

1.10. Waves

ma07 - Schallwellen in Festkörpern

Why do we get different pitches?



⇒ **Study waves**

- Waves describe transport in **matter, fields, and even spacetime**, with or without a medium
- **Energy, information, and structure** propagate without net matter flow
- The same wave concepts apply from **sound and light to seismic, and gravitational waves as well as biological (neural) dynamics**

What Is a Wave?

ms25 - Gekoppelte Pendel & Julius

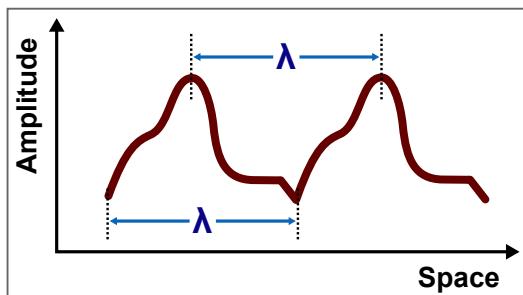
- A **wave** is a disturbance that propagates through **coupled oscillators**
- Each element oscillates about an **equilibrium position**
- Neighboring elements interact via **restoring forces**
- Energy is transferred **locally from oscillator to oscillator**
- **No net transport of matter** along the medium
- The wave emerges from **collective motion**, not a single particle

Important Characteristics of Waves

- **Amplitude A :** maximum displacement → energy content
- **Wavelength λ :** distance between points in the same phase
- **Frequency f :** oscillations per second (Hz)
- **Period T :** time for one oscillation, $T = 1/f$
- **Wave speed v :** speed of propagation of the disturbance
- Fundamental relation:

$$v = f\lambda = \frac{\lambda}{T}$$

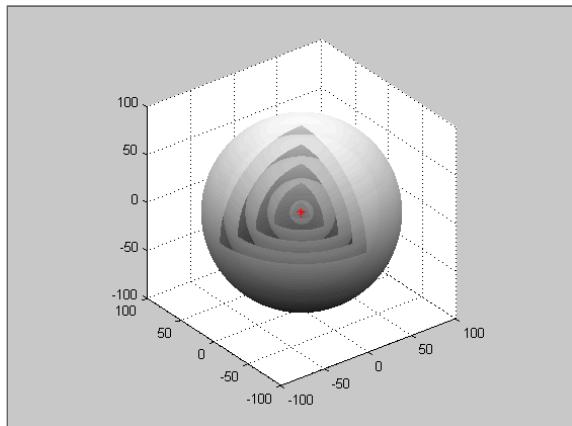
- **Frequency set by the source; wavelength adapts to the medium**

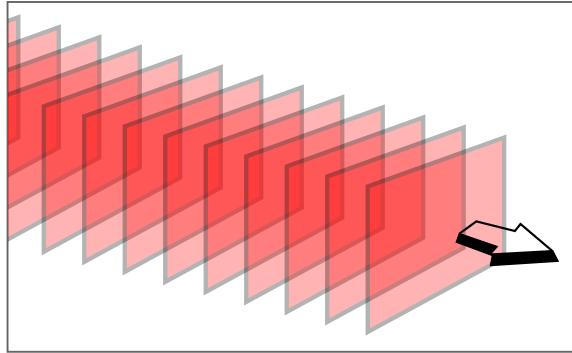


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Beyond 1D: Plane Waves & Spherical Waves

- **Wavefront:** a surface connecting points that oscillate with the same phase
- **Spherical waves:**
 - Originate from a **point source**
 - Wavefronts are expanding spheres
- **Plane waves:**
 - Parallel wavefronts
 - Uniform phase and amplitude across each front
 - Good approximation far from the source



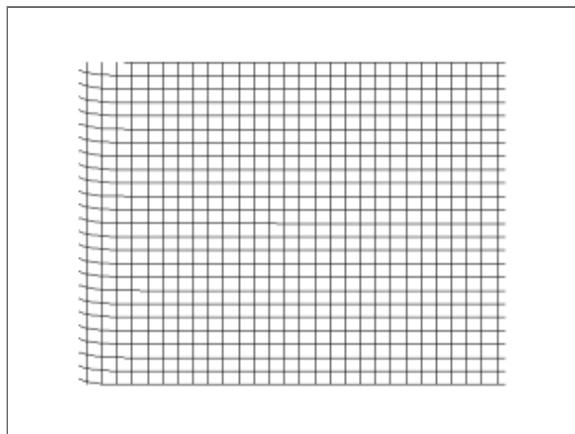


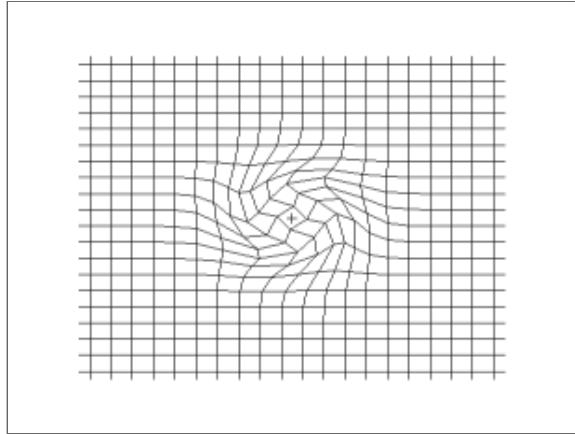
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Transverse Waves

ms22 - robe

- Particle oscillation **perpendicular** to direction of propagation
- Characterized by **crests** and **troughs**
- Examples:
 - Waves on strings or ropes
 - Water surface waves
 - Electromagnetic waves



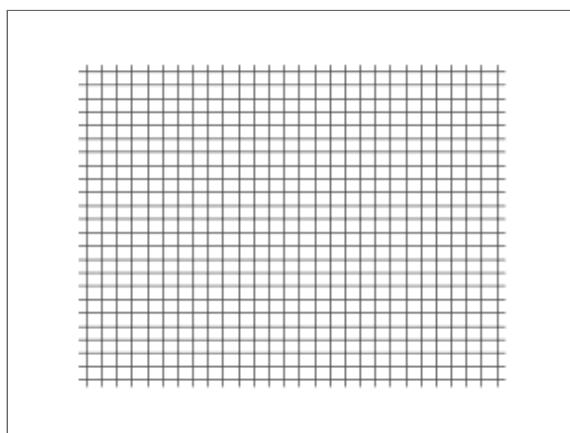


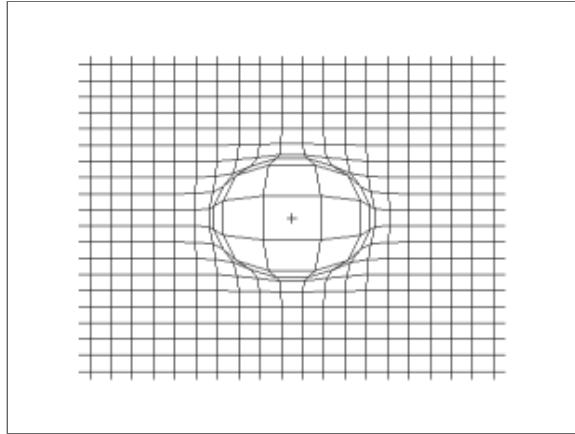
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Longitudinal Waves

ms36 - Demonstration einer Longitudinalwelle

- Particle oscillation **parallel** to direction of propagation
- Wave consists of **compressions** and **rarefactions**, no crests or troughs
- Requires a **compressible medium**
- Examples:
 - Sound waves in air
 - Compression waves in springs
 - Seismic P-waves





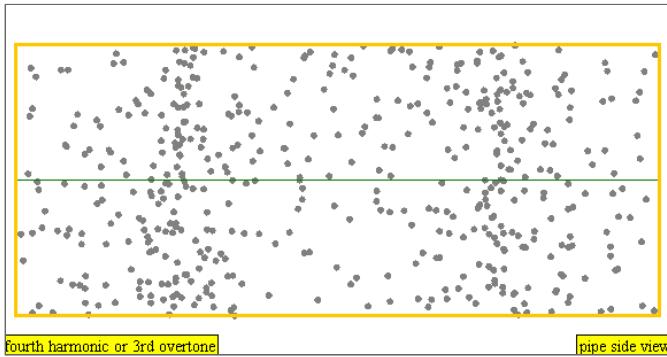
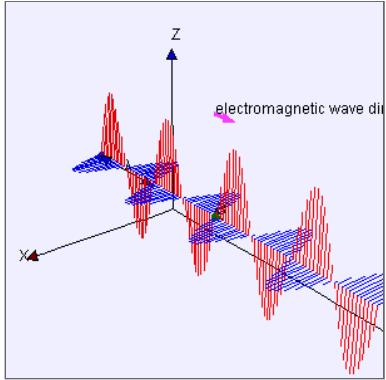
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Transverse vs. Longitudinal Waves — Summary

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Wave type	Particle motion relative to propagation	Characteristic features	Medium requirement
Transverse wave	Perpendicular to propagation direction	Crests and troughs	Can occur with or without a medium
Longitudinal wave	Parallel to propagation direction	Compressions and rarefactions	Requires a compressible medium

In both cases, **energy propagates through the medium while matter oscillates locally** about equilibrium positions.



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Wave kinematics: Spatial and Temporal Structure

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- One-dimensional wave: $D = D(x, t)$
- Spatial profile at fixed time:

$$D(x) = A \sin\left(\frac{2\pi}{\lambda}x\right)$$

Wave kinematics: Spatial and Temporal Structure (cont')

sim - Wave function

- Wave translation with speed v :

$$D(x, t) = A \sin\left(\frac{2\pi}{\lambda}(x - vt)\right)$$

- Relations for phase velocity v , wave number k & angular frequency ω

$$v = \lambda f, \quad k = \frac{2\pi}{\lambda}, \quad \omega = 2\pi f$$

- **Standard traveling-wave form:**

$$D(x, t) = A \sin\left(\frac{2\pi}{\lambda}(x - \lambda \frac{\omega}{2\pi} t)\right) = A \sin(kx - \omega t)$$

Wave kinematics: Wave Parameters and Direction

ms04 - Alter Schwingungsapparat

- **Standard traveling-wave form:**

$$D(x, t) = A \sin(kx - \omega t)$$

- Phase:

$$\phi = kx - \omega t$$

- Phase velocity:

$$v = \lambda f = \frac{2\pi}{k} \frac{\omega}{2\pi} = \frac{\omega}{k}$$

- Wave traveling in $-x$ direction:

$$D(x,t)=A\sin(kx+\omega t)$$

The Wave Equation — Motivation and 1D Form

- From **wave function** $y(x, t)$ → to **dynamics**
- *Which equation governs wave propagation in time and space?* ⇒ **wave equation**
- Example: sinusoidal traveling wave

$$y(x, t) = A \sin(kx - \omega t), \quad v = \frac{\omega}{k}$$

- Second derivatives:

$$\frac{\partial^2 y}{\partial x^2} = -k^2 A \sin(kx - \omega t) = -k^2 y, \quad \frac{\partial^2 y}{\partial t^2} = -\omega^2 A \sin(kx - \omega t) = -\omega^2 y$$

- Rearrange gives the **one-dimensional wave equation**

$$\frac{1}{-k^2} \frac{\partial^2 y}{\partial x^2} = \frac{1}{-\omega^2} \frac{\partial^2 y}{\partial t^2} \Rightarrow \boxed{\frac{\partial^2 y}{\partial x^2} = \frac{1}{v^2} \frac{\partial^2 y}{\partial t^2}}$$

Generality, Physical Meaning, and 3D Form

- Valid for **any waveform**, not only sinusoidal:

$$y(x, t) = f(x - vt), \quad y(x, t) = f(x + vt)$$

- **Physical meaning**
 - $\partial^2 y / \partial x^2$: spatial curvature
 - $\partial^2 y / \partial t^2$: particle acceleration
- **Three-dimensional wave equation**

$$\boxed{\nabla^2 \psi = \frac{1}{v^2} \frac{\partial^2 \psi}{\partial t^2}}$$

- Laplacian:

$$\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$$

- Governs sound, water waves, strings, and electromagnetic waves

Energy Transport by a Traveling Wave

- **Instantaneous energy (per string element):**

$$dE = dK + dU = \mu A^2 \omega^2 \cos^2(kx - \omega t) dx$$

(energy oscillates between kinetic and potential forms)

- **Time-averaged energy per unit length:**

$$\frac{dE_{\text{avg}}}{dx} = \frac{1}{2} \mu A^2 \omega^2$$

(using $\langle \cos^2 \rangle = \frac{1}{2}$ over one period)

- **Average power transported by the wave:**

$$P = \frac{dE}{dt} = \frac{dE_{\text{avg}}}{dx} v = \frac{1}{2} \mu A^2 \omega^2 v$$

(wave speed v converts energy per length into energy per time; $P \propto A^2$)

Intensity of a Spherical Wave

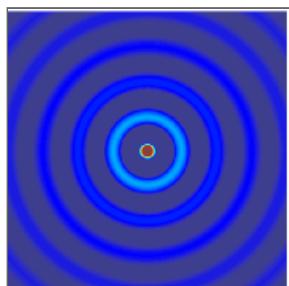
- Assume a **point source** → **spherical wave**
- Total power P spreads over spherical wavefront

$$A_{\text{cross}}(r) = 4\pi r^2$$

- **Intensity** (*power per area* or *energy per time per area*):

$$I(r) = \frac{P}{A_{\text{cross}}} = \frac{P}{4\pi r^2}$$

- Energy is conserved, **but** intensity decreases with distance due to **geometric spreading**



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Wave Reflection and Transmission at Boundaries

- **Boundaries** cause partial **reflection** and **transmission**
- Reflection and transmission depend on **medium properties** (wave speed, impedance)
- Boundaries impose **constraints** (fixed, free, or continuity conditions)
- Energy is **redistributed**, not lost: reflected + transmitted = incident
- Valid for **strings, sound, and light**
- (⇒ more details on wave phenomena in Physics II)

Reflection & Phase Change

ms22 - Rope for fixed and free end

Reflection from...	Equivalent situations	Reflected wave	Phase change	Physical interpretation
Higher impedance	Fixed end (string); $n_1 < n_2$ (light)	Inverted	180° phase shift	Boundary resists motion → displacement/field must reverse to satisfy constraints
Lower impedance	Free end (string); $n_1 > n_2$ (light)	Upright	No phase shift	Boundary conditions satisfied without sign reversal

Superposition

ms17 - Wasserwellengerät

ms24 - Wellenmaschine

$$\frac{\partial^2 D}{\partial x^2} = \frac{1}{v^2} \frac{\partial^2 D}{\partial t^2}$$

- **Superposition:** multiple waves overlap → total displacement = **sum of individual displacements**
- Wave equation's linearity implies that if D_1 and D_2 are solutions, then $D = aD_1 + bD_2$ is also a solution
- Overlapping waves do **not interact**: after overlap, each wave continues unchanged
- Superposition is the basis of **interference patterns, standing waves, and resonance**; it holds only for **small amplitudes** (linear restoring forces)



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Interference of Traveling Waves

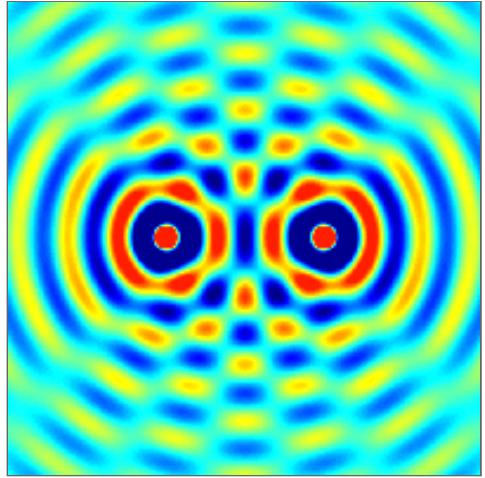
- **Interference** arises when **coherent** waves (i.e. constant phase relationship over time) overlap and superpose
- Resulting pattern depends on the **phase difference** ϕ
- For two equal-amplitude waves traveling in the same direction:

$$y_1 = A \sin(kx - \omega t), \quad y_2 = A \sin(kx - \omega t + \phi)$$

- Using $\sin \alpha + \sin \beta = 2 \sin\left(\frac{\alpha+\beta}{2}\right) \cos\left(\frac{\alpha-\beta}{2}\right)$:

$$y = 2A \cos\left(\frac{\phi}{2}\right) \sin\left(kx - \omega t + \frac{\phi}{2}\right)$$

- Amplitude depend on phase: $A_R = 2A \cos\left(\frac{\phi}{2}\right)$



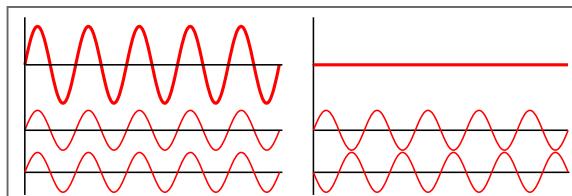
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Constructive and Destructive Interference

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- Stable interference patterns require **coherence** (same f , fixed ϕ)
- Energy is **redistributed**, not destroyed
- Phase difference often arises from path difference: $\phi = \frac{2\pi}{\lambda} \Delta x$

Interference type	Phase difference ϕ	Path difference Δx	Result
Constructive	$0, 2\pi, 4\pi, \dots$	$\Delta x = n\lambda$	Maximum amplitude
Destructive	$\pi, 3\pi, 5\pi, \dots$	$\Delta x = (n + \frac{1}{2})\lambda$	Cancellation



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Standing Waves: Mathematical Formation

ms22 - rope

- Arise from **superposition of two identical waves** traveling in opposite directions
- Incident and reflected waves:

$$y_1(x, t) = A \sin(kx - \omega t), \quad y_2(x, t) = A \sin(kx + \omega t)$$

- Using $\sin \alpha + \sin \beta = 2 \sin\left(\frac{\alpha+\beta}{2}\right) \cos\left(\frac{\alpha-\beta}{2}\right)$, resulting standing wave:

$$y(x, t) = 2A \sin(kx) \cos(\omega t)$$

- **Spatial factor** $\sin(kx)$ fixes the pattern, **temporal factor** $\cos(\omega t)$ sets the oscillation frequency

Standing Waves on a String and Resonance

- String of length L fixed at both ends:

$$y(0, t) = 0, \quad y(L, t) = 0$$

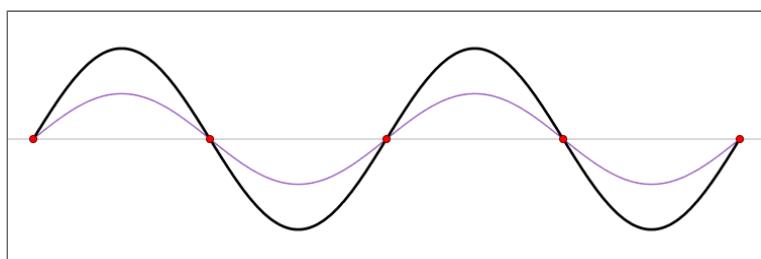
- Boundary condition:

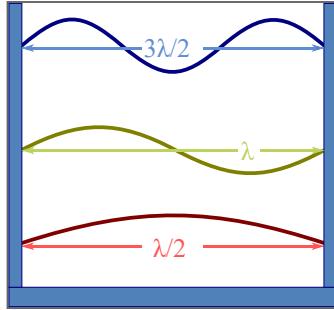
$$\sin(kL) = 0 \Rightarrow kL = n\pi$$

- Allowed wavelengths and frequencies with $k = \frac{2\pi}{\lambda}$ and $v = \lambda f$:

$$\lambda_n = \frac{2L}{n}, \quad f_n = \frac{nv}{2L}$$

- Discrete **normal modes** (harmonics), lowest is the **fundamental**





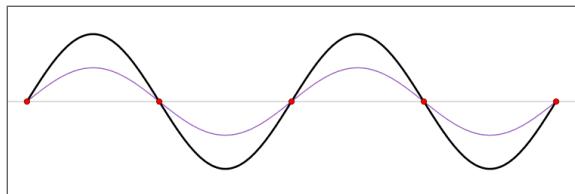
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Nodes, Antinodes, and Energy

$$y(x, t) = 2A \sin(kx) \cos(\omega t)$$

- All points oscillate with the same angular frequency ω (SHM)
- Position-dependent amplitude: $A(x) = 2A \sin(kx)$
- **Nodes:** $\sin(kx) = 0 \Rightarrow x_n = n\frac{\lambda}{2}$
 - Zero displacement and zero kinetic energy
 - Potential energy maximal
- **Antinodes:** $|\sin(kx)| = 1$
 - Maximum displacement amplitude
- **No net energy transport:** energy oscillates locally between kinetic and potential forms



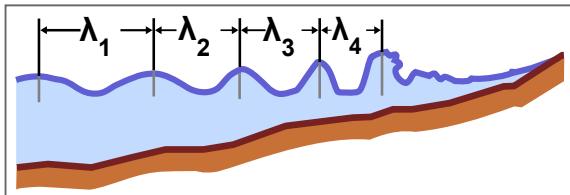
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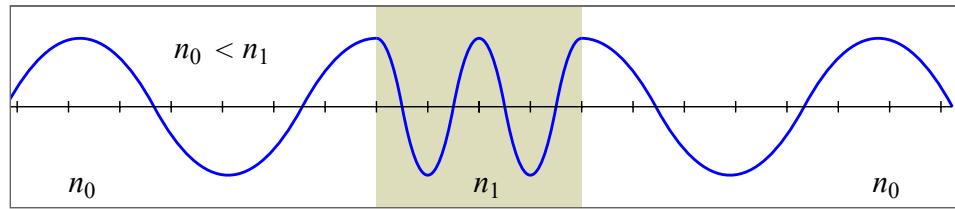
Wave Speed Variations: Refraction

- Wave behavior is controlled by the **wave speed** v , set by medium properties

$$v = \lambda f$$

- **Refraction** occurs when a wave enters a region with a different wave speed
- The **frequency remains constant** (set by the source)
- Changes in wave speed lead to changes in **wavelength** and **direction**
- Refraction occurs for mechanical waves, sound, seismic waves, and light





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Universal

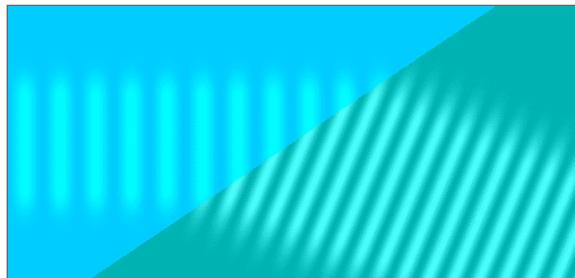
Wave Speed Variations: Refraction (cont')

- Wave speed, frequency, wavelength: $v = f\lambda$
- Frequency unchanged \Rightarrow wavelength adjusts at the boundary:

$$\frac{\lambda_1}{\lambda_2} = \frac{v_1}{v_2}$$

- Oblique incidence causes wavefront rotation
- Law of refraction for waves:

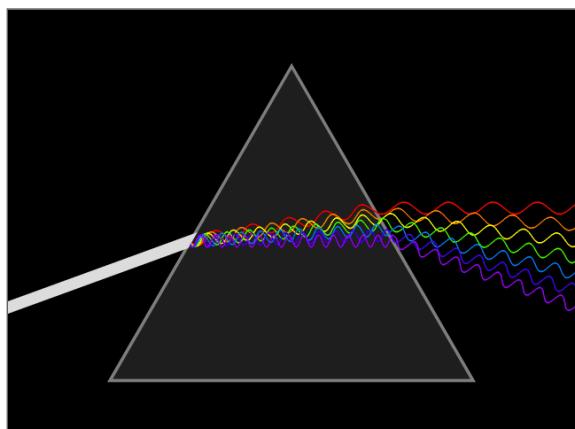
$$\frac{\sin \theta_1}{\sin \theta_2} = \frac{v_1}{v_2}$$



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Wave Speed Variations: Dispersion

- A medium is **dispersive** if **wave speed depends on frequency**
- Different frequency components propagate at different speeds
- **Refraction vs. dispersion:**
 - Both effects arise from **variations in wave speed**
 - **Refraction:** wave speed varies **in space** → change in wavelength and propagation direction
 - **Dispersion:** wave speed varies **with frequency** → separation of spectral components and waveform distortion

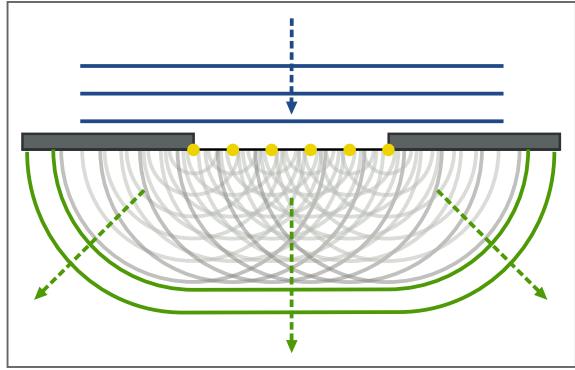


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Diffraction and Huygens' Principle

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- **Diffraction:** spreading/bending of waves at edges, apertures, or obstacles
- Strength of diffraction depends on **wavelength λ vs object size a**
 - $a \gg \lambda$: weak diffraction → nearly straight-line propagation
 - $a \sim \lambda$: strong diffraction → pronounced spreading
 - $a < \lambda$: wave spreads broadly, often nearly spherical
- Explained by **Huygens' principle**:
 - Every point on a wavefront acts as a source of secondary wavelets
 - New wavefront = envelope of these wavelets
- Explains sound bending around corners, fuzzy shadows, limits of resolution in optics and imaging



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Revisit initial experiment: Escapement,
oscillations, & clocks

ma07 - Schallwellen in Festkörpern

Why do we get different pitches?

- longitudinal and transversal wave generated depending on how *excited*
- → compression vs. vibration

