Physics 498 Physics of Music/Musical Instruments
Lecture I:

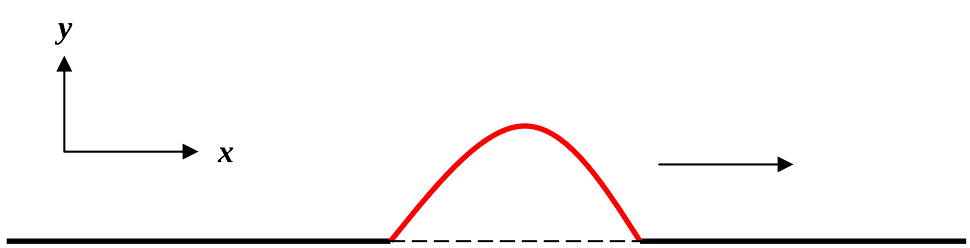
Introduction

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 causes an auditory sensation in one's ears.
  - 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 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.

- Food for Thought: 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, compared to e.g. 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).
    - Practical problem: 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. $d = v*t$ 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 gas density and gas pressure (via ideal gas law: $PV = NRT$).
    - True also for fluids – not truly incompressible….
    - Solids are in fact elastic – 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 Music?

- What *is* music??? Answer(s) to this question are profound….
  - An aesthetically pleasing *sequence* of tones? *Why* are they aesthetically pleasing?
    - Anthropocentric – because of the way our (1-D) vocal chords vibrate, the human voice is rich in harmonic overtones, related by integer multiples to the frequency of the fundamental (lowest frequency): $\boxed{f_n = nf_1,\ n = \text{integer} = 1, 2, 3, 4, 5...}$
    - It is ***not*** an accident/random coincidence that the musical instruments we humans have developed over the millennia 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 having 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???
    - 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…
    - 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 music memory so strong, ⇒ music *must* be important to us! *Why/how*?
  - 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!
    - Music is innate - runs very deep in human psyche. *Why*? *How*?

<u>Basic/Foundations of Physics</u>: <u>There exist three (3) fundamental physical quantities</u>:

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

<u>Length</u>: — meter (m): 1m = 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)

<u>Mass</u>: — kilogram (kg)
1 kg = 1000 grams
1 gm = 1/1000 kg

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

<u>Additional physical quantities we will need in this course</u>:

<u>Position</u>: = instantaneous location of a point in space. 3-D vector quantity (SI Units: m):

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

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

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

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

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

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 is the partial derivative of the instantaneous position with respect to time (= instantaneous <u>slope</u> of $\vec{r}(t)$ vs. t graph):

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

<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: $$\boxed{\vec{a}(\vec{r},t) = a_x(\vec{r},t)\hat{x} + a_y(\vec{r},t)\hat{y} + a_z(\vec{r},t)\hat{z}}$$ (Cartesian Coordinates)

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

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

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>: $\vec{a}(\vec{r},t) = \vec{a}_o$

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

$$\boxed{\vec{r}(t) = \vec{r}_o + \vec{v}_o t + \tfrac{1}{2}\vec{a}_o t^2}$$ (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):

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

<u>Force</u>: — (SI units = Newtons = kg-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.

$$\underset{kg}{m} \qquad \underset{m/sec^2}{\vec{a}}$$

1 Newton of force = 1 kg -m/(sec)^2

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

Earths gravitational acceleration: $g = 9.81$ m/sec^2 (at sea level) $g = \frac{G_N * M_{earth}}{(R_{earth})^2}$

$$\boxed{W = mg}$$

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

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

Metric units of pressure ≡ Pascal, Pa 1 Pa = 1N/m2.
1 Atmosphere (14.7 psi) = 101,325 Pascals

Work & Energy: — Work $\boxed{W = \int_C \vec{F}(\vec{r}) \bullet d\vec{r}}$. 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 $W = mg$ a distance, d

energy

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

1 kilowatt = 1000 watts

1 megawatt = 1 million watts

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