Chapter 2. Meeting 2, Foundations: The Science and Visualization of Sound

2.1. Announcements

- Check course notes for reading and listening discussion leaders
- We will cover the basics of using PD and Martingale during Meeting 5, next week

2.2. Reading: Sousa

- Sousa, J. P. 1993. “Machine Songs IV: The Menace of Mechanical Music.” *Computer Music Journal* 17(1): 14-18.
- What technologies is Sousa concerned about?
- What does Sousa claim are the detriments? What is being lost?
- What other causes, ignored by Sousa, might lead to the conditions he describes?
- Sousa suggest that the goal of music is the “expression of soul states”; is this true?
- What generalities does Sousa suggest about American music, and the history of music?
- For Sousa, can mechanically reproduced music have expression?
- Did copyright law, during this period, see recordings as a copy of a musical work? Why or why not?
- Dose Sousa attribute agency to machines? Why is this relevant?

2.3. Listening: Young

- La Monte Young: “Excerpt 31 | 69 c. 12:17:33-12:25:33 PM NYC” & “31 | 69 C. 12:17:33-12:24:33 PM NYC”
- What are we hearing, and how is it made?
- Is the timbre constant; when does it change?

- What sort of performance context might this work within?
- What affect does this music have on the audience? What is the role of the listener?

2.4. The Science of Sound

- The attributes and measurements of sounds
- How we visualize and display these attributes
- How these measurements relate to human hearing and the brain: psychoacoustics

2.5. Relevance to the Study of Music and Technology

- To describe and understand the abilities of various technologies
- To measure technological progress or decline
- To compare products and evaluate claims
- To measure the efficacy of various technologies for humans

2.6. What Is Sound?

- Variations in pressure through a medium

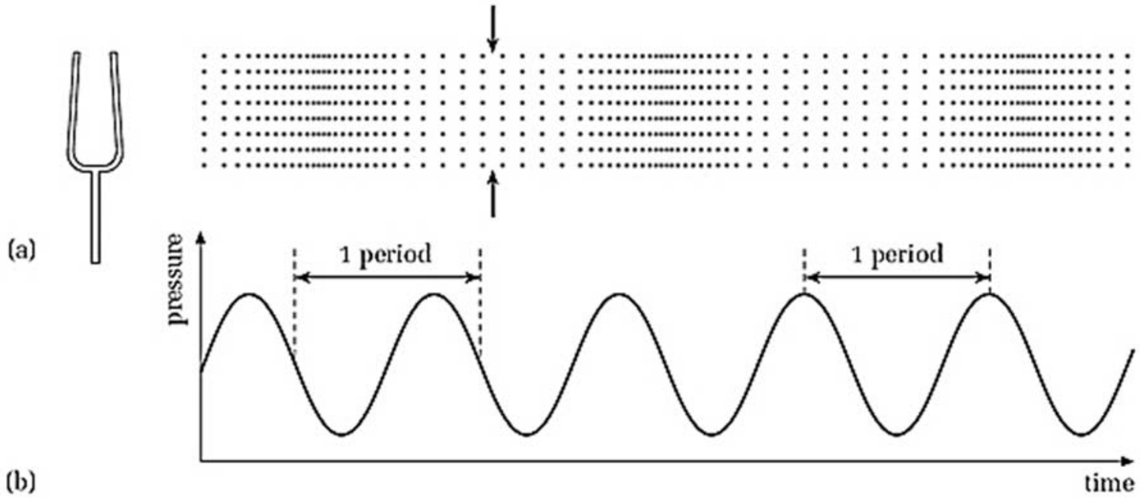
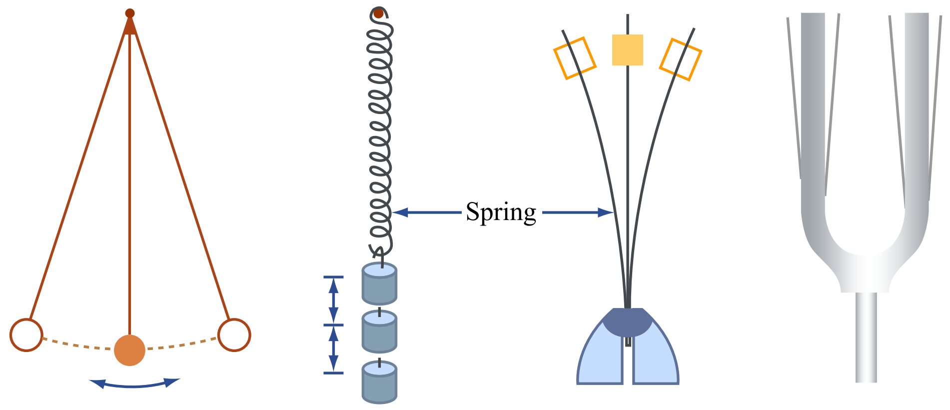


Image: "Sinusoidal pressure waves" from *Sound for music technology: an introduction*. http://openlearn.open.ac.uk/mod/resource/view.php?id=285732.
(c) The Open University.

- A disturbance in equilibrium
- Vibration: special kind of disturbance
- Vibration: an oscillating disturbance in an elastic medium

2.7. Oscillation: The Simplest Case

- Oscillation is the natural motion of many physical objects disturbed from equilibrium



Four types of vibrating objects: simple pendulum, spring pendulum, vibrating strip, and tuning fork.

Figure by MIT OpenCourseWare.

- Oscillation is a back and forth motion (up and down) over time
    - Pendulums (Swings)
    - Strings
- A natural point of oscillation in an object is a resonance
- Perfect oscillations are periodic
- Perfect oscillations are impossible in nature
- Noise breaks perfection: damping, friction, resistance

2.8. An Artificial Case: Perfect Oscillation

- A sine wave is a perfect oscillation
    - An unraveled circle; back and forth over time

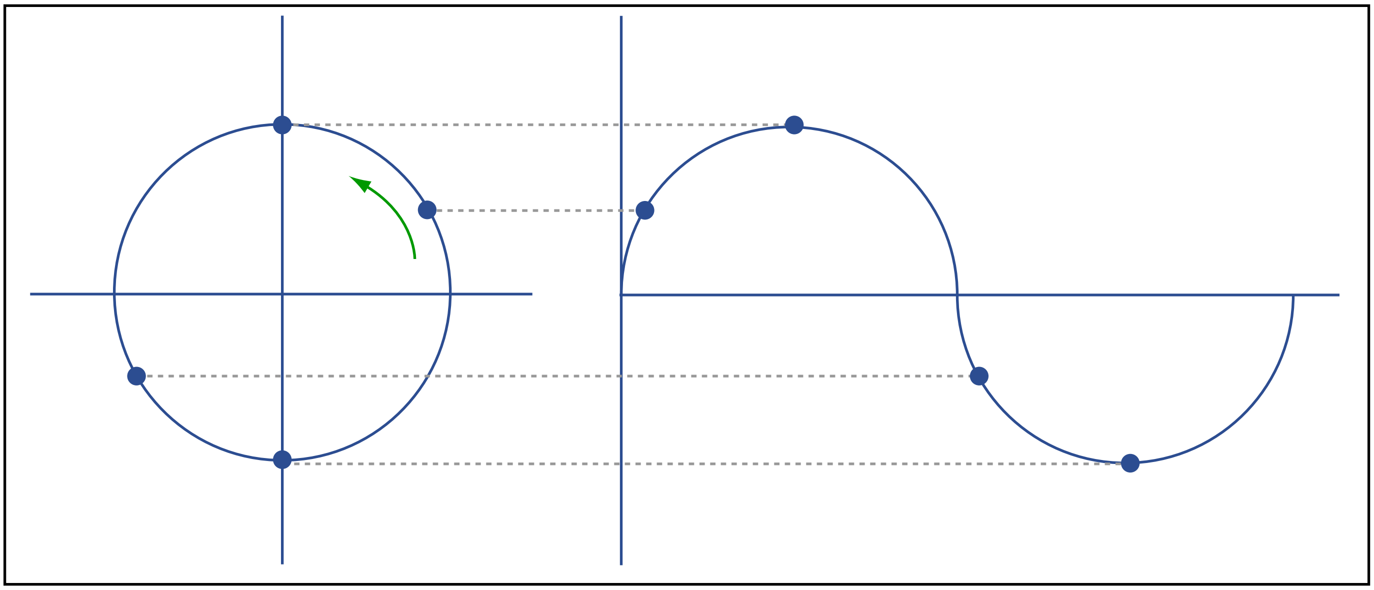
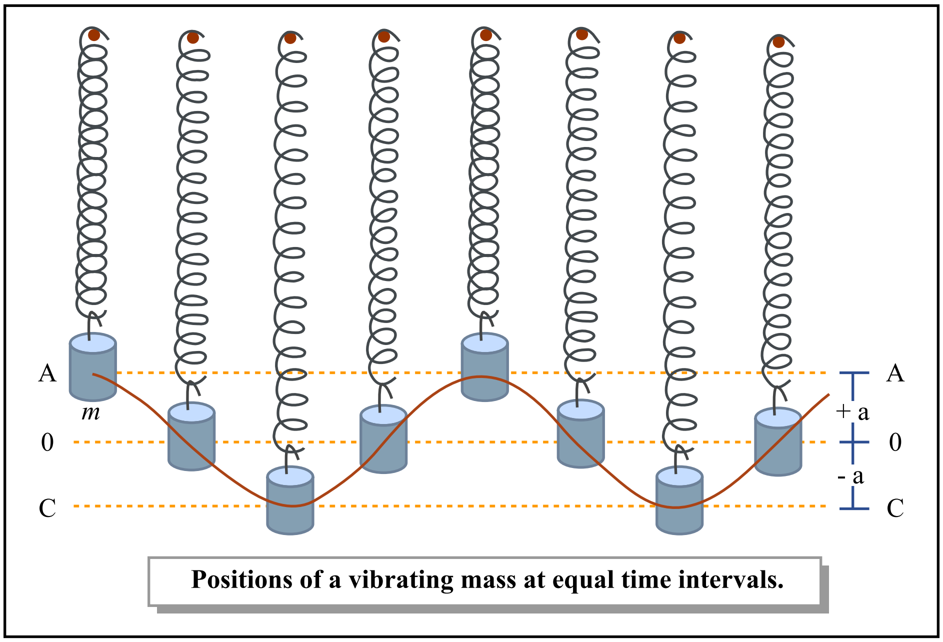


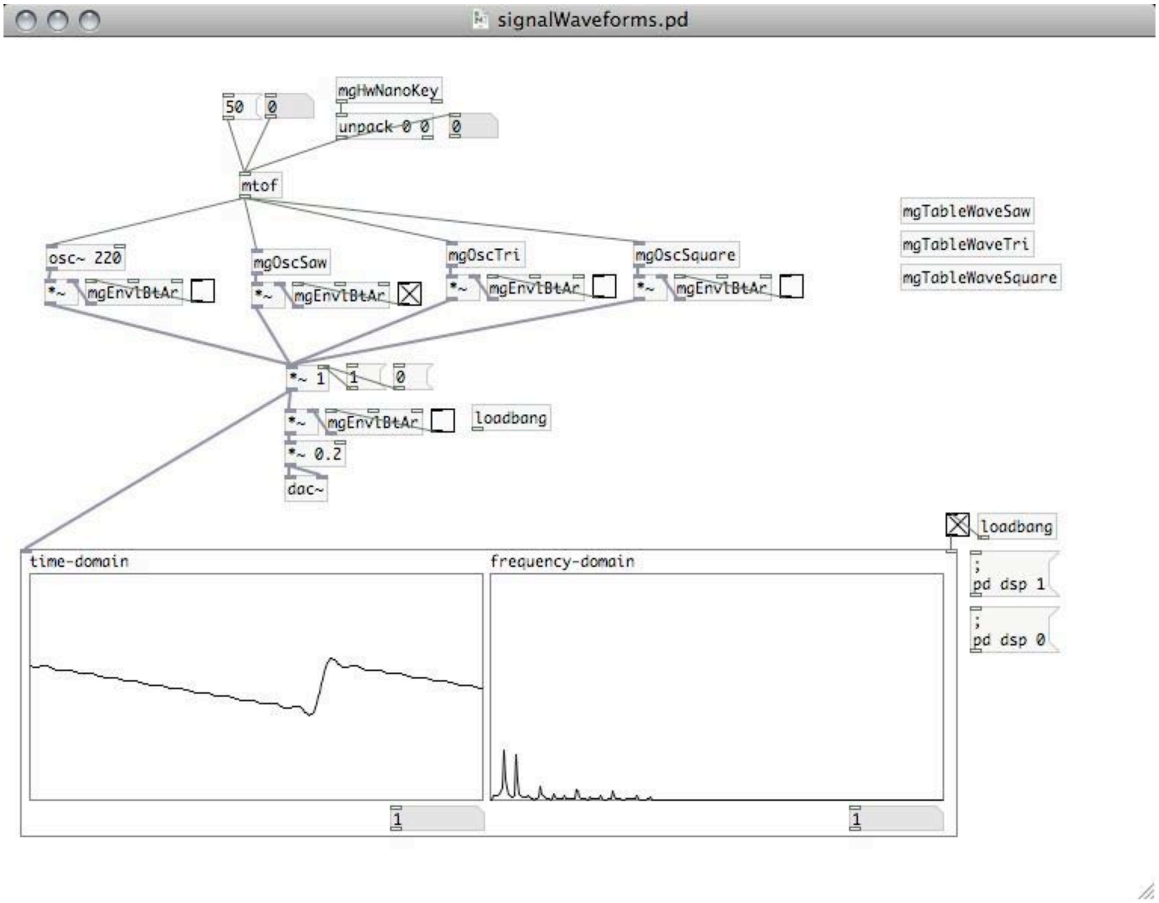
Figure by MIT OpenCourseWare.



Positions of a vibrating mass at equal time intervals.

Figure by MIT OpenCourseWare.

  - No damping or resistance
  - No noise
  - Machine-made
- With machines, other shapes can be perfectly oscillated [demo/signalWaveforms.pd]



  - Sine wave: a circular oscillation
  - Square (rectangle) wave
  - Triangle wave
  - Sawtooth wave
- When things oscillate, humans hear a tone
- The shape of the oscillation makes a difference in the quality of the tone
- The sine wave has advantages
  - It is easy to generate mechanically and mathematically
  - It resembles natural resonances in physical objects (simple harmonic motion)
  - It sounds as a simple, single isolated tone
  - An excellent point of oscillation (frequency) reference

2.9. Measuring: Time

- Sound requires time
- Measured in seconds
- 1 millisecond is equal to .001 second
- 1 second is equal to 1000 milliseconds
- The ear can hear discrete time intervals down to about 30 milliseconds [demo/earLimits.pd]

2.10. Measuring a Sine Wave: How Often?

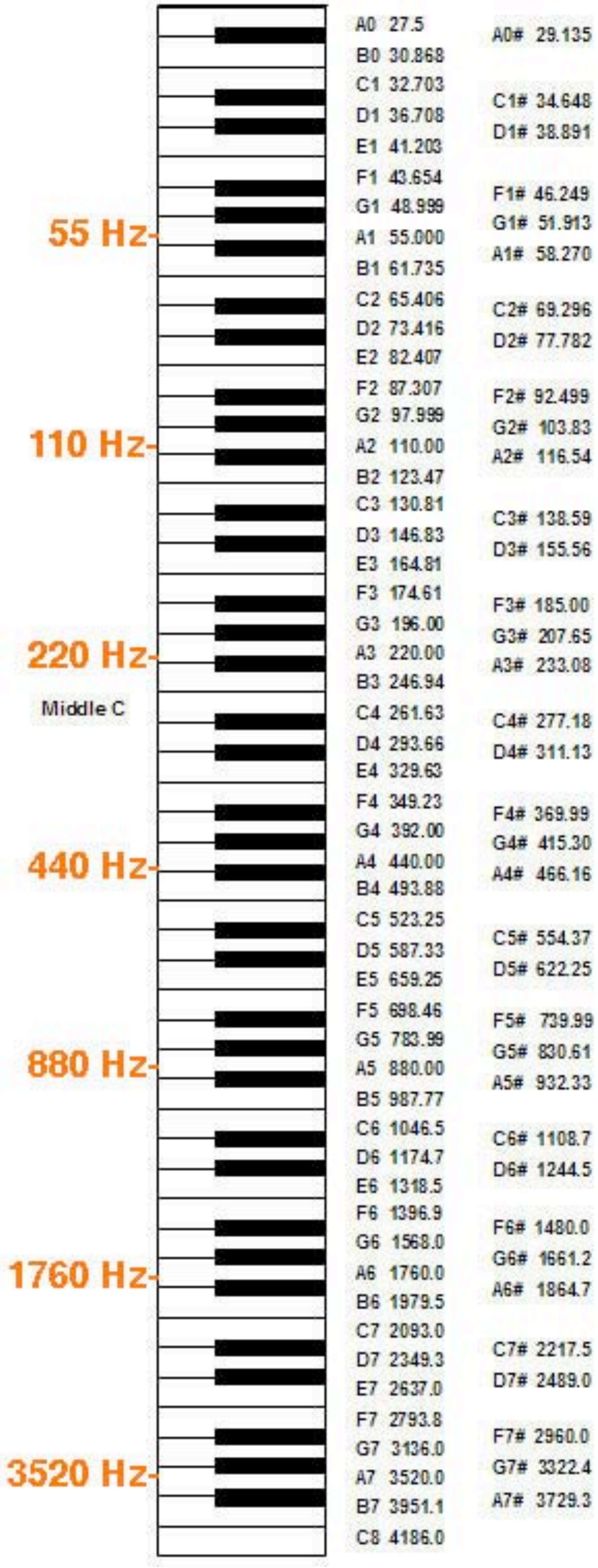
- How often it oscillates: its frequency
  - Measured in Cycles Per Second (CPS) or Hertz
  - Measure from crest to crest, or one period
- Low frequencies correlate to what we call “low” sounds; high frequencies correlate to what we call “high” sounds
- Frequency is similar to pitch, but not the same
- An octave, or a frequency ratio of 2:1, is a fundamental unit of pitch
- Ideal frequency range of the human ear: 20 to 20,000 Hertz
  - Piano keyboard: 8 octaves: A0 (27 Hz) to C8 (4186 Hz)
  - Audible range: 10 octaves: 20 to 20000 Hz [demo/earLimits.pd]

2.11. Frequency and Time

- Frequency is a another way of specifying a duration
- 1 Hz means is a cycle with duration of 1000 ms
- 0.5 Hz is a duration of 2000 ms
- 440 Hz is a duration of 2.27273 ms
- Milliseconds and frequency can be converted each way

2.12. Our Ear Hears Logarithmically: Pitch

- Octave: an equal unit of perceived pitch, a 2:1 ratio of frequencies
- Octaves are frequently divided into 12 half steps (or semitones)
- MIDI pitch values provide a numerical reference to pitch (where middle C is 60 and half-steps are integers)
- A change from 55 to 110 Hz (a difference of 55 Hz) sounds the same to our ear as a change from 1760 to 3520 Hz (a difference of 1760 Hz) [demo/earLogFrequency.pd]



A0	27.5
B0	30.868
C1	32.703
D1	36.708
E1	41.203
F1	43.654
G1	48.999
A1	55.000
B1	61.735
C2	65.406
D2	73.416
E2	82.407
F2	87.307
G2	97.999
A2	110.00
B2	123.47
C3	130.81
D3	146.83
E3	164.81
F3	174.61
G3	196.00
A3	220.00
B3	246.94
C4	261.63
D4	293.66
E4	329.63
F4	349.23
G4	392.00
A4	440.00
B4	493.88
C5	523.25
D5	587.33
E5	659.25
F5	698.46
G5	783.99
A5	880.00
B5	987.77
C6	1046.5
D6	1174.7
E6	1318.5
F6	1396.9
G6	1568.0
A6	1760.0
B6	1979.5
C7	2093.0
D7	2349.3
E7	2637.0
F7	2793.8
G7	3136.0
A7	3520.0
B7	3951.1
C8	4186.0

A0#	29.135
C1#	34.648
D1#	38.891
F1#	46.249
G1#	51.913
A1#	58.270
C2#	69.296
D2#	77.782
F2#	92.499
G2#	103.83
A2#	116.54
C3#	138.59
D3#	155.56
F3#	185.00
G3#	207.65
A3#	233.08
C4#	277.18
D4#	311.13
F4#	369.99
G4#	415.30
A4#	466.16
C5#	554.37
D5#	622.25
F5#	739.99
G5#	830.61
A5#	932.33
C6#	1108.7
D6#	1244.5
F6#	1480.0
G6#	1661.2
A6#	1864.7
C7#	2217.5
D7#	2489.0
F7#	2960.0
G7#	3322.4
A7#	3729.3

Courtesy of Tom Irvine. Used with permission.

- 10 octaves of the audible frequency range:

  20-40 Hz

  40-80 Hz

  80-160 Hz

  160-320 Hz

  320-640 Hz

  640-1280 Hz

  1280-2560 Hz

  2560-5120 Hz

  5120-10240 Hz

  10240-20480 Hz

- Frequency domain graphs often use a logarithmic graph of frequency

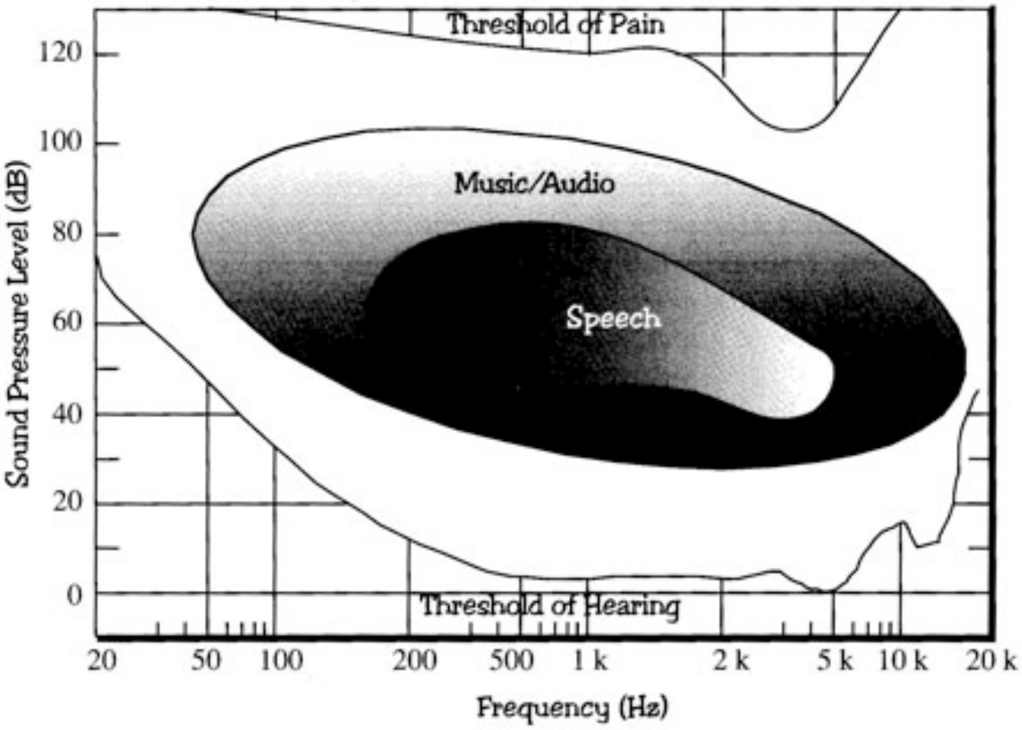


Fig. 11.1. *A more detailed picture of our audio window. Most music does not exceed a range of level of about 75 dB from softest to loudest. Similarly, most recorded music does not contain much information above 18 kHz.*

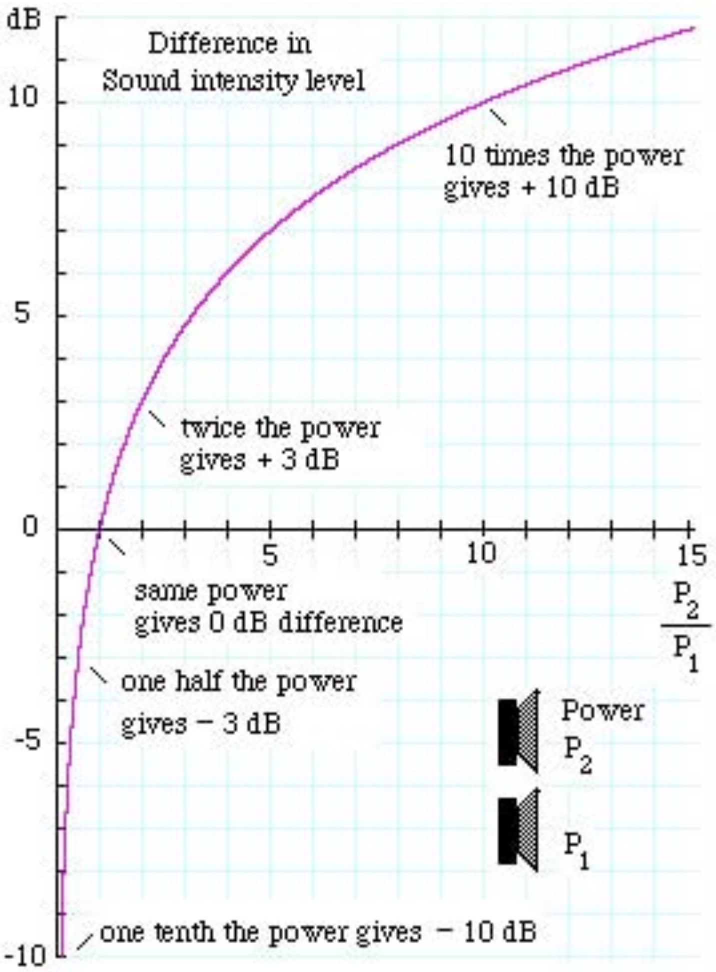
2.13. Measuring a Sine Wave: Where?

- Phase refers to position or offset within oscillation or wave shape
- Only meaningful in relation to a reference point or another wave
- Often measured between -1 and 1, 0 to 360 degrees, or 0 to 2 π radians
- 180 degrees is one half-cycle out of phase
- Flipping the phase is multiplying a signal times -1
- The combination of signals in and out of phase is frequently used as a creative way to shape timbre

2.14. Measuring a Sine Wave: How Much?

- How large are the oscillations: its amplitude

- Numerous measurement types
  - Acoustical power, a measure of pressure: watts, dynes/cm2, pascals (force over area)
  - In relation to a minimum and a maximum: 0% to 100%, or -1.0 to 1.0
  - In relation to some defined measure: Bels, decibels (dB)
- Decibels: condense a wide range of numbers into a smaller range
  - A non-linear measure in relation to power



Courtesy of Joe Wolfe. Used with permission. http://www.phys.unsw.edu.au/music

  - -3 dB change is a factor of .5 (half power/intensity)
  - -6 dB change is a factor of .25 (but half the voltage/linear amplitude)
- Numerous types of dB

  - Sound Pressure Levels (SPL)
  - Voltages: dBV, dBu
  - Digital Bits: dBFS
- High dBs (SPLs) correlate to what we call loud; low dBs (SPLs) correlate to what we call quiet
- Amplitude is similar to loudness, but not the same
- Root mean square (RMS) averaging is frequently used to approach a measure of loudness
- A range of usable amplitudes is called a dynamic range
- Amplitude range of human ear: from 0 to 120 dB SPL, or 120 dB of dynamic range

2.15. Our Ear Hears Logarithmically: Amplitude

- The ear can handle a range of pressure from .00002 to 1000000 pascals
- dB is a logarithmic measure: adding 3 dB *doubles* the audio power

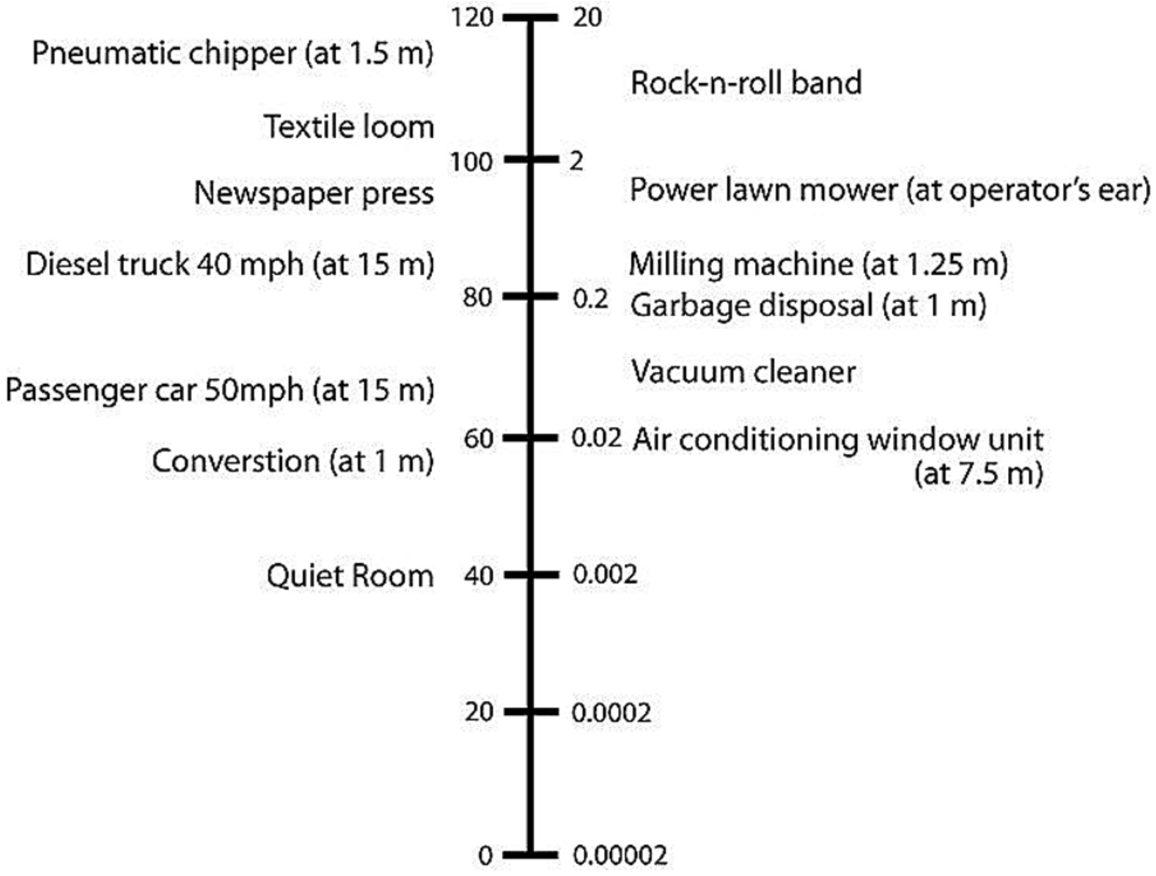


Image: "Sound Pressure Level (SPL) and Sound Pressure (Pa)"
from *Principles of Industrial Hygiene*. Available at: http://ocw.jhsph.edu.

- dB is not the same as perceived loudness [demo/earLogAmp.pd]

2.16. Aesthetic Considerations of a Sine Wave

- Unnaturally unending, simple, and perfect

- Musical applications still exist

2.17. The Power of Frequency Ratios

- The Dream House (Krueger 2008)

- 35 sine tones distributed over four speakers

- The Base 9:7:4 Symmetry in Prime Time When Centered above and below The Lowest Term Primes in The Range 288 to 224 with The Addition of 279 and 261 in Which The Half of The Symmetric Division Mapped above and Including 288 Consists of The Powers of 2 Multiplied by The Primes within The Ranges of 144 to 128, 72 to 64 and 36 to 32 Which Are Symmetrical to Those Primes in Lowest Terms in The Half of The Symmetric Division Mapped below and Including 224 within The Ranges 126 to 112, 63 to 56 and 31.5 to 28 with The Addition of 119 (Krueger 2008)

- A very poor simulation, yet still a complex timbre with extreme sensitivity to head position [demo/sinePrimeRatios.pd]

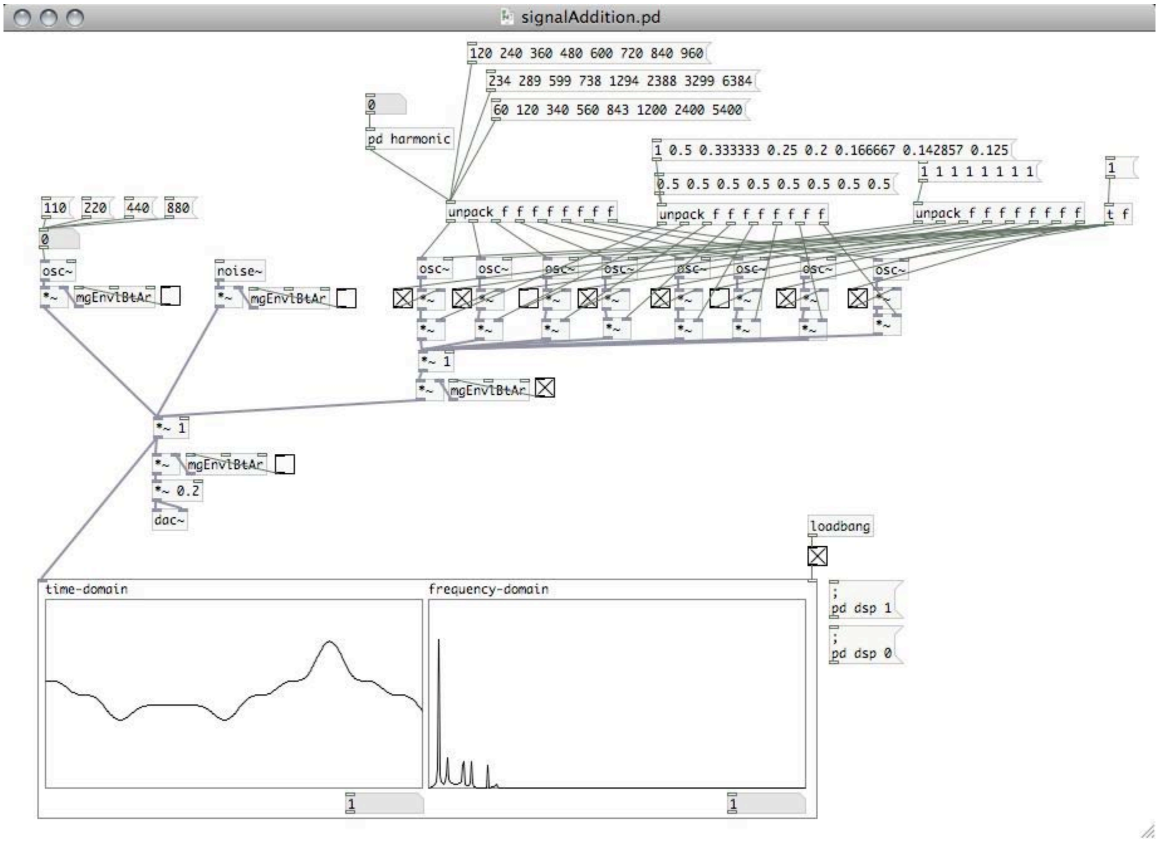
2.18. Listening

- Sine drone as thematic content

- Aphex Twin: “Ventolin,” *I Care Because You Do*, 1994

2.19. Visualizing Sounds, Waves, and Signals

- Waves can store multiple signals at multiple frequencies
- Waves can be added (mixed together) to result in more complex waves
- Sometimes these combined waves can be later decomposed into simple waves
- A single wave can store a tremendous amount of complexity (information)
- Noise can ride on sine waves [demo/signalAddition.pd]

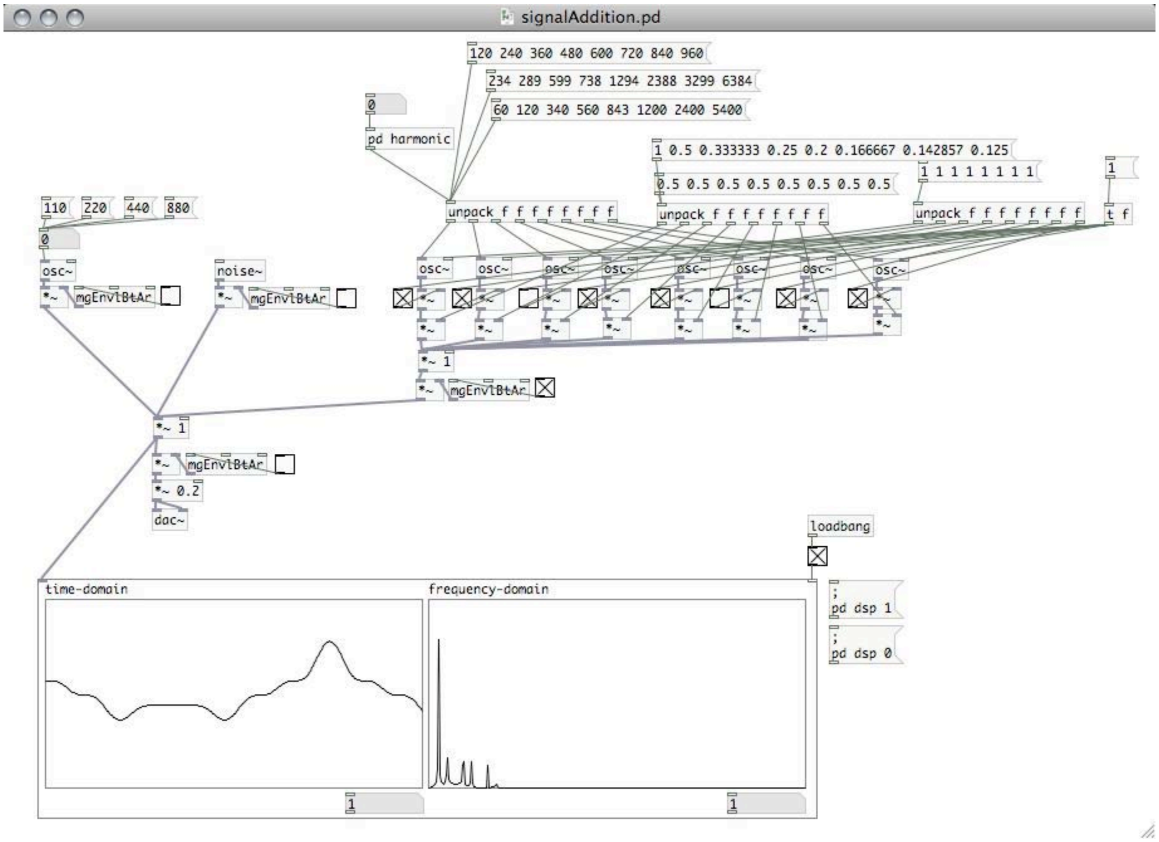


2.20. Visualizing Sounds: Time Domain

- Graph of displacement (amplitude, pressure, voltage) over time [demo/signalAddition.pd]
- Graph amplitude change (y-axis) over time (x-axis)
- Illustrates the movement of a speaker, microphone, or other transducer in two dimensions
- Acoustical pressure is similar but more complex
- Common representation of digital sound files
- Computationally easy to do

2.21. Visualizing Sounds: Frequency Domain

- Graph of frequency amplitudes within a single time window [demo/signalAddition.pd]

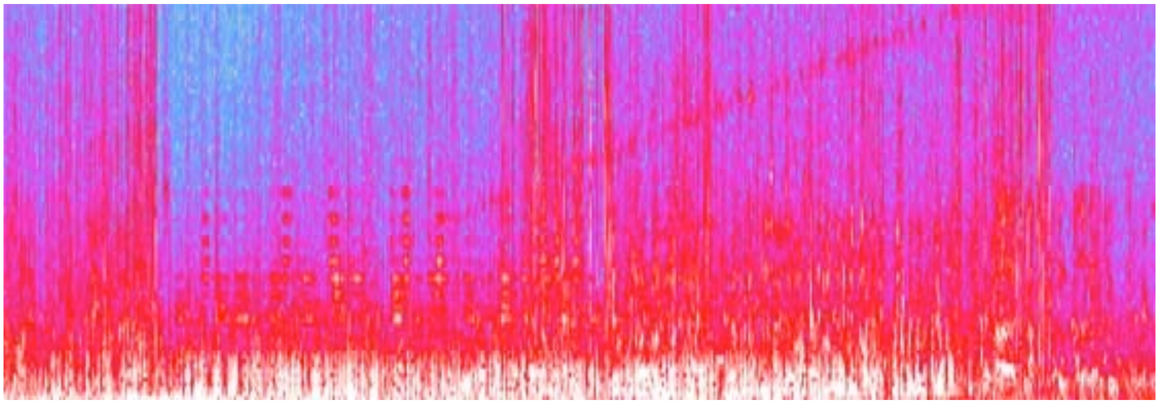


- Graph amplitude (y-axis) over frequency (x-axis)

- Illustrates what the ear hears at a given moment
- Requires mathematical decoding: Fourier Transform
- Reveals the spectrum of a sound
- Computationally taxing

2.22. Visualizing Sounds: Three Dimensions

- At least wo ways:
    - Graph of frequency (x-axis), amplitude (color), and time (y-axis)



    - Graph of frequency (x-axis), amplitude (y-axis), and time (z-axis)

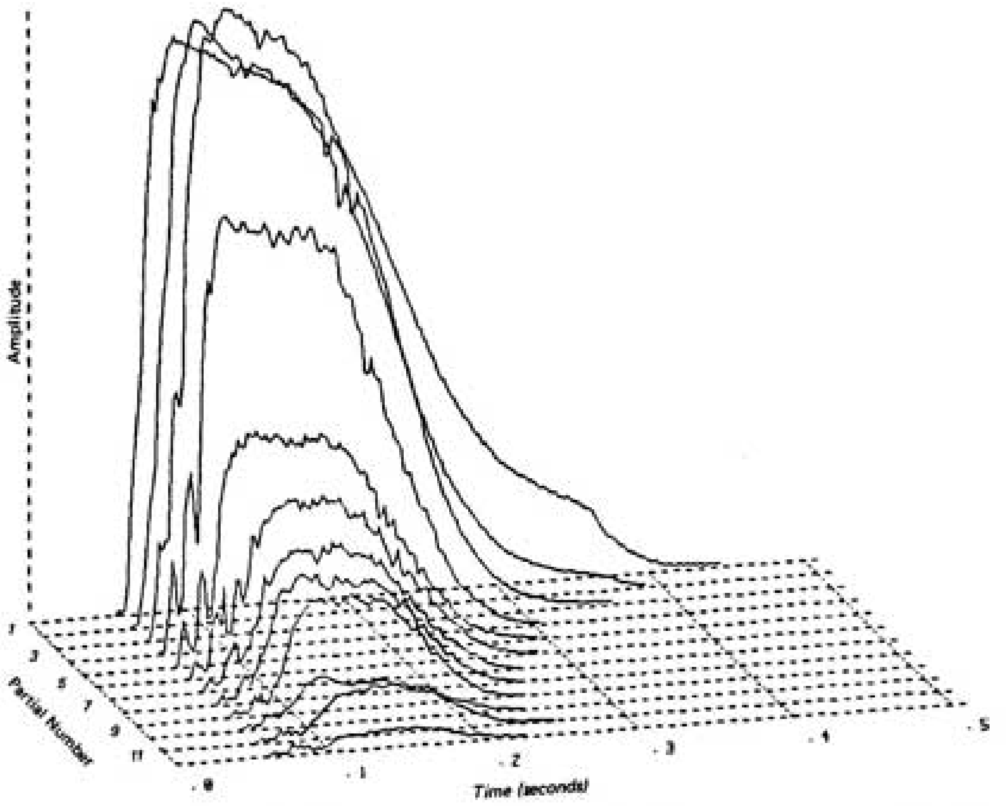


FIGURE 2.30 The amplitude progression of the partials of a trumpet tone as analyzed by Grey and Moorer.

Source: Moorer, J., J. Grey, and J. Strawn. "Lexicon of Analyzed Tones (Part 3: The Trumpet)." Computer Music Journal 2, no 2 (1978): 23-31.

- Closest representation to our experience of sound
- Not perfect for technical and psychoacoustic reasons

2.23. History of Sound Analysis

- Manometric flames for waveform analysis (Roads 1996)

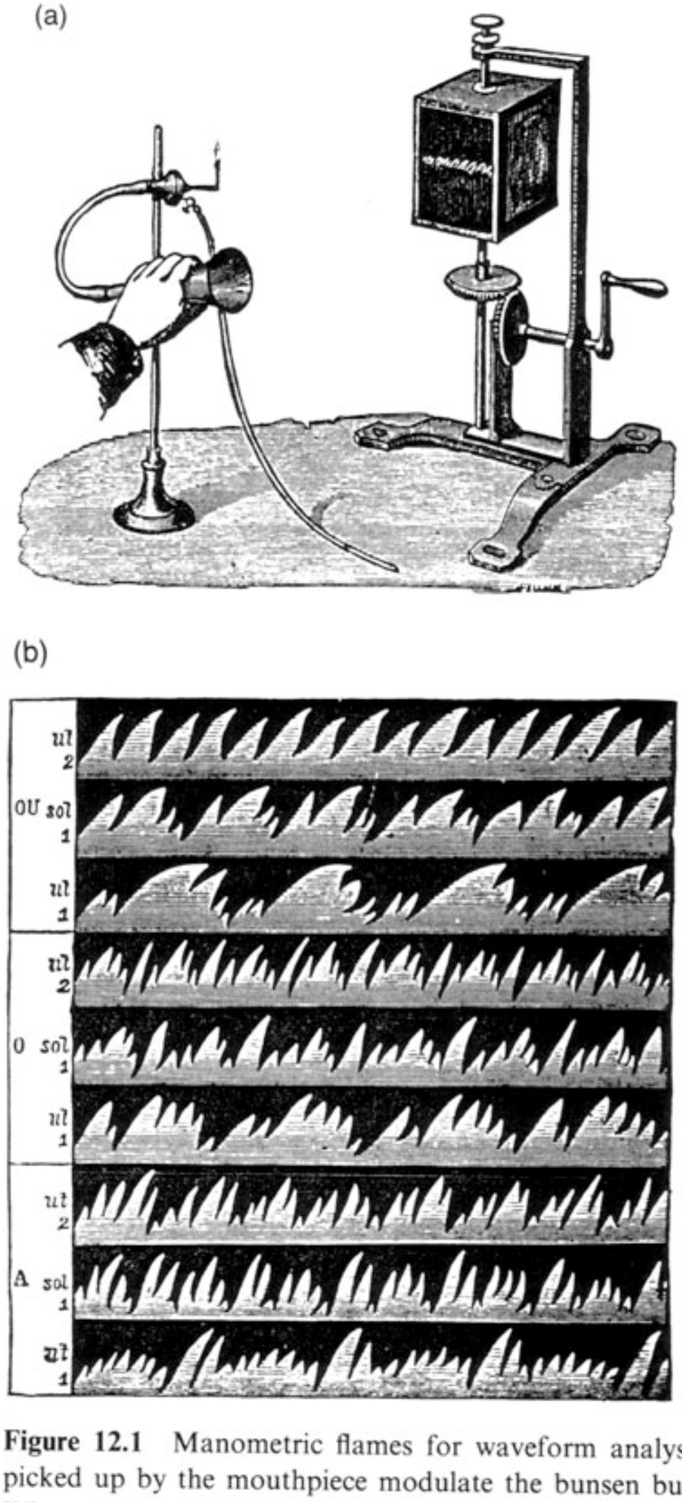


Figure 12.1 Manometric flames for waveform analysis. (*a*) Apparatus. Sounds picked up by the mouthpiece modulate the bunsen burner flame within the box. When the box is rotated, mirrors on the outside of the box project the flame as a continuous band with jagged edges or teeth corresponding to the pitch and spectrum of the input sound. (*b*) Flame pictures of the French vowel sounds [OU], [O], and [A] by R. Koenig, sung at the pitches C1 (bottom of each group), G1 (middle of each group), and C2 (top of each group). (After Tyndall 1875.)

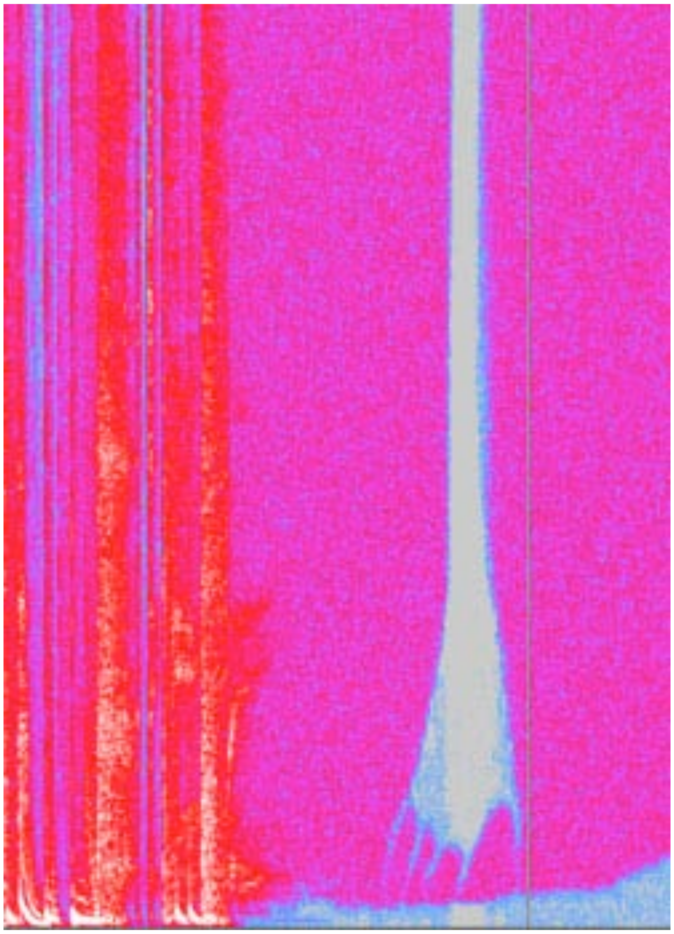
Courtesy of MIT Press. Used with permission.
Source: Roads, C. *The Computer Music Tutorial.* Cambridge, MA: MIT Press, 1996.

- Recognized that different vowels had different wave forms

2.24. Spectrum as Thematic Content: NIN

- NIN: Year Zero, album cover

- Pre/post apocalyptic mass-hallucinations of hands descending from the sky
- Encoding a visual thematic element in the spectral analysis of a sound
- NIN: Year Zero, "The Warning," spectral analysis



- Audio: Nine Inch Nails, “The Warning,” *Year Zero*, 2007

2.25. Making the Sine Wave More Natural: Shaping Amplitude

- Envelopes: dynamic changes in amplitude applied to a sound
- A simplification of acoustic instruments: ADSR [demo/envelopes.pd]

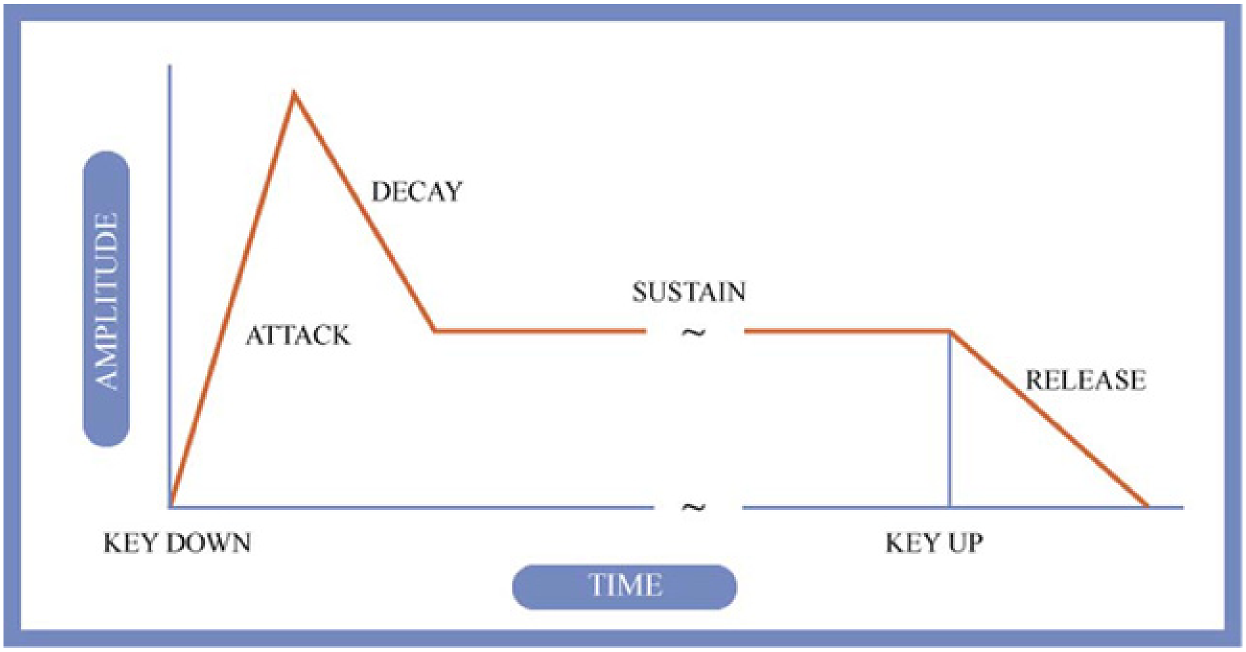
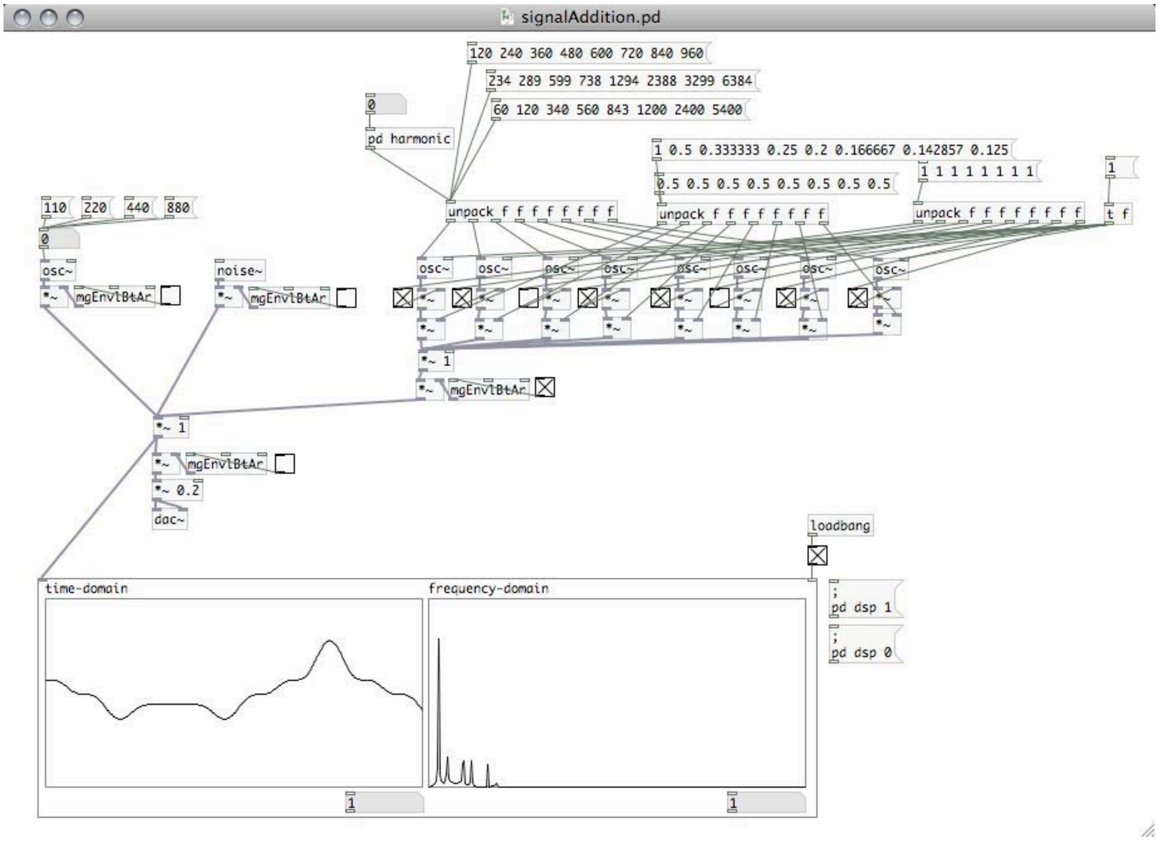


Figure by MIT OpenCourseWare.

- Attack: the initial and rapid increase in amplitude
- Decay: from the peak to a steady state
- Sustain: the amplitude (usually a percentage ratio) of the steady state
- Release: damping from steady state to silence

2.26. Making the Sine Wave More Natural: More Complexity

- Acoustic instruments do not make sine waves
- Acoustic instruments produce multiple resonances from a single tone combined with various types of noise
- These multiple resonances are called harmonics (sometimes overtones or partials), and create timbre
- Each harmonic can be modeled as an additional sine wave [demo/signalAddition.pd]

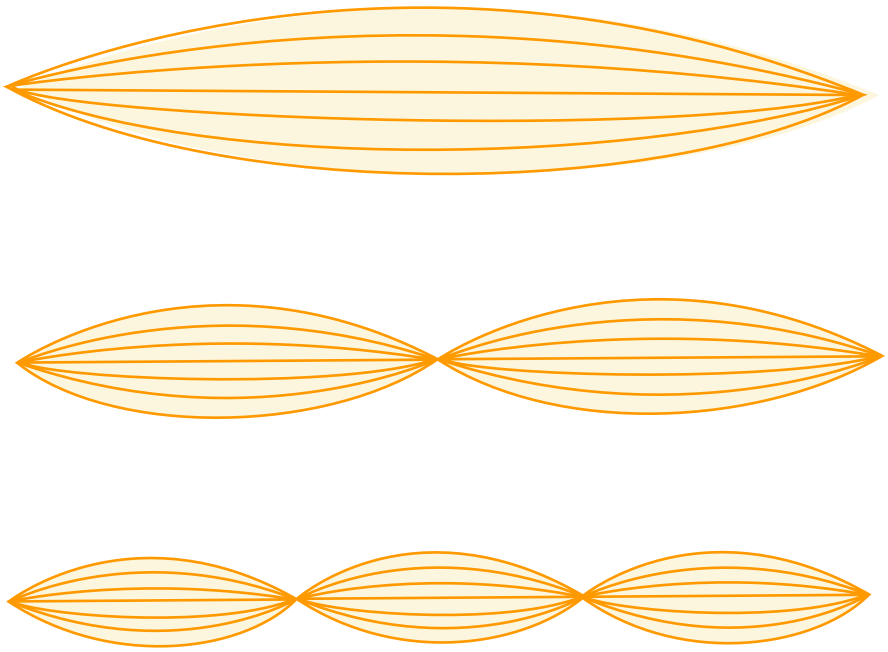


2.27. Timbre

- Timbre is the combination of frequencies (sometimes sine-like waves) that make up a rich tone
- Our ears are designed to distinguish sounds based on timbre
- We hear in the frequency domain

2.28. Harmonics, Overtones, and Partials

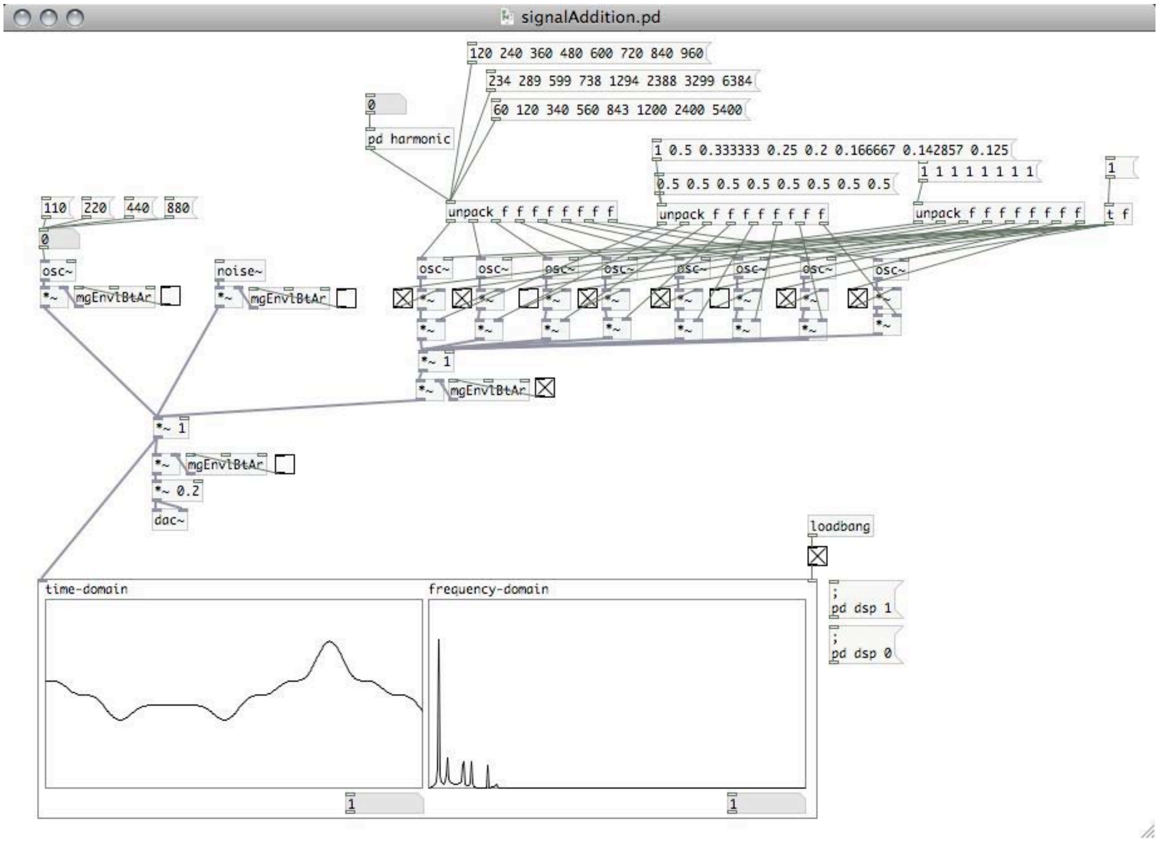
- All sounds in nature are more complex than a sine wave (pure frequency)
- Many physical objects (strings, air-columns) have multiple points of resonance



Characteristic vibrations of a stretched string. Vibrating in one, two or three equal parts emits the fundamental tone, octave and twelfth respectively.

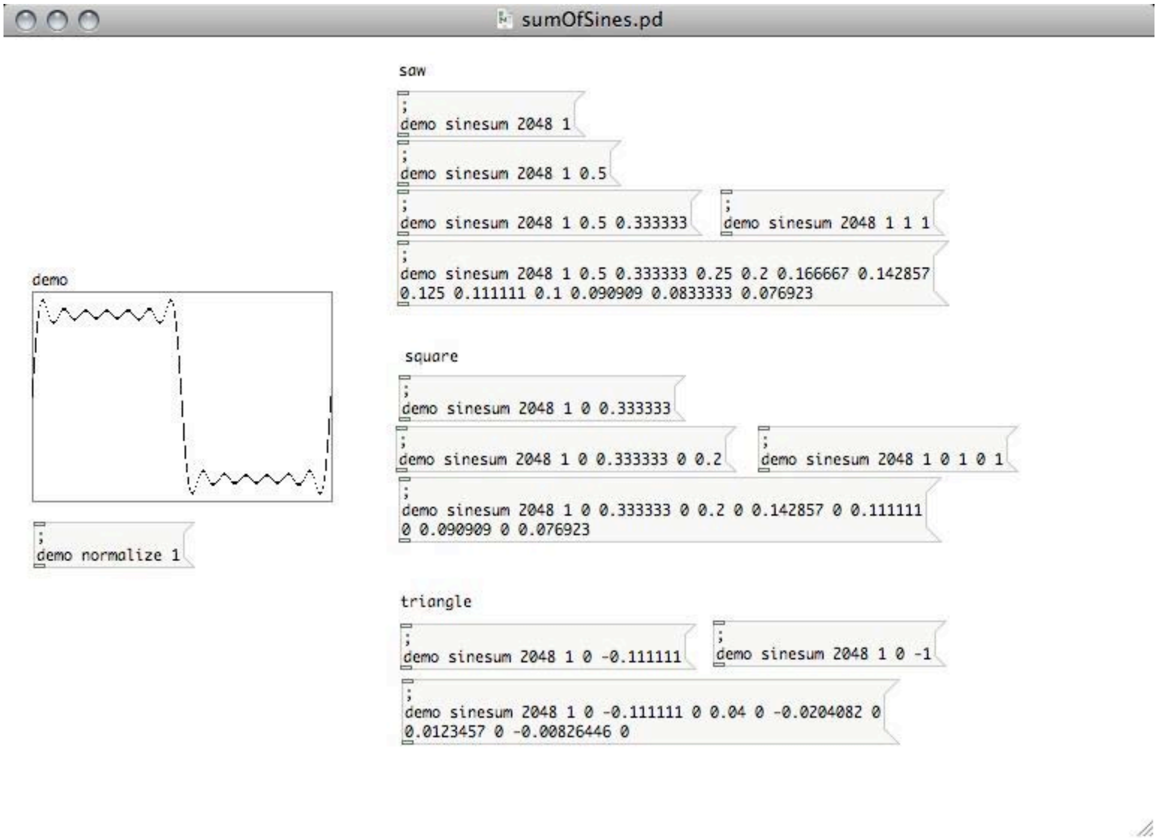
Figure by MIT OpenCourseWare.

- The difference in the sound between two instruments has to do with which resonances are prominent
- The lowest resonance is called the fundamental, or the first harmonic (f0)
- Higher resonances are called harmonics, partials, or overtones
- These components define the spectrum (or timbre or tone color) of a sound
- In some objects these modes are in predictable arrangements: harmonic
- In other objects these modes are in complex arrangements: inharmonic [demo/signalAddition.pd]



2.29. Common Waveforms and Timbre

- Harmonically related sine tones, when summed, produce familiar shapes [demo/sumOfSines.pd]



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;
demo normalize 1
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saw

```
;
demo sinesum 2048 1
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;
demo sinesum 2048 1 0.5
```

```
;
demo sinesum 2048 1 0.5 0.333333
```

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;
demo sinesum 2048 1 1 1
```

```
;
demo sinesum 2048 1 0.5 0.333333 0.25 0.2 0.166667 0.142857
0.125 0.111111 0.1 0.090909 0.0833333 0.076923
```

square

```
;
demo sinesum 2048 1 0 0.333333
```

```
;
demo sinesum 2048 1 0 0.333333 0 0.2
```

```
;
demo sinesum 2048 1 0 1 0 1
```

```
;
demo sinesum 2048 1 0 0.333333 0 0.2 0 0.142857 0 0.111111
0 0.090909 0 0.076923
```

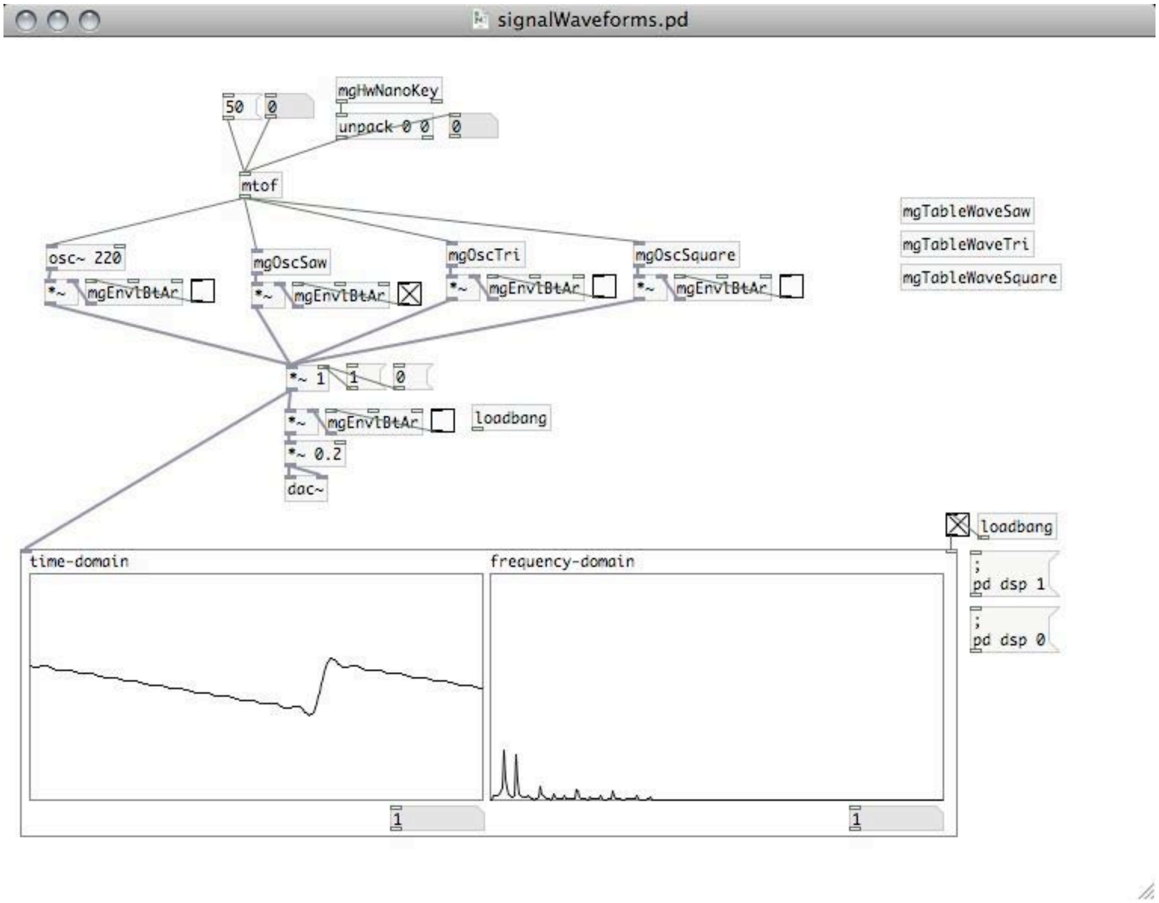
triangle

```
;
demo sinesum 2048 1 0 -0.111111
```

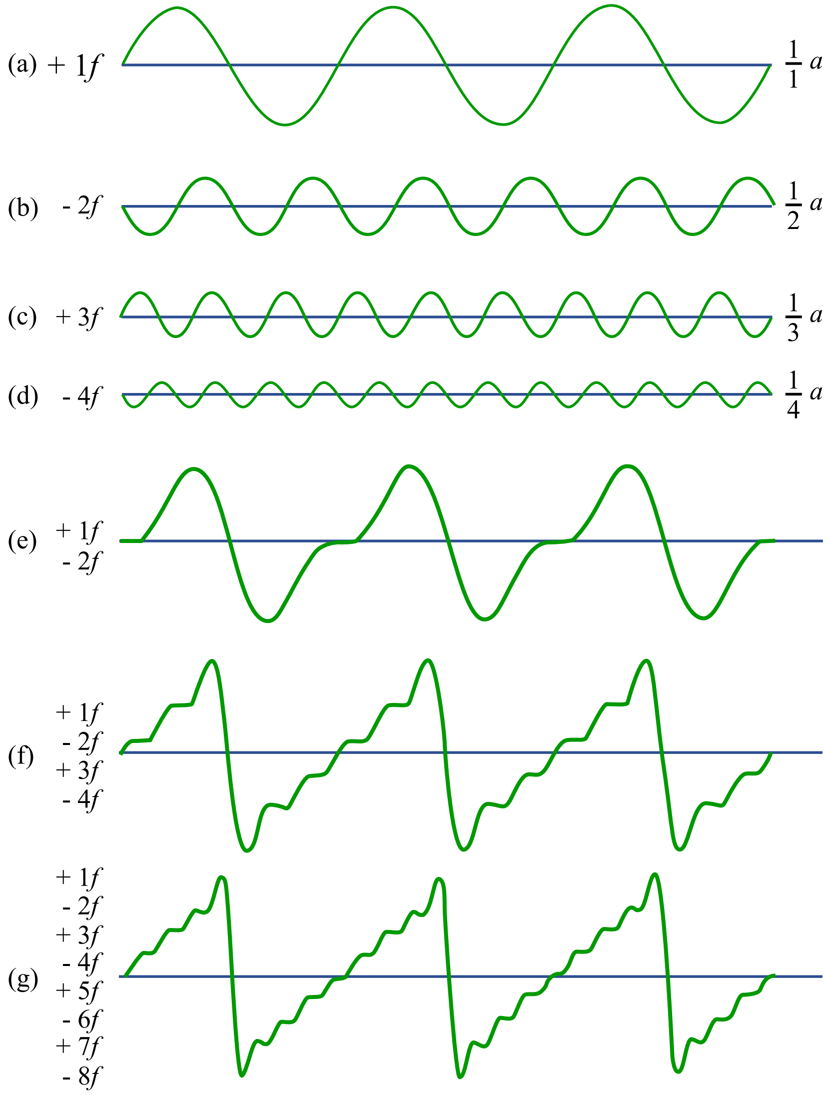
```
;
demo sinesum 2048 1 0 -1
```

```
;
demo sinesum 2048 1 0 -0.111111 0 0.04 0 -0.0204082 0
0.0123457 0 -0.00826446 0
```

- Oscillating common waveforms is a shortcut to getting rich timbre [demo/signalWaveforms.pd]



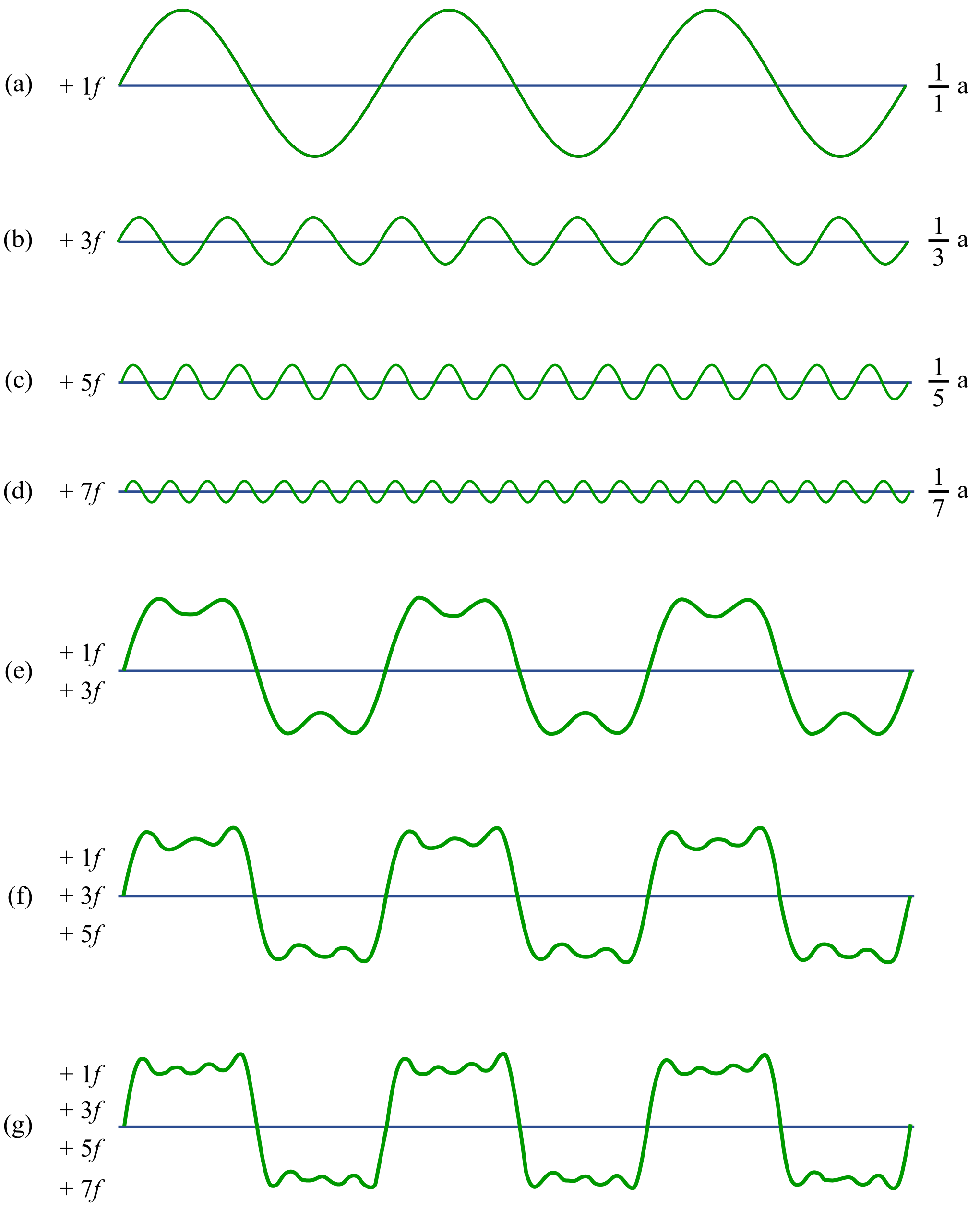
- Sawtooth wave: the sum of sines with decreasing amplitude (for each overtone n the amplitude is 1/n)



Sawtooth waves, analyzed as an additive series of harmonics.

Figure by MIT OpenCourseWare.

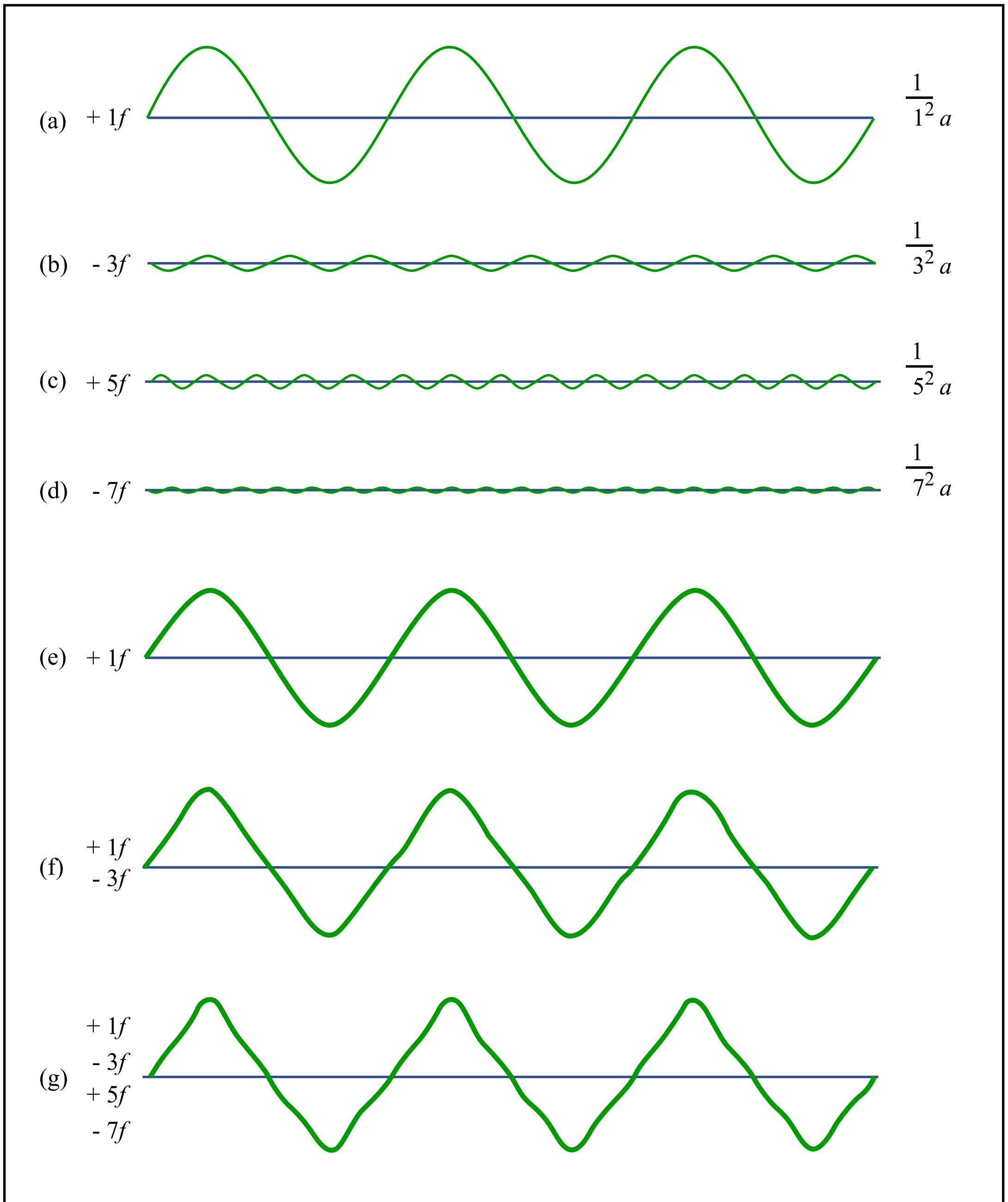
- Square wave: the sum of odd harmonics with decreasing amplitude



Square waves, analyzed as an additive series of harmonics.

Figure by MIT OpenCourseWare.

- Triangle wave: only add harmonics with decreasing amplitude and alternating inversion



Triangle waves, analyzed as an additive series of harmonics.

Figure by MIT OpenCourseWare.

2.30. Noise Spectra

- Noise can be represented as a random set of amplitude points
- White noise, averaged, produces equal amplitude for all frequencies
- A sine tone has all energy at one frequency; white noise has energy at all frequencies

2.31. How the Ear Works: Components

- The components of the ear

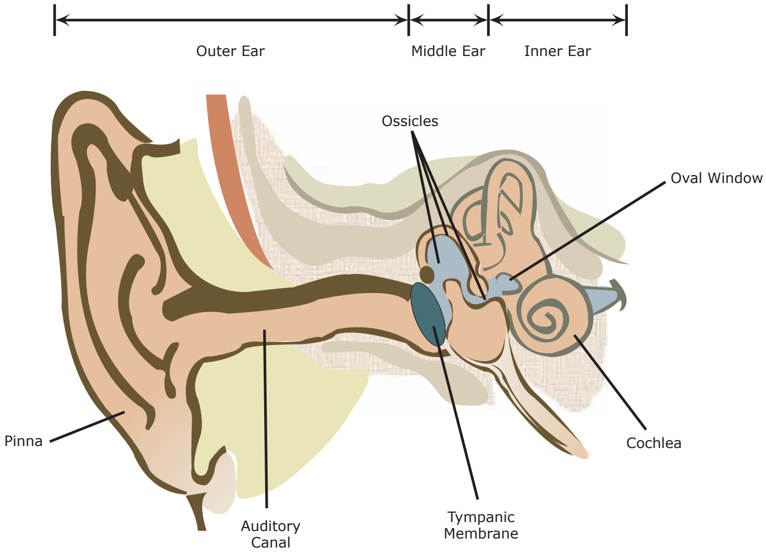
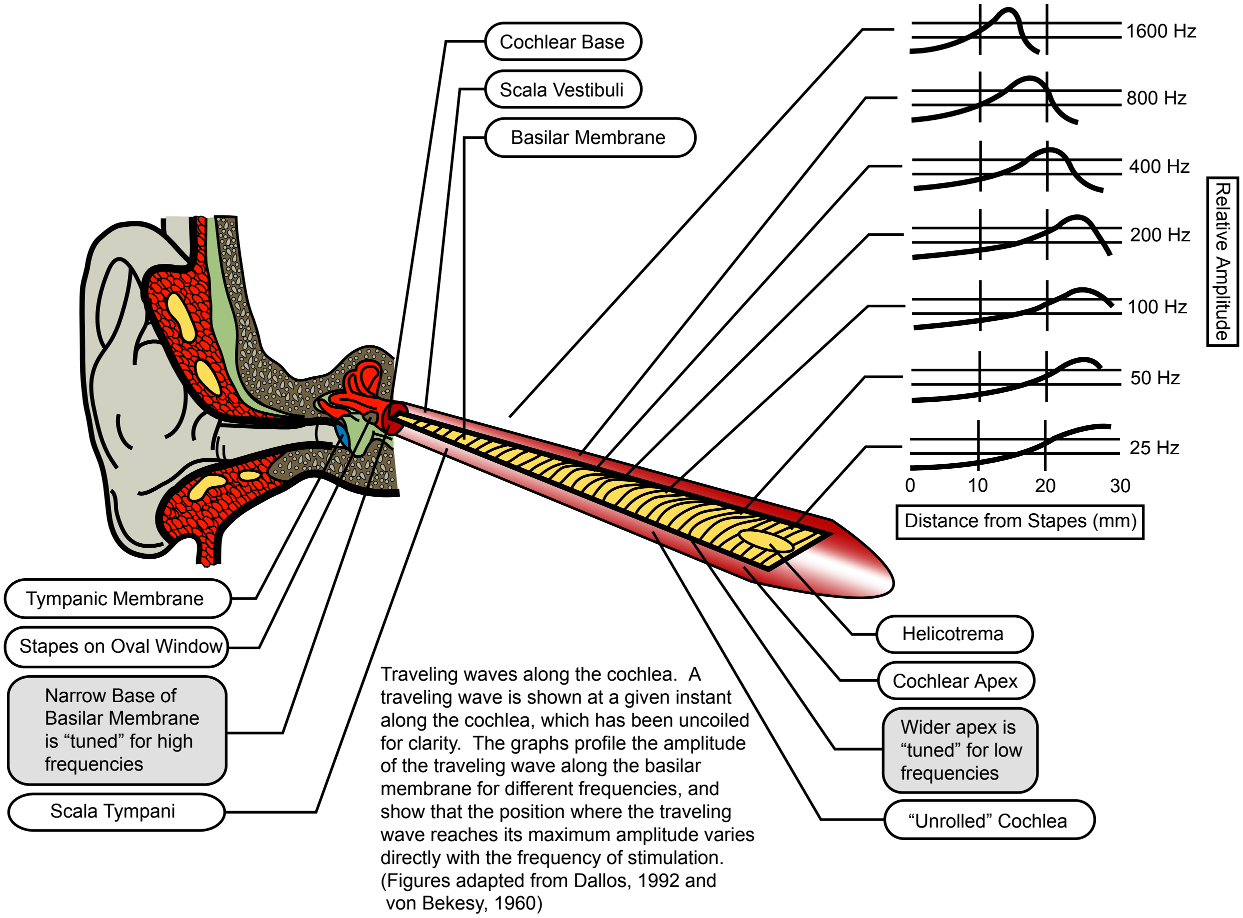


Figure by MIT OpenCourseWare. After figure 11.3 in: Bear, Mark F.,Barry W.Connors, and Michael A. Paradiso*. Neuroscience: Exploring the Brain*. 2nd ed. Baltimore, Md.:Lippincott Williams & Wilkins, 2001. ISBN: 0683305964.

2.32. How the Ear Works: The Pathway of Sound

- Transduction: the process of converting sound from on medium into another
- Sound is transduced from air to skin (tympanic membrane), from skin to bone (ossicles), from bone to skin (oval window), from skin to fluid (perilymph), from fluid to hair (basilar membrane)



Traveling waves along the cochlea. A traveling wave is shown at a given instant along the cochlea, which has been uncoiled for clarity. The graphs profile the amplitude of the traveling wave along the basilar membrane for different frequencies, and show that the position where the traveling wave reaches its maximum amplitude varies directly with the frequency of stimulation. (Figures adapted from Dallos, 1992 and von Bekesy, 1960)

Figure by MIT OpenCourseWare.

2.33. How the Ear Works: The Cochlea

- The basilar membrane gets more narrow and more thin from base to tip
- Lower frequencies resonate near the tip (least stiff); higher frequencies resonate near the base (most stiff, near the oval window)
- Basilar membrane resonates at each component frequency in a sound

- 20,000 hair cells on basilar membrane send messages to the brain
- The cochlea performs spectral analysis with hair

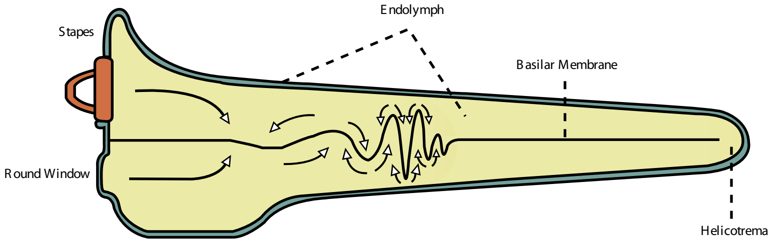


Figure by MIT OpenCourseWare. After figure 11.9 in: Bear, Mark F., Barry W. Connors, and Michael A. Paradiso. *Neuroscience: Exploring the Brain*. 2nd ed. Baltimore, Md.: Lippincott Williams & Wilkins, 2001. ISBN: 0683305964.

2.34. Our Ear is Tuned for Speech

- Amplitude is not the same as loudness
- Perceived loudness is measured in phons, not dB
- Fletcher Munson (Robinson and Dadson/ISO 226:2003) equal loudness curves define phones

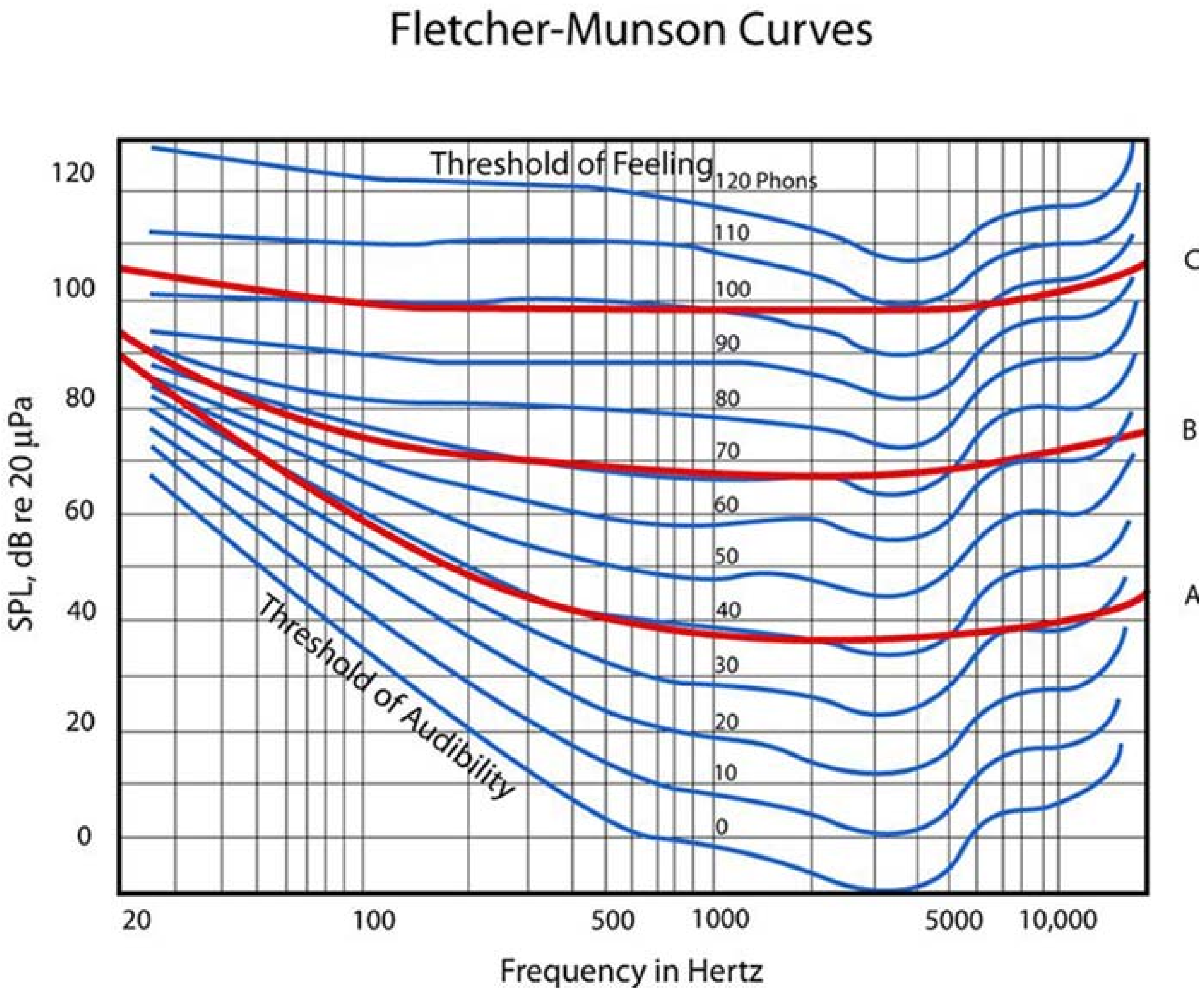


Image: "Fletcher-Munon Curves" from *Principles of Industrial Hygiene*.
Available at: http://ocw.jhsph.edu.

- The ear is tuned for speech: low and high frequencies require more amplitude to sound equally loud

2.35. Listening

- Sine tones in context
- Audio: Alva Noto and Ryuichi Sakamoto, “Noon,” *Vrioon* 2002

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