# Lectures: Physics 3306

Provides an introduction to a wide variety of topics in classical (pre-quantum) physics as a bridge to prepare students for subsequent upper-level courses in physics. The topics covered include thermodynamics, fluid mechanics, mechanical waves, optics, radiation, electromagnetic phenomena, atoms, and laboratory techniques. Prerequisites: C- or better in PHYS 1106; and in PHYS 1304 or PHYS 1308.

**Saptaparna Bhattacharya**

**April 20th, 2026**

**Based on Simon Dalley's lectures taught in Spring 2025**

Labs

Lectures

# Schedule

No class

| Month | Monday | Tuesday | Wednesday | Thursday | Friday | Saturday | Sunday |
|---|---|---|---|---|---|---|---|
| January | 19 | 20 | 21 ✅ | 22 | 23 ✅ | 24 | 25 |
| | 26 ❄️🌨️❄❄❄ | 27 | 28 ❄️🌨️❄❄❄ | 29 | 30 ✅ | 31 | 1 |
| February | 2 ✅ | 3 | 4 ✅ | 5 | 6 ✅ | 7 | 8 |
| | 9 ✅ | 10 | 11 HWB due ✅ | 12 | 13 ✅ | 14 | 15 |
| | 16 ✅ | 17 | 18 ✅ | 19 | 20 HWC due ✅ | 21 | 22 |
| | 23 Hegi Center ✅ | 24 | 25 HWD due ✅ | 26 | 27 ✅ | 28 | 1 |
| March | 2 ✅ | 3 | 4 HWE due | 5 | 6 ✅ | 7 | 8 |
| | 9 ✅ | 10 | 11 | 12 | 13 Midterm | 14 | 15 |
| | 16 | 17 | 18 | 19 | 20 | 21 | 22 |
| | 23 ✅ | 24 | 25 | 26 | 27 ✅ | 28 | 29 |
| April | 30 Lecture 11 ✅ | 31 | 1 HWF due | 2 | 3 | 4 | 5 |

Labs

Lectures

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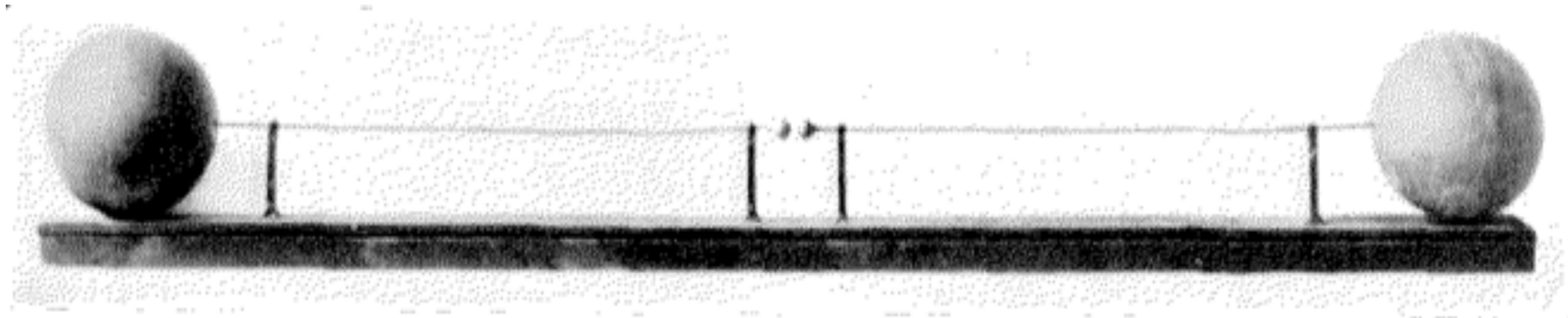
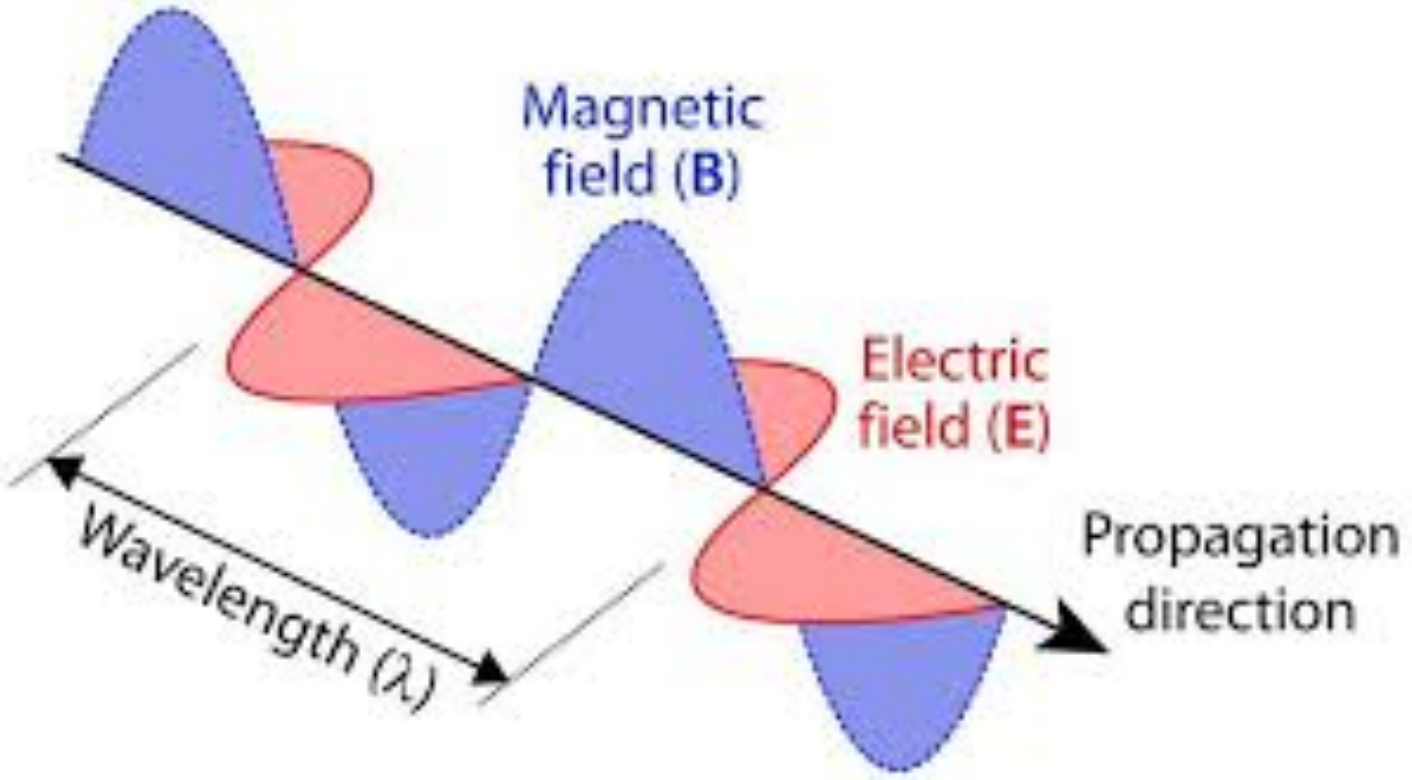
No class

| Month | Monday | Tuesday | Wednesday | Thursday | Friday | Saturday | Sunday |
|---|---|---|---|---|---|---|---|
| April | 6 Midterm 2 ✅ | 7 | 8 HWG due | 9 | 10 Lecture 15 ✅ | 11 | 12 |
| | 13 Lecture 16 ✅ | 14 | 15 HWH due | 16 | 17 Lecture 17 ✅ | 18 | 19 |
| | 20 Lecture 18 | 21 | 22 HWI due | 23 | 24 Lecture 19 | 25 | 26 |
| May | 27 Lecture 20 | 28 | 29 HWJ due | 30 | 1 Lecture 21 | 2 | 3 |
| | 4 Lecture 22 | 5 Lecture 23 | 6 | 7 | 8 | 9 | 10 |

**Heinrich Hertz**
(1857 – 1894) German physicist

In1888 first conclusively proved the existence of the electromagnetic waves theorized by James Clerk Maxwell from his equations in 1865.





"*this is just an experiment that proves Maestro Maxwell was right - we just have these mysterious electromagnetic waves that we cannot see with the naked eye. But they are there.*" - Heinrich Hertz, 1888

Asked about the ramifications of his discoveries, Hertz replied,
"*Nothing, I guess.*"

Marconi's first wireless radio transmission over large distances (~6 km over water) was in 1897.

# Electromagnetic spectrum

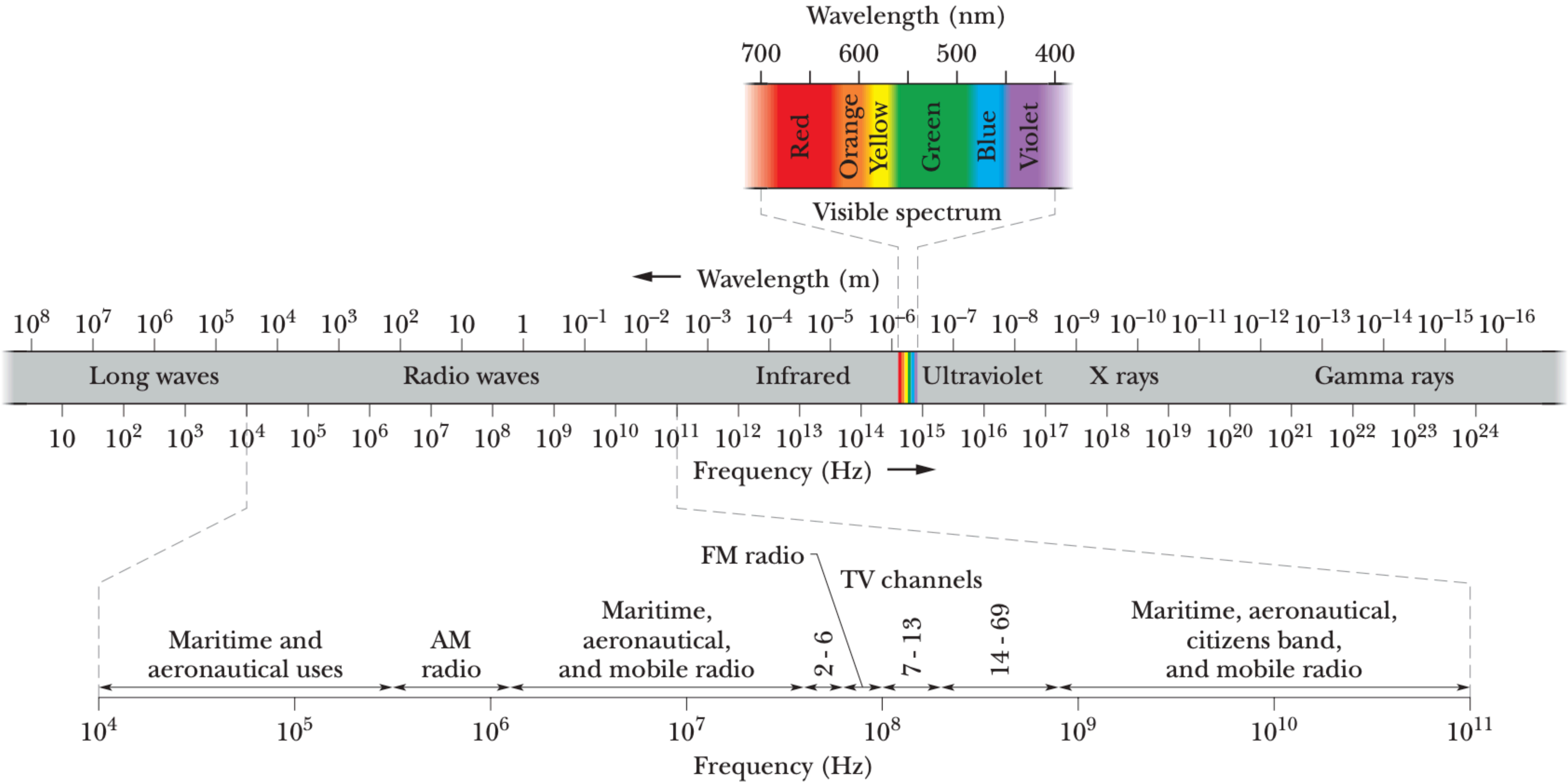


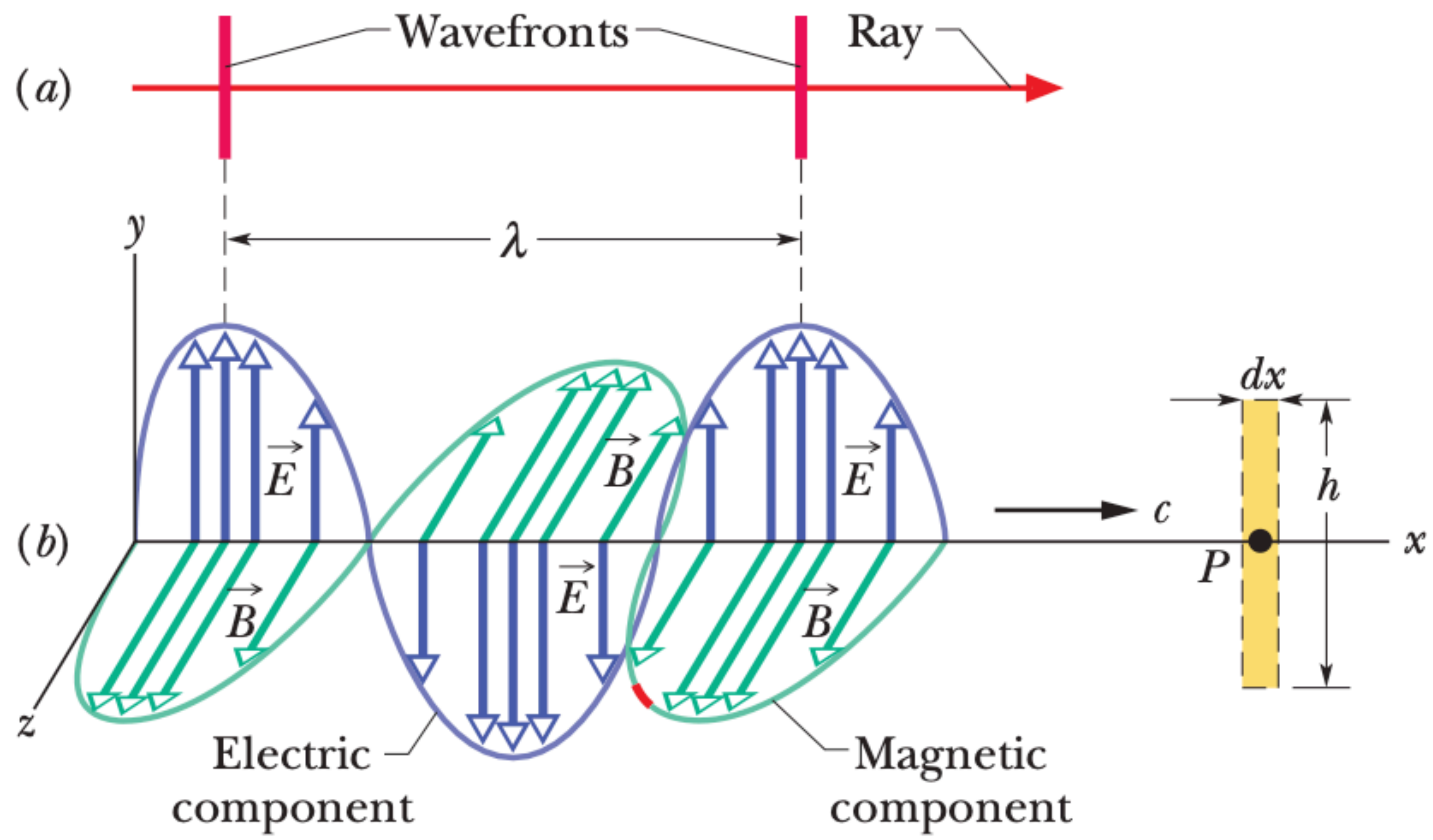

**Figure 33-1** The electromagnetic spectrum.

# Key concepts: Electric and magnetic fields

- The electric and magnetic fields $\overrightarrow{E}$ and $\overrightarrow{B}$ are always perpendicular to the direction in which the wave is traveling. Thus, the wave is a *transverse wave*
- The electric field is always perpendicular to the magnetic field
- The cross product $\overrightarrow{E} \times \overrightarrow{B}$ always gives the direction in which the wave travels
- The fields always vary sinusoidally, just like the transverse waves
    - Moreover, the fields vary with the same frequency and *in phase* (in step) with each other
- $E = E_m \sin(kx - \omega t)$, $B = B_m \sin(kx - \omega t)$
- Wave speed: $c = \dfrac{1}{\sqrt{\mu_0 \epsilon_0}}$
- $\dfrac{E_m}{B_m} = c$

# Key concepts: Electric and magnetic fields

**Figure 33-5** (*a*) An electromagnetic wave represented with a ray and two wavefronts; the wavefronts are separated by one wavelength $\lambda$. (*b*) The same wave represented in a "snapshot" of its electric field $\vec{E}$ and magnetic field $\vec{B}$ at points on the $x$ axis, along which the wave travels at speed $c$. As it travels past point $P$, the fields vary as shown in Fig. 33-4. The electric component of the wave consists of only the electric fields; the magnetic component consists of only the magnetic fields. The dashed rectangle at $P$ is used in Fig. 33-6.



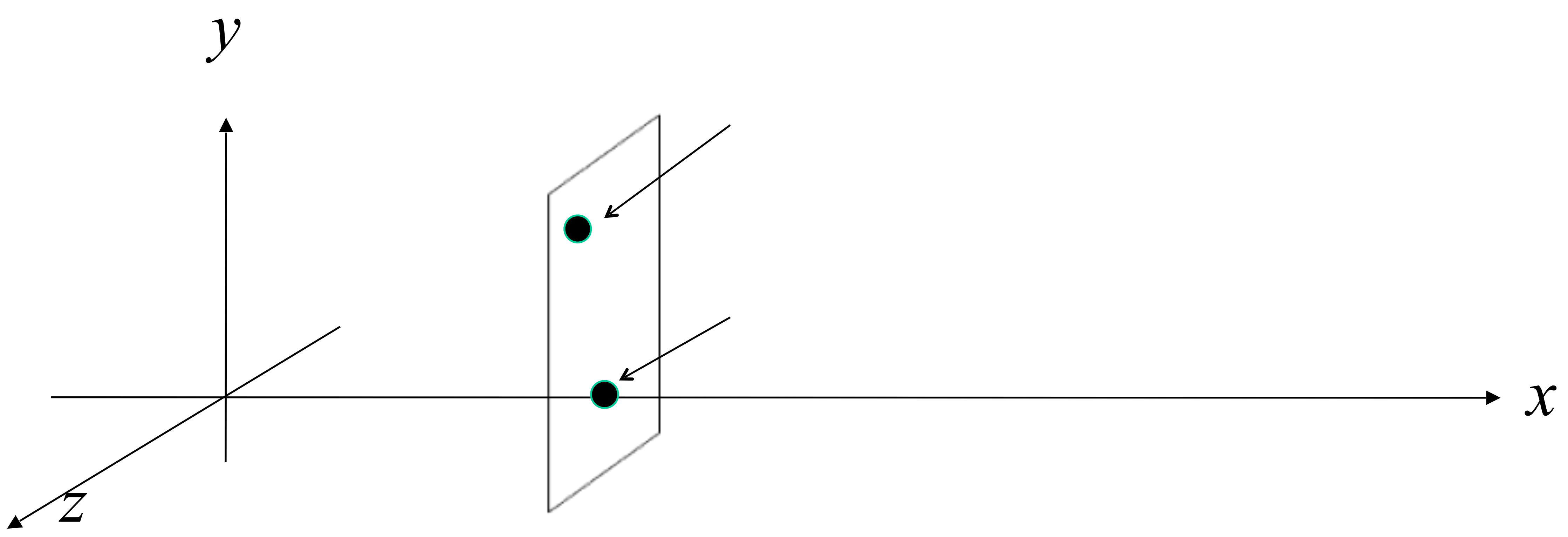
A wave is moving in the $+x$ direction:

$$f(x,y,z,t) = \sin(kx - \omega t + \delta)$$

The value of $f$ at $(x_0, 0, 0, t)$ and at $(x_0, y, z, t)$ are related how?

A) They are equal

B) They depend on the value of $z$ and $y$



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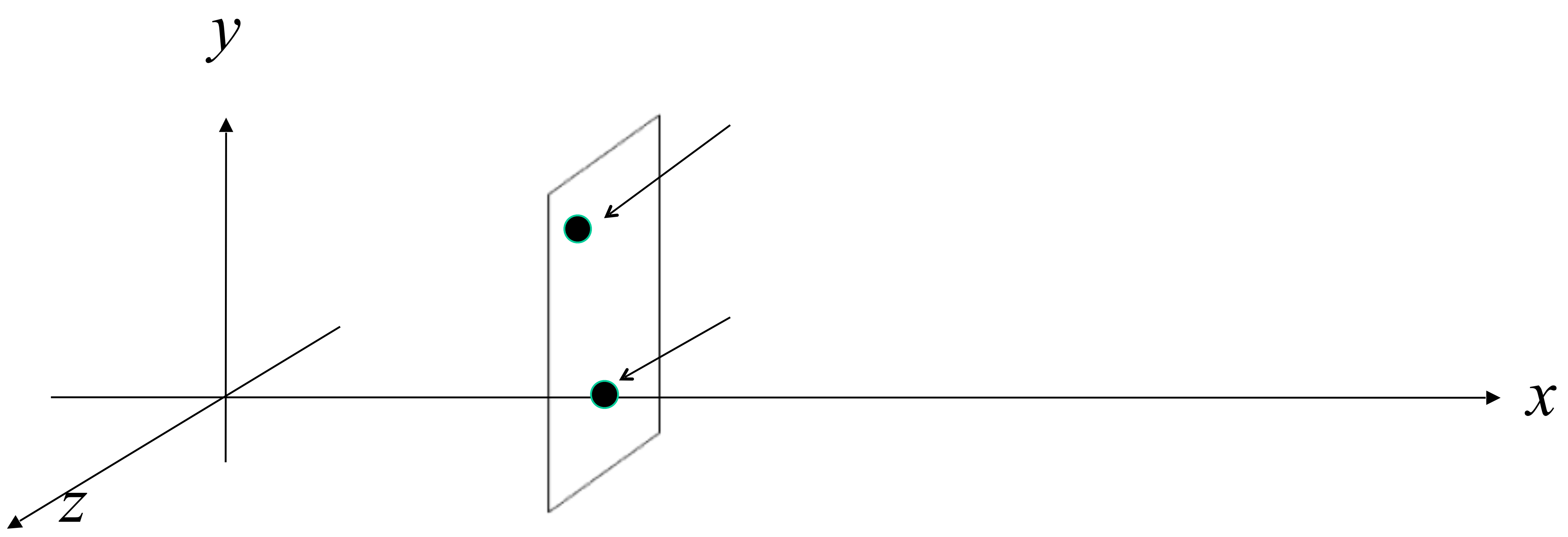
The wave equation provided is:

$$f(x, y, z, t) = \sin(kx - \omega t + \delta)$$

Notice that the spatial variables $y$ and $z$ do not appear anywhere in the equation. This means the value of the function $f$ depends *only* on the $x$-coordinate and time $t$.



The electric field magnitudes of two EM waves in vacuum are both described by:

$$E = E_m \sin(kx - \omega t)$$

The "wave number" $k$ of wave 1 is larger than that of wave 2, $k_1 > k_2$.

Which wave has the larger frequency $f$?

A) Wave 1 B) Wave 2 C) impossible to tell

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Which wave has the larger frequency $f$?

A) Wave 1    B) Wave 2    C) impossible to tell

**Solution:**
The correct answer is **A) Wave 1**.

### 1. Constant Wave Speed

All electromagnetic (EM) waves traveling through a vacuum propagate at the exact same speed: the speed of light, $c$. Therefore, the wave speed $v$ for both Wave 1 and Wave 2 is $c$.

### 2. Relate Speed to Wave Number and Frequency

The speed of any wave is the ratio of its angular frequency ($\omega$) to its wave number ($k$):

$$v = \frac{\omega}{k}$$

Since the speed is the constant $c$, we can write:

$$c = \frac{\omega}{k} \implies \omega = ck$$

### 3. Convert Angular Frequency to Regular Frequency

We know that angular frequency $\omega$ is related to regular frequency $f$ by the equation $\omega = 2\pi f$. Substituting this into our previous expression yields:

$$2\pi f = ck$$

Solving for $f$, we get:

$$f = \left(\frac{c}{2\pi}\right) k$$

### 4. Conclusion

Because $\frac{c}{2\pi}$ is a positive constant, this final equation demonstrates that a wave's frequency $f$ is **directly proportional** to its wave number $k$.

Therefore, if Wave 1 has a larger wave number ($k_1 > k_2$), it must also have a proportionally larger frequency ($f_1 > f_2$).

The electric field of a transverse EM plane wave is described by

$$\underline{\boldsymbol{E}} = E_m \, \underline{\hat{\mathbf{y}}} \sin(kx - \omega t)$$

If the magnetic field is

$$\underline{\boldsymbol{B}} = B_m \, \underline{\mathbf{?}} \sin(kx - \omega t)$$

what is the direction of **?**

A) +x B) +y C) –x D) +z E) -z

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The correct answer is **D) +z**.

Here is the step-by-step breakdown of how to find the direction:

### 1. Find the Direction of Propagation ($\hat{k}$)

The phase of the wave is given by the argument of the sine function: $(kx - \omega t)$. Because the signs in front of the spatial term $(kx)$ and the temporal term $(\omega t)$ are opposite, the wave is traveling in the positive direction of that spatial variable. Therefore, the wave propagates in the $+x$ direction. We can write the unit vector for propagation as $\hat{k} = \hat{\mathbf{x}}$.

### 2. Find the Direction of the Electric Field ($\vec{E}$)

The equation explicitly provides the unit vector for the electric field amplitude: $\hat{\mathbf{y}}$. This means the electric field oscillates back and forth along the **$y$-axis**. So, the electric field direction is $\hat{E} = \hat{\mathbf{y}}$.

### 3. Apply the Right-Hand Rule ($\vec{B}$)

In an electromagnetic plane wave traveling through a vacuum or uniform medium, the electric field ($\vec{E}$), the magnetic field ($\vec{B}$), and the direction of propagation ($\hat{k}$) are always mutually perpendicular.

Their orientation follows the right-hand rule, defined by the cross product:

$$\hat{B} = \hat{k} \times \hat{E}$$

Plugging in the unit vectors we determined from the equations:

$$\hat{B} = \hat{\mathbf{x}} \times \hat{\mathbf{y}}$$

Using the standard Cartesian right-hand rule (point your fingers in the $+x$ direction, curl them toward the $+y$ direction, and your thumb points in the $+z$ direction), the cross product evaluates to:

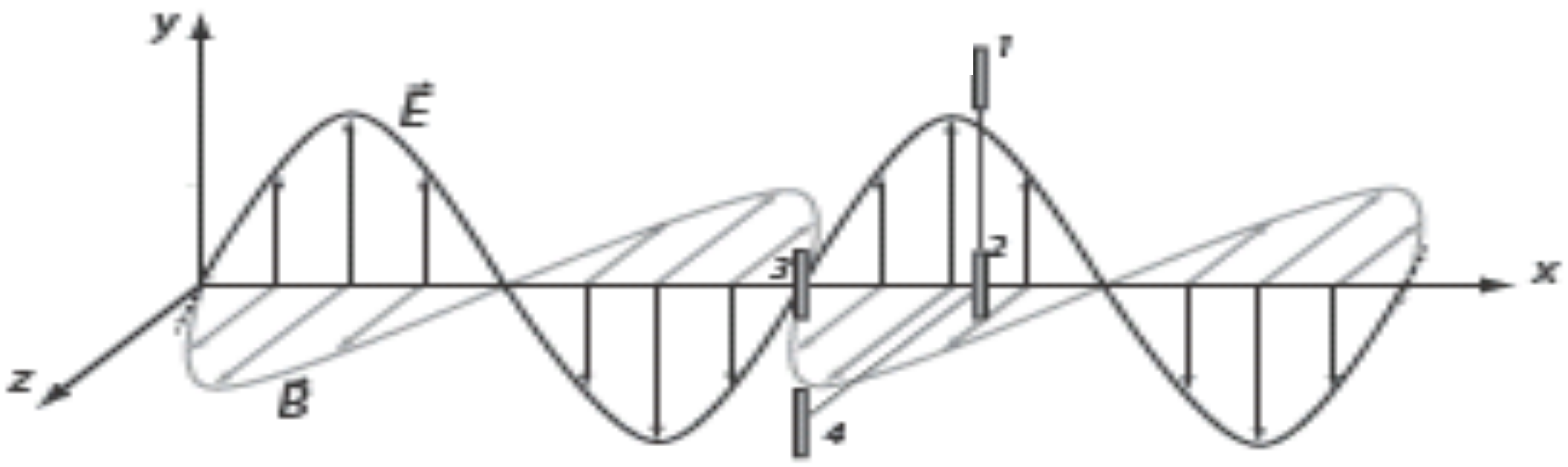
$$\hat{B} = \hat{\mathbf{z}}$$

Therefore, the magnetic field must oscillate along the $+z$ axis.

An electromagnetic plane wave propagates to the right (+$x$).
Four vertical antennas are labeled 1 – 4.
1, 2, and 4 have the same $x$-coordinate. Antenna 4 is located further out in the $z$-direction while antenna 1 is located further out in the $y$-direction. Antenna 3 has a different $x$ value.

Rank the time-averaged signals received by each antenna.

A) 1 = 2 = 3 > 4   B) 3 > 2 > 1 = 4   C) 1 = 2 = 4 > 3
D) 1 = 2 = 3 = 4   E) 3 > 1 = 2 = 4



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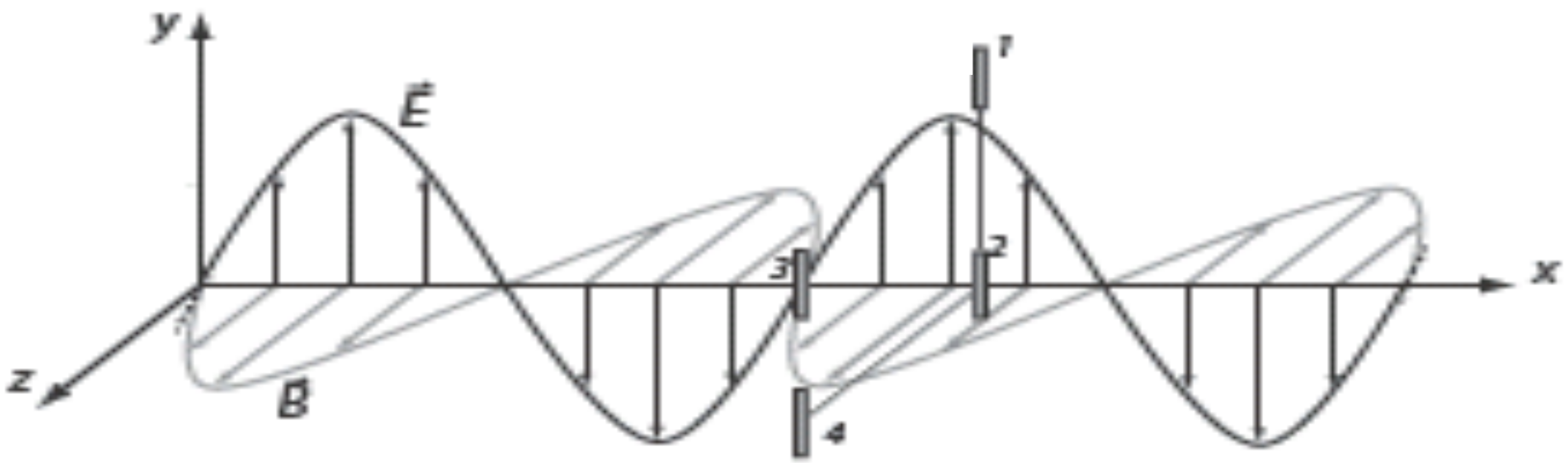

**1. The "Plane Wave" Concept (y and z independence)**

The problem states this is an electromagnetic **plane wave**. For a wave traveling in the +x direction, the wavefronts are infinite flat planes spanning the yz-plane.

Because it is a plane wave, the electric field amplitude is completely uniform across any cross-section perpendicular to the direction of travel. Moving an antenna up along the y-axis (Antenna 1) or out along the z-axis (Antenna 4) does not change the amplitude of the signal it interacts with compared to the origin (Antenna 2).

- Therefore: **1=2=4**

**2. The Time-Average Concept (x independence)**

Antenna 3 is located at a different x-coordinate. At any *specific instant in time*, the electric field at Antenna 3 will likely be different from the field at Antennas 1, 2, and 4 because it sits at a different point in the wave's phase (kx).

However, the question specifically asks for the **time-averaged** signal. Over a full oscillation cycle, every point in space along the x-axis experiences the exact same sequence of maximums, minimums, and zero-crossings. The time-averaged intensity (power) of an unattenuated plane wave is constant everywhere in space.

- Therefore: **3 equals the rest.**

**3. Antenna Orientation**

The problem explicitly states that all four antennas are **vertical**. In the context of the provided coordinate system, this means they are all oriented parallel to the y-axis.

Looking at the diagram, the electric field E

is also polarized along the y-axis. Because all four antennas are perfectly and identically aligned with the electric field vectors, they all perfectly couple to the wave. Orientation does not cause any difference in their received signals.

For a localized source to radiate power, the integral of the intensity (the Poynting vector $(\underline{\boldsymbol{E}} \times \underline{\boldsymbol{B}})/\mu_0$ ) must be non-zero and finite across any closed surface around the source.

How must each of $E$ and $B$ fall off with distance $r$, for the source to radiate power to infinity?

A) $1/r^{1/2}$
B) $1/r$
C) $1/r^2$
D) $1/r^{3/2}$
E) $1/r^3$

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**1. The Poynting Vector Dependence**

The intensity of the electromagnetic radiation is given by the magnitude of the Poynting vector, $S$. For an electromagnetic wave in a vacuum, the electric and magnetic fields are proportional to each other ($E = cB$). Therefore, they must share the same dependence on the distance $r$. Let's assume they both fall off as $1/r^n$:

$$E \propto \frac{1}{r^n} \quad \text{and} \quad B \propto \frac{1}{r^n}$$

Since the Poynting vector is proportional to the cross product of $\vec{E}$ and $\vec{B}$, its magnitude scales as:

$$S \propto E \times B \propto \left(\frac{1}{r^n}\right)\left(\frac{1}{r^n}\right) = \frac{1}{r^{2n}}$$

**2. The Area of the Closed Surface**

If we integrate this intensity across a closed spherical surface of radius $r$ around the source, the total surface area $A$ grows with the square of the distance:

$$A = 4\pi r^2 \propto r^2$$

**3. The Power Integral**

The total power $P$ radiated outward through this spherical surface is the integral of the Poynting vector over the area ($P = \oint \vec{S} \cdot d\vec{A}$). Scaling-wise, this is the product of the intensity and the area:

$$P \propto S \cdot A \propto \left(\frac{1}{r^{2n}}\right)(r^2) = r^{2-2n}$$

A charge moves at constant velocity.

Does it radiate electromagnetic waves?

A) Yes, and I can defend my answer

B) Yes, but I cannot explain why I believe this

C) No, and I can defend my answer

D) No, but I cannot explain why I believe this

E) It depends on the inertial reference frame of the observer!

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E) It depends on the inertial reference frame of the observer!

According to classical electrodynamics, a point charge must **accelerate** to radiate electromagnetic waves.

We can see this rigorously through the **Larmor formula**, which describes the total power P radiated by a non-relativistic point charge:

$$P = \frac{q^2 a^2}{6\pi\epsilon_0 c^3}$$

Where:

- q is the charge of the particle
- a is the acceleration
- $\epsilon_0$ is the vacuum permittivity
- c is the speed of light

Because the charge in the prompt is moving at a *constant velocity*, its acceleration is exactly zero (a=0). Therefore, the radiated power is zero.

While a charge moving at a constant velocity does generate a magnetic field (in addition to its electric field), these fields are static in the particle's rest frame. They remain "bound" to the charge and do not pinch off to form the self-propagating ripples of energy that constitute electromagnetic radiation.

Option E is a clever distractor. While it is true that different inertial observers will disagree on the specific configurations of the electric and magnetic fields (E and B ) transform into one another depending on your reference frame), **radiation is a Lorentz invariant phenomenon**.

Radiation carries away energy and momentum. All inertial observers must agree on whether an irreversible loss of energy (radiation) occurred. Because the charge has zero acceleration in its own rest frame, it has zero acceleration in all inertial reference frames, meaning no observer will see it radiate.