http://www.mit.edu/~fadel/courses/MAS.wireless

MAS.S61

Wireless & Mobile Sensing

Lecture 3:
Fundamentals of Wireless Sensing & Localization

Lecturers
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NEWS TECH APPLE

Apple announces AirPods Pro 3 with ‘world’s best ANC’ and heart rate sensing

/ The AirPods Pro 3 will ship on September 19th for $249.

by Tom Warren

custom photoplethysmography (PPG) sensor that “shines invisible infrared light pulsed at 256 times per second to measure light absorption in blood flow.”

The sensor works with the AirPods Pro accelerometers, gyroscope, GPS, and a new on-device AI model on an iPhone to track heart rate, calories burned, and activity. There’s also a new workout experience, Workout Buddy, in the iPhone Fitness app that uses Apple Intelligence to track workout data and fitness history.

Feedback on reviews

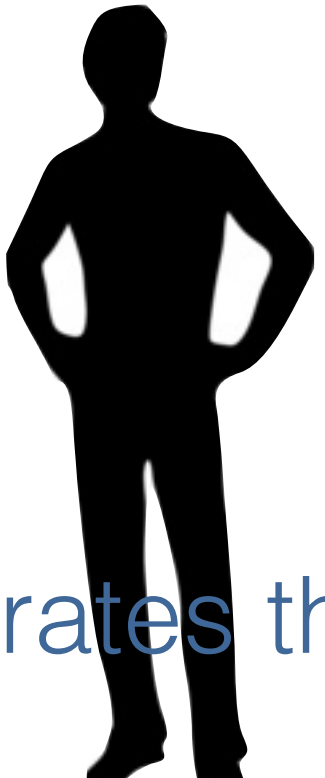
- Overall: very good reviews by everyone (WiTrack)

Last Week

Device-based Localization

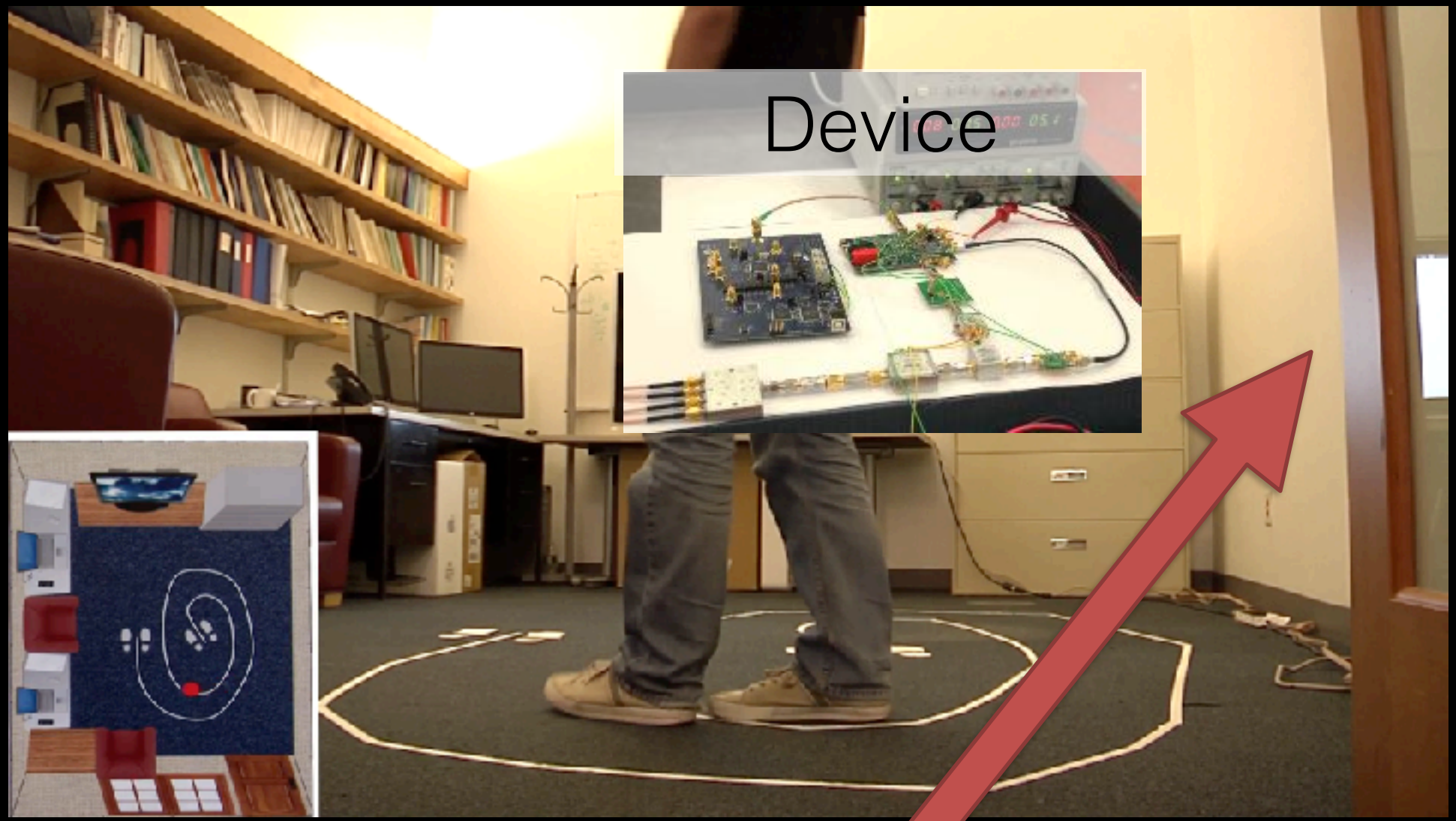
Today: Device-Free Localization (aka Wireless Sensing)

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



Operates through occlusions

Example: WiTrack


Device
Device in another room

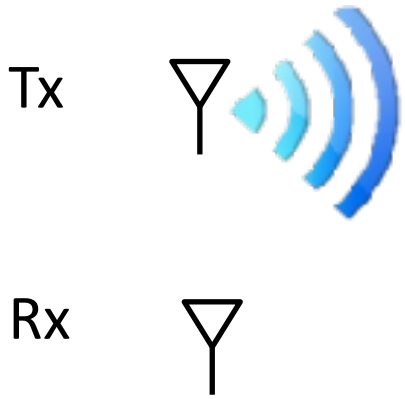
Applications

Smart Homes

Energy Saving

Gaming & Virtual Reality

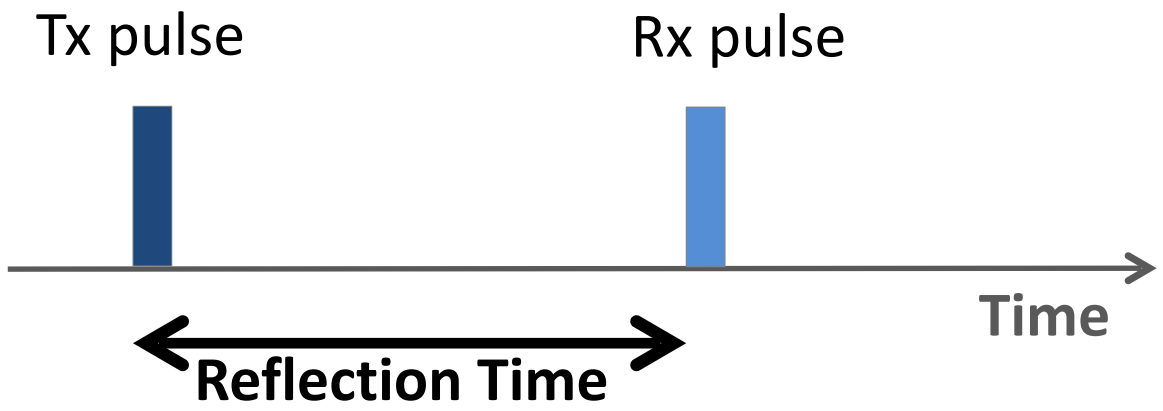
Measuring Distances



Distance = Reflection time x speed of light

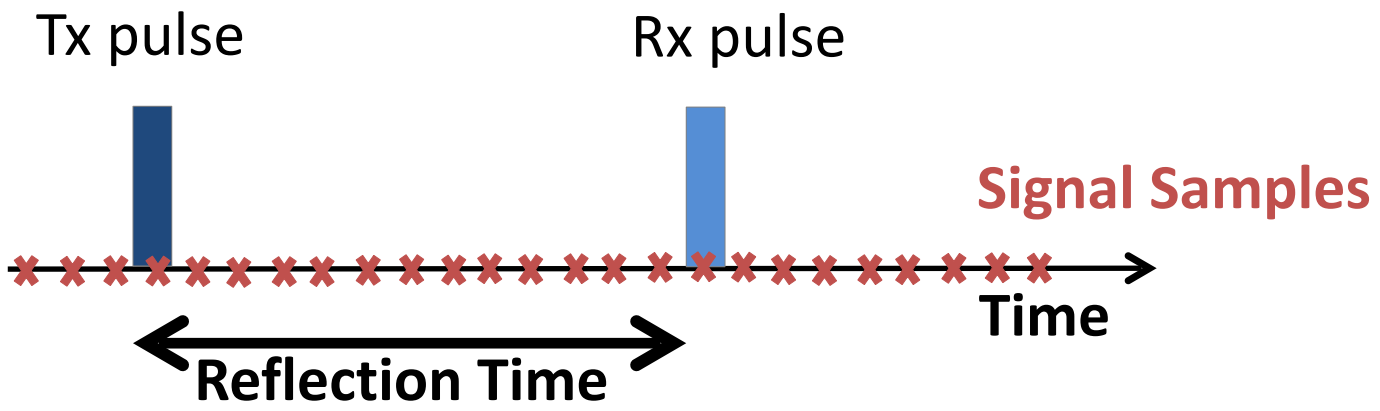
Measuring Reflection Time

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

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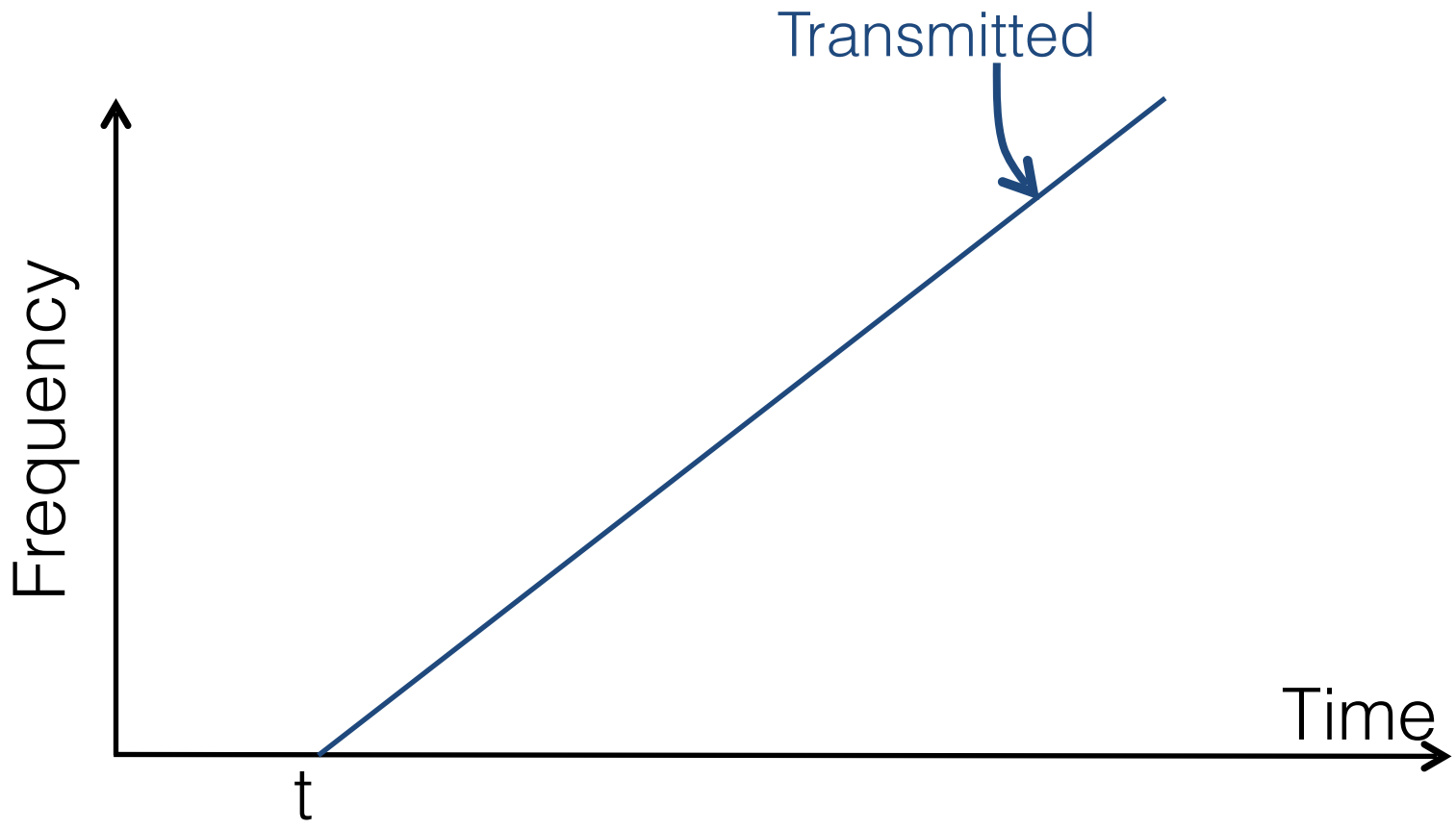
Why if instead of RF we use ultrasound?

because speed of ultrasound

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

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

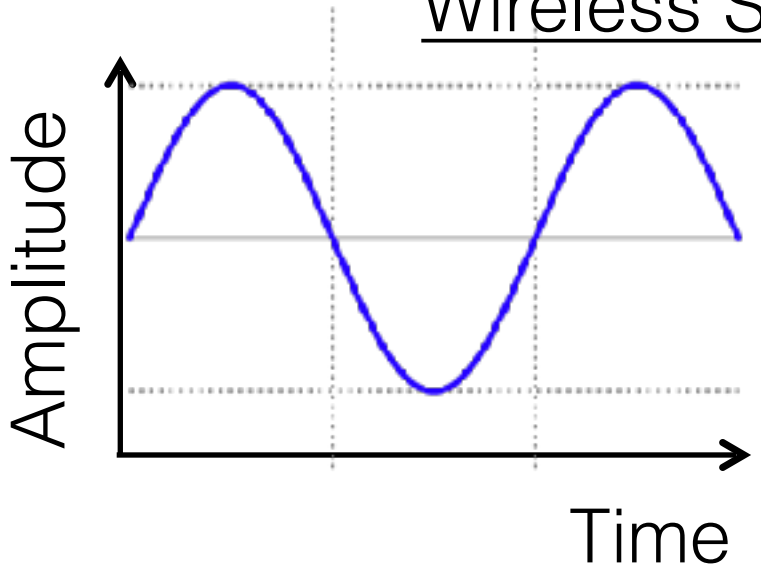
FMCW: Measure time by measuring frequency

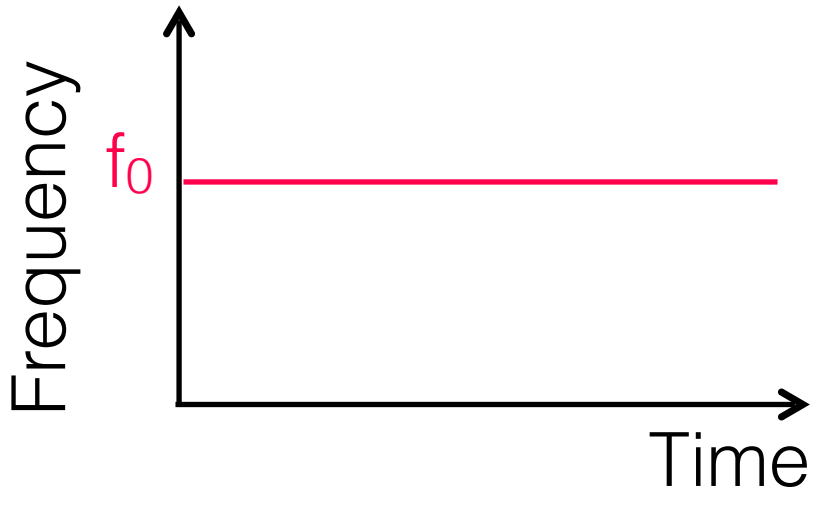


How does it look in time domain?
(and in comparison to single frequency)

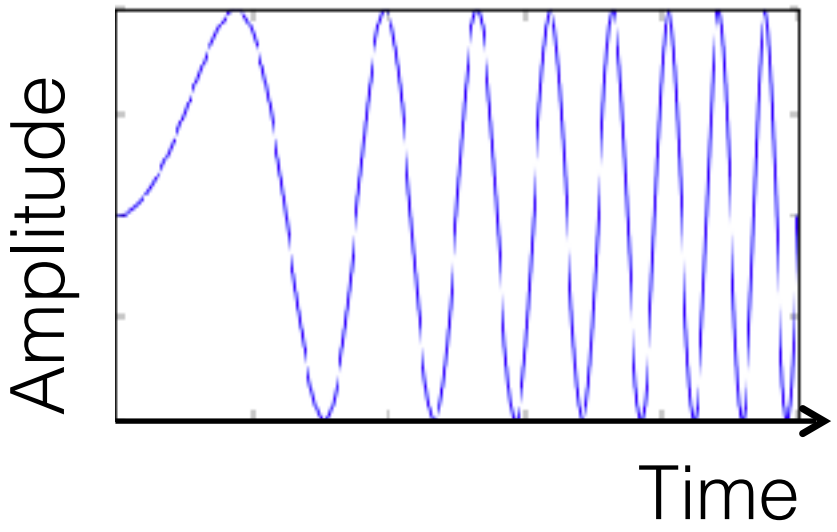
More intuitive understanding of FMCW

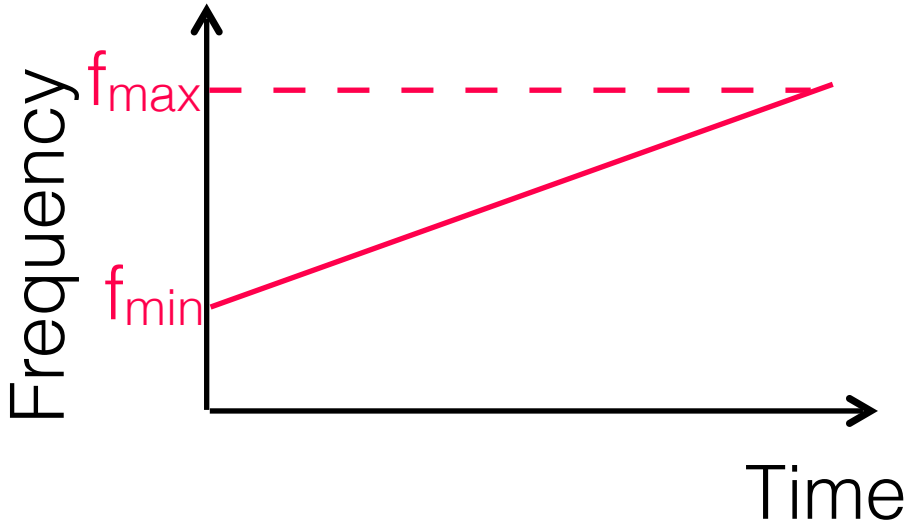
Wireless Signal at frequency f_0



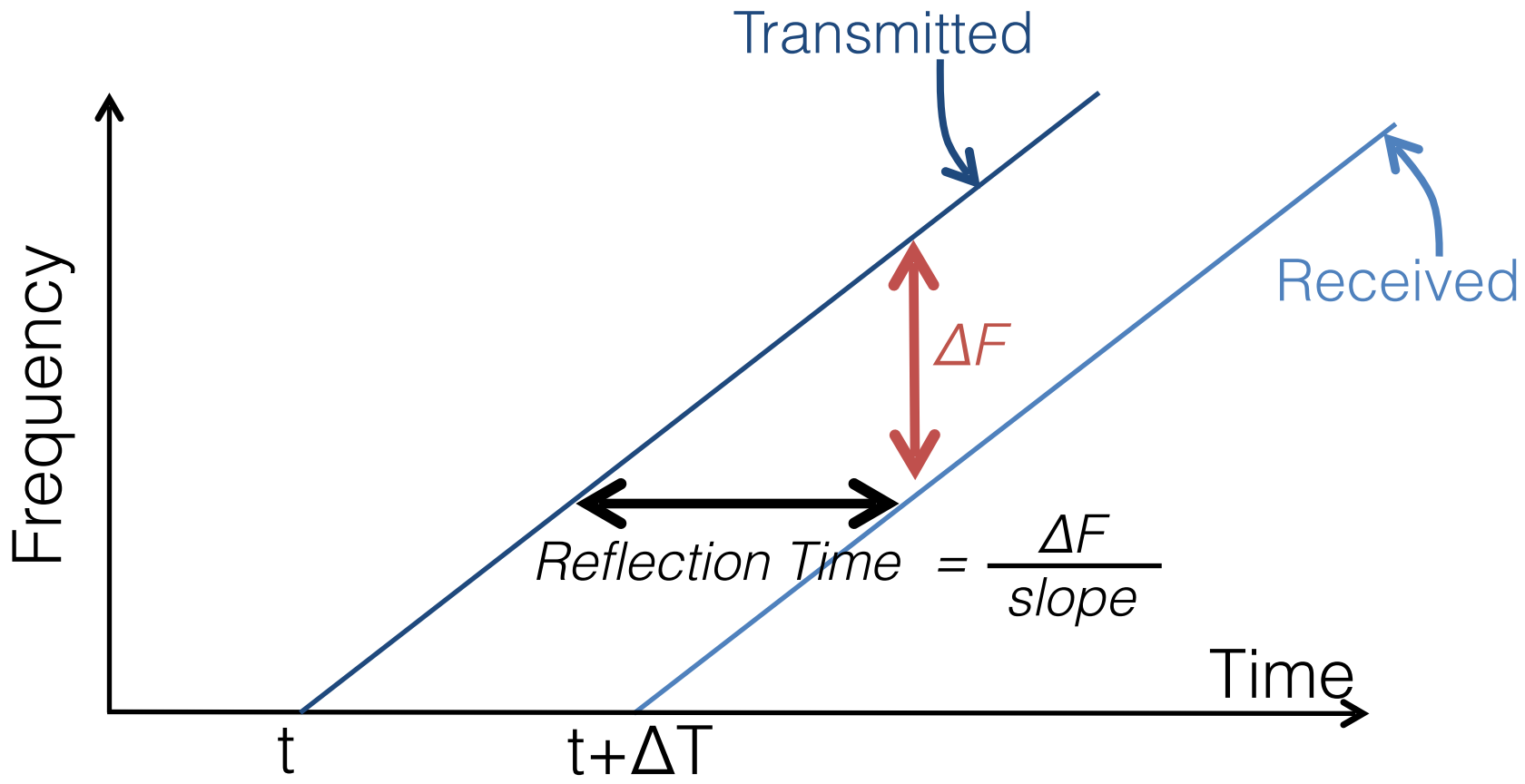


FMCW signal





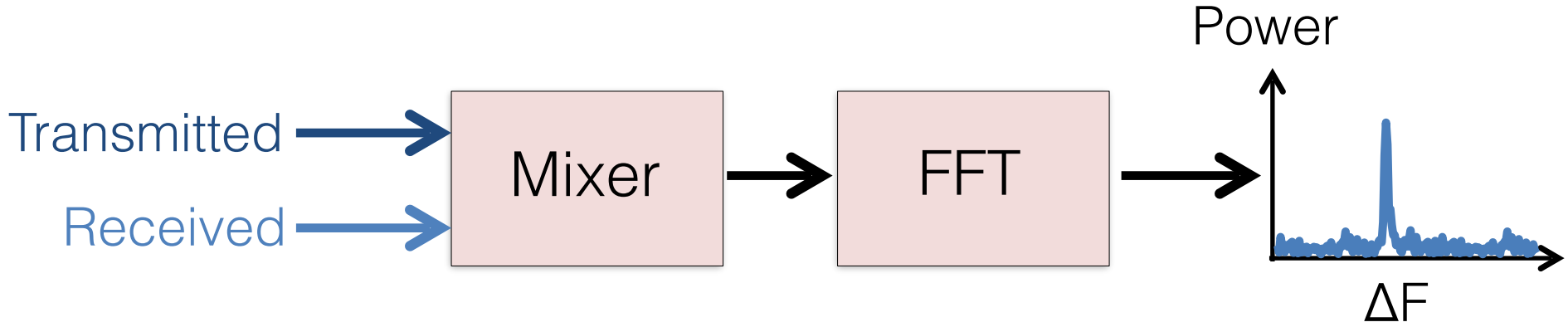
FMCW: Measure time by measuring frequency



How do we measure ΔF?

Measuring ΔF

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



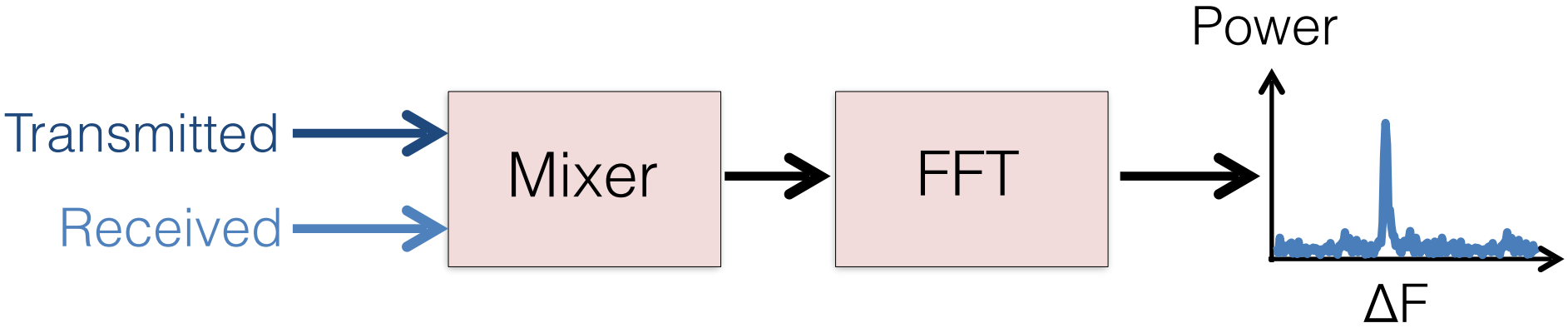
Signal whose frequency is ΔF

let's talk about FFTs a bit — freq

Basics of Fourier Transform

Measuring ΔF

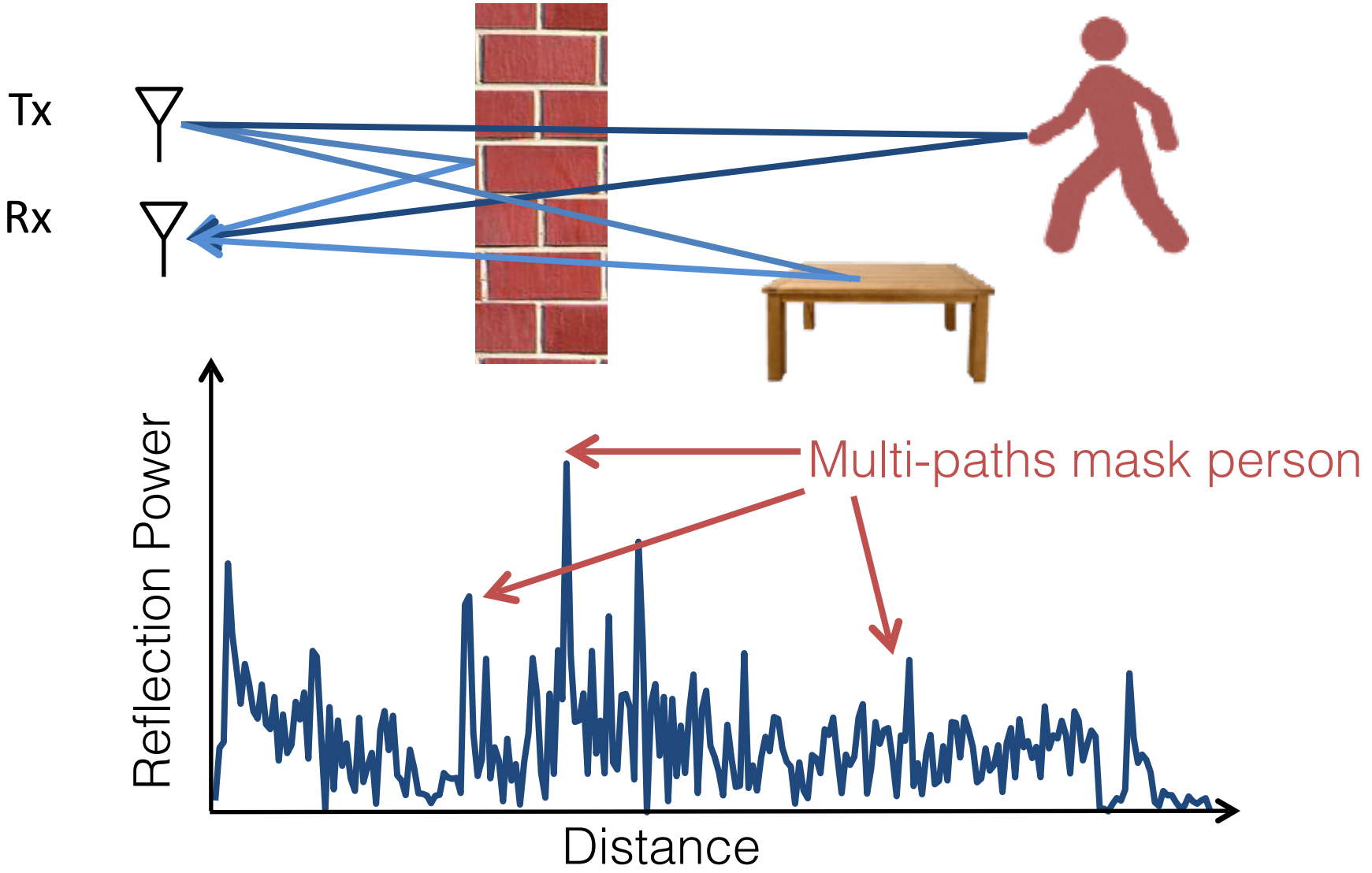
- Subtracting frequencies is easy (e.g., removing carrier in WiFi)
- Done using a mixer (low-power; cheap)



Signal whose frequency is ΔF

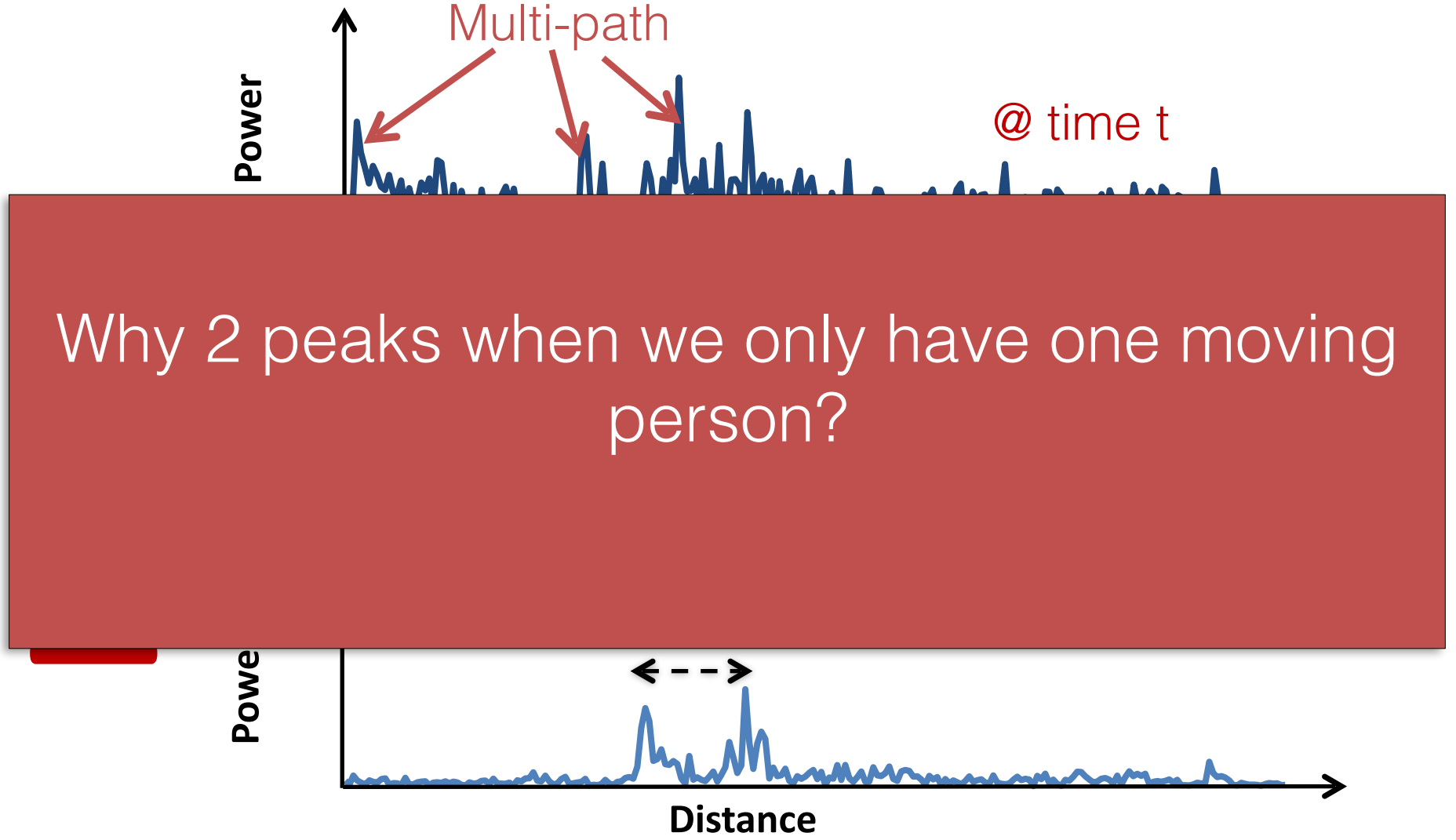
ΔF →Reflection Time → Distance

Challenge: Multipath➔ Many Reflections

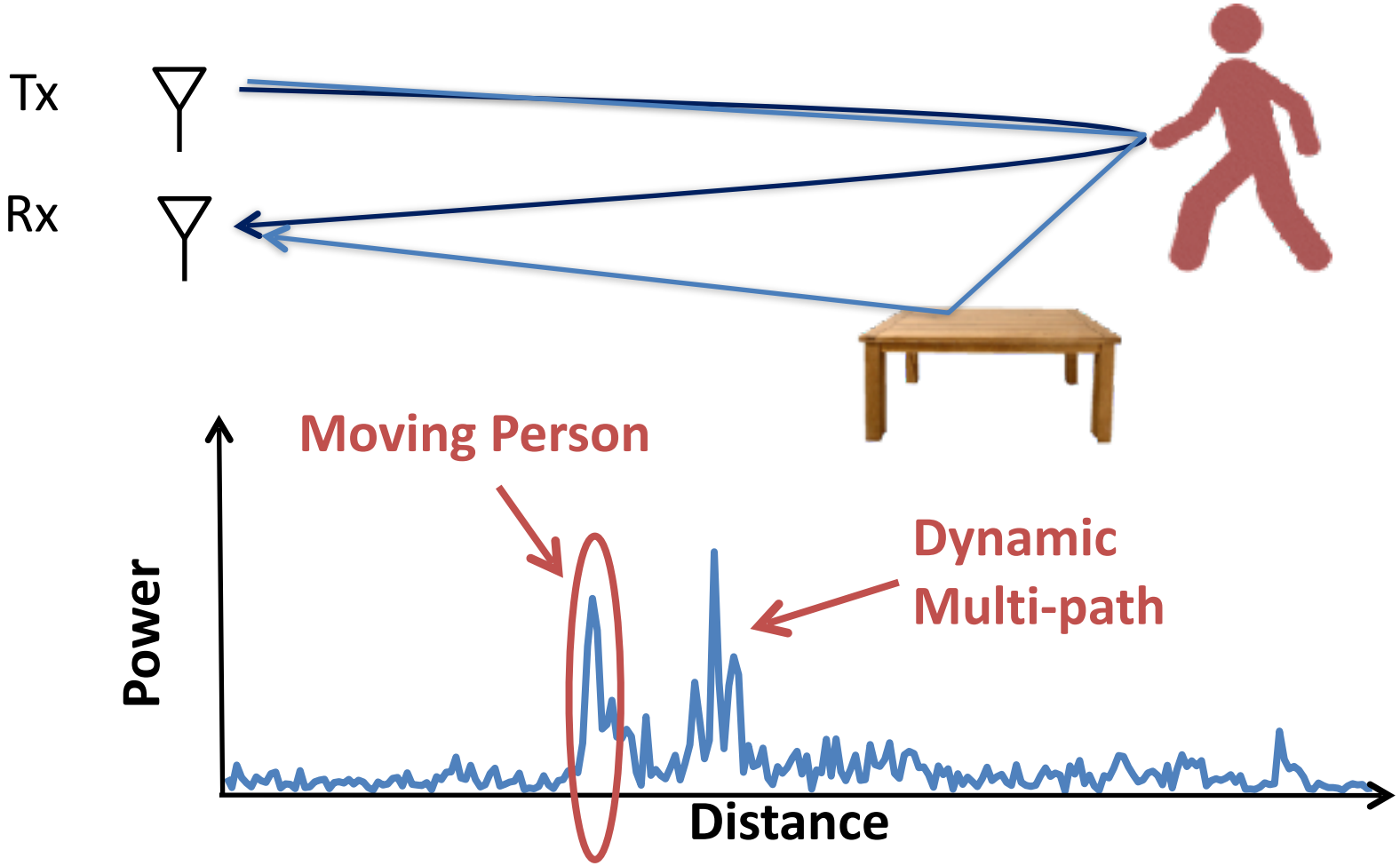


Static objects don't move

➔ Eliminate by subtracting consecutive measurements

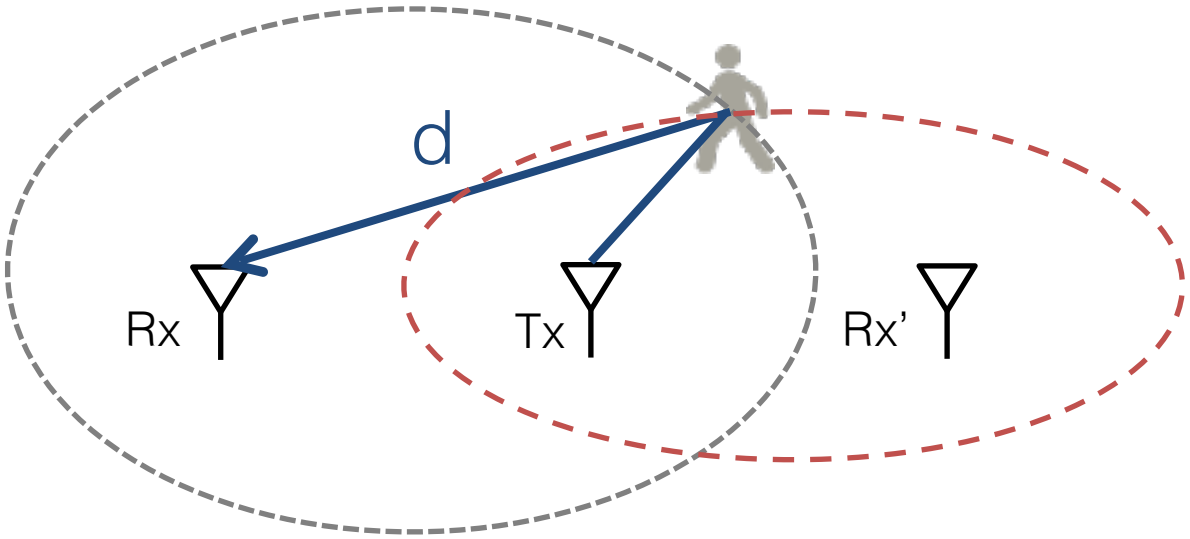


The direct reflection arrives before dynamic multipath!



Mapping Distance to Location

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

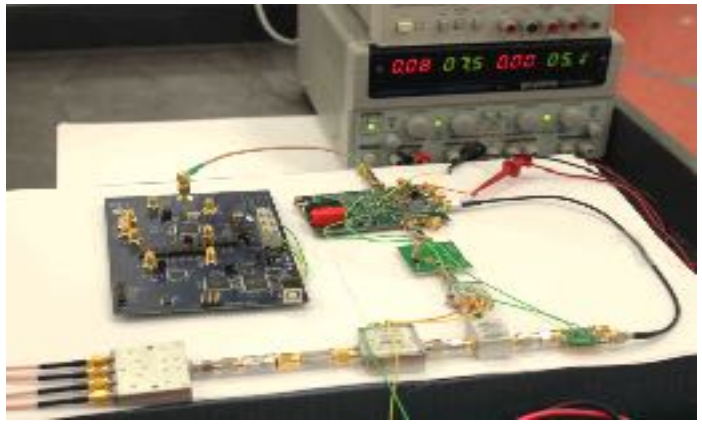


By adding another antenna and intersecting the ellipses, we can localize the person

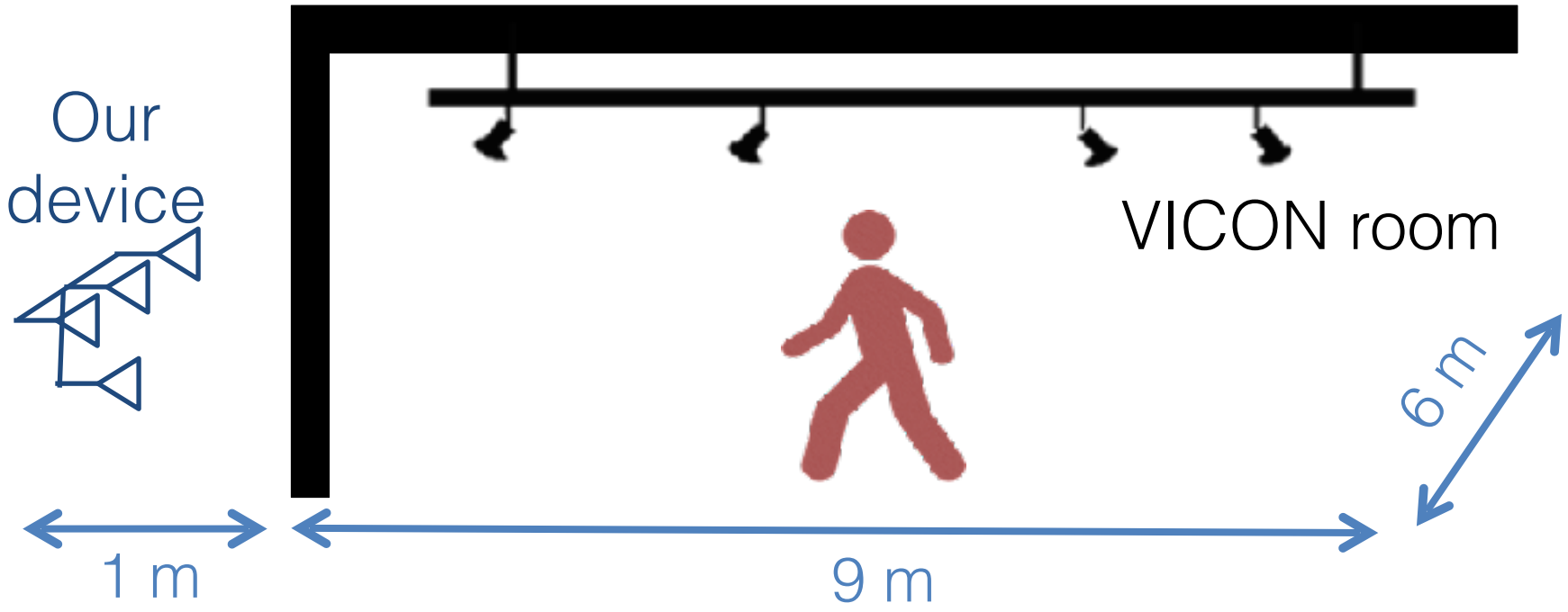
From Location to tracking (over time)

Implementation

- Built FMCW front-end
  - Connected to USRP
- Band: 5.5-7.2 GHz
- Transmit 70 μW
  - 1000x lower power than WiFi Access Point
- 5 Tx, 5 Rx antennas



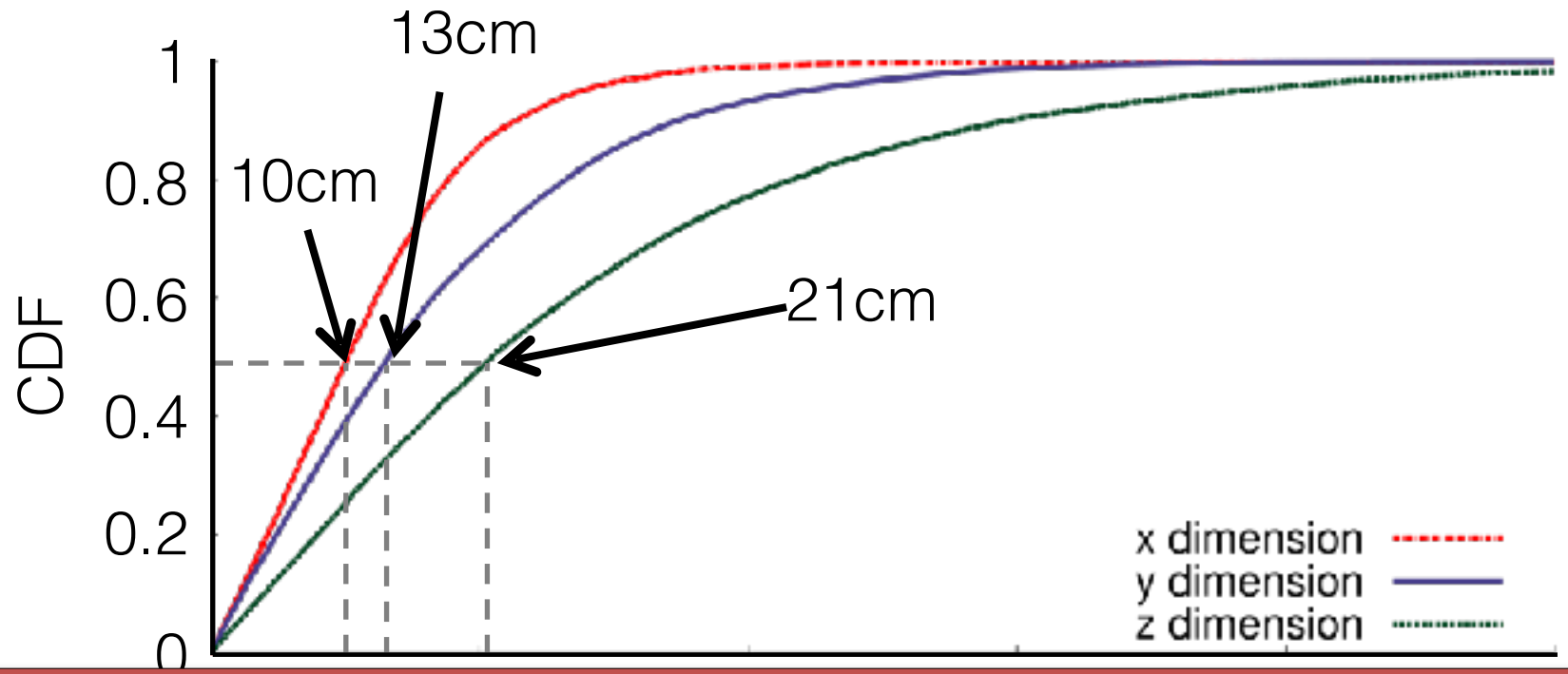
Ground Truth via VICON



- 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

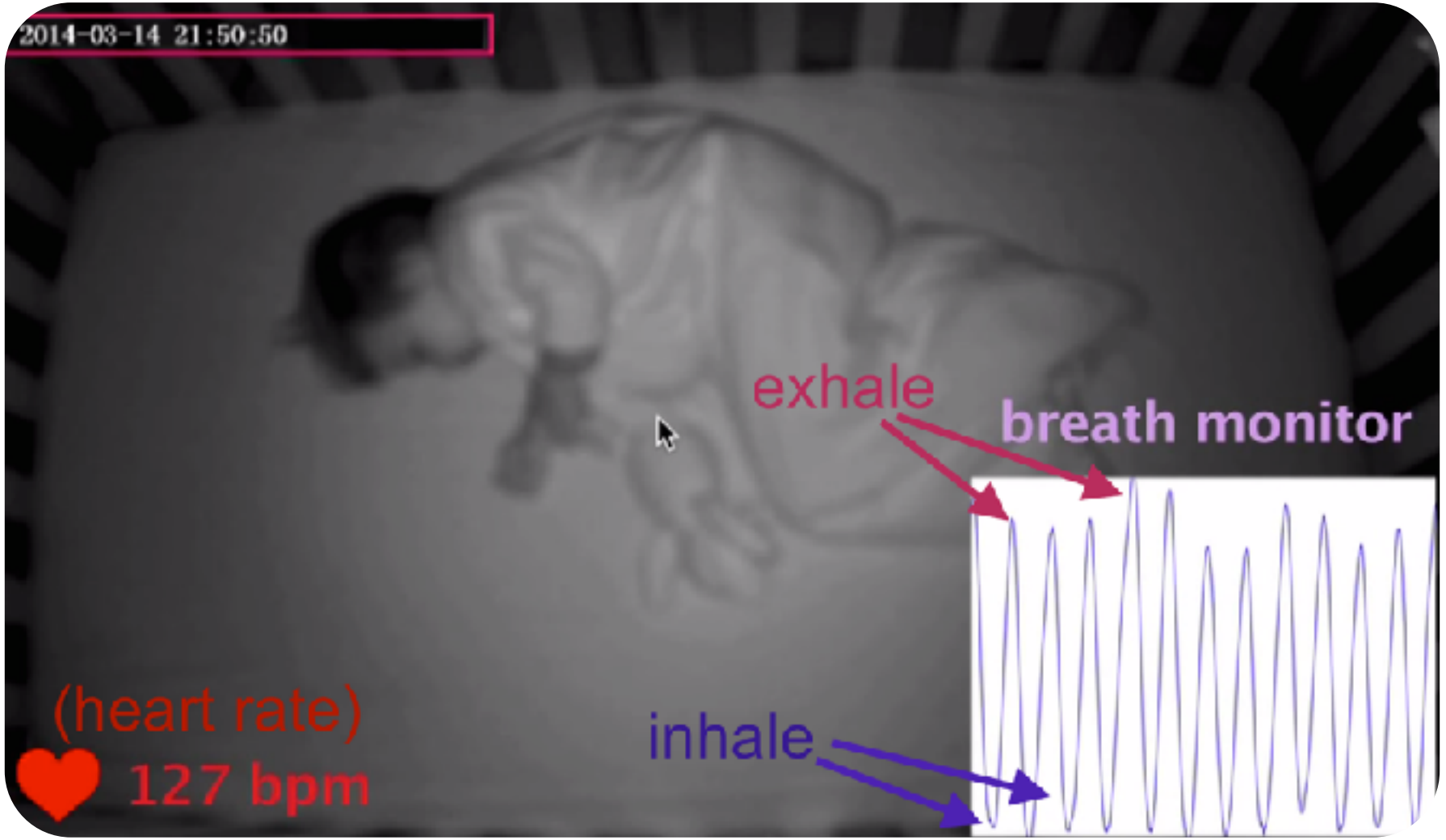
100 experiments: ½ million location measurements



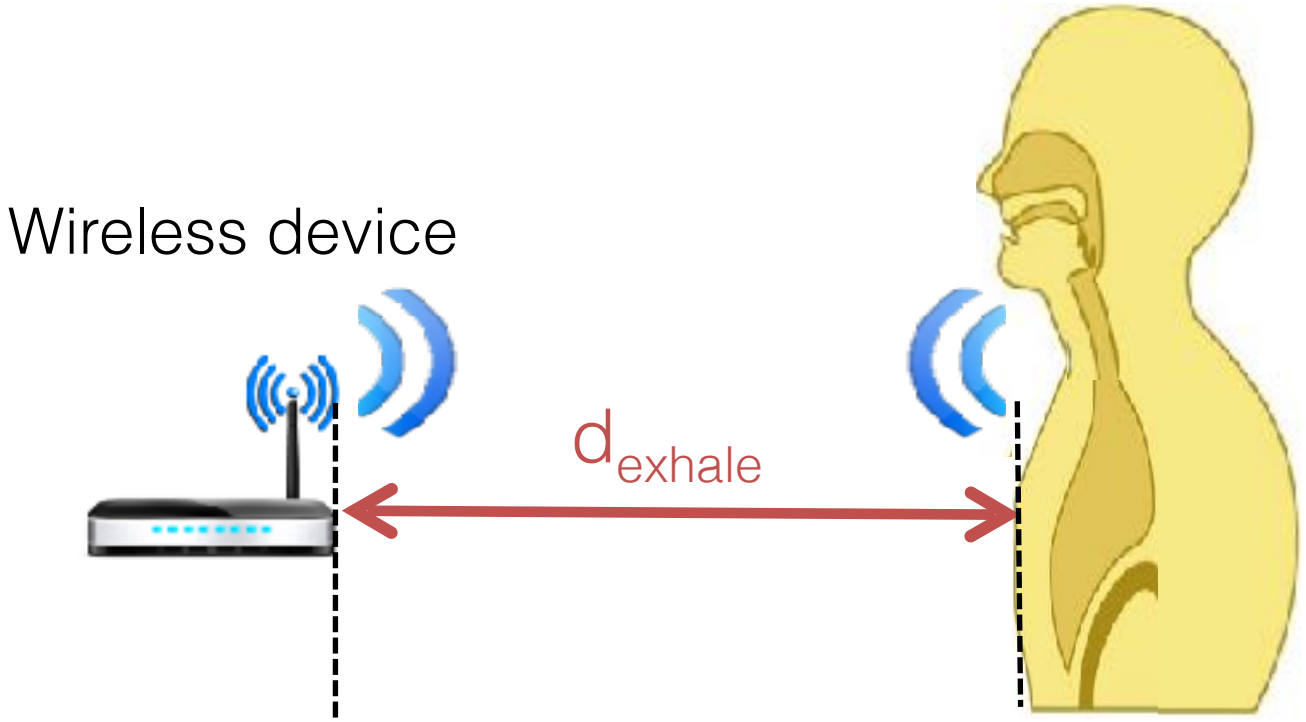
Centimeter-scale localization without requiring the user to carry a wireless device

Remotely Measuring Breathing and HR

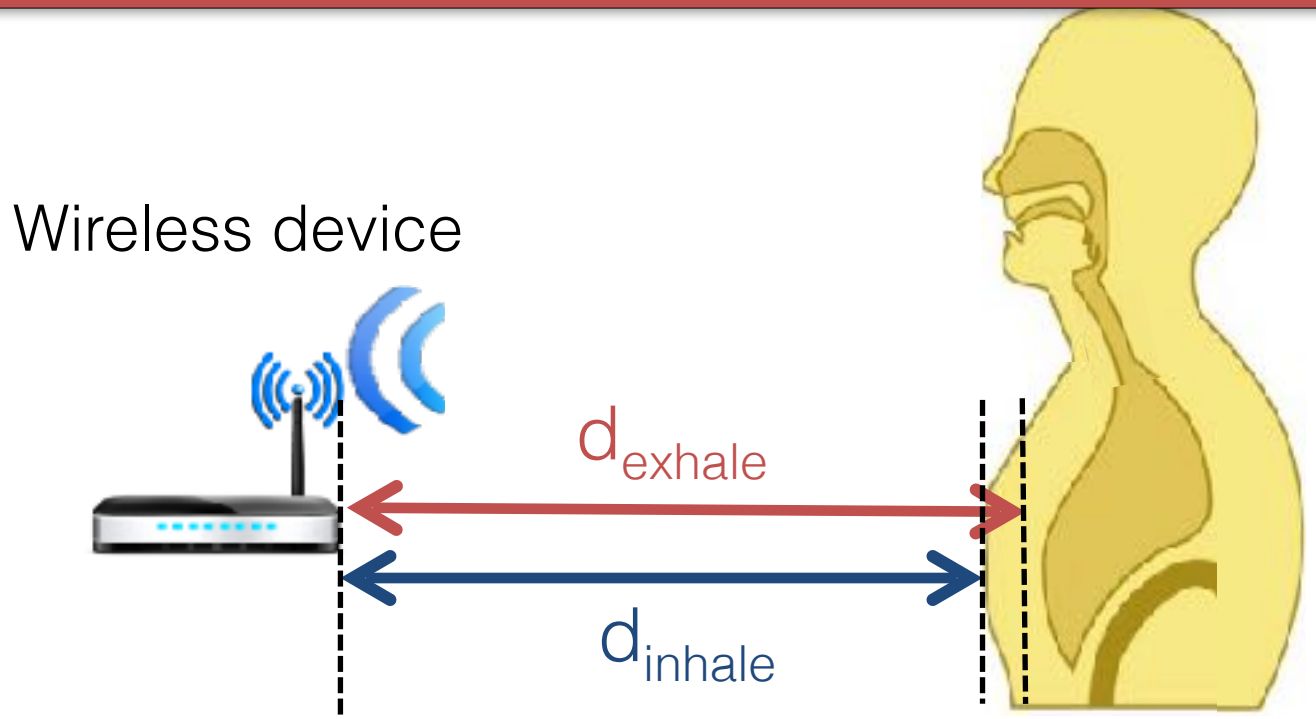
[CHI'15]



Idea: Use wireless reflections off the human body

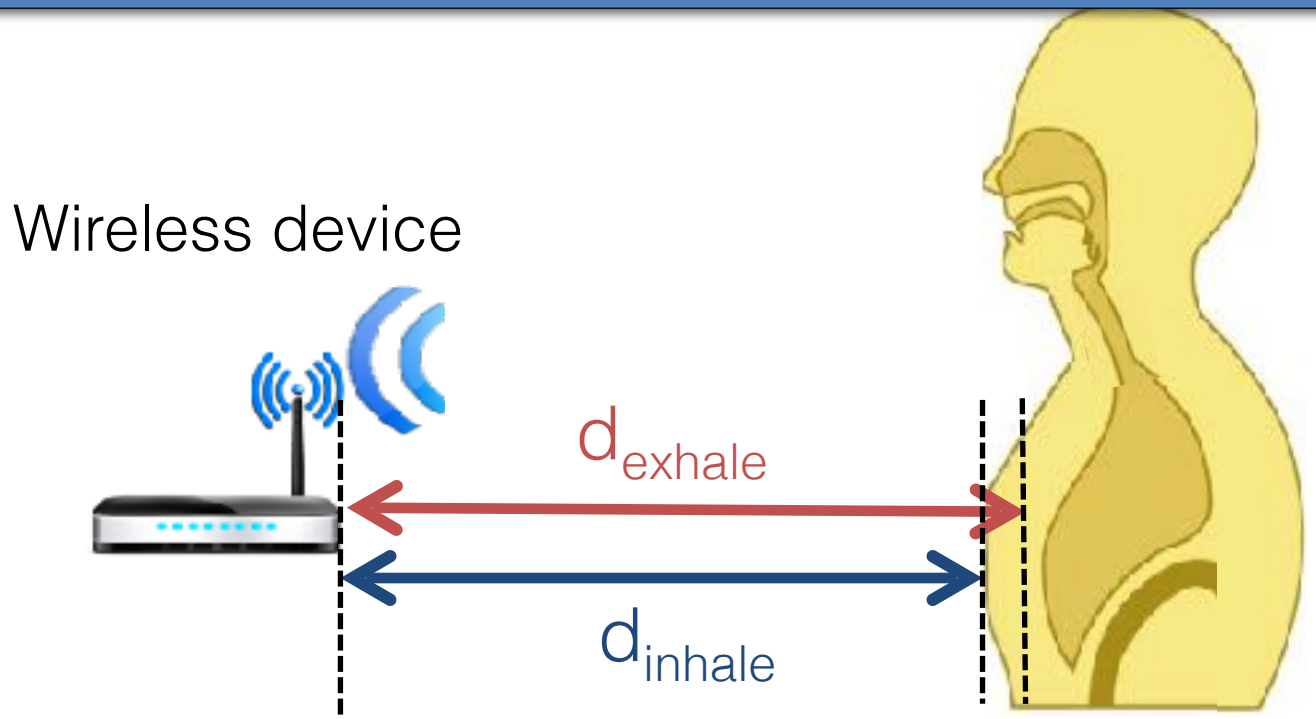


Problem: Localization accuracy is only 12cm and cannot capture vital signs



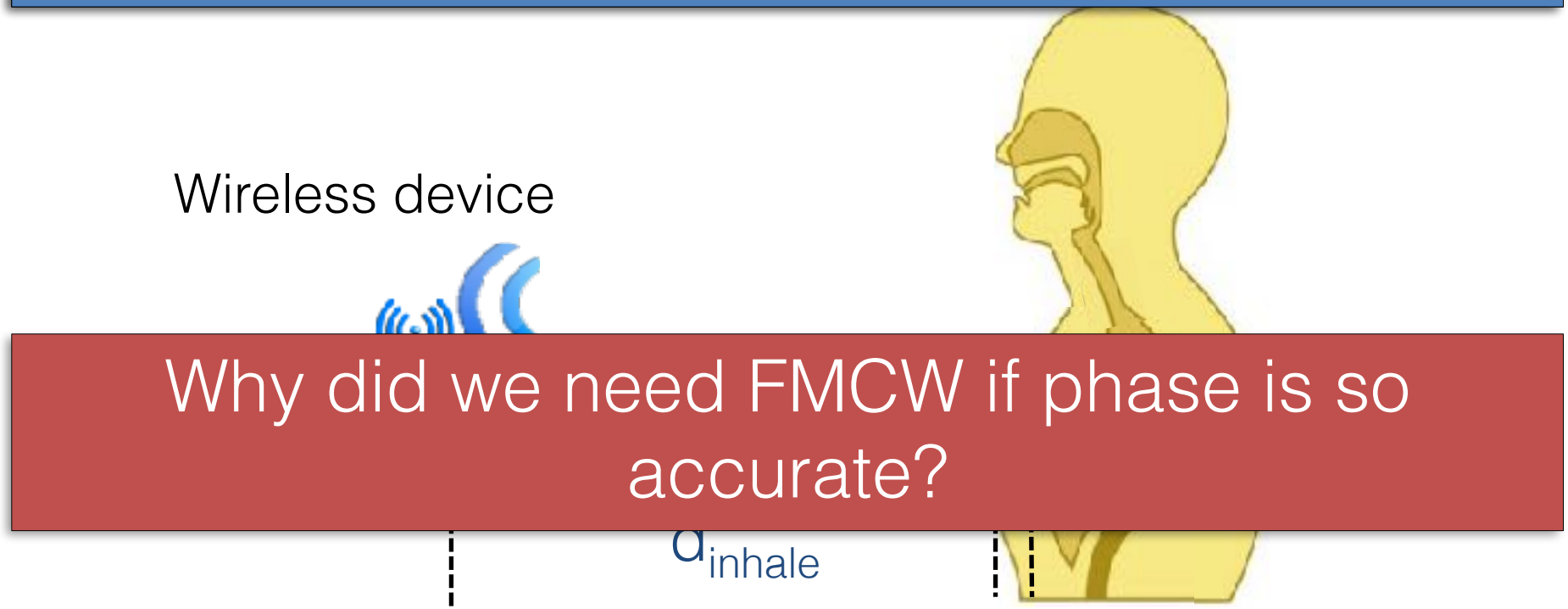
Why? How did we compute the resolution?

Solution: Use the phase of the wireless reflection



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

Solution: Use the phase of the wireless reflection

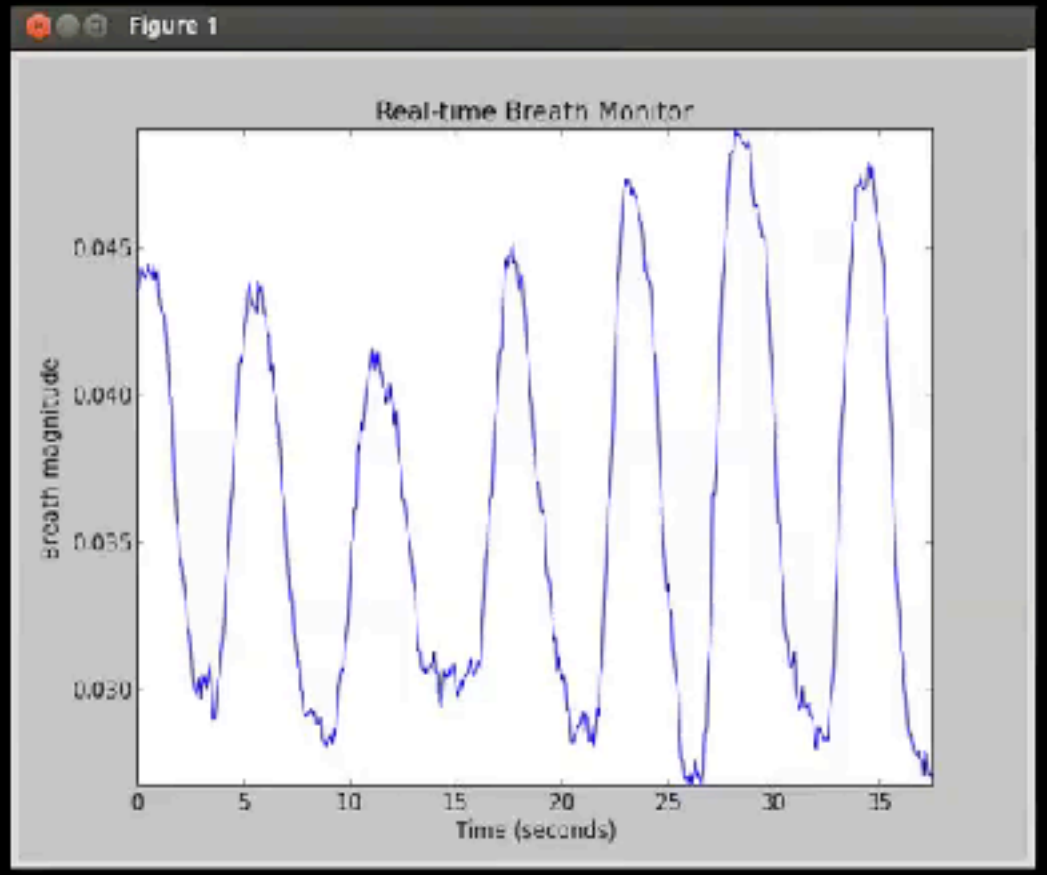


Why did we need FMCW if phase is so accurate?

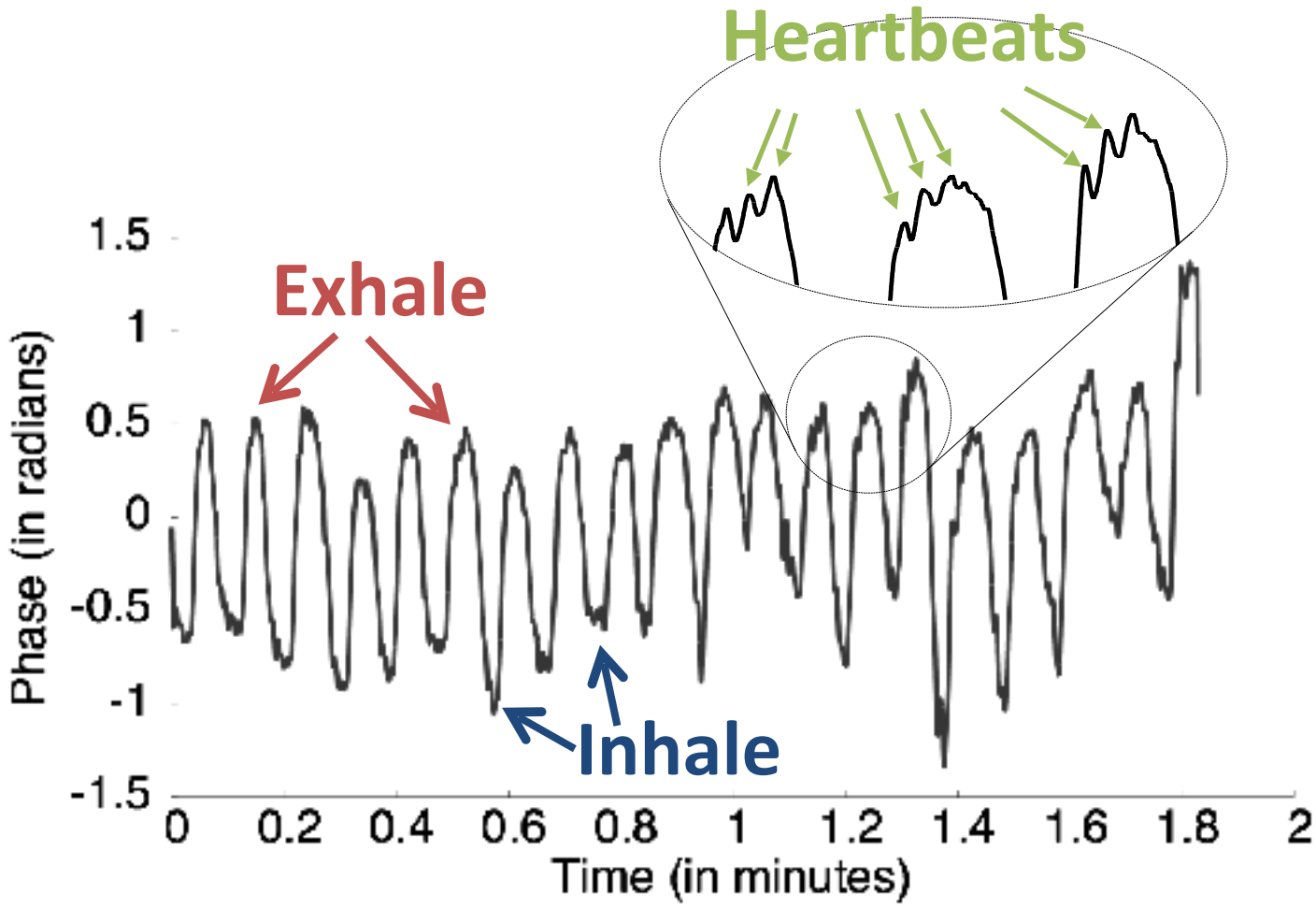
Wireless wave has a phase: $\Phi = 2\pi \frac{\text{distance}}{\text{wavelength}}$

- Chest Motion changes distance
- Heartbeats also change distance

Breath Monitoring using Wireless (Vital-Radio, 2015)



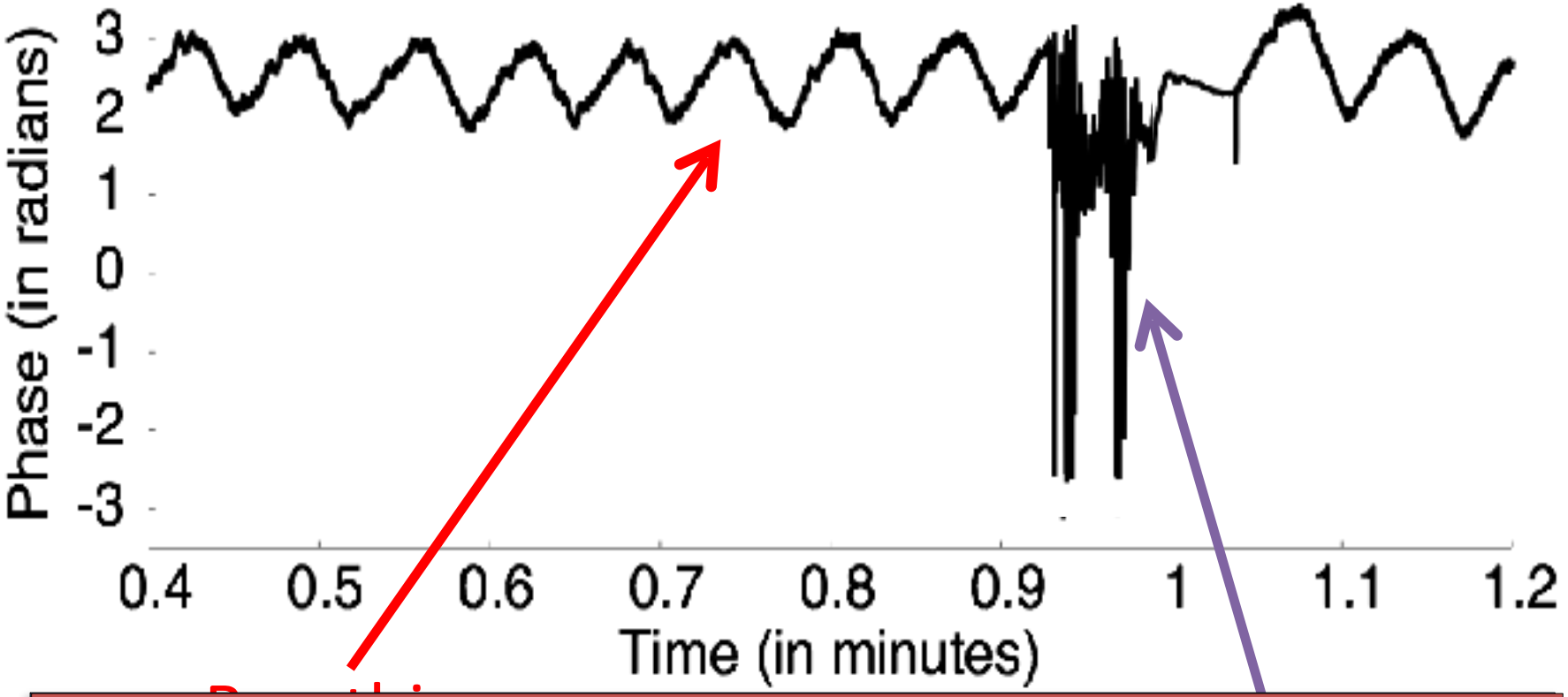
Let’s zoom in on these signals



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?

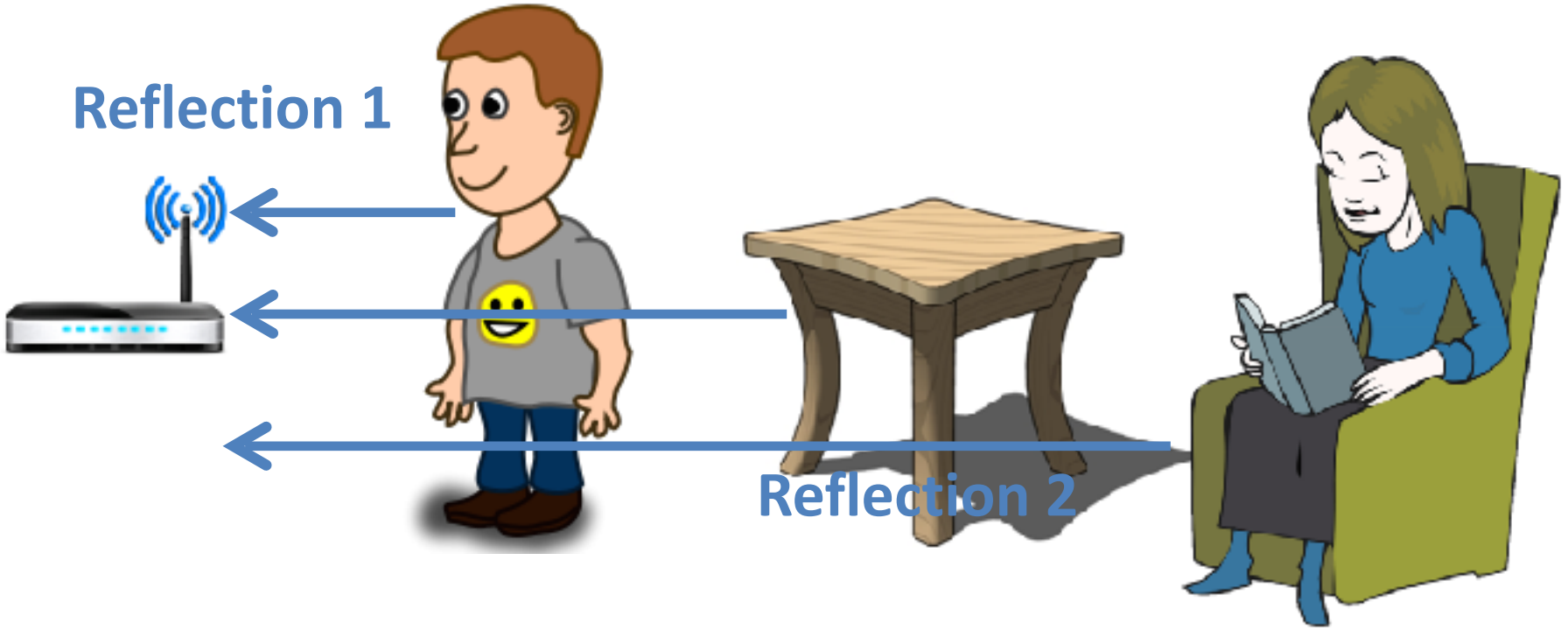


Band-pass filter the cleaned signals to extract breathing and heart rate

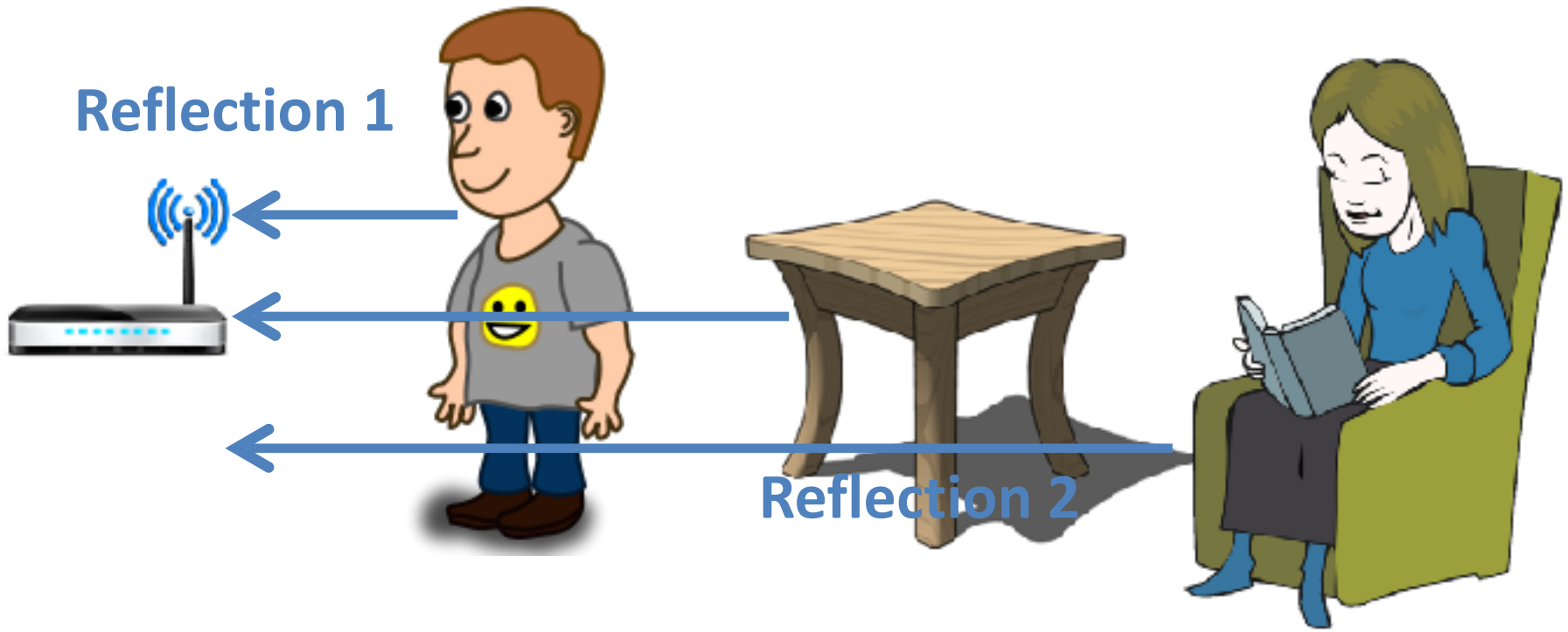
What happens with multiple users in the environment?

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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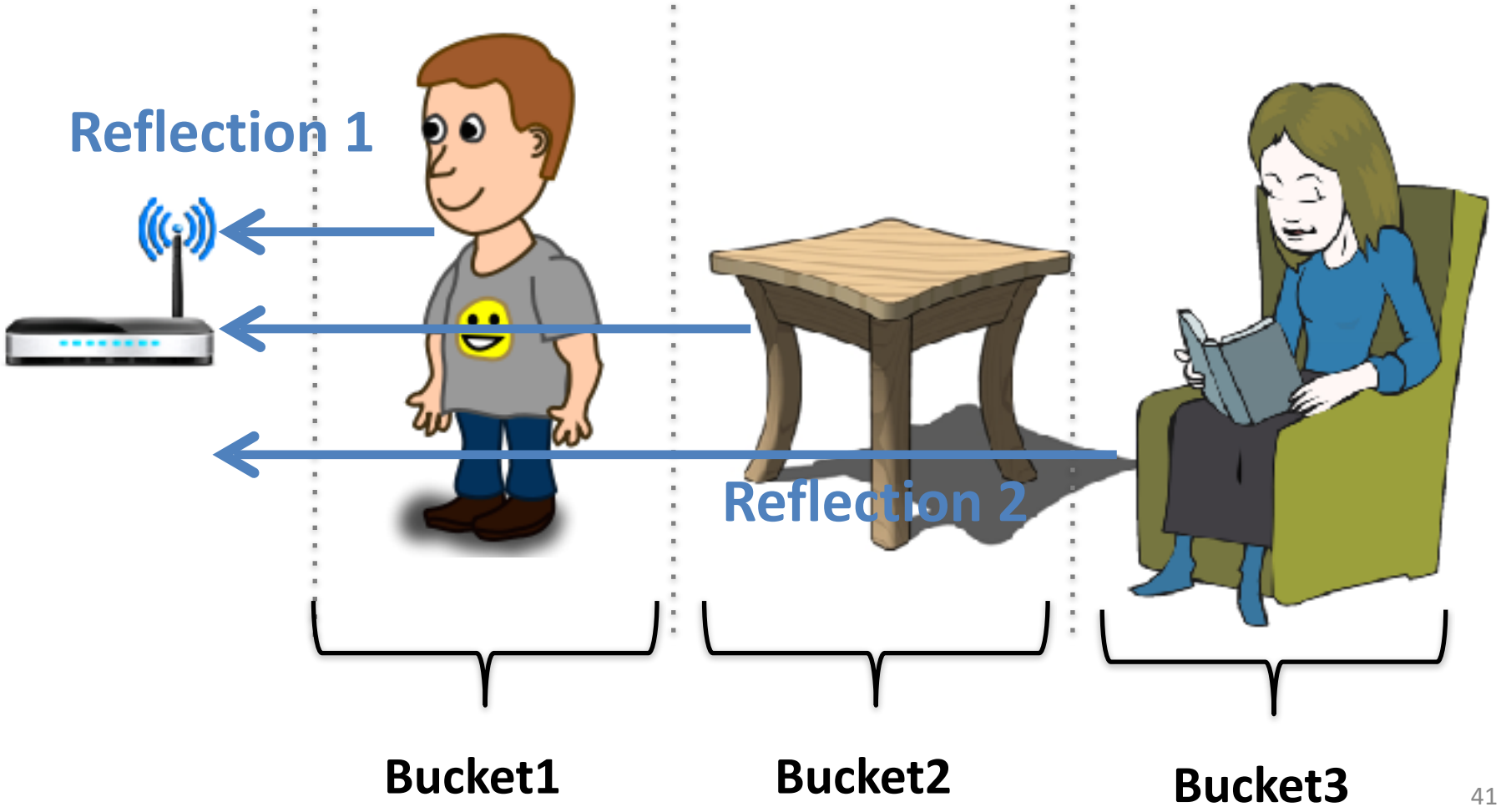

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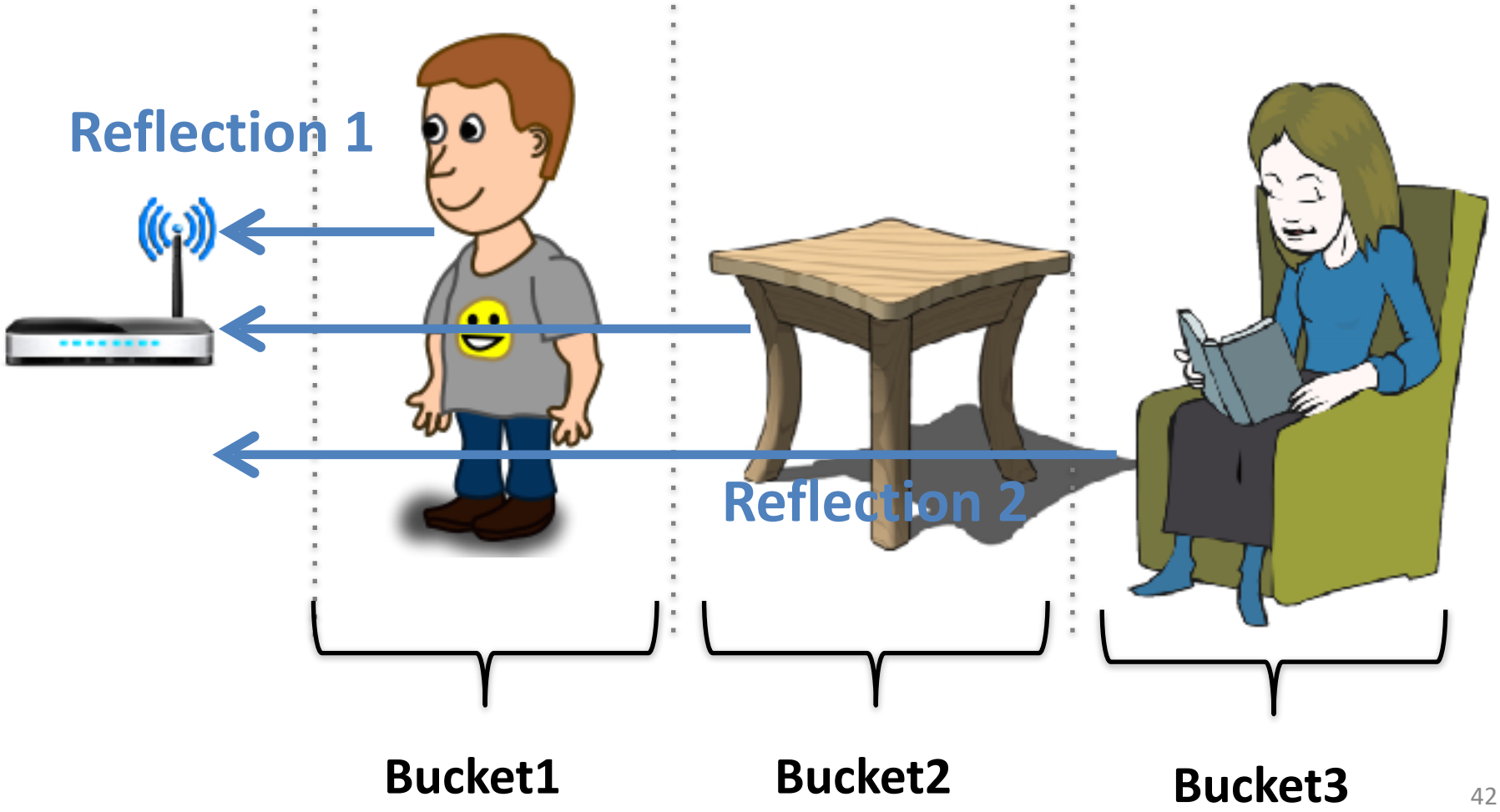


Recall Formulation with FMCW

Recall Formulation with FMCW

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

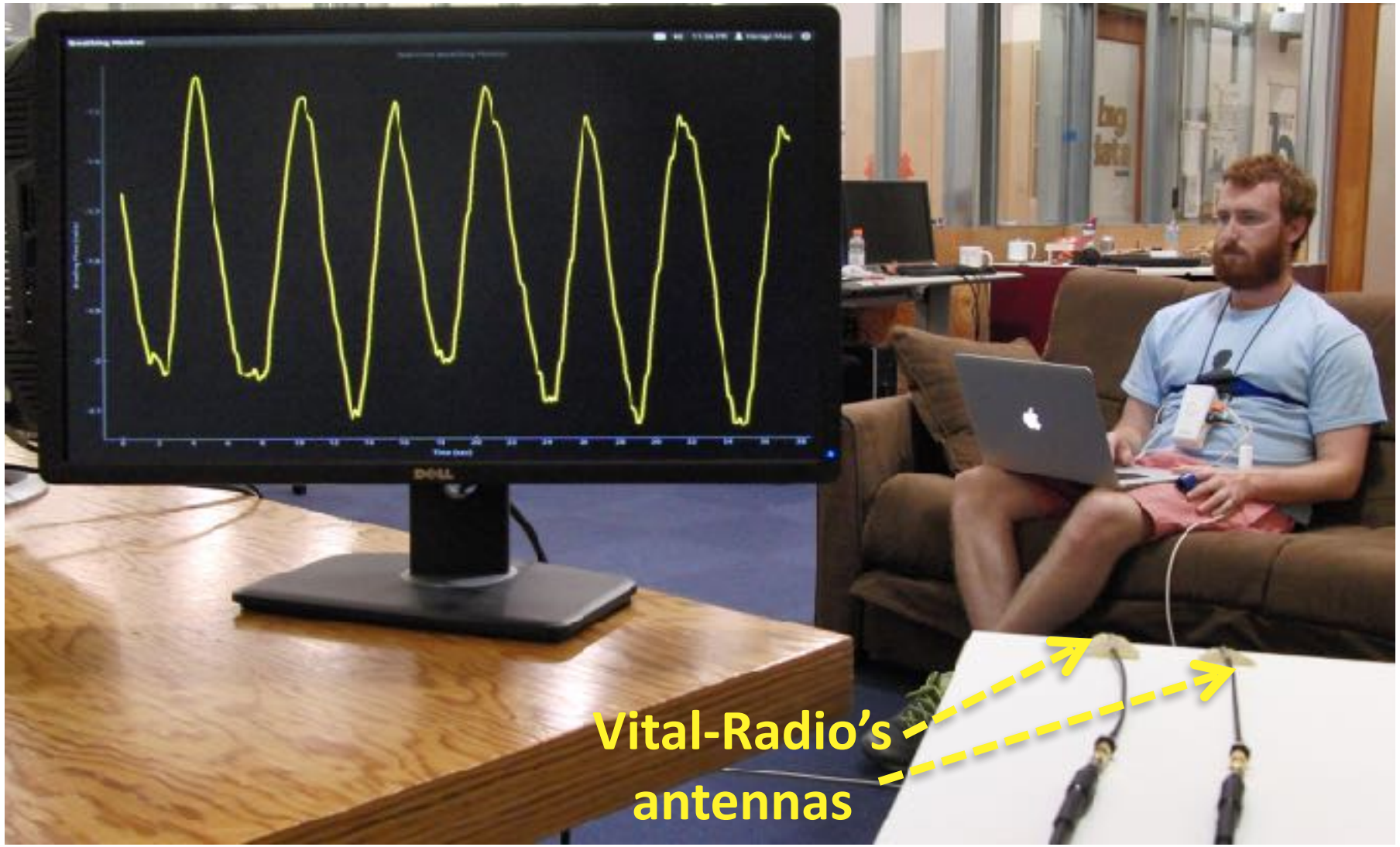
Putting It Together

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



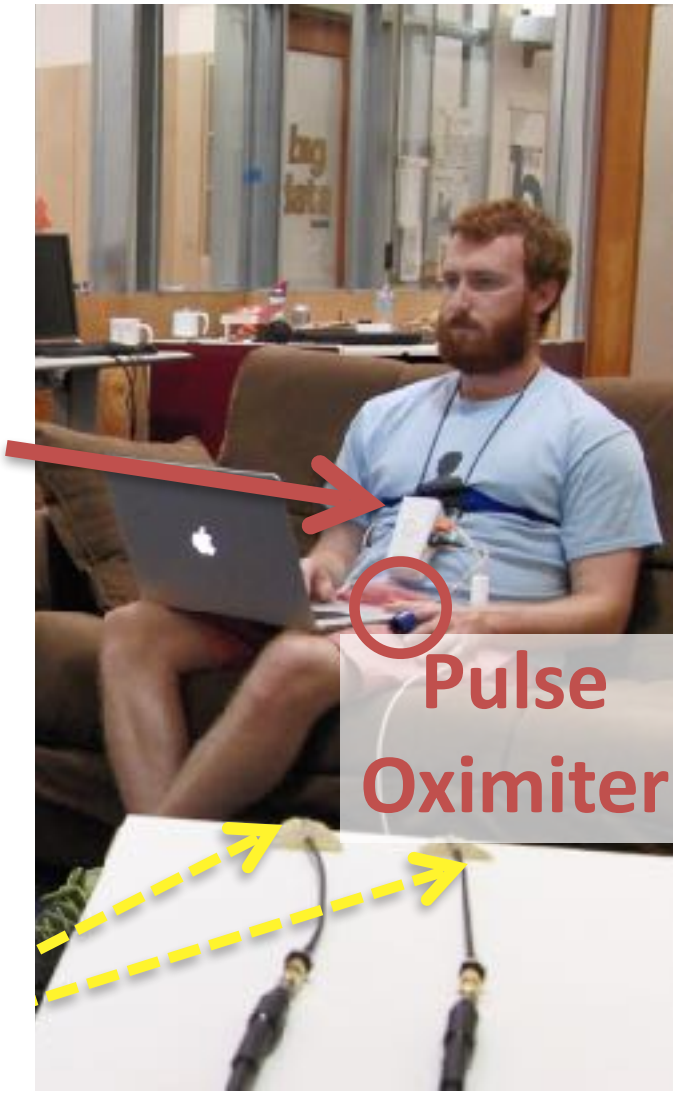
Vital-Radio Evaluation

Baseline:

- FDA-approved breathing and heart rate monitor

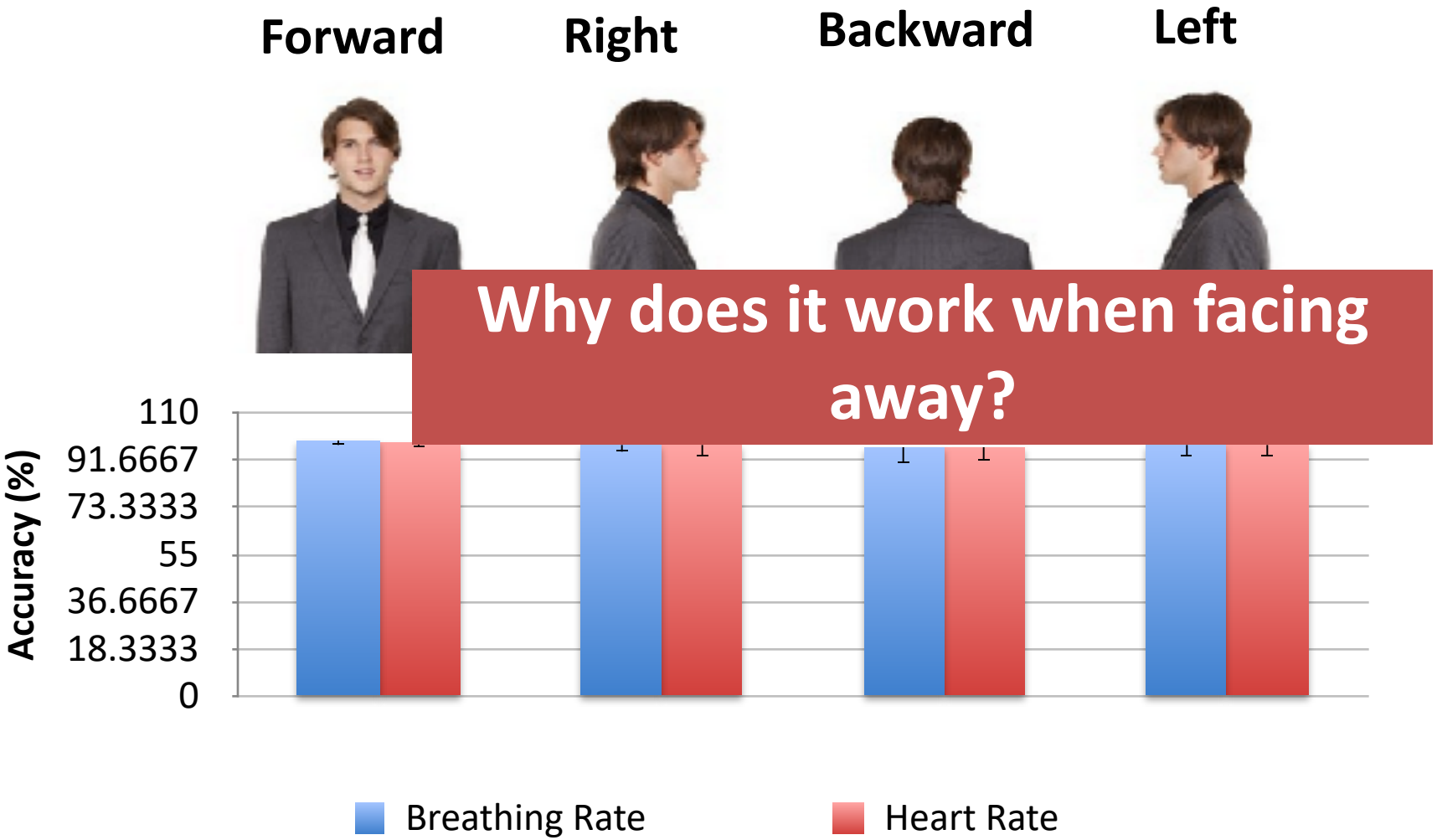
Experiments:

- 200 experiments
- 14 participants
- 1 million measurements



Accuracy vs. Orientation

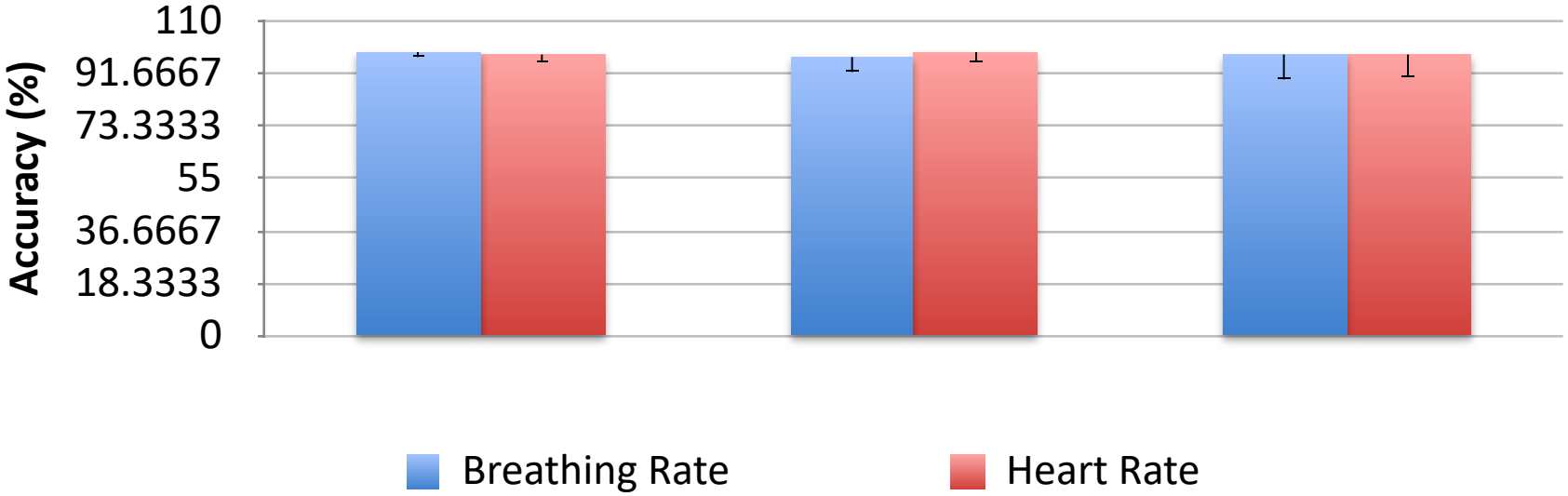
User is 4m from device, with different orientations



Accuracy for Multi-User Scenario

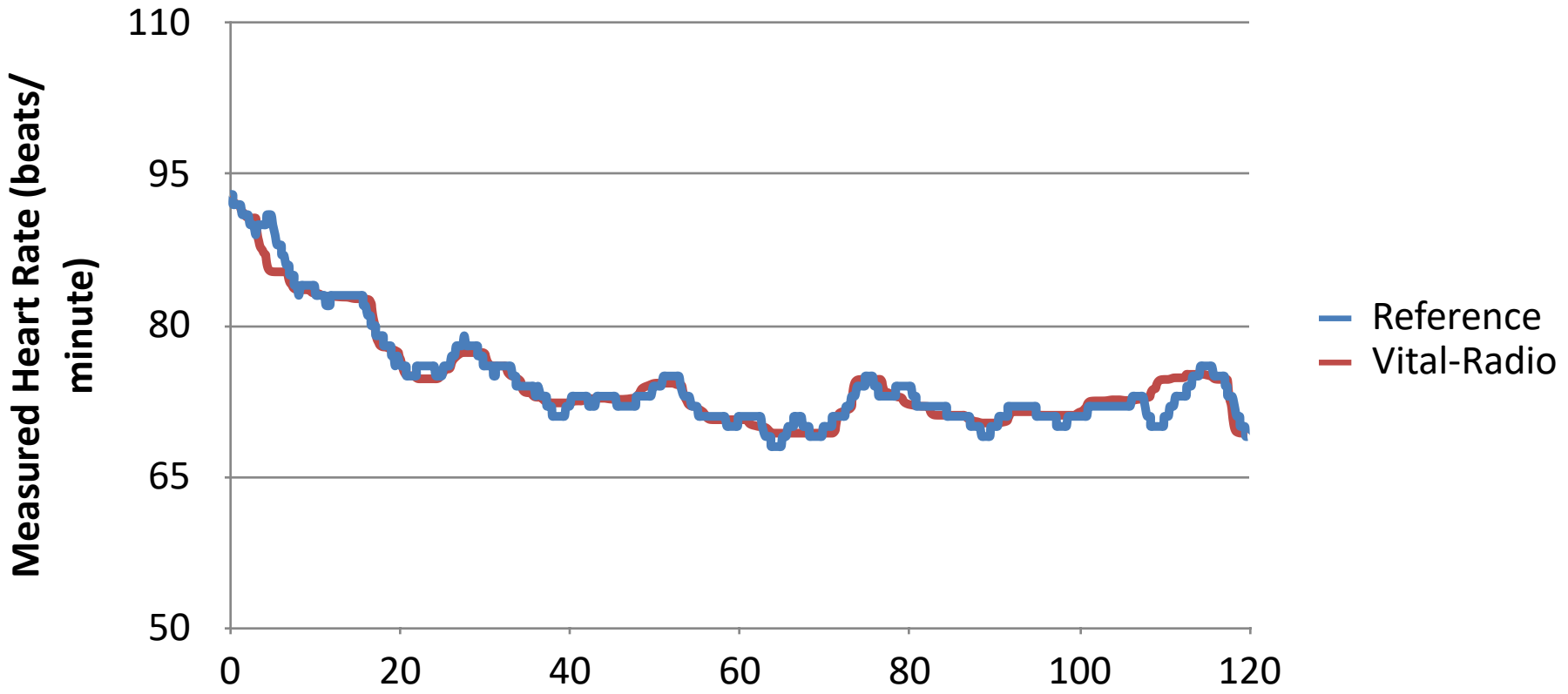
Multiple users sit at different distances

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



Accuracy for Tracking Heart Rate

Measure user's heart rate after exercising

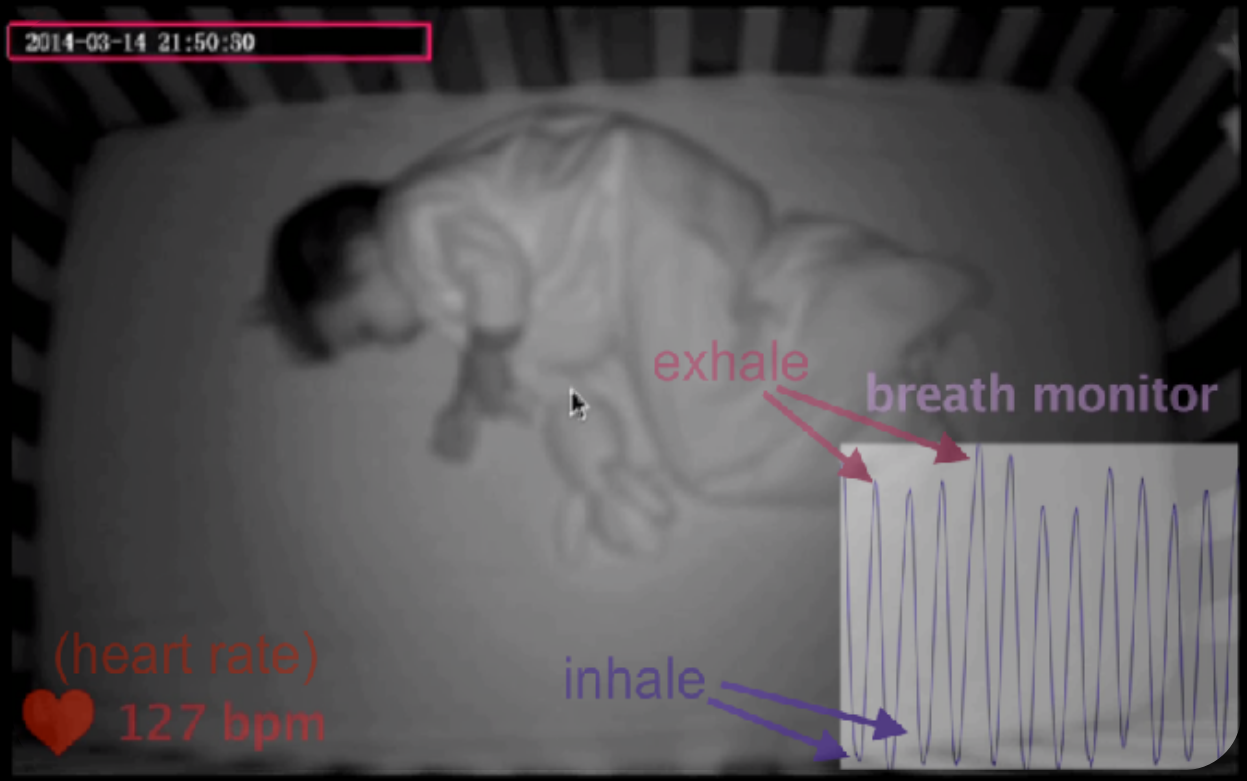


Vital-Radio accurately tracks changes in vital signs

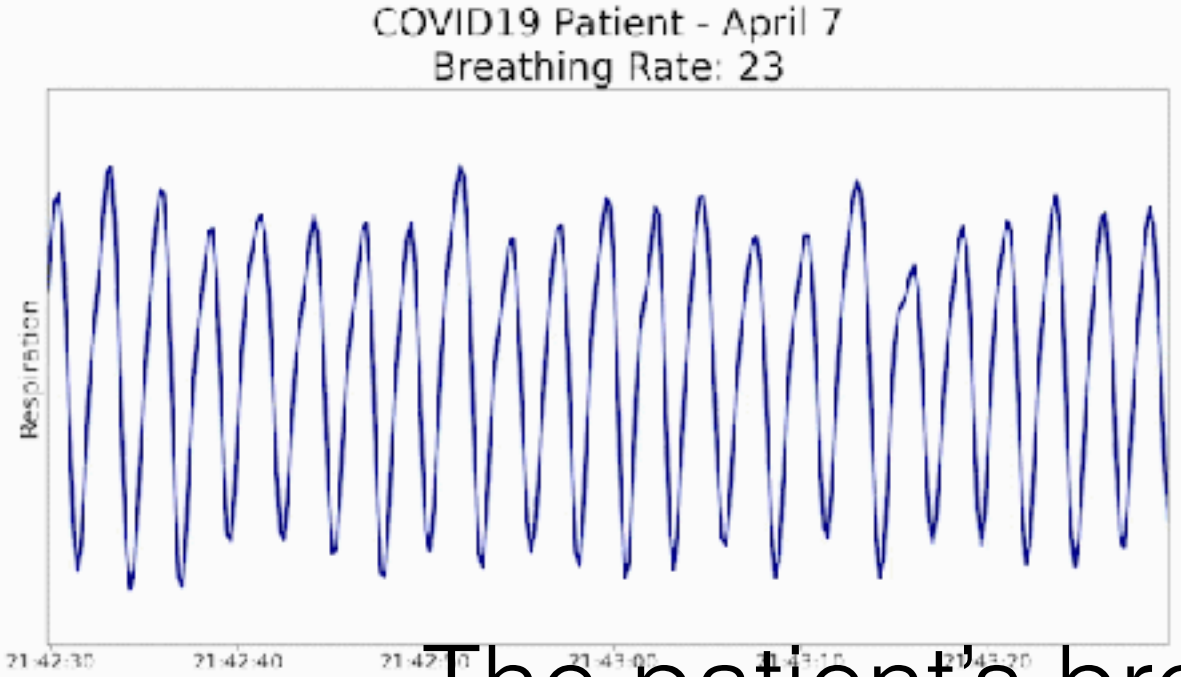
Vital-Radio Limitations

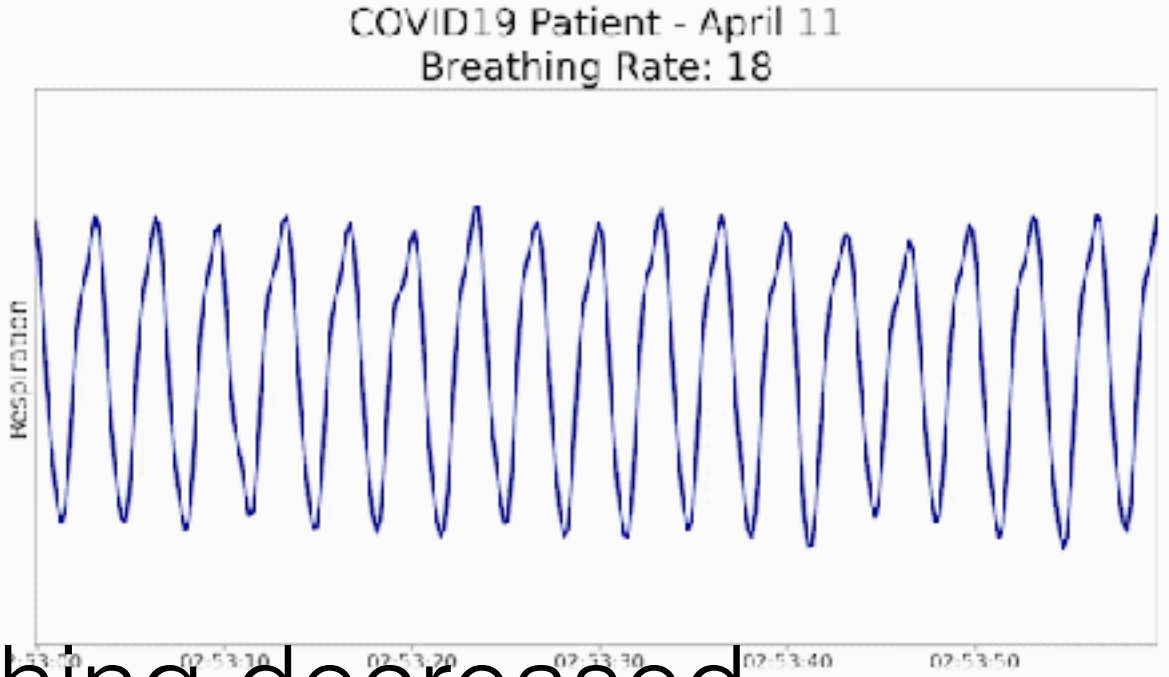
- Minimum separation between users: 1-2m
- Monitoring range: 8m
- Collects measurements when users are quasi-static

Baby Monitoring

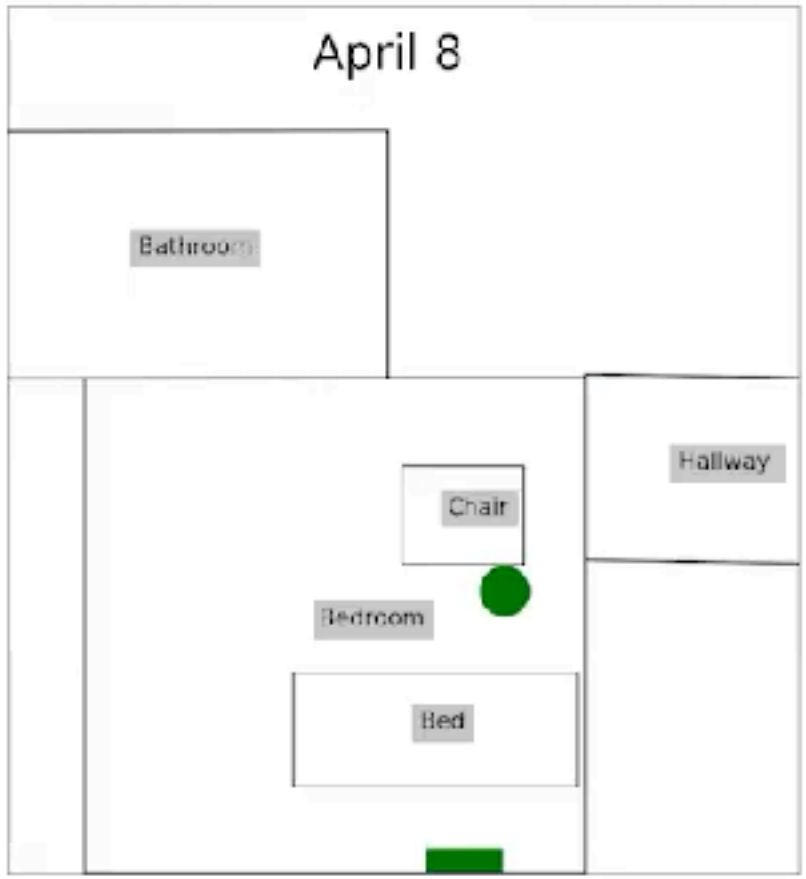


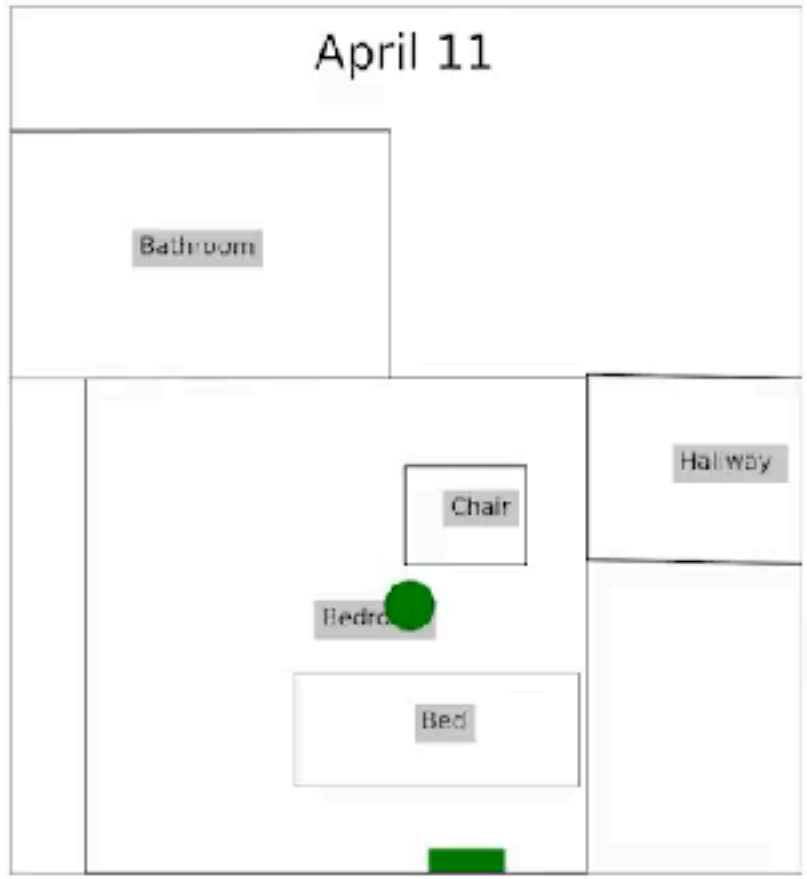
Monitoring COVID-19 Patient





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





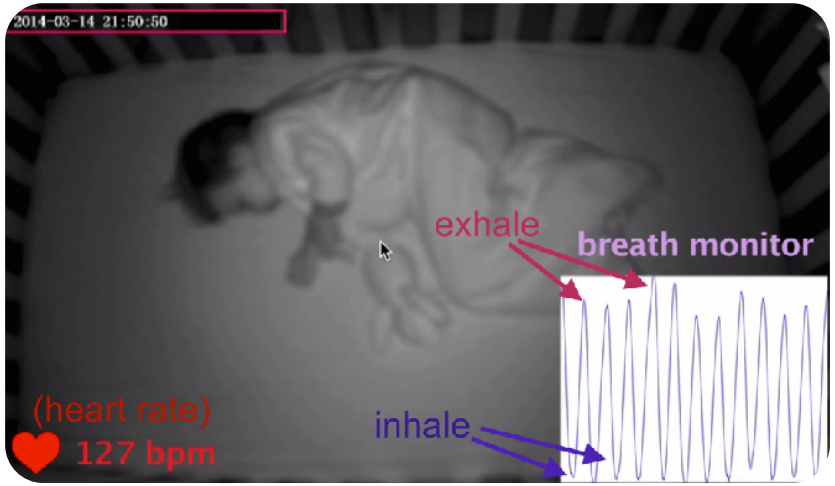
The patient's movements also demonstrate a marked improvement.

How can we capture heart recordings?

98-99% accuracy in timing micro-cardiac events

[ACM MobiCom'20]

Breathing & Heart Rate

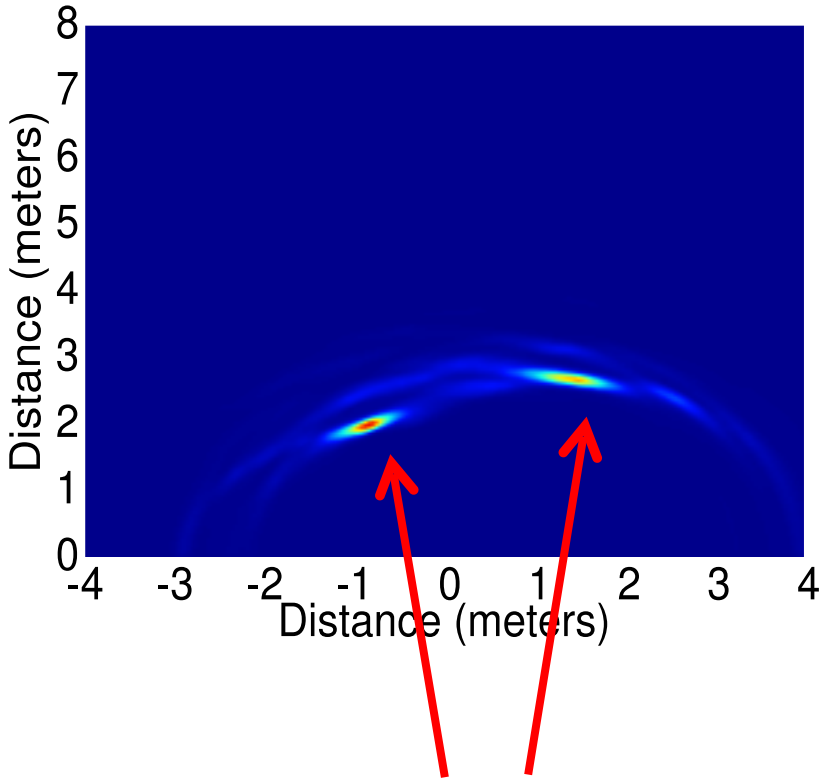


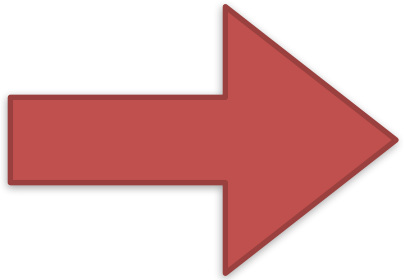
Want Emotions

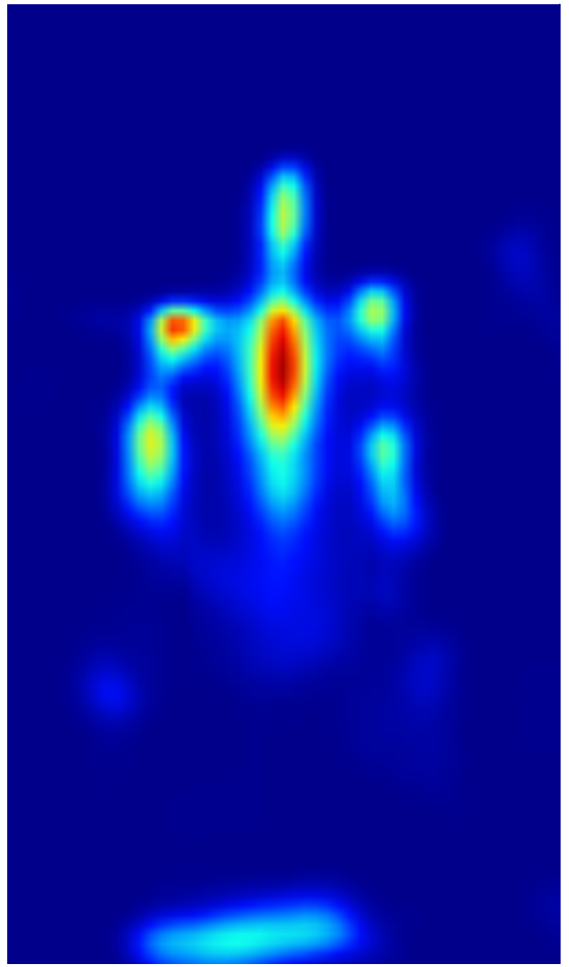
Why and how would you be able to get from BR/HR -> emotions?

Want a silhouette

People are points



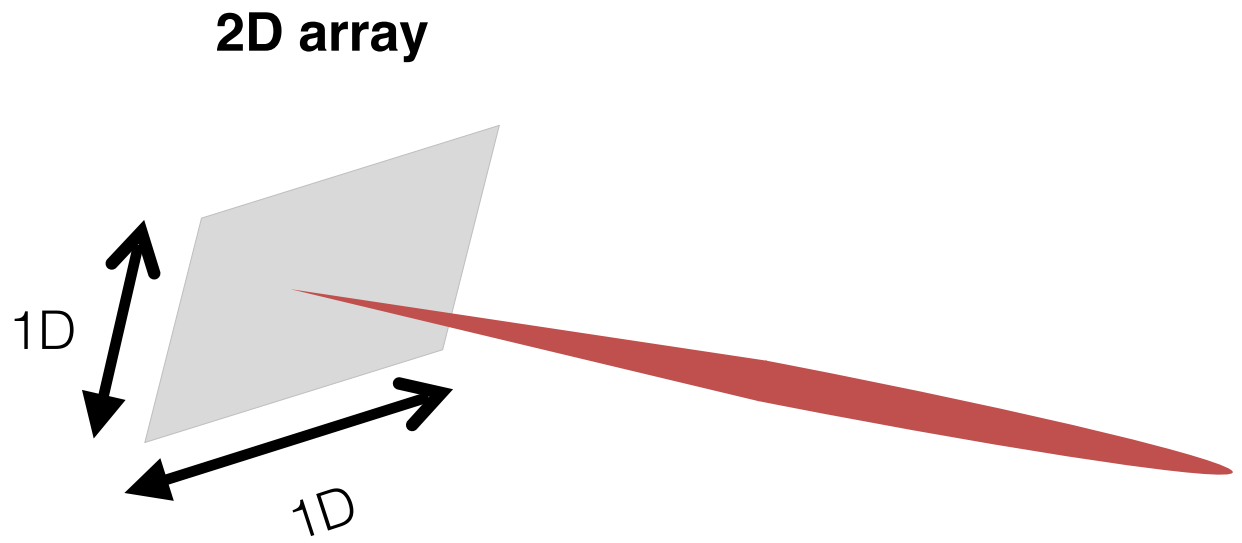




Localize the two users

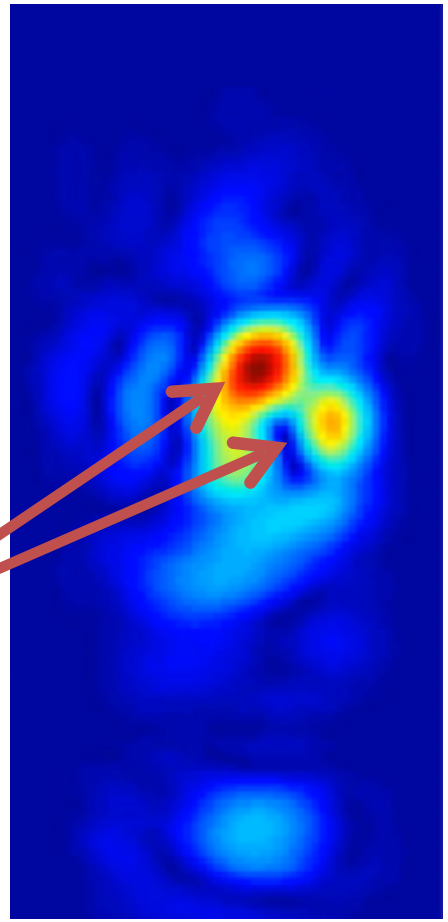
Approach: Combine antenna arrays with FMCW to get 3D image

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



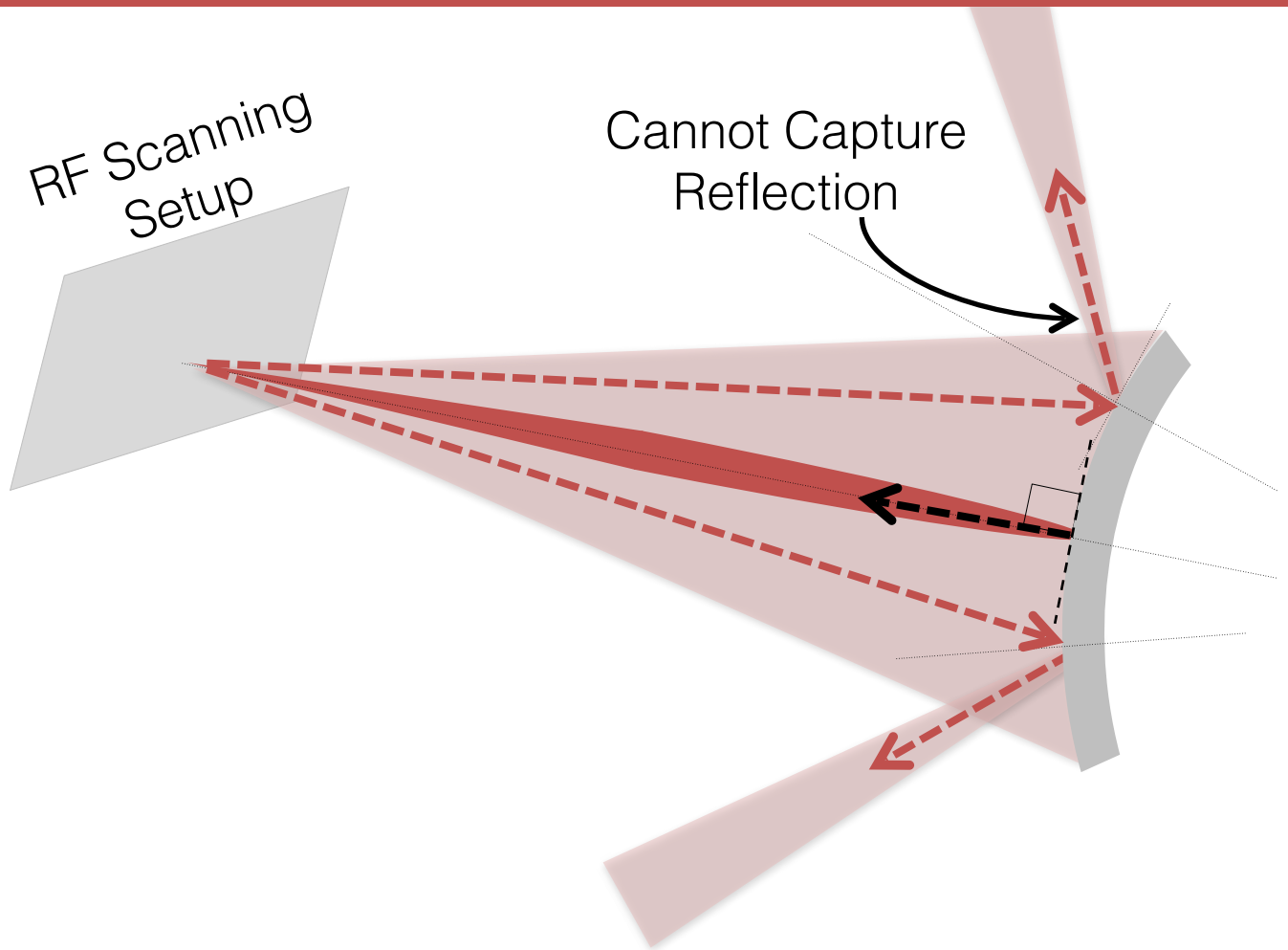
Challenge: We only obtain blobs in space

Output of 3D RF Scan

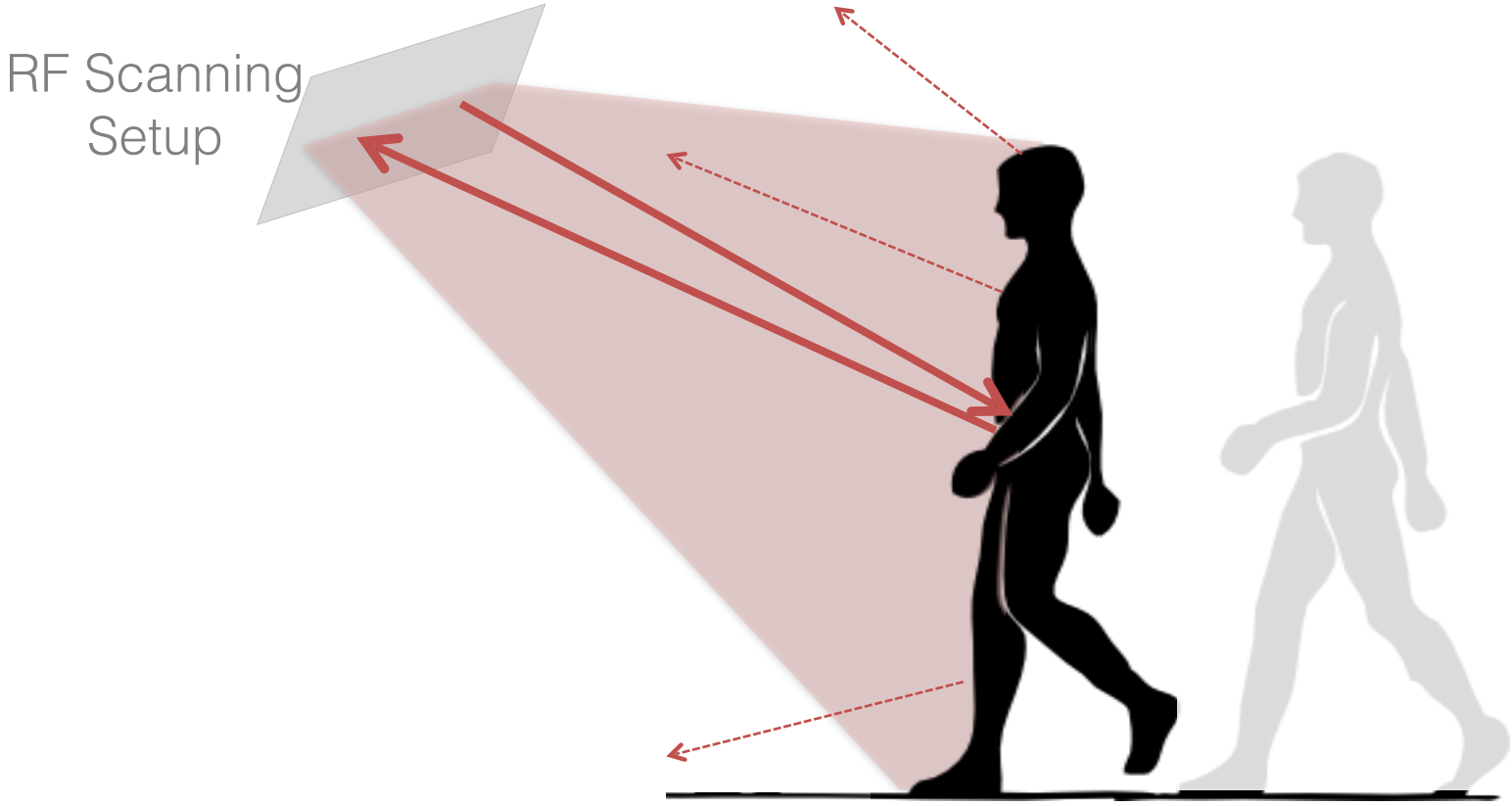


Blobs of reflection power

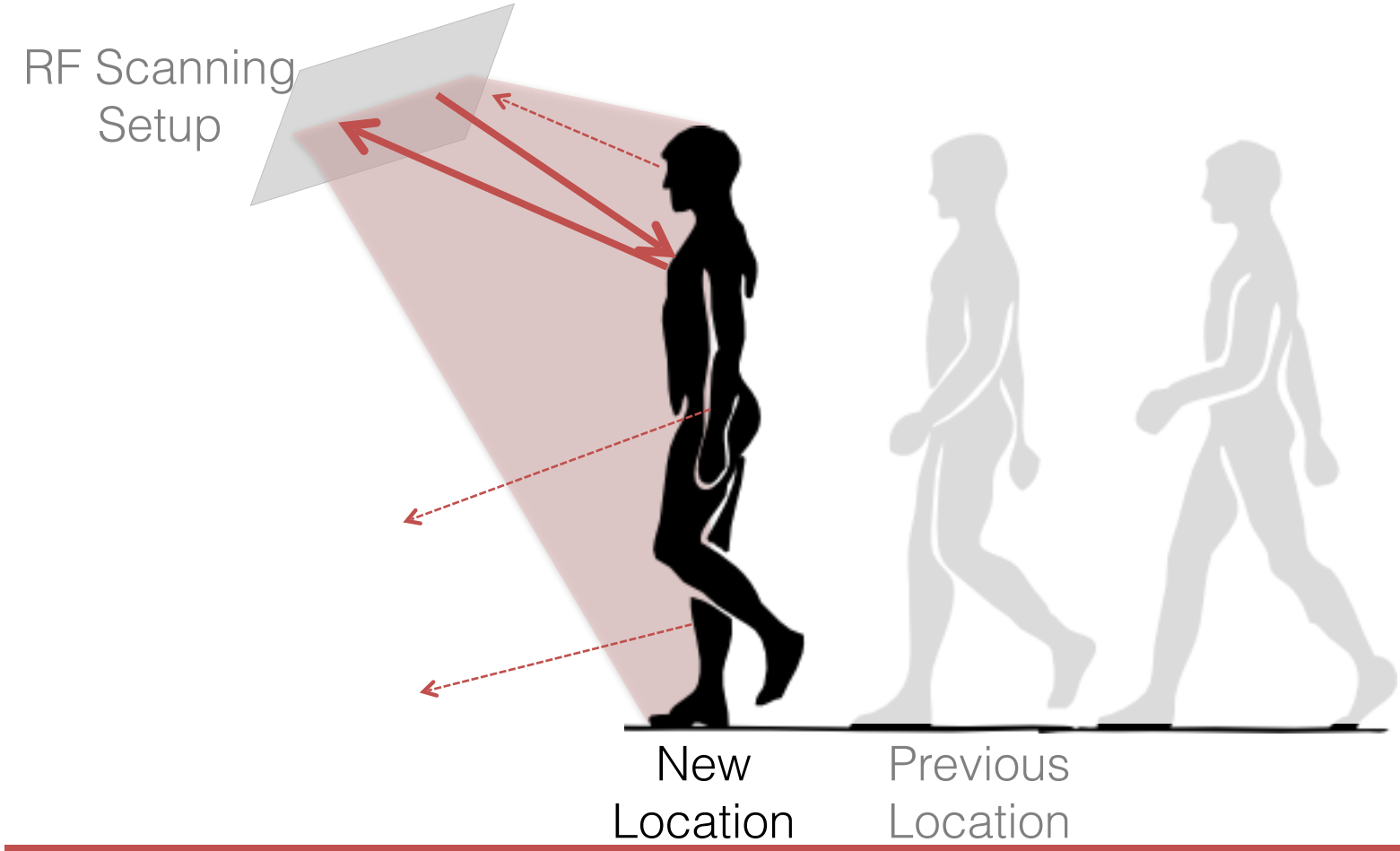
At every point in time, we get reflections from only a subset of body parts.



Solution Idea: Exploit Human Motion and Aggregate over Time

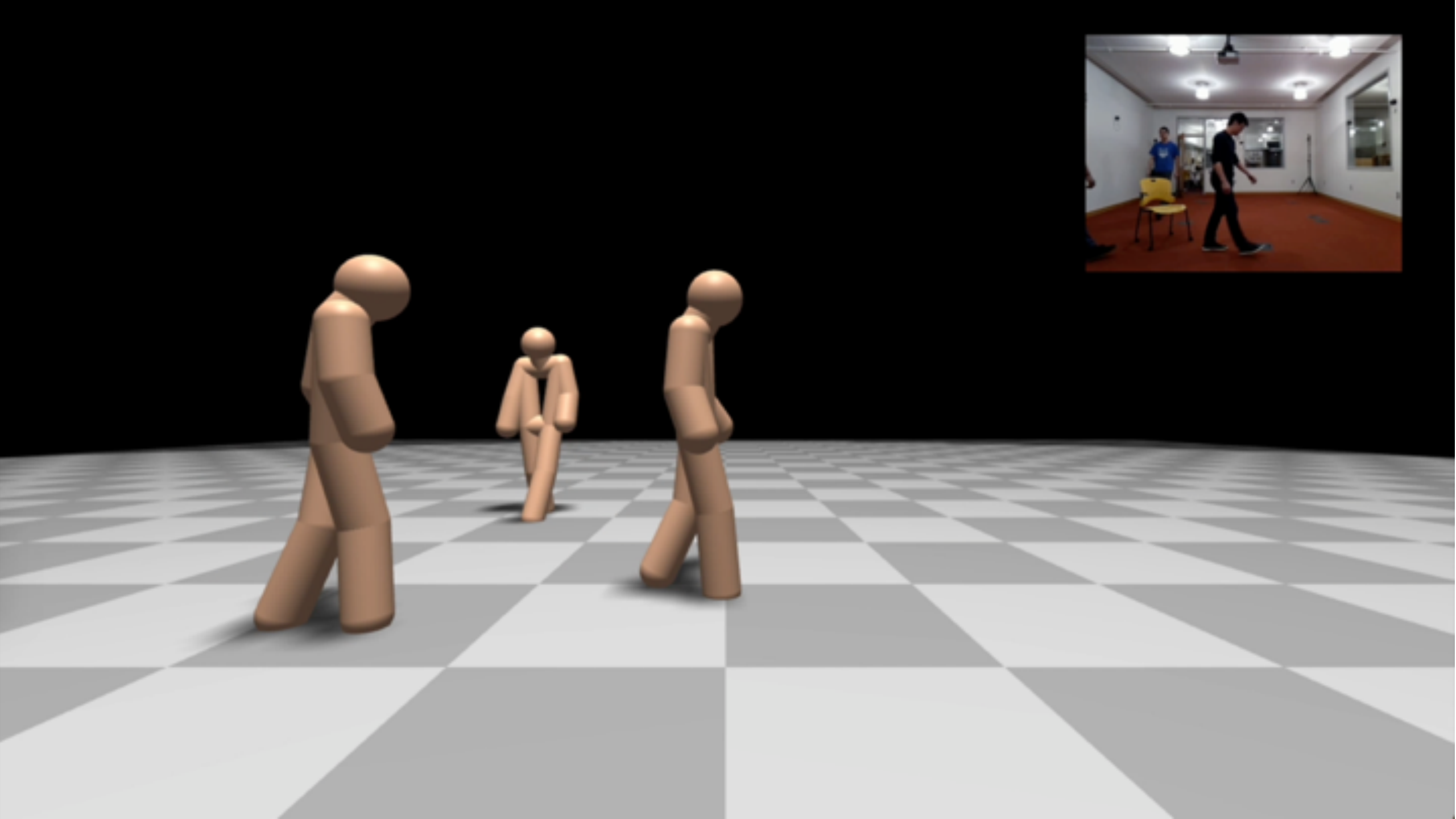


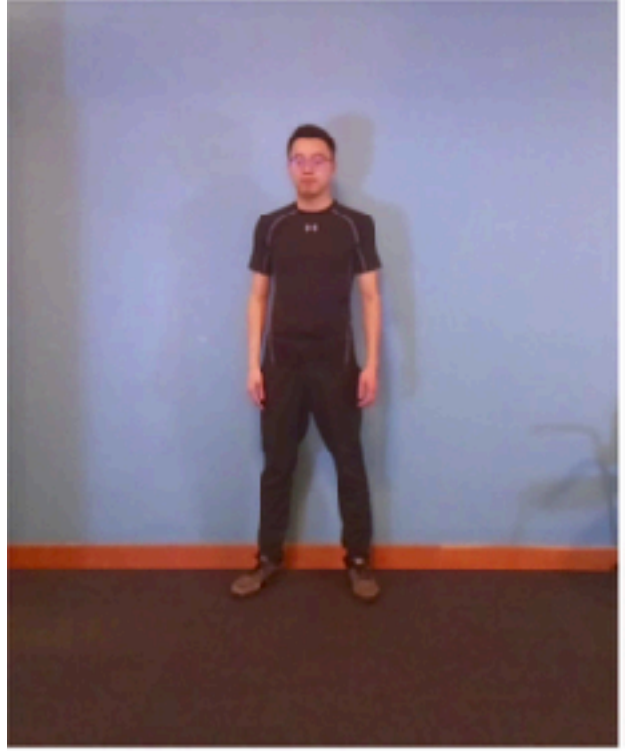
Solution Idea: Exploit Human Motion and Aggregate over Time



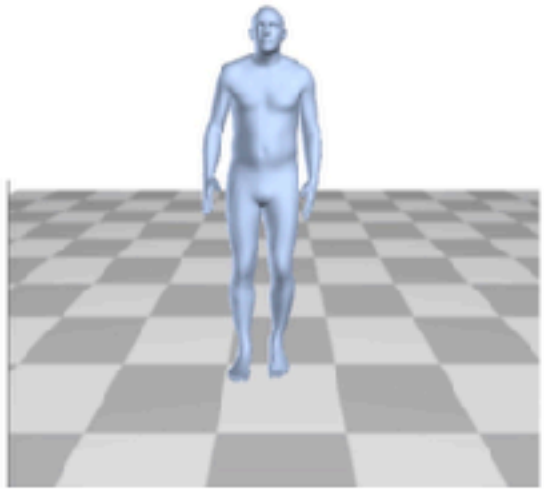
Combine the various snapshots

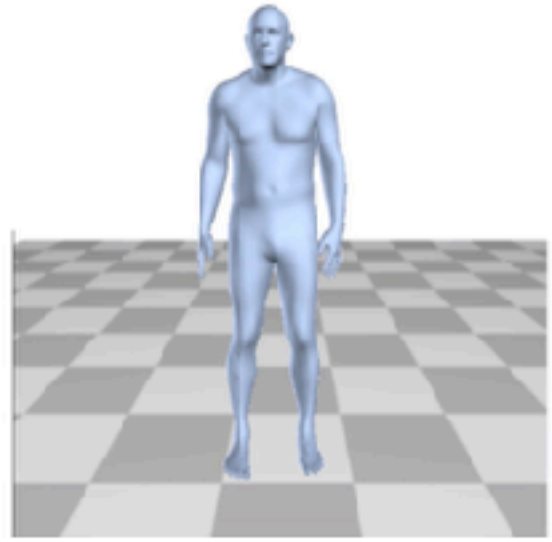

COMMUNICATIONS
ACM

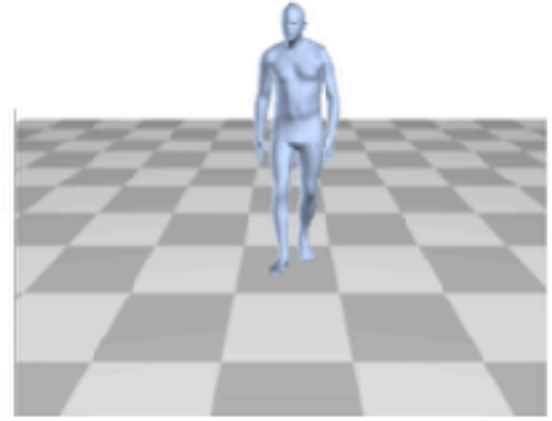





Person behind the wall







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

Objectives of Today's Lecture

Learn the fundamentals, applications, and implications of

wireless localization and sensing

1. What are the unifying principles of wireless positioning & wireless sensing?
2. How do systems like GPS, WiFi positioning, seeing through walls work?
3. How do state-of-the-art positioning systems work?
4. What are the industry opportunities and societal implications of wireless positioning and sensing (today and in the near+far future)?

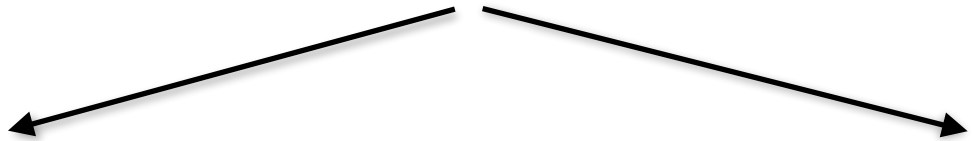
Sign Up to Presenting a Paper

Each class attendee (registered or listener) is expected to sign up to present a paper:

- 2 papers on RF-SLAM
- 3 on wireless + AI: wireless NeRF, FCC LLM, multi-modal LLM
- 2 on multipath localization
- 1 on mobile health sensing

Check the website and email me which paper you want to present

Wireless & Mobile Sensing

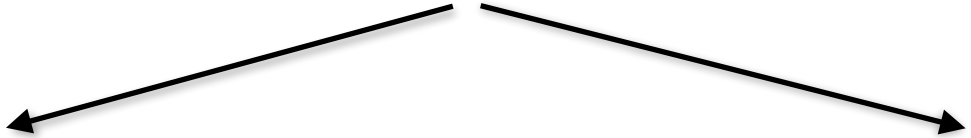


sensing the physical world &
transmitting data wirelessly

sensing via the wireless
signals or mobile devices

so far

Wireless & Mobile Sensing



sensing the physical world & transmitting data wirelessly

Next

sensing via the wireless signals or mobile devices

so far