Waves: Frequency, Wavelength, and Energy

- A wave is a disturbance that transfers energy without permanently displacing matter
- Three core properties: frequency (f), wavelength (λ), and energy (E)
- This general model applies to sound, light, and other wave types
- Everyday examples: water ripples, musical notes, sunlight

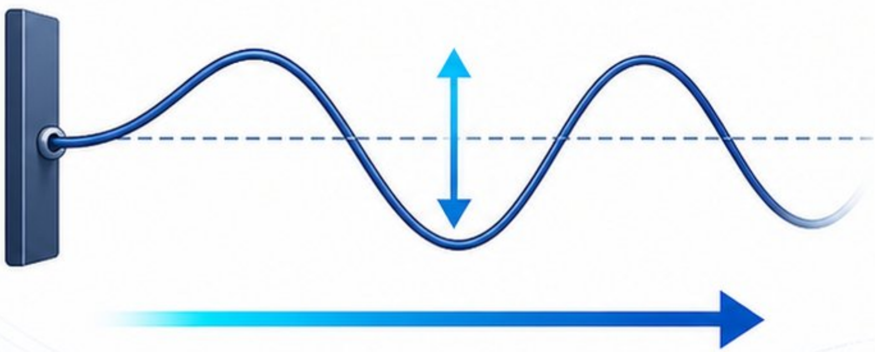
What Is a Wave?

- A wave is a disturbance that transfers energy without displacing matter
- Mechanical waves require a medium; electromagnetic waves do not
- Waves transport energy, not matter—like a seagull bobbing on water
- A single pulse versus a repeating periodic wave sets the stage for frequency

Transverse and Longitudinal Waves

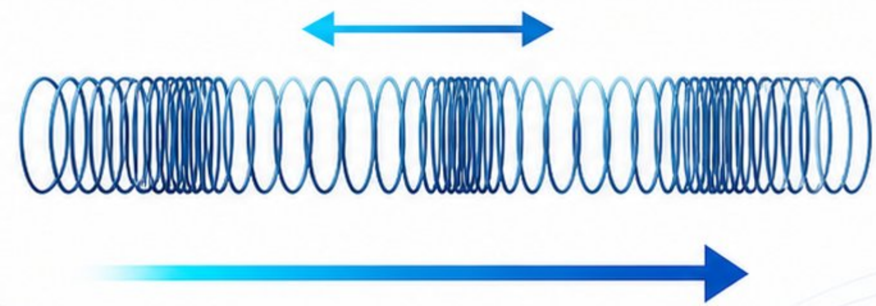
TRANSVERSE WAVE

GUITAR STRING



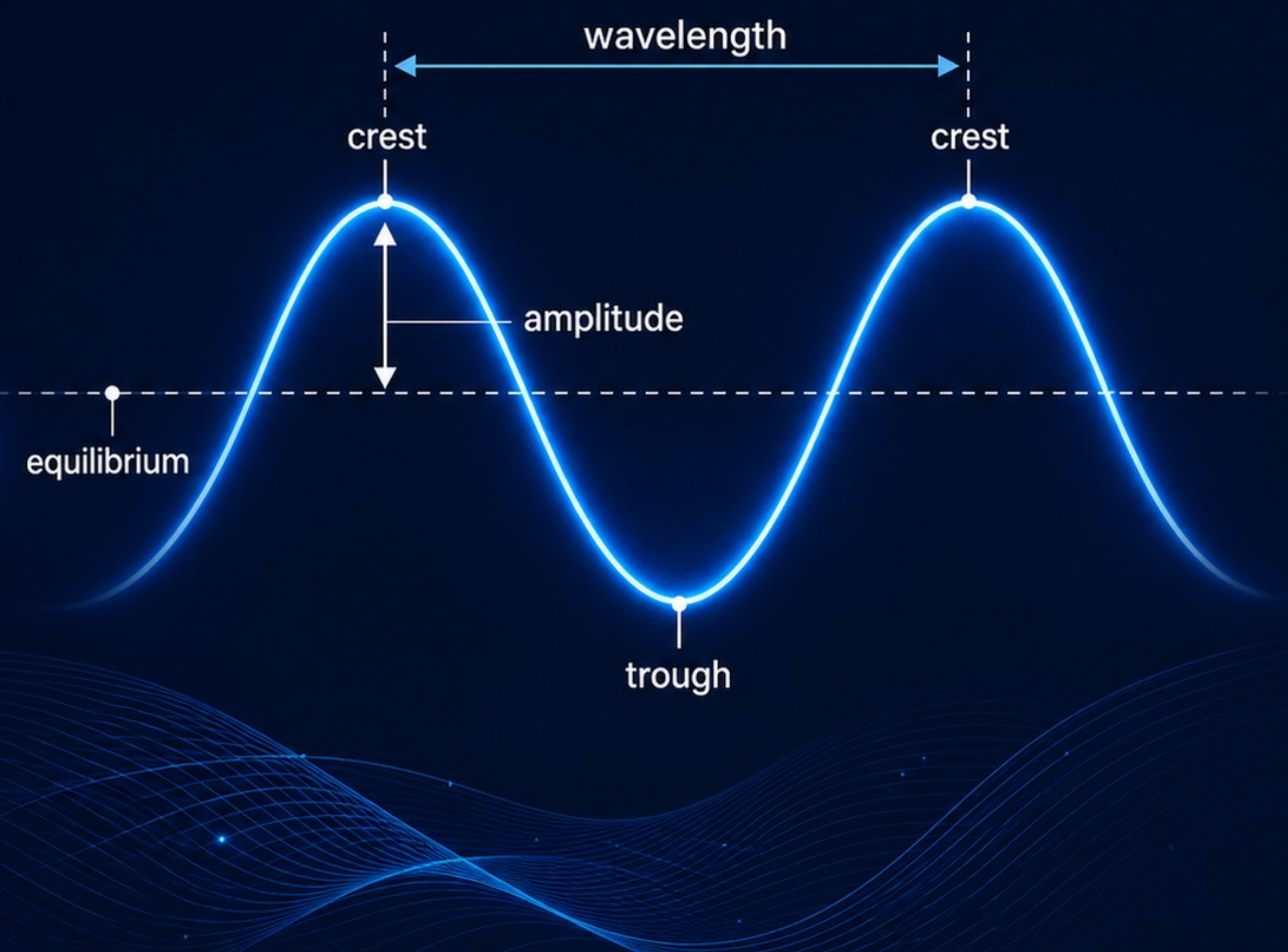
LONGITUDINAL WAVE

SLINKY SPRING



- Transverse: particle motion perpendicular to energy transfer
- Longitudinal: particle motion parallel to energy transfer
- Crests & troughs vs. compressions & rarefactions
- Light, water ripples, strings are transverse
- Sound and ultrasound are longitudinal

Anatomy of a Wave: Amplitude, Wavelength, and Frequency

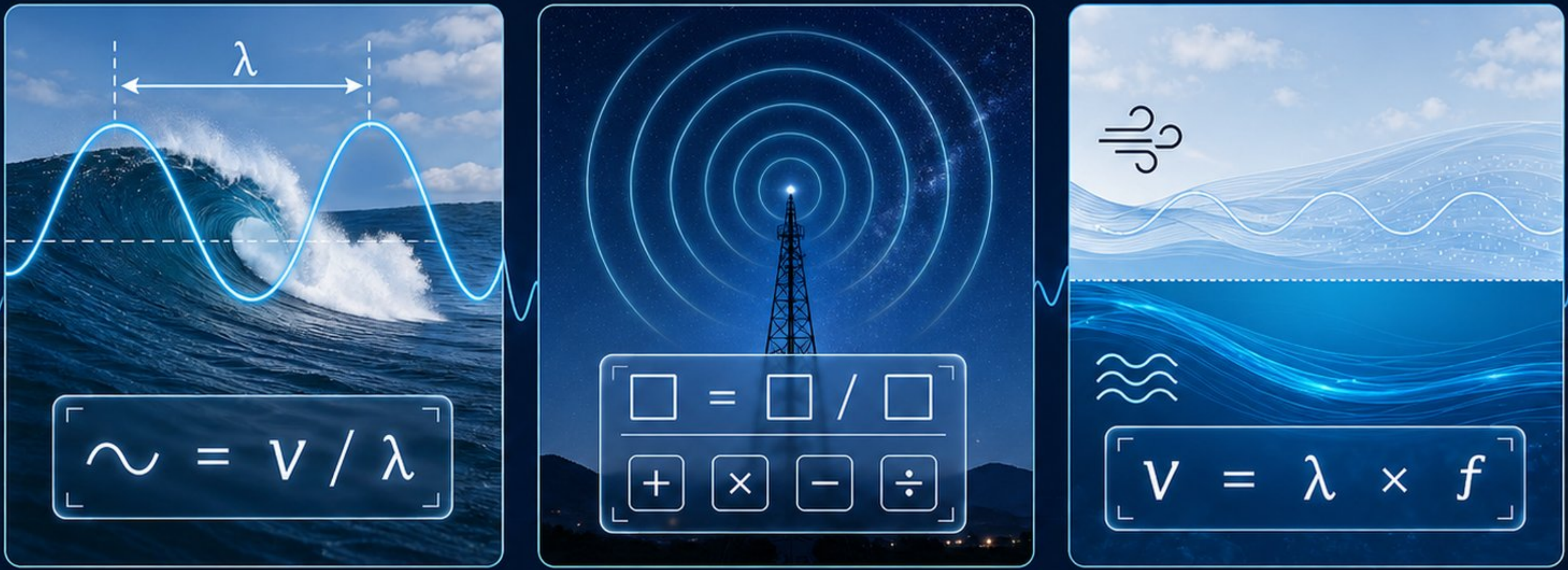


- **Amplitude:** maximum displacement from equilibrium; linked to wave energy
- **Wavelength (λ):** distance between two identical points (crest to crest)
- **Frequency (f):** cycles per second, measured in Hertz (Hz)
- **Period (T):** time for one cycle; $T = 1/f$

The Wave Equation: $v = f\lambda$

- Wave speed equals frequency × wavelength: $v = f\lambda$
- Wave speed depends on medium properties, not frequency
- Higher frequency → shorter wavelength in same medium
- Example: 440 Hz sound in air, $\lambda \approx 0.78$ m

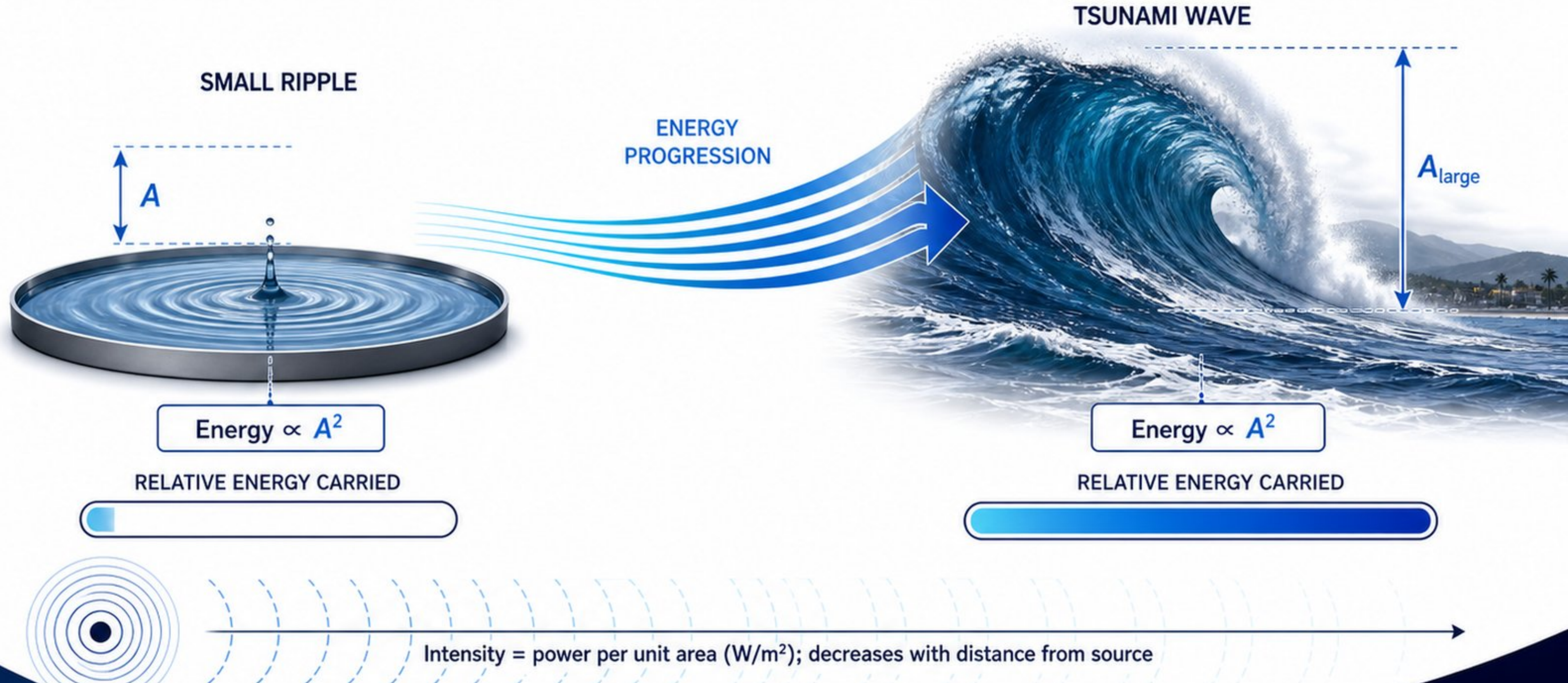
Applying the Wave Equation: Practice and Insights



- Rearrange $v = f\lambda$ to solve for frequency ($f = v/\lambda$) or wavelength ($\lambda = v/f$)
- Ocean wave: frequency 0.5 Hz, wavelength 4 m → speed = 2 m/s
- Radio wave: frequency 100 MHz, speed $c \rightarrow \lambda \approx 3$ m
- Same medium, same speed: higher frequency means shorter wavelength
- Wave speed changes when the medium changes (faster in water than air)

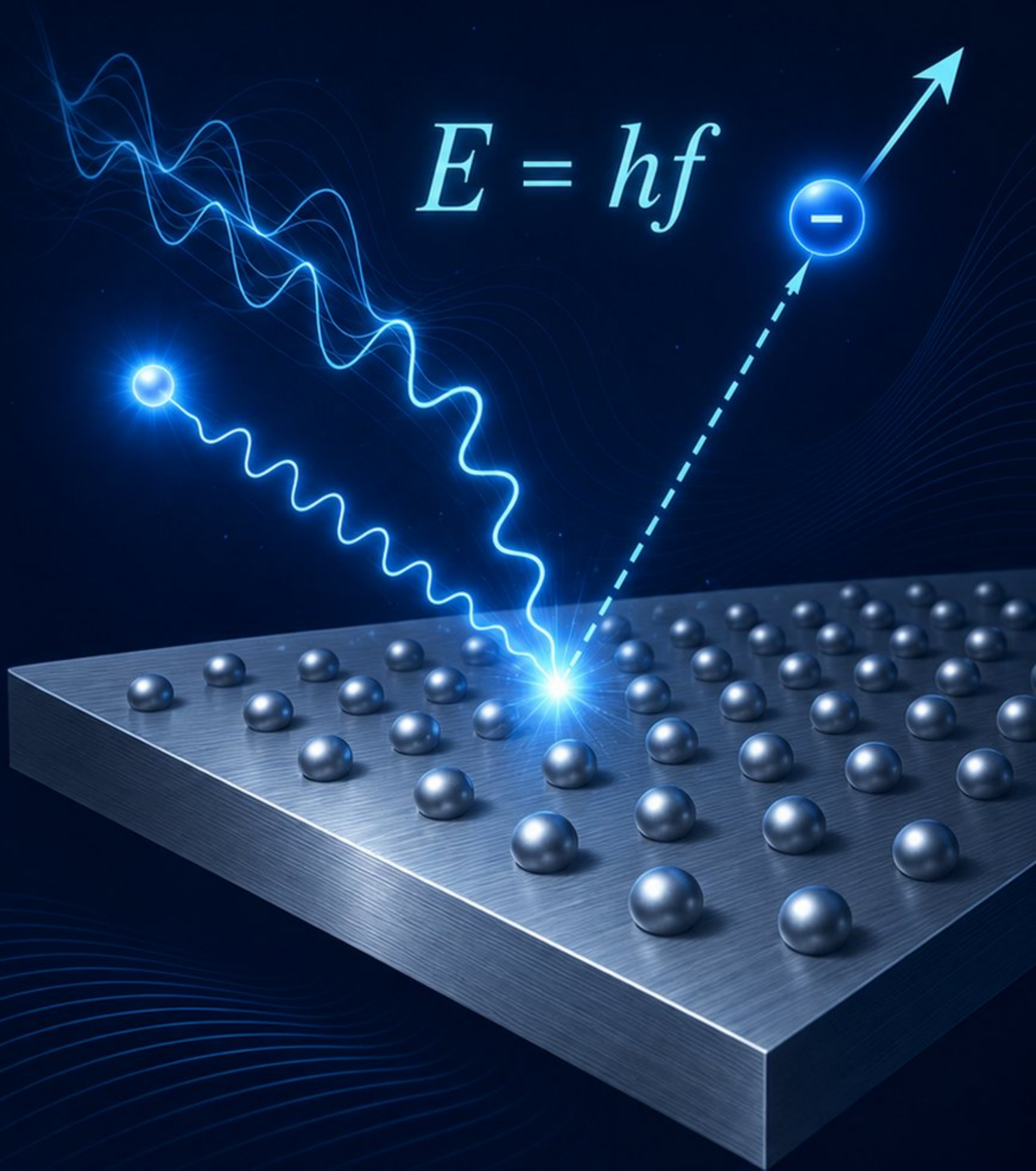
Energy in Waves: Amplitude and Intensity

- Waves transport energy, not matter; energy transfer rate is power
- Mechanical wave energy $\propto$ (amplitude)^2 and depends on frequency^2
- Doubling amplitude quadruples the energy carried by the wave
- Intensity = power per unit area (W/m^2); decreases with distance from source

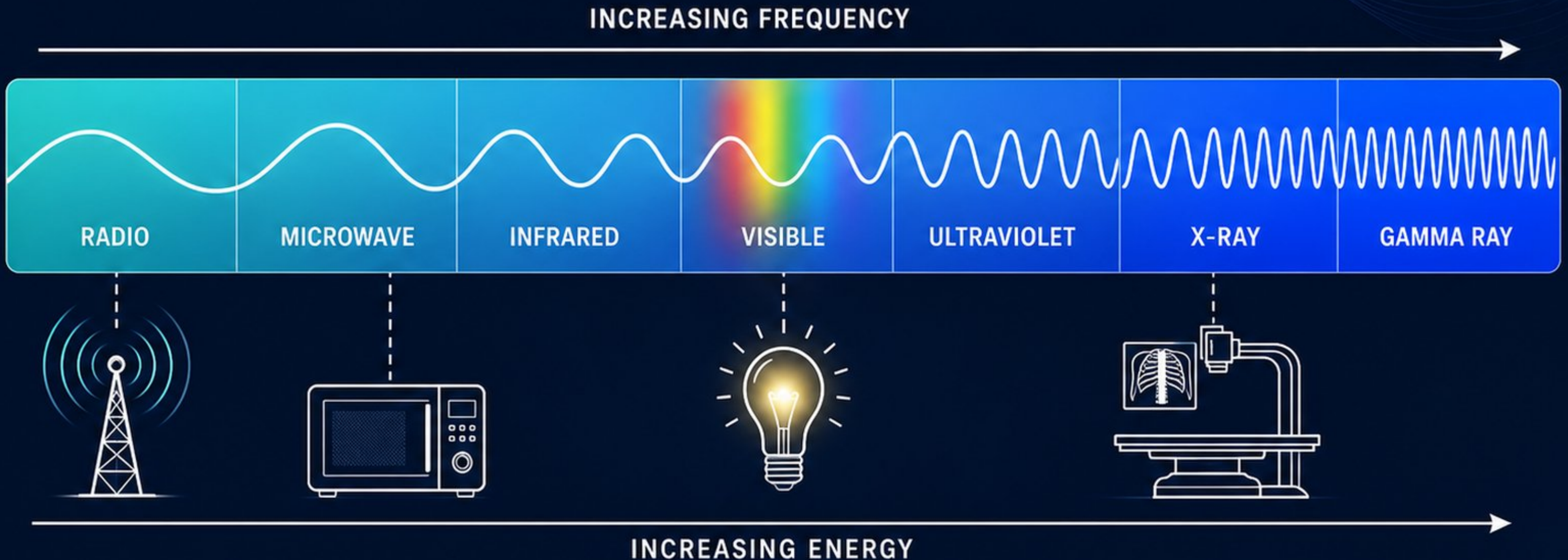


Photon Energy and the Electromagnetic Wave

- EM wave energy can be described at the photon level using Planck's relation: $E = hf$
- High-frequency waves (X-rays, gamma rays) carry more energy per photon
- Classical wave energy depends on amplitude squared; photon energy depends on frequency
- This dual description is essential for understanding the photoelectric effect



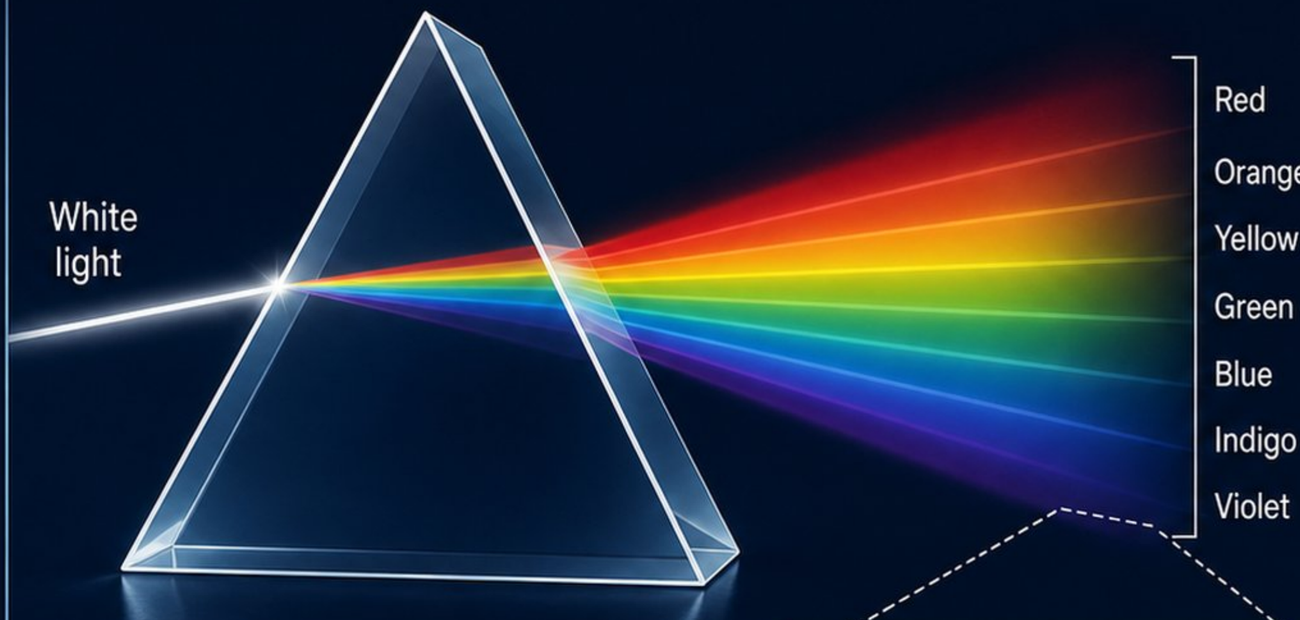
The Electromagnetic Spectrum

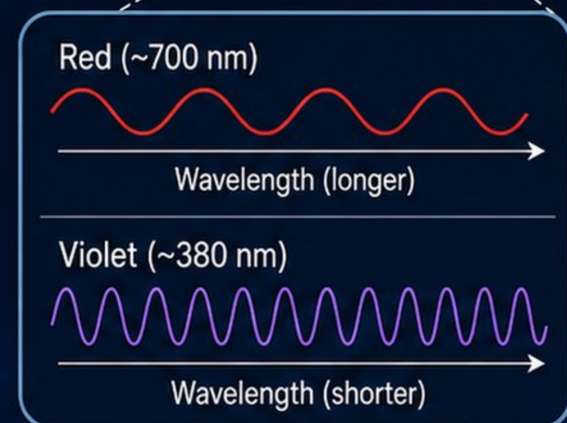


- Light is a transverse EM wave traveling at $c = 3.00 \times 10^8$ m/s in vacuum
- Spectrum ordered by increasing frequency: radio, microwave, infrared, visible, ultraviolet, X-ray, gamma ray
- As frequency increases, wavelength decreases; photon energy ($E = hf$) increases
- Real-world bands: radio for broadcasting, microwaves for Wi-Fi, X-rays for medical imaging

Visible Light: Color, Frequency, and Wavelength

- Visible spectrum spans roughly 380–750 nm
- ROYGBIV: red lowest frequency, violet highest frequency
- Blue light (~475 nm) carries more photon energy than red (~700 nm)
- Color perception links frequency to hue
- Prisms separate white light by wavelength





Connecting to Sound Waves

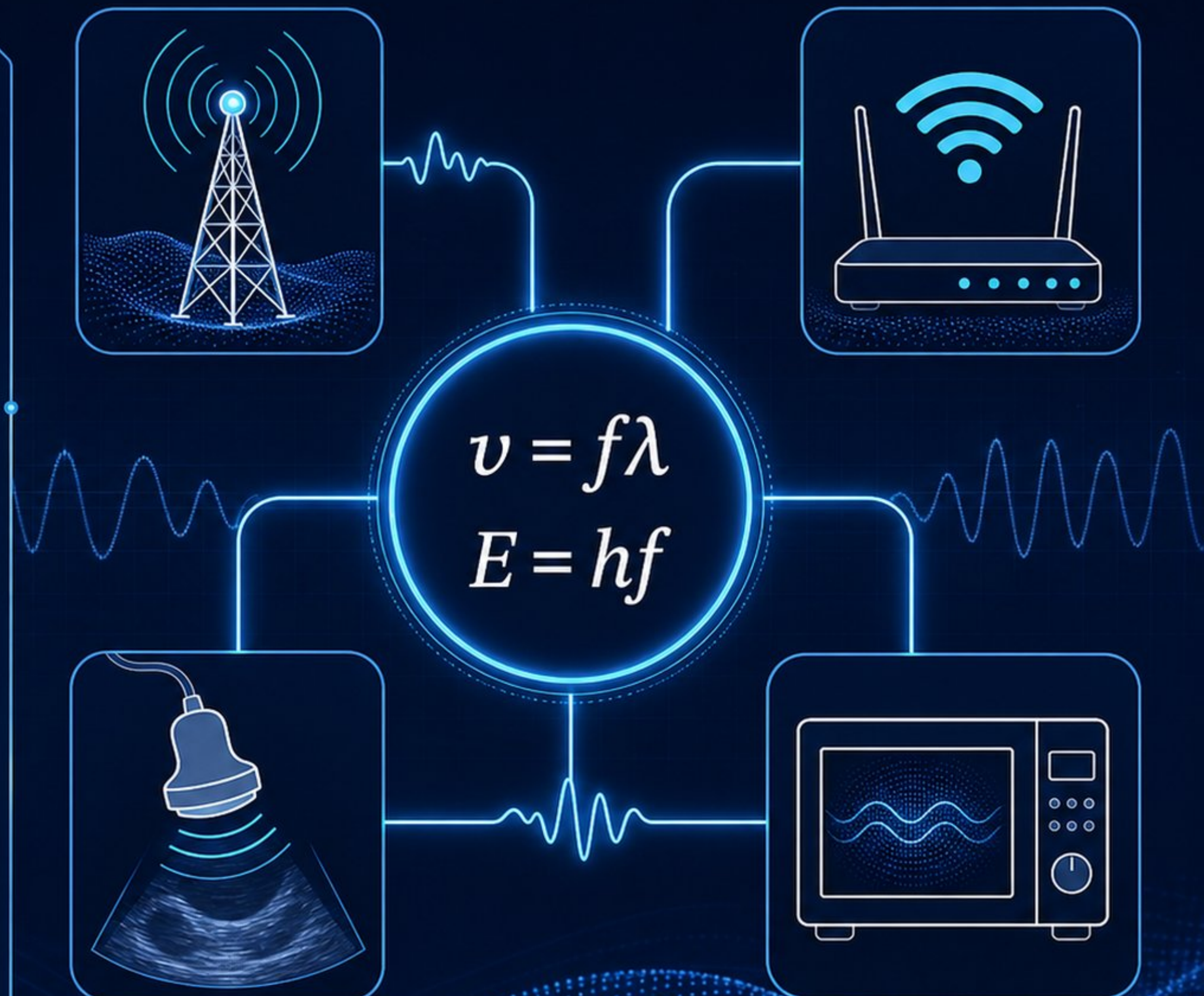
- Sound is a longitudinal mechanical wave requiring a medium
- Pitch corresponds to frequency; loudness corresponds to amplitude
- $v = f\lambda$ in air: 343 m/s → Middle C (262 Hz) yields $\lambda \approx 1.31$ m
- Same wave model underpins acoustics, instruments, and ultrasound

Connecting to Light and Optics

- Light is an electromagnetic wave; travels through vacuum, unlike sound
- Color perception links to frequency/wavelength in the visible spectrum
- Higher frequency = higher photon energy ($E = hf$)
- Photon energy explains the photoelectric effect
- Wave model underlies reflection, refraction, and diffraction study

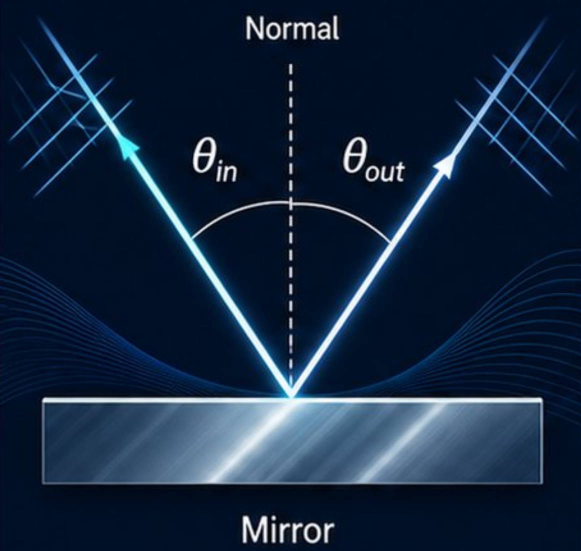
Practical Applications and Technology

- Radio, Wi-Fi, and fiber optics rely on different EM bands
- Ultrasound uses high-frequency sound for medical imaging
- X-rays and gamma rays treat cancer and scan bones
- Microwave ovens absorb energy at specific frequencies
- The same core equations apply to all wave types

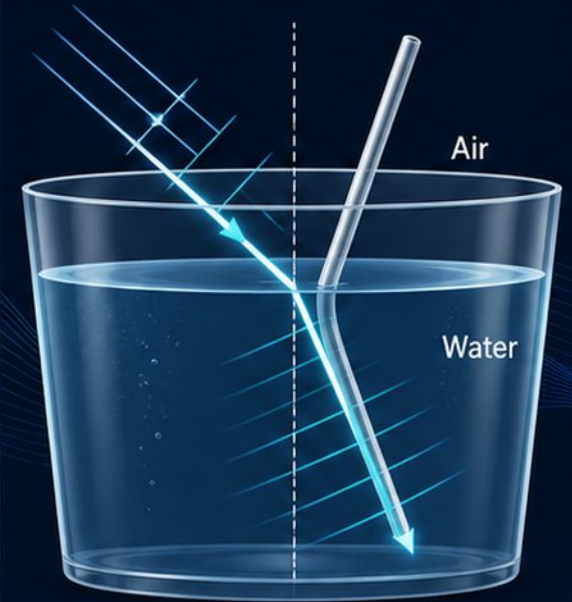


Wave Behavior Preview: Reflection, Refraction, and Diffraction

REFLECTION



REFRACTION



DIFFRACTION

- "Waves reflect off surfaces with angle in equal to angle out"
- "Refraction bends waves when speed changes in a new medium"
- "Diffraction spreads waves through openings or around obstacles"

- "These behaviors underpin sonar, lenses, and resolution limits"

Summary and Core Relationships

- Frequency (f), wavelength (λ), and energy (E) are the three central wave pillars
- $v = f\lambda$ applies to all waves; $E = hf$ describes photon energy for EM waves
- For a given speed, higher frequency means shorter wavelength
- Higher EM frequency means higher photon energy
- This model underpins sound, optics, and the EM spectrum

Check Your Understanding

- If frequency doubles, wavelength halves (medium unchanged)
- Sound wave: $f = 500$ Hz, $v = 340$ m/s → $\lambda = 0.68$ m
- Identify a real-world wave and its f, λ, energy traits
- Self-check: review reasoning and correct misconceptions