Lecture I:

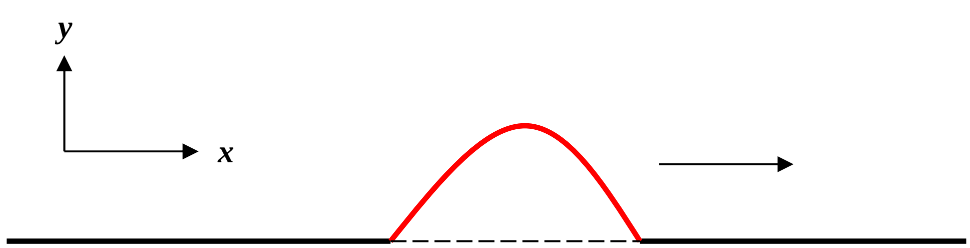
Introduction

What is Sound?

- The word **Sound** is used to describe two different physical phenomena:
  - Auditory sensation in one's ear(s) (one's brain?) – what is this exactly?
  - Disturbance (= local energy over-density) in a physical medium (*e.g.* air, water – a gas, liquid, or solid) which *propagates* in that medium, which in turn causes an auditory sensation in one's ears/brain.
  - Humans (and many other animal species) have developed ability to *hear* sounds, because sounds/sound waves *exist* in the natural environment. Two ears are the *minimum* requirement for ability to locate the *source* of a sound – evolutionarily an extremely beneficial capability.

- The scientific study of the phenomenon of sound is known as **Acoustics**.
  - Broad interdisciplinary field – physics, engineering, psychology, speech, music, physiology, neuroscience, architecture, etc.
  - Different branches of Acoustics:
    - Physical Acoustics
    - Musical Acoustics
    - Psycho-Acoustics
    - Physiological Acoustics
    - Architectural Acoustics
    - *etc*….

- Sound propagates in a physical medium (gas/liquid/solid) as a **wave.**
  - An acoustical disturbance (localized excess energy) propagates as a *collective* excitation (*i.e.* vibration) of a group of atoms and/or molecules that make up the physical medium.
    - Visualize a pulse traveling down a stretched rope, string or wire:



    - This kind of wave is known as a **transverse** wave – because the *displacement,* $y(x)$ of the medium from its equilibrium position due to the disturbance is *transverse* (*i.e.* perpendicular) to the direction of propagation of the disturbance.

    - Now visualize an acoustical pulse propagating in a gas, liquid or solid (*e.g.* air, water, or a metal – steel or aluminum).

    - This kind of wave is known as a **longitudinal** wave – because atoms in these media are displaced *longitudinally* (*i.e*. parallel) to the direction of propagation of the disturbance, as the disturbance passes through a given region of the medium.

- Thus, sound waves that we can hear with our own ears are the result of physical vibrations of matter – collective, vibrations of atoms/molecules.

- <u>Food for Thought:</u> Is it possible to "hear" the sound associated with *one* atom or one molecule vibrating? – Answer: yes – *e.g*. via use of various of today's nanoscale technologies! But atomic/molecular vibrations "heard" not as sound waves – the frequencies associated with quantum-mechanical vibrations are usually *very* high (*e.g*. *GHz* {10^9 *Hz*} – molecular or *THz* {10^{12} *Hz*} – atomic), compared to *e.g*. 20 *KHz*. The high frequencies would need to be scaled down (by a huge amount) in order for us to Hear/perceive them – in the audio frequency range (20 *Hz* – 20 *KHz*).

- Sound waves propagating in a physical medium propagate with a characteristic speed in that medium – known as the **speed of sound**.
    - Speed of sound in (dry) air (at sea level) is v_{air} ~ 345 meters/second (m/s)
    - A more accurate relation is: $v_{air} \sim 331.4 + 0.6*T$ m/s where *T* is the temperature of the air (in Celsius degrees).
    - <u>Practical problem:</u> If lightning strikes the ground 1 mile away from you (= 5280 ft = 1609.3 *m*), how long after you see the lighting will you hear the thunder? Distance (*m*) = speed (m/s) * time (s), *i.e*. $d = vt$, so therefore $t = d/v$. The answer is $t \sim 4.7$ *s*.

- Sound waves propagating in a physical medium also carry **energy**, *E* (Joules, *J*) in the wave and also carry **momentum**, *p* (*kg-m/s*) in the wave.

- Sound waves propagating in a physical medium exert a **force**, *F* (Newtons, *N*) on the atoms/molecules in the medium in the vicinity of the wave disturbance.
    - In a gas, such as air, these forces create local hi/lo variations in the density ρ and pressure *P* (via ideal gas law: $PV = NRT$).
    - True also for fluids – not truly incompressible….
    - Solids are in fact *<u>elastic</u>* – atoms bound together (via *EM* force!) making up the solid in some kind of 3-D lattice arrangement of atoms in the solid deforms/stretches as the acoustic disturbance passes through the solid material.

What **is Human Music?**

- What ***is*** human music??? Answer(s) to this question are profound….
  - An aesthetically pleasing ***sequence*** of tones? ***Why*** are they aesthetically pleasing?
    - Anthropocentric – humans (*n.b* we are ***social*** creatures!) are primarily most interested in the sounds that we humans make. Because of the way our 1-D vocal chords vibrate (obeys the 1-D wave equation), the human voice is ***rich*** in harmonic overtones, related by ***integer*** multiples of the frequency of the fundamental (lowest frequency): $\boxed{f_n = nf_1,\ n = \text{integer} = 1,2,3,4,5...}$ ⇐ Has ***profound*** implications for human music…
    - **Question:** What was the ***first*** human musical instrument?
      Answer: The human voice!
    - It is ***not*** an accident/random coincidence that the musical instruments we humans have developed over the millennia artistically mimic/emulate the human voice (some to greater extent than others) – thus our musical instruments ***also*** have overtone structures of $f_n = nf_1$ as opposed to *e.g*. completely arbitrary or no relation.

      (*n.b*. percussion instruments & the beat/tempo/rhythms of music emulate the ***internal rhythms*** of humans – *e.g*. our heart beat, & also play on our internal sense of the ***rate*** of passage of time…)
    - The musical scale(s), chords and chord progressions that we humans have developed for our music reflect our anthropocentric interest/enjoyment in hearing complex sounds that have human, voice-like $f_n = nf_1$ harmonic structure.
  - ***Why*** is music pleasurable to humans?
    - Can trace music in human society back to stone age/paeleolithic era/prehistoric times (*i.e*. ~ 30,000-40,000 years ago). Does it go back even earlier???
      Homo sapiens as distinct primate species is ~ 200,000 years old.
    - Music ***is*** an intimate part of human culture, apparently from way back…
    - Music ***is*** of fundamental importance to humans – ***Why***?
      - Important in/for human evolution? To what degree? ***Why***? ***How***?
      - Have you ever met anyone who ***hates*** music? {Yes – problems with their brain...}
  - Music has been shown to ***stimulate*** the human brain, in many ways…
    - Auditory signal processing center(s) in our brain also connected to emotional centers.
    - Participation/listening to music produces "feel-good" brain chemicals – dopamine, serotonin, oxyocin, reduces stress hormones (*e.g*. cortisol), boosts immune system!
    - Choirs singing together ***synchronizes*** heartbeats (via vagus nerve excitation)!
    - Music ***facilitates*** brain development of young children and in ***learning***. ***Why***? ***How***?
    - Memory of music is different from that of normal "everyday" memory – very strong!!
      - Can recall/"play" entire songs/albums back in one's head. ***How/why***?
      - If musical memory is so strong, ⇒ music ***must*** be important to us! ***Why/how***? Written human language only ~ 6000-7000 years old (coincides with development of agrarian societies – recording "financial" transactions) worldly wisdom before that (hunter-gatherer societies) only passed down orally – spoken word – but perhaps also in songs?

- Music is important for other living creatures – birds, whales, frogs, etc. ***Why***? **How**?
  - Other living creatures don't ***need/use*** a formal musical scale, like we humans do!
  - Singing animals certainly don't know anything about formal musical scales.
  - Yet, the songs of many animals ***are*** quite musical-sounding! ***Why***???
  - Use of a formal musical scale enables humans to more easily learn/play each others music; also to impose structure/form & rules for music genres.

- Human Development of Musical Instruments
  - Emulate/mimic the human voice (some instruments more so than others, and *n.b.* not all musical instruments!!!), with $f_n = nf_1$ harmonic structure.
  - Sounds from musical instruments can evoke powerful emotional response(s) in humans – happiness, joy, sadness, *etc*. because auditory signals are wired into various emotional centers of our brains! ⇐ ***Why*** is this? ***How*** did this happen?
    - Music is innate - runs very deep in human psyche. ***Why***? ***How***?

Basic/Foundations of Physics: **There exist three (3) fundamental physical quantities**:

We use the Systeme International (SI)/metric system of units: kilograms – meters – seconds:

Length: — *meter* (*m*): 1*m* = 39.37 *inches* = 3.28 *ft*
1 *ft* = 0.3048 *m*

1 *cm* = 1/100 *m* (*centi-meter*)
1 *mm* = 1/1000 *m* (*milli-meter*)
1 μm = 1/1,000,000 *m* (*micro-meter*)

Mass: — *kilogram* (*kg*)
1 *kg* = 1000 *grams*
1 *gm* = 1/1000 *kg*

Time: — second (s) (or *sec*)
1 *day* = 24 *hours* = 24 ∗ 60 *minutes* = 1440 *minutes*
= 24 ∗ 60 ∗ 60 *seconds* = 86,400 *seconds*

Additional physical quantities we will need in this course:

Position: = instantaneous location of a point in space. 3-D vector quantity (*SI* units: *m*):

$$\boxed{\vec{r}(t) = x(t)\hat{x} + y(t)\hat{y} + z(t)\hat{z}} \qquad \text{(Cartesian Coordinates)}$$

Velocity: = instantaneous time rate of change of position $\vec{r}(t)$, and specifies the instantaneous direction in which the time rate of change of position is occurring. 3-D vector quantity:

$$\boxed{\vec{v}(\vec{r},t) = v_x(\vec{r},t)\hat{x} + v_y(\vec{r},t)\hat{y} + v_z(\vec{r},t)\hat{z} = \partial\vec{r}(t)/\partial t} \qquad \text{(SI units: } m/s\text{)}$$

<u>Speed</u>: = instantaneous time rate of change of position = <u>magnitude</u> of velocity:

$$v(\vec{r},t)=\left|\vec{v}(\vec{r},t)\right|=\sqrt{v_x^2(\vec{r},t)+v_y^2(\vec{r},t)+v_z^2(\vec{r},t)}$$ (Cartesian Coordinates)

Thus, <u>Velocity</u> = instantaneous speed in a given <u>direction</u>, *e.g*. in east direction, or up, or down, *etc*.

From calculus, we know that the instantaneous velocity $\vec{v}(\vec{r},t)$ is the partial derivative of the instantaneous position with respect to time (= instantaneous *<u>slope</u>* of $\vec{r}(t)$ *vs*. *t* graph):

Velocity: $$\vec{v}(\vec{r},t)=\frac{\partial\vec{r}(t)}{\partial t}=\frac{\partial x(t)}{\partial t}\hat{x}+\frac{\partial y(t)}{\partial t}\hat{y}+\frac{\partial z(t)}{\partial t}\hat{z}=v_x(\vec{r},t)\hat{x}+v_y(\vec{r},t)\hat{y}+v_z(\vec{r},t)\hat{z}$$

<u>Acceleration</u>: = instantaneous time rate of change of velocity, and a direction (up, down, east, west, *etc*.) specifying the direction in which the time rate of change of velocity is occurring. 3-D vector quantity (*SI* units = meters per second squared, *i.e*. m/s^2)

Speed increasing with time —accelerating
Speed <u>decreasing</u> with time —<u>decelerating</u>

Acceleration: $$\vec{a}(\vec{r},t)=a_x(\vec{r},t)\hat{x}+a_y(\vec{r},t)\hat{y}+a_z(\vec{r},t)\hat{z}=\partial\vec{v}(\vec{r},t)/\partial t$$ (Cartesian Coordinates)

Magnitude (size) of instantaneous acceleration: $$a(\vec{r},t)=\left|\vec{a}(\vec{r},t)\right|=\sqrt{a_x^2(\vec{r},t)+a_y^2(\vec{r},t)+a_z^2(\vec{r},t)}$$

From calculus, we also know that the instantaneous acceleration is the partial derivative of the instantaneous velocity with respect to time (= instantaneous <u>slope</u> of $\vec{v}(\vec{r},t)$ vs. *t* graph):

Acceleration: $$\vec{a}(\vec{r},t)=\frac{\partial\vec{v}(\vec{r},t)}{\partial t}=\frac{\partial v_x(\vec{r},t)}{\partial t}\hat{x}+\frac{\partial v_y(\vec{r},t)}{\partial t}\hat{y}+\frac{\partial v_z(\vec{r},t)}{\partial t}\hat{z}=a_x(\vec{r},t)\hat{x}+a_y(\vec{r},t)\hat{y}+a_z(\vec{r},t)\hat{z}$$

Motion in 3-D is independent in *x-y-z* directions for a <u>free particle</u> (unless geometrically <u>constrained</u> somehow – *e.g*. bead on a helix or circular ring):

3-D Equations of motion of a <u>free particle</u> with <u>constant acceleration</u>: $\vec{a}(\vec{r},t)=\vec{a}_o$

$$\vec{v}(\vec{r},t)=\vec{v}_o+\vec{a}_o t$$ (v_o = 3-D vector velocity at time t = 0)

$$\vec{r}(t)=\vec{r}_o+\vec{v}_o t+\tfrac{1}{2}\vec{a}_o t^2$$ (r_o = 3-D vector position at time t = 0)

Short-hand way to write out the separate *x-y-z* equations of motion (decouple for a free particle):

$$v_x(\vec{r},t)=v_{ox}+a_{ox}t \qquad x(t)=x_o+v_{ox}t+\tfrac{1}{2}a_{ox}t^2$$
$$v_y(\vec{r},t)=v_{oy}+a_{oy}t \qquad y(t)=y_o+v_{oy}t+\tfrac{1}{2}a_{oy}t^2$$
$$v_z(\vec{r},t)=v_{oz}+a_{oz}t \qquad z(t)=z_o+v_{oz}t+\tfrac{1}{2}a_{oz}t^2$$

Force: — (*SI* units = Newtons = $kg\text{-}m/s^2$)

Newton's 2nd Law of motion: Instantaneous Force = (mass, m) $*$ (instantaneous acceleration, a)

$$\boxed{\vec{F}(\vec{r},t) = m\vec{a}(\vec{r},t)}$$

Force is a 3-D vector quantity.

kg $\quad$ m/sec^2

1 Newton of force = 1 $kg\text{-}m/(sec)^2$

Weight, W = (mass, m) × (gravitational acceleration, g). *n.b.* Weight, W is a force!

Earth's gravitational acceleration: $g = 9.81\ m/sec^2$ (at sea level) $\quad g = \dfrac{G_N * M_{earth}}{(R_{earth})^2}$

$$\boxed{W = mg}$$

Pressure: — Pressure = force F per unit area, A. *n.b.* Pressure, p is a *scalar* (not vector) quantity!

$$\boxed{p = F/A} \quad (Newtons/(meter)^2)$$

SI / metric units of pressure ≡ Pascal, *Pa* $\quad 1\ Pa = 1 N/m^2$.
1 Atmosphere (14.7 *psi*) = 101,325 Pascals = 1.01325×10^5 Pascals.

Work & Energy: — Work $\boxed{W = \int_C \vec{F}(\vec{r}) \bullet d\vec{\ell}(\vec{r})}$. If force is *constant*: Work W = Force, F × Distance, d

For *constant* force: $\boxed{\boldsymbol{W = Fd}}$ = energy required to *e.g.* move an object of weight $W = mg$ upwards a distance d on earth's surface (= uniform gravitational field).

energy

SI / metric units of work & energy = *Joules*

Energy is (*always*) conserved

Energy required to move an object can be electrical, gravitational, wind, chemical, *etc*.

Power: = instantaneous time rate of change of energy (*SI* units = *Watts*)

Power $\boxed{P(t) = \dfrac{\partial E(t)}{\partial t}}$ *Watts* = *Joules* per *second* = *Joules/sec*

1 *kilo-Watt* = 1000 *Watts* = 10^3 *Watts*

1 *mega-Watt* = 1 million *Watts* = 10^6 *Watts*

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