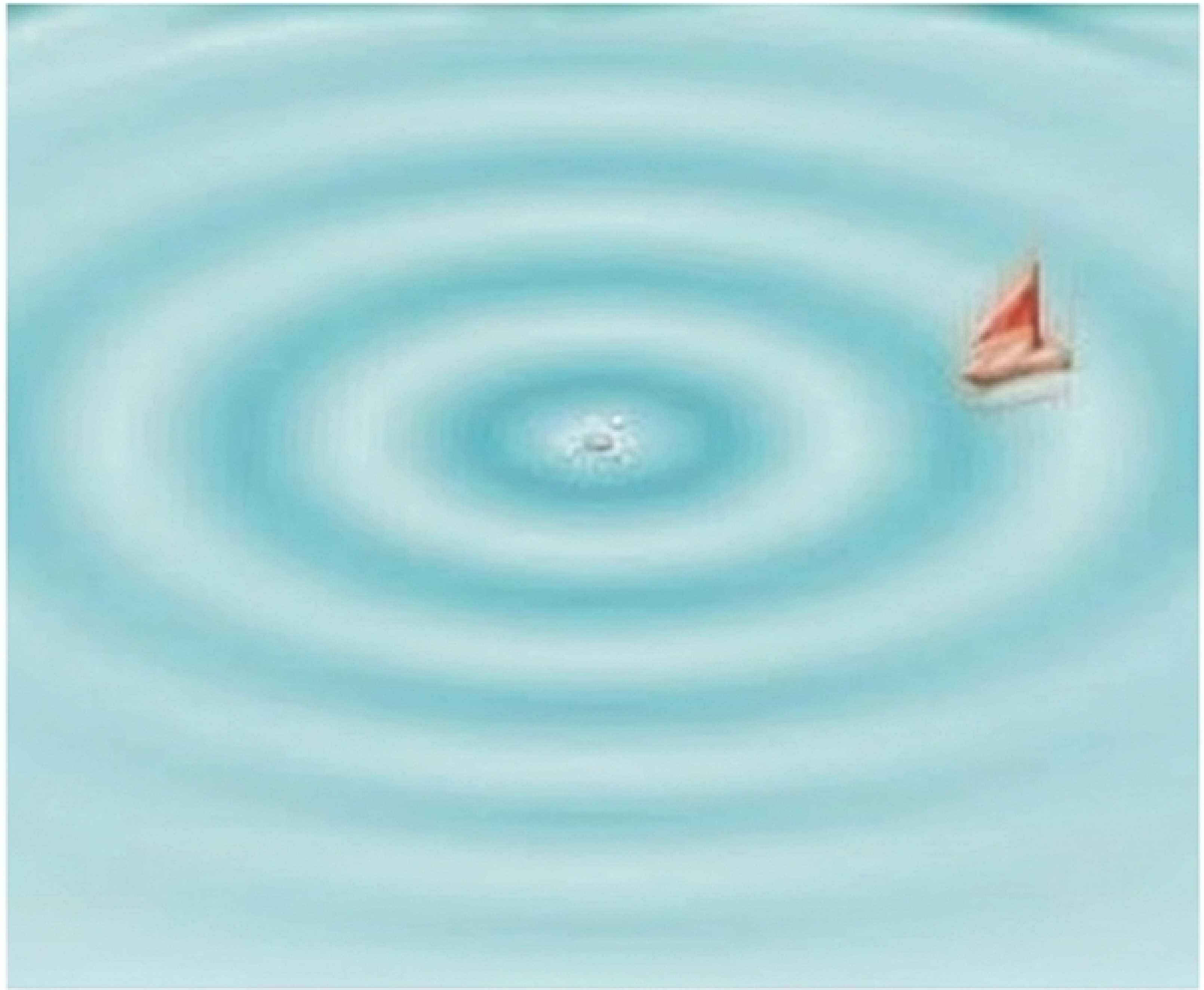
Chapter 11: Hearing

From Pressure Changes to Perceptual Experience

We live in a complex auditory world. Sitting at a riverside table, we simultaneously hear conversations, boat engines, and music from distant loudspeakers. Despite this chaotic mix of pressure waves, our auditory system successfully parses 'where' sounds are coming from and 'what' created them.

What is Sound? Two Definitions

The 'Tree in the Forest' Paradox



Analogy: The medium (water/air) moves up and down in place; the energy travels outward.

Physical Definition

Sound is pressure changes in the air.

Question: If a tree falls and no one is there, is there sound?

Answer: Yes. The pressure waves exist regardless of a listener.

Perceptual Definition

Sound is the experience we have when we hear.

Question: If a tree falls and no one is there, is there sound?

Answer: No. Without a brain to process it, there is no experience.

The Stimulus: Pressure Changes

Compression and Rarefaction

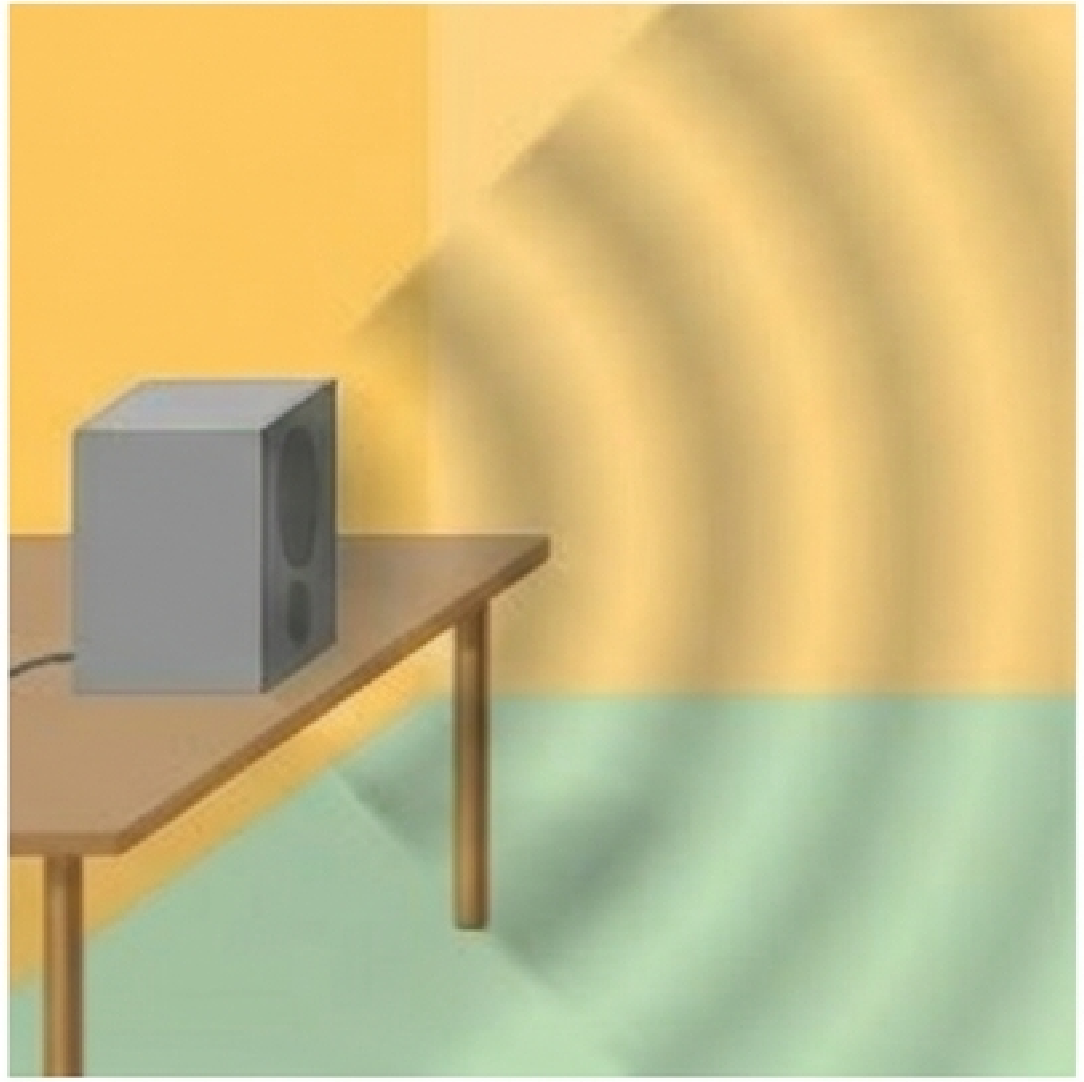


Figure 1: Sound waves generated by a speaker.

Mechanism of a Wave:

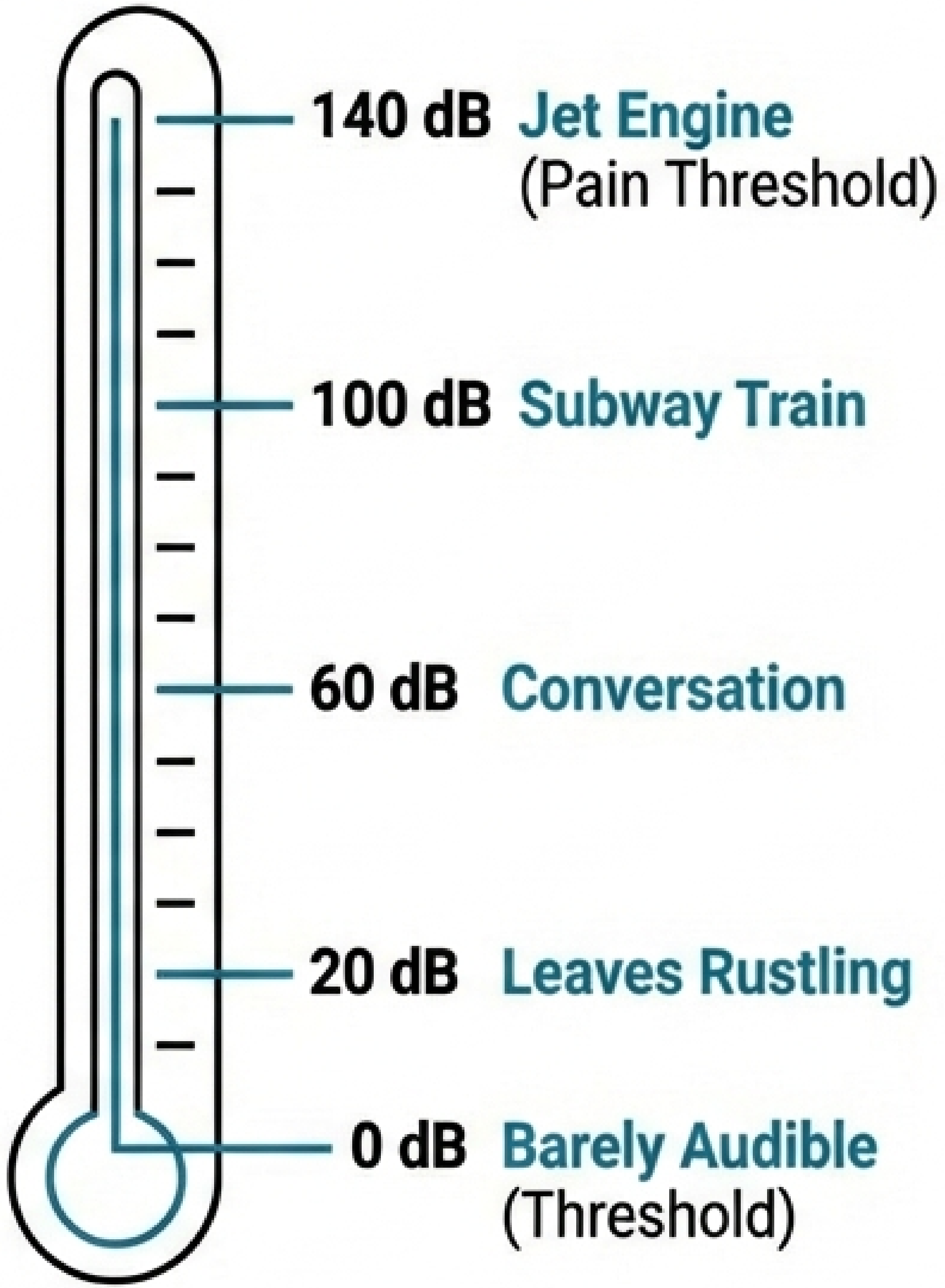
- **Compression**: Speaker diaphragm moves OUT -> Air molecules pushed together (High Pressure).
- **Rarefaction**: Speaker diaphragm moves IN -> Air molecules spread out (Low Pressure).

Key Metric

Defining a Pure Tone (Sine Wave):

- **Frequency (Hz):** Cycles per second = **PITCH**
- **Amplitude (dB):** Size of pressure change = **LOUDNESS**

Measuring the Signal: The Decibel Scale



The Problem: The range of environmental sound pressures is astronomical (ratio of 1 to 10,000,000).

The Solution: The Logarithmic Scale.

Equation: $dB = 20 \times \log(p/p_o)$

Key Insight: Multiplying sound pressure by 10 adds only **20 decibels**.

Beyond Pure Tones

Complexity and Timbre

Complex Tones

Most natural sounds are not pure sine waves. They are composed of a Fundamental Frequency (repetition rate) + Harmonics (multiples of the fundamental).

Timbre (TAM-ber)

The quality that distinguishes a flute from an oboe playing the same note.

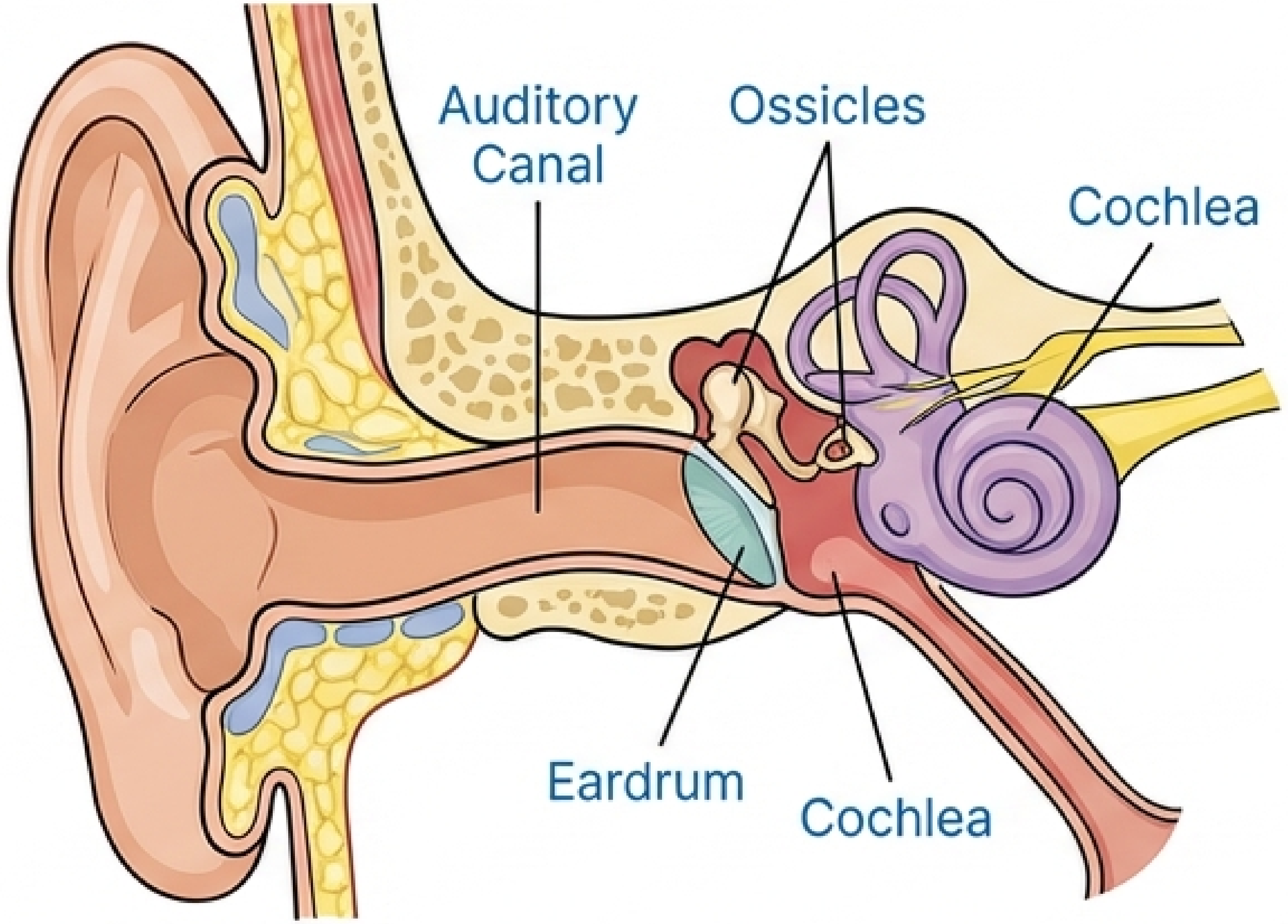
- Depends on Harmonic Structure (relative strength of harmonics).
- Depends on Attack (buildup) and Decay (fade).

Illustrative Example

A piano tone played backward sounds like an organ because the decay becomes the attack.

The Architecture of the Ear

Divisions 1 (Outer) & 2 (Middle)



Outer Ear

- **Pinna:** Localization.
- **Auditory Canal:** Protection & Resonance (Amplifies 1k-5k Hz).

Middle Ear (The Impedance Matcher)

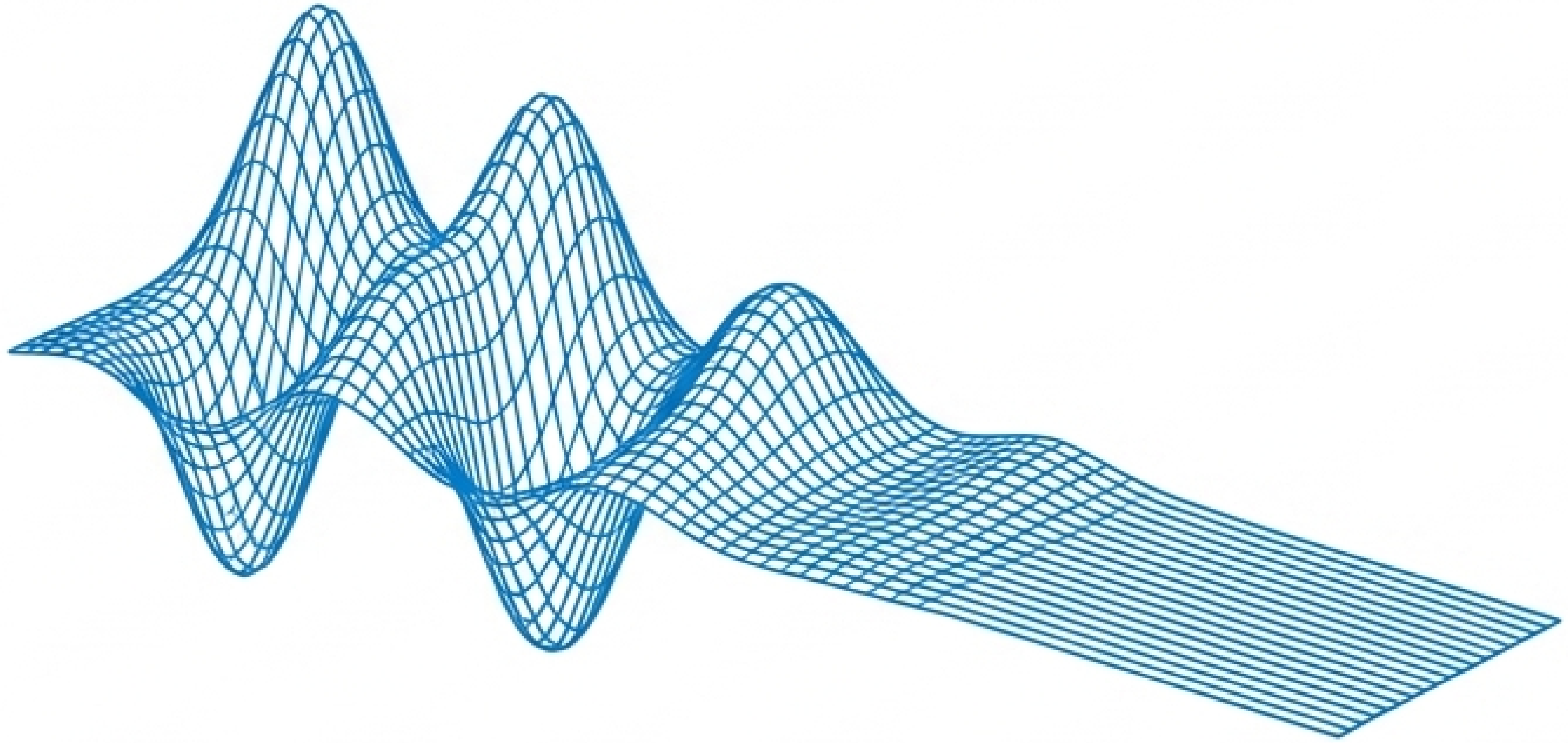
- Contains **Ossicles:** Malleus, Incus, Stapes.
- **The Challenge:** Transmitting sound from AIR (outer) to LIQUID (inner). Without help, 99% of energy is lost.
- **The Solution:** Ossicles act as a lever, concentrating force from the eardrum to the stapes, amplifying pressure by 20x.

The Inner Ear: The Cochlea

Békésy’s Traveling Wave

Anatomy

Liquid-filled structure containing the Scala Vestibuli and Scala Tympani, separated by the Cochlear Partition.



Békésy’s Discovery: The Basilar Membrane vibrates like a traveling wave.

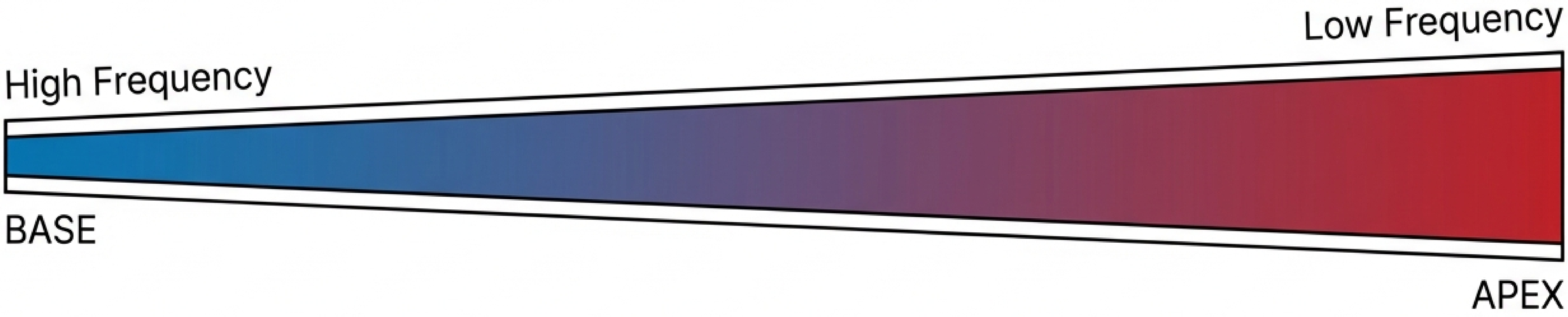
The Envelope

The membrane functions as a frequency filter.

- High Frequencies: Peak vibration at the Base.
- Low Frequencies: Peak vibration at the Apex.

The Cochlea as a Frequency Filter

The Tonotopic Map

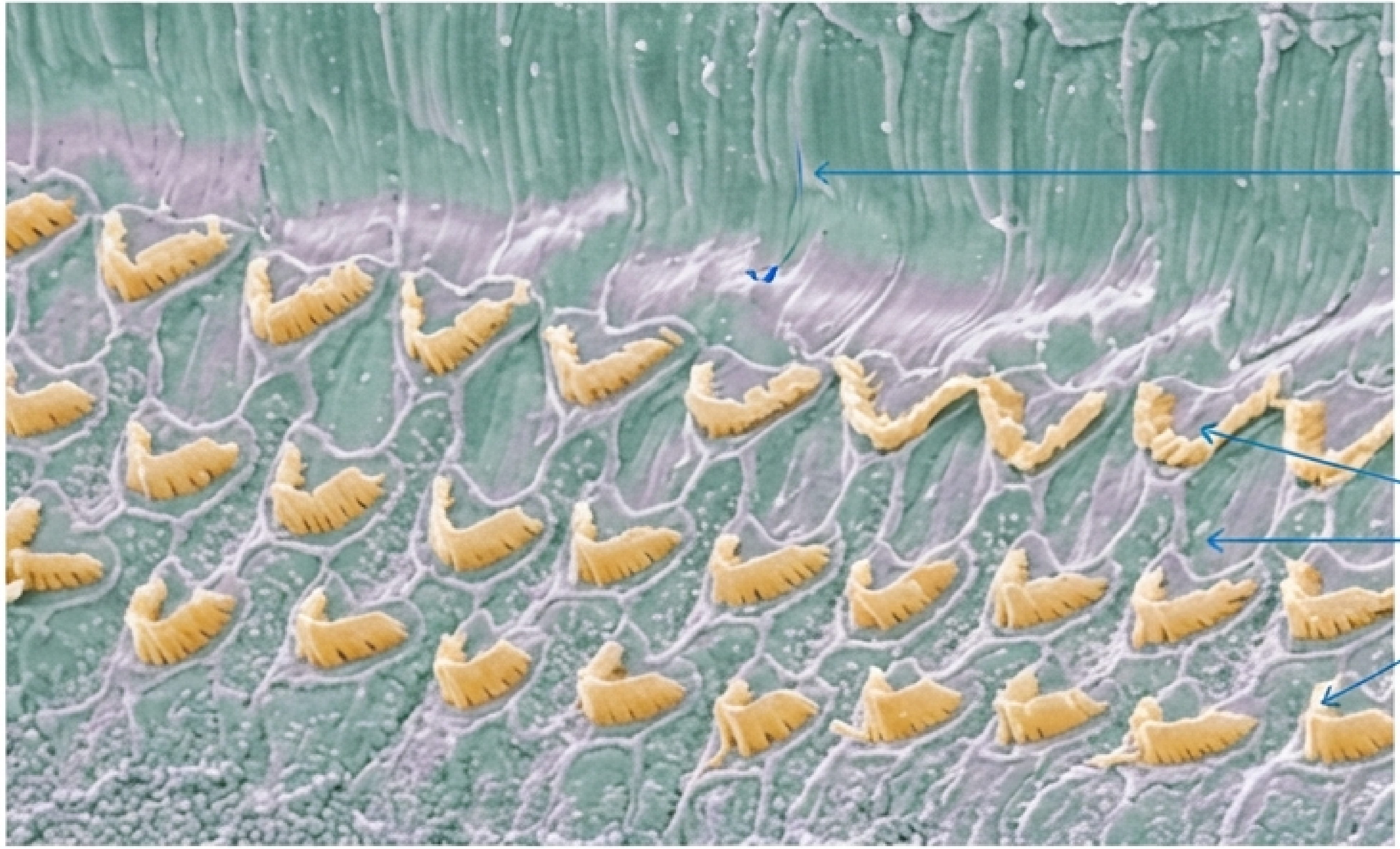


Place Theory: The brain determines pitch based on WHERE the neural activity originates along the cochlea.

Analogy: A sieve sorting coffee beans by size—the cochlea sorts sound by frequency.

The Organ of Corti

The Receptor Site



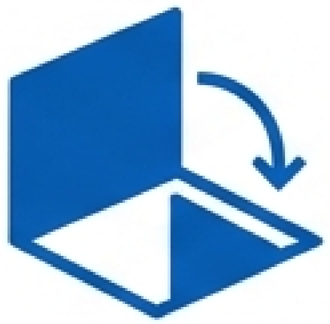
Mechanism: When the basilar membrane vibrates, the tectorial membrane slides across these cells, bending the stereocilia.

TRANSDUCTION

From Motion to Electricity

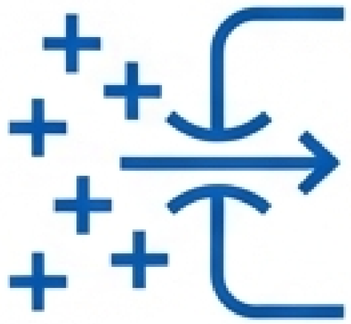
1 Bending

Cilia bend, stretching tip links.



2 Opening

Ion channels open like trapdoors.



3 Influx

Potassium (K+) flows into the cell.

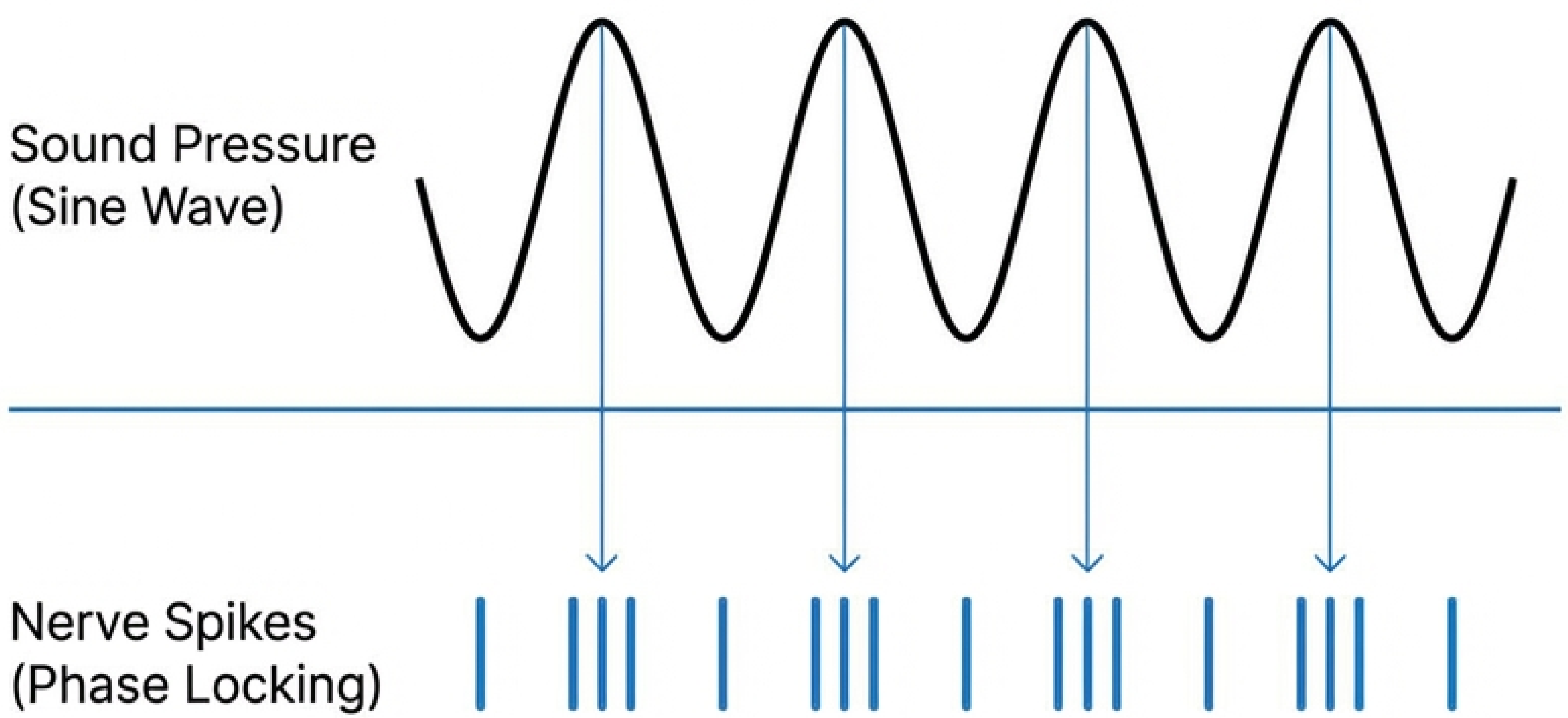
4 Firing

Electrical signal is generated.

This mechanical-to-electrical conversion is the spark of auditory perception.

The Code: Phase Locking

Time as Information



Phase Locking: Auditory nerve fibers fire in synchrony with the pressure changes.

- Fibers fire at the peak of the wave.
- The Volley Principle: Groups of fibers fire in lockstep to represent the frequency.
- Limitation: Effective only up to ~5,000 Hz.

The Cochlear Amplifier

Sharpening the Signal

The Active Process:

Early research on dead cochleas showed broad, passive vibrations. In living ears, the tuning is incredibly sharp. Why?

Mechanism:

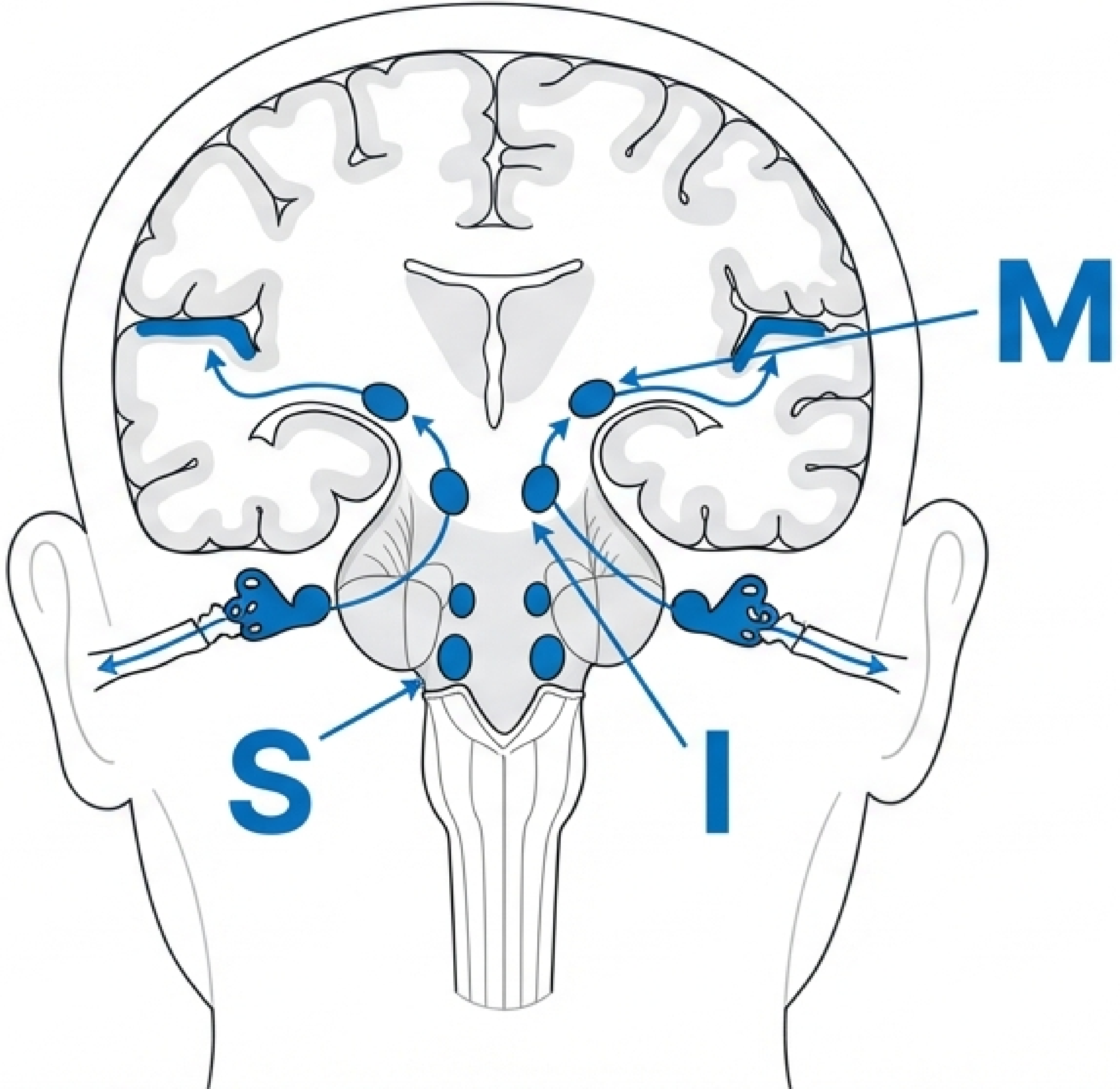
Outer Hair Cells are not just passive receptors. They actively elongate and contract in response to sound, pushing and pulling on the basilar membrane.

Result:

- Increased Sensitivity (Low thresholds)
- Sharp Frequency Tuning (Selectivity)

From Ear to Cortex

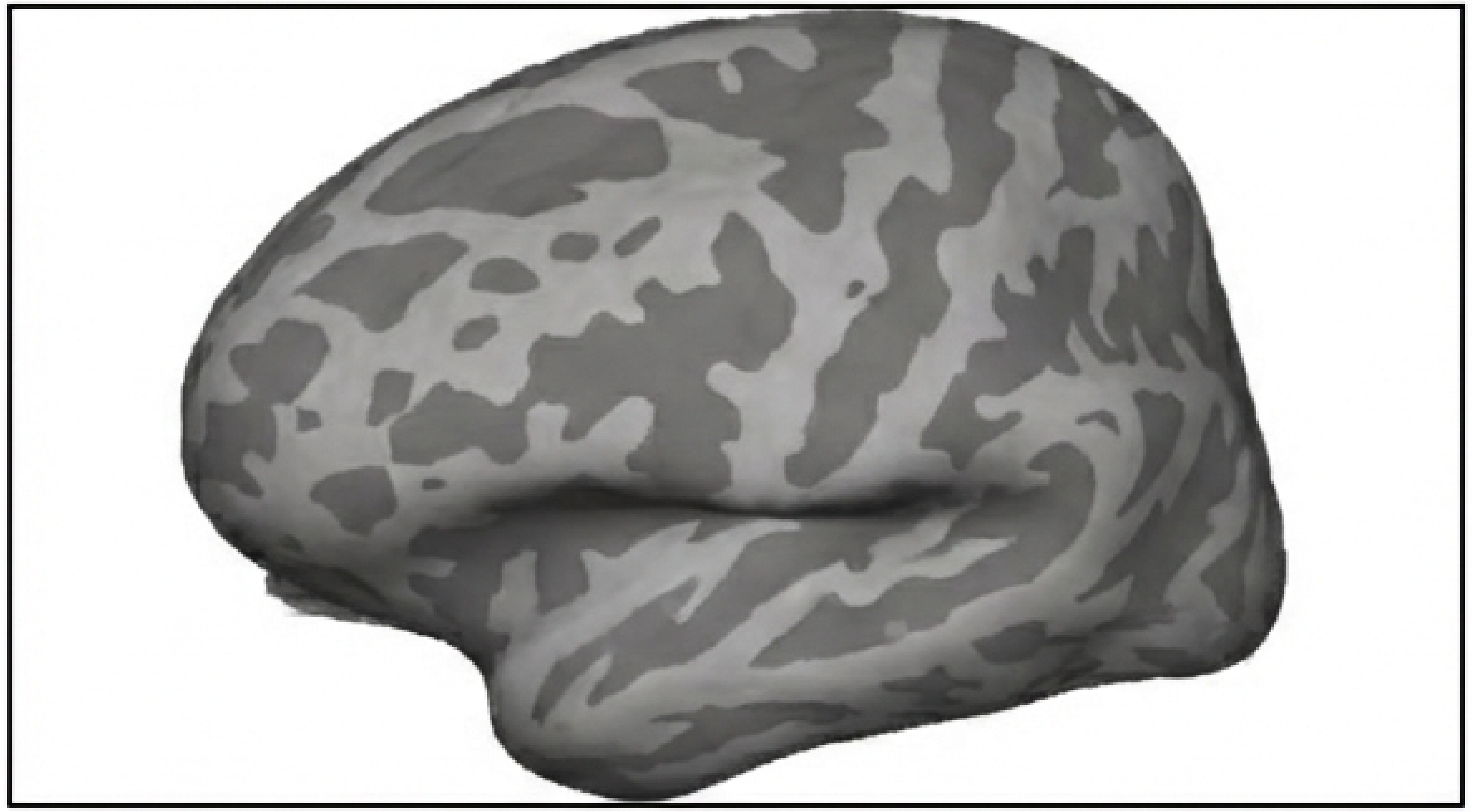
The SONIC MG Pathway

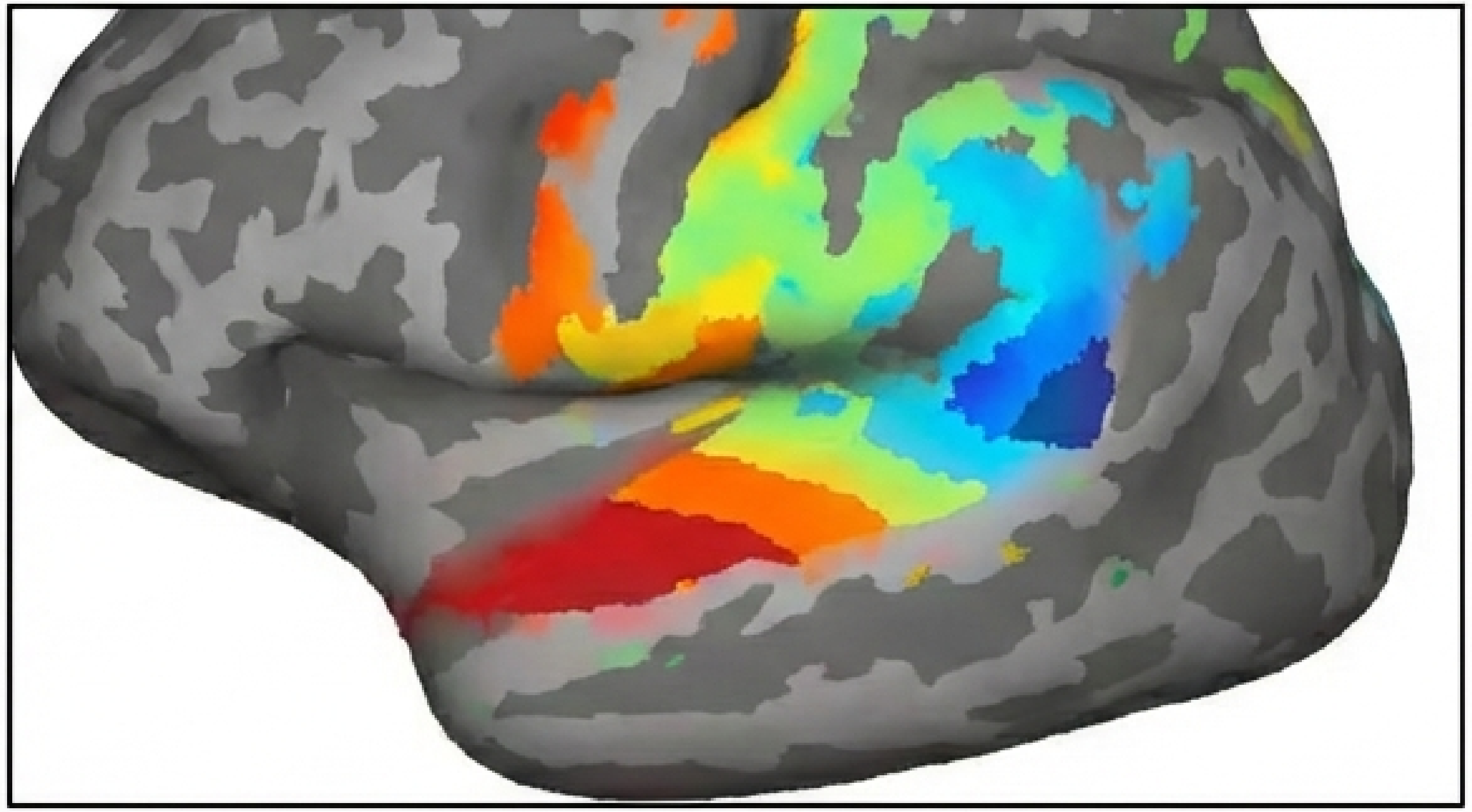


SONIC MG Pathway Legend:

- S - Superior Olivary Nucleus (Binaural processing)
- O
- N
- I - Inferior Colliculus
- C
- M - Medial Geniculate Nucleus (Thalamus)
- G
- → A1 (Primary Auditory Cortex).

Mapping Pitch in the Brain





Pitch Neurons (Marmoset Data):

Specific neurons respond to a fundamental frequency (e.g., 182 Hz) even if the fundamental is missing physically. They respond to the *pitch perception*.

Human Cortex:

fMRI reveals specific areas in the Anterior Auditory Cortex that respond strongly to pitch-evoking sounds (resolved harmonics) versus noise.

The Physiology of Pitch Perception
Conflict and Synthesis

Place Theory	Temporal Coding
• Pitch determined by WHERE the membrane vibrates. • Supports High Frequencies. • Challenge: The "Missing Fundamental" effect.	• Pitch determined by timing of nerve firing (Phase Locking). • Supports Low Frequencies (< 5,000 Hz). • Challenge: Fails at high frequencies.

Synthesis: The brain likely uses both. Resolved harmonics (low) create distinct peaks (Place), while unresolved harmonics (high) rely on timing cues.

When the Machinery Fails

Types of Hearing Loss

Presbycusis (Age-Related)

- Degeneration of hair cells, typically starting at the base (High Frequencies).
- More severe in industrial societies and males.

Noise-Induced Hearing Loss

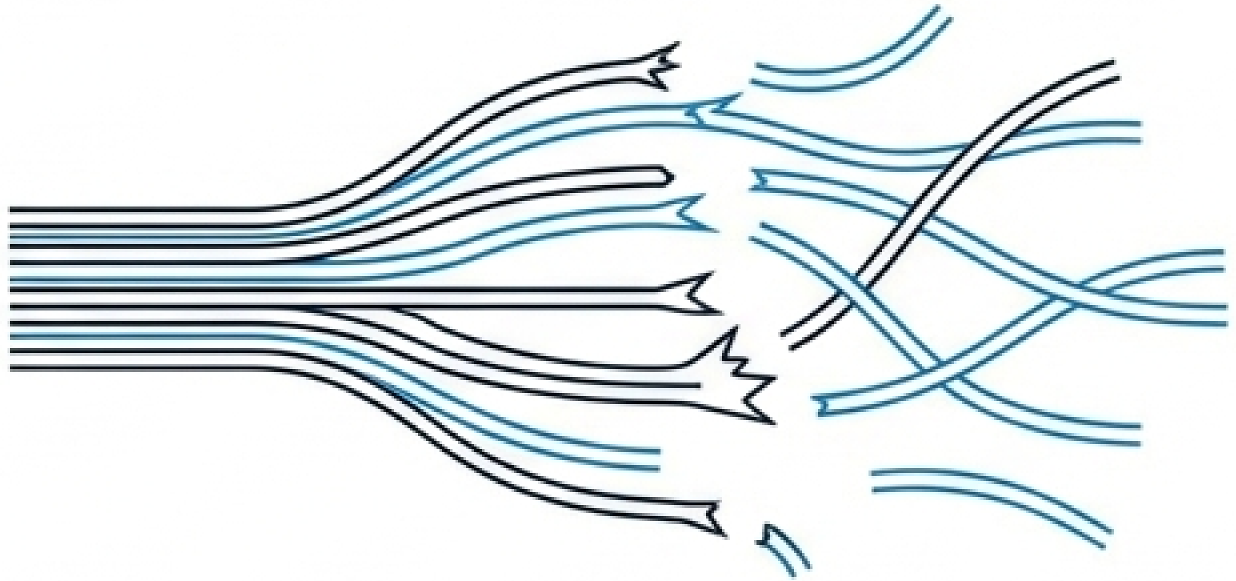
- Physical damage to hair cells from loud environments (Industrial, Concerts, Power Tools).
- Safety Limit: 85 dB for 8 hours (OSHA).

Pathology Visualization

- Broad tuning curves and loss of sensitivity due to Outer Hair Cell damage.

The Invisible Damage: Hidden Hearing Loss

Clinical Standard	Underlying Reality
Clinicica Now Display	Clinicica Now Display



Normal Audiogram
0 dB loss

Loud noise permanently damages Auditory Nerve Fibers even if Hair Cells remain intact.

The Phenomenon: "Normal" audiograms but difficulty hearing in noisy environments.
The Cause: Loud noise can permanently damage Auditory Nerve Fibers even if Hair Cells remain intact.
Consequence: A degraded signal that makes separating speech from noise difficult.

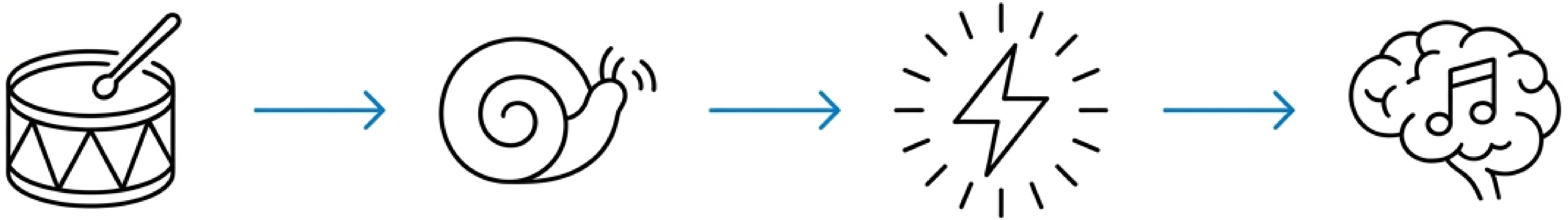
Developmental Dimension

Infant Hearing

Prenatal	Newborn	6 Months
Hearing in the womb. Fetuses learn prosody and prefer mother's voice.	Recognizes native language. Regulates sucking to hear familiar sounds.	Audibility curve within 10-15 dB of adult thresholds.

"Newborns are not deaf; they enter the world with a functioning auditory system primed for language."

The Miracle of Hearing
An 11-Year-Old’s Guide



VIBRATION
(Pressure Waves)

TRANSLATION
(Hair Cells Moving)

SPARK
(Electricity)

EXPERIENCE
(Perception)

> Hearing extends our awareness around corners and into the dark. It is the process of translating physical air pressure into the emotional experience of a mother’s voice or a favorite song.

Recap: The Journey of the Signal

1. AIR: Pressure Waves (Sound)

2. EAR: Mechanical Amplification (Ossicles) & Frequency Analysis (Cochlea)

3. TRANSDUCTION: Hair Cells convert motion to electricity (Phase Locking)

4. PATHWAY: SONIC MG (Brainstem -> Thalamus)

5. CORTEX: Pitch Maps & Perception

A complex biological interface turning physics into feeling.