PHY 103: Loudness and Amplification

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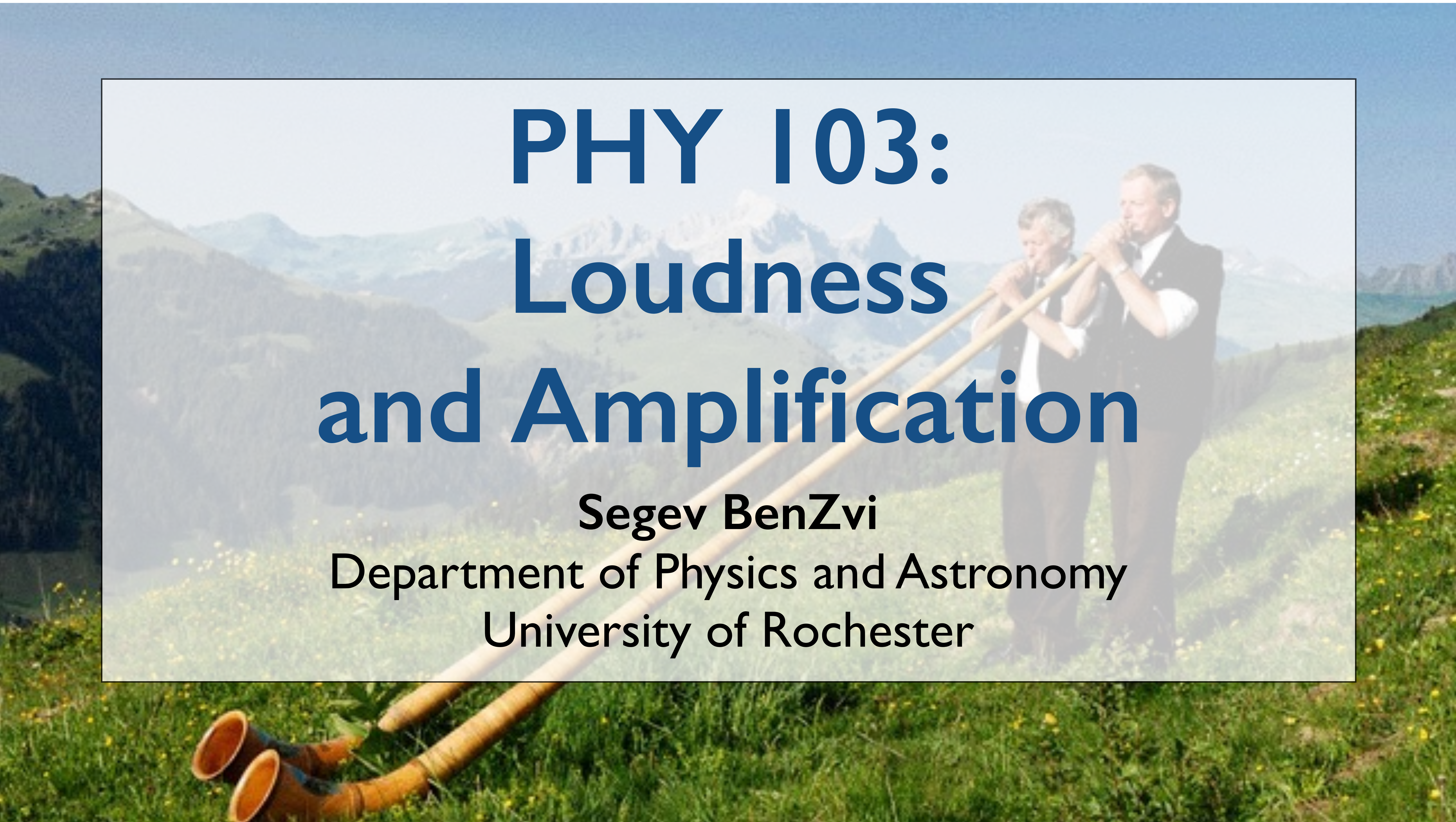
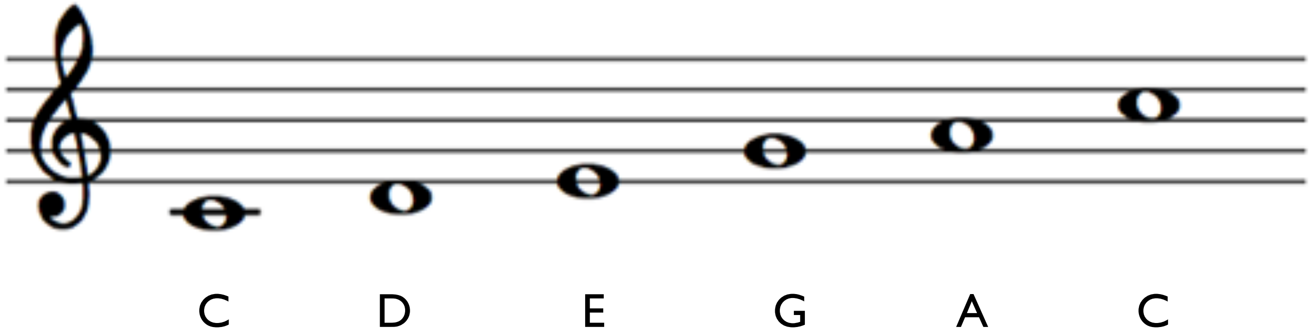


Last Time

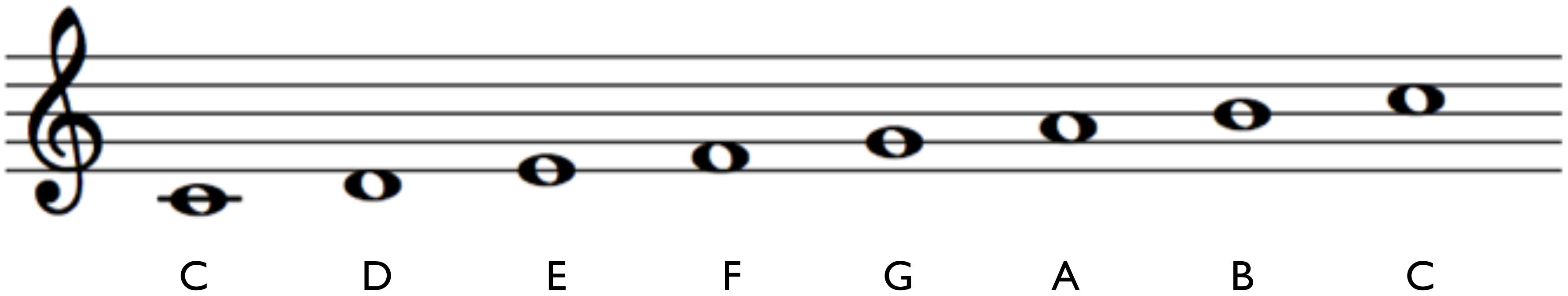
- Basic scales built on consonant tones with low-integer frequency ratios:
  - Octaves (1:2), Fifths (3:2), Fourths (4:3)
  - Triads: 4:5:6 ratio (C-E-G, F-A-C, G-B-D)
  - Question: why do these combinations sound good?
- Pentatonic and diatonic scales
- Pythagorean tuning → generate chromatic scale
- Just intonation
- Equal temperament

Basic Scales

- Pentatonic



- Diatonic



- Chromatic

Need for Amplification

- Instruments produce sound by vibrating some element (a string, a drumhead, a reed, your lips, …)
- There is typically very little energy in this vibration
  - For plucked string, total energy is $E = 1/4\ \mu\omega_n^2 A_n^2 L$
  - First E string on a guitar: $\omega_1 = 2\pi \times 329.63$ Hz
  - $\mu = 0.4$ g/m
  - $L = 0.6$ m, $A = 3$ mm
  - Energy is about 2 mJ. Energy required to lift an apple (100 g) vertically by 1 meter against gravity: 1 J

Amplification

- In order to actually hear an instrument and project its sound we have to amplify it
- Acoustic resonators have been used for thousands of years for this purpose
- Now we can couple instruments to electroacoustic transducers, amplifiers, and loudspeakers
- Before we get into acoustic amplification, let's talk about sound power (a physical quantity) and loudness (a perceived quantity)…

Relative Power: dB

- Energy in an oscillating wave: $E \sim A^2$ [Joules]
- Power: P = energy per unit time [Joule/sec = Watts]
- Intensity: I = power per unit area [W/m^2]
- Relative sound level between two sounds is given in decibels [dB]
  - Sound 1 has power P_1 and sound 2 has power P_2
  - Relative difference: $10 \log(P_2 / P_1)$ dB
  - $P_2 = 2 P_1 \rightarrow 10 \log 2 = 3$ dB difference

The Decibel Scale

- Sample: noise decreased in steps of 6 dB
- Sample: noise decreased in steps of 3 dB
- Sample: speaker moving away from microphone. The sound intensity decreases as $1/r^2$, where r is the distance to the microphone

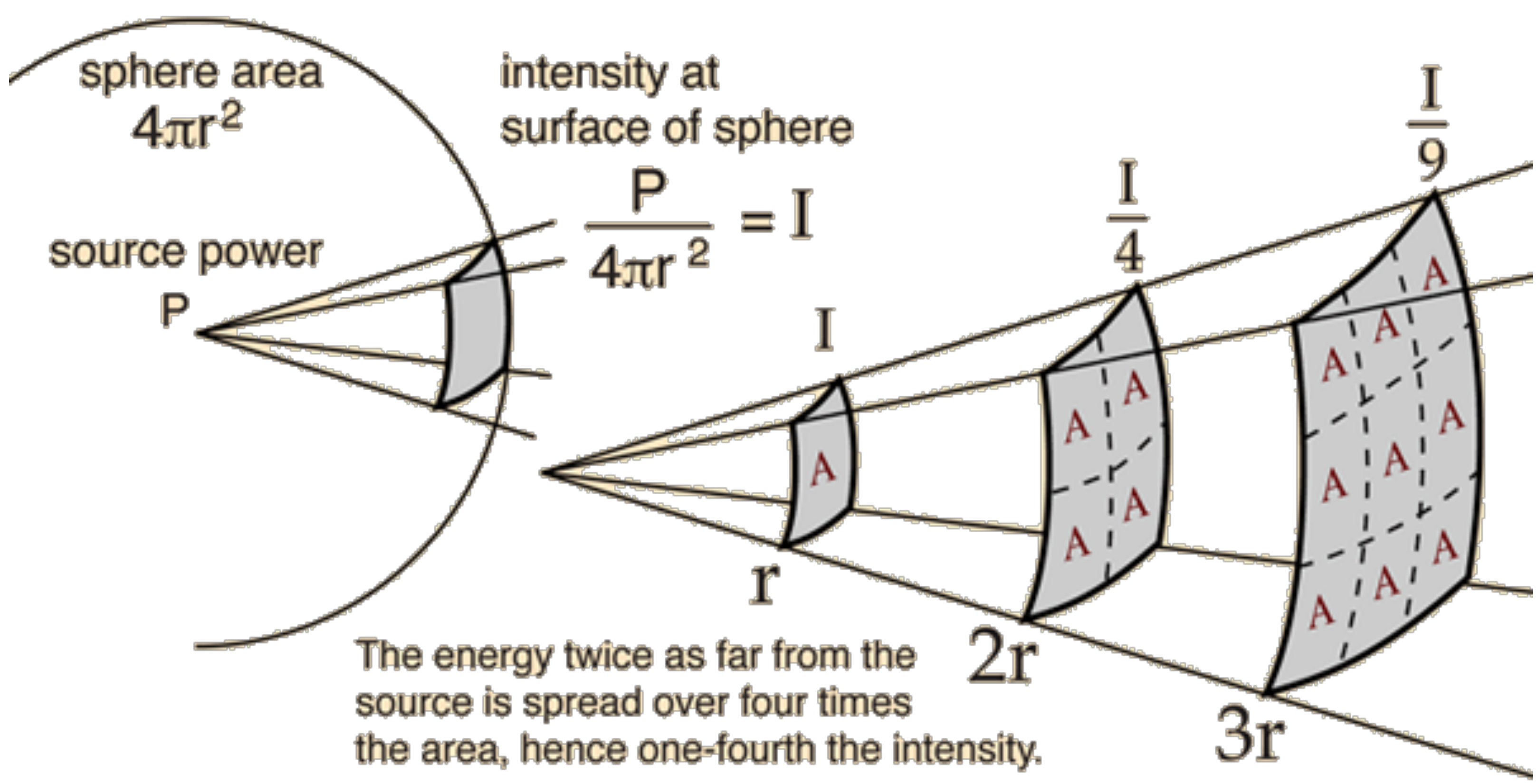


Image from hyperphysics

Samples from *Auditory Demonstrations* by Houtsma, Rossing, and Wagenaars

Time-Averaged Power

- Note: when we talk about power in this context, we don't mean the instantaneous power at one time *t*
- We are talking about the time-averaged power of an oscillating pressure wave

$$p(t) = A\cos(\omega t)$$

$$P(t) \propto p(t)^2$$

$$\langle P_{\text{avg}} \rangle = \frac{1}{\tau}\int_0^\tau P(t)\,dt \propto \frac{1}{\tau}\int_0^\tau A^2\cos^2(\omega t)\,dt = A^2/2$$

$$\propto P_{\max}/2$$

Sound Intensity Reference

- Decibels measure a relative power (or intensity) ratio between two sounds
- So when we talk about a sound being 60 dB (for example), what is the reference point we are using?
- Remember that sound corresponds to pressure variations propagating through air in longitudinal waves
- Reference point: p_0 = 0.02 µPa or about 2×10^{-10} atm
- So you can think of dB as the amplitude variation of sounds (in pressure) relative to this reference point
  - sound level = $10 \log(p / p_0)^2 = 20 \log(p / p_0)$ dB

Power of Common Sounds

Sound Source	Sound Level	Intensity
Hearing threshold	0 dB	1 pW/m^2
Whispering in library, 2 m distance	30 dB	1 nW/m^2
Normal conversation, 1 m distance	60 dB	1 μW/m^2
City traffic noise inside a car	85 dB	
Hearing loss threshold (sustained exposure): 90 dB		1 mW/m^2
Jackhammer at 20 m distance	95 dB	
Hand drill	98 dB	
Power mower	107 dB	
Rock concert	115 dB	
Pain threshold: 120 dB		1 W/m^2
Pneumatic riveter at 1 m	125 dB	
Permanent damage threshold (short exposure)		
Jet engine at 30 m	140 dB	100 W/m^2
12 gauge shotgun blast	165 dB	
Death of hearing tissue	180 dB	1 kW/m^2
Loudest sound possible at 0C and 1 atm	194 dB	

From gcaudio.com

What Happens >194 dB?

- 194 dB corresponds to a pressure amplitude of 1 atm
- Sound levels >194 dB require sound pressures >1 atm
- Sound waves become distorted (like a shock wave), with valleys clipped at 0 Pa (vacuum)

Mt. Tavurvur, Papua New Guinea, August 2014 (P. McNamara)

Sound Safety

- OSHA guidelines for sound level exposure:

Sound Level [dB]	Power/Intensity difference	Exposure Time
90	—	8 hr/day
92	1.58	6 hr/day
95	3.16	4 hr/day
97	5.01	3 hr/day
100	10	2 hr/day
102	15.85	90 min/day
105	31.62	60 min/day
110	100	30 min/day
115	316.23	<15 min/day

From gcaudio.com

- Q: how did I go from dB to intensity difference?

Combining Sound Levels

- Suppose you have a 70 dB speaker and you add a second 70 dB speaker. How loud is the combined set?
- Consider two possible cases:

1. Coherence: signals have same frequency and are in phase
2. Incoherence: signals have different frequencies

Combining Sound Levels

- If the speakers are in phase (coherent) where you are sitting, then the amplitudes of the waves add
- Power ~ Energy ~ Amplitude^2

$$p(t) = A\cos(\omega t)$$

$$P(t) \propto [p(t) + p(t)]^2$$

$$= 4A^2\cos^2(\omega t)$$

$$\langle P_{\text{avg}} \rangle = \frac{1}{\tau}\int_0^\tau P(t)\,dt = \propto 2A^2$$

- Average power is 4x the power of one signal ($A^2/2$)

Combining Sound Levels

- If the two speakers aren't playing the same frequency, they are incoherent and the calculation changes
- Remember that we're dealing with time-averaged power when we combine the signals:

$$p_1(t) = A\cos(\omega t), \quad p_2(t) = A\cos(\Omega t)$$

$$P(t) \propto [p_1(t) + p_2(t)]^2$$

$$= A^2\cos^2(\omega t) + A^2\cos^2(\Omega t) + 2A\cos(\omega t)\cos(\Omega t)$$

time average: $A^2/2$ time average: $A^2/2$ time average: 0

$$\langle P_{\text{avg}} \rangle \propto A^2$$

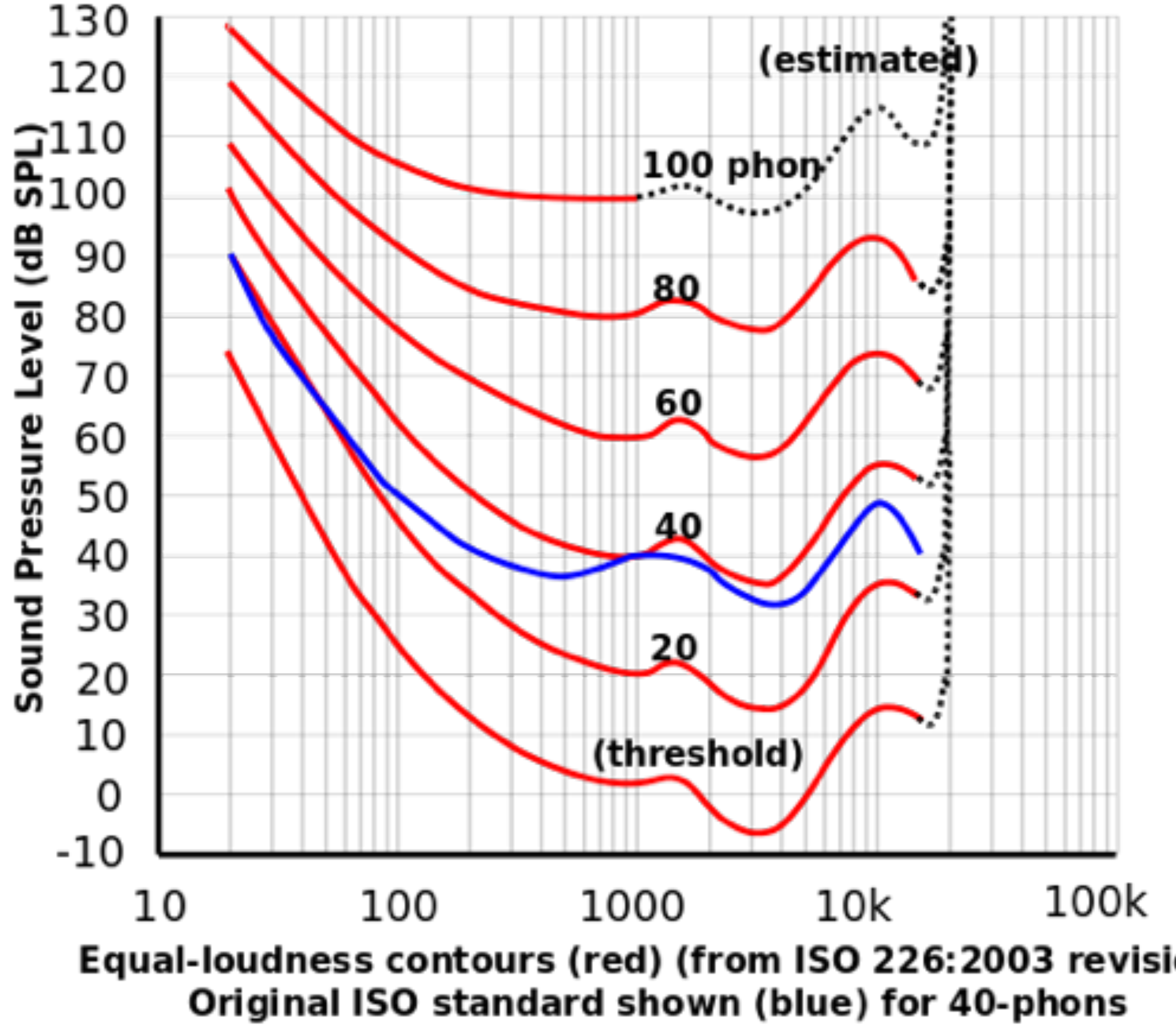
2x the power of 1 signal alone

Combining Sound Levels

- **Coherent case:**
  - Difference in sound level = 10 log (4) = 6 dB
  - Therefore, the total sound power of the two speakers is 70 dB + 6 dB = 76 dB
- **Incoherent case:**
  - Different in sound level = 10 log (2) = 3 dB
  - Therefore, the total sound power of the two speakers is 70 dB + 3 dB = 73 dB

Loudness Perception

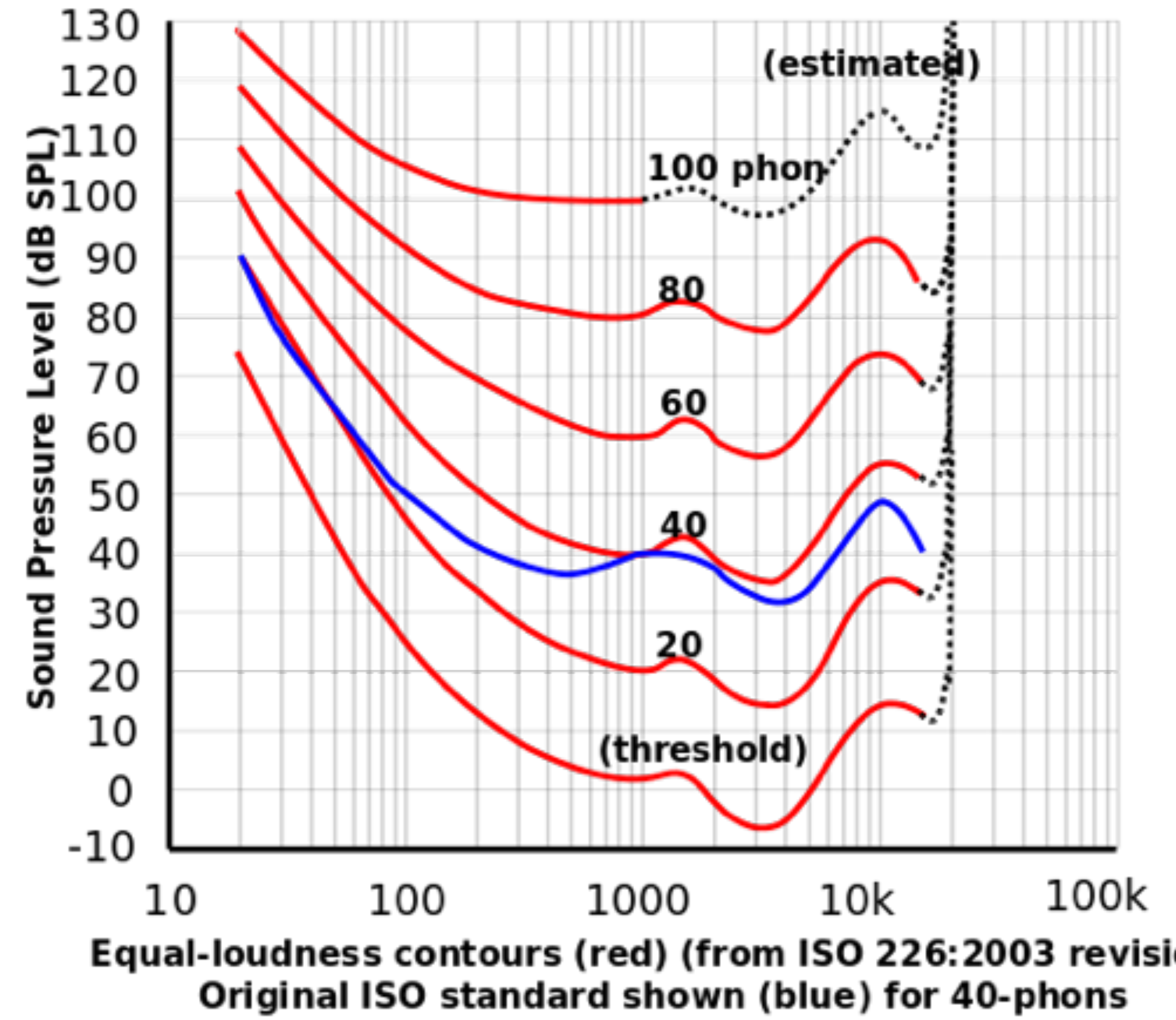
- dB gives us an objective measurement of sound level power, but we don't perceive loudness equally at all frequencies



frequency [Hz]

dB and Phons

- Phon: psychophysical loudness measure
- At 1 kHz, phon scale = dB
- Everywhere else, phons are tuned to subjective response
- Equal-loudness curve: at a given frequency, what dB sound produces same loudness w.r.t. 1 kHz?
- We have a strong frequency-dependent response to sounds



frequency [Hz]

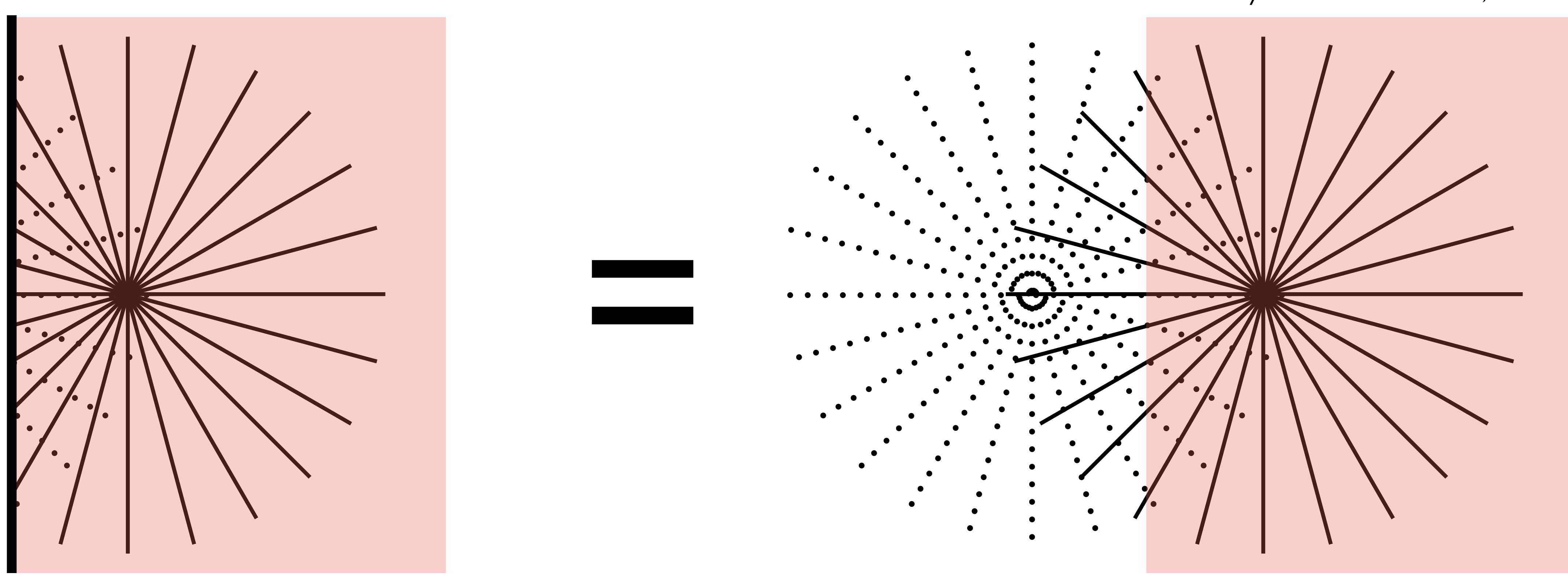
Back to Amplification

- Take any oscillating device (string, music box, etc.) and it will produce very little energy on its own
- But couple it to an acoustic resonator and you can get a huge sound
- Technical: the oscillating device has a mismatched acoustic impedance w.r.t. the surrounding air, while the resonator has a better-matched impedance
- We'll return to the concept of impedance in a few weeks

Amplification by Reflection

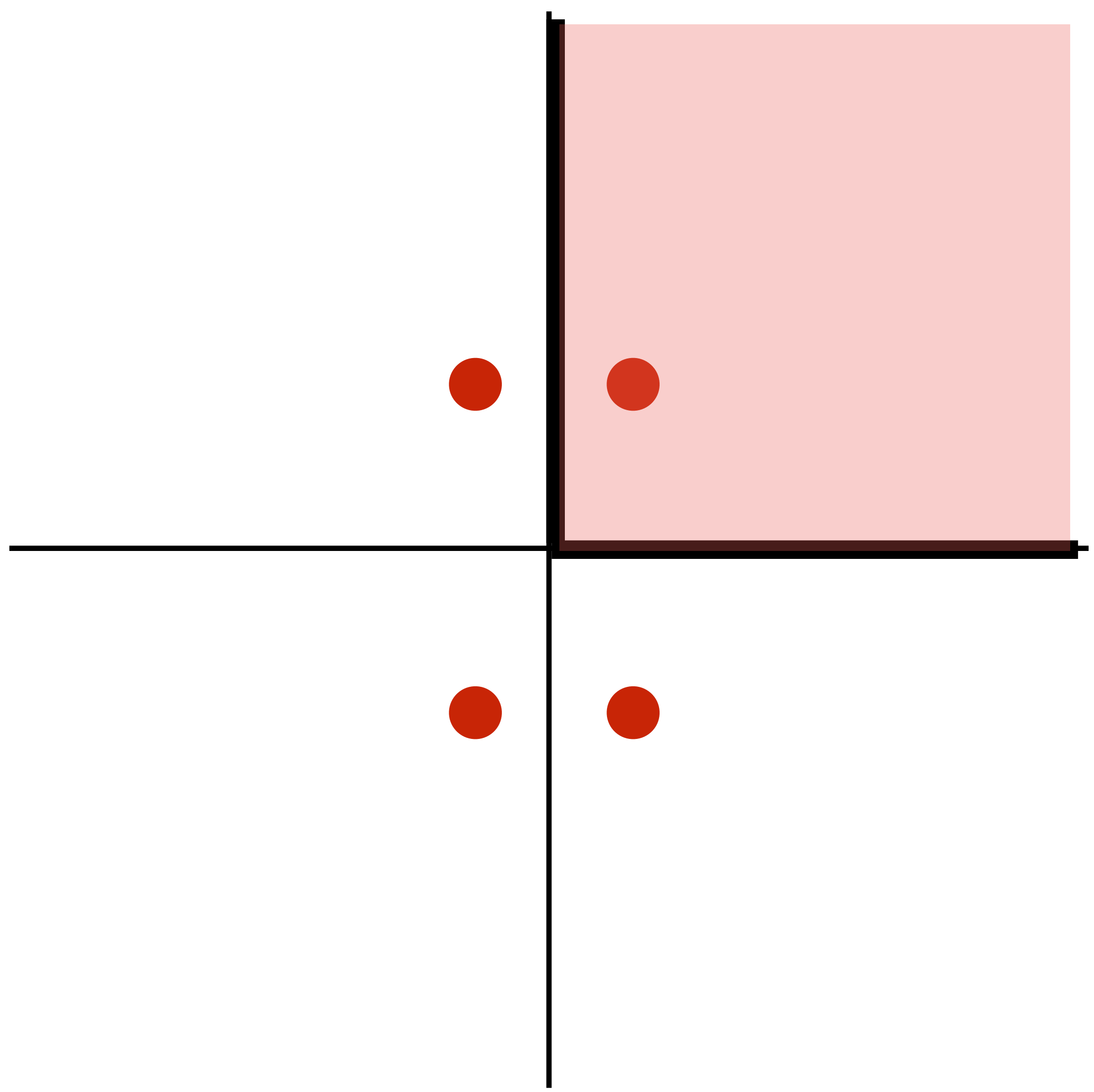
- If you hold a sound source next to a wall, the waves will be reflected off the wall back at you
- You can get amplification, as if there were a second source behind the wall

From *Why You Hear What You Hear*, E. Heller

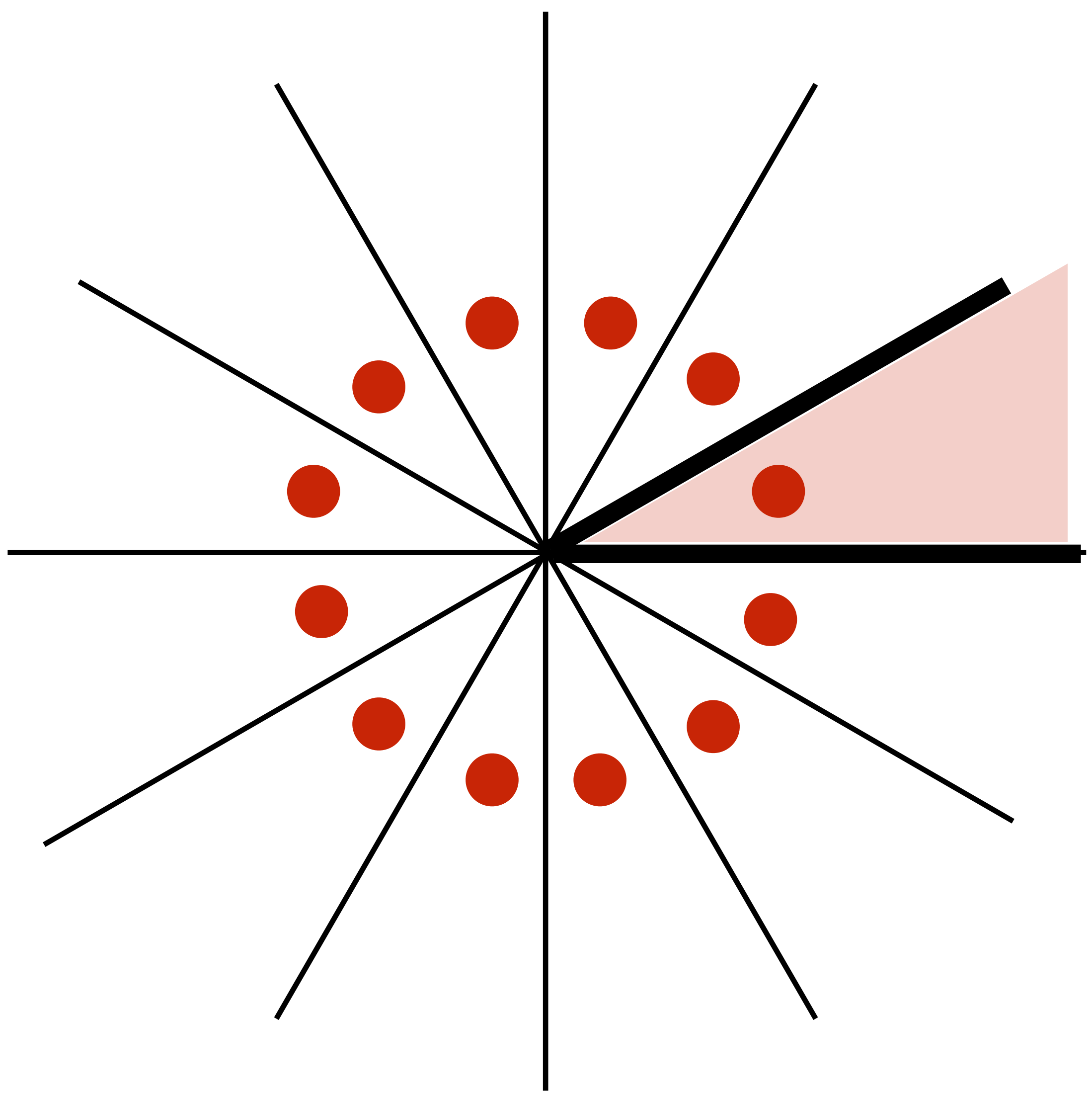


Reflection from a Corner

- If wavelength is large compared to the distance between the source and its N-1 images, the power in the physical region goes up by N^2

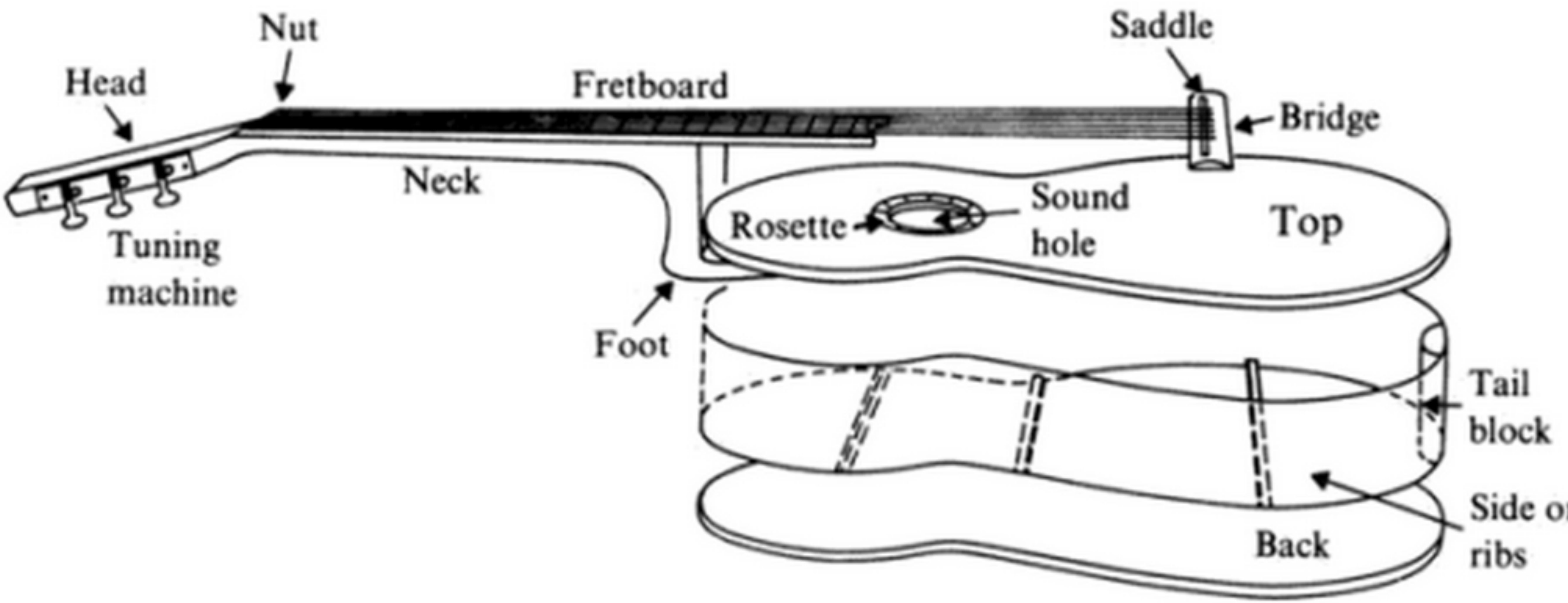


Reflection from a 30° Wedge



Amplification: the Guitar

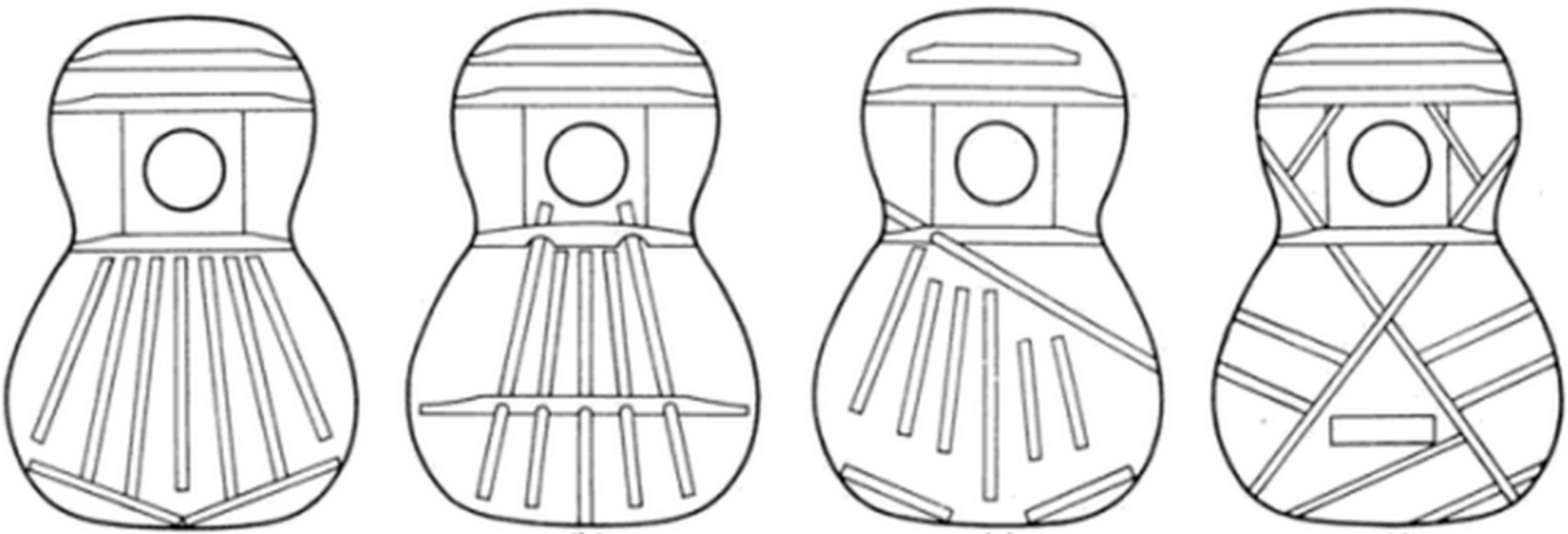
- A guitar is a fretted board of strings coupled to two flat vibrating panels



From *The Physics of Musical Instruments*, N. Fletcher and T. Rossing

Soundboard Bracing

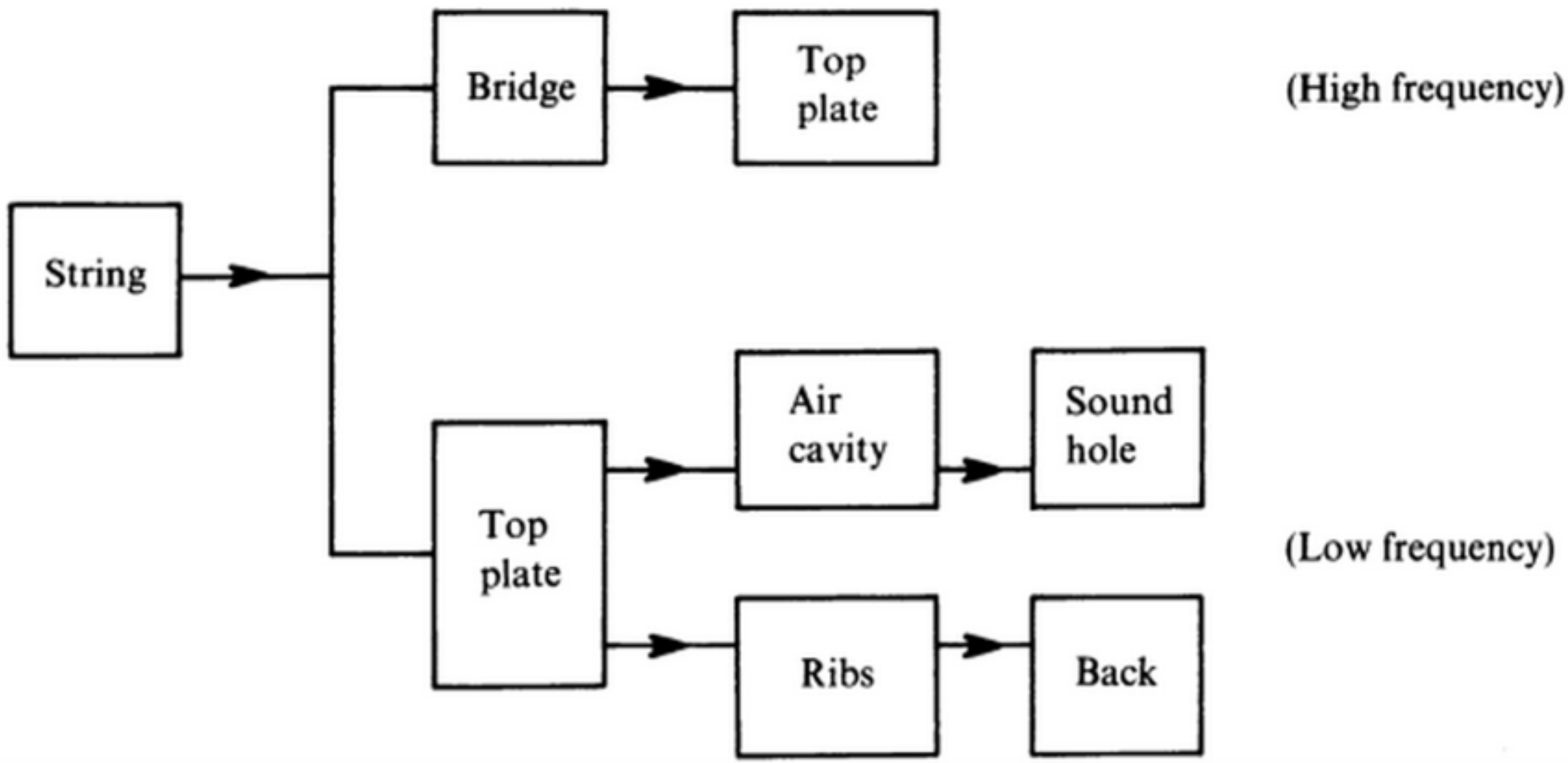
- Designs for bracing a guitar soundboard: Torres, Bouchet (France), Ramirez (Spain), crossed bracing
- Bracing affects the vibrational modes of the board



From *The Physics of Musical Instruments*, N. Fletcher and T. Rossing

Guitar Schematic

- Different pieces of the guitar resonate in different frequency regimes

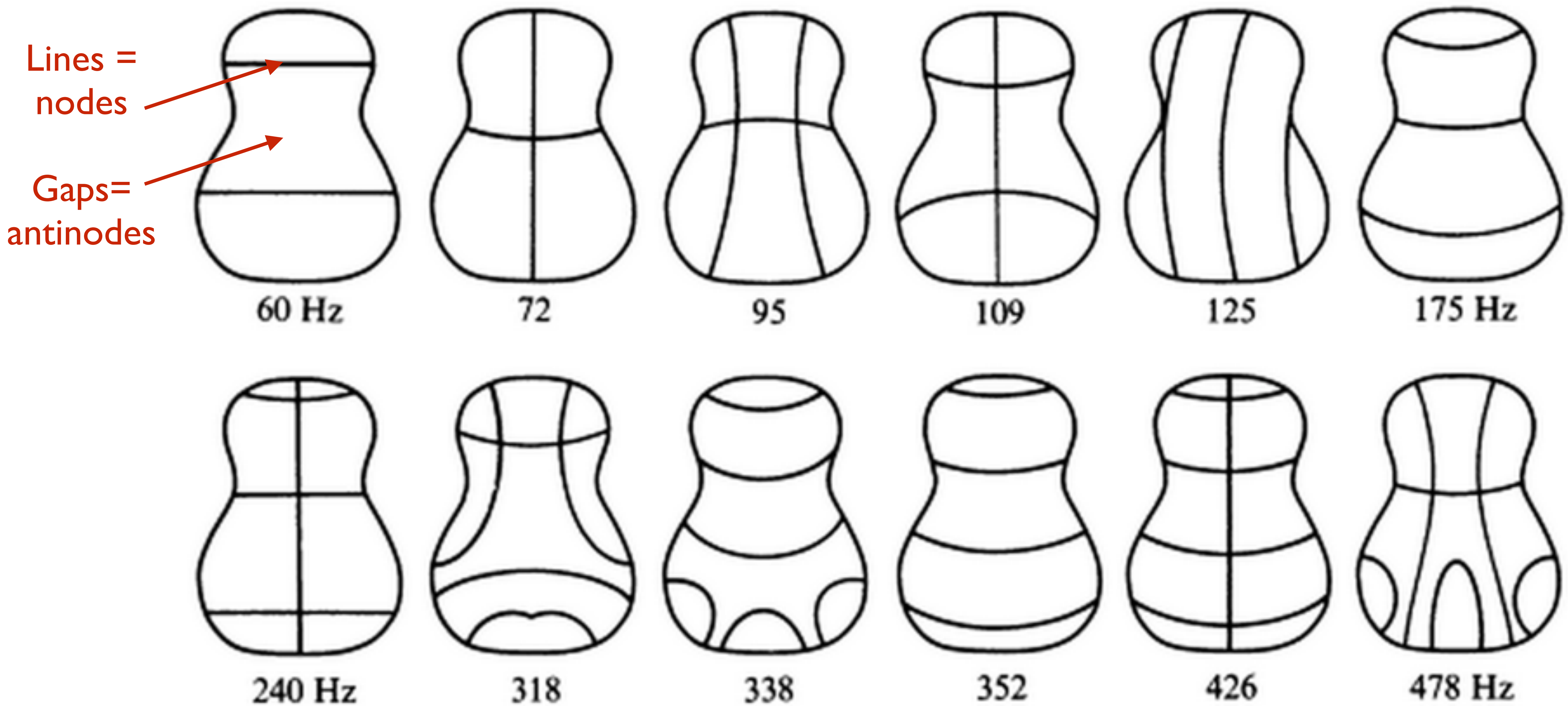


From *The Physics of Musical Instruments*, N. Fletcher and T. Rossing

Guitar Plate Modes

- Vibrational modes of a guitar plate blank without braces

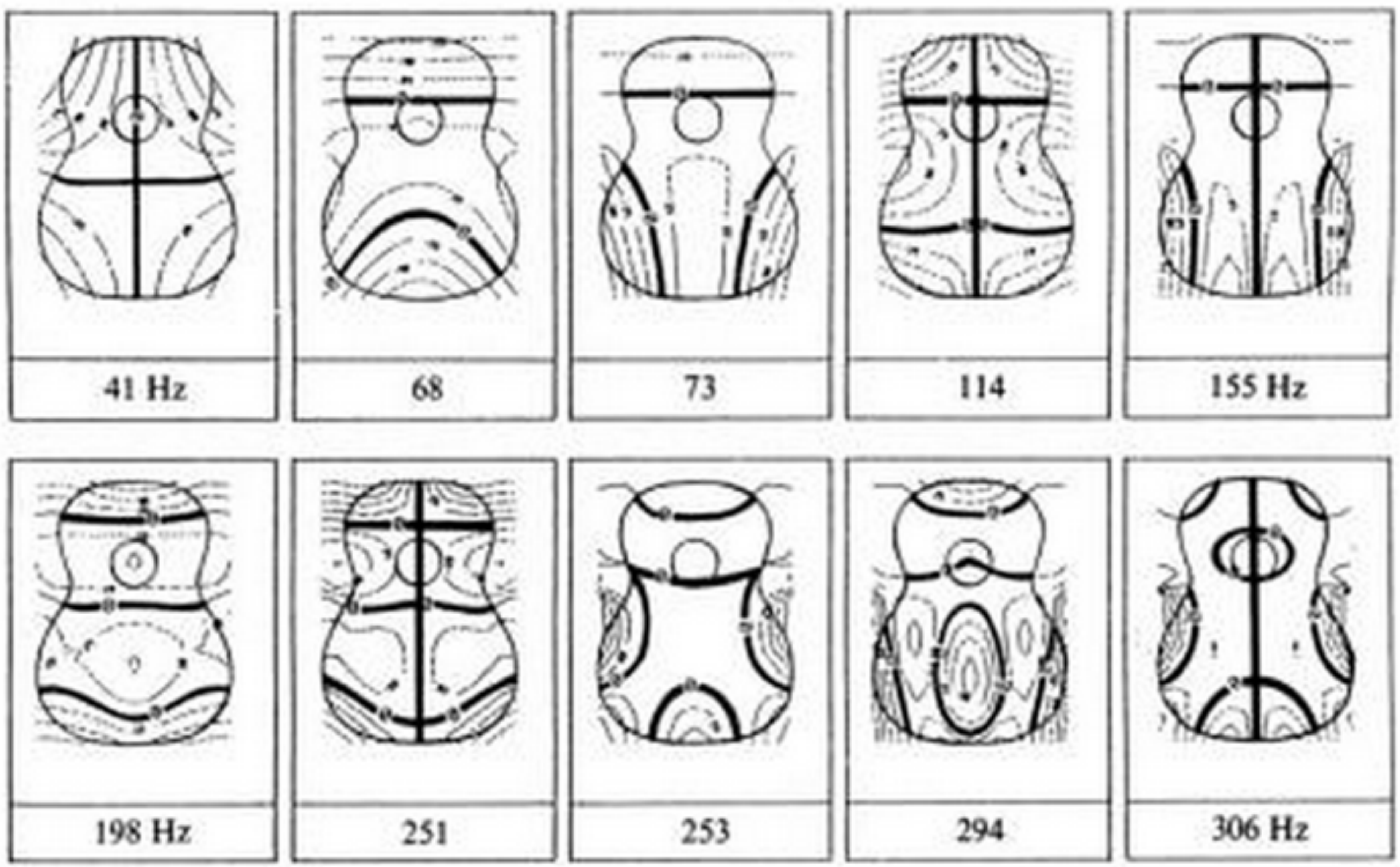
From *The Physics of Musical Instruments*, N. Fletcher and T. Rossing



Effect of Braces

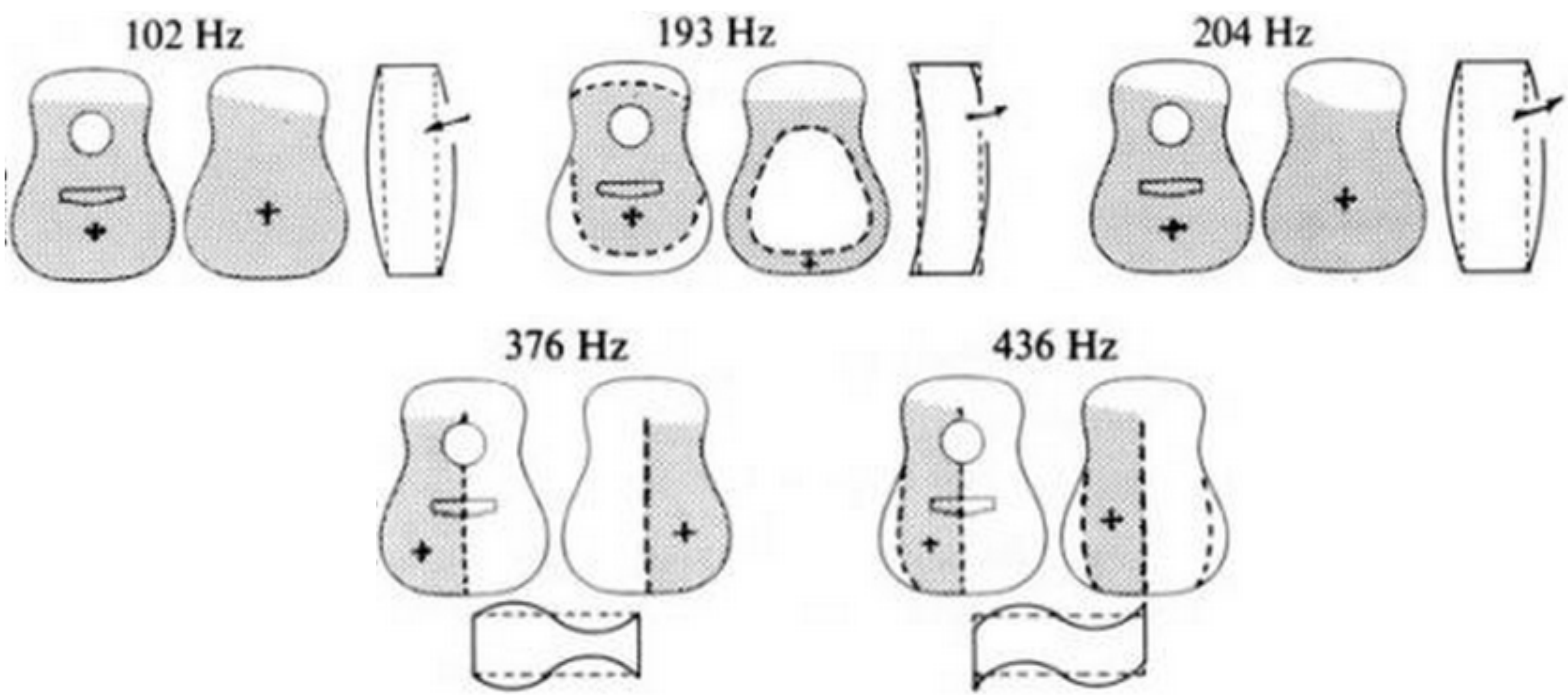
- Vibrational modes of guitar top plate with traditional fan bracing

From *The Physics of Musical Instruments*, N. Fletcher and T. Rossing



Full Guitar Modes

- The whole guitar cavity has vibrational modes that are combinations of the modes of the plates and sides put together



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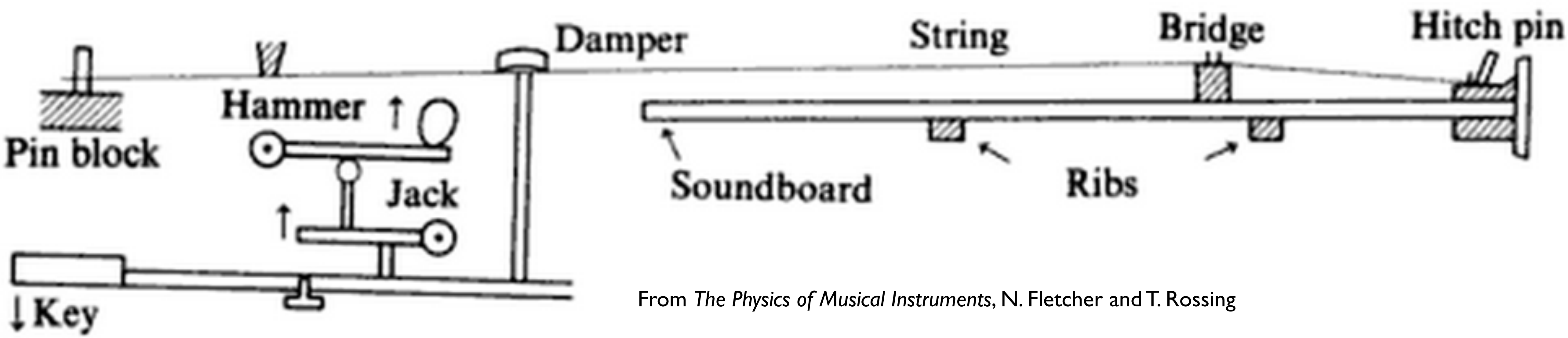
The Piano

- The piano also uses an acoustic resonator: the soundboard



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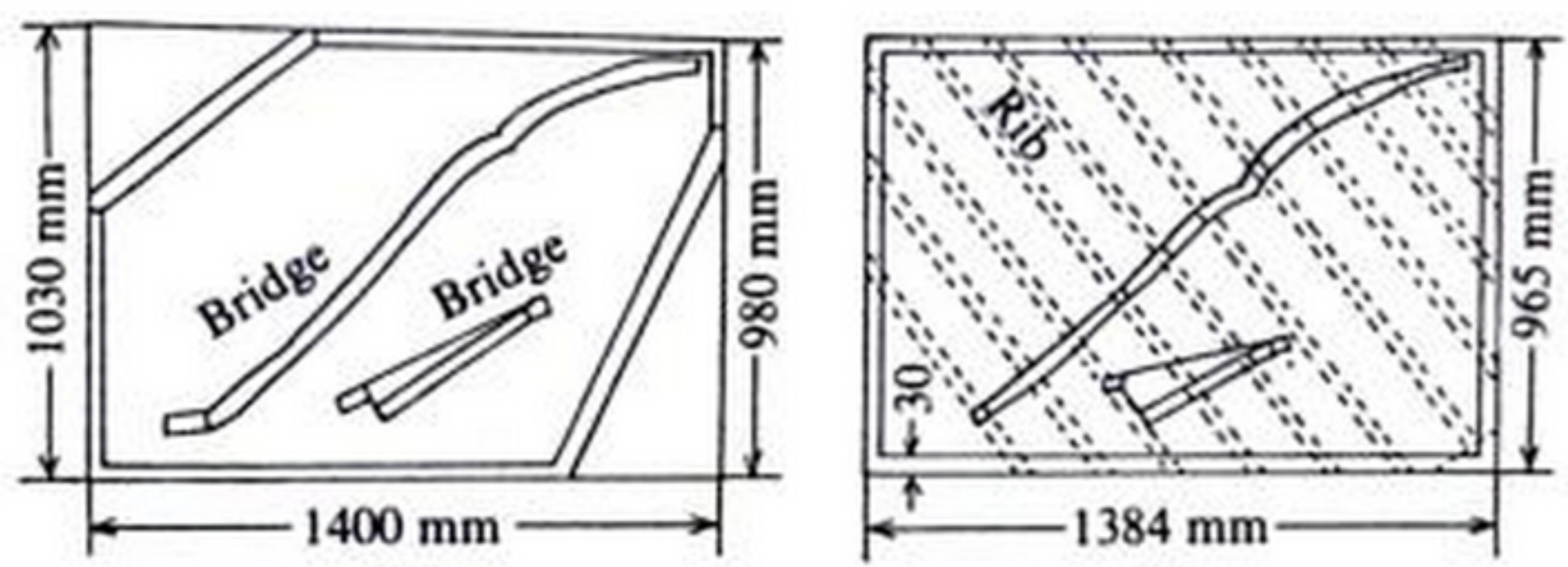
- The soundboard opposes the vertical components of the string tension (lots of force: 20 N per string)
- Acoustically, it's also the main radiating component

Upright Piano Soundboard

- An upright piano has a vertically oriented rectangular soundboard

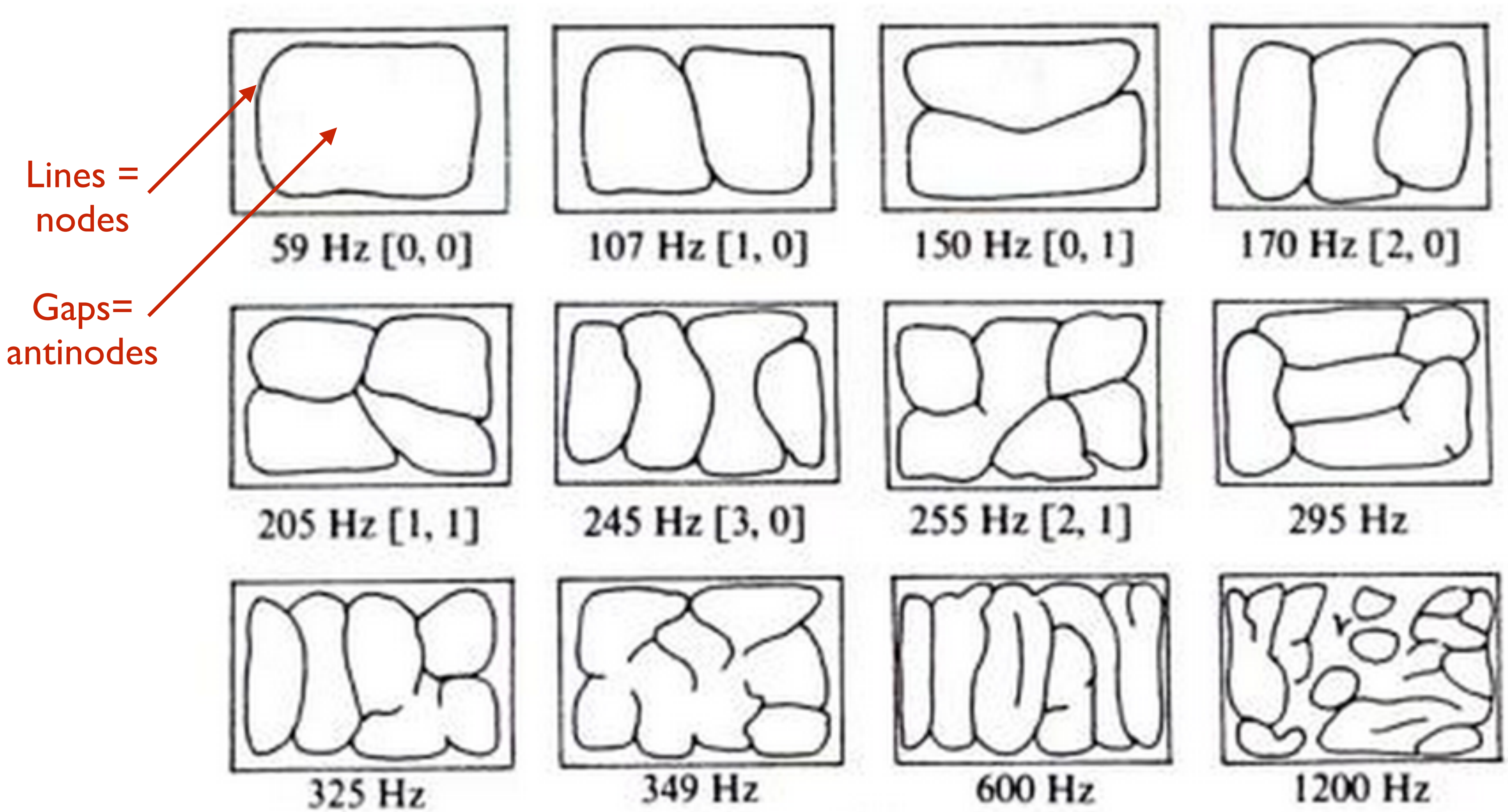


From *The Physics of Musical Instruments*, N. Fletcher and T. Rossing

- Frame members restrict the vibrations to a trapezoidal section where the bridges run diagonally

Upright Piano Modes

- Vibrational modes of the upright piano soundboard



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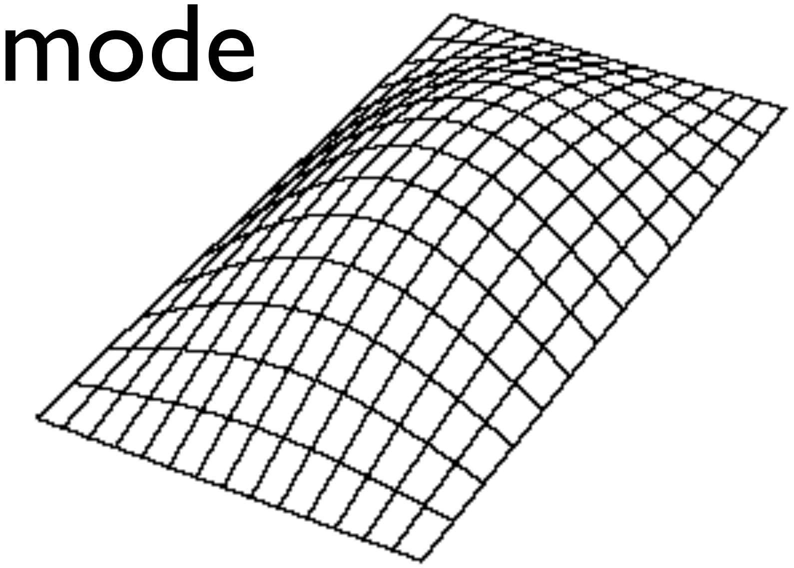
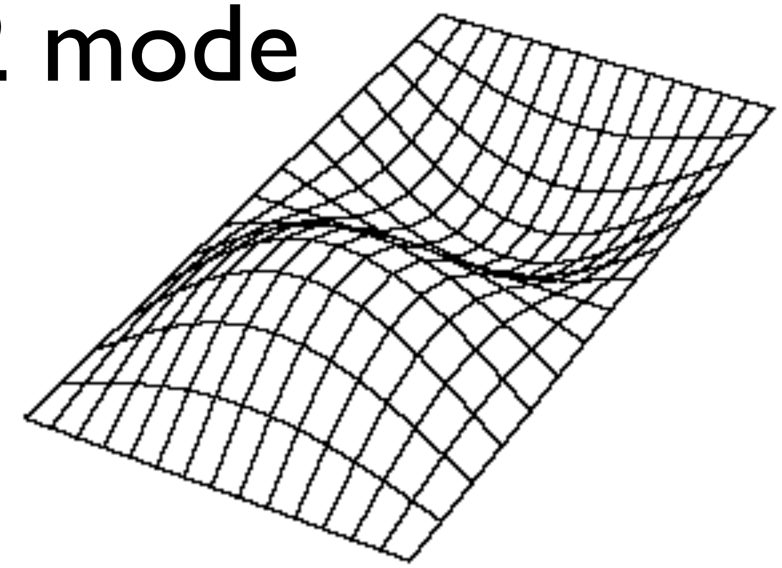
Rectangular Membrane Modes

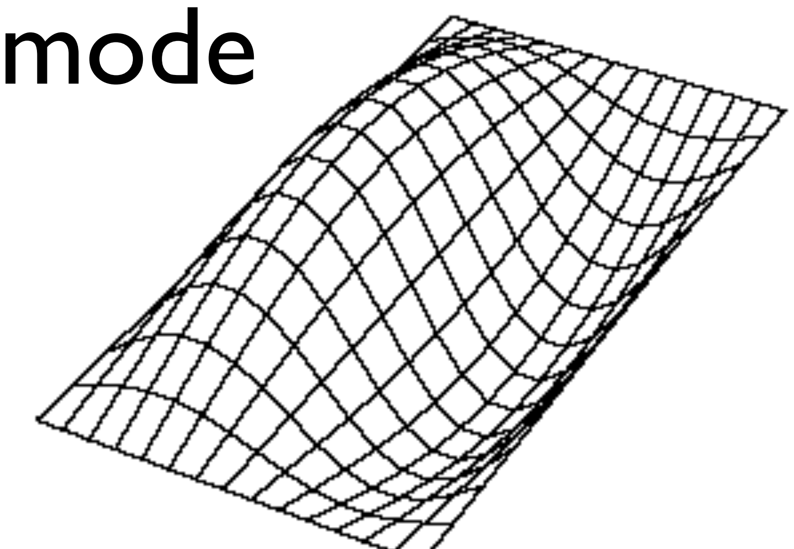
1,1 mode



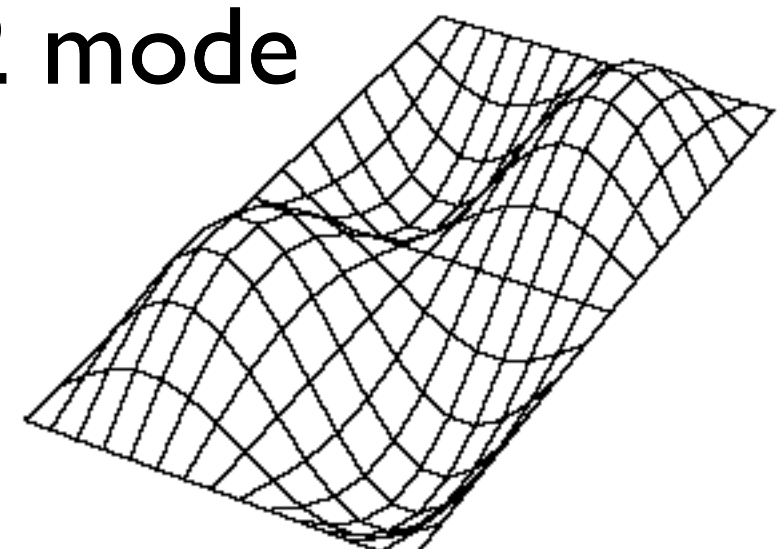
1,2 mode



2,1 mode



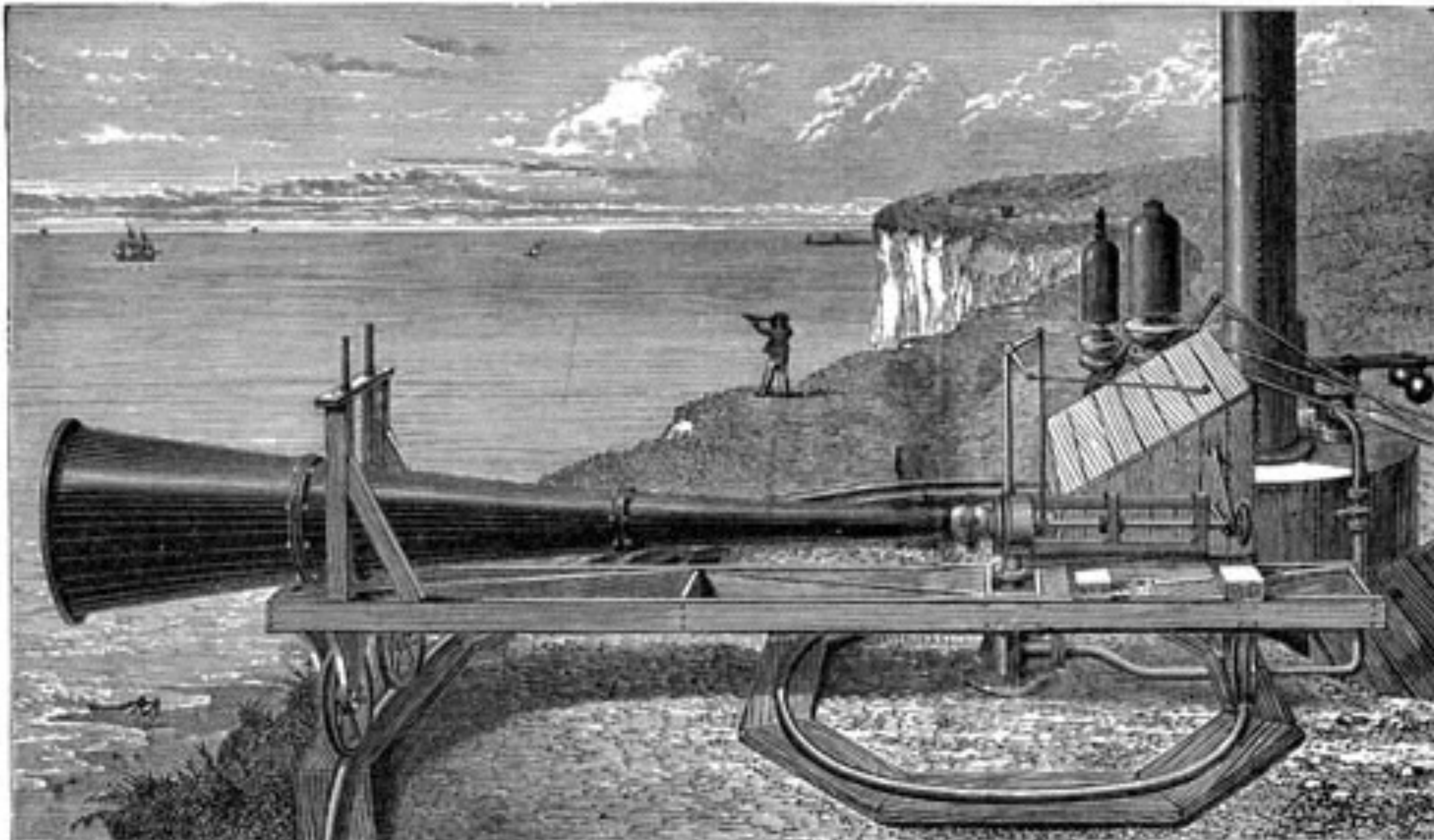
2,2 mode



Courtesy Dan Russell, Grad. Prog. in Acoustics, PSU

Horns

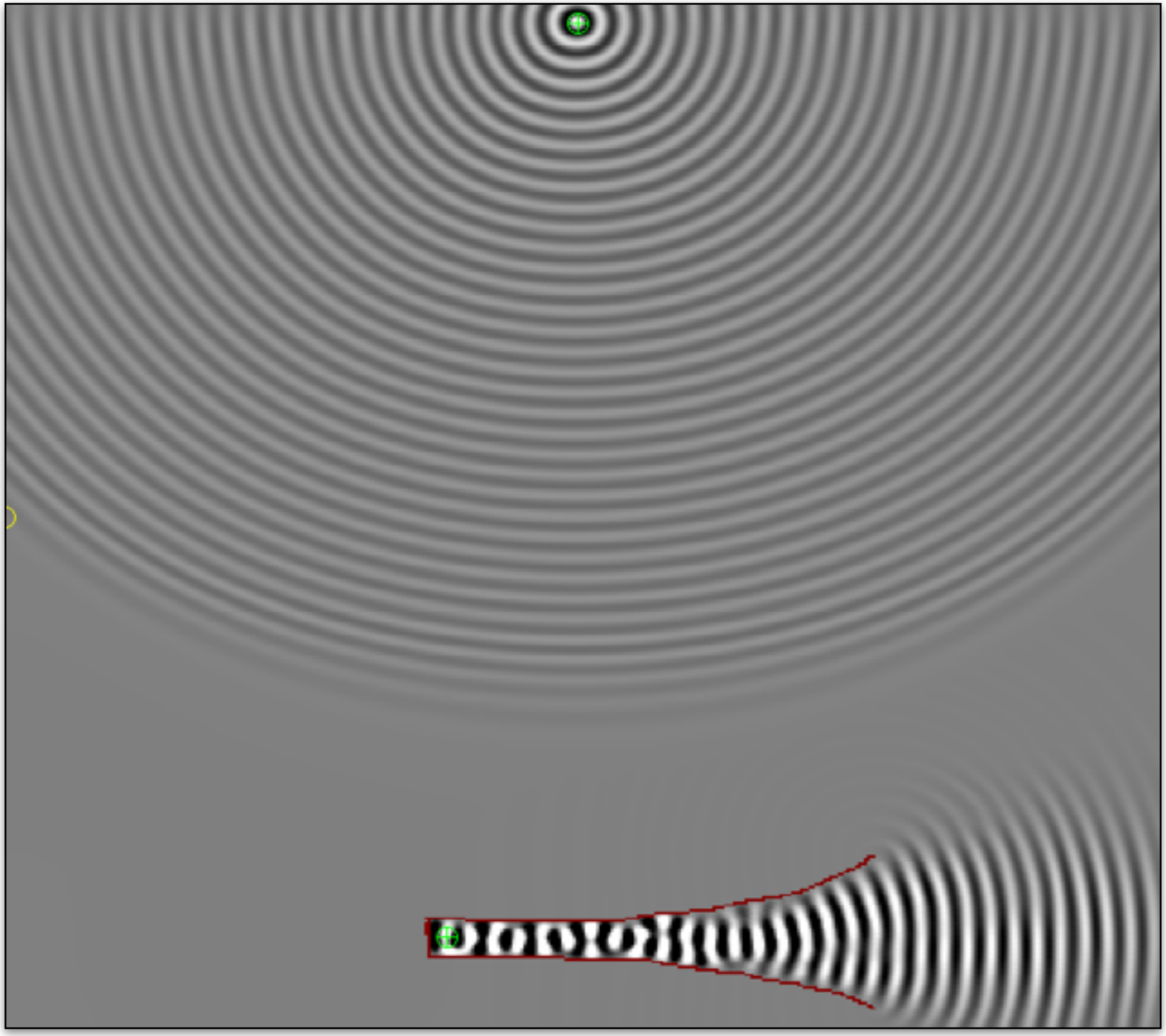
From *Why You Hear What You Hear* by Eric Heller



Horns

- Horns are built in a cone + bell shape, usually with the width of the cone growing exponentially towards the end of the bell
- The narrow end of the horn "loads the source"
  - Lots of constructive interference of certain wavelengths
  - Sound is confined to a small space, reducing $1/r^2$ losses
- The wide end of the horn lets all vibrations with wavelength < bell diameter escape without strong reflections. Technical: no impedance mismatch

Ripple Tank Simulation



Horns in Reverse

From *Why You Hear What You Hear* by Eric Heller

Summary

- Decibel scale: logarithmic ratio of sound level power or intensity with respect to a reference point
  - sound level = 10 log (P_1 / P_2) dB
- We perceive loudness differently depending on the frequency of the sound
- Amplification can be achieved by reflection from a surface, if the distance between the surface and sound source is much bigger than the wavelength of the sound
- In musical instruments, amplification is achieved by coupling vibrating elements to a resonator with low impedance — sound effectively transmitted into the air