Handout for note-taking

# Session 2
# Fundamentals of Sound

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Science of Music

# Terminology

Wave, amplitude, displacement, velocity, phase, frequency, node/antinode, dB, standing wave, resonance, spectrogram, Fourier component, sine, cosine, oscillator, impedance, pressure, logarithm

Scale, chord, interval, pitch, timbre, tempo, harmonic, fundamental, partial, fifth, octave, envelope (attack/decay/sustain/release), consonance, dissonance, temperament, loudness

# Outline

Sound = a vibration in the air

More specifically: a pressure wave with frequency around 20 Hz to 20 kHz

Sound source = something which vibrates the air around it at these frequencies

More specifically: some kind of oscillator

# Outline

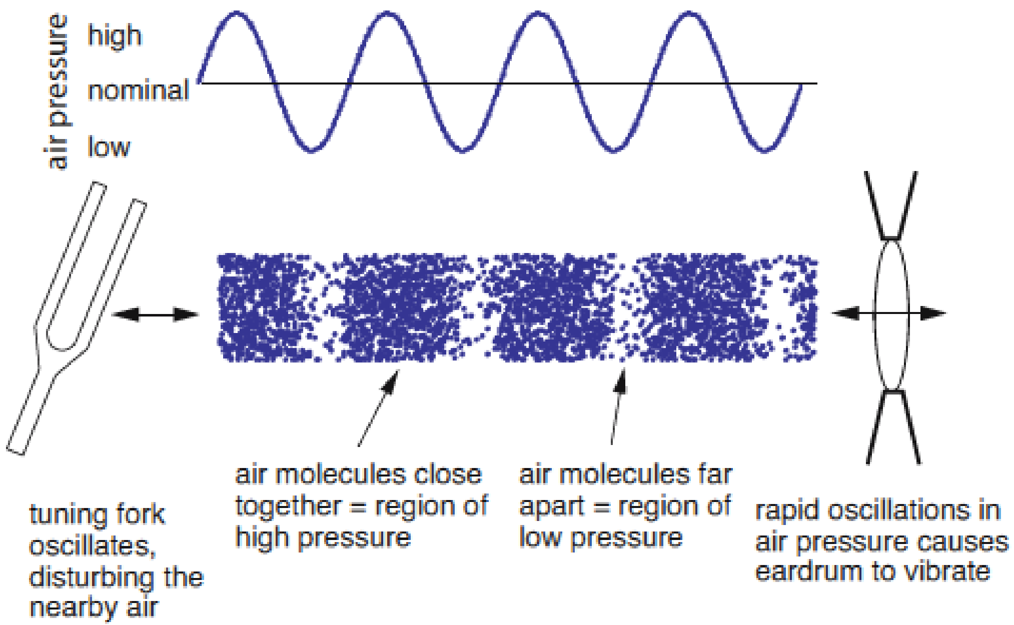



Figure from:
William A. Sethares *Tuning, Timbre, Spectrum, Scale* Second Edition
ISBN 1852337974
Library e-book

# Elasticity

http://www.roberthooke.org.uk

- *Ut tensio, sic vis...* or perhaps... *ut pondus sic tensio.*
- $F = -k x$
- In general: *deformation* leads to a *restoring force*
- Hooke thought about a stretched spring. Applies also to:
  - Stretched / deflected violin or guitar string
  - Deformed drum skin
  - Bent reed
  - Compressed gas (wind / brass / organ)
- Hooke also measured “the spring of air” and frequencies of musical notes

# Oscillators

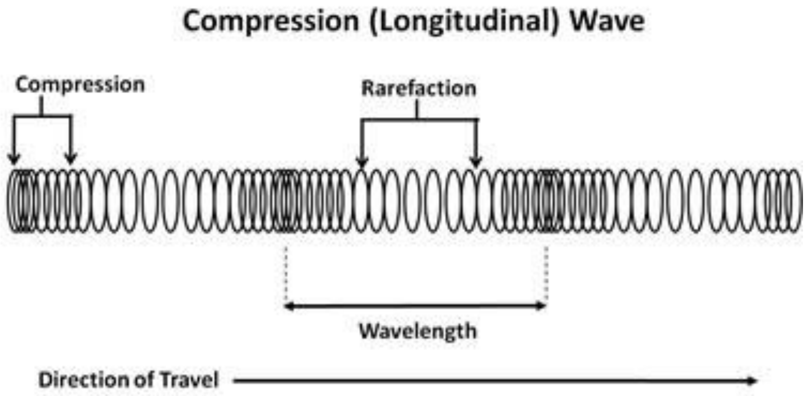
- *Deformation* leads to a *restoring force*
- *Restoring force* plus *inertia* leads to an *oscillation*

http://www.foucaultpendulums.com (!)

# Oscillators

# Elastic waves

- What happens when we "connect lots of oscillators together"?
  - Deformation in one part of our system causes force on neighbouring part.
  - Usually talking about a continuous elastic medium, not lots of discrete oscillators.
- We can get *waves* – oscillations which travel.

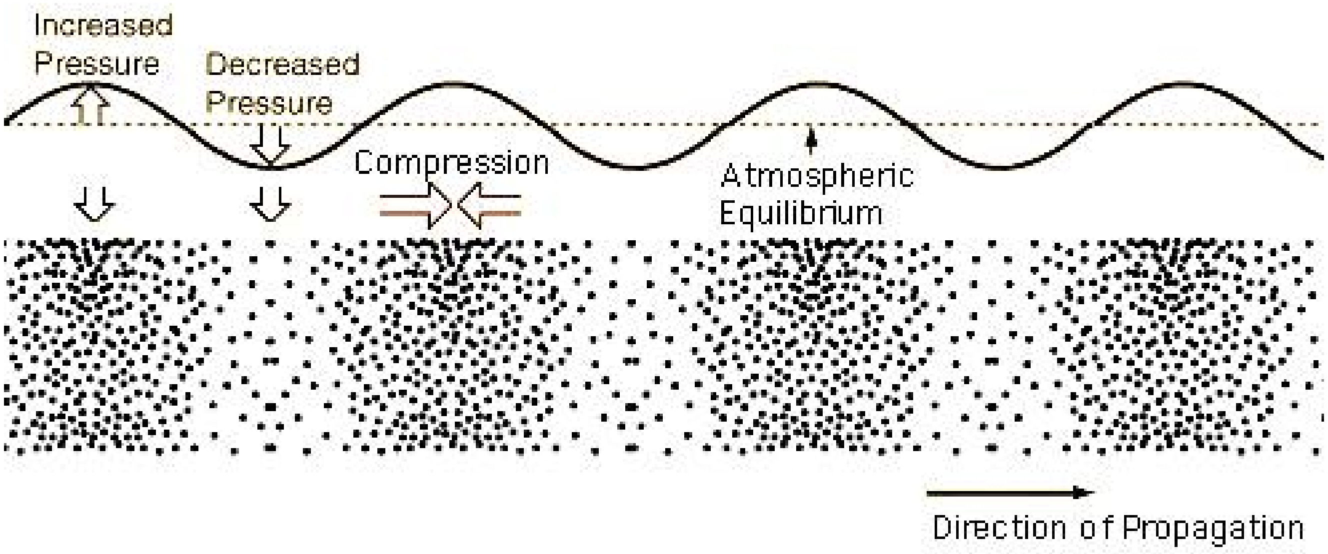



Wavelength $\lambda$ (m)
Wave speed $c$ (m/s)
Frequency $f$ (Hz)

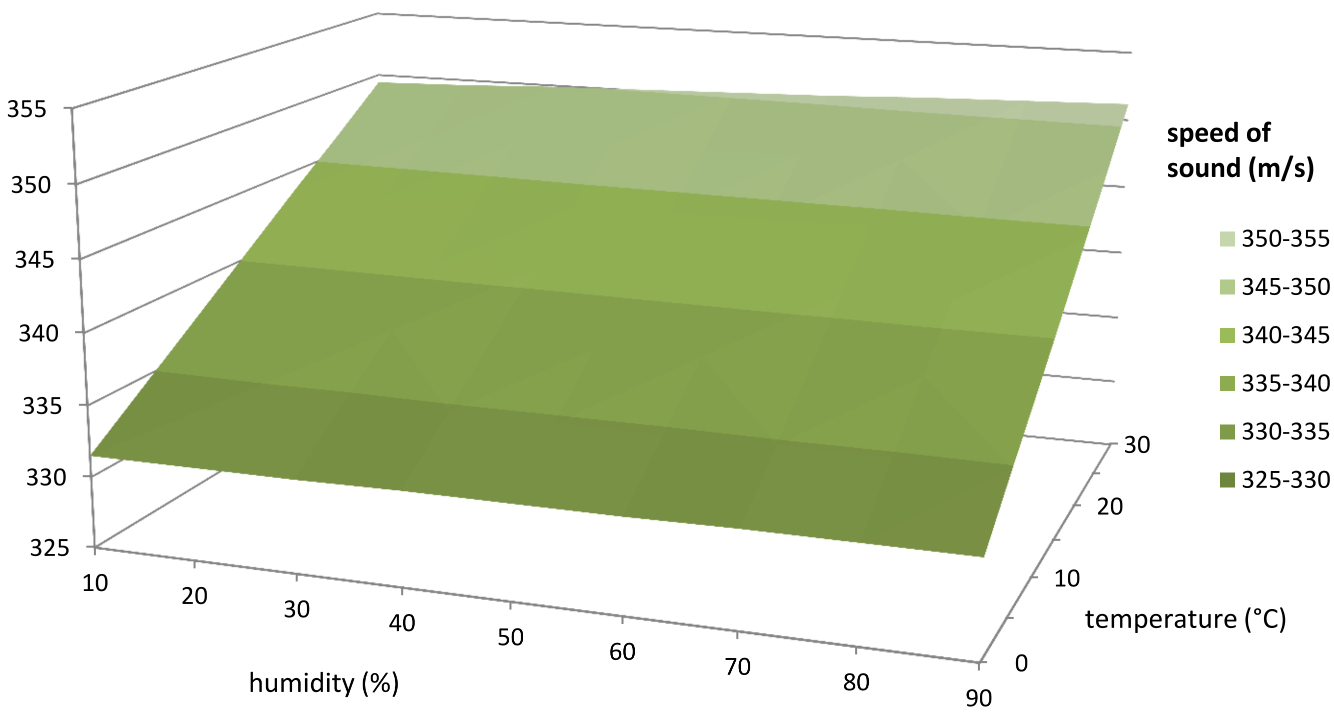
$$c = f\lambda$$

# Sound waves in air

- Speed of sound depends on
  - Density of air ("inertia")
  - Air pressure ("restoring force")



# Temperature and humidity




What is the wavelength of a 440 Hz sound wave in air at 10% humidity, 20°C?

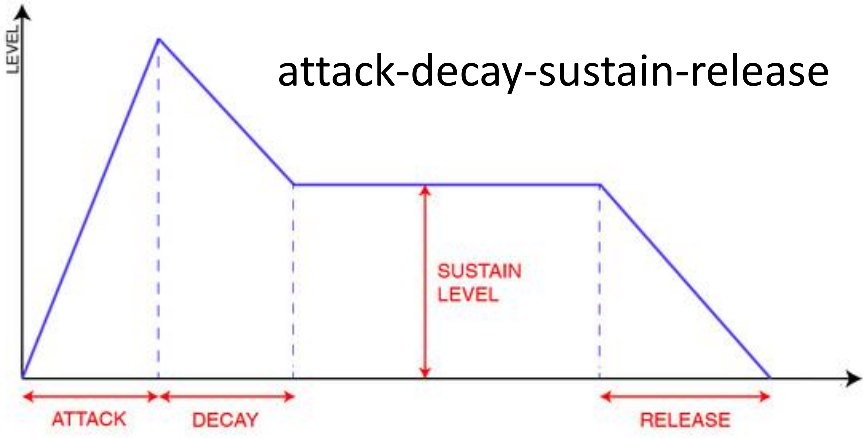
# Properties of sound

- Frequency
- Loudness
- Envelope
- Timbre

We need to combine **time-domain** and **frequency-domain** information to describe a sound.

Envelope –
loudness as a function of time

Timbre - the feel of the sound
"the character or quality of a musical sound or voice as distinct from its pitch and intensity"



# Loudness

See MT
Appendix 5

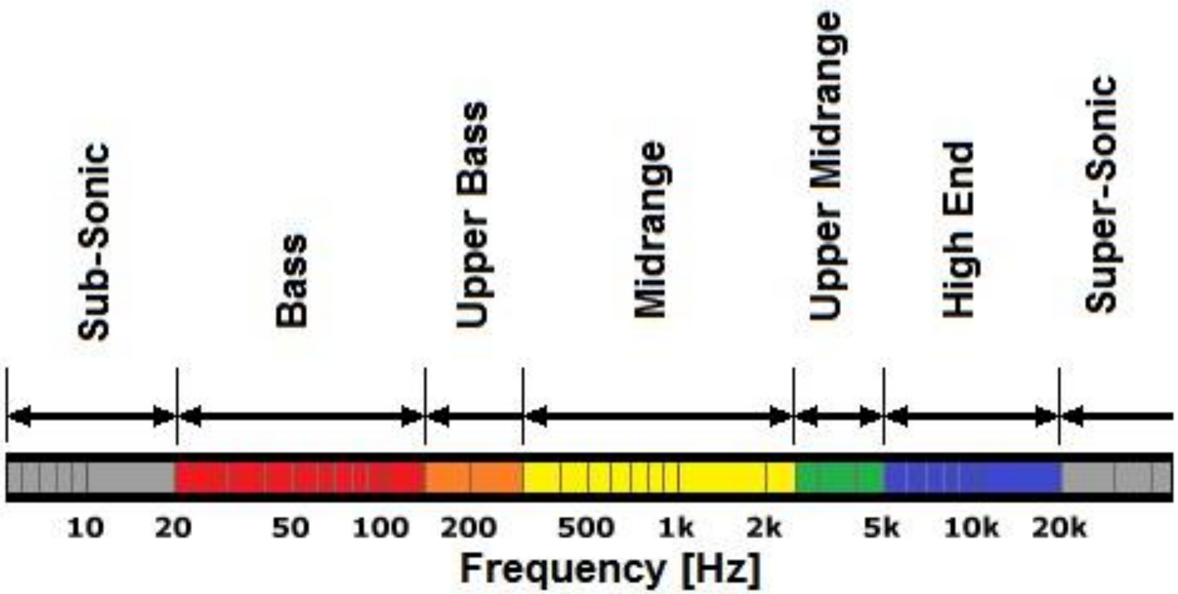
We talked about the energy in a sound wave in session 1.

- Energy per unit time is **power**, in watts W.
- Power per unit area tells us the **sound intensity** in W $m^{-2}$.
- The ear is sensitive to sound over a huge range of intensities.
- So we use a logarithmic scale to measure loudness: decibel (dB).

Sound intensity level in dB
$= 120 + 10 \times \log_{10}(\text{sound intensity in units } 10^{-12}\ \text{Wm}^{-2})$

Lower hearing threshold: 0 dB
Trumpet at 10 paces: 80 dB
Pain threshold: 120 dB

# Frequency




These descriptors are not universal.

Also see MT p. 34

A simple sine wave has just one frequency.
Any more complicated wave is “made out of” more than one frequency.

# Frequency

## Note Frequency Chart

| | Octave 0 | Octave 1 | Octave 2 | Octave 3 | Octave 4 | Octave 5 | Octave 6 | Octave 7 | Octave 8 |
|---|---|---|---|---|---|---|---|---|---|
| C | 16.35 | 32.70 | 65.41 | 130.81 | 261.63 | 523.25 | 1046.50 | 2093.00 | 4186.01 |
| C# | 17.32 | 34.65 | 69.30 | 138.59 | 277.18 | 554.37 | 1108.73 | 2217.46 | 4434.92 |
| D | 18.35 | 36.71 | 73.42 | 146.83 | 293.66 | 587.33 | 1174.66 | 2349.32 | 4698.64 |
| D# | 19.45 | 38.89 | 77.78 | 155.56 | 311.13 | 622.25 | 1244.51 | 2489.02 | 4978.03 |
| E | 20.60 | 41.20 | 82.41 | 164.81 | 329.63 | 659.26 | 1318.51 | 2637.02 | 5274.04 |
| F | 21.83 | 43.65 | 87.31 | 174.61 | 349.23 | 698.46 | 1396.91 | 2793.83 | 5587.65 |
| F# | 23.12 | 46.25 | 92.50 | 185.00 | 369.99 | 739.99 | 1479.98 | 2959.96 | 5919.91 |
| G | 24.50 | 49.00 | 98.00 | 196.00 | 392.00 | 783.99 | 1567.98 | 3135.96 | 6271.93 |
| G# | 25.96 | 51.91 | 103.83 | 207.65 | 415.30 | 830.61 | 1661.22 | 3322.44 | 6644.88 |
| A | 27.50 | 55.00 | 110.00 | 220.00 | 440.00 | 880.00 | 1760.00 | 3520.00 | 7040.00 |
| A# | 29.14 | 58.27 | 116.54 | 233.08 | 466.16 | 932.33 | 1864.66 | 3729.31 | 7458.62 |
| B | 30.87 | 61.74 | 123.47 | 246.94 | 493.88 | 987.77 | 1975.53 | 3951.07 | 7902.13 |

# Harmonics and overtones

| COMPONENT | FREQUENCY | RATIO | INTERVAL |
|---|---|---|---|
| Fundamental | $f$ | | |
| | | 2/1 | octave |
| 2nd harmonic | $2f$ | | |
| | | 3/2 | perfect fifth |
| 3rd harmonic | $3f$ | | |
| | | 4/3 | perfect fourth |
| 4th harmonic | $4f$ | | |
| | | 5/4 | major third |
| 5th harmonic | $5f$ | | |
| | | 6/5 | minor third |
| 6th harmonic | $6f$ | | |
| | | 7/6 | (3– semitones) |
| 7th harmonic | $7f$ | | |
| | | 8/7 | (2+ semitones) |
| 8th harmonic | $8f$ | | |
| | | 9/8 | major tone |
| 9th harmonic | $9f$ | | |
| | | 10/9 | minor tone |
| 10th harmonic | $10f$ | | |
| | | | etc... |

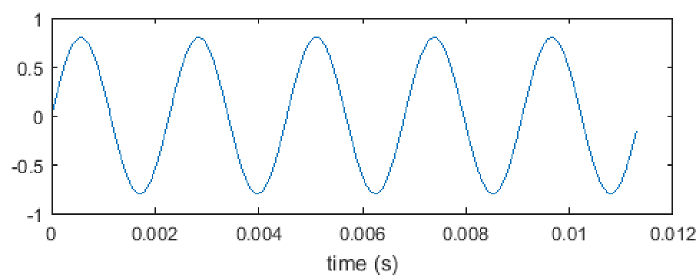
From MT p. 99

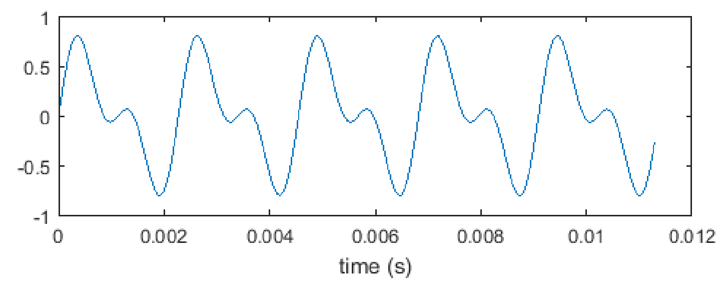
fundamental = 1$^{st}$ harmonic

2$^{nd}$ harmonic = 1$^{st}$ overtone
3$^{rd}$ harmonic = 2$^{nd}$ overtone
etc.

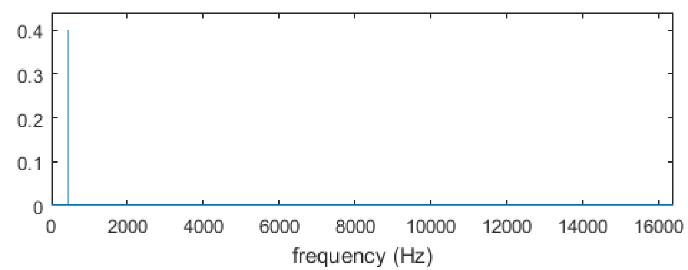
# Simple sine waves 1

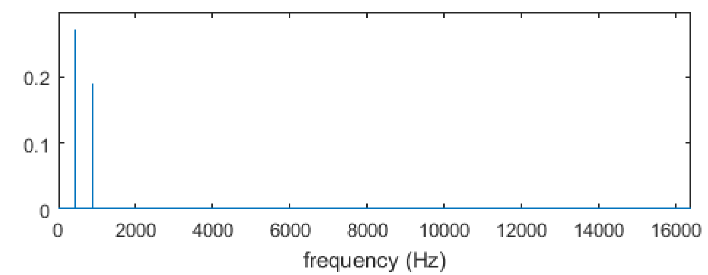
Time domain




Freq. domain



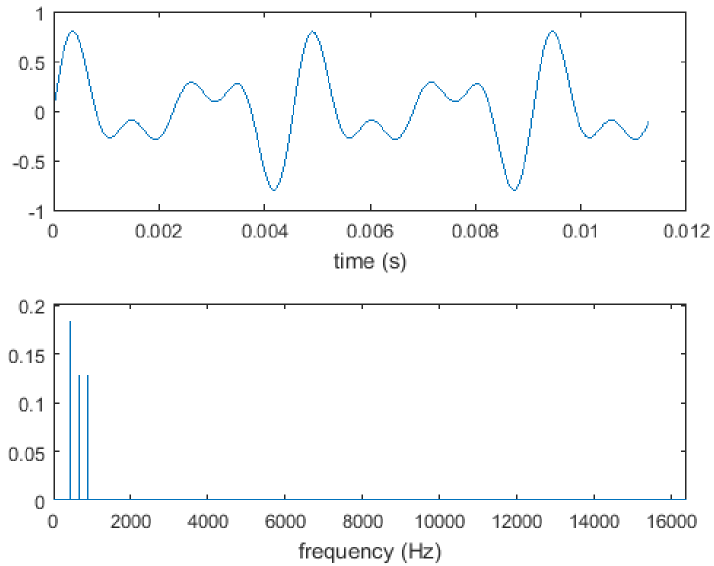

A 440 Hz

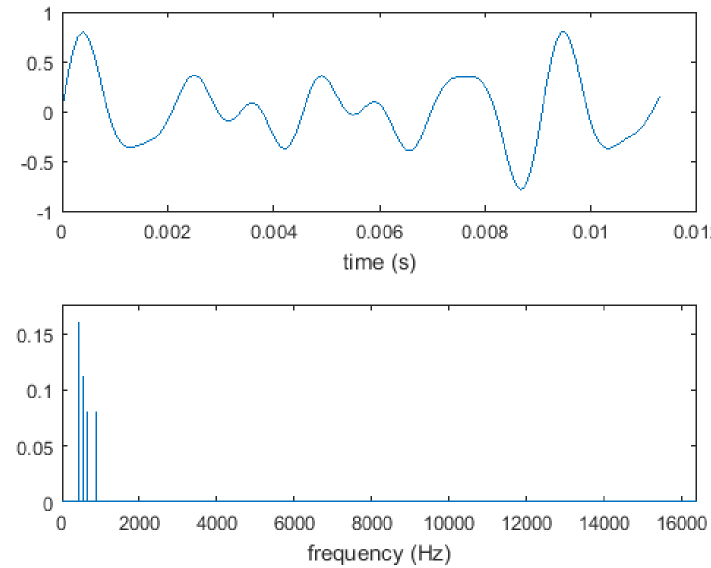
mSy1.wav

| | | |
|---|---|---|
| A | 440 Hz | 1 |
| octave | 880 Hz | 0.7 |

mSy2.wav

# Simple sine waves 2

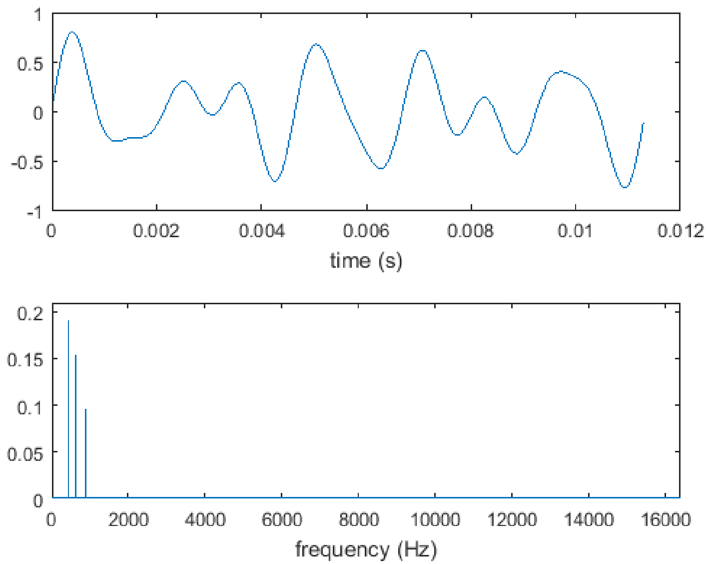


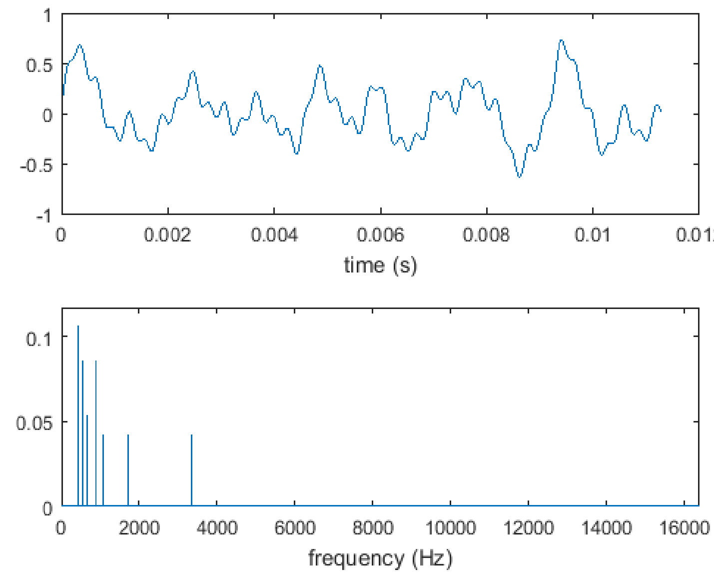




| | | |
|---|---|---|
| A | 440 Hz | 1 |
| fifth | 660 Hz | 0.7 |
| octave | 880 Hz | 0.7 |

| | | |
|---|---|---|
| A | 440 Hz | 1 |
| major 3$^{rd}$ | 554 Hz | 0.7 |
| fifth | 660 Hz | 0.5 |
| octave | 880 Hz | 0.5 |

# Simple sine waves 3



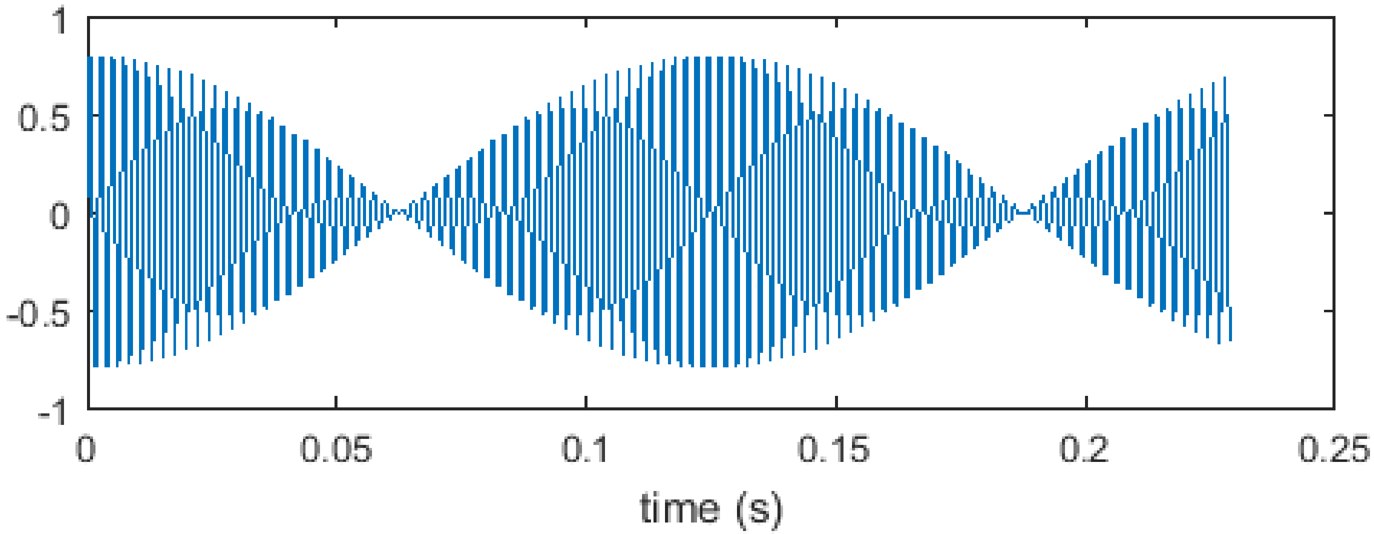

| | | |
|---|---|---|
| A | 440 Hz | 1 |
| flattened fifth | 622Hz | 0.8 |
| octave | 880 Hz | 0.5 |

mSy5.wav

| | | |
|---|---|---|
| A | 440 Hz | 1 |
| major 3rd | 554 Hz | 0.8 |
| fifth | 660 Hz | 0.5 |
| octave | 880 Hz | 0.8 |

plus 3 inharmonic components @ 0.4: 1059, 1727, 3333

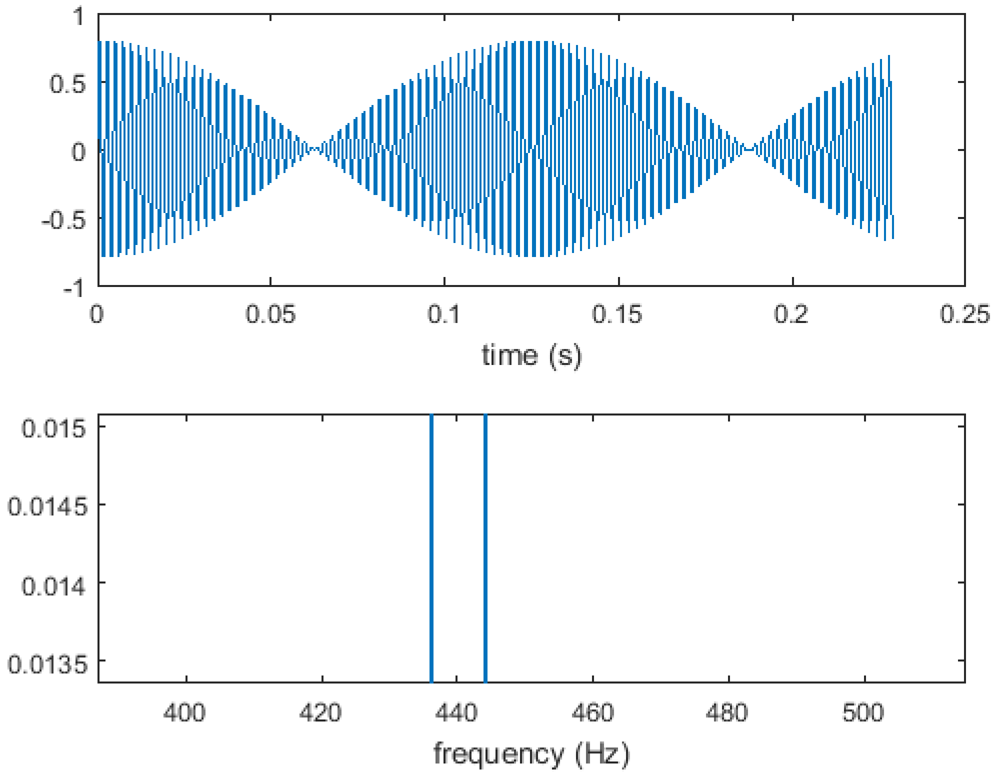
# Simple sine waves 4




Two sine waves close to 440 Hz.

What is the difference in their frequencies?

# Beating




Two waves of similar frequencies produce an audible “beat” pattern.

Waveform looks like a high frequency wave with a low frequency envelope.

# Linearity

- Linear elastic regime: amplitude “not too big”
  - $F = -k\,x$
  - *k* does not change at high amplitude
  - wave speed *c* does not change
  - frequency *f* does not change
- Not true for e.g. cheap ‘n’ nasty recorders!
  - Blow hard → pitch changes
- Linear systems: we can add (“superpose”) waves
  - Wave shapes can be thought of as adding simpler shapes
  - We often consider adding simple sine waves
  - *Fourier decomposition*: **any*** periodic signal can be made out of sine (and cosine) waves

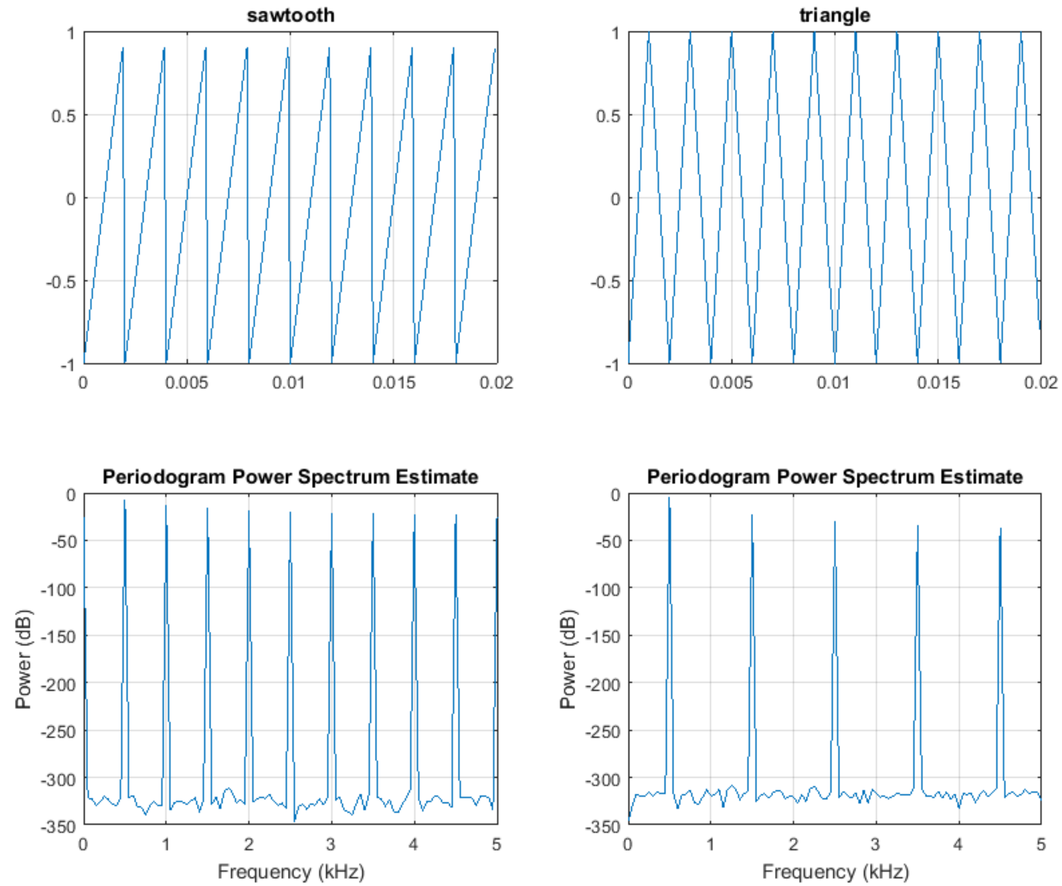
# Harmonic analysis

- Fourier's theorem
  - Any periodic oscillation with period $T = 1 / f$ can be made up from a superposition of sine waves with frequencies $f$, $2f$, $3f$, etc.
  - Each sine wave has its own amplitude
  - The set of amplitudes is the frequency domain representation
- This only works, formally, for oscillations which go on forever
  - Blow hard → pitch changes
- Linear systems: we can add ("superpose") waves
  - Wave shapes can be thought of as adding simpler shapes
  - We often consider adding simple sine waves
  - *Fourier decomposition*: **any*** periodic signal can be made out of sine (and cosine) waves

# Sawtooth and Triangle

500 Hz

**Sawtooth** contains both odd and even multiples of the fundamental. **Triangle** contains only odd multiples of 500 Hz.




Need lots of high frequencies to cope with the sharp changes in these wave forms. Example: **percussive sounds**.

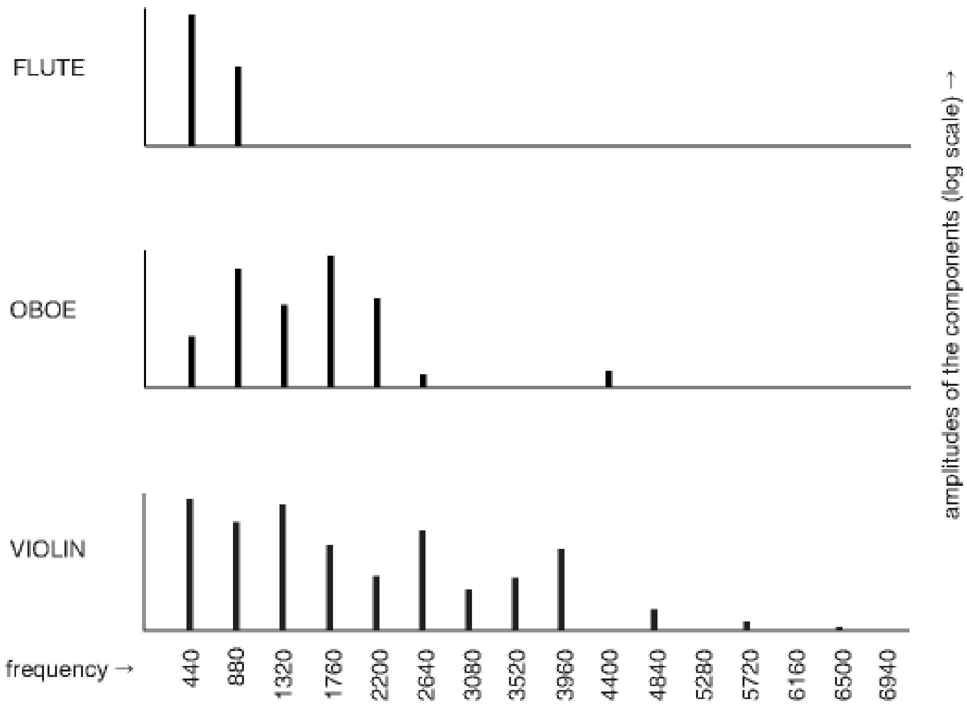
# Real instruments

MT p. 100.

Playing steady notes → waveform goes on effectively "forever" so we expect *f*, 2*f*, etc.

Violin has very complex harmonic content while flute is relatively simple.

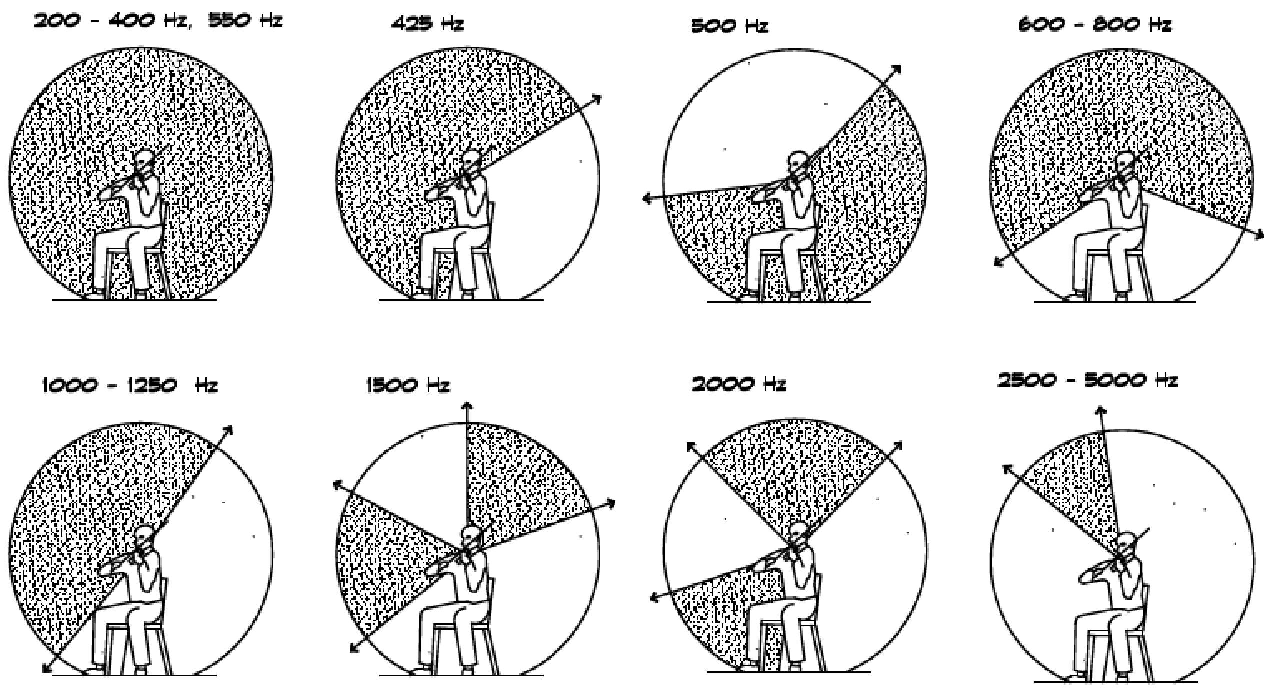
Physical complexity of the oscillators in these three instruments is very different!



# Other considerations

- The combination of frequency domain and time domain description gives us the *timbre* of the sound.
  - "the character or quality of a musical sound or voice as distinct from its pitch and intensity"
  - timbre relates to *harmonic* or *anharmonic* content and *envelope*
  - **But overtones themselves are not necessarily constant in time**
  - Example: click of a bass string against frets has lots of high *f*
- Real sound waves have *spatial* properties too
  - Travel from source to the ear
  - Directionality of source
  - Mixing of direct sound and that reflected from walls

# Wave direction



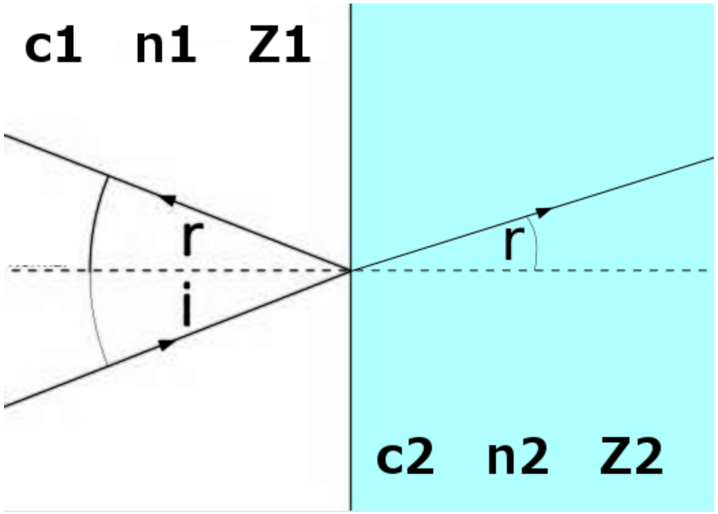

Violin directionality – *Architectural Acoustics*, Marshall Long, ISBN: 978-0-12-398258-2 (Library e-book).
Originally: J. Meyer, "The Sound of the Orchestra," J. Audio Eng. Soc., 41.

# Acoustic impedance

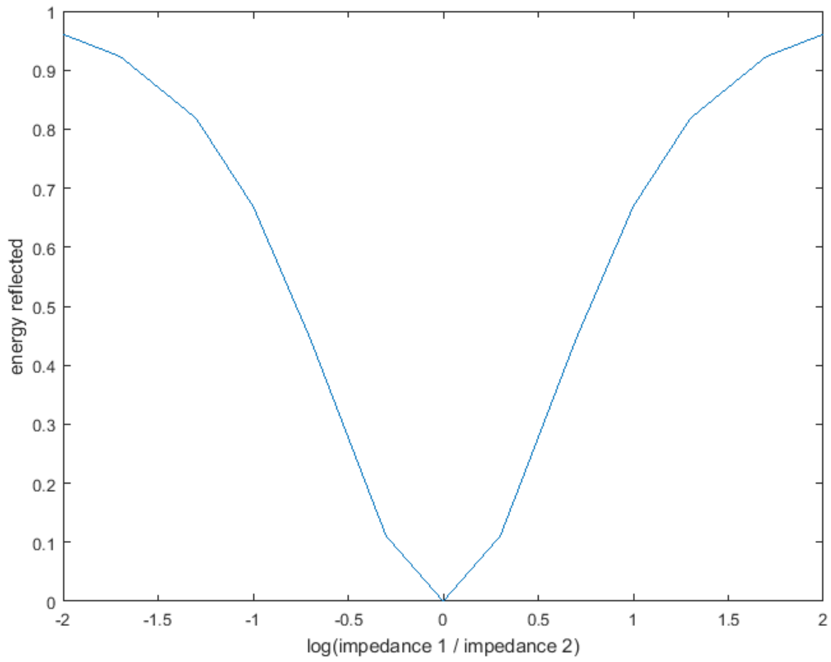
- What happens when the medium through which a wave travels changes, e.g.
  - air → water
  - sound wave in air hits a wall
  - sound wave inside an organ pipe meets the pipe exit

Some wave energy is reflected and some is transmitted (in a different direction).

Describe the reflection and transmission efficiencies by wave speed difference, “refractive index” difference or **acoustic impedance** difference.



# Reflection of sound waves




No reflection when impedances are the same [i.e. log(1/1) = 0]. **Impedance matching.**

Maximum reflection when impedances are very different.

Plot of data in Appendix 6 of MT.

Amplitude reflected = (impedance 1 – impedance 2) / (impedance 1 + impedance 2)