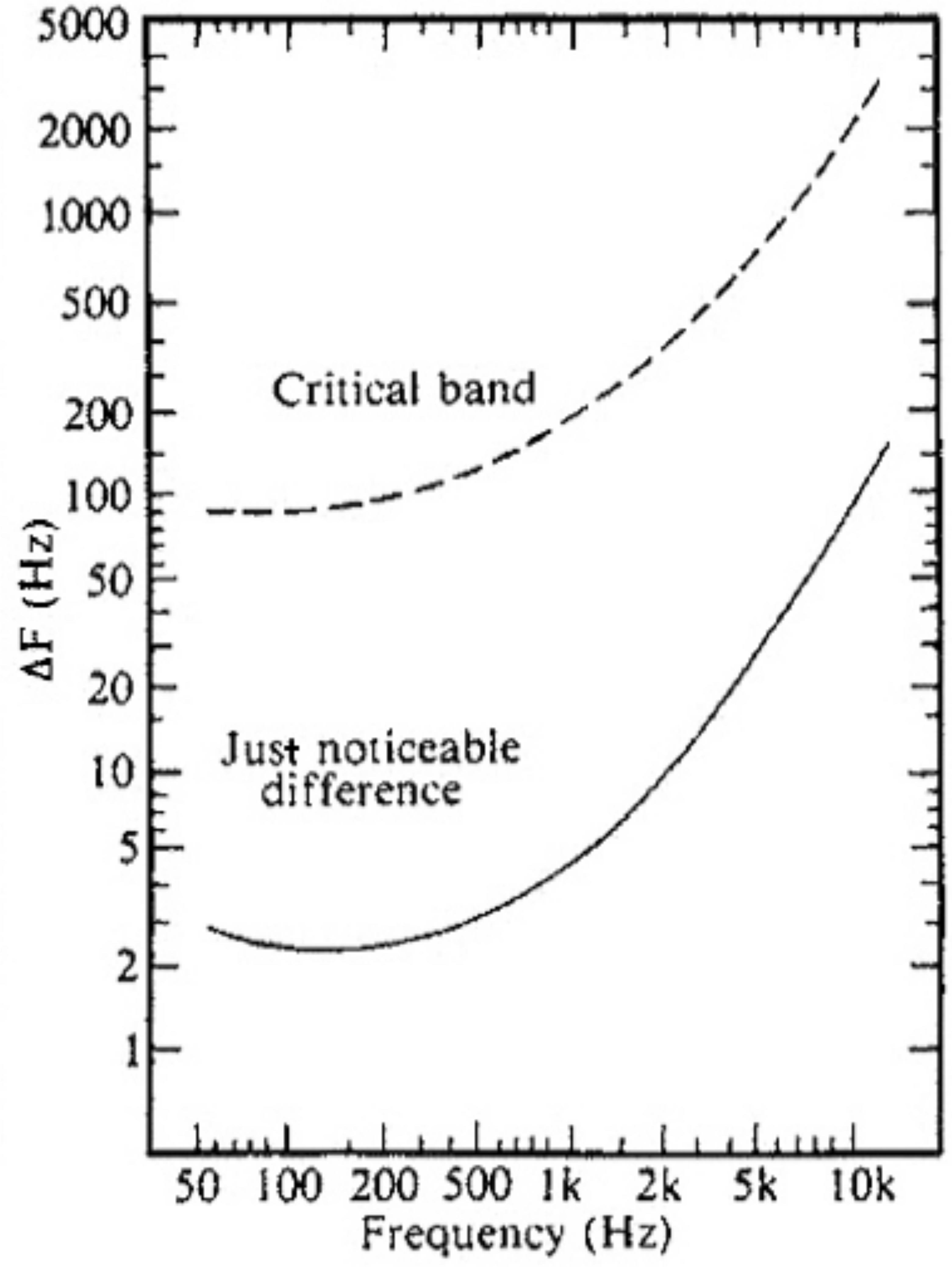
11. Pitch & timbre

What distinguishes one musical note from another?

- **Pitch**, **timbre**, **duration**, **loudness** (intensity), **attack & decay transients**
- **Perfect pitch**: ability to determine **absolute pitch** without regard to a reference (only 1 out of ~10,000 people have it)
- **Pitch discrimination**: ability to distinguish two different pitches
    - depends on whether you play the two notes **sequentially** or **simultaneously**
    - **JND**: just noticeable difference (**sequential**; 0.5% of center frequency; 1/10th of a semitone)
    - **LFD**: limit of frequency discrimination (**simultaneous**; 10% of center frequency; 2 semitones)
    - Analogy with **sense of touch**: placing two pencil points on your arm



Where does pitch determination occur, in the ear or the brain?

- **Place theory**: pitch determined by the **location on the basilar membrane** excited by the sound wave

- **Periodicity theory**: pitch inferred by the brain from the **timing of electrical impulses** triggered by the period of the sound wave

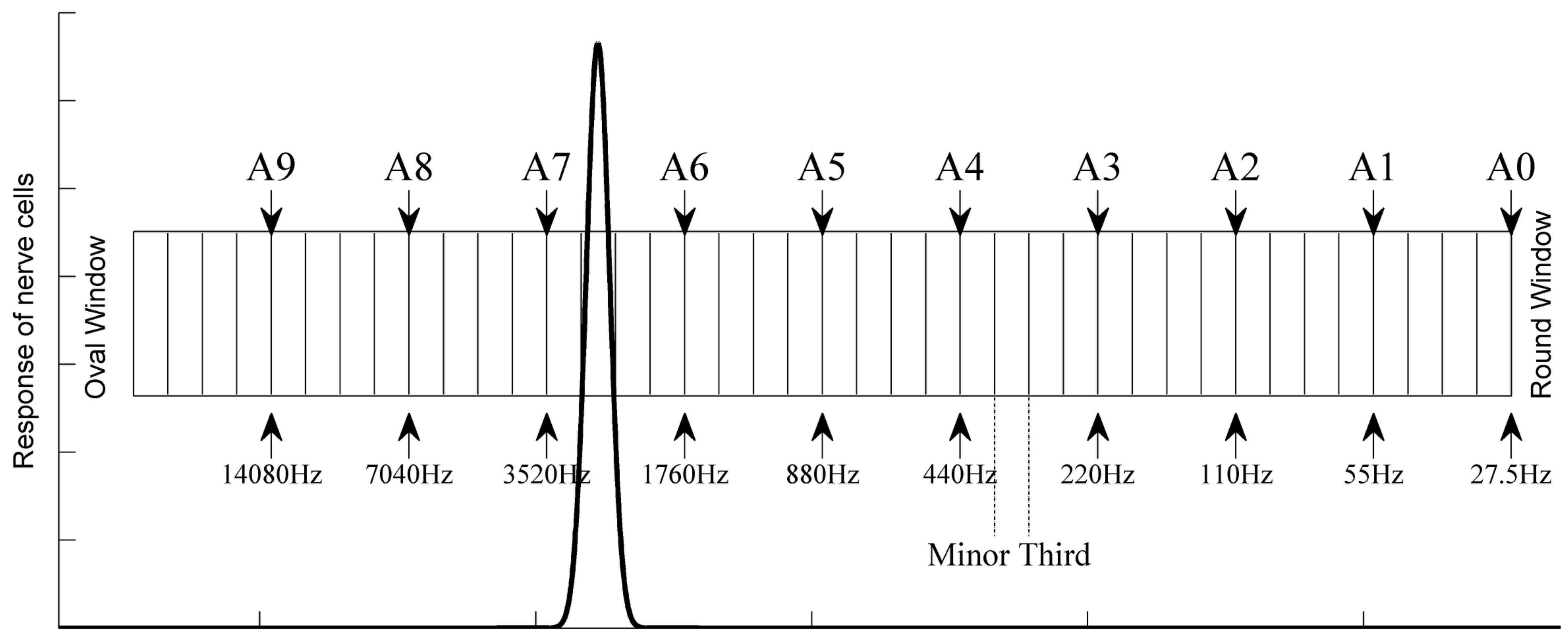
- **Missing fundamental** in support of periodicity theory:

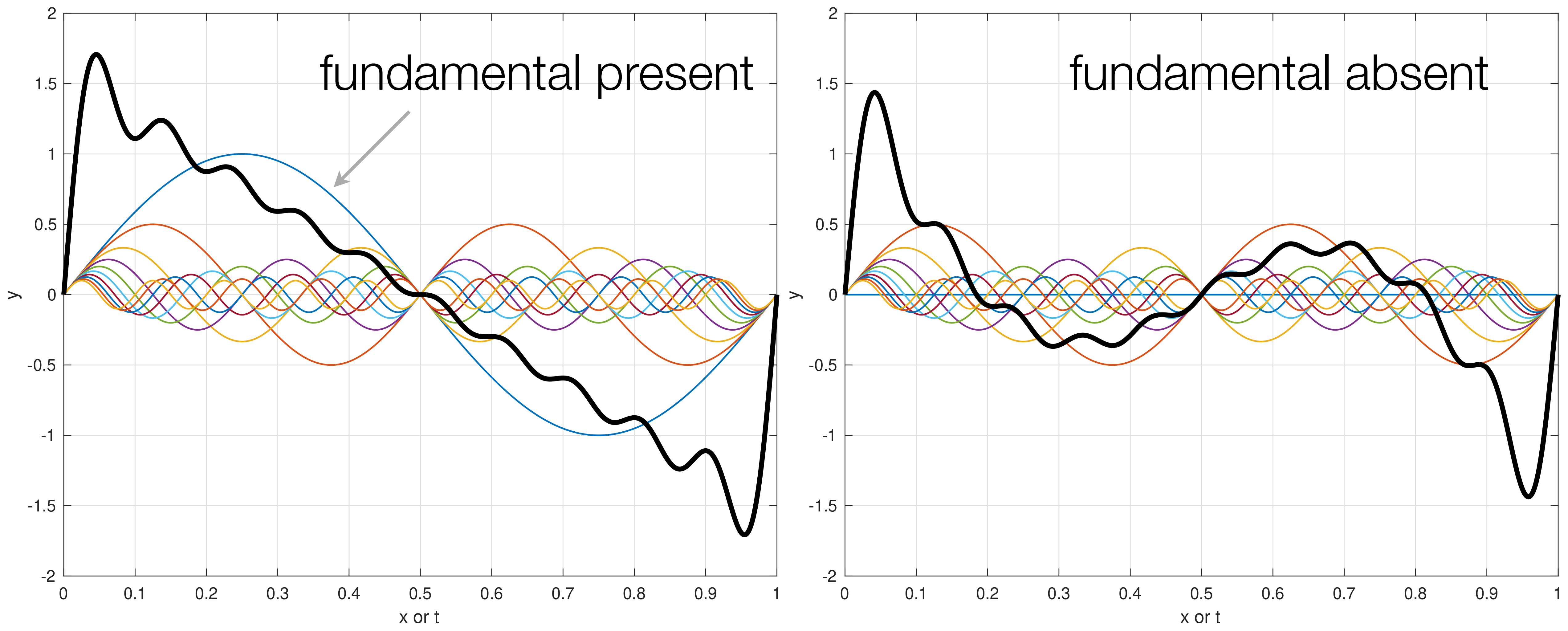
  - 200 Hz, 300 Hz, 400 Hz, …. –> hear 100 Hz

  - 300 Hz, 500 Hz, 700 Hz, …. –> hear ??? Hz

  - https://www.youtube.com/watch?v=AZ8qZCGg4Bk

Basilar membrane (schematic)

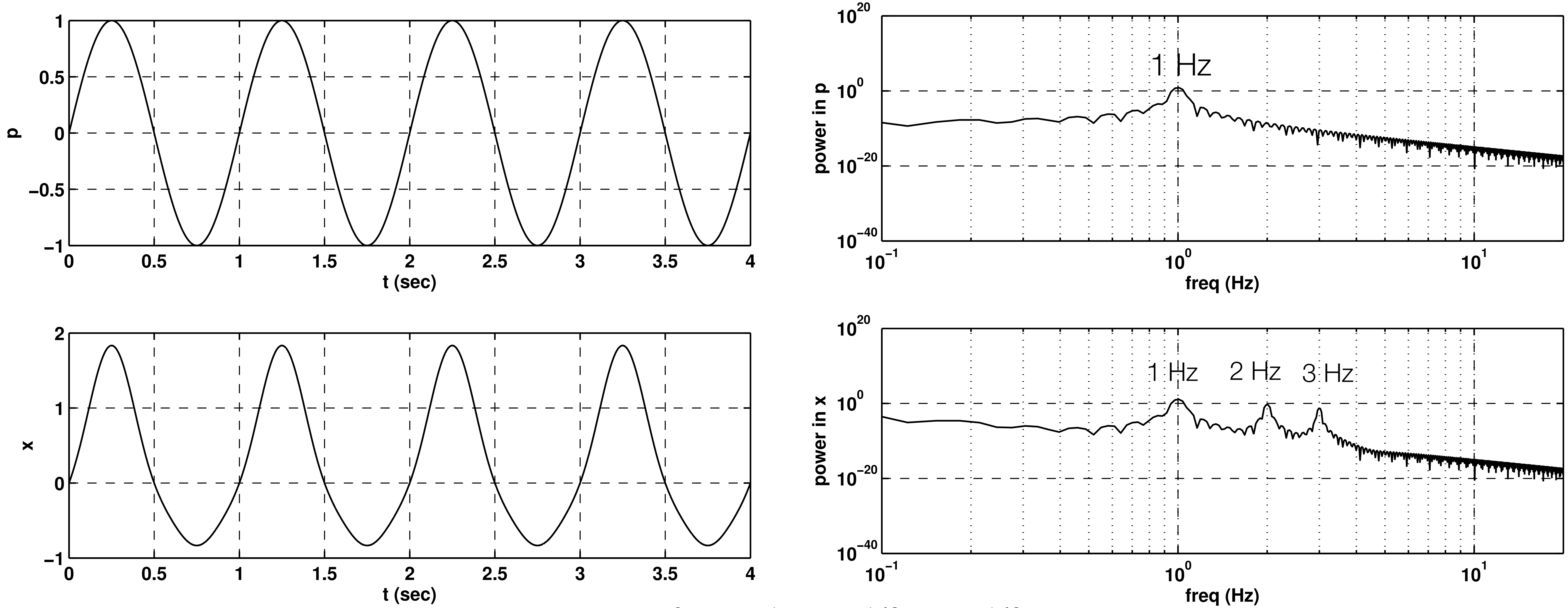




Aural harmonics – harmonics produced by the ear

- Ear introduces **distortions** which converts a pure tone to one having multiple harmonics

$$x(t) = a_0 + a_1\,p(t) + a_2\,p^2(t) + a_3\,p^3(t) + \cdots$$

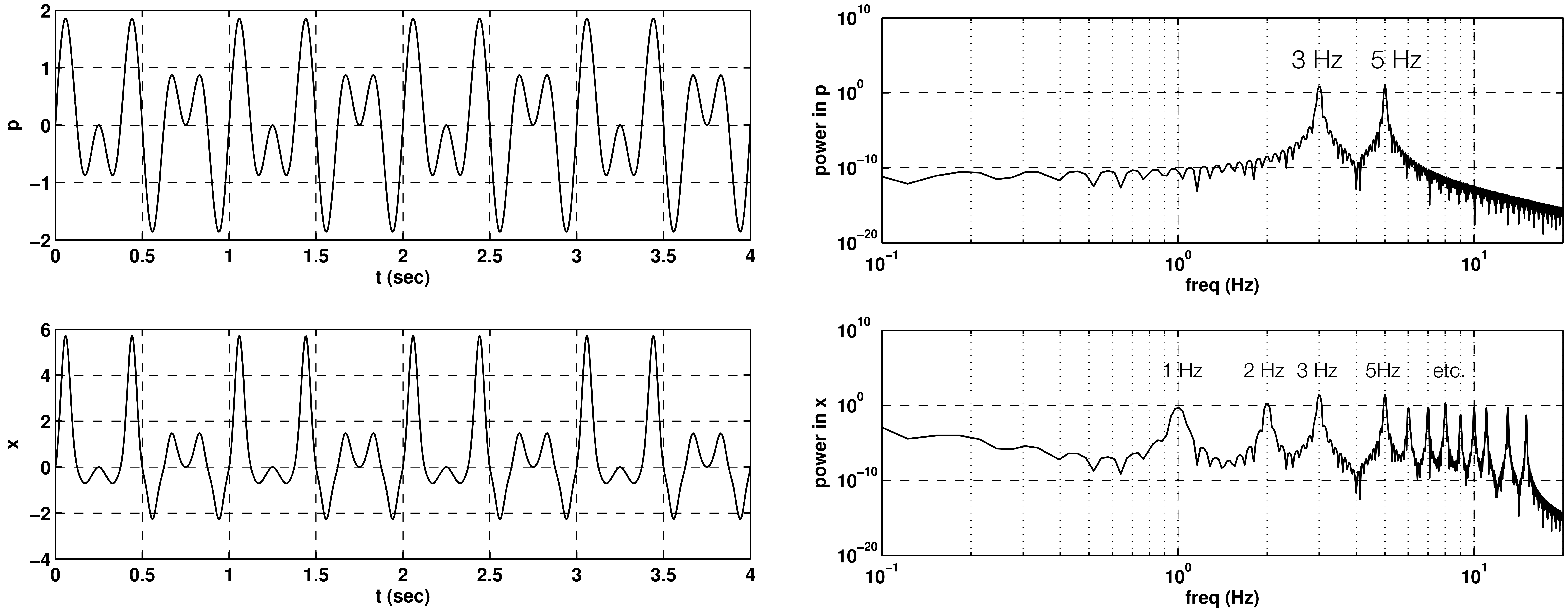


$a_0 = 0\,,\ a_1 = 1\,,\ a_2 = 1/2\,,\ a_3 = 1/3$

Aural combination tones — aural harmonics for complex tones

- If two pure tones f_1 and f_2 are played simultaneously and sufficiently loudly, one hears **sum and difference combination tones**

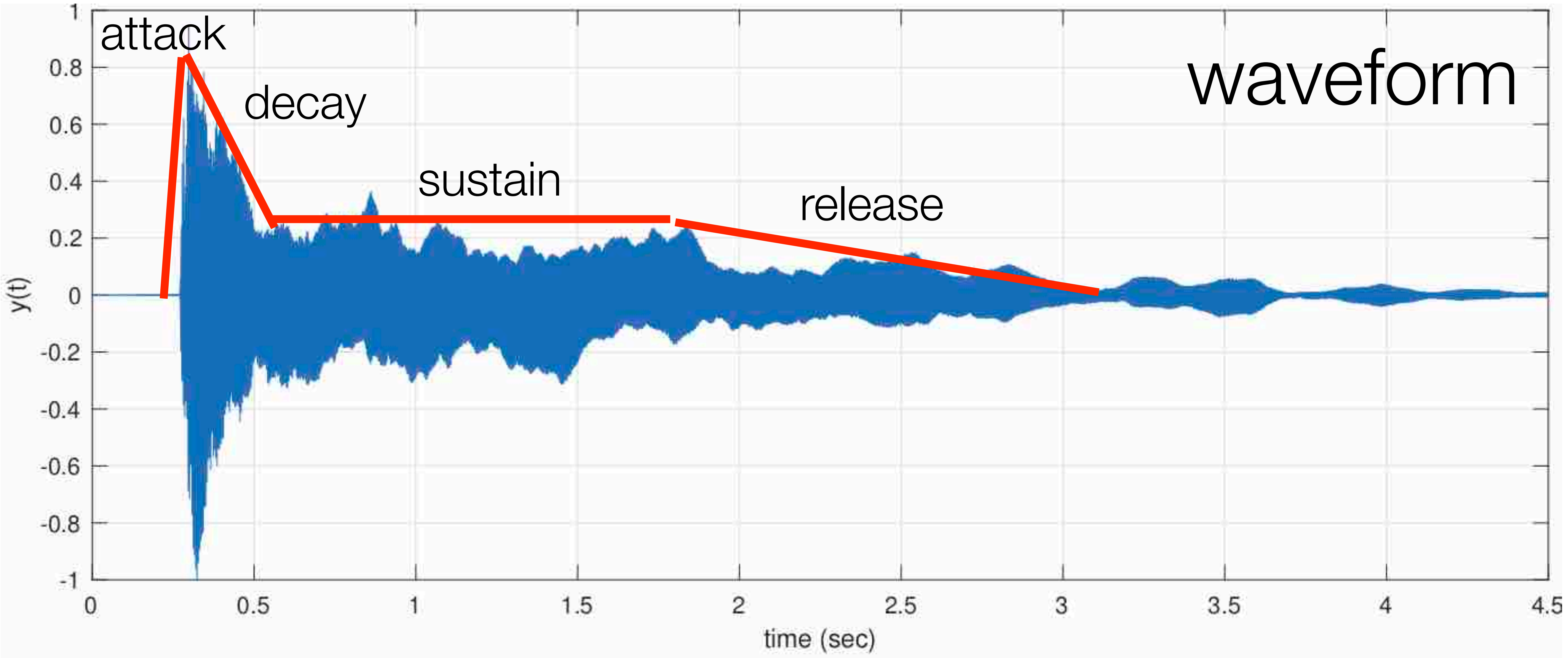
$$f_c = |mf_1 \pm nf_2| \quad \Rightarrow \quad |f_1 - f_2|,\ |2f_1 - f_2|,\ |3f_1 - f_2|, \cdots$$

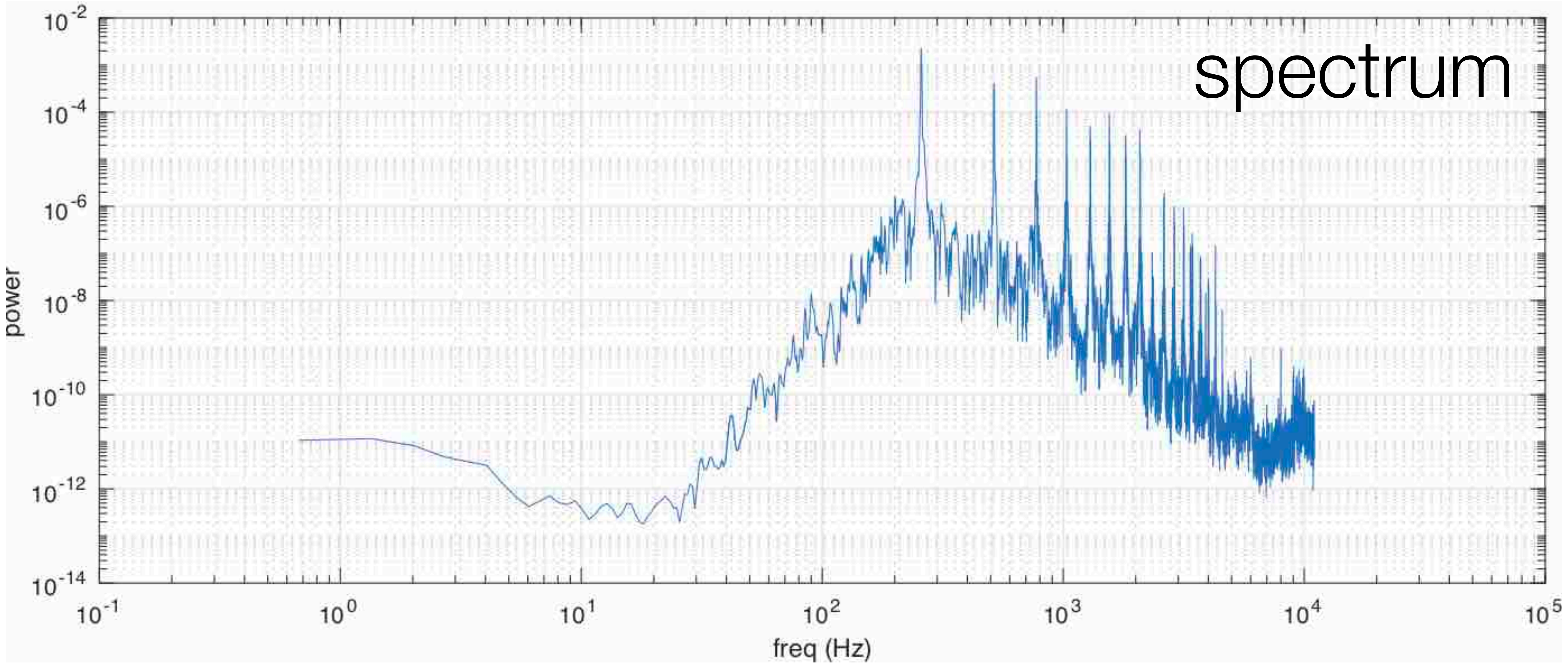


$$a_0 = 0\,,\ a_1 = 1\,,\ a_2 = 1/2\,,\ a_3 = 1/3$$

Attack and decay transients

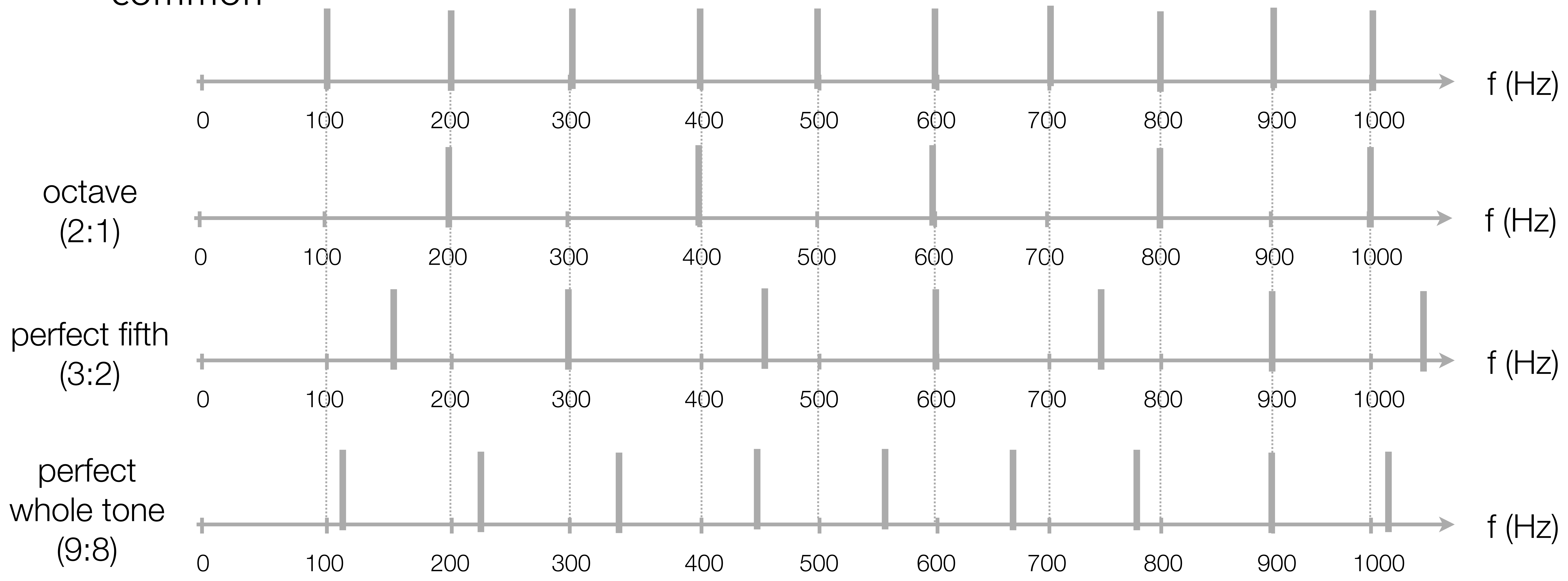
- How a note starts and ends affects how it sounds
- Piano C4
- Piano C4 (reversed)
- Happy birthday
- Happy birthday backwards
- Happy birthday backwards (reversed)





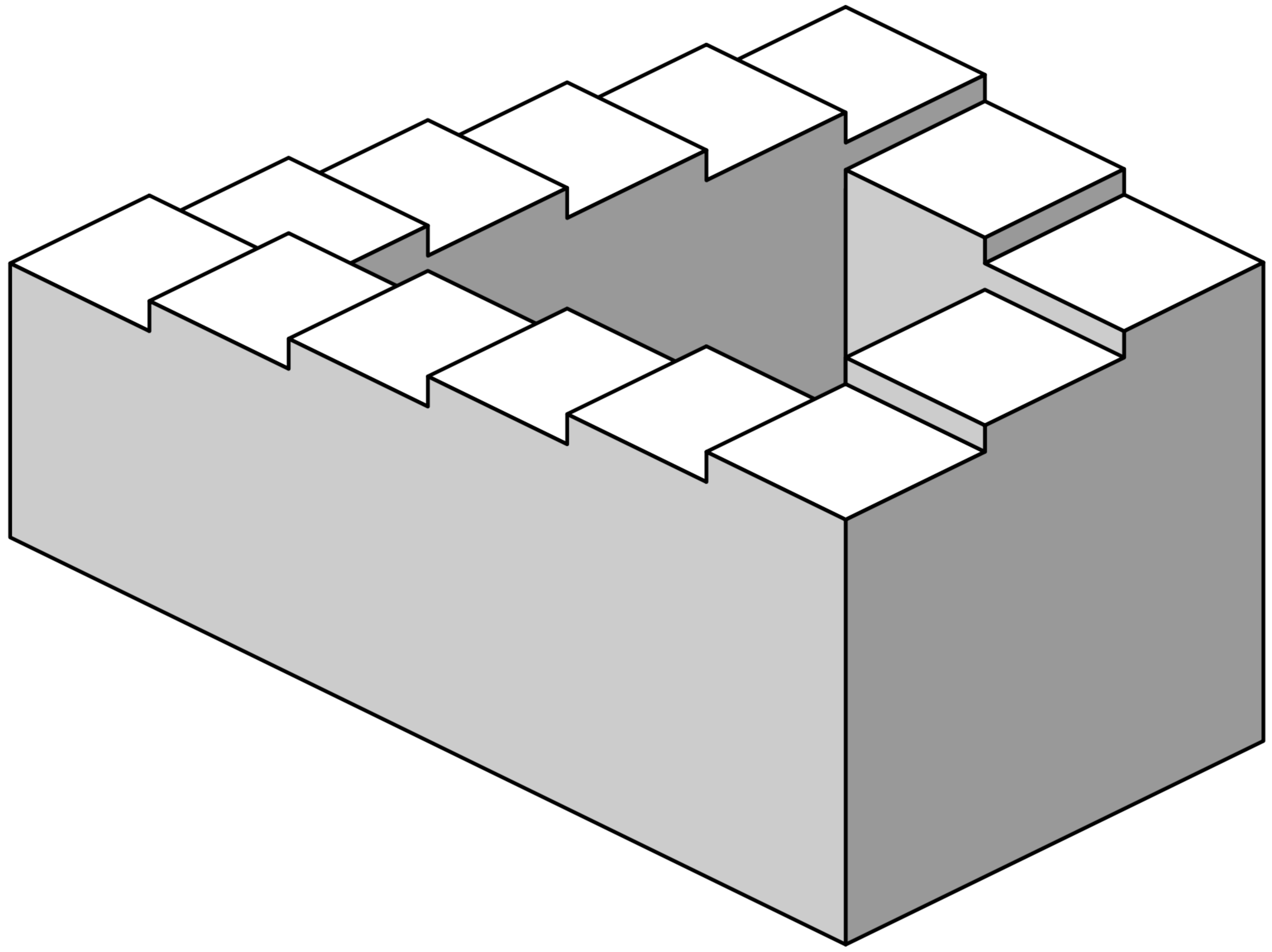
What makes two notes pleasing when they are played together?

- Two notes are pleasing (**consonant**) when they have many harmonics in common
- Two notes clash with one another (**dissonant**) when they have very few harmonics in common



Pitch paradox — the audio equivalent of an optical illusion

- **Shepard scale**: never-ending scale (pitch seems to increase indefinitely)
- YouTube videos:
    - http://www.youtube.com/watch?v=PCs1lckF5vI
    - http://vimeo.com/34749558



Never-ending staircase
(L. Penrose; M.C. Escher)

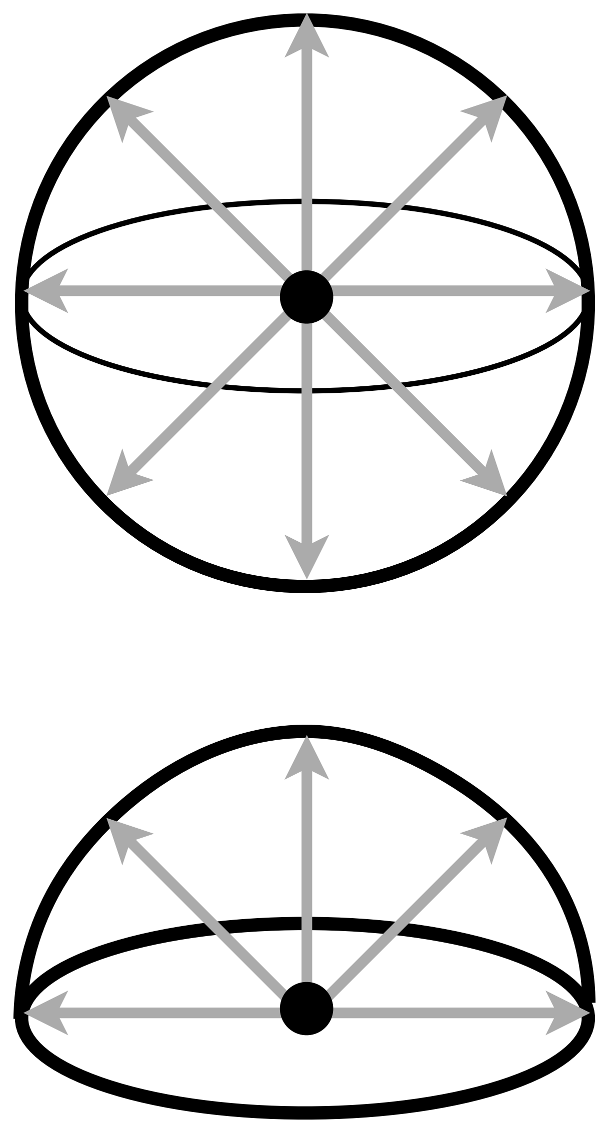
12. Auditorium & room acoustics

Auditorium and room acoustics — overview

- What makes for a good concert hall?
- Why do you sound good when you sing in a shower?
- Difference between “direct”, “reflected”, and “reverberant” sound
- Reverberation time is the most important characteristic of a room
- YouTube video / soundfile:
    - Anechoic chamber (https://www.youtube.com/watch?v=BYBSA9v8IRE)
    - “Sonic wonders” sound file (listen to -32:40)

Direct sound

- Sound received from a source in the absence of any reflections (e.g., anechoic chamber)
- Intensity: $I = \dfrac{P}{4\pi r^2}$ (omni-directional); $I = \dfrac{QP}{4\pi r^2}$ (directional source; Q is the directivity factor)



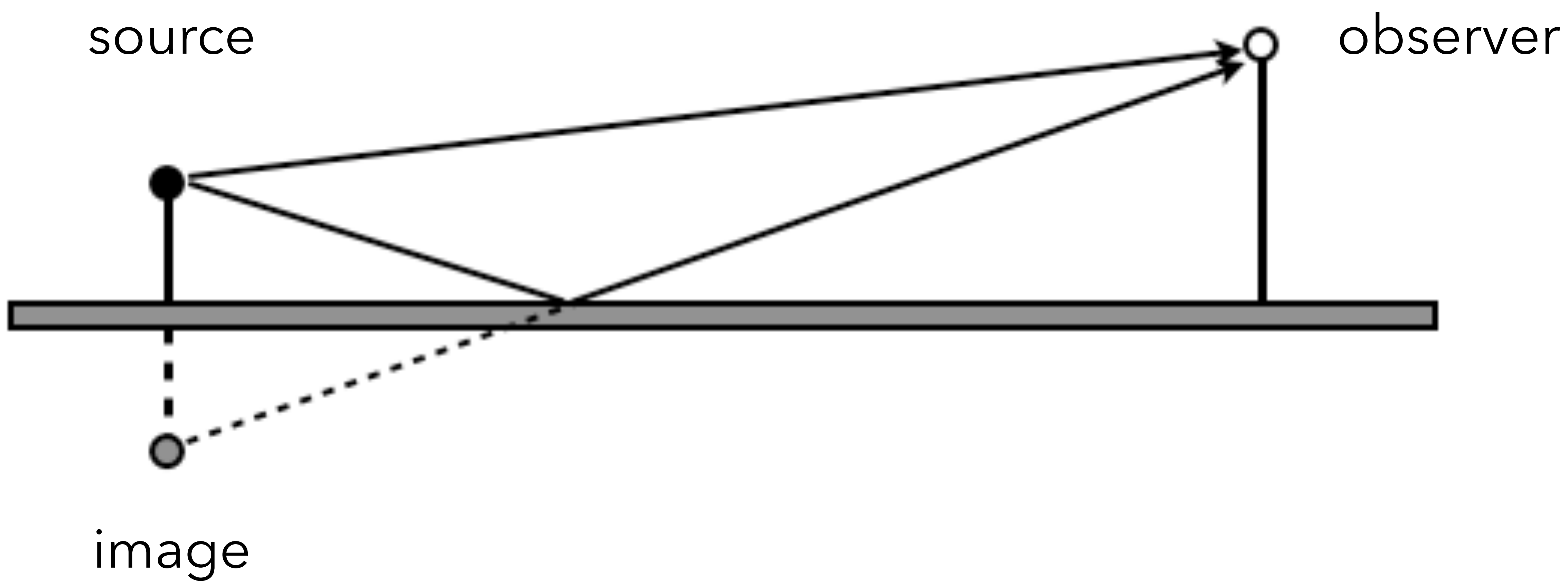
$Q = 1$

$Q = 2$

$Q = 0$

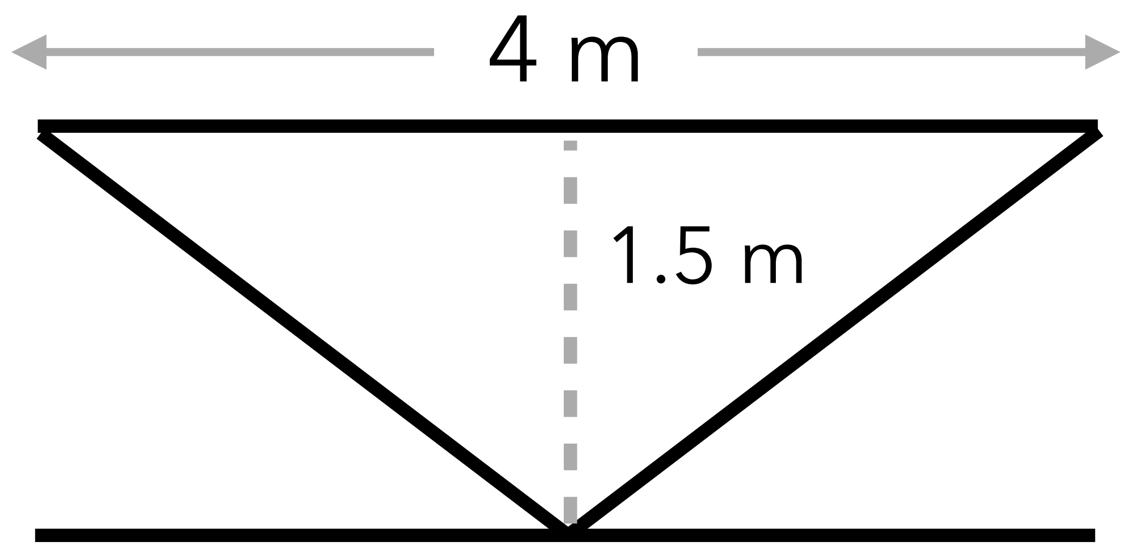
Reflected sound

- Hear an echo if the reflected sound is heard greater than 35 msec after the direct sound
- Recall: $v = 346\ \mathrm{m/s} \approx 1000\ \mathrm{ft/s} = 1\ \mathrm{ft/msec}$
- $\mathrm{SIL}_{\mathrm{reflected}} < \mathrm{SIL}_{\mathrm{direct}}$ (reflected sound travels farther and can be partially absorbed)



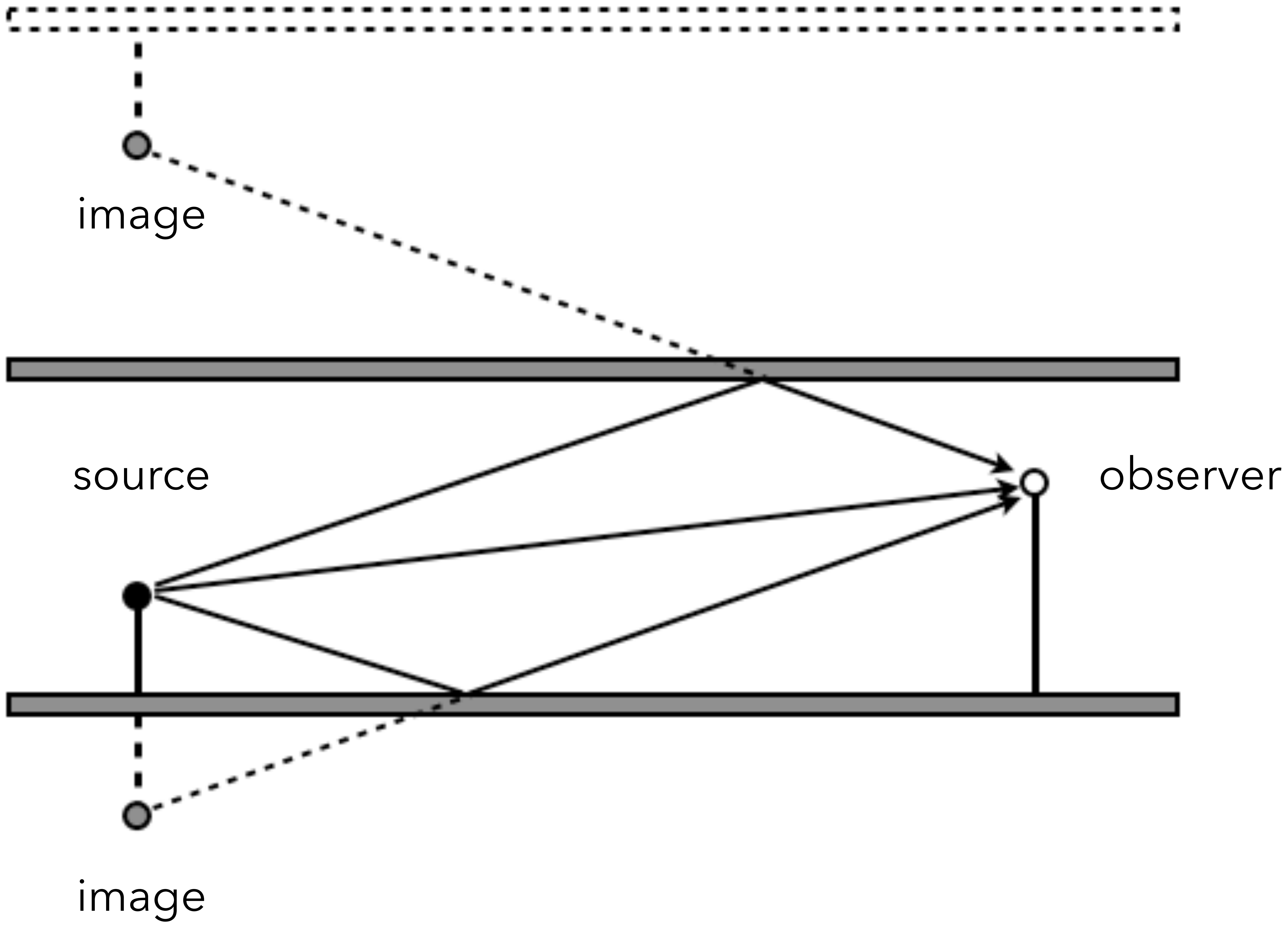
Reflected sound - example

- A listener stands 4 m in front of an omni-directional loudspeaker that is 1.5 m from a reflecting wall.
- Calculate:
  - the time of arrival for both the direct and reflected sound
  - the decrease in SIL for the reflected sound due to the larger distance traveled
  - the decrease in SIL for the reflected sound assuming an absorption coefficient $a = 0.2$ for the wall

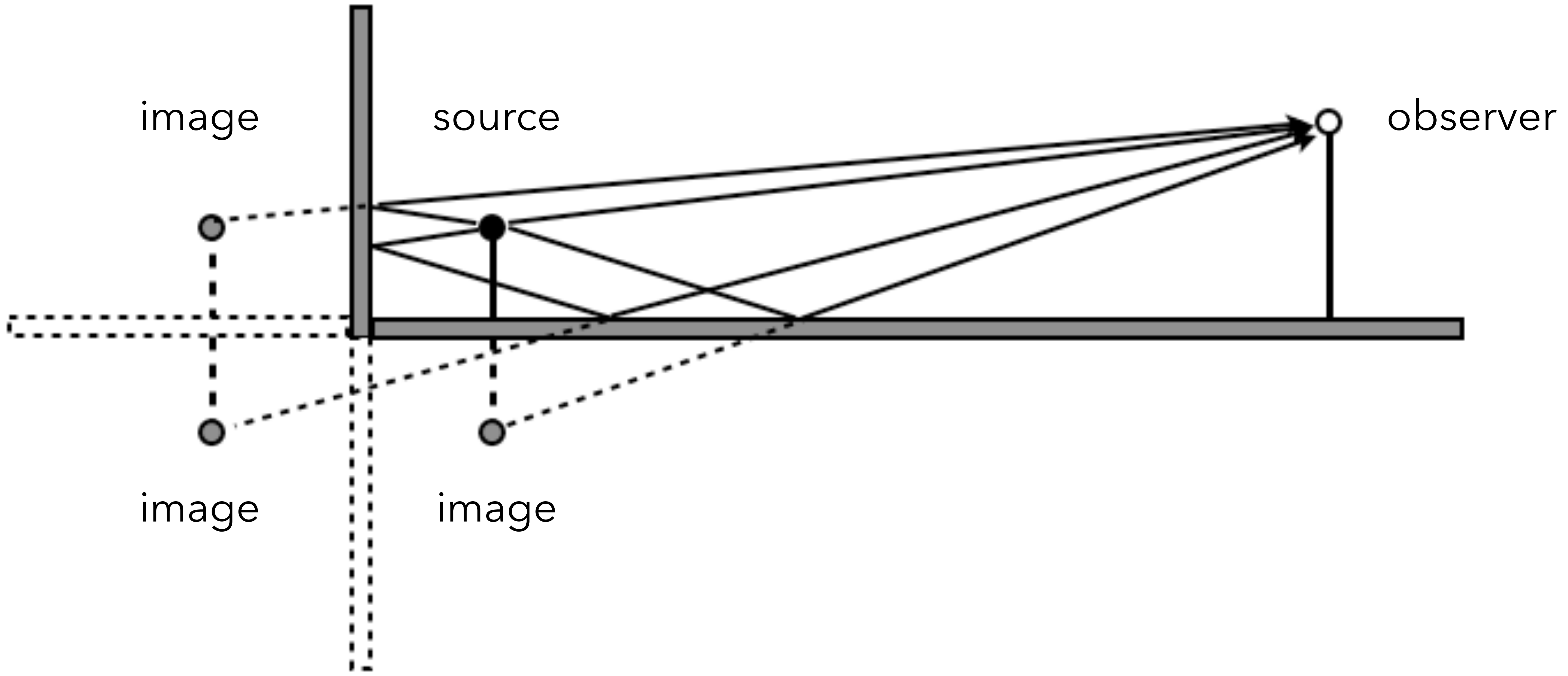


- Answer:
  - Reflected sound travels 5 meter: $t_{\text{direct}} = \dfrac{4 \text{ m}}{346 \text{ m/s}} = 12 \text{ msec}$, $t_{\text{reflected}} = \dfrac{5 \text{ m}}{346 \text{ m/s}} = 15 \text{ msec}$
  - $\Delta\text{SIL} = 10 \log \left[1/(r_{\text{reflected}}/r_{\text{direct}})^2\right] \text{ dB} = 10 \log \left[(4/5)^2\right] \text{ dB} = -2 \text{ db}$
  - $\Delta\text{SIL} = 10 \log(1 - a) \text{ dB} = 10 \log(1 - 0.2) \text{ dB} = -1 \text{ db}$

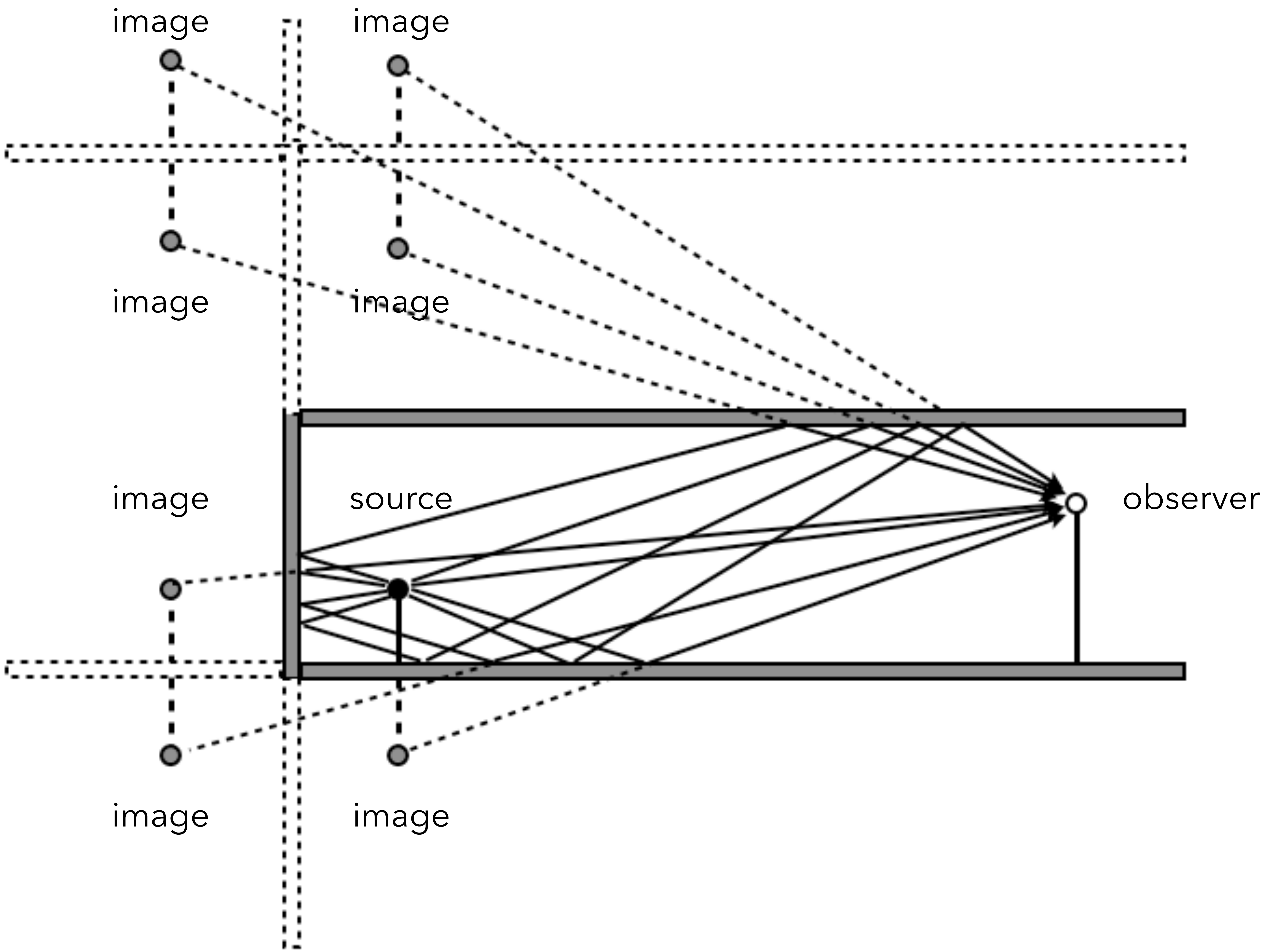
Multiple reflections – floor and ceiling



Multiple reflections — floor and back wall

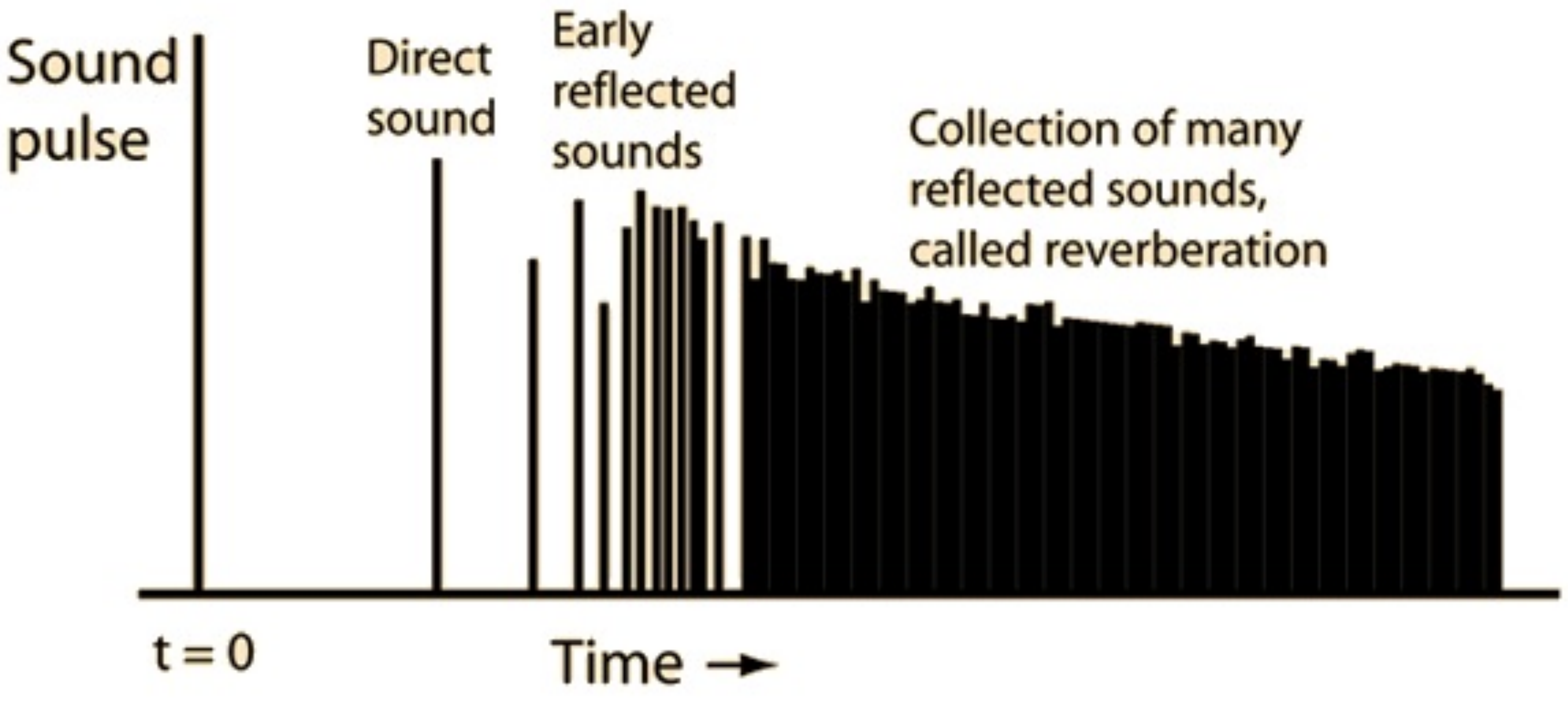


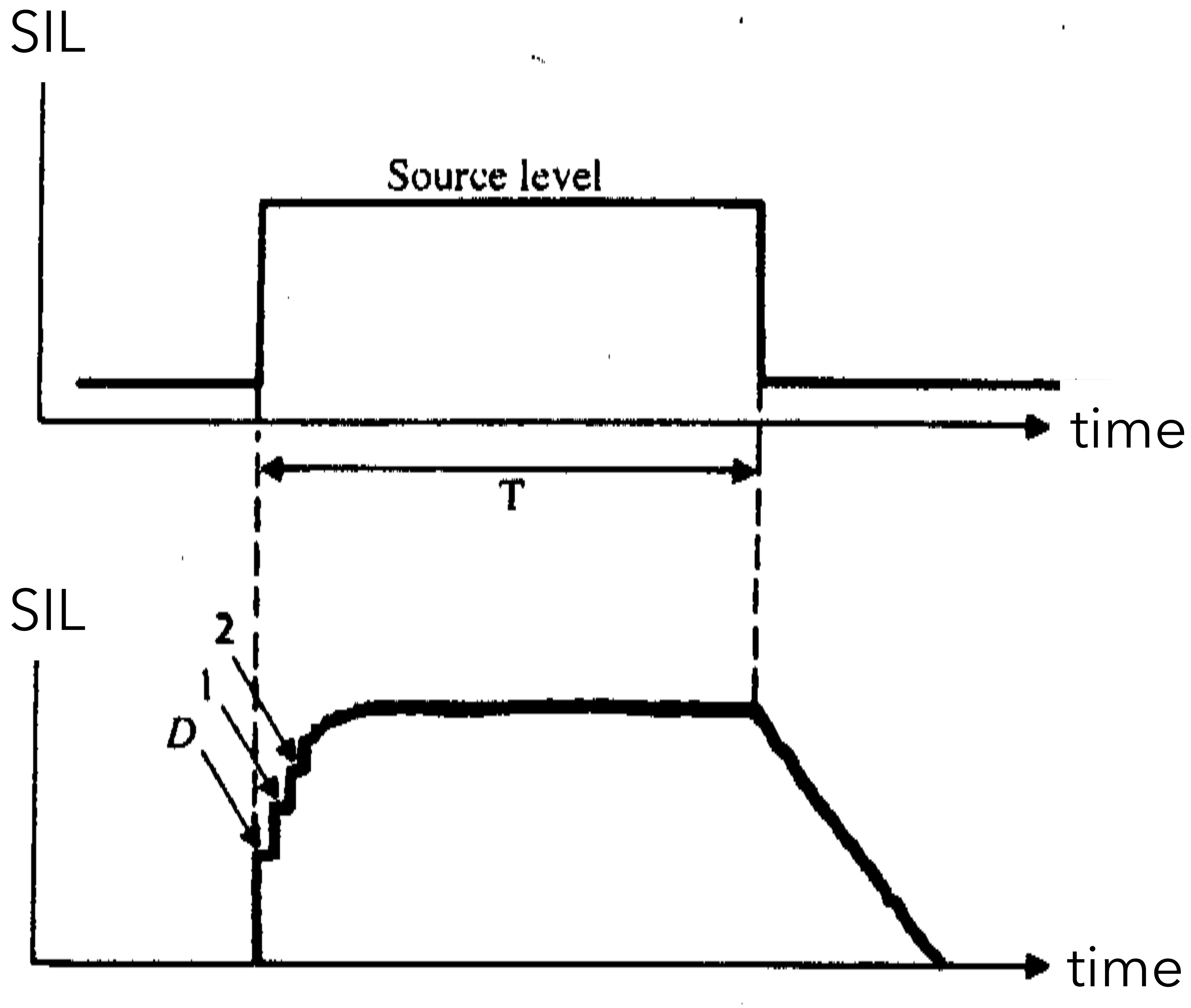
Multiple relfections — floor, back wall, and ceiling



Reverberant sound

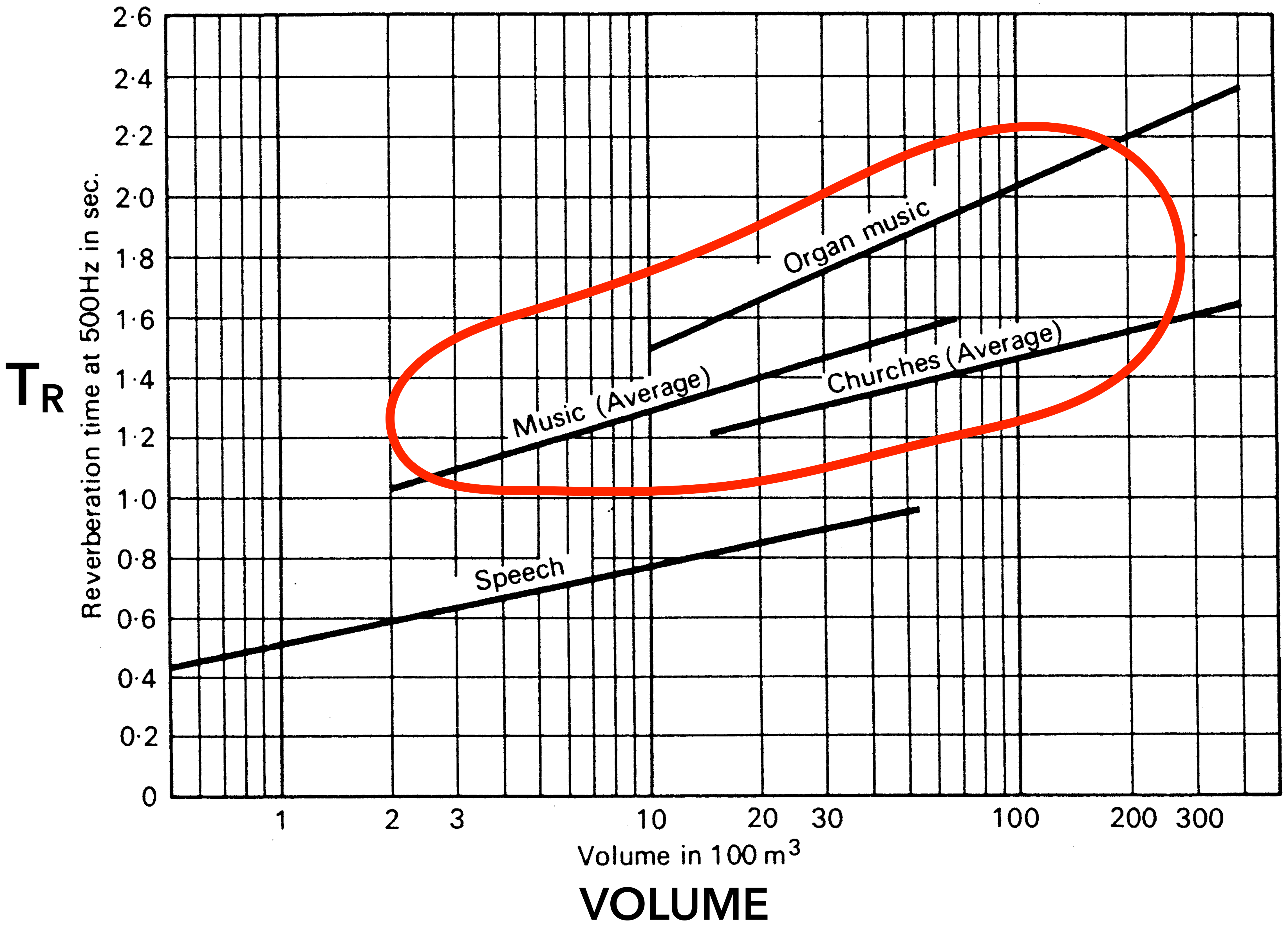
- sound formed from multiple reflections, coming from many different directions, and overlapping in time





Reverberation time

- time required for the reverberant SIL to decrease by 60 dB ($1/10^6$ in intensity)
- frequency dependent (low-frequency sounds typically have larger reverberation times)



Acoustical characteristics of various concert halls

	Year built	Volume (m^3)	Number of seats	Reverberation time (sec) Frequency (Hz) 125	500	2000
Teatro alla Scala, Milan	1778	11,245	2289		1.2	
Royal Opera House	1858	12,240	2180		1.1	
Royal Albert Hall	1871	86,600	6080	3.4	2.6	2.2
Carnegie Hall, New York	1891	24,250	2760	1.8	1.8	1.6
Symphony Hall, Boston	1900	18,740	2630	2.2	1.8	1.7
Royal Festival Hall	1951	22,000	3000	1.4	1.5	1.4
Philharmonic Hall, Berlin	1963	36,030	2200		2.0	
St. David's Hall, Cardiff	1983	22,000	2200	1.8	1.9	1.8

Calculating reverberation time

$$T_R = 0.05 \frac{V}{A_{\text{eff}}} \text{ s}$$

V : volume in (ft^3)

$$A_{\text{eff}} = A_1 a_1 + A_2 a_2 + \cdots + B_1 + B_2 + \cdots$$

- A_{eff}: total absorption in sabin (1 ft^2 of perfectly absorbing surface)
- $A_1, A_2, \cdots$: surface area of walls, etc. (in ft^2)
- $a_1, a_2, \cdots$: absorption coeffs (dimensionless, freq-dependent)
- $B_1, B_2, \cdots$: absorption for seats, people, etc. (in sabin)

absorption coefficients (dimensionless)

	Frequency (Hz)					
Material	125	250	500	1000	2000	4000
Concrete (painted)	0.10	0.05	0.06	0.07	0.09	0.08
Plywood panel	0.28	0.22	0.17	0.09	0.10	0.11
Plaster on lath	0.14	0.10	0.06	0.05	0.04	0.03
Gypsum board, 1/2 in.	0.29	0.10	0.05	0.04	0.07	0.09
Glass window	0.35	0.25	0.18	0.12	0.07	0.04
Curtains	0.14	0.35	0.55	0.72	0.70	0.65
Carpet (on concrete)	0.02	0.06	0.14	0.37	0.60	0.65
Carpet (on pad)	0.08	0.24	0.57	0.69	0.71	0.73
Acoustical tile, suspended	0.76	0.93	0.83	0.99	0.99	0.94

absorption (in m^2) [multipy by 10.8 to convert to sabin]

	Frequency (Hz)					
Material	125	250	500	1000	2000	4000
Wood or metal seat, unoccupied	0.014	0.018	0.020	0.036	0.035	0.028
Upholstered seat, unoccupied	0.13	0.26	0.39	0.46	0.43	0.41
Adult	0.23	0.32	0.39	0.43	0.46	—
Adult in an upholstered seat	0.27	0.40	0.56	0.65	0.64	0.56

Example

<u>Exercise</u>: Calculate the reverberation time at 500 Hz for a room with dimensions 20 m × 15 m × 8m (high). The walls are painted concrete, the ceiling is plaster, and the floor is carpet on pad. Also, assume that there are 200 upholstered seats, and that they are half-filled with people.

$$L = 20 \text{ m} \times 3.28 \text{ ft/m} = 65.6 \text{ ft}$$
$$W = 15 \text{ m} \times 3.28 \text{ ft/m} = 49.2 \text{ ft}$$
$$H = 8 \text{ m} \times 3.28 \text{ ft/m} = 26.24 \text{ ft}$$

$$V = L \times W \times H = 2400 \text{ m}^3 = 8.47 \times 10^4 \text{ ft}^3$$

$$A_{\text{eff}} = \underset{\text{painted concrete}}{0.06}\left[2(L \times H) + 2(W \times H)\right] + \underset{\text{plaster}}{0.06}(L \times W) + \underset{\text{carpet on pad}}{0.57}(L \times W) + 10.8(100 \times \underset{\text{empty upholstered}}{0.39} + 100 \times \underset{\text{occupied}}{0.56})$$
$$= 3.42 \times 10^3 \text{ sabin}$$

$$T_R = 0.05 \frac{V}{A_{\text{eff}}} \text{ s} = 1.2 \text{ s}$$ –> ideal for music (for V=2400 m^3)

Acoustical design

Criteria for good design

- Loudness
- Uniformity (no “live” or “dead” spots)
- Reverberance or liveness (feeling of being “bathed” in sound)
- Clarity (opposite of reverberance)

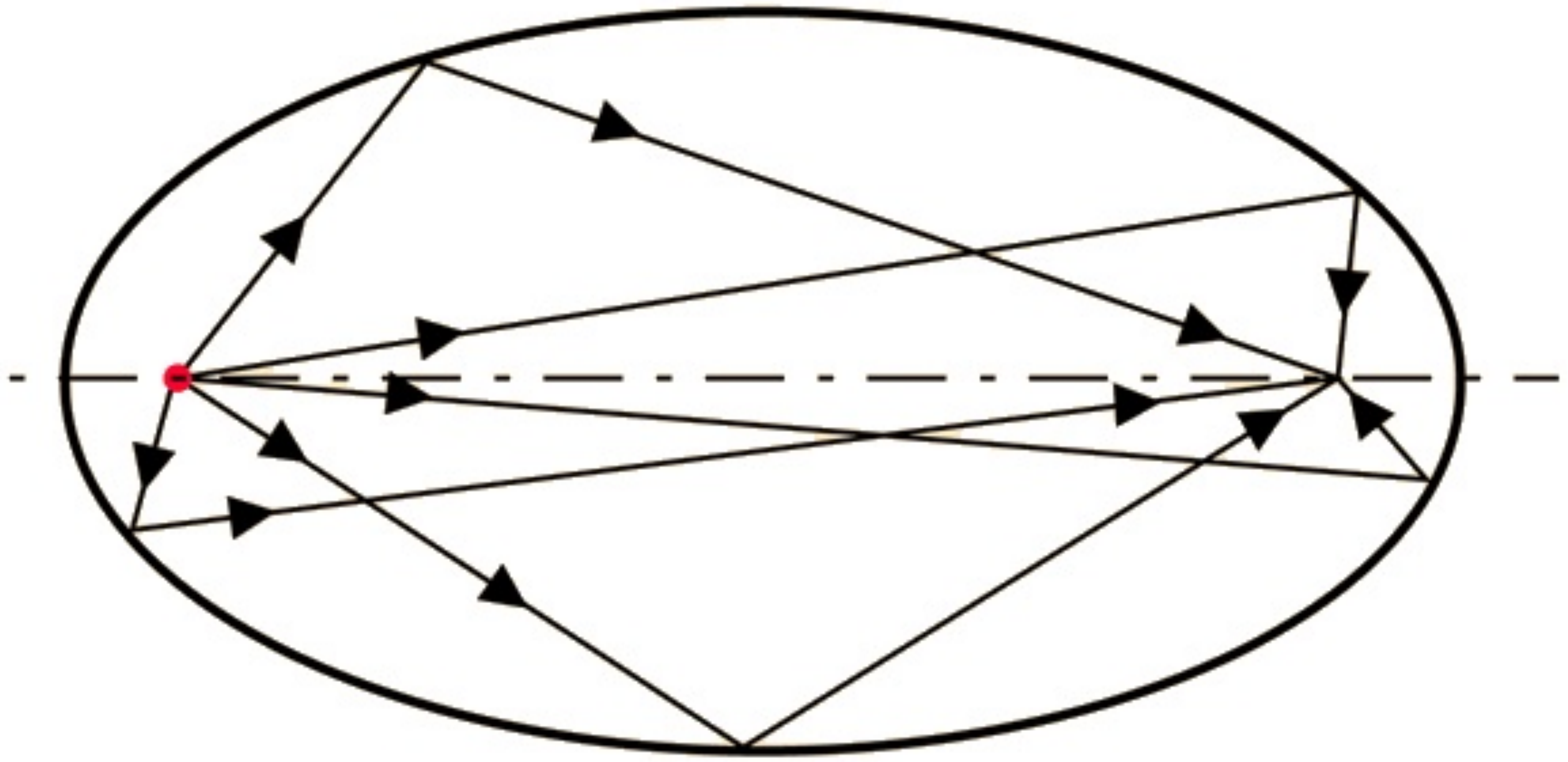
Problems to avoid

- Background noise (external noise due to heating, A/C, …)
- Shadow areas (produced by balconies, columns, …)
- Focusing of sound (“whispering room” effect)
- Echoes
- Room resonances (“shower stall” effect)

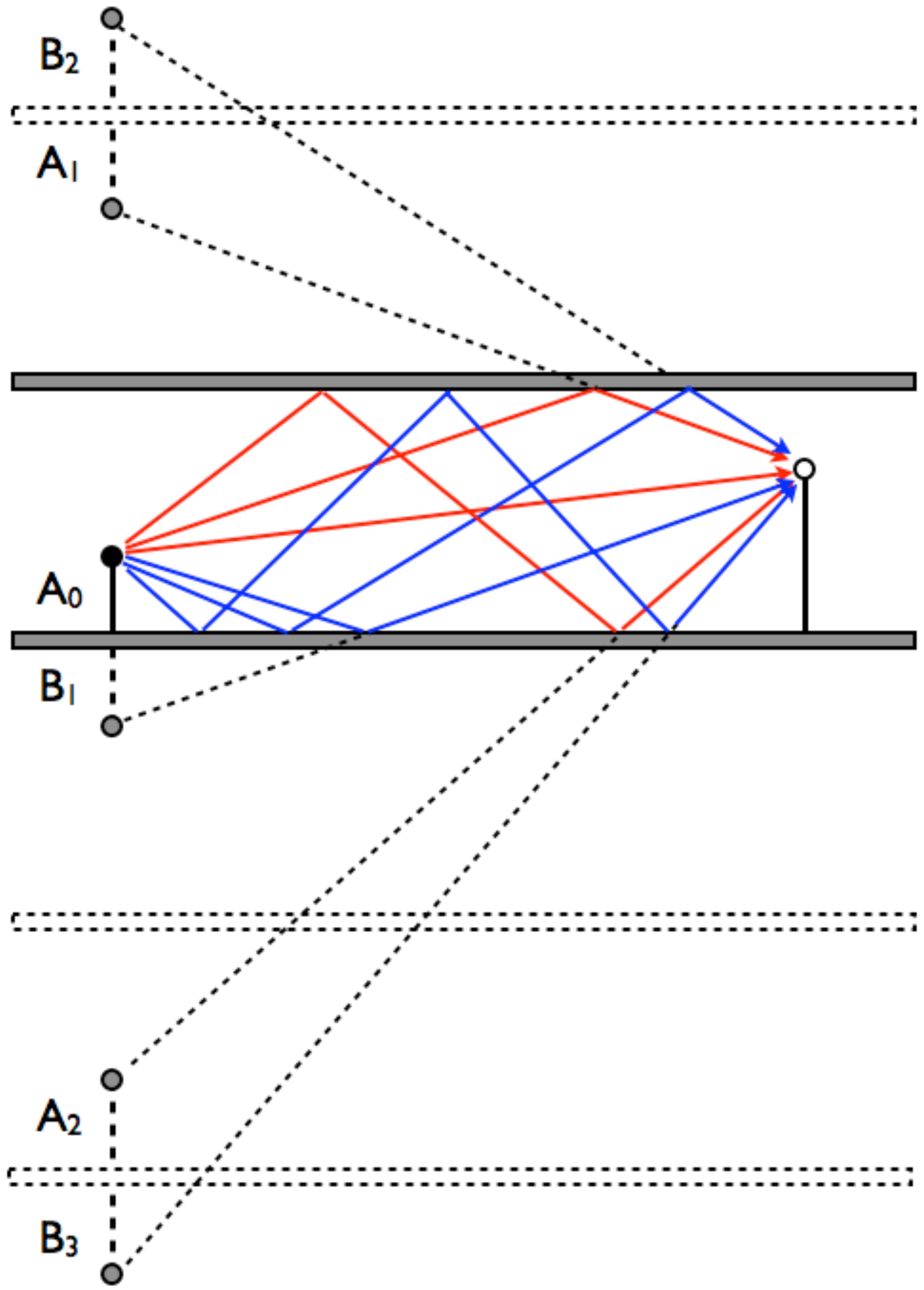
$$f_{lmn} = \frac{v}{2}\sqrt{\left(\frac{l}{L}\right)^2 + \left(\frac{m}{W}\right)^2 + \left(\frac{n}{H}\right)^2}$$

$$l, m, n = 0,1,2,\cdots$$

Problems to avoid



Whispering room effect



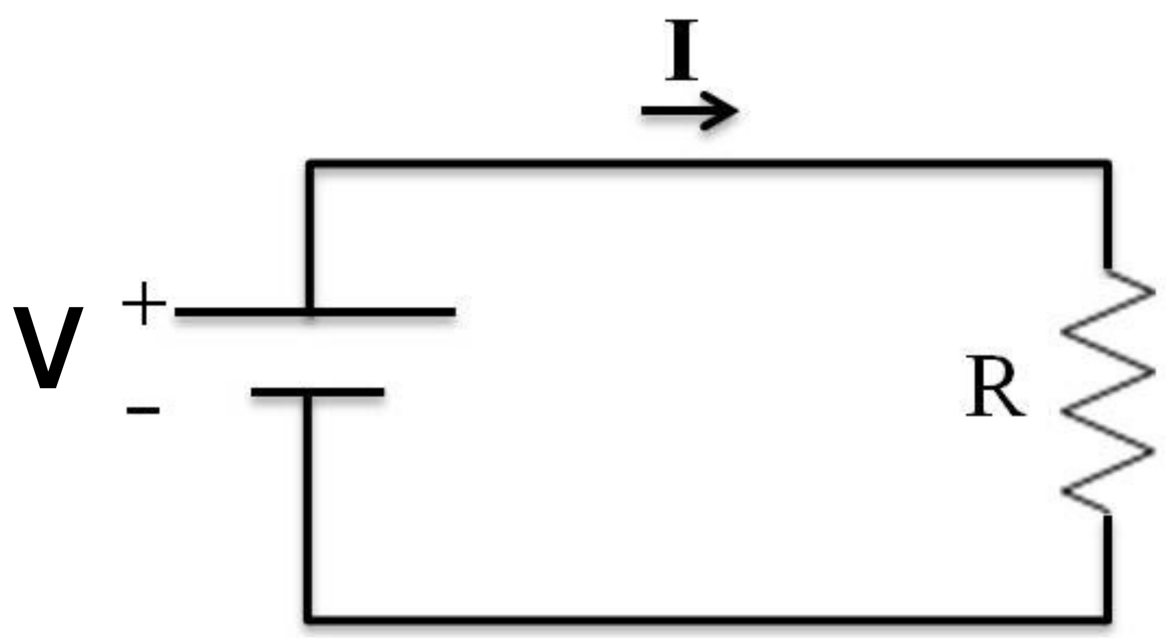
Flutter echoes

13. Electrical reproduction of sound

Electrical reproduction of sound — overview

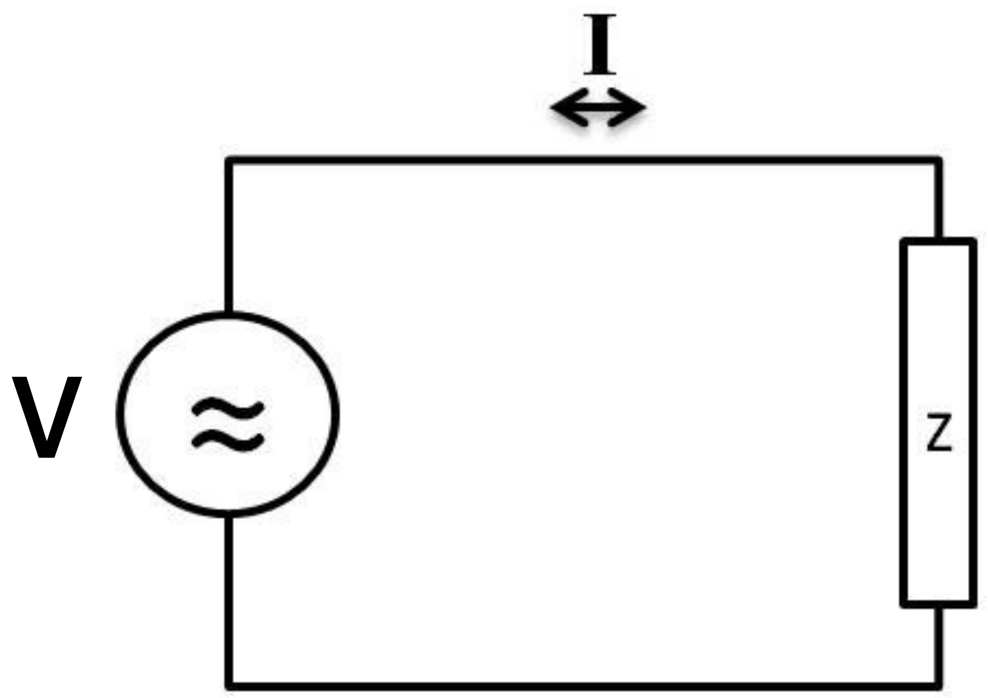
- Goal: Understand how microphones and loudspeakers work
- Need basic understanding of:
    - electricity and magnetism
    - Faraday’s law of induction

Basic electricity



(DC circuit)

e.g., a battery connected to a flashlight bulb



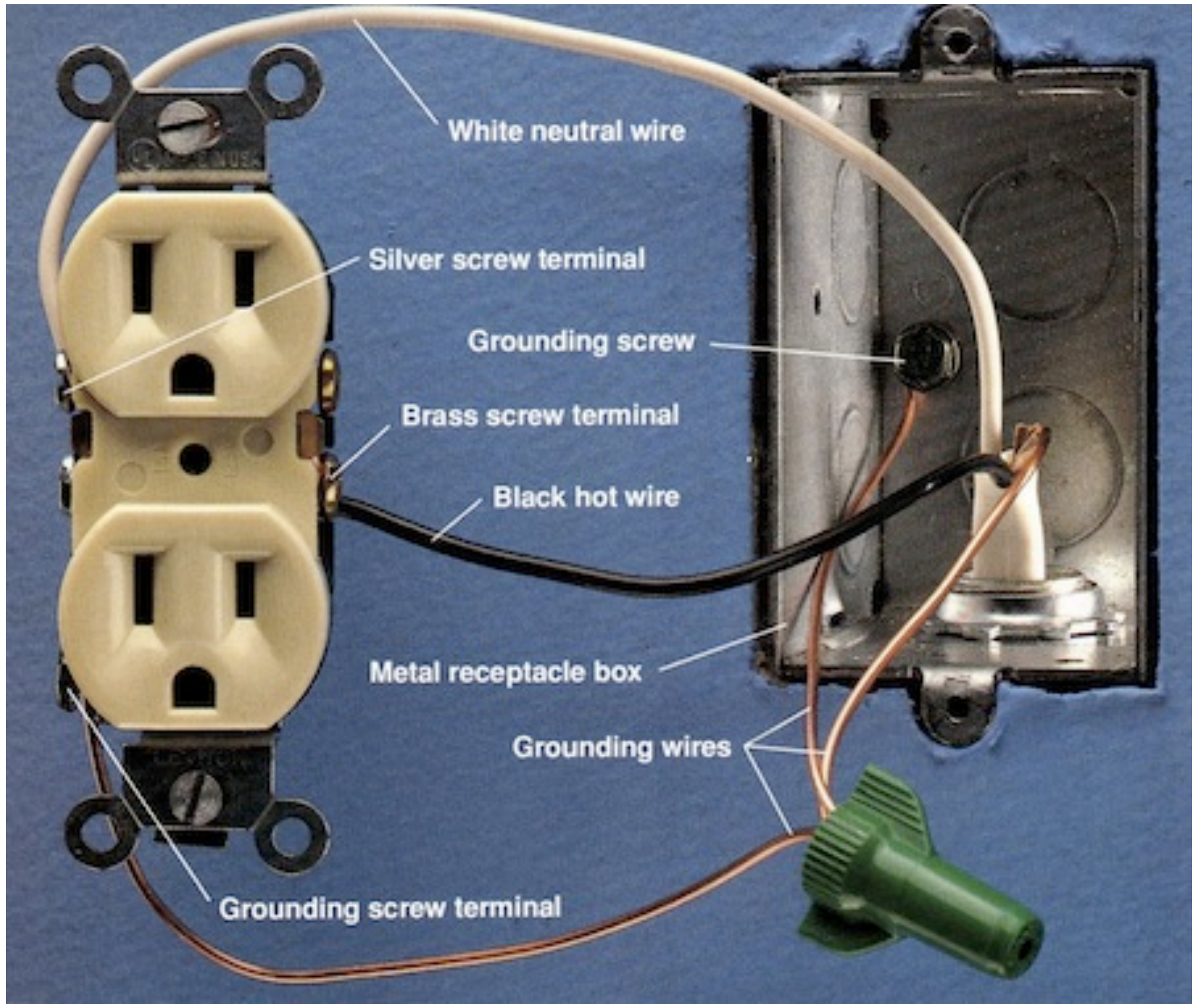
(AC circuit)

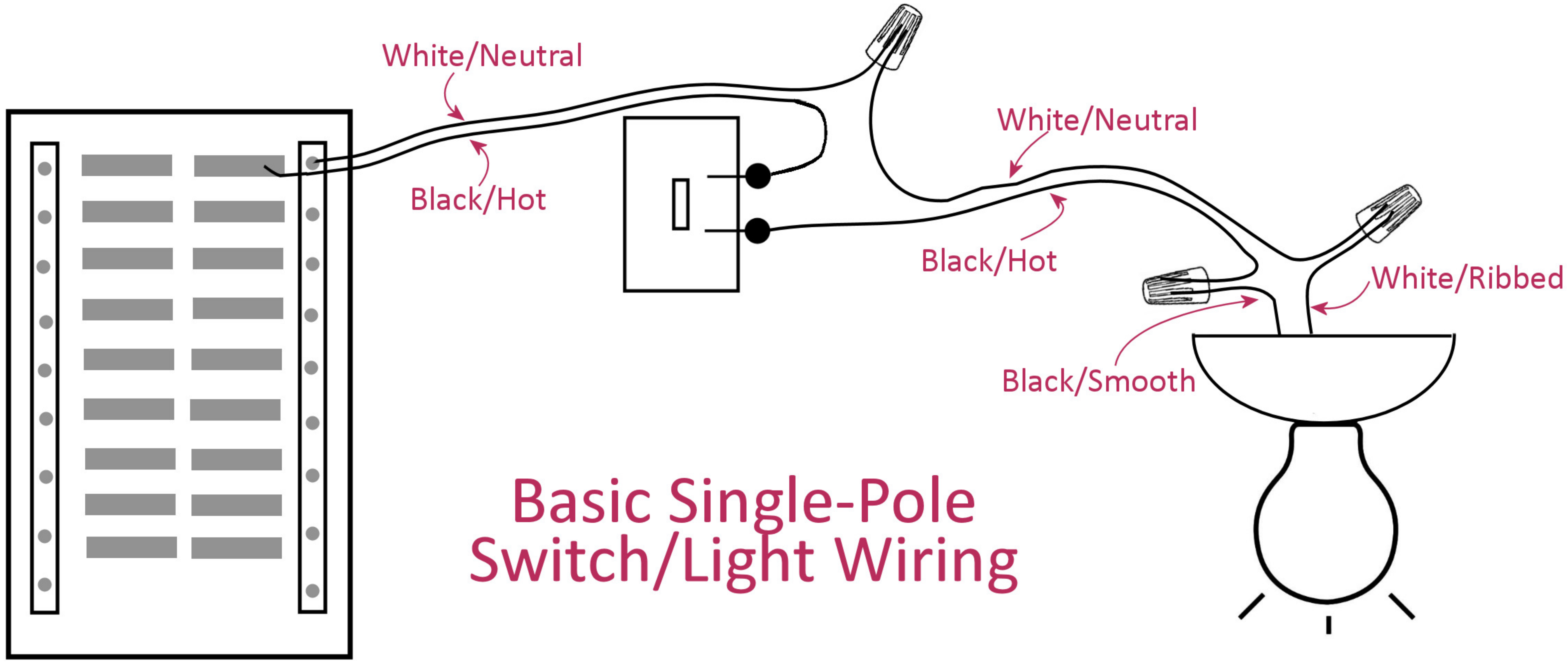
e.g., a household wall outlet connected to a vacuum cleaner

- Voltage V (volts)
- Current I (amperes or amps)
- Resistance R or impedance Z (ohms, Ω)
- Direct current (DC) and alternating current (AC) circuits
- Ohm's law of electricity: $V = IR$
- Electrical power: $P = VI = I^2R$ (Watts)
- Relation to work or energy:

$$P = W/\Delta t \text{ (Watts)} \quad \text{or} \quad W = P\,\Delta t \text{ (Joules)}$$

Example – home wiring





https://gardnerbenderfaq.wordpress.com/tag/outlet/

https://www.addicted2decorating.com/how-to-wire-single-pole-light-switch.html

Example — kilowatt-hr and your electric bill

- A kilowatt-hr is a convenient unit of energy:

$$1 \text{ kWh} = 1 \text{ kW} \times 1 \text{ hr} = 1000 \text{ W} \times 3600 \text{ s} = 3.6 \times 10^6 \text{ J}$$

- Exercise: Suppose you paid $100 for last month's electric bill at a cost of $0.13/kWh.

  (a) How much energy (in kWh) did you use?

  (b) What was the average power consumption (in Watts) over the month (assume 30 days)?

- Answer:

  (a) $W = \$100 \div \$0.13/\text{kWh} = 769 \text{ kWh}$

  (b) $P = \dfrac{W}{\Delta t} = \dfrac{769 \text{ kWh}}{30 \times 24 \text{ h}} = 1.1 \text{ kW} = 1{,}100 \text{ W}$ (eleven 100-Watt lightbulbs on continuously)

Basic magnetism

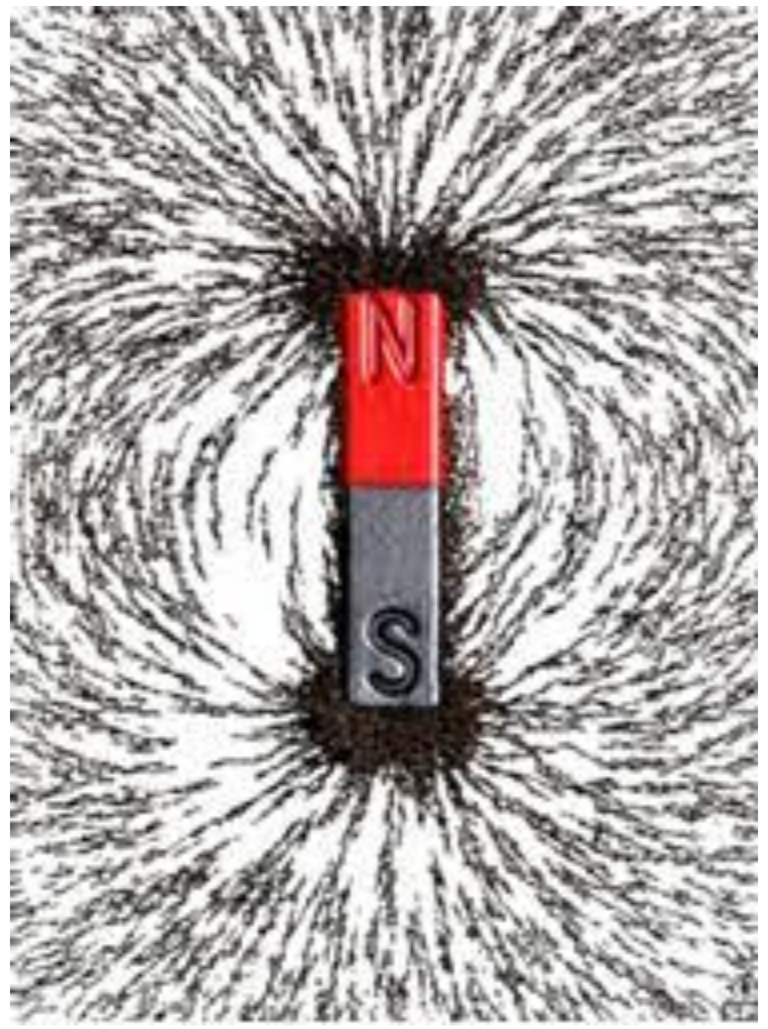
- A permanent magnet has **N** and **S poles** that attract pieces of iron

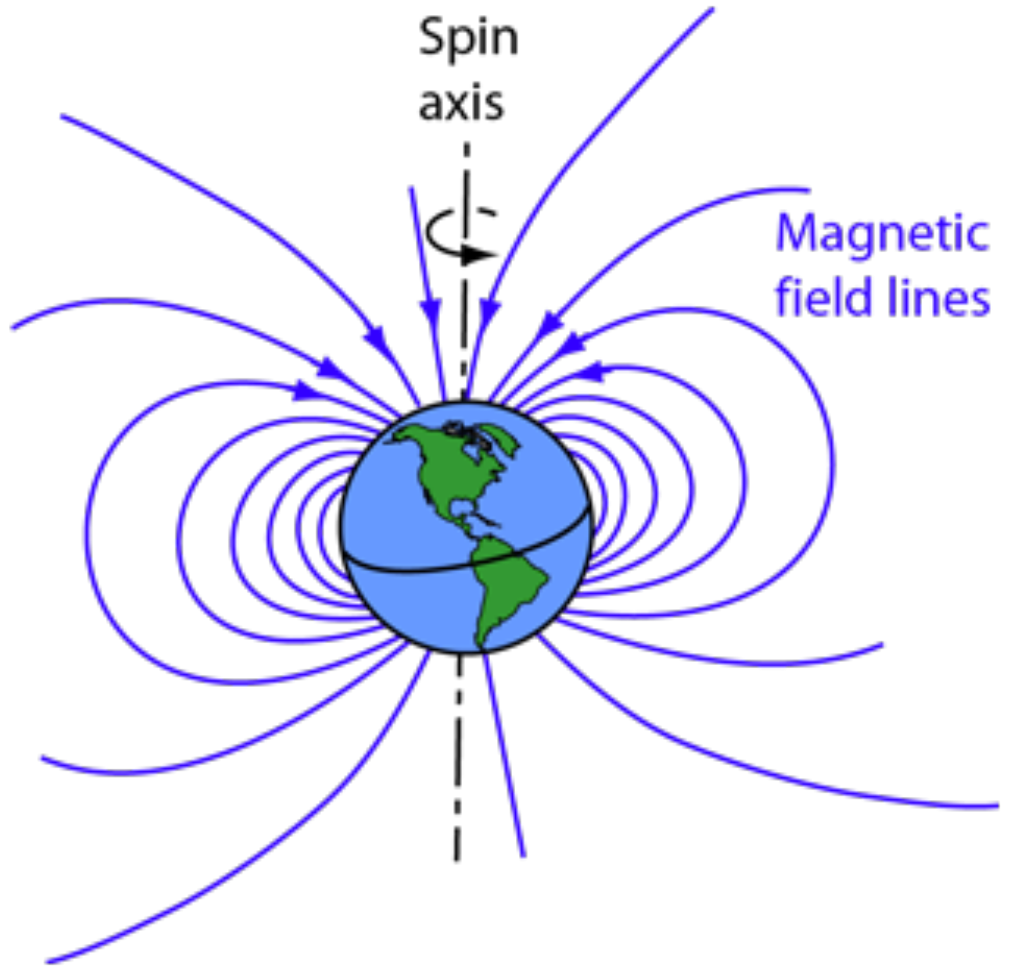
- **Like poles repel; unlike poles attract** (just like + and – electrical charges). But no isolated magnetic poles.

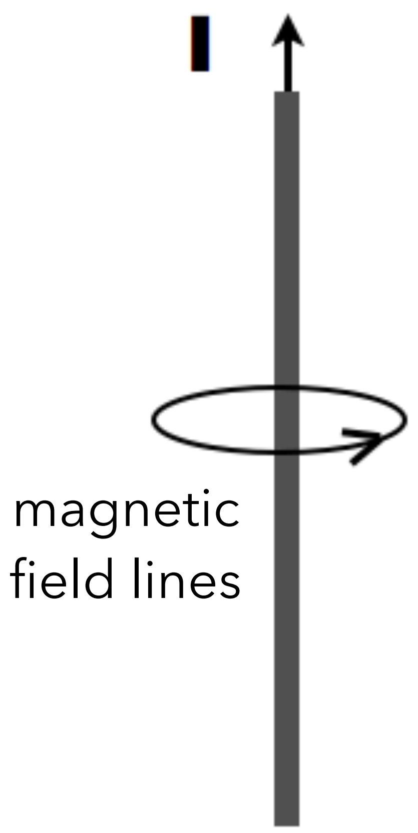
- A **compass needle is a tiny magnet** that is attracted to Earth's South magnetic pole.

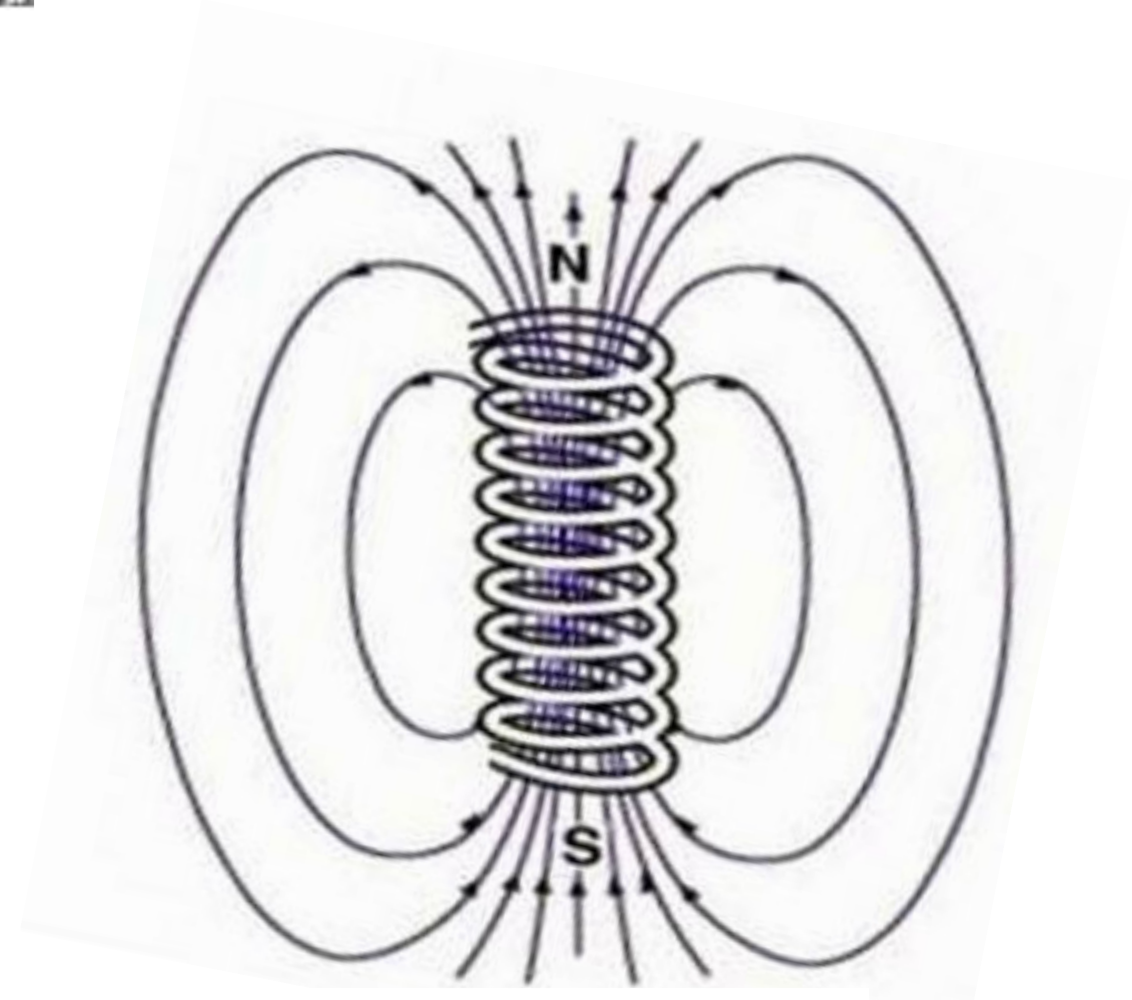
- Oersted (1820): discovered that an **electric current produces a magnetic field**

- Can create an **electromagnet** by sending an electric current through a coil of wire









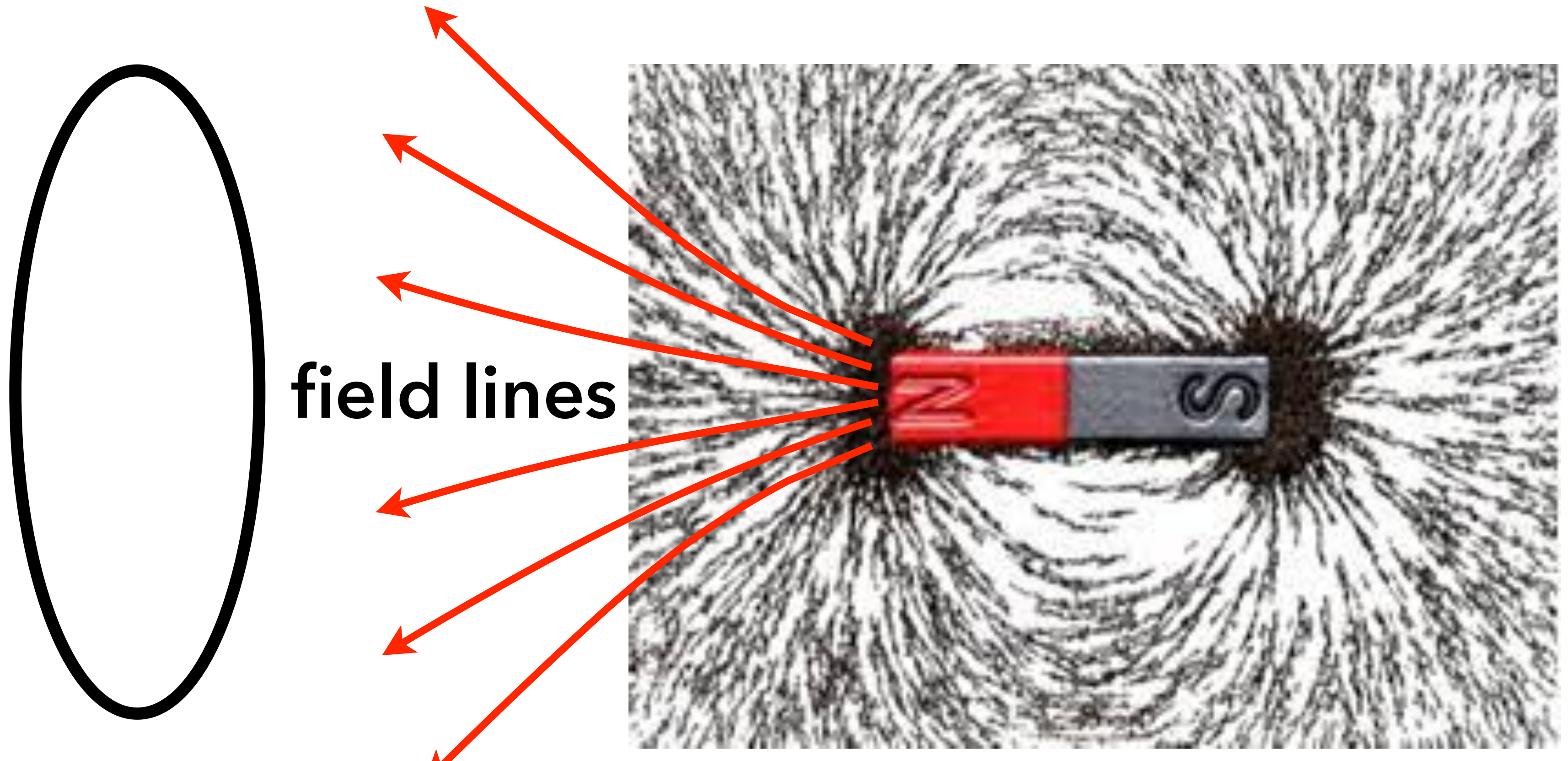
electromagnet

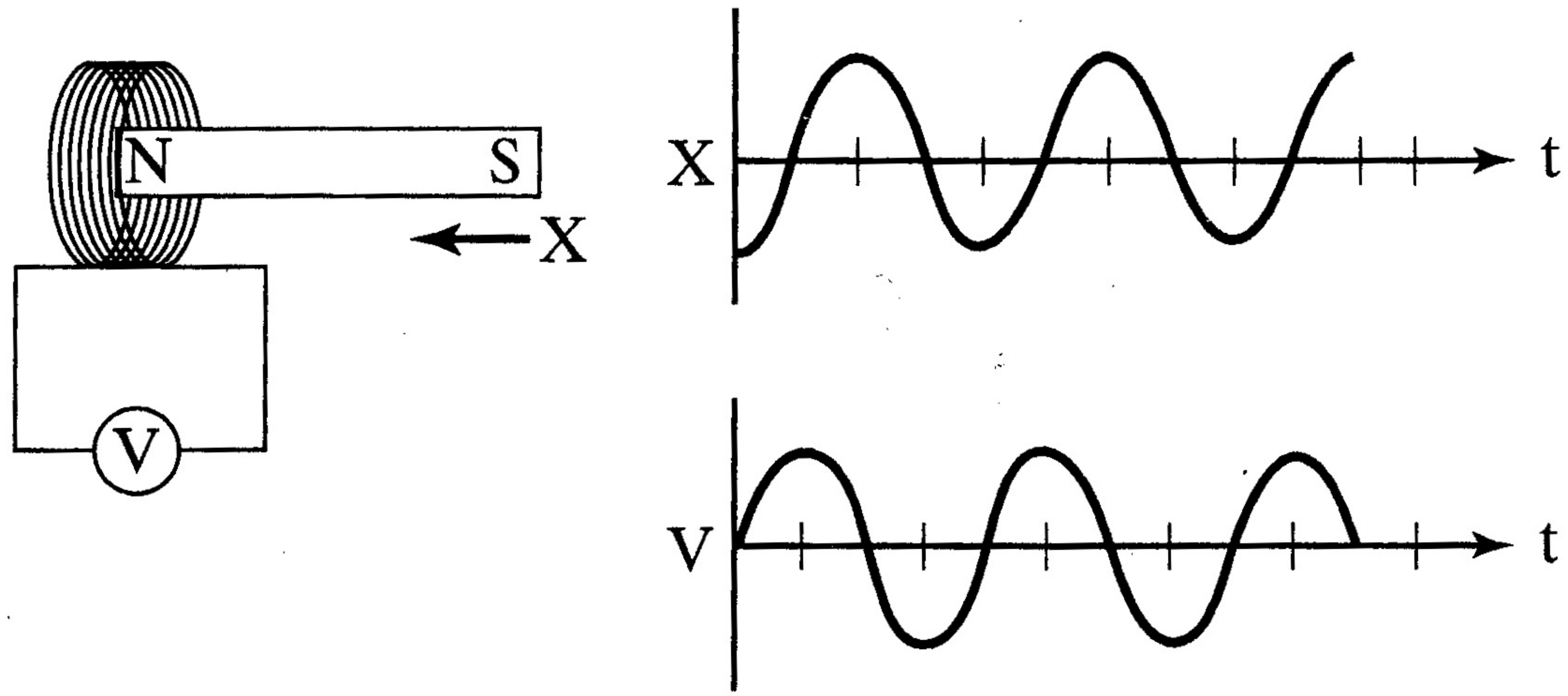
Faraday’s law of induction (1831)

- A **change in magnetic flux** through a coil of wire induces a voltage in the coil:

$$V = -N\,\frac{\Delta\Phi}{\Delta t}$$

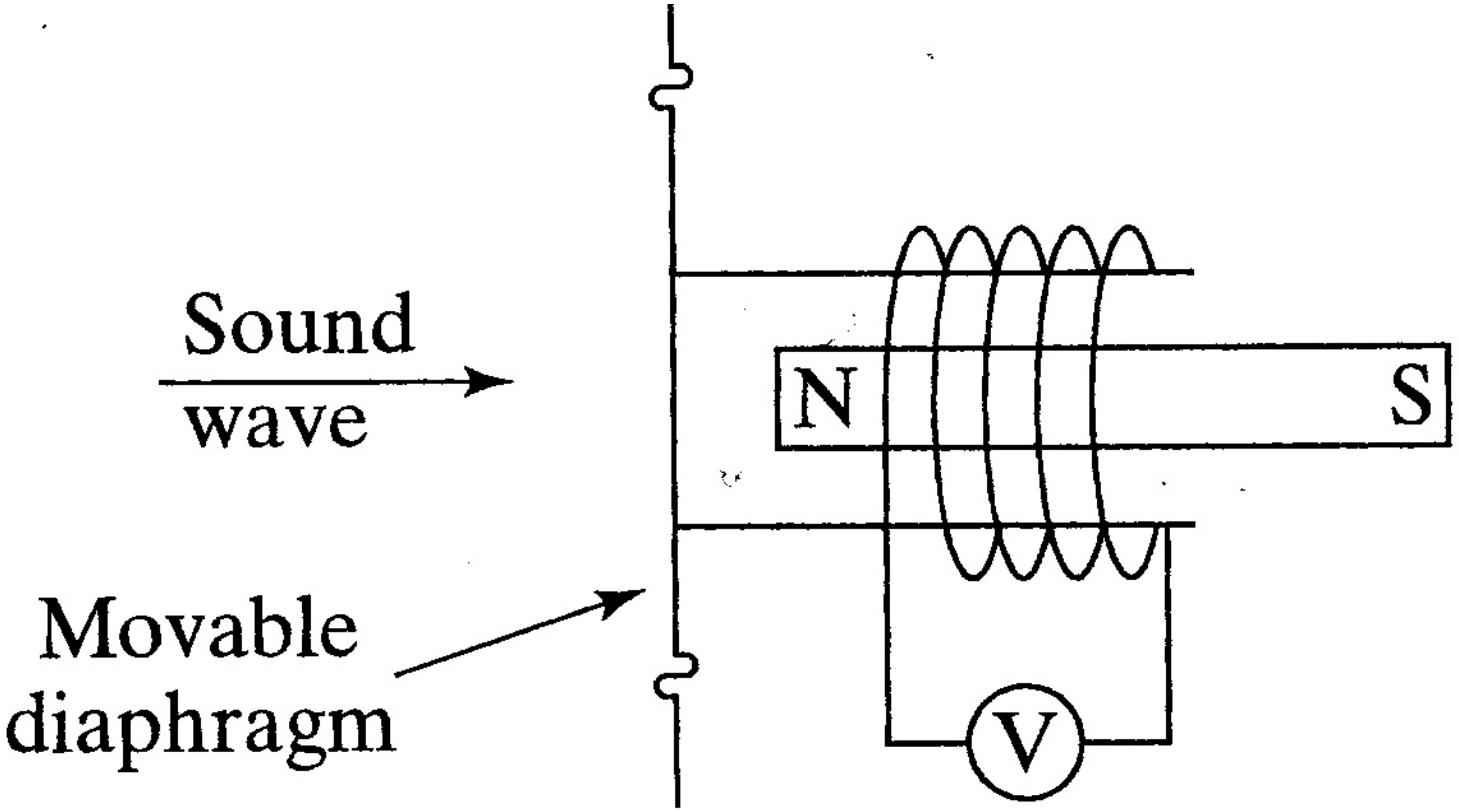
- Only **relative motion** is important
- Underlies the operation of **electric generators** and **electric motors**
- **Electric generator**: mechanical energy converted to electrical energy
- **Electric motor**: electrical energy converted to mechanical energy





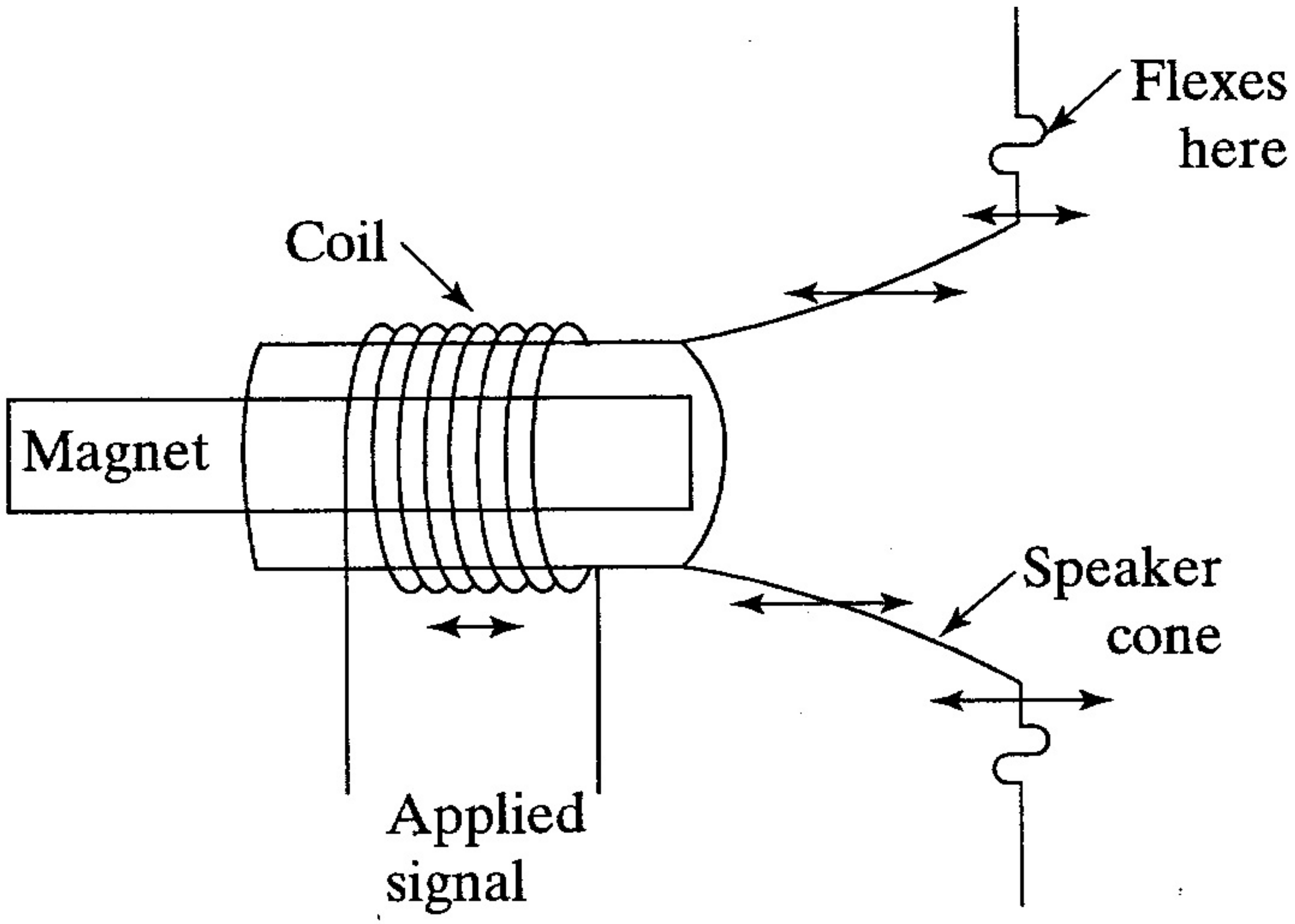
Application – microphones and loudspeakers

Dynamic microphone



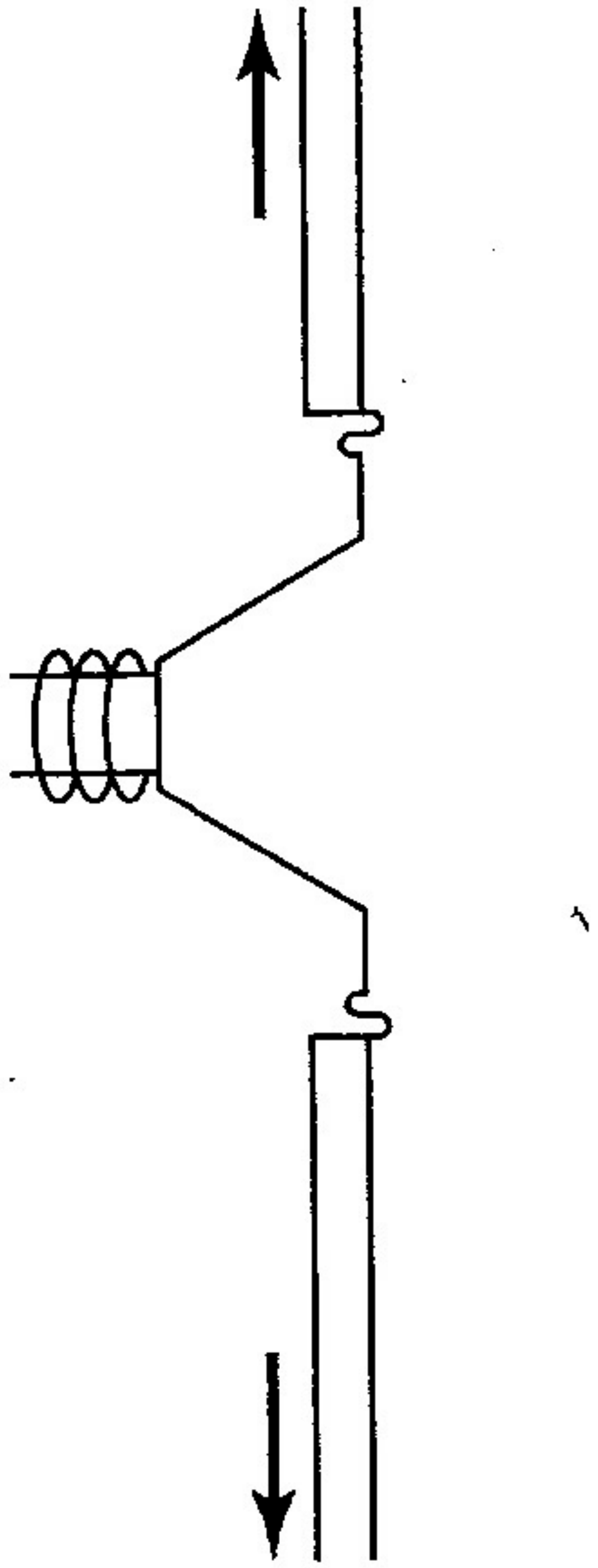
sound wave –> electrical signal

Loudspeaker

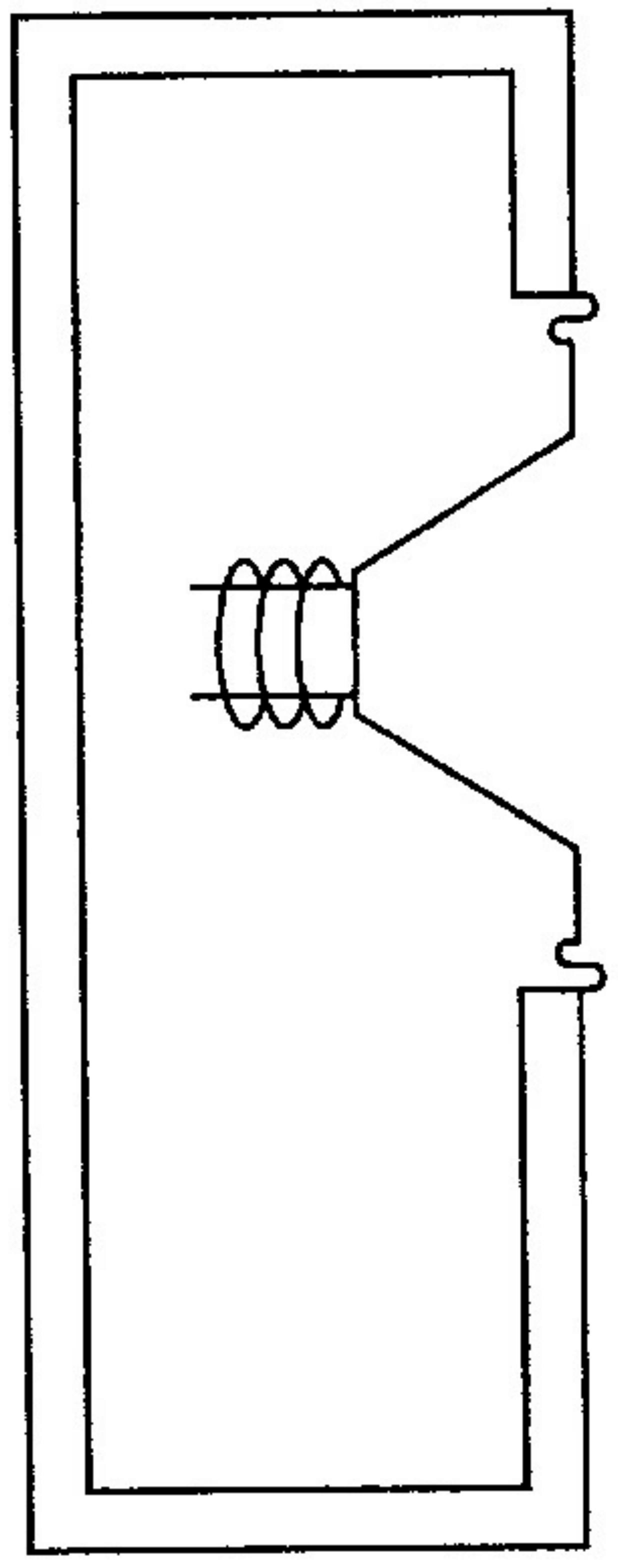


electrical signal –> sound wave

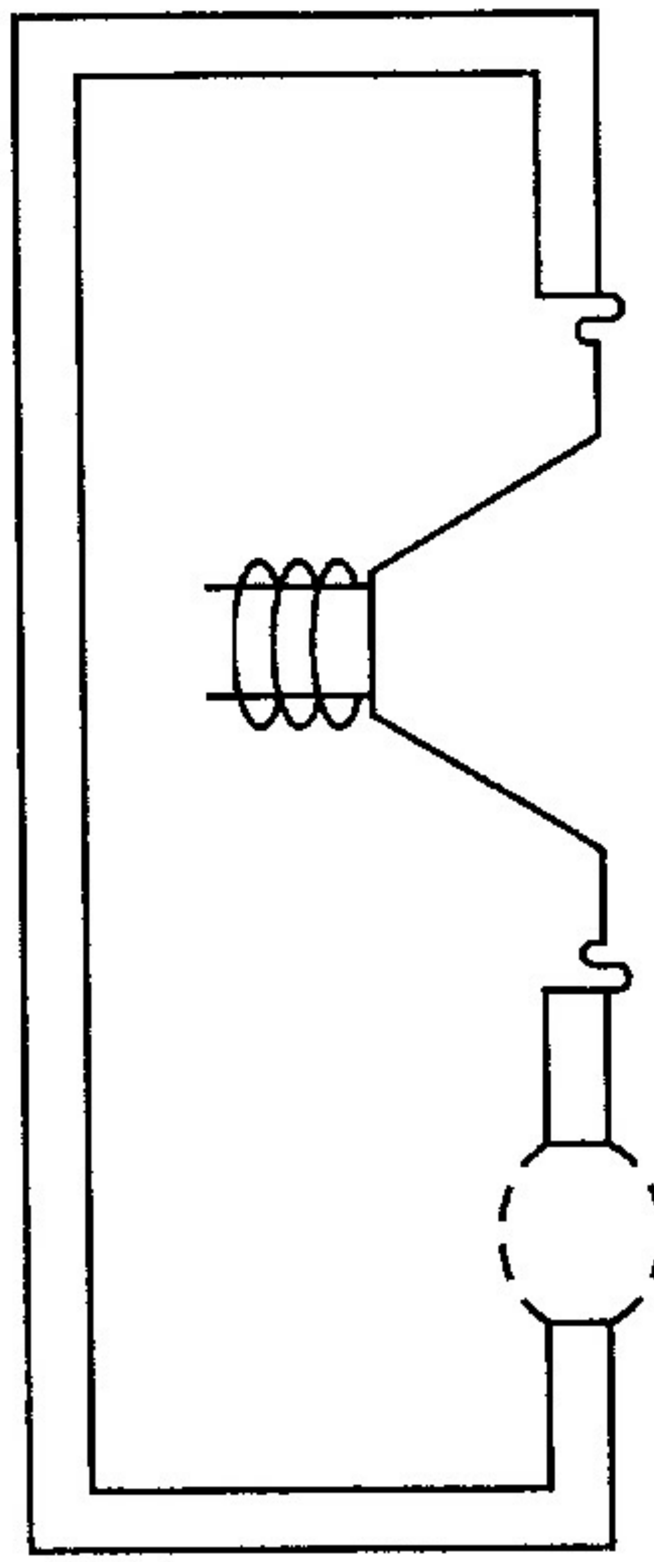
Loudspeakers



Infinite baffle

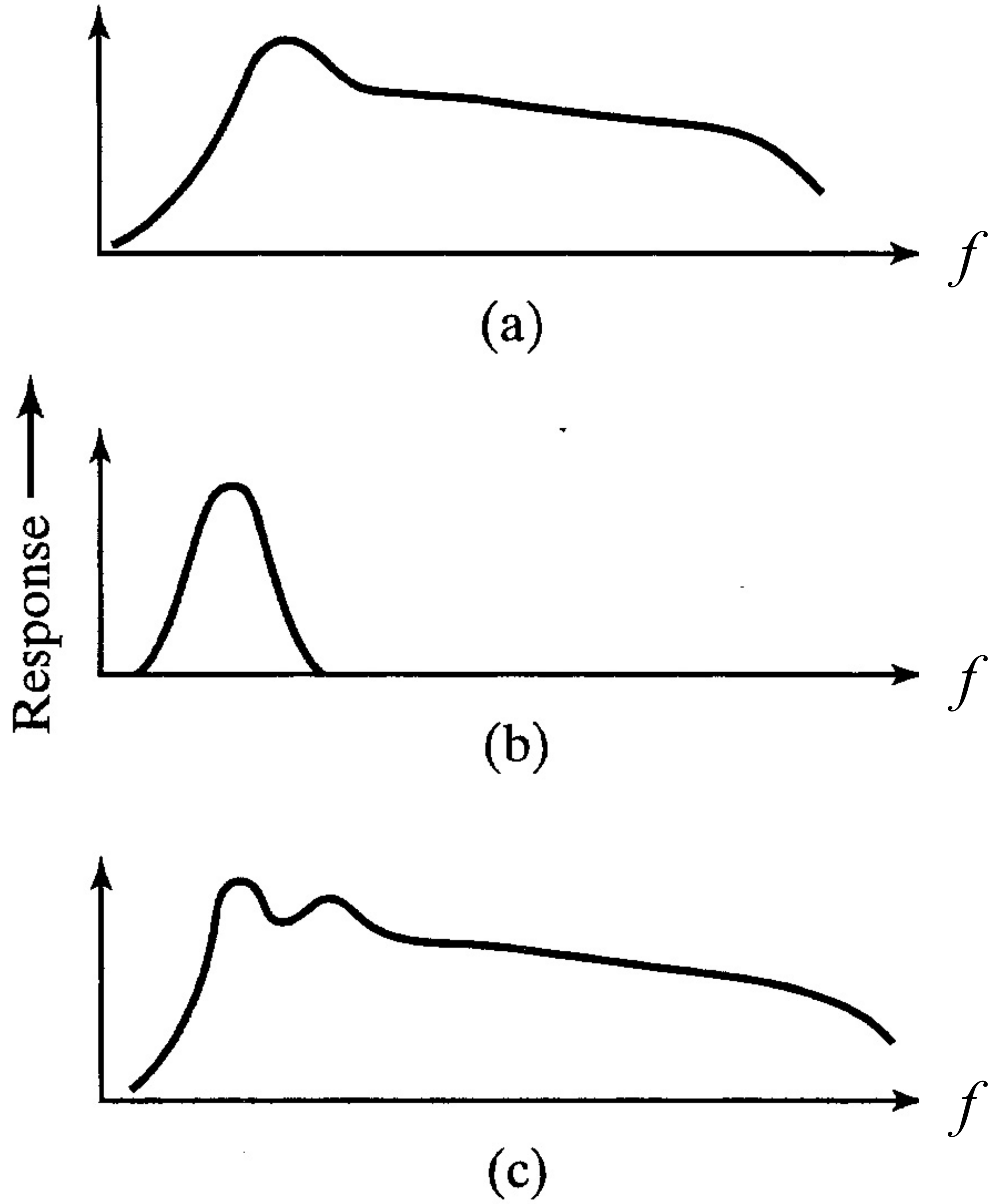


Acoustic suspension



Tuned port (bass reflex)

Frequency response curves
(acoustic suspension, tuned port)



14. Elementary music theory

Music theory — the need to standardize musical notes

- A **tuning system** is an **assignment of precise frequencies** to all musical notes in an octave (reference note is **A4 = 440 Hz**; decided upon in 1939)
- Three standard tuning systems:
  - **Equal temperament**
  - **Pythagorean temperament**
  - **Just temperament**
- Each tuning system has its own **advantages and disadvantages**
- What tuning systems do real musicians use? (comments from the musicians in class??)

Musical scales — dividing up the octave into pieces

- **Chromatic scale**: 12 pieces (semitones)

  C - C# - D- Eb - E - F - F# - G - Ab - A- Bb - B - C′ (white and black keys on a piano)

- **Diatonic scale**: 7 pieces (semitones and whole tones)

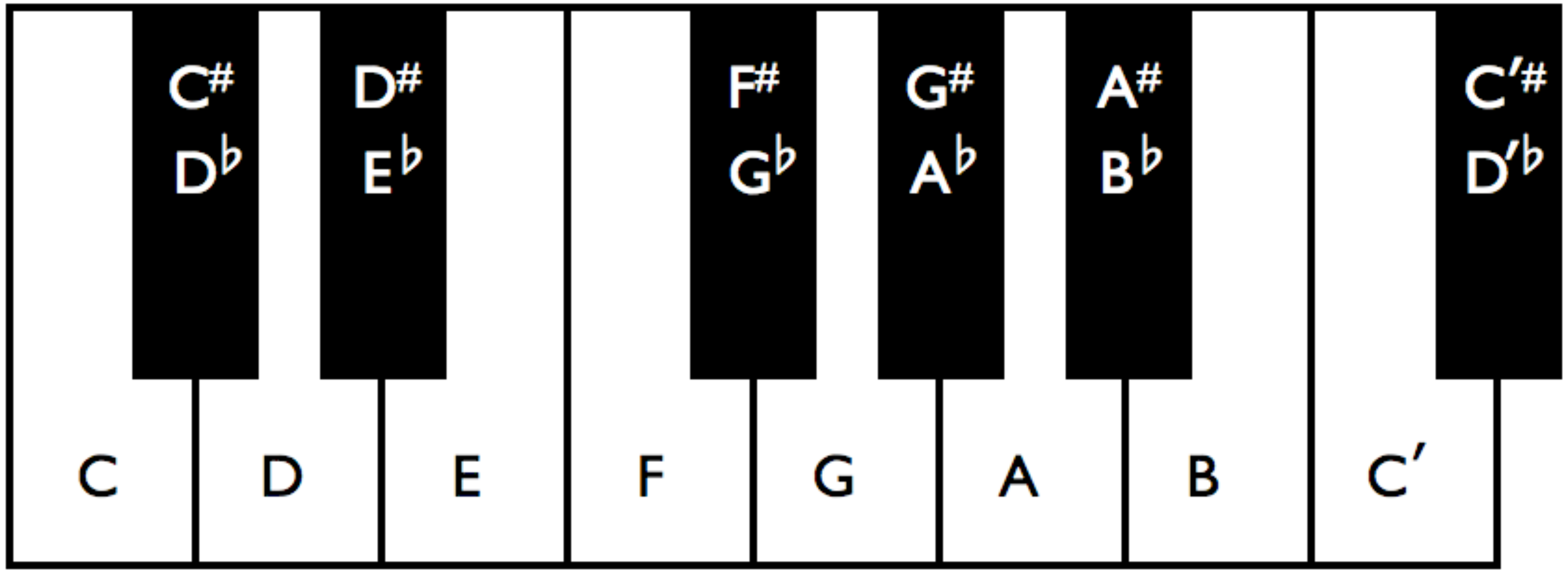
  T-T-S-T-T-T-S (do-re-mi-fa-sol-la-ti-do; white keys on a piano)

- **Pentatonic scale**: 5 pieces (whole tones and 3 semitones intervals)

  T-T-3-T-3 (F# - G# - A# - C# - D# - F#′; black keys on a piano)

Equal temperament

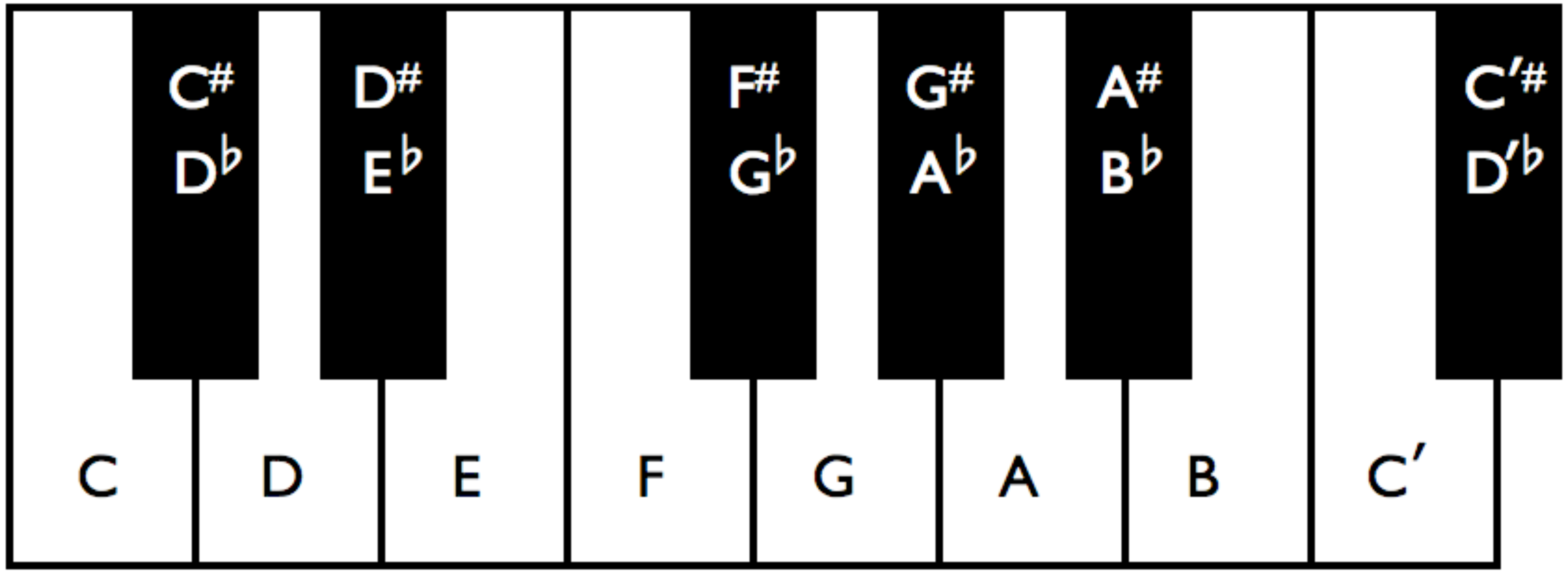
- **All semitones** intervals are **equal**: $2^{1/12} = 1.059$
- Cent (100 cents = semitone): $2^{1/1200} = 1.000578$ (JND: ~10 cents)
- **All sharps and flats** are **equal** to one another



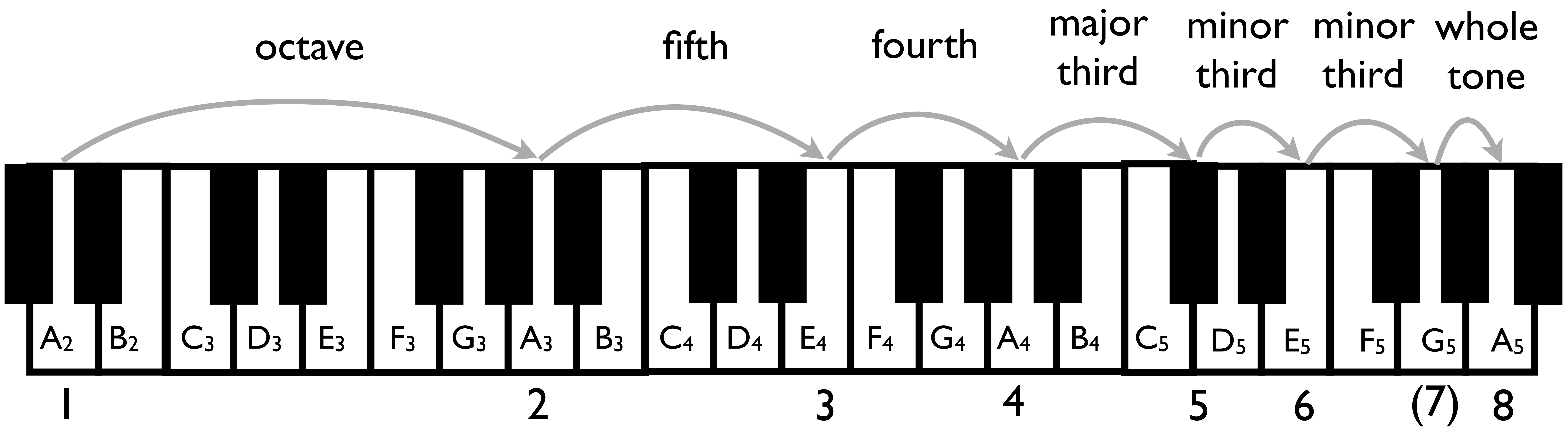
Note	ET freq ratio
C	$2^{0/12} = 1.000$
$C^\sharp/D^\flat$	$2^{1/12} = 1.059$
D	$2^{2/12} = 1.122$
$D^\sharp/E^\flat$	$2^{3/12} = 1.189$
E	$2^{4/12} = 1.260$
F	$2^{5/12} = 1.335$
$F^\sharp/G^\flat$	$2^{6/12} = 1.414$
G	$2^{7/12} = 1.498$
$G^\sharp/A^\flat$	$2^{8/12} = 1.587$
A	$2^{9/12} = 1.682$
$A^\sharp/B^\flat$	$2^{10/12} = 1.782$
B	$2^{11/12} = 1.888$
C'	$2^{12/12} = 2.000$

Musical intervals

Interval	# semitones	Just freq ratio	ET freq ratio	Difference (cents)	Example
Octave	12	$2:1=2.000$	2.000	0	C-C′
Fifth	7	$3:2=1.500$	1.498	2	C-G
Fourth	5	$4:3=1.333$	1.335	-2	C-F, G-C′
Major third	4	$5:4=1.250$	1.260	-14	C-E
Minor third	3	$6:5=1.200$	1.189	16	C-E$^\flat$, A-C′

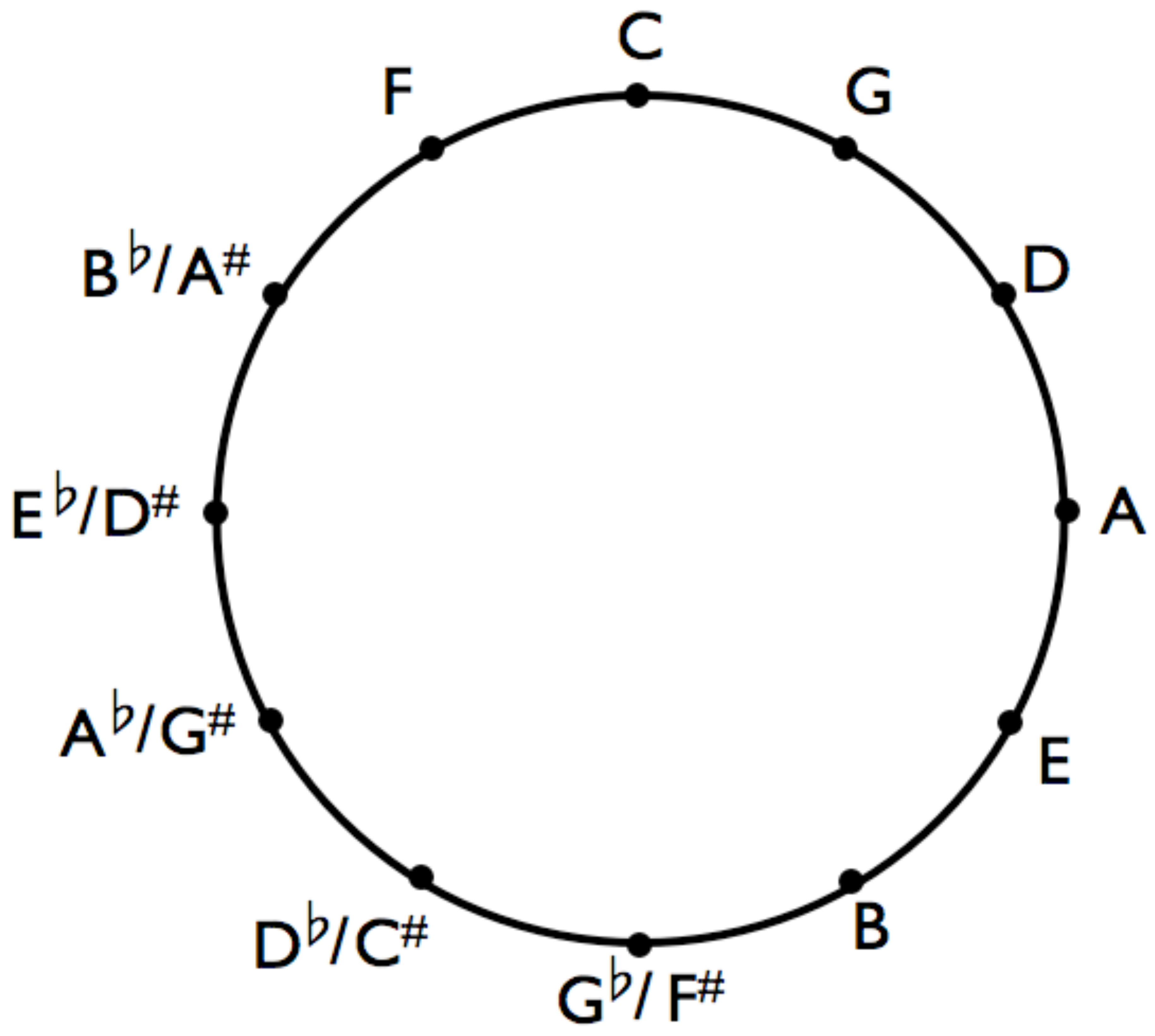


Harmonics

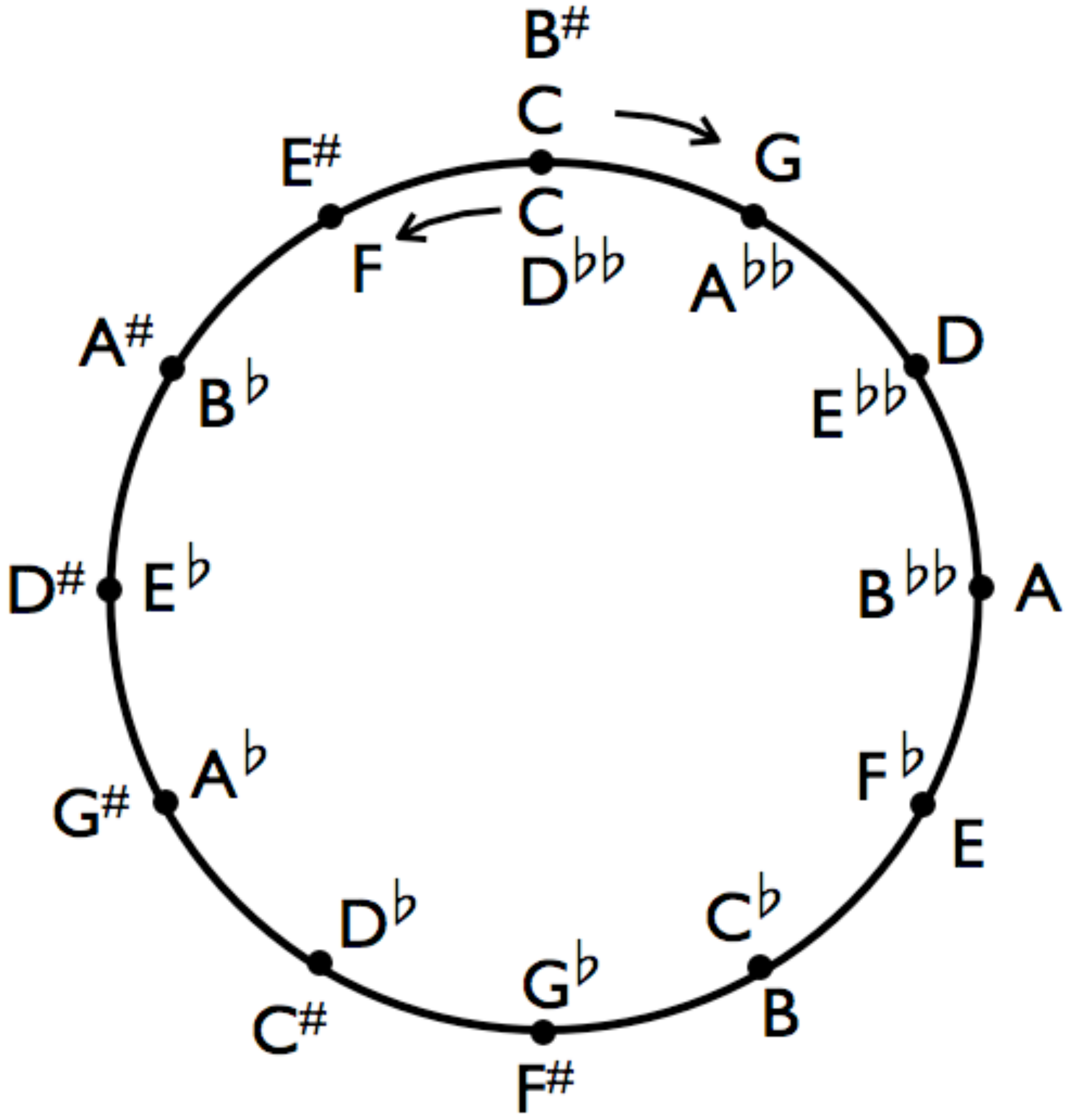


Harmonic	Exact freq (Hz)	Equal-tempered freq (Hz)	Difference (cents)	Piano note
1	110	110.00	0	A_2
2	220	220.00	0	A_3
3	330	329.63	2	E_4
4	440	440.00	0	A_4
5	550	554.37	-14	$C_5^\sharp$
6	660	659.26	2	E_5
7	770	783.99	-31	G_5
8	880	880.00	0	A_5

Circle of fifths

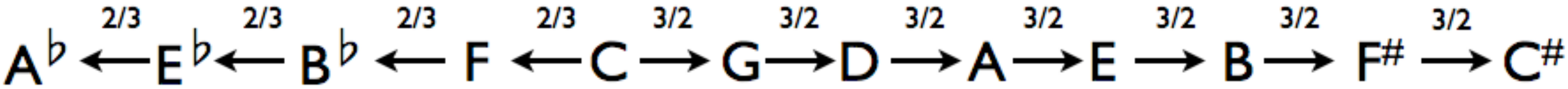


Equal Temperament



Other tuning systems

Pythagorean temperament



- Constructed from **perfect fifth** and **octave** intervals
- For example:

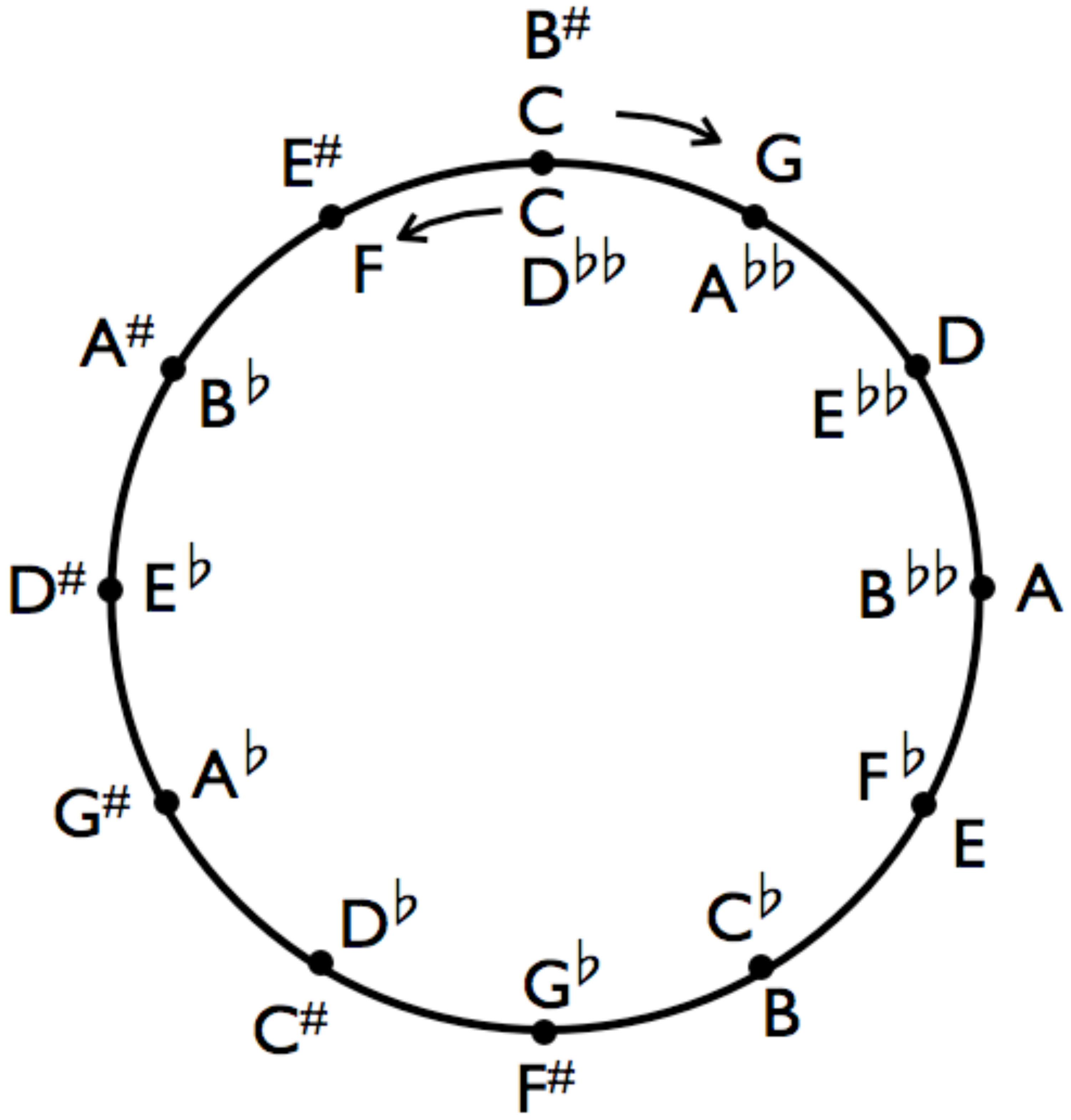
  G: 3/2

  D: $(3/2)^2 \times (1/2) = 9/8$

  A: $(3/2)^3 \times (1/2) = 27/16$

  E: $(3/2)^4 \times (1/2)^2 = 81/64$

  F: $(2/3) \times 2 = 4/3$



Just temperament

- Constructed from **perfect fifth**, **major third**, and **octave** intervals

- For example:

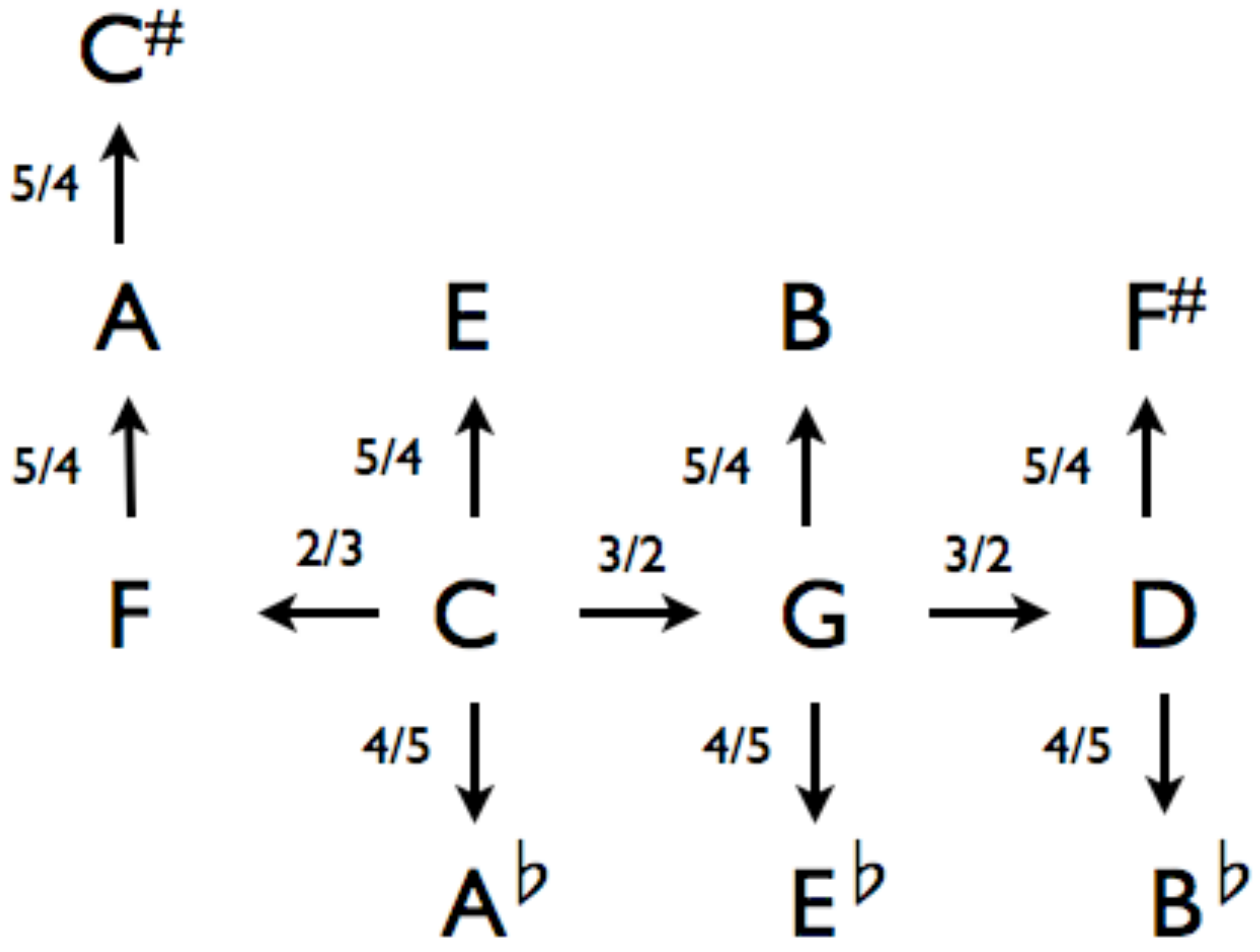
  G: 3/2

  D: $(3/2)^2 \times (1/2) = 9/8$

  A: $(2/3) \times (5/4) \times 2 = 5/3$ (vs 27/16)

  E: 5/4 (vs 81/64)

  F: $(2/3) \times 2 = 4/3$



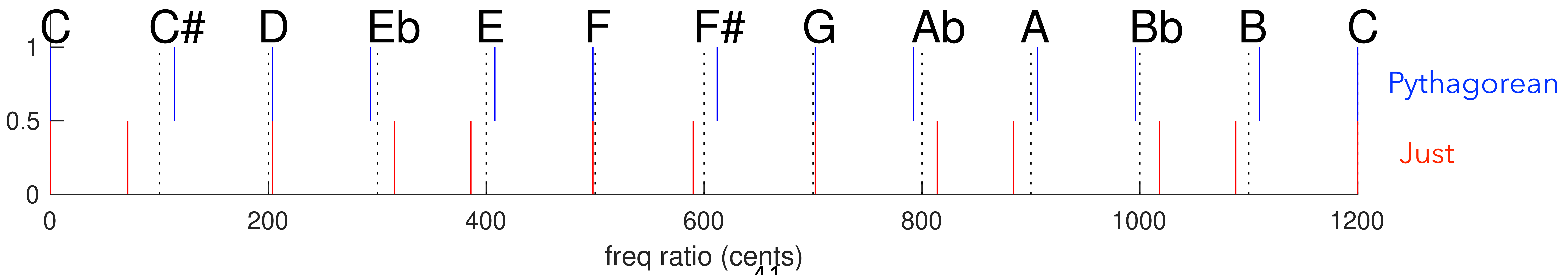
Comparing different tuning systems

Pythagorean vs Equal Temperament

Note	Pyth freq ratio	ET freq ratio	Difference (cents)
C	$1:1=1.000$	1.000	0
C♯	$2187:2048=1.068$	1.059	14
D	$9:8=1.125$	1.122	4
E♭	$32:27=1.185$	1.189	-6
E	$81:64=1.266$	1.260	8
F	$4:3=1.333$	1.335	-2
F♯	$729:512=1.424$	1.414	12
G	$3:2=1.500$	1.498	2
A♭	$128:81=1.580$	1.587	-8
A	$27:16=1.688$	1.682	6
B♭	$16:9=1.778$	1.782	-4
B	$243:128=1.898$	1.888	10
C′	$2:1=2.000$	2.000	0

Just vs Equal Temperament

Note	Just freq ratio	ET freq ratio	Difference (cents)
C	$1:1=1.000$	1.000	0
C♯	$25:24=1.042$	1.059	-29
D	$9:8=1.125$	1.122	4
E♭	$6:5=1.200$	1.189	16
E	$5:4=1.250$	1.260	-14
F	$4:3=1.333$	1.335	-2
F♯	$45:32=1.406$	1.414	-10
G	$3:2=1.500$	1.498	2
A♭	$8:5=1.600$	1.587	14
A	$5:3=1.667$	1.682	-16
B♭	$9:5=1.800$	1.782	18
B	$15:8=1.875$	1.888	-12
C′	$2:1=2.000$	2.000	0



All tuning systems have problems!!

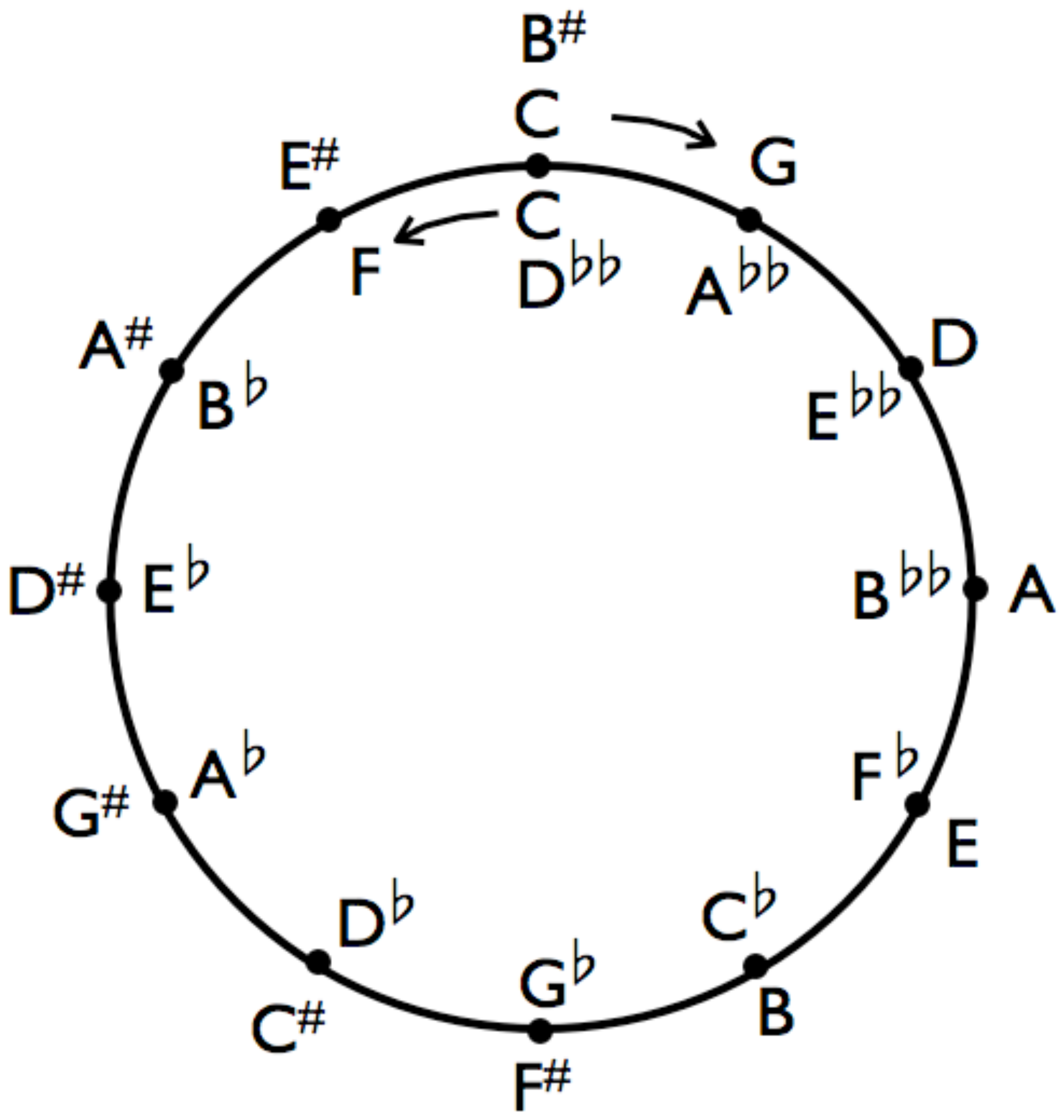
- **Equal-tempered** fifths, fourths, etc. are **never perfect** (only an octave)

- **Pythagorean circle of fifths doesn't close** (12 perfect fifths is not equal to 7 octaves)

- Pythagorean "**comma**":

$$\frac{\mathrm{B}^\sharp}{\mathrm{C}'} = \frac{(3/2)^{12}}{2^7} = 1.0136 \quad \text{(23 cents too large)}$$

- Fifth $\mathrm{C}^\sharp$ to $\mathrm{A}^\flat$ is too flat in Pythagorean temperament (**"wolf" fifth**) and too sharp in just temperament



Fifth	Temperament	Freq ratio	Difference (cents)
C-G	equal	1.498	-2
C-G	pyth	1.500	0
C-G	just	1.500	0
$\mathrm{C}^\sharp$-$\mathrm{A}^\flat$	equal	1.498	-2
$\mathrm{C}^\sharp$-$\mathrm{A}^\flat$	pyth	1.480	-23
$\mathrm{C}^\sharp$-$\mathrm{A}^\flat$	just	1.536	41

"The Well-Tempered Clavier"

- Written by Johannes Sebastian Bach in 1722
- Piece played in all 24 major and minor keys
    - Major interval order: T-T-S-T-T-T-S
    - Minor interval order: T-S-T-T-S-T-T
- Demonstrates the usefulness of equal temperament tuning (the piece sounds good only in the equal temperament tuning system)

https://www.youtube.com/watch?v=nPHIZw7HZq4

C Major - 846 0:00 / 2:41c minor - 847 4:39 / 6:26C# Major - 848 8:22 / 9:39c# minor - 849 12:13 / 15:12D Major - 850 17:51 / 19:25d minor - 851 21:13 / 22:51Eb Major - 852 24:59 / 28:32eb/d# minor - 853 30:21 / 34:19E Major - 854 38:14 / 39:58e minor - 855 41:20 / 43:20F Major - 856 44:50 / 45:54f minor - 867 47:22 / 50:14F# Major - 858 54:12 / 55:52f# minor - 859 57:58 / 59:03G Major - 860 1:02:19 / 1:03:14g minor - 861 1:05:50 / 1:08:03Ab Major - 862 1:09:58 / 1:11:30g# minor - 863 1:13:29 / 1:15:31A Major - 864 1:17:48 / 1:19:21a minor - 865 1:21:16 / 1:22:41Bb Major - 866 1:26:45 / 1:28:02bb minor - 867 1:29:59 / 1:32:26B Major - 868 1:35:44 / 1:36:43b minor - 869 1:38:33 / 1:41:01