Exam 2 Information

- Exam Date: Wednesday Mar. 27, 6 -7:25 pm.
- Conflict Exam, Thursday Mar. 28, 6 – 7:25 pm.
    - Available to students with legitimate time conflict with regularly scheduled exam.
    - You must submit a request to your section professor and Prof. Ciolek by email by 5 pm Monday, Mar. 25 that you would like to take the conflict exam and state the reason why.
    - We reserve the right to deny a student from taking the conflict exam if it is determined that there is not a legitimate reason for taking the exam at that alternate time, or if they have not submitted a request from instructors in advance, as required above.
- Students with accommodations
    - Remind your section instructor of your exam accommodations.
    - Exam will be taken in 2C14 of the J-Rowl Science Center. Bring a copy of your official notice of accommodations to the exam room.
    - Start at the regular time and complete at the agreed time.

Exam 2 Information (2)

- Allowed resources –
  - You may use you a calculator with capabilities and functions up to the TI-Nspire. Devices with communication/internet capability are not allowed.
  - You are allowed a single $8.5'' \times 11''$ sheet of paper (both sides) crib sheet. Must be a single piece of paper – no taped or stapled pages.
  - Writing instruments (pencils, pens). For pens, darker inks are preferred.
- A short table of physical constants (same as done for Exam 1) will be included on the first page of the Exam 2 test booklet.

Exam 2 Information (3)

- Exam will focus on topics presented in classes 11 – 16. Classes 17 and 18 material will instead be on Exam 3.
- Exam Structure
  - Multiple choice and numerical short answer questions for ~ 70% to 80% of exam pts.
    - ✓ ~ ½ conceptual and scaling questions
    - ✓ ~ ½ numerical solution
  - Free response questions for the remaining % of exam pts. Free response answers will be written in spaces provided on the back side of the bubble sheets (as was done for Exam 1).
- Good resources
  - MasteringPhysics: Lecture quizzes; Practice Problems; Homework
  - Exam Archives (LMS)
  - Activity worksheets
  - Lecture slides
  - Text
- Monitor your email and LMS announcements for exam information and updates.

Exam 2 Rooms

Class Section	Instructor	Exam Room
1, 2	Robles Sanchez	West Hall Auditorium
3, 4	Zheng	Amos Eaton 214
5	Persans	Sage 3303
6,7	Schroeder/Ciolek	West Hall Auditorium
8, 9	Martin	Sage 3303
Accommodations	All	2C14 J-Rowl SC

Physics 1200
Lecture 18
Spring 2024

EM Wave & Light, Wave Fronts & Rays, Index of Refraction, Huygens' Principle

Transverse Electromagnetic Waves

- For a wave propagating in the $+x$-direction solutions of the electromagnetic wave equations have form:

$$\vec{\boldsymbol{E}}(x,t) = E_m \cos(kx - \omega t)\,\hat{\boldsymbol{j}}\text{ , and }\vec{\boldsymbol{B}} = -B_m \cos(kx - \omega t)\,\hat{\boldsymbol{k}}\text{ ,}$$

where E_m and B_m are amplitudes of the waves, $\omega = 2\pi f$ is angular frequency of the wave (f is the linear frequency of the wave), and $k = 2\pi/\lambda$ is the wave number of the wave (λ is the wavelength of the wave). Additionally, waves have speed (“phase speed”)

$$\boxed{v = \frac{\omega}{k} = f\lambda}\,.$$

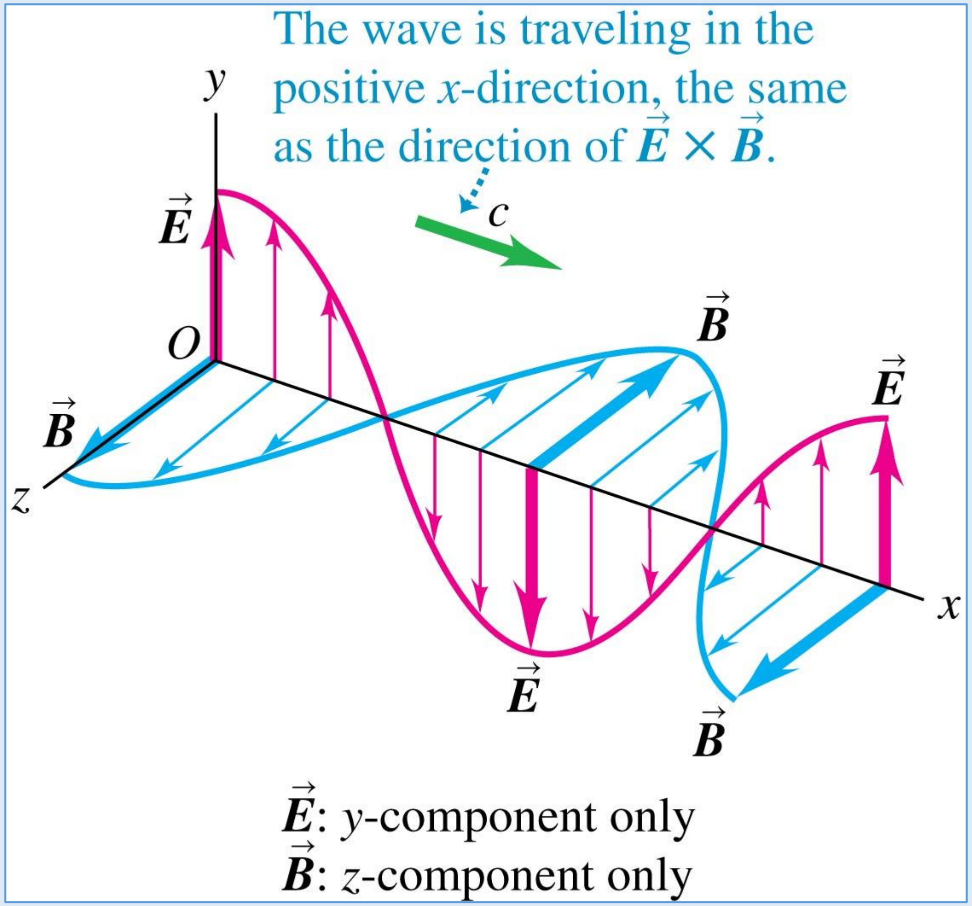
- From wave equation solutions, find that the speed for EM waves in vacuum is

$$\boxed{v = \frac{1}{\sqrt{\mu_0 \epsilon_0}} = c}\,,$$

where $c = 2.998 \times 10^8 \mathrm{m/s}$ is the speed of light.

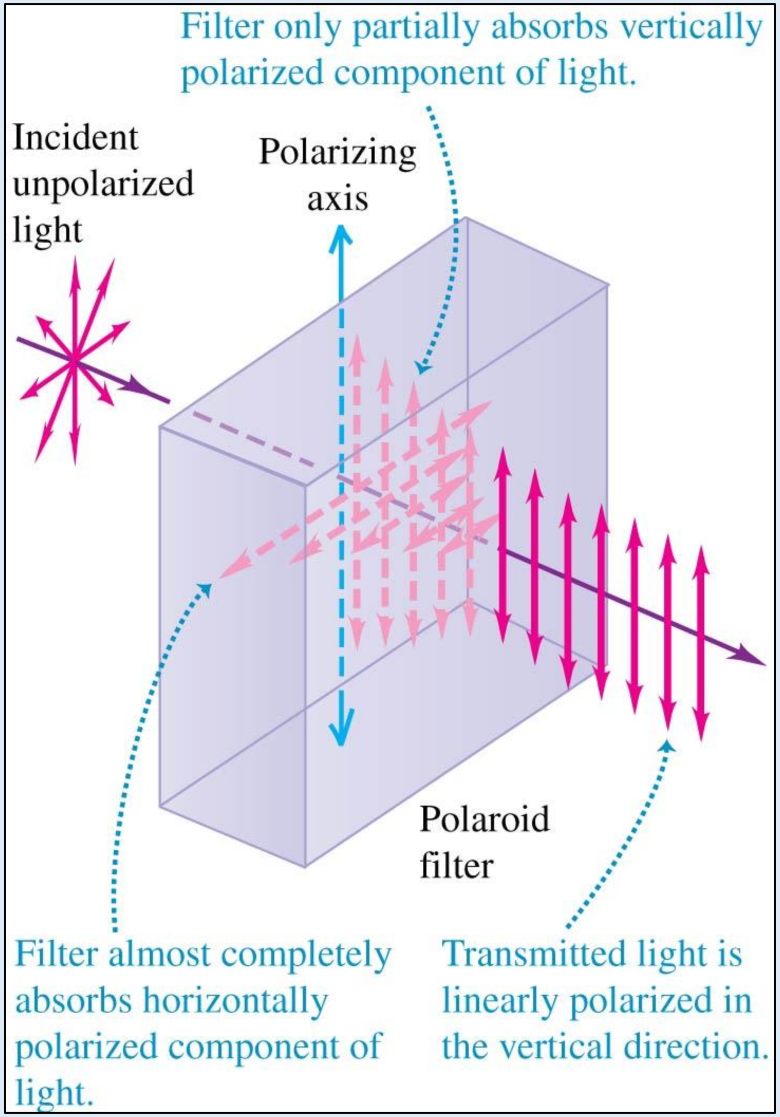
Field of a Sinusoidal Wave

- Shown is a <u>linearly polarized</u> sinusoidal EM wave <u>traveling in the $+x$-direction</u>.
- One wavelength of the wave is shown at time $t = 0$.
- Fields are shown for only a few points along the x-axis.



Polarization of EM Waves/Light

- An EM wave is linearly polarized if the electric field has only one component along a fixed (constant) axis direction.
- Light from many sources (such as the sun, or light bulbs) is a random mixture of waves linearly polarized in all possible transverse directions; such light is called unpolarized light or natural light.
- A polarizing filter can convert unpolarized light to linearly polarized light.
- Other polarization states exist, such as circularly or elliptically polarized light. Those types involve specific phase relations between perpendicular field components We won't be covering those in this course.

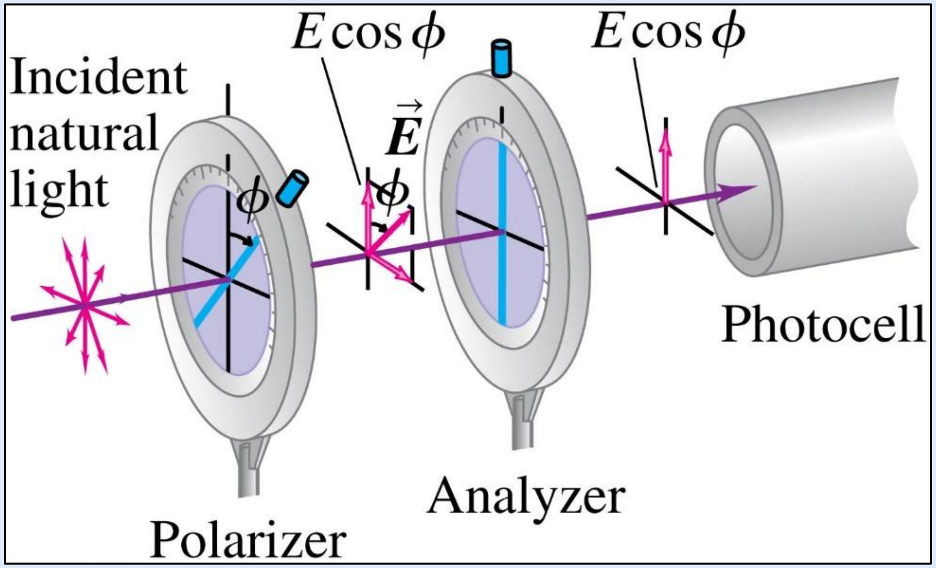


Polarization of EM Waves/Light (2)

- When unpolarized (natural) light of intensity I_0 is incident on a polarizing filter used as an analyzer, the intensity that is passed by the polarizer is

$$\boxed{I = \frac{1}{2} I_0} \; ,$$

that is, only half of the light intensity is transmitted. The light that is transmitted through is polarized along the polarizer's axis.



- When polarized light of intensity I_0 is incident on a polarizing filter used as an analyzer, the intensity I of the light transmitted through the analyzer depends on the angle ϕ between the polarization direction of the incident light and the polarizing axis of the analyzer. This is known as Malus's law:

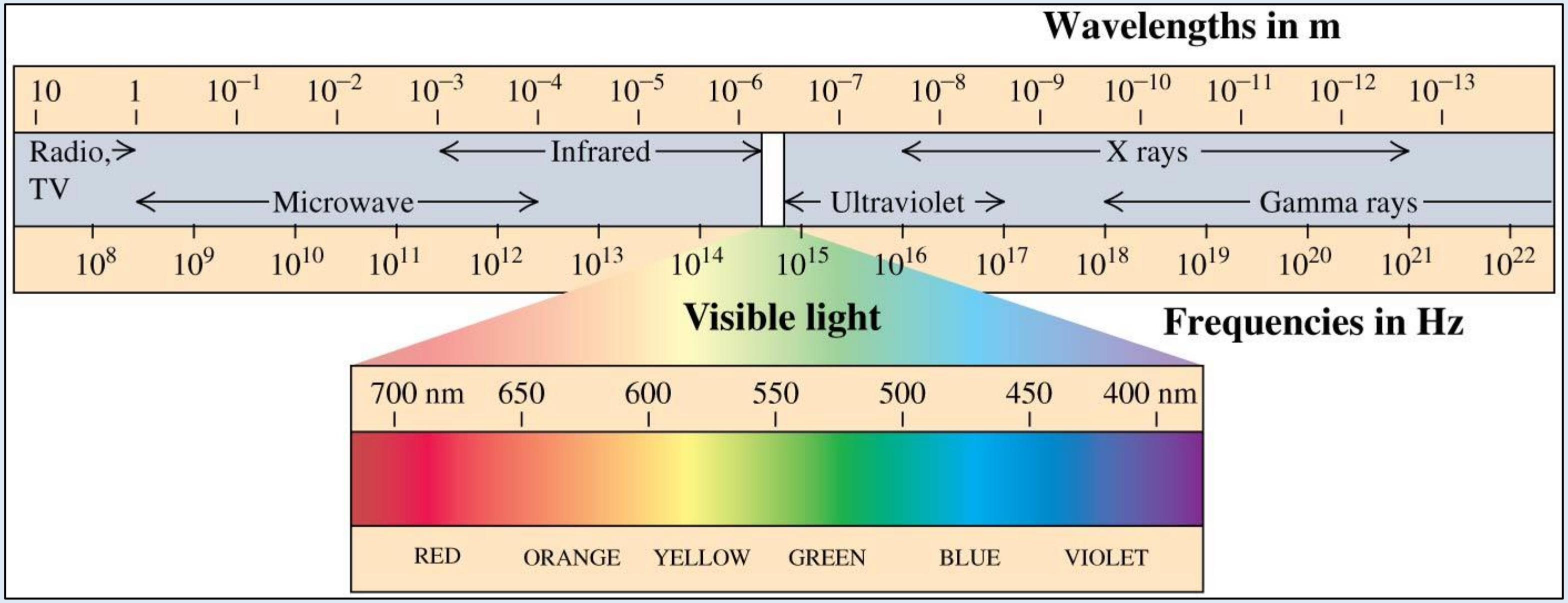
$$\boxed{I = I_0 \cos^2 \phi} \; .$$

It is again the case that the light that passes through the polarizer is aligned with the polarizer's polarization axis.

EM Waves and Light

- Maxwell's EM wave solutions describe propagation of light. That is, how EM/light waves travel from one place to another.
- Wave solutions also predict interference effects, which is how light waves interact with each other. This topic (and related subjects) are discussed in upcoming classes.
- However, the wave solutions do not well describe certain interactions that light has with matter. These interactions can be understood if one instead uses a model where light consists of particle-like entities. This aspect of light – the photon model – will also be discussed in later classes.
  - In his studies on light, Isaac Newton advocated the "corpuscular" theory of light: light consisted of small, discreet corpuscles. He described his theory in his book, Opticks.

Properties of EM/Light Waves: Spectrum



- All EM waves have the universal characteristic:

$$\boxed{\text{EM vacuum wave speed} = c = \frac{\omega}{k} = \lambda f = \frac{\lambda}{T}}\ .$$

- Frequencies and wavelengths of EM waves found in nature extend over a wide range. Must use a logarithmic scale to show all the important bands.
- Boundaries between bands decided by conventional use.

Properties of EM/Light Waves: Visible Light

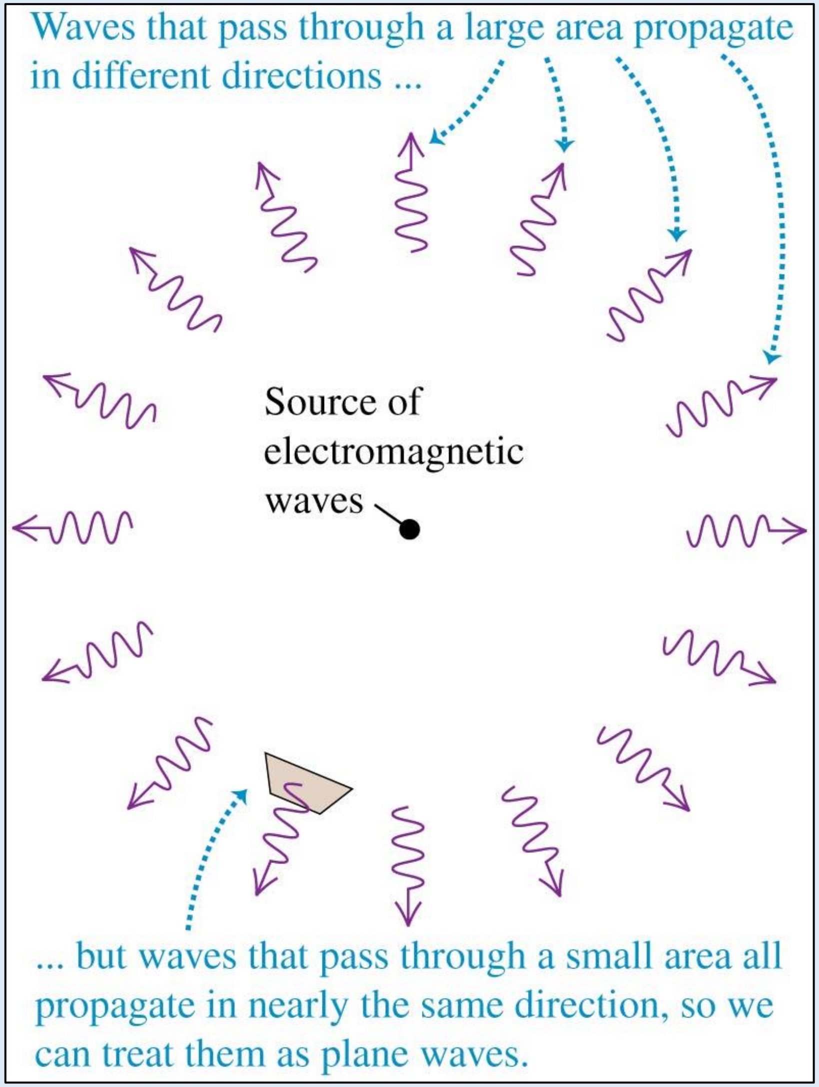
- Visible light is the segment of the electromagnetic spectrum that we can see.
- Visible light extends from the violet end (~ 400 nm) to the red end (~ 700 nm).

TABLE 32.1 **Wavelengths of Visible Light**

380–450 nm	Violet
450–495 nm	Blue
495–570 nm	Green
570–590 nm	Yellow
590–620 nm	Orange
620–750 nm	Red

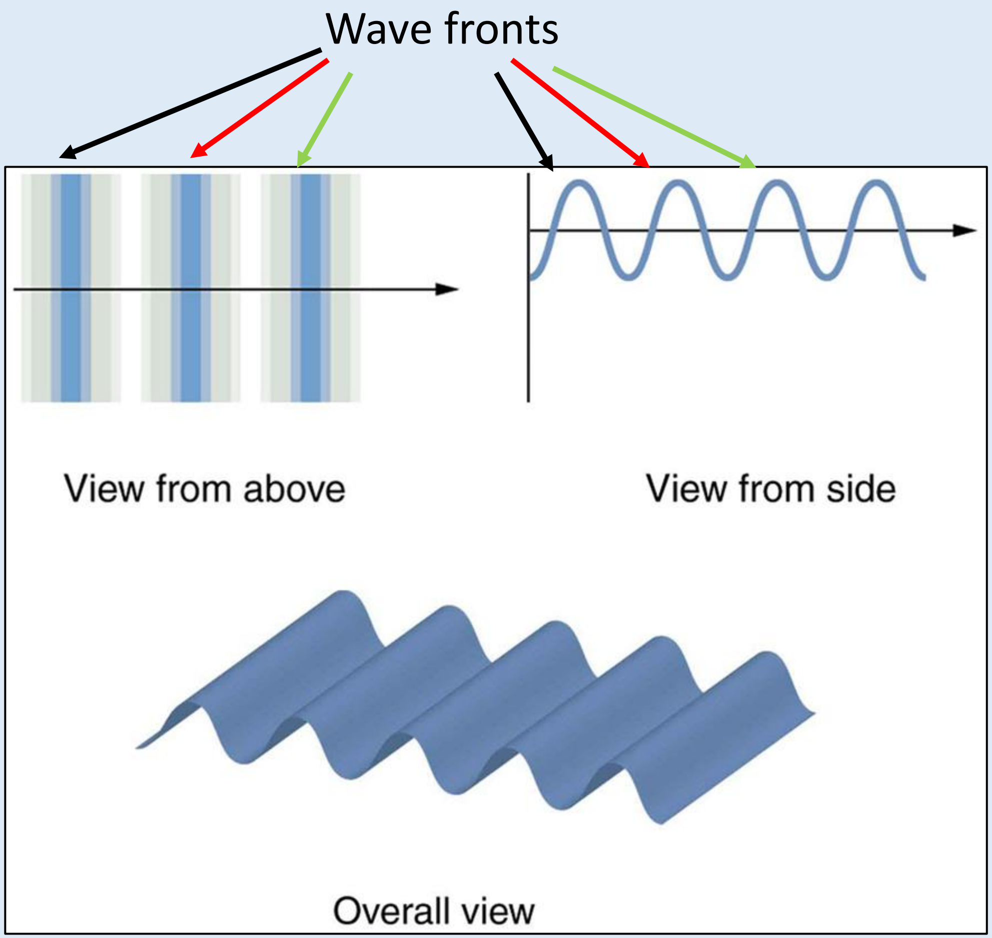
EM Waves: Non-Planar and Planar

- Spherical electromagnetic waves produced by an oscillating point charge are an example of sinusoidal waves that are <u>not</u> plane waves.
  - ➢ From Maxwell's equations with source terms, one finds for a radial distance r away from a point source that $E(r,t) \propto 1/r$, and $B(r,t) \propto 1/r$.
    - ❖ This is consistent with intensity $I \propto EB \propto 1/r^2$ for spherical waves, found earlier.
- If observations are restricted to a relatively small region of space (of size Δr) at a sufficiently great distance from the source (i.e., $\frac{\Delta r}{r} \ll 1$), the waves are well-approximated by plane waves.



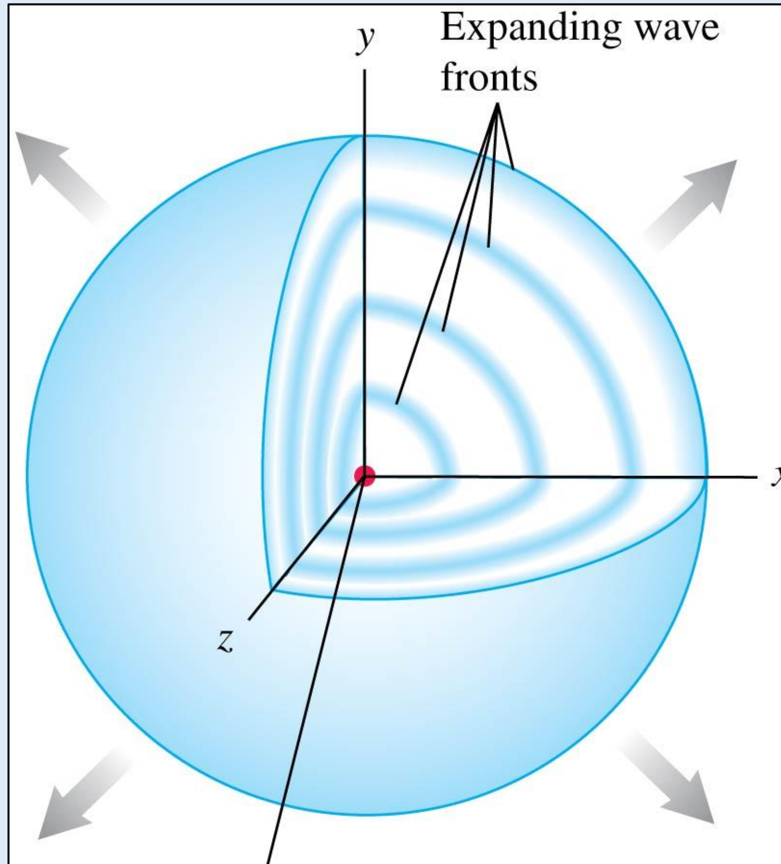
EM Waves: Waves and Wave Fronts

- Wave diagrams can be made simpler by just considering propagation of wave fronts.
- A wave front is a surface (or line) of constant phase in a wave, such as the instantaneous location of a wave crest.
- <u>Space between consecutive fronts is one wavelength, λ.</u>



EM Waves: Waves and Wave Fronts (2)

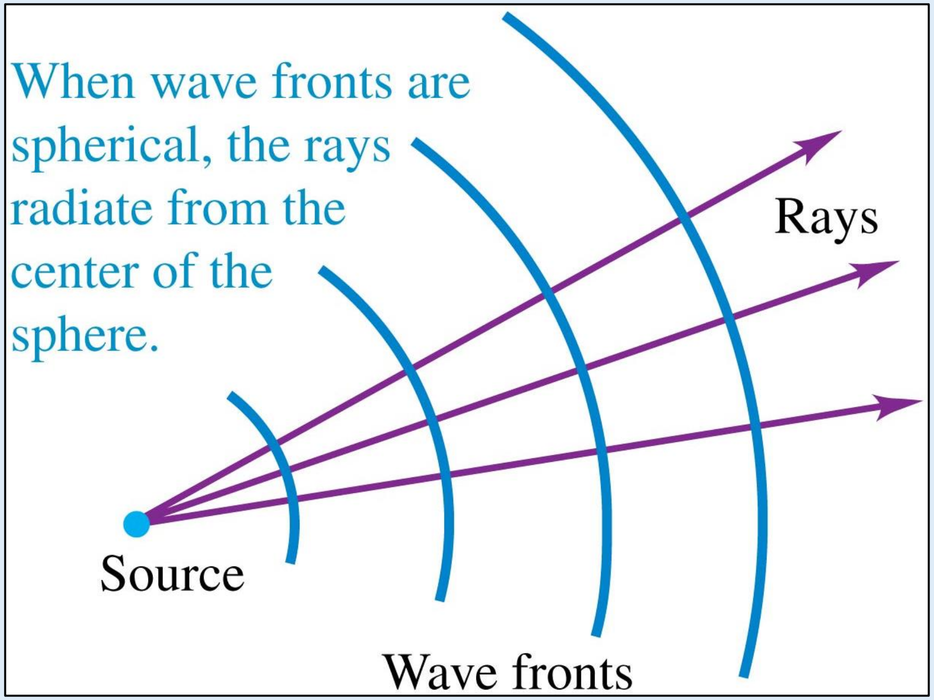
- A wave front is the locus of all adjacent points at which the phase of a wave is the same.
- Example: spherical wave fronts of sound spread out uniformly in all directions from a point source.
- Electromagnetic waves in vacuum also spread out as shown.



Point sound source producing spherical sound waves (alternating compressions and rarefactions of air)

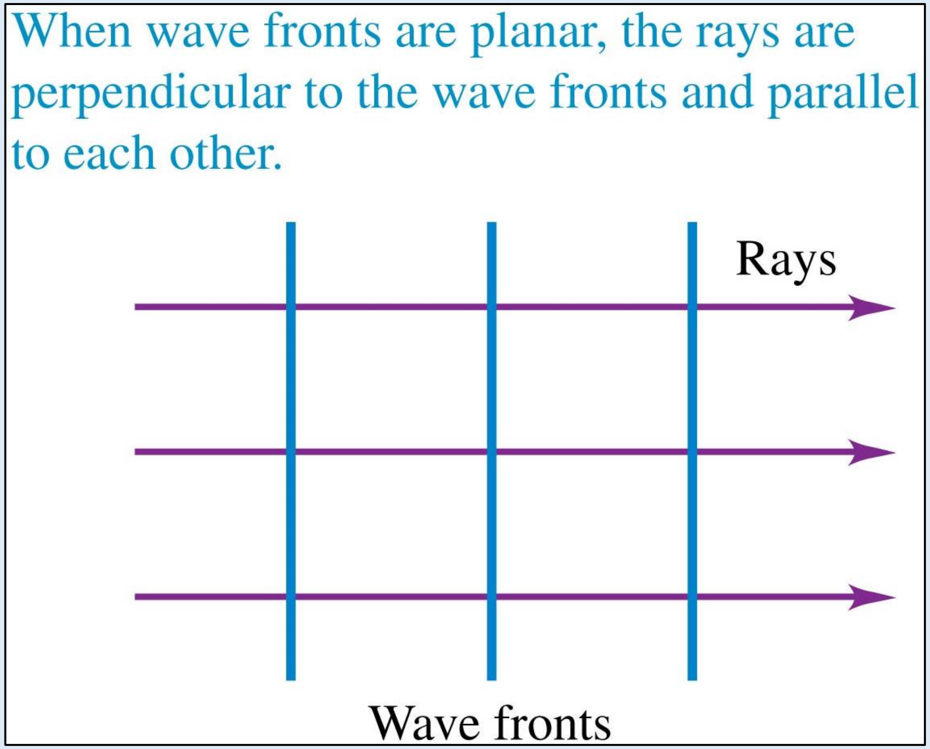
EM Waves: Wave Fronts and Rays

- Another simplification that can be made with waves and fronts is the concept of rays.
- A ray is an imaginary line along the direction of travel of the wave.
- For waves traveling in a homogeneous isotropic medium (i.e., one with no preferred directions), the rays are straight lines that are locally normal (perpendicular) to the wave fronts.



EM Waves: Wave Fronts and Rays (2)

- Far away from an EM wave source, where radii r of the wave front spheres are very large relative to a local region of size Δr (i.e., $\Delta r \ll r$), a section of the spherical wave surface can be considered planar.
  - For that situation the wave is essentially a plane wave, and has parallel wave fronts and parallel rays.



Index of Refraction

- We derived wave solutions for EM waves in vacuum.
- EM waves also exist in non-vacuum, material media.
- In many situations EM waves in material media are like vacuum EM waves, except that they have a phase speed given by the relation $\boxed{v_n = c/n}$, where n is the index of refraction of the medium.
  - For vacuum, $n = 1$.
  - For most naturally occurring material media, $n > 1$. Wave speeds in those media $v < c$.
    - Exception: an electron-ion plasma, which has $0 \leq n \leq 1$. This is the cause of radio 'blackouts' during rapid re-entry of a spacecraft into a planet's atmosphere: heating ionization creates a temporary hot plasma around the craft and prevents radio waves from reaching its receiver/transmitter. We won't discuss this topic in this class.
    - Another exception: constructed devices called 'meta-materials.' These have $n < 0$ for certain wavelengths/frequencies. Again, we won't be discussing them in this class.

Index of Refraction (2)

- When waves travel in one medium and then enter a new medium, they:

  1) Reflect part of their energy at the interface between the new and the previous medium.

  2) Transmit part of their energy into the new medium at the interface.

  3) Retain their linear frequency f (or, equivalently, angular frequency ω) inside the new medium.

- Relation between wave phase speed v_n, frequency $f_n (= f)$, and wavelength λ_n in the medium of index of refraction n still holds, namely:

$$\boxed{v_n = f\lambda_n},$$

it follows that

$$\boxed{\lambda_n = \frac{v_n}{f} = \frac{\left(\frac{c}{n}\right)}{f} = \frac{1}{n}\left(\frac{c}{f}\right) = \frac{\lambda_{\mathrm{V}}}{n}},$$

λ_{V} = wavelength of the light of frequency f in vacuum.

Index of Refraction (3)

- Relation

$$\boxed{\lambda_n = \frac{\lambda_{\mathrm{v}}}{n}}$$

  tells us that when a wave of vacuum wavelength λ_{V} travels in a medium of index $n > 1$, the wave fronts are closer together (wavelength λ_n is shorter than in vacuum); if wave speed decreases (n becomes larger) wavelength gets "stretched out" (λ_n becomes longer), and if wave speed increases (n gets smaller) waves are "compressed" (λ_n becomes shorter).
- Tables of refractive indices (often as a function of vacuum wavelength) can be found in your text and other references.
- For air, $n = 1.0003$.

Index of refraction of yellow light, $\lambda_{\mathrm{v}} = 589$ nm.

Substance	**Index of Refraction, *n***
Ice (H_2O)	1.309
Water (H_2O) at 20°C	1.333
Glycerine at 20°C	1.473
Crown glass (typical value)	1.52
Rock salt (NaCl)	1.544
Quartz (SiO_2)	1.544
Diamond (C)	2.417

Huygens' Principle

- Proposed by 17th – century physicist/astronomer Christian Huygens to explain wave motion. (Predates Maxwell's solution for EM waves.)
- Originally a heuristic explanation for wave motion: it 'felt right,' but was lacking a complete, rigorous math-physics solution backing it up at the time it was originally proposed.
- Can be put on a rigorous foundation using modern mathematical techniques and physical knowledge. However, requires graduate-level math/physics to do the job right.
- We'll take it as a given that the basic idea he proposed is correct.

Huygens’ Principle (2)

- Huygens’s principle states: every point of a wave front acts a source of secondary “wavelets” that spread out in all directions with a speed equal to the speed of propagation of the wave.
- New wave front at a later time is found by constructing a surface tangent to the secondary wavelets or, as it is called, the envelope of the wavelets.
- Figure shows application of Huygens’s principle to a wave front at an instant in time to construct a new wave front at a later instant of time.
- Idea will be useful in explaining diffraction of waves around corners and edges.