Demonstrating Phase with Binaural Hearing from Stereo Speakers

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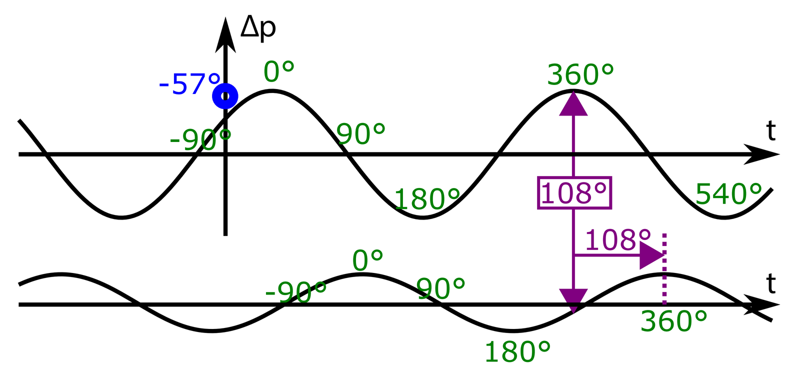
Making Phase Less Abstract & Confusing

- Radian units involve an irrational number (despite it being the most familar of them, π.) ⟹ Use degrees.
- Three different things are sometimes called phase and/or symbolized by φ . ⟹ Use different symbols.

Name	Symbol	Nature	Physically Meaningful
(true) **phase**	φ	Variable	Yes
initial phase or **phase constant**	ϕ_0	Constant	No
phase difference	Δφ	Variable	Yes

$$\Delta p = p_m \cos\phi = p_m \cos(360° \, f\, t - kx + \phi_0)$$

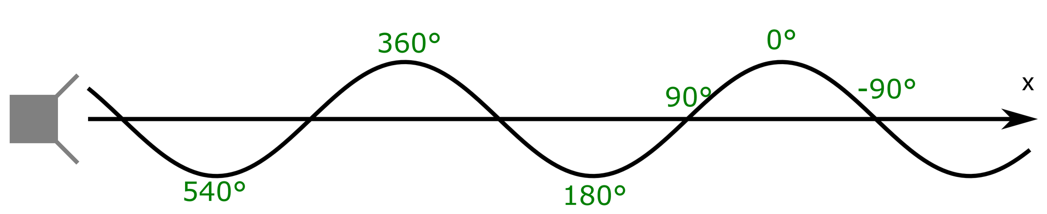


Two ways to understand Δφ :
- The difference in phase between two oscillations at a given time.
- How much one oscillation (of the same frequency) has been shifted.

- In waves, phase varies with both position and time.
- The phase of a wave does not itself convey information. Only when waves combine in some way does the relative phase become important.

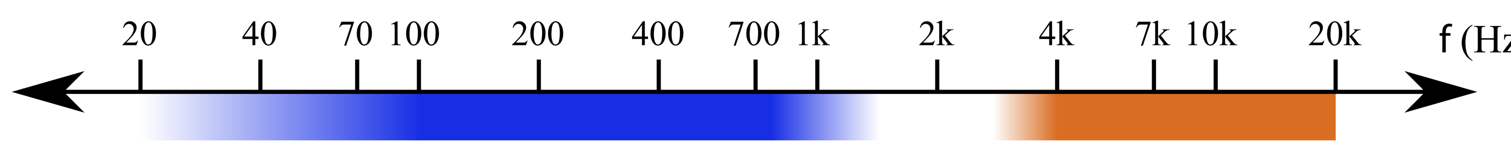
Provide a specific example with concrete consequences.

In order for phase to increase with time at each point, phase must spatially increase in the opposite direction from the wave propagation. The traditionally taught equations for oscillations [φ =ωt] and waves [φ =kx−ωt] are inconsistent with each other.
Using the form above [φ =ωt−kx] resolves this inconsistency.



- For the **sine** function, correctly locating φ = 0 is entangled with this confusion about the increasing phase direction.
- The **cosine** function, has the advantage that φ = 0 is always at a maximum of the function.

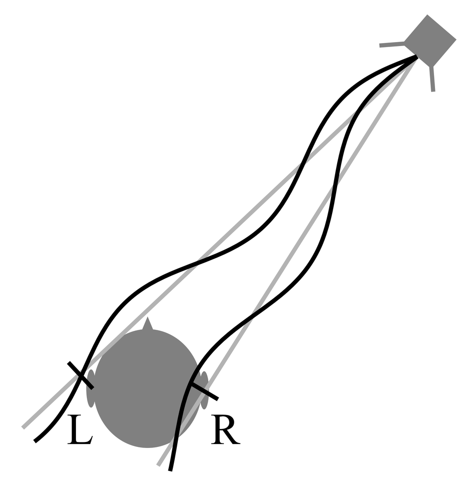
Mechanisms of Directional Hearing



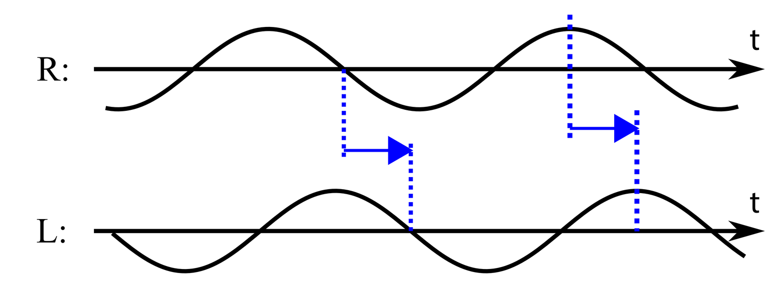
time difference / phase difference

level (loudness) difference

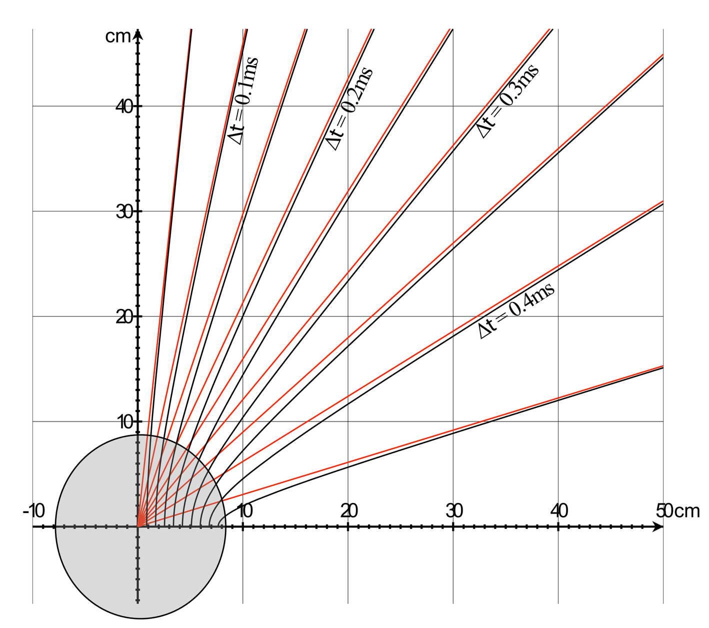
Direction From Phase Difference: Delayed Wave



Distance difference to two ears leads to a larger travel time for sound to far ear, so that sound wave phase is different at the two ears.



$$\Delta\phi = \frac{360°}{T}\Delta t = 360° f\, \Delta t$$

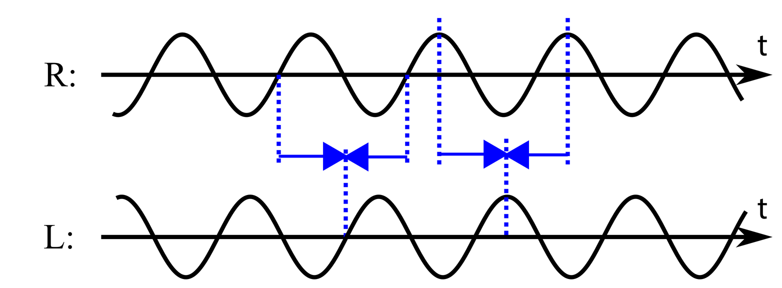


Contours of time delay versus source position within 0.5m of listener.

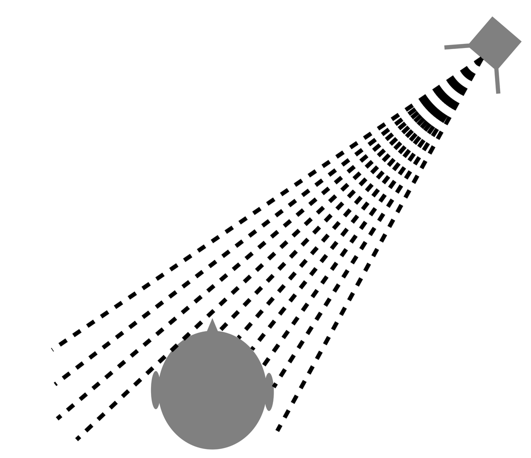
Black curves are exact hyperbolas.

Red lines use the (distance ear separation) approximation. (The same approximation typically used for interference patterns.)

This mechanism is only effective for wavelengths longer than roughly two head diameters, or f < 1.1kHz. Shorter wavelengths lead to ambiguity about which signal is delayed.
(Reports of the measured lower bound range from 800Hz to 1kHz.)



Direction From Level Difference: Sound Shadow



In order to reach the far ear, the sound must diffract around the head. Due to this "sound shadow," the intensity level is reduced at the far ear by up to 30dB, depending on frequency.

This mechanism is only effective for wavelengths shorter than roughly one head diameter, or f > 2.1kHz. Longer wavelengths diffract very effectively, leading to small level differences.
(Reports of the measured lower bound range from 1.6kHz to 3kHz.)

A secondary mechanism, similar to the phase difference mechanism, depends on the time delay in the onset of sounds.

Typical Values Used

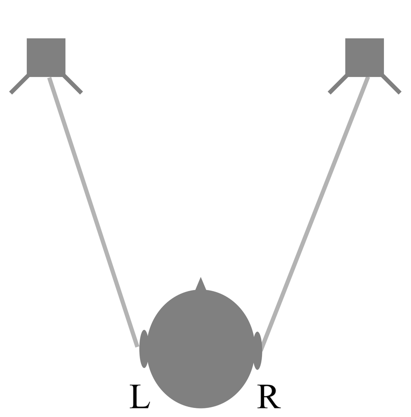
Typical ear seperation = 16 cm
Some references use larger, unrealistic values.

Typical sound airspeed = 340 m/s = 34 cm/ms
This is the speed at 14.5°C = 58°F.

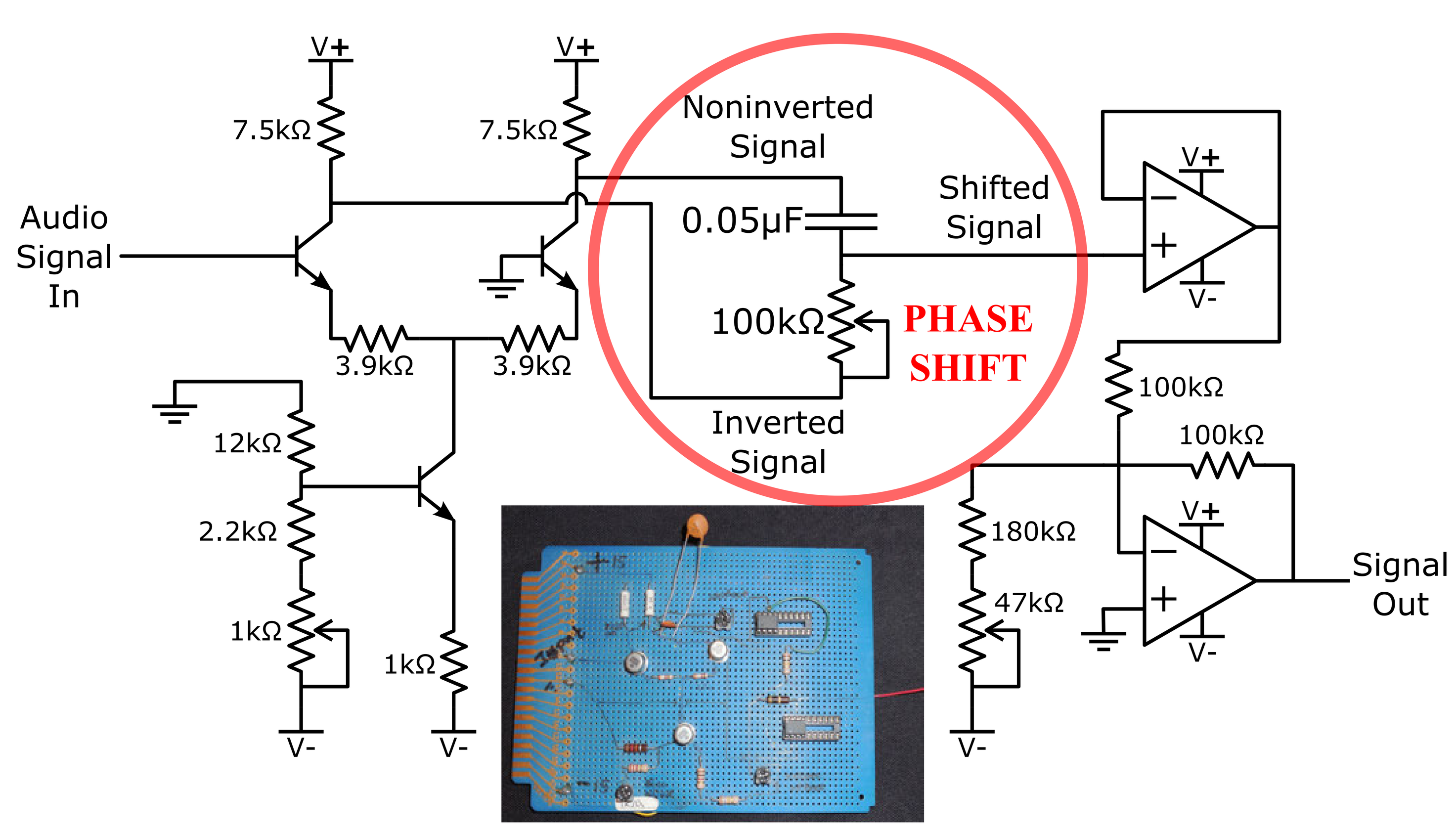
Demonstrating This Effect With Stereo Imaging

The "Headphone Approximation"

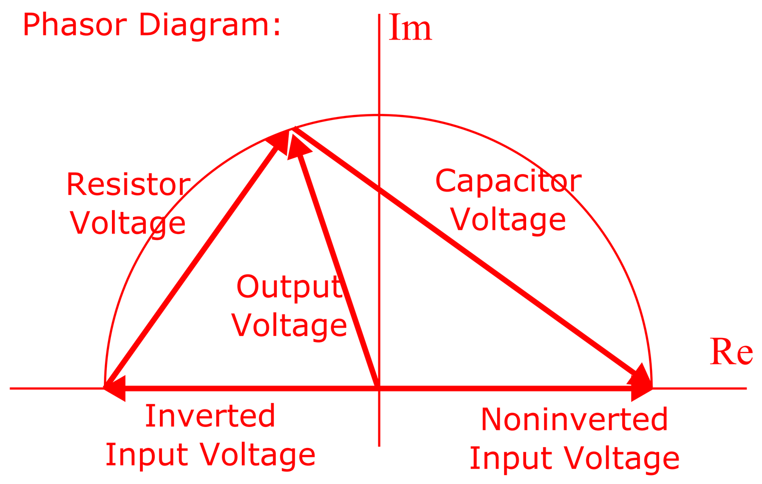
What each ear hears is dominated by the speaker on that side.



The Phase Shifter Circuit



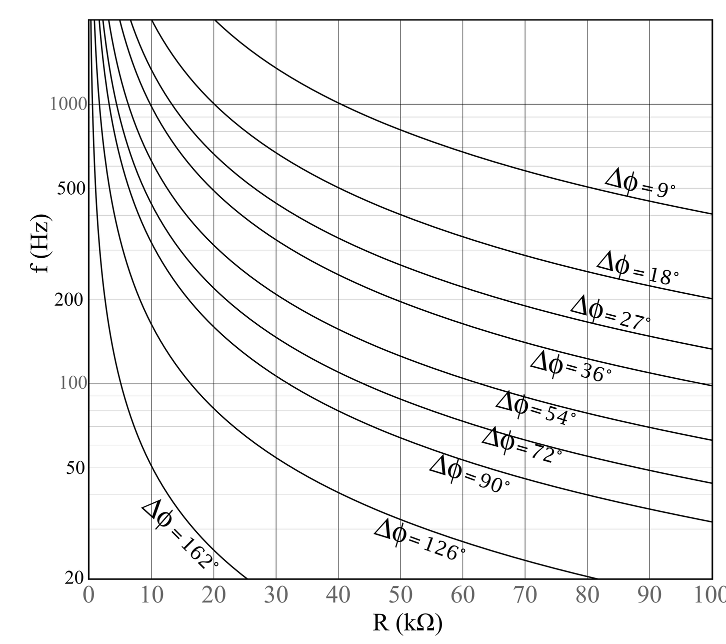
Circuit Operation



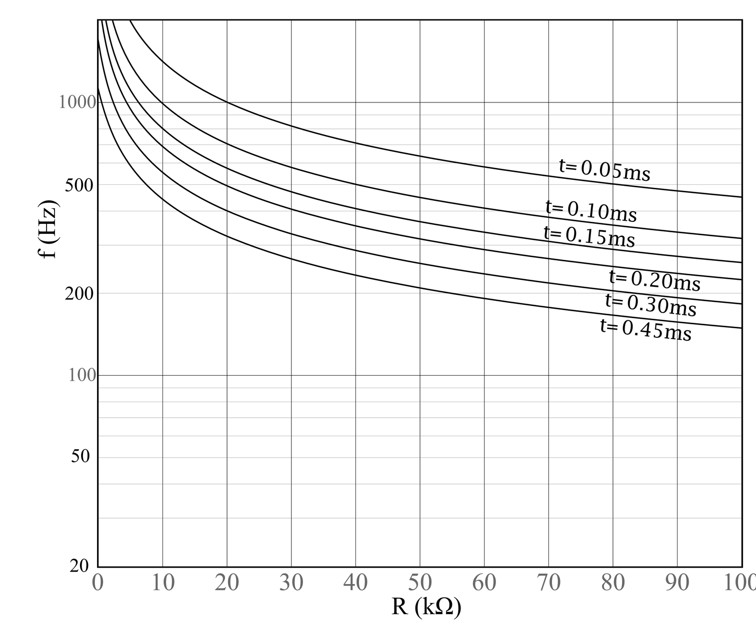
- Because the resistor impedance is real and the capacitor impedance is imaginary, their voltages must be at right angles in phasor space.
- The resistor and capacitor voltages must also add up to the difference between the inverted and noninverted input (supplied by a differential amplifier).
- As a result, the output has an amplitude equal to the input, but a variable phase.
- Note that the phase difference created does depend on frequency, through the capacitor impedance.

Circuit Output

A wide range of phase shifts is accessible in the low audio frequencies using these component values.



The time delays pertinent to directional hearing can be obtained for frequencies from about 300Hz to 1kHz.



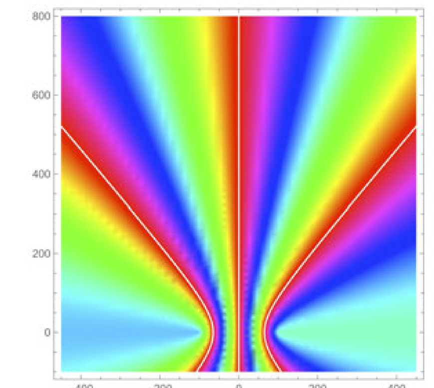
Results of Demonstration

A sinusoidal tone and its phase-shifted partner are played from a pair of speakers set up in front of students in a 100-seat auditorium. The students are asked to close their eyes and listen for the direction of the sound.

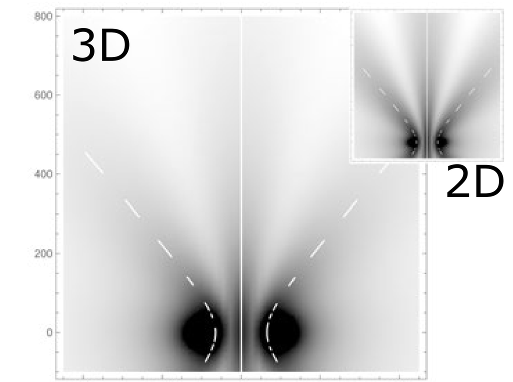
A majority report hearing the apparent sound location changing as the phase is shifted.

Beyond the Headphone Approximation

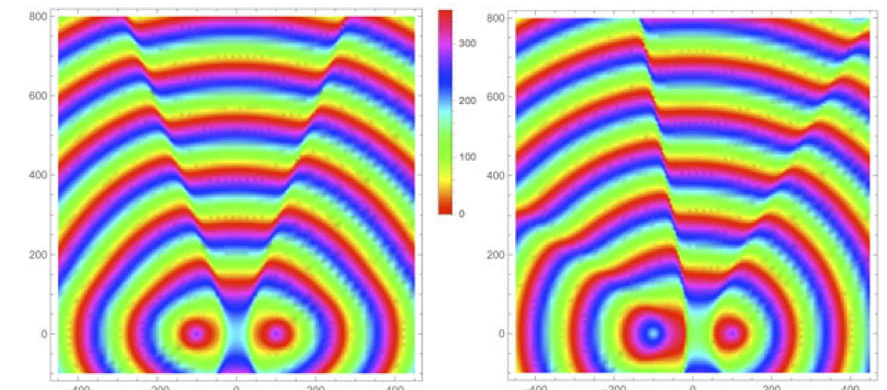
Images for sound from two speakers separated by 2m, sounding middle-C (λ=1.30m).



Phase difference Δφ between the two waves. The classic interference result, but not helpful for directional hearing.

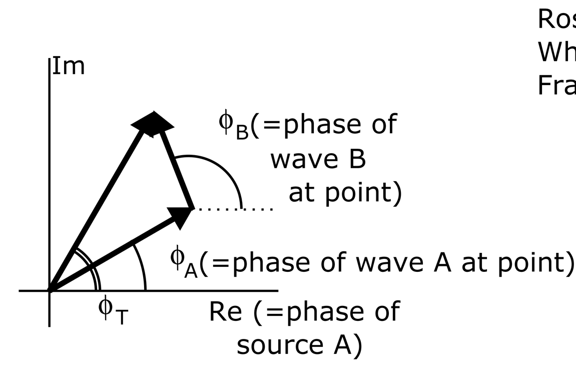


Amplitude of combined waves. The typical demonstration of interference, but still not helpful for directional hearing.



Phase of combined waves ϕ_T, relative to phase of right source. Two ears sampling this in two locations is the cause of phase-based directional hearing.

To find these results, it is crucial to include the decrease of amplitude with distance from the sources. The easiest way to do this is by adding phasors.



References

Phase shifting circuit
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Rossing, Thomas, F. Richard Moore, and Paul Wheeler. The Science of Sound, 3rd ed. San Francisco: Addison Wesley, 2002: pp. 89-90.