# Wave Property and Wave-based Sensing

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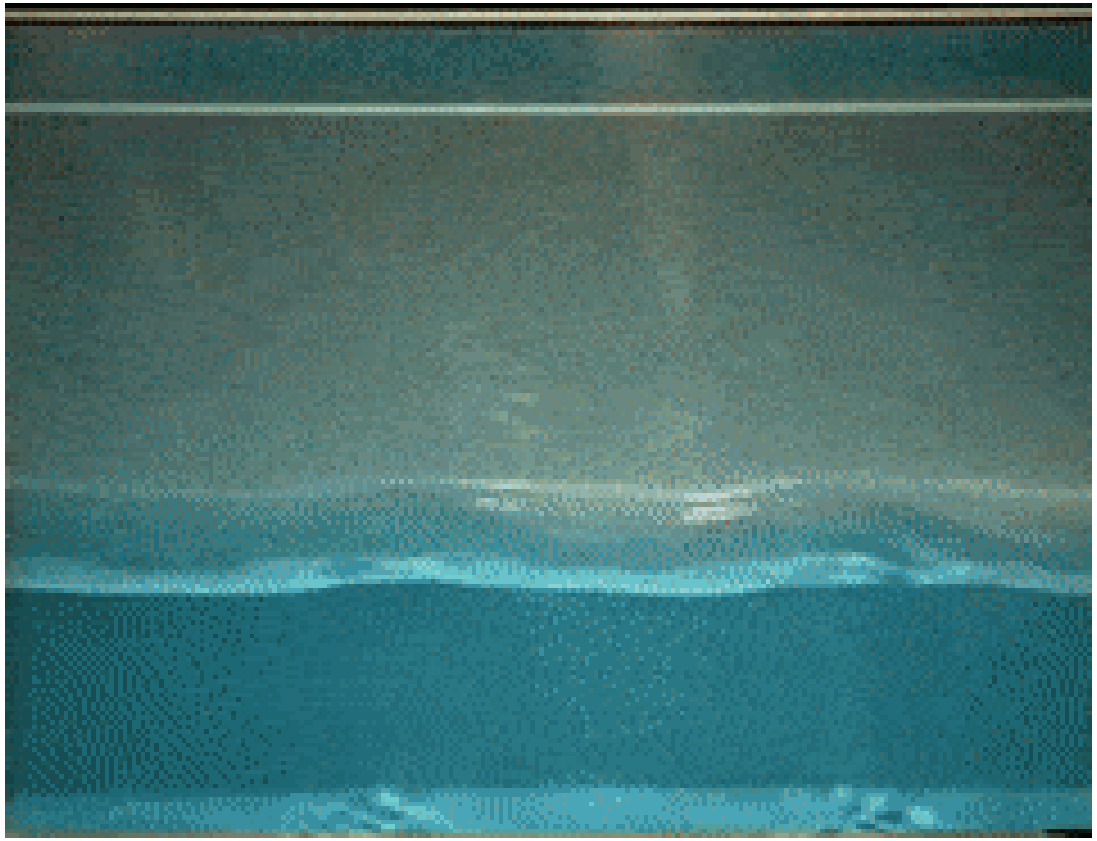
# Waves

# Waves: Transfer of energy, not mass



# Waves

Sound

Physical vibrations

Ripples in water

…

Visible light

WiFi signal

Infrared

…

# Waves

| Mechanical Wave | Electromagnetic Wave |
| --- | --- |
| Sound | Visible light |
| Physical vibrations | WiFi signal |
| Ripples in water | Infrared |
| … | … |

# Waves

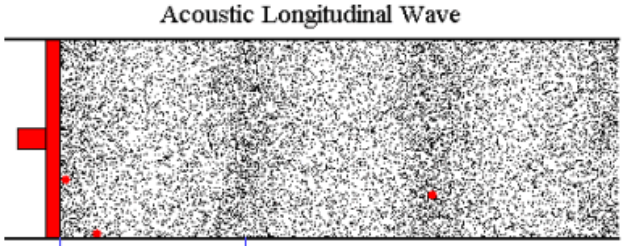
## Mechanical Wave

Sound

Physical vibrations

Ripples in water

...



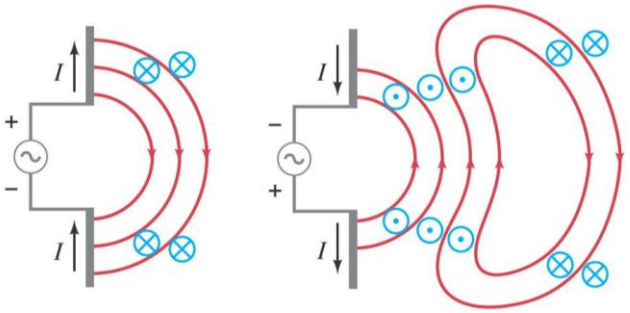

## Electromagnetic Wave

Visible light

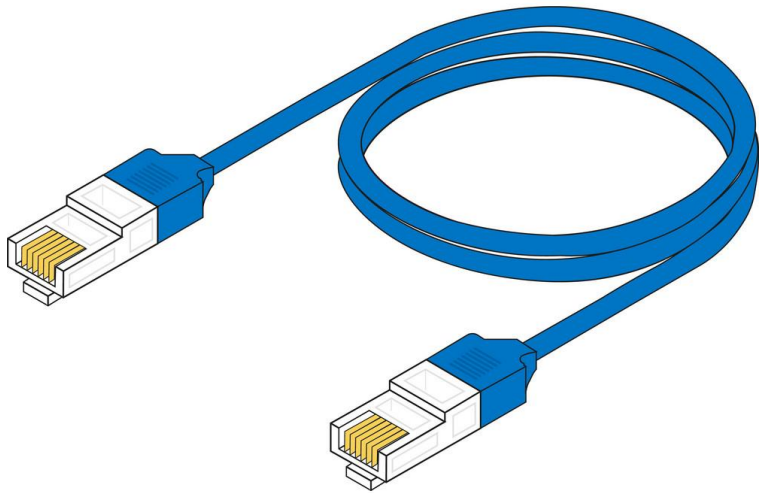
WiFi signal

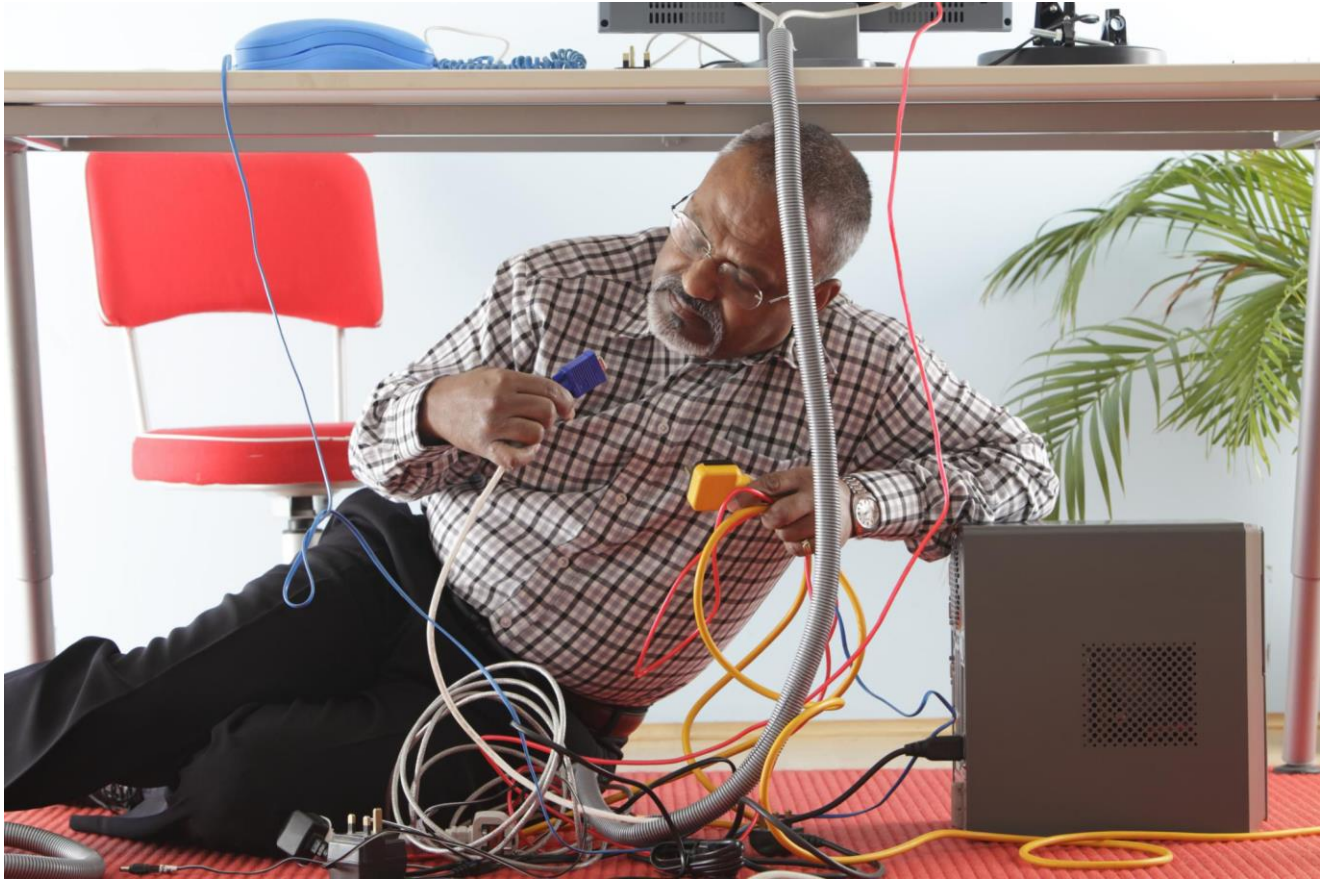
Infrared

...

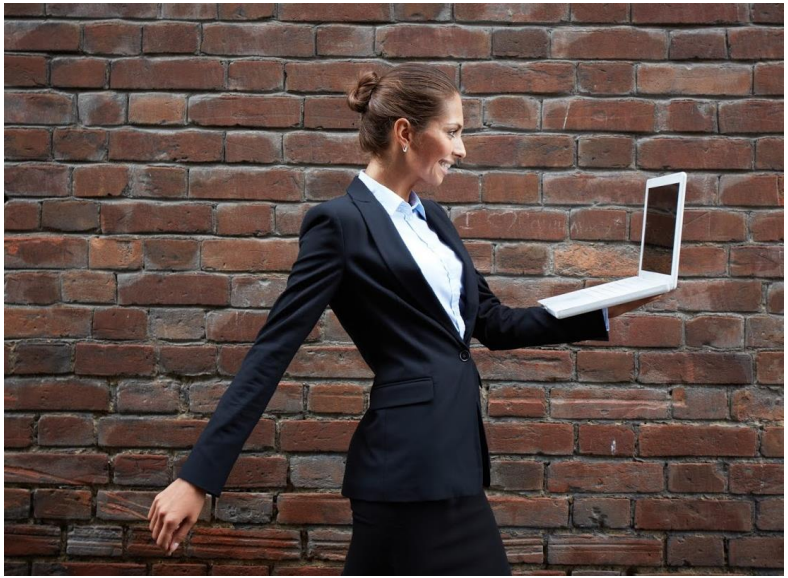


# THE BREAKER OF CHAINS





# Waves made this possible



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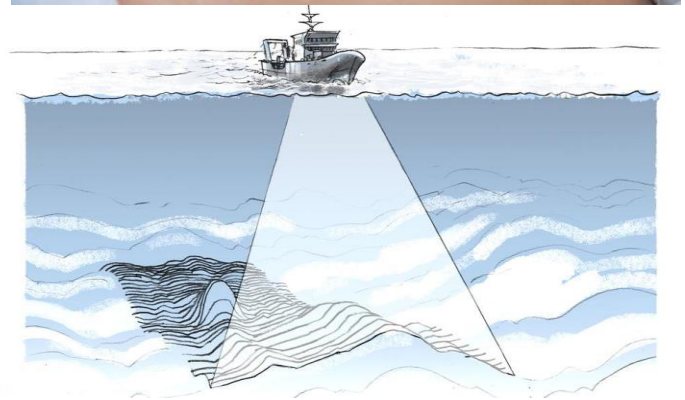
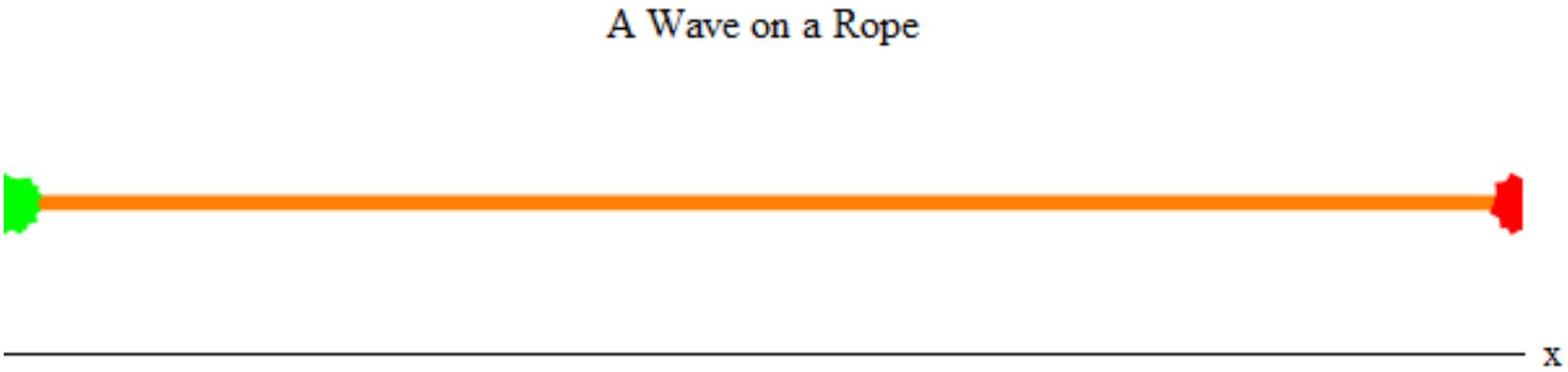


# Waves Properties



# Waves in time and space

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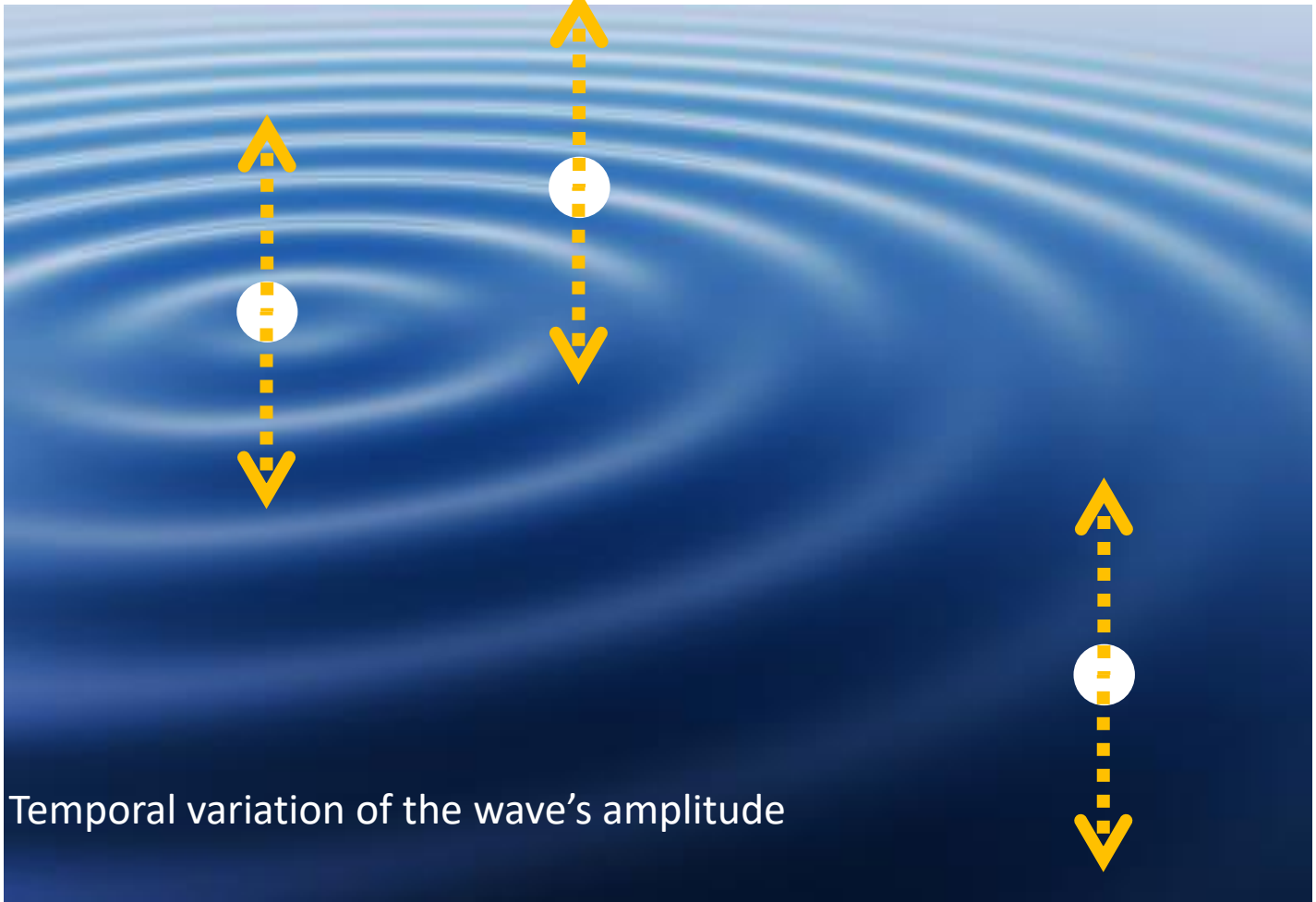
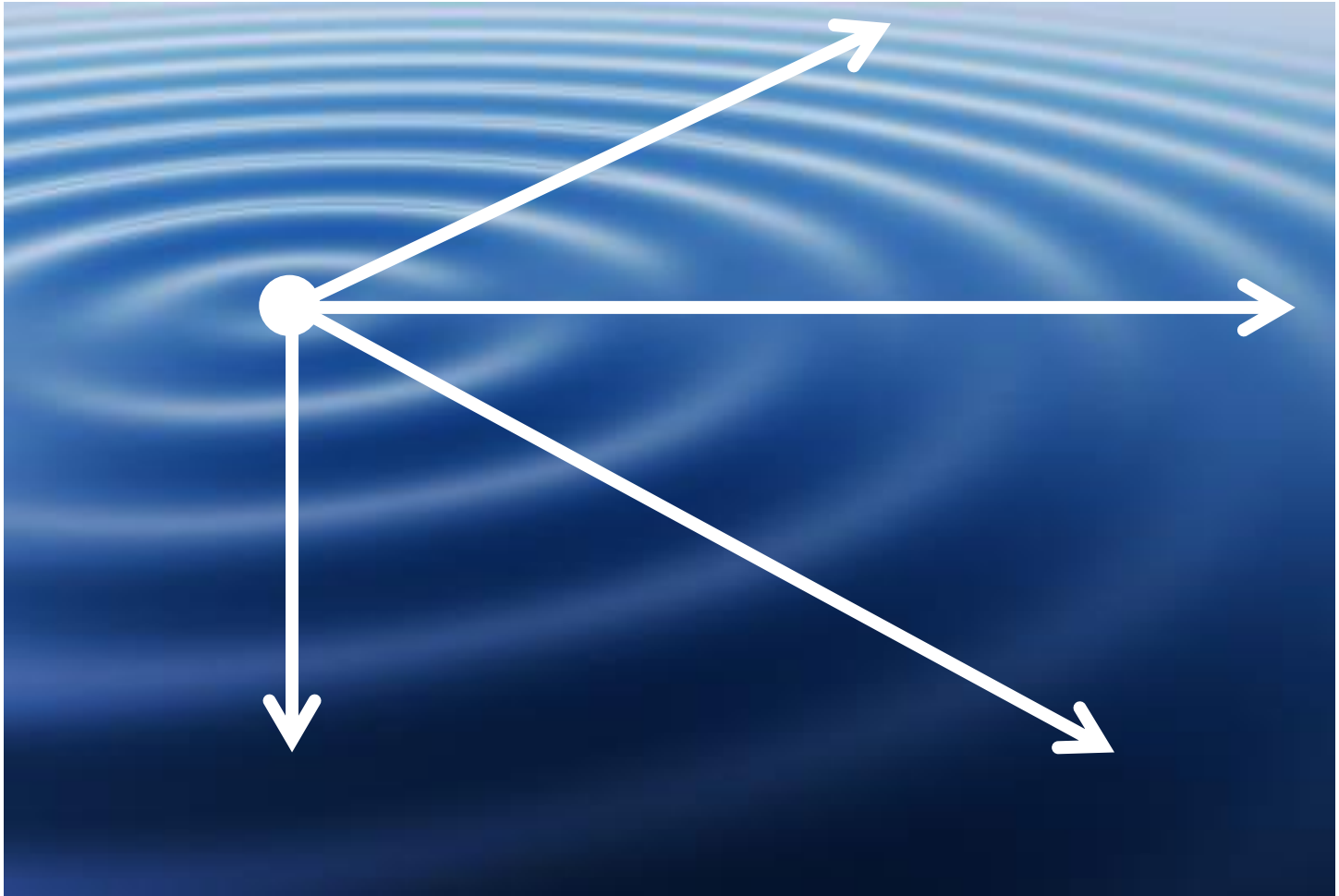
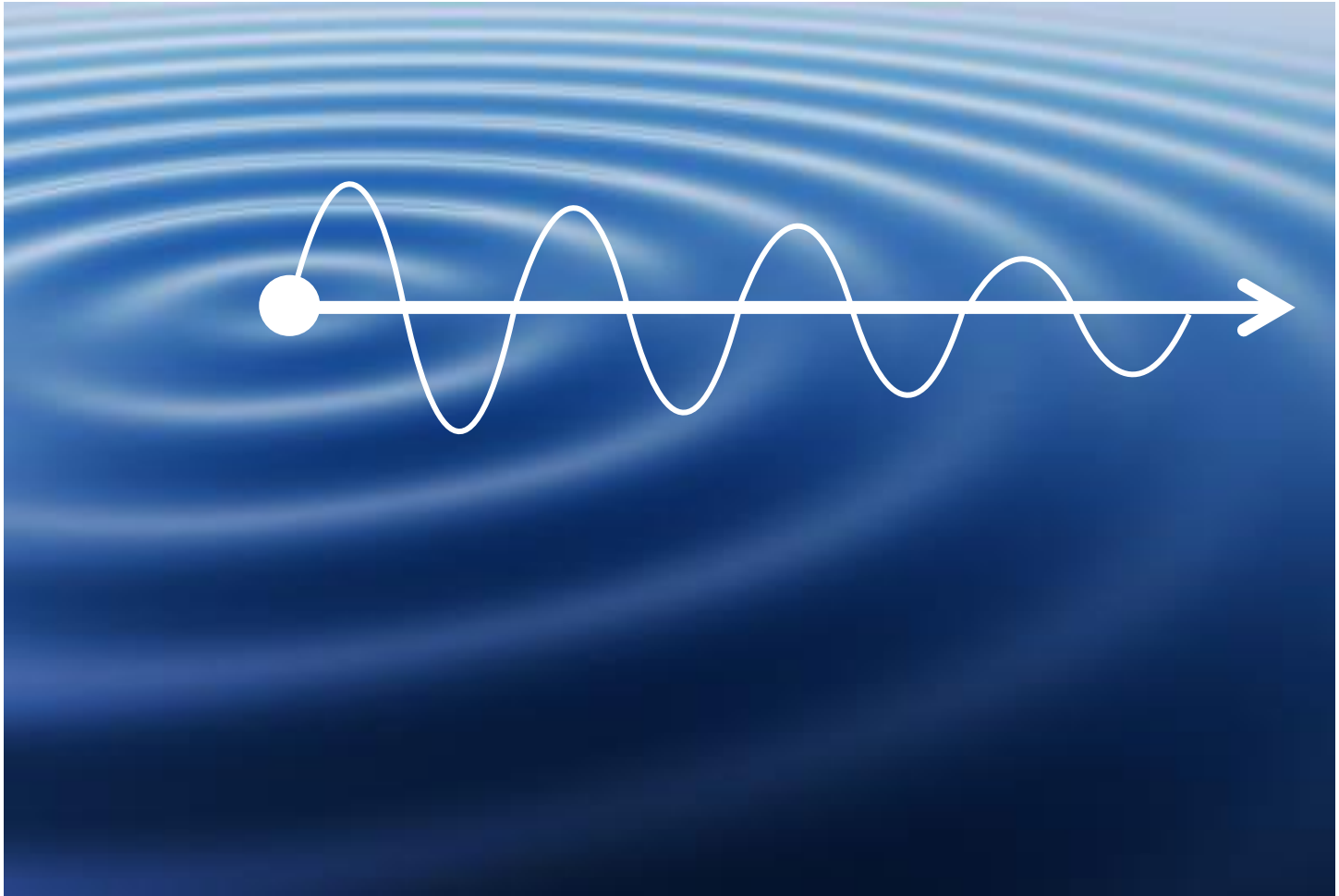


# Waves in time and space

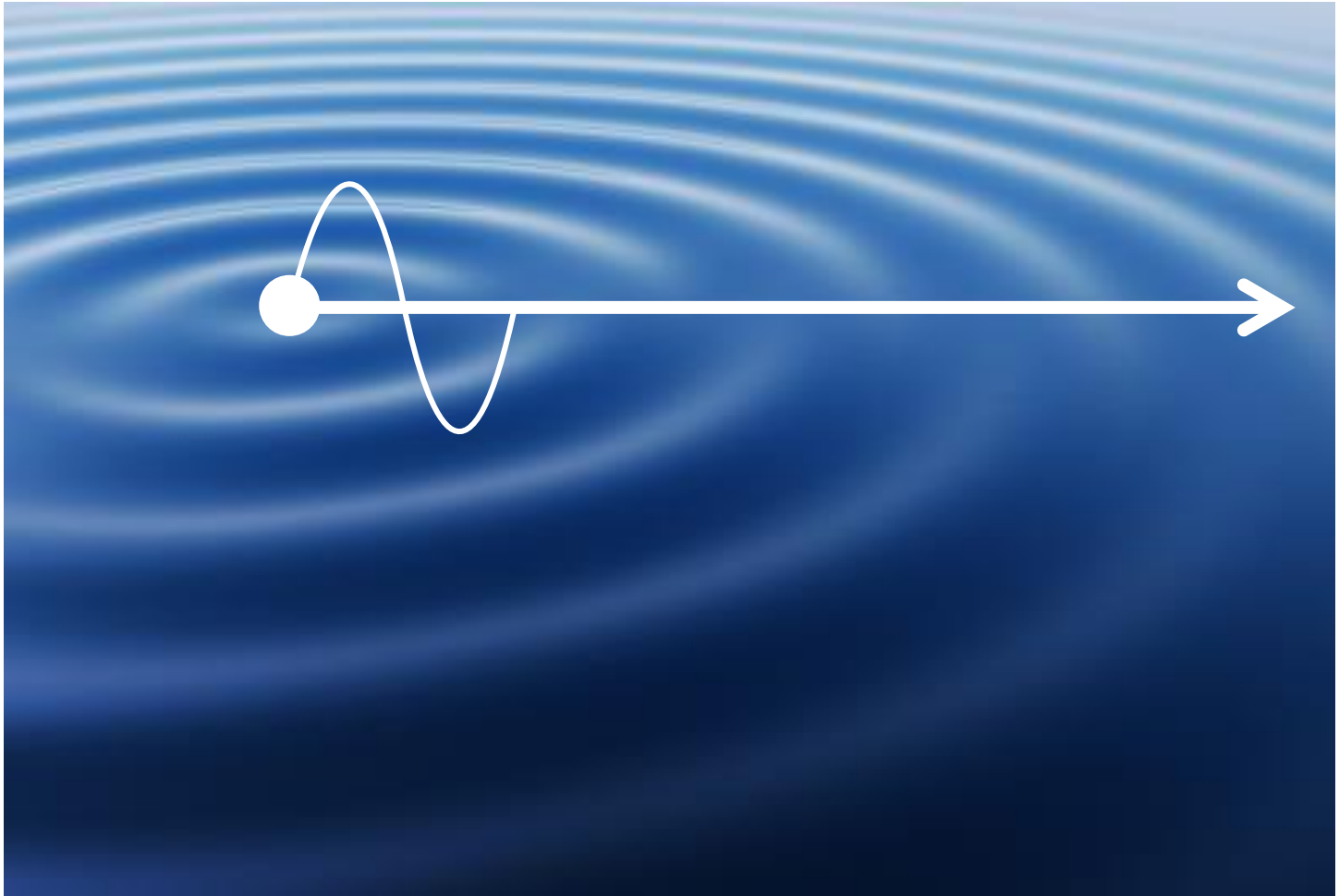
# Equation of waves in time and space



# Equation of waves in time and space



# Equation of waves in time and space



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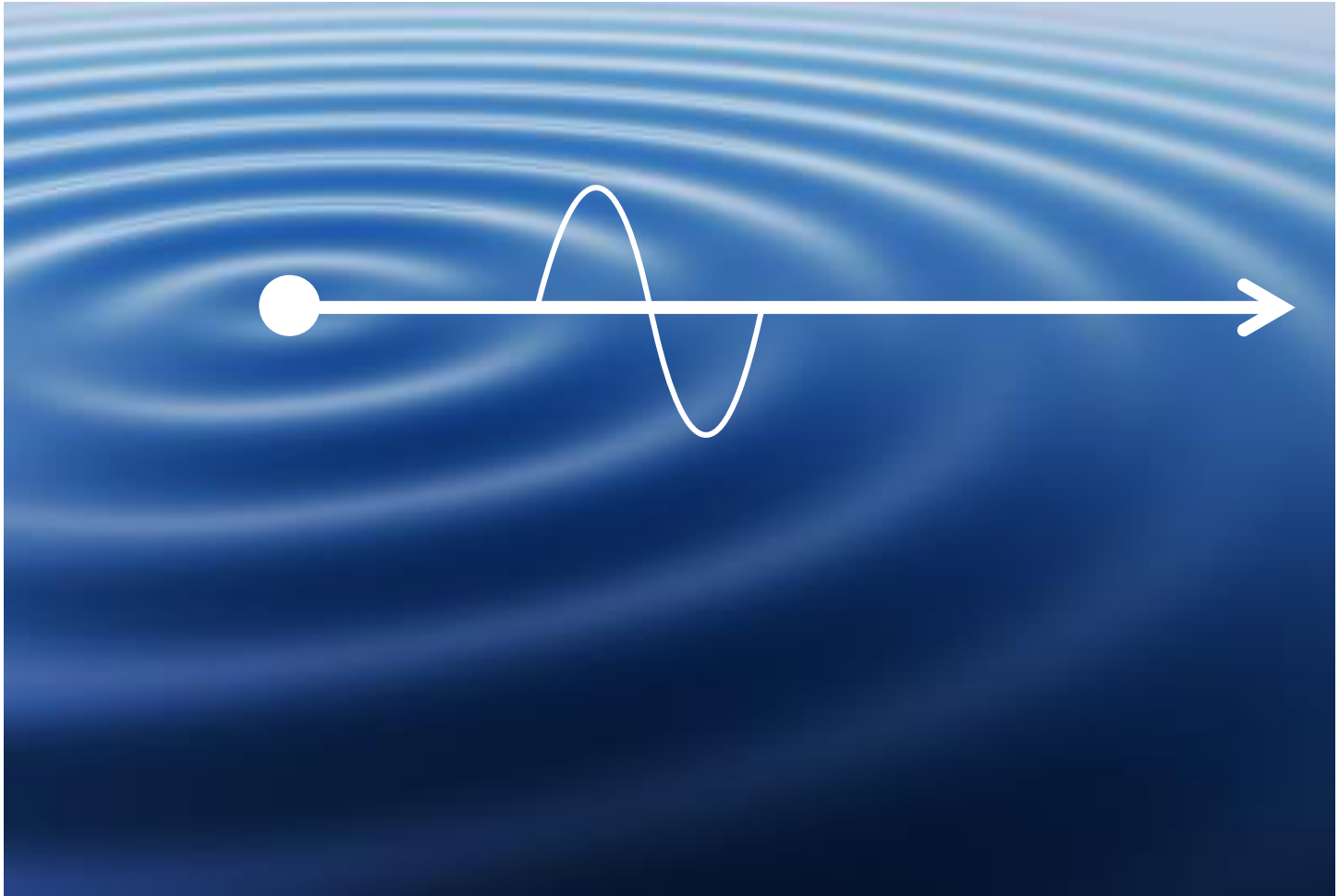

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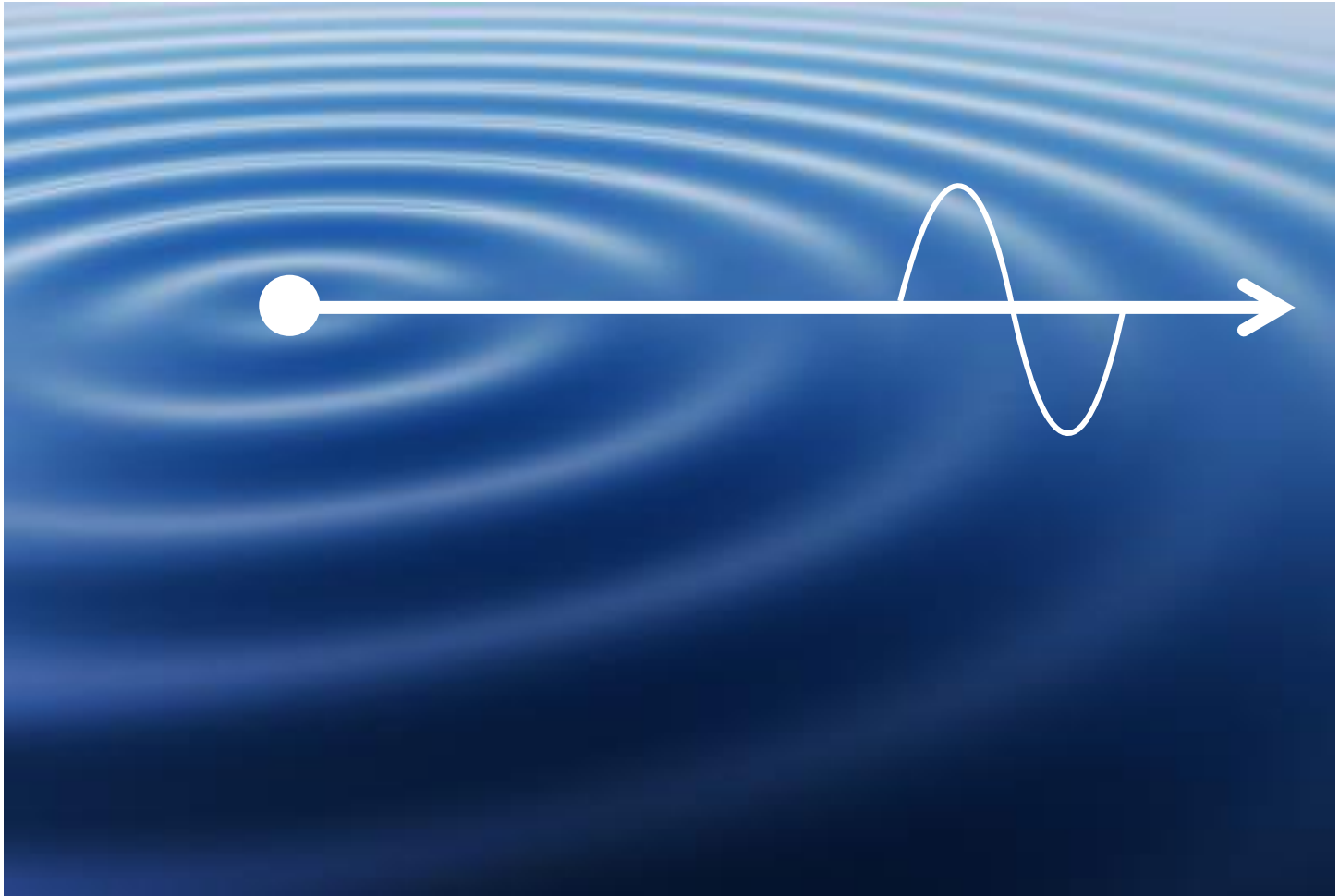
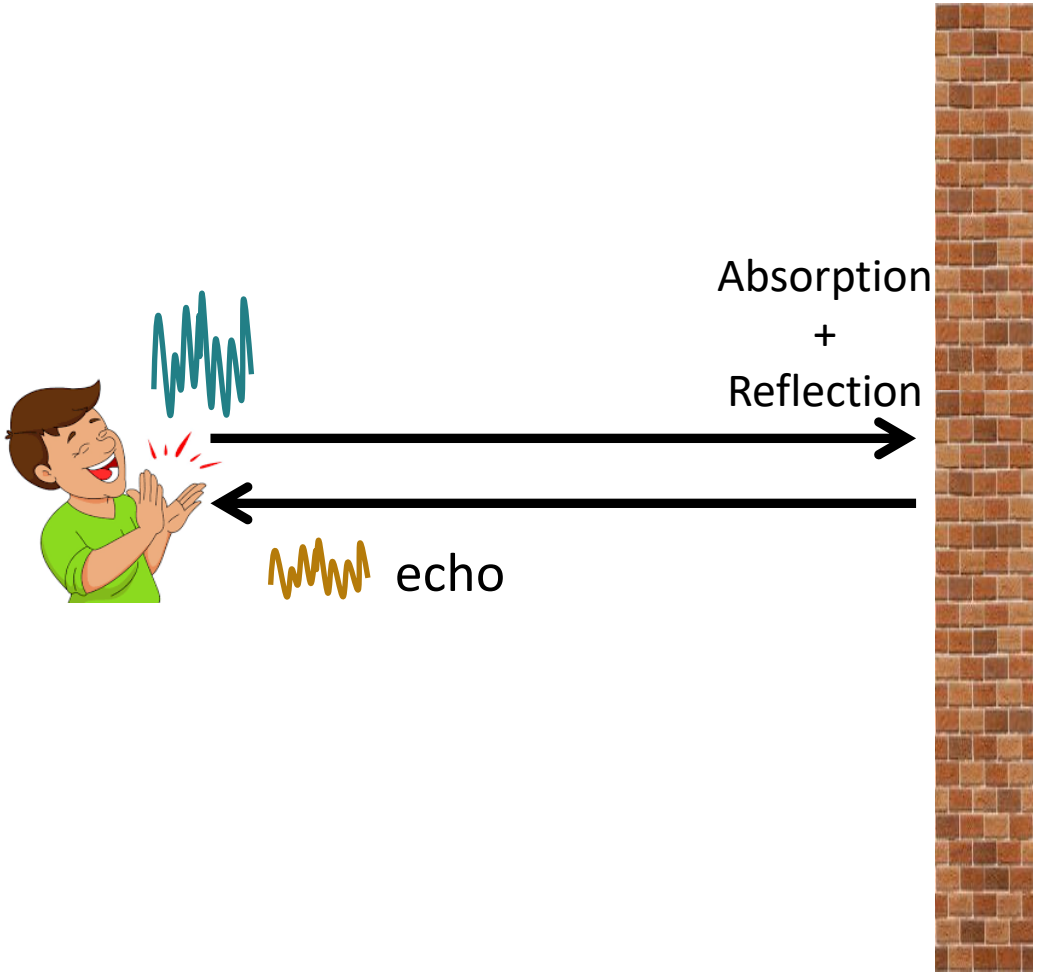


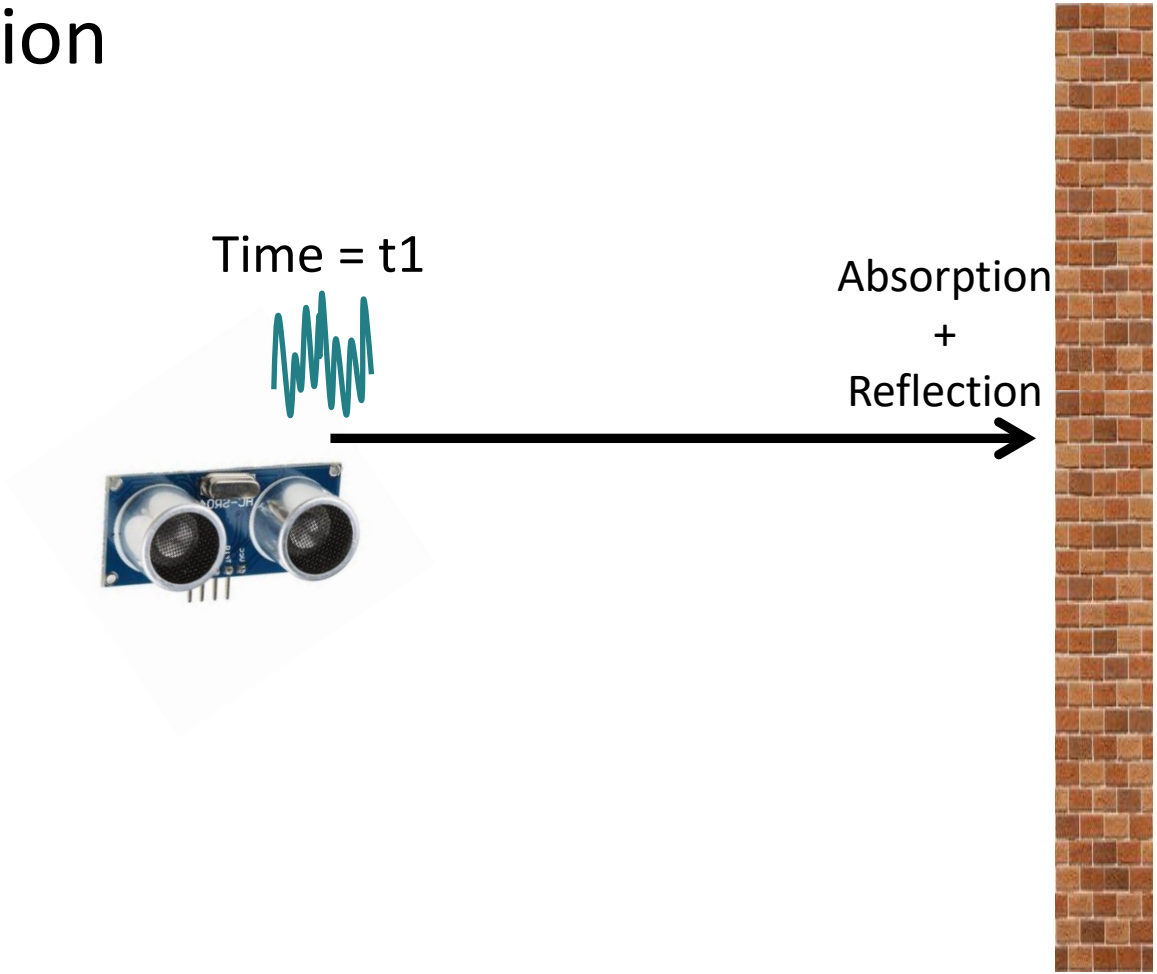
# Reflection



# Reflection

Time = t1

# Reflection



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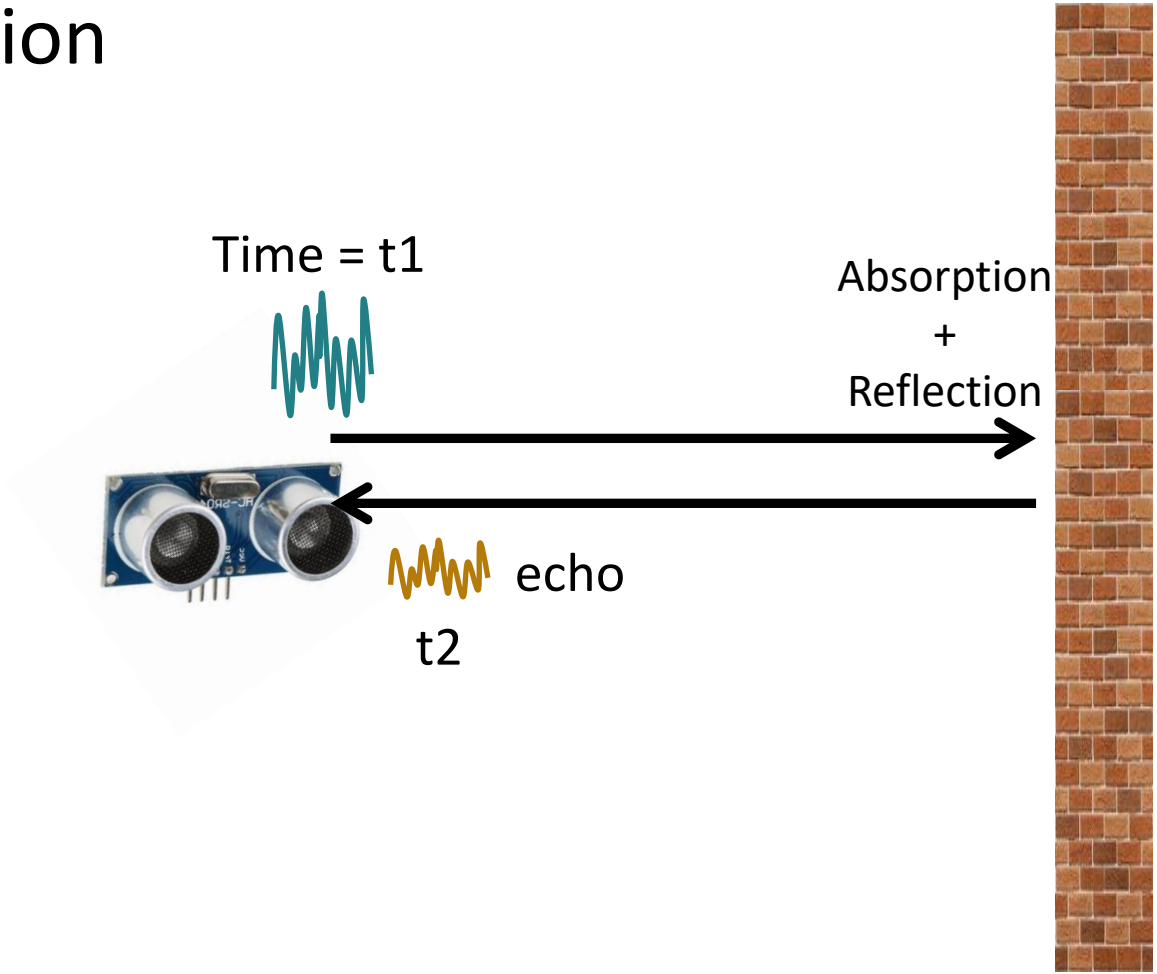
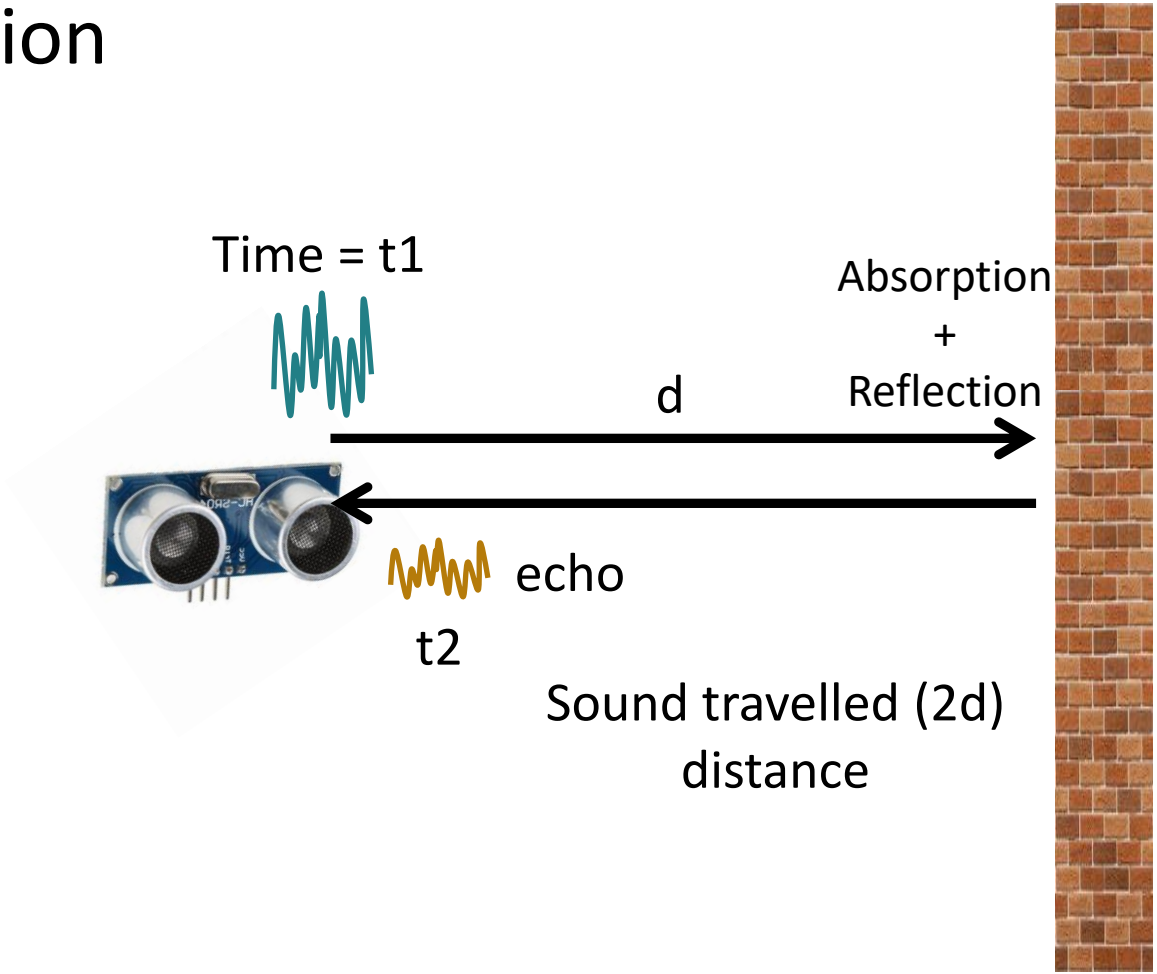


# Reflection


Time = t1
Absorption
+
Reflection
d
echo
t2
Sound travelled (2d)
distance

# The speed of the wave is known

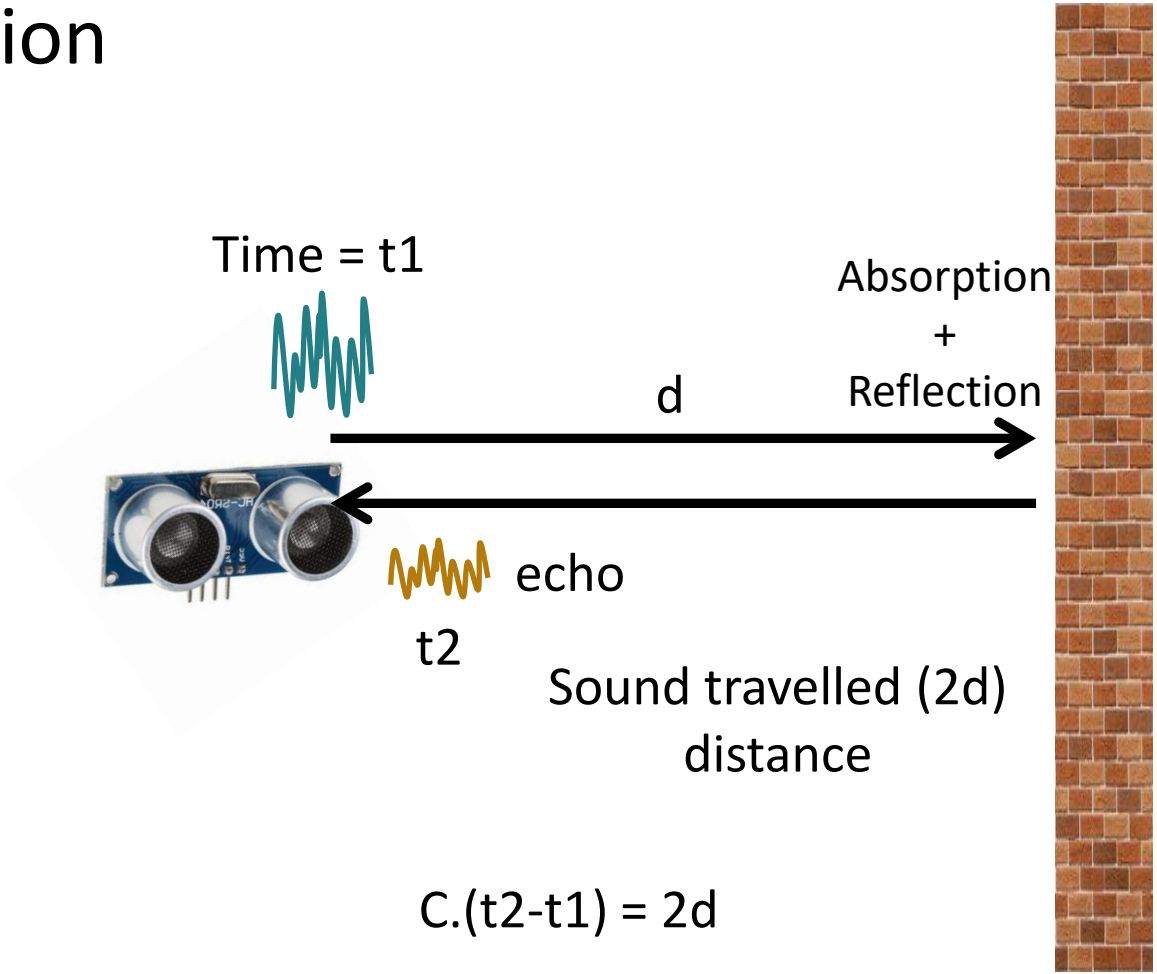
the speed of light =

299 792 458 m / s

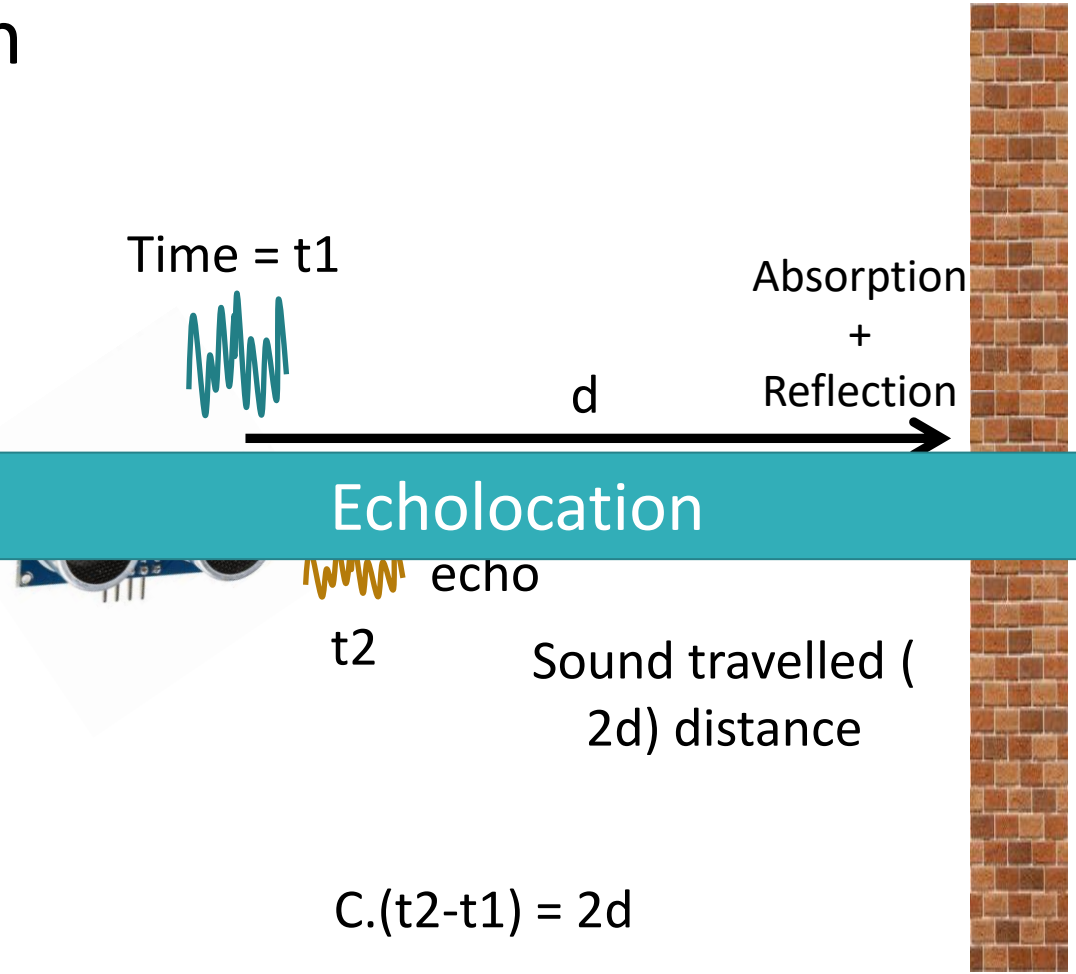
speed of sound in dry air at 20 °C =

343 m / s

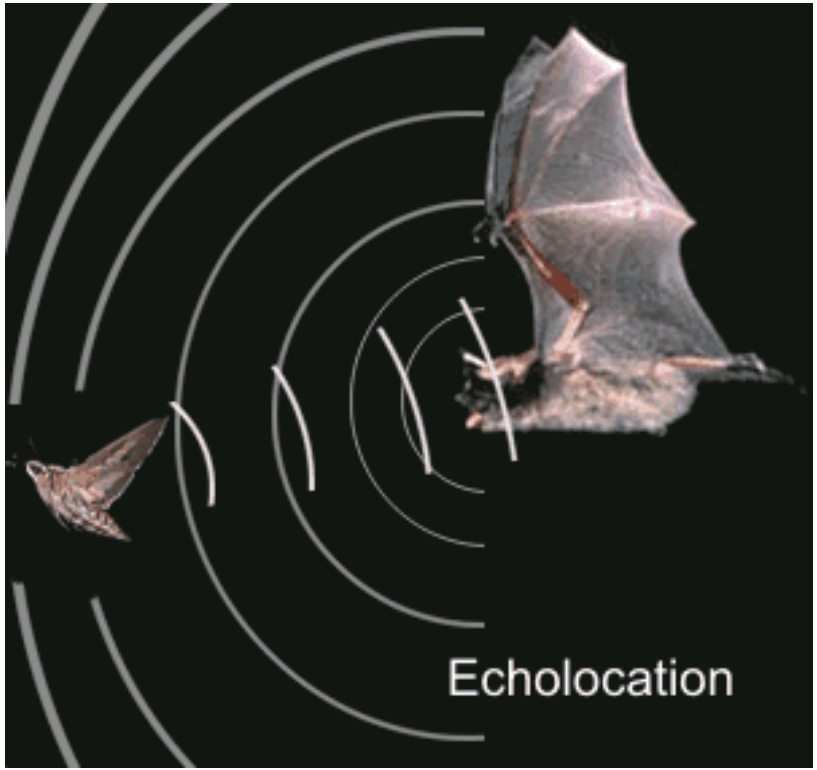
# Reflection


Time = t1
Absorption
+
Reflection
d
echo
t2
Sound travelled (2d)
distance
C.(t2-t1) = 2d

# Reflection


Time = t1
Absorption
+
Reflection
d
Echolocation
echo
t2
Sound travelled (
2d) distance
C.(t2-t1) = 2d

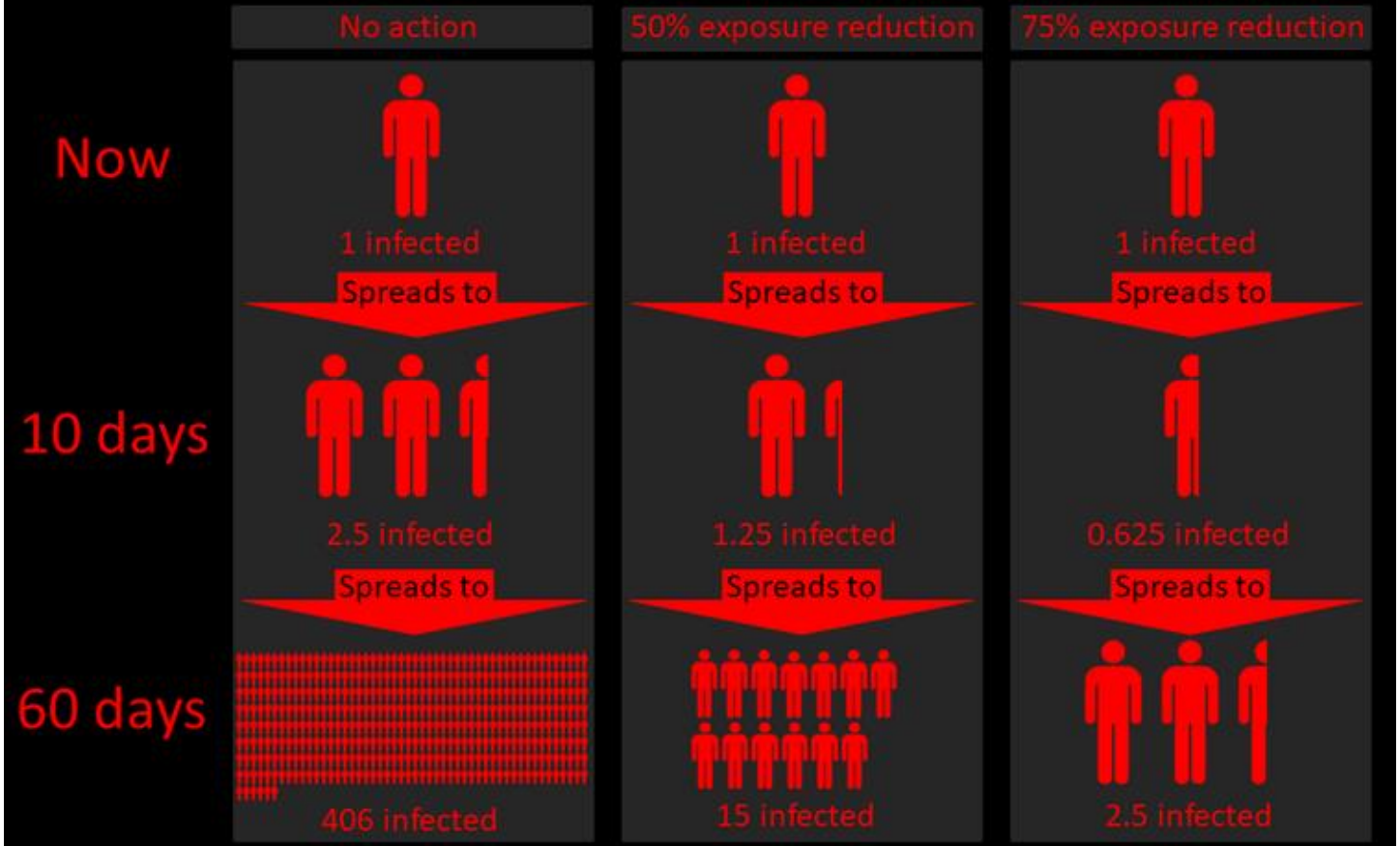
# Echolocation in Nature




Bat

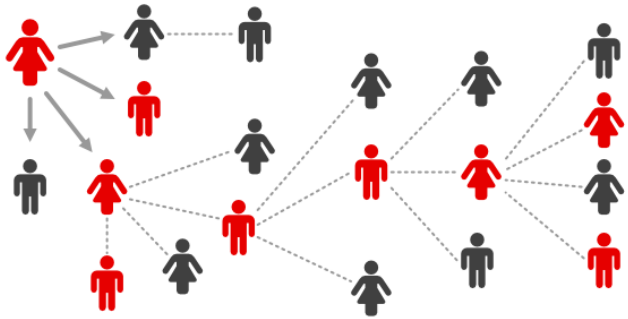
# Application: Contact tracing

# Infection rate




Credit: Kit Yates. Senior Lecturer in Mathematical Biology at the University of Bath and author of the Maths of Life and Death.

## What is contact tracing?



Contact tracing aims to identify and alert people who have come into contact with a person infected with coronavirus.

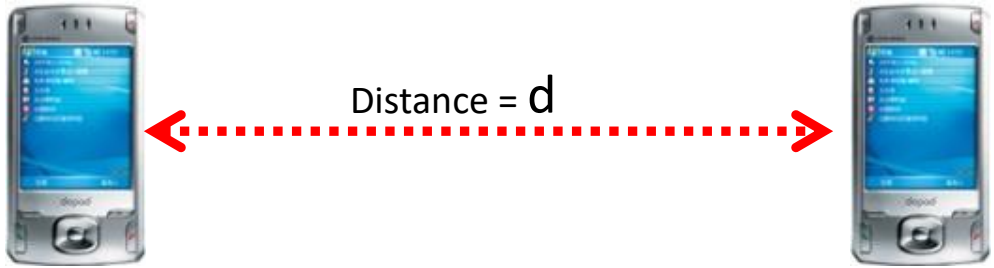
# How to find the proximity between two smartphones?

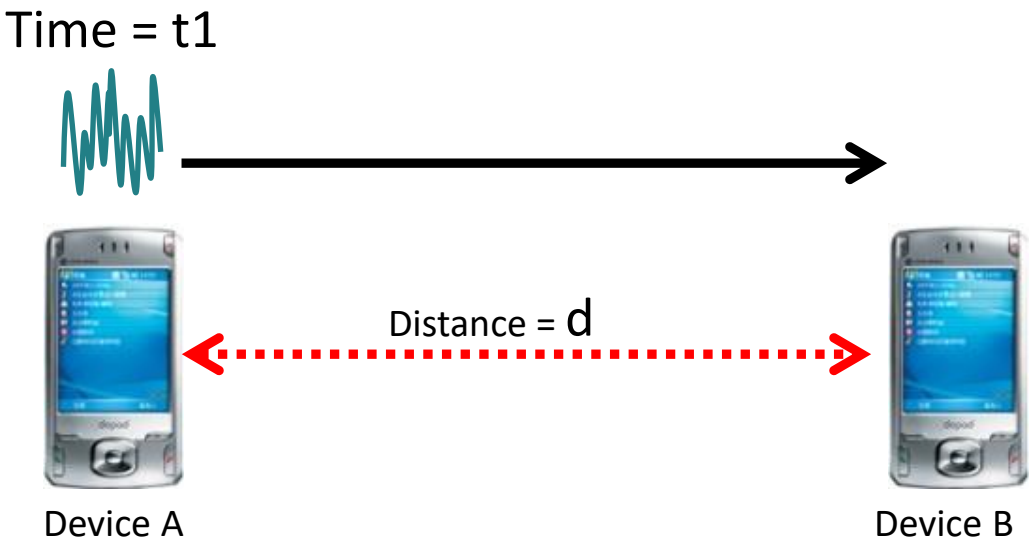
Smartphones can be used to quickly and automatically determine whether somebody has been in contact with an infected person.

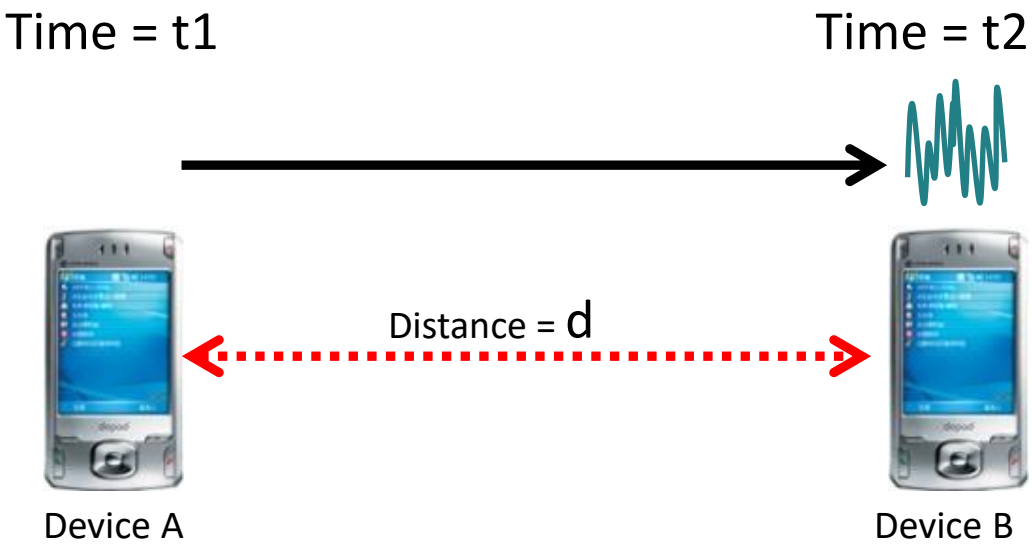
# A simple acoustic ranging technique
# BeepBeep – SenSys 2007

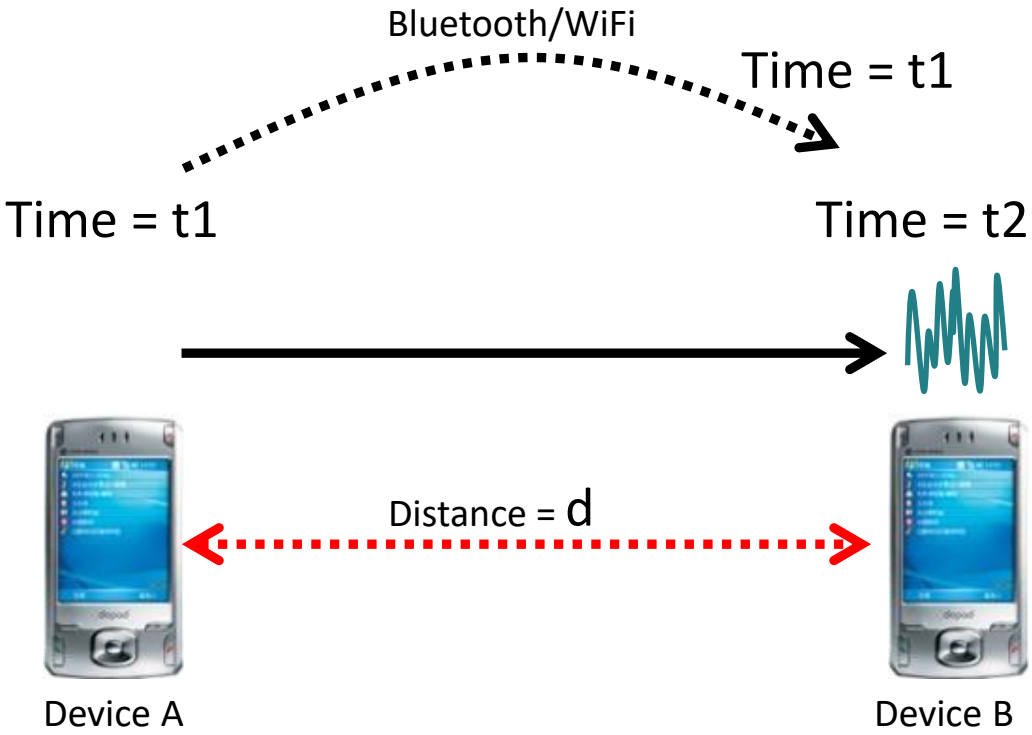
# The Requirement

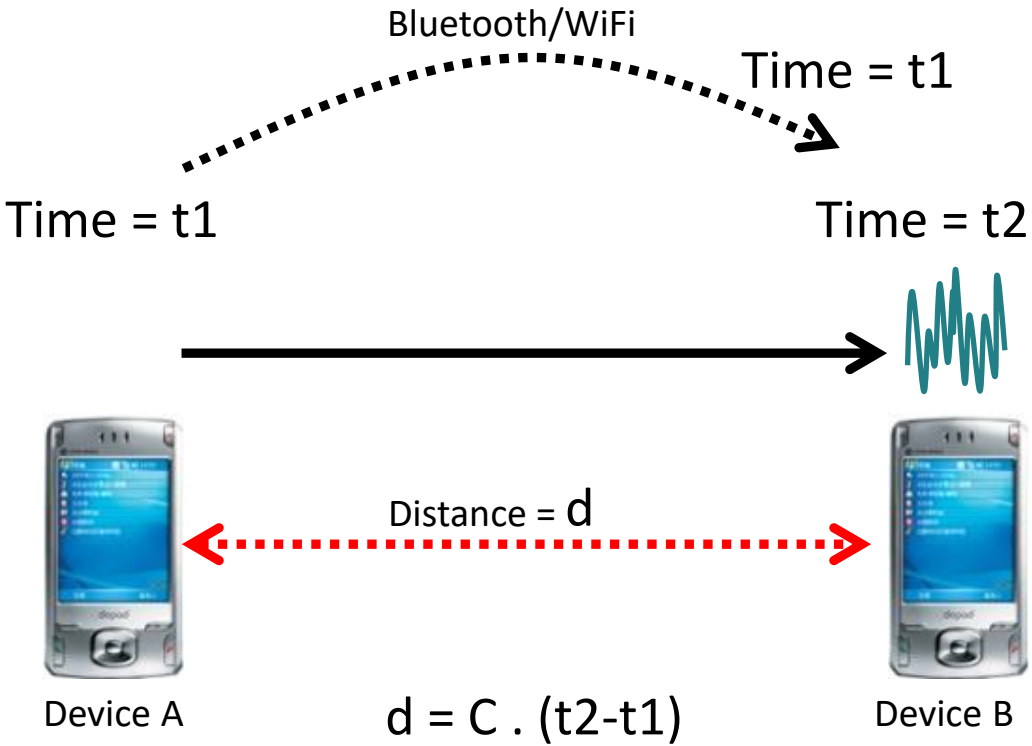
- A widely applicable solution
  - Work on COTS devices
    - No additional hardware
    - Pure user space software (no change to OS/driver)
  - Not dependent on infrastructure
    - Applicable in spontaneous, ad hoc situations
  - Minimum set of sensors
- High accuracy!


Distance = d
Device A
Device B


Time = t1
Distance = d
Device A
Device B


Time = t1
Time = t2
Distance = d
Device A
Device B


Bluetooth/WiFi
Time = t1
Time = t1
Time = t2
Distance = d
Device A
Device B




$d = C \cdot (t2 - t1)$

C = speed of the wave
= ~340m/s for sound

Device A

“Beep”!

# Signal Design

- Good signal design helps detection
  - Easily detectable in digital recording
  - Robust against ambient noise
  - Robust against acoustic distortion
    - Low-fidelity speaker & mic in COTS mobile device
  - Within hardware capability
    - Most COTS devices have limited voice frequency range
- Our empirical design (“chirp” sound)
  - 50ms long, shifting frequency from 2 to 6 kHz

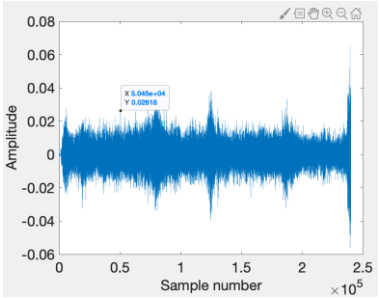
# Signal Detection Algorithm Design

- Efficient and fast signal detection algorithm
  - Quickly locate possible signal regions
- Robust against low SNR
  - Utilize noise floor to boost SNR
- Combat multipath effect
  - Multipath: big issue indoor environment
  - We derived special algorithm to detect first “sharp peak” signal correlation

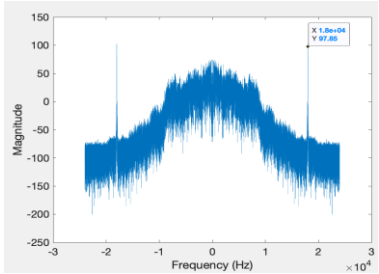
Device A

“Beep”

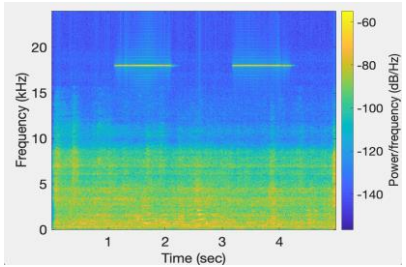
Time domain signal



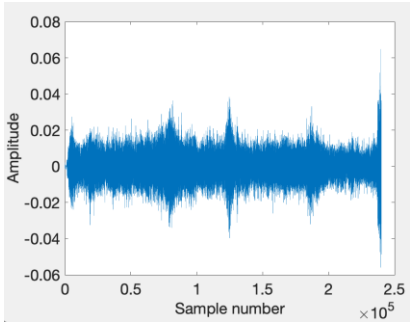

FFT Plot



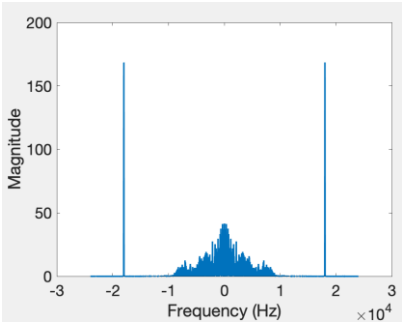

STFT Plot



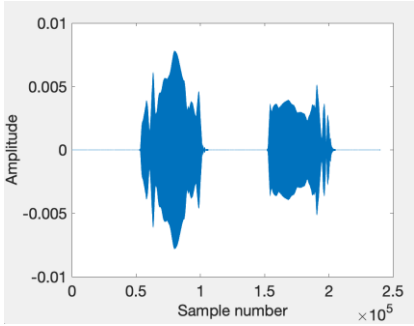
Time domain

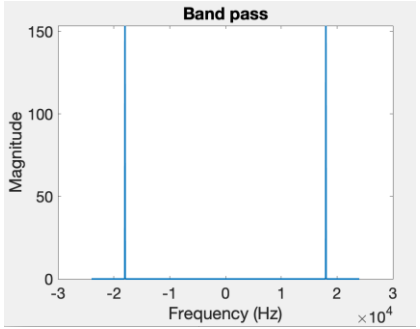


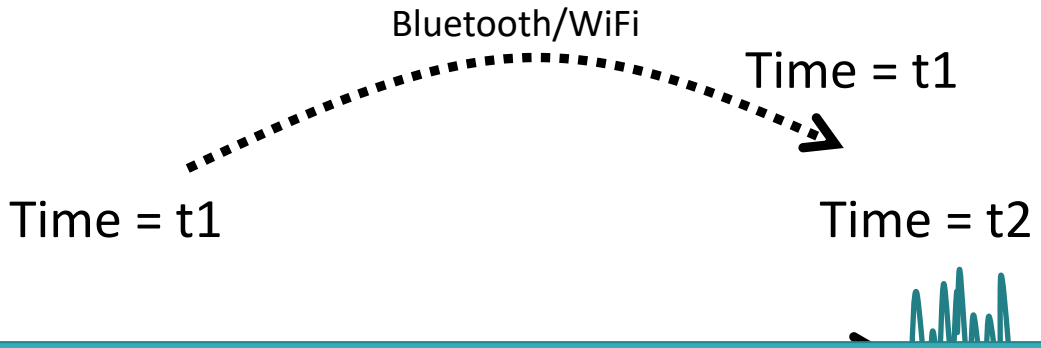

Freq. domain



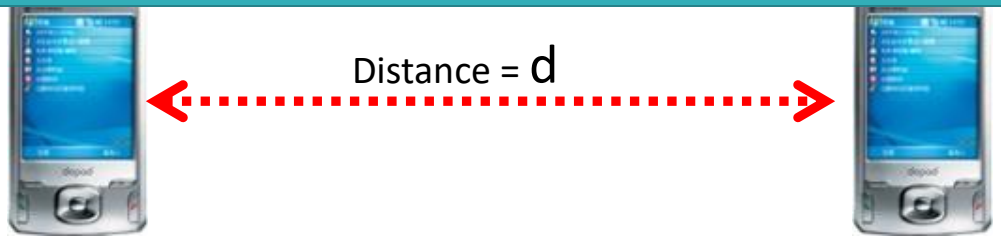

After bandpass filter





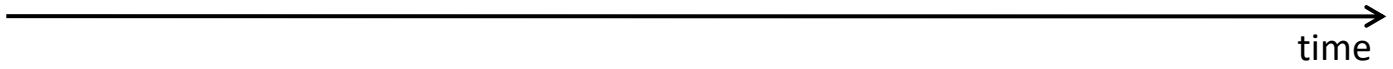

# Problem: Clock synchronization




$d = C \cdot (t2 - t1)$

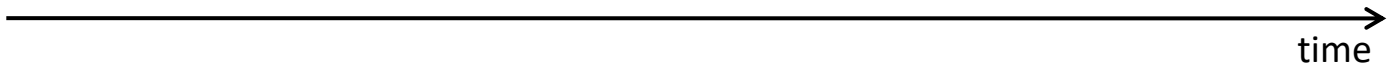
# The root cause of inaccuracy – three uncertainties

- Clock synchronization uncertainty



# The root cause of inaccuracy – three uncertainties

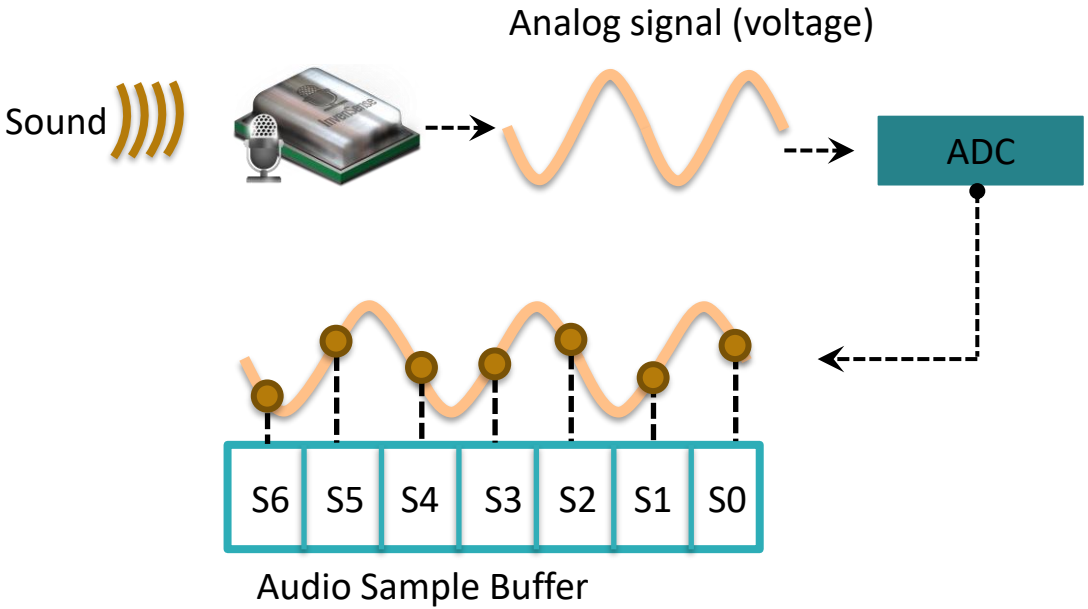
- Clock synchronization uncertainty
- Sending uncertainty
- Receiving uncertainty



# Sound production and recording

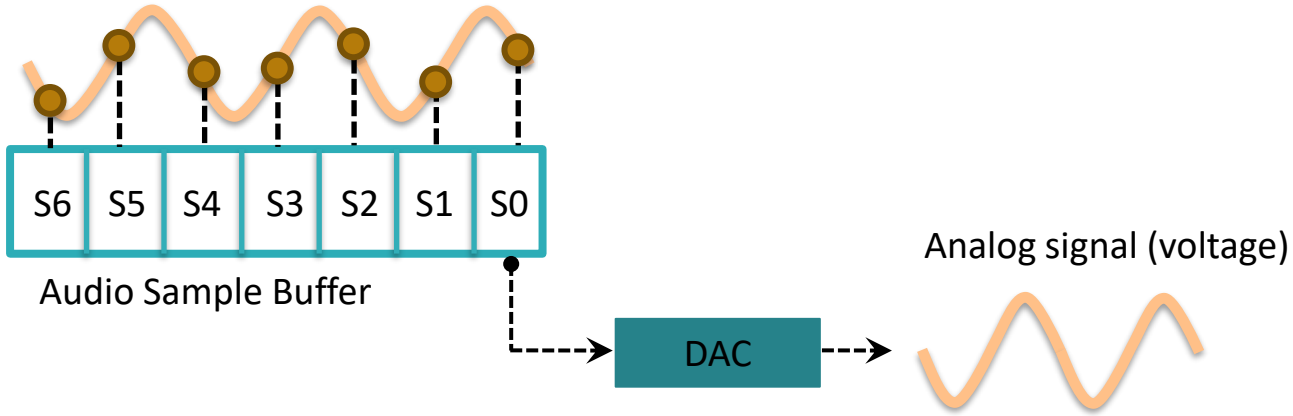
# Sound recording with microphone

# Sound recording with microphone



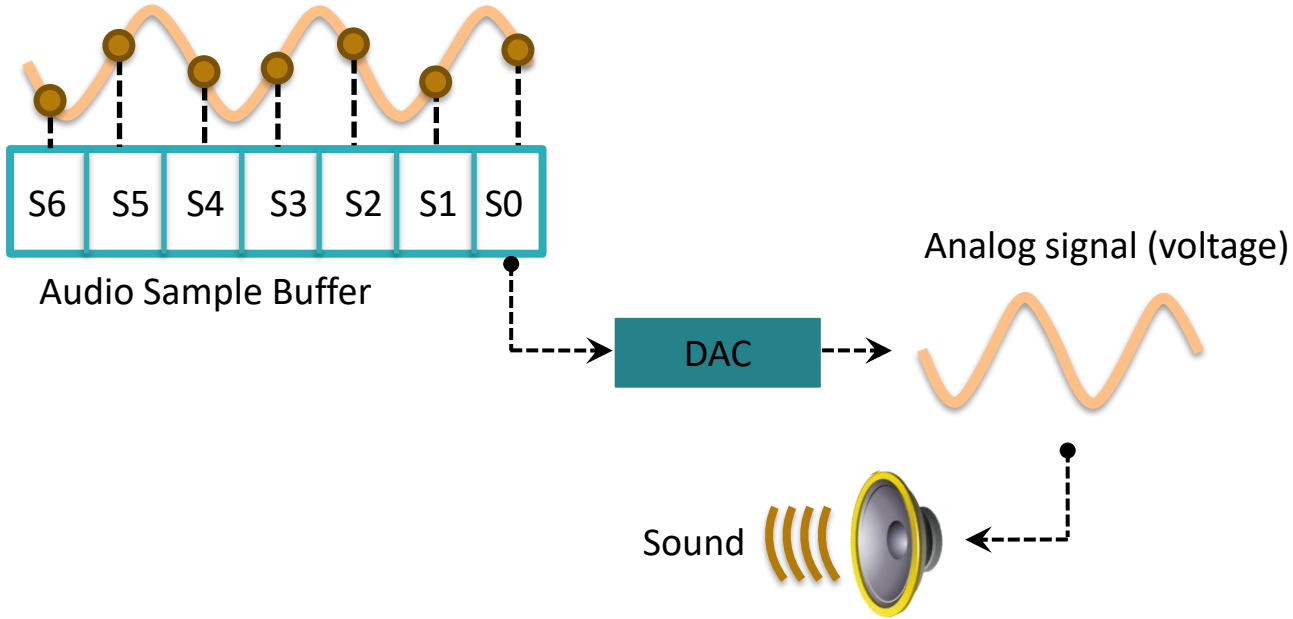

ADC = Analog-to-Digital Converter

# Sound recording with microphone




DAC = Digital-to-Analog Converter

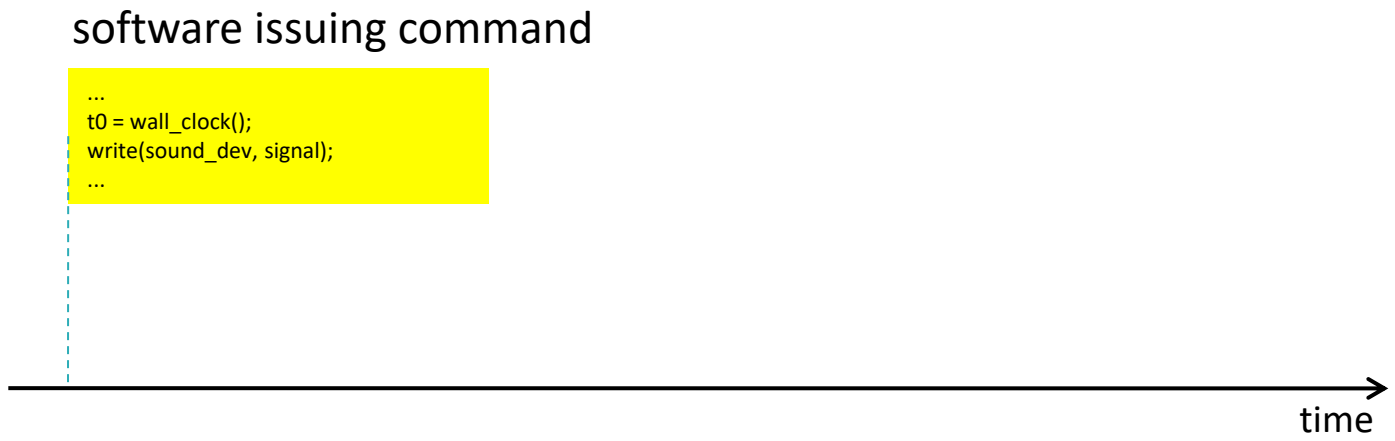
# Sound recording with microphone




DAC = Digital-to-Analog Converter

# The root cause of inaccuracy – three uncertainties

- Clock synchronization uncertainty
- Sending uncertainty



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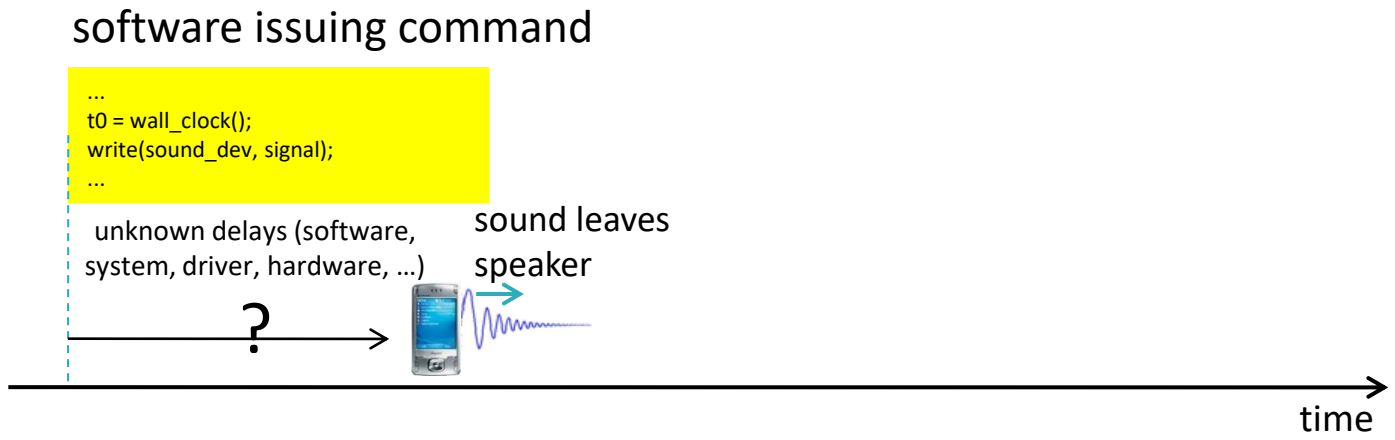
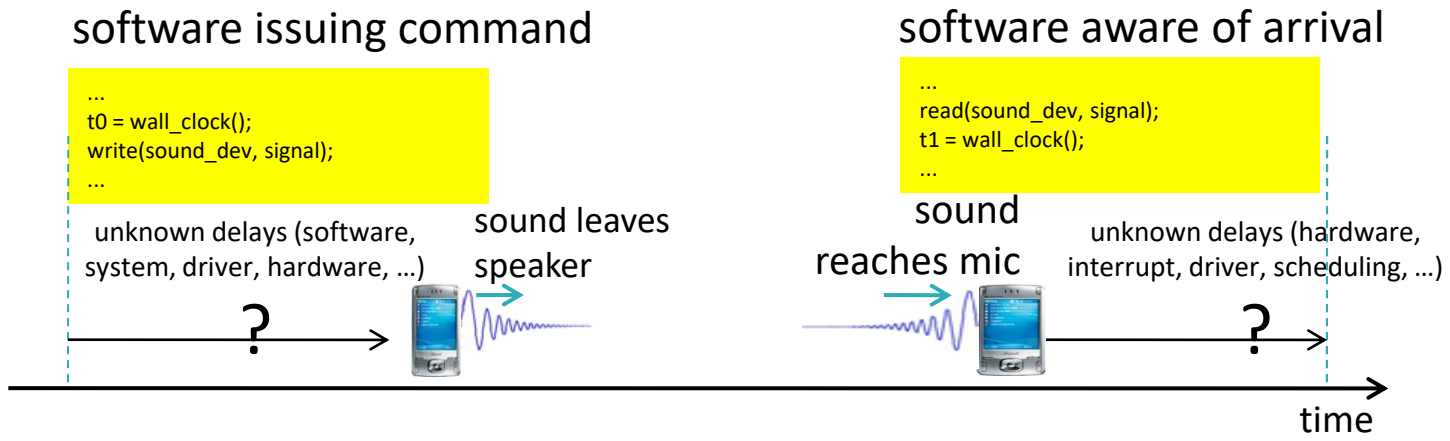
- Clock synchronization uncertainty
- Sending uncertainty



# The root cause of inaccuracy – three uncertainties

- Clock synchronization uncertainty
- Sending uncertainty
- Receiving uncertainty

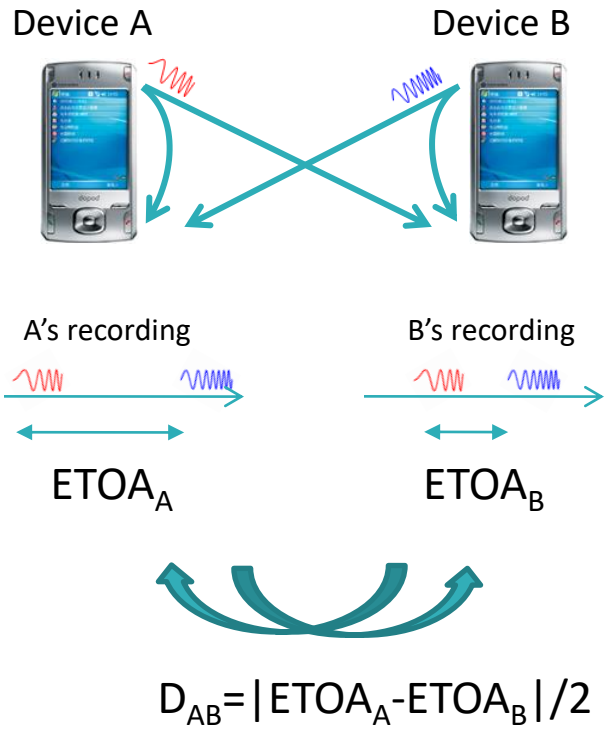


# BeepBeep

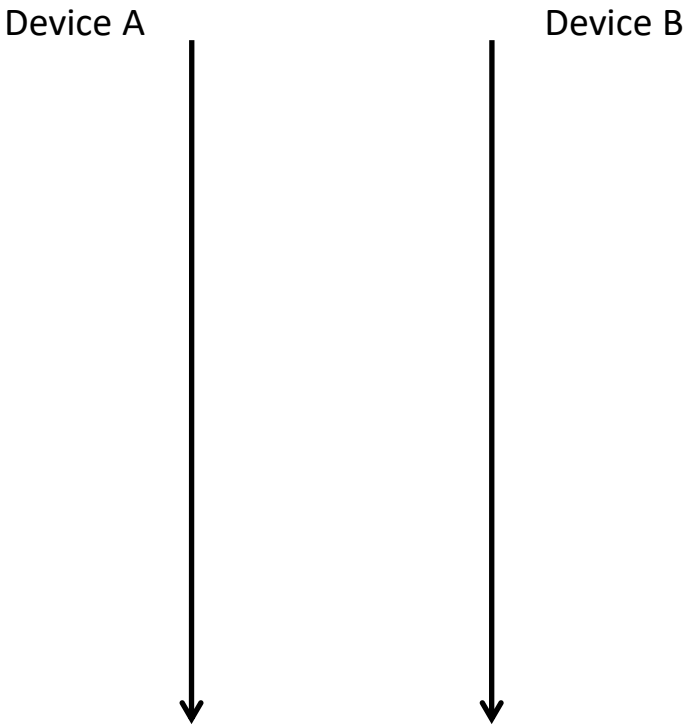
- A simple and effective solution
  - Each device just needs to emit a sound signal and record them simultaneously
  - Only require a speaker, a mic, and some way of communicating with the other device
- Achieving 1cm accuracy while satisfying all the requirements

# Beepbeep's basic procedure

1. Device A emits a beep while both recording
2. Device B emits another beep while both continue recording
3. Both devices detect TOA of the two beeps and obtain respective ETOAs
4. Exchange ETOAs and calculate the distance



# Timeline



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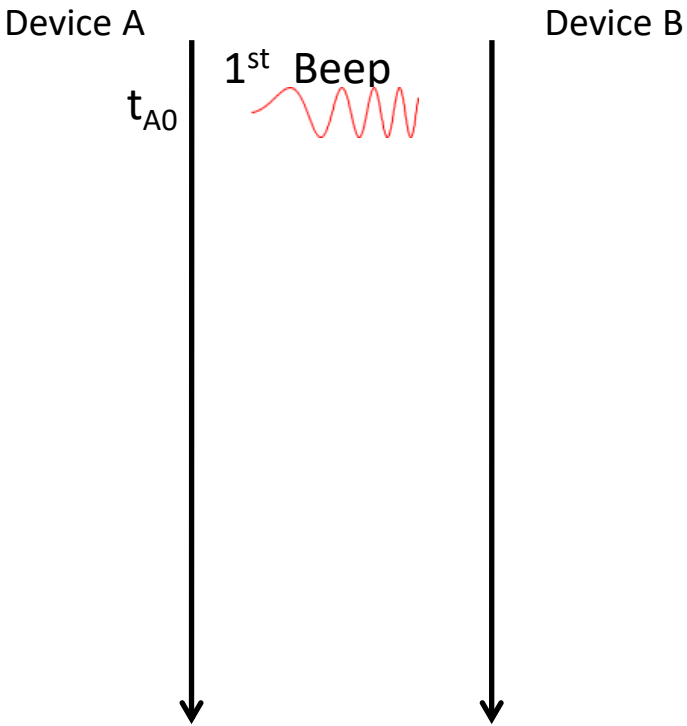

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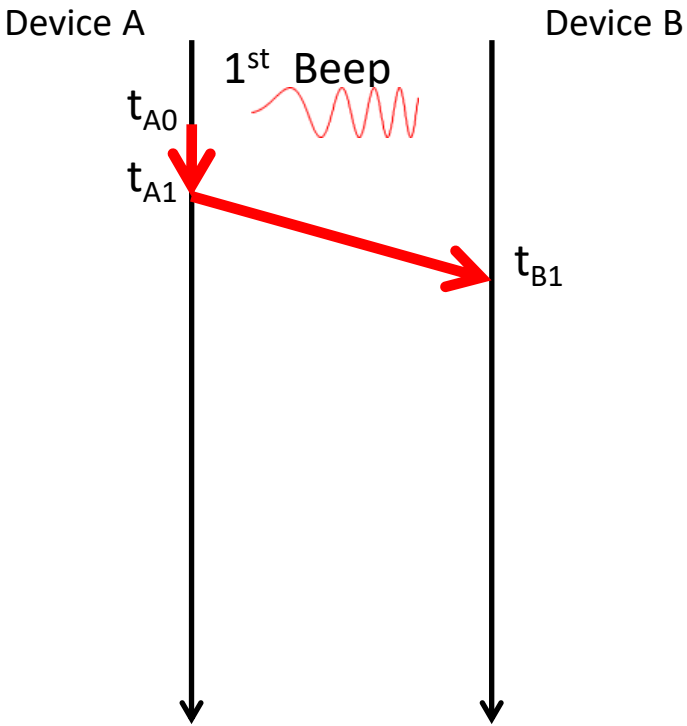

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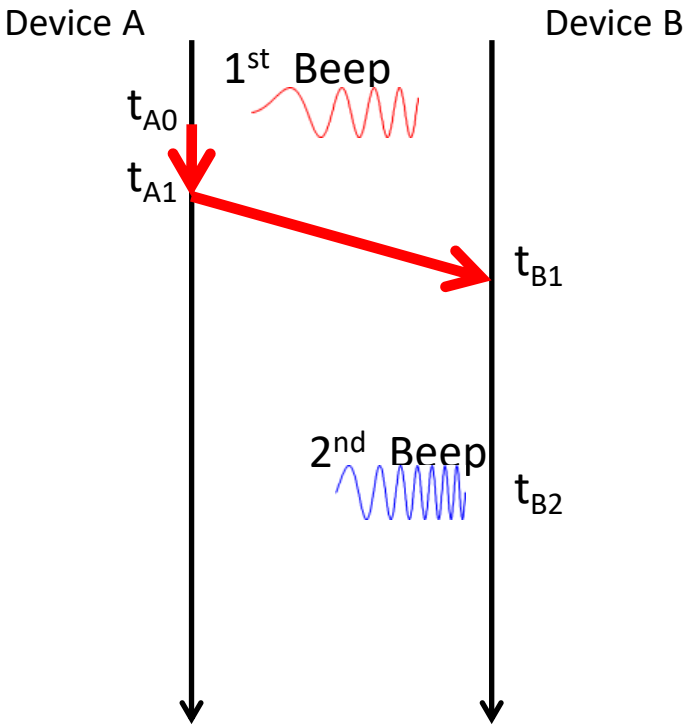

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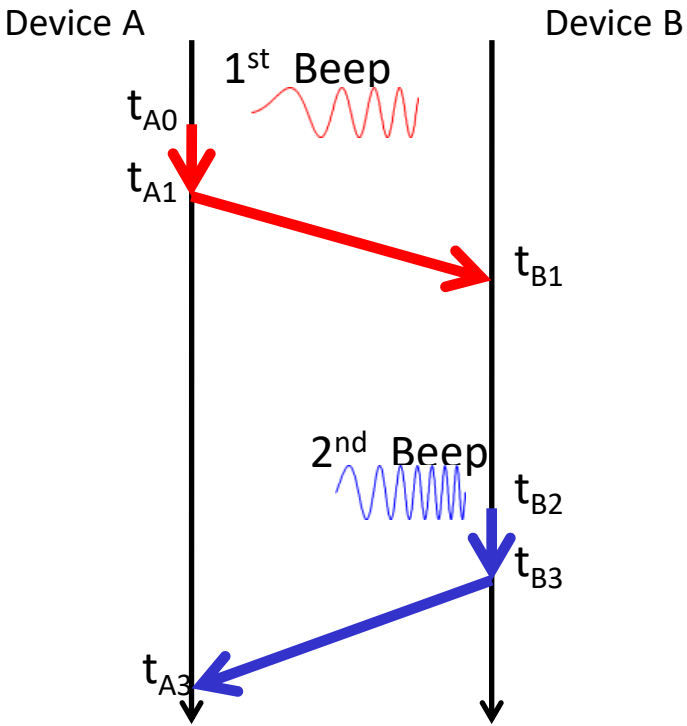
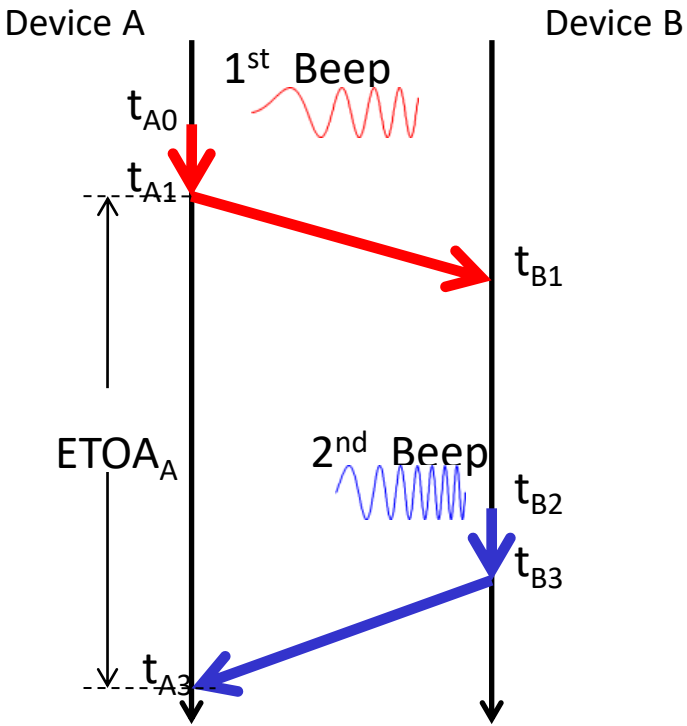
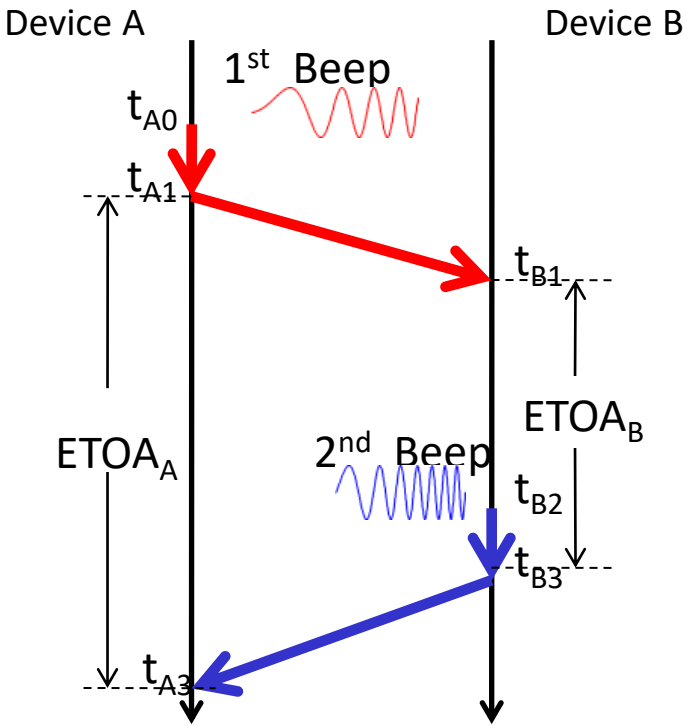


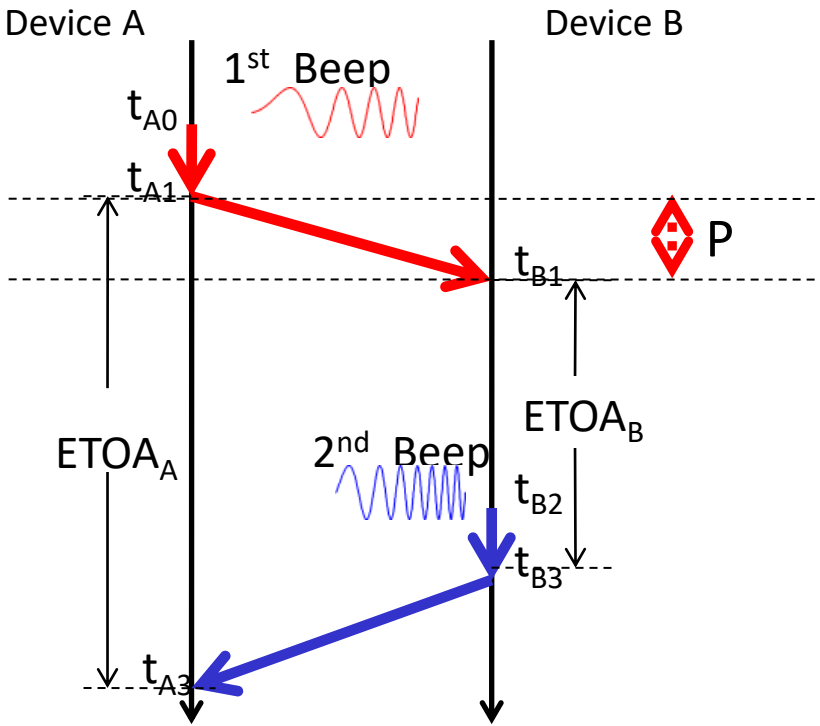
# Timeline


Device A
Device B
1st Beep
tA0
tA1
tB1
ETOAA
2nd Beep
tB2
tB3
tA3

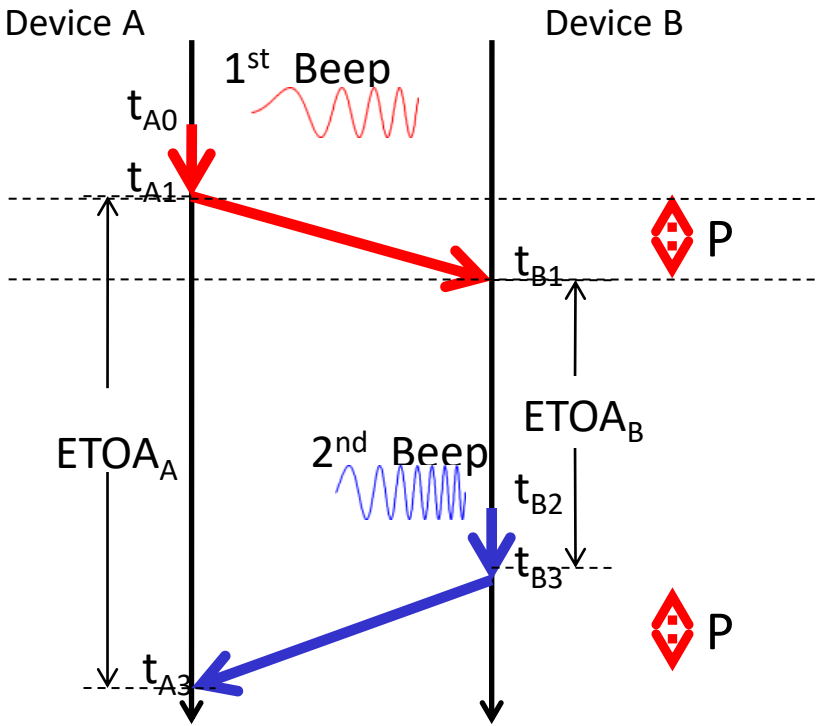
# Timeline


Device A
Device B
1st Beep
tA0
tA1
tB1
ETOAB
ETOAA
2nd Beep
tB2
tB3
tA3

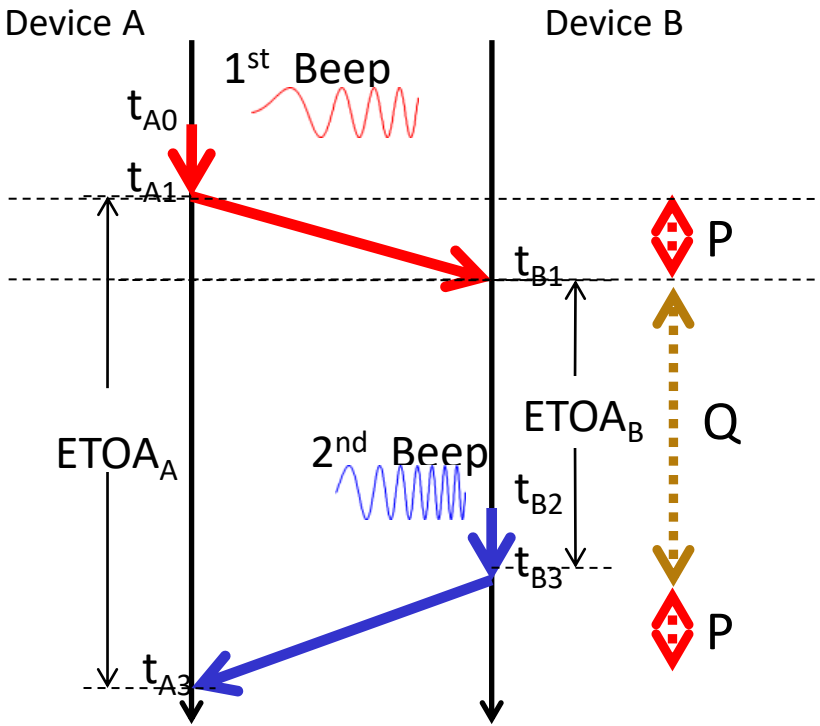
# Timeline


Device A
Device B
1st Beep
tA0
tA1
P
tB1
ETOAB
ETOAA
2nd Beep
tB2
tB3
tA3

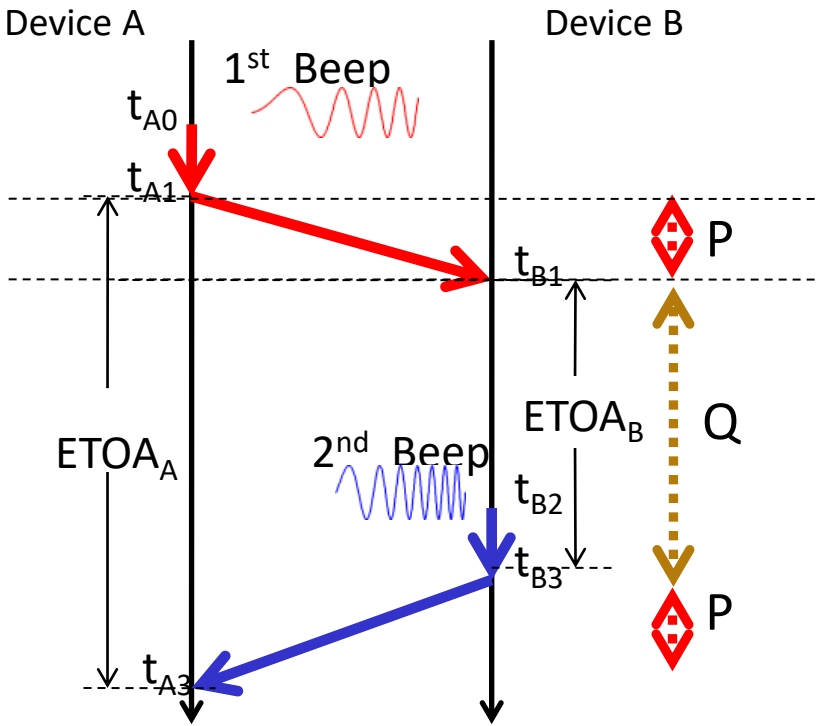
# Timeline


Device A
Device B
1st Beep
tA0
tA1
P
tB1
ETOAB
ETOAA
2nd Beep
tB2
tB3
P
tA3

# Timeline


Device A
Device B
1st Beep
tA0
tA1
tB1
P
ETOAB
Q
ETOAA
2nd Beep
tB2
tB3
P
tA3

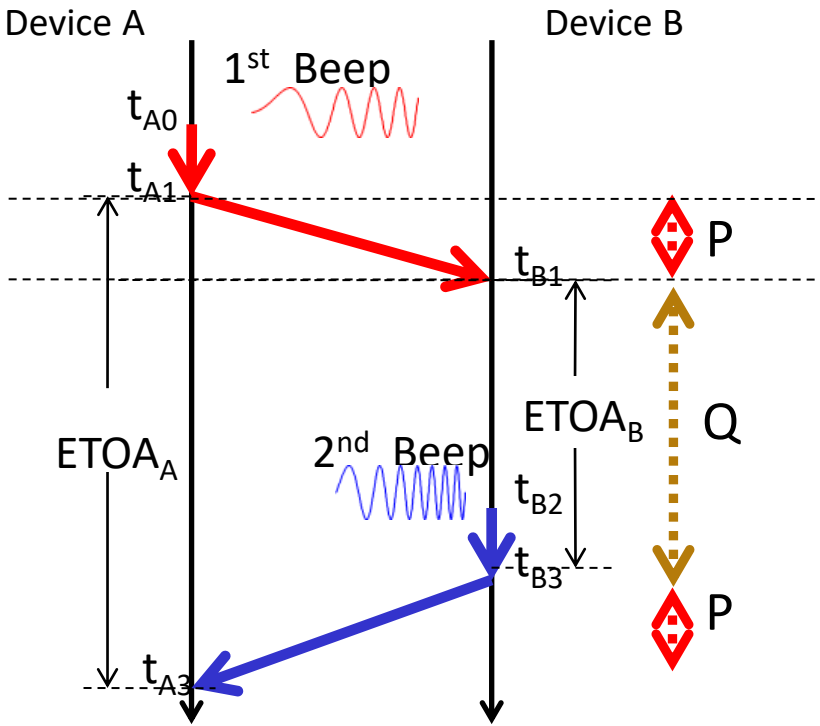
# Timeline




$|ETOA_A - ETOA_B|$

$= (P+Q+P) - (Q)$

# Timeline




$|ETOA_A - ETOA_B|$

$= (P+Q+P) - (Q)$

$= 2P$

$= 2$ (time of flight)

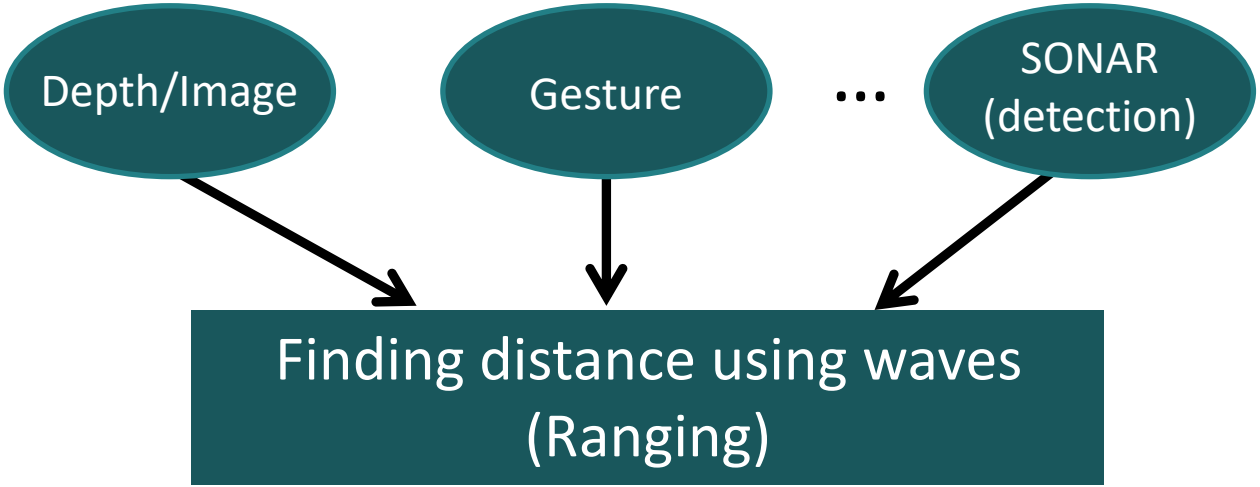
# Design Rationale

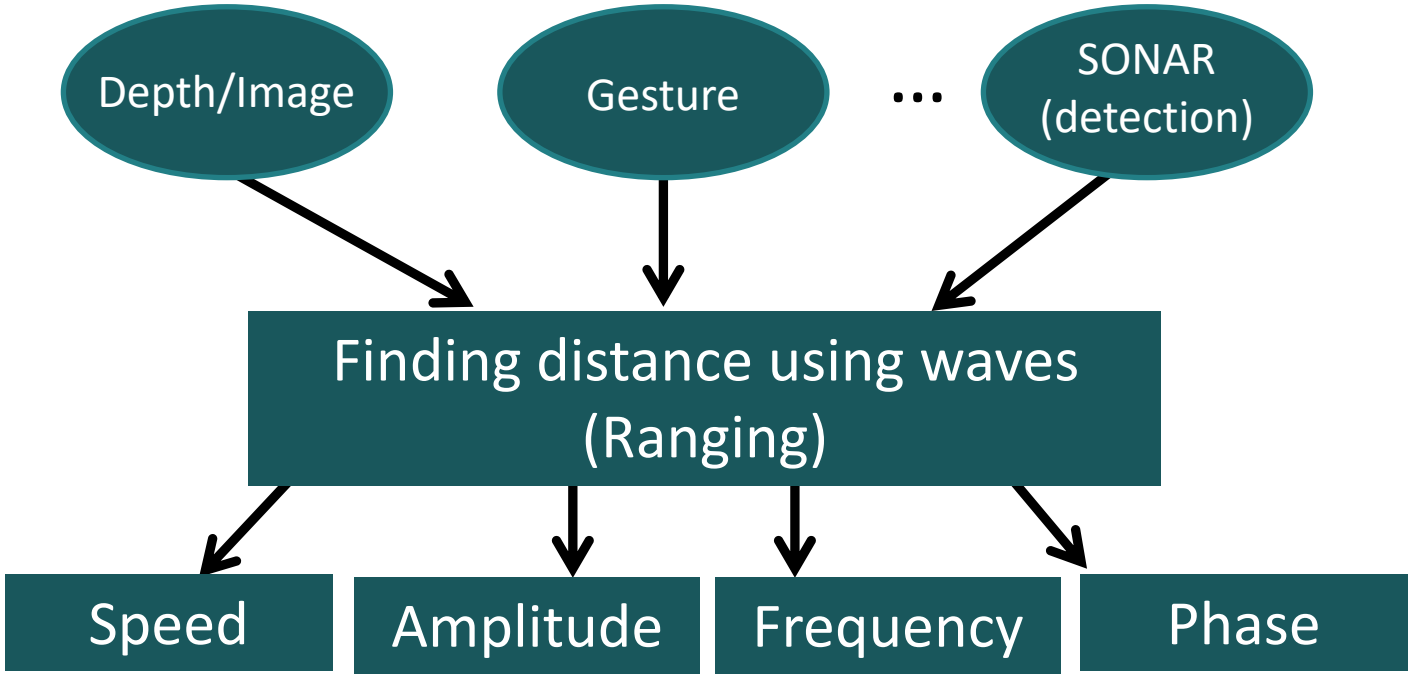
- Self-recording
  - Record signals from both the other party and itself
  - Establish the starting reference point of the whole ranging process
  - Duplex audio channel
- Two-way sensing
  - Avoid clock synchronization uncertainty
  - To capture the ending reference point of the whole ranging process
    - not attempt to capture any system time info

# Design Rationale

- Sample counting
  - Avoid referring to system clocks for timing info
  - Dedicated A/D converter, w/ fixed sampling rate
    - Achievable precision is determined by the sampling frequency: 0.8cm at 44.1kHz sampling rate
- Putting together:
  - Bypass all the three uncertainties by making time measurement irrelevant to system clocks

# Finding distance using waves


Depth/Image
Gesture
...
SONAR
(detection)
Finding distance using waves
(Ranging)


Depth/Image
Gesture
...
SONAR (detection)
Finding distance using waves (Ranging)
Speed
Amplitude
Frequency
Phase

- Distance from the speed information
  - Techniques
  - Signal detection
- Distance from the amplitude information
  - Absorption
  - Propagation loss
- Distance from the frequency information
  - Doppler effect
  - A case study (Doppler + Triangulation)

- Distance from the speed information
  - Techniques
  - Signal detection
- Distance from the amplitude information
  - Absorption
  - Propagation loss
- Distance from the frequency information
  - Doppler effect
  - A case study (Doppler + Triangulation)

# Distance from the speed information

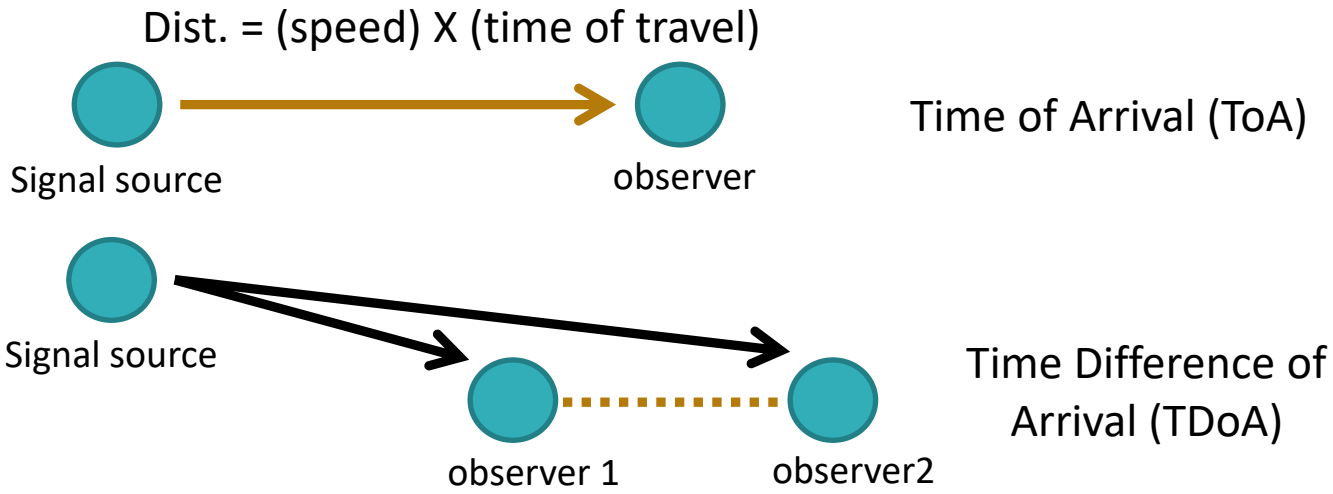
Dist. = (speed) X (time of travel)

Signal source

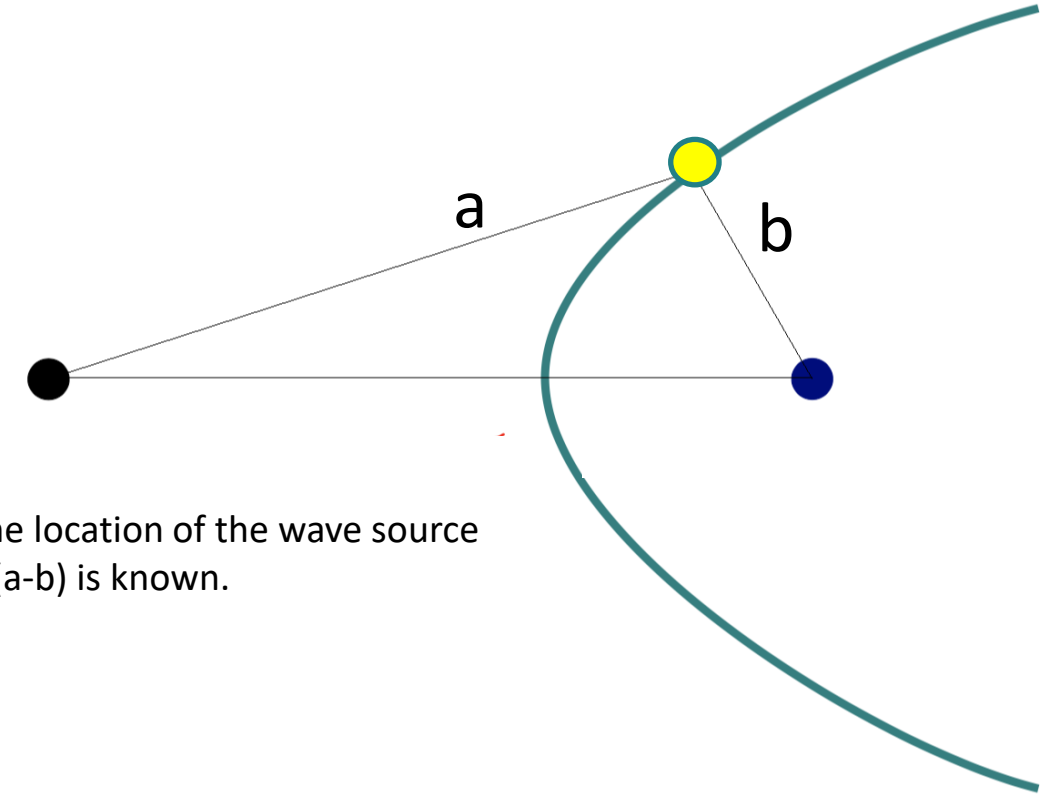
observer

Time of Arrival (ToA)

# Distance from the speed information

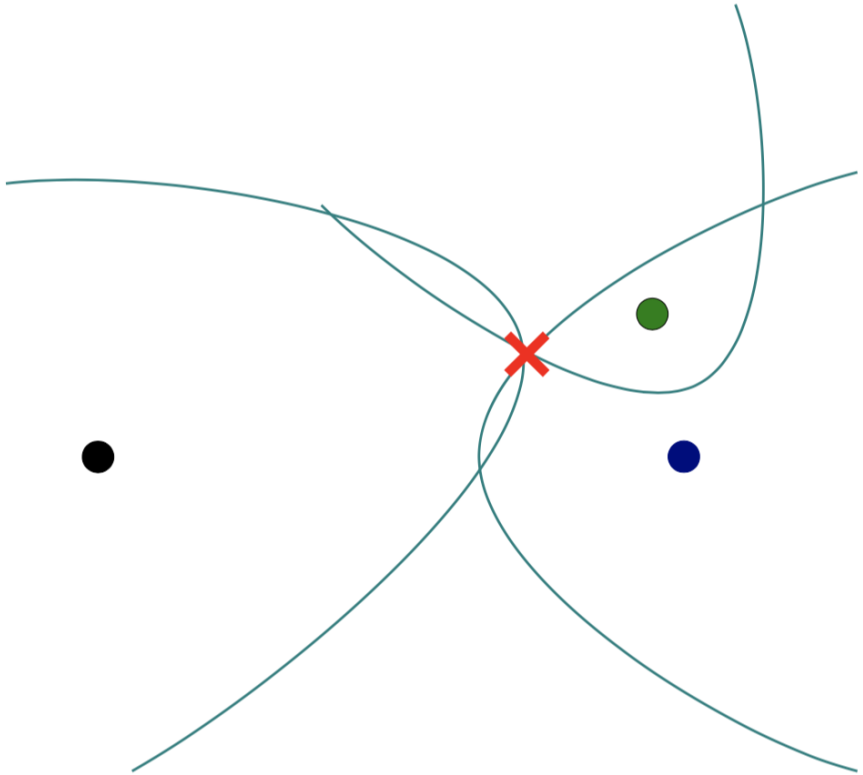


# TDoA

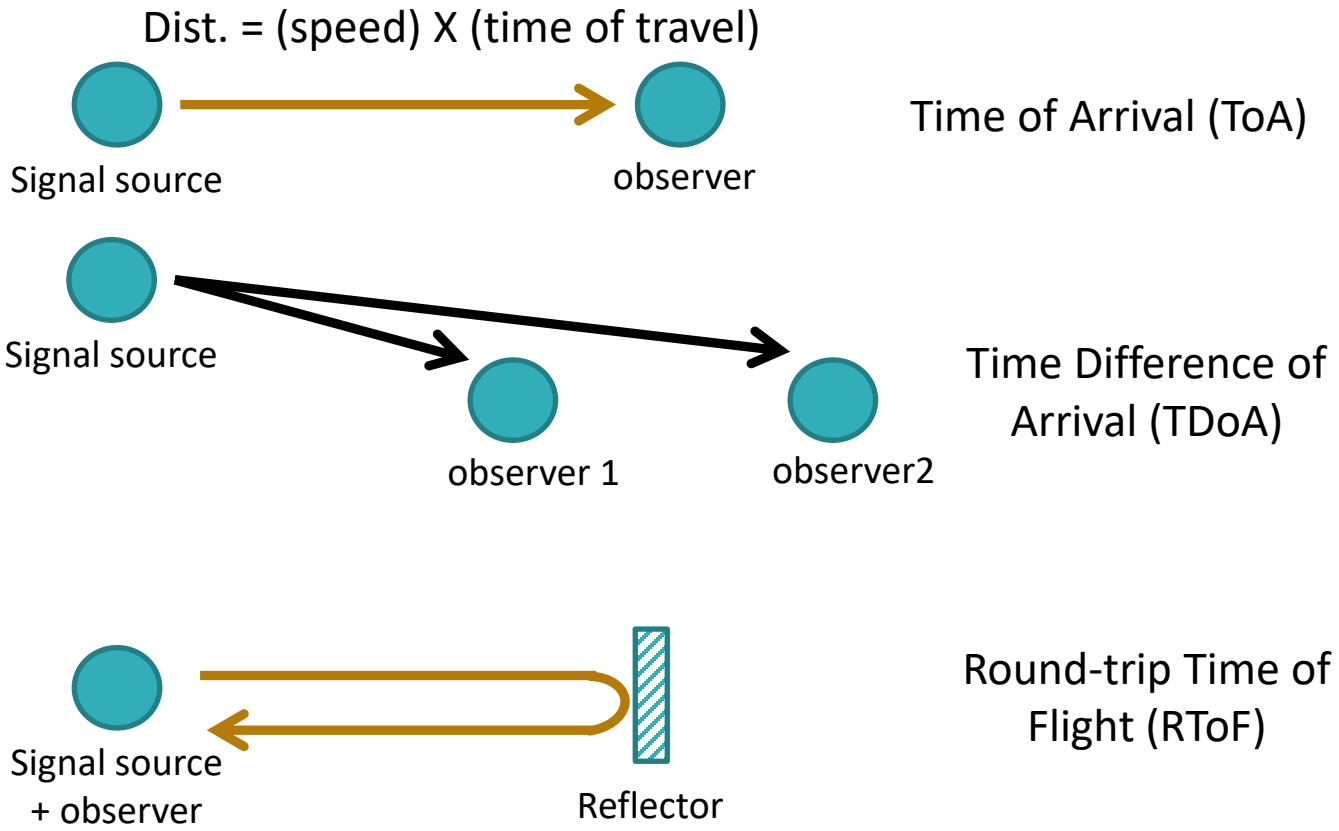



Find the location of the wave source when (a-b) is known.

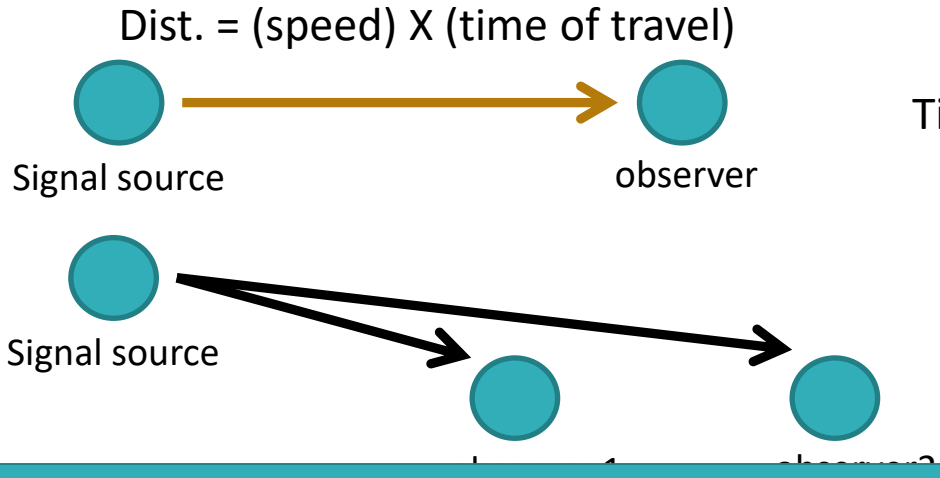
# TDoA



# Distance from the speed information

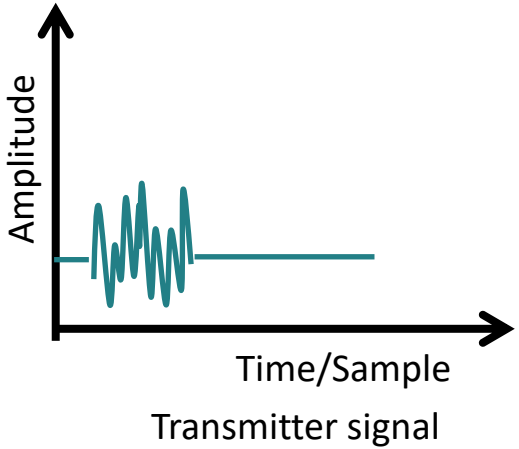


# Distance from the speed information

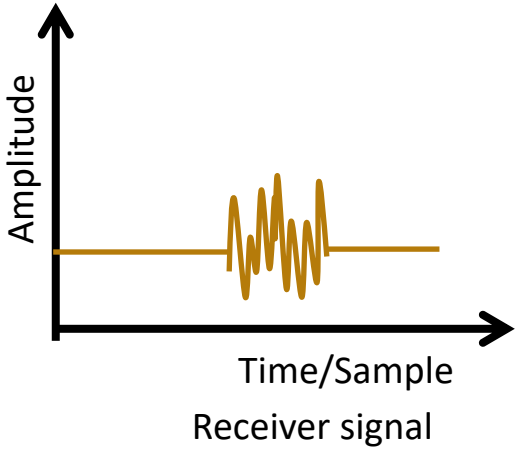



How to detect the signal at the receiver/observer?

# Signal Detection

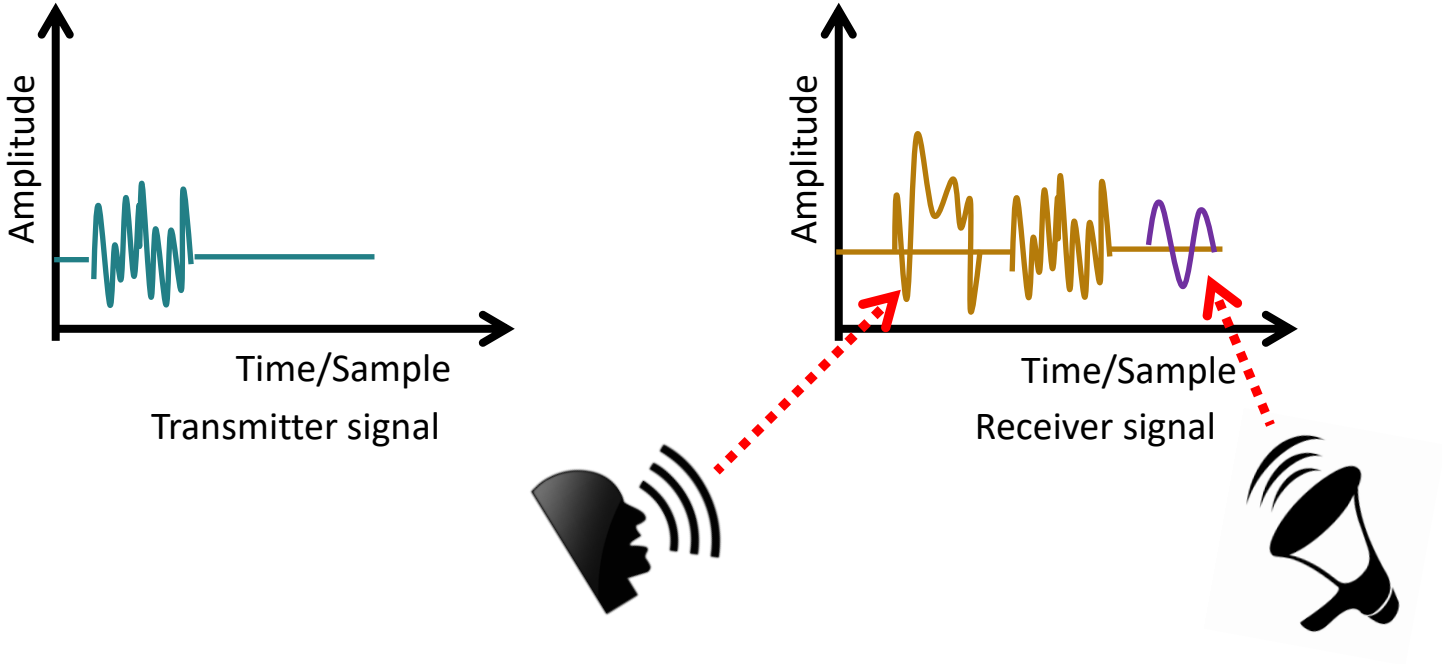



Transmitter signal

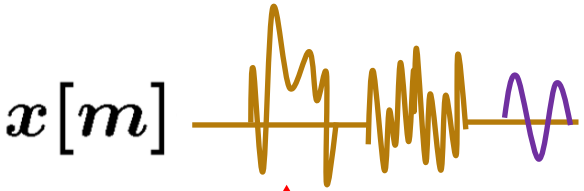



Receiver signal

# Signal Detection



# Signal Detection




Received signal

Signal matching

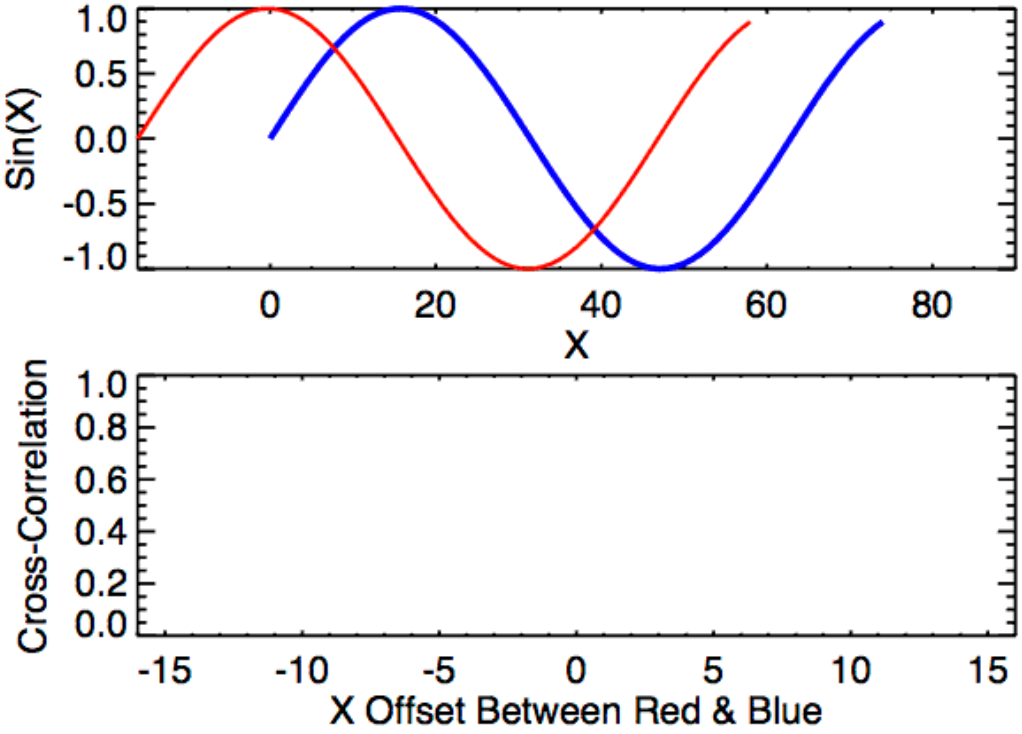

Transmit signal template

## Correlation

$$R_{xy}[k] = \sum_{m=-\infty}^{\infty} x[m]y[m-k]$$

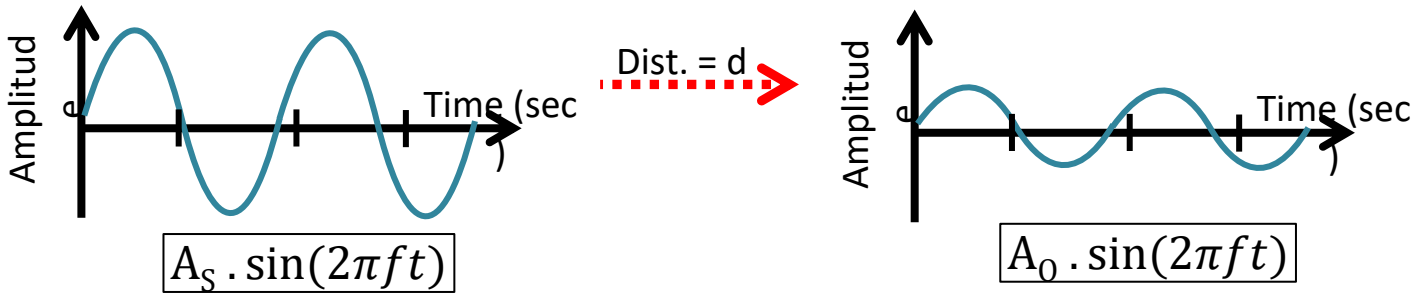
# Signal Detection

## Correlation

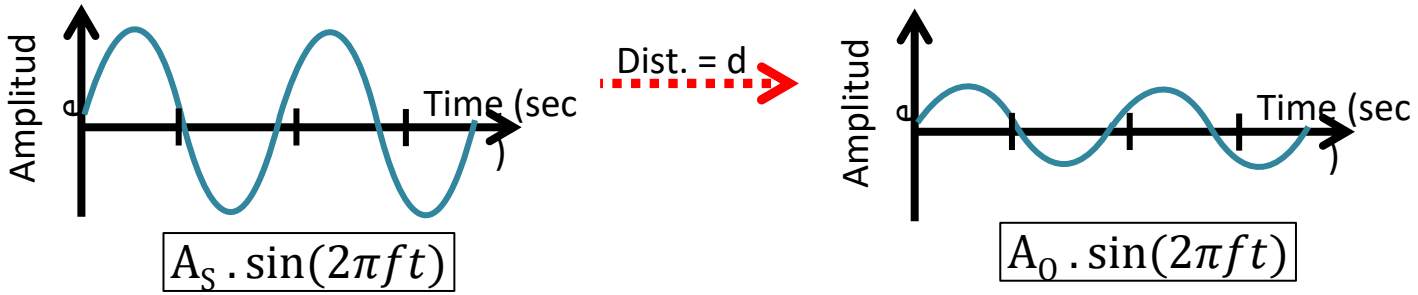


- Distance from the speed information
  - Techniques
  - Signal detection
- Distance from the amplitude information
  - Absorption
  - Propagation loss
- Distance from the frequency information
  - Doppler effect
  - A case study (Doppler + Triangulation)

# Distance from the amplitude information



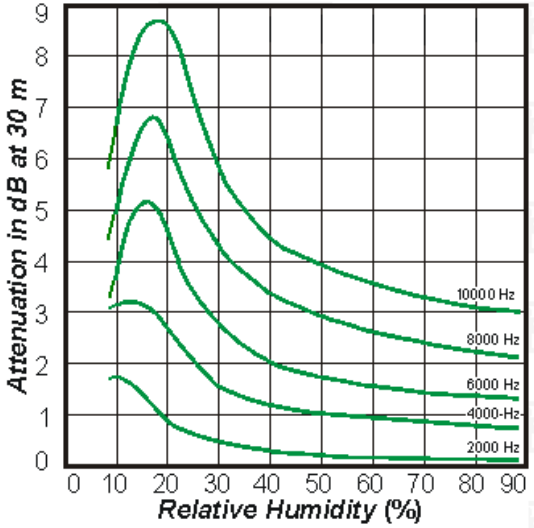
# Distance from the amplitude information




$A_S \cdot \sin(2\pi f t)$

$A_0 \cdot \sin(2\pi f t)$

Attenuation due to atmospheric absorption and diffraction



- Distance from the speed information
  - Techniques
  - Signal detection
- Distance from the amplitude information
  - Absorption
  - Propagation loss
- Distance from the frequency information
  - Doppler effect
  - A case study (Doppler + Triangulation)

# Distance from the frequency information

- Motion of the sound source and/or the observer changes the frequency of the observed signal.
- The change depends on the velocity of the source/observer.
- This phenomena is known as Doppler effect or Doppler shift.

# Doppler Effect

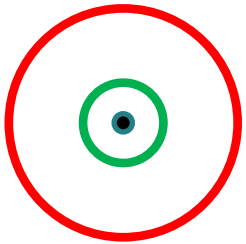
# Doppler Effect

## Simple wave model: Stationary source

Time = t1

# Doppler Effect

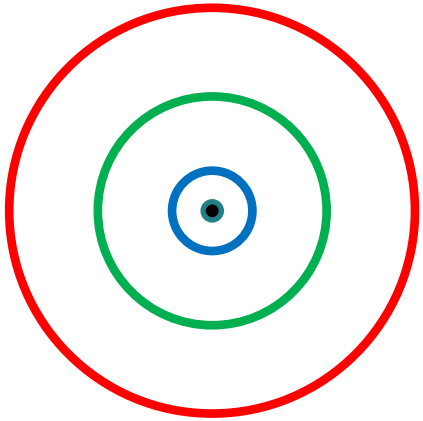
## Simple wave model: Stationary source



Time = t2

# Doppler Effect

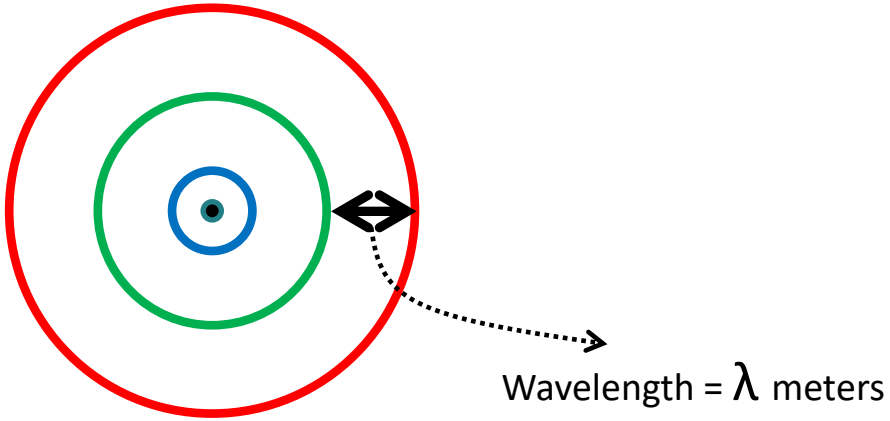
## Simple wave model: Stationary source



Time = t3

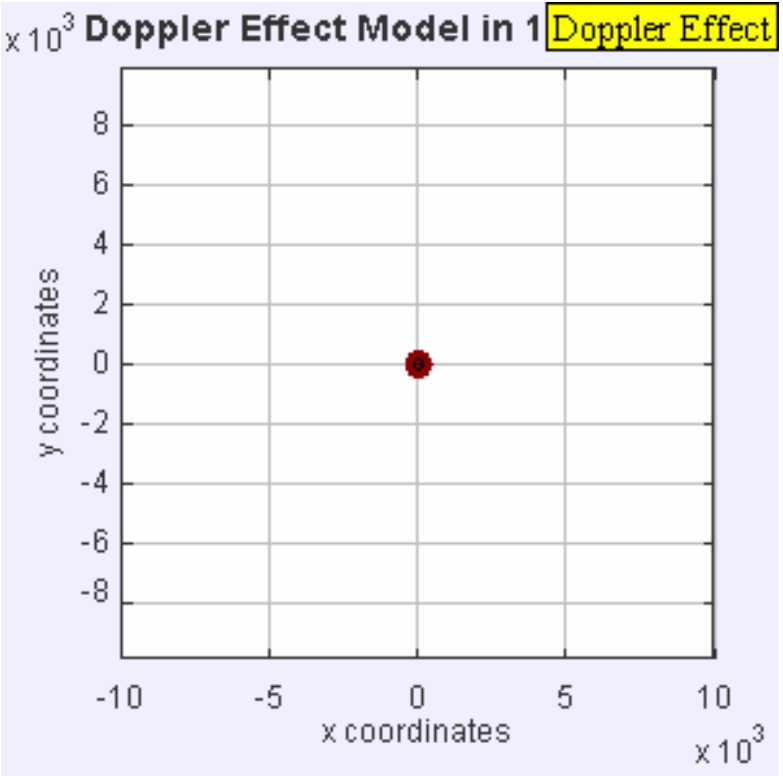
# Doppler Effect

## Simple wave model: Stationary source




## Time = t3

# Doppler Effect



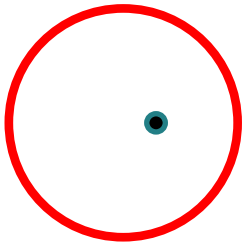
# Doppler Effect

Simple wave model: Moving source

Time = t1

# Doppler Effect

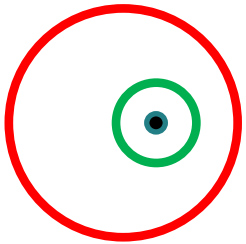
## Simple wave model: Moving source



Time = t2

# Doppler Effect

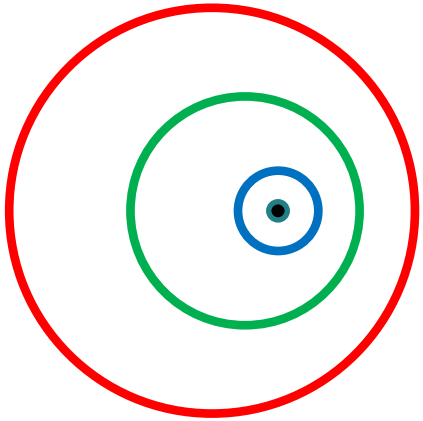
## Simple wave model: Moving source



Time = t2

# Doppler Effect

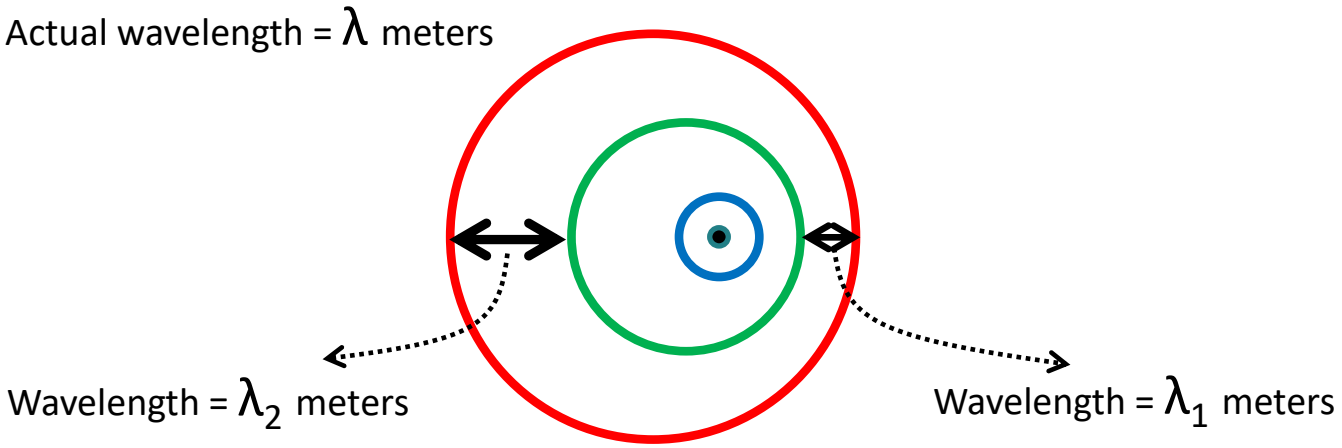
Simple wave model: Moving source



Time = t3

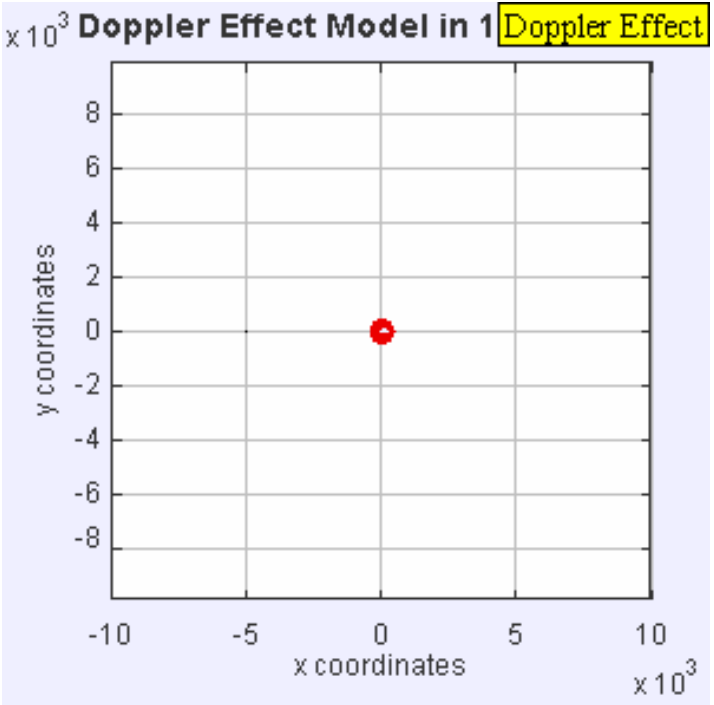
# Doppler Effect

## Simple wave model: Moving source




## Time = t3

# Doppler Effect



# End of This Chapter