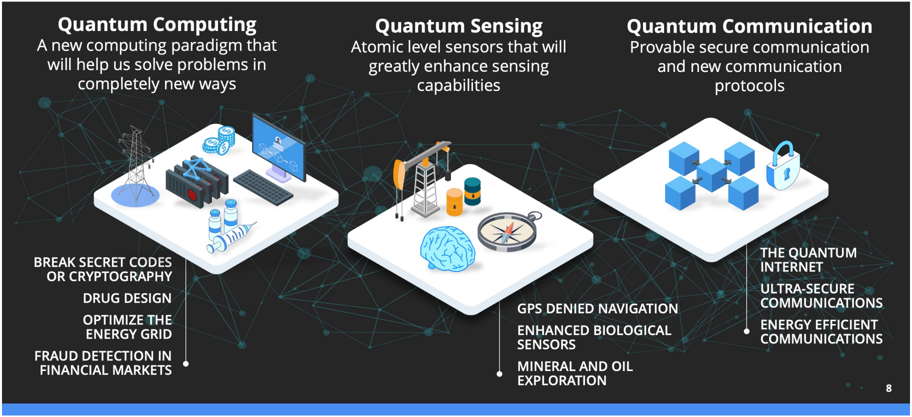
Introduction

Quantum Has Been With Us



Introduction

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

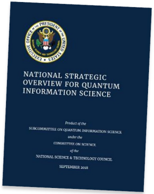


Introduction

Quantum is one of the top emerging technologies in the world

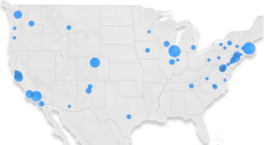
Federal legislation

- **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"

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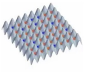
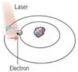
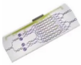
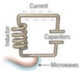
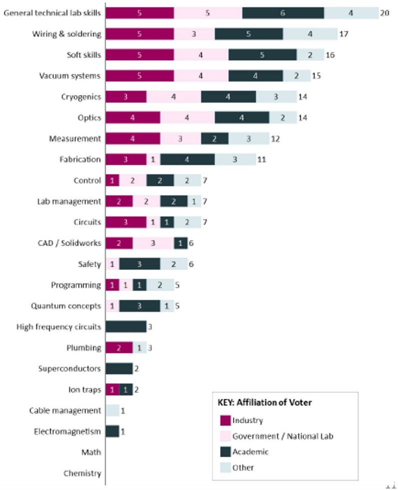
Introduction

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 Ψ PsiQuantum	IBM OQC ATLANTIC QUANTUM IQM Google AI	intel diraq QUANTUM MOTION QUANTUM BRILLIANCE Silicon Quantum Computing

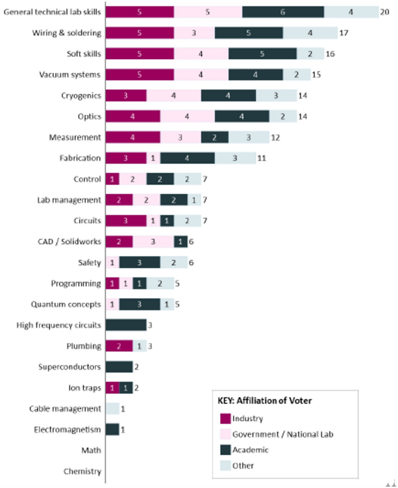
Introduction

Quantum Technician Skills



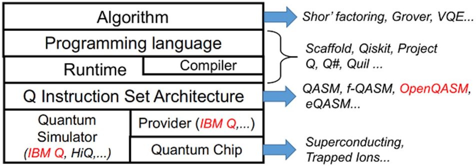
Introduction

Quantum Technician Skills



Introduction

Quantum Programming Languages



QuTiP
Quantum Toolbox in Python

Ocean

Qiskit

Cirq

Q#

JAQAL

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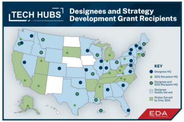
Introduction

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 Pratt School of Engineering · MIT · Tufts University · University of Maryland · Université de Sherbrooke · UNM · USC · Texas (The University of Texas at Austin)

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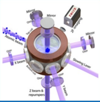
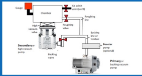
Introduction

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

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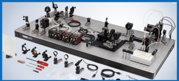

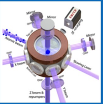

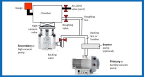

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Quantum Technician Bootcamp

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

Course Overview

Overview

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

Optics

- Lab Safety and Handling of Optical Components
- Reflection and Refraction: Prisms, Waveguides, and Dispersion
- Focusing, Imaging, and the Paraxial Approximation
- Thin Lens
- Think Lens and Compound Lens
- Apertures, Stops, Pupils, Windows
- Mirrors: Convex, Concave
- Cameras: Focusing, Resolution, and Contrast
- Aberrations
- Telescopes / Microscopy
- Spectra and Filters

Laser and Photonics

- Laser Safety
- Introduction to Lasers and Atomic Energy Levels
- Beam Properties: laser modes, beam profile, and coherence.
- Interferometry
- Polarization – polarizers, half/quarter wave plates
- Optical intensity. Single-mode and multi-mode optical fibers
- Optical detectors: photodiode, photomultiplier tubes, avalanche photodiodes, infrared detectors
- Optical spectra and emission spectroscopy
- Absorption Spectroscopy
- Optical Tweezers
- Industrial Applications of Laser and Photonics

Ultra-High Vacuum Systems

- Vacuum System Safety including Lock-out Tag-out (LOTO) of electrical and mechanical hazards
- Foundations of Vacuum Technology
- Vacuum Pump Technologies – Displacement: Backing Pumps, Turbomolecular Pumps.
- Vacuum Measurement: Pirani and Ion Gauges
- Vacuum System Assembly
- Vacuum System Contamination
- Leak Detection
- High Vacuum vs Ultra-High Vacuum

Quantum Phenomenon

- Introduction to Quantum
- Superposition, Quantum Gates
- Entanglement
- Particle/Wave Dual Nature of Light, Polarization, and Quantum Eraser
- Quantum Measurements
- Cryogenics
- Superconducting and Spin Qubits
- Laser Cooling
- Atomic, Molecular, and Optical Qubits
- Neutral Atom QIS Operations
- Quantum Sensors: Diamond NV

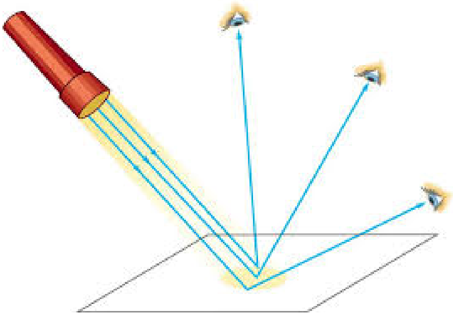
Applied Math

- College Algebra
- Vectors
- Trigonometry
- Linear Algebra
- Statistics

Geometric Optics

Ray Nature of Light

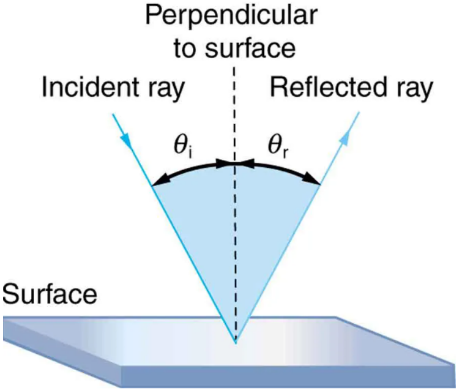
The word "ray" means a straight line that originates at some point.



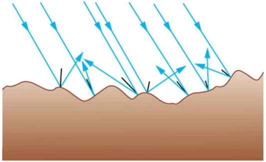
The part of optics dealing with the ray aspect of light is called "geometric optics."

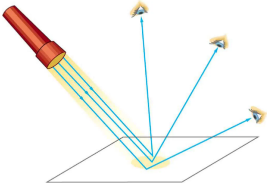
Reflection

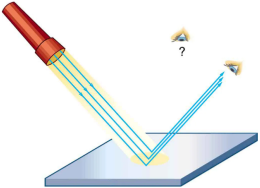
The angle of reflection equals the angle of incidences



Rough vs Smooth Surfaces

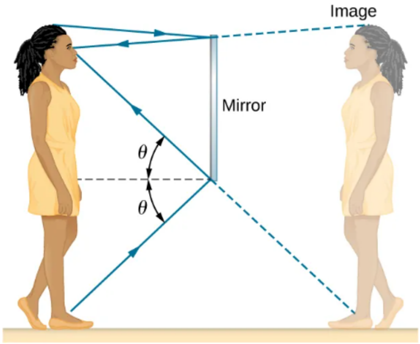






Mirrors and Virtual Images

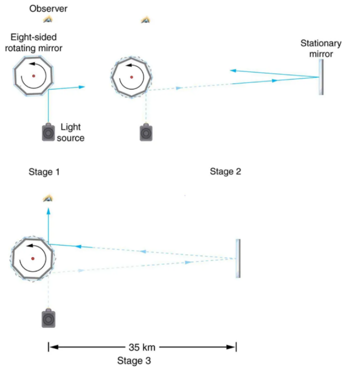
When we see ourselves in a mirror, it appears that our image is actually behind the mirror.



Speed of Light

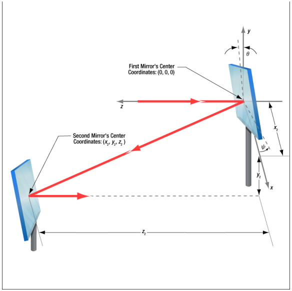
- In 1676, Danish astronomer Ole Roemer noted the change in orbital period of Jupiter's moons depending of if the earth was moving towards or away from Jupiter. He as able to calculate speed of light to be $2.26x10^8(\frac{m}{s})$.
- In 1887, American physicist Albert Michelson used a rotating mirror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

$$c = 2.99792458 10^8(\frac{m}{s}).$$



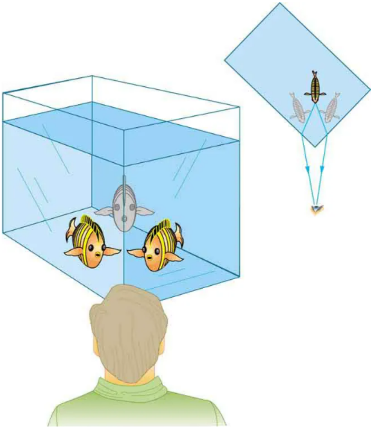
Two Mirror Walk

- Center of first mirror should match incoming height of incoming beam path and the second mirror set to the height of of the target beam path.
- Set alignment target at height of target.
- Course adjust both mirrors by hand.
- Place the alignment target along the beampath to the target
- Fine tune the beampath by using the adjusters on both mirrors. Note: adjusting the first mirror affects the placement of the second mirror.
- Move the alignment target along the output beampath to endure it is level



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

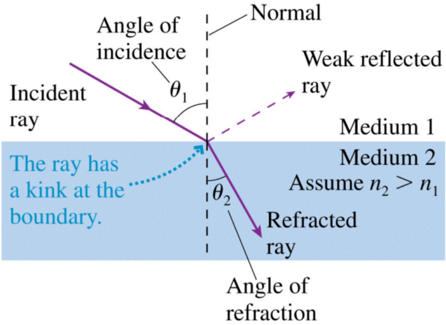
$$n = \frac{c}{v}$$

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

Medium	$\boldsymbol{n}$
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 $\theta_2 = 22^\circ$

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

Total Internal Reflection

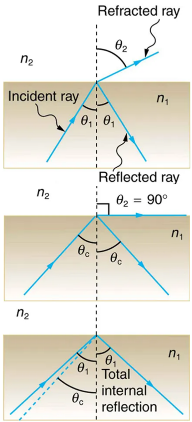
Good mirrors reflect $> 90\%$ of the light; however, total reflection can be produced via refraction.

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 $\theta_2 = 90°$

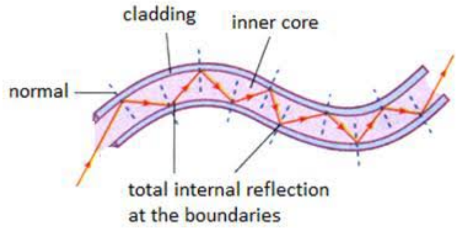
The critical angle is given by:

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



Fiber Optic Cable

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



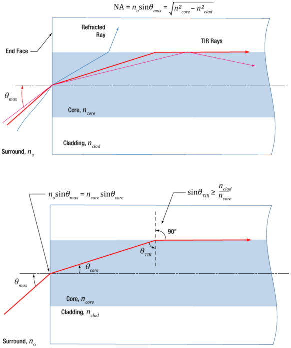
Fiber: Acceptance Angle

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:

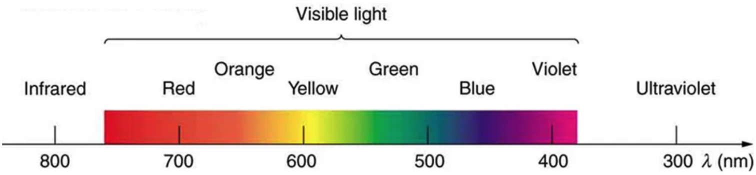
$$NA = n_0 sin(\theta_{max}) = \sqrt{n_{core}^2 + n_{clad}^2}$$

- 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.



Dispersion

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



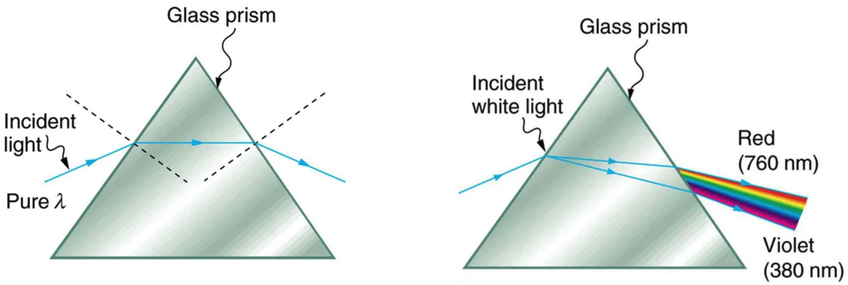
- The angle of refraction depends on the index of refraction.
- The index of refraction (n) depends on the properties of the medium.
- However, for a given medium, n also depends on the optical wavelength.

Index of Refraction by Wavelength

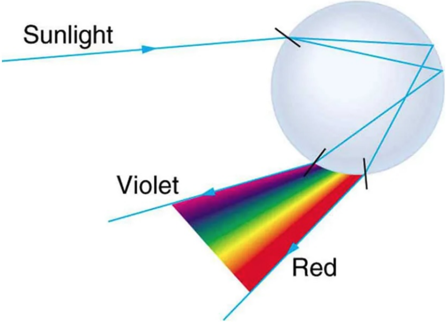
Index of refraction (n) by wavelength (λ):

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

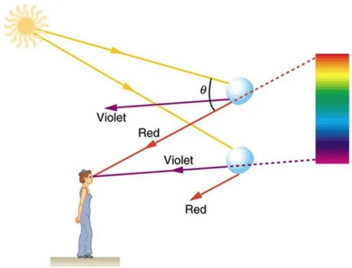

Glass prism
Incident
light
Pure λ
Glass prism
Incident
white light
Red
(760 nm)
Violet
(380 nm)

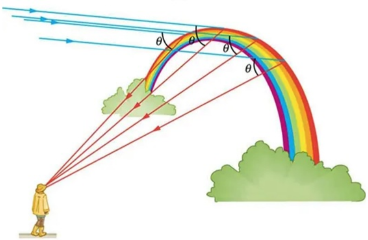
Rainbow



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



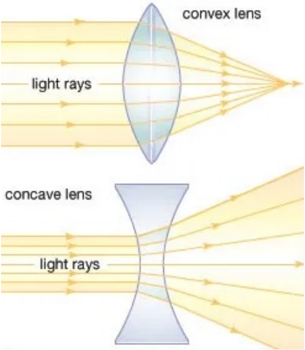


Lens

Lens

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

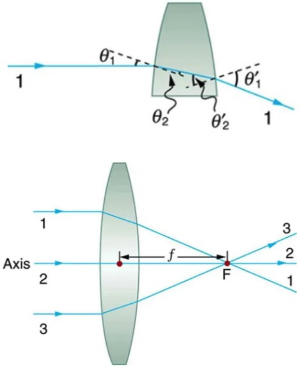
- The word lens comes from the Latin word for lentil bean, the shape of which is similar to a convex lens.
- Convex Lens: all light rays that enter parallel to the axis cross one another at a single point on the opposite side of the lens, i.e., they converge.
- Concave Lens: all light rays that enter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



Convex Lens

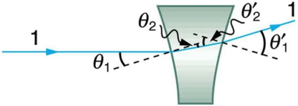
With the Law of Refraction, we can explore the properties of lens and how images are formed.

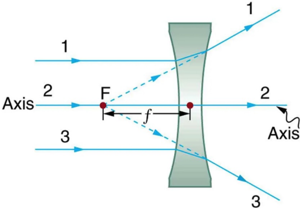
- A ray of light bends (refracts) at both interface, and for convex lens converge.
- The point at which the rays crossed is defined as the Focal point (F) of the lens.
- The distance from the center of the lens to its focal point is called the focal length (f).
- The Power of the lens, measuring in Diopters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





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.

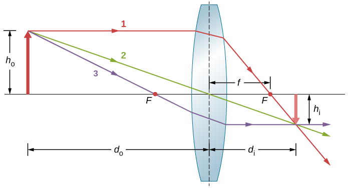
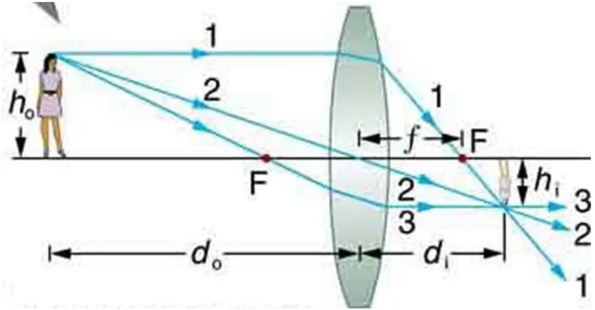


Image Formation

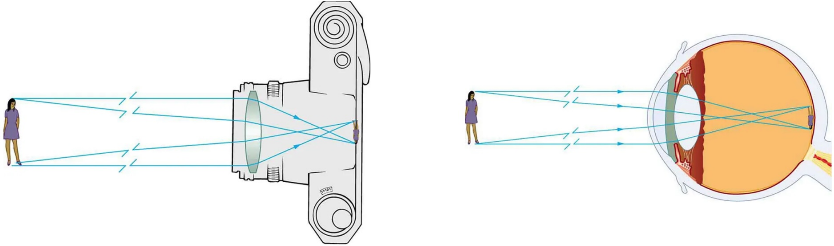


Thin Lens equations:

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

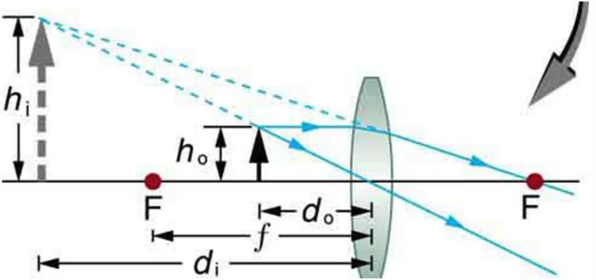
$$\frac{h_i}{h_o} = -\frac{d_i}{d_o} = m$$

Image Formation - Real Image



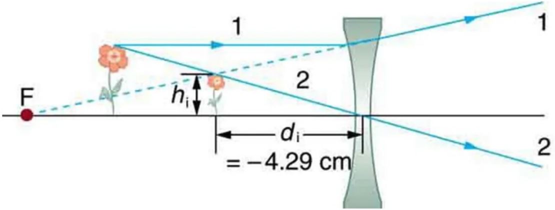
The image in which light rays from one point on the object actually cross at the location of the image and can be projected onto a screen, a piece of film, or the retina of an eye is called a real image.

Image Formation - Virtual Image

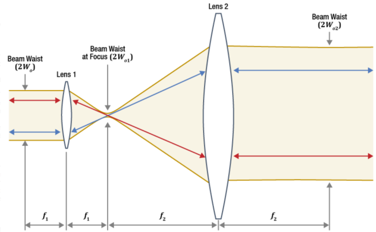


If an object is held closer to the converging lens than its focal length (f), then the rays from a common point continue to diverge after passing through the lens. They all appear to originate from a point at the location of the image, on the same side of the lens as the object. This is a virtual image.

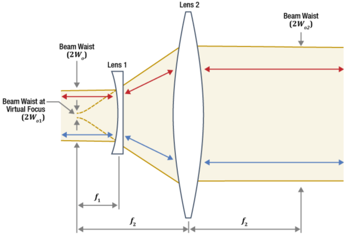
Image Formation - Concave Lens



Beam Expander/Reducer - Telescope



Galilean Design

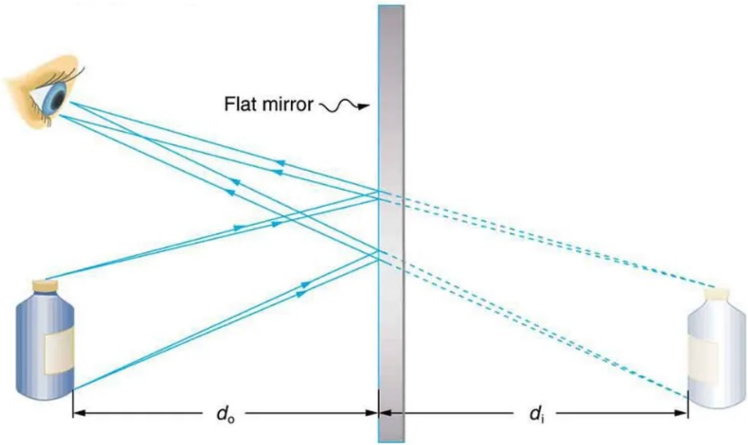


Galilean Design

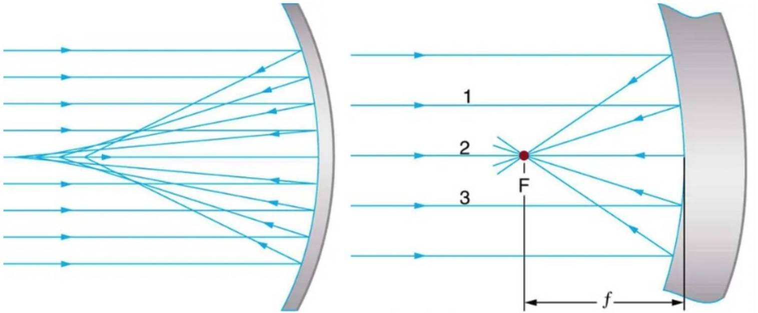
Both the bean's waist $(2W_0)$ and the divergence angle (θ) are affected by by the beam expanders and reducers. If Lens 2 is the output lens, then the beam expansion ratio (m_{12}) is:

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

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

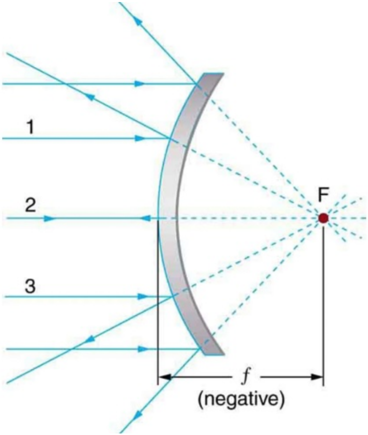


Image Formation - Concave Mirrors

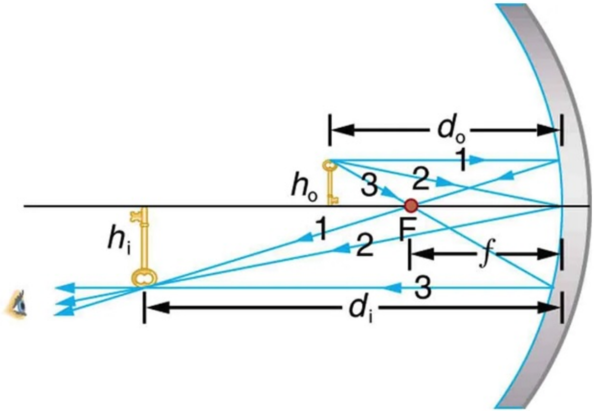


Image Formation - Concave Mirrors

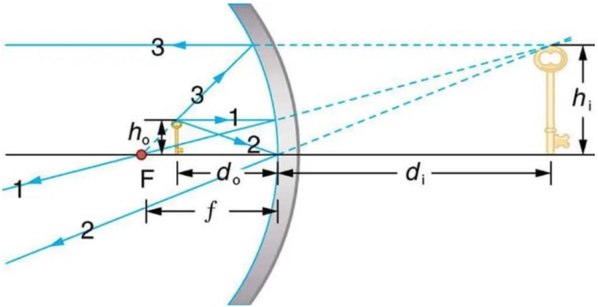
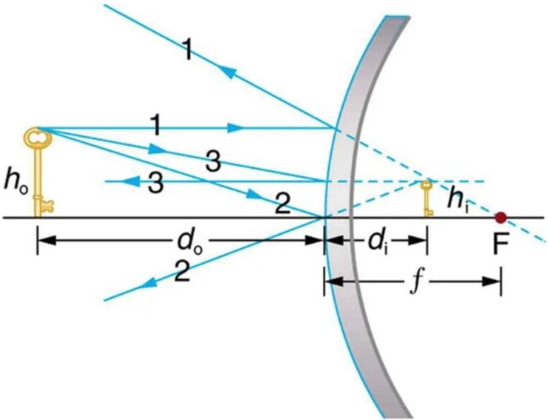
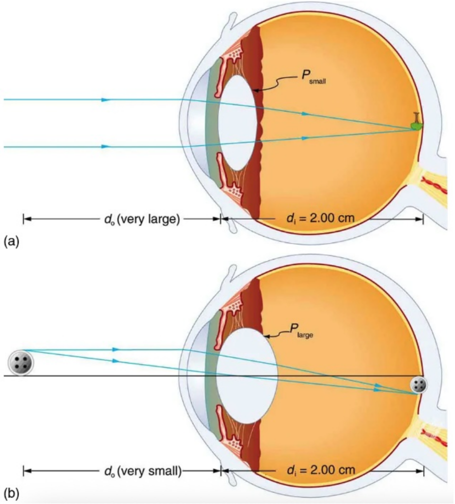


Image Formation - Convex Mirrors



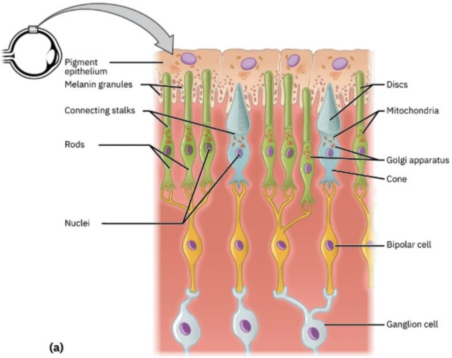
Vision

The Eye

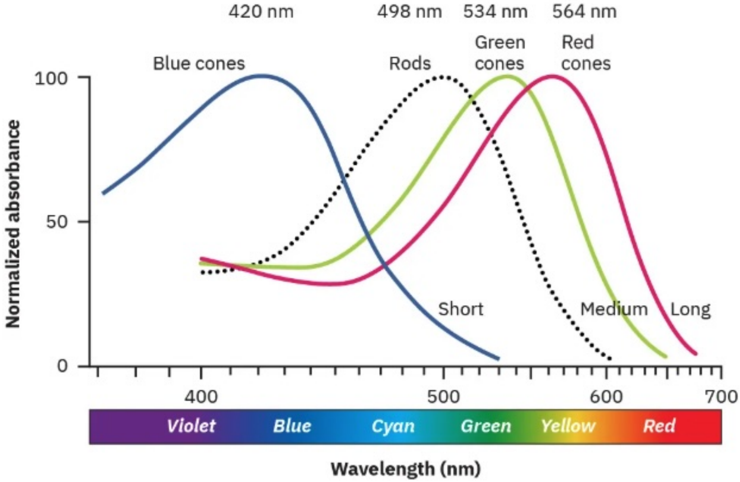


P_{small}
d_o (very large)
d_i = 2.00 cm
(a)
P_{large}
d_o (very small)
d_i = 2.00 cm
(b)

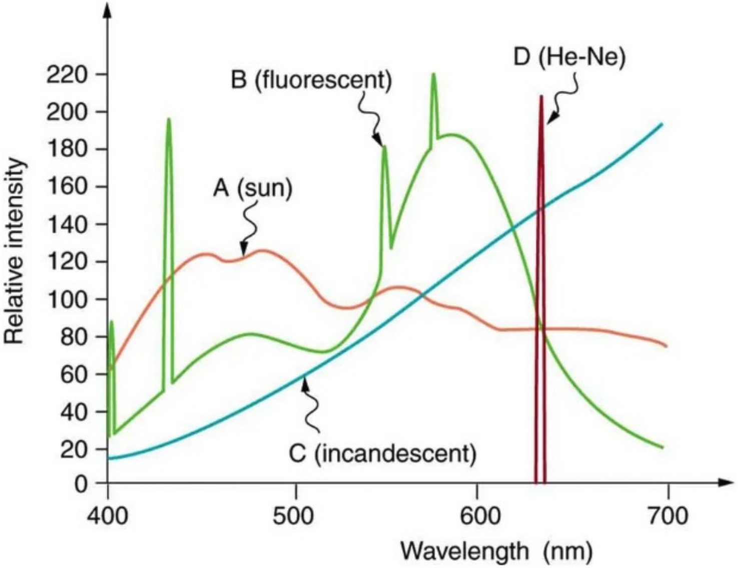
Rods and Cones and Color



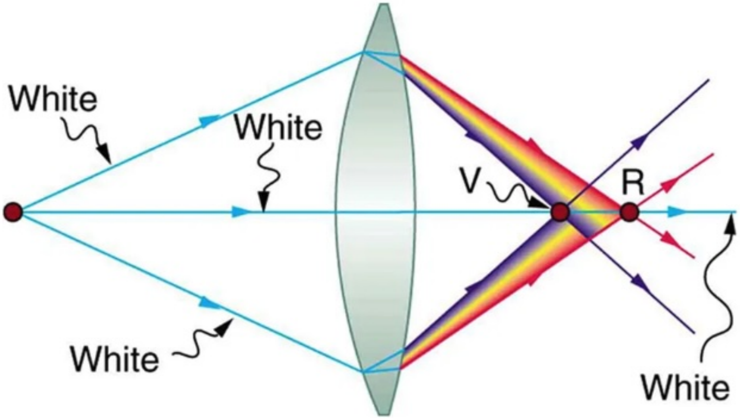
Visible Spectrum



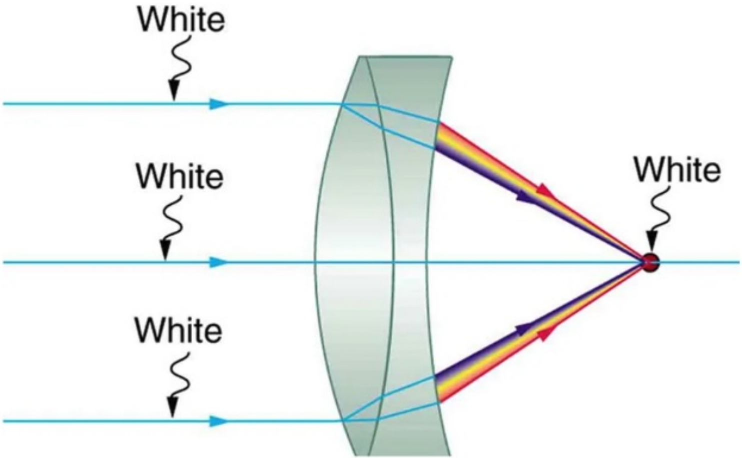
Spectrum of Light Sources



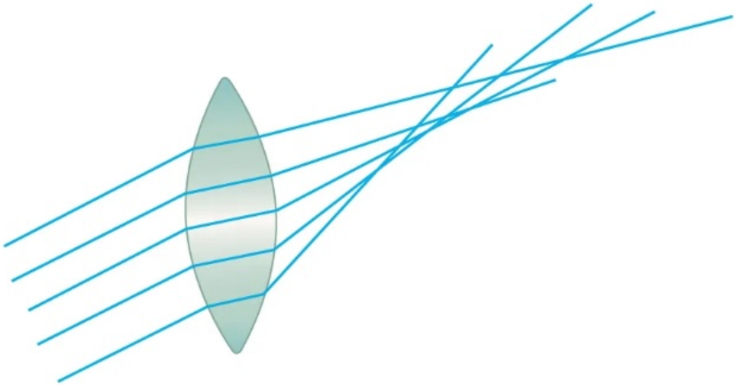
Chromatic Aberrations



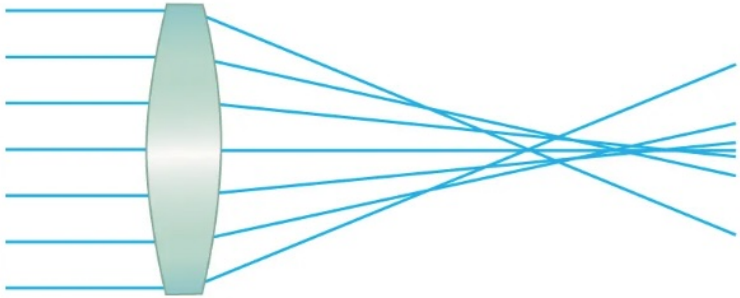
Correcting Chromatic Aberrations



Coma - Off Axis Abberation



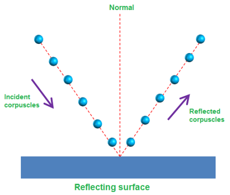
Spherical Aberrations

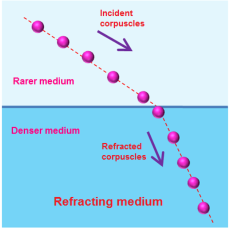


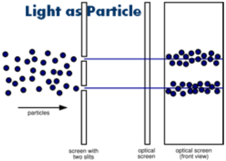
Interlude: Light - a particle or a wave?

Corpuscular Theory of Light

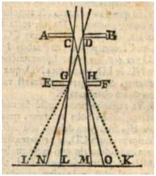
In 1675, Sir Isaac Newton hypothesized that light was made up corpuscules (small particles) with the size/mass of the corresponding to different colors.

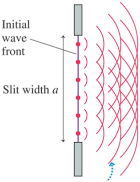






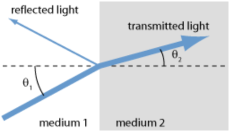
Huygens Principle

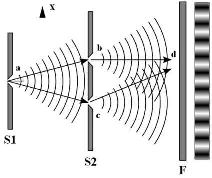




- Francesco Maria Grimaldi (mid-1600's) made accurate observations of the diffraction of light.
- In 1678, Christian Huygens, in order to explain the diffraction of light, proposed that every point on a wavefront (of light) is a wavelet that spreads.

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

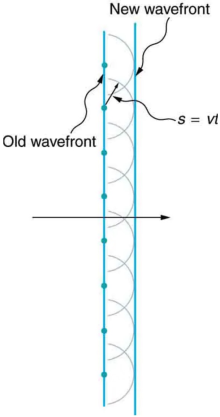
Divide both sides of the above equation by n yields:

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

where λ_n is the wavelength in the medium.

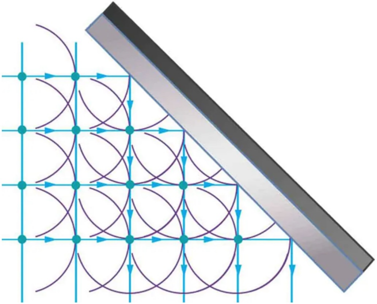
Huygens's Principle: Diffraction

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.



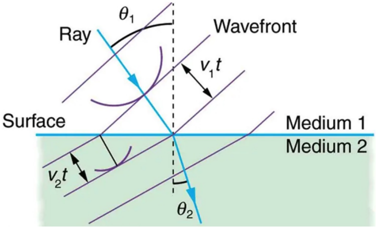
Huygens's Mirror

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.



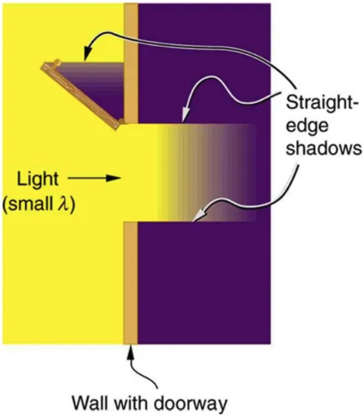
Huygens's Refraction

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.

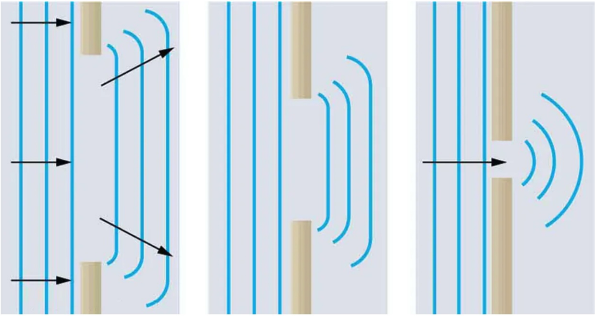


Diffraction

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.

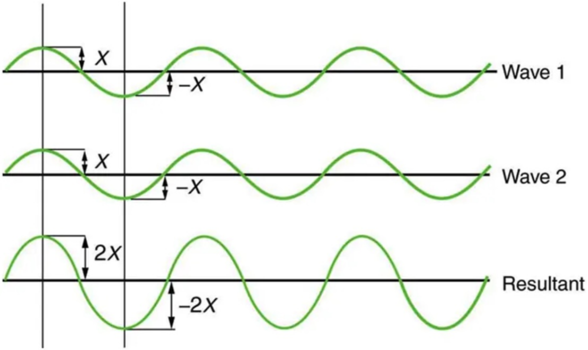


Diffraction

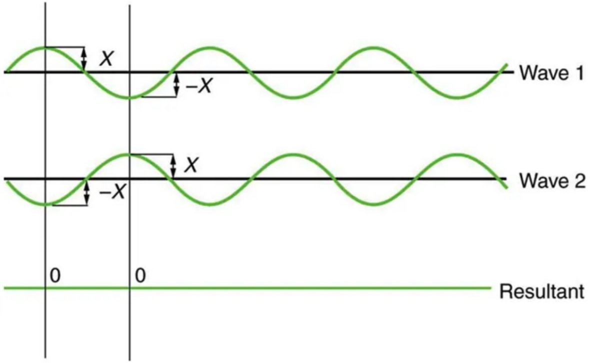


If we pass light through smaller openings, often called slits, we can use Huygens's principle to see that light bends. The bending of a wave around the edges of an opening or an obstacle is called diffraction. Diffraction is a wave characteristic and occurs for all types of waves.

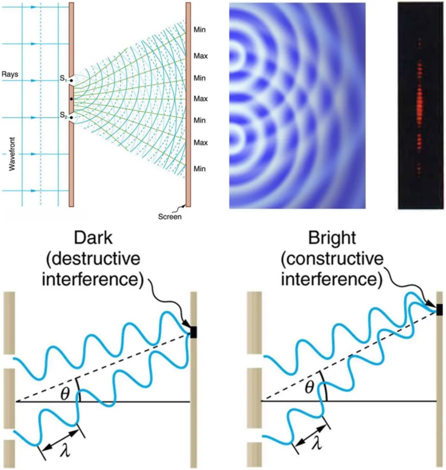
Constructive Interference



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

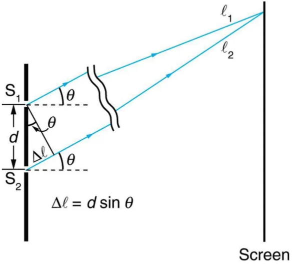
Path Length Difference

- Constructive Interference - peaks are in phase

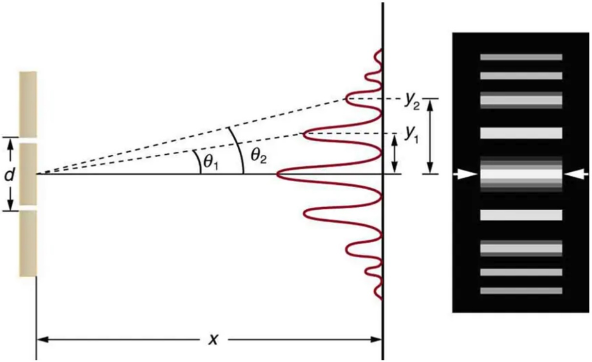
$$d \sin(\theta) = m\lambda, m = 0, 1, -1, 2, -2, ...$$

- Destructive Interference - peaks are perfectly out of phase

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



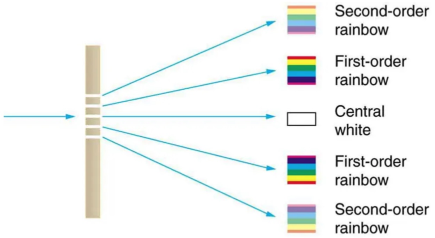
Double Slit - Constructive Interference



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.

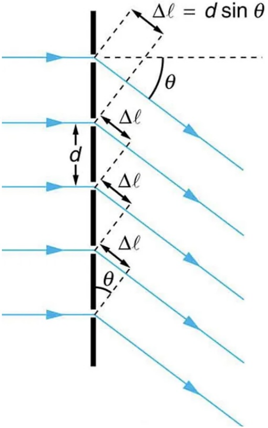


Diffraction Grating - Constructive Interference

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

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

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

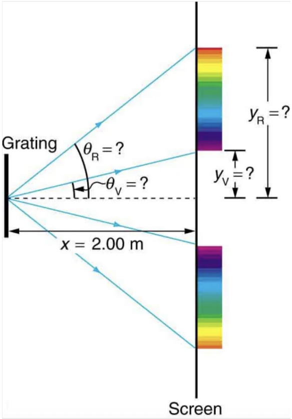


Diffraction Grating - Spread of Wavelength

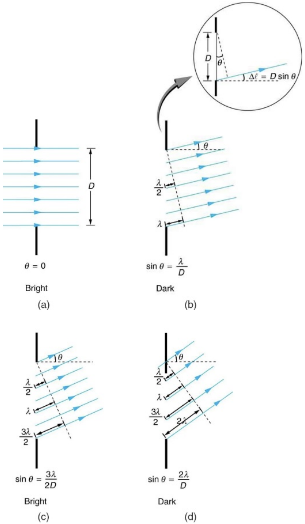
We can find θ_R, y_R, θ_V, and y_V by using:

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

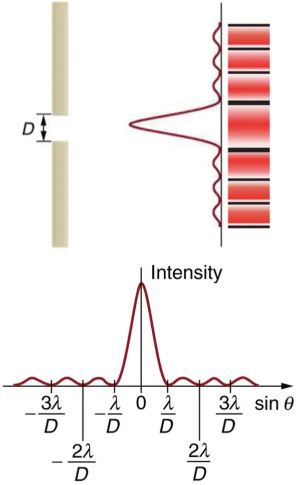
for, $m = 1$.



Single Slit



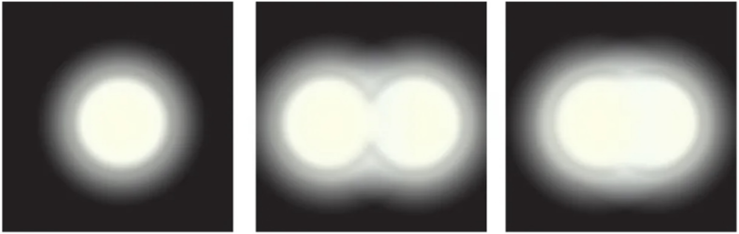
D
θ = 0
Bright
(a)
Δℓ = D sin θ
θ
λ/2
λ
sin θ = λ/D
Dark
(b)
λ/2
λ
3λ/2
sin θ = 3λ/2D
Bright
(c)
λ/2
λ
3λ/2
2λ
sin θ = 2λ/D
Dark
(d)



D
Intensity
−3λ/D
−2λ/D
−λ/D
0
λ/D
2λ/D
3λ/D
sin θ

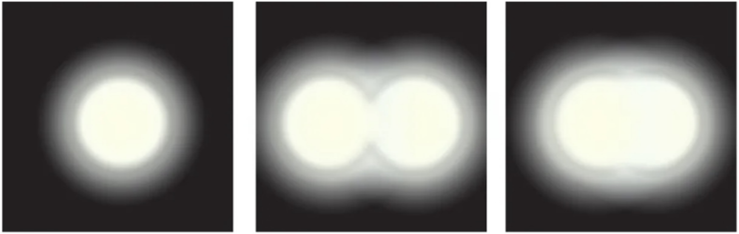
Limits of Resolution

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



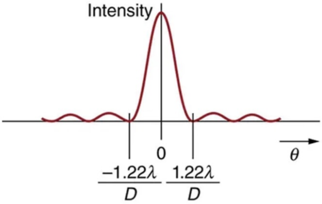
Limits of Resolution

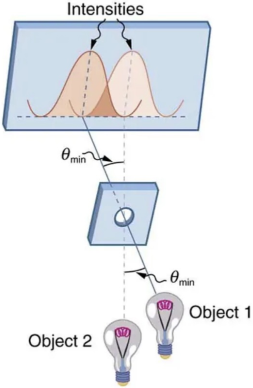
Diffraction affects the detail that can be observed when light passes through an aperture.



Rayleigh Criterion

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



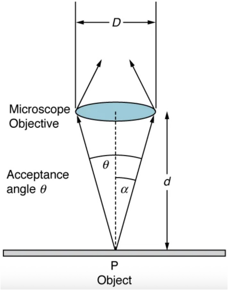


Resolving Power

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.



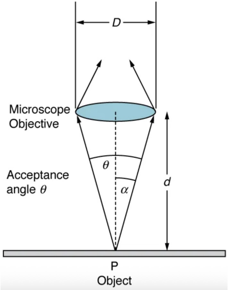
Numerical Aperture (NA)

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.



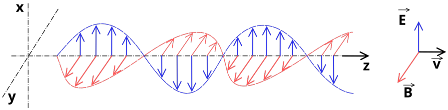
$$x = 1.22\frac{\lambda d}{D} = 1.22\frac{\lambda}{2sin(\alpha)} = 0.61\frac{\lambda n}{NA}$$

[1]

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

Polarization

Electromagnetic Wave

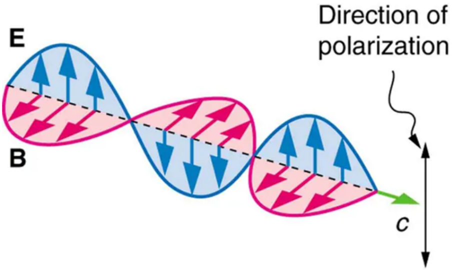


An Electromagnetic (EM) wave is a transverse wave where the electric and magnetic fields are perpendicular to each other and to the direction of propagation.

- 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.

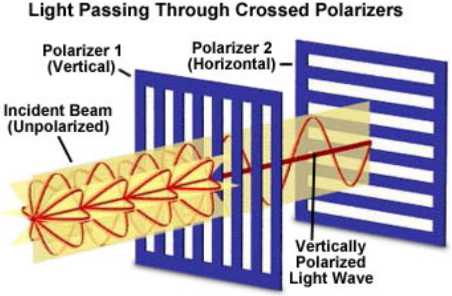
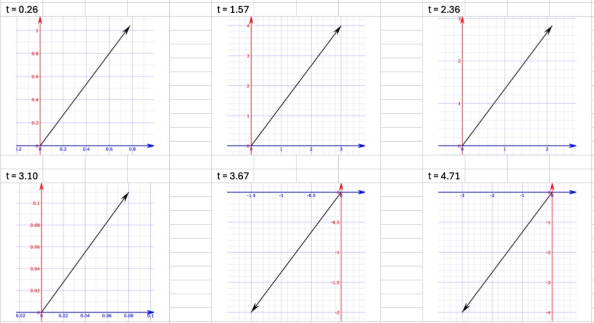


Figure 1

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

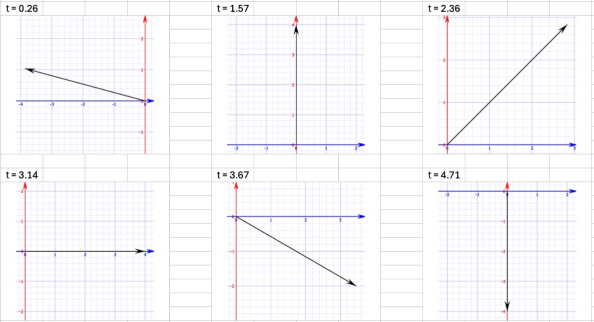


$$\vec{E} = 3\sin(t)\vec{i} + 4\sin(t)\vec{j} \quad (8)$$

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

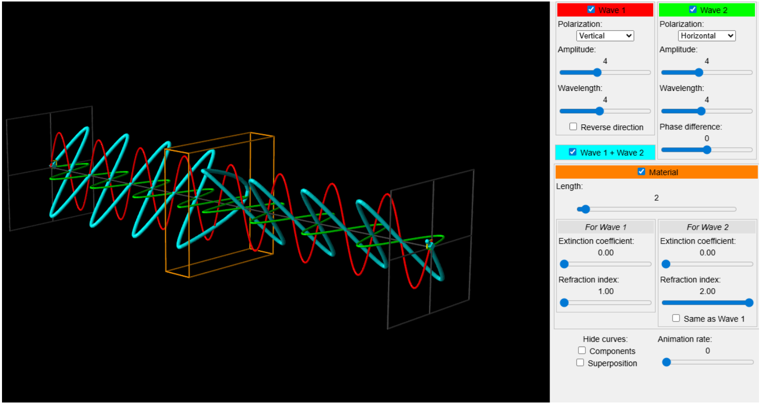


X lags Y by $\frac{\pi}{2}$:

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

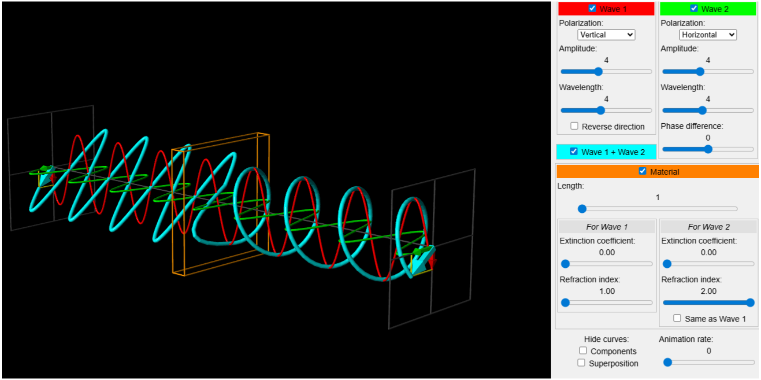
Incoming 45° with Half-Wave Plate

From `https://emanim.szialab.org/`



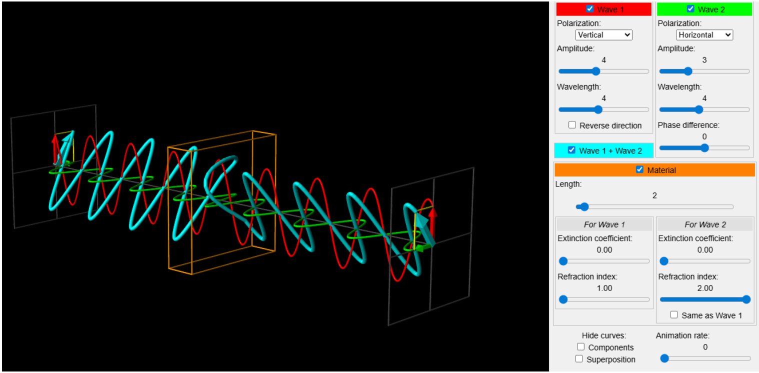
Incoming 45° with Quarter-Wave Plate

From https://emanim.szialab.org/



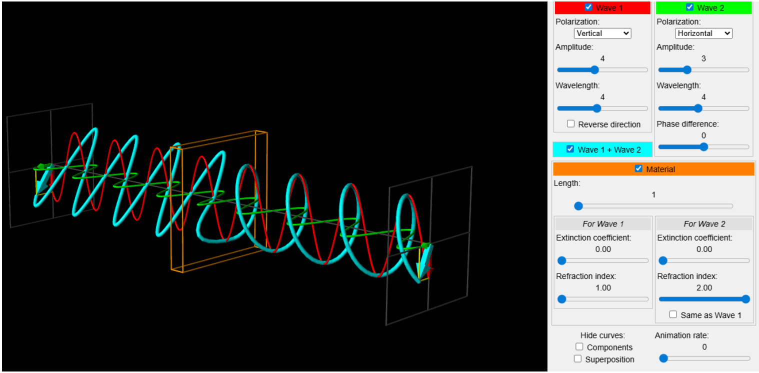
Incoming 37° with Half-Wave Plate

From https://emanim.szialab.org/



Incoming 37° with Quarter-Wave Plate

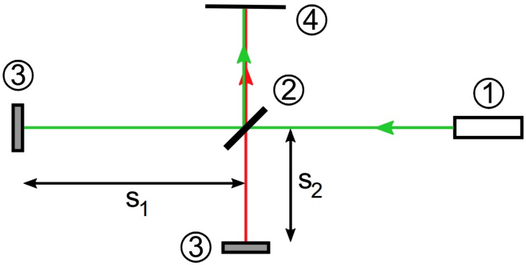
From https://emanim.szialab.org/



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

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

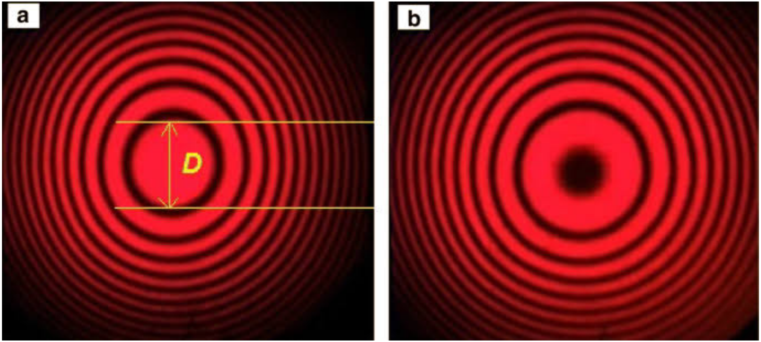
- If we assume that the transmission and reflection capacity are 0.5 then the average intensity ($\bar{I}$) is given by

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

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

Interferometer Math - what does it mean

Compare the centers:



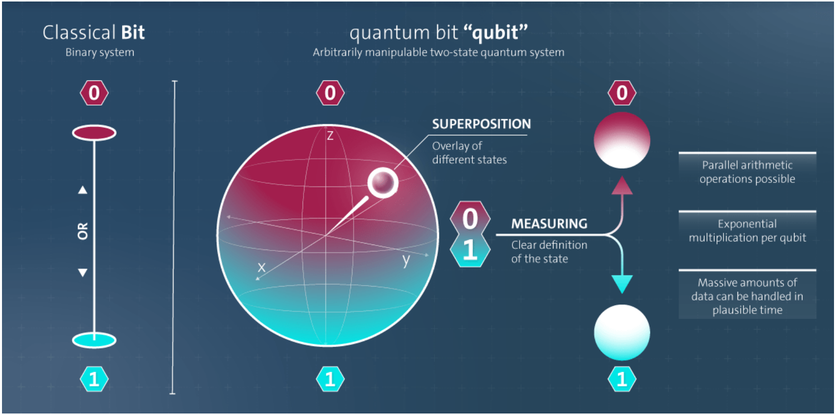
Why are there alternating concentric circles?

Intro to Quantum Phenomenon

Let there be light

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.

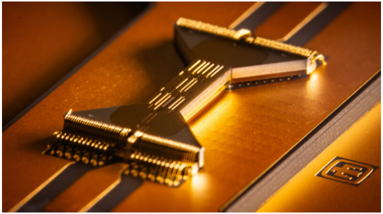
Quantum Computing: Photonics

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