http://www.mit.edu/~fadel/courses/MAS.s60/index.html

MAS.S60

# How to Wirelessly Sense Almost Anything

## Lecture 3:
## Fundamentals of Wireless Sensing


Lecturers

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TA

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# *This Week in Wireless Sensing*

GIZMODO

GADGETS

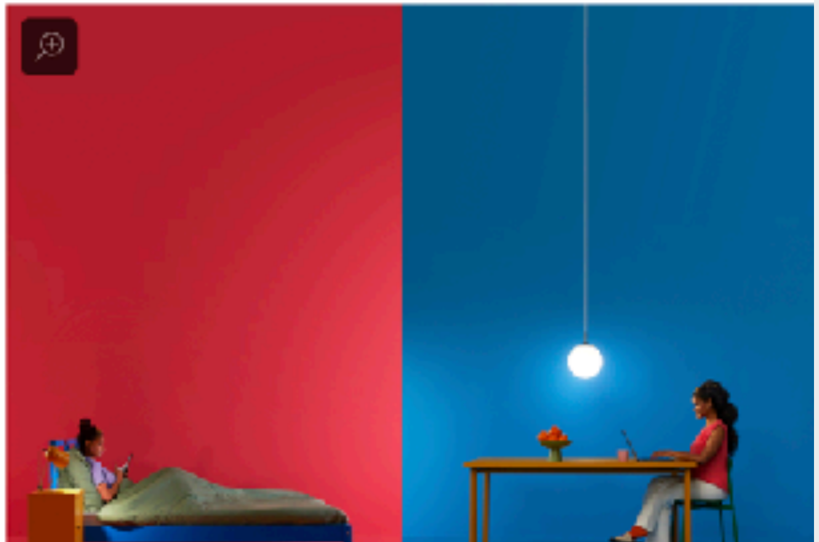
## WiZ's Smart Lights Can Detect Presence Now—No Motion Se

Required

It makes automatic lighting accessible without having to set up a rou

By Florence Ion

9/16/22 4:00PM | Comments (7) | Alerts



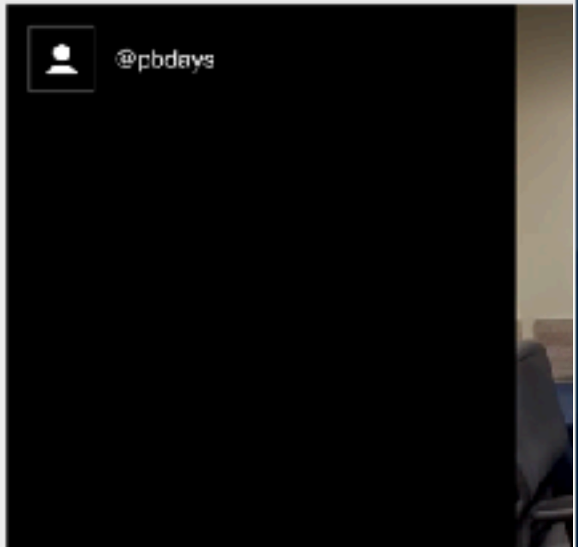
## Your Raptor Lake PC sleep when you leave

By Jacob Ridley published 13 days ago

Using only standard Wi-Fi technology.

COMMENTS

Listen to this article




## This at-home radio sensor could help monitor symptoms of patients with Parkinson's

The router-like device can track treatments for the neurological disease, too.

# Objectives of Today's Lecture

Learn the fundamentals, applications, and implications of
**contactless wireless sensing**

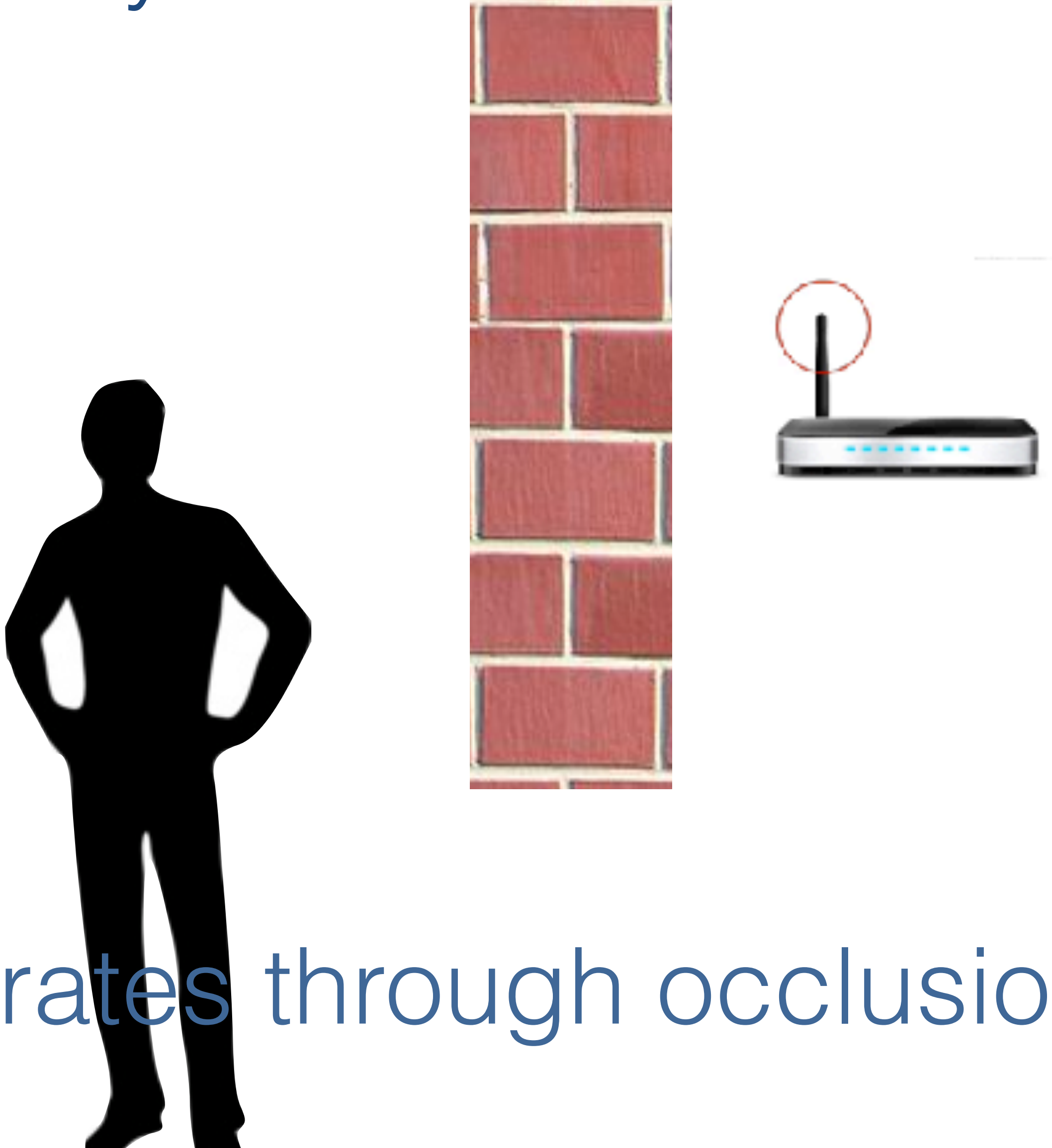
1. What is wireless (aka WiFi) sensing?
2. How do seeing through wall systems work?
3. How can we monitor human vital signs using wireless signals?
4. What are the industry opportunities and societal implications of wireless sensing (today and in the near+far future)?

# Last Week

## Device-based Localization

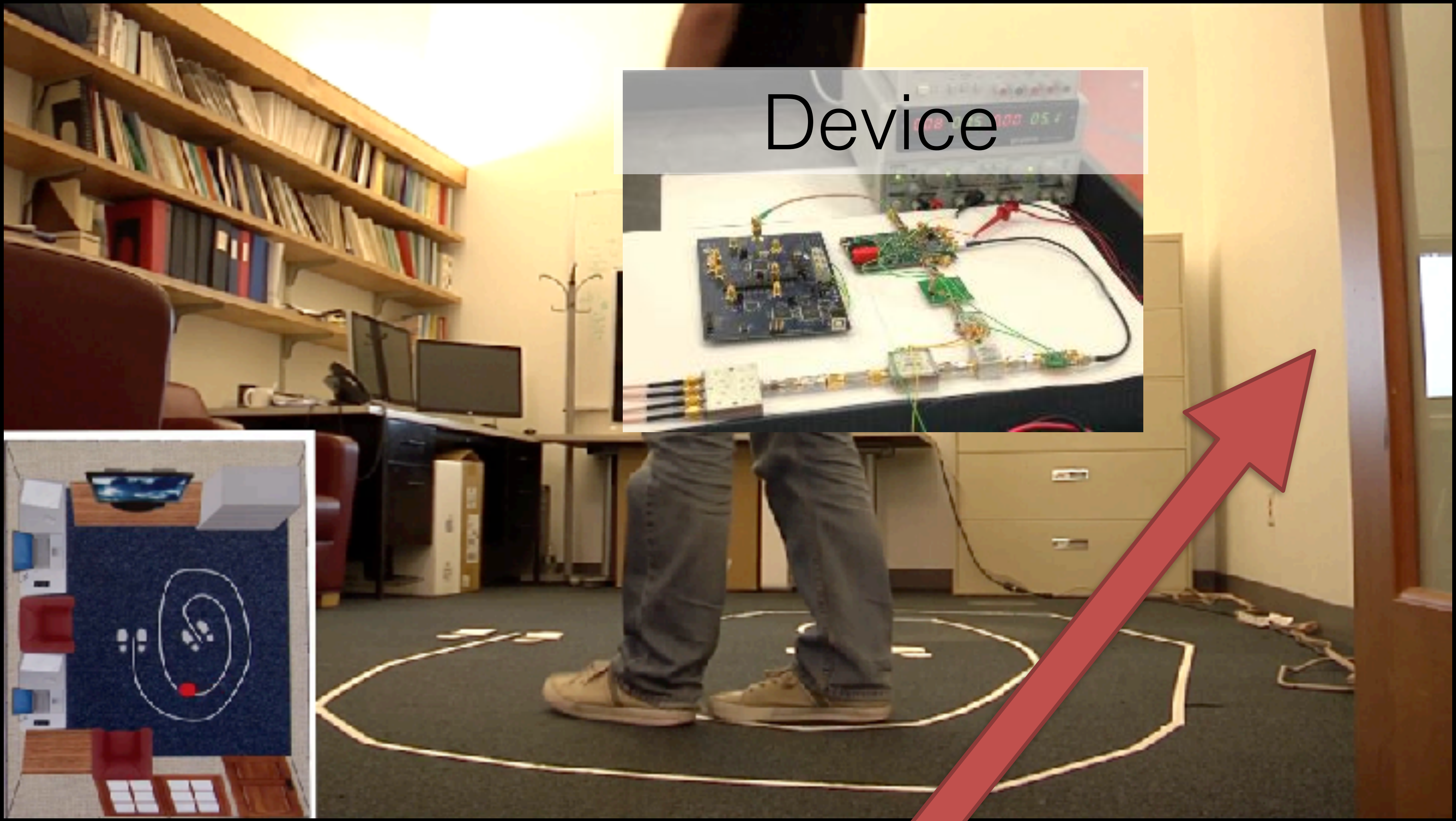
# Today: Device-Free Localization
# (aka Wireless Sensing)

Using radio signals to track humans without any sensors on their bodies



Operates through occlusions

# Example: WiTrack

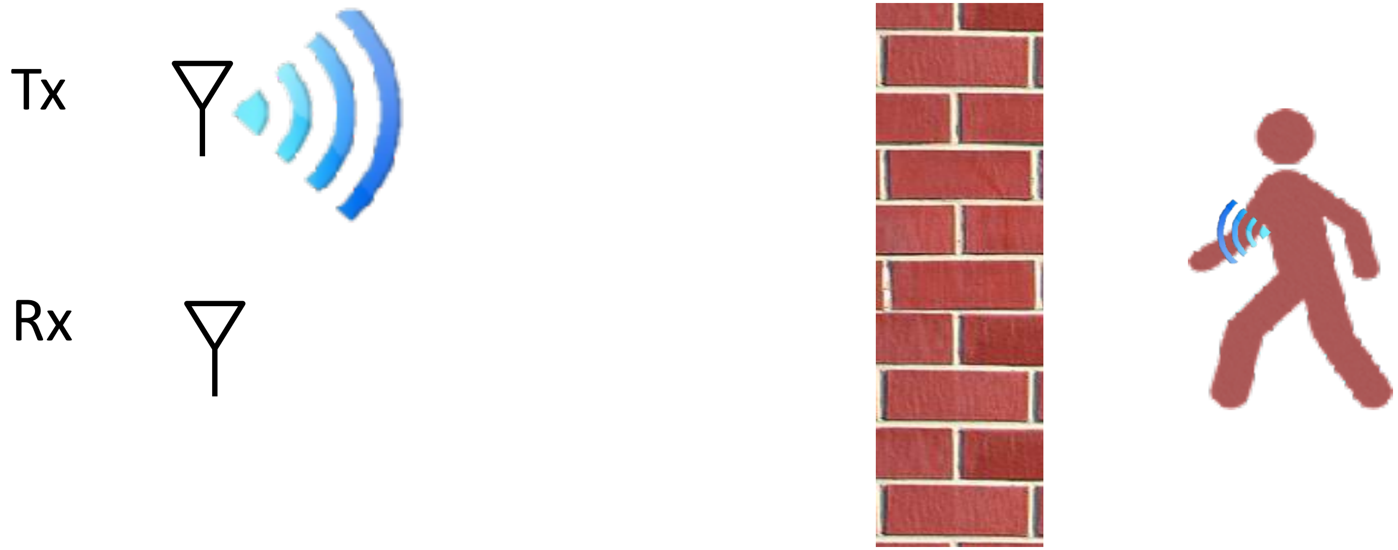



Device in another room

# Applications



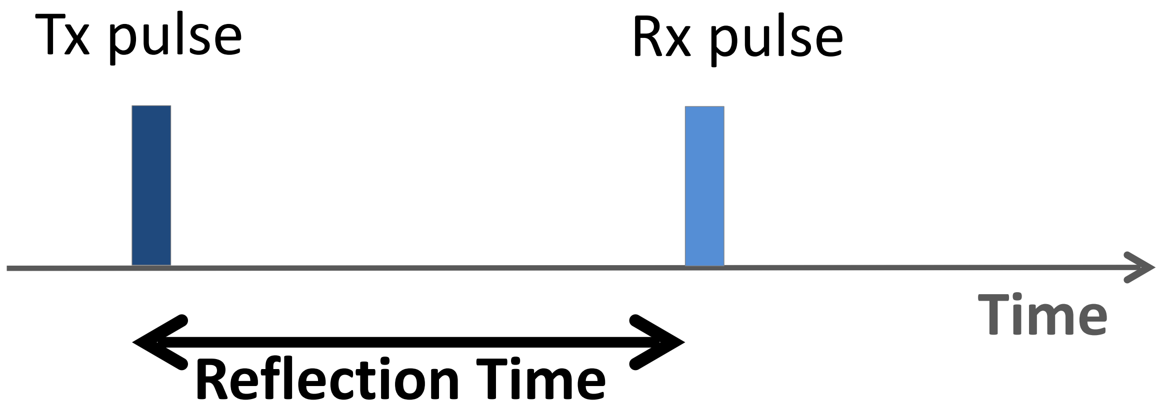
# Measuring Distances




Distance = Reflection time x speed of light

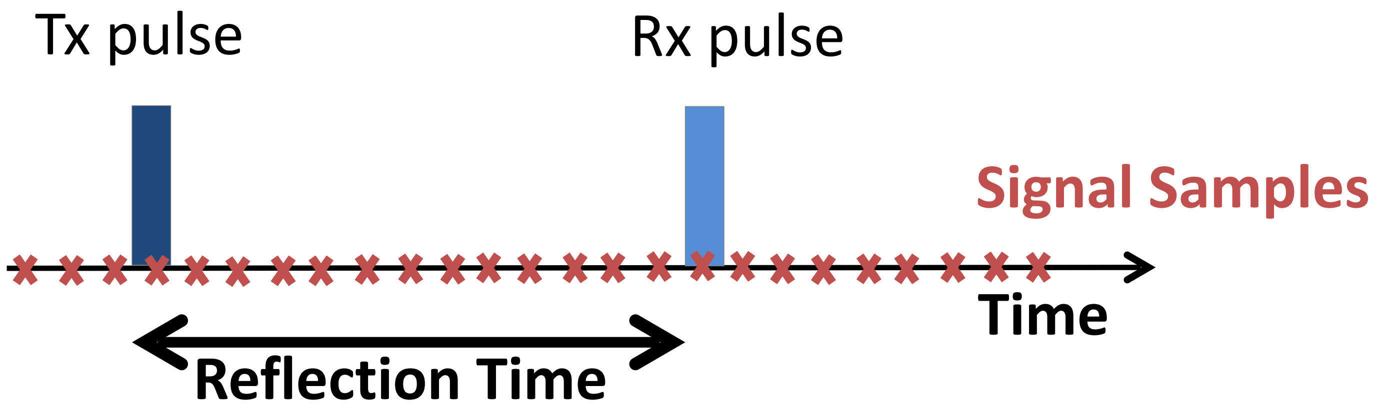
# Measuring Reflection Time

Option1: Transmit short pulse and listen for echo



# Measuring Reflection Time

Option1: Transmit short pulse and listen for echo




**Capturing the pulse needs sub-nanosecond sampling**

**Why?**

What if instead of RF we use ultrasound?

## Capturing the pulse needs sub-nanosecond sampling

**Why?**

Distance = time x speed

"smallest distance resolution"

"smallest time"

$$10cm = \Delta t \times (3 \times 10^8)$$

$$\Delta t = 0.3ns$$

0.3ns period => how many samples per second?

$$SamplingRate = \frac{1}{\Delta t}$$

3GSps! >> MSps for WiFi, LTE…

Multi-GHz samplers are expensive, have high noise, and create large I/O problem

---

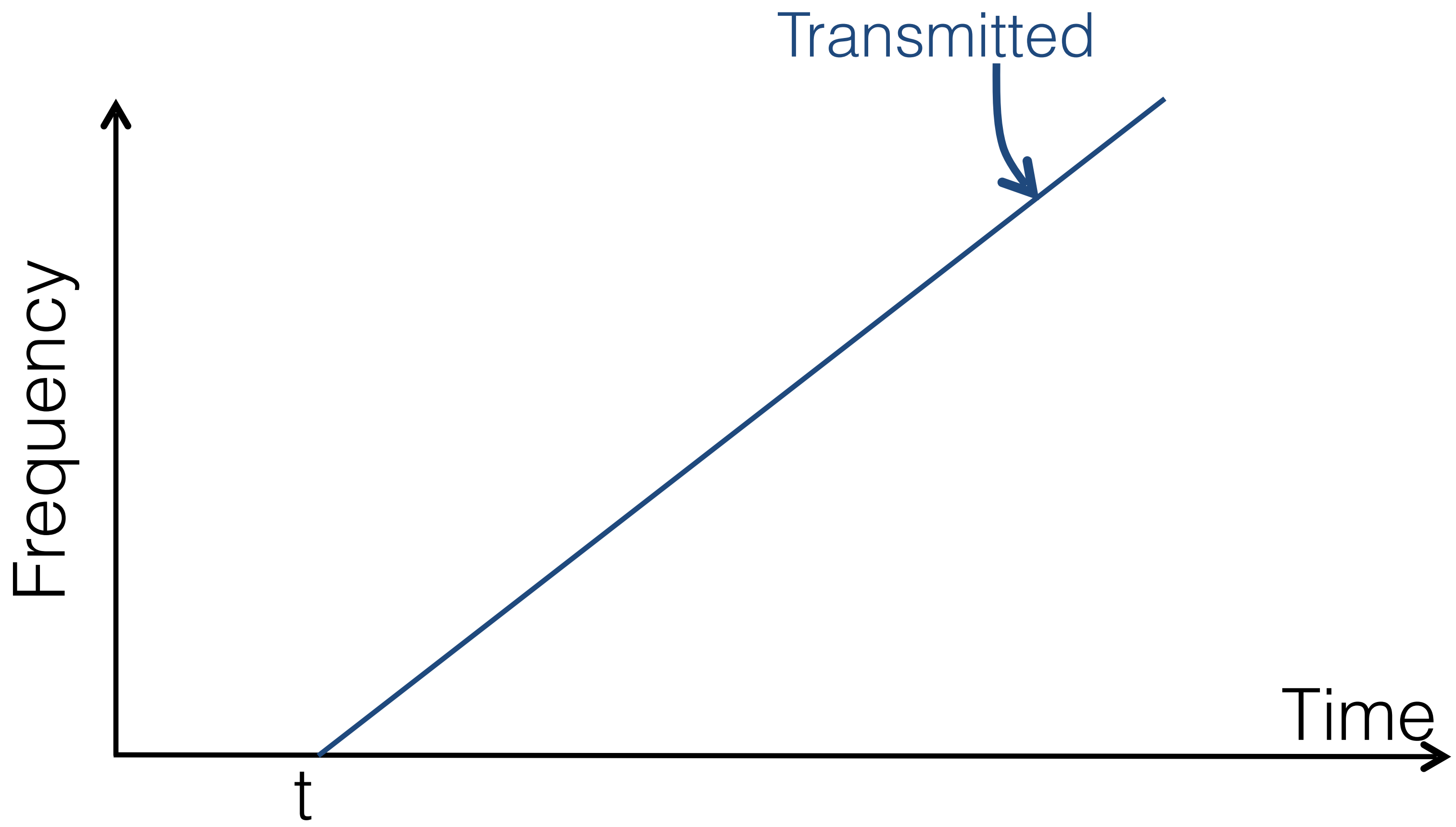
## Why if instead of RF we use ultrasound?

because speed of ultrasound

$$10cm = \Delta t \times 345$$

$$SamplingRate = \frac{1}{\Delta t} \approx 3kbps$$

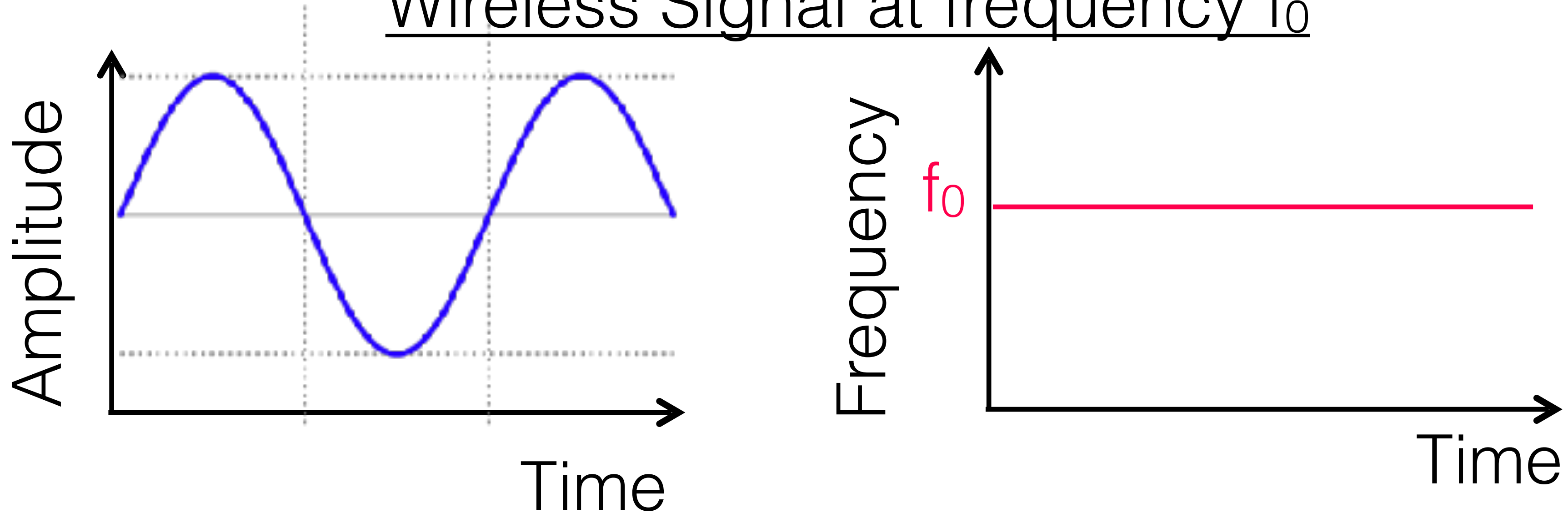
# FMCW: Measure time by measuring frequency



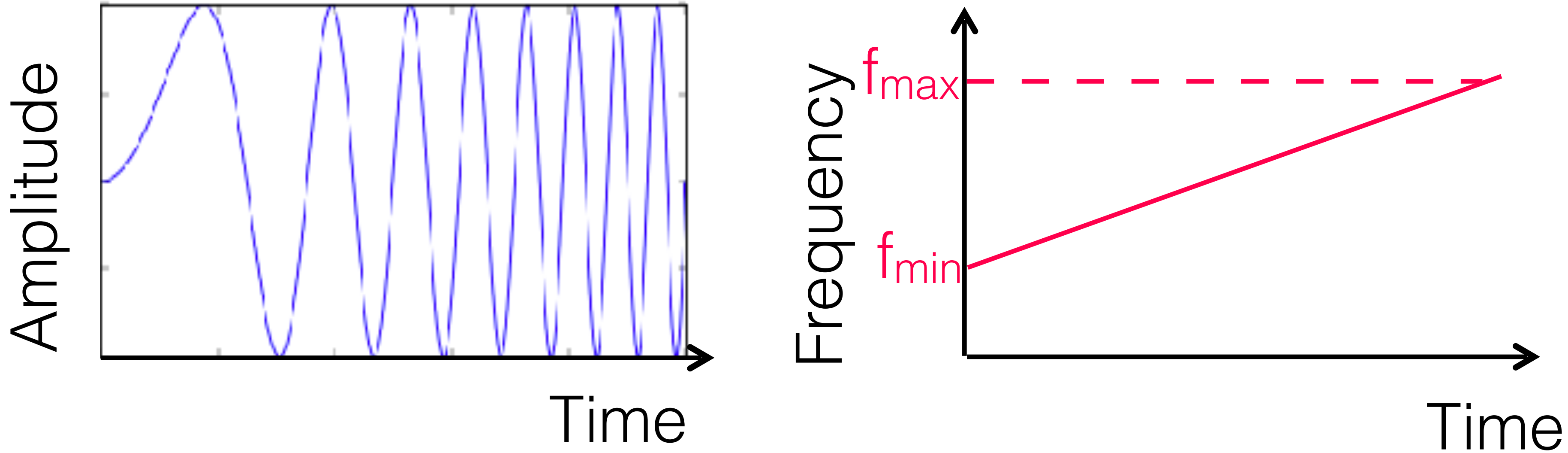

**How does it look in time domain?**
**(and in comparison to single frequency)**

# More intuitive understanding of FMCW

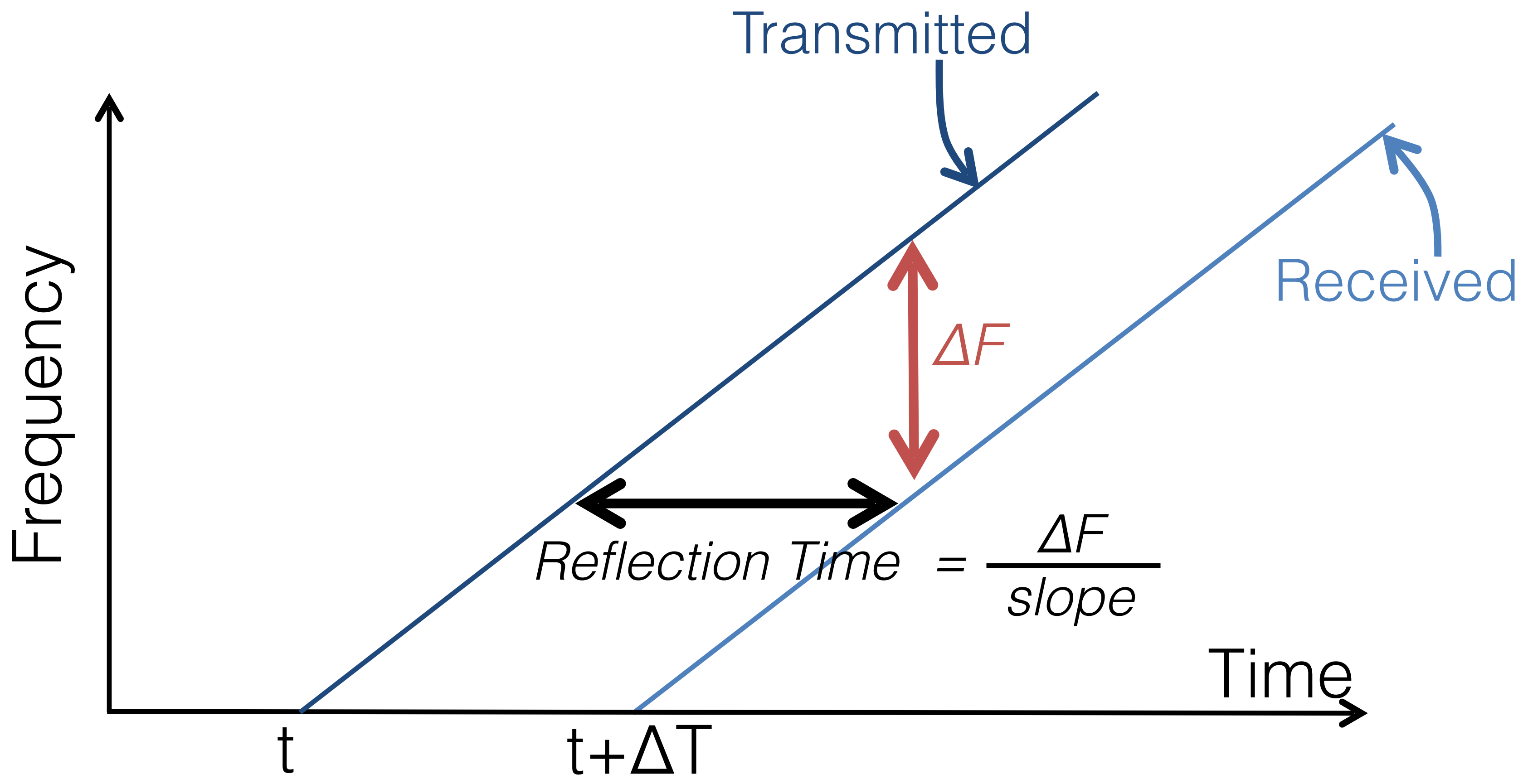
Wireless Signal at frequency $f_0$




FMCW signal



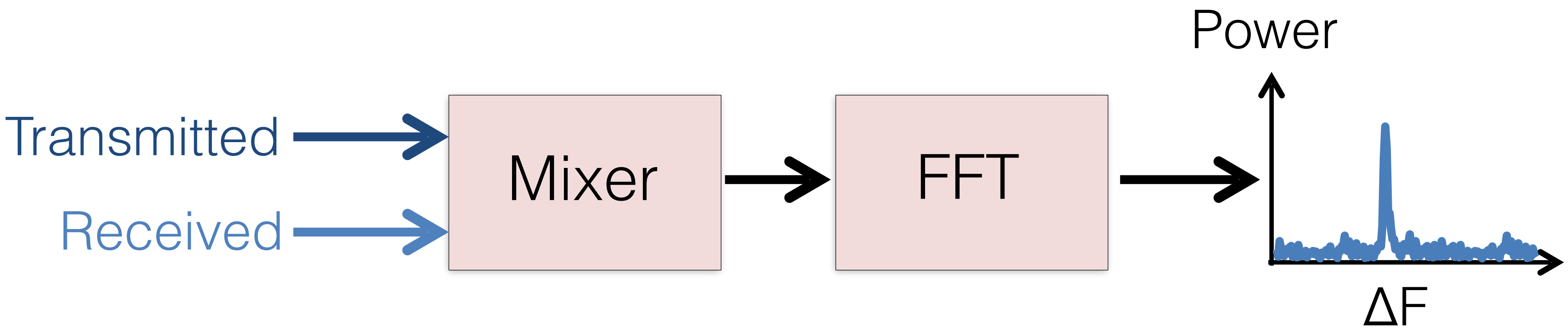
# FMCW: Measure time by measuring frequency




How do we measure ΔF?

# Measuring ΔF

- Subtracting frequencies is easy (e.g., removing carrier in WiFi)
- Done using a mixer (low-power; cheap)

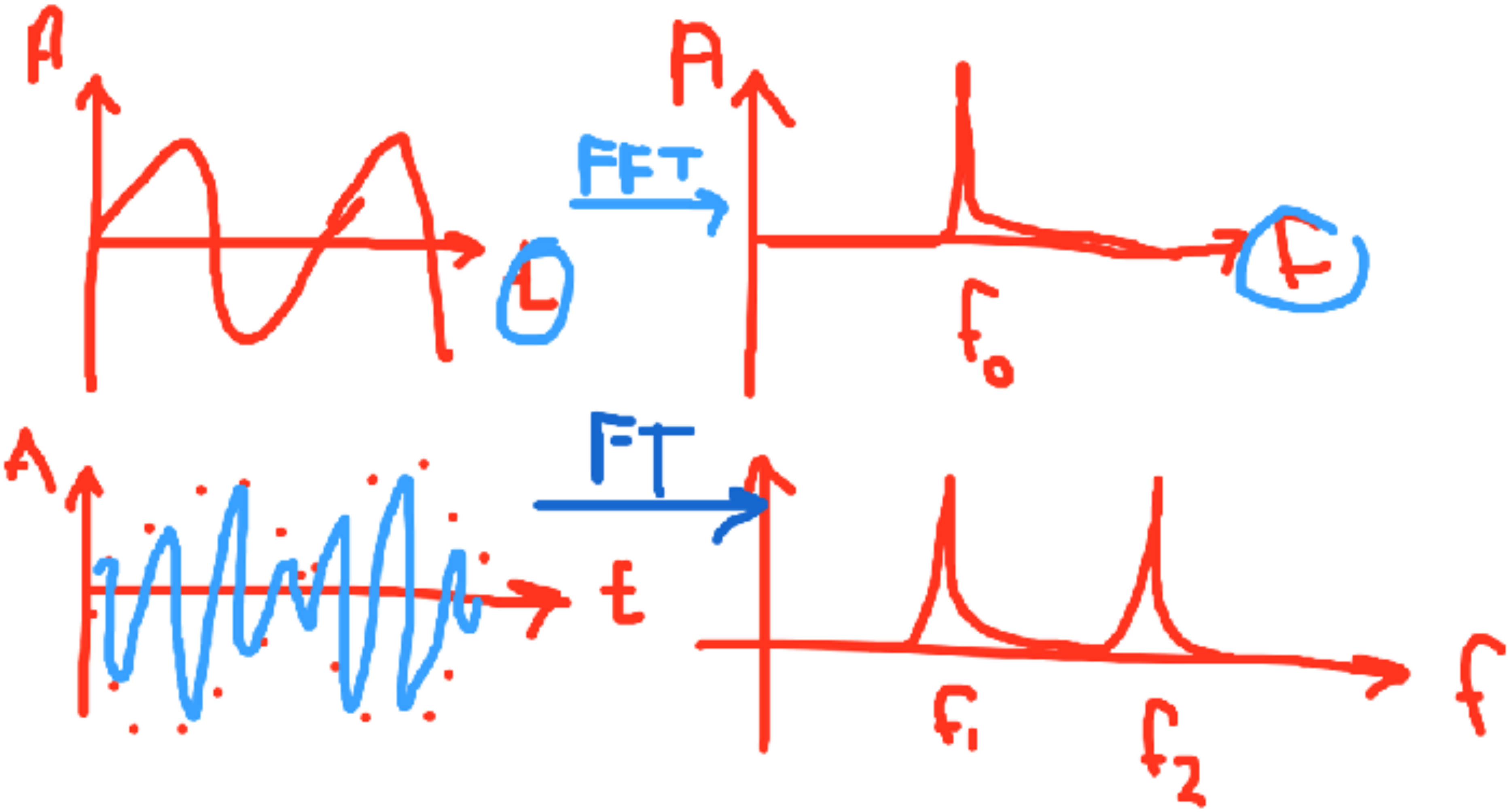



Signal whose frequency is ΔF

let's talk about FFTs a bit — freq

# Basics of Fourier Transform

# Basics of Fourier Transform



# Measuring ΔF

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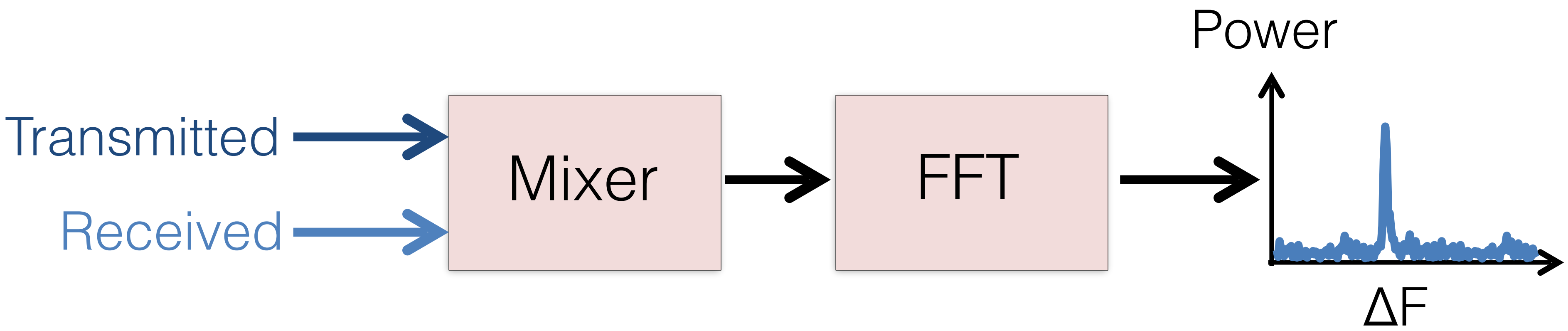
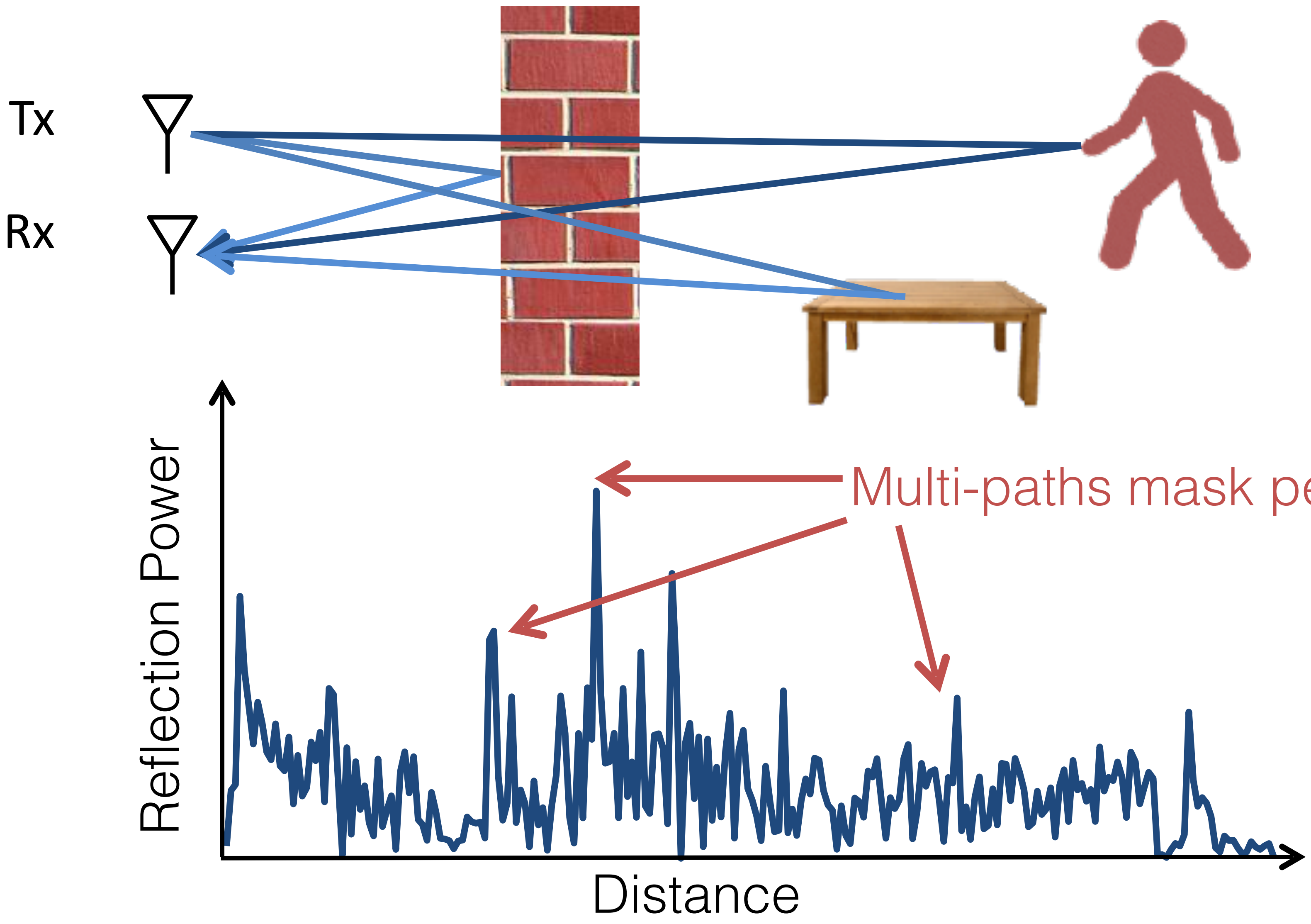



Signal whose frequency is ΔF

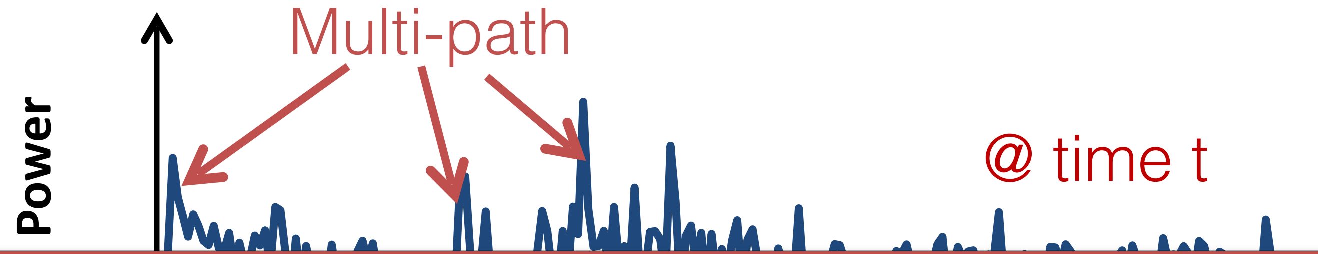
**ΔF → Reflection Time → Distance**

# Challenge: Multipath→ Many Reflections

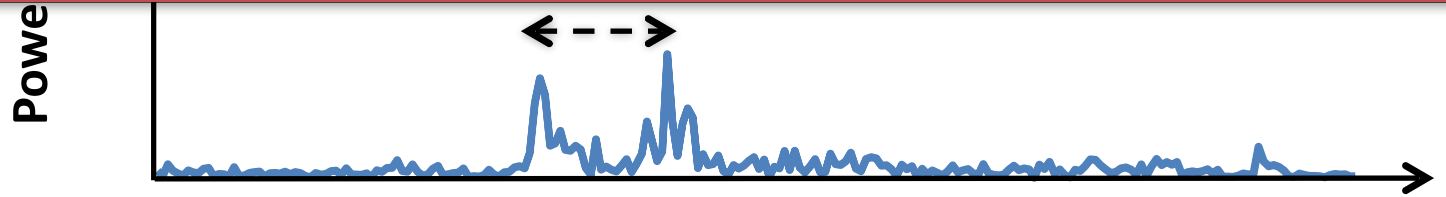


Static objects don't move

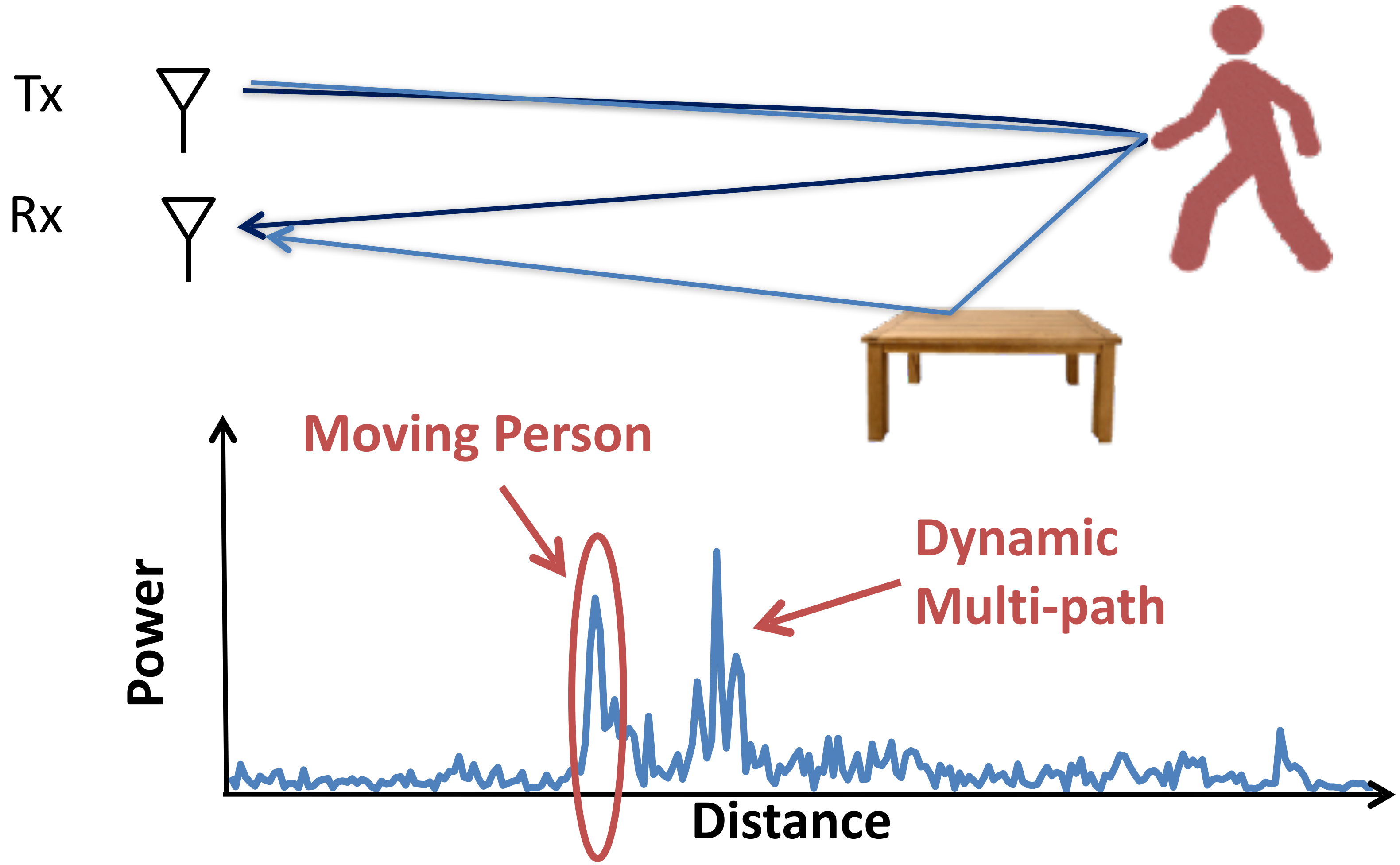
➔ Eliminate by subtracting consecutive measurements




Why 2 peaks when we only have one moving person?

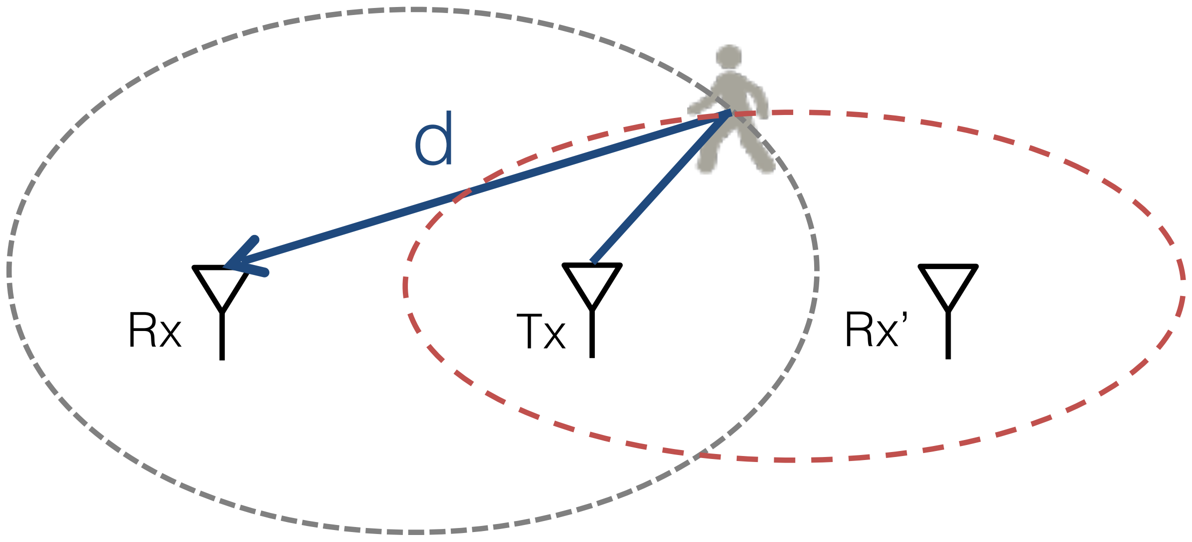


# The direct reflection arrives before dynamic multipath!



# Mapping Distance to Location

Person can be anywhere on an ellipse whose foci are (Tx,Rx)

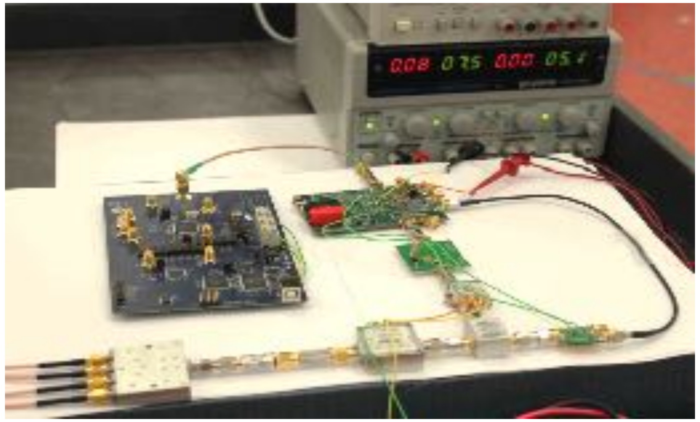



By adding another antenna and intersecting the ellipses, we can localize the person

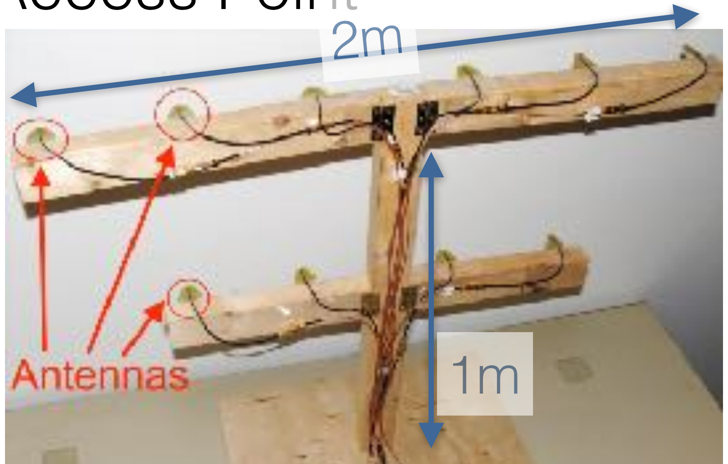
# From Location to tracking (over time)

# Implementation

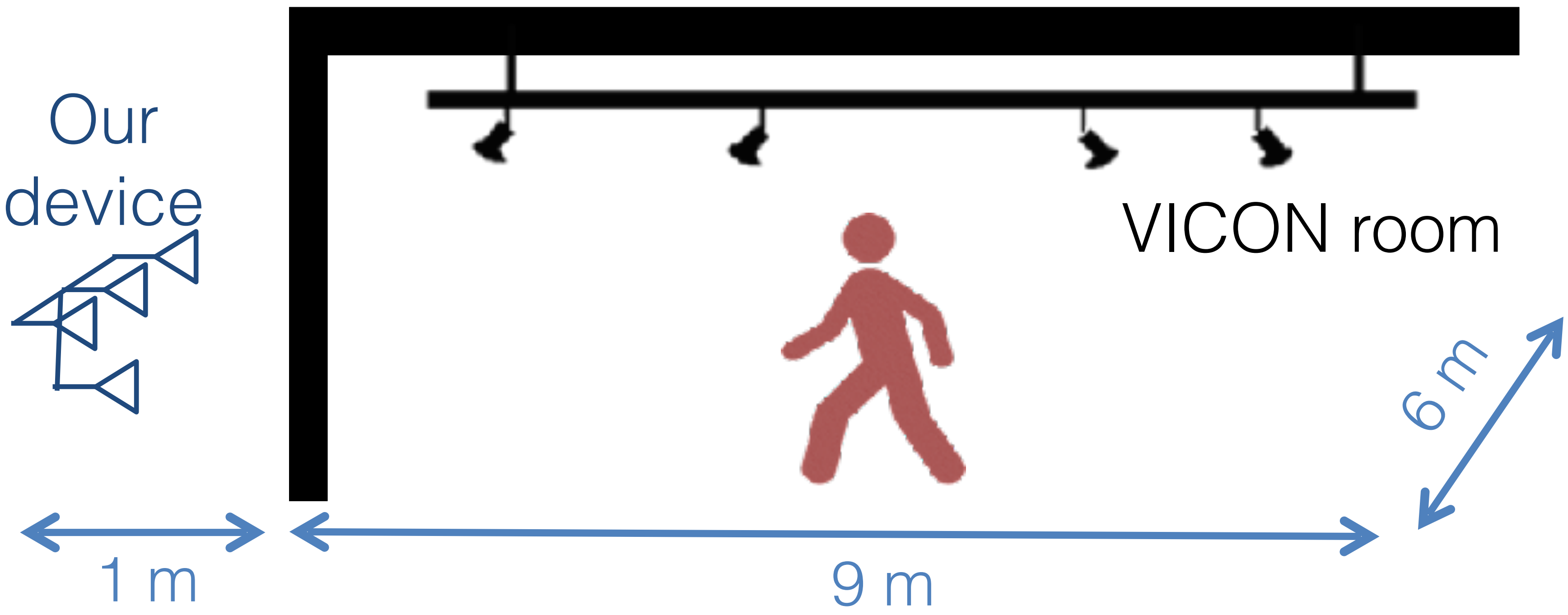
- Built FMCW front-end
  - Connected to USRP



- Band: 5.5-7.2 GHz
- Transmit 70 $\mu$W
  - 1000x lower power than WiFi Access Point
- 5 Tx, 5 Rx antennas



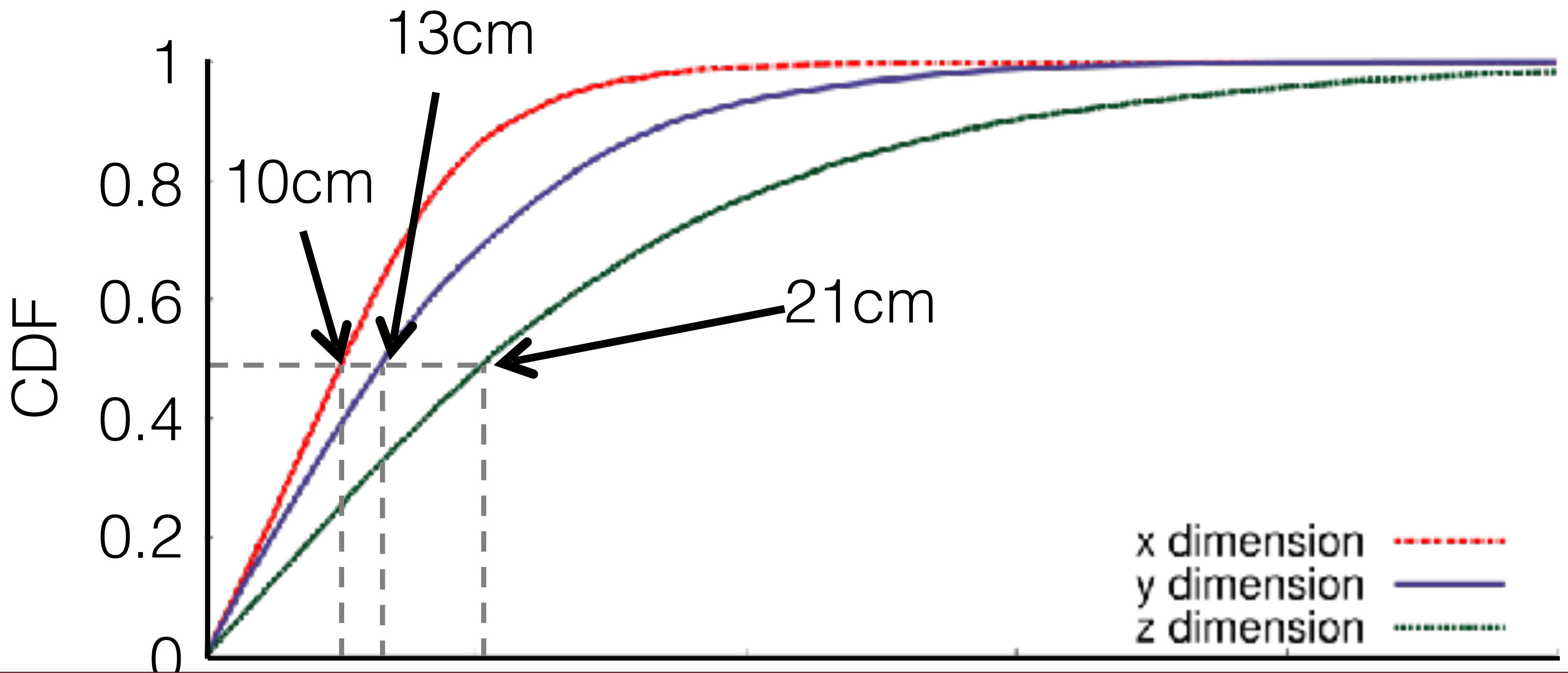
# Ground Truth via VICON




- VICON uses an array of infrared cameras on the ceiling and operates in line-of sight
  - It achieves sub-cm-scale accuracy
- Our device is placed outside the room

# Through-Wall Localization Accuracy

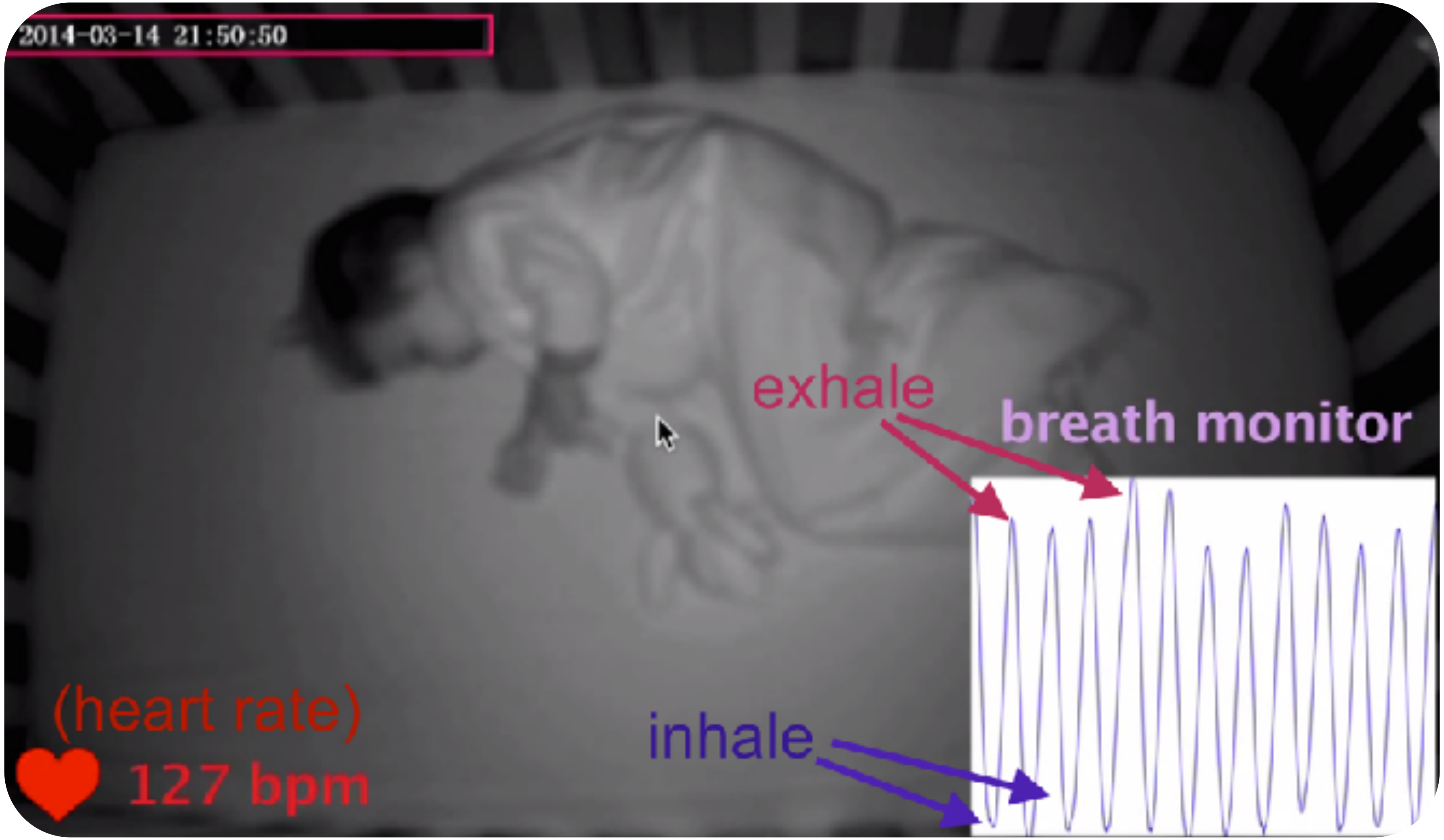
100 experiments: ½ million location measurements



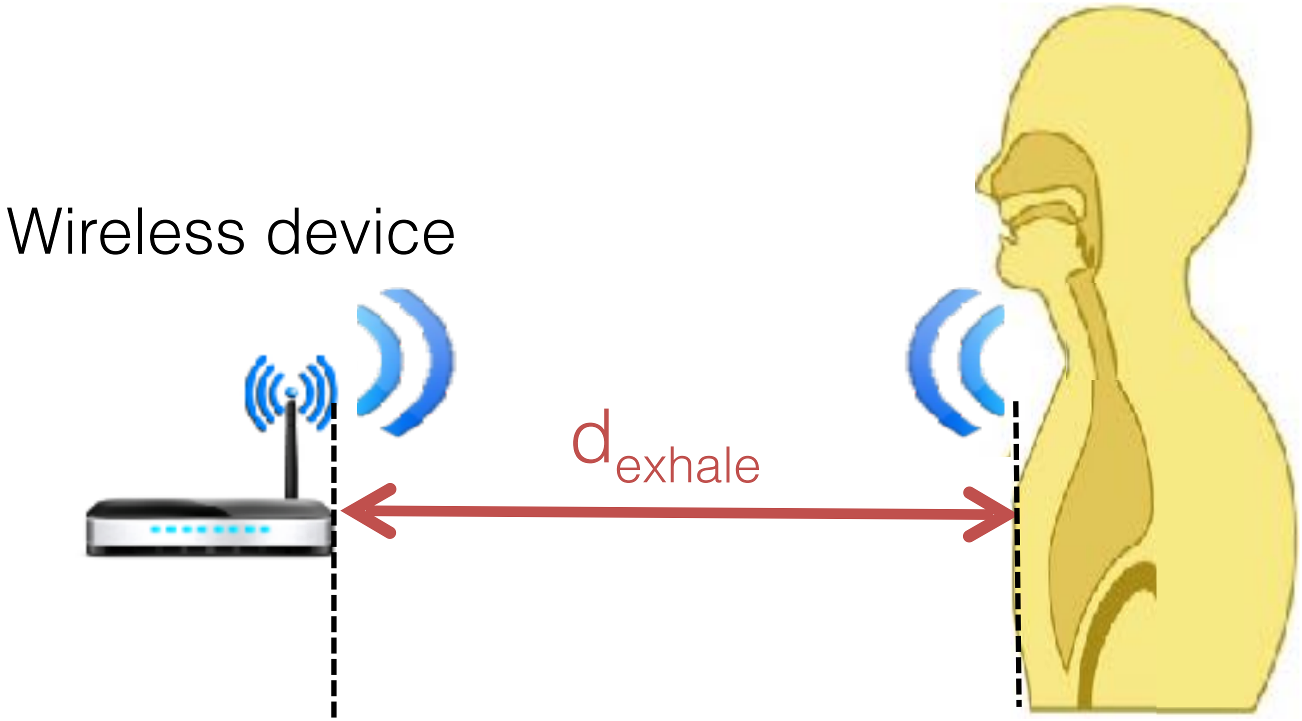

Centimeter-scale localization without requiring the user to carry a wireless device

# Remotely Measuring Breathing and HR

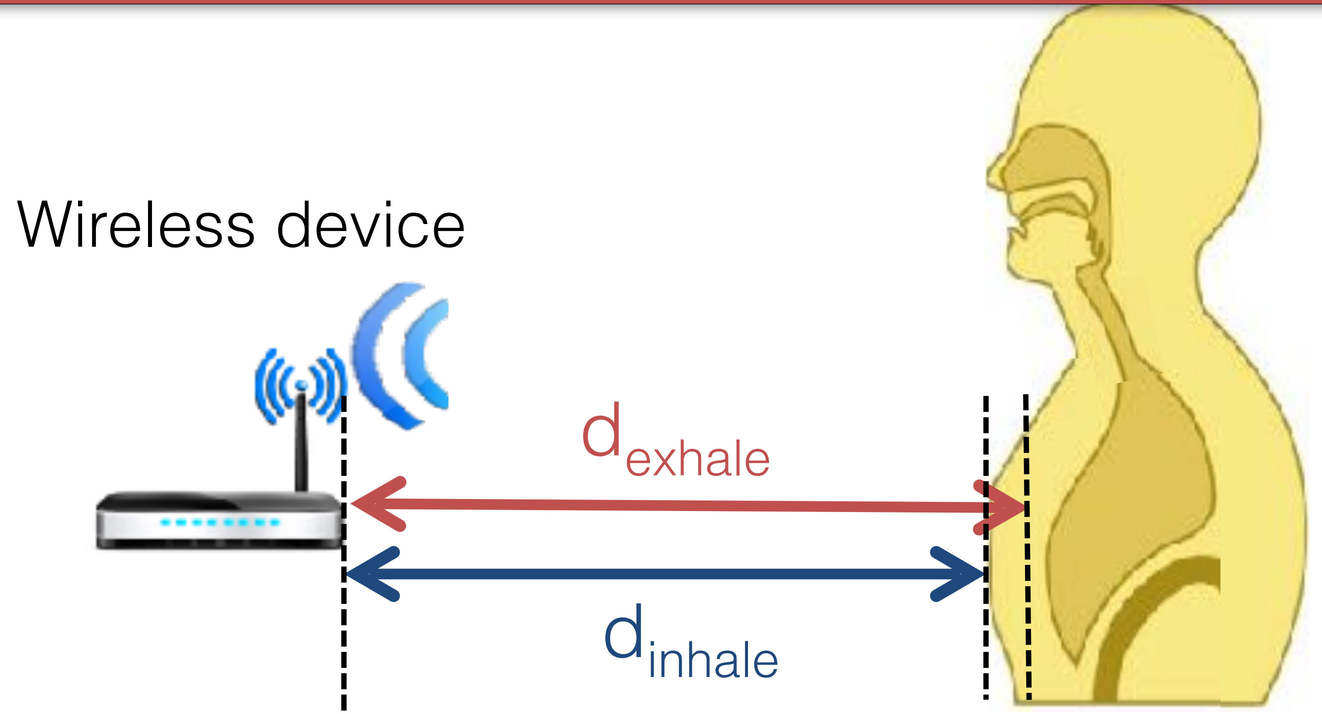
[CHI'15]



# Idea: Use wireless reflections off the human body

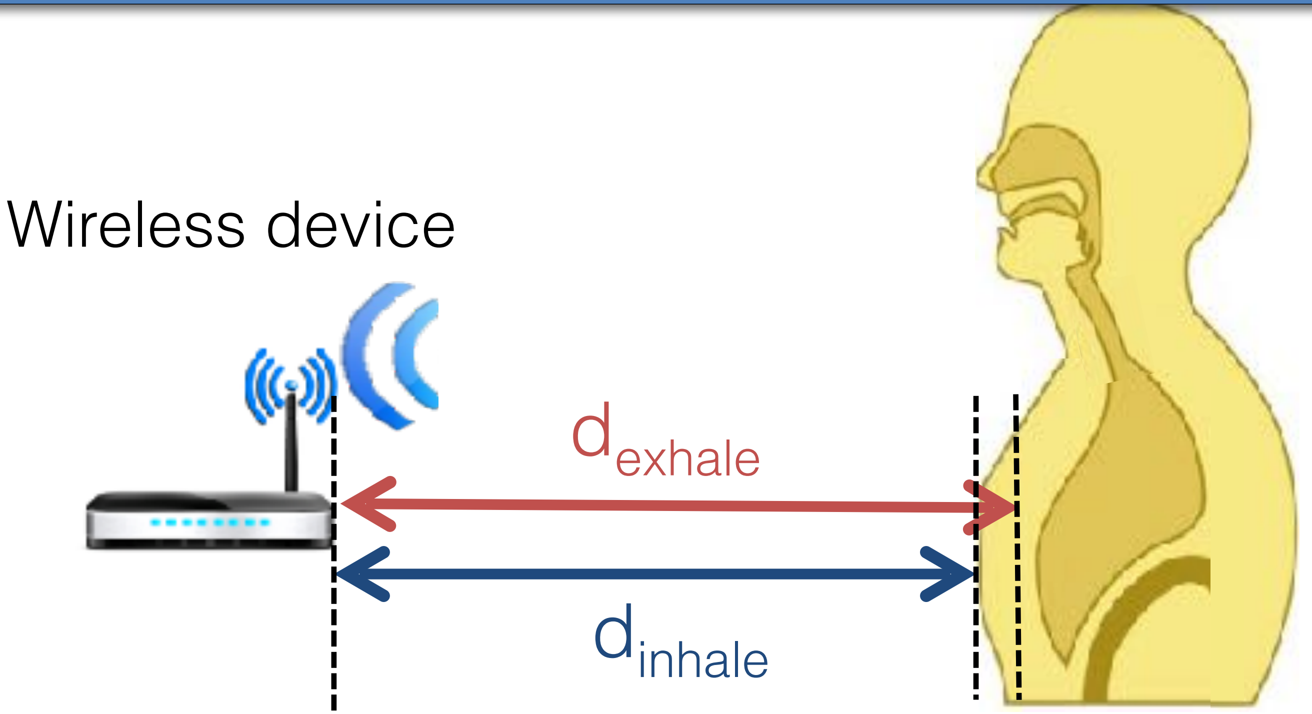


Problem: Localization accuracy is only 12cm and cannot capture vital signs




Why? How did we compute the resolution?

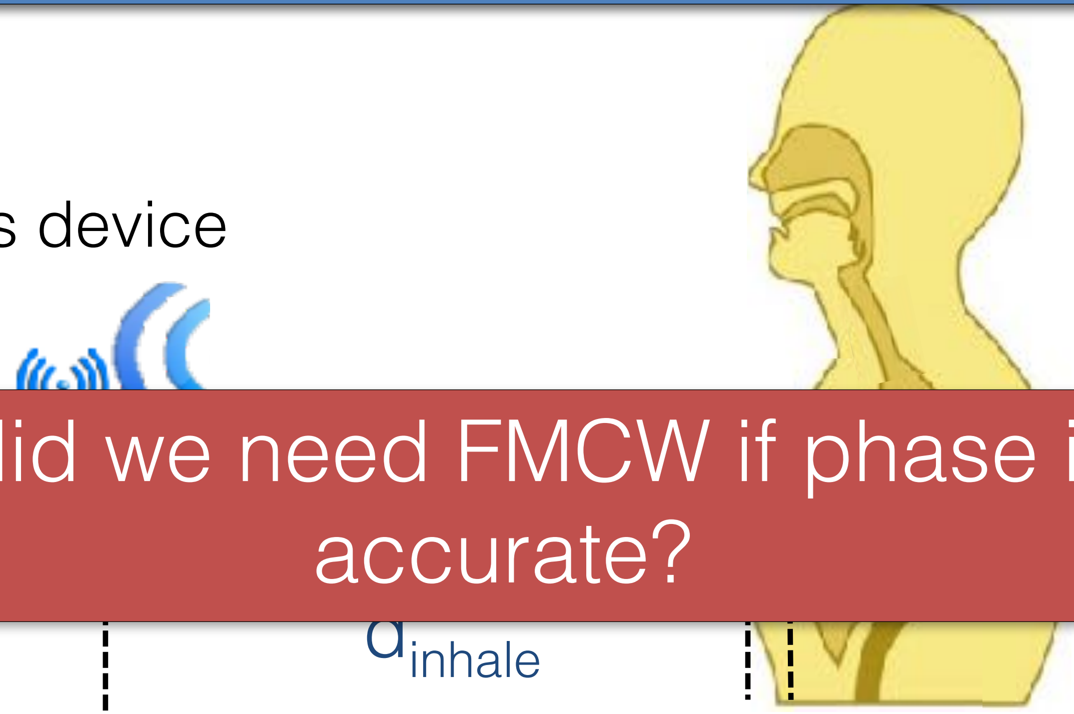
# Solution: Use the phase of the wireless reflection




Why does phase allow us to get the distance at higher granularity?

# <u>Solution:</u> Use the phase of the wireless reflection

Wireless device

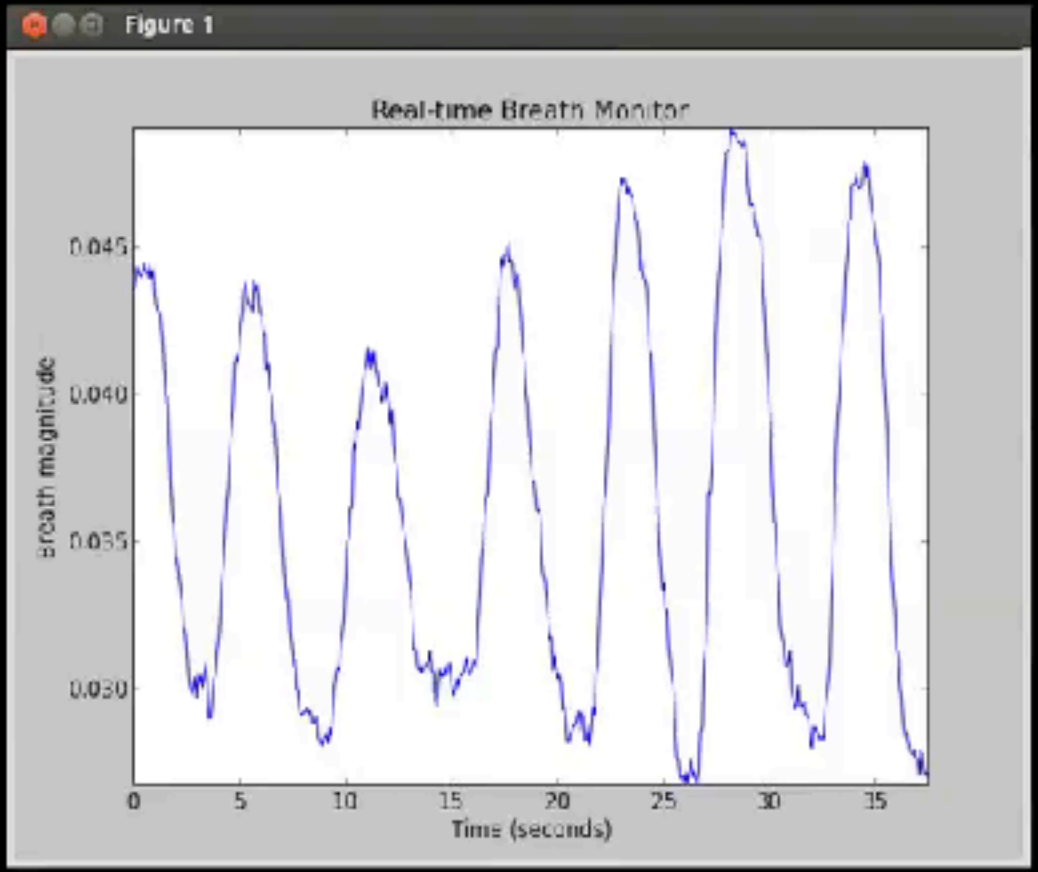



**Why did we need FMCW if phase is so accurate?**

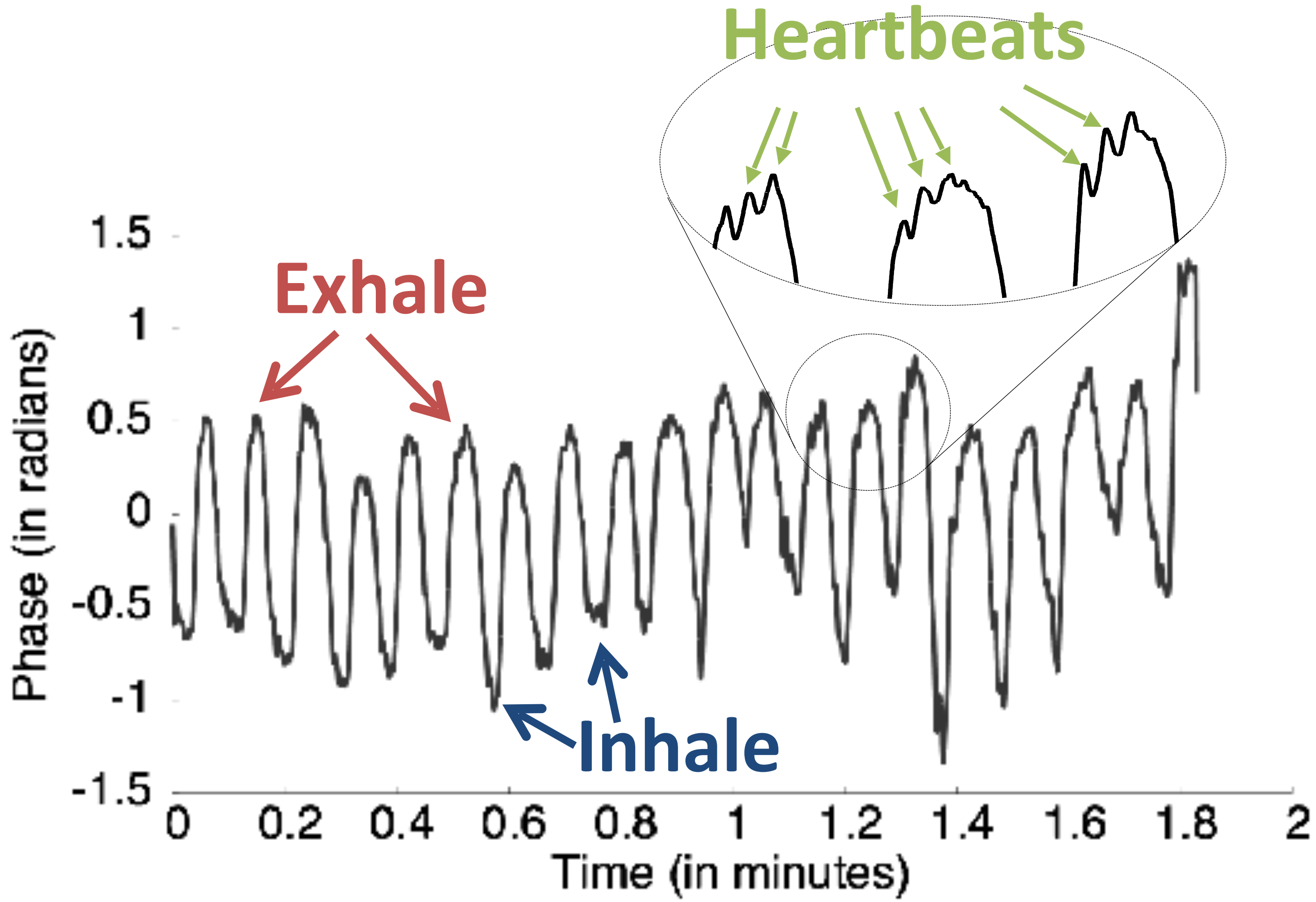
Wireless wave has a phase: $\phi = 2\pi \frac{distance}{wavelength}$

- Chest Motion changes distance
- Heartbeats also change distance

# Breath Monitoring using Wireless (Vital-Radio, 2015)



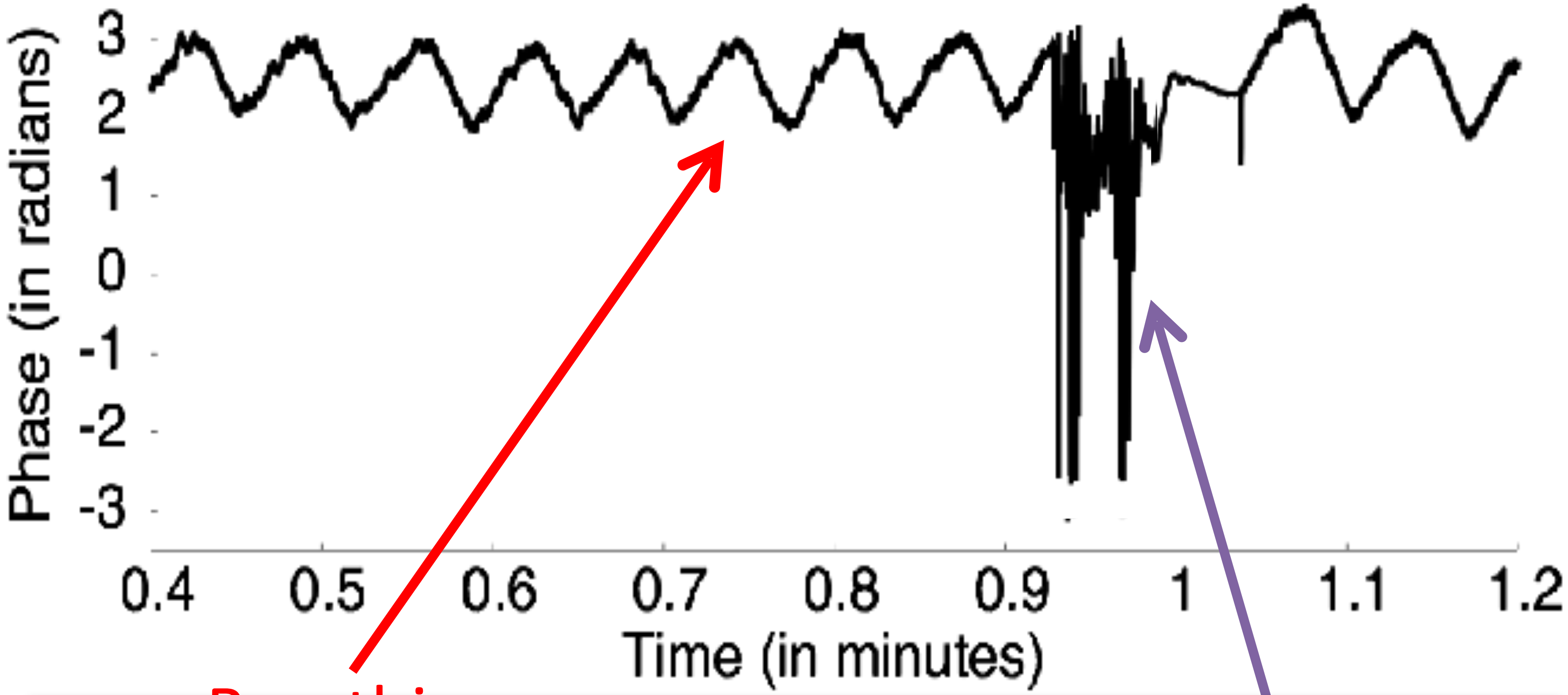

Let’s zoom in on these signals




How do we get from here to extracting breathing rate and heart rate?

# What happens when a person moves his limb?

# What happens when a person moves his limb?

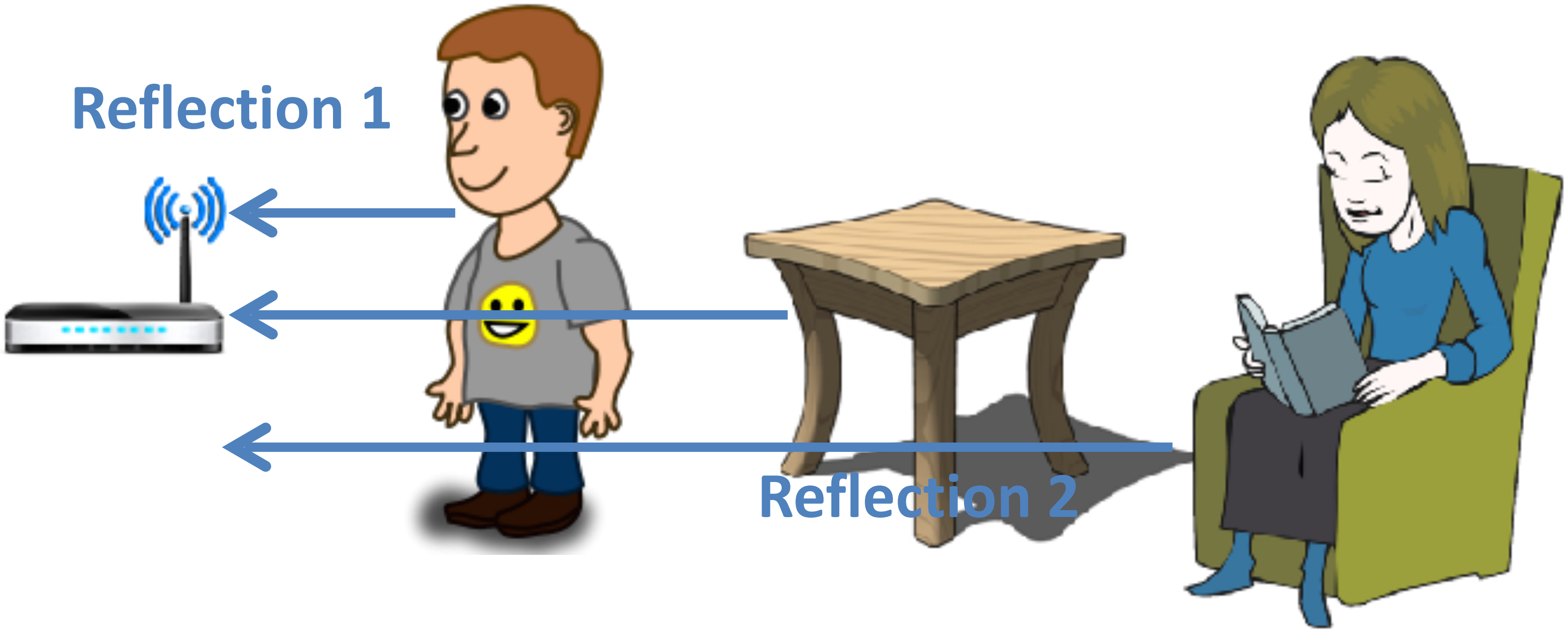



**Band-pass filter the cleaned signals to extract breathing and heart rate**

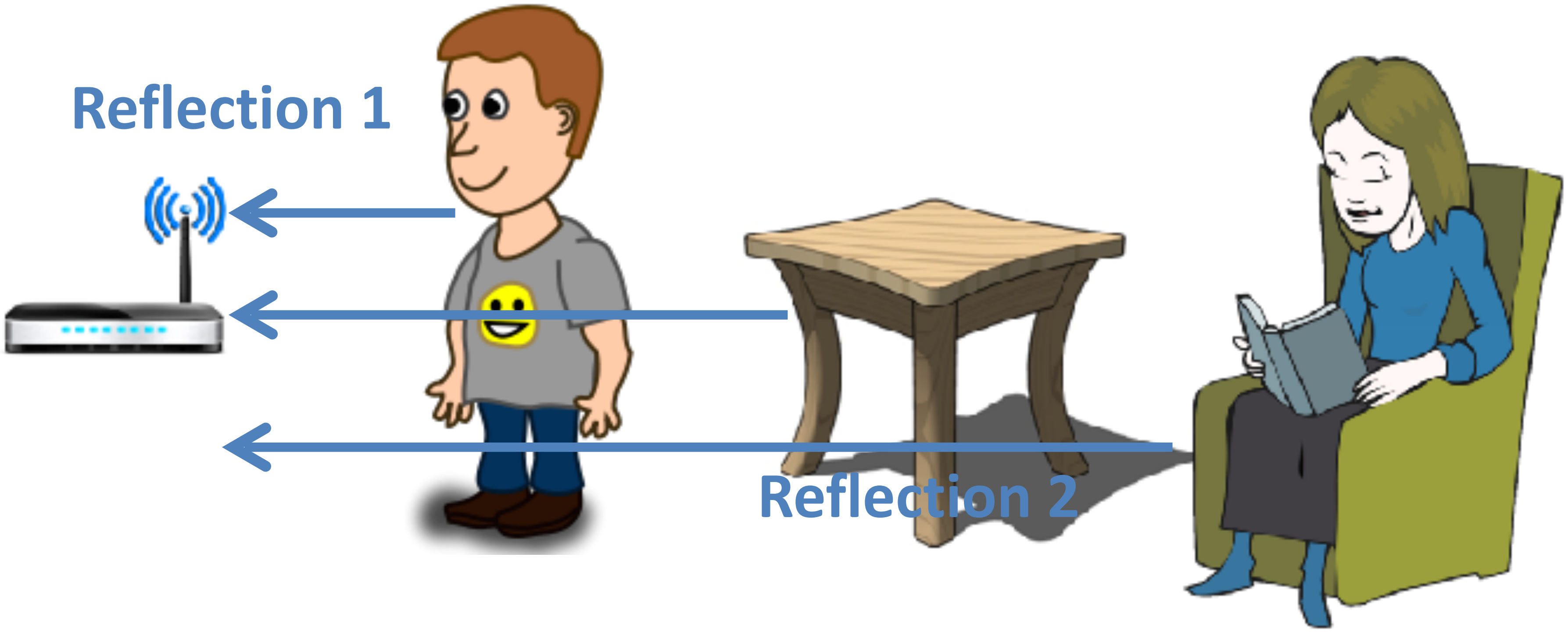
# What happens with multiple users in the environment?

# Reflections from different objects collide

**<u>Problem:</u> Phase becomes meaningless!**



# Solution: Use WiTrack as a filter to isolate reflections from different positions



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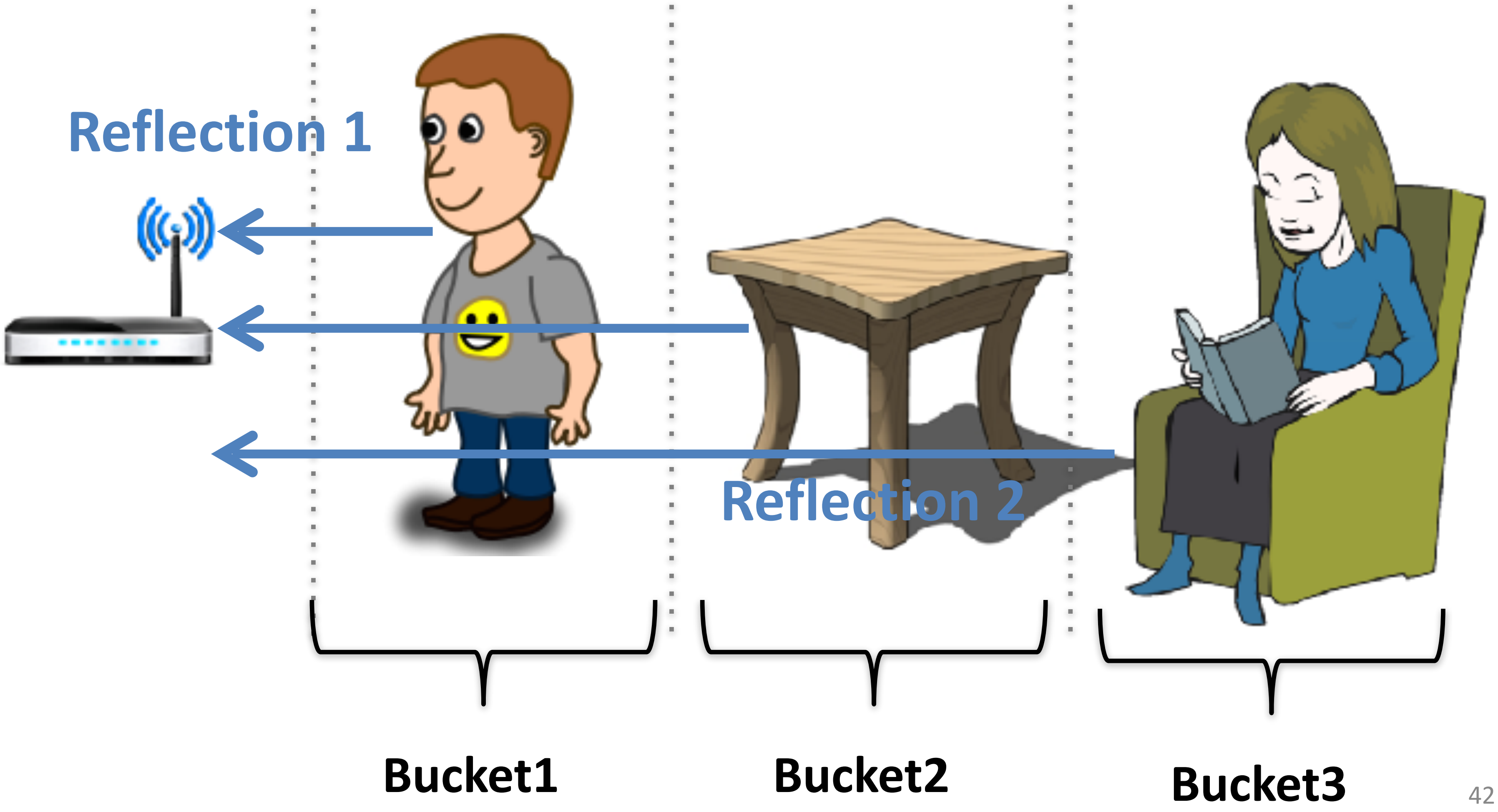

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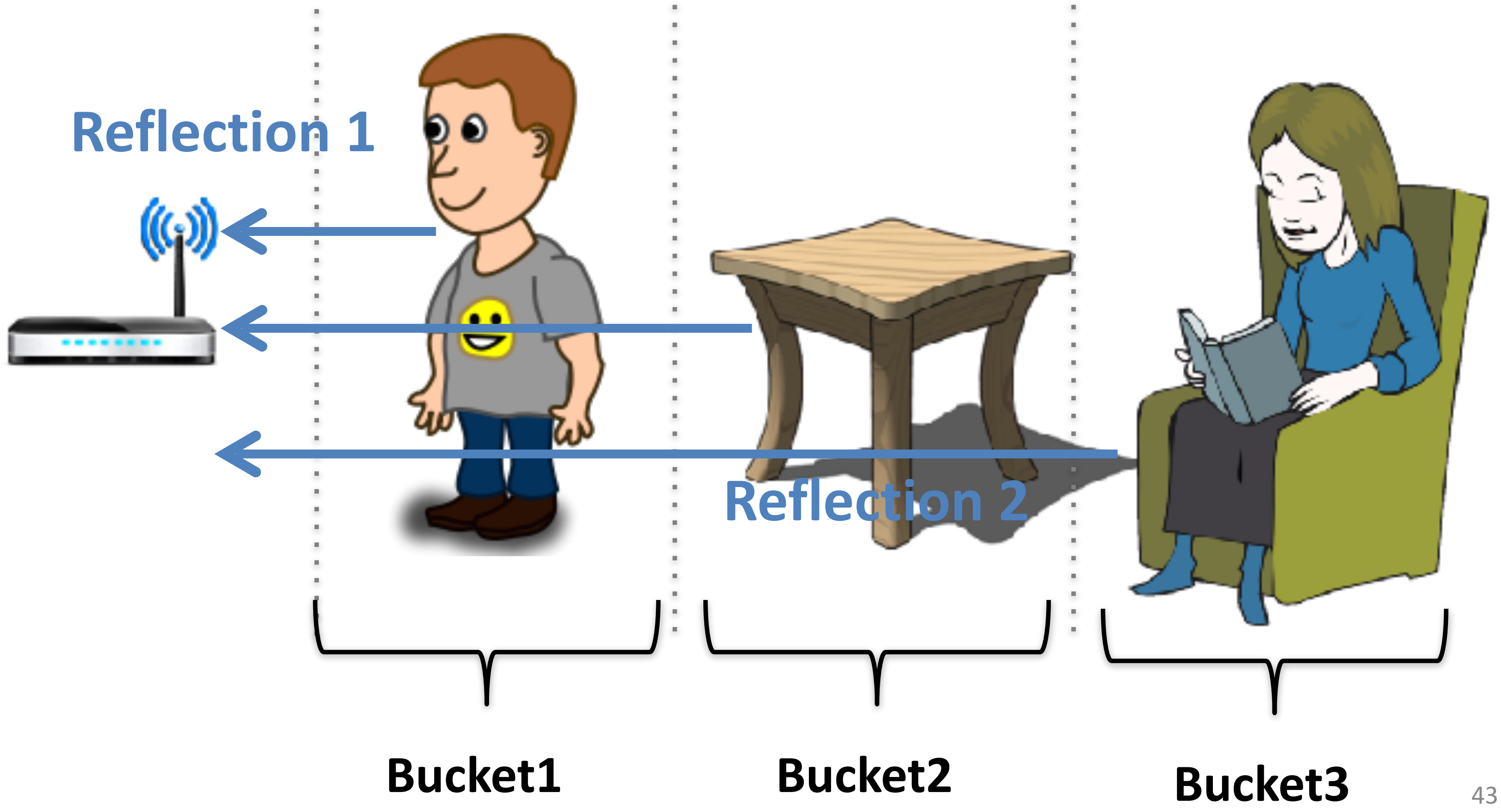


# Recall Formulation with FMCW

# Recall Formulation with FMCW

- Output of FFT with reflectors
- Looked at the amplitude only
- Now will also look at phase

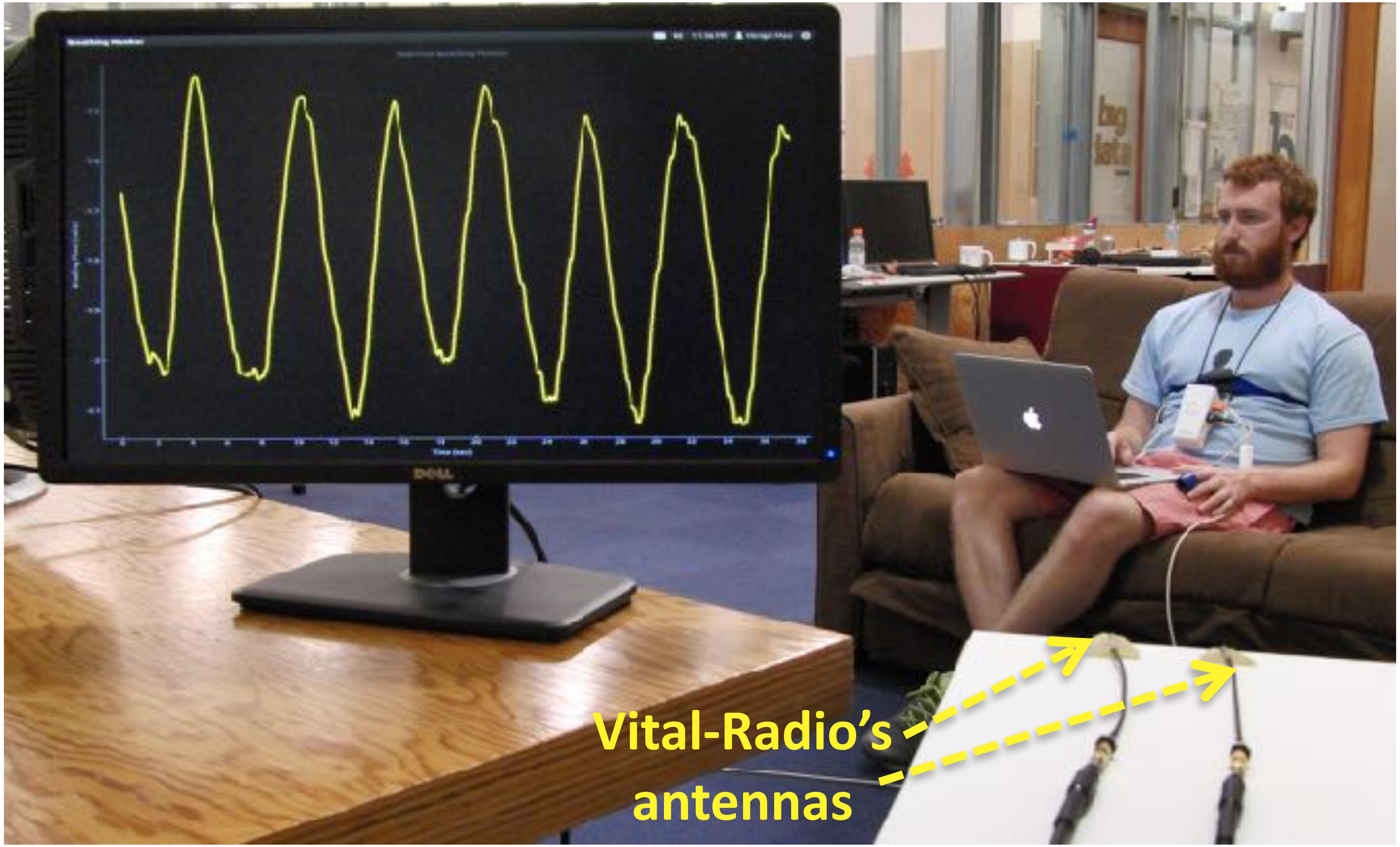
# Putting It Together

**Step 1:** Transmit a wireless signal and capture its reflections

**Step 2:** Isolate reflections from different objects based on their positions

**Step 3:** Zoom in on each object's reflection to obtain phase variations due to vital signs

# Vital-Radio Evaluation



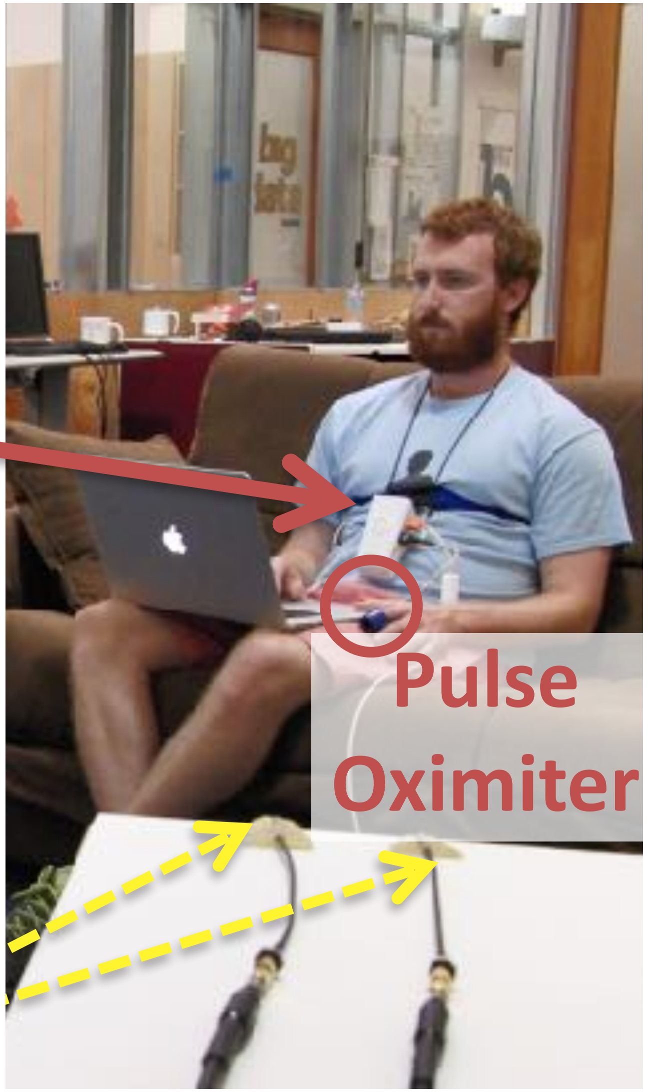
# Vital-Radio Evaluation

Baseline:

- FDA-approved breathing and heart rate monitor

Experiments:

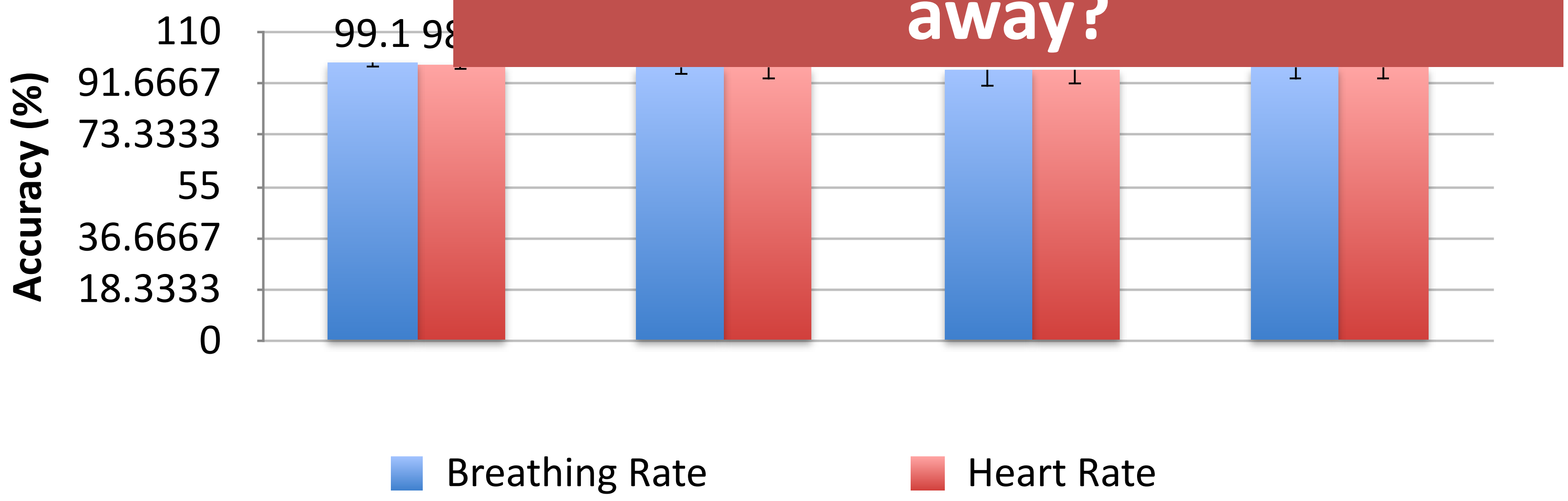
- 200 experiments
- 14 participants
- 1 million measurements



# Accuracy vs. Orientation

User is 4m from device, with different orientations

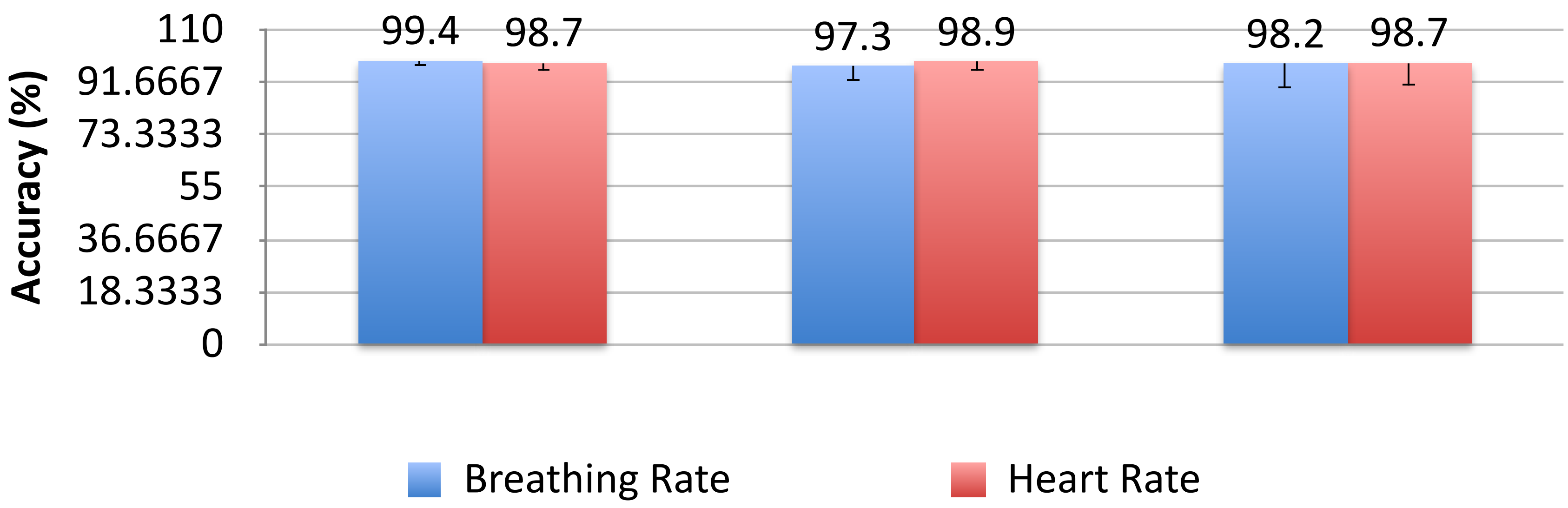

**Why does it work when facing away?**



# Accuracy for Multi-User Scenario

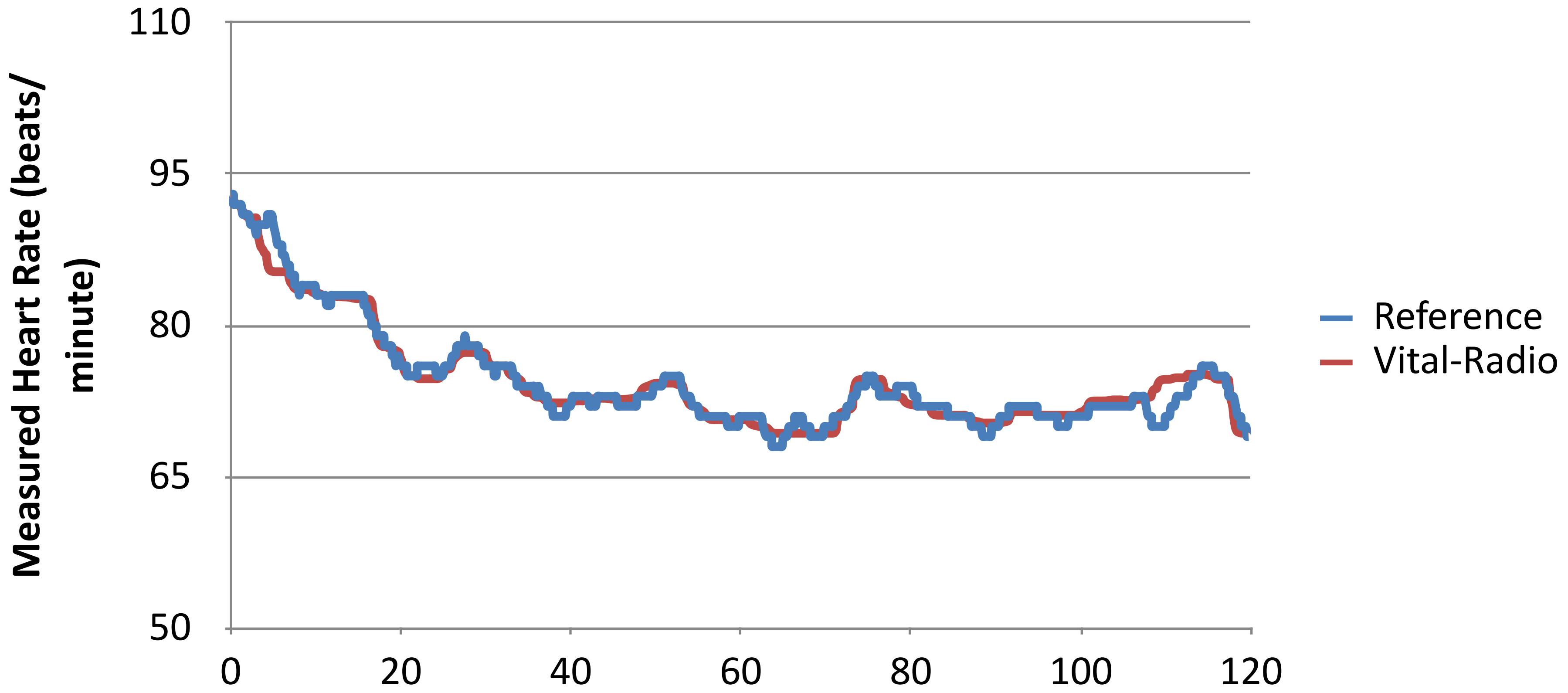
Multiple users sit at different distances

Nearest (at 2m) Middle (at 4m) Furthest (at 6m)



# Accuracy for Tracking Heart Rate

Measure user's heart rate after exercising

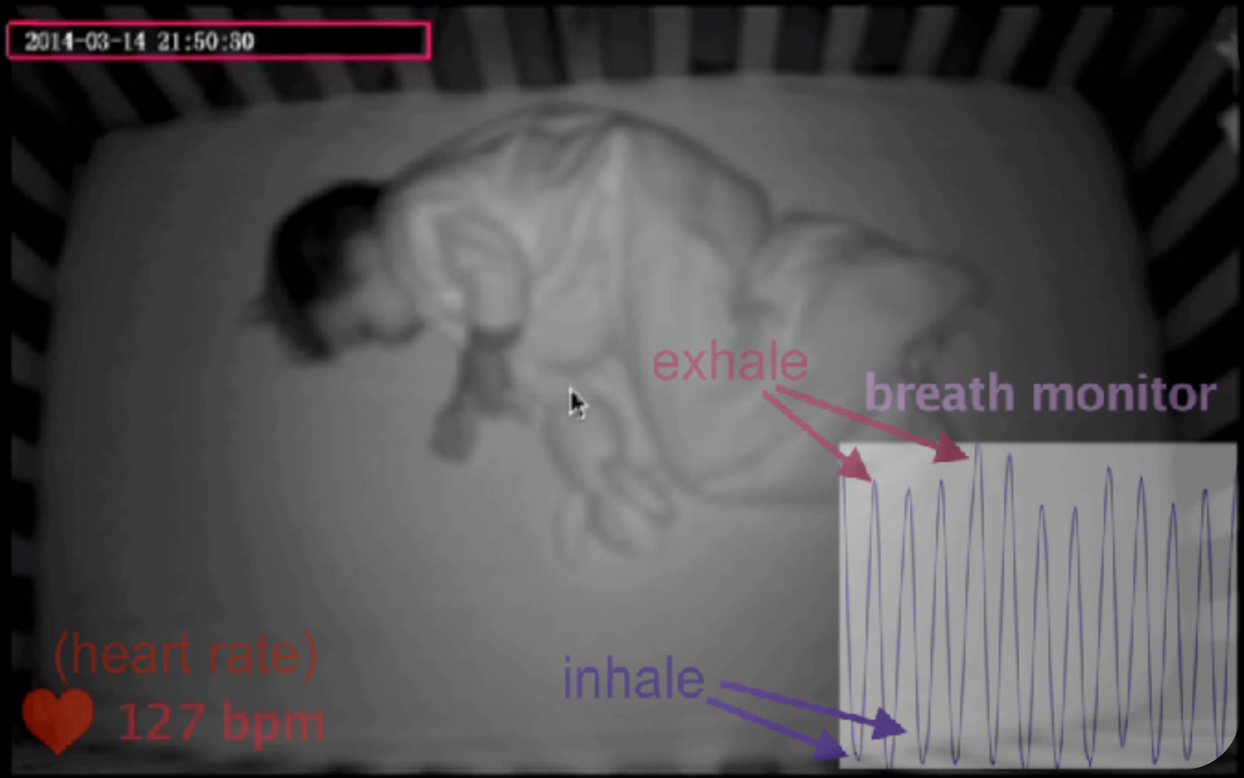



**Vital-Radio accurately tracks changes in vital signs**

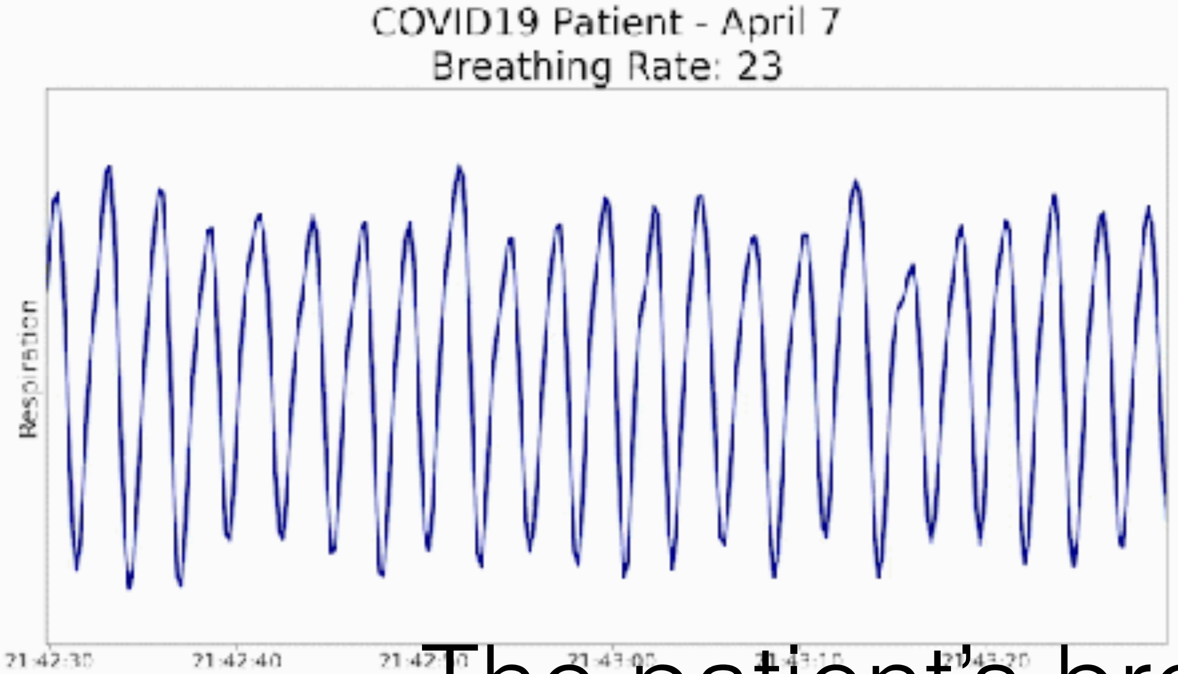
# Vital-Radio Limitations

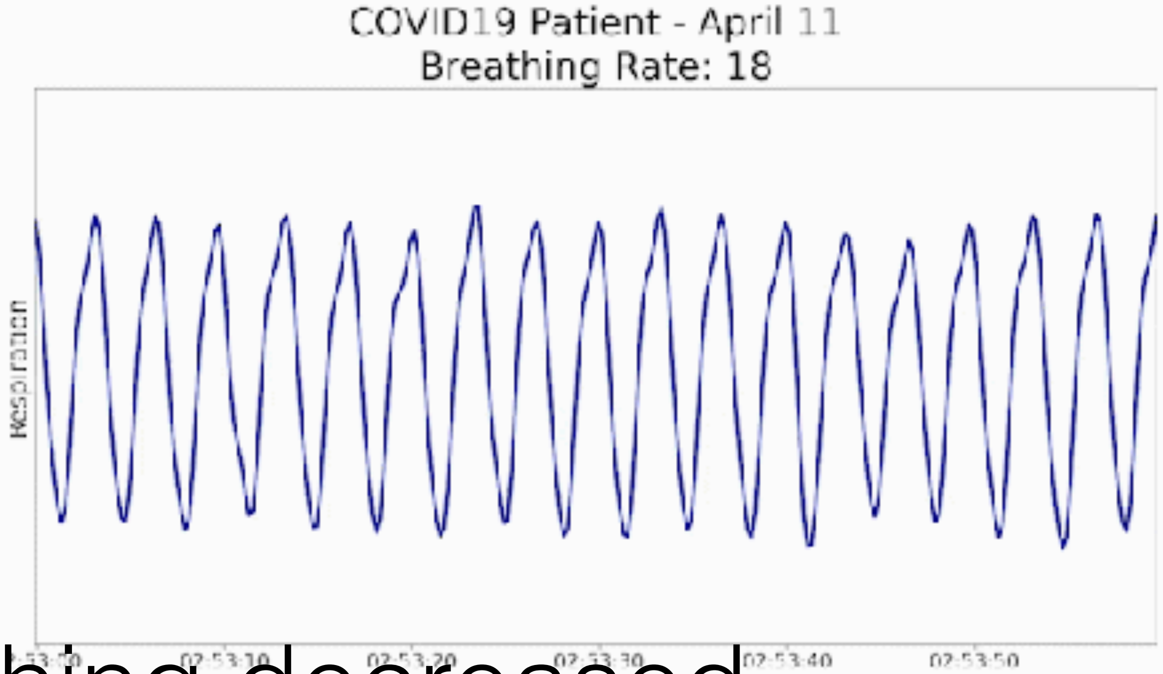
- Minimum separation between users: 1-2m
- Monitoring range: 8m
- Collects measurements when users are quasi-static

# Baby Monitoring

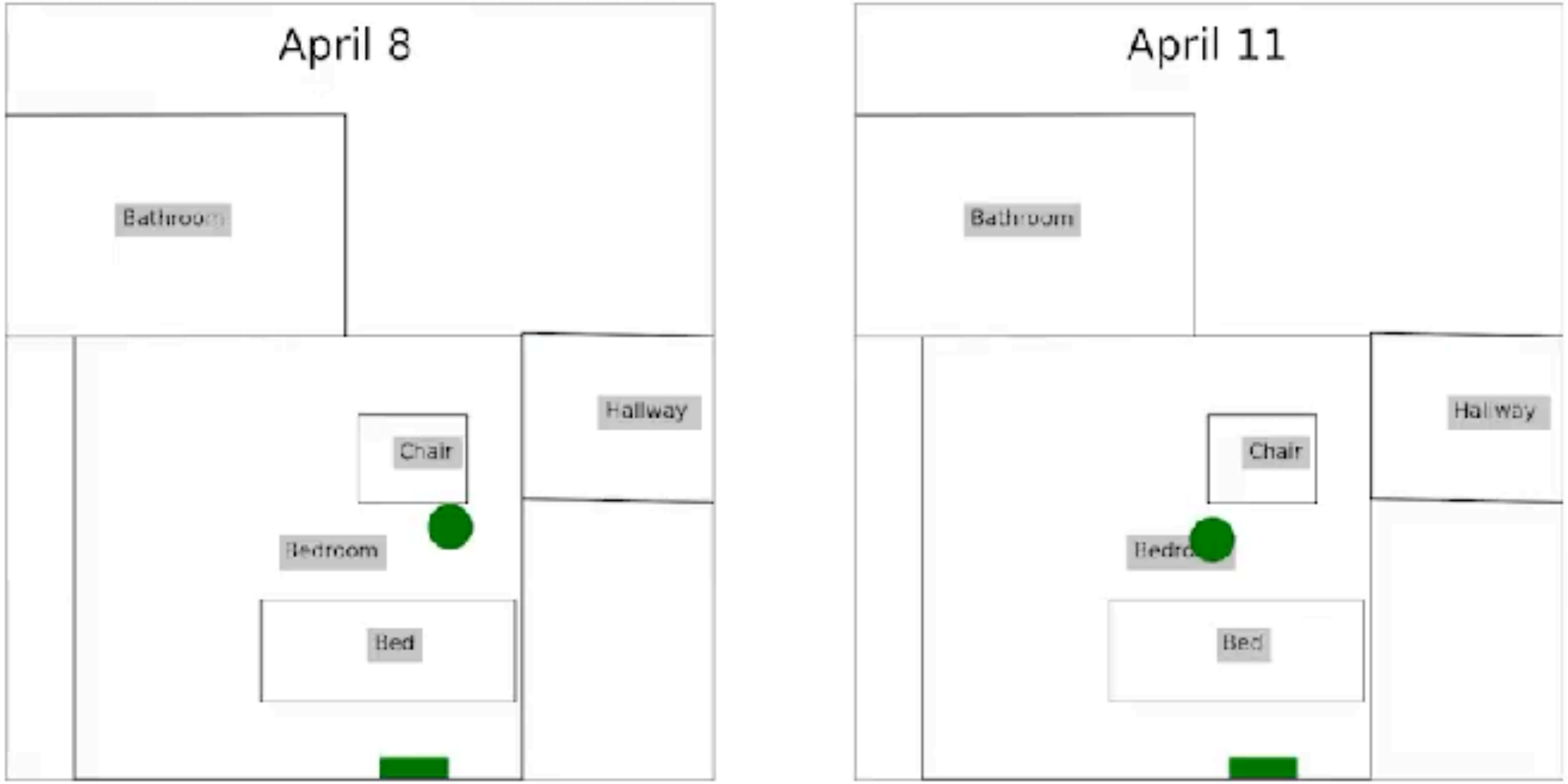


# Monitoring COVID-19 Patient




The patient’s breathing decreased
as it went back to normal



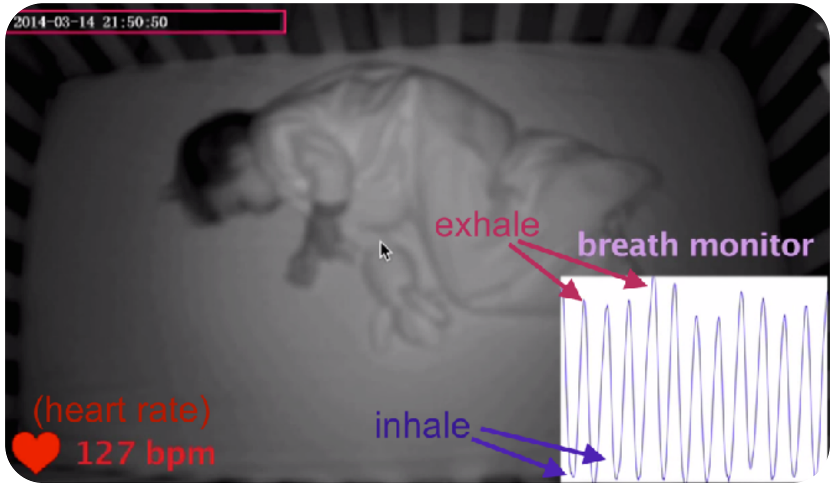

The patient's movements also demonstrate a marked improvement.

# How can we capture heart recordings?

98-99% accuracy in timing micro-cardiac events

[ACM MobiCom’20]

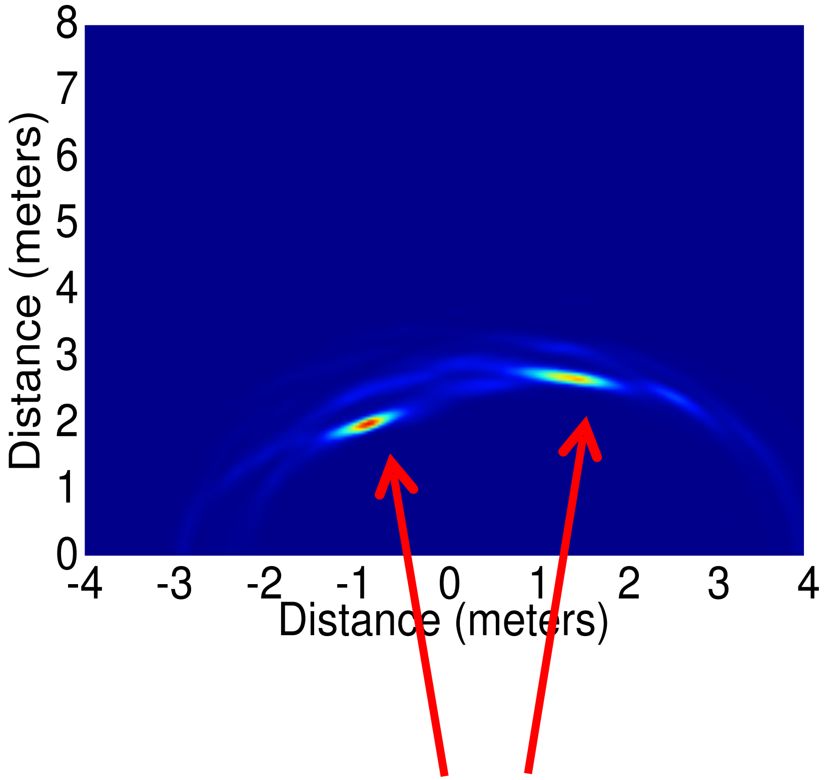
## Breathing & Heart Rate




## Want Emotions

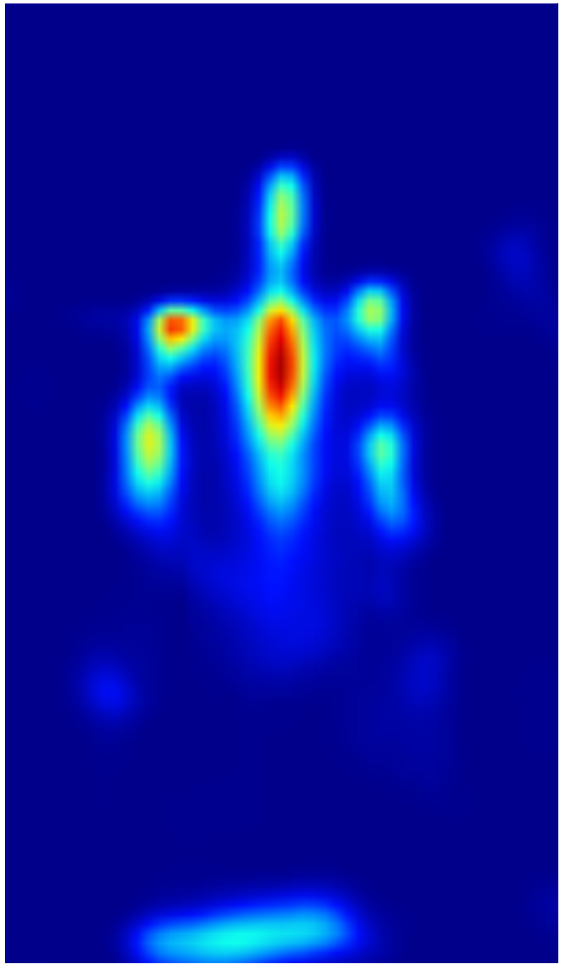
Why and how would you be able to get from BR/HR -> emotions?

People are points



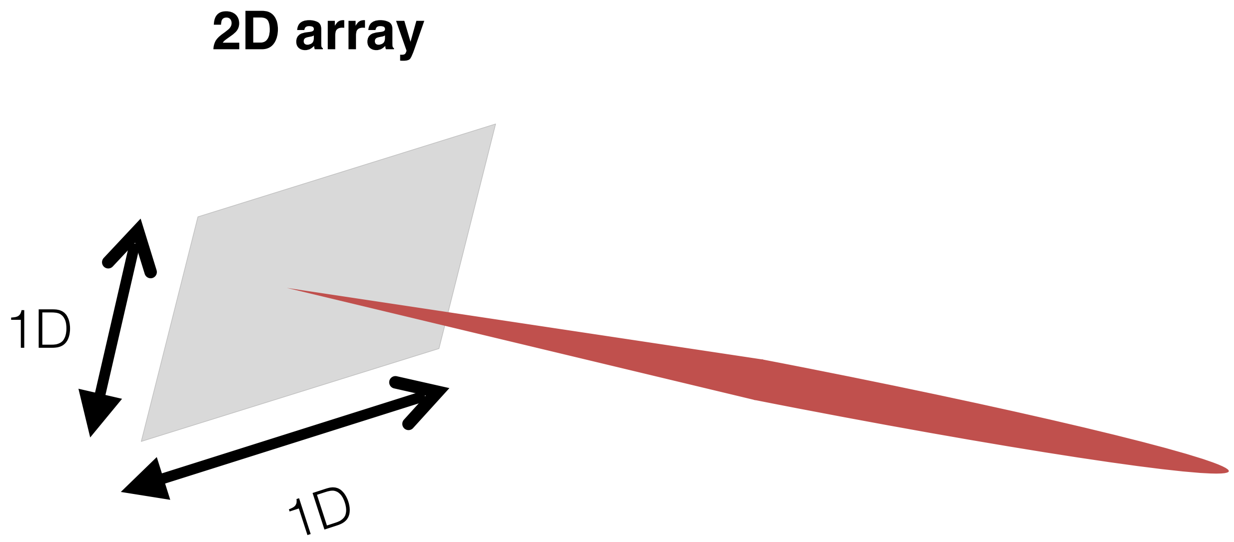

Localize the two users

Want a silhouette



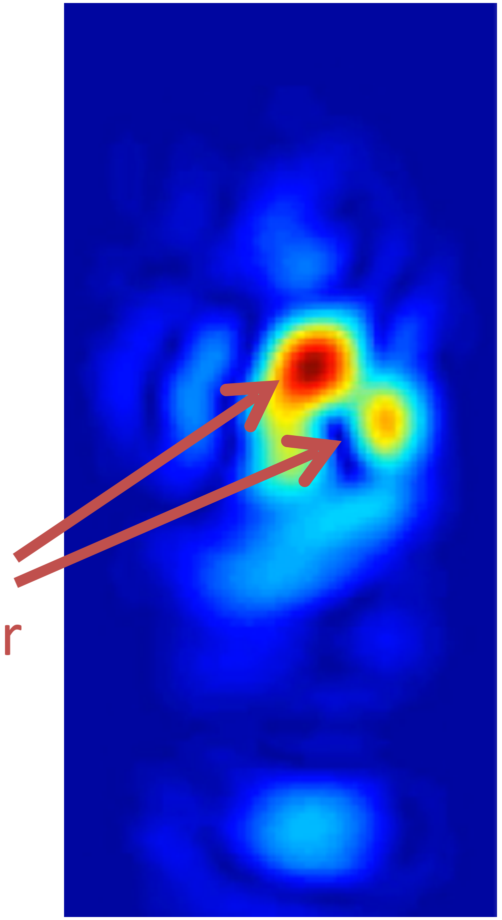
Approach: Combine antenna arrays with FMCW to get 3D image

- 2D Antenna array gives 2 angles
- FMCW gives depth (1D)



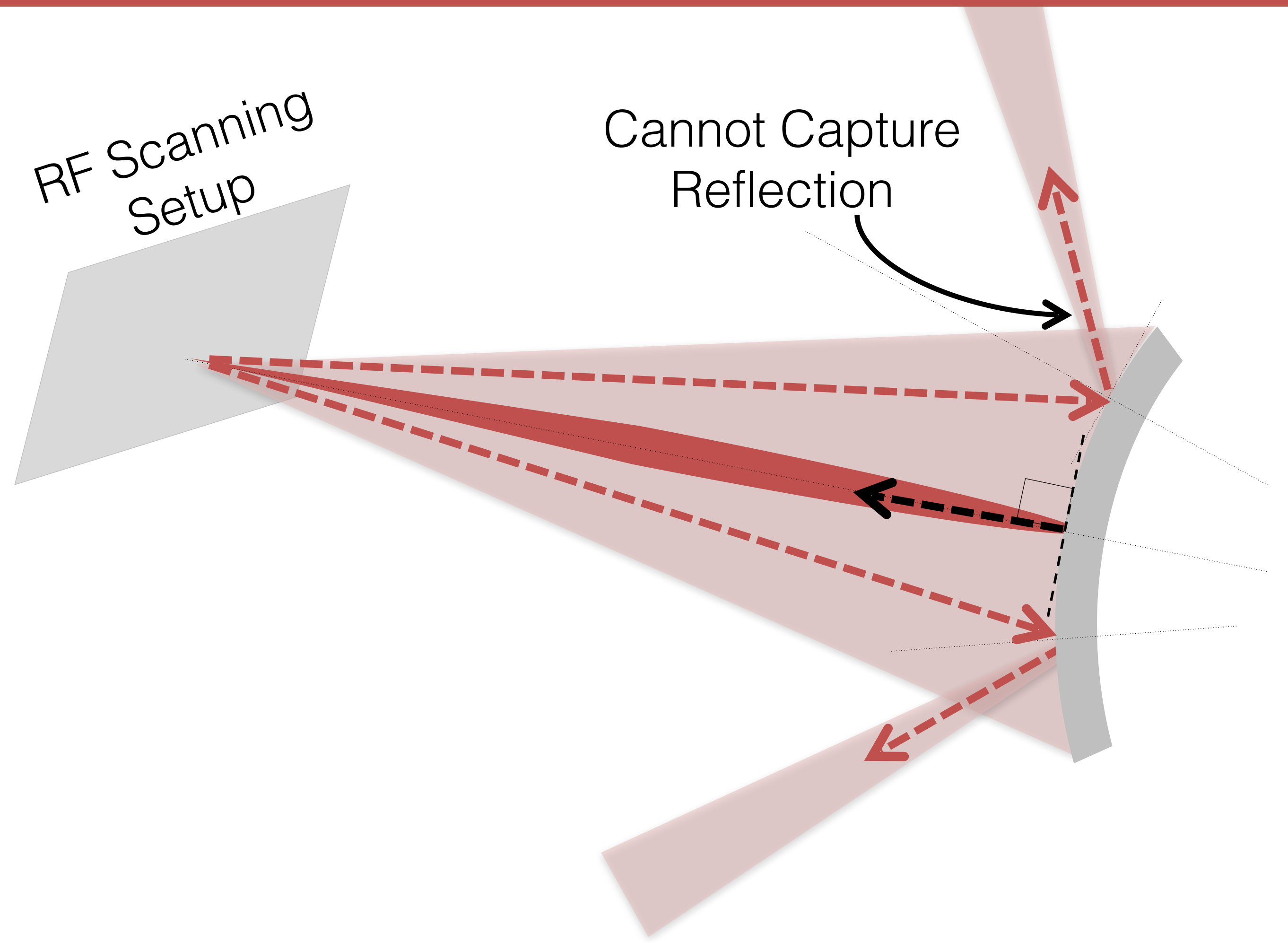
# <u>Challenge:</u> We only obtain blobs in space

Output of 3D RF Scan

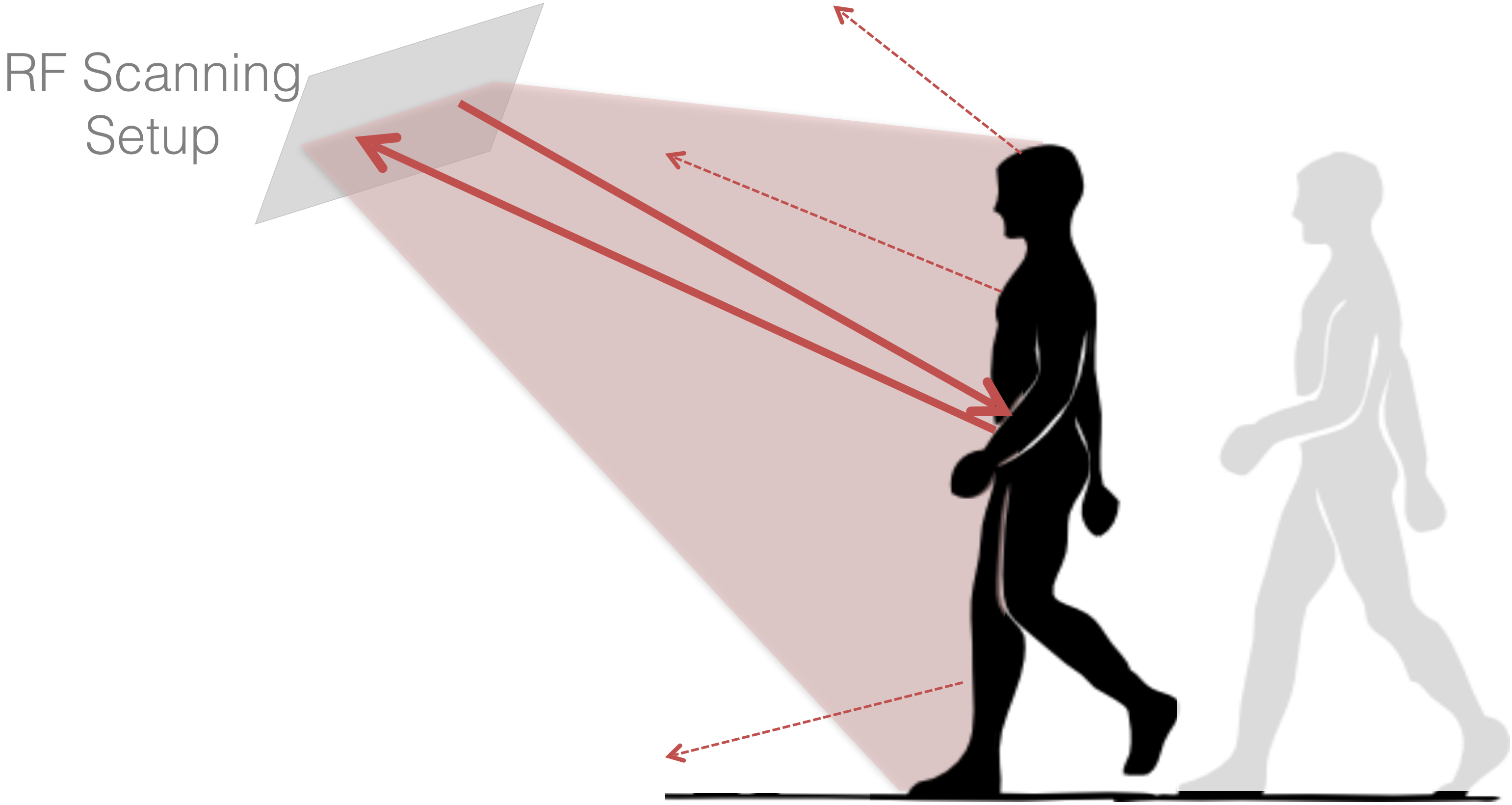


Blobs of reflection power

At every point in time, we get reflections from only a subset of body parts.



# Solution Idea: Exploit Human Motion and Aggregate over Time



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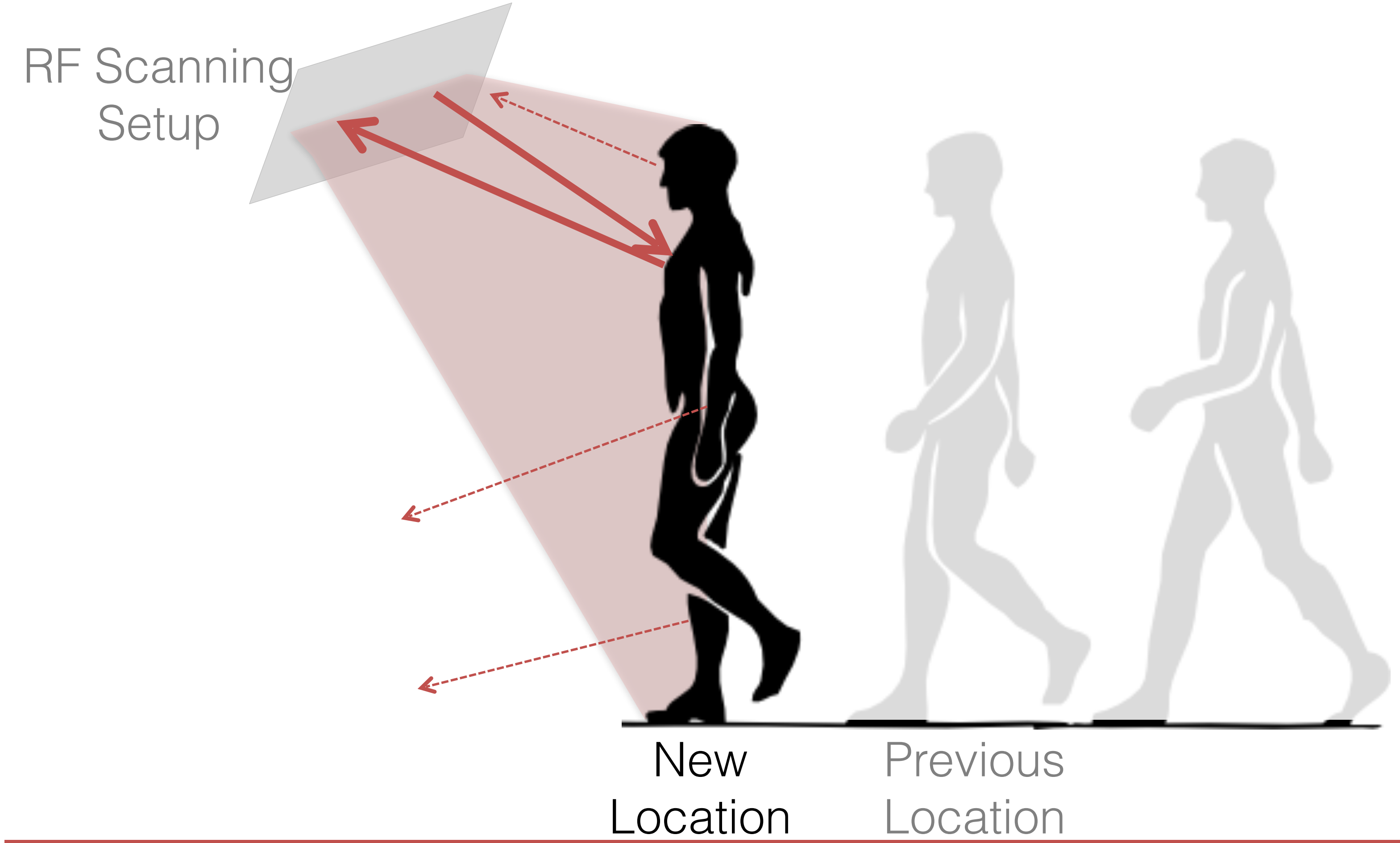



Combine the various snapshots


COMMUNICATIONS
ACM

# Where is Wireless Sensing today?

1. **Research-wise:**
    - Sensitivity: close to ECG in measuring micro-cardiac events (2020)
    - Reconstruction: can recover 3D human skeleton + meshes (2020)
    - Can monitor new affective metrics: stress levels (2021)
    - Technologies: WiFi, millimeter wave, etc.
2. **Real-world Uses:**
    - Multiple startups in the space
    - Medical use in monitoring 1,000s of patients with Alzheimer's, Parkinson's, COVID-19, Multiple Sclerosis, etc.
    - Influenced the design of sensors like Google Soli and others
3. **Standards:**
    - Upcoming WiFi standard (802.11bf)
    - Planning for 6G

How can you use this technology in the metaverse?

# Objectives of Today's Lecture

Learn the fundamentals, applications, and implications of
**contactless wireless sensing**

1. What is wireless (aka WiFi) sensing?
2. How do seeing through wall systems work?
3. How can we monitor human vital signs using wireless signals?
4. What are the industry opportunities and societal implications of wireless sensing (today and in the near+far future)?

# How to Wirelessly Sense Almost Anything

sensing the physical world & transmitting data wirelessly

sensing via the wireless signals themselves

So far

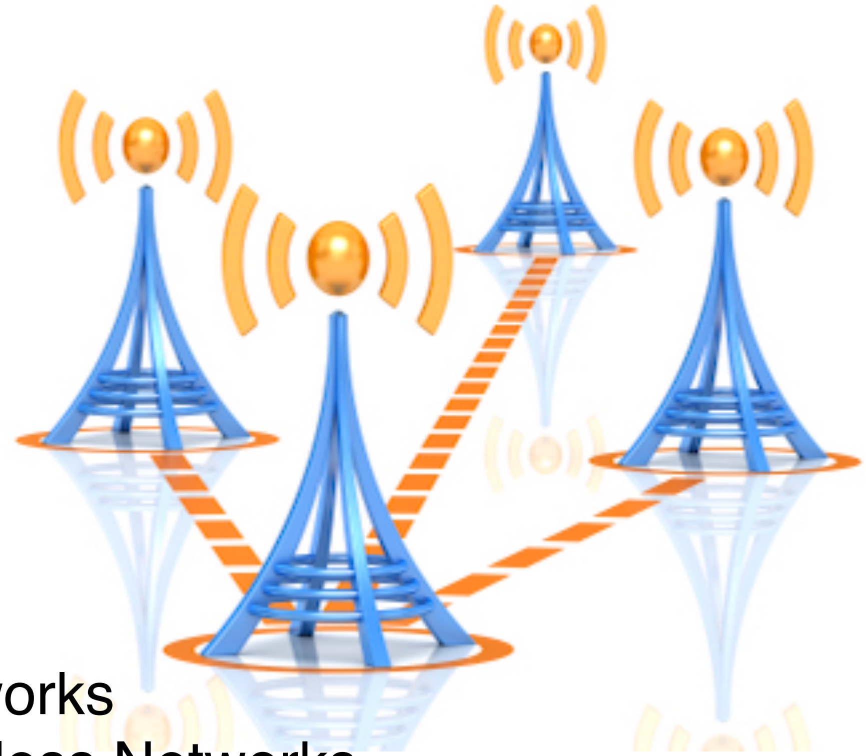
# How to Wirelessly Sense Almost Anything

sensing the physical world & transmitting data wirelessly

next

sensing via the wireless signals themselves

# Next Class: Wireless Communications



## 1) Required

- The Wireless Channel (Chapter) - summary required
- Underwater-to-Air Communications - review required

## 2) Optional

- 802.11n+: Random Access Heterogeneous MIMO Networks
- ZigZag Decoding: Combating Hidden Terminals in Wireless Networks
- Full-Duplex Practical, Real-time, Full Duplex Wireless