What is Optics? Photonics?

- Think of optics as the science of light. It’s a branch of physics that describes the behavior and properties of light and the interaction of light with matter. It’s about what light is made of and how it behaves.

- Light allows us to see, but it also transmits sound, cuts things, and controls electrical circuits. That’s where photonics comes in.
- Photonics is the science and technology of generating and harnessing light. This includes the emission, transmission, amplification, detection, modulation, and switching of light—much of which is centered around the use of lasers and photodetectors. Light sensors, telecommunications equipment, holographs, CDs, laser surgery, fiber optics, and the Internet are all based on photonics.

Among photonics-based technologies we take for granted today are:

- Barcode scanners, printers, remote control devices;
- Laser surgery, drilling, and surface modification;
- Range finding, navigation;
- Computer networking, circuit boards, and chips;
- CDs, DVDs; and
- Digital cameras.

Class Objectives

Cover the fundamental properties of light propagation and interaction with matter under the approximations of geometrical optics and scalar wave optics, emphasizing physical intuition and underlying mathematical tools.

Topics

- Geometrical optics
  - Basic ray-tracing
  - Image formation and imaging systems
  - Optical system design
- Wave optics
  - Scalar linear wave propagation
  - Wave properties of light
  - Polarization
  - Interference and interferometers
  - Fourier Optics (a more systematic approach to light propagation)
  - Spatial filtering, resolution, coherent & incoherent image formation, space-bandwidth product
  - Wavefront modulation, holography, diffractive optics
- Modern Optics
  - Lasers
  - Optical Trapping

What you need

- Necessary
  - Euclidean geometry
  - calculus with complex variables
  - Taylor series approximation
- Helpful if you know but we will cover here
  - basic electrodynamics
  - basic wave propagation
  - Fourier analysis

Example Applications/Projects

- Confocal microscopy
  - optical slicing
  - Fluorescence
  - two-photon
  - real-time
  - Holographic
  - Spectroscopic
  - bio-imaging, imaging through turbulence
- Super-resolution
  - apodizing filters
  - hybrid (optics+signal processing) approaches
  - information-theoretic viewpoint
  - meta-materials (invisible cloak?)
- Optical data storage
  - optical disks (CD's, DVD's, MO disks)
  - holographic memories

- Optical Communication
  - Fiber Optics
  - Optical switching and modulation
    - optical MEMS
    - electro-optics
    - acousto-optics
- Statistical optics
  - Coherence imaging (van Cittert-Zernicketheorem, radio astronomy)
  - Optical coherence tomography
  - X-ray tomography
- Lasers Spectroscopy
- Laser cooling of atoms/molecules
- Laser trapping (optical tweezers) of atoms/molecules

Brief (*western-*)History of Optics

- Ancient Greeks (~5-3 century BC)
  - Pythagoras (rays emerge from the eyes)
  - Democritus (bodies emit “magic” substance, simulacra)
  - Plato (combination of both of the above)
  - Aristotle (motion transfer between object & eye)
- Middle Ages
  - Alkindi, Alhazen defeat emission hypothesis (~9-10 century AD)
  - Lens is invented by accident (northern Italy, ~12thcentury AD)
  - Della Porta, da Vinci, Descartes, Gallileo, Kepler formulate geometrical optics, explain lens behavior, construct optical instruments (~15thcentury AD)
- Beyond the middle ages:
  - Newton (1642-1726) and Huygens (1629-1695) fight over nature of light

Brief History of Optics

- 18^{th} –19^{th} centuries
  - Fresnel, Young experimentally observe diffraction, defeat Newton's particle theory
  - Maxwell formulates electro-magnetic equations, Hertz verifies antenna emission principle (1899)
- 20^{th} century
  - Quantum theory explains wave-particle duality
  - Invention of holography (1948)
  - Invention of laser (1956)
  - Optical applications proliferate: computing, communications, fundamental science, medicine, manufacturing, entertainment.

An Anecdotal History of Optics from Aristophanes to Zernike http://www.ece.umd.edu/~taylor/optics.htm

- I. ANCIENT HISTORY: Aristophanes, Democ ritus, Aristotle, Archimedes, Seneca, Nero, Ptolemy, Alhazan.
- II. SPECTACLES: Bacon, Keppler, Franklin, Airy, Fick.
- III. THE TELESCOPE: Lippershey, Galileo, Newton, Gregory, Cassegrain, Hall, Dolland, Schmidt.
- IV. THE MICROSCOPE: Jansen, Hooke, Huygens, van Leeuwenhoek, Lister, Gauss, Abbe.
- V. RAY OPTICS , CORPUSCLES AND WAVELETS: Snell, Descartes, Fermat, Hamilton, Bradley, Euler.
- VI. WAVE OPTICS: Young, Fresnel, Arago, Laplace, Fourier, Poisson, Malus, Brewster, Foucault, Fizeau, Doppler.
- VII. OPTICS, ELECTROMAGNETIC WAVES AND QUANTA: Maxwell, Hertz, Luneburg, Fraunhofer, Planck, Einstein, Bohr.
- VIII. SOME ROOTS OF MODERN OPTICAL SYSTEMS: Chappe, Niepce, Wheatstone, Baird, Gabor, Zernike.

Nobel Laureates in the field of Optics

The Nobel Prize in Physics 2009 was divided, one half awarded to Charles K. Kao *"for groundbreaking achievements concerning the transmission of light in fibers for optical communication"*,the other half jointly to Willard S. Boyle and George E. Smith *"for the invention of an imaging semiconductor circuit – the CCD sensor"*.

- **R. Galuber, J. Hall, T. Haensch (Physics 2005)**
- **W. Ketterle, E. Cornell, C. Wieman Physics 2001**
- **Z. Alferov, H. Kroemer, J. Kilby –Physics 2000**
- **A. Zewail – Chemistry 1999**
- **S. Chu, C. Cohen-Tannoudji, W. Phillips –Physics 1997**

E. Ruska –Physics 1986 N. Bloembergen, A. Schawlaw, K. Siegbahn –Physics 1981 A. Cormack, G. Housefield –Biology or Medicine 1979 M. Ryle, A. Hewish –Physics 1974•D. Gabor –Physics 1971•A. Kastler –Physics 1966•C. Townes(MIT), N. Basov, A. Prokhorov–Physics 1964 •F. Zernicke–Physics 1953•C. Raman –Physics 1930•W. H. Bragg, W. L. Bragg –Physics 1915•G. Lippman–Physics 1908•A. Michelson –Physics 1907•J. W. Strutt(Lord Rayleigh) –Physics 1904•H. Lorentz, P. Zeeman–Physics 1902•W. Röntgen–Physics 1901

What is Light?

"And said God let there be light, and there was light“

And God said

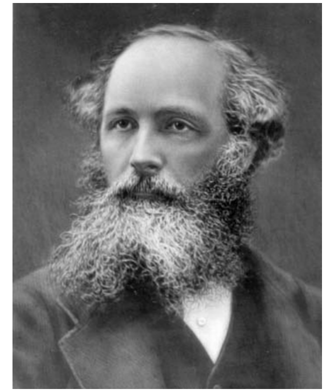
$$\oint \overline{E} \bullet \overline{dl} = -\int \frac{\partial \overline{B}}{\partial \tau} \bullet \overline{ds} \qquad \nabla \times \overline{E} = -\mu \frac{\partial \overline{H}}{\partial \tau} \qquad \nabla \times \overline{\mathrm{E}} = -\mu \frac{\partial \overline{\mathrm{H}}}{\partial \tau}$$

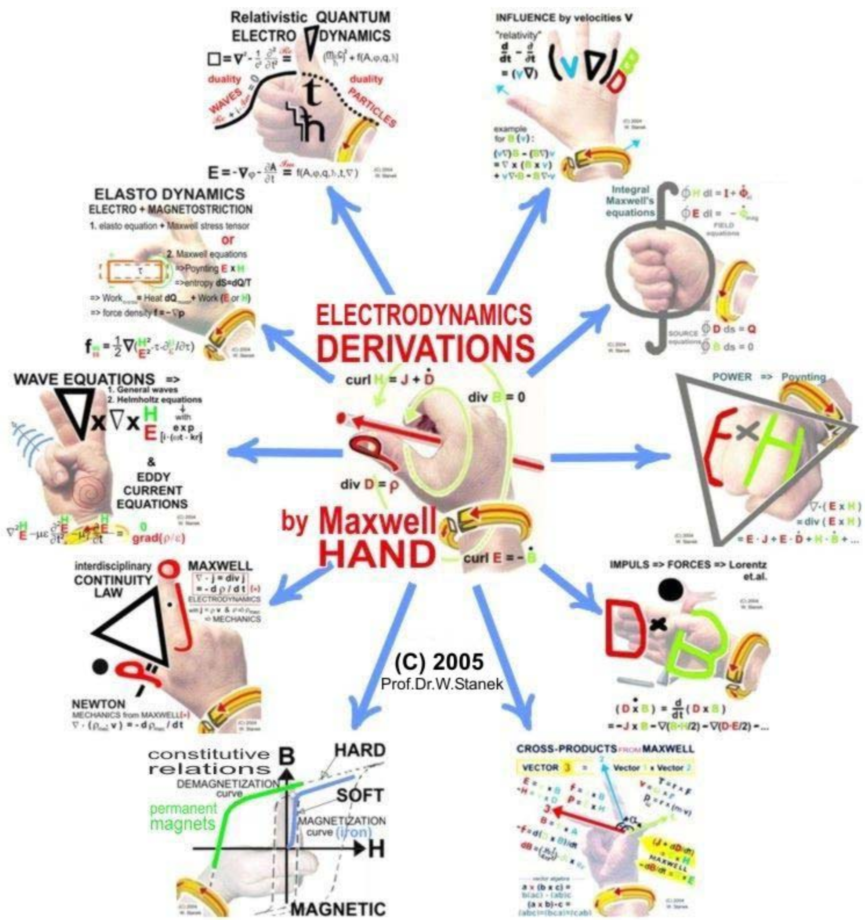
$$\oint \overline{H} \bullet \overline{dl} = \int \left(\overline{J}_c + \frac{\partial \overline{D}}{\partial \tau} \right) \bullet \overline{ds} \quad \text{OR} \quad \nabla \times \overline{H} = \overline{J}_C + \varepsilon \frac{\partial \overline{E}}{\partial \tau} \quad \text{OR} \quad \nabla \times \overline{\mathrm{H}} = \mathrm{J}_c + \varepsilon \frac{\partial \overline{\mathrm{E}}}{\partial \tau}$$

$$\oint \overline{D} \bullet \overline{ds} = \int \nabla \bullet \overline{D}\, dv \qquad \nabla \bullet \overline{D} = \rho_v \qquad \nabla \bullet \overline{\mathrm{D}} = \rho_v$$

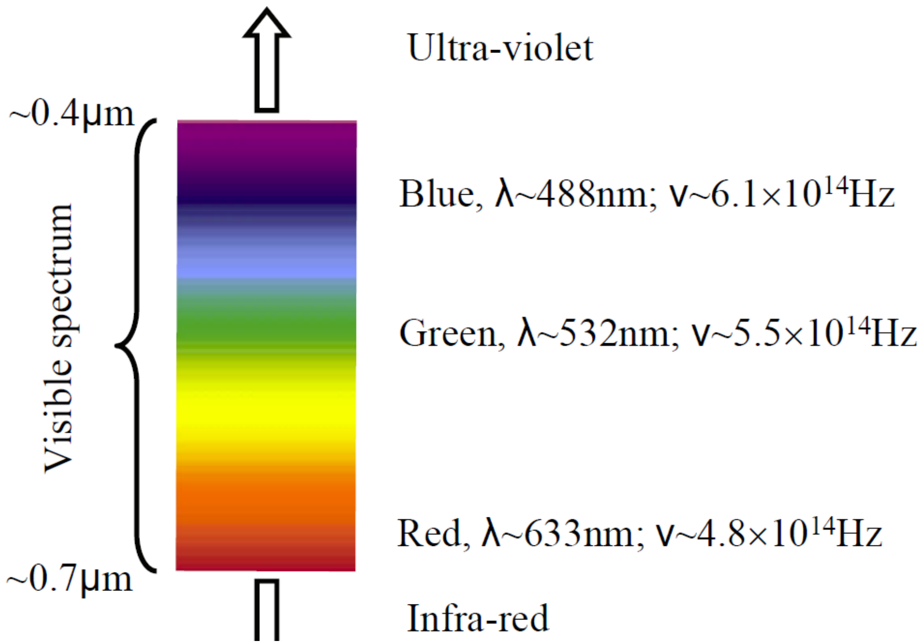
$$\oint \overline{B} \bullet \overline{ds} = 0 \qquad \nabla \bullet \overline{B} = 0 \qquad \nabla \bullet \overline{\mathrm{B}} = 0$$

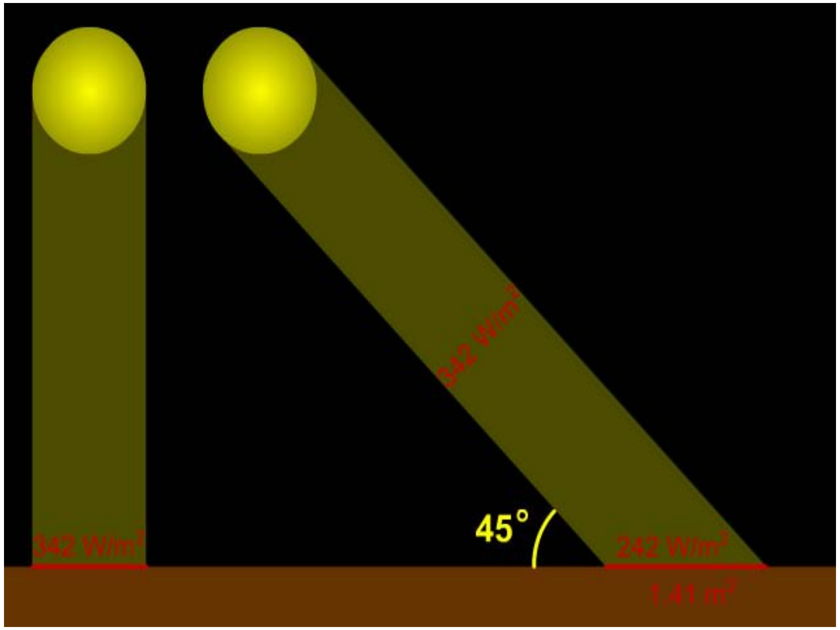
and there was light





What is Light?





When the Sun is directly overhead, its rays strike Earth perpendicular to the ground and so deliver the maximum amount of energy. When the Sun is lower in the sky, a sunbeam strikes the ground at an angle (in the example above, 45°) and so its energy is "spread out" over a larger area... thus "diluting" its energy. In this example, the energy is spread over an area of 1.41 square meters (instead of 1 square meter when the Sun is directly overhead), so the energy per unit area is reduced from 342 W/m2 to 242 W/m2 (342 ÷ 1.41 = 242).
Credit: Artwork by Randy Russell.

http://www.windows2universe.org/earth/climate/sun_radiation_at_earth.html

What is light?

- Light is a form of **electromagnetic energy** – detected through its effects, e.g. heating of illuminated objects, conversion of light to current, mechanical pressure (“Maxwell force”) etc.
- Light energy is conveyed through particles: “photons”
  - –ballistic behavior, e.g. shadows
- Light energy is conveyed through waves
  - –wave behavior, e.g. interference, diffraction
- Quantum mechanics reconciles the two points of view, through the “wave-particle duality” assertion

Wave Nature of Light

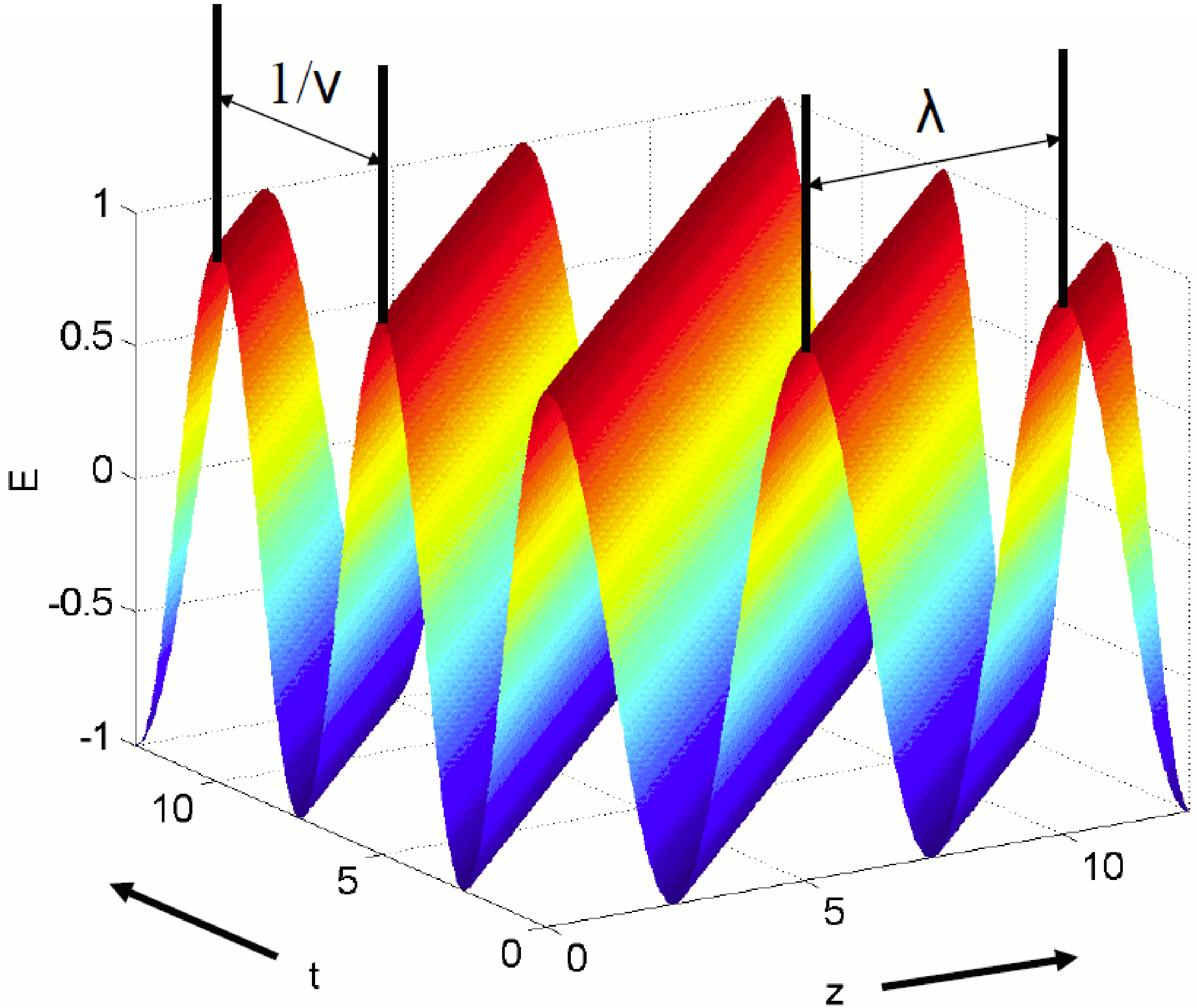
λ: **wavelength**
(spatial period)

$k = 2\pi/\lambda$
wavenumber

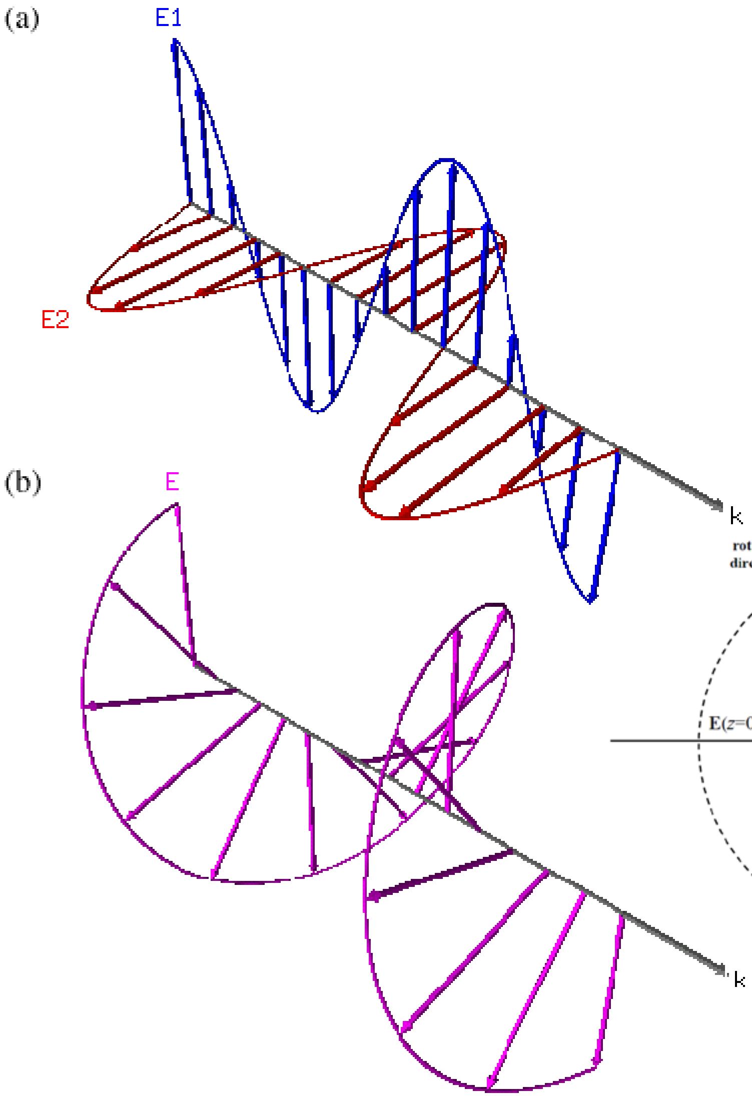
ν: temporal
frequency

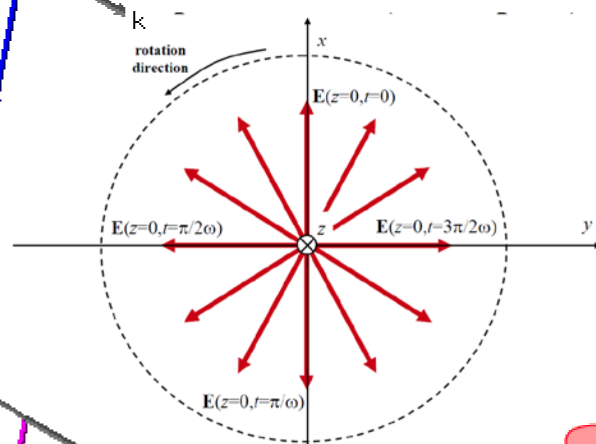
$\omega = 2\pi\nu$
angular frequency

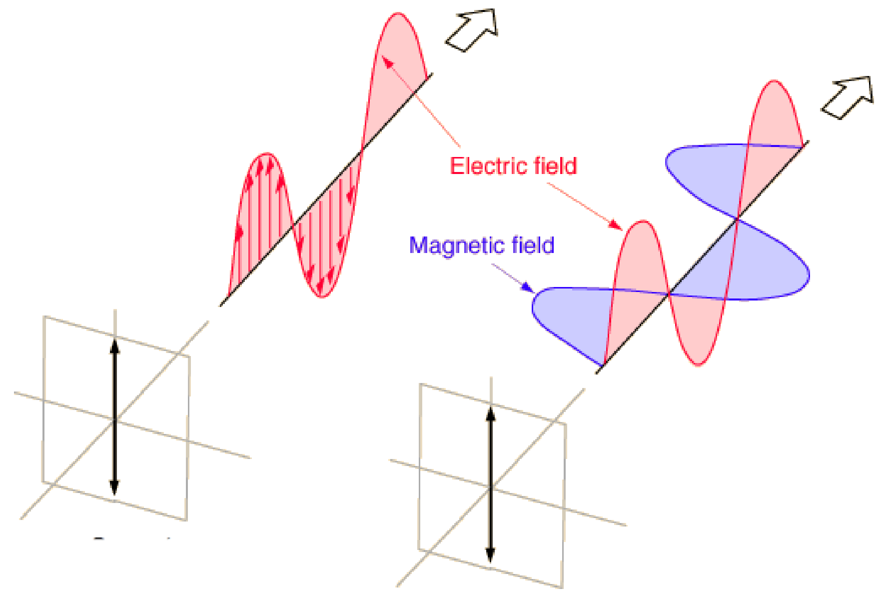
E: electric
field

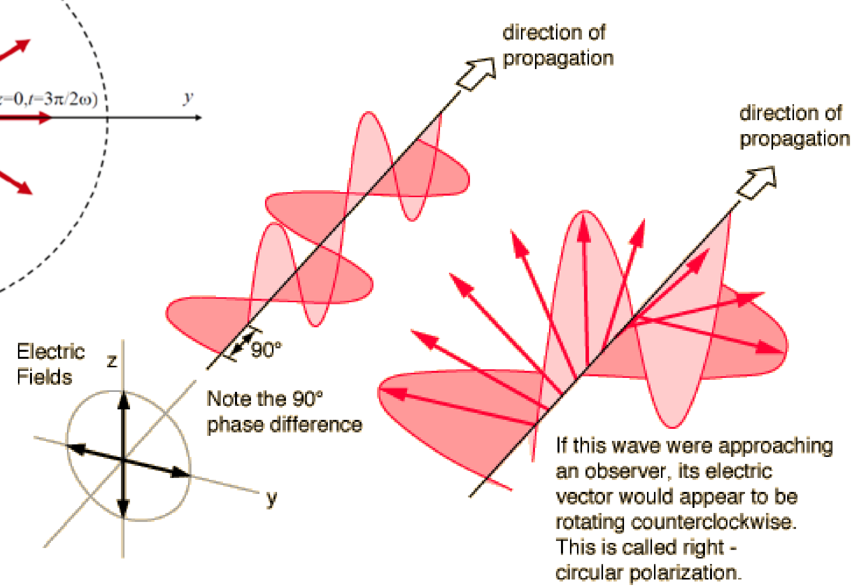


Linear versus Circular polarization









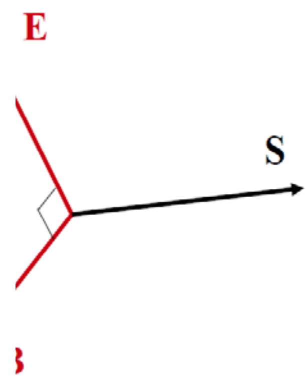
Poynting vector & Intensity of Light

$$\mathbf{S} = \mathbf{E} \times \mathbf{H}$$

Summary (free space or isotropic media)

$$\mathbf{S} = \frac{1}{\mu_0}\mathbf{E} \times \mathbf{B}; \quad \|\mathbf{S}\| = c\varepsilon_0 \|\mathbf{E}\|^2$$ Poynting vector

$$\left\langle \|\mathbf{S}\| \right\rangle = \frac{1}{T}\int_t^{t+T} \|\mathbf{S}\| \mathrm{d}t$$ Irradiance (or intensity)



$$\mathbf{S} = \frac{1}{\mu_0}\mathbf{E} \times \mathbf{B} = c^2 \varepsilon_0 \mathbf{E} \times \mathbf{B}$$

so in free space

$$\mathbf{S} \parallel \mathbf{k}$$

S has units of W/m^2 so it represents energy flux (energy per unit time & unit area)

- Poynting vector describes flows of E-M power
- Power flow is directed along this vector
  - Usually parallel to **k**
- Intensity is equal to the magnitude of the time averaged Poyning vector: I=<**S**>

$$\left|\left\langle \mathbf{S} \right\rangle\right| = I \equiv \left| \left\langle \mathbf{E}(t) \times \mathbf{H}(t) \right\rangle \right| = \frac{c\varepsilon_0}{2} E^2 = \frac{c\varepsilon_0}{2}\left(E_x{}^2 + E_y{}^2\right)$$

$$c\varepsilon_0 \approx 2.654 \times 10^{-3}\, A/V$$

example

$$E = 1V/m$$

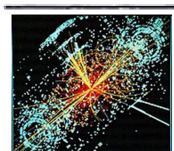
$$I = ?\, W/m^2$$

$$\hbar\omega[eV] = \frac{1239.85}{\lambda[nm]}$$

$$\hbar = 1.05457266 \times 10^{-34}\, Js$$

Summary of the Various Branches of Spectroscopy

Branch	Frequency, Hz	Wavelength	Typical Energy Unit: Name	Typical Energy Unit: Value in Joules	Phenomenon	Typical Radiation Generator	Typical Detector
Static	0–60		Joule Calorie	1 4.186		Battery	Ammeter Voltmeter
Low or audio frequency	10^3–10^5	3–300 km	kHz	6.62377×10^{-31}	Dielectric absorption	Mechanical	Ammeter Voltmeter
Radio frequency	10^6–10^8	300–3 m	Joule cm^{-1}	1 1.98574×10^{-23}	NQR, NMR, dielectric absorption	Tuned circuit Crystal	Antenna
Microwaves	10^9–10^{11}	30 cm to 3 mm	MHz	6.62377×10^{-28}	Molecular rotations, ESR	Klystron Magneton Solid State generator	Antenna Crystal Bolometer
Infrared	10^{12} to 3×10^{14}	300–1 μm	cm^{-1} kcal/M Joule	1.98574×10^{-23} 4.186×10^3 1	Molecular vibrations	Heat source	Bolometer PbS cell
Visible, ultraviolet	4×10^{14} to 3×10^{15}	0.8–0.1 μm	Erg eV MHz	1×10^{-7} 1.60207×10^{-19} 6.62377×10^{-28}	Electronic transitions	Incandescent lamp	Photocell
X rays	10^{16}–10^{19}	30–0.03 nm	eV keV	1.60207×10^{-19} 1.60207×10^{-16}	Electronic transitions	Discharge tube	Photocell
γ rays	10^{19}–10^{22}	3×10^{-9} to 3×10^{-12} cm	MeV	1.60207×10^{-13}	Inner shell electronic transitions	heavy element bombardment	Geiger counter Photomultiplier
Low energy, nuclear	10^{19}–10^{23}	3×10^{-9} to 3×10^{-13} cm	MeV	1.60207×10^{-13}	Nuclear energy level transitions	Radioactive nuclei	Scintillation detector
High energy, nuclear	10^{23}–10^{26}	3×10^{-13} to 3×10^{-17} cm	BeV GeV	1.60207×10^{-10} 1.60207×10^{-7}	Strange particle creation	Accelerator (e.g., synchrotron)	Bubble chamber Spark chamber
High-energy cosmic rays	$> 10^{25}$		BeV GeV	1.60207×10^{-10} 1.60207×10^{-7}	Extraterrestrial	Star, magnetic field in galaxy	Extensive shower detector



LHC (Large Hardron Collider): proton 7TeV/particle➔🡐 lead nuclear 574 TeV/particle

Particle Nature of Light

Photon=elementary light particle

Mass=0

Speed $c=3\times10^{8}$ m/sec

According to Special Relativity, a mass-less particle travelling at light speed can still carry energy (& momentum)!

Energy $E=h\nu$

relates the dual particle & wave nature of light;

h=Planck's constant $=6.6262\times10^{-34}$ J sec

ν is the temporal oscillation frequency of the light waves

Wave-Particle Duality of Light

Photon=elementary light particle

Energy $E=h\nu$

$$\boxed{c=\lambda\nu}$$

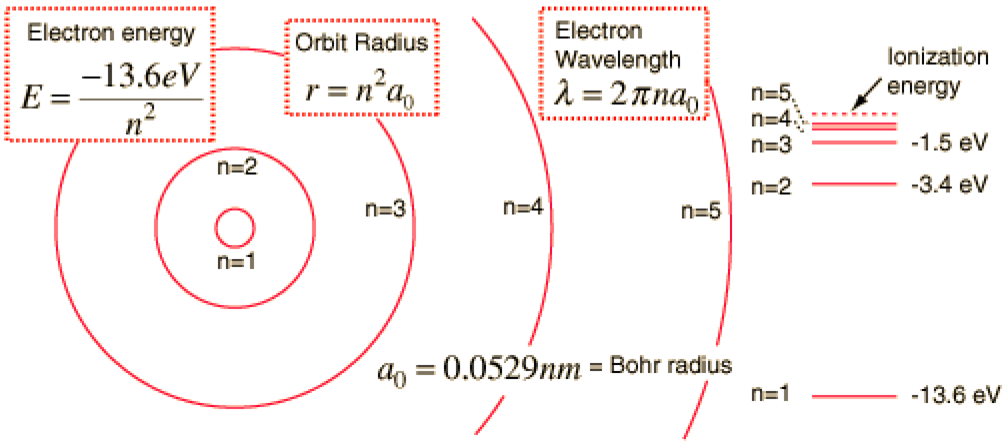
"Dispersion relation"

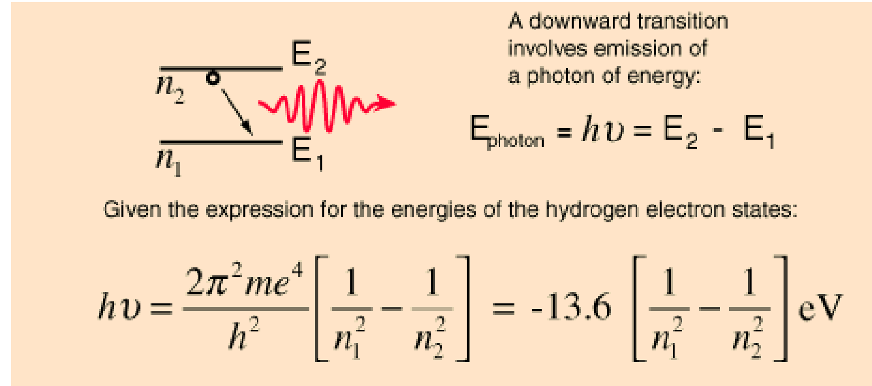
(holds in vacuum only)

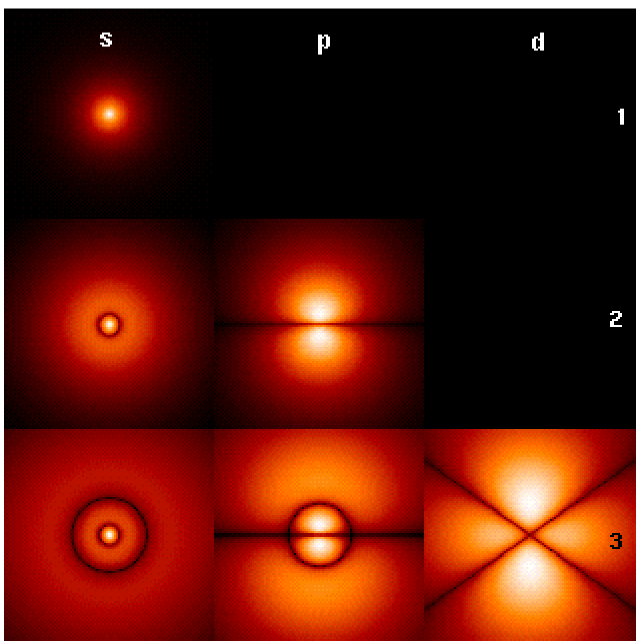
h=Planck's constant
$=6.6262\times10^{-34}$ J sec

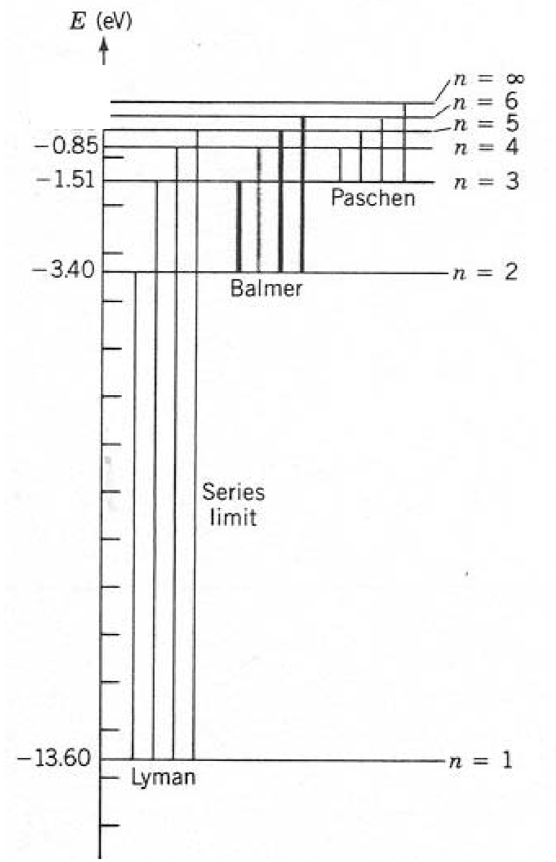
ν=frequency (sec^{-1})
λ=wavelength (m)

Electronic transitions and Bohr Model

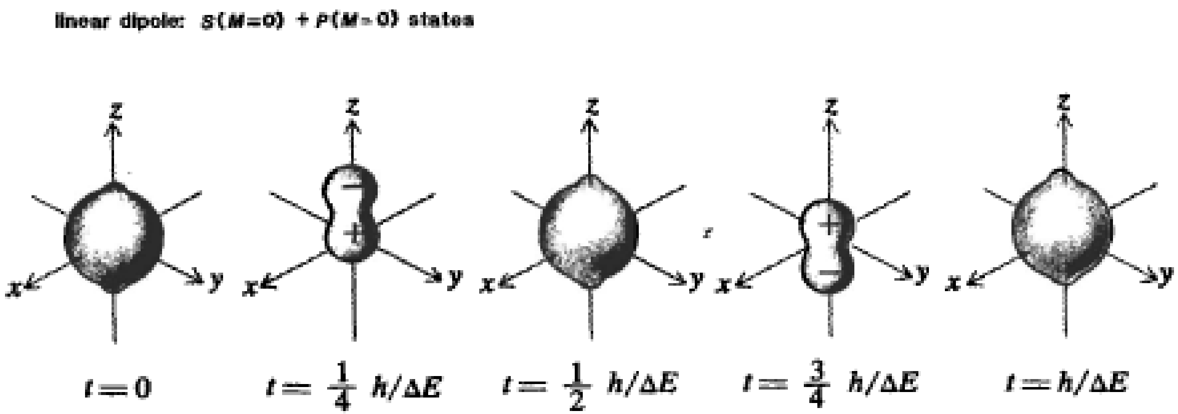


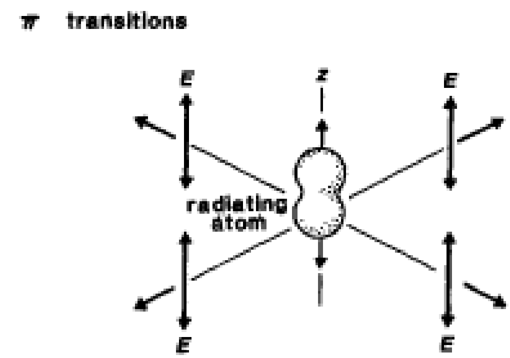


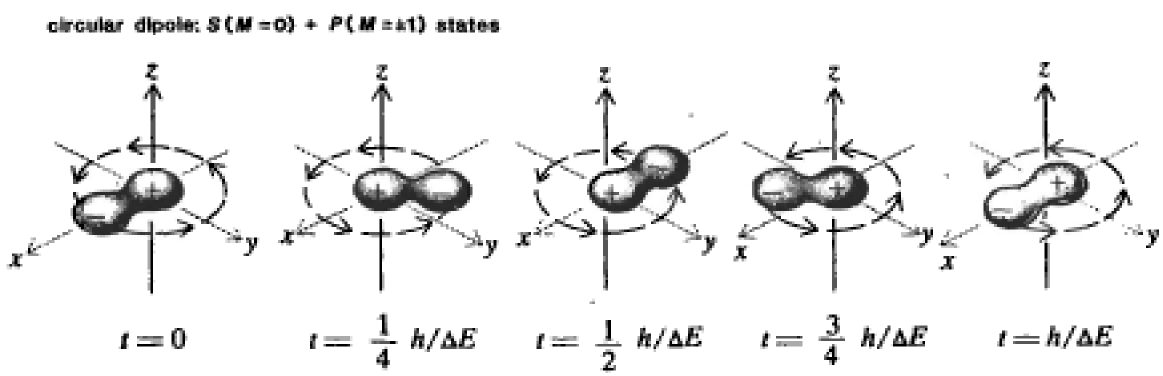


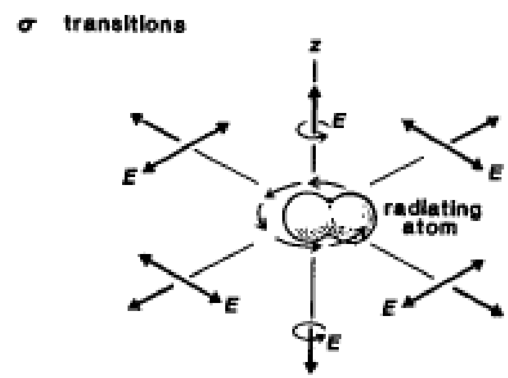


Graphical ("classical") description of optical transitions

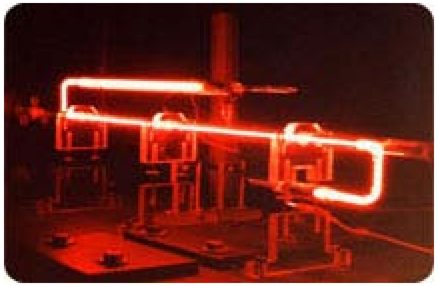


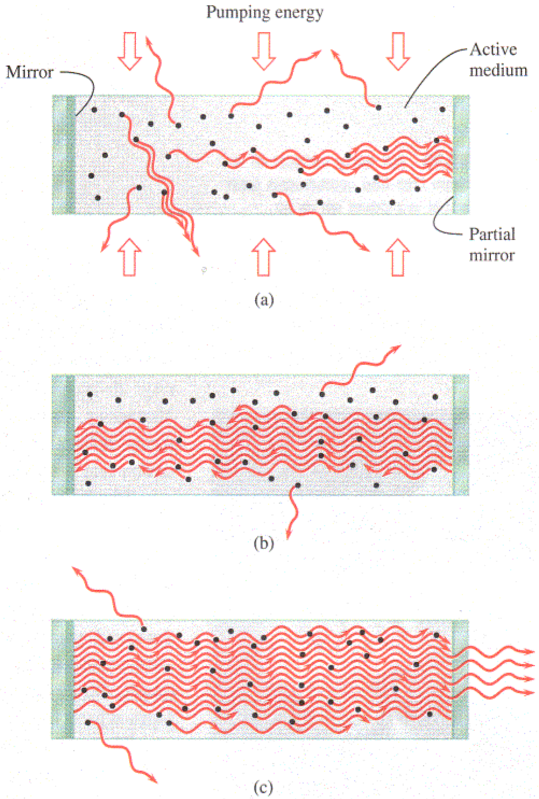




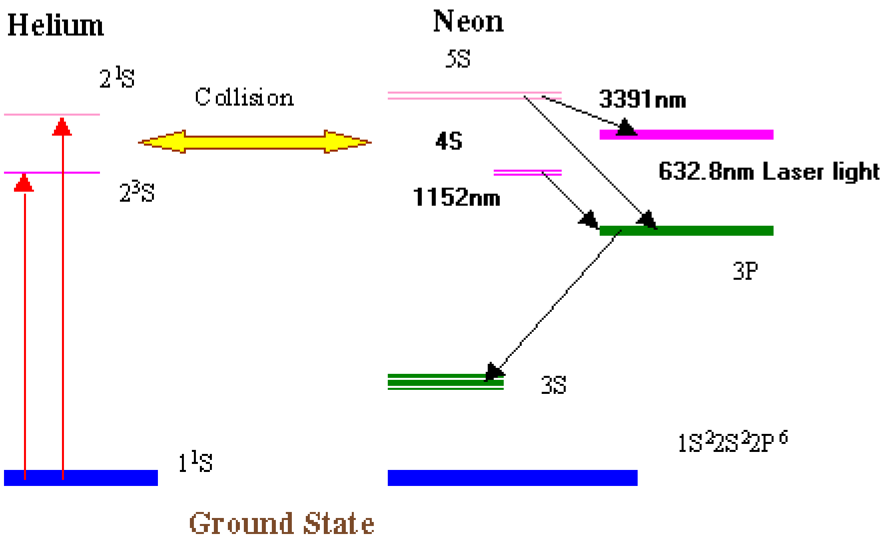


HeNe Lasers





Pumping energy
Mirror
Active medium
Partial mirror
(a)
(b)
(c)



Helium
Neon
2^1S
Collision
5S
3391nm
4S
632.8nm Laser light
2^3S
1152nm
3P
3S
$1S^22S^22P^6$
1^1S
Ground State