PHYS 536: Introduction to Acoustics*

R. J. Wilkes

We'll start class at 7:05 tonight to give people time to arrive/log in

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<u>Session 1</u>

Course intro:

Fundamental quantities

Overview of wave properties

- "...and DSPs" was from a legacy course name picked up by time schedulers…

1/3/2023

Course information

- T-Th, 7:00-8:50 pm, A110 Physics-Astronomy, and/or Zoom
  - **We will meet by Zoom only for most sessions**
  - In-person (optional) meetings this week, and a few later dates for demos
- R. J. Wilkes
  - 206-543-4232 , wilkes@uw.edu
    Office hrs: after class, or by appointment via zoom/phone
- Website: http://courses.washington.edu/phys536
- Books:
  - *Fundamentals of Acoustics* 3rd ed. (1982) or 4th ed. (2000), Lawrence E. Kinsler, A. R. Frey, A. B. Coppens, J. V. Sanders; Wiley
  - *Why you hear what you hear*, Eric J. Heller, Princeton University Press, 2013, ISBN: 978-0691148595
  - Books are on 2 hr reserve in the UW Odegaard Undergraduate Library – see http://www.lib.washington.edu/about/hours/
- Grades – see class calendar on website for due dates
  - Two 5 p term papers (100 points each) - submit proposed topics by email
  - End-of-term exam (100 pts, take-home; *no* final exam in exam week)

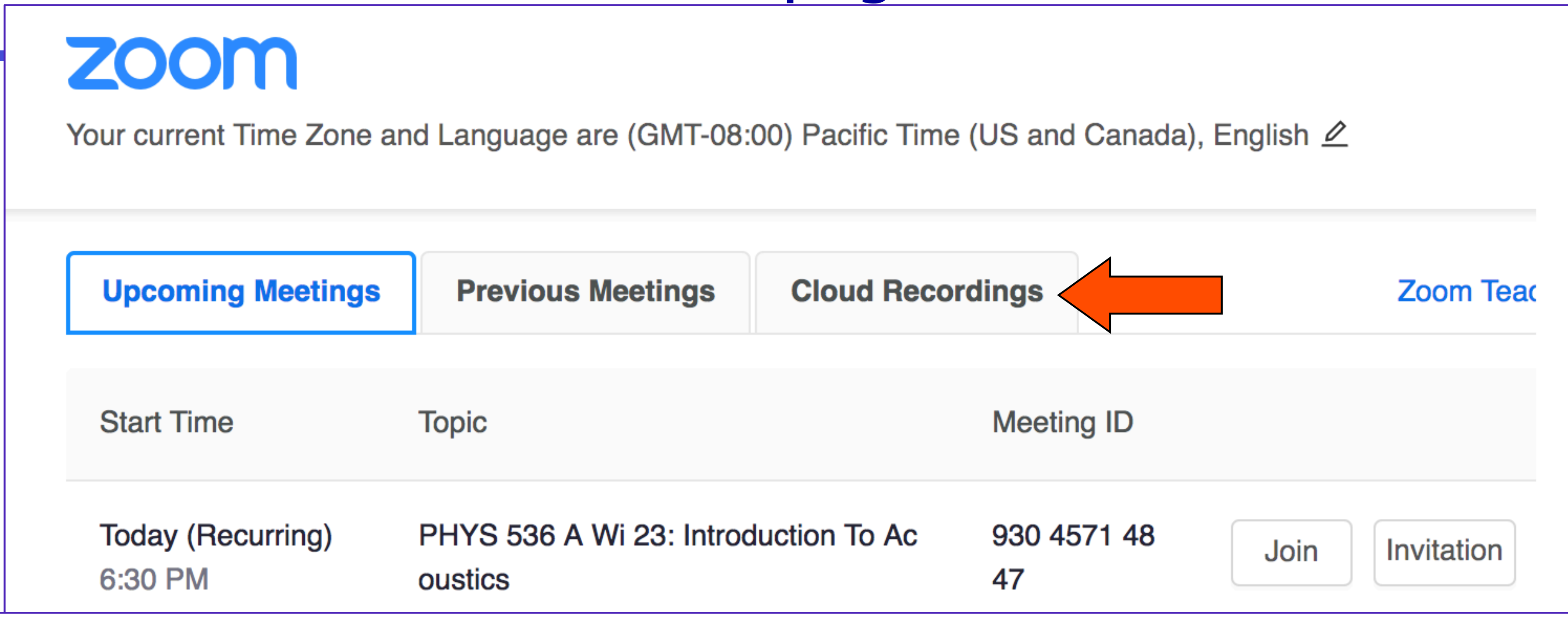
Course home page

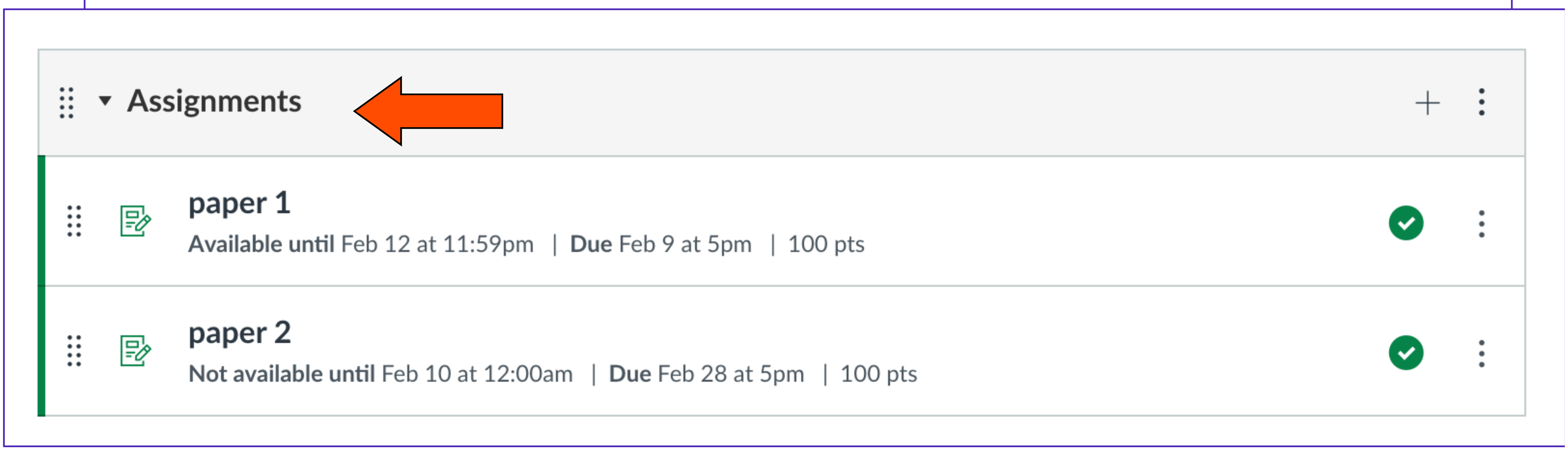
- Class will meet in-person in A-110 Physics-Astronomy on Tuesdays, and online-only on Thursdays. However**, ALL LECTURE SESSIONS WILL BE AVAILABLE ONLINE**, using the Zoom videoconferencing system. Click on "How to connect" link below. I will open the session at 6:45pm each night.
  Practice using zoom before class - IF YOU HAVE TROUBLE CONNECTING, email me, wilkes@uw.edu
  Zoom sessions will be recorded, see below for links.
  All slides shown will be posted on this website, see link below.

  Textbooks:
  Fundamentals of Acoustics, by Lawrence E. Kinsler, et al, Wiley, 3rd or 4th edition
  Why You Hear What You Hear, by Eric J. Heller, Princeton University Press, 2013
  Copies available at the University Book Store, UW branch.

1. Course information
2. Syllabus and calendar
3. How to connect to online sessions (links on course Canvas page).
   Here is a pdf copy of Zoom instructions for students)
4. Lecture notes (will appear here before class - but possibly as late as 6:45 pm!)
5. Books on reserve
6. Suggestions for term paper topics
7. Suggested problem sets and solutions
8. Canvas course page - will **not** be used except for posting grades.
   (**This** is the course home page.)
9. link to lecture recordings on Zoom
   Files will be available the day after class. NOTE: due storage limit in Canvas, the first few lecture recordings will later be archived and deleted from Canvas. Contact me if you need the files.

Canvas pages





Course syllabus and schedule – first part…

See : http://courses.washington.edu/phys536/syllabus.htm

Session	date	Day	Readings:	K=Kinsler, H=Heller	Topic
1	3-Jan	Tue	K ch. 1	H: Ch. 1, 2	Course intro, acoustics topics, overview of wave properties; pulses, transverse and longitudinal waves, overview of sound speeds ← Tonight
2	5-Jan	Thu	K ch. 1	H: Ch. 9, 10	harmonic oscillators: simple, damped, driven; complex exponential solutions, electrical circuit analogy, resonance, Q factor
3	10-Jan	Tue	K ch. 1	H: Ch. 3	Fourier methods: Fourier series, integrals, Fourier transforms, discrete FTs, sampling and aliasing
4	12-Jan	Thu	K. chs 10	H: Ch. 4, 11	Frequencies and aliasing; convolution and correlation; discrete convolution; digital filtering, optimal filters, FIR filters, noise spectra; power spectra. REPORT 1 PROPOSED TOPIC DUE
5	17-Jan	Tue	K. ch. 2, 3, 4	H: Ch. 13, 15	waves in strings, bars and membranes; Acoustic wave equation; speed of sound; Harmonic plane waves, intensity, impedance.
6	19-Jan	Thu	K. Ch. 5, 6	H: Ch. 1	Spherical waves; transmission and reflection at interfaces
7	24-Jan	Tue	K. Ch. 8	H: Ch. 7	Radiation from small sources; Baffled simple source, piston radiation, pulsating sphere;
8	26-Jan	Thu	K: Ch. 10	H: Chs. 13-15	Near field, far field; Radiation impedance; resonators, filters
9	31-Jan	Tue	K. Ch. 9-10	H: Chs. 16-19	Musical instruments: wind, string, percussion
10	2-Feb	Thu	K. Ch 14		Transducers for use in air: Microphones and loudspeakers
11	7-Feb	Tue	K. Ch 11	H: Chs. 21-22	The ear, hearing and detection
12	9-Feb	Thu	K. Chs 5,11		Decibels, sound level, dB examples, acoustic intensity; noise, detection thresholds. REPORT 1 PAPER DUE by 7 PM; REPORT 2 PROPOSED TOPIC DUE

…rest of schedule

Session	date	Day	Readings:	K=Kinsler, H=Heller	Topic
13	14-Feb	Tue	K. Ch. 12	H: Ch. 28	Environmental acoustics and noise criteria; industrial and community noise regulations
14	16-Feb	Thu	K. Ch. 15		Underwater acoustics; sound speed in seawater; undersea sound propagation.
15	21-Feb	Tue	K. Ch. 15		Sonar equations, undersea noise; transducers for use in water (hydrophones and pingers), sonar and positioning systems
16	23-Feb	Thu	Notes		Applications: acoustical positioning, seafloor imaging, sub-bottom profiling;
17	28-Feb	Tue			Course wrapup. Student report 2 presentations
18	2-Mar	Thu			Student report 2 presentations
19	7-Mar	Tue			Student report 2 presentations
20	9-Mar	Thu			Student report 2 presentations. TAKE-HOME FINAL EXAM ISSUED
--	17-Mar	Fri			FINAL EXAM ANSWERS DUE by 5 PM

Class is over after you turn in your take-home exam. No in-person final exam during finals week.

If you do not regularly check your @uw.edu email, please send me a message from your primary email account so I can use that.

These classic books are also available, not reserve, in the libraries indicated:

Acoustic measurements.
Leo L. (Leo Leroy) Beranek, 1914-2016.
1949 New York, J. Wiley
Available at Engineering Library Stacks-Floors 3&4 (QC227 .B4) and other locations

Principles of underwater sound for engineers
Robert J. Urick
1967 New York, McGraw-Hill
Available at Engineering Library Stacks-Floors 3&4 (QC225 .U7) and other locations

Physics of sound in the sea.
Sonar Analysis Group.
1968]- New York, Gordon and Breach
Available at Engineering Library Stacks-Floors 3&4 (QC225 .P48) and other locations

Principles of noise.
Jacob Joachim Freeman, 1913-
1958 New York, Wiley
Available at Engineering Library Stacks-Floors 3&4 (TK5981 .F72 1958) and other locations

Science & music
James Jeans, 1877-1946.
1937 New York : The Macmillan Company ; Cambridge, Eng. : The University Press
Available at Music Library Library Downstairs (ML3805.J43 S3) and other locations

Announcements

(Look for a slide like this at the beginning of each session)

- All slides shown in class will be posted on the course website *
  http://courses.washington.edu/phys536
  - Check the website at least weekly, for new postings and corrections
  - Homework set 1 has been posted there
- All lectures will be broadcast on Zoom and recorded there
  - You can replay the slides and audio later if desired
  - Recordings will be available 24 hr after session
- You should meet, discuss and work with your classmates !
- Tonight:
  1. Course info and overview
  2. Review of wave properties
  3. Fundamental quantities in acoustics
  4. Introduction/review on Fourier methods

* Slides will be available (link posted on the class website) shortly **before** each session

About term paper 1

- Term paper 1, due Feb 9
  - 5 page paper on a topic of your choice, relevant to the course material
    - Any legible type size or line spacing!
  - Goal: research a topic and communicate what you learned
  - See link on course home page for suggestions, but best is to choose a topic *you* want to learn more about
  - Papers should be in the form of a technical paper, with abstract and references – no special template or format, just make sure basic components are all there
  - To ensure topic is appropriate (and encourage you to get started early!), you must send me a brief email proposal describing your topic, and the resources you will use to research it, on or before January 12.
  - Papers must be submitted on or before 5 pm on February 9, as .doc, .pdf or .txt files, via the Canvas assignments page
  - Due to the unusually large class size, it may take more than one week to grade all the papers…

About term paper 2

- Term paper 2, due Feb 28
  - Presentation to the class on a topic of your choice, relevant to the course material, equivalent in content to a 5 p paper
  - Due to the unusually large class size, we are limited to 15 minutes per student – more about how to prepare your presentation later…
  - You may further study the topic of your first paper, but all content must be new
  - You must send me a brief email proposal describing your topic, and the resources you will use to research it, on or before February 9.
  - Slides must be submitted on or before 5 pm on February 17, as .ppt, .pdf or equivalent files, via the Canvas assignments page.
    - You can tweak your slides after submission, but what you submit on 2/17 should be a complete report
  - We will spend the last 4 days of the term listening to your presentations - I will ask for volunteers for the first night (2/28) and then randomly assign the remaining slots

Acoustics in the news

New York Philharmonic's Geffen Hall is opening after a renovation aimed at breaking its acoustic curse

NY Times, 11/3/22

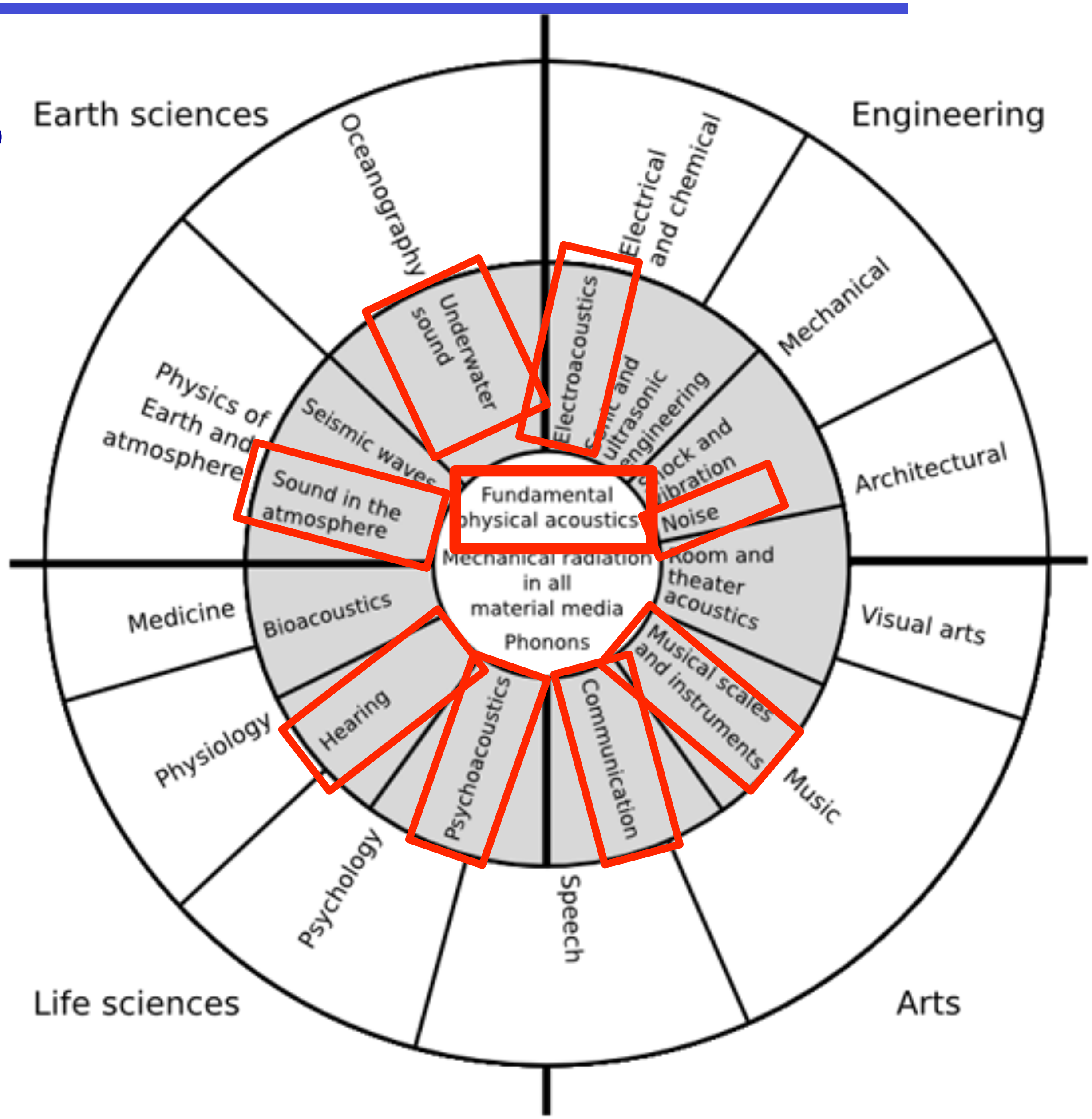
"It was the first theater to open at Lincoln Center, in September 1962. And everyone with ears instantly realized that the new hall was a disaster. Musicians couldn't hear each other. Listeners couldn't hear the violas and cellos. Trumpets, trombones and clarinets echoed like yodelers in the Alps. Bernstein later described an "acoustical-psychological" effect: in such an extremely big, long hall, where nearly a third of the audience was more than 100 feet from the stage, the orchestra, which doesn't use amplification, sounded distant because it appeared as if "through the wrong end of a telescope."...

The new design team included…the acoustician Paul Scarbrough, of the firm Akustiks. In past iterations of the building, acousticians always played second fiddle to architects. It says a lot about Geffen's priorities that Akustiks got to set the specifications for the hall, recommended the layout and signed off on everything…They built a scale model of Geffen large enough to walk into. Imagine a hinged box split vertically down the middle. Both men recounted how Leo Beranek, Abramovitz's acoustician for Philharmonic Hall…ended up sidelined on the decision about enlarging the hall. "Acousticians were just expected to sign off on an architect's plans," Scarbrough said, "and in fact the example of Philharmonic Hall became proof why that had to change."."

www.nytimes.com/interactive/2022/11/03/arts/music/geffen-hall-tuning.html

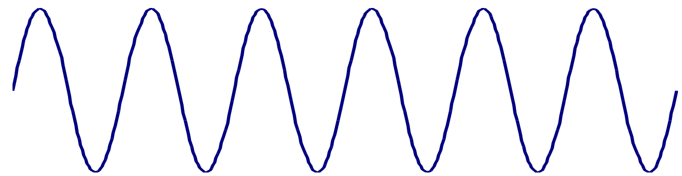
Introduction to Acoustics

- Huge field!
- We'll only be able to partially cover a fraction of topics (marked)

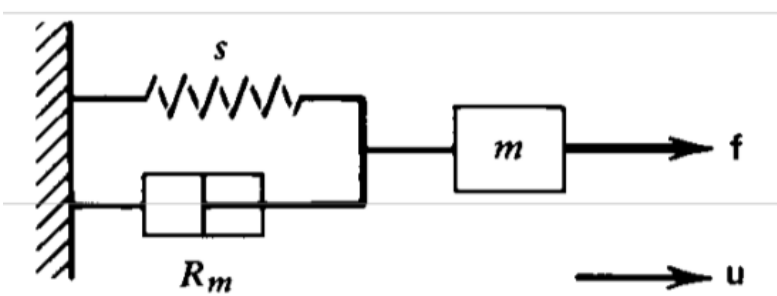


Course overview

- Review of waves
  - Wave motion, properties of waves, description of waves
    - Harmonic functions
    - Frequency, wavelength, speed
    - Sound terminology
    - Overview of interference and phase relationships

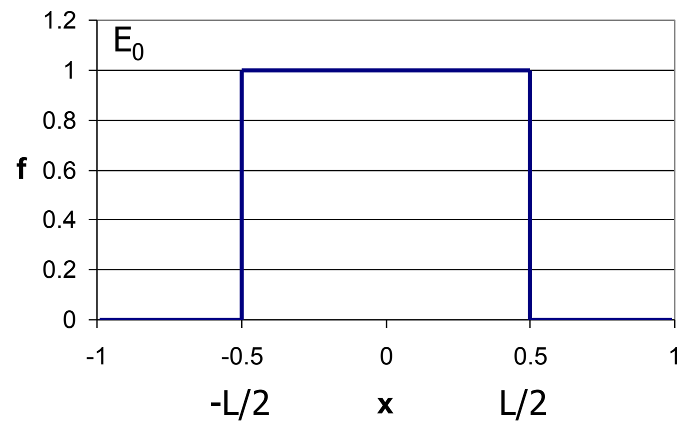


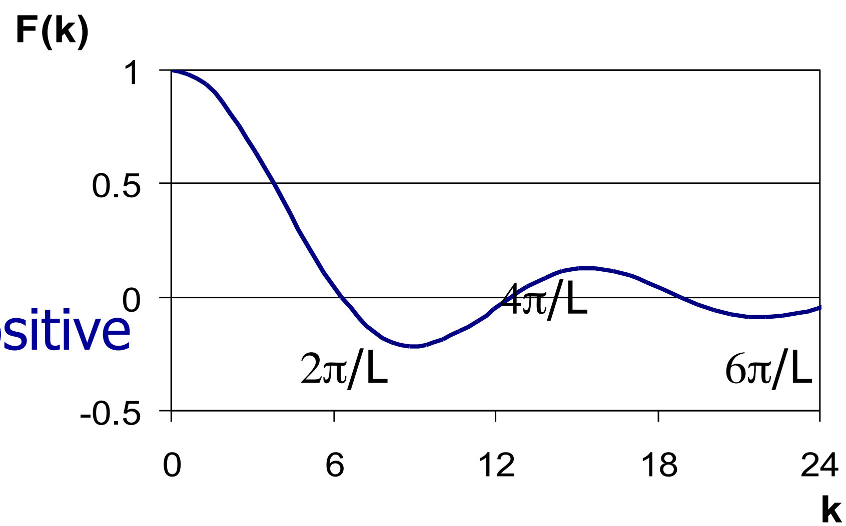
- Harmonic oscillators (model for sources/receivers)
    - Simple, damped, driven
    - Acoustical Impedance
    - Transient response
    - Electrical analogues
    - Resonance



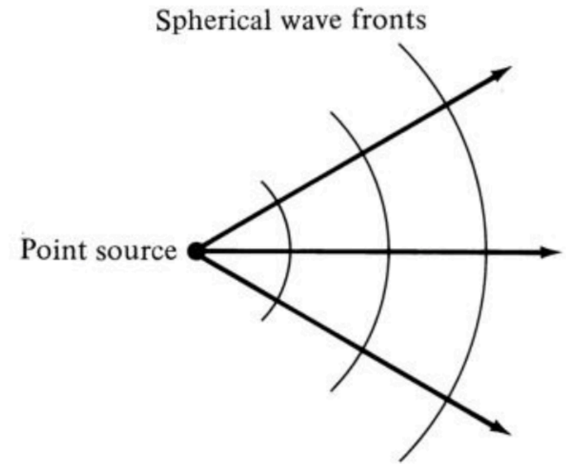
Course overview

- Fourier methods
  - Fourier analysis:
    - Periodic and aperiodic functions
    - Discrete and continuous spectra
  - Fourier transforms:
    - Fourier integrals
    - Famous FT pairs
  - Discrete FTs
    - Sampling and aliasing
    - Frequencies – negative and positive
  - Convolution and correlation
    - Application in acoustics
    - Digital filtering
    - Noise spectra
    - Resolution and windowing

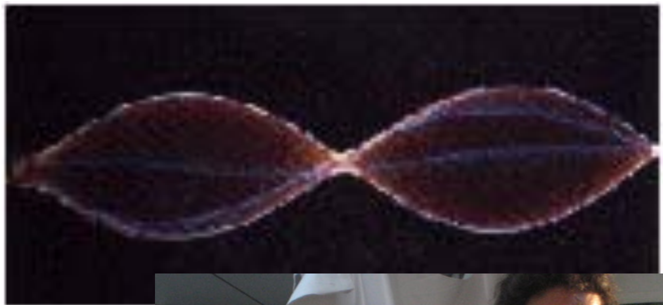




Course overview



- Sound propagation
  - Reflection and refraction of sound waves
  - Acoustic wave equation
  - Spherical waves
  - Radiation from small sources, near/far field
  - Resonators

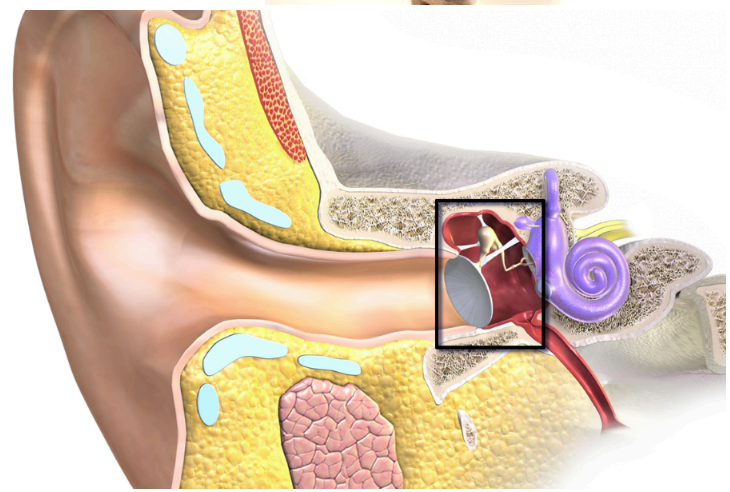


- Interference phenomena
  - Phase relationships
  - Beats
  - Standing waves on strings and in tubes

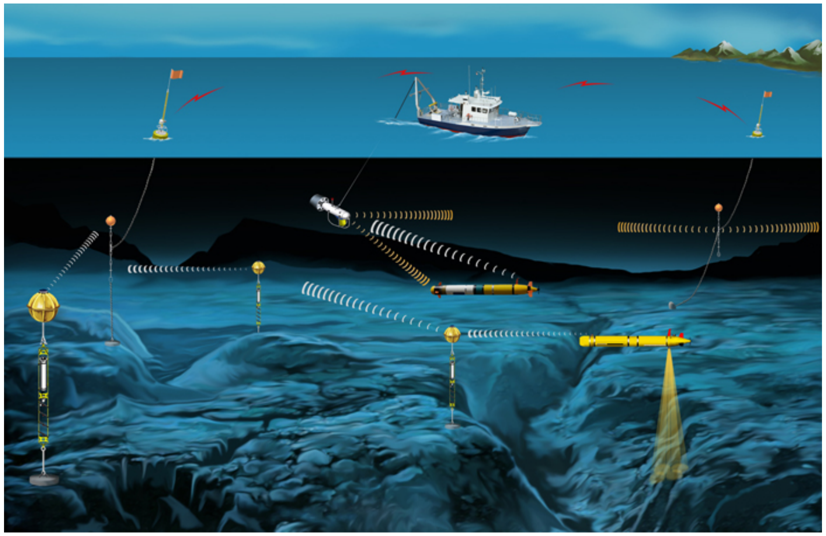
- Musical instruments
  - String instruments (guitar)
  - Wind instruments (organ pipes, horns)
  - Percussion instruments (membranes and sheets)

Course overview

- Transducers
  - For air: microphones and loudspeakers
  - For water: pingers and hydrophones
- Hearing
  - The ear
  - Sound perception
  - Noise measurement and analysis
    - Decibels
    - Sound pressure and intensity levels
    - Instruments and applications
    - Statistical analysis of data,
    - Environmental noise regulations



Course overview

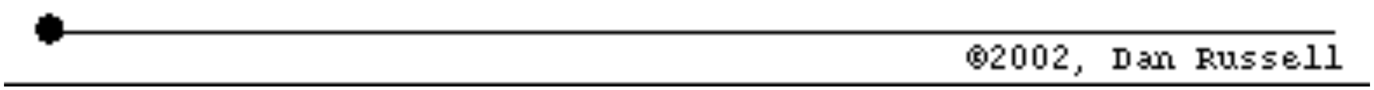


- Underwater acoustics
  - sound speed in seawater
  - undersea sound propagation
  - Sonar equations, undersea noise
  - Sonar and positioning systems
  - Acoustical imaging and mapping
- Guest speakers (tentative)
  - oceanography with acoustics
  - High resolution acoustic seafloor imaging
- Student presentations
  - Your second term paper project
- End-of-term exam
  - Take-home, open book/notes; issued 3/9, due 3/17

Sound: Propagating disturbances

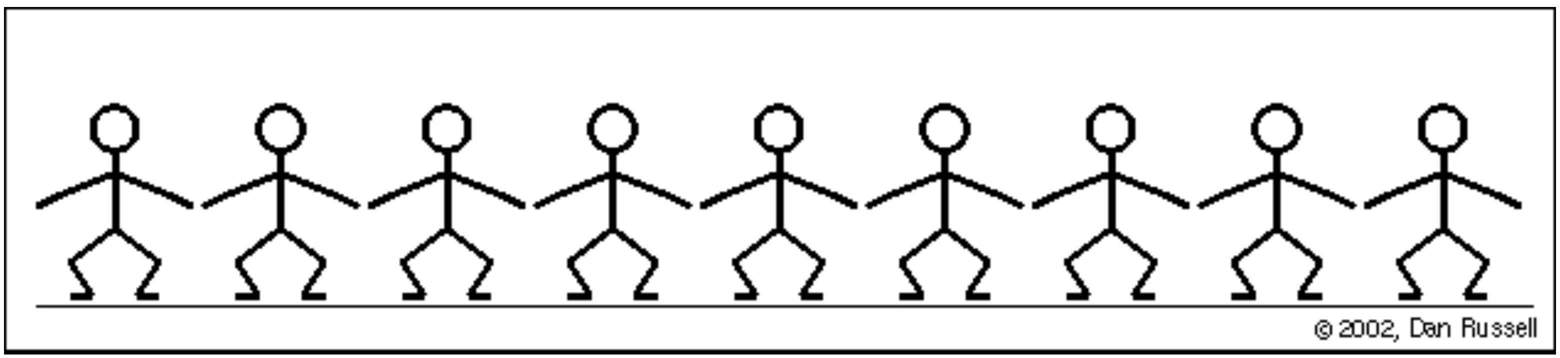
- Sound = mechanical *waves* propagating in a material medium
- Before we look at waves: *pulses* (non-repeating disturbances)

Pulse on a string:



(we'll come back to pulses on strings later tonight)

Pulse in a line of people ("doing The Wave"):



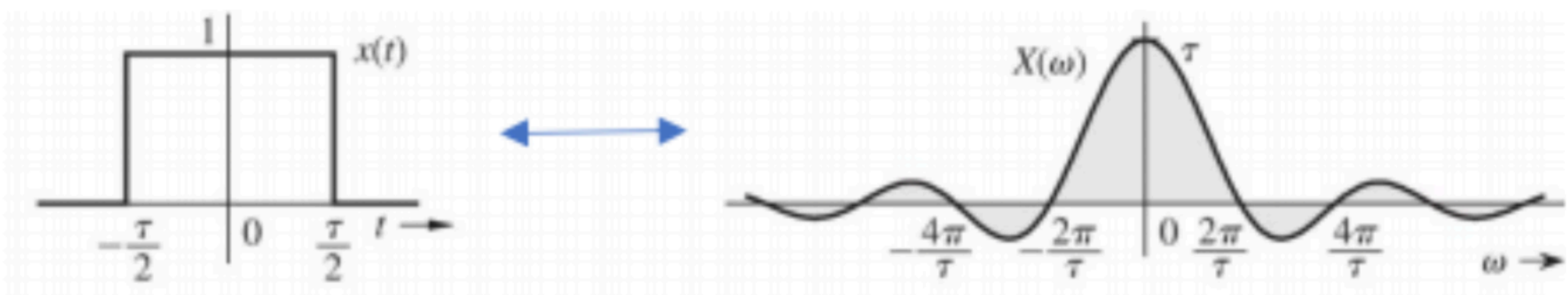
Review: Basics of Waves

- *Many* physical phenomena involve *wave motion*
  - ripples on a rope
  - compression waves in a slinky
  - water waves on the ocean
  - sound waves in the air
  - Light waves in intergalactic space

  (Quantum theory says *everything* is a wave, sometimes…)
- Waves move in both *space* and time:
  - Wave = *repetitive disturbance* that *propagates in space*
- First step is to *describe* waves, in unified and unambiguous terms

Space, time and frequency

- Wave motion = phenomenon that *connects* space and time
  - Crucial point of departure for Einstein !
- Another parameter of propagating waves: frequency (in time domain)
  - Related to wavelength (in space) or wave number = cycles per meter), via speed of propagation c
  - Time domain (voltage vs time) is connected to frequency domain (amplitude vs f), via Fourier transforms: h(t) → H(f)
    - H, h = Fourier transform pair (more on this later)
    - Same for spatial location and wave number: h(x) → H(k)



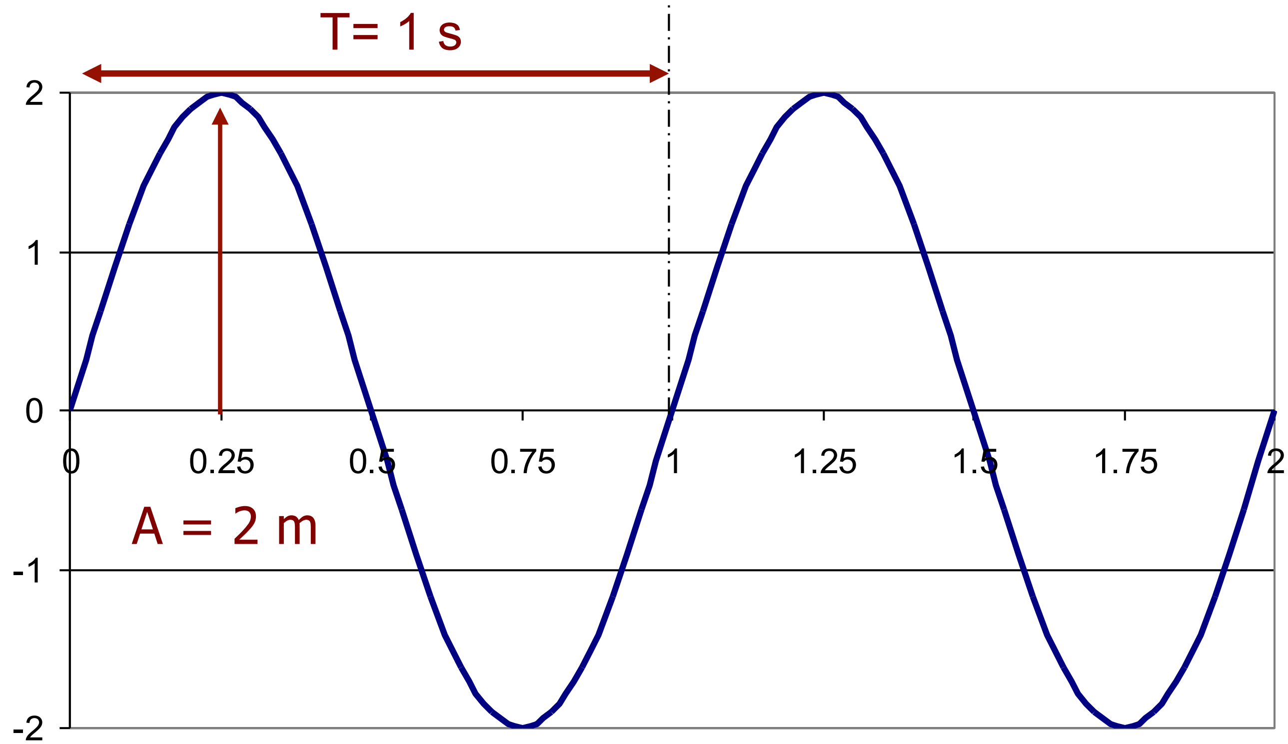
Time domain

Frequency domain
(what do negative values represent here?)

Displacement vs time picture of waves

- We can stand at one place and watch wave move past us vs *time*
    - Graph of displacement vs time
    - *Period* T = time for one cycle ("wavelength" in time units) to go past
    - *Frequency* f = cycles passing per second (hertz, Hz) = 1/T
  - This wave on the rope has 1 cycle in 1s, so T = 1 s
  - *Amplitude* is 2 meters

variation with time at a *fixed point in space*



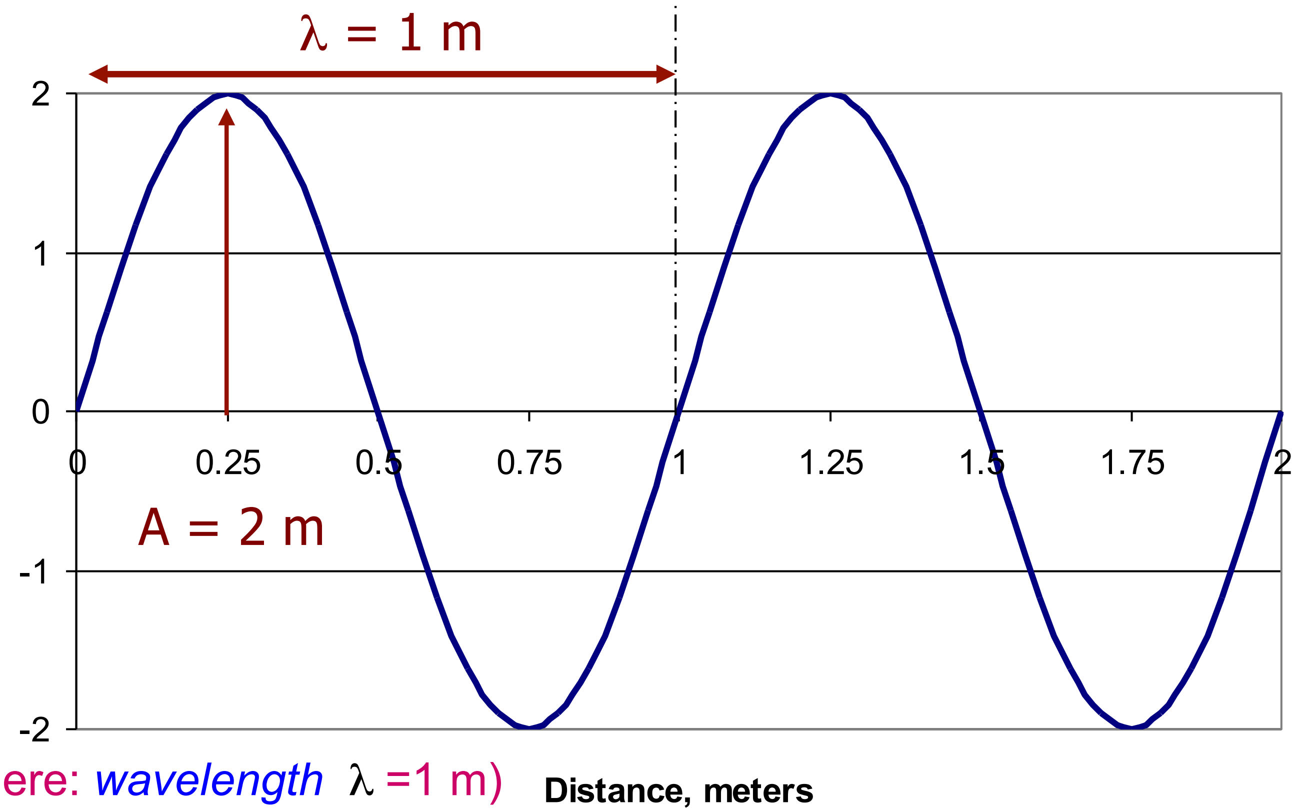
time, seconds
(Here: *period* T=1sec)

Displacement vs position: At one instant, a snapshot

- Previous picture was graph of displacement vs time at one location
- Here: Picture of rope at one instant of time (say, t=0):
  - We see rope's displacement vs position along rope (y vs x)
- *Wavelength* λ = length of one full cycle (distance between peaks)
- *Amplitude* A = maximum displacement (height)

snapshot =
picture of rope,
frozen at one
instant of time:

configuration
in space at a
fixed point in
time



(Here: *wavelength* λ =1 m)

Harmonic functions to describe wave motion

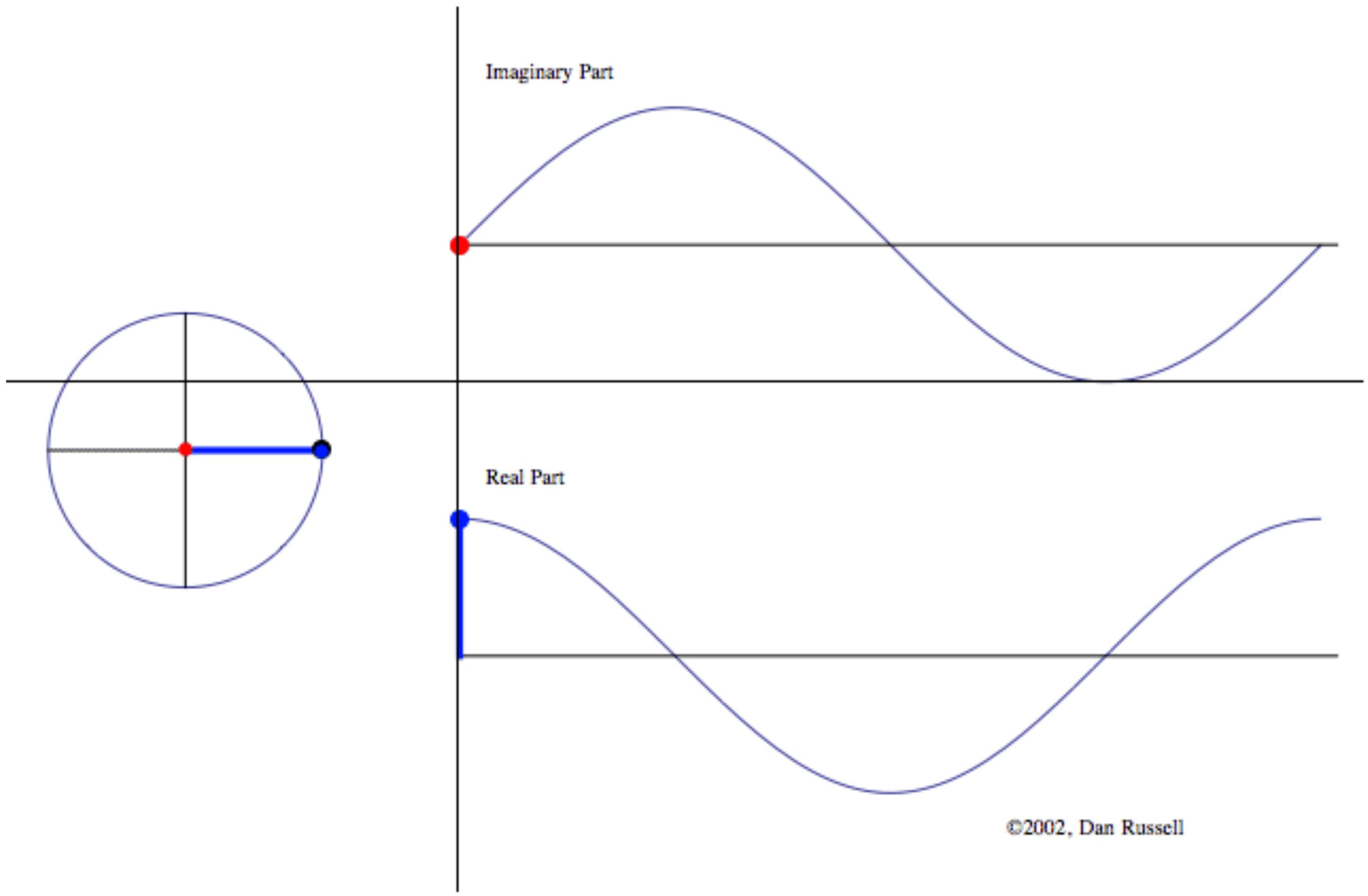
- To describe waves, we need to specify {disturbance} = y (x, t)
- From our "snapshot" plot we see $$y(x) = A\sin\left(\frac{2\pi x}{\lambda}\right)$$
- From our "standing in one place" plot, we see that the position of the peak that was at x=0 at t=0, has moved to the right after time t, by a distance $$x = \frac{t}{T}\lambda$$
- So the value of the wave function at time t is equal to the value at time t=0 for *any combination* of x and t such that $$x - \frac{t}{T}\lambda = 0$$
- So we can describe the wave with the "harmonic function" *

$$y = A\sin\left(\frac{2\pi}{\lambda}x - \frac{2\pi}{T}t\right); \quad \frac{2\pi}{\lambda} = \text{ wave number } k; \quad \frac{2\pi}{T} = 2\pi f = \text{ angular frequency } \omega,$$

* The circular functions sin/cos are "harmonic" because they can describe sound waves that are multiples of some base frequency – next time…

Connection between Circular motion and Harmonic functions

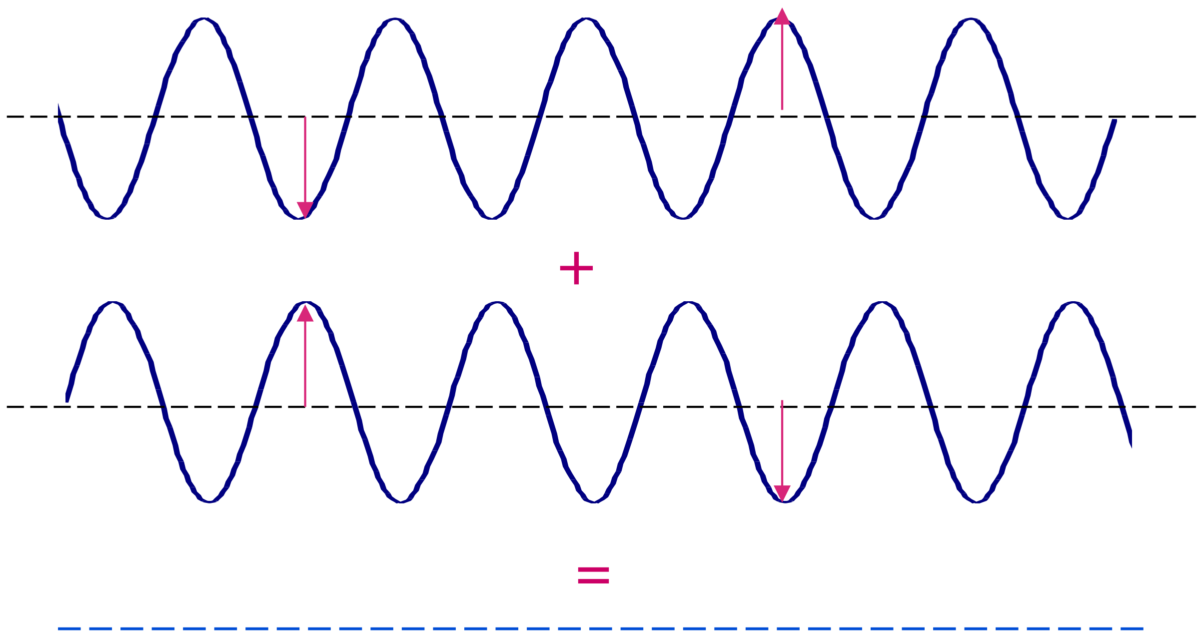
- Phasor rotating around a circle traces sin/cos vs time
- The y-axis may be imaginary axis in complex plane



Interference

More on this later…

- Important (defining!) properties of waves:
  - They can *add* to each other (*superposition*), because of which…
  - They can *interfere* with each other
    - Add 2 waves (colliding water waves, merging sound waves, etc) and their *amplitudes add*
      - **If one is going down while the other is going up, result = 0**



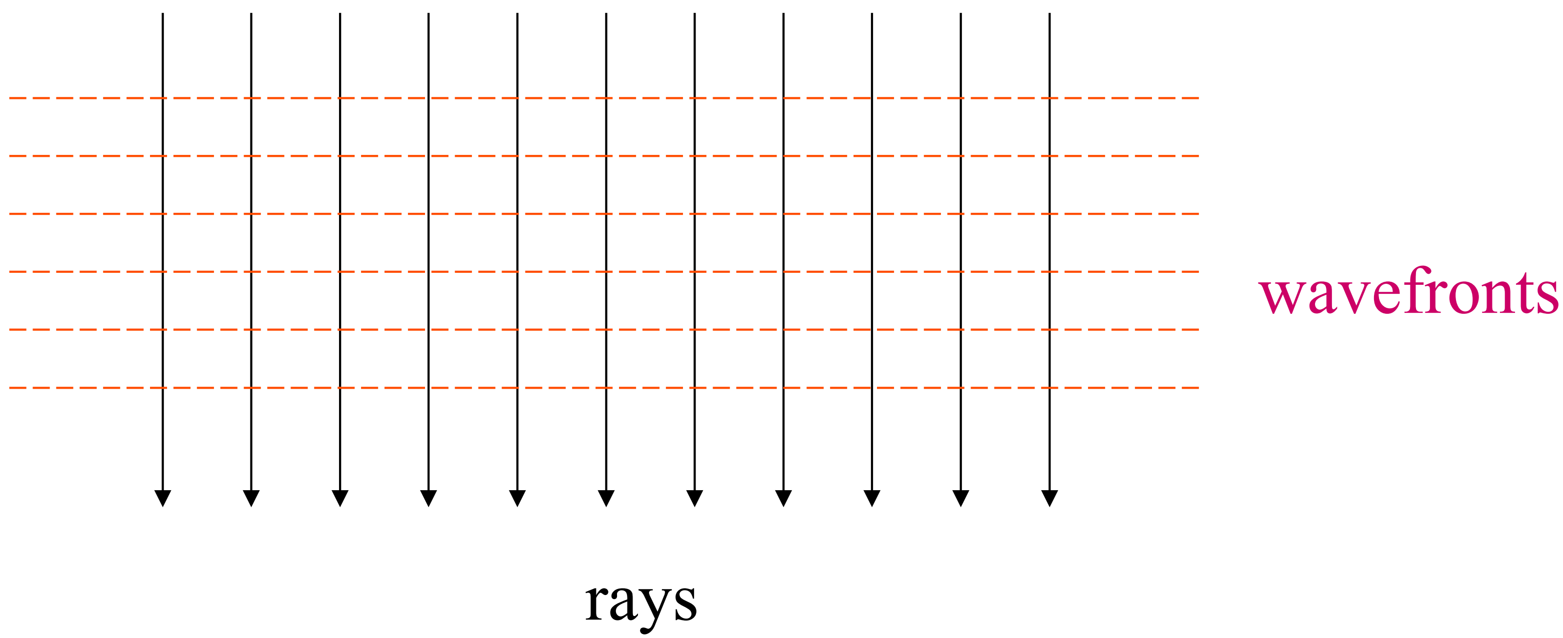
At each point along the waves, they add up to zero:
We say they are "out of phase"

Note: doesn't matter if the horizontal axis is time or space…

OR: if their variations *align* they are "in phase":
result = wave with 2X amplitude

Rays vs waves: handy fiction

- We know sound travels in the form of waves, but
  - We can picture sound "rays" as lines from source outward
  - We define rays as lines perpendicular to the wavefronts
  - "Ray tracing" is useful for following paths of sound waves



Example

- A transverse wave has λ = 2.6 m, and moves in the + x direction ("to the right") with speed 14.3 m/s
- Its amplitude is 0.11 m and it has y=0.11 m at t=0
- Give an equation describing y(x,t) for this wave

General form for a wave moving in +x direction* is (for y=A at t=0 *)

$$y = A\cos\left(\frac{2\pi}{\lambda}x - \frac{2\pi}{T}t\right)$$

For this wave, $T = \frac{1}{f} = \frac{\lambda}{v} = \frac{2.6\text{ m}}{14.3\text{ m/s}} = 0.18\text{ s}$

So $y(x,t) = \left(0.11\text{ m}\right)\cos\left(\frac{2\pi}{2.6\text{ m}}x - \frac{2\pi}{0.18\text{ s}}t\right)$

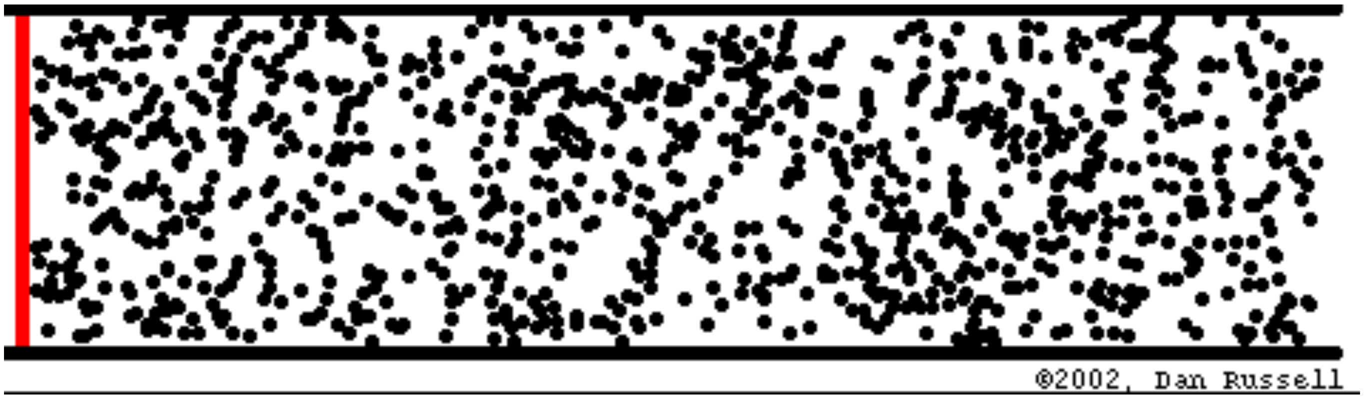
* What if it were moving to the left (-x)? $y = A\cos\left(\frac{2\pi}{\lambda}x + \frac{2\pi}{T}t\right)$

what if it had y=0 at t=0, with y increasing at that time? $y = A\sin\left(\frac{2\pi}{\lambda}x - \frac{2\pi}{T}t\right)$

what if it had y= -1 at t=0, with y increasing? $y = A\cos\left(\frac{2\pi}{\lambda}x - \frac{2\pi}{T}t + \pi\right)$

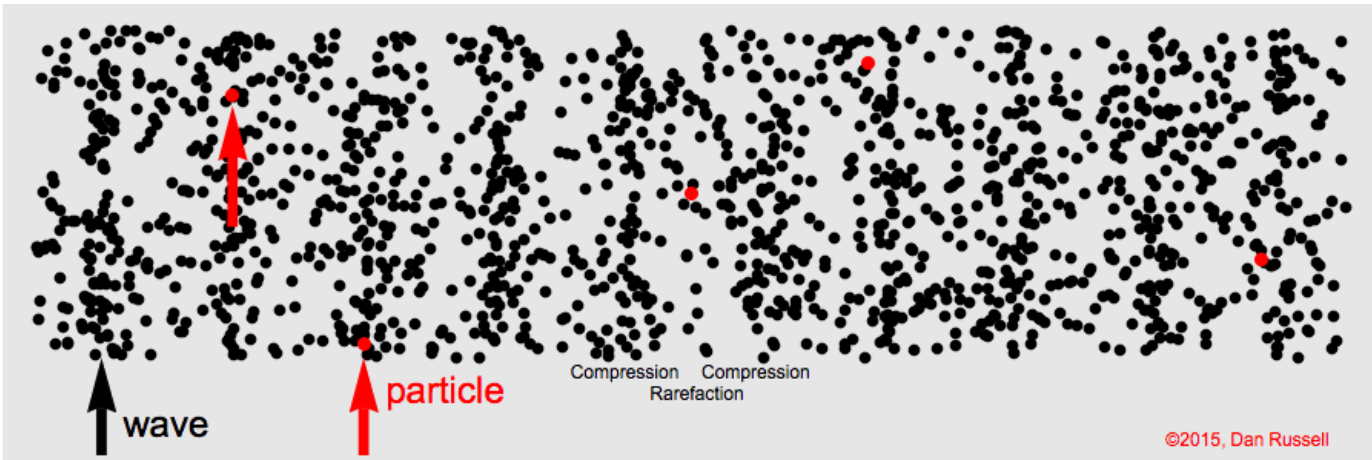
Transverse vs longitudinal waves

- Pulses or waves on a string are transverse waves
  - Displacement is **transverse to** direction of propagation



Single longitudinal pulse in gas or fluid

- Sound waves are longitudinal waves
  - Displacement is **along** direction of propagation

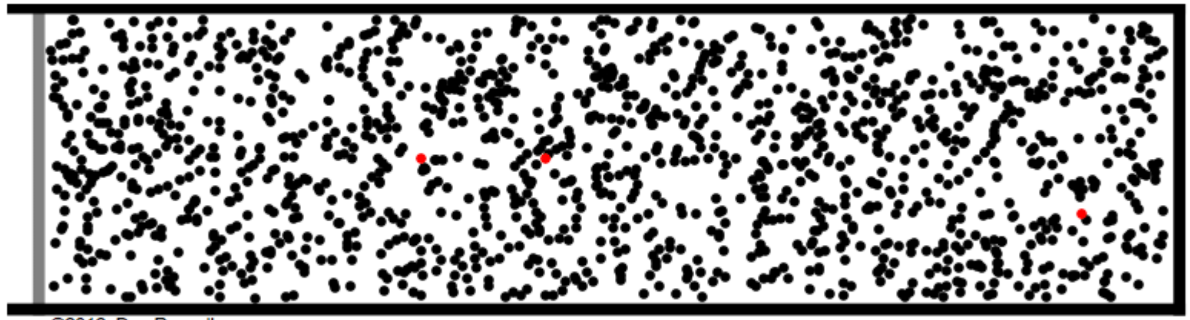


Longitudinal waves

Compression / longitudinal waves

- Sound waves are pressure and density fluctuations in materials
  - Propagate by particles pushing on neighbors
  - Displacement of any given particle is small and back-and-forth along direction of propagation;
  - density fluctuation is what propagates long distances
  - These plots of density vs position are for "standing waves" in a pipe

    more on that later…



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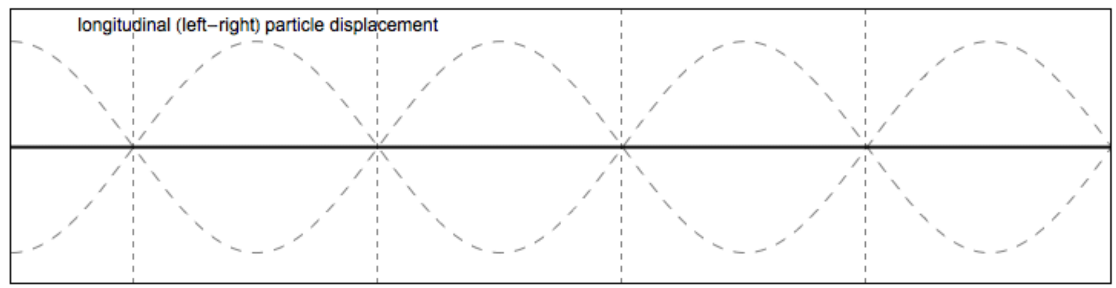
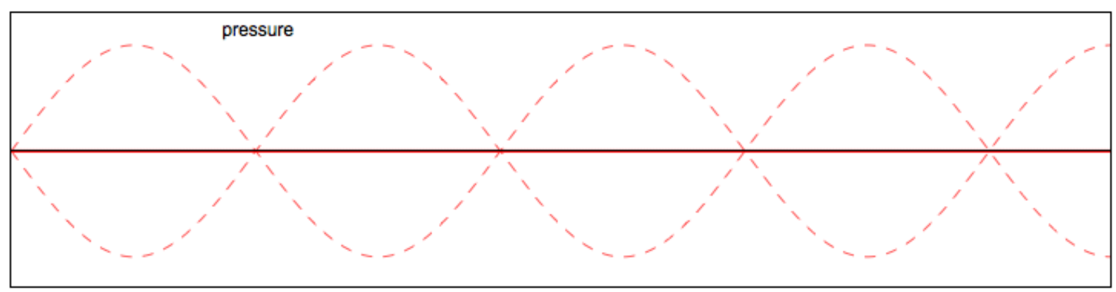
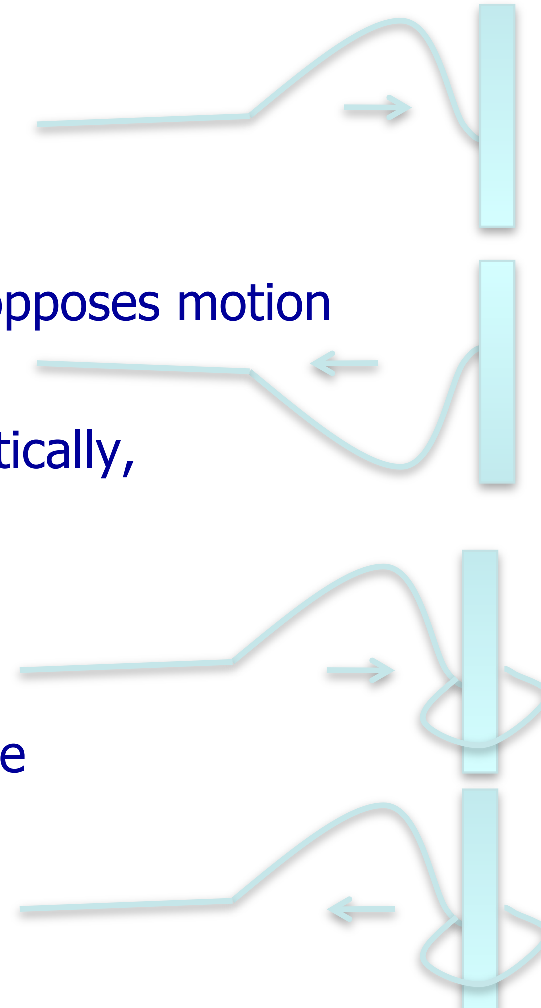




Waves on strings and ropes



- End effects:
  - If end of rope is fixed in wall and can't move,
    - reaction force from wall (Newton's 3rd Law) opposes motion
    - Pulse is inverted
  - If end of rope is unconstrained and can move vertically,
    - no reaction force
    - pulse is reflected without inversion
- Wave speed on a rope or string depends on
  - Tension in string : if F=0 wave does not propagate
  - Mass of string : really, mass per unit length

$$\mu = M(\text{kg}) / L(\text{m})$$

- Speed of wave on a string $v = \sqrt{\dfrac{F}{\mu}}$

More on this later…

Does this give a speed?
Dimensional analysis:

$$v[\text{m/s}] = \sqrt{\frac{F\left[\text{kg-m/s}^2\right]}{\mu[\text{kg/m}]}} \rightarrow \sqrt{\left[\text{m}^2/\text{s}^2\right]}$$

Speed of wave, frequency, and wavelength

Wave *speed* connects the space and time pictures of wave motion

- Different kinds of waves propagate with varying speeds
  - Speed sets relationship between wavelength (from snapshot at one t) and period or frequency (counting waves at one spot)
- Relationship between frequency, speed and wavelength:

$$f \cdot \lambda = v$$

f is frequency in cycles per second (Hz)

λ is wavelength (meters)

v is speed of propagation of wave (m/s)

Wavelength of radio signal from KNKX-FM (88.5 MHz)

$$\lambda = v/f = \text{(speed of light)}/88{,}500{,}000 \text{ Hz}$$
$$= (3\times10^{8} \text{ m/s}) / (8.85\times10^{7} \text{ cycles/s}) = 3.4 \text{ m}$$

Wavelength of musical note "A above middle C" (A440)

$$\lambda = v/f = \text{(speed of sound)}/440 \text{ Hz}$$
$$= (343 \text{ m/s}) / (440 \text{ cycles/s}) = 0.8 \text{ m}$$

Big difference in speed between E-M waves and sound waves!

Speed of sound

- Speed of sound *c* is about 343 m/s in air (depends on air density, temperature and humidity) = 1235 km/hr = 770 mph
  - So sound travels 1 mile in about 5 sec (lightning vs thunder)
- Speed is faster at higher temperatures:

  At 0°C, c = 331 m/s

  At 15°C, c = 340 m/s

  At 20°C, c = 343 m/s

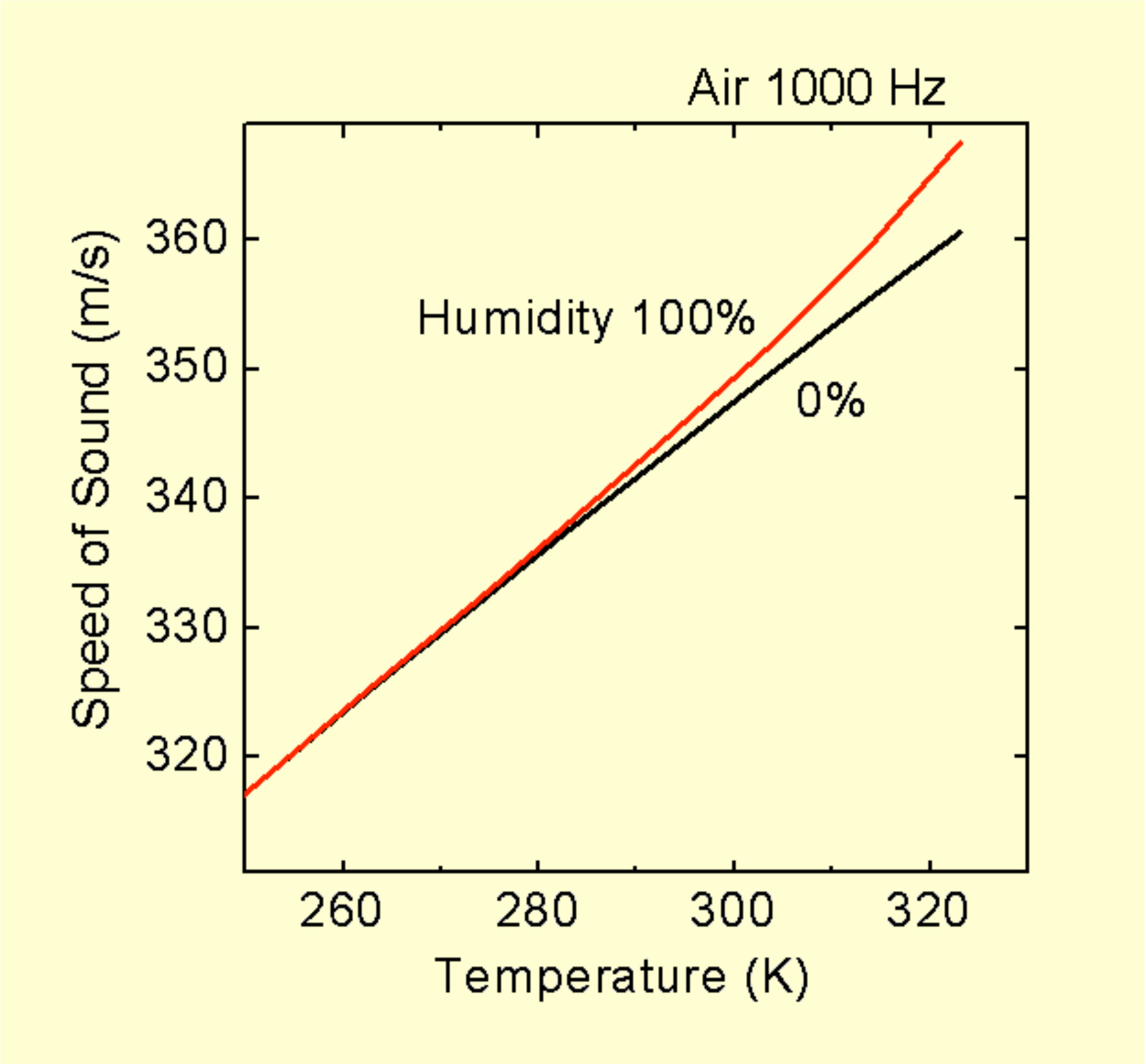
  At 25°C, c = 346 m/s
- Speed is faster in denser materials:
- Example:

  A pirate sees cannon flash on pursuing ship, and counts 8 seconds before he hears the boom. How far away is the Royal Navy?

$$X = vT = 343\ \text{m/s}\left(8\ \text{s}\right) = 2.7\ \text{km}$$

Substance	Temp (°C)	Speed (m/s)
Gases		
Carbon Dioxide	0	259
Oxygen	0	316
Air	0	331
Air	20	343
Helium	0	965
Liquids		
Chloroform	20	1004
Ethanol	20	1162
Mercury	20	1450
Water	20	1482
Solids		
Lead		1960
Copper		5010
Glass		5640
Steel		5960

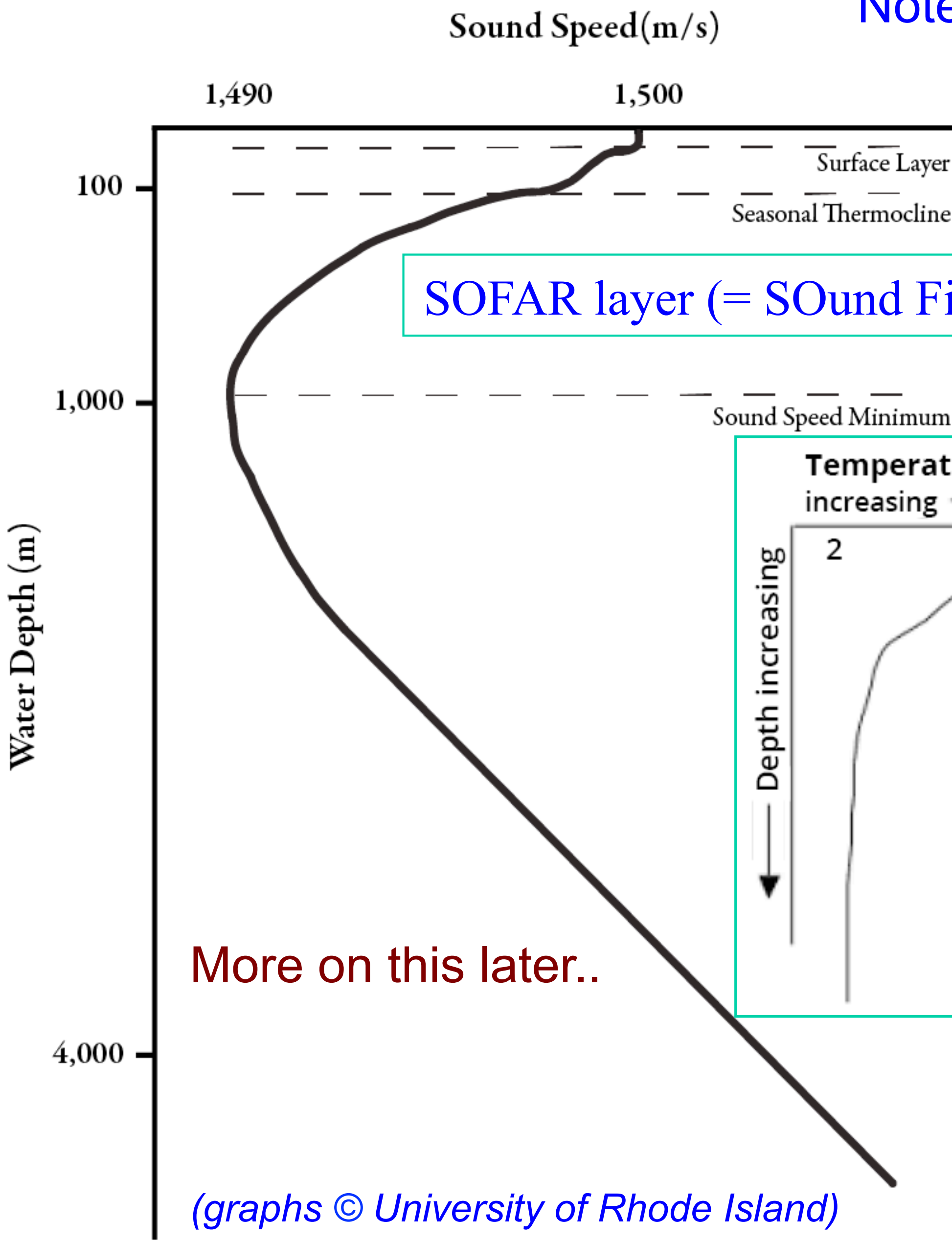
Speed of sound vs T and RH



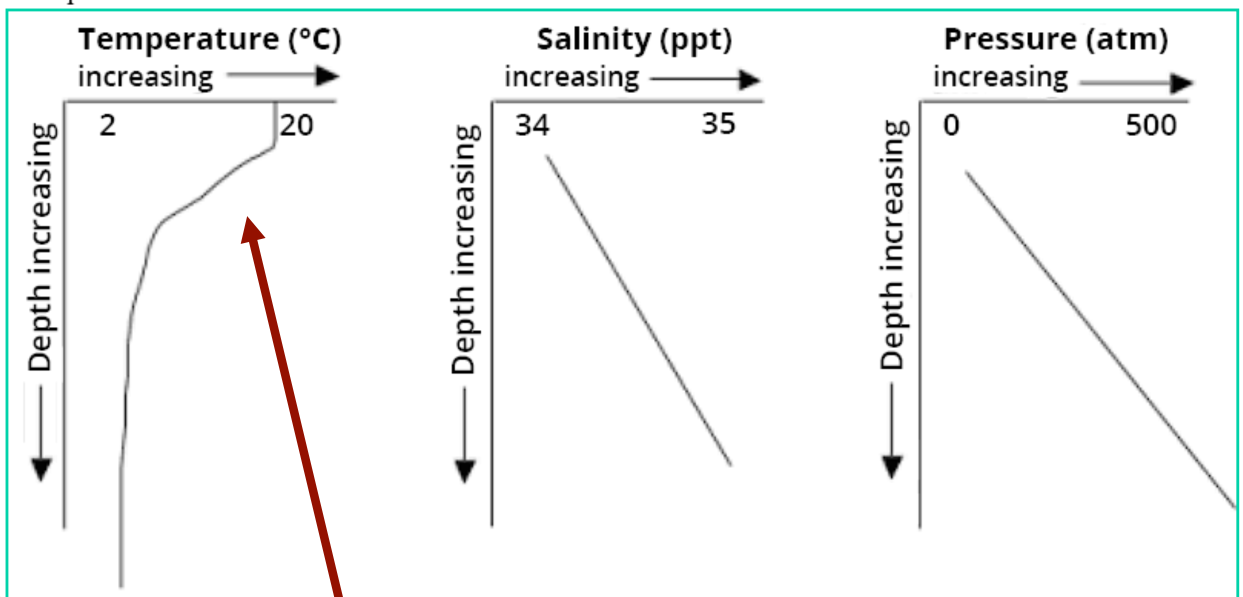
https://pages.mtu.edu/~suits/SpeedofSound.html

Sound speed in seawater vs depth

Note the sound speed minimum at ~1000 m.



SOFAR layer (= SOund Fixing And Ranging) − channels sound waves



More on this later..

Thermocline = layer from depths 200 m ~ 1,000 m where temperatures drop steeply.

(graphs © University of Rhode Island)