SonicDoor: Scaling Person Identification with Ultrasonic Sensors by Novel Modeling of Shape, Behavior and Walking patterns

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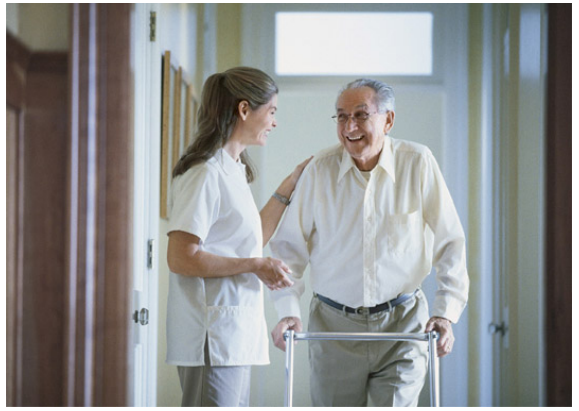
Non-intrusive Identification is useful

Customize climate based on users' preference



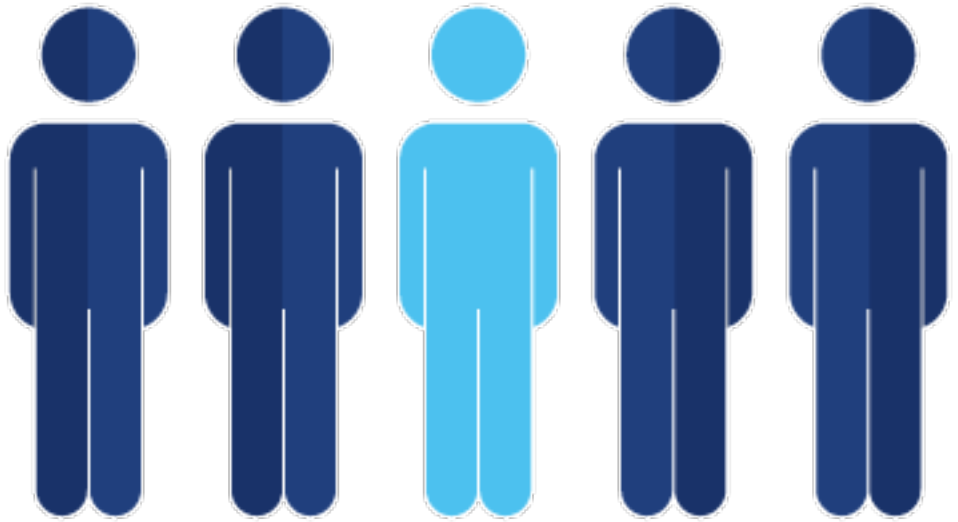
Monitor occupants in nursing homes

Problems with Current Identification Methods

Device-based Methods

Requiring user to carry a device

Device-Free Methods



Identifying only limited number of people

- We present SonicDoor
  - Sense height and width of walker as she walks through the door

- We accurately identify 100 people
  - Suitable for building related applications

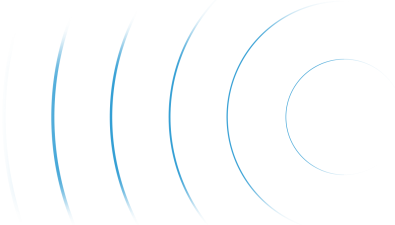
1. Introduction
2. **Related Work**
3. System Overview
4. Evaluation
5. Conclusion

Technologies for Building Occupant Identification

1. Device-based Methods
   - RFID, Smartphones, iBeacon
   - Fail if user forgets to carry device

2. Strong Biometrics
   - Facial, Fingerprint, iris
   - Privacy infringing
   - Require active authentication with the system

3. Weak Biometrics
   - Height, weight, footstep vibration, Wi-Fi sensing
   - Only identify limited number of occupants



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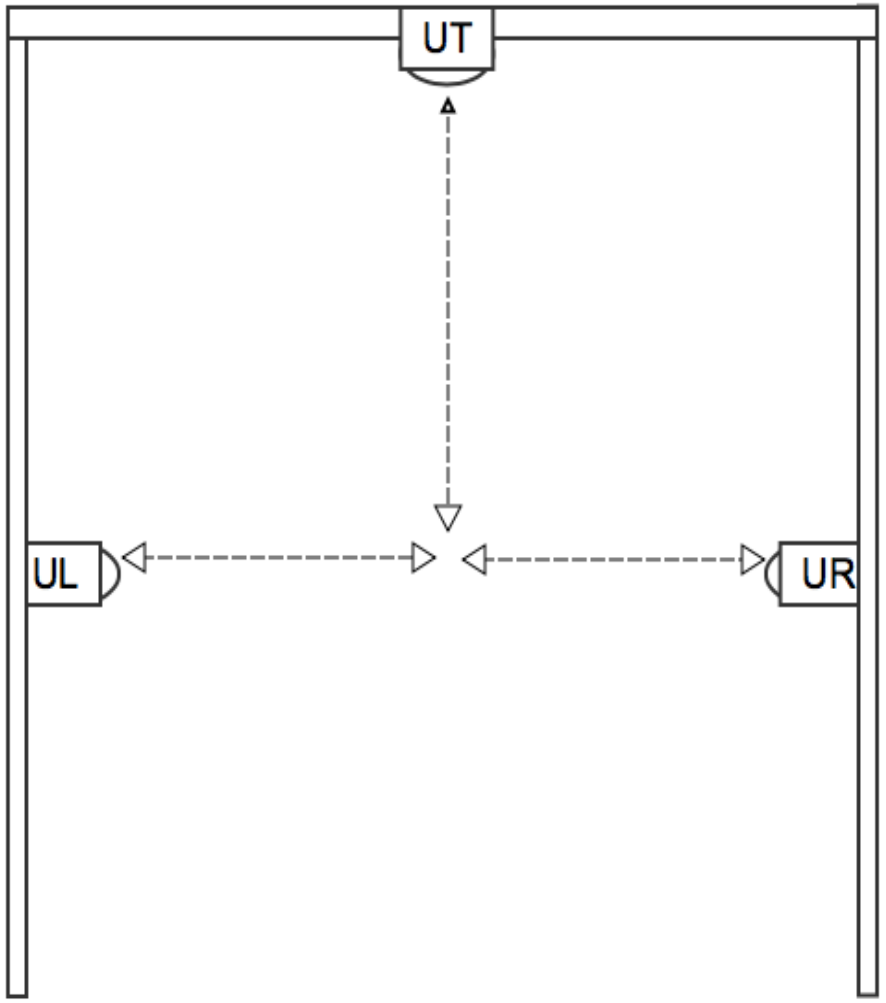
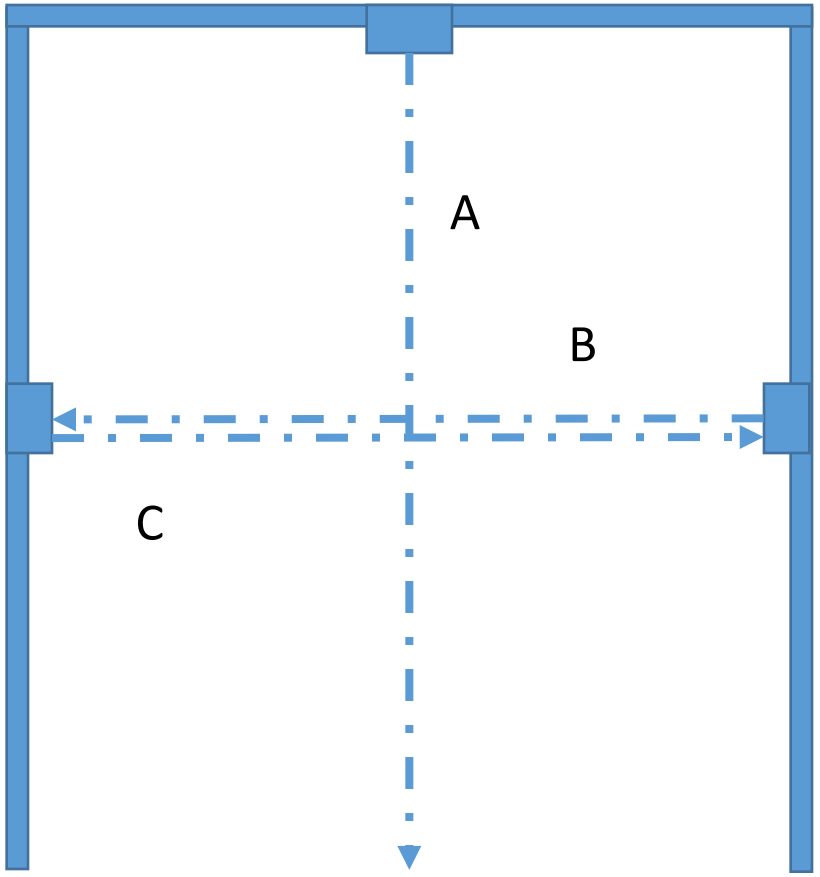
Design of SonicDoor

- SonicDoor: A door instrumented with three ultrasonic sensors
- Correction for variations in walking patterns across time
- Network of SonicDoors collaborating to improve accuracy



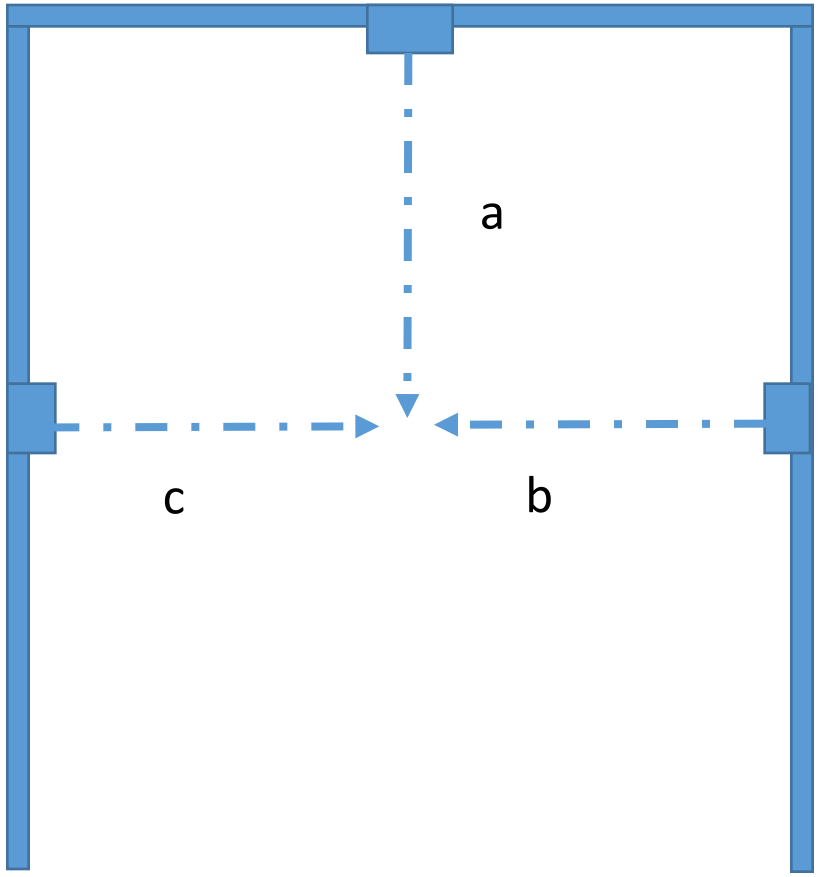
Sensing: Truncating Sampling Interval



$$A + B + C = T$$

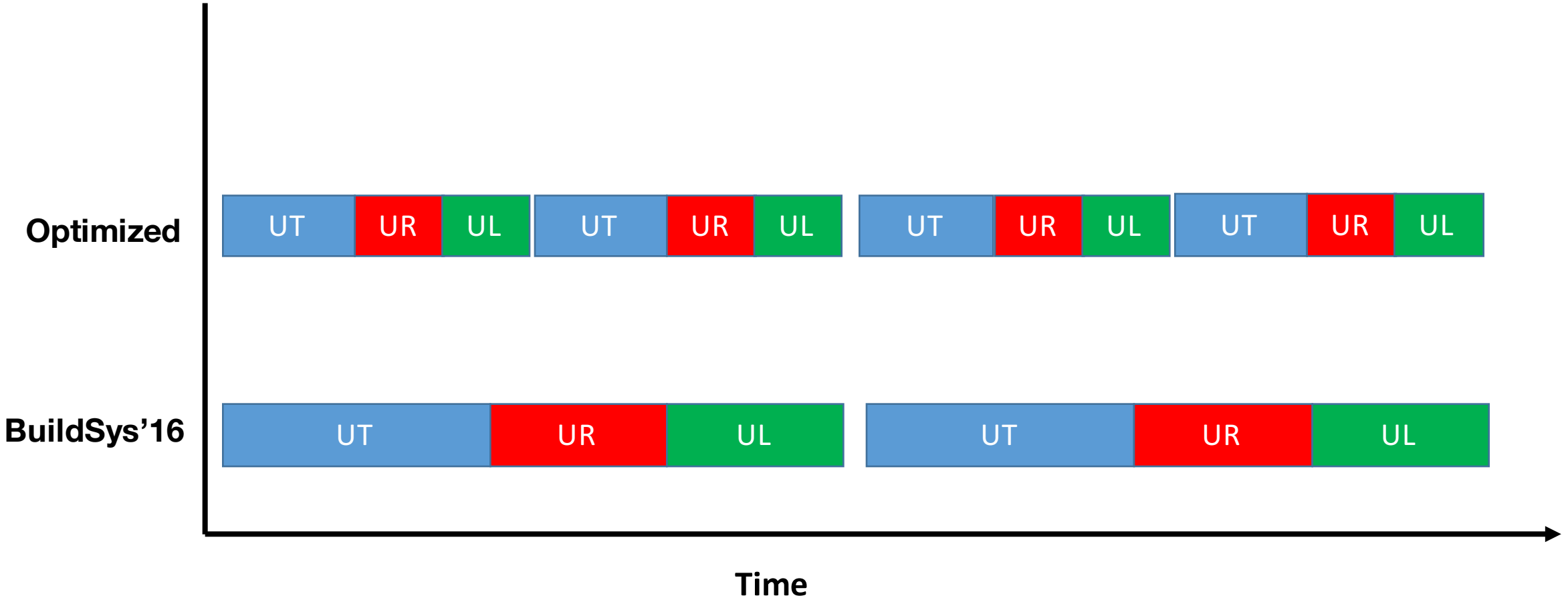
$$a + b + c = t$$

$$t \sim \frac{1}{2} T$$



We double the sampling rate to 70Hz

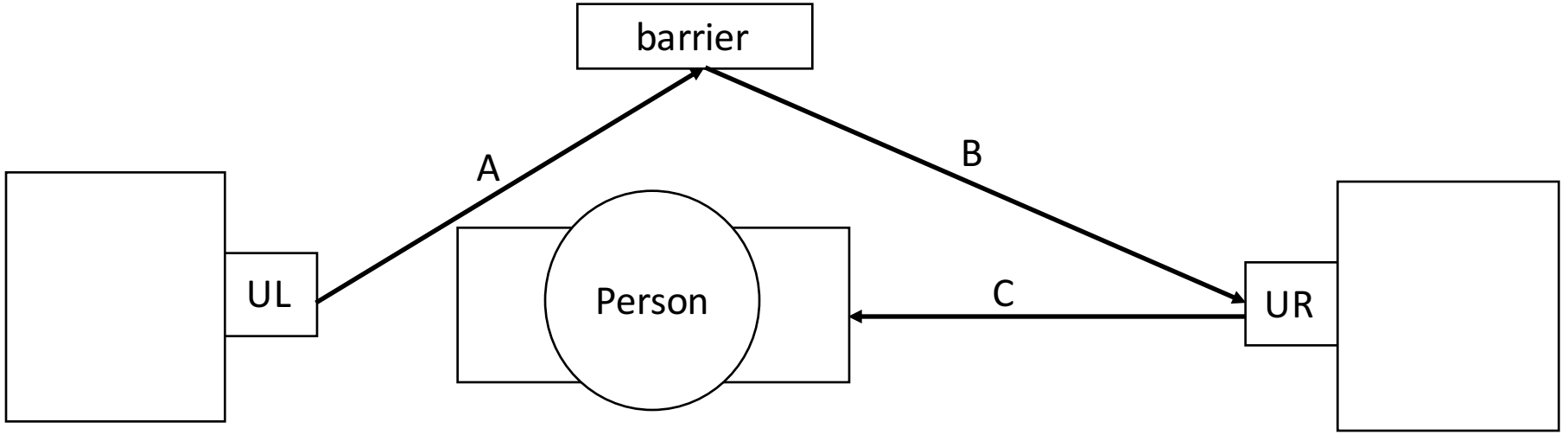
Sensing in Time Domain



Sensing: Sensing Concurrently

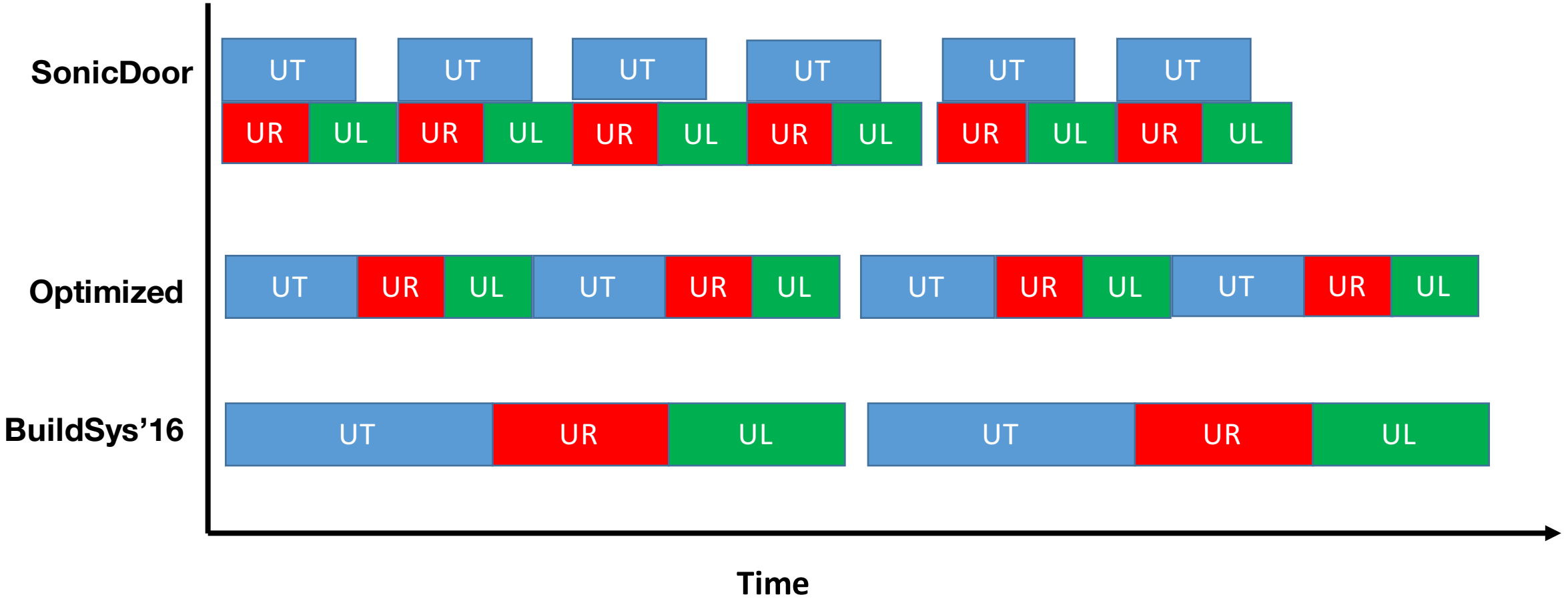
Can we sample all three in parallel?

- Yes
- This would introduce crosstalk



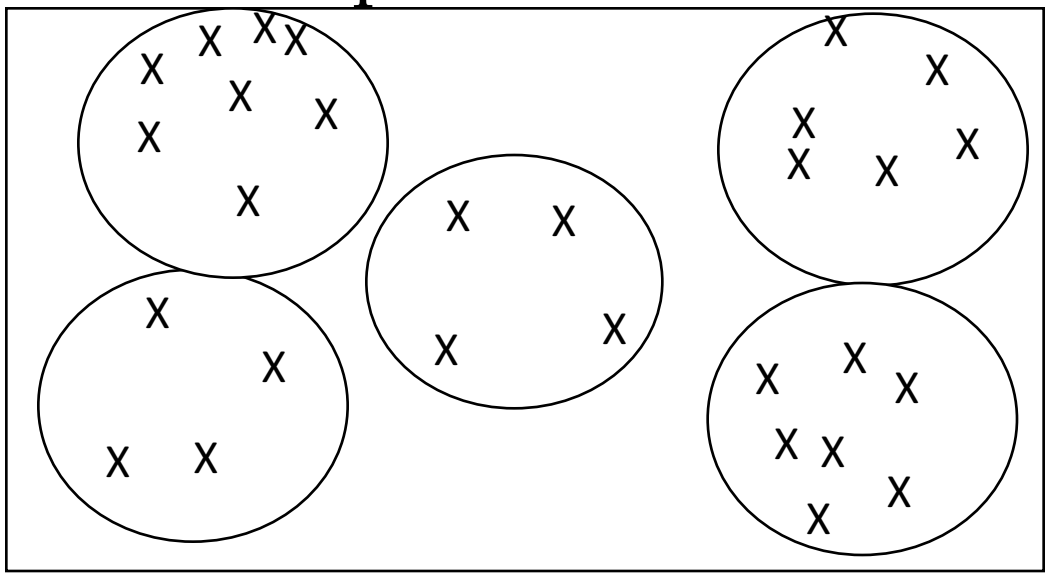
We increase sampling to 132Hz

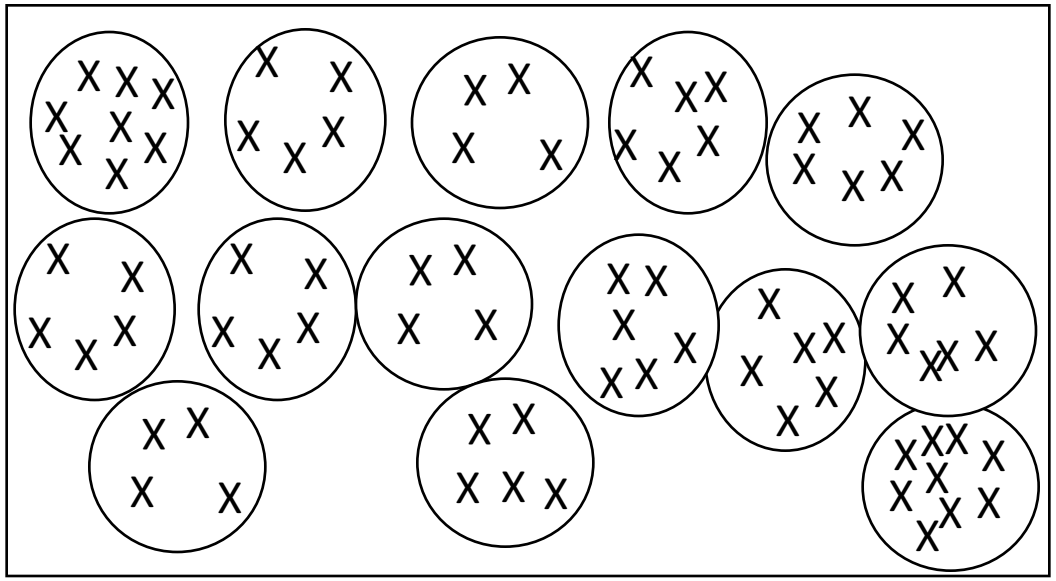
Sensing in Time Domain



Behavior: Variations in Walking Patterns

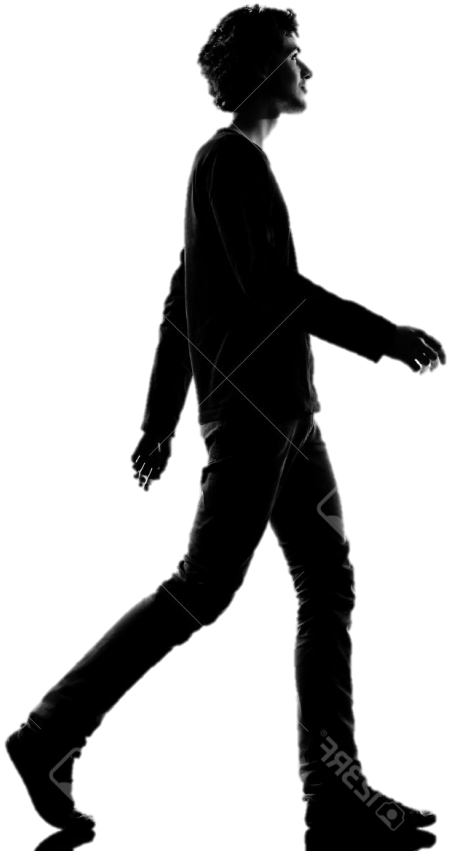
- People wear different clothes and walk differently
  - Need larger clusters
- When you scale the system to lots of people, these differences become problematic

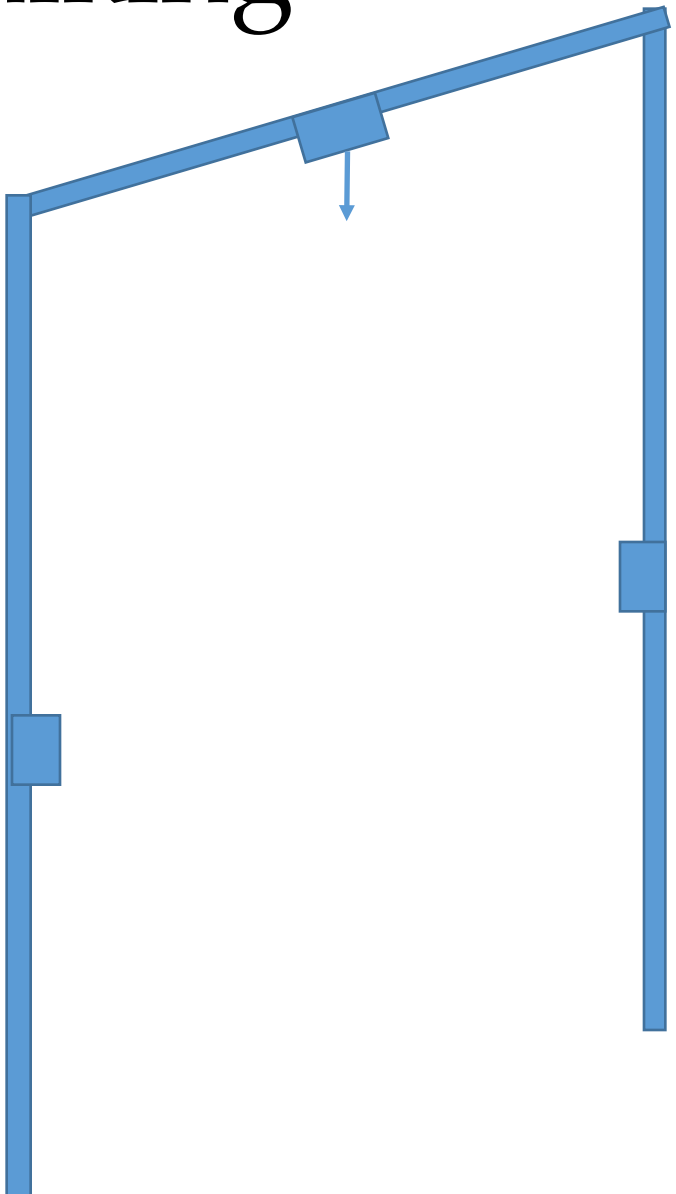


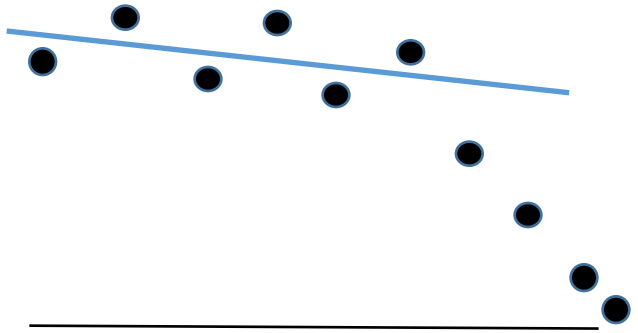


By lowering variance we can increase the population

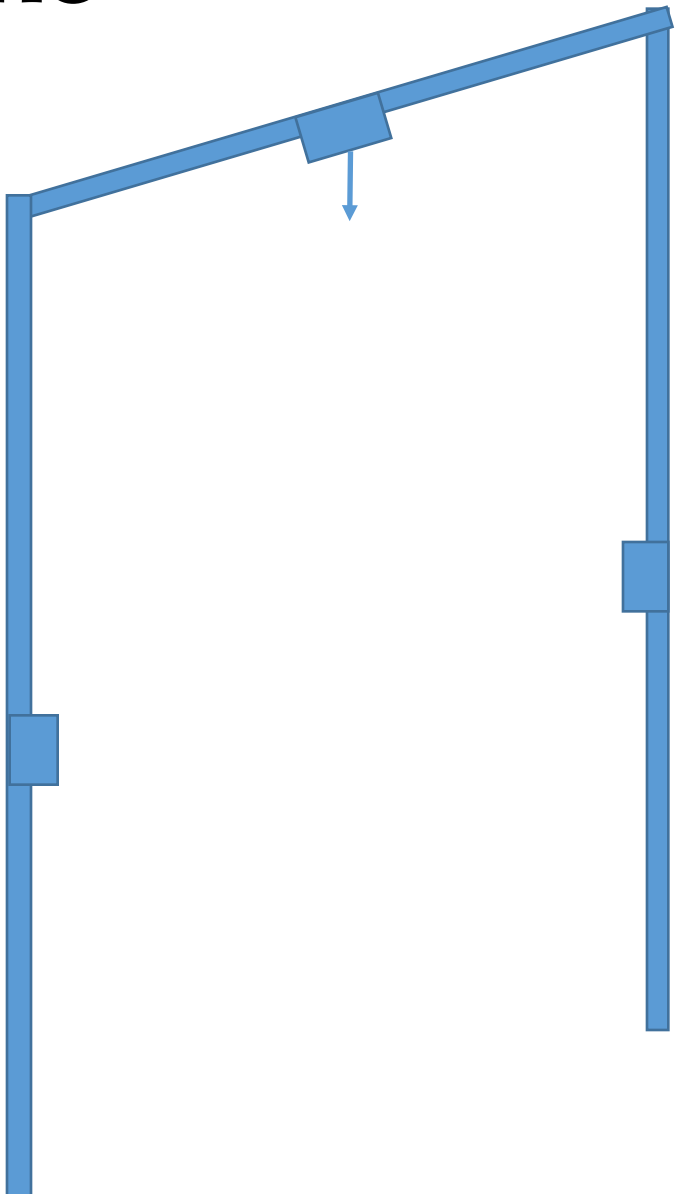
Normal Walking

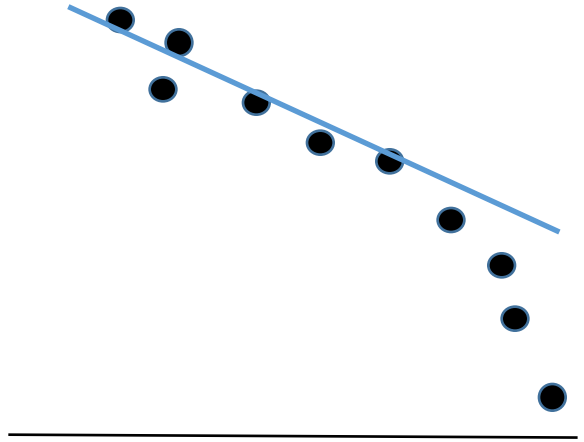




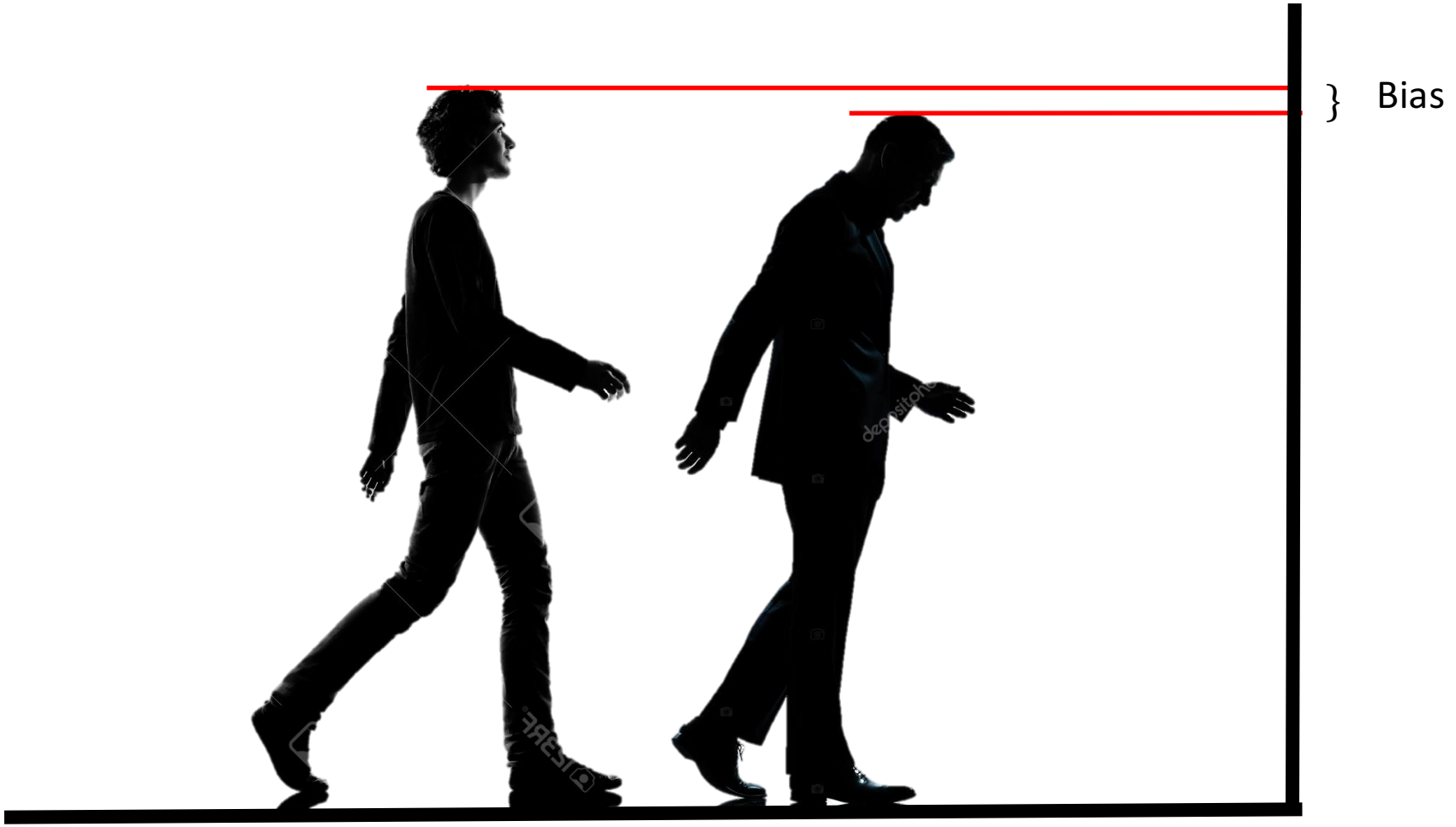


Using Phone



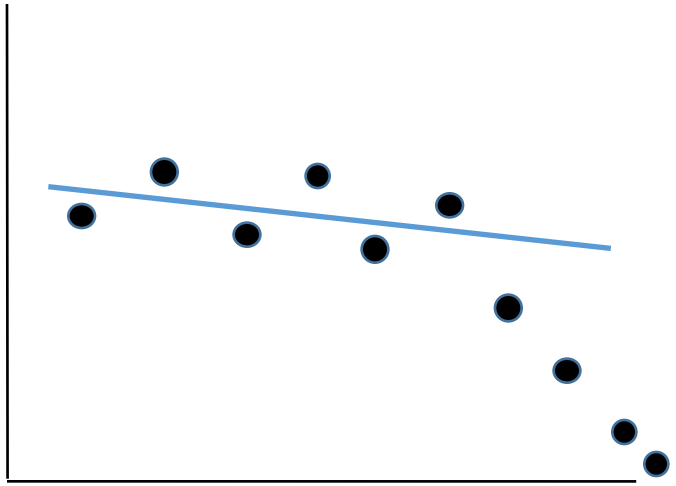


Comparing Effect of Behavior on Data

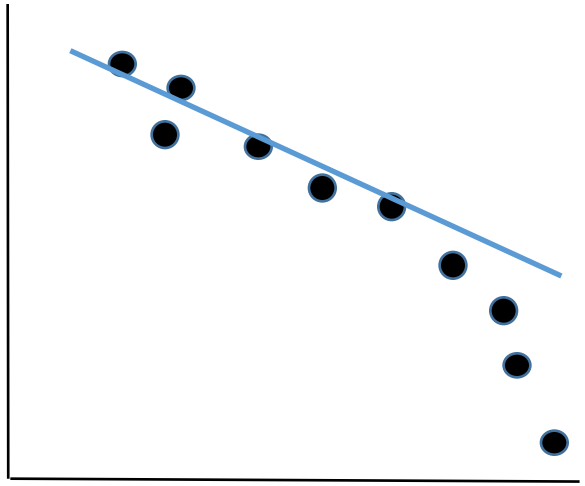


Behavior Comparison

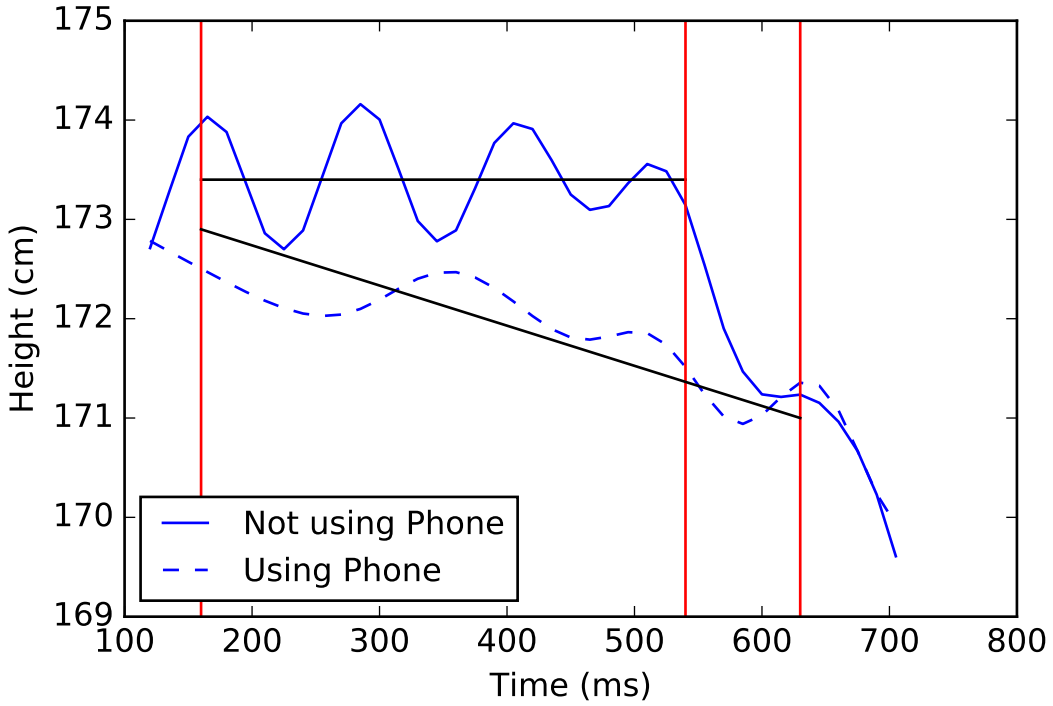
No Phone



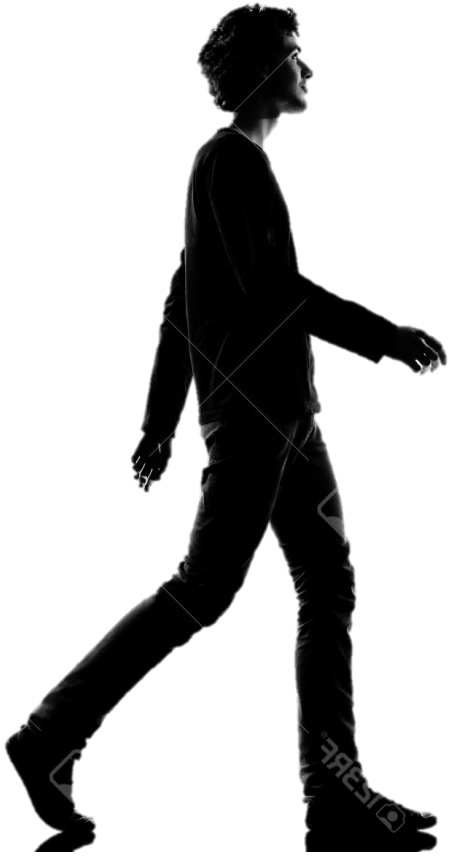
With Phone

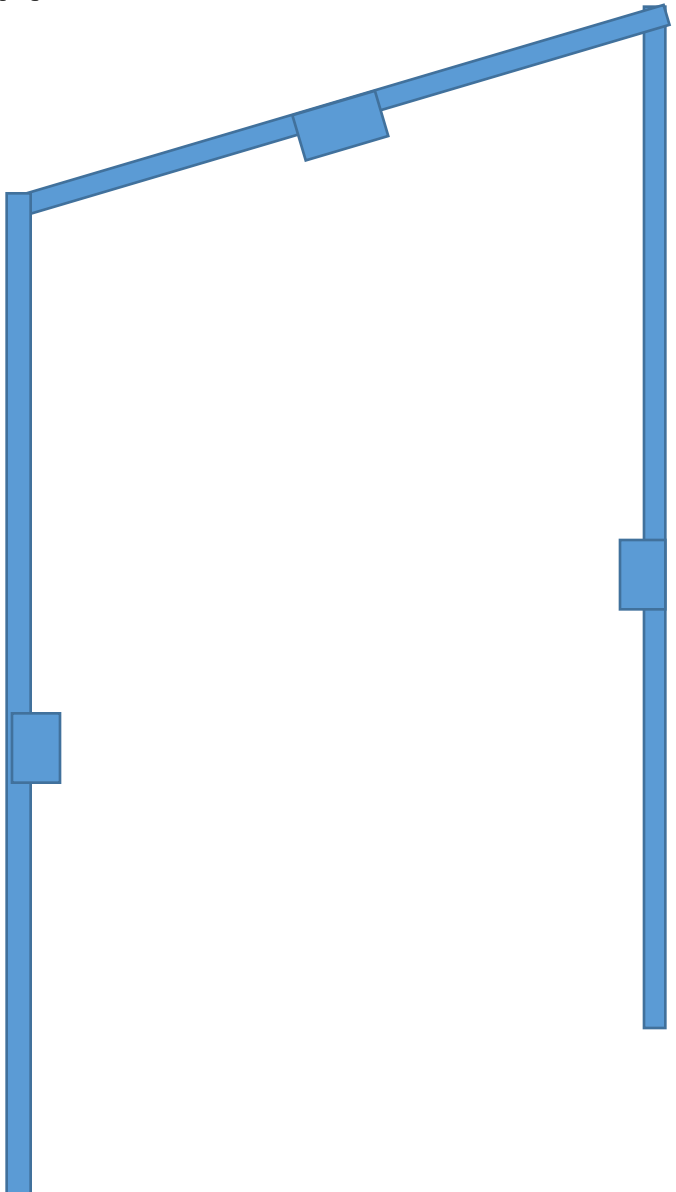


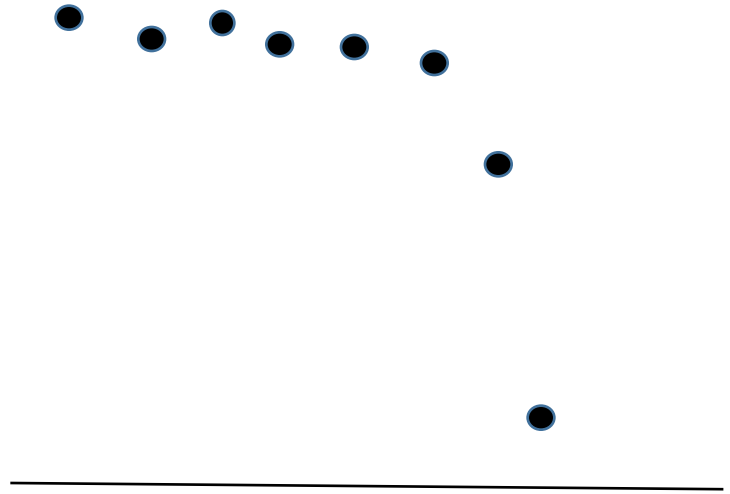
Using Phone: User Data



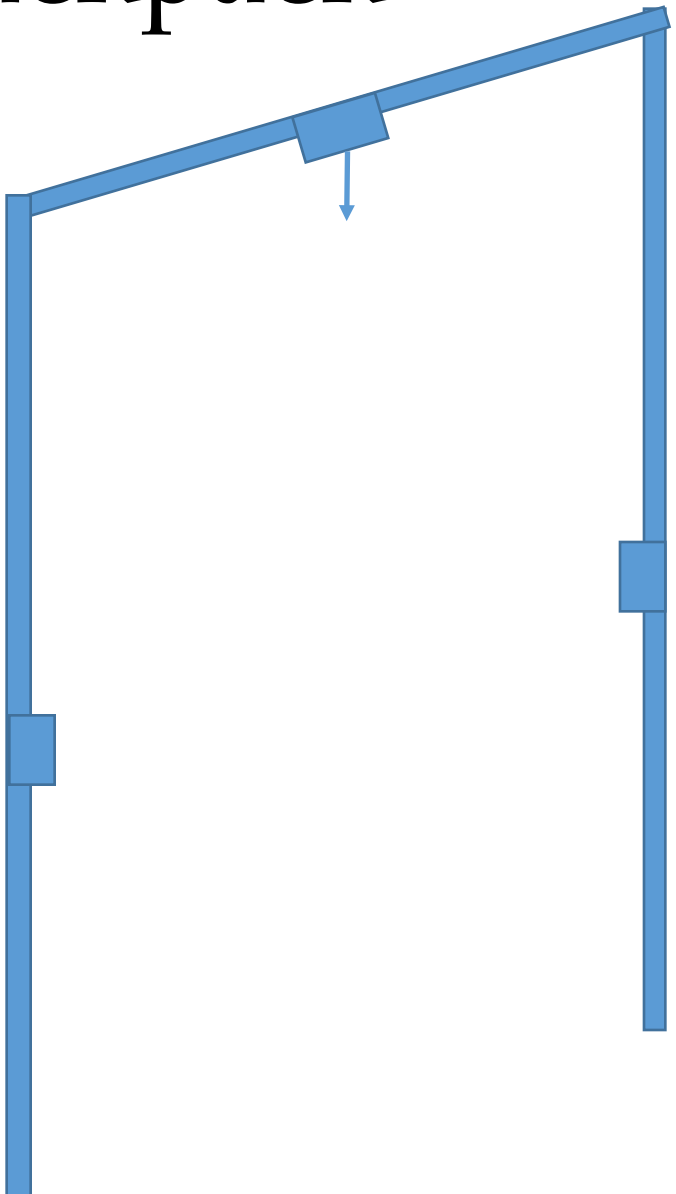
Normal Walk

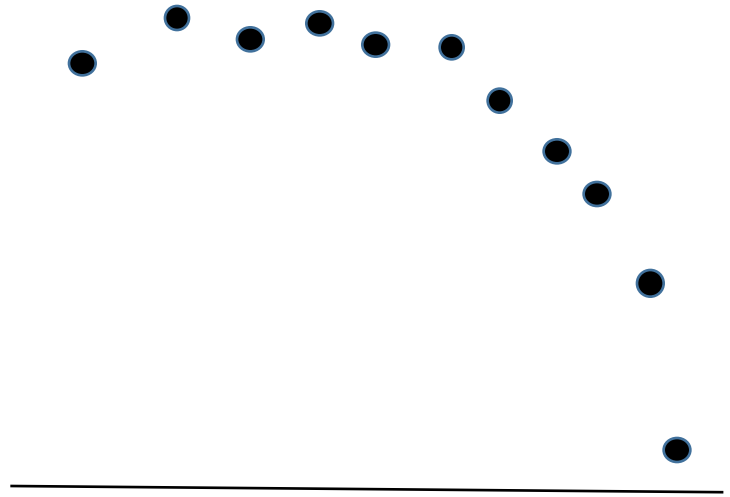






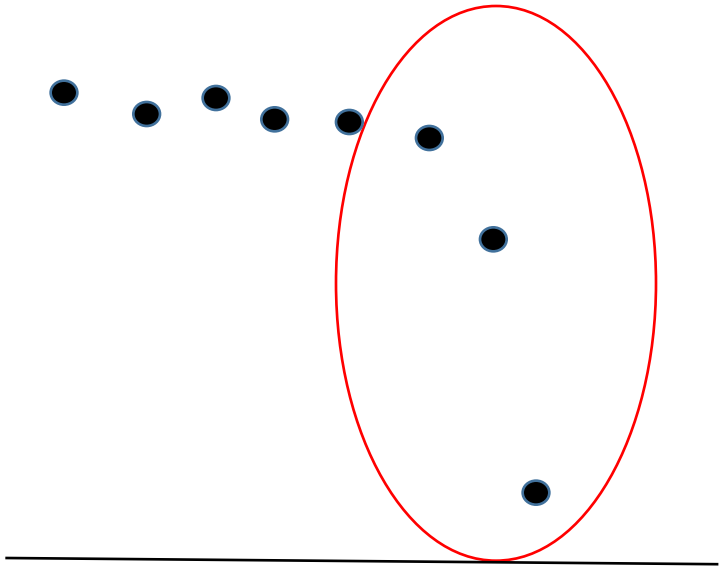
Wearing Backpack



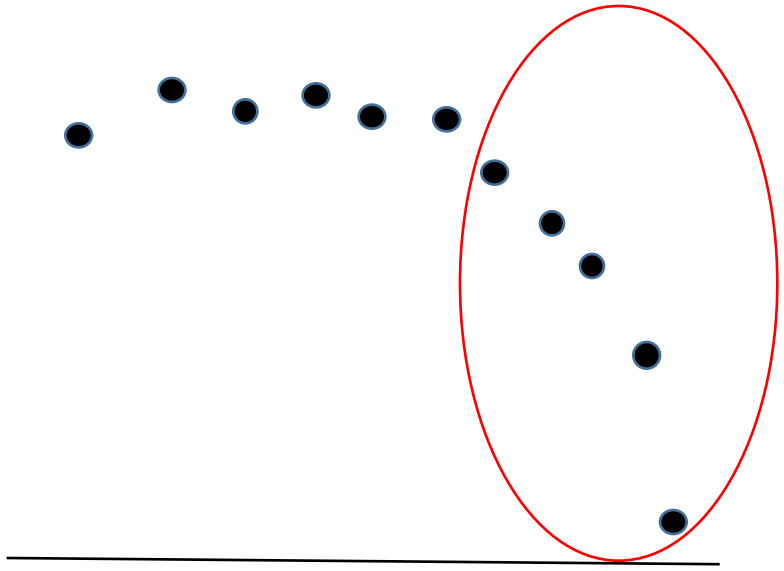


Wearing Backpack

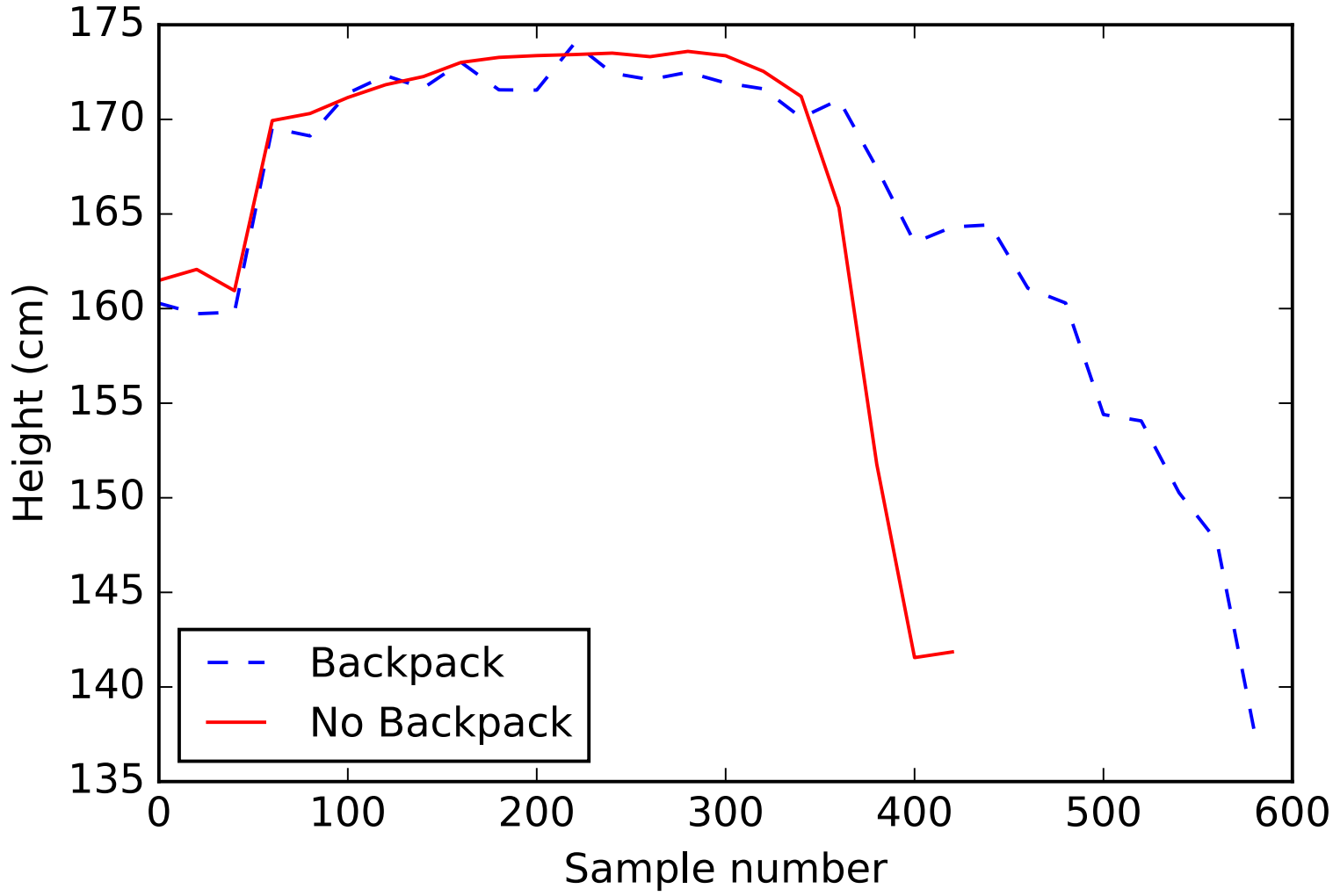
No Backpack



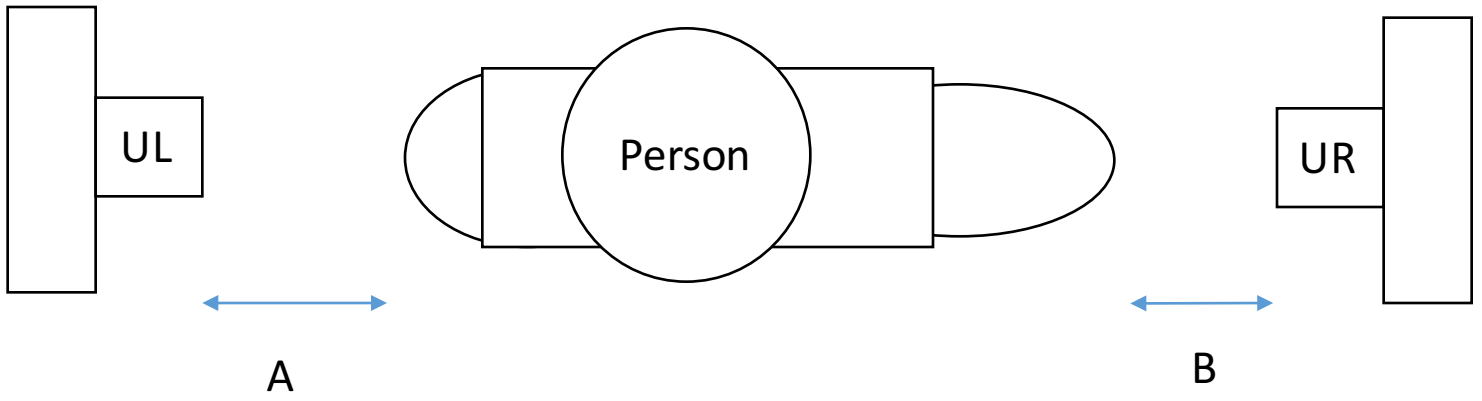
Backpack



Wearing backpack



Holding Handbag



Behavior Data Correction

- Understand how behavior changes measured features
- $F_{behavior}$ (Feature) $\longrightarrow$ Corrected Feature

Behavior Detection

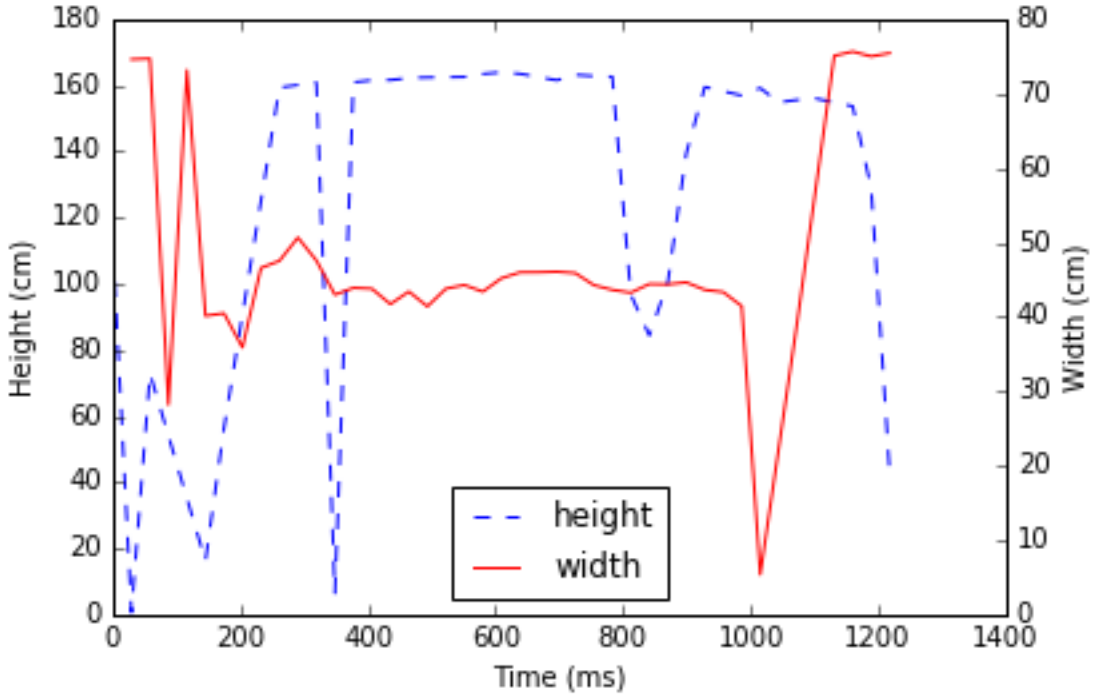
- Behaviors distort the data
  - The person will appear shorter/taller when performing a behavior
- Behaviors we consider
  - Holding a phone
  - Carrying a backpack
  - Carrying a handbag
- We can detect and correct them

Useful Features

We extract the following features:

- Minimum, Maximum, Average Height
- Minimum, Maximum, Average Width
- Time under the Door: Temporal length of the walking event
- Bounce: Maximum - Minimum Height
- Girth: is the waist perimeter of a person (BuildSys'16)

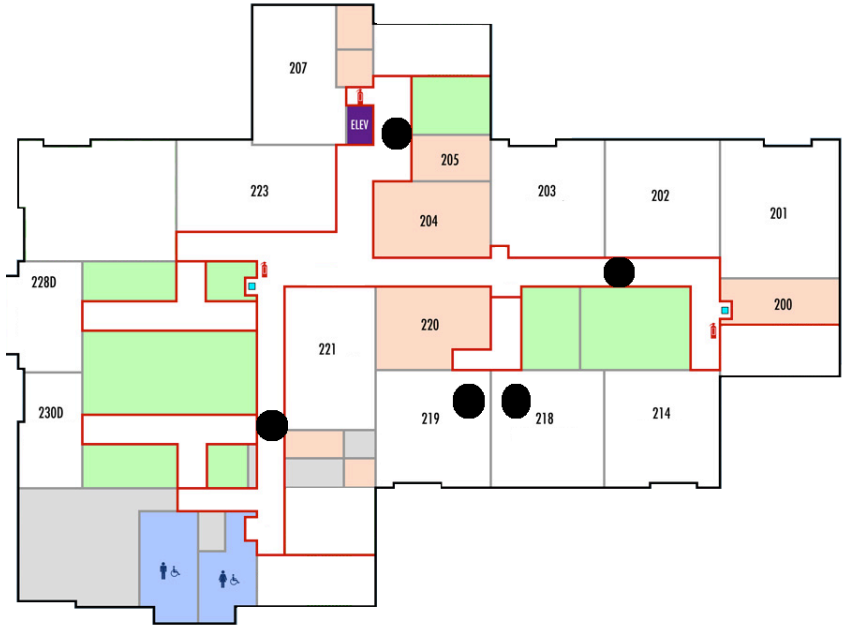
Feature Extraction

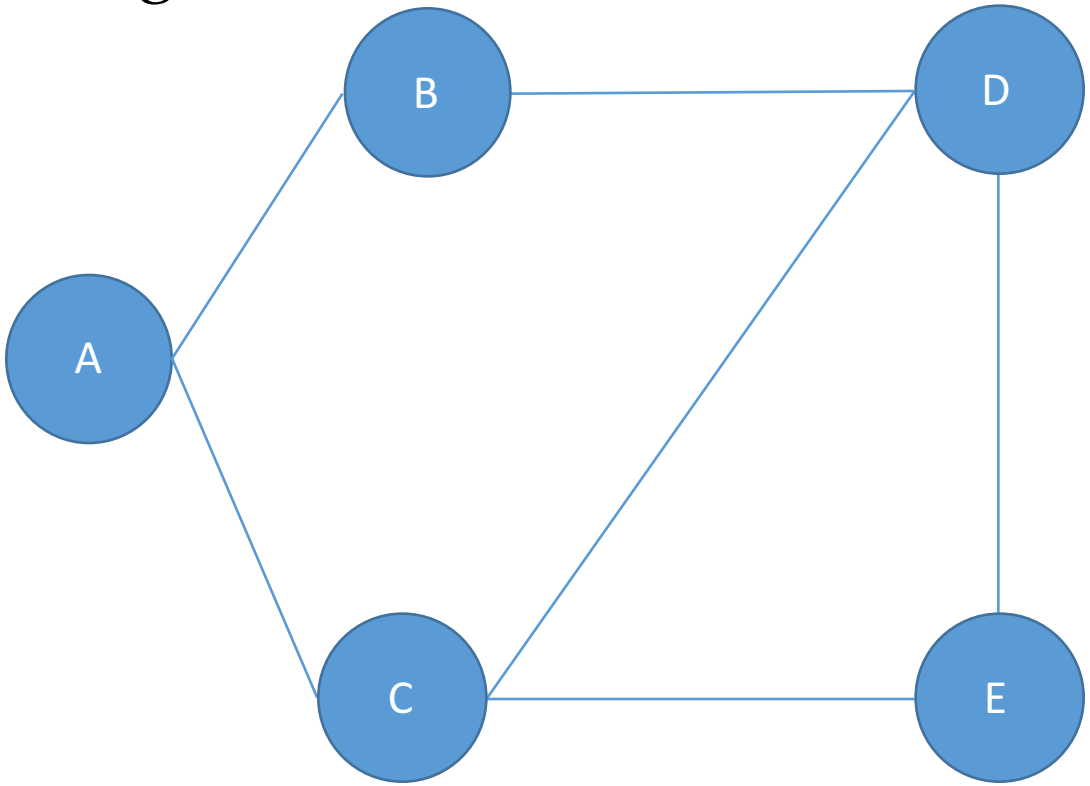


Feature	Value
Mean height	156.1
Maximum Height	163.8
Mean Width	39.5
Maximum Width	42.1
Girth	83.1
Hand-waist Distance	13.2
Bounce	19.7

Decision Making Prerequisites

- We deploy a network of doorframes
- Occupants walk a few times through the doors

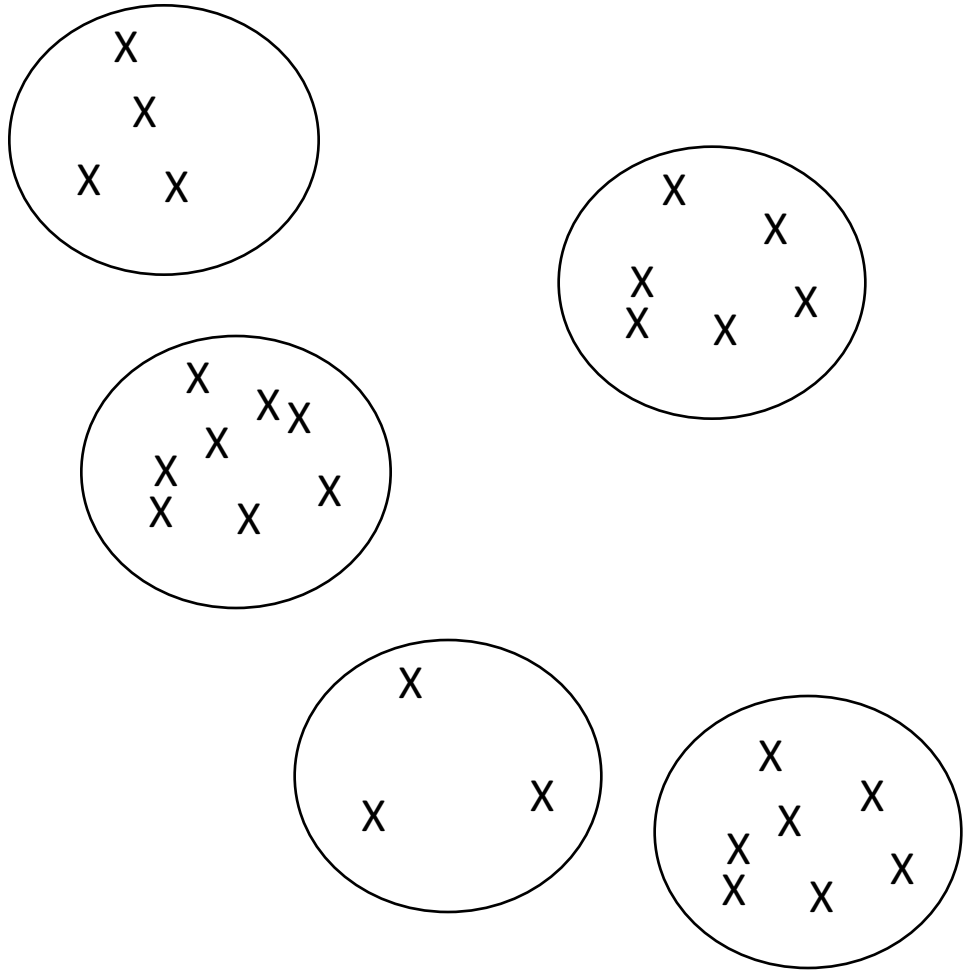




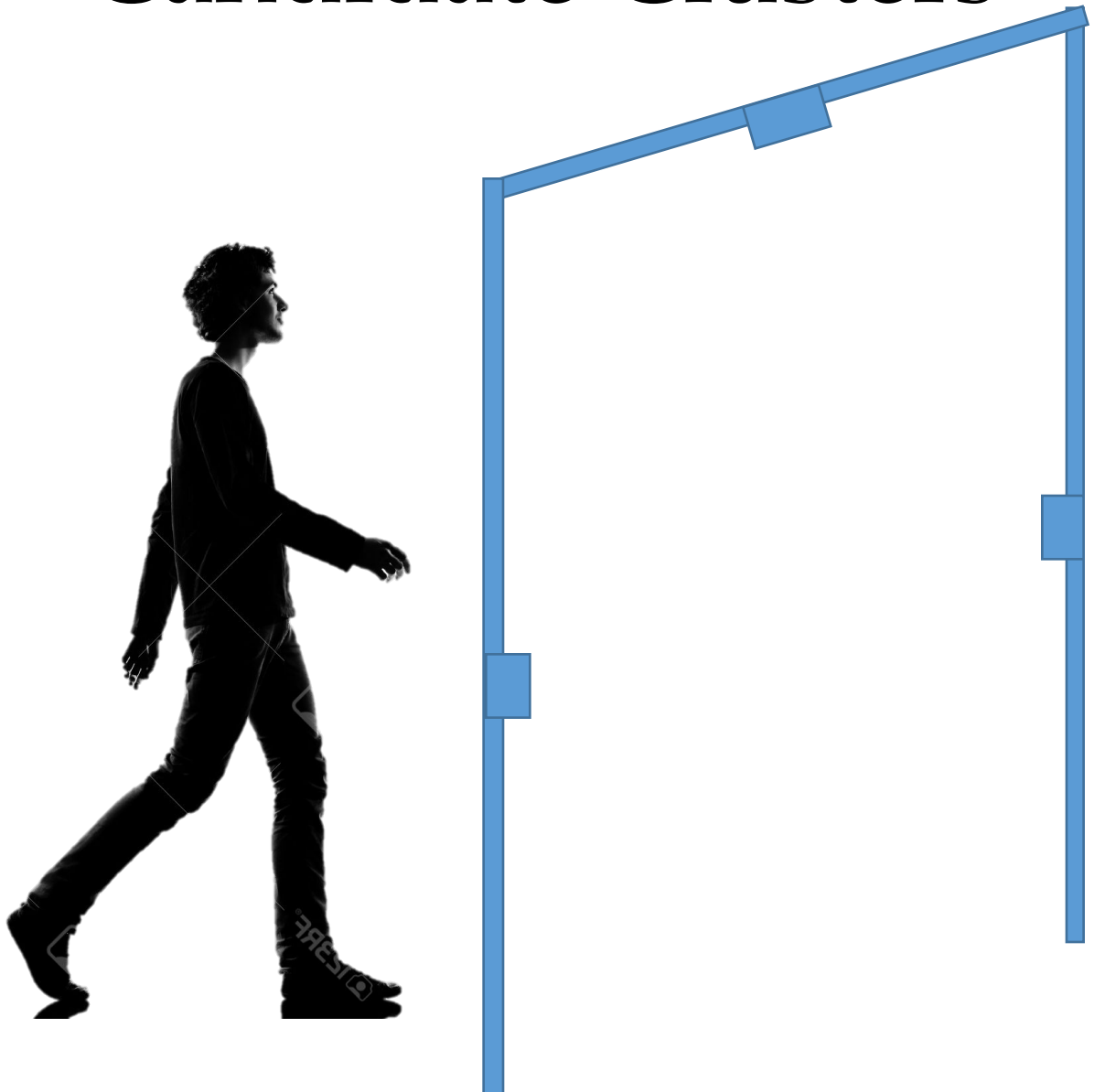
Clustering

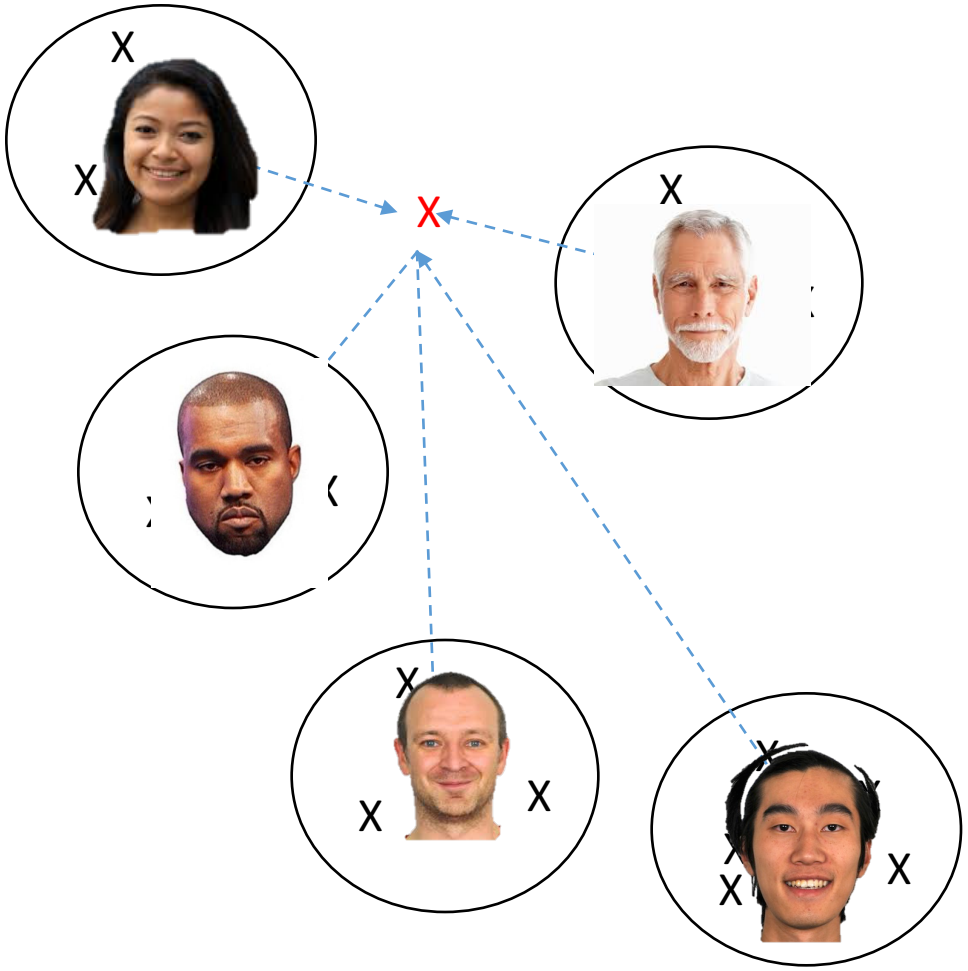
We use initial data to create clusters using HDBSCAN because:

- It copes better with clusters of varying frequencies
- Is able to better find the number of clusters



Candidate Clusters

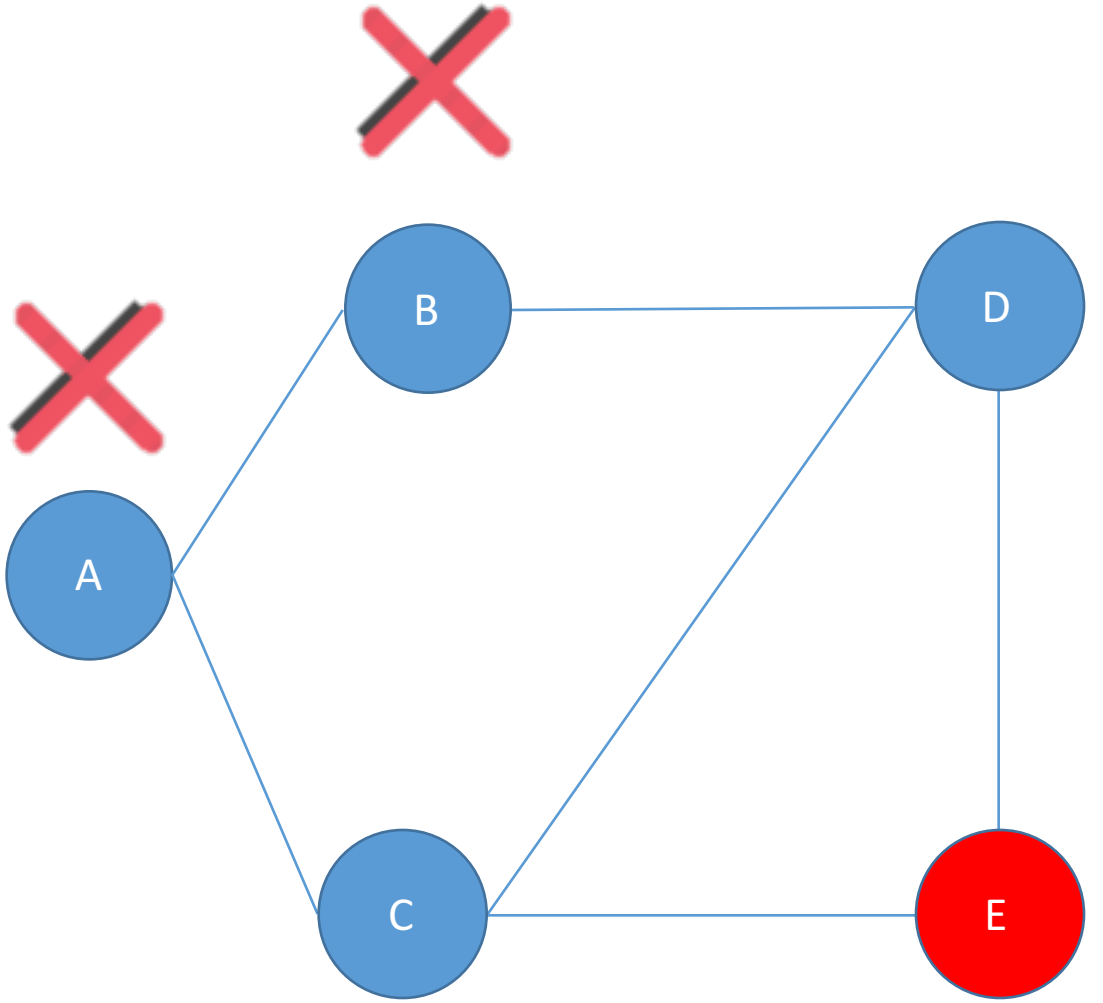


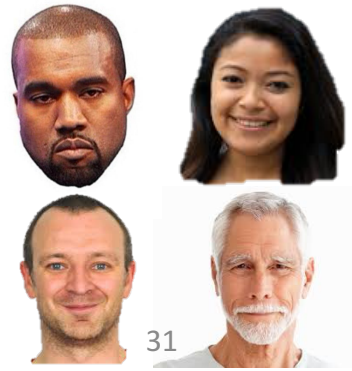


Filter by Topology

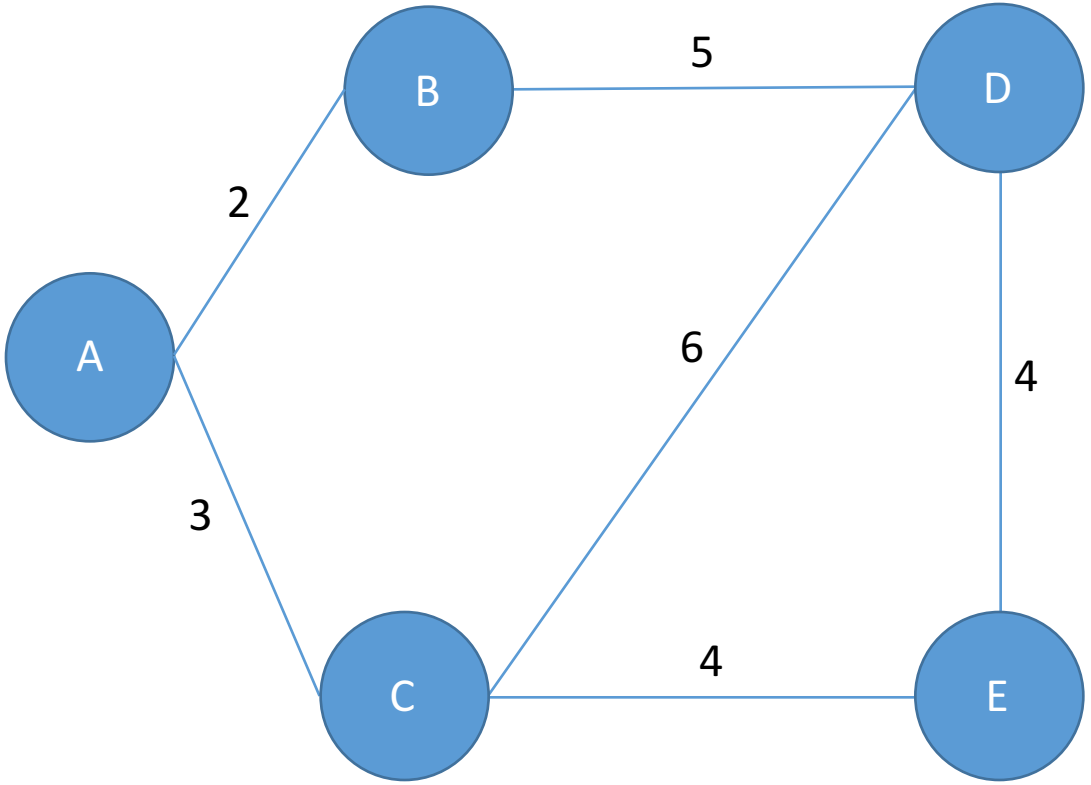
- Select closest 4 candidates
- For each candidate, lookup previous location
- Eliminate candidate if path does not exist



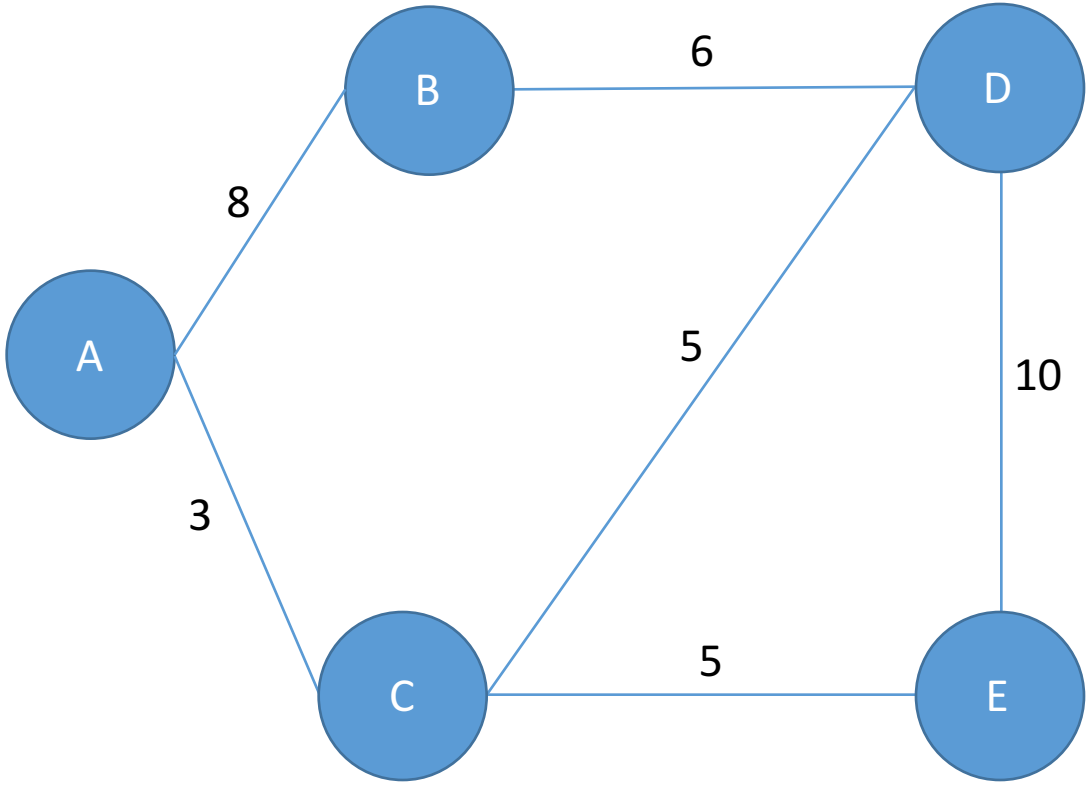





Decision Making based on Markov Chain



$$\text{Path Probability} = \frac{4}{4+5+6} = 28\%$$



$$\text{Path Probability} = \frac{5}{5+5+3} = 38\%$$

Decision Making based on Markov Chain

For K closest candidates:

- Retrieve path probability
- Distance to candidate cluster

Decision Making

The chosen candidate is

$$\text{Max}\left(\frac{Path\ probability_i}{Distance\ to\ candidate_i}\right)\ for\ i\ in\ candidates$$

Distance to Candidate= 2
Path Probability= 28%

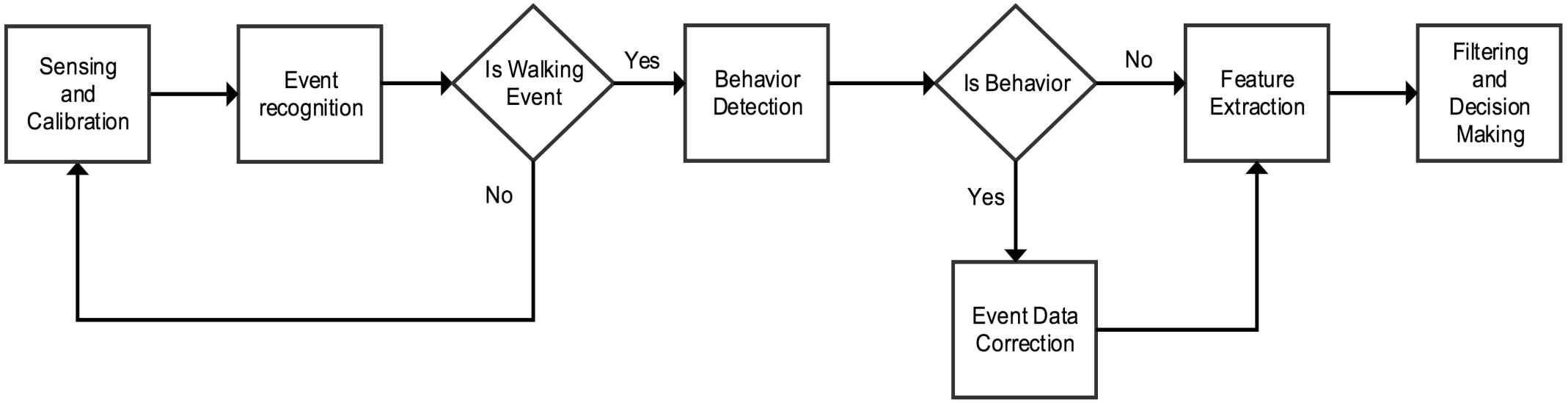
Decision score $= \frac{0.4}{2} = 0.14$

Distance to Candidate= 3
Path Probability= 38%

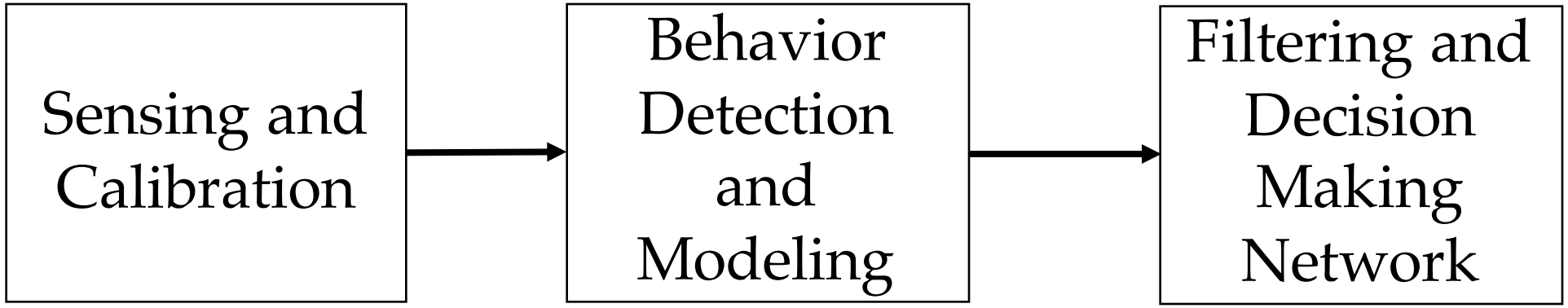
Decision score $= \frac{0.5}{2.5} = 0.13$

Decision is not biased towards shape or path history

SonicDoor Recap



SonicDoor Recap



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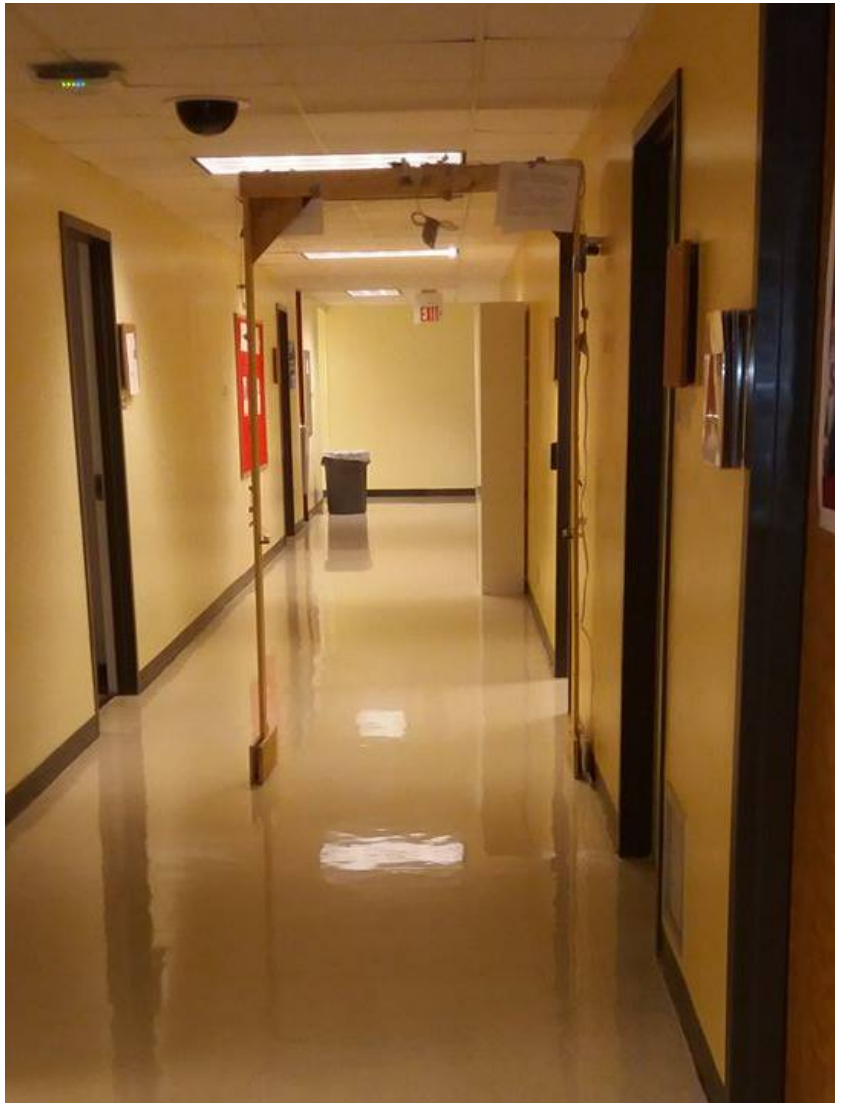
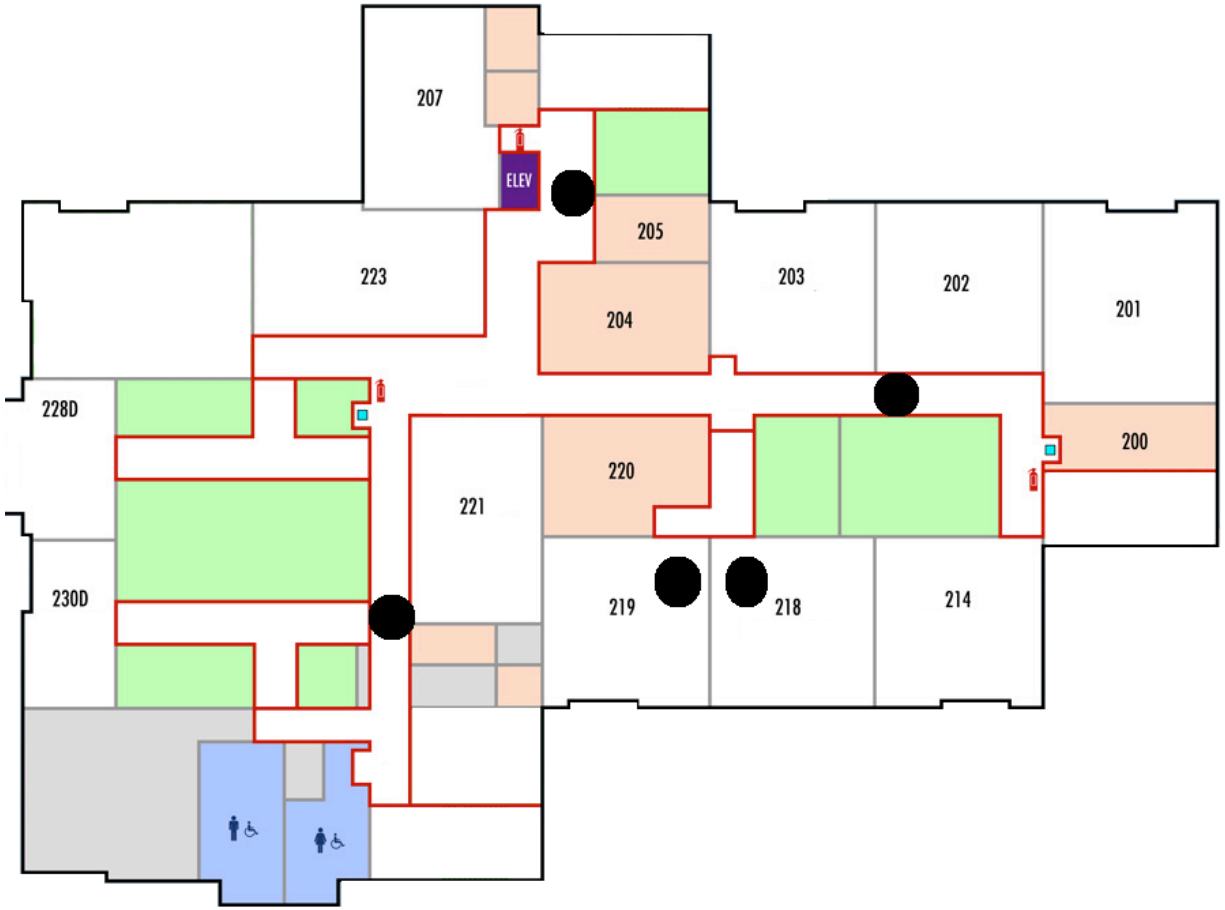
Experiment Design

- We deployed five doorframes for two months
- Each doorframe is composed with 3 off-the-shelf ultrasonic sensors
  - $50 per door
- 215 participants
  - 170 walked more than twice during the experiment
  - Over 50 walks per person on average
  - Collected about 9000 walking events
  - Users were encouraged to walk naturally
- IRB approved protocol


EXIT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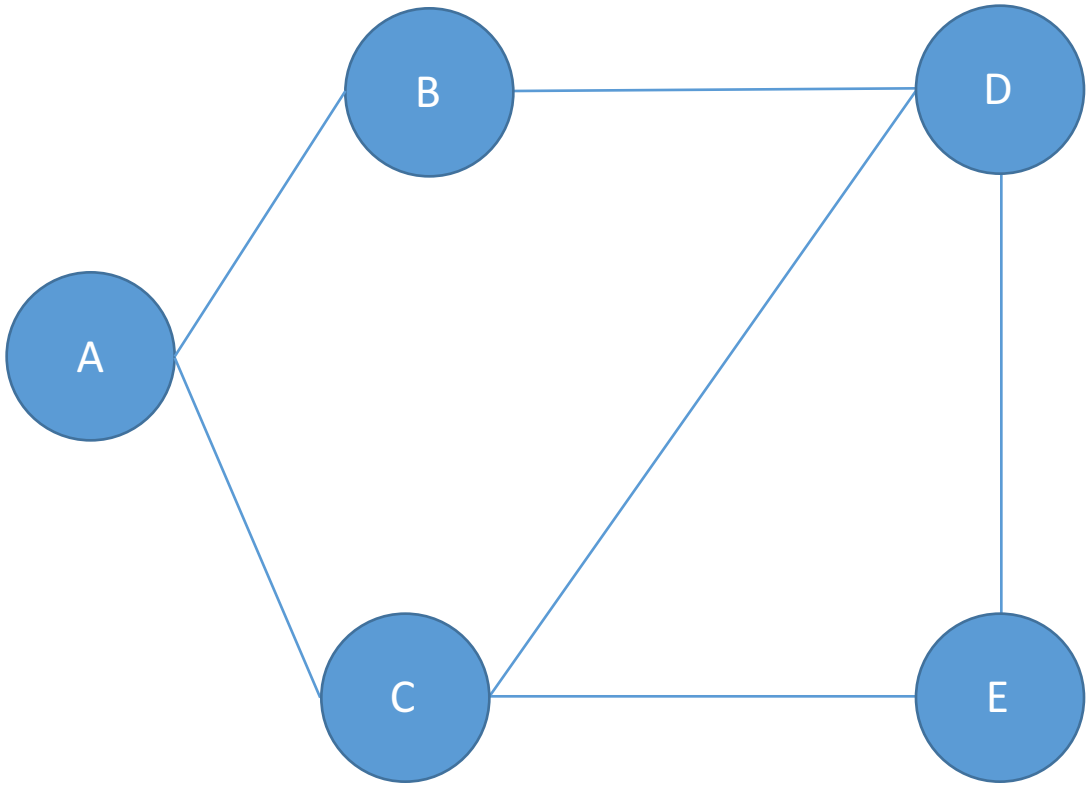

A
B
C
D
E

Data Annotation for Ground Truth

Camera based Annotation using Facenet

- Camera on each door for ground truth
- Too many images to label manually
- We used Facenet (CVPR 2015) to label the faces

Camera-based Annotation is more efficient and reliable

Evaluating Behavior Detection Models

We arbitrarily select 300 walking events with 40 people

We annotate it manually by answering the following questions?

- Is walker using her phone?
- Is walker holding handbag?
- Is walker holding backpack?

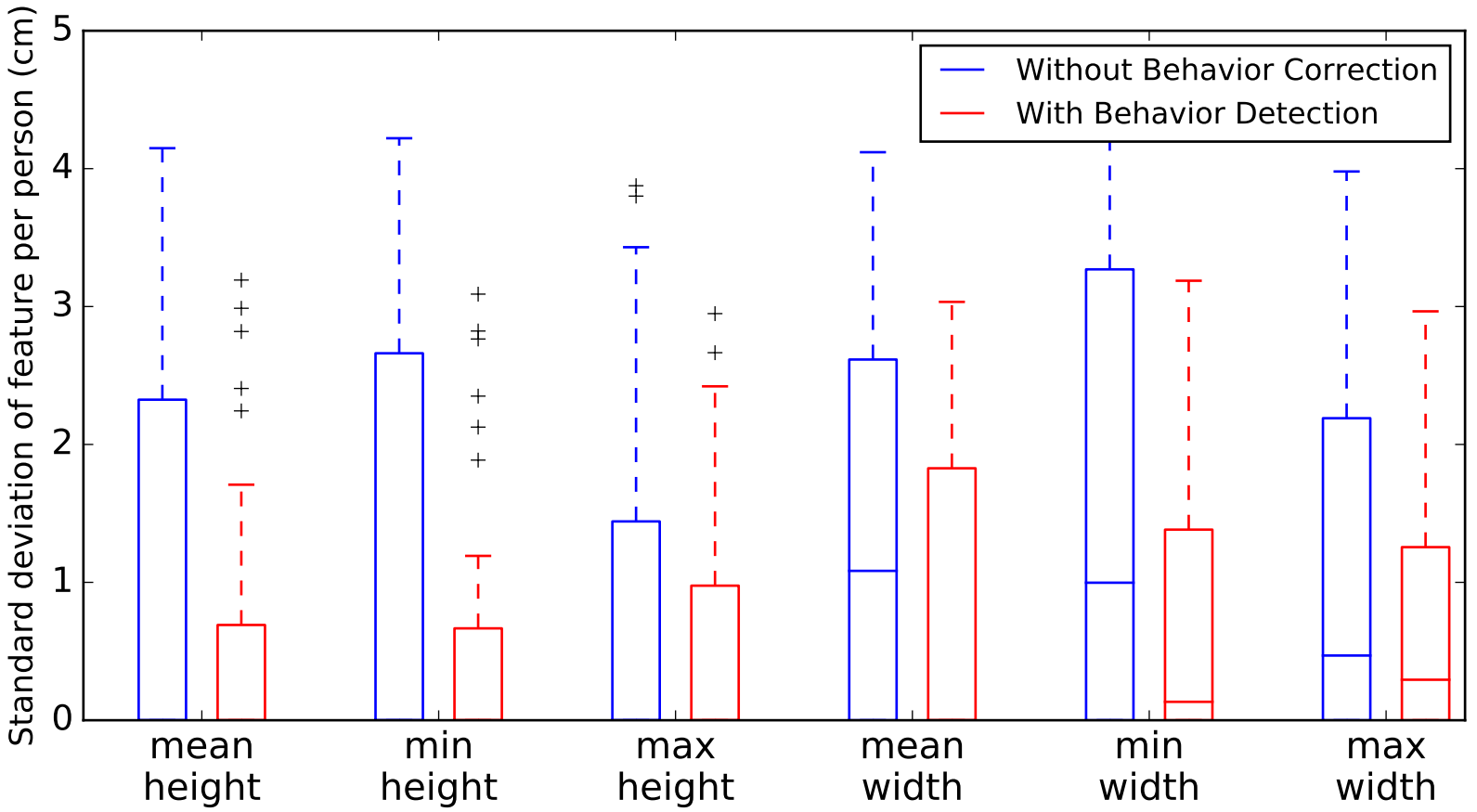
Feature	Accuracy
Detecting Phone	89.10%
Detecting Handbag	90.10%
Detecting Backpack	84.60%

Building Behavior Correction Models

Detect:	Phone		Backpack		Handbag	
	β	α	β	α	β	α
Mean Height	1.019	1.765	0.973	-1.28	1.005	-0.031
Min Height	1.0345	0.72	1.452	0.742	0.992	0.752
Max Height	1.025	1.523	1.009	0.873	0.991	1.023
Mean Width	1.001	0.023	0.987	1.173	0.965	0.458
Min Width	0.996	1.031	1.0145	1.02	0.969	2.346
Max Width	1.01	0.783	0.993	0.4	0.931	0.759
Girth	1.016	-1.25	1.007	-0.563	0.874	-1.573
Bounce	1.029	-1.245	0.682	1.249	1.004	0.238

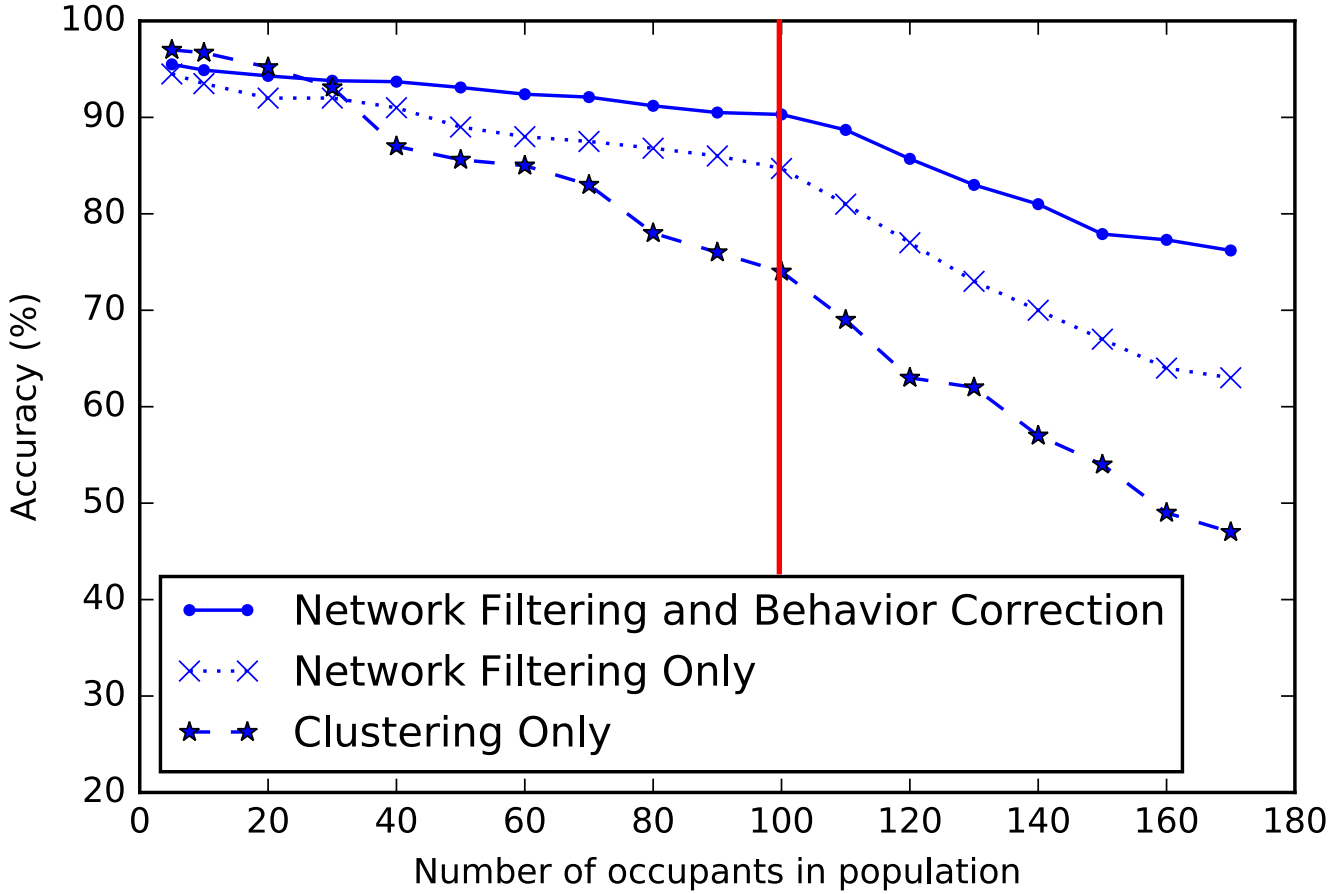
Some behaviors affect features more than others

Evaluating Behavior Detection Models



Lower Feature Variances means more stable clusters

Evaluating System Performance



Network Filtering and Behavior Modeling are Key to scaling to 100+ people

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Conclusions

SonicDoor uses three techniques to identify building occupants:

- Fast sampling of height and width as occupants walk through a door
- Detects and corrects behaviors that bias the data.
- Uses the door-network topology to further improve accuracy

Our system is able to accurately identify occupants up to 100 people, 5x improvement over the state of the art.