PHYSICAL SENSORS FOR ENVIRONMENTAL SIGNALS

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Master Degree in Artificial Intelligence for Science and Technology (AI4ST)

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OUTLINE OF THE COURSE

- Lecture 1: Introduction to environmental signals and physical sensors
- Lab 1: Introduction to instruments for measurements
- Lecture 2: Vibrations: sources and detection
- Lab 2: Characterisation of an acoustic system
- Lecture 3: Distance, position and speed measurement
- Lab 3: Measuring distance with ultrasounds and speed with an accelerometer
- Lecture 4: Electromagnetic radiation: sources and detection
- Lab 4: Detecting and generating light

SENSING THE ENVIRONMENT

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Sources

- Temperature
- Pressure
- Distance and position
- Speed
- Vibrations
- Acoustic
- Radiations: particles & light
- Chemical pollutants

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VIBRATIONS

Vibrations, a fundamental phenomenon in physics and engineering, manifest as oscillatory motions of objects around equilibrium positions.

The study of vibrations constitutes a significant branch of science, with far-reaching applications in diverse fields such as mechanical engineering, structural dynamics, acoustics, and materials science.

These oscillations can take various forms, encompassing mechanical vibrations in machinery, acoustic vibrations in sound waves, and even molecular vibrations in the microscopic world.

The understanding and manipulation of vibrational behavior are crucial for the design, optimization, and performance assessment of structures, systems, and devices. This scientific exploration involves a detailed analysis of factors like frequency, amplitude, and damping, as well as the dynamic interactions between components.

03-rao_cap1_fundamentals-of-vibrations

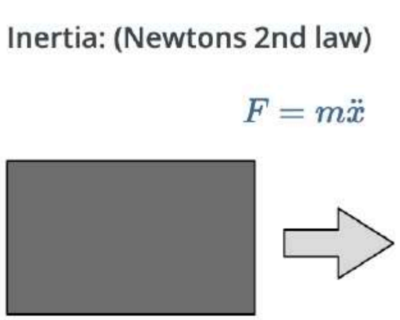
VIBRATIONS: SIMPLE HARMONIC OSCILLATOR

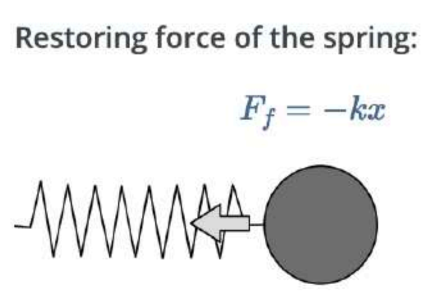
The most important example of vibration is *simple harmonic motion* (SHM).

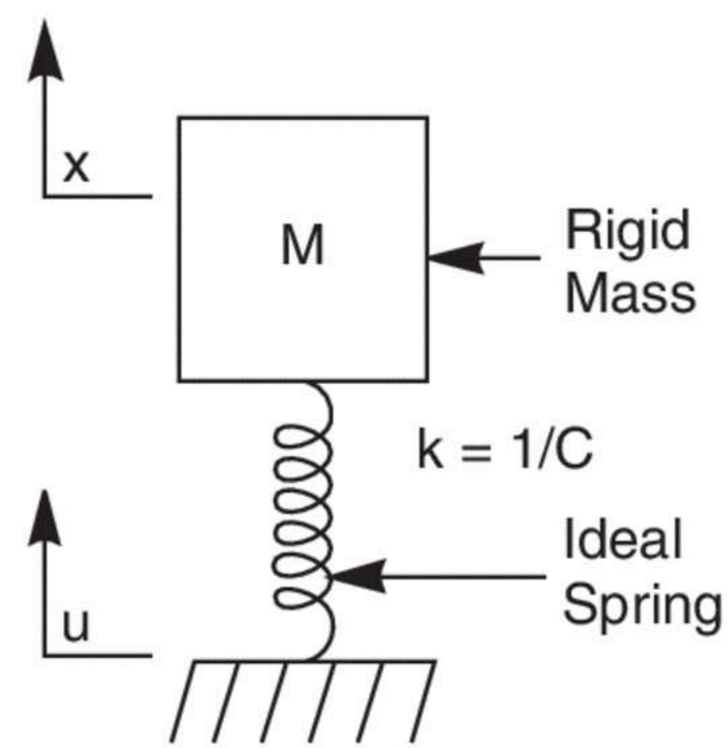
Simple Harmonic Motion (SHM) is a type of periodic motion that occurs when a restoring force proportional to the displacement acts on an object, pulling it back towards an equilibrium position. The motion is sinusoidal (can be represented by a sine or cosine function) and is characterized by its amplitude, frequency, and phase.

The Simple Harmonic Oscillator consists of a rigid mass M connected to an ideal linear spring

$$M\frac{\partial^2 x}{\partial t^2} + kx = 0 \qquad \omega_0 = \sqrt{\frac{k}{M}}$$







ω_0 = natural frequency of the system

VIBRATIONS: SIMPLE HARMONIC OSCILLATOR

The most important example of vibration is *simple harmonic motion* (SHM).

The general formula for simple harmonic motion is expressed as:

$$x(t) = A \cdot cos(\omega_0 t + \phi)$$

$$v(t) = -A \cdot \omega_0 \cdot sin(\omega_0 t + \phi)$$

$$a(t) = -A \cdot \omega_0^2 \cdot cos(\omega_0 t + \phi)$$

- $x(t)$ is the displacement of the object at time t,
- A is the amplitude (maximum displacement from equilibrium),
- ω is the angular frequency ($\omega = 2\pi f$, where f is the frequency),
- t is time,
- ϕ is the phase angle.

VIBRATIONS: SIMPLE HARMONIC OSCILLATOR

Free Vibration. If a system, after an initial disturbance, is left to vibrate on its own, the ensuing vibration is known as free vibration. No external force acts on the system. The oscillation of a simple pendulum is an example of free vibration.

Driven/Forced Vibration. If a system is subjected to an external force F(t) (often, a repeating type of force), the resulting vibration is known as forced vibration.

$$\frac{\partial^2 x}{\partial t^2} + \omega_0^2 x = F_0 cos(\omega t)$$

The general solution is the sum of two periodic functions, one with the natural frequency ω_0 and one with the frequency of the driving force ω

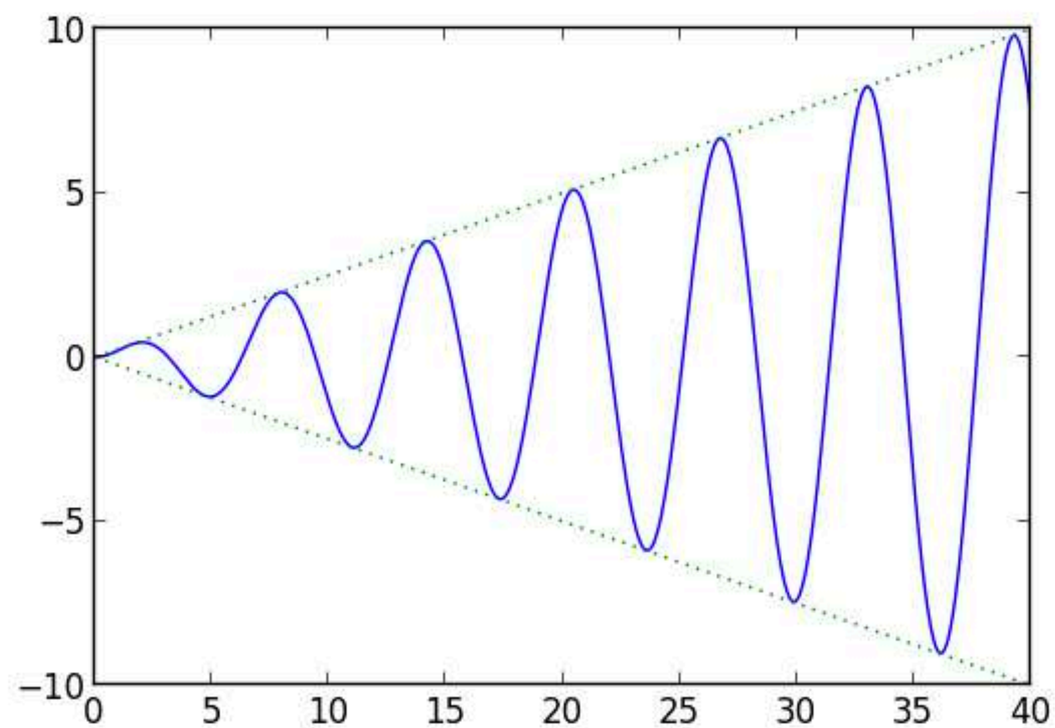
$$x(t) = A \cdot cos(\omega_0 t + \phi) + \frac{F_0}{M(\omega_0^2 - \omega^2)} \cdot cos(\omega t)$$

VIBRATIONS: SIMPLE HARMONIC OSCILLATOR

Driven vibration and resonance condition

If the frequency ω of the external force coincides with one of the natural frequencies of the system (ω_0), a condition known as **resonance** occurs, and the system undergoes dangerously large oscillations.

$$x(t) = \frac{F_0}{2M\omega} \cdot t \cdot sin(\omega t)$$



Failures of such structures as buildings, bridges, turbines, and airplane wings have been associated with the occurrence of resonance.

https://www.math.utah.edu/~gustafso/2250resonance.pdf

VIBRATIONS: SIMPLE HARMONIC OSCILLATOR

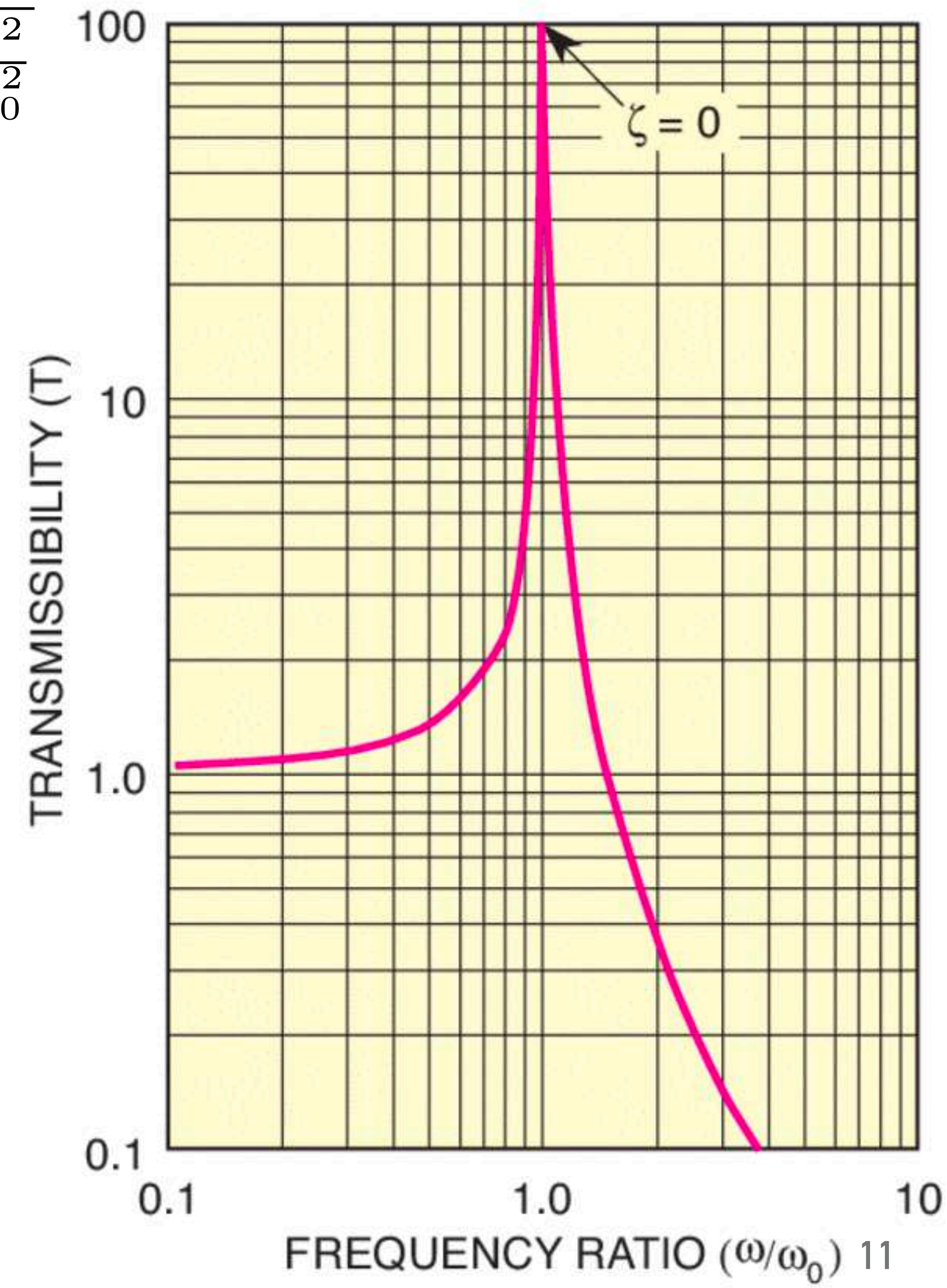
Driven vibration and resonance condition

Transmissibility is defined as the ratio of the force transmitted to the force applied.

$$T = \frac{1}{1 - \frac{\omega^2}{\omega_0^2}}$$

The three characteristic features of a driven harmonic oscillator system are:

1. For ω « ω0, well below the resonance frequency, T = 1, the motion of the mass is the same as the motion at the other end of the spring.
2. For ω ≈ ω0, near resonance, the motion of the spring end is amplified, and the motion of the mass lxl is greater than that of lul. For an undamped system, the motion of the mass becomes theoretically infinite for ω = ω0.
3. For ω » ω0, the displacement of the mass decreases in proportion to $1/\omega^2$. The displacement applied to the system is not transmitted to the mass. The spring acts as an isolator.



VIBRATIONS: SIMPLE HARMONIC OSCILLATOR

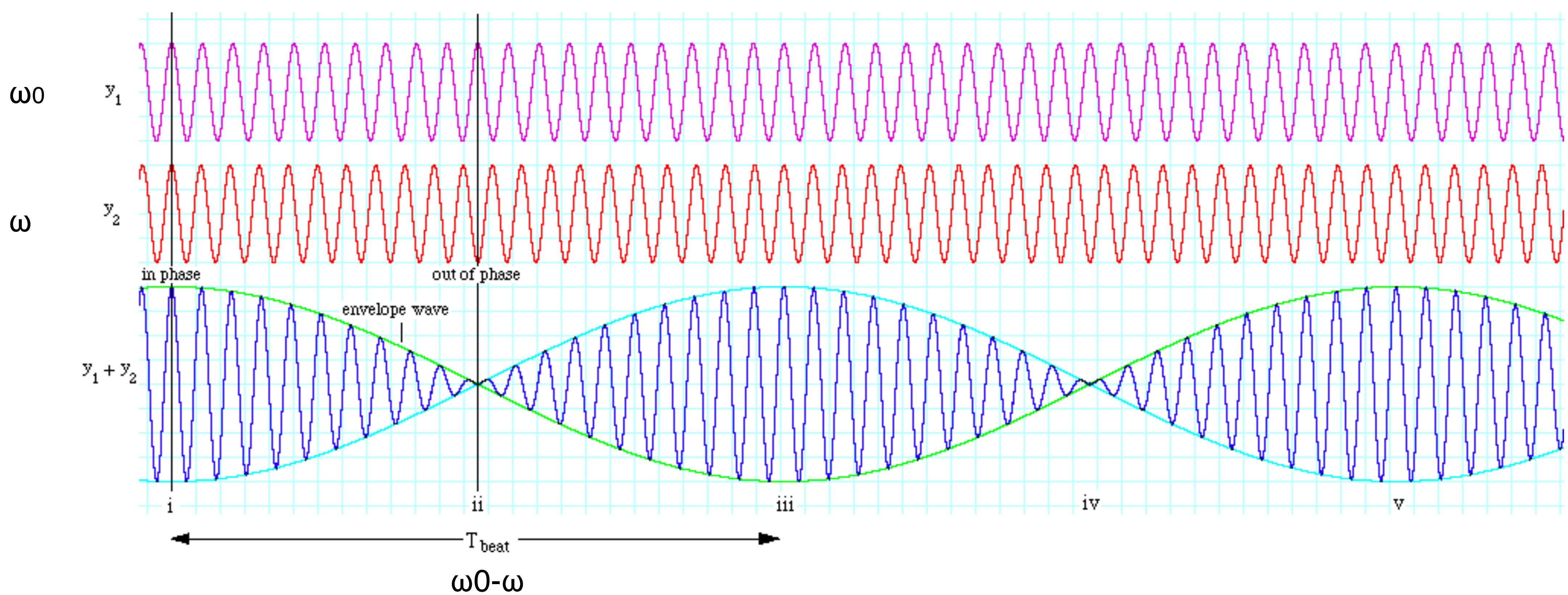
Driven vibration and beats condition

If the displacement starts at position 0 and with velocity 0, the solution is:

$$x(t) = \frac{F_0}{M(\omega_0^2 - \omega^2)} \cdot (cos(\omega t) - cos(\omega_0 t)) =$$

$$\frac{2F_0}{M(\omega_0^2 - \omega^2)} \cdot sin((\omega_0 - \omega)t/2) \cdot sin((\omega_0 + \omega)t/2)$$

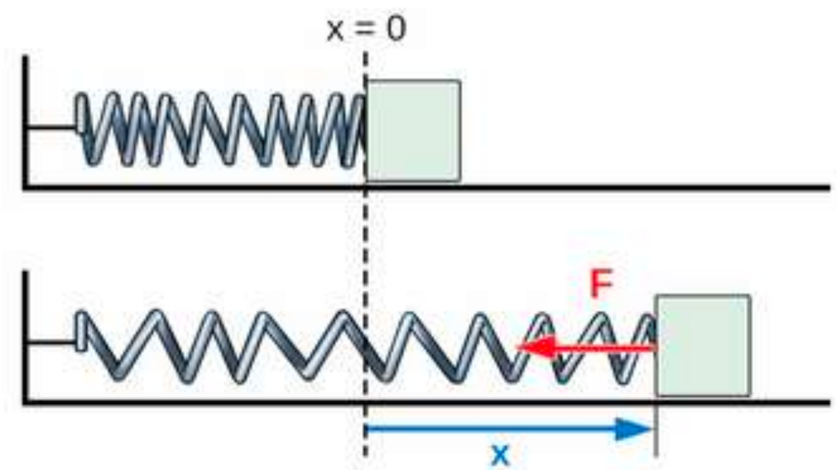
If the natural and driving frequencies are similar, i.e. |ω0 – ω| is small, then the first term is a low frequency factor multiplying the second high frequency term. This phenomena is known as **beats**.



VIBRATIONS: SIMPLE HARMONIC MOTION

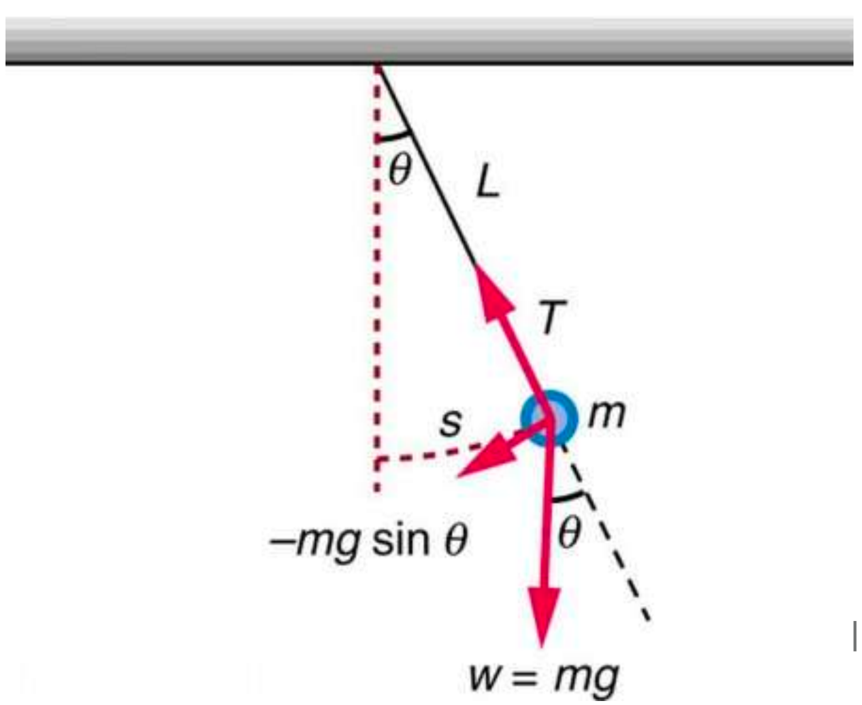
Here are a few examples of simple harmonic motion. The restoring force is proportional to the displacement, and the resulting motion follows the sinusoidal pattern characteristic of simple harmonic motion. The amplitude, frequency, and phase angle depend on the specific system and conditions.

1. Mass-Spring System:



Consider a mass attached to a spring. When the mass is displaced from its equilibrium position and released, it undergoes simple harmonic motion. The restoring force is provided by Hooke's Law F = -k x, where k is the spring constant.

2. Pendulum Motion:

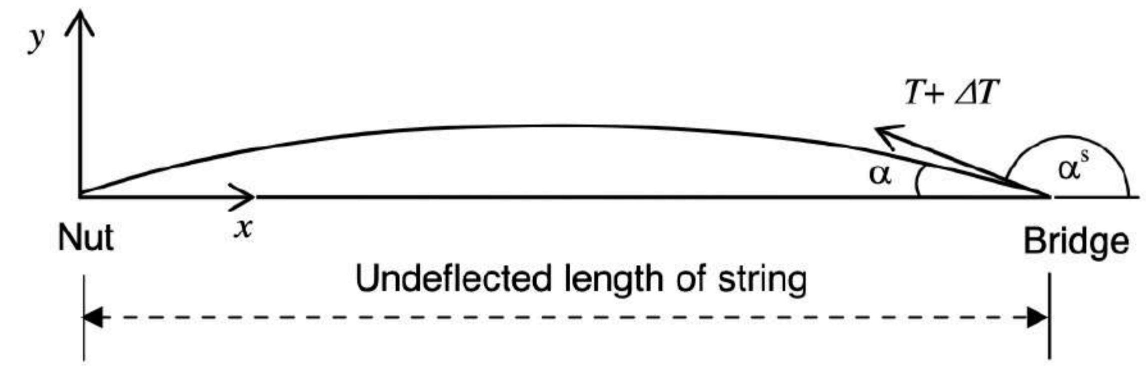


A simple pendulum, consisting of a mass attached to a string, exhibits simple harmonic motion when displaced from its vertical equilibrium position. For small angles, the motion can be approximated as simple harmonic, $F = -mg\sin\theta \approx -mg\theta$.

VIBRATIONS: SIMPLE HARMONIC MOTION

3. Vibrating Guitar/Violin String:

Plucking a tighten string causes it to vibrate with simple harmonic motion. The tension in the string provides the restoring force, and the length and mass of the string affect the frequency.



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4. Tuning Fork Vibration:

When a tuning fork is struck, its tines vibrate with simple harmonic motion. The restoring force is provided by the elasticity of the metal.

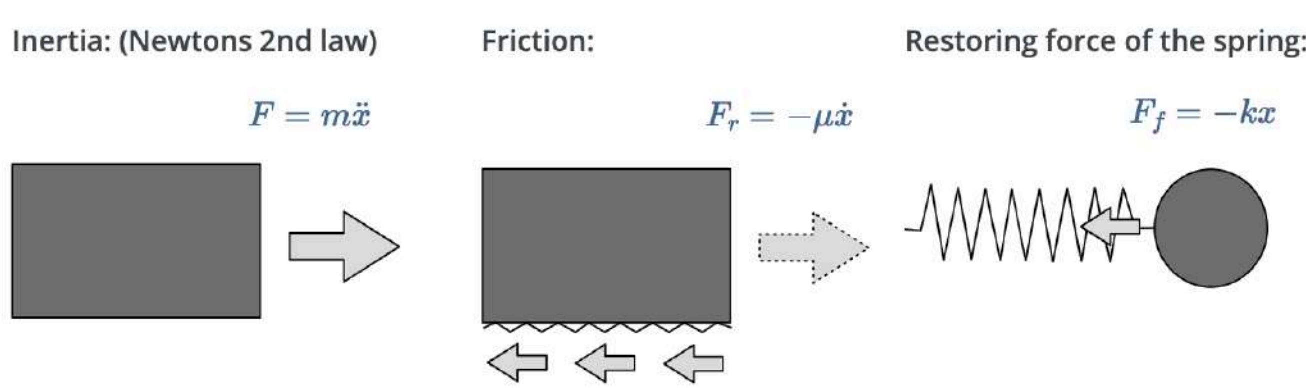
'LA' 440 Hz

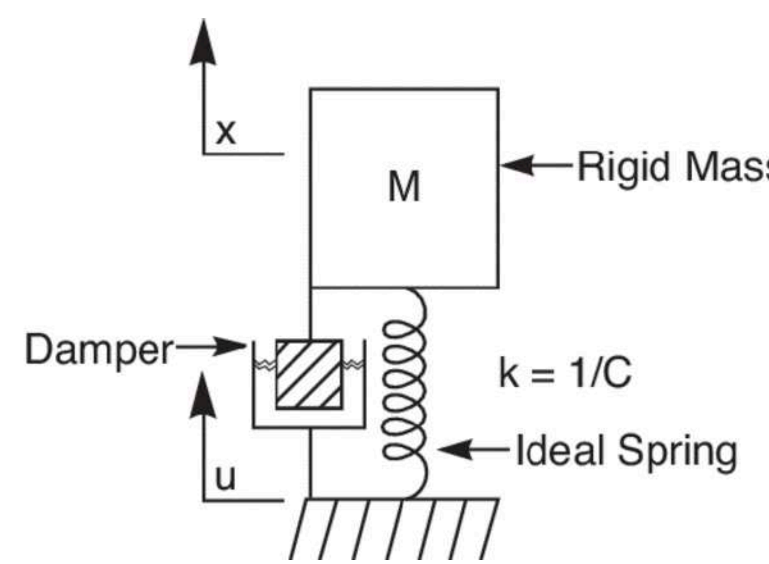
VIBRATIONS: DAMPED SIMPLE HARMONIC OSCILLATOR

If some mechanical energy is lost or dissipated in friction or other resistance during oscillation, the vibration is known as damped vibration. Damping refers to a mechanism that removes the mechanical energy from the system—very often as heat

A Damped Simple Harmonic Oscillator is shown schematically adding a rigidly connected damper to the ideal spring system. That is expressed mathematically by adding a damping term proportional to the velocity of the mass and to the differential equation describing the motion.

$$M\frac{\partial^2 x}{\partial t^2} + b\frac{\partial x}{\partial t} + kx = 0$$





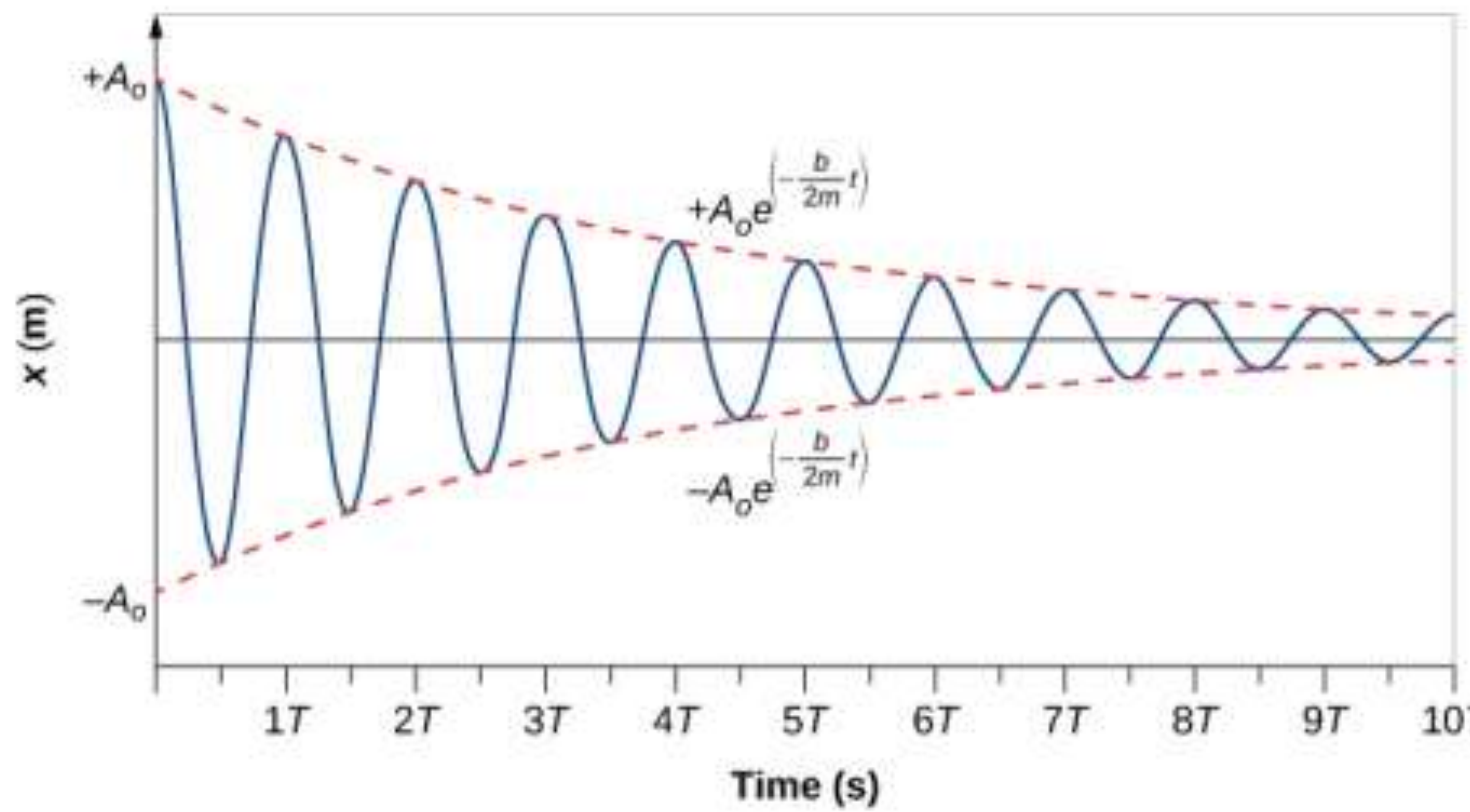
VIBRATIONS: DAMPED SIMPLE HARMONIC OSCILLATOR

A Damped Simple Harmonic Oscillator

The general formula for damped simple harmonic motion is expressed as:

$$x(t) = A_0 \cdot e^{-\frac{b}{2M}t} \cdot cos(\omega t + \phi)$$

$$\omega = \sqrt{\omega_0^2 - \frac{b^2}{(2M)^2}}$$



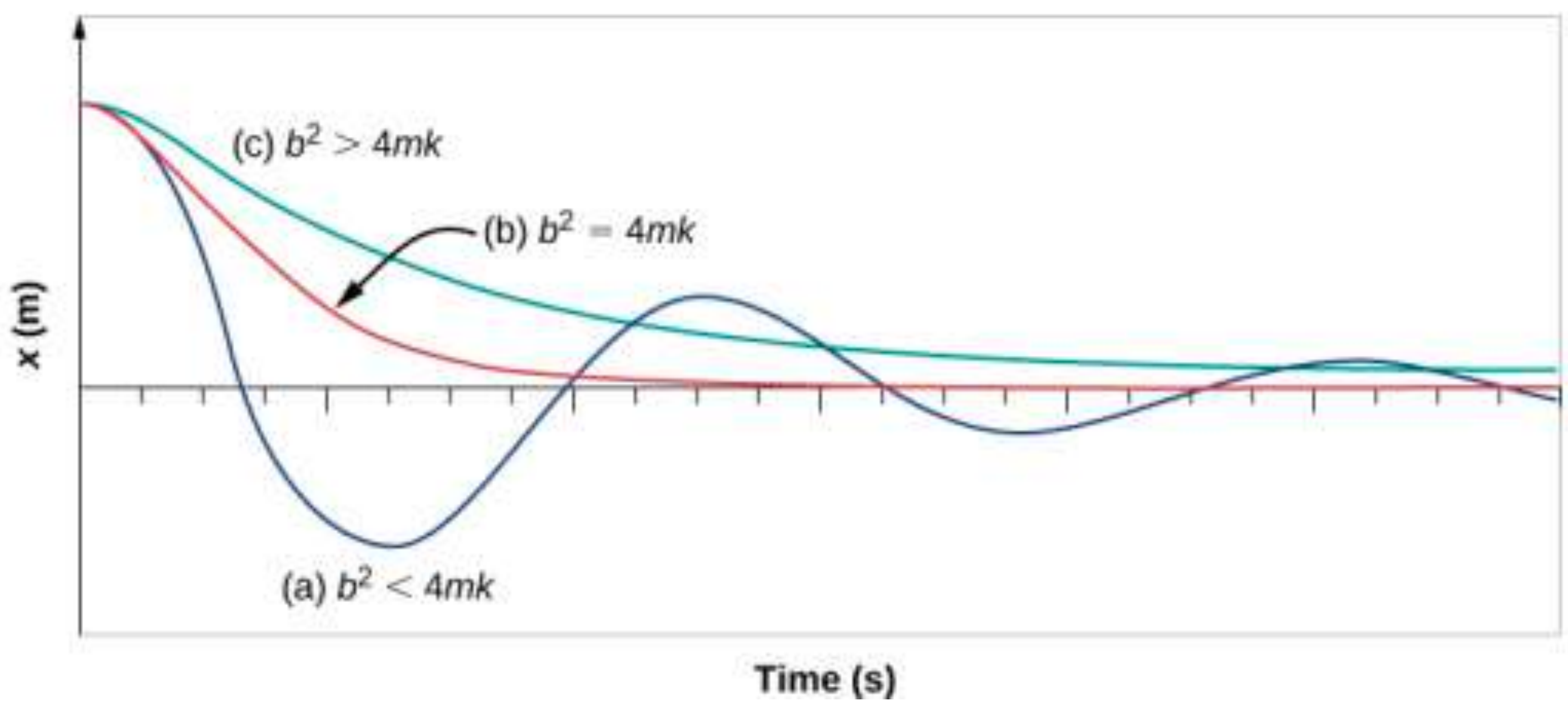
VIBRATIONS: DAMPED SIMPLE HARMONIC OSCILLATOR

A Damped Simple Harmonic Oscillator

1. Underdamped system: b < √ (4 M k), the system oscillates while the amplitude of the motion decays exponentially.

2. Critically damped system: b = √ (4 M k), the system does not oscillate, but asymptotically approaches the equilibrium condition as quickly as possible

3. Overdamped system: b > √ (4 M k), the system will approach equilibrium over a longer period of time



http://hyperphysics.phy-astr.gsu.edu/hbase/oscda.html

VIBRATIONS: DAMPED SIMPLE HARMONIC OSCILLATOR

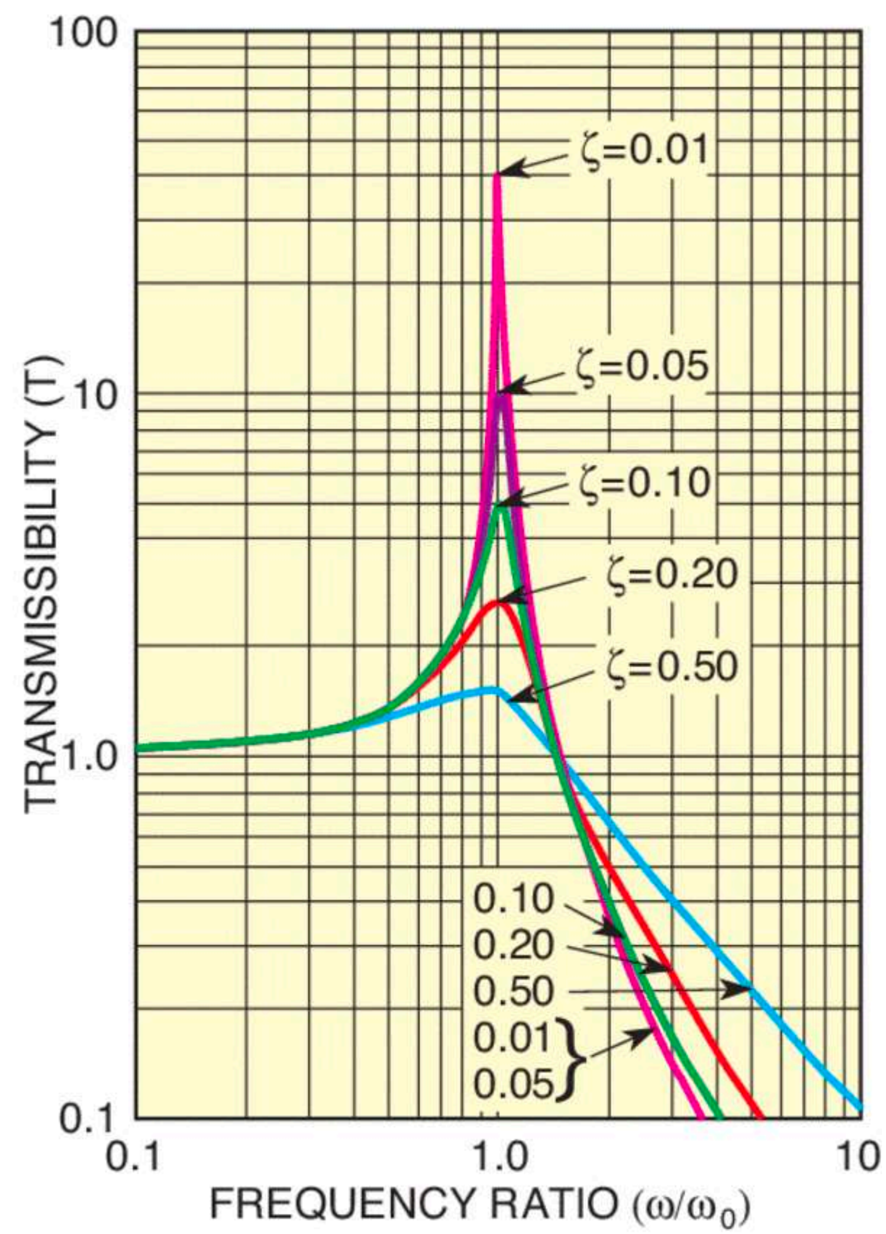
Driven vibration and resonance condition

The **widths** of the resonance curves depend on **damping**: the less the damping, the narrower the resonance.

- $b = \zeta \longrightarrow 0$, the curve becomes exactly the same as in the undamped case, infinite amplification at the resonance frequency ω_0.

- As the damping $b=\zeta$ increases, the amplitude at resonance decreases.

However, the “roll-off” at higher frequencies decreases (i.e. the transmissibility declines more slowly as damping increases). For $\omega/\omega_0 \gg 1/\zeta$, the motion of x is proportional to $1/\omega$



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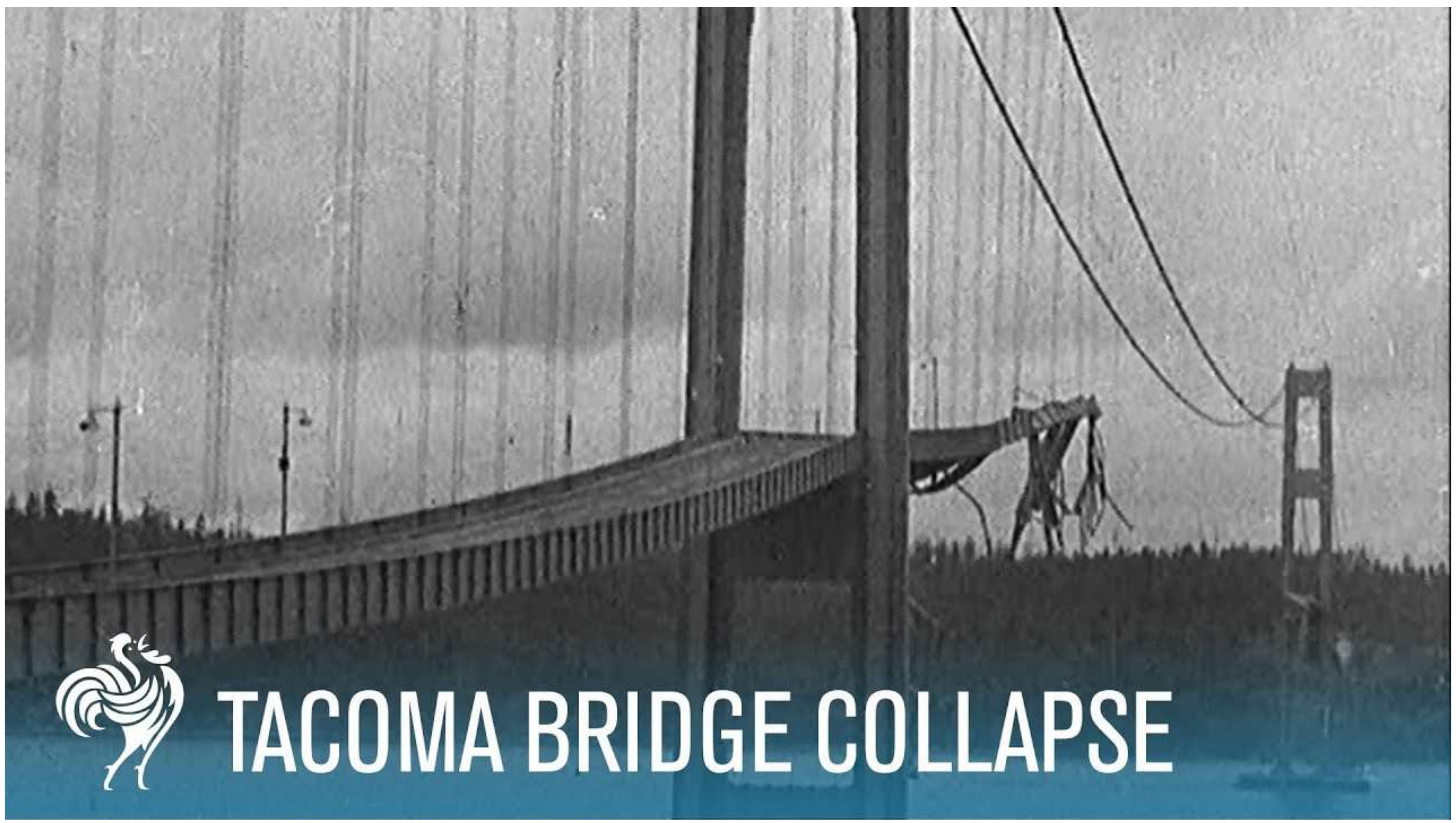
VIBRATIONS: DRIVEN VIBRATION AND RESONANCE

Failures of such structures as buildings, bridges, turbines, and airplane wings have been associated with the occurrence of resonance.



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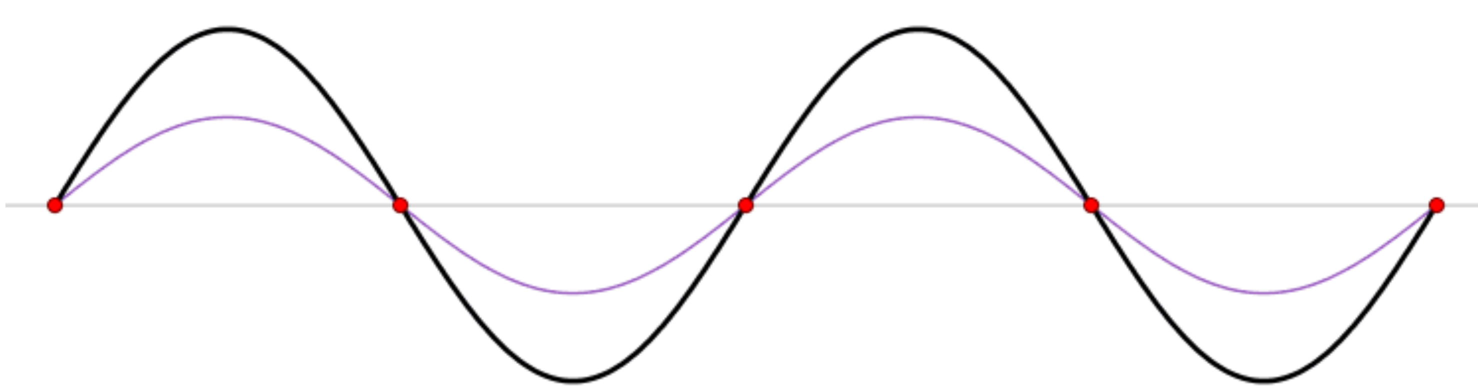
VIBRATIONS: STANDING WAVES

Standing waves result from the interference of two waves traveling in opposite directions within the same medium.

They form when the reflected waves to interfere constructively or destructively with the incident waves. The constructive and destructive interference creates specific points along the medium called nodes and antinodes. Unlike traveling waves that move through space, standing waves appear to be stationary, with specific points along the medium exhibiting minimal or no displacement.



A standing wave (black) depicted as the sum of two propagating waves traveling in opposite directions (red and blue). The red dots are the nodes of the stationary wave.

$$y_{\mathrm{R}}(x,t) = y_{\max} \sin\left(\frac{2\pi x}{\lambda} - \omega t\right)$$

$$y_{\mathrm{L}}(x,t) = y_{\max} \sin\left(\frac{2\pi x}{\lambda} + \omega t\right)$$

$$y(x,t) = y_{\mathrm{R}} + y_{\mathrm{L}}$$

$$y(x,t) = 2y_{\max} \sin\left(\frac{2\pi x}{\lambda}\right) \cos(\omega t)$$

VIBRATIONS: STANDING WAVES

Standing waves on a string with two fixed ends

Boundary conditions: $y = 0$ at $x = 0$ and $x = L$

Waves can only form standing waves on this string if they have a wavelength that satisfies

$$\lambda = \frac{2L}{n},$$

$$n = 1, 2, 3, \ldots$$

The standing wave with n = 1 oscillates at the fundamental frequency and has a wavelength that is twice the length of the string. Higher integer values of n correspond to modes of oscillation called harmonics or overtones.

VIBRATIONS: LONGITUDINAL AND TRANSVERSE WAVES

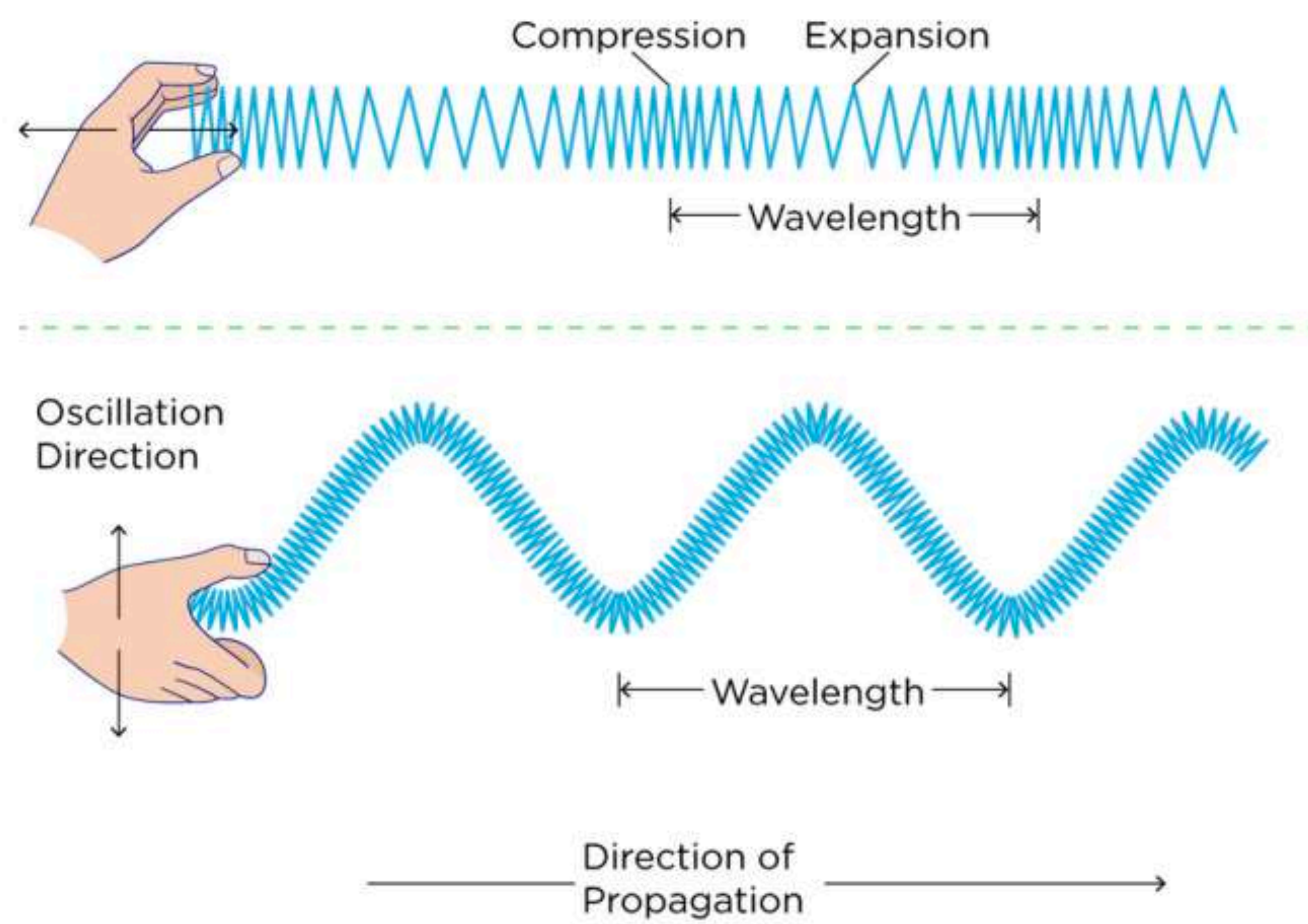
Longitudinal and transverse waves are two classifications of mechanical waves based on the direction of particle motion relative to the direction of wave propagation.

1. Longitudinal Waves:

In a longitudinal wave, the particles of the medium oscillate parallel to the direction of wave propagation.

The motion of particles occurs along the same axis as the wave travels, creating compressions (regions of high pressure or high density) and rarefactions (regions of low pressure or low density) in the medium.

Examples of longitudinal waves include sound waves in gases (like air), liquids, and solids.



2. Transverse Waves:

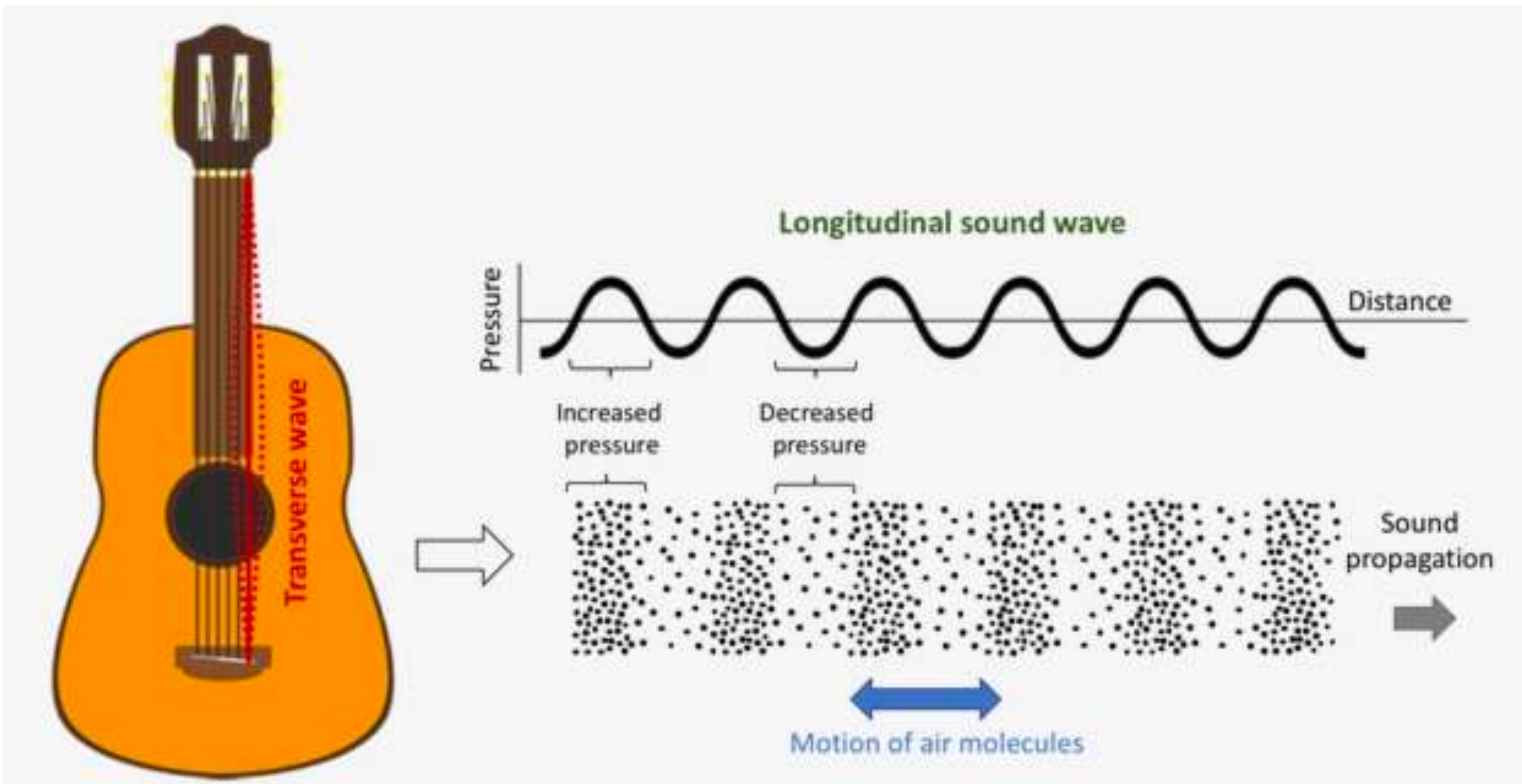
In a transverse wave, the particles of the medium oscillate perpendicular to the direction of wave propagation.

The motion of particles occurs perpendicular to the wave's direction, causing the medium to move up and down or side to side as the wave travels.

Examples of transverse waves include electromagnetic waves (like light waves) and waves on a string or a water surface.

VIBRATIONS: LONGITUDINAL AND TRANSVERSE WAVES

Acoustics



VIBRATIONS

Environmental vibrations refer to mechanical oscillations in the surroundings caused by natural or human-induced factors. Here's a list of examples of environmental vibrations:

Examples of **natural environmental vibrations**:

1. Seismic Vibrations:

Ground vibrations resulting from seismic activity, such as earthquakes or volcanic eruptions.

2. Tidal Vibrations:

Vibrations caused by tidal forces in bodies of water (sea/ocean/..), impacting coastal structures and environments

3. Wind-Induced Vibrations:

Vibrations in structures caused by the wind, especially in tall buildings, bridges, and towers.

VIBRATIONS

Examples of **anthropic environmental vibrations**:

4. Construction-Related Vibrations:

Vibrations generated during construction and foundation work operations, including pile driving, excavation, and heavy machinery operation.

5. Transportation Vibrations:

Vibrations generated by aboveground and underground trains, transportation systems and vehicular traffic.

6. Mining-Induced Vibrations:

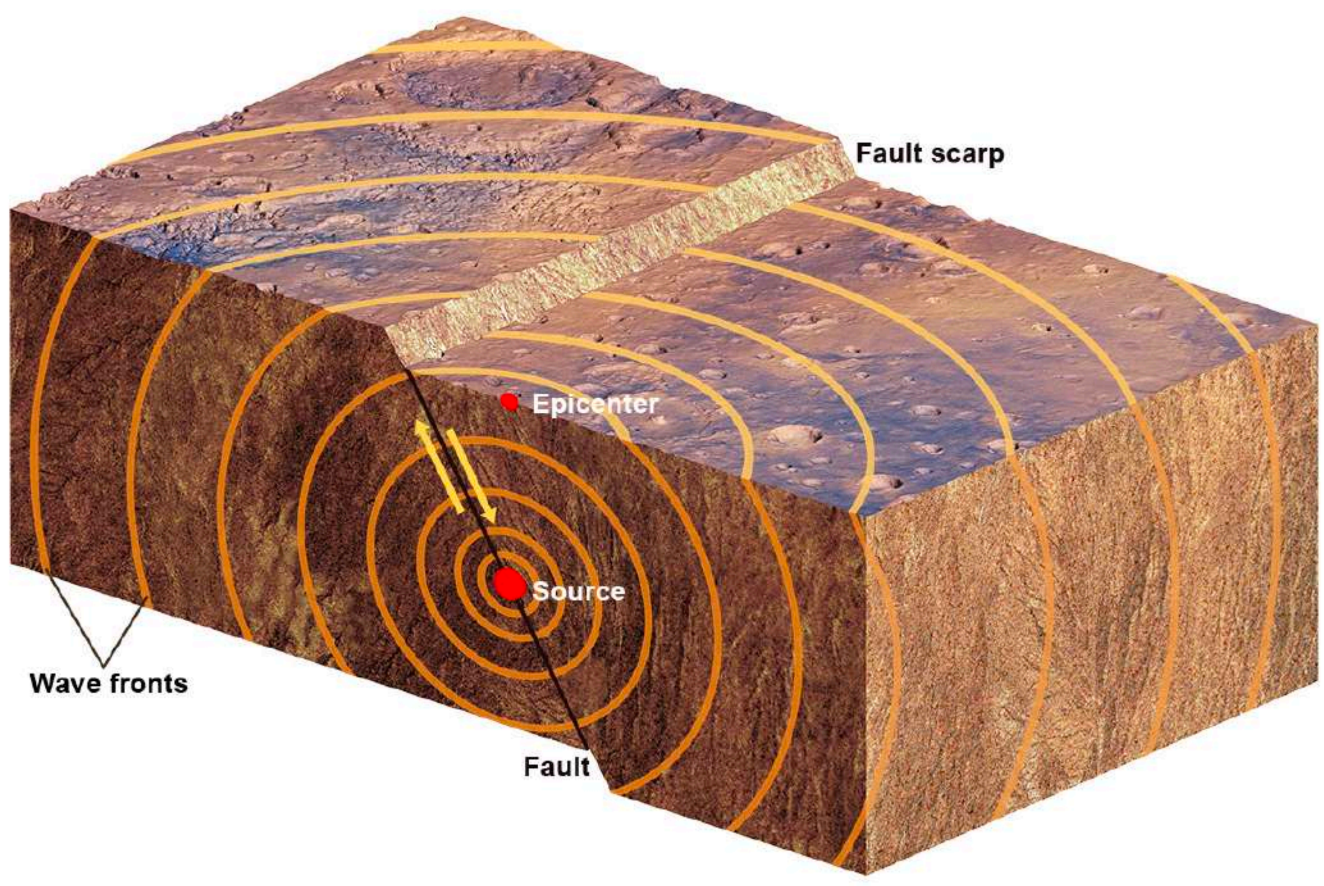
Vibrations resulting from mining and/or oil/gas extraction activities, including drilling, blasting, and ore extraction.

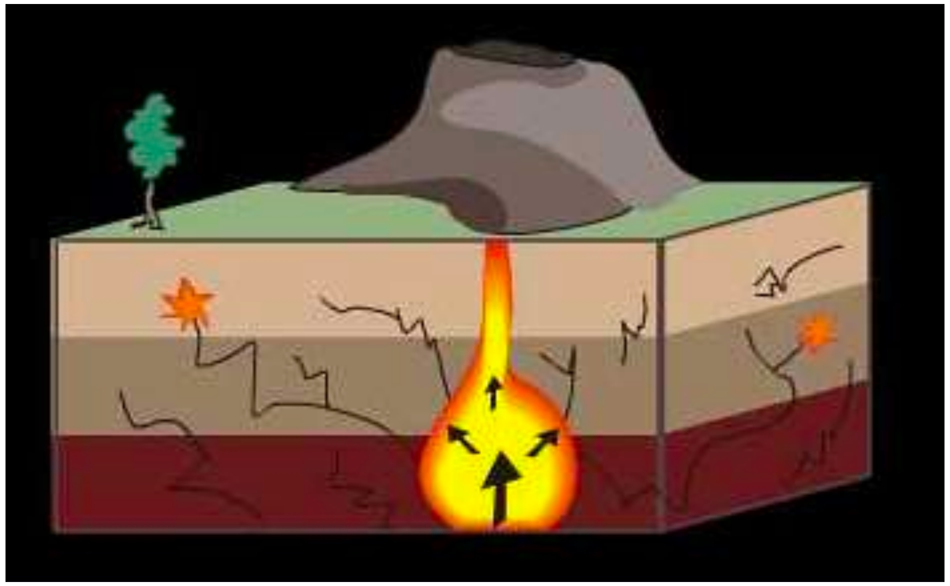
7. Power Plant Operations Vibrations:

Vibrations associated with the operation of power plants, including thermal, nuclear, and renewable energy facilities.

VIBRATIONS: SEISMIC WAVES

Seismic waves are waves of energy that travel through the Earth's layers following the release of energy caused by the sudden movement of materials within the Earth. Earthquakes, volcanic eruptions, explosions, landslides, avalanches, and even rushing rivers can cause seismic waves. These waves transmit energy from the source of the disturbance, propagating through the Earth's interior in various ways.



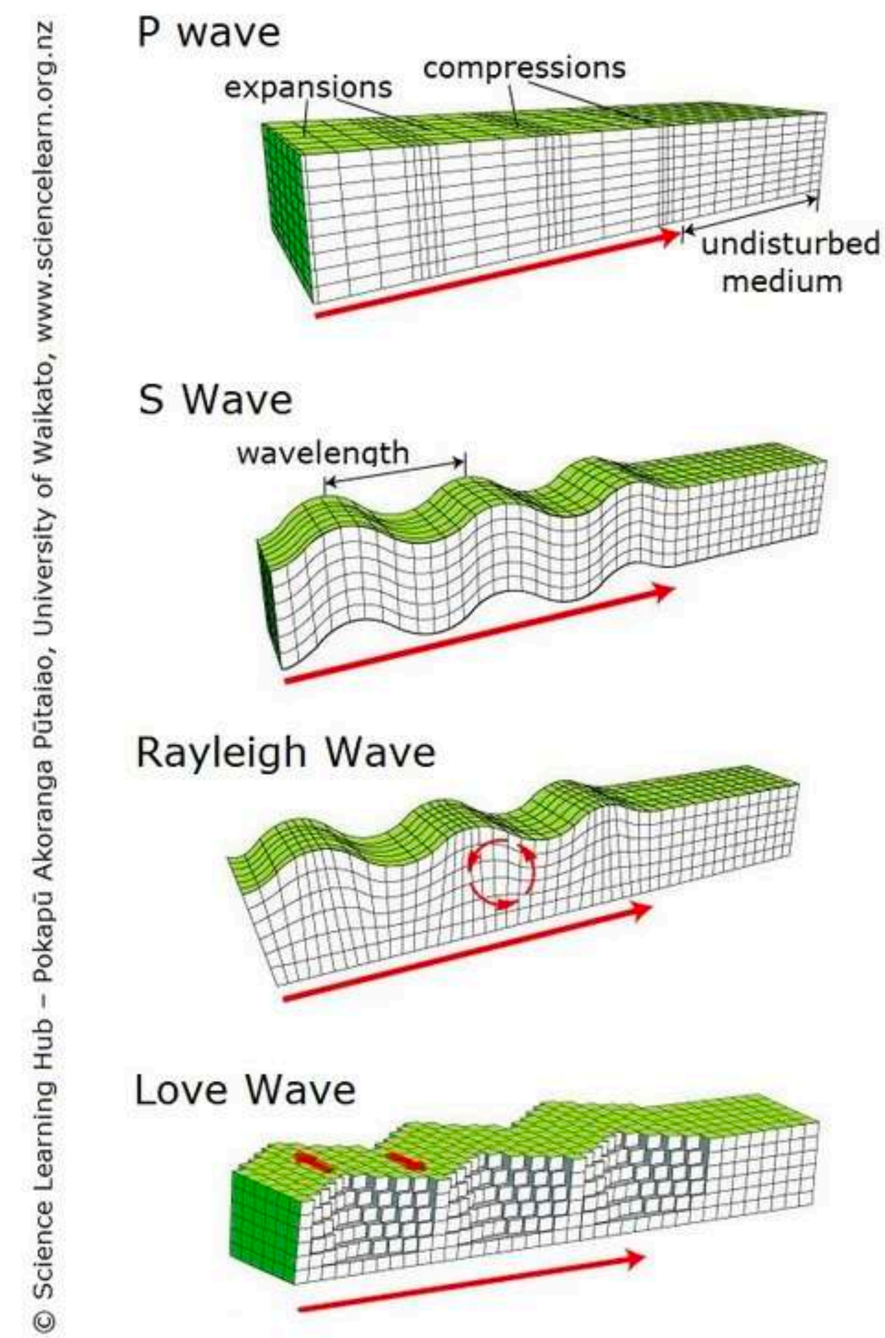


VIBRATIONS: SEISMIC WAVES

There are primarily two types of seismic waves:

- **Body Waves**:
  - **P-waves** (Primary or Compressional Waves): These are the fastest seismic waves and are longitudinal waves that compress and expand the material in the direction of wave propagation. P-waves can travel through solids, liquids, and gases.
  - **S-waves** (Secondary or Shear Waves): S-waves are slower than P-waves and are transverse waves that cause particles to move perpendicular to the direction of wave propagation. They cannot travel through liquids or gases and are only observed in solid materials.

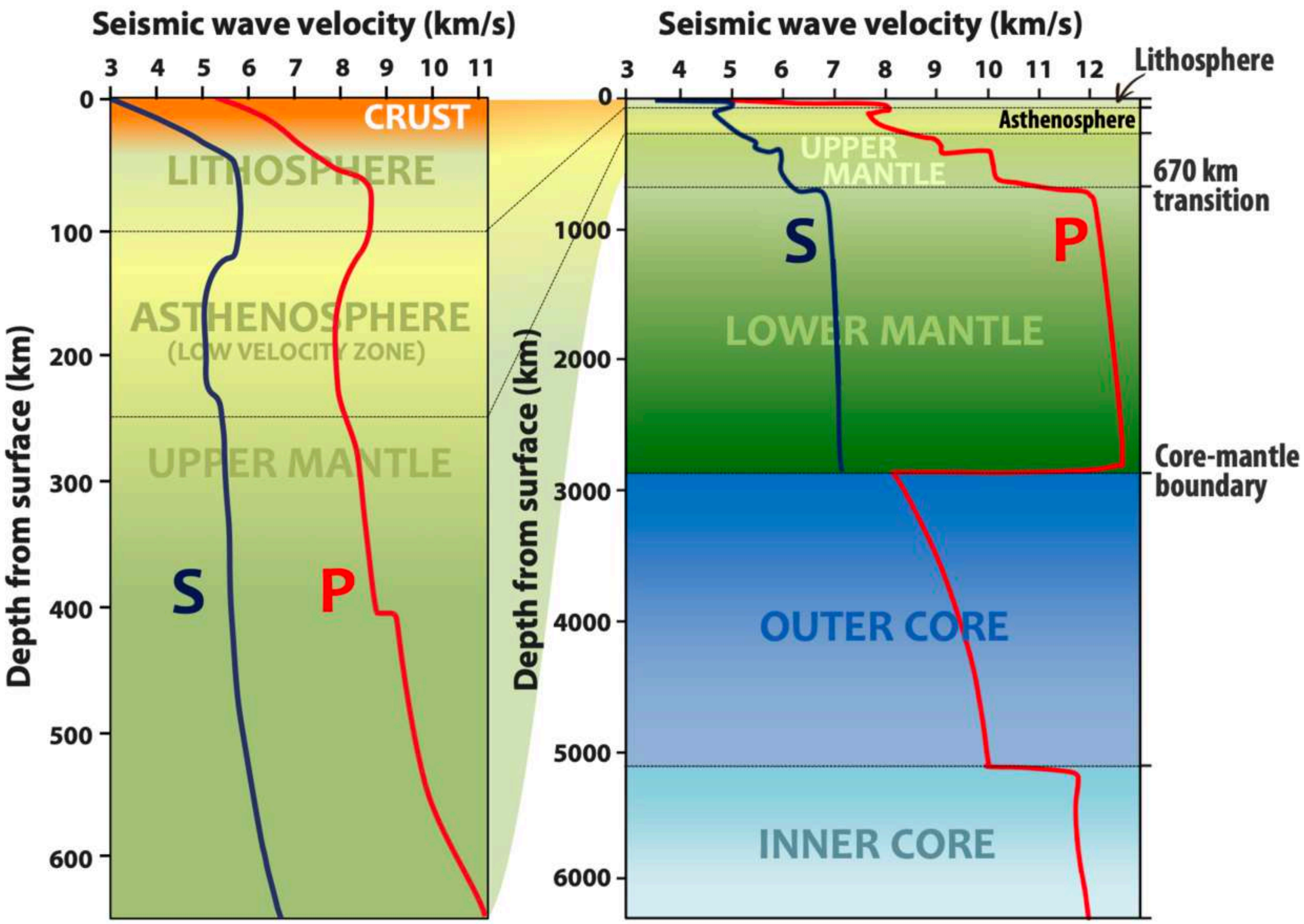
- **Surface Waves**:
  - **Love Waves**: Surface waves that propagate horizontally and perpendicular to the direction of wave travel. They produce shearing motions in the Earth's crust.
  - **Rayleigh Waves**: Surface waves that have both vertical and horizontal motion, causing elliptical particle movements. Rayleigh waves are responsible for the rolling motion observed during earthquakes.



VIBRATIONS: SEISMIC WAVES

Propagation of seismic body-waves: speed and depth

P-waves can travel through any type of material, including fluids, and can travel nearly 1.7 times faster than the S-waves. In air, they take the form of sound waves, hence they travel at the speed of sound. Typical speeds are 330 m/s in air, 1450 m/s in water and about 5000 m/s in granite. In rock, S waves generally travel about 60% the speed of P waves.



VIBRATIONS: SEISMIC WAVES

Seismic waves detection

Low-frequency environmental vibrations can have a significant impact on sensitive scientific instruments and experiments.

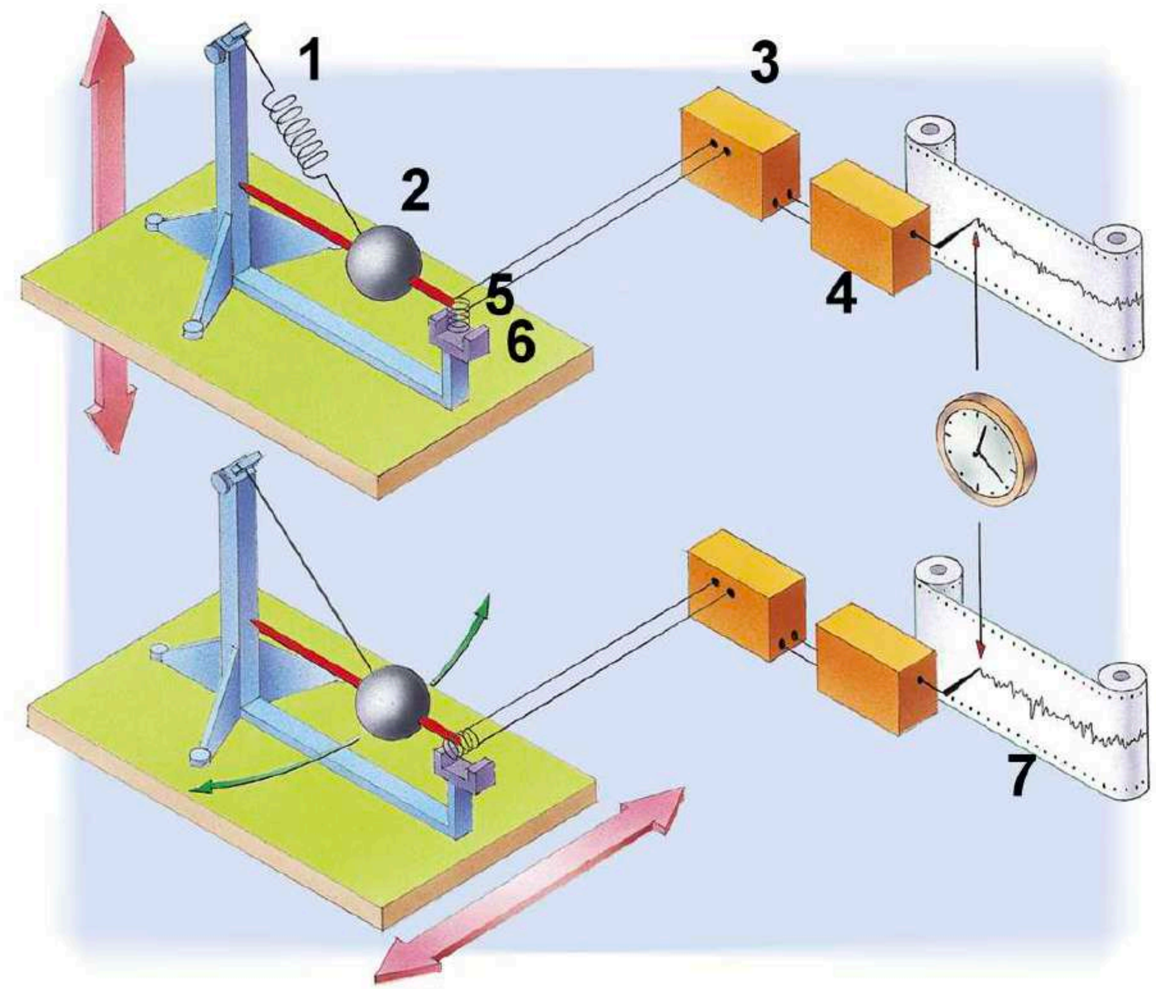
Seismometric devices are designed to detect and analyze these environmental vibrations, allowing to get an insight into the complex interplay of natural and anthropogenic forces to the intricate dynamics of the Earth's surface.

A seismometer, also known as a seismograph or geophone, is a sensitive instrument designed to detect and record ground motions caused by seismic waves generated by earthquakes or other sources of ground motion, like volcanic eruptions or large water masses motions. Its operation is based on the principle of relative motion between a stationary mass and the moving Earth.

VIBRATIONS: SEISMIC WAVES

Seismic waves detection: seismometers

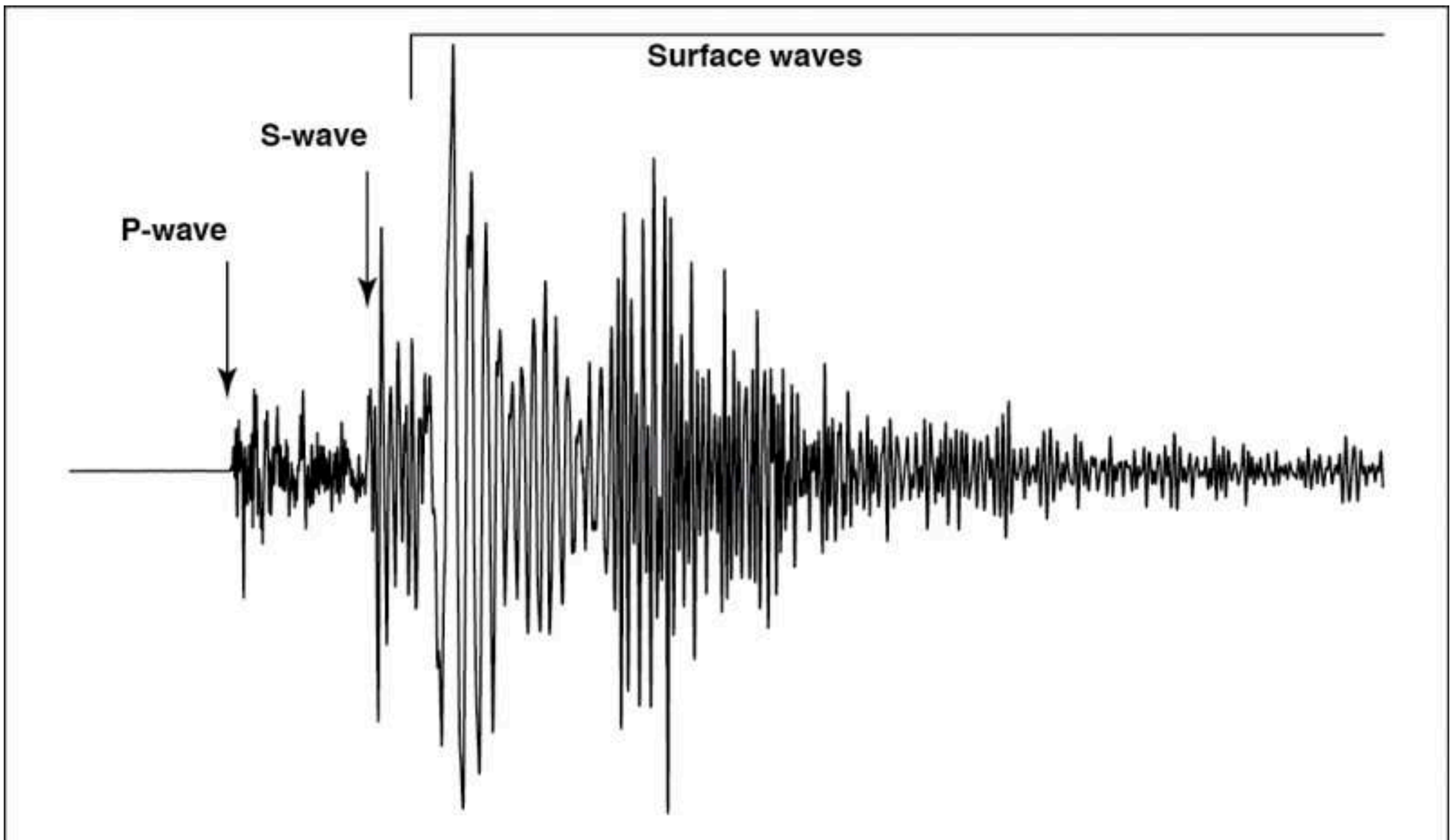
At the core of a seismometer there is a mass-spring system. This system consists of a heavy mass (known as the seismometer's pendulum) attached to a fixed frame by a flexible spring. The mass is typically suspended in a way that it can move freely in response to ground motion. When a source of ground motion generates seismic waves, those propagate through the Earth. The waves cause the ground to move, and this motion is transmitted to the seismometer's frame. The latter accelerates, but the suspended mass, due to its large inertia, lags behind. The relative motion between the mass and the frame is precisely what the seismometer is designed to detect.



Attached to the suspended mass there is an electromagnetic or optical sensor, that can detect the relative displacement between the mass and the frame. This sensor generates an electrical signal proportional to the displacement. The electrical signal from the sensor is then amplified, digitized and recorded. The recorded data (a seismogram) can be analyzed to determine the characteristics of the seismic waves, including their amplitude, frequency, and arrival times.

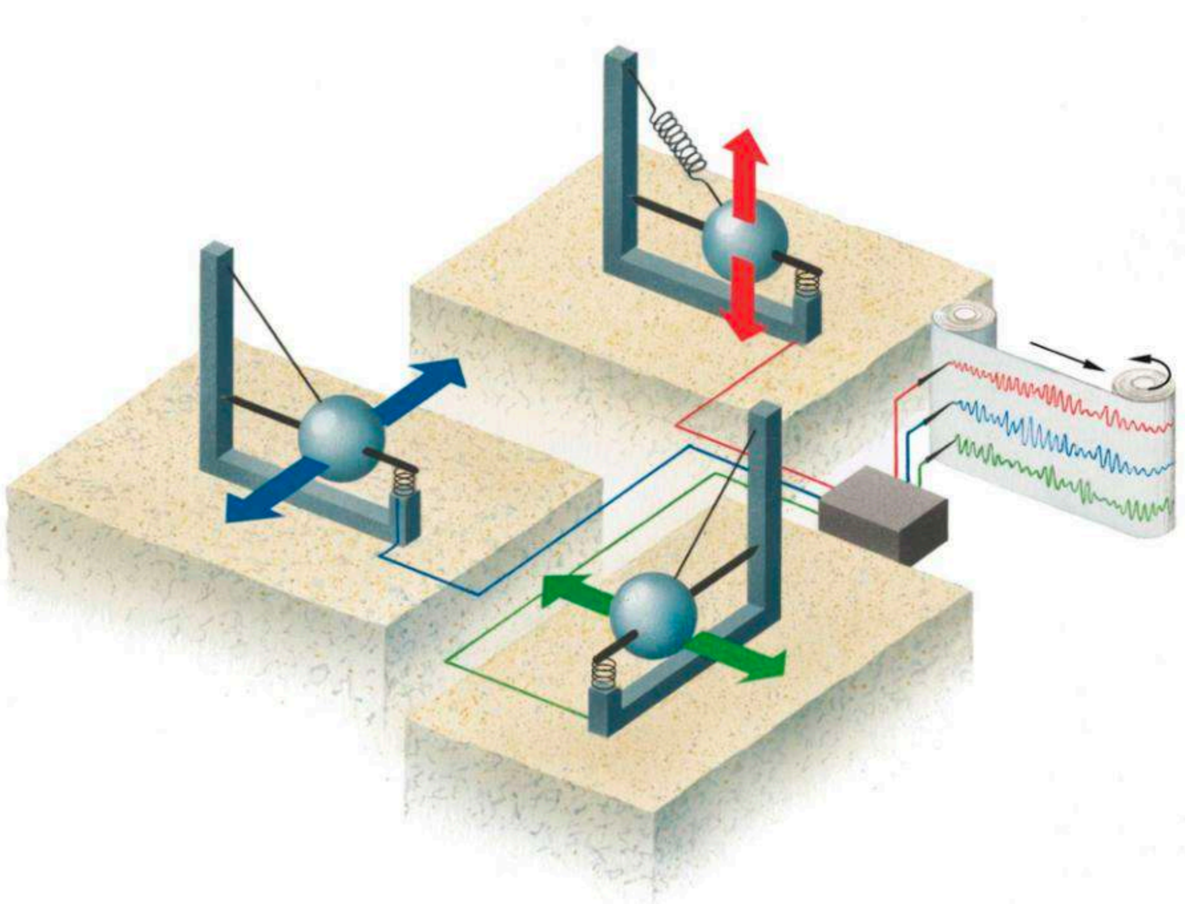
VIBRATIONS: SEISMIC WAVES

Seismometers output: the seismogram



VIBRATIONS: SEISMIC WAVES

Seismometers output



To record the actual motion of the ground in all three dimensions, seismologists need to use three separate sensors within the same instrument. Each sensor records the vibrations in a different directions:

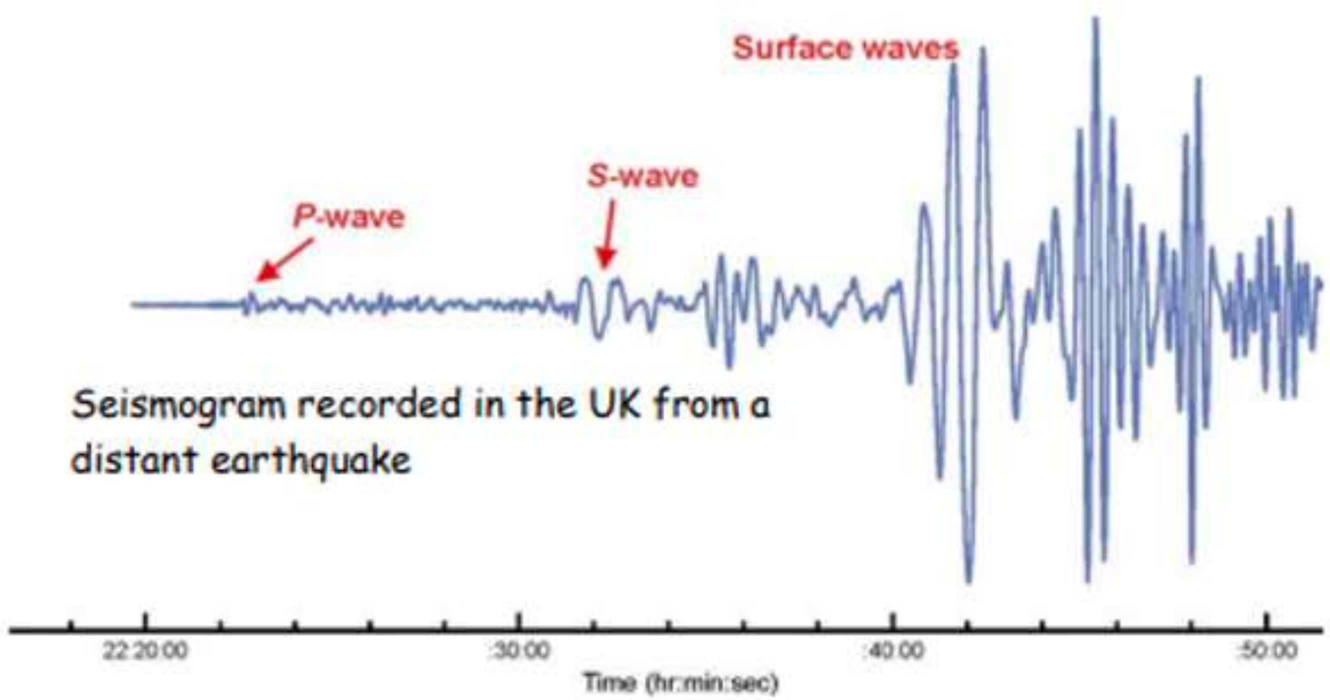
- the Z component (red) measures up/down motion
- the E component (green) measures east/west motion
- the N (blue) component measures north-south motion

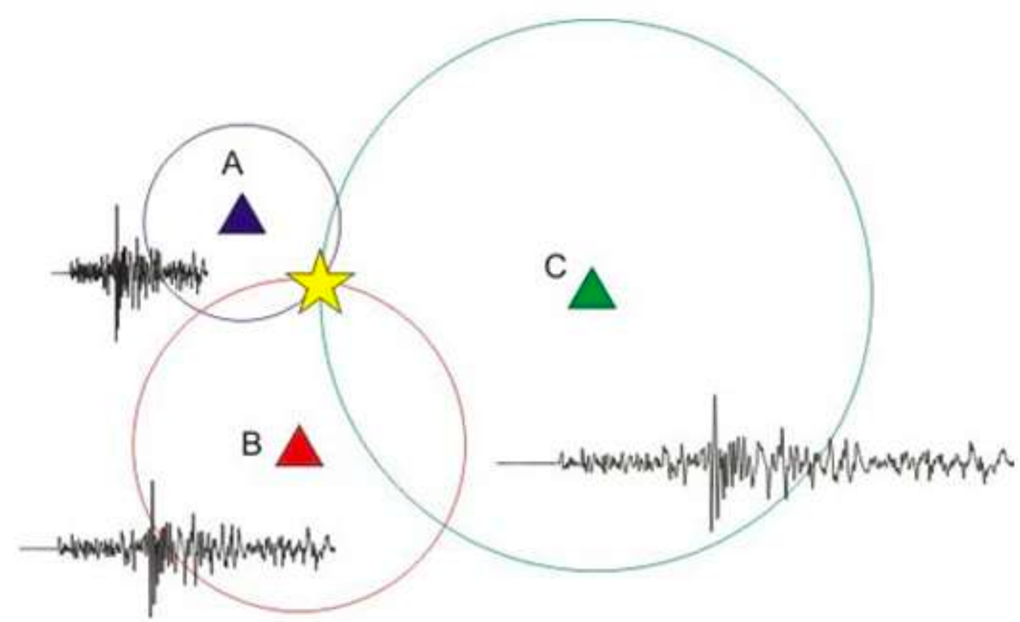
https://www.bgs.ac.uk/discovering-geology/earth-hazards/earthquakes/how-are-earthquakes-detected/

VIBRATIONS: SEISMIC WAVES

Seismic waves: detecting earthquakes

Assuming that we know the relative speed of P- and S-waves, the time difference between the arrivals of the P- and S-waves determines the distance the earthquake is from the seismometer. By looking at the seismograms from different recording stations (triangulation), we can find out the epicentre of the earthquake.





https://www.bgs.ac.uk/discovering-geology/earth-hazards/earthquakes/how-are-earthquakes-detected/

VIBRATIONS: SEISMIC WAVES

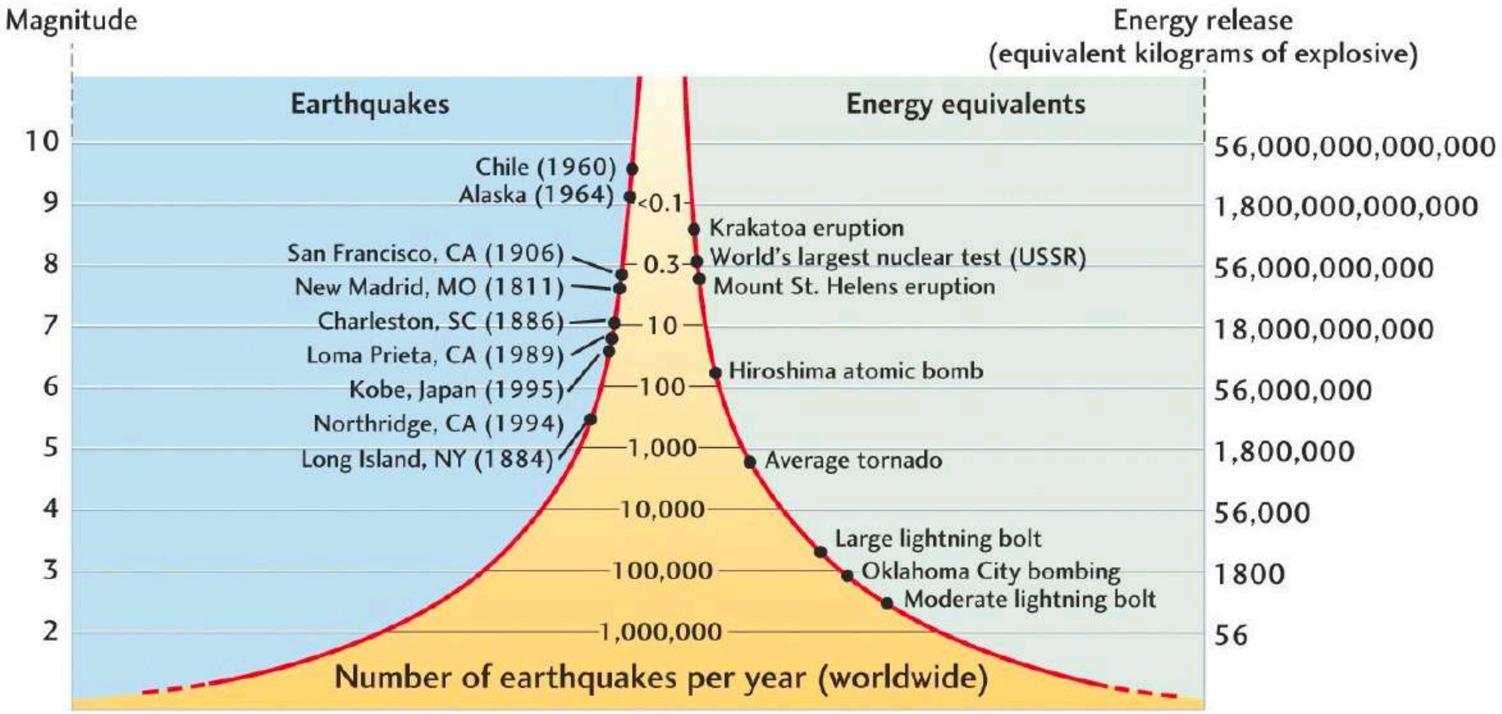
Seismic waves: detecting earthquakes

- **Earthquake intensity**: Intensity is a qualitative measure of the strength of shaking caused by an earthquake determined from the observed effects on people, objects and buildings. For a given earthquake, the intensity normally decreases with distance from the epicentre. European Macroseismic scale (EMS) is used to quantify the effect of earthquake shaking on people, objects and buildings

- **Earthquake magnitude**: Magnitude is a measure of the amount of energy released during an earthquake and can be estimated from the amplitude of ground motions recorded by seismometers. It is independent of distance from the epicentre. Earthquake magnitude scales are logarithmic, i.e. a one unit increase in magnitude corresponds to a tenfold increase in amplitude.

    - Richter scale (ML): local magnitude (D < 600 km). ML = (log A) + 2.56(log D) – 1.67, where A is the measured ground motion (in um) and D is the distance from the event (in km)

    - Moment scale (Mw): based on seismic 'moment'. Moment is related to the area of the earthquake fault rupture and the amount of slip on the rupture, as well as the strength of the rocks themselves. Mw = 2/3(log Mo) – 10.7, with seismic moment Mo = µ × rupture area × slip length where µ is the shear modulus of the crust (approximately 3 × 10^{10}N/m)



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VIBRATIONS: SEISMIC WAVES

Seismic waves: Earthquakes and microseisms

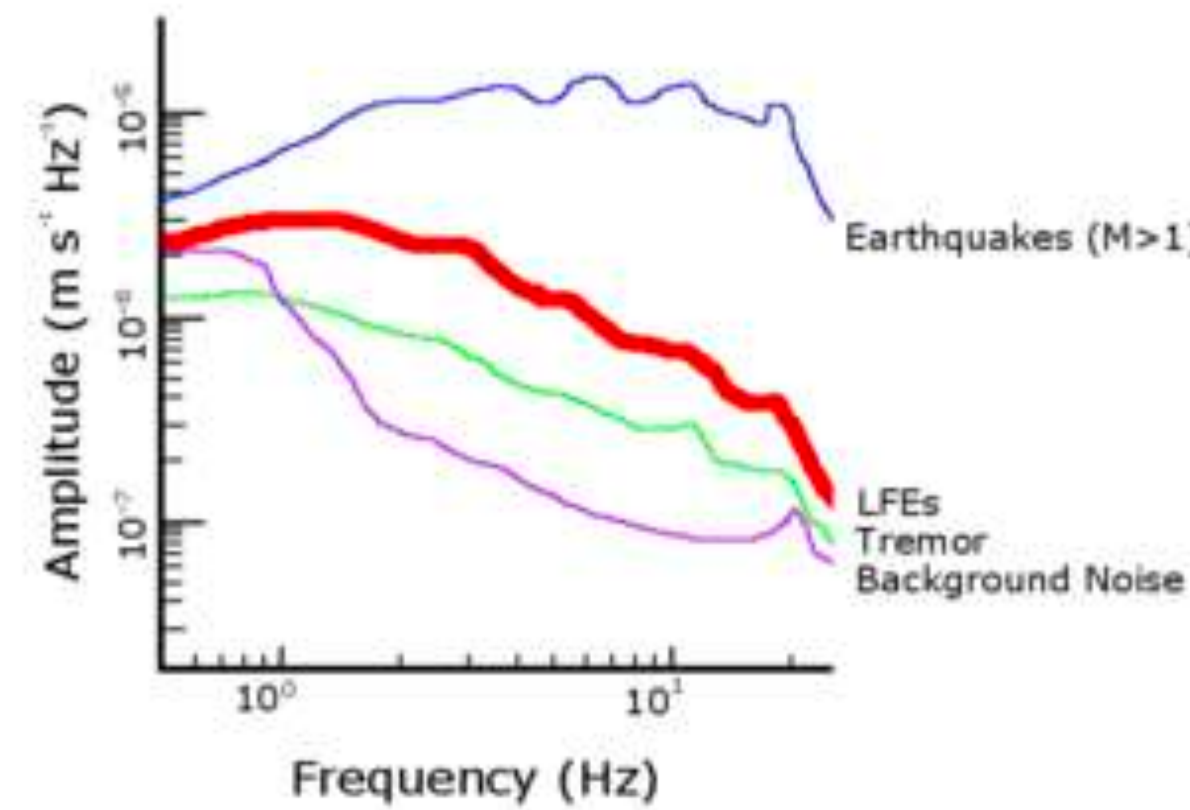
The seismic vibrations occur at frequencies from less than 0.1 Hz to 20 Hz. This is just below the range of ordinary sound vibrations.

Earthquakes (high Mw): > 10Hz

LFEs: tectonic tremor or low-frequency earthquakes, 1-10 Hz

VLFEs: very slow earthquakes in the 0.01–0.10 Hz band

Microseisms: microseismic noise at 0.1–1.0 Hz.

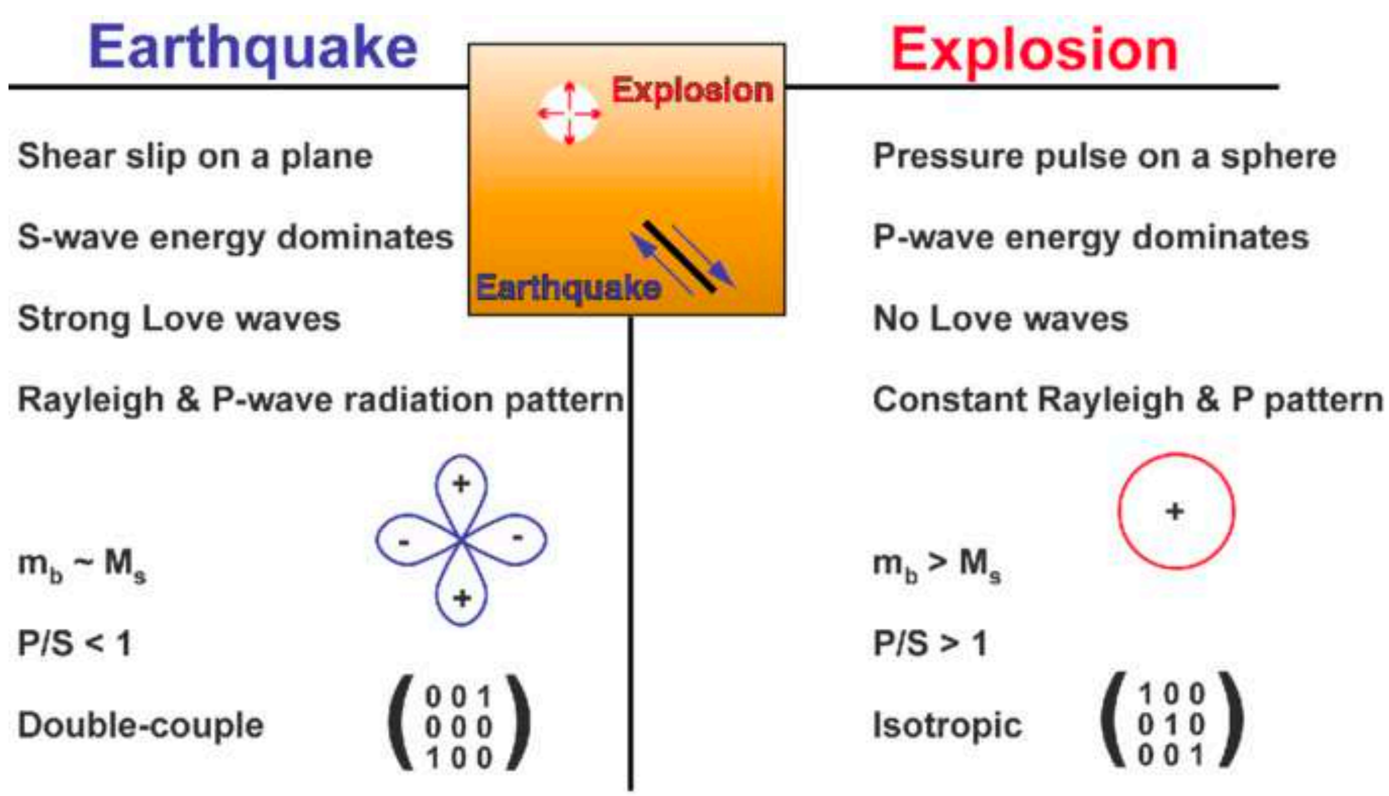


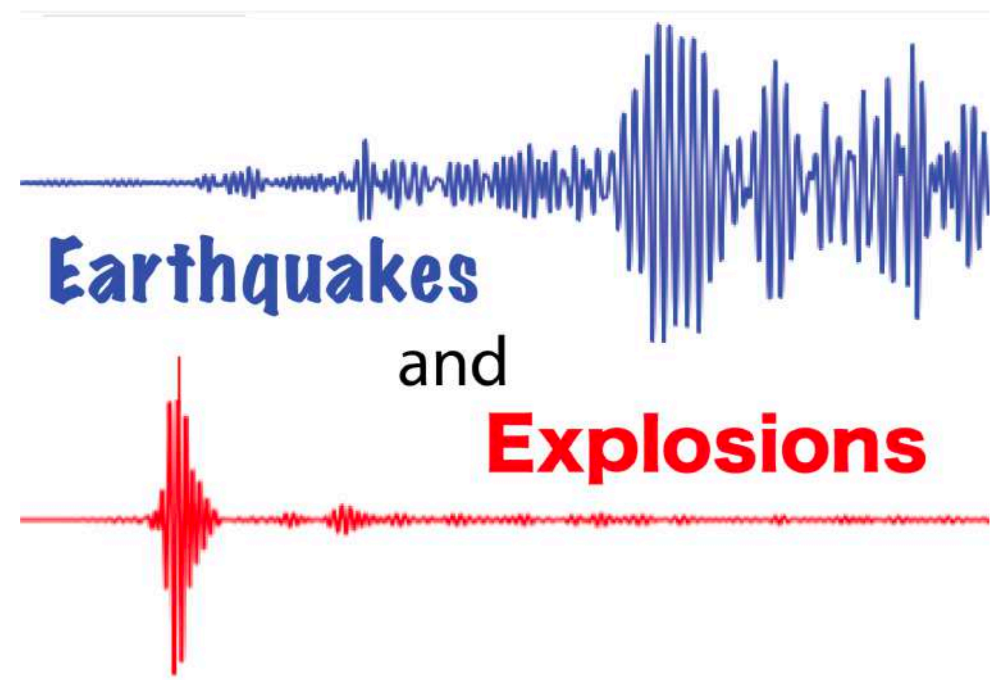
https://link.springer.com/article/10.1007/s10950-021-10071-8

VIBRATIONS: SEISMIC WAVES

Seismic waves: earthquakes vs explosions

During an earthquake, rock breaks in a shear fracture, which results in the rapid sideways movement of two flanks of a fault. In an explosion, however, the origin is indeed a point, from which elastic pressure waves travel concentrically outward

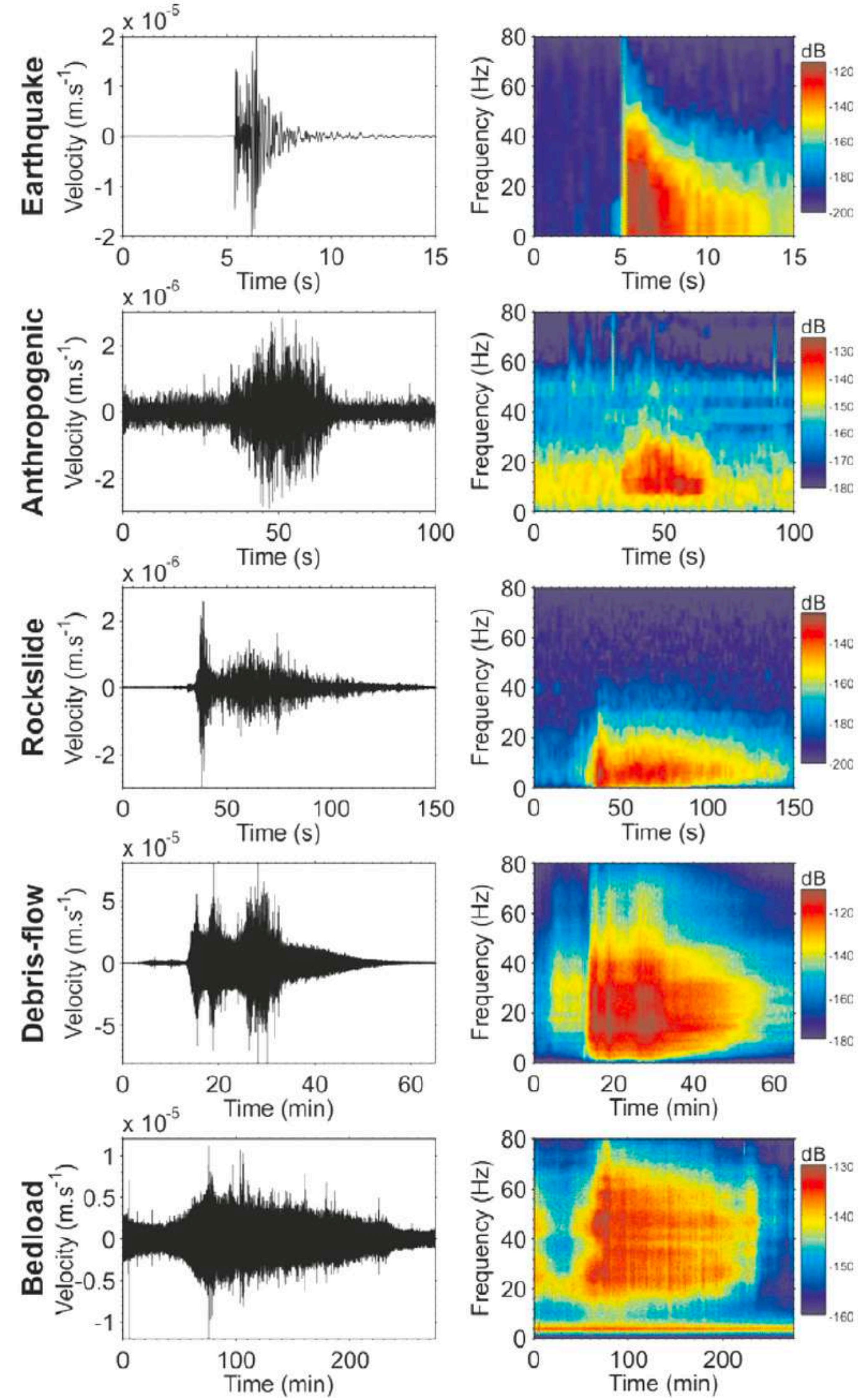




https://blog.education.nationalgeographic.org/2016/09/12/how-do-scientists-tell-the-difference-between-natural-earthquakes-and-earthquakes-caused-by-nuclear-tests/

VIBRATIONS: SEISMIC WAVES

Seismic waves from different sources: time and frequency diagrams



10.5194/esurfd-2-1217-2014

VIBRATIONS: SEISMIC WAVES

Seismic waves detection (Italy): INGV

The INGV (Istituto Nazionale di Geofisica e Vulcanologia) is Italy's National Institute for Geophysics and Volcanology, renowned for its leading role in monitoring and researching geological phenomena in the Mediterranean region. Located across various sites in Italy, the center operates a network of seismometers, GPS stations, and volcanic observatories

https://www.ingv.it/

VIBRATIONS: SEISMIC WAVES

Seismic waves: correlation of seismic activity and other environmental sources

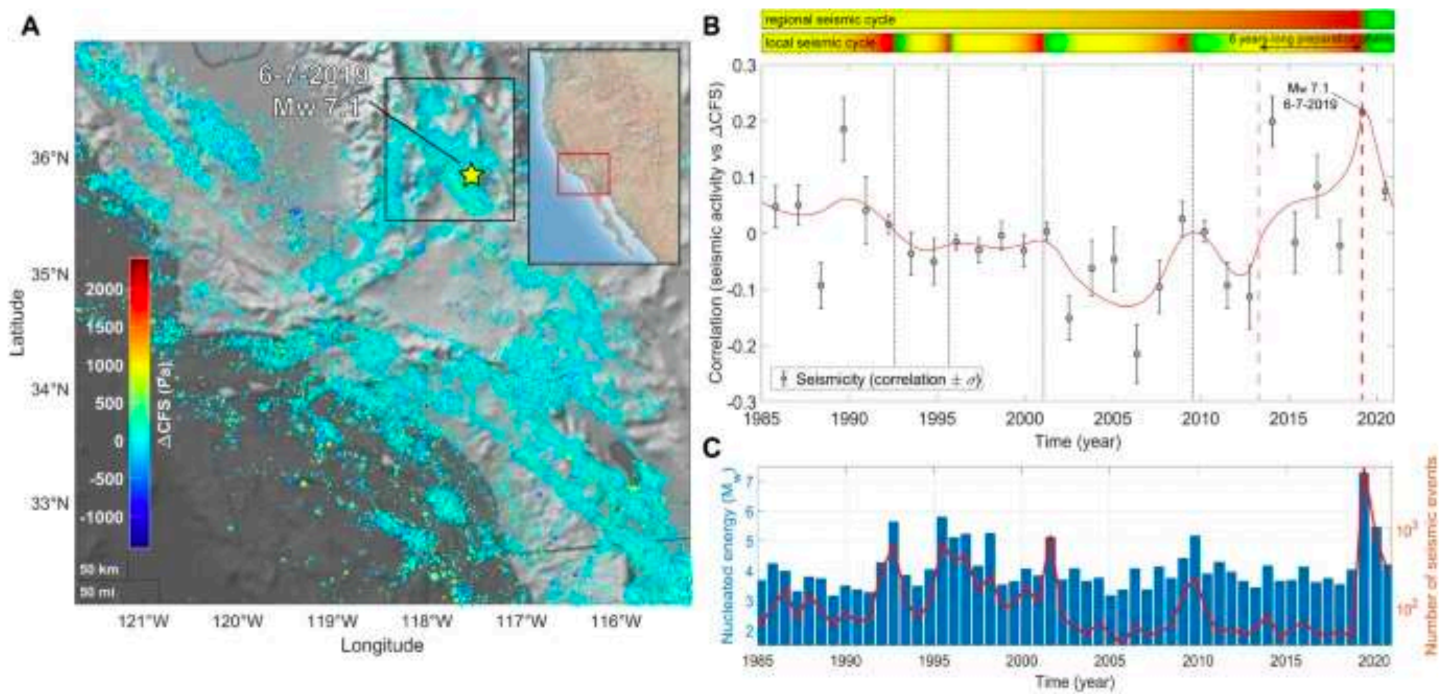
Seismic activity can exhibit correlations with various environmental factors. While the direct influence of phenomena like sea waves, tides, moon phases, wind, or atmospheric pressure on seismic events remains an area of ongoing study and debate, some correlations have been observed.

For instance, particularly in regions near coastlines, high-tide periods might show a slight increase in seismic activity, potentially due to changes in stress on faults caused by tidal forces.

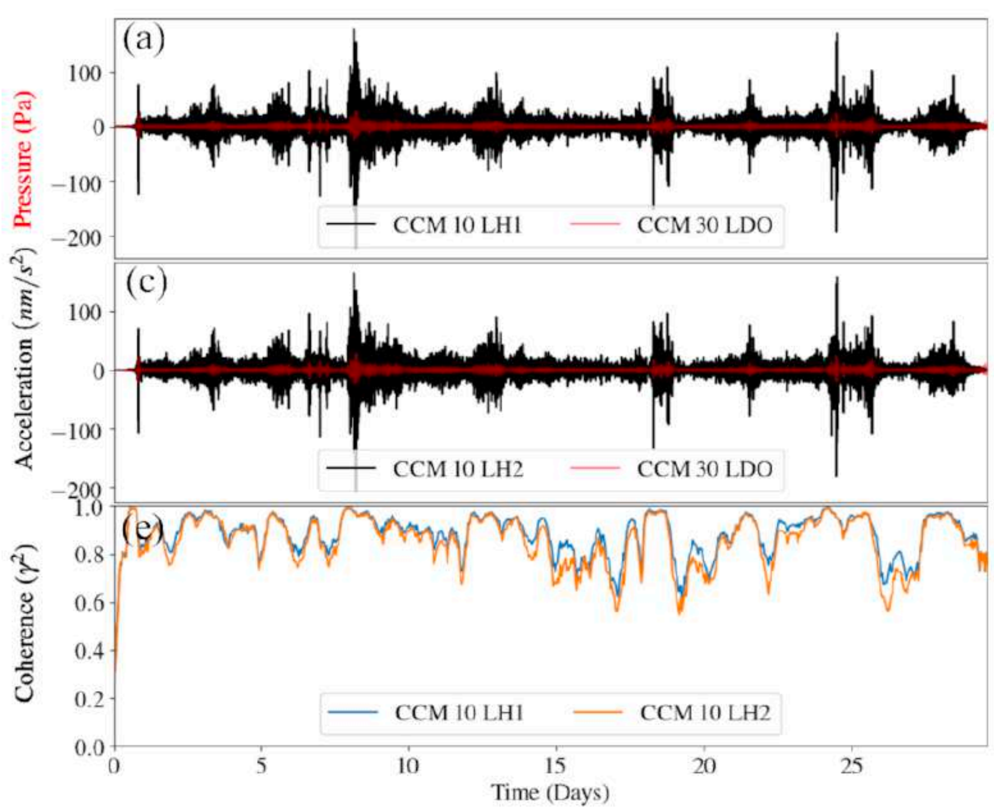
Additionally, seismic signals can be affected by the movement of ocean waves or the atmospheric pressure variations associated with weather systems.

VIBRATIONS: SEISMIC WAVES

Seismic waves: correlation seismic activity and other environmental sources



Correlation between tidal Coulomb failure stress and energy nucleation in seismic activity
https://www.nature.com/articles/s41598-022-11328-z

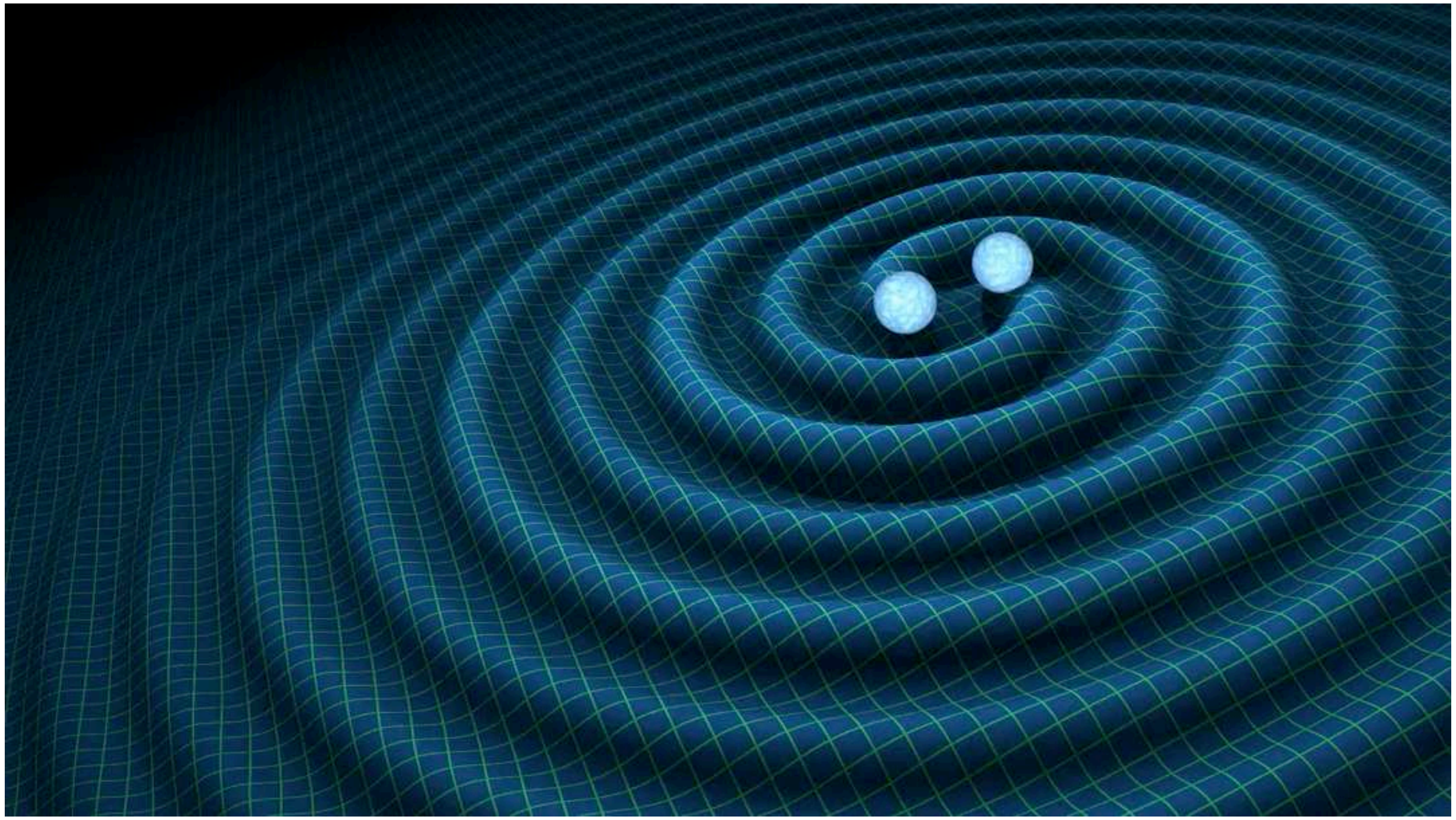


Correlation between atmospheric pressure variations and long-period horizontal seismic data

https://academic.oup.com/gji/article/223/1/676/5872488

EXCURSUS: SPACE-TIME VIBRATIONS - GWS

Gravitational waves are ripples in spacetime.
When objects move, the curvature of spacetime changes and these changes move outwards (like ripples on a pond) as gravitational waves. A gravitational wave is a stretch and squash of space and so can be found by measuring the change in length between two objects



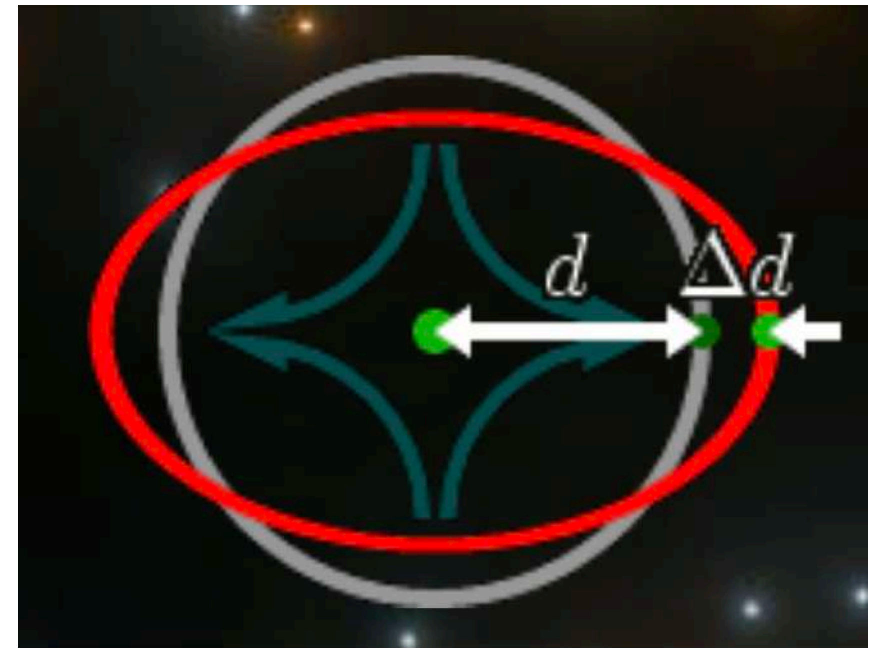
From: https://www.ligo.caltech.edu/video/gravitational-waves

EXCURSUS: SPACE-TIME VIBRATIONS - GWS

The fractional change in displacement between two nearby masses due to the gravitational wave crossing related with the GWs 'strain' h.

The change in displacement occurs in the plane transverse to the direction of radiation, and causes a stretch along one axis and a squeeze along the orthogonal axis.

The *strongest* GWs (generated by colliding black holes) we expect to observe passing the Earth will have $h \sim 10^{-20}$ or less. This is enough to distort the shape of the Earth by 10^{-13} metres, or about 1% of the size of an atom!

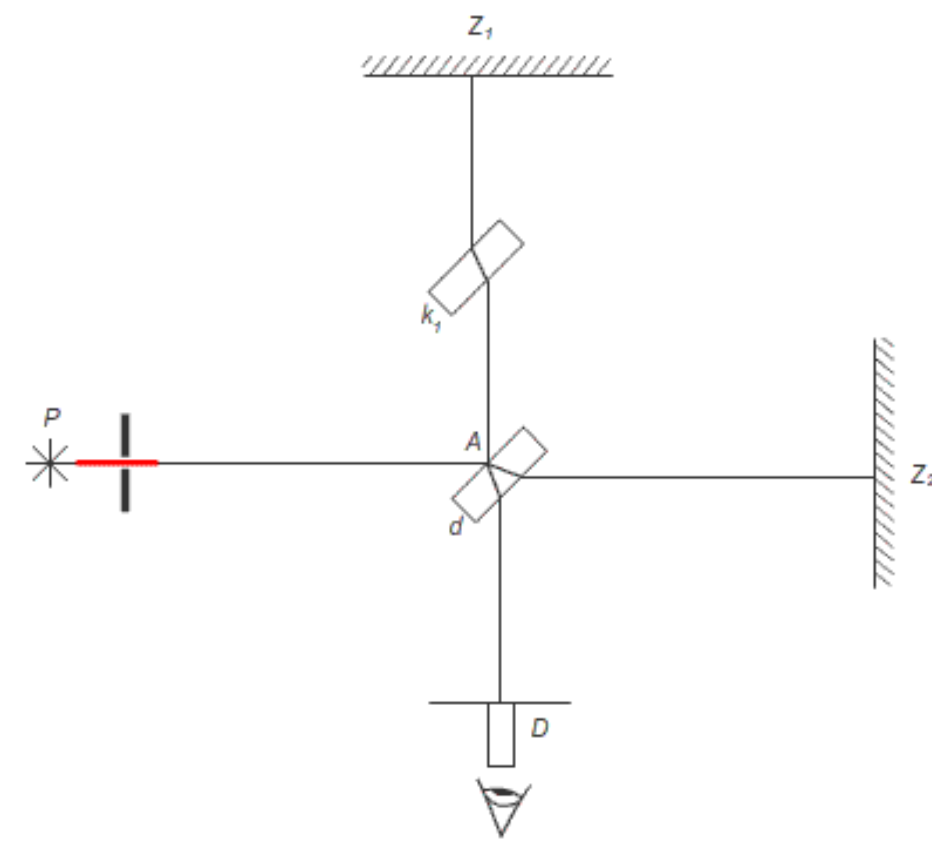


$$h = \frac{2\Delta d}{d}$$

EXCURSUS: SPACE-TIME VIBRATIONS - GWS

GW detection: the interferometric technique

Gravitational wave detection with interferometers involves using precise instruments called interferometers to capture the incredibly subtle ripples in spacetime caused by cataclysmic cosmic events. These detectors, such as **LIGO and Virgo**, consist of long, perpendicular arms equipped with lasers and mirrors. When a gravitational wave passes through the detector, it slightly alters the lengths of the arms, causing minute changes in the distance traveled by the laser beams. The interferometer precisely measures these changes by splitting a laser beam, sending portions along the arms, and recombining them. As gravitational waves pass, they induce tiny fluctuations in the interference patterns of the recombined beams, allowing scientists to infer the presence, direction, and characteristics of the passing gravitational waves.



EXCURSUS: SPACE-TIME VIBRATIONS - GWS

GW detection: the interferometric technique

From: https://spaceplace.nasa.gov/gravitational-waves/en/

https://www.ligo.caltech.edu/video/ligo20160211v6

EXCURSUS: SPACE-TIME VIBRATIONS - GWS

Noise sources for GW detection

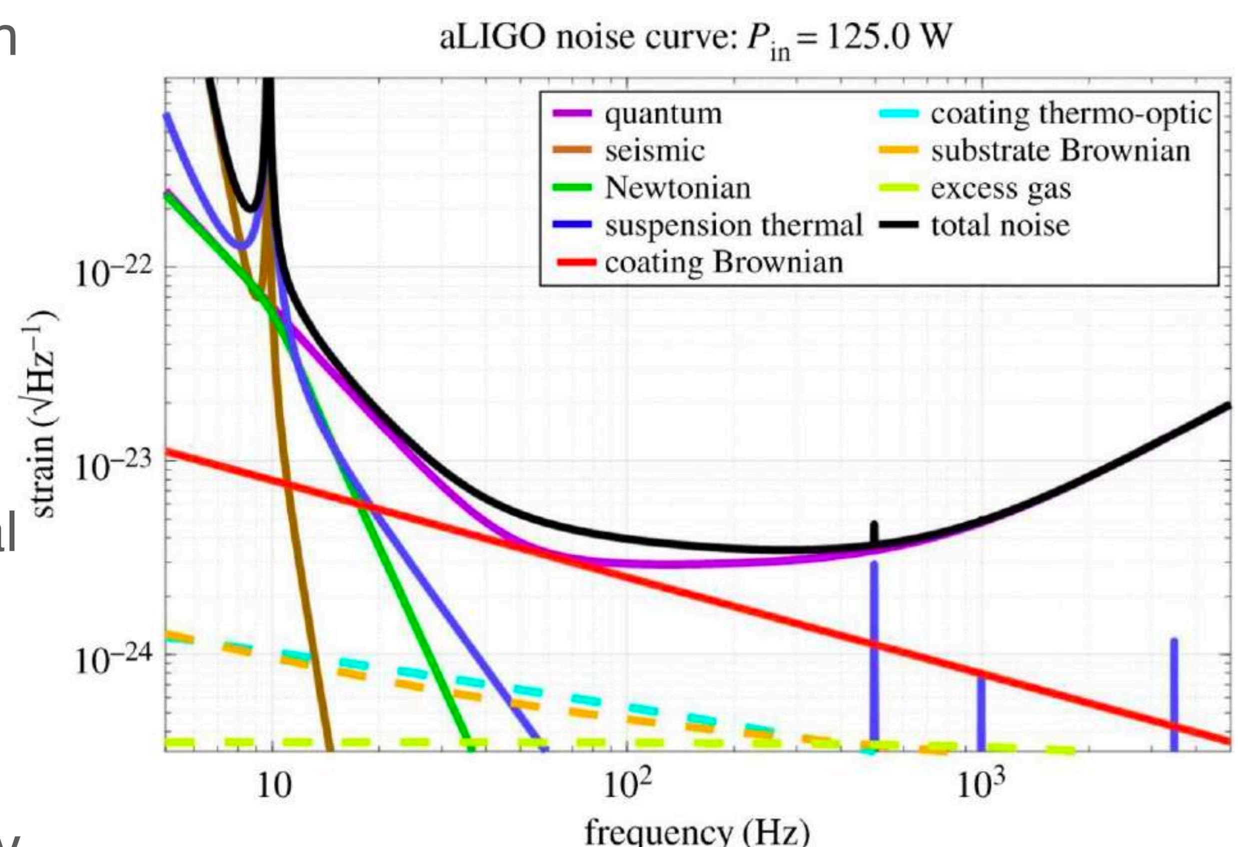
Noise in the GW detectors can stem all the possible sources of vibrations and displacement, that can mimic the passage of a real GW.

- Seismic vibrations from Earth's movements, such as seismic waves or ground tremors, and environmental disturbances from nearby human activities

- Thermal noise due to atomic/molecular motion within the detector's components

- Quantum noise arising from quantum mechanical effects, such as quantum fluctuations and shot noise

- Newtonian noise, gravitational perturbations caused by mass fluctuations in the Earth or nearby objects



Scientists continuously refine these detectors, implementing advanced technologies and meticulous isolation techniques to minimize these sources of interference and enhance the sensitivity of the detectors.

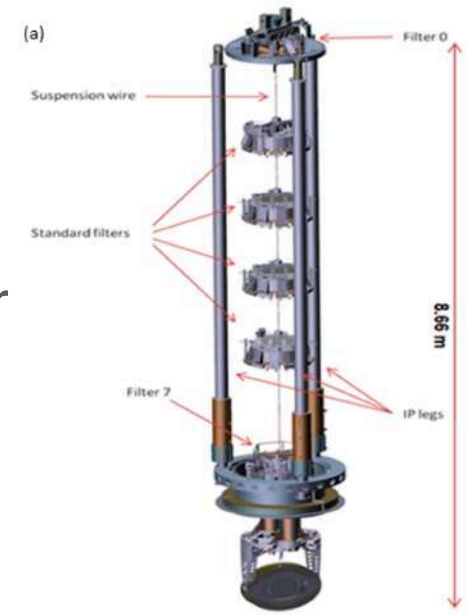
EXCURSUS: SPACE-TIME VIBRATIONS - GWS

Noise abatement for GW detection

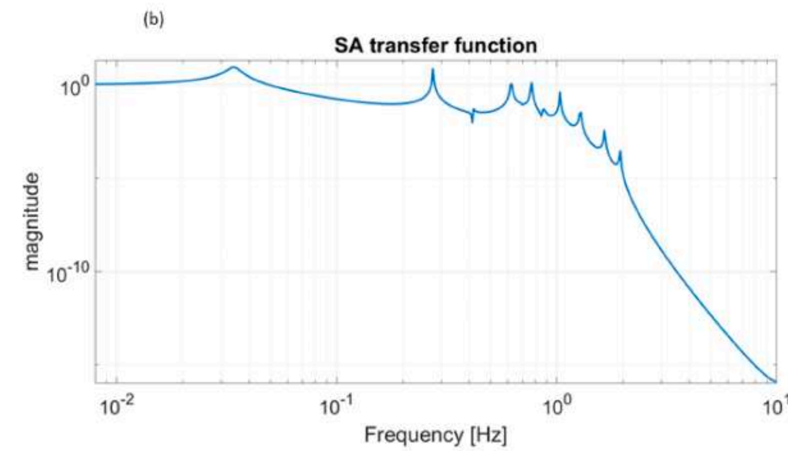
Examples:

- The interferometer sits on the ground and the ground is moving all the time. To reduce it drastically, the Virgo mirrors are suspended via a **long chain of pendula**, hosted in towers 10-meter tall, the *Superattenuators*. Their combined effect is such that the amplitude of the ground motions at frequencies of 10 Hz or higher is reduced by a factor in excess of 10^{12}

- The Newtonian Noise can be caused by density fluctuations propagating in the soil surrounding the detector, atmospheric density perturbations and tidal moon effects. It impacts the detector capability of detecting GWs with frequencies between about 1 and 20 Hz. To mitigate Newtonian Noise, we can monitor the local gravitational field perturbations using an array of **strategically-disposed sensors**, such as microphones and seismometers, and then subtract the measured Newtonian Noise from the data



Virgo Super-Attenuator

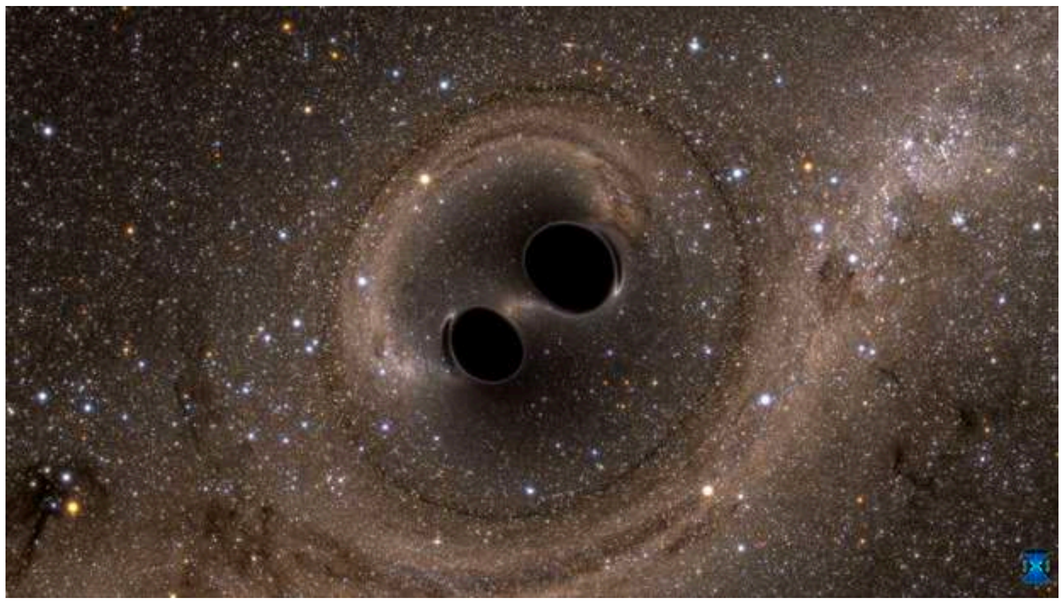


From https://www.mdpi.com/2075-4434/10/1/20

https://www.virgo-gw.eu/it/science/detector/fighting-noises/

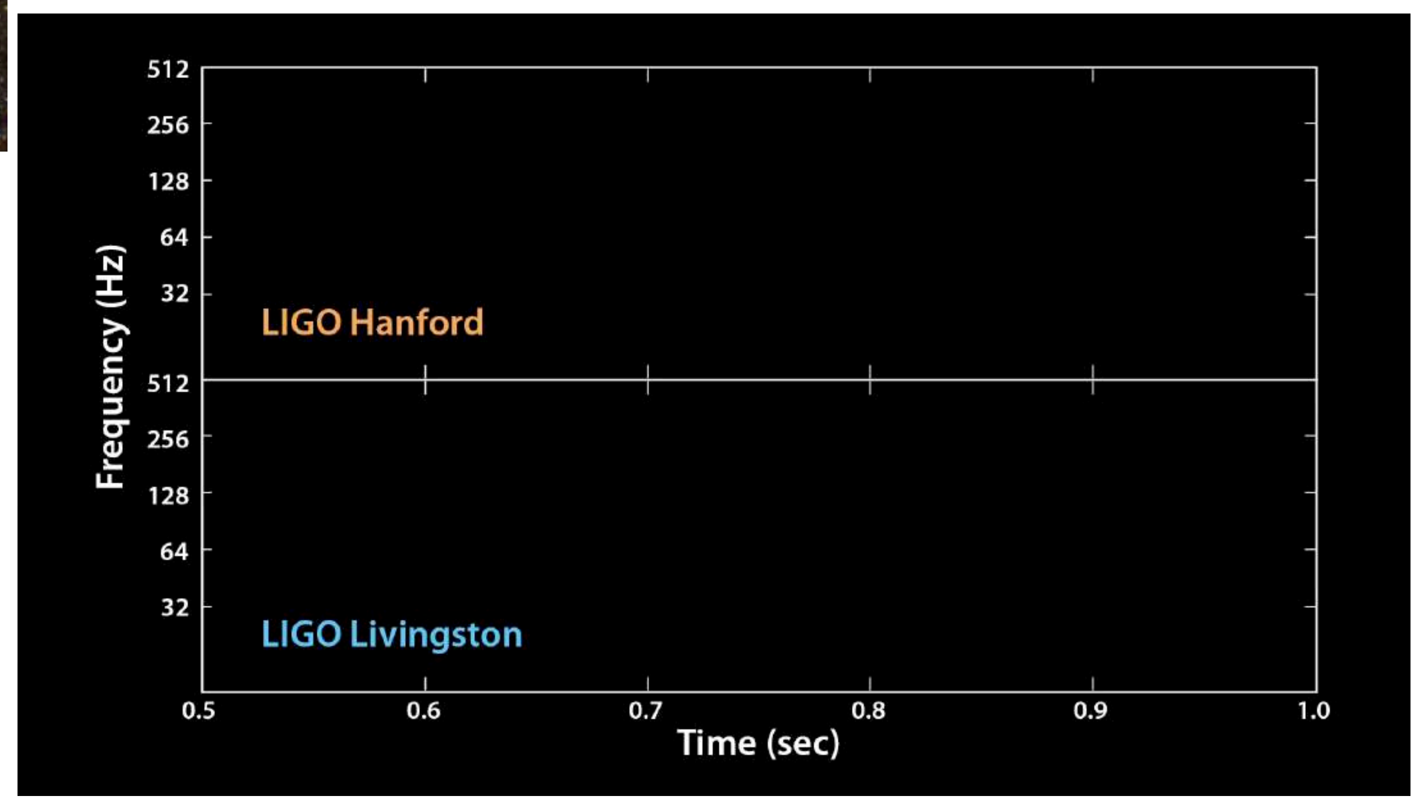
EXCURSUS: SPACE-TIME VIBRATIONS - GWS

The sound of a gravitational wave



GWs from two colliding black holes

https://www.ligo.caltech.edu/video/ligo20160211v10.



https://www.ligo.caltech.edu/video/ligo20160211v2

ACOUSTICS

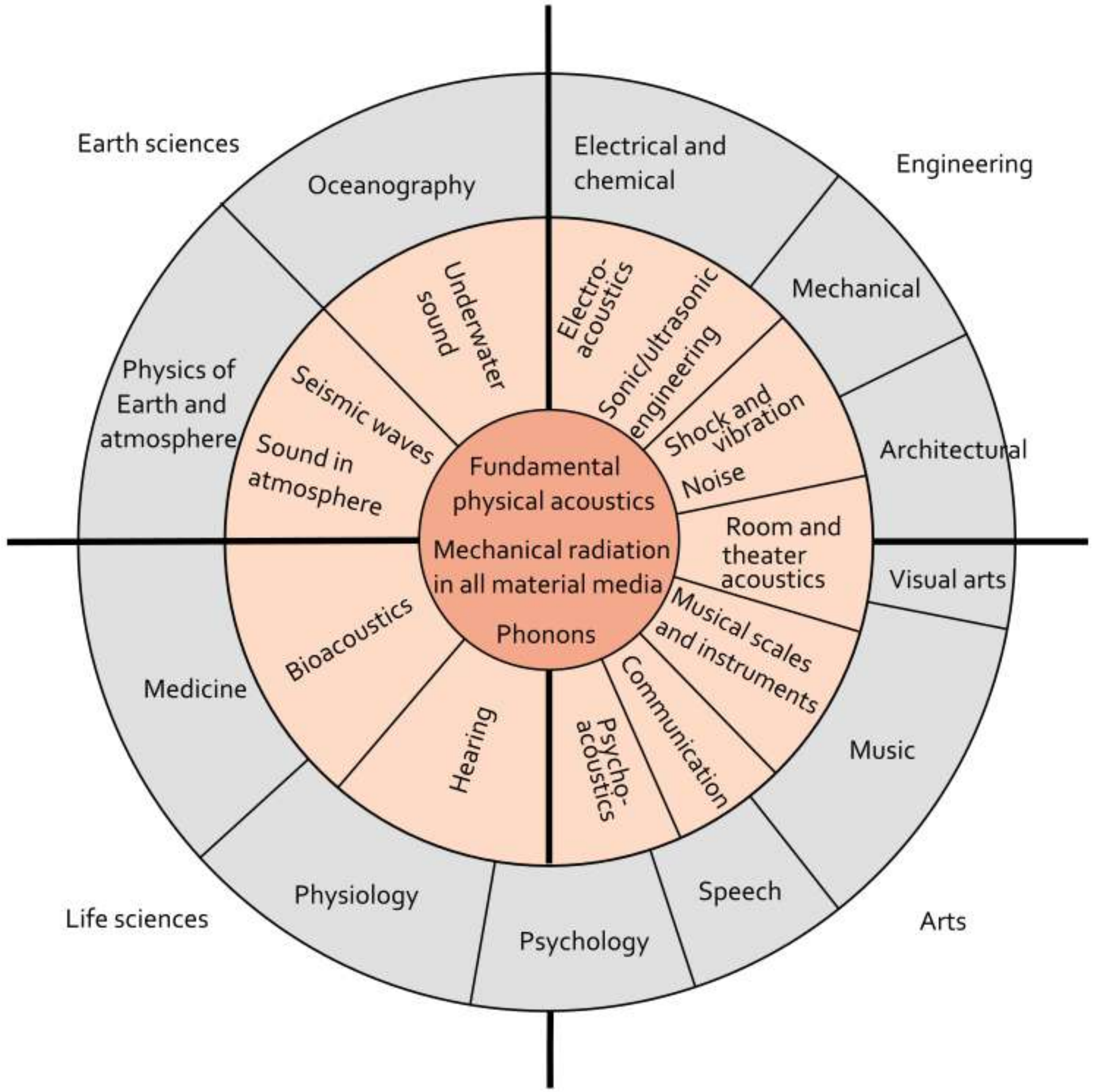
Acoustics is the interdisciplinary study of sound, encompassing its generation, transmission, propagation, and reception.

It explores the behaviour of sound waves in various mediums, such as air, water, and solids, and how they interact with different structures and environments.

Acoustics delves into understanding the physical properties of sound, including frequency, amplitude, wavelength, and speed, and how these factors influence the perception of sound by humans and other organisms.

Acoustics covers a broad spectrum of applications for understanding and manipulation of sound for communication, entertainment, scientific research, and practical engineering applications across numerous industries.

ACOUSTICS

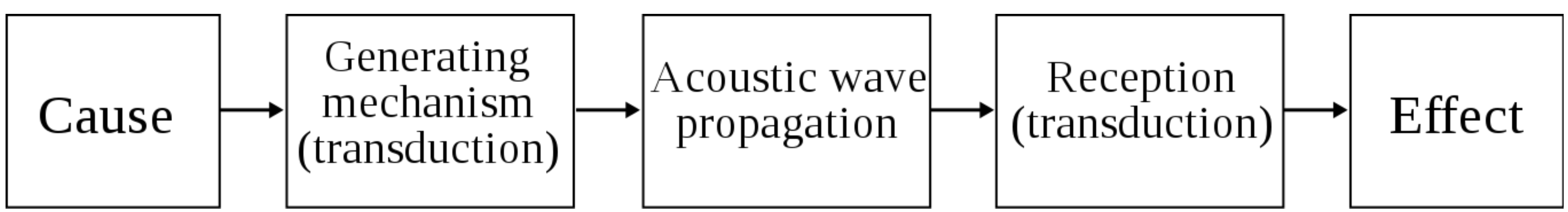


Lindsay's Wheel of Acoustics - Fields within acoustics

ACOUSTICS

The study of acoustics revolves around the generation, propagation and reception of mechanical waves and vibrations.

- Causes: natural and volitional
- Generating mechanisms: transduction process that convert energy from some other form into sonic energy, producing a sound wave
- Sound wave propagation: acoustic wave equation. The wave carries energy throughout the propagating medium. In fluids, sound propagates primarily as a **pressure wave**. In solids, mechanical waves can take many forms including longitudinal waves, transverse waves and surface waves
- Reception: the energy is transduced again into other forms, in ways that again may be natural and/or volitionally contrived.



Acoustics looks first at the pressure levels and frequencies in the sound wave and how the wave interacts with the environment. This interaction can be described as either a diffraction, interference or a reflection or a mix of the three. If several media are present, a refraction can also occur.

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ACOUSTICS

Wave propagation: sound speed

The speed of sound represents the velocity at which mechanical waves propagate through a medium, determined by the medium's physical properties such as density, elasticity, and temperature.

Different mediums: $v_s \sim \sqrt{\gamma/\rho}$

- $v_s \sim 343$ m/s in dry air @ 20°C
- $v_s \sim 1480$ m/s in water, due to water's higher density and stiffness
- $v_s \sim 5960$ m/s in solids like steel, due to the tightly packed molecular structure

Temperature dependence: $v_s \sim \sqrt{T}$

$v_s \sim 331$ m/s @ 0°C, $v_s \sim 353$ m/s @ 37°C

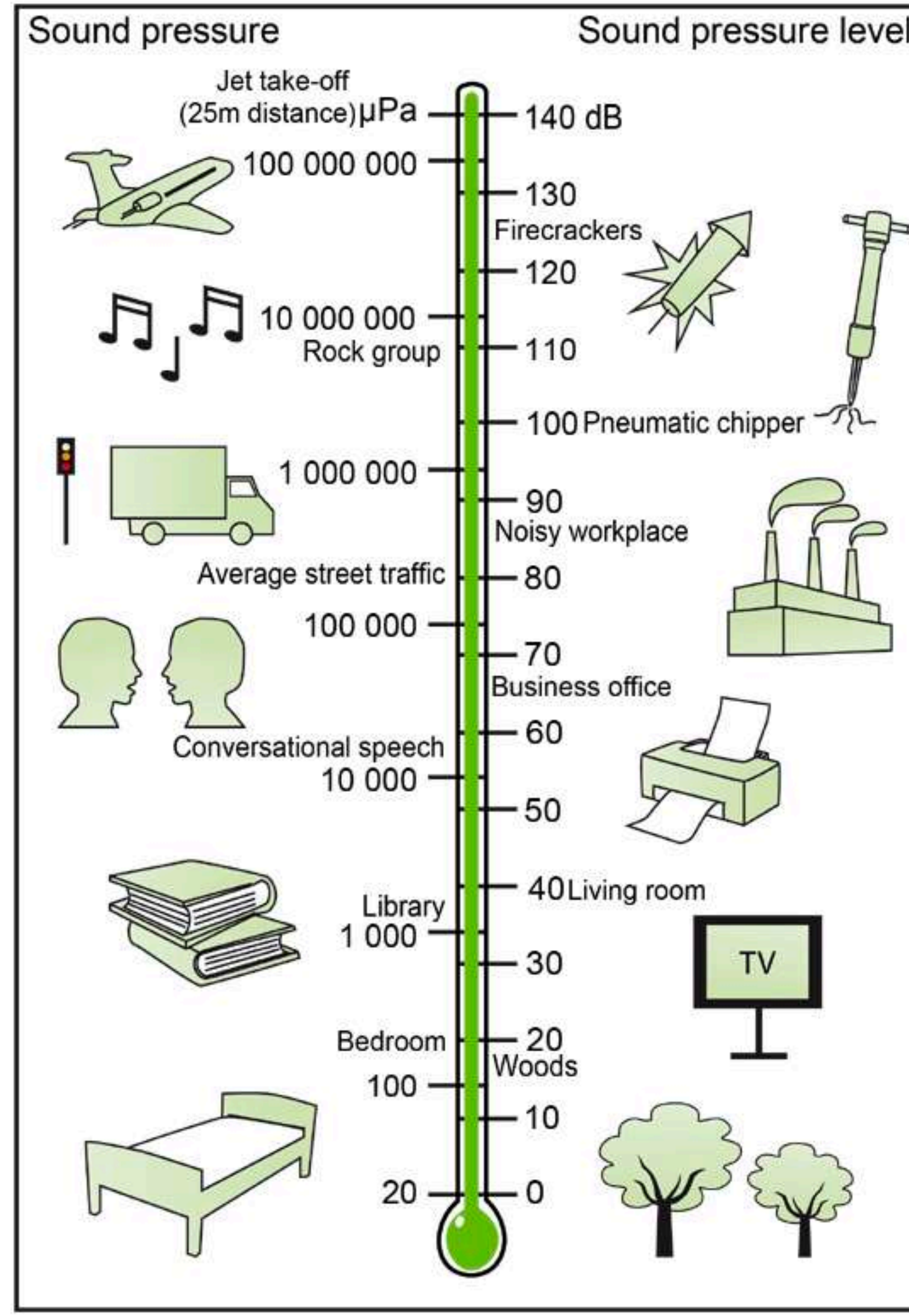
ACOUSTICS

Wave propagation: sound pressure

In fluids such as air and water, sound waves propagate as disturbances in the ambient pressure level. The intensity or strength of sound waves in the air is related to the **sound/ acoustic pressure level** (SPL) which is measured on a logarithmic scale in decibels (dB).

$$L_p = 20 \cdot \log_{10}\left(\frac{p}{p_{\text{ref}}}\right)$$

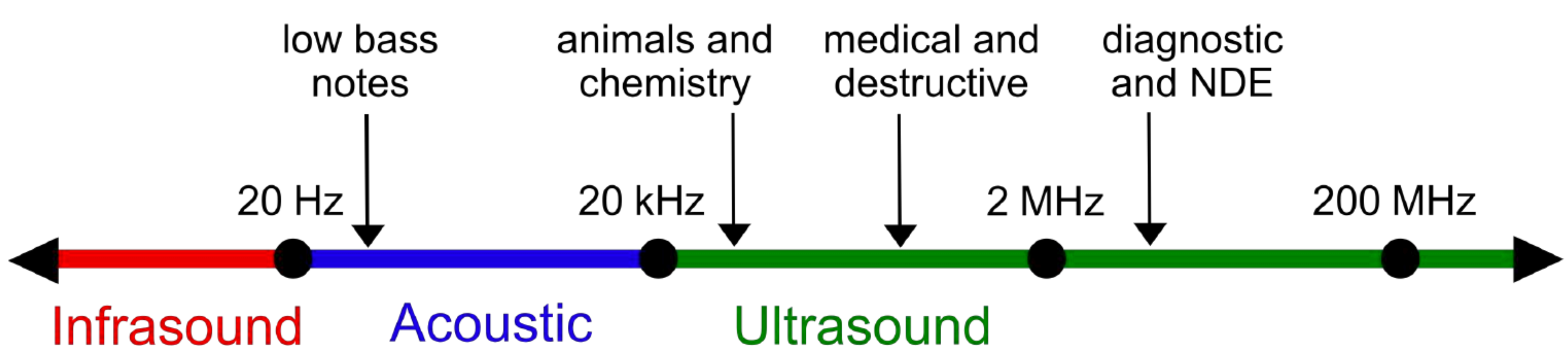
- L_p is the acoustic pressure level in decibels (dB),
- p is the measured sound pressure,
- p_{ref} is the reference sound pressure level, often set at 20 micropascals (µPa), which is considered the threshold of human hearing at a frequency of 1,000 Hz.



ACOUSTICS

Wave propagation: frequency

Physicists and acoustic engineers tend to discuss sound pressure levels in terms of frequencies, partly because this is how our ears interpret sound. What we experience as "higher pitched" or "lower pitched" sounds are pressure vibrations having a higher or lower number of cycles per second.



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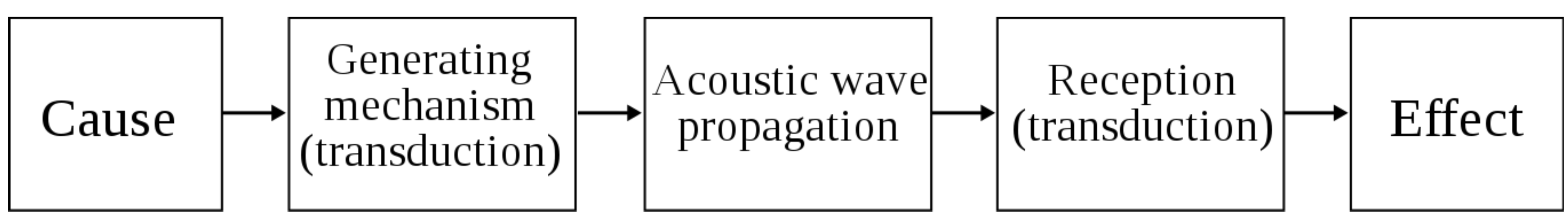

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ACOUSTICS

Transduction in acoustics

Acoustic transducers are devices that convert acoustic energy, in the form of sound waves, into electrical signals or vice-versa.

- *Sound to electrical signal*: conversion of variations in air pressure (sound waves) into electrical signals, es. microphones
- *Electrical signals to sound*: conversion of electrical signals into mechanical vibrations to produce sound waves, es. speakers or loudspeakers

Acoustic transducers find widespread use in audio systems, telecommunications, medical imaging (ultrasound), sonar, industrial measurements, and numerous other fields generate sound

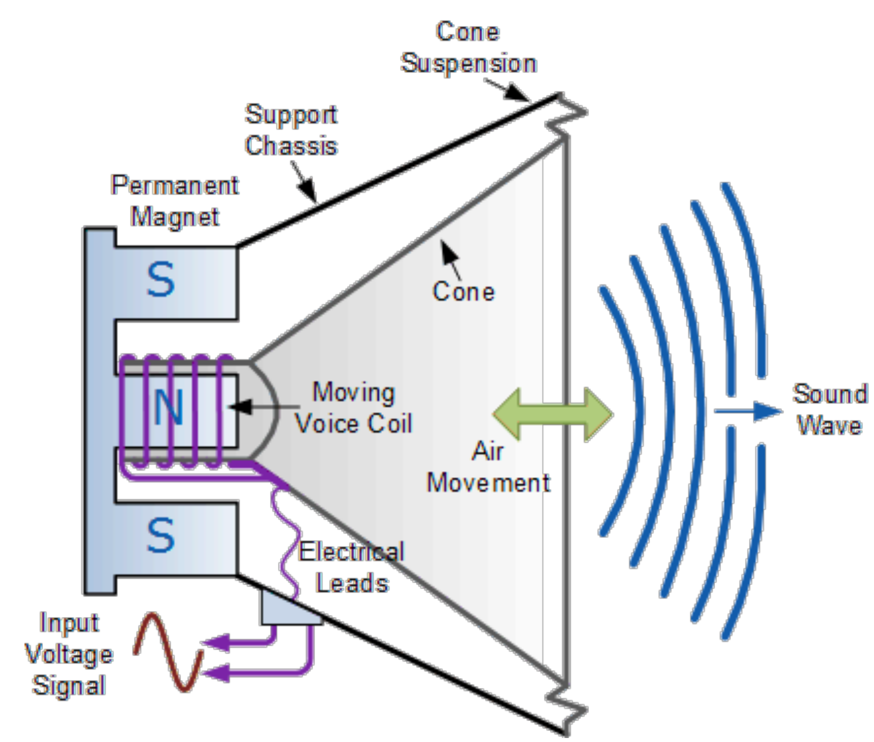
https://www.montana.edu/rmaher/ee417/transducer_tutorial.pdf

ACOUSTICS

Transduction in acoustics: generation of sound waves

Acoustic transducers for sound generation, like **loudspeakers**, operate on the principle of converting electrical energy into mechanical vibrations, which then produce sound waves in the air.

An electromagnet (*moving voice coil*) is placed within a magnetic field created by a permanent magnet. When an electrical current passes through the voice coil, it generates a magnetic field that interacts with the fixed magnetic field of the magnet, causing the voice coil to move back and forth rapidly. This movement drives a diaphragm or cone connected to the voice coil, causing it to vibrate sympathetically. As the diaphragm vibrates, it pushes and pulls the surrounding air, creating compression and rarefaction, which in turn generates sound waves. The frequency, amplitude, and quality of the sound produced depend on the electrical signal applied to the voice coil and the design of the speaker components.



Transduction in acoustics: detection of sound waves

1. Sound is a pressure disturbance: need for a pressure gauge

2. Sound exerts a pressure: use it to drive an electrical generator

3. Sound is a wave: measure simultaneously at two (or more) different positions to identify the wave direction

Diaphragm

Membrane that can be set into motion by sound waves

Sensitivity: how much motion from a given sound intensity

Generating element

Electromechanical device that converts motion of the diaphragm into an electrical current and voltage

Sensitivity: how much electrical signal power is obtained from a given sound intensity

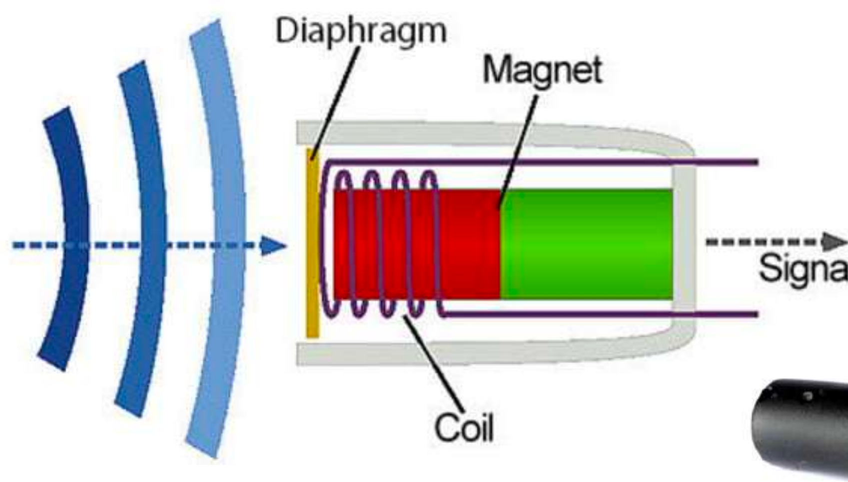
ACOUSTICS: MICROPHONES

Transduction in acoustics: detection of sound waves

Microphone types:

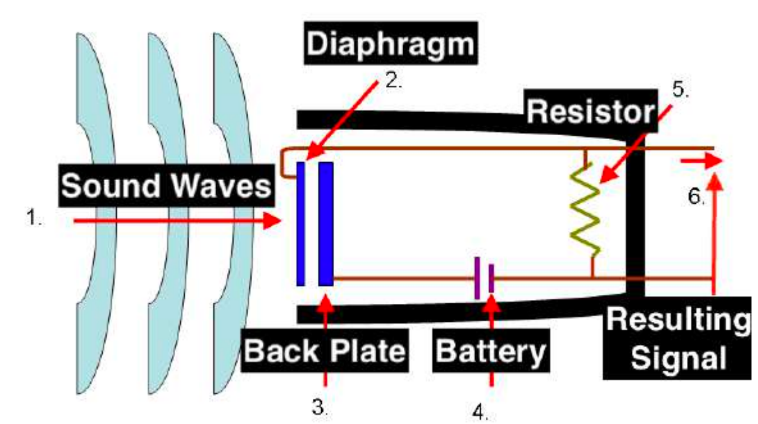
1. **Dynamic Microphones:**

Robust and versatile, these microphones use a coil attached to a diaphragm within a fixed magnetic field. The diaphragm moves the coil of wire, induced current (Faraday Law) is generated



2. **Condenser Microphones:**

High sensitivity and accuracy, condenser microphones use a charged diaphragm and a fixed plate (backplate) to capture sound. They require power, either through batteries or phantom power from an external source.



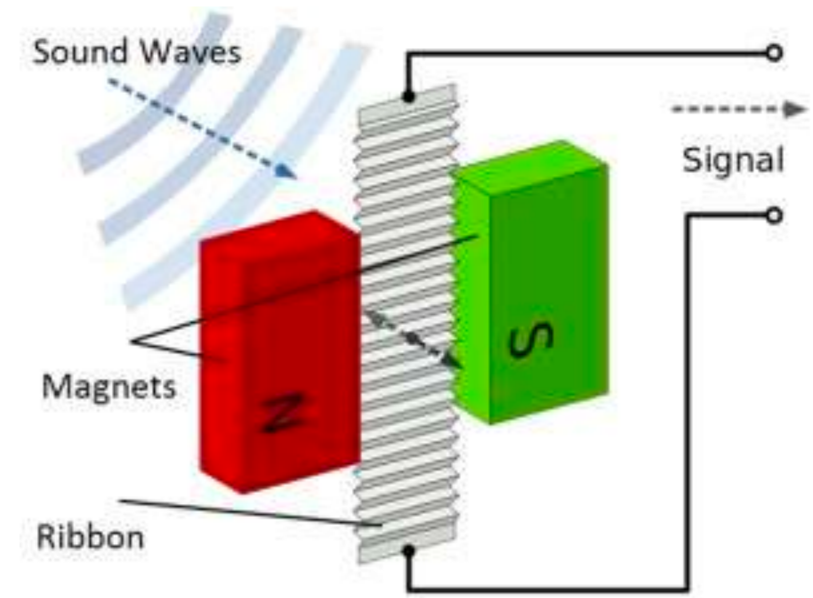
ACOUSTICS: MICROPHONES

Transduction in acoustics: detection of sound waves

Microphone types:

3. **Ribbon Microphones:**

These microphones use as a diaphragm a thin aluminum ribbon suspended in a magnetic field.



4. **Piezoelectric Microphone**

Piezoelectric generating element and diaphragm attached to piezo element. Rugged, reasonably sensitive, not particularly linear

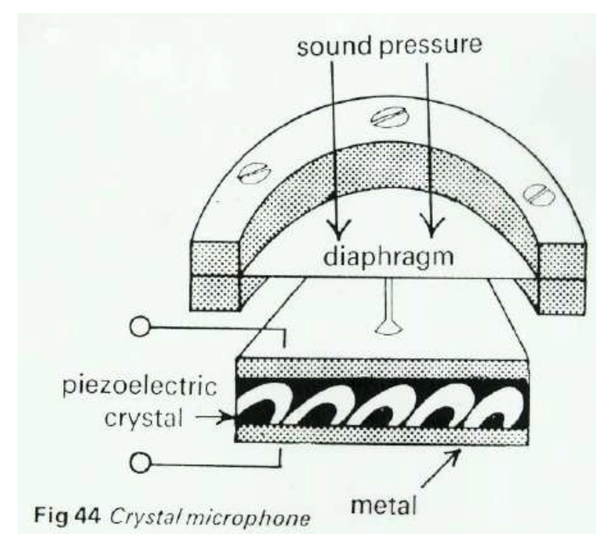
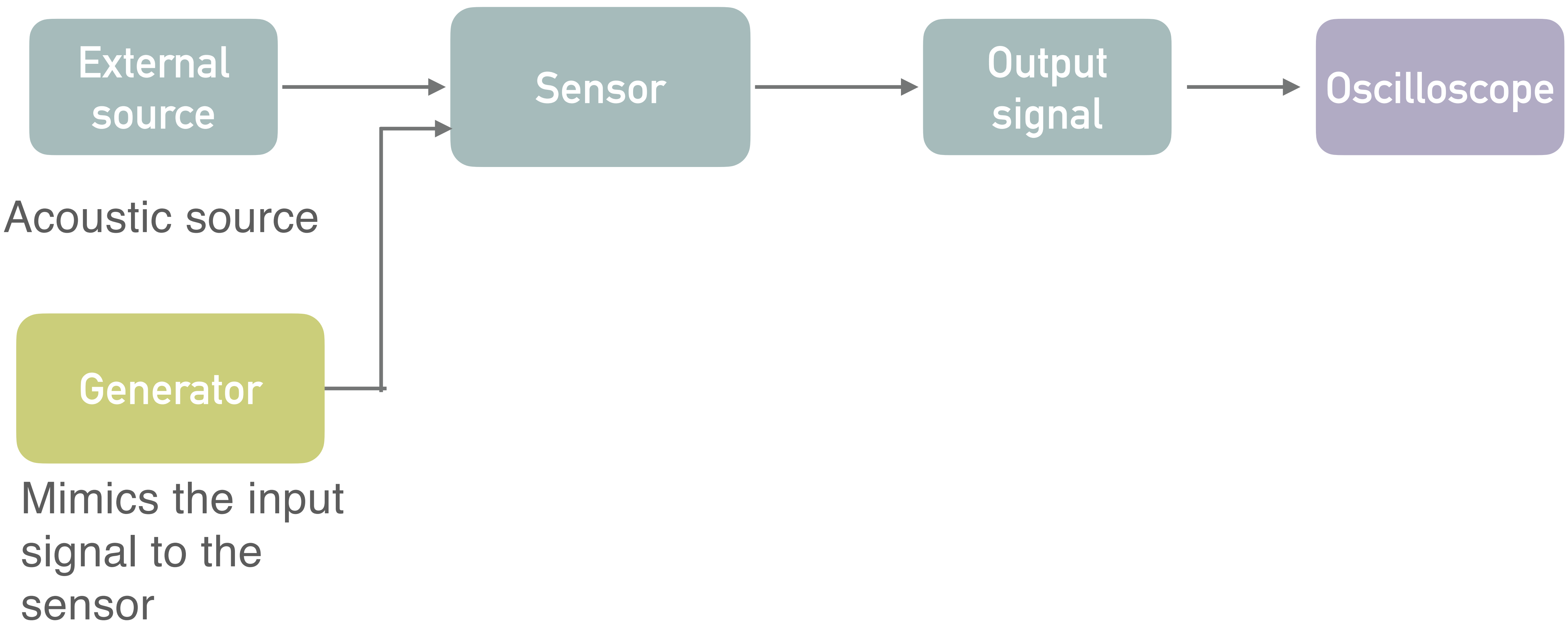


Fig 44 *Crystal microphone*

Each microphone type has unique characteristics and is suited to specific applications based on factors like sound quality, directionality, sensitivity, and intended use, catering to diverse needs in recording, broadcasting, live sound reinforcement, and more.

EXAMPLE: MICROPHONE/SPEAKER READOUT CHAIN



- Generate a signal: (waveform generator + speaker) vs (natural acoustic source)
- Sensor: microphone
- Read the signal output: oscilloscope

See Lab.2