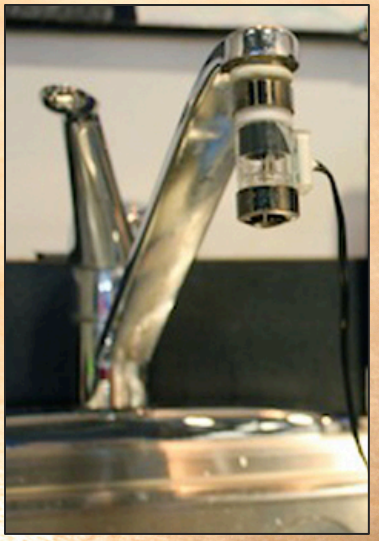
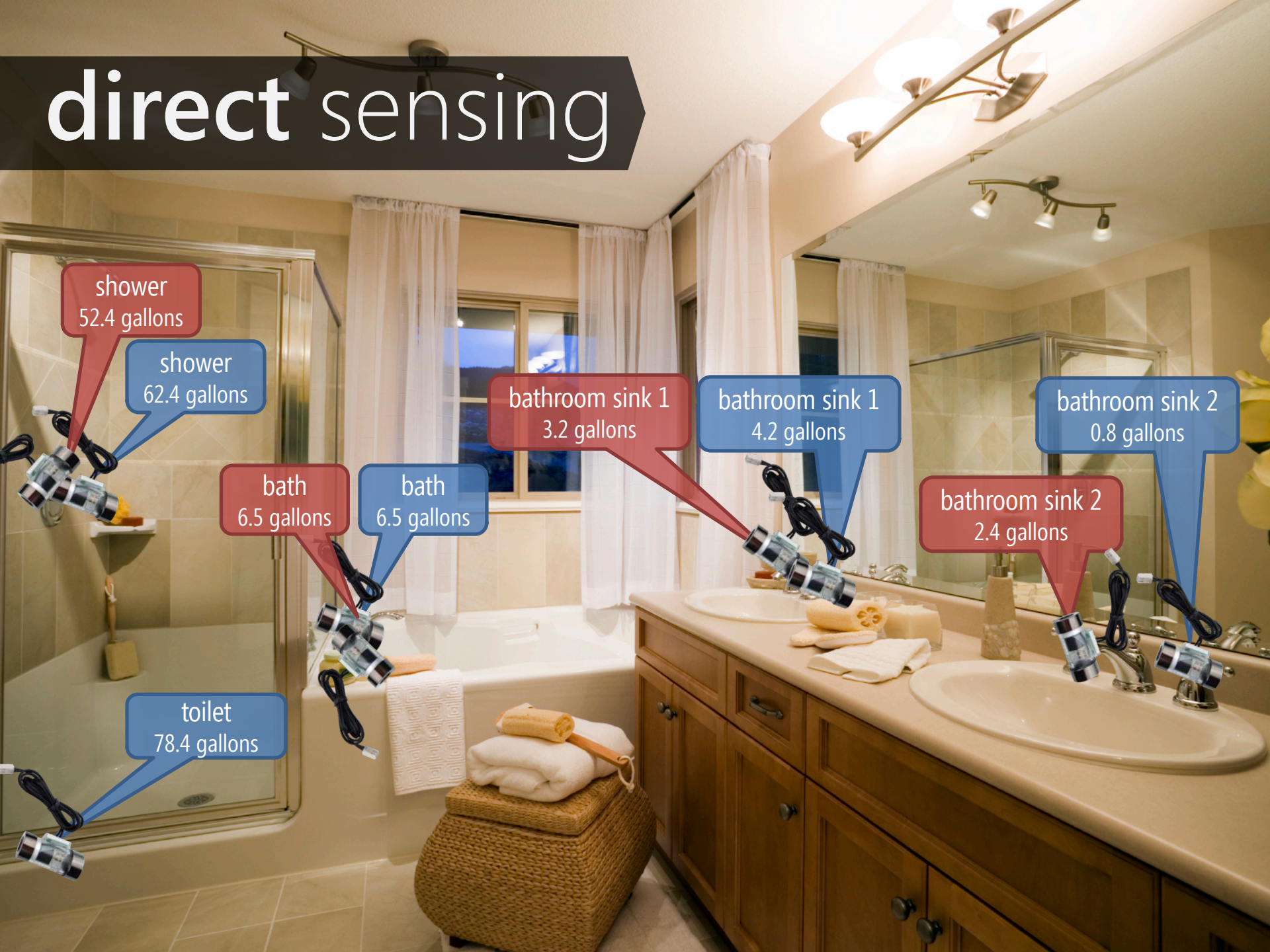
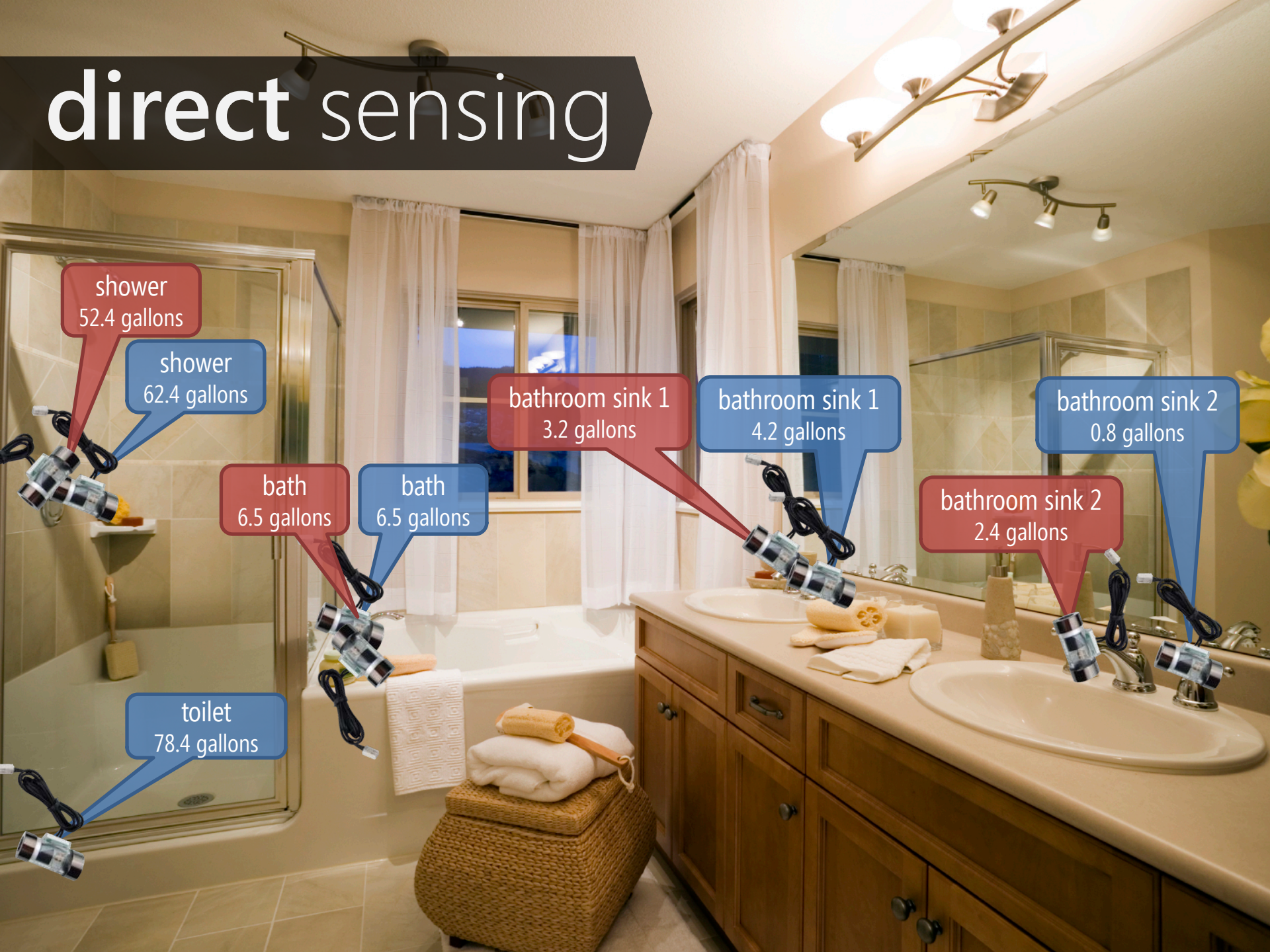
direct sensing



[Teague Labs, Arduino Water Meter, http://labs.teague.com/?p=722]


direct sensing
shower
62.4 gallons
bath
6.5 gallons
toilet
78.4 gallons
bathroom sink 1
4.2 gallons
bathroom sink 2
0.8 gallons


direct sensing
shower
52.4 gallons
shower
62.4 gallons
bath
6.5 gallons
bath
6.5 gallons
toilet
78.4 gallons
bathroom sink 1
3.2 gallons
bathroom sink 1
4.2 gallons
bathroom sink 2
2.4 gallons
bathroom sink 2
0.8 gallons


direct sensing
shower
52.4 gallons
shower
62.4 gallons
bath
6.5 gallons
bath
6.5 gallons
bathroom sink 1
3.2 gallons
bathroom sink 1
4.2 gallons
bathroom sink 2
0.8 gallons
bathroom sink 2
2.4 gallons
toilet
78.4 gallons

indirect sensing

shower
52.4 gallons

shower
62.4 gallons

bath
6.5 gallons

bath
6.5 gallons

toilet
78.4 gallons

bathroom sink 1
3.2 gallons

bathroom sink 1
4.2 gallons

bathroom sink 2
2.4 gallons

bathroom sink 2
0.8 gallons

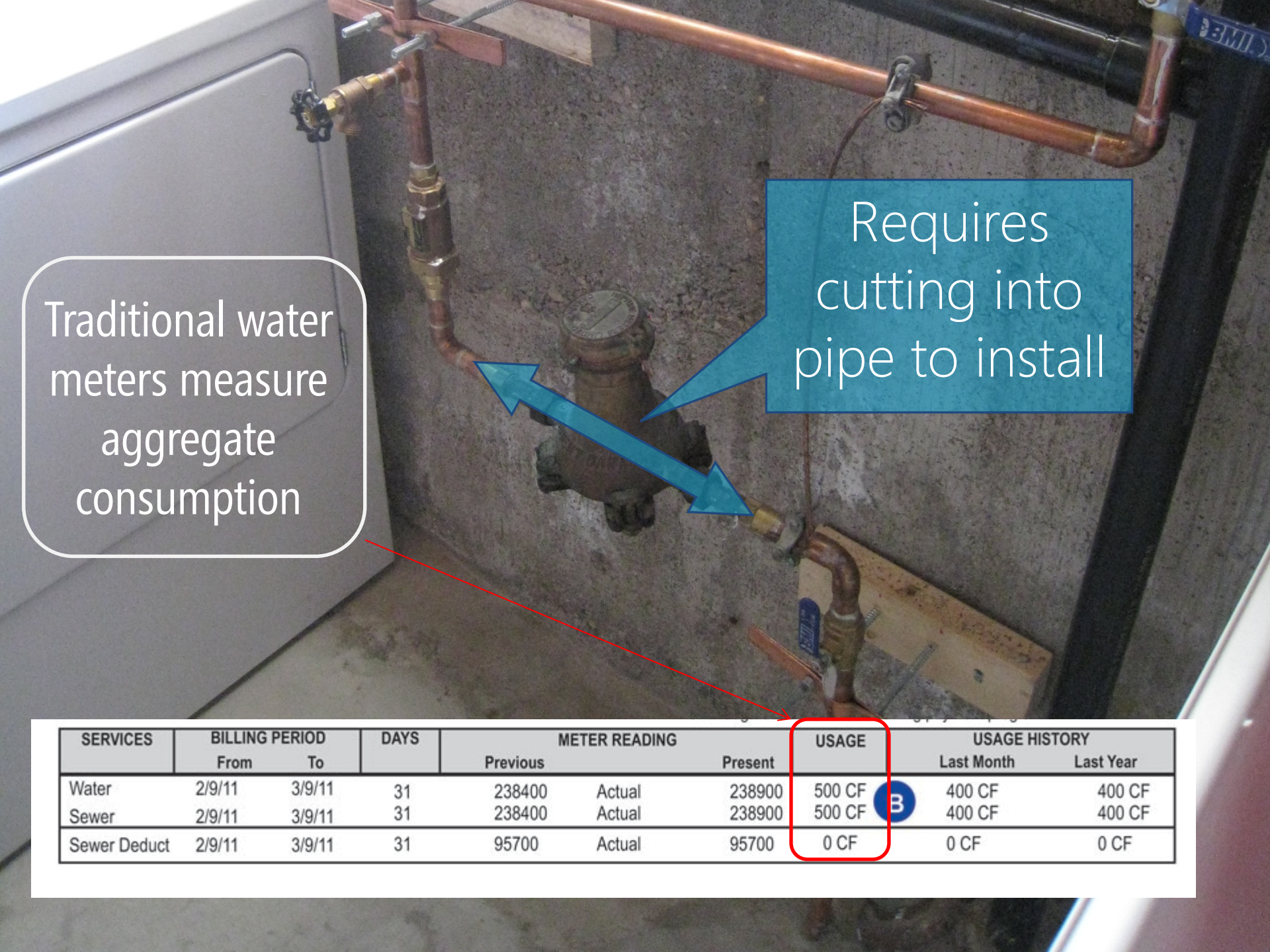
[HydroSense, UbiComp 2009]

indirect sensing

HydroSense attempts to infer fixture-level usage for the entire home from a **single** point.

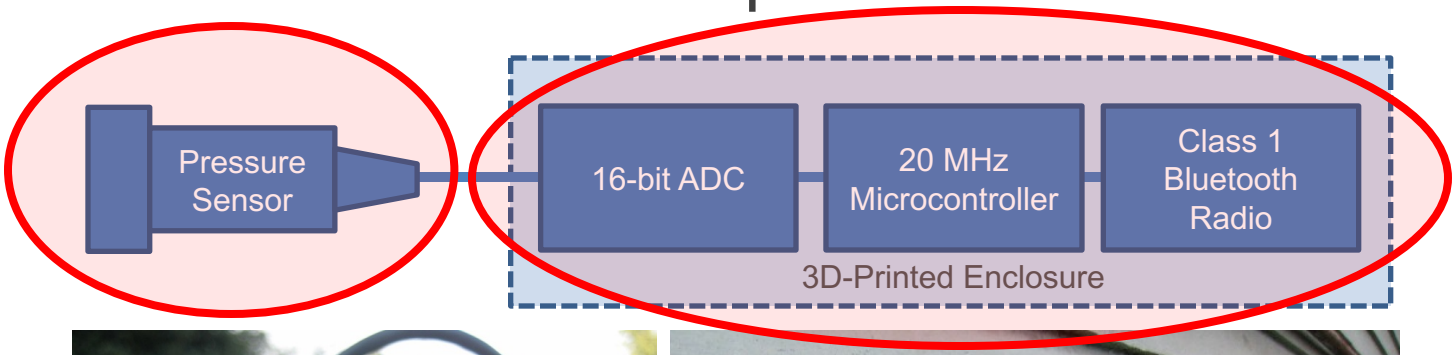
[HydroSense, UbiComp 2009]

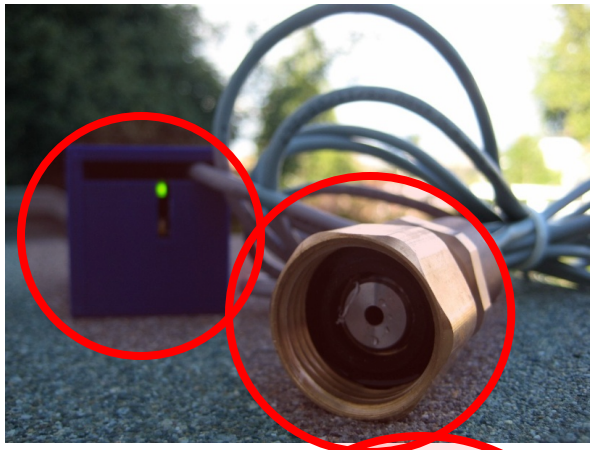

hydrosense
• single, screw-on sensor
• identifies fixture usage
• estimates flow
Froehlich et al., UbiComp2009; Larson et al., PMC2010

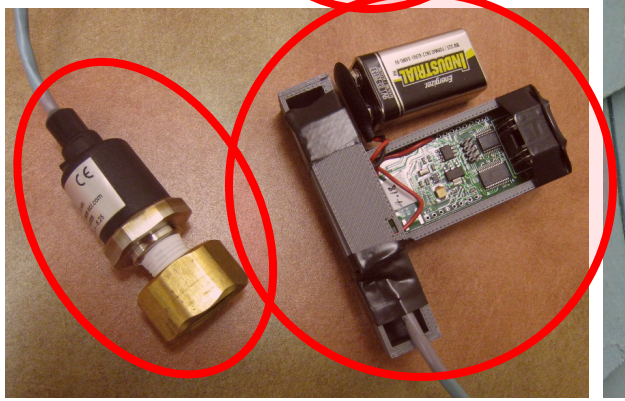


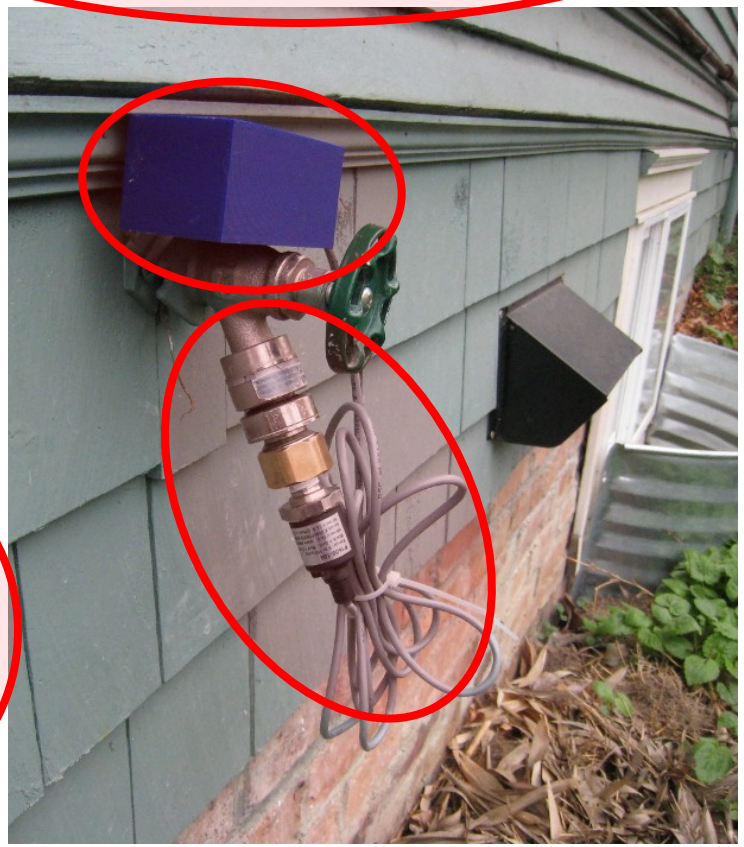
SERVICES	BILLING PERIOD From	To	DAYS	METER READING Previous		Present	USAGE		USAGE HISTORY Last Month	Last Year
Water	2/9/11	3/9/11	31	238400	Actual	238900	500 CF	B	400 CF	400 CF
Sewer	2/9/11	3/9/11	31	238400	Actual	238900	500 CF		400 CF	400 CF
Sewer Deduct	2/9/11	3/9/11	31	95700	Actual	95700	0 CF		0 CF	0 CF

hydrosense implementation





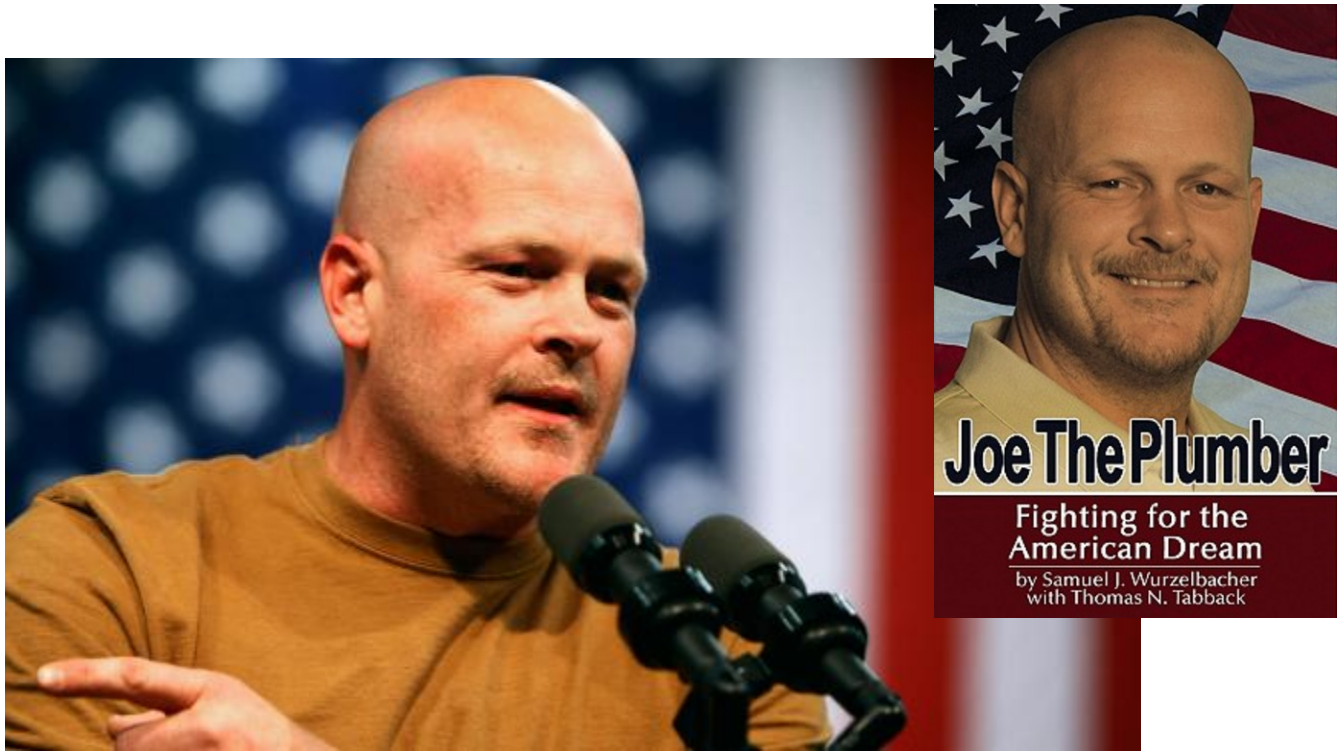




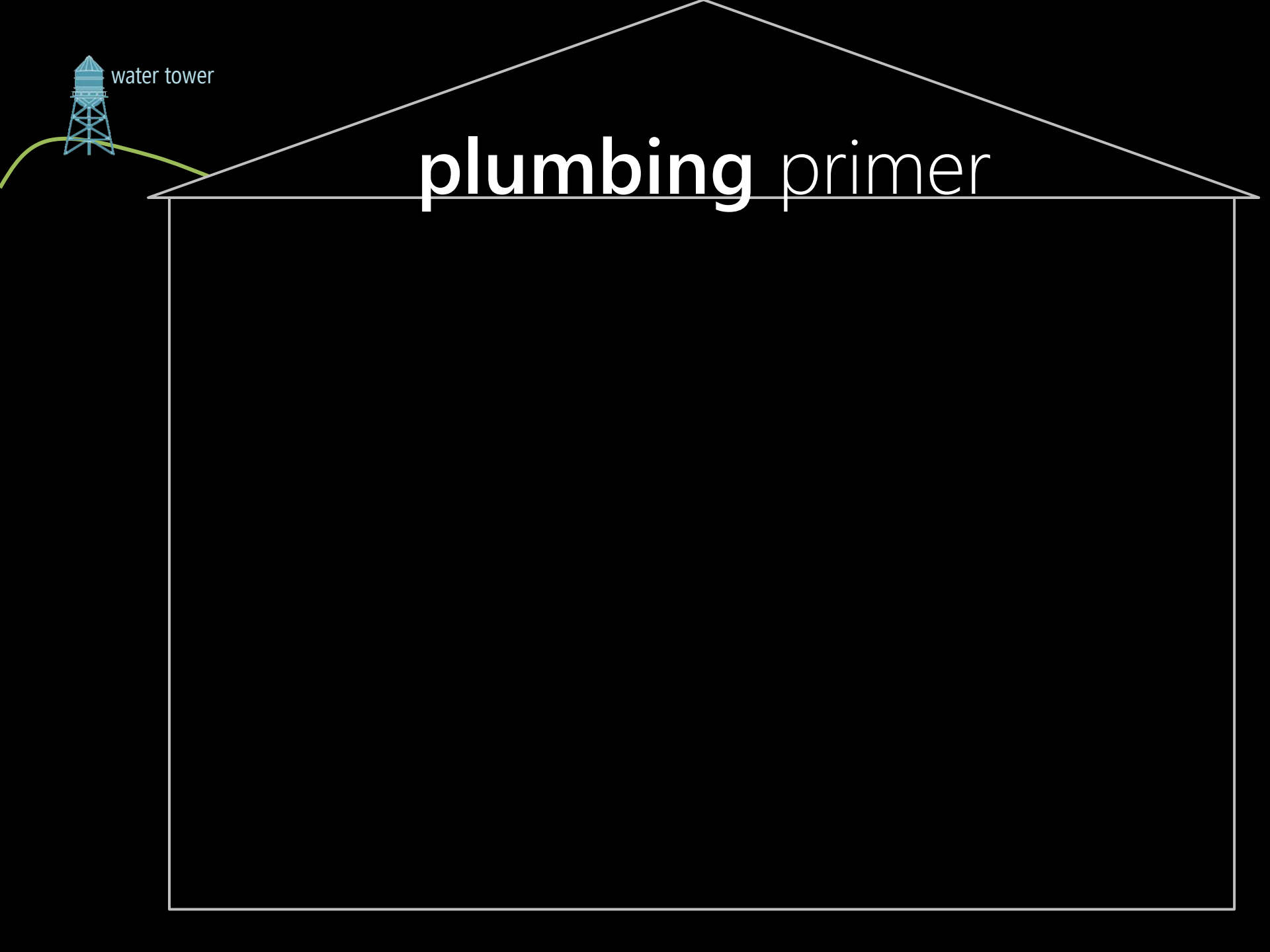
brief plumbing primer

brief plumbing primer

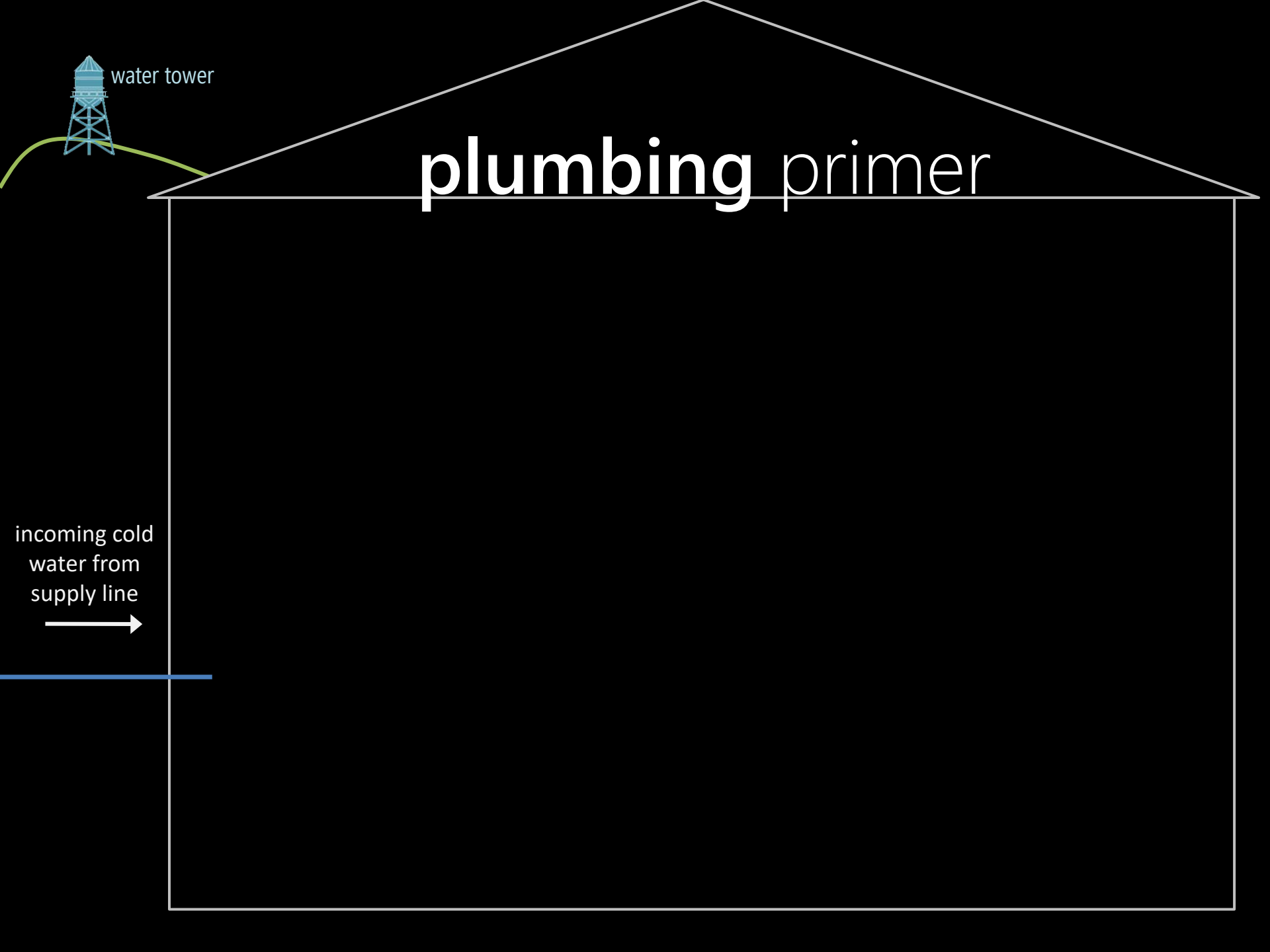
brief plumbing primer

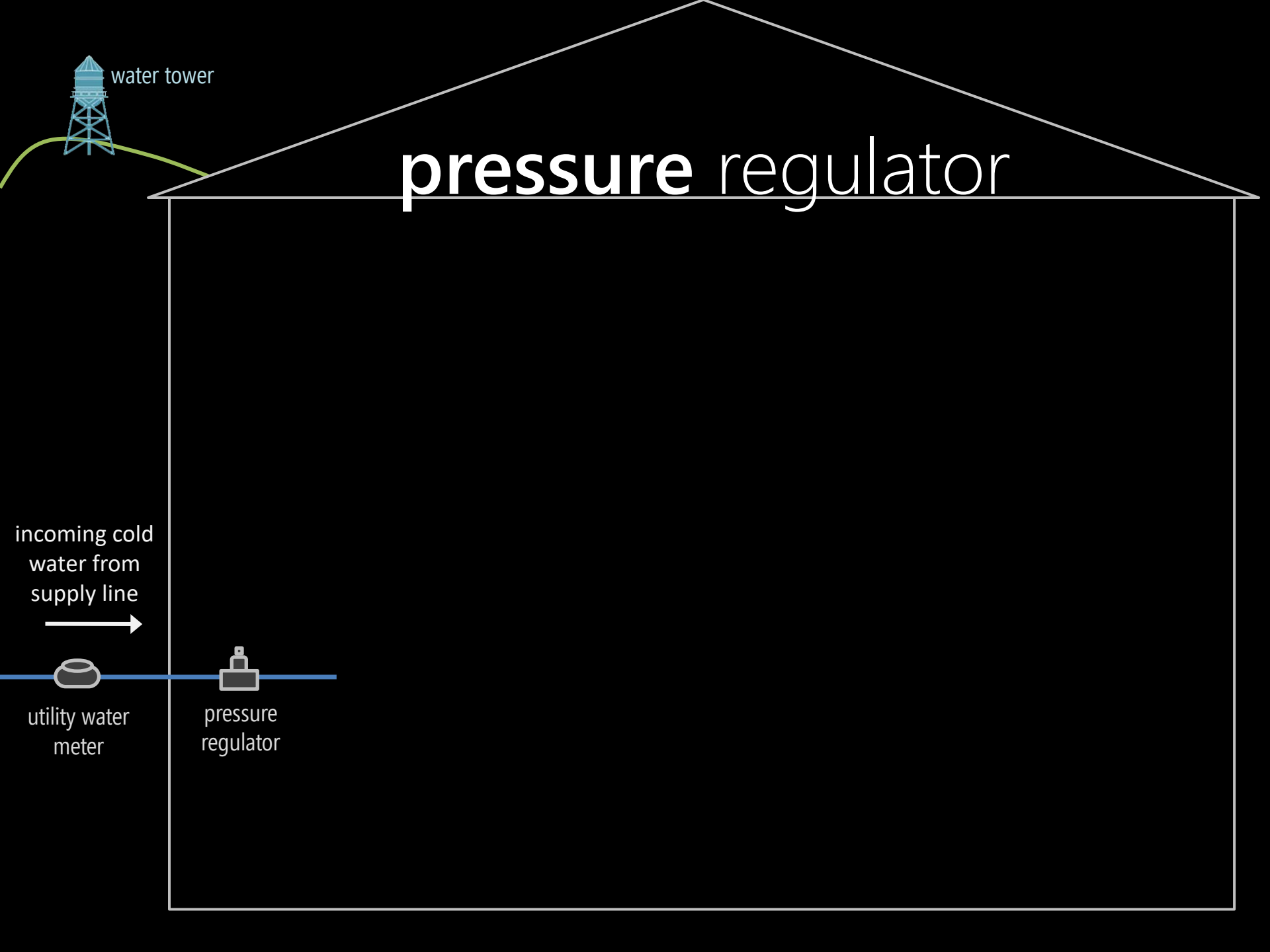


It's Samuel Joseph Wurzelbacher!

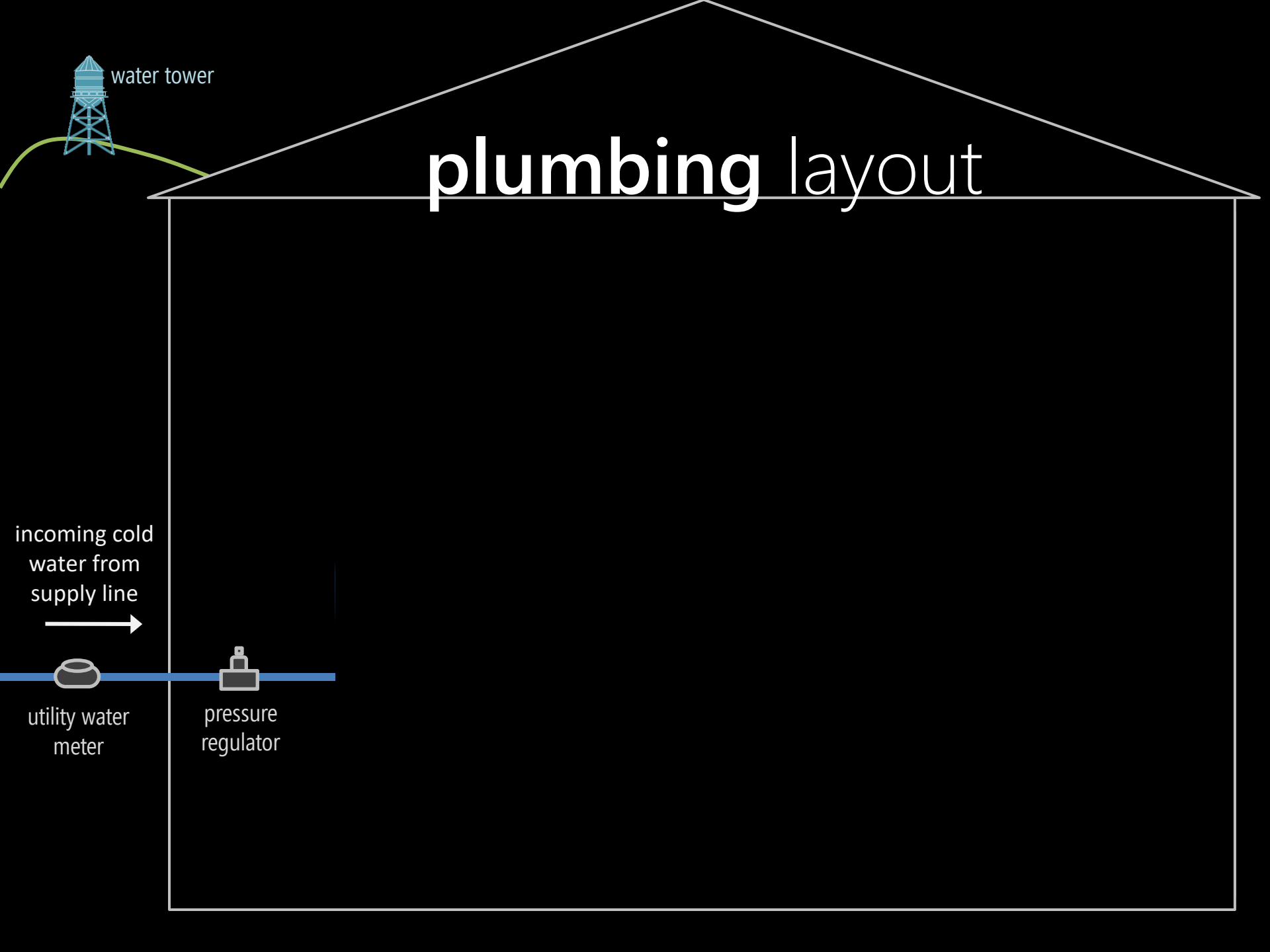


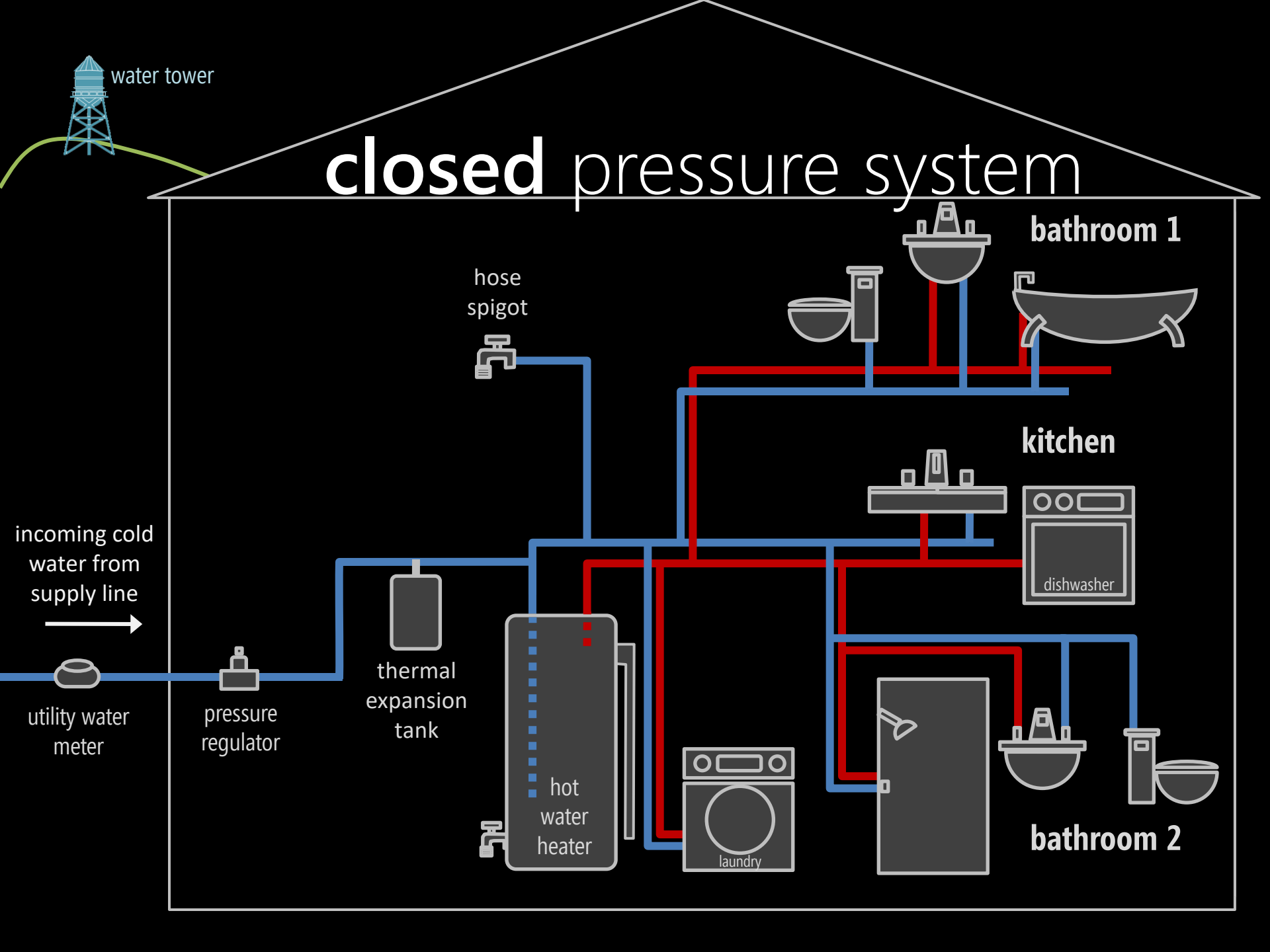
plumbing primer

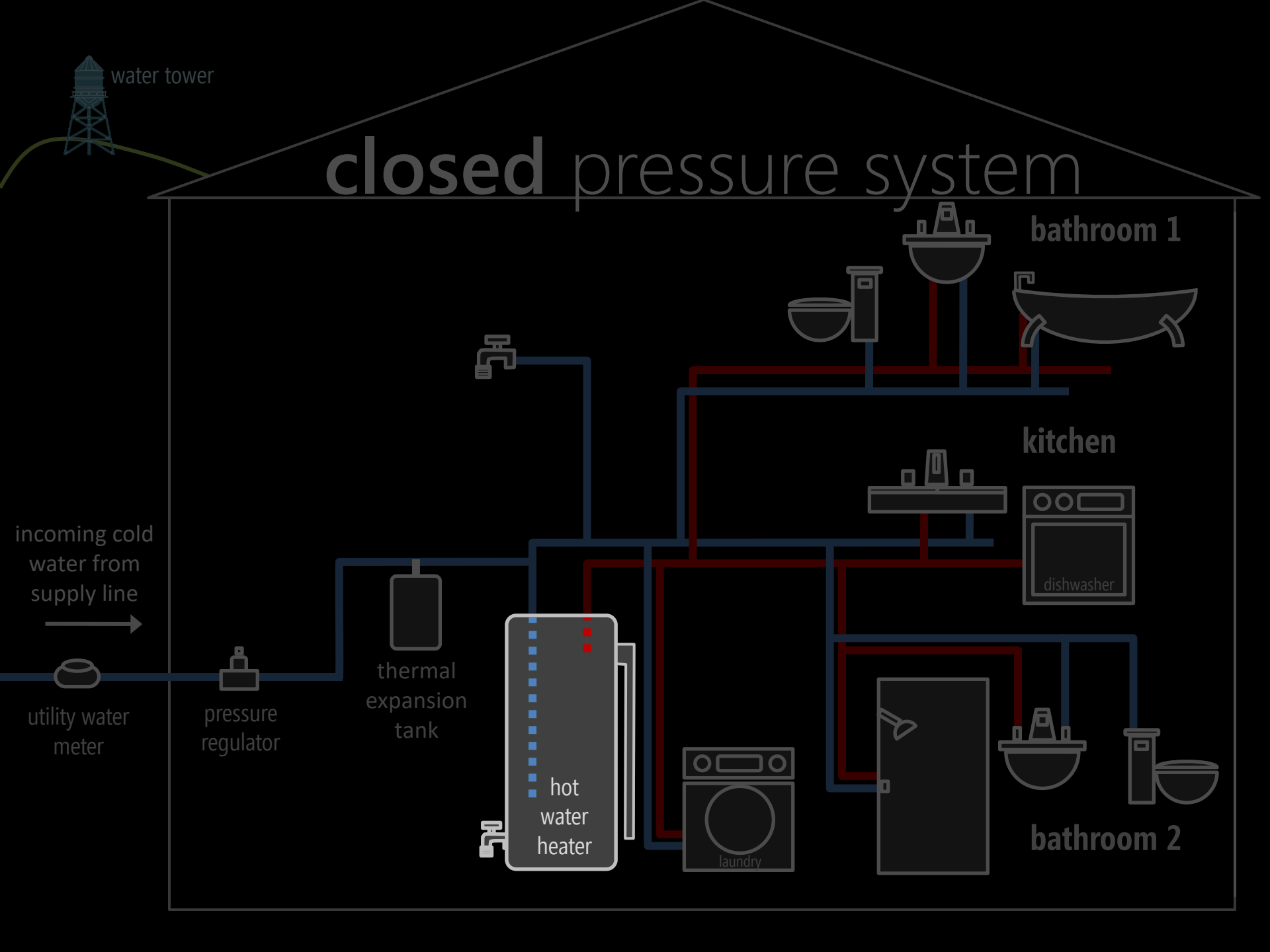

water tower
plumbing primer
incoming cold water from supply line

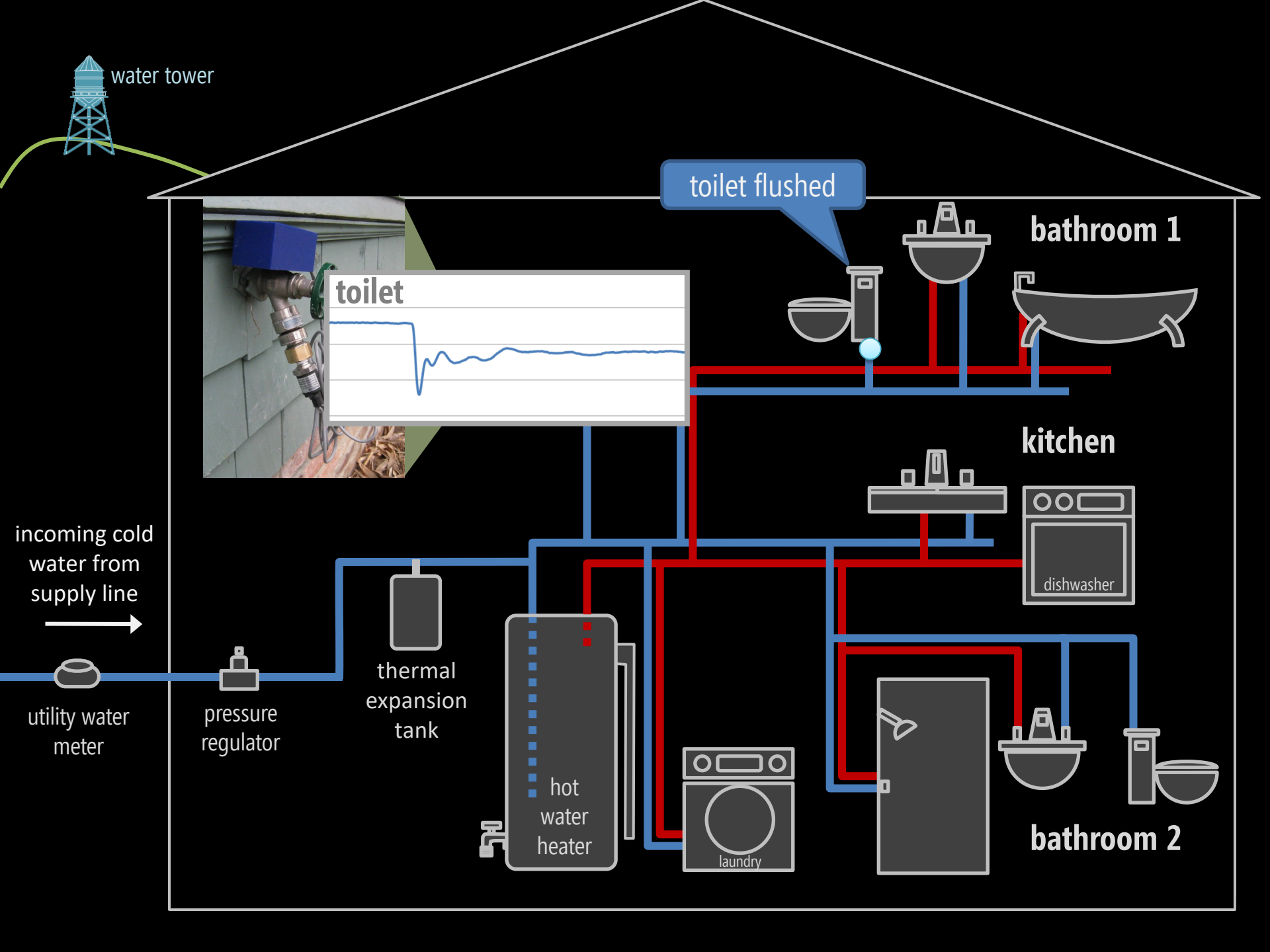

water tower
pressure regulator
incoming cold water from supply line
utility water meter
pressure regulator

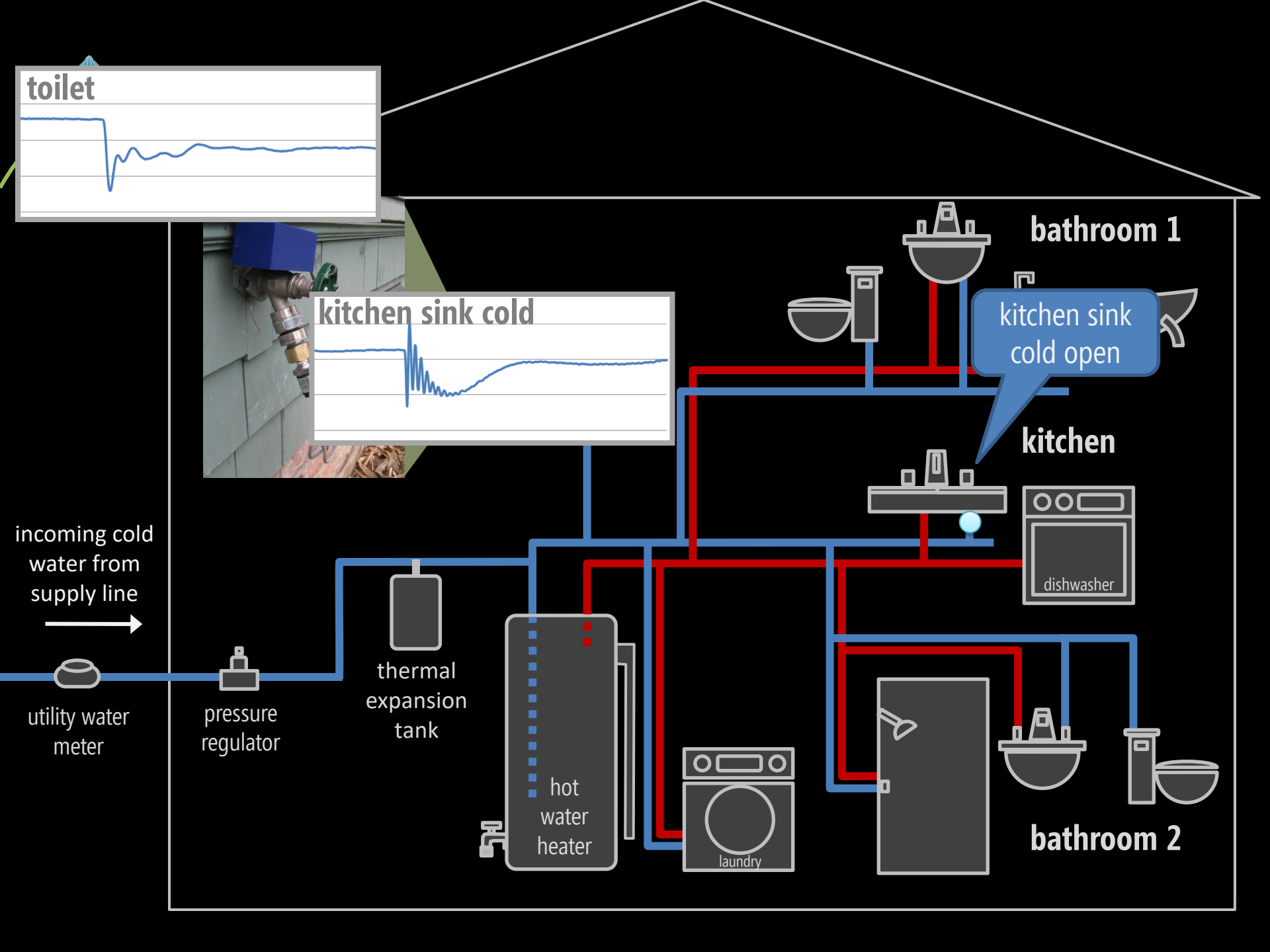
plumbing layout

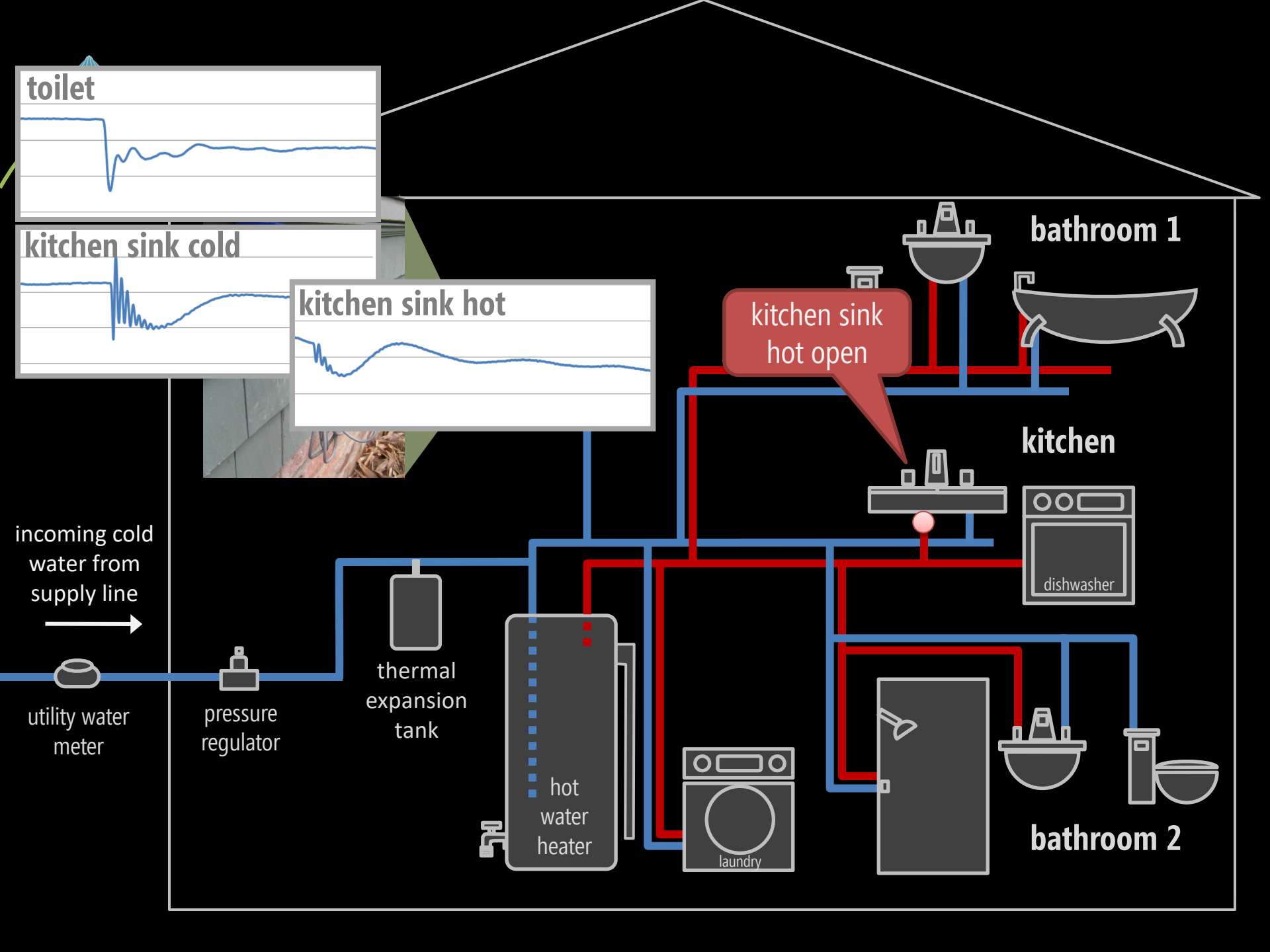


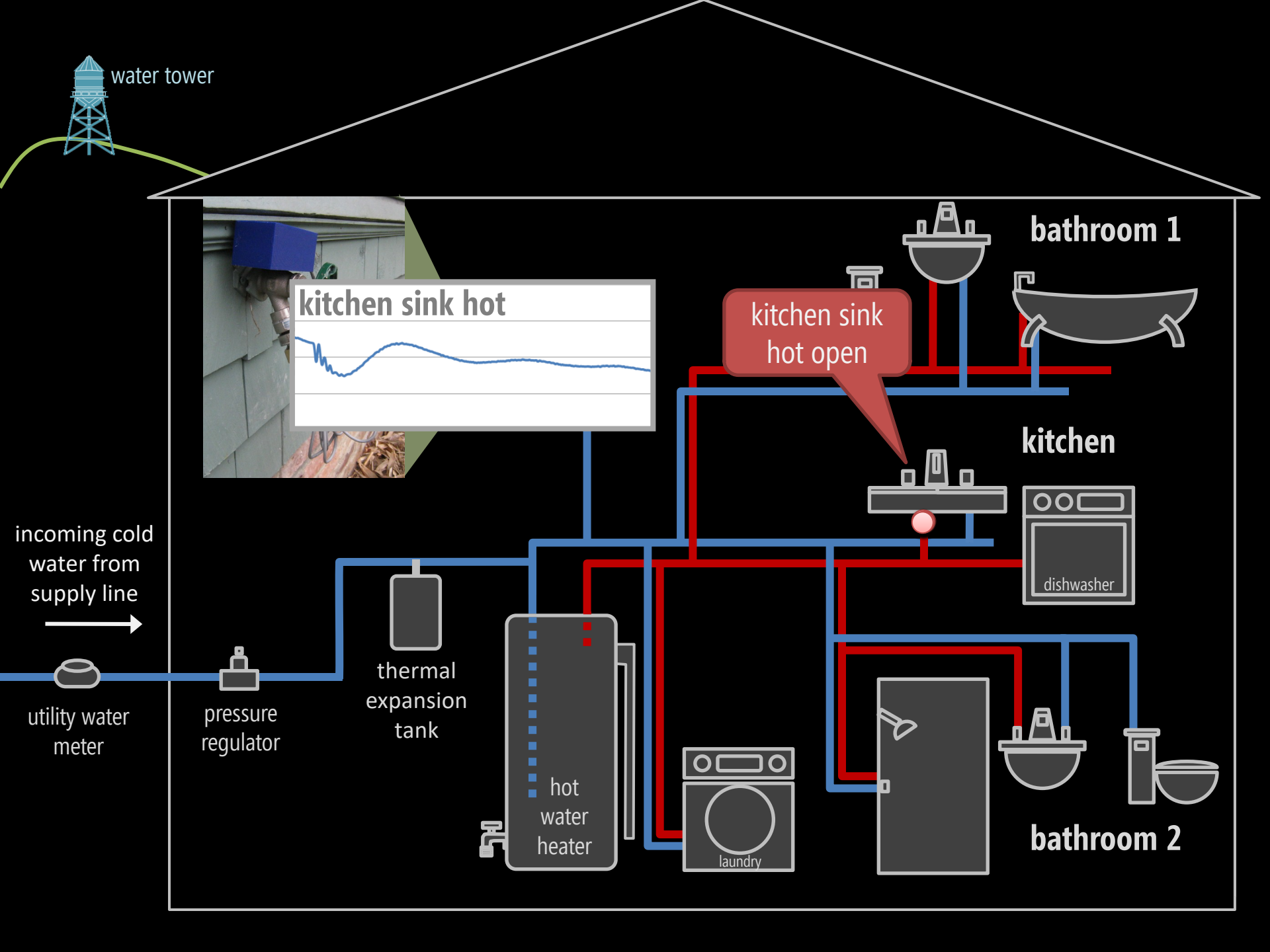

water tower
closed pressure system
bathroom 1
hose spigot
kitchen
dishwasher
incoming cold water from supply line
utility water meter
pressure regulator
thermal expansion tank
hot water heater
laundry
bathroom 2

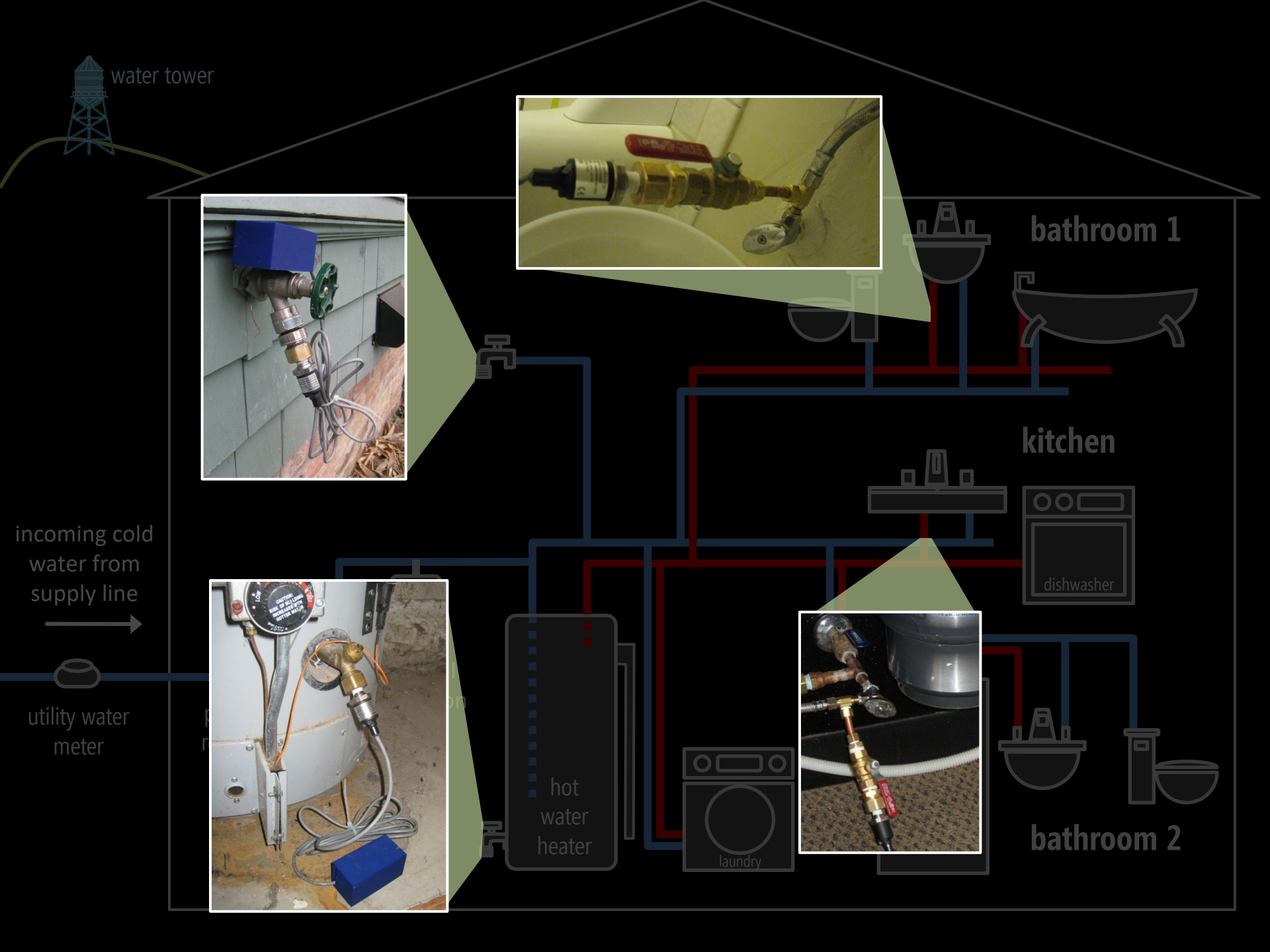

water tower
closed pressure system
bathroom 1
kitchen
dishwasher
incoming cold water from supply line
utility water meter
pressure regulator
thermal expansion tank
hot water heater
laundry
bathroom 2


water tower
toilet flushed
toilet
bathroom 1
kitchen
dishwasher
incoming cold water from supply line
utility water meter
pressure regulator
thermal expansion tank
hot water heater
laundry
bathroom 2

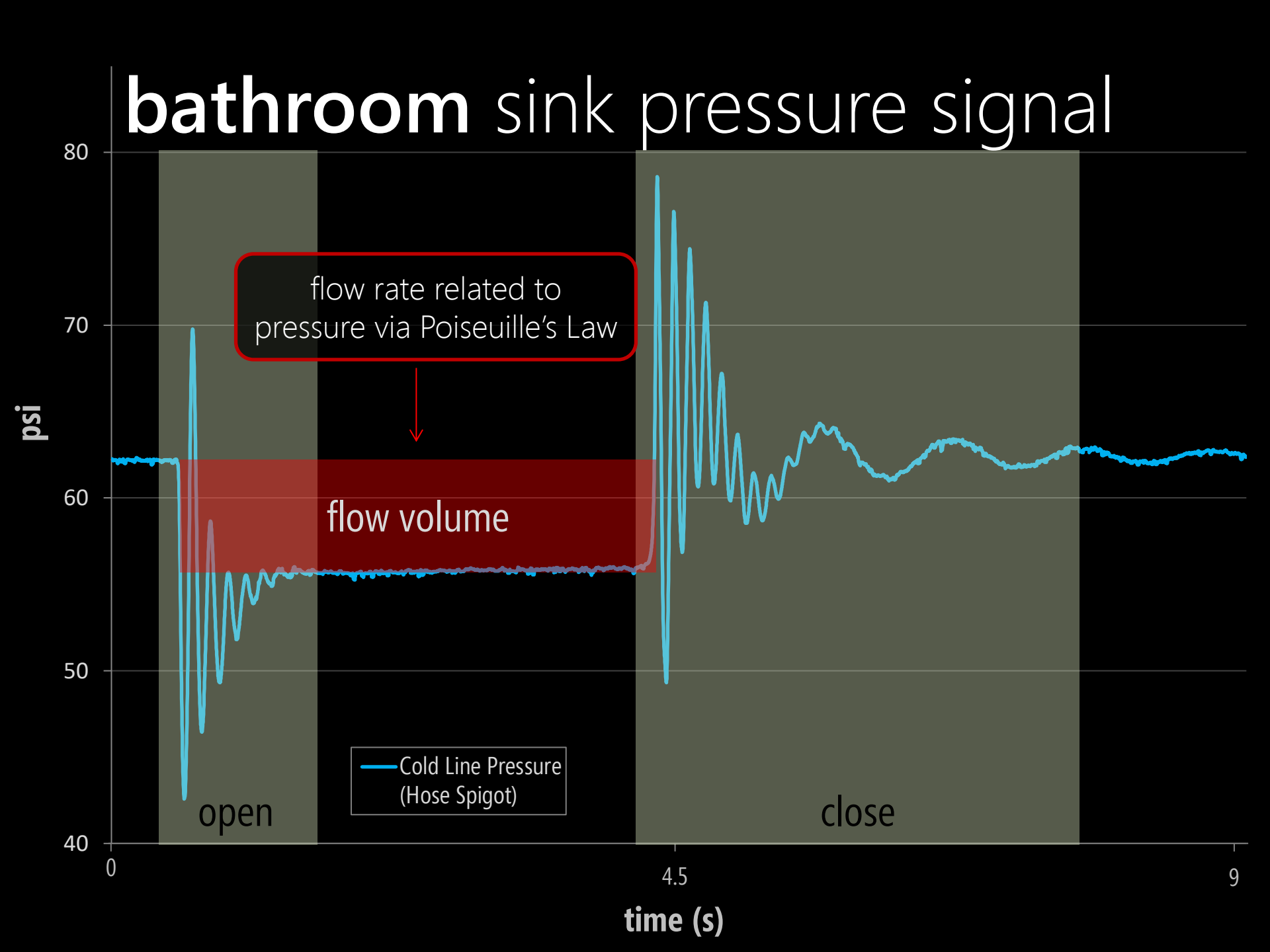

toilet
kitchen sink cold
bathroom 1
kitchen sink cold open
kitchen
dishwasher
incoming cold water from supply line
utility water meter
pressure regulator
thermal expansion tank
hot water heater
laundry
bathroom 2

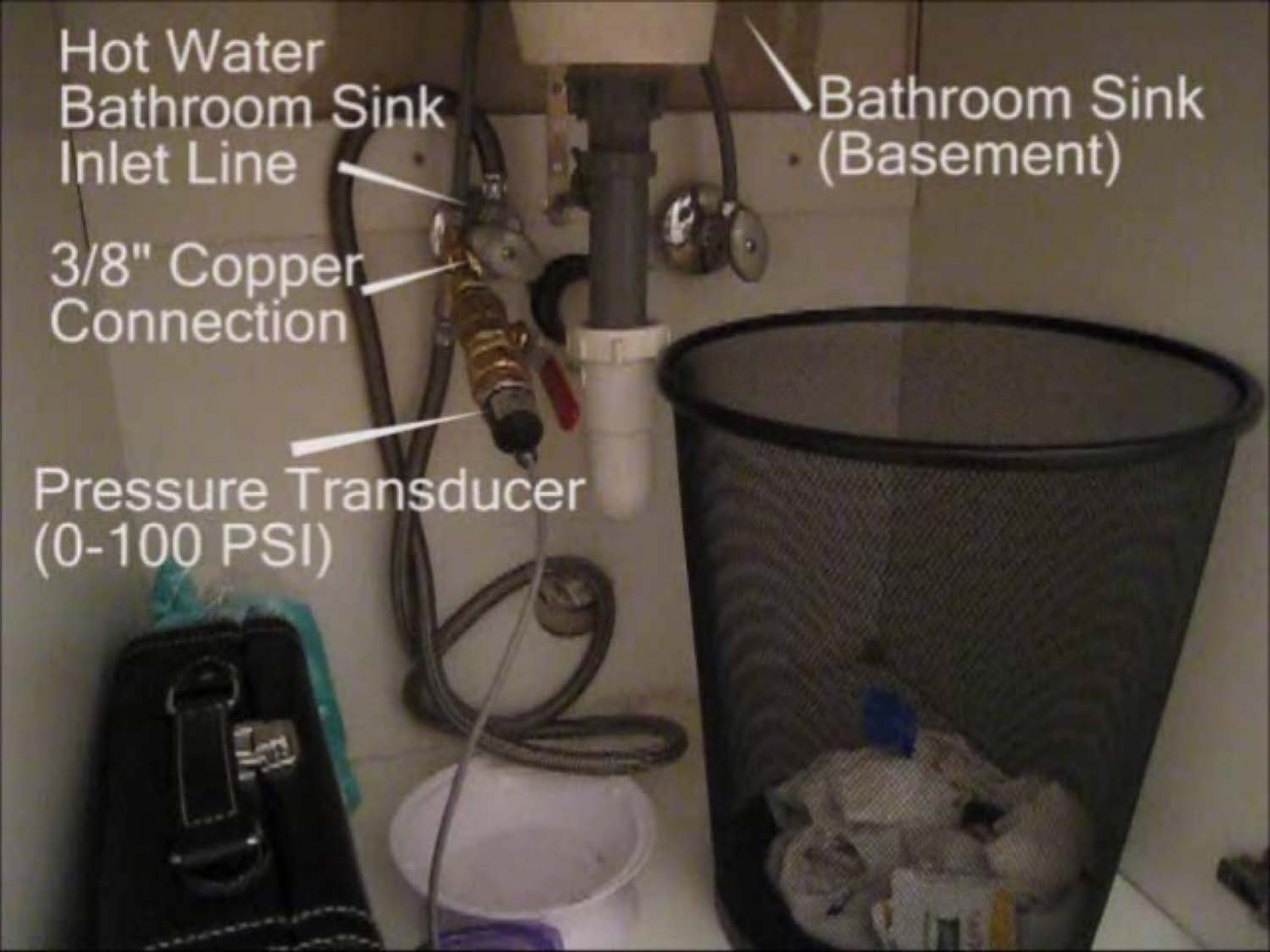

toilet
kitchen sink cold
kitchen sink hot
bathroom 1
kitchen sink hot open
kitchen
dishwasher
incoming cold water from supply line
utility water meter
pressure regulator
thermal expansion tank
hot water heater
laundry
bathroom 2


water tower
kitchen sink hot
kitchen sink hot open
bathroom 1
kitchen
dishwasher
incoming cold water from supply line
utility water meter
pressure regulator
thermal expansion tank
hot water heater
laundry
bathroom 2

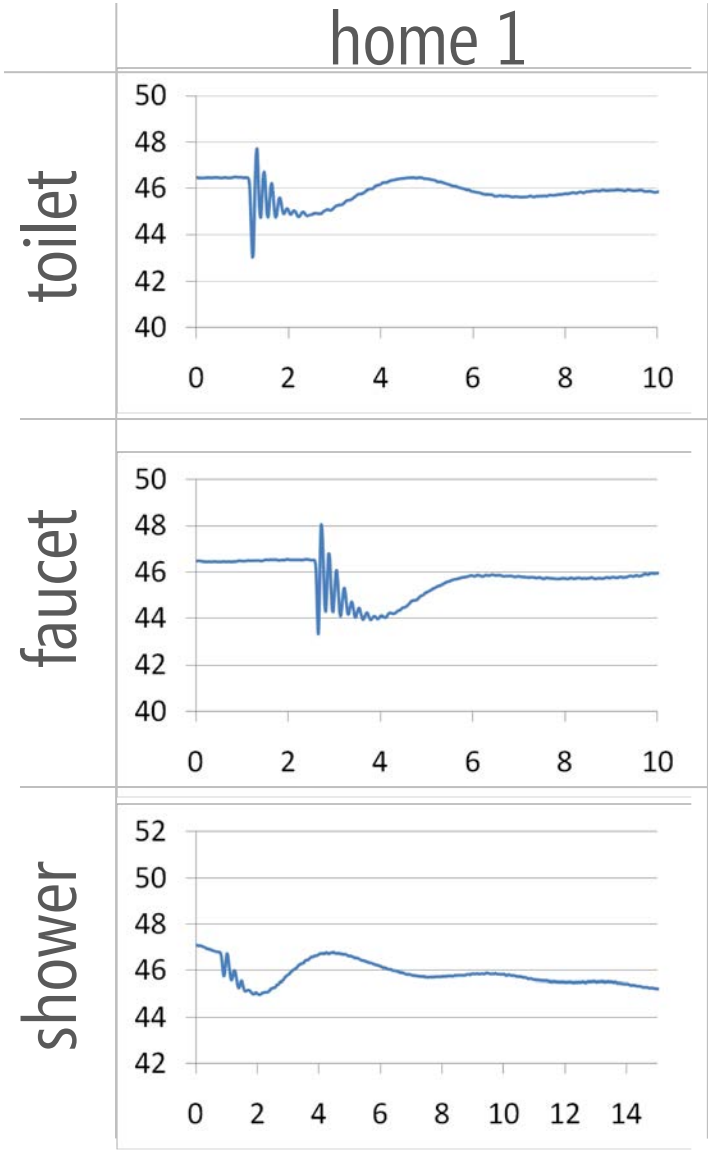

water tower
bathroom 1
kitchen
dishwasher
incoming cold water from supply line
utility water meter
hot water heater
laundry
bathroom 2


bathroom sink pressure signal
80
70
60
50
40
psi
0
4.5
9
time (s)


bathroom sink pressure signal
80
70
60
50
40
psi
flow rate related to
pressure via Poiseuille's Law
flow volume
Cold Line Pressure
(Hose Spigot)
open
close
0
4.5
9
time (s)

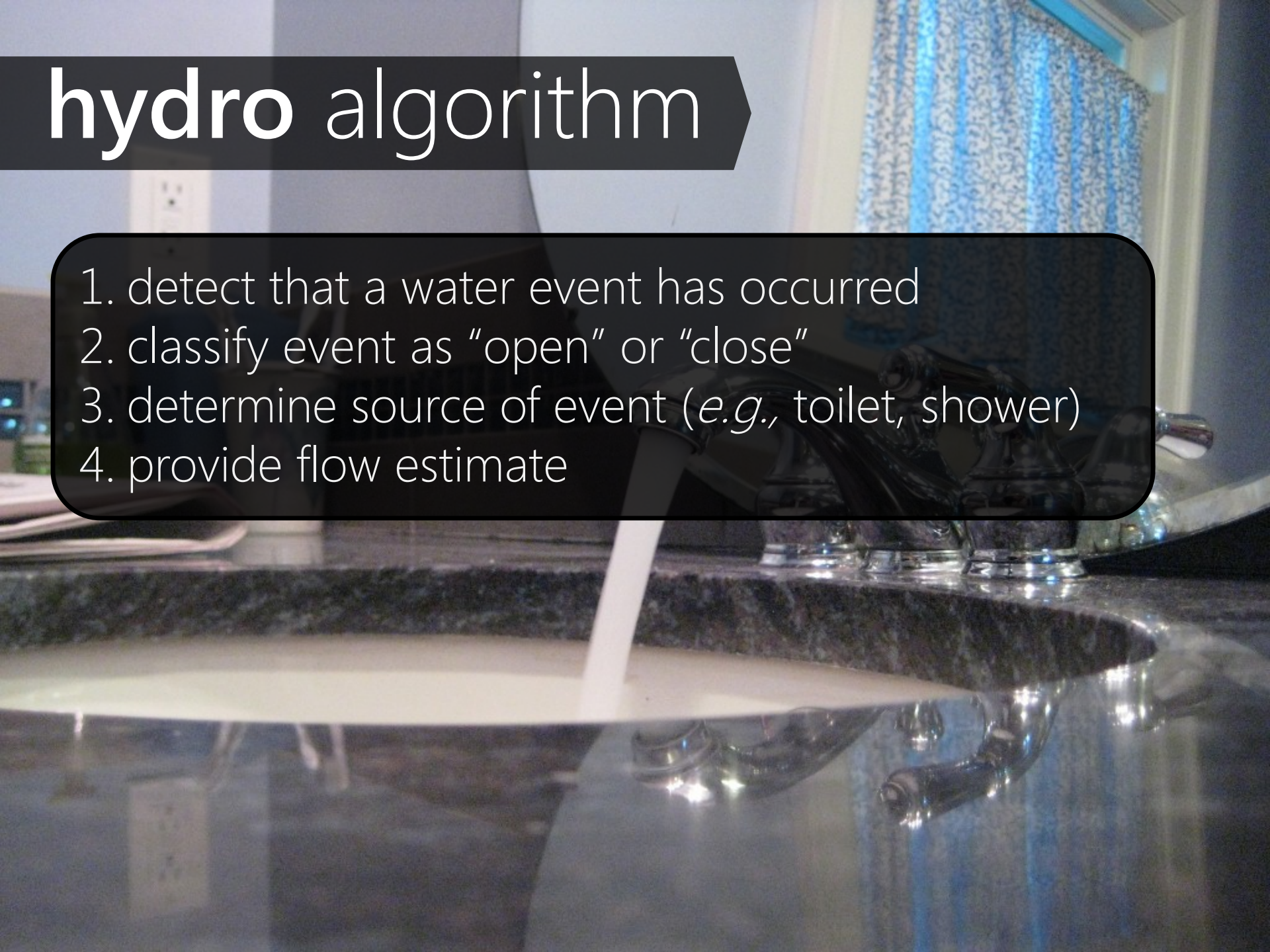

Hot Water
Bathroom Sink
Inlet Line
3/8" Copper
Connection
Pressure Transducer
(0-100 PSI)
Bathroom Sink
(Basement)

example open events



signature dependent on:

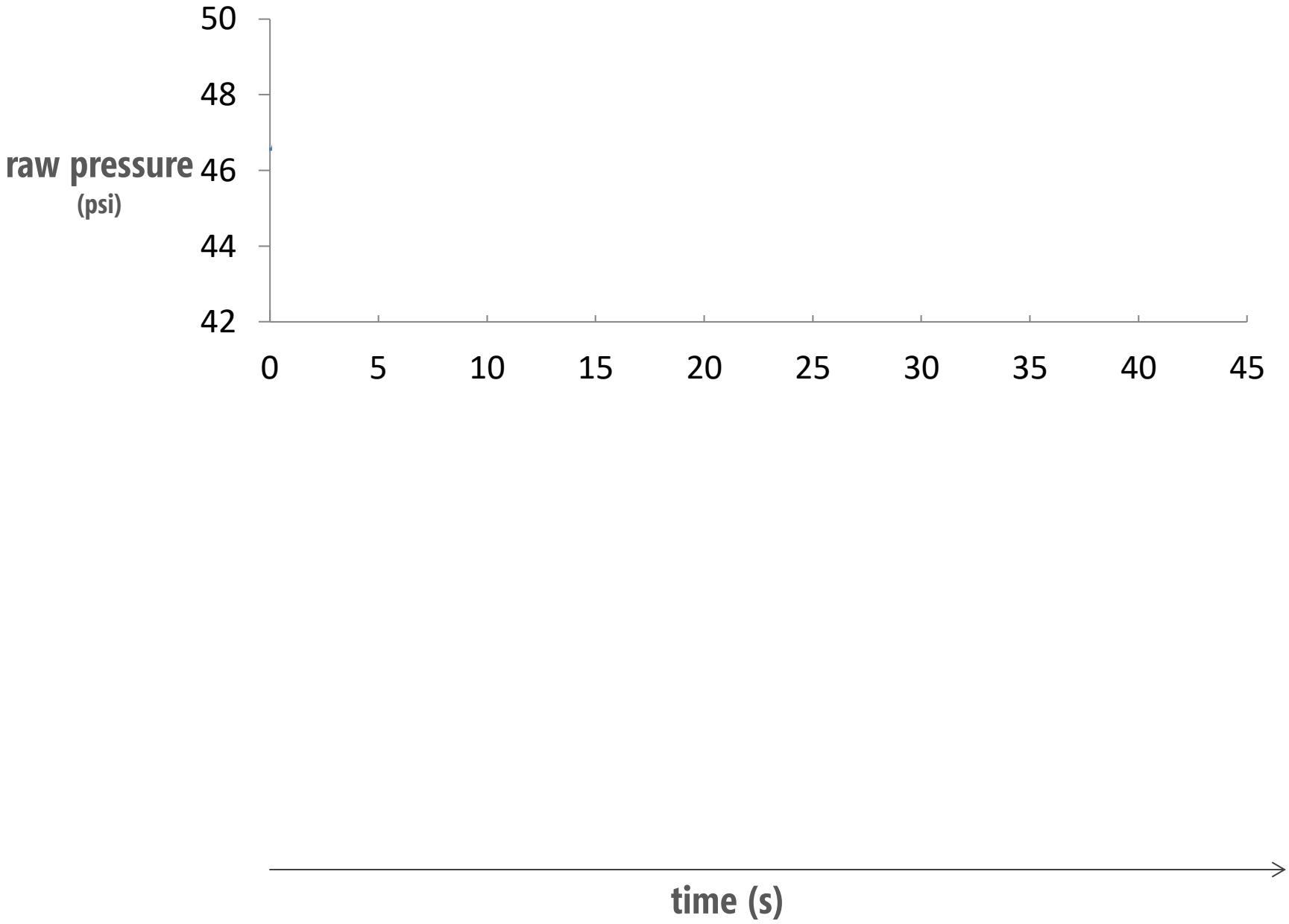
- fixture type
- valve type
- valve location in home



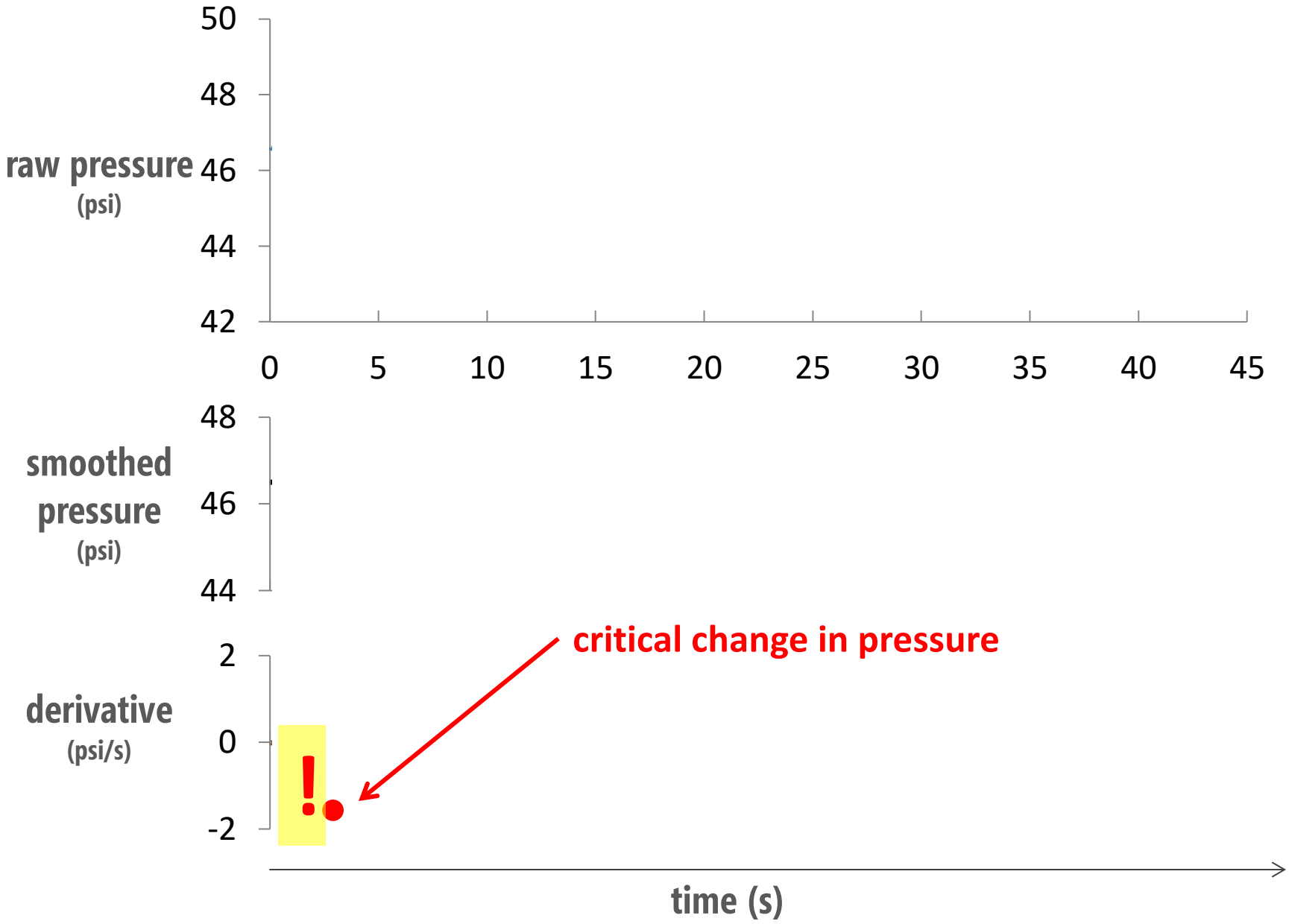
hydro algorithm

1. detect that a water event has occurred
2. classify event as “open” or “close”
3. determine source of event (*e.g.,* toilet, shower)
4. provide flow estimate

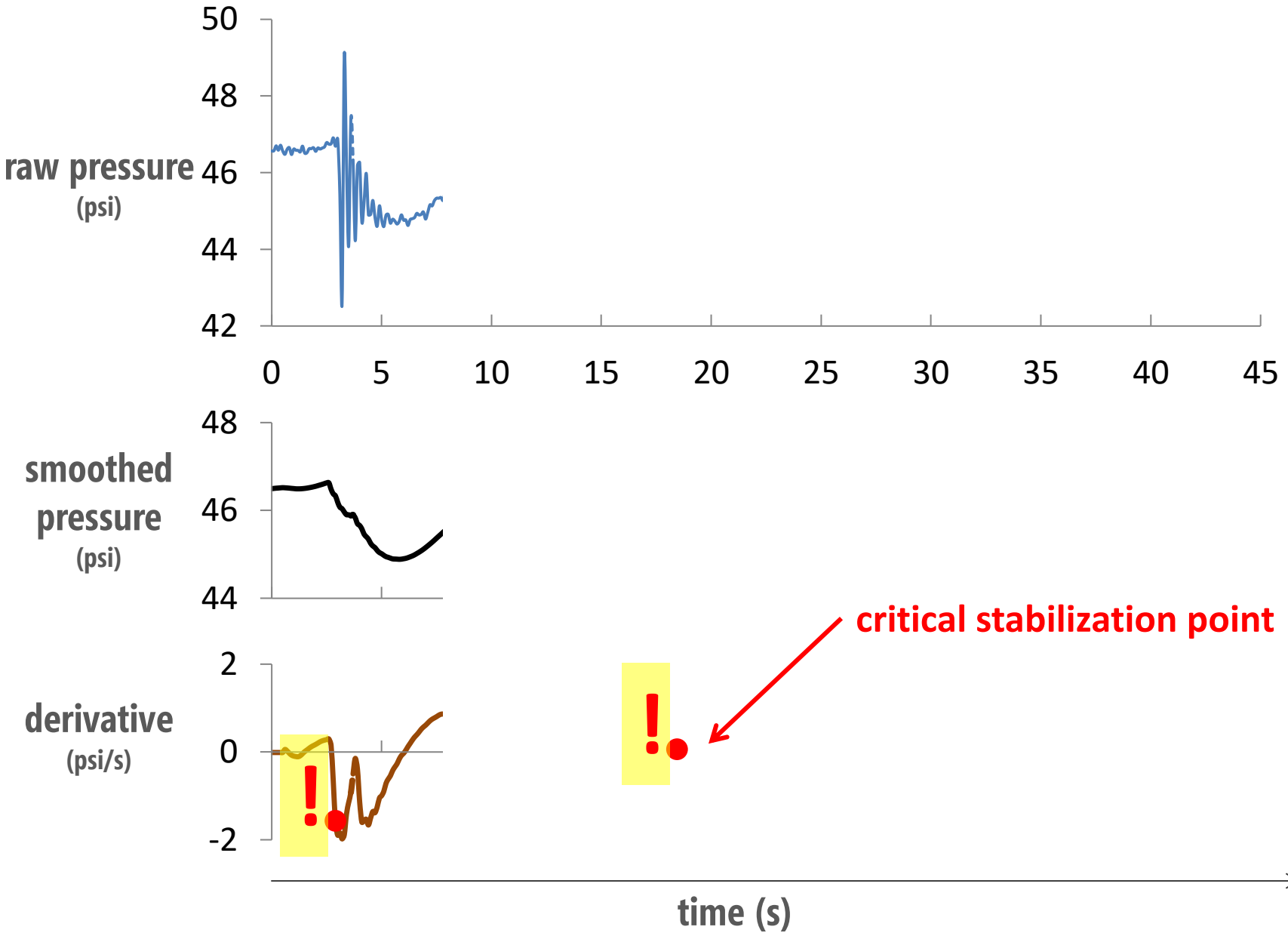
event detection/segmentation



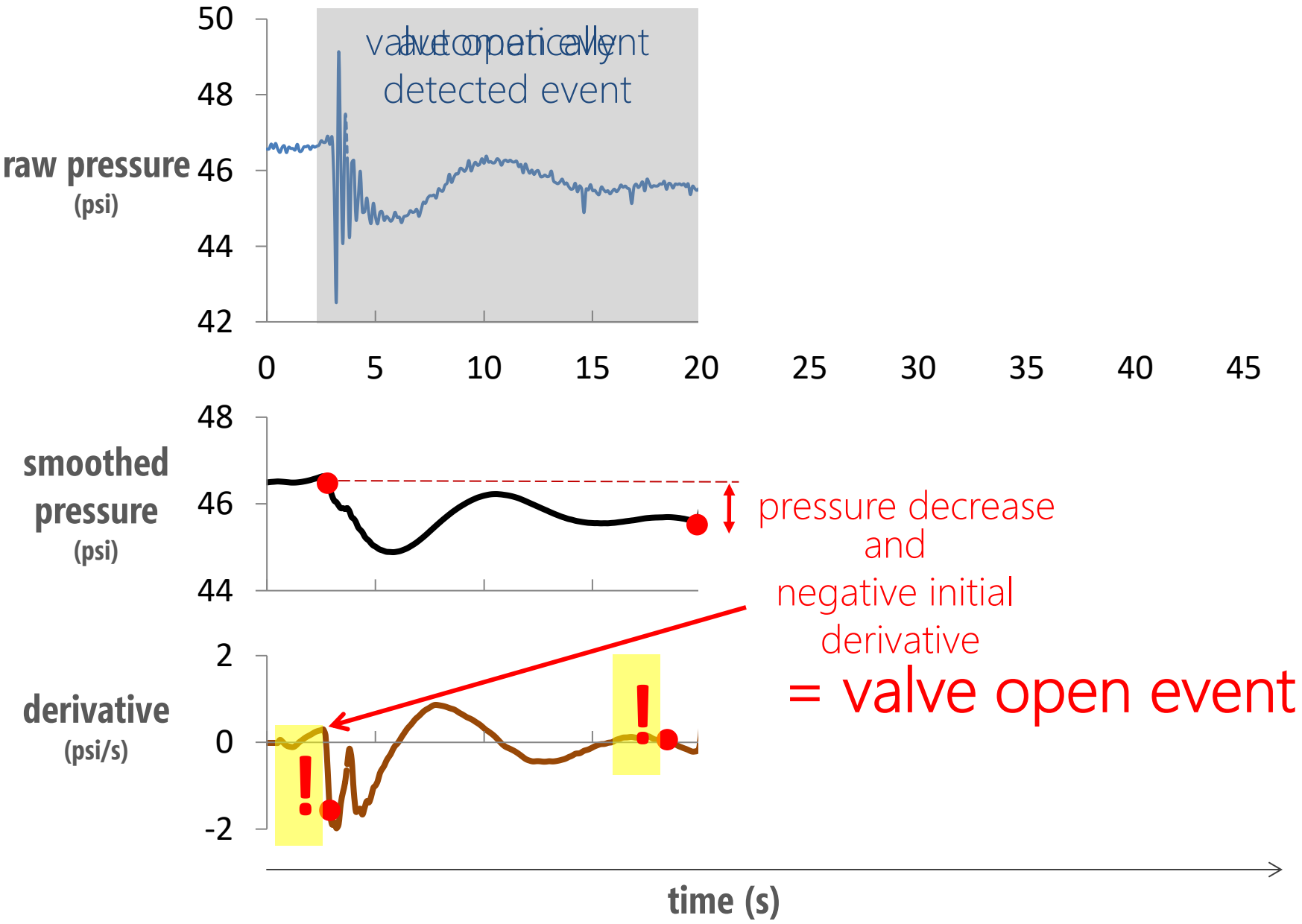
event detection/segmentation



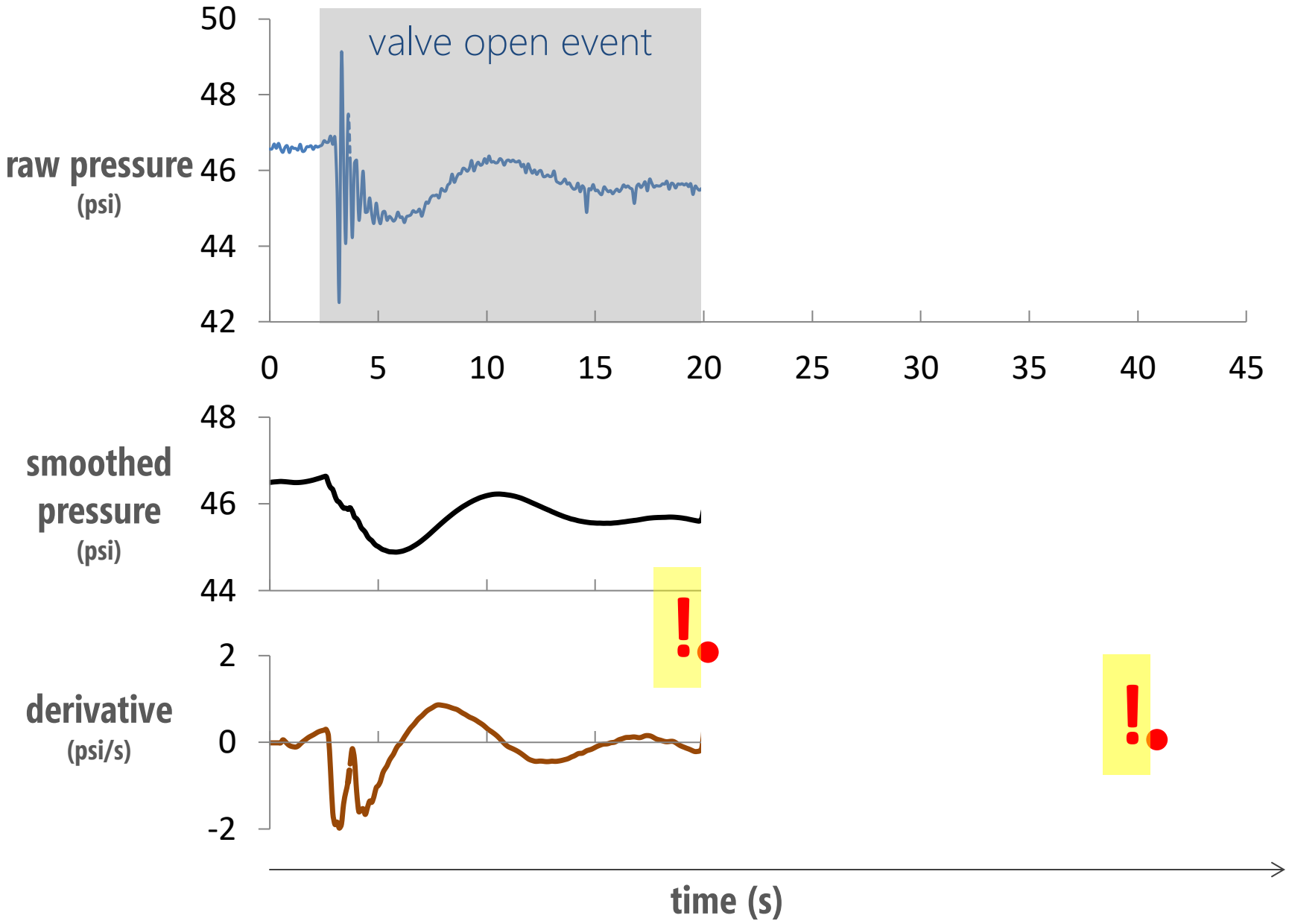
event detection/segmentation



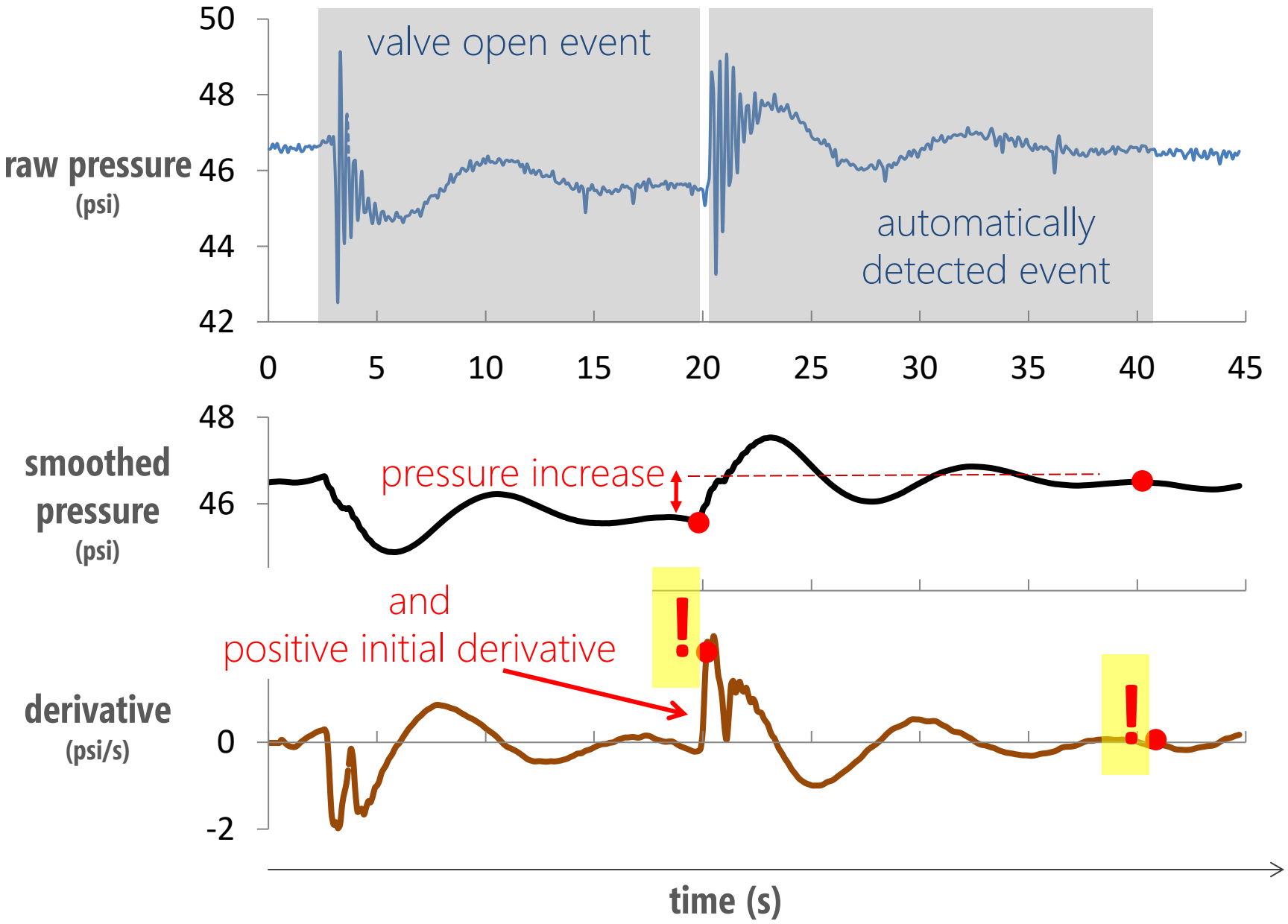
event detection/segmentation



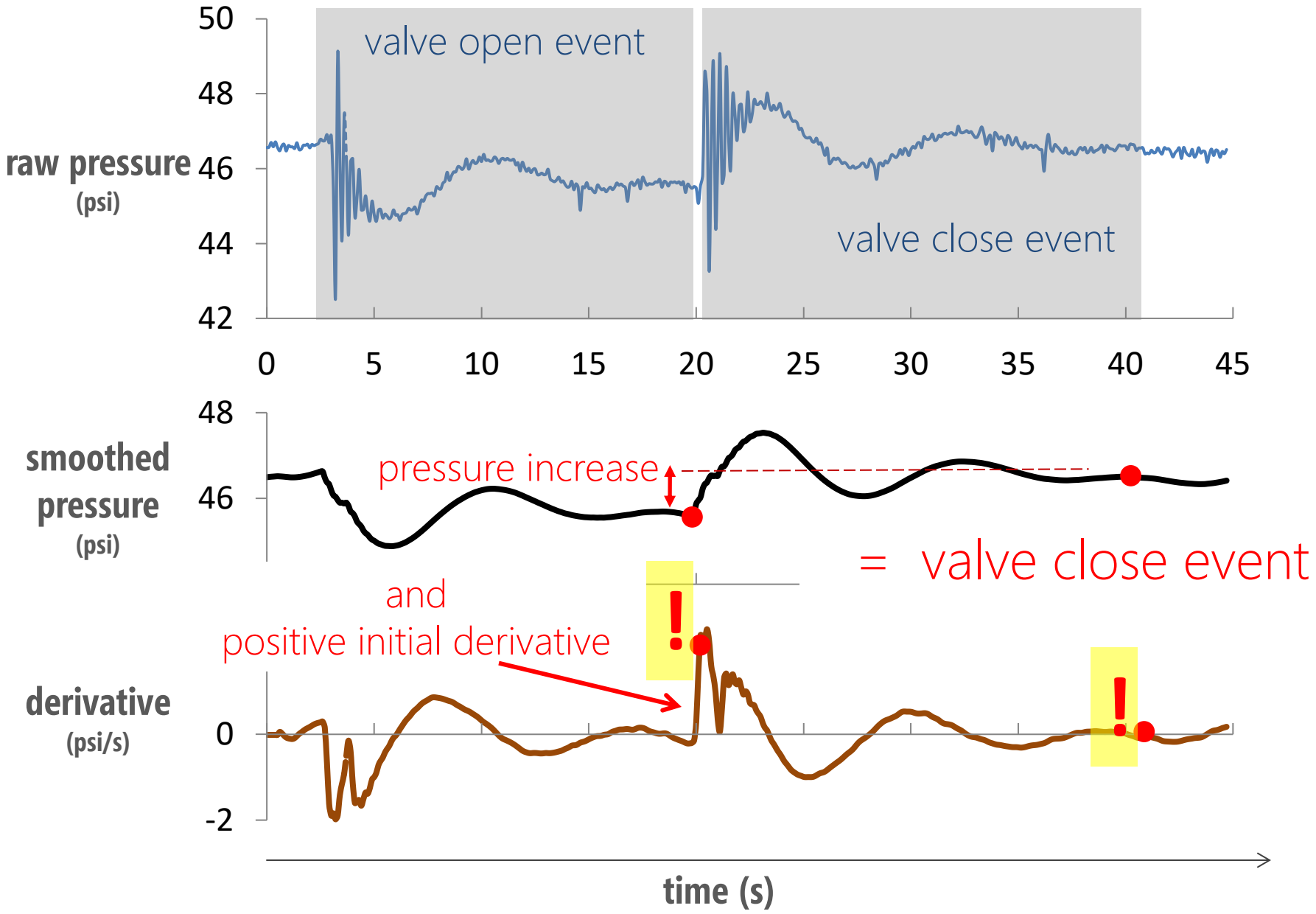
event detection/segmentation



event detection/segmentation

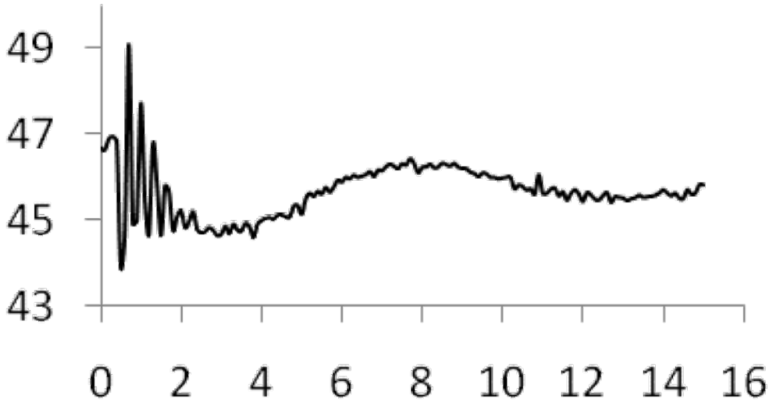


event detection/segmentation

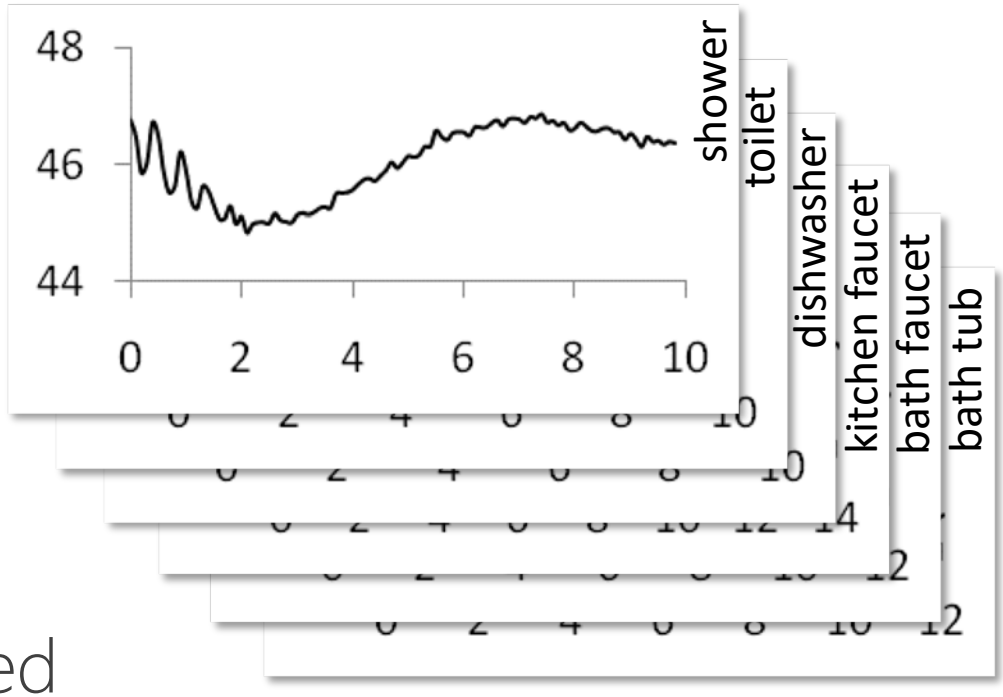


fixture classification

unclassified open event



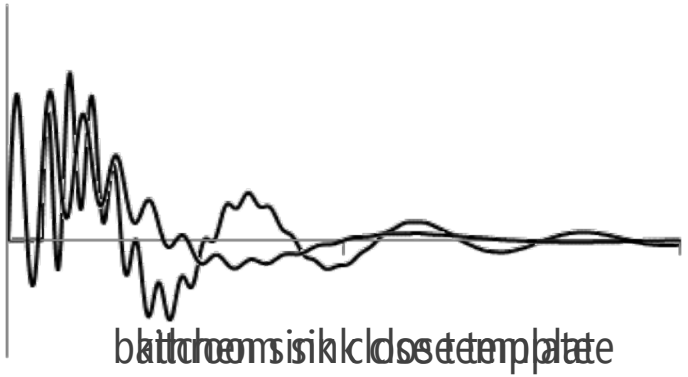
open event library

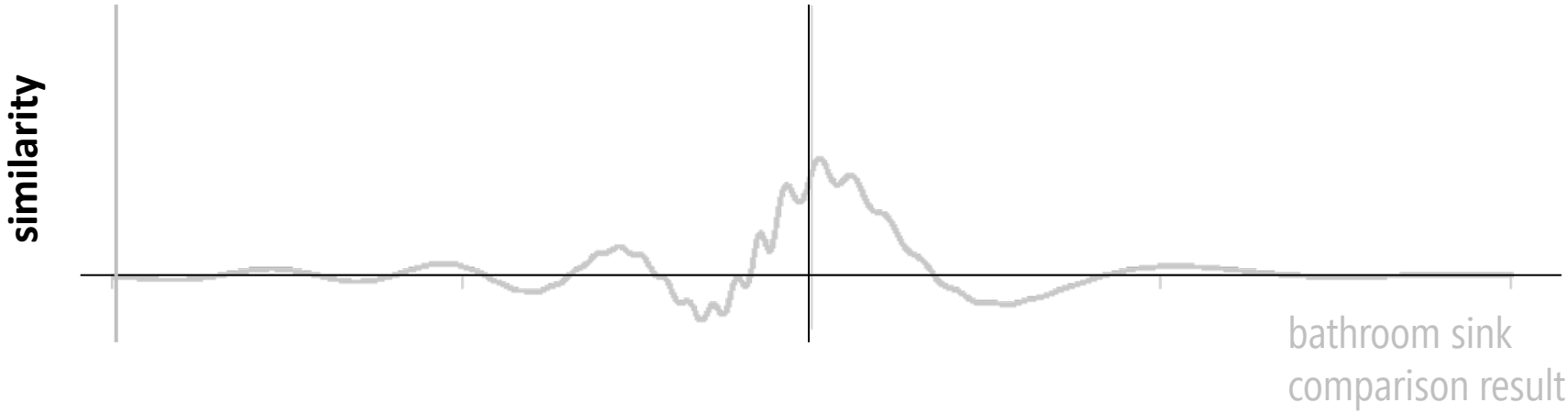


compare via matched filtering across multiple signal transformations

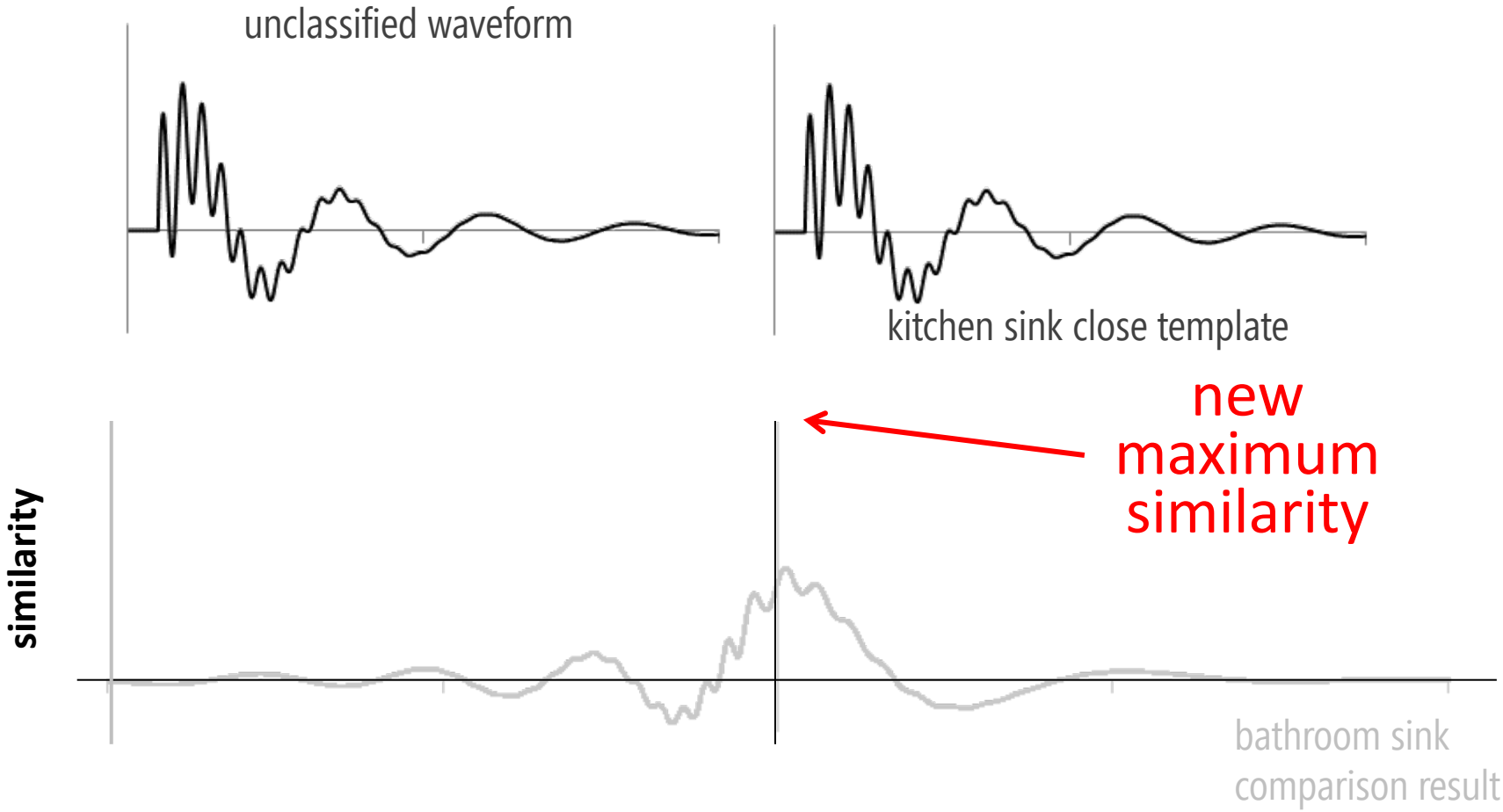
matched filtering

matched filtering

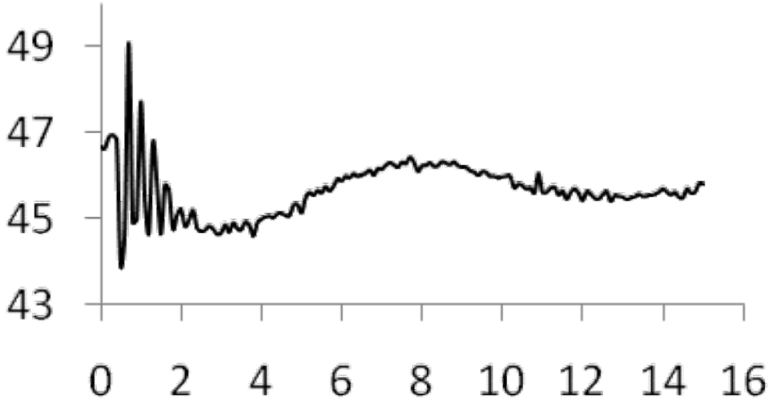




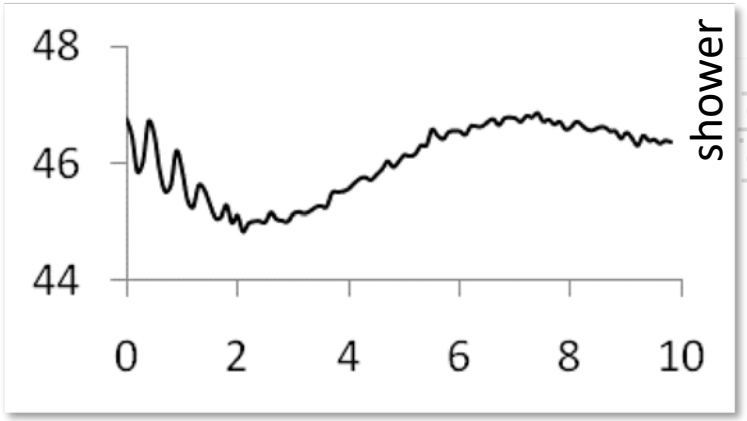
matched filtering



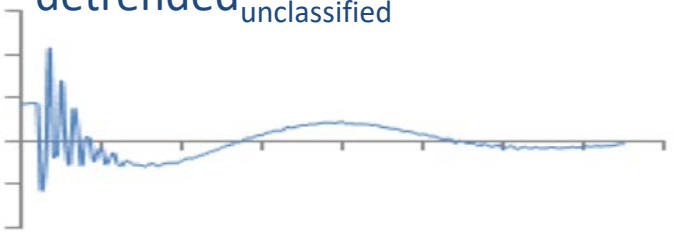
unclassified open event



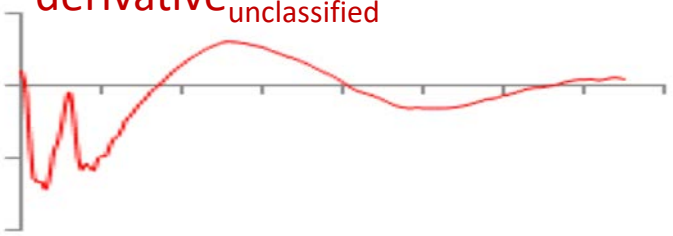
open event library



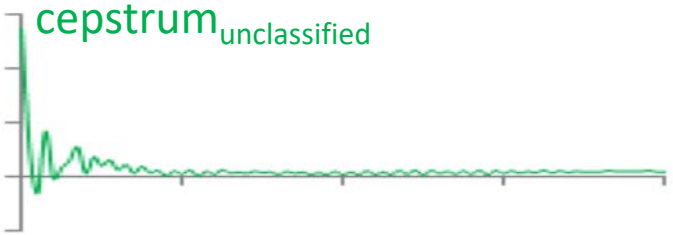
detrended$_{unclassified}$



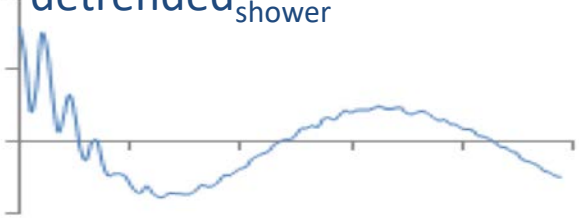
derivative$_{unclassified}$



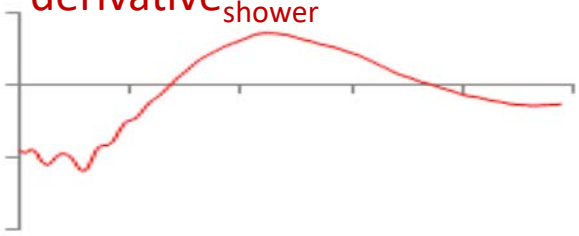
cepstrum$_{unclassified}$



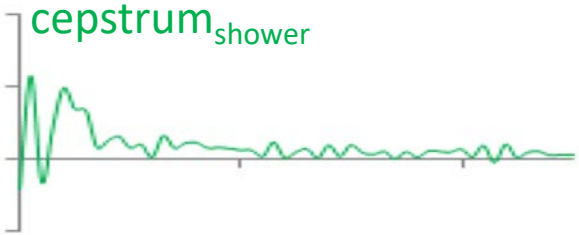
detrended$_{shower}$

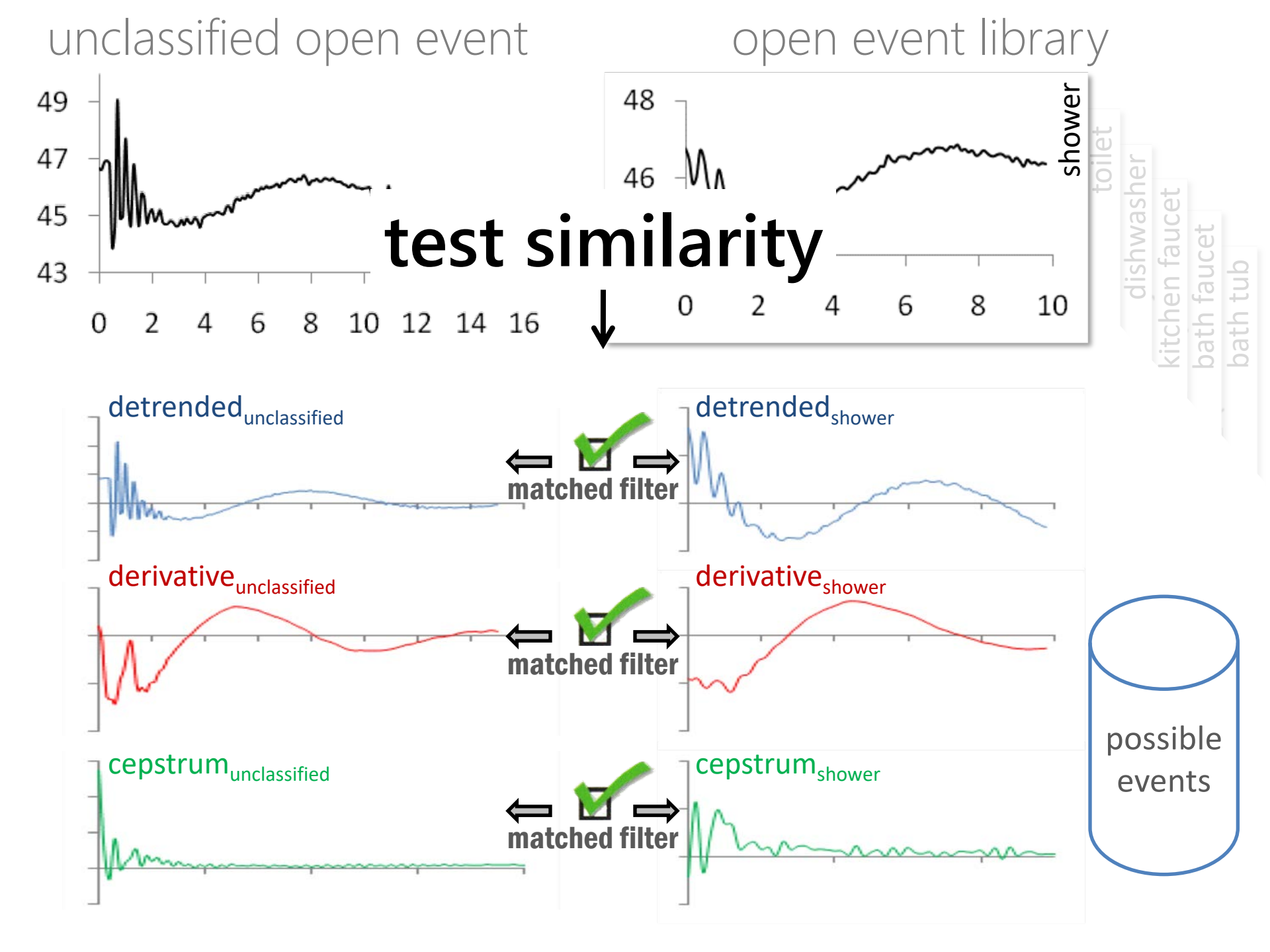


derivative$_{shower}$

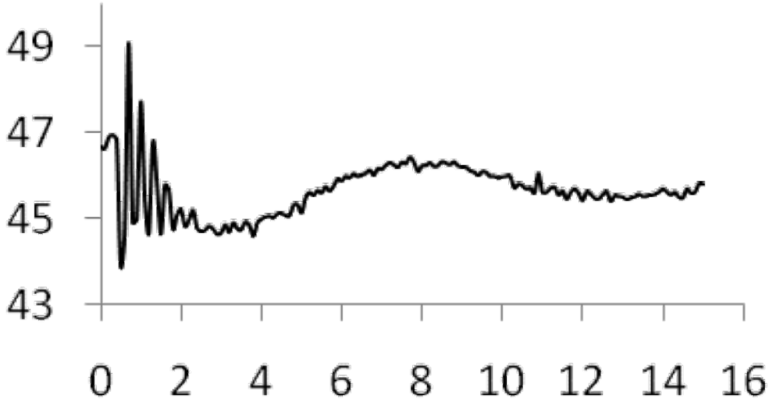


cepstrum$_{shower}$

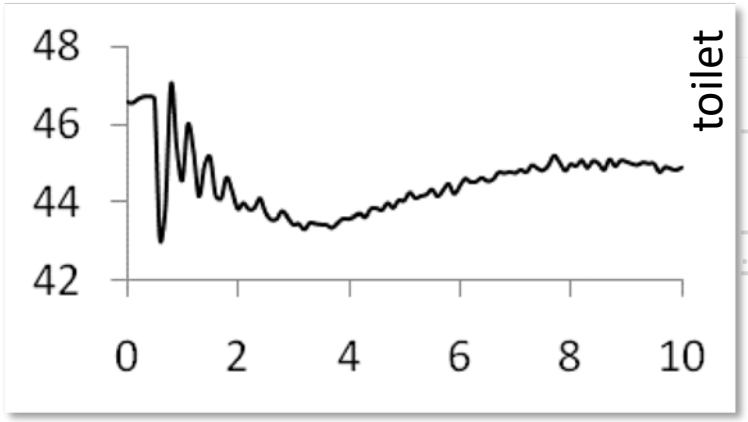


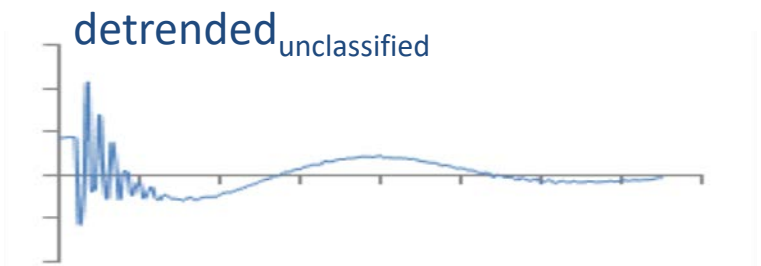

unclassified open event
open event library
49
47
45
43
0 2 4 6 8 10 12 14 16
48
46
shower
0 2 4 6 8 10
toilet
dishwasher
kitchen faucet
bath faucet
bath tub
test similarity
detrended unclassified
detrended shower
matched filter
derivative unclassified
derivative shower
matched filter
cepstrum unclassified
cepstrum shower
matched filter
possible events

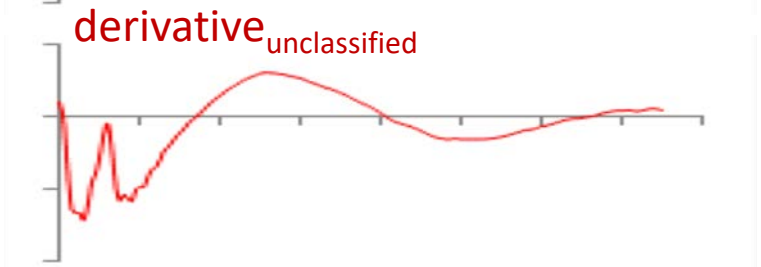
unclassified open event

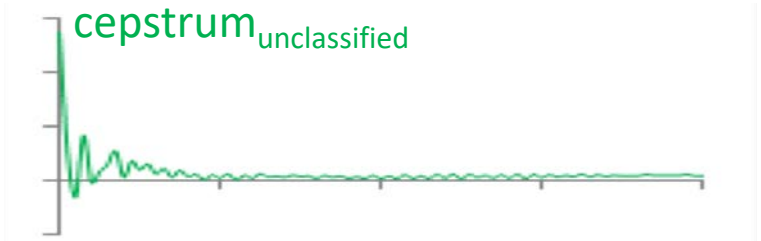


open event library

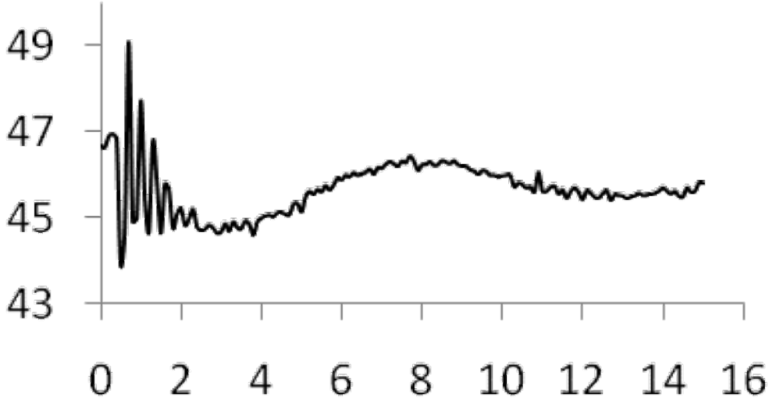




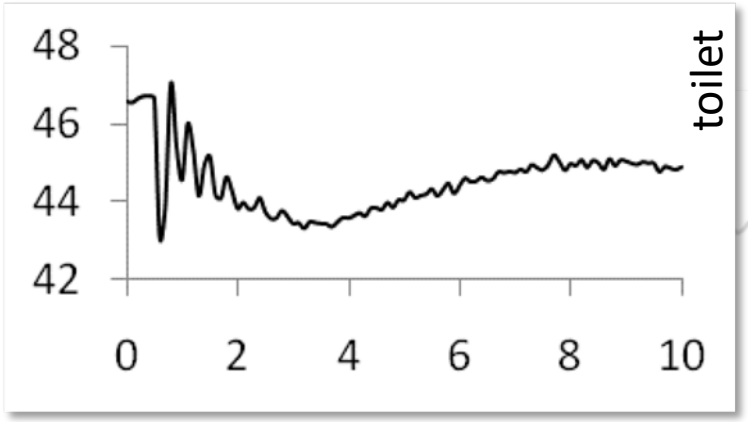




unclassified open event

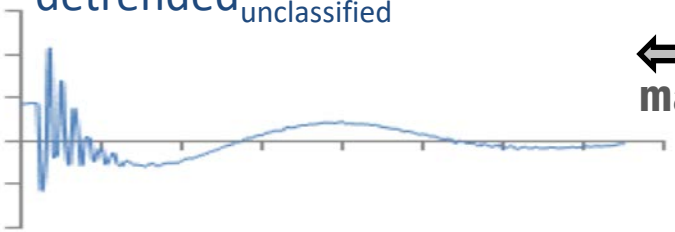


open event library



dishwasher
kitchen faucet
bath faucet
bath tub

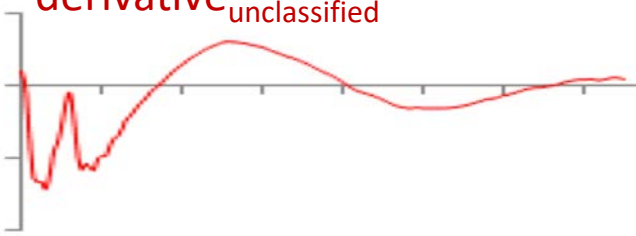
detrended$_{unclassified}$



matched filter

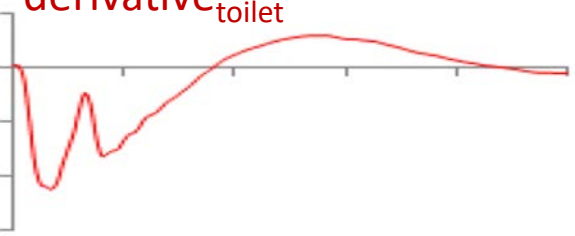
detrended$_{toilet}$

derivative$_{unclassified}$

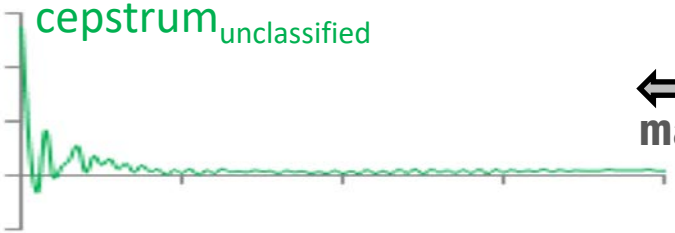


matched filter

derivative$_{toilet}$



cepstrum$_{unclassified}$

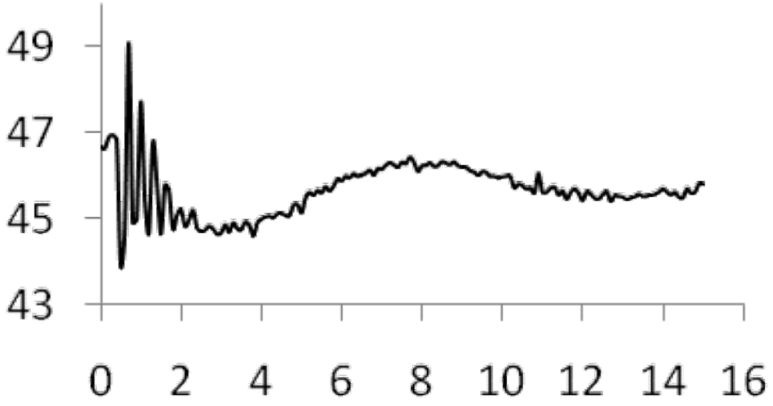


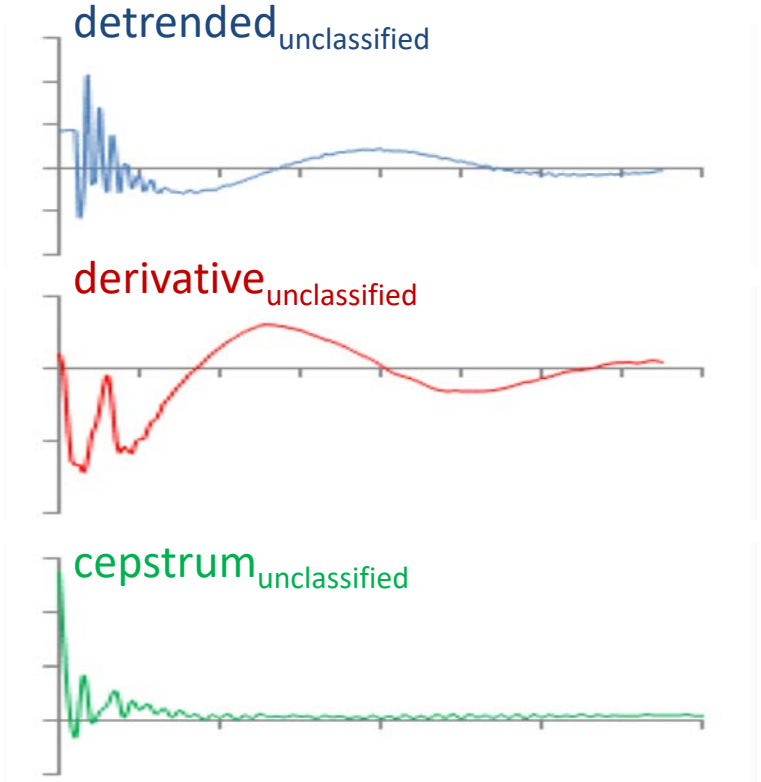
matched filter

cepstrum$_{toilet}$

possible events

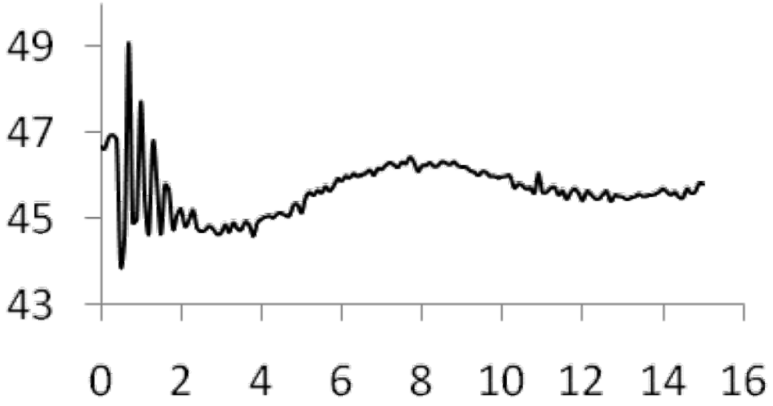
unclassified open event

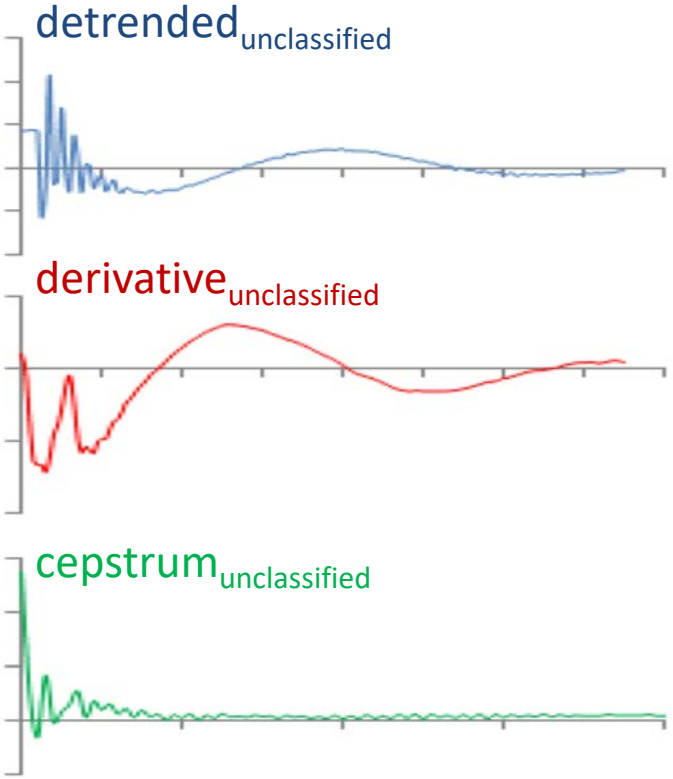




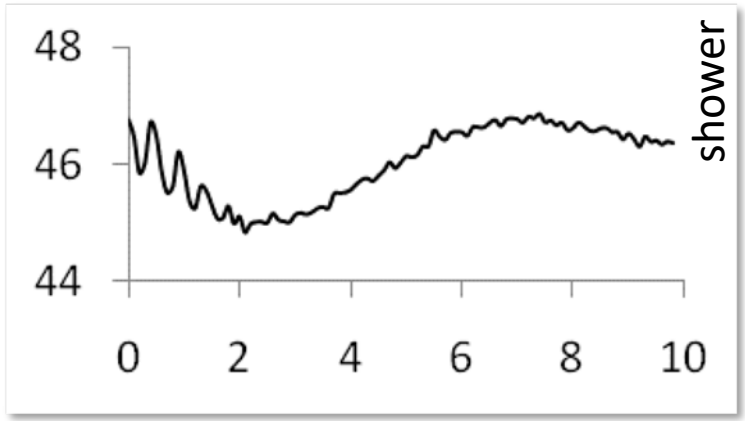
open event library

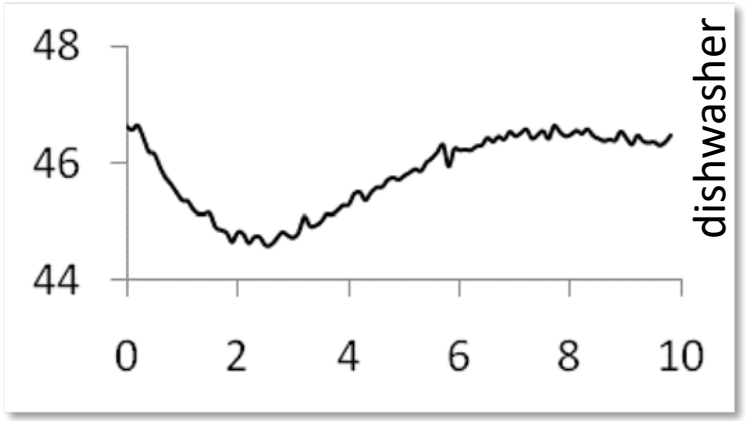
unclassified open event

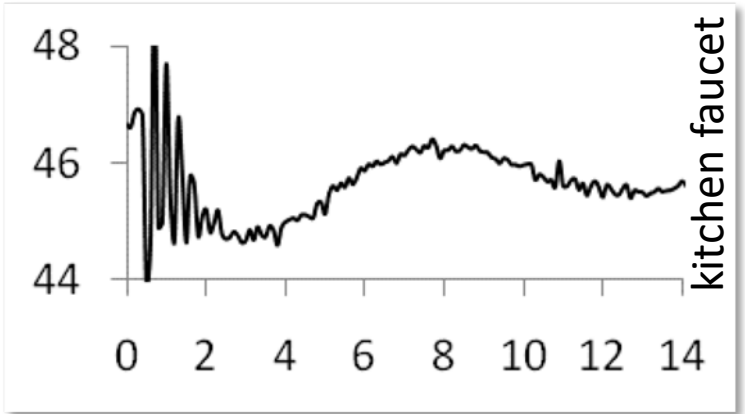




open event library

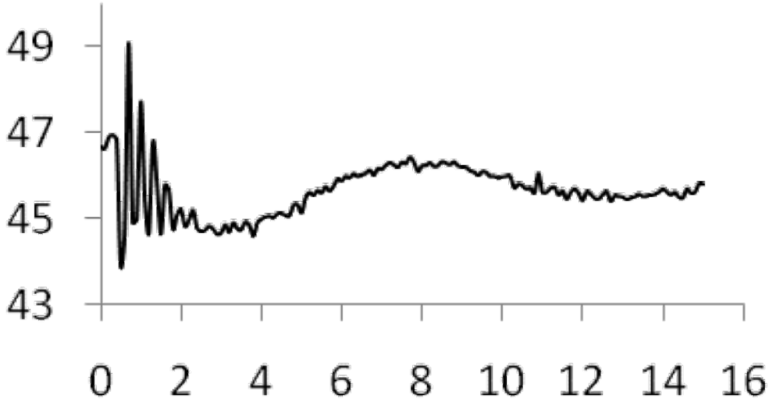


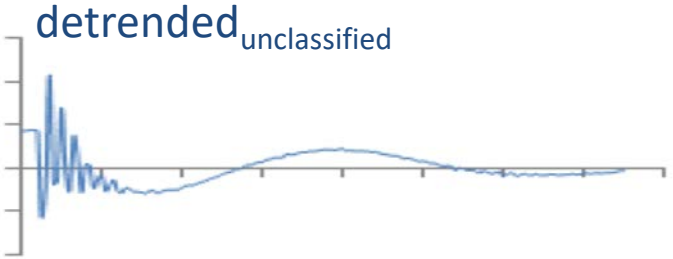


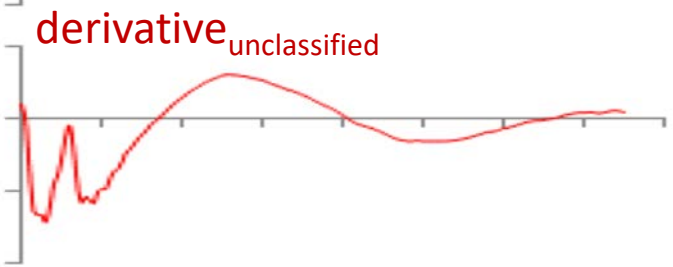


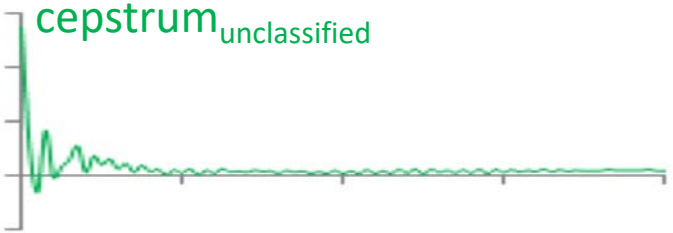
possible events

unclassified open event

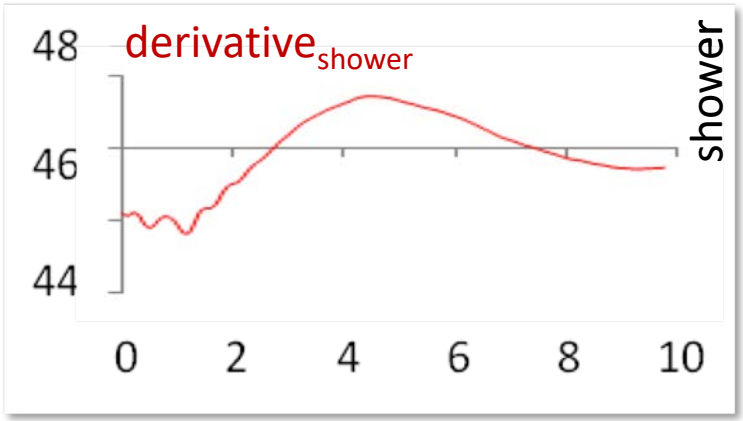


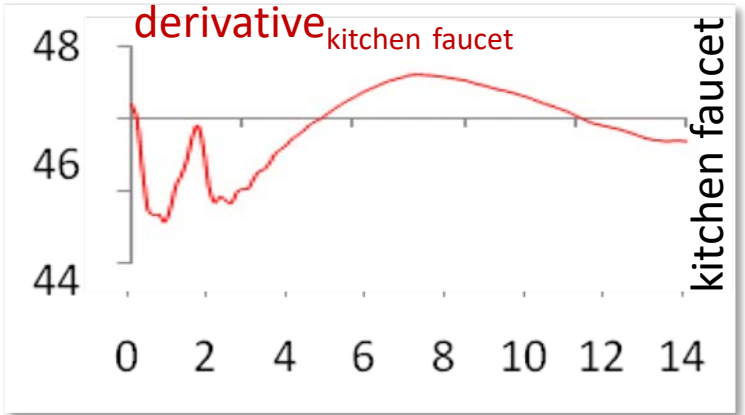






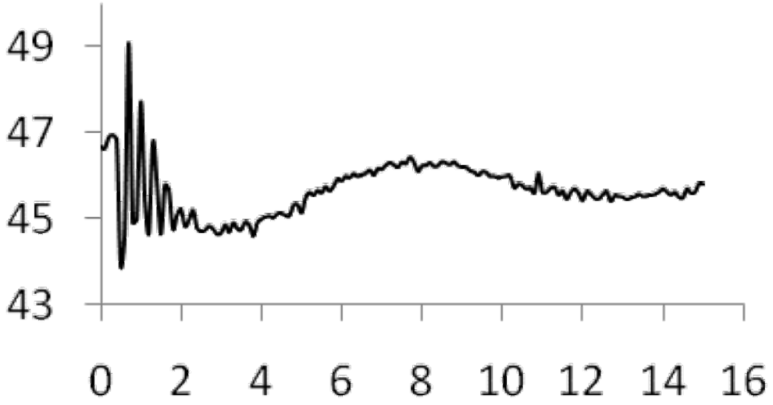
open event library



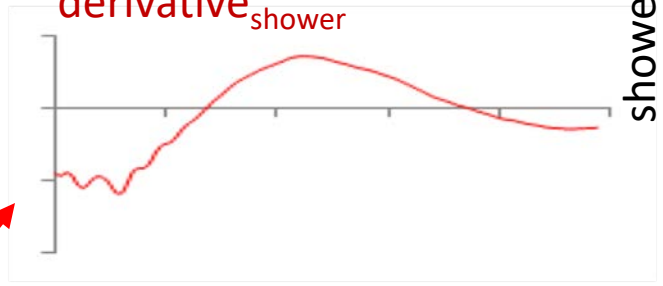


possible events

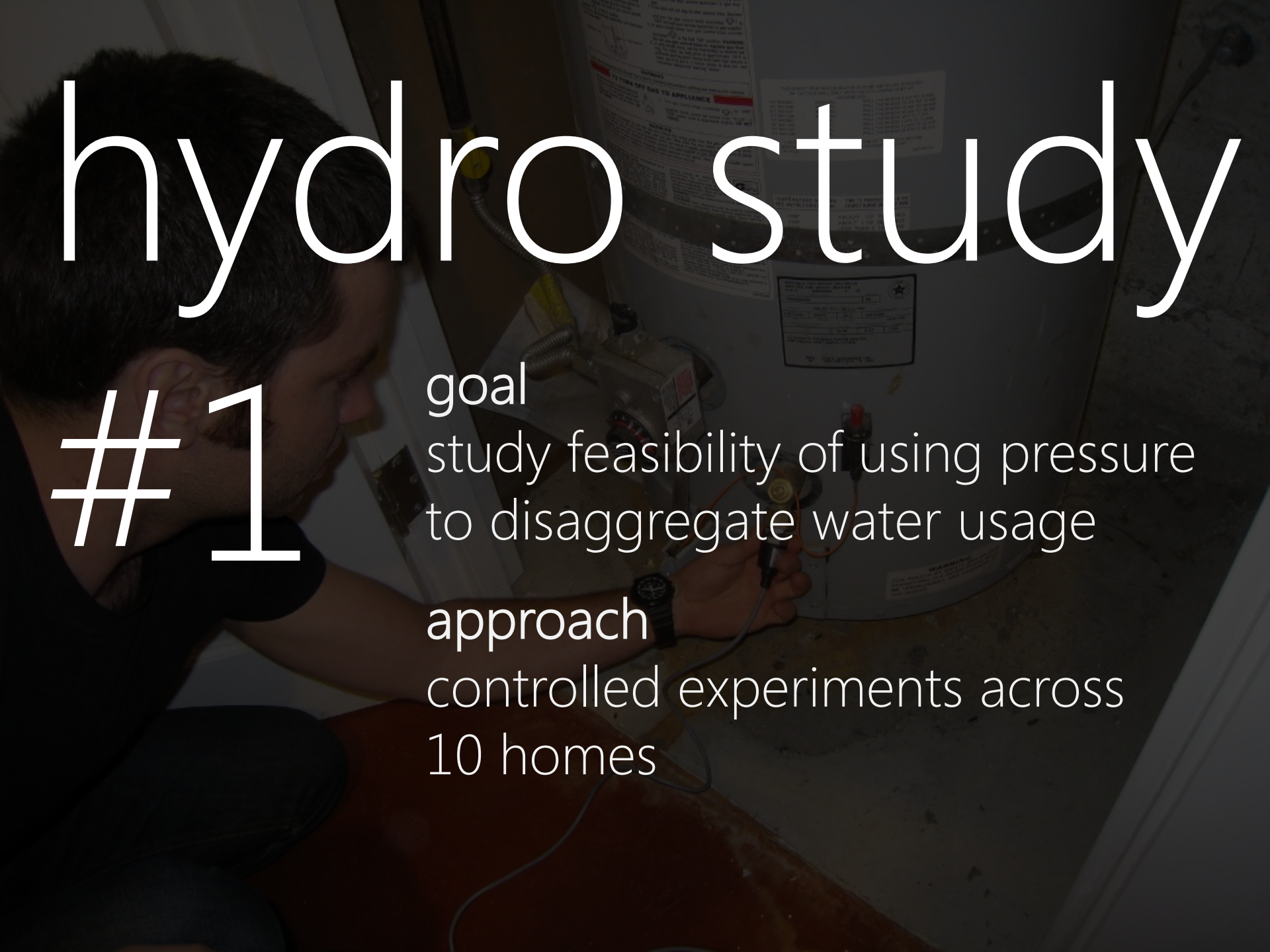
unclassified open event



open event library



nearest neighbor match

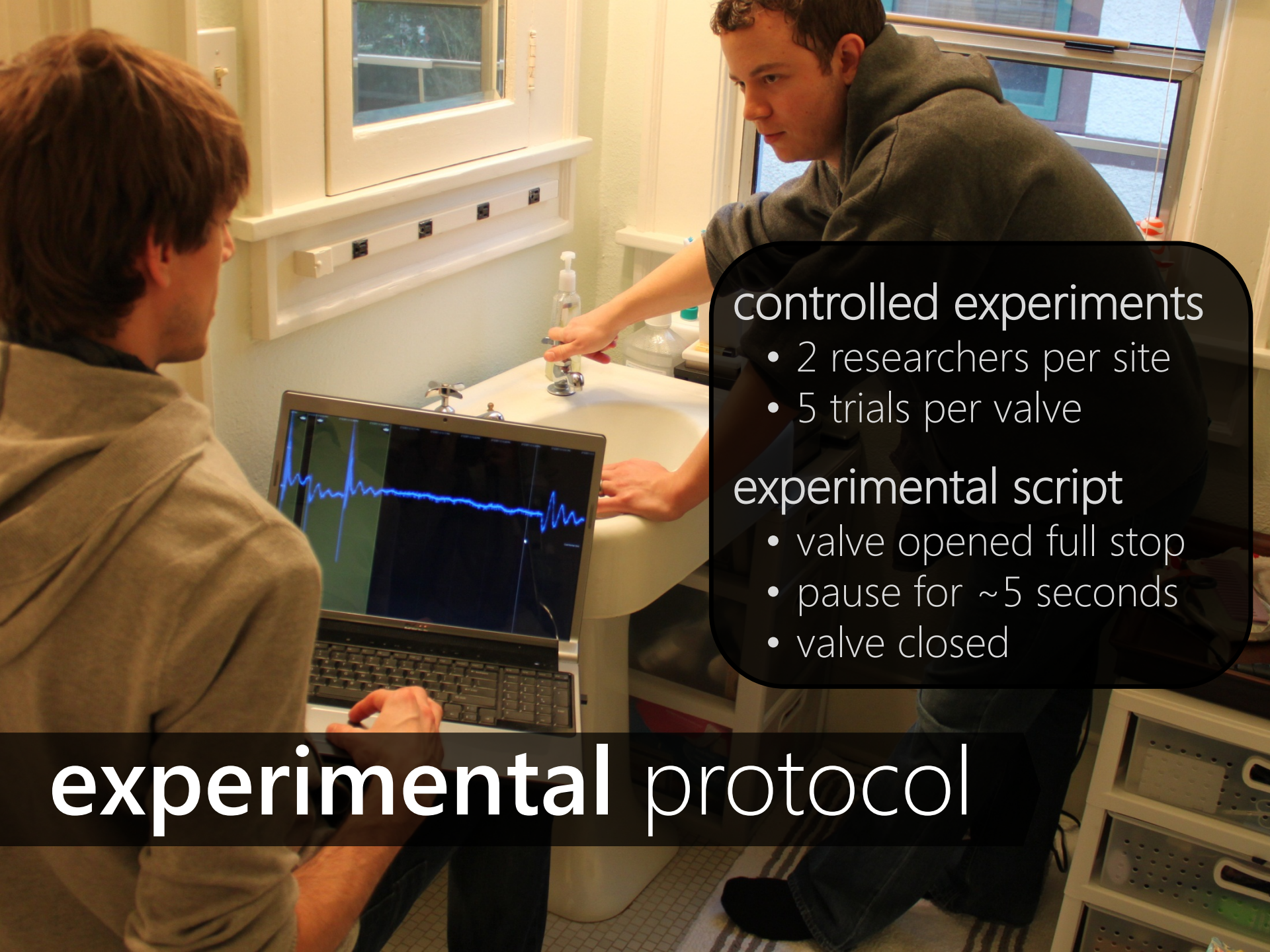


hydro study

#1

goal
study feasibility of using pressure to disaggregate water usage

approach
controlled experiments across 10 homes



controlled experiments

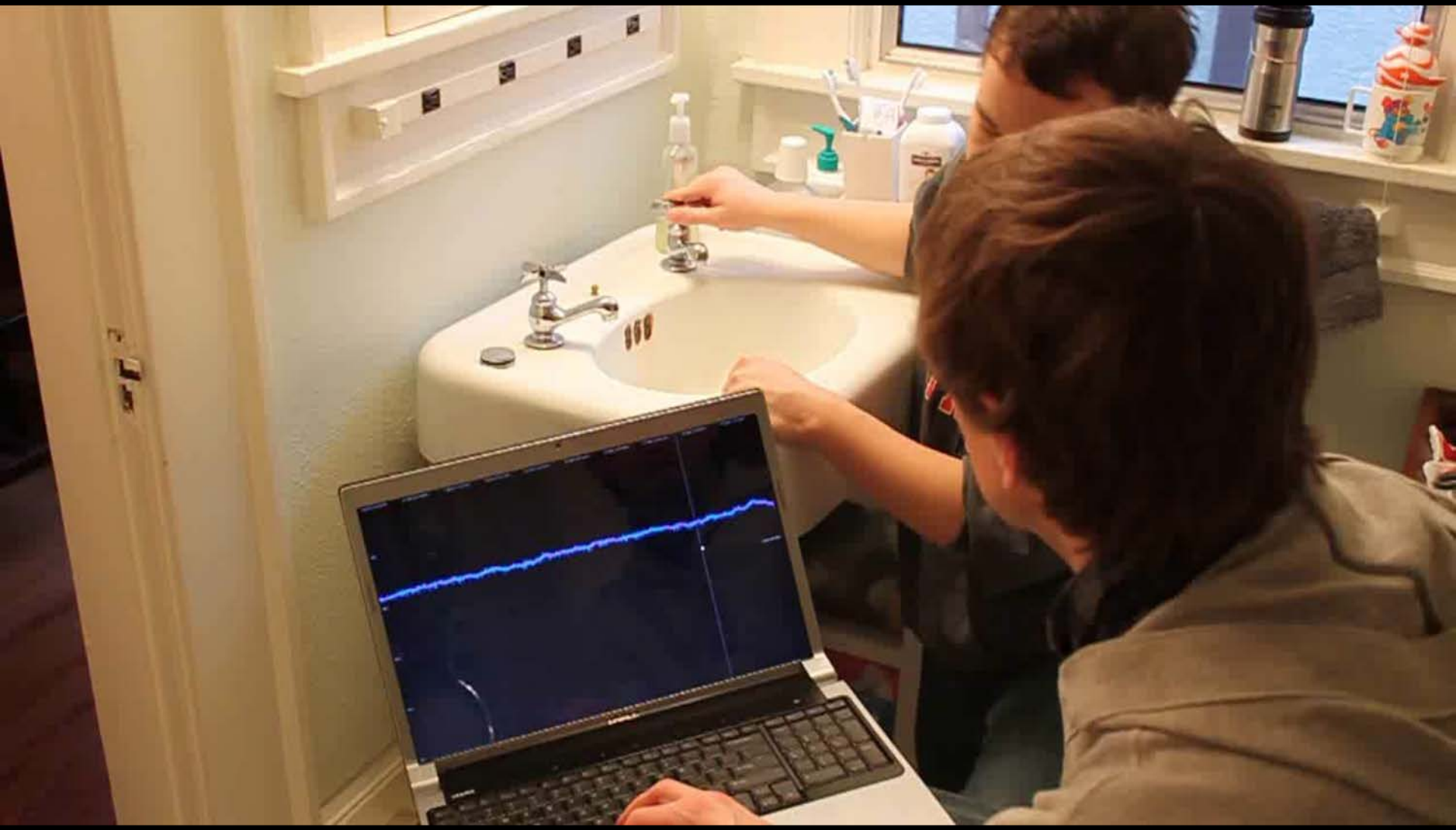
- 2 researchers per site
- 5 trials per valve

experimental script

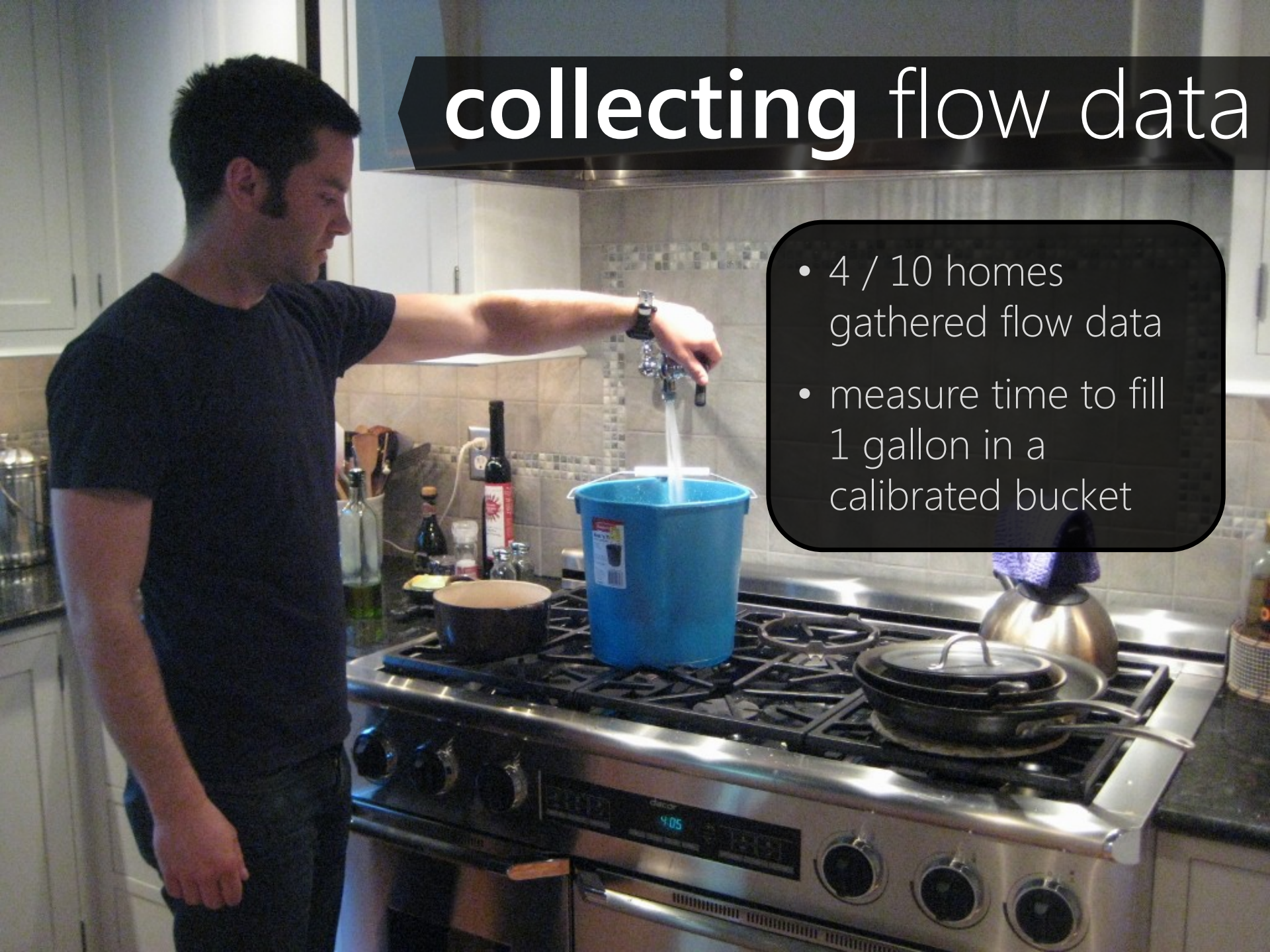
- valve opened full stop
- pause for ~5 seconds
- valve closed

experimental protocol

controlled data collection



collecting flow data



- 4 / 10 homes gathered flow data
- measure time to fill 1 gallon in a calibrated bucket

data collection stats

ten test sites

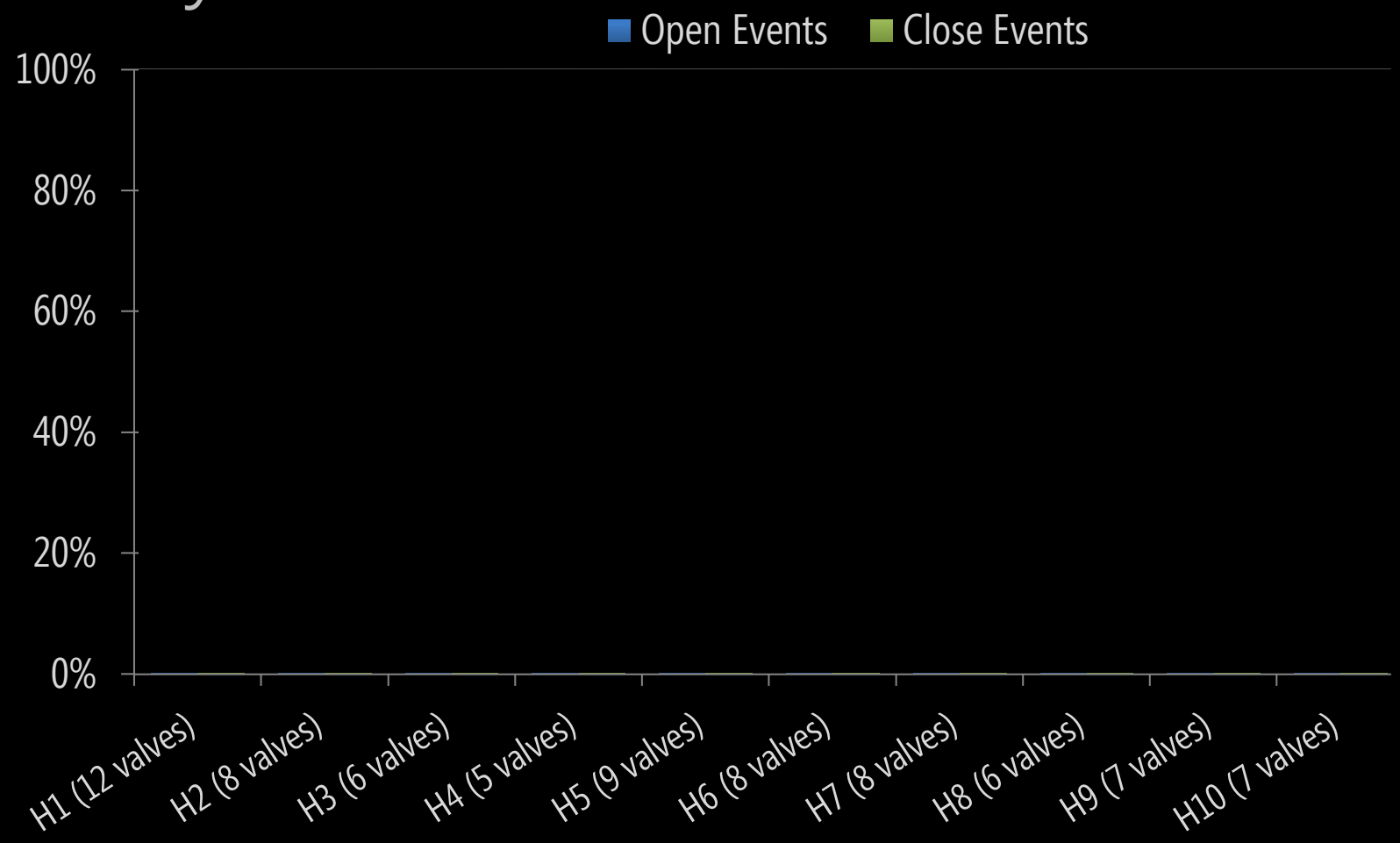
- 706 trials
- 155 flow trials
- 84 total fixtures tested

classification experiments

10-fold cross validation

1. break data into 10 sets of size n/10
2. train on 9 datasets and test on 1
3. repeat for each combination of datasets
4. take mean accuracy

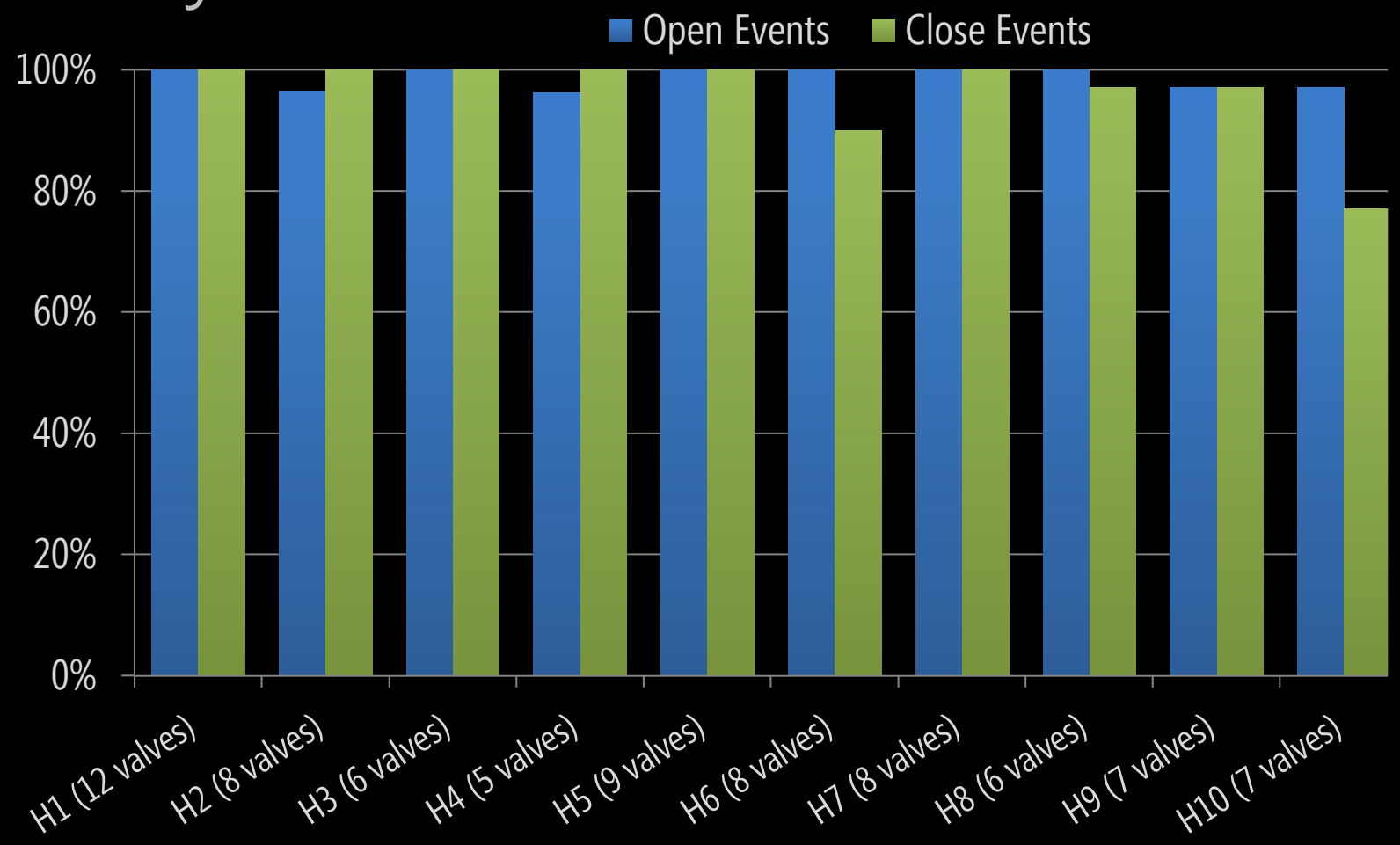
fixture classification results
by home



10-fold cross validation

fixture classification results

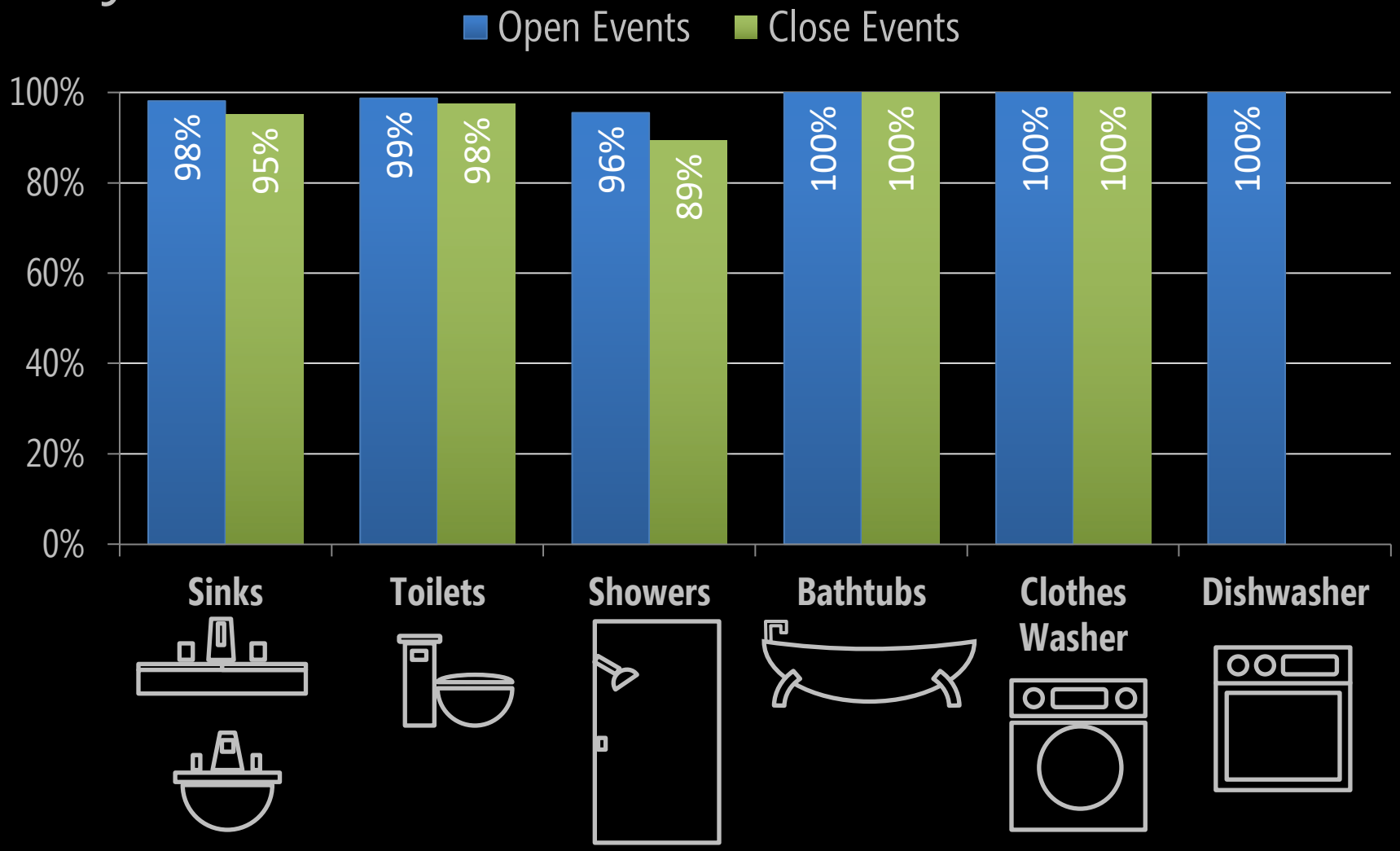
by home



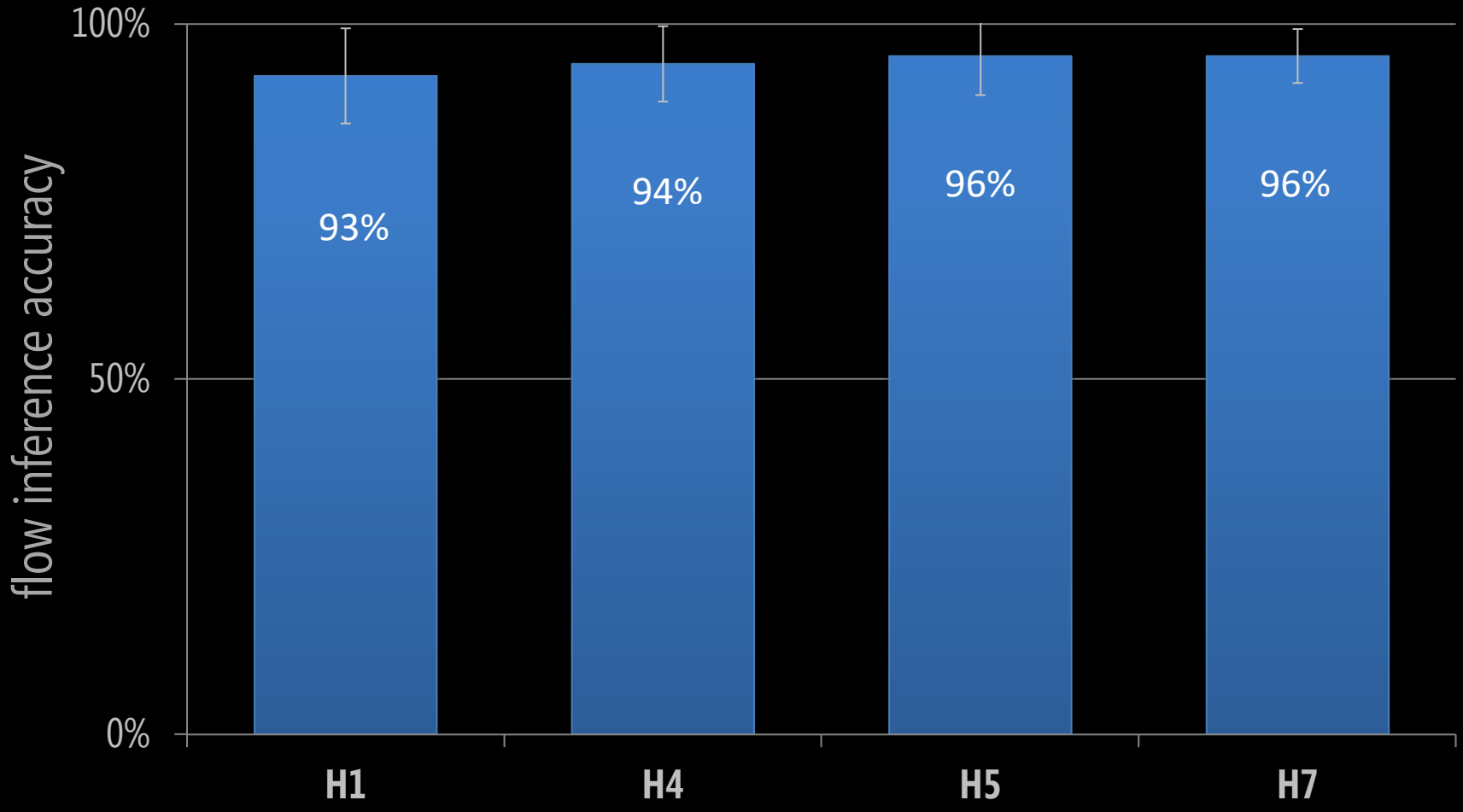
10-fold cross validation

fixture classification results

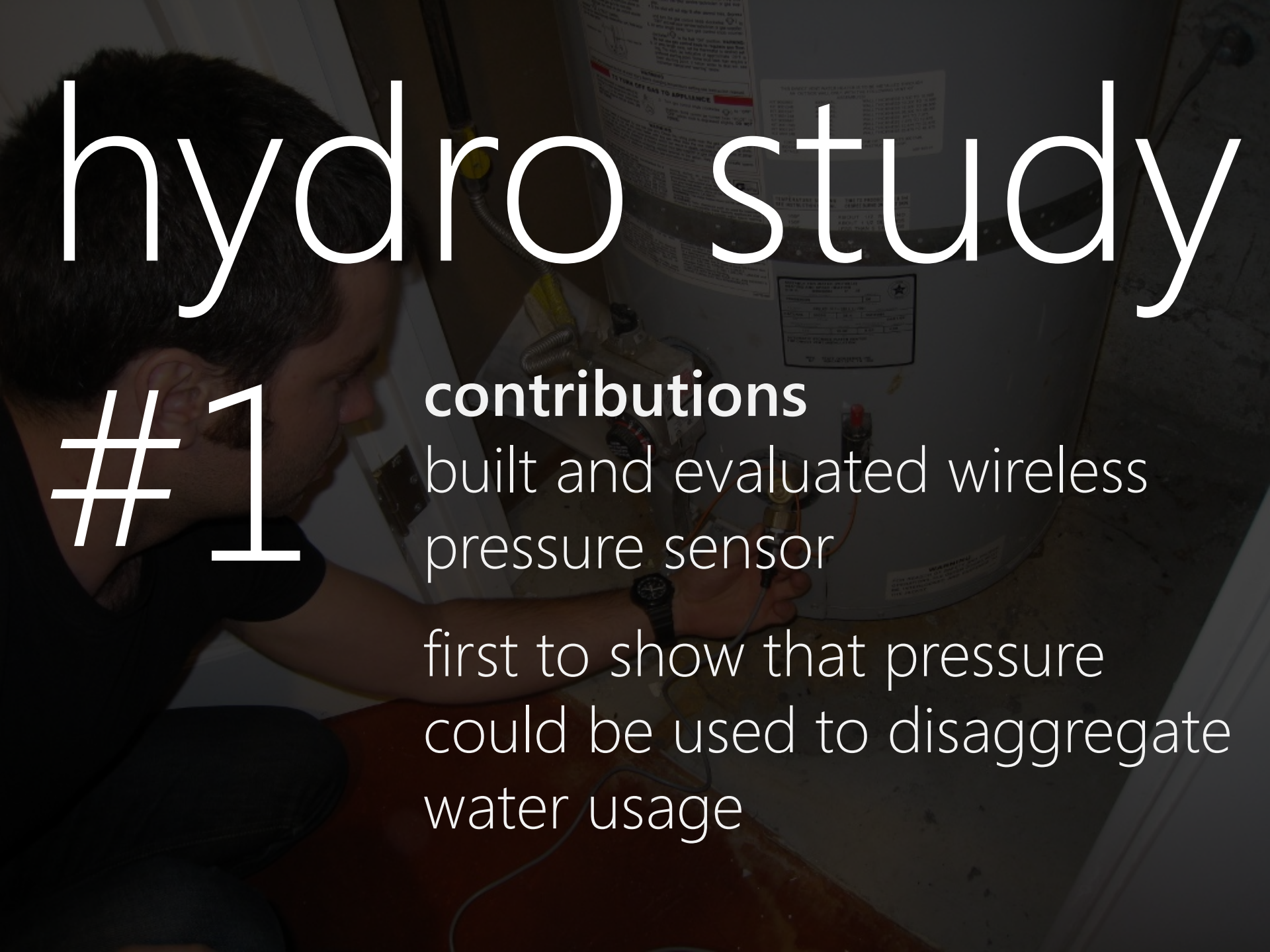
by fixture



flow inference results
by home



Within tolerances of domestic water meter accuracy; see [Arregui, 2003]



hydro study

#1

contributions

built and evaluated wireless pressure sensor

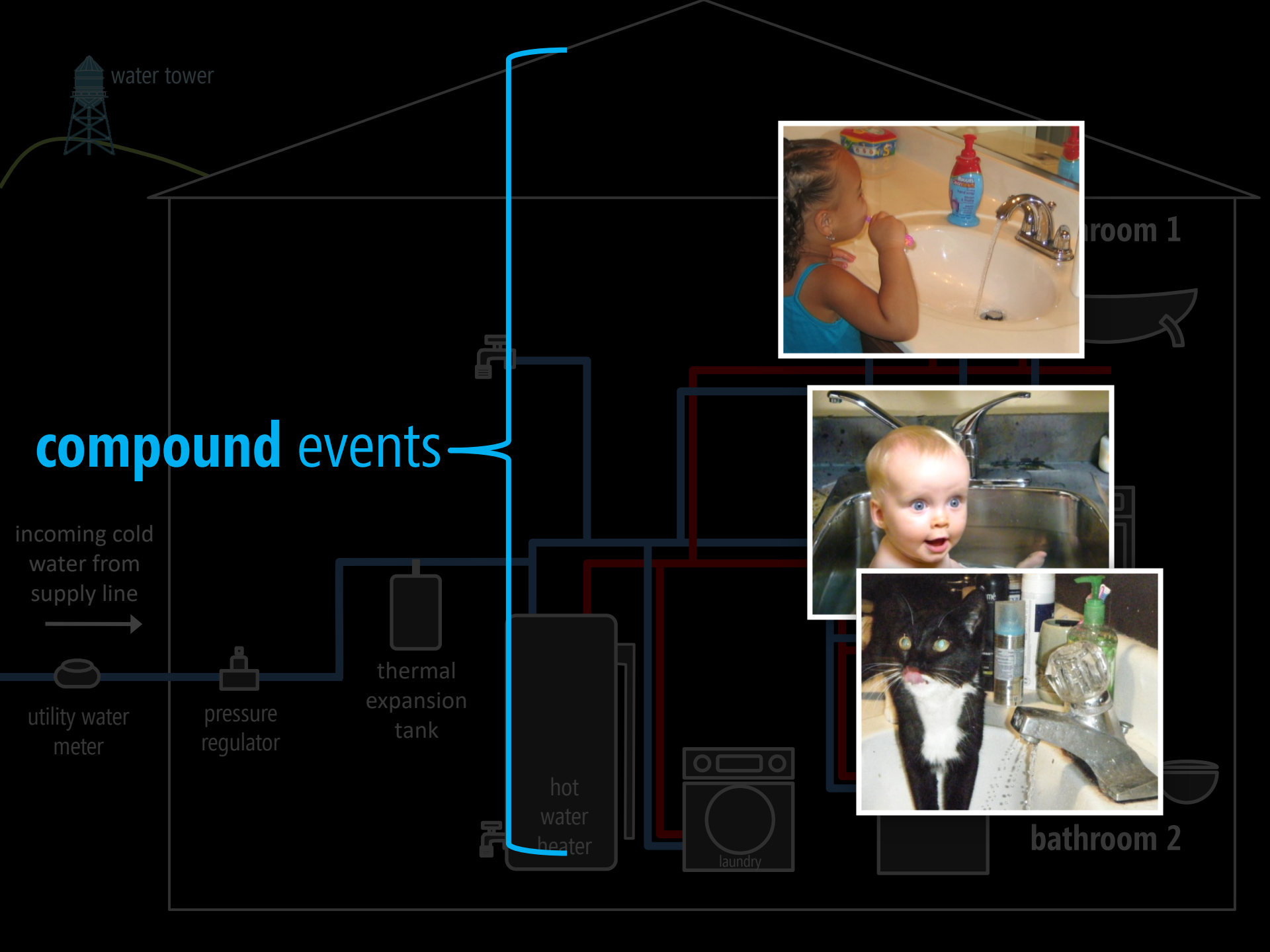
first to show that pressure could be used to disaggregate water usage

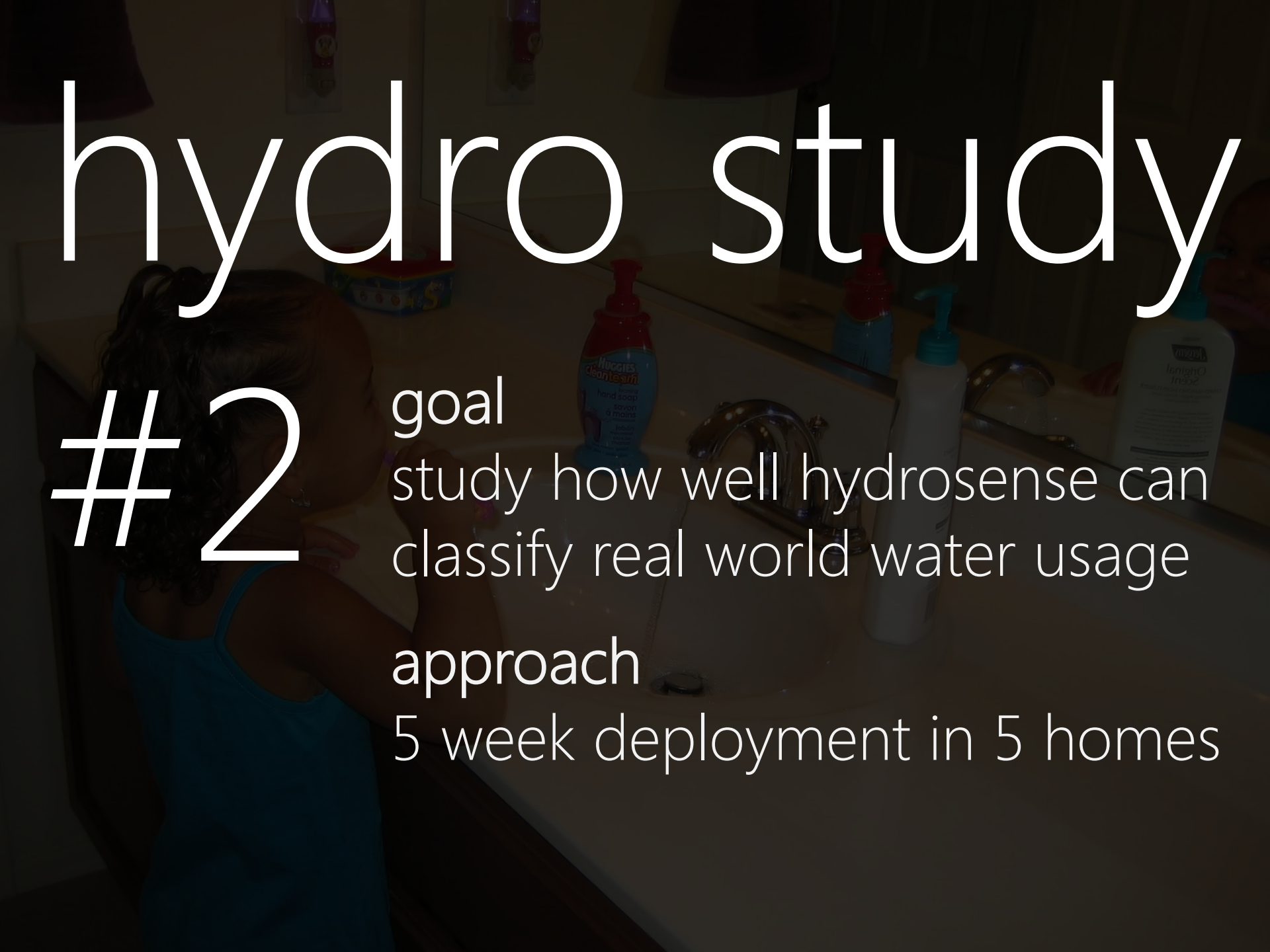

brushing teeth
HUGGIES
hand soap
savon à mains
Original
Scent

shaving


bathing


paw washing


water tower
compound events
incoming cold water from supply line
utility water meter
pressure regulator
thermal expansion tank
hot water heater
laundry
bathroom 2



hydro study #2

goal

study how well hydrosense can classify real world water usage

approach

5 week deployment in 5 homes


in the first study, pressure waves were **manually** annotated with "ground truth labels" describing:
• the fixture used
• the water temperature

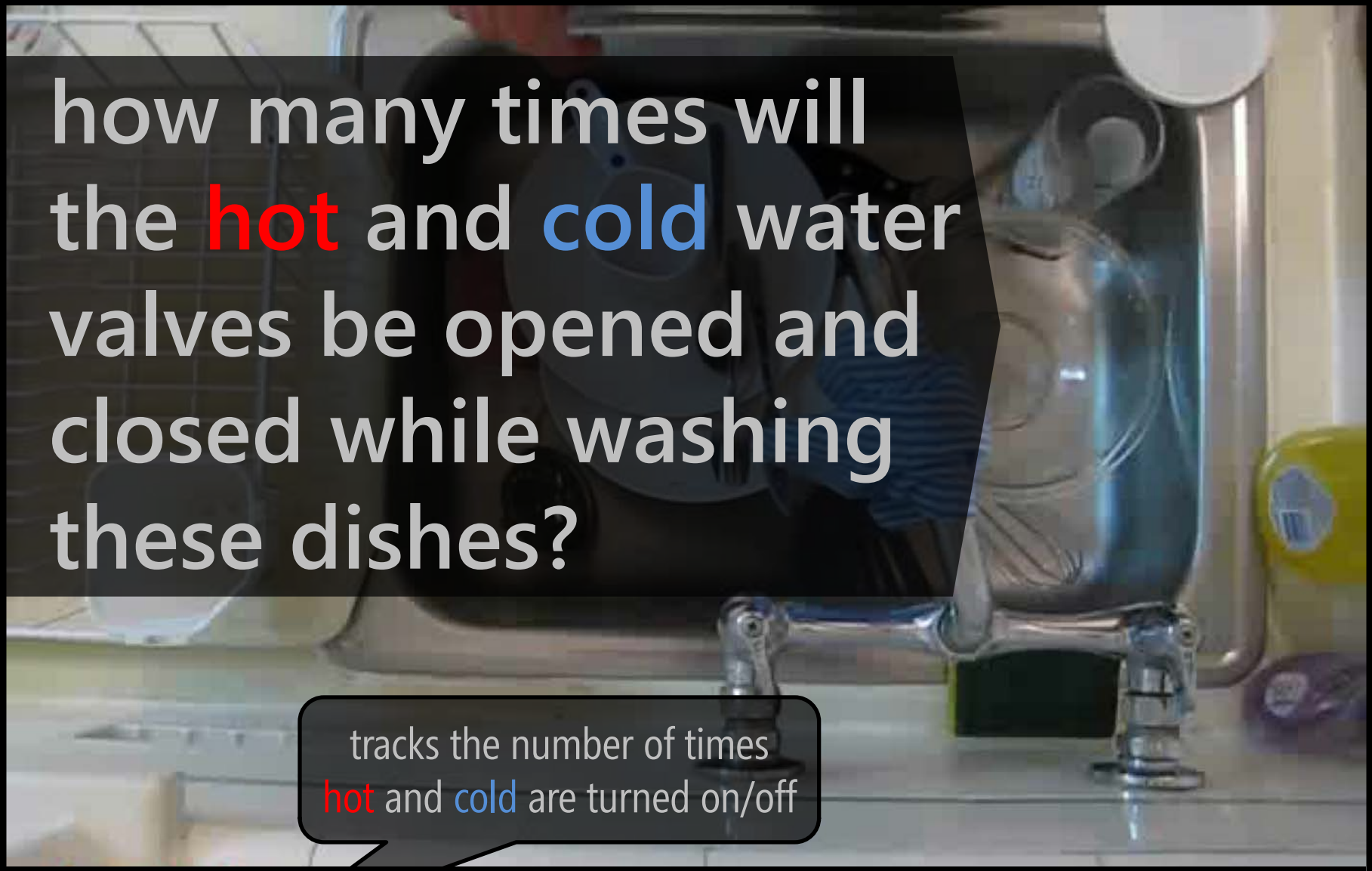

I’m about to flush the toilet!
Awesome! Marked it. Thanks Mr. Johnson

how

collect ground truth labels of

can we record **real-world** water usage?

wireless buttons


how many times will the hot and cold water valves be opened and closed while washing these dishes?
tracks the number of times hot and cold are turned on/off


hot: 0
cold: 0

wireless buttons

other failed solutions

intel labs shake sensors

thermistors

nike+ piezo sensor

Firefox

Can the Nike+iPod Detect Water Facuet ...

www.youtube.com/watch?v=TKhlFs0EBTQ

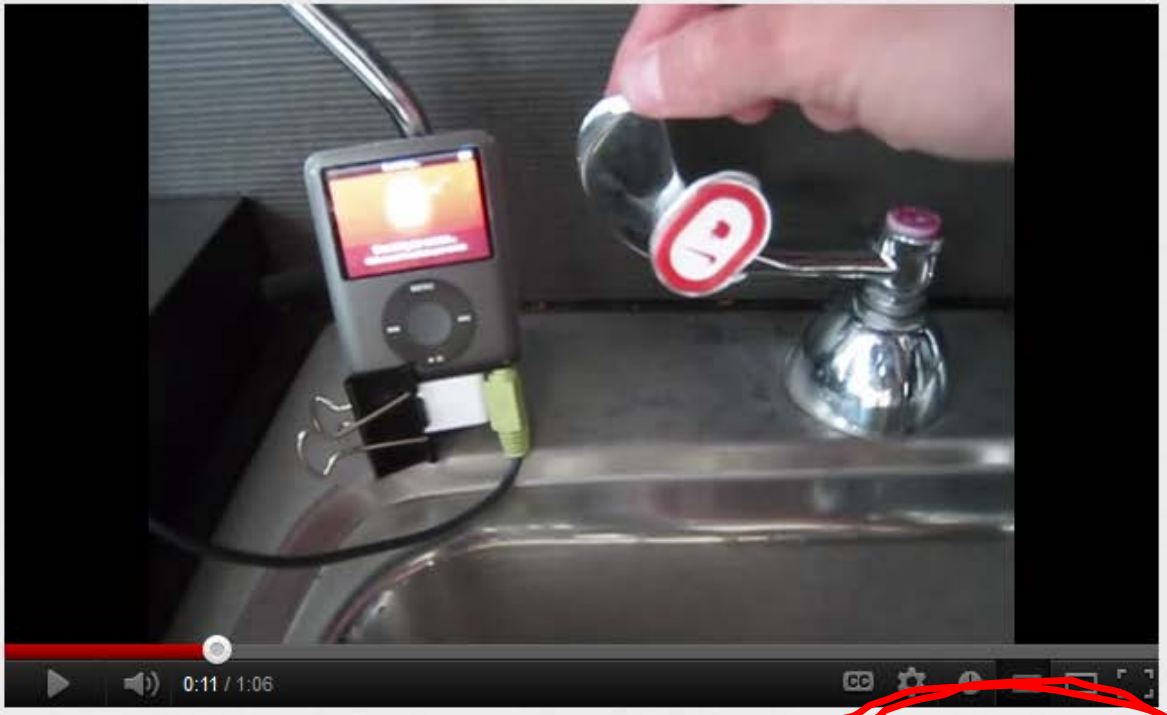
Google

YouTube

Browse | Movies | Upload | Create Account | Sign In

Can the Nike+iPod Detect Water Facuet Handle Movement

jonfroehlich | Subscribe | 6 videos



Like | Share | Download

4,244

0 likes, 16 dislikes

Uploaded by jonfroehlich on Aug 7, 2009

The HydroSense team conducted a set of short, simple experiments investigating whether the Nike+iPod piezoelectric sensor could be used to detect faucet open/close handle movements.

Show more

Top Comments

our solution...


custom
direct
sensors
2.16

automated ground truth labeling method

design goals

hardware capabilities

1. wireless communication
2. low-power
3. water resistant

sensing capabilities

1. work across fixtures/appliances
2. detect opens/closes
3. discriminate hot/cold/mixed

function across fixtures

kitchen sink

bathroom sink

bath

shower

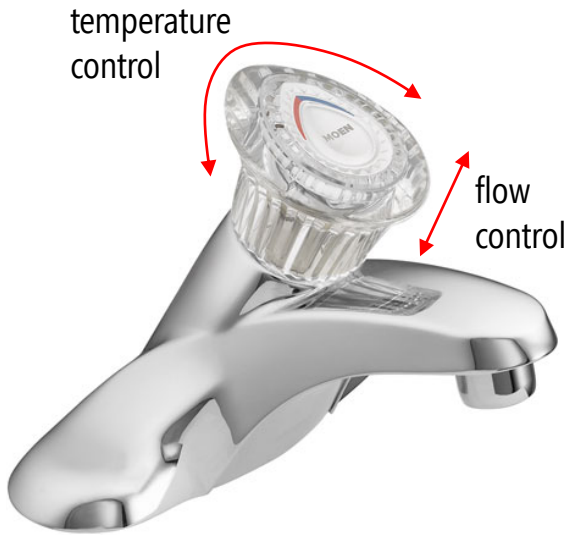
toilet

laundry basin

washing machine

dishwasher

challenge: fixture diversity

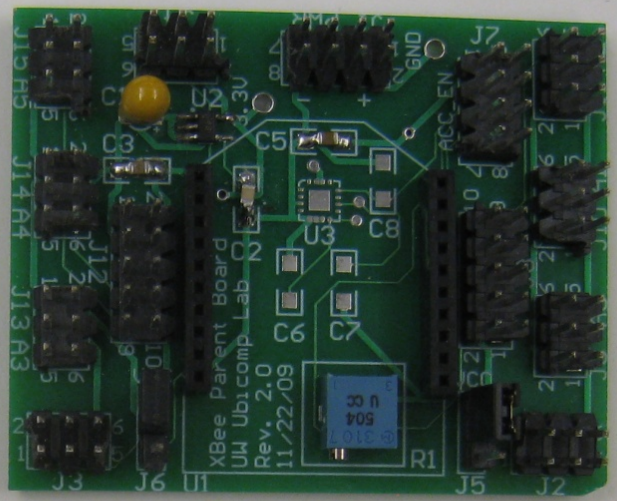


single handle faucet

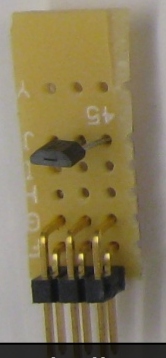
dual handle faucet

custom ground truth data collection system

xbee wireless modem

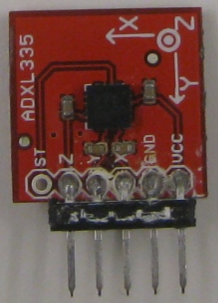


fixture usage sensor board

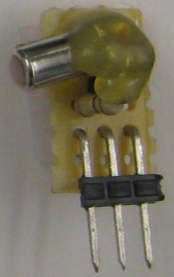


hall effect

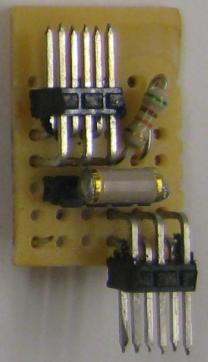
reed switch



3-axis accelerometer



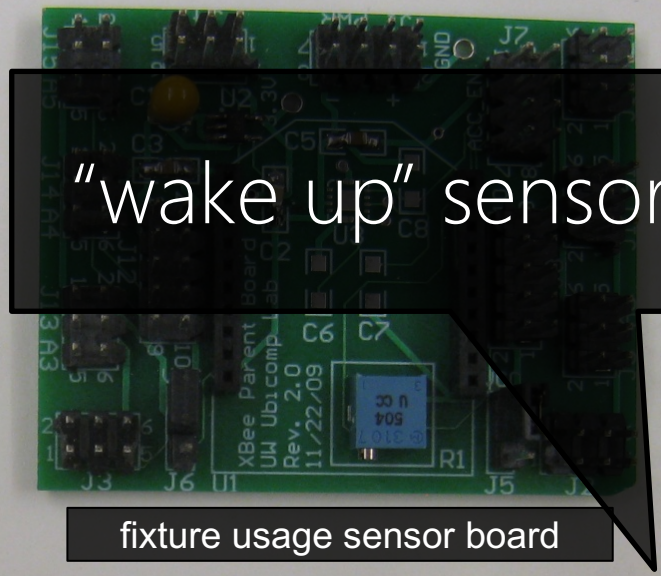
unidirectional ball switch



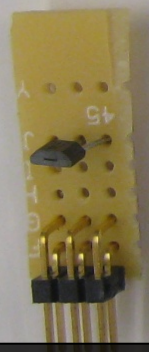
omnidirectional ball switch

custom ground truth data collection system

xbee wireless modem

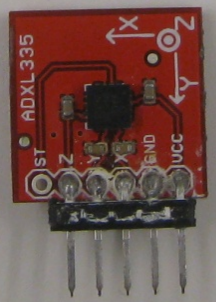


fixture usage sensor board

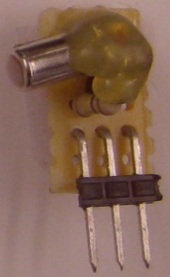


hall effect

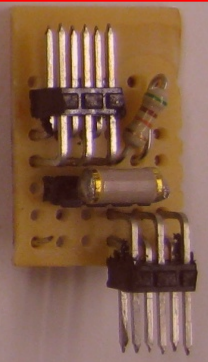
reed switch



3-axis accelerometer

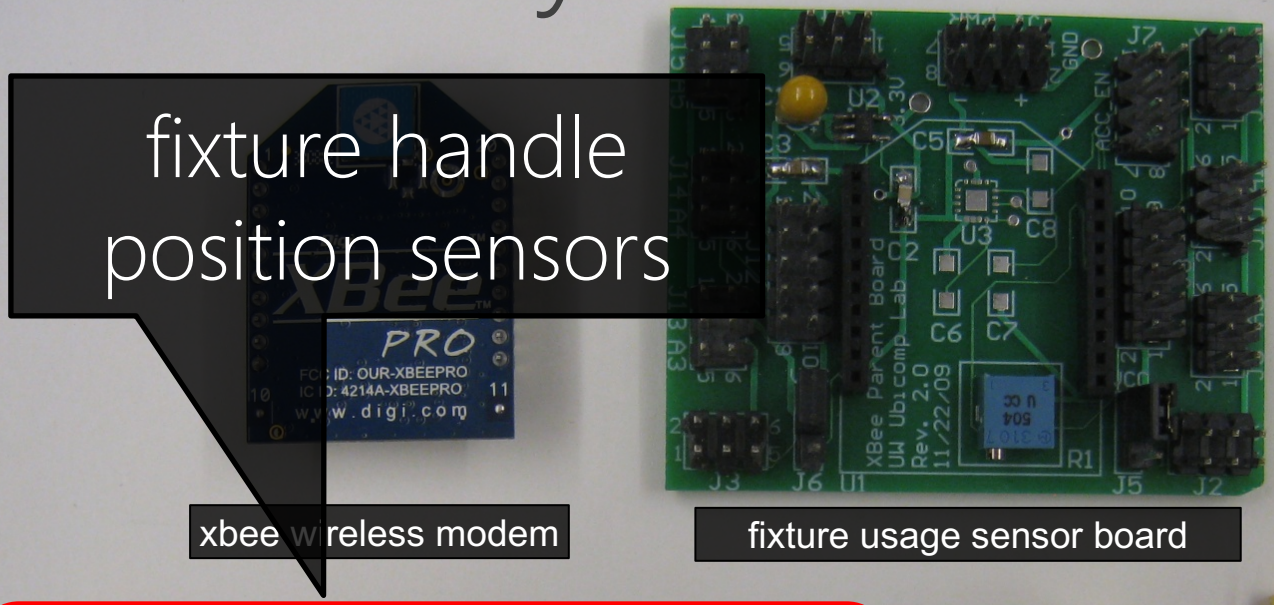


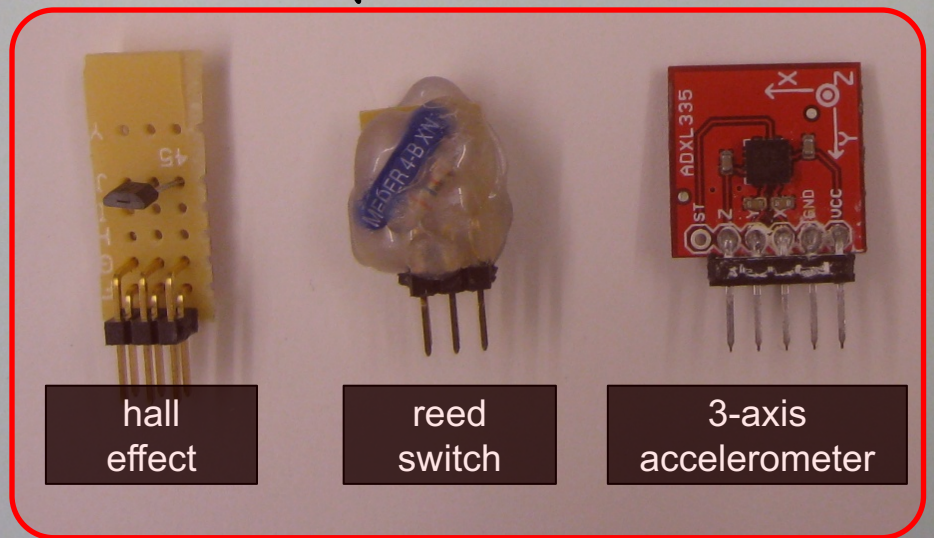
unidirectional ball switch

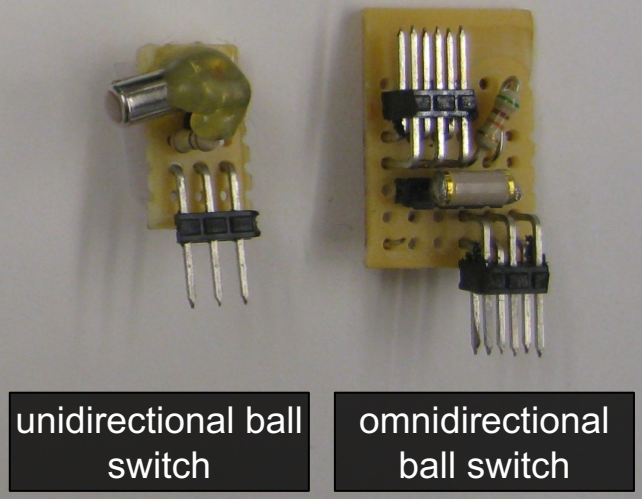


omnidirectional ball switch

custom ground truth data collection system

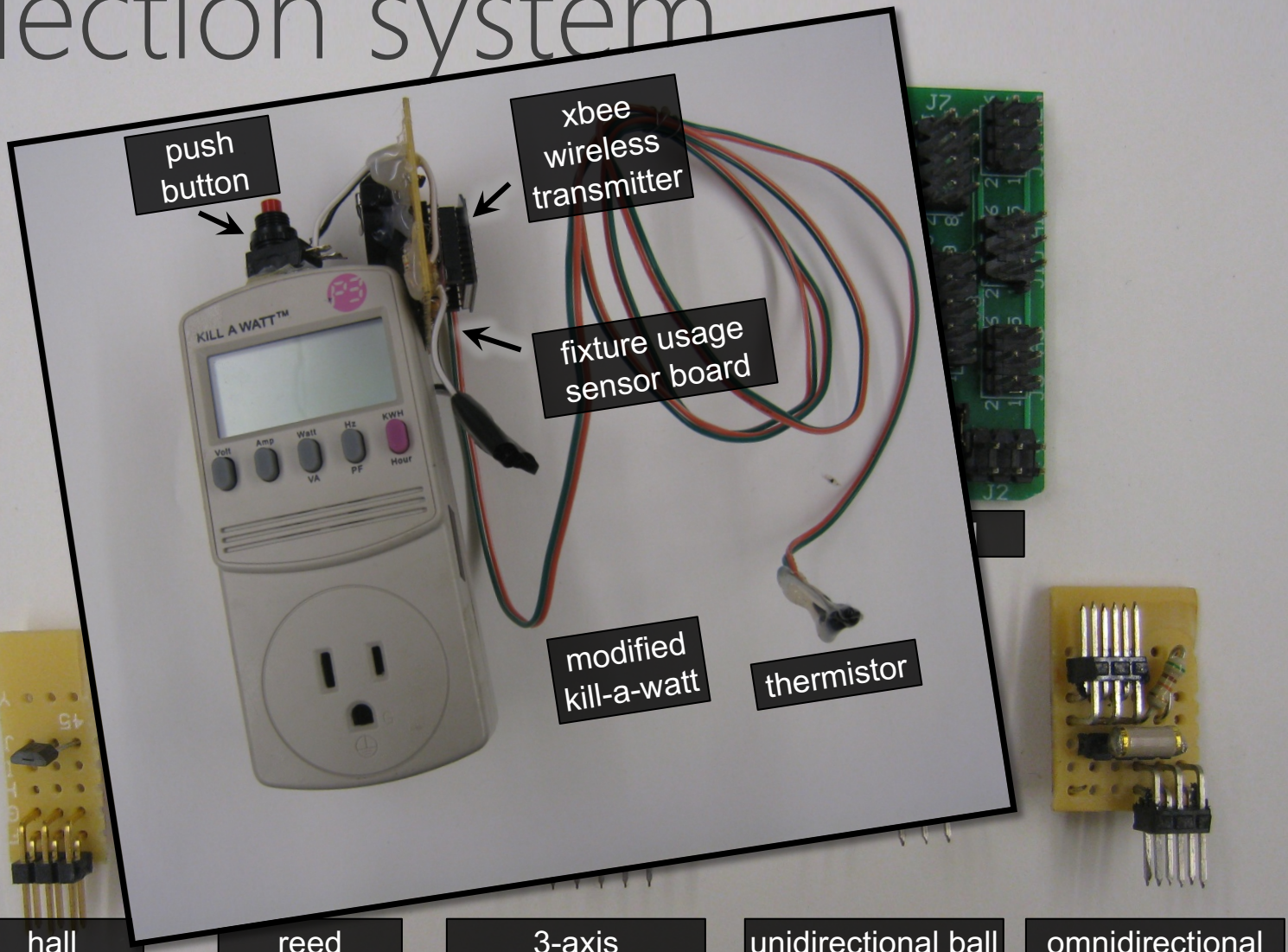







accelerometer
Accelerometer
& Ball Switch
Taped on

custom ground truth data collection system



hall effect

reed switch

3-axis accelerometer

unidirectional ball switch

omnidirectional ball switch

deployment sites

					
residents	2	2	4	2	2
size	3000 sqft	750 sqft	1200 sqft	700 sqft	750 sqft
floors	3	2	2	3rd flr	6th flr
fixtures	17	8	13	8	8
valves	28	13	21	13	13





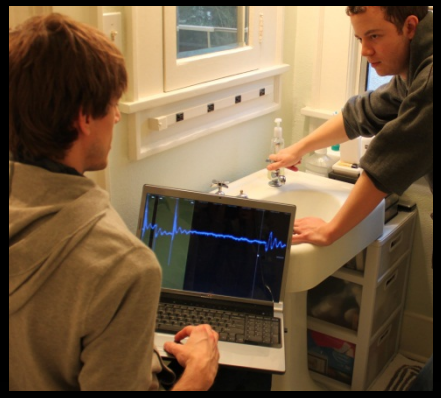


DELL


HOT
COLD

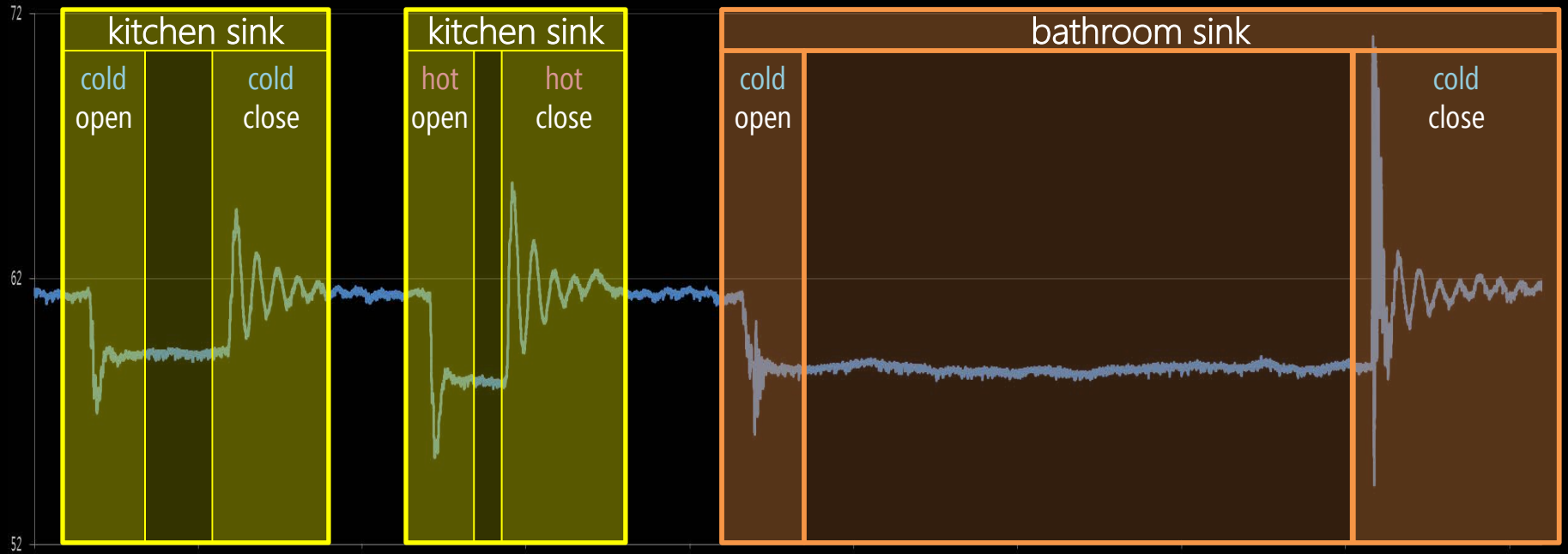

PB32
XBee
PULL KNOB TO START-PUSH TO STOP
XTRA RINSE
SET
COTTONS
REGULAR
PERMANENT PRESS
KNITS
PERMANENT
PRESS
DELICATES
LIGHT SOIL
MEDIUM
HEAVY
POWER WASH
30 MIN
AUTO SOAK
vy Duty Super Capacity
= RINSE
= EXTRA RINSE
= SPIN

ground truth labels

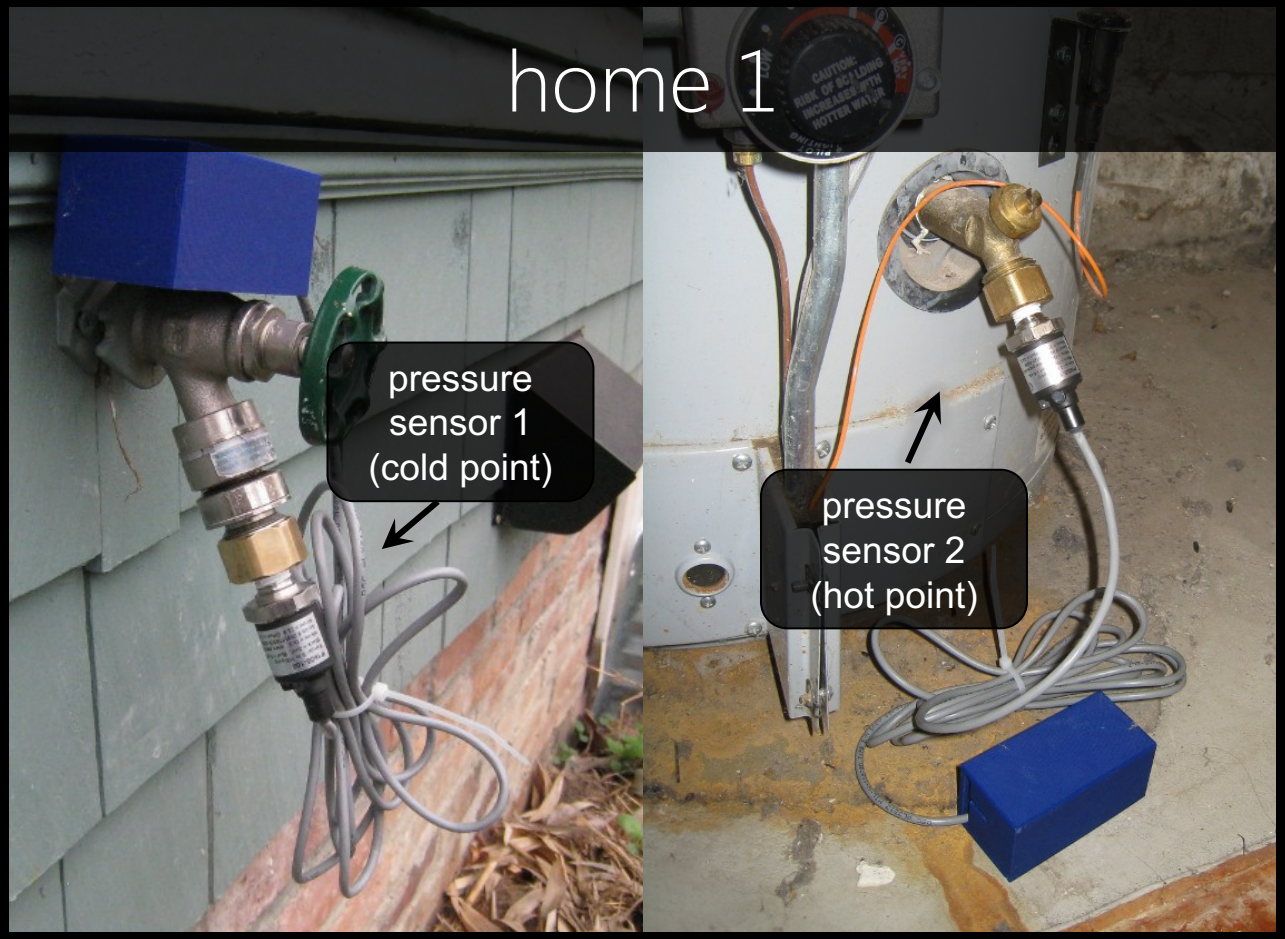


manual

automatic

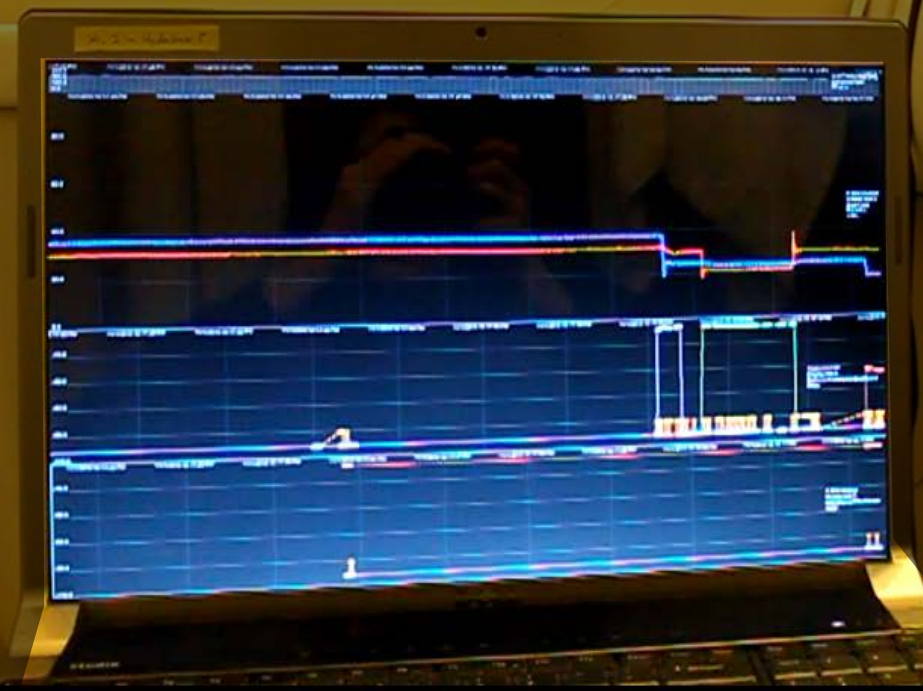


two pressure sensors per home



hydrosense data logger

records ground truth sensor data plus
two pressure streams for each home

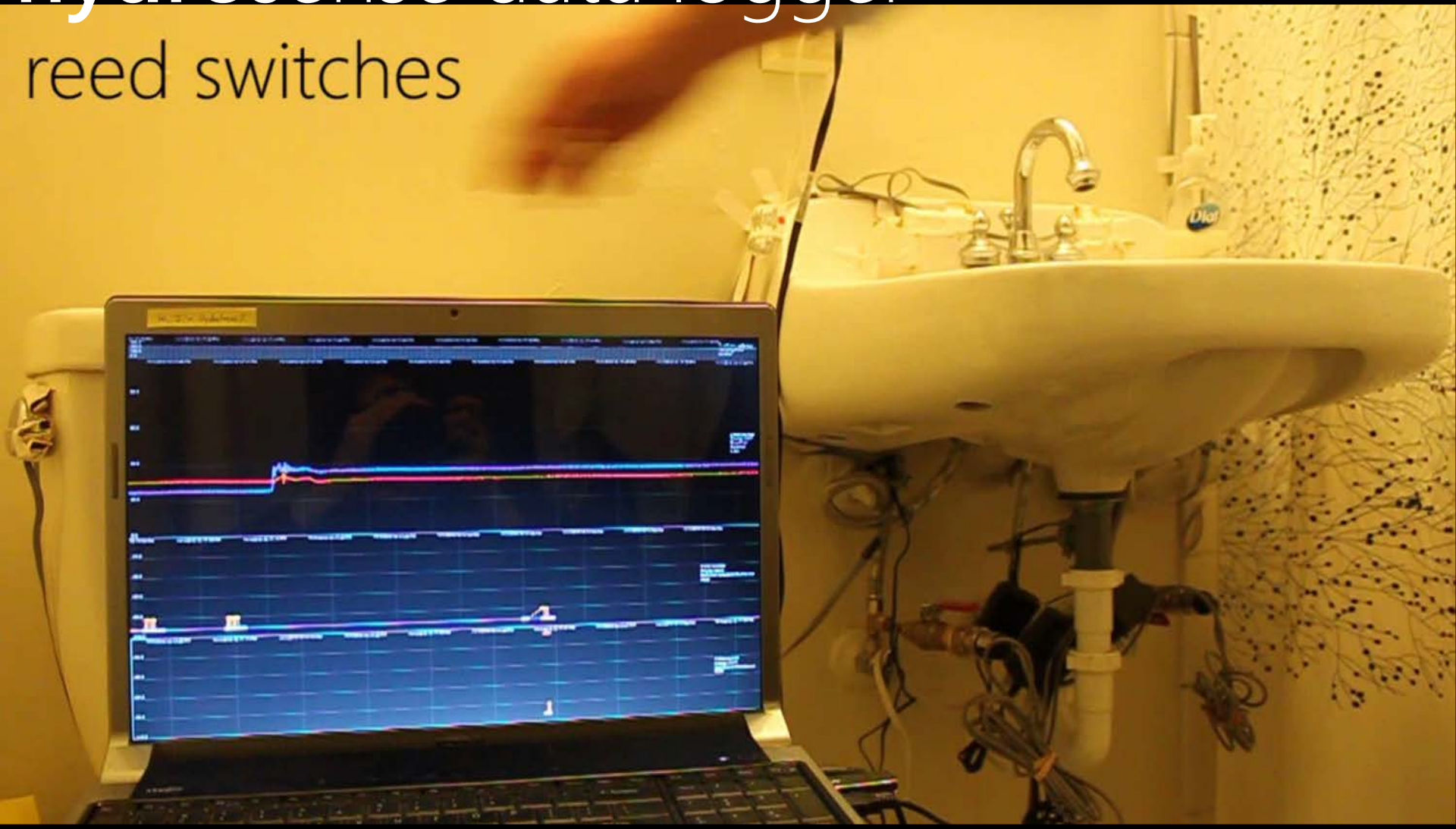


pressure stream
red = hot line
blue = cold line

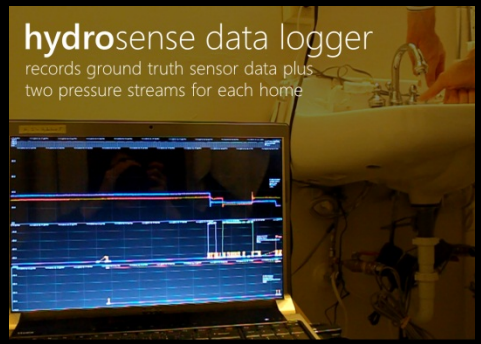
reed switches
high = active
low = inactive

hydrosense data logger

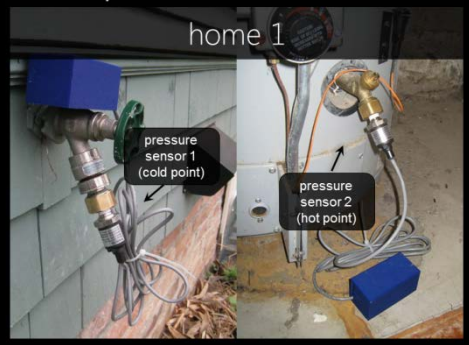
reed switches



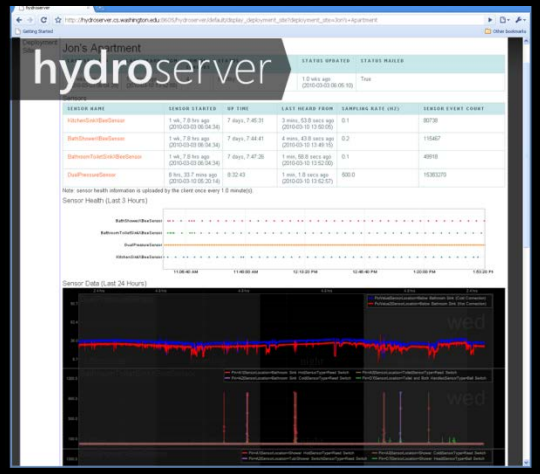
hydro deployment infrastructure



two pressure sensors

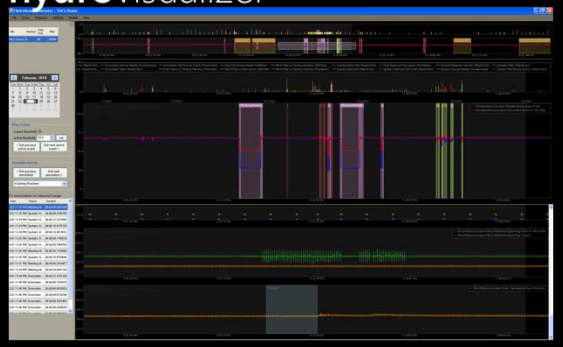


on-site sensing infrastructure

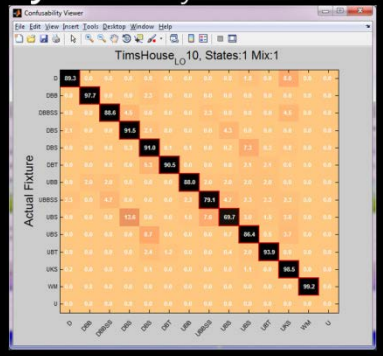


python web backend

hydrovisualizer



hydroanalyzer



c# and matlab analysis tools

hydrosense annotations

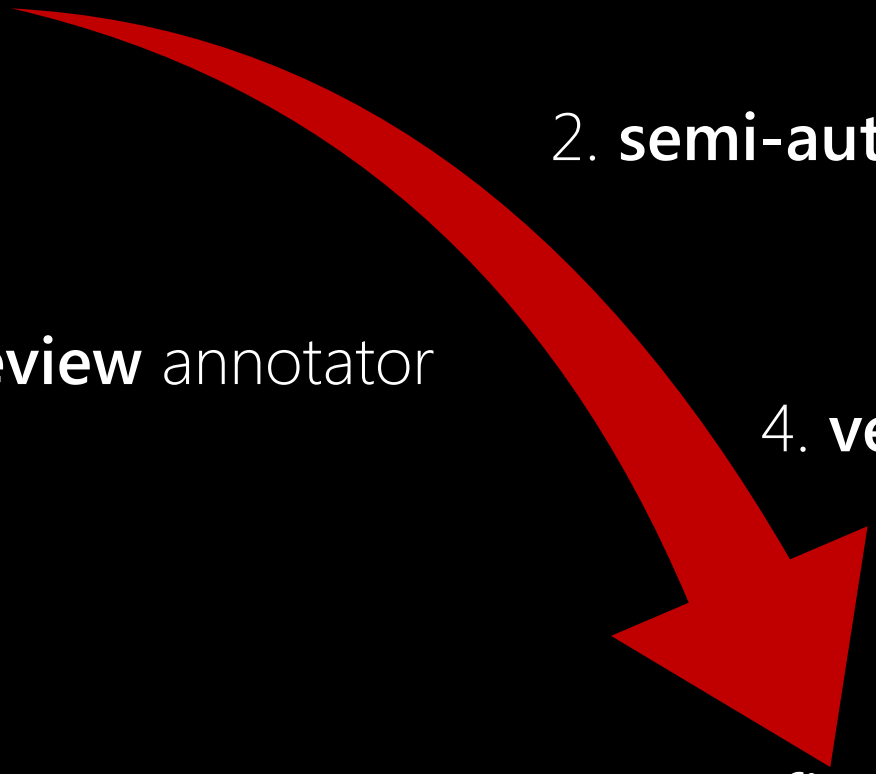
1. **ground truth** sensor

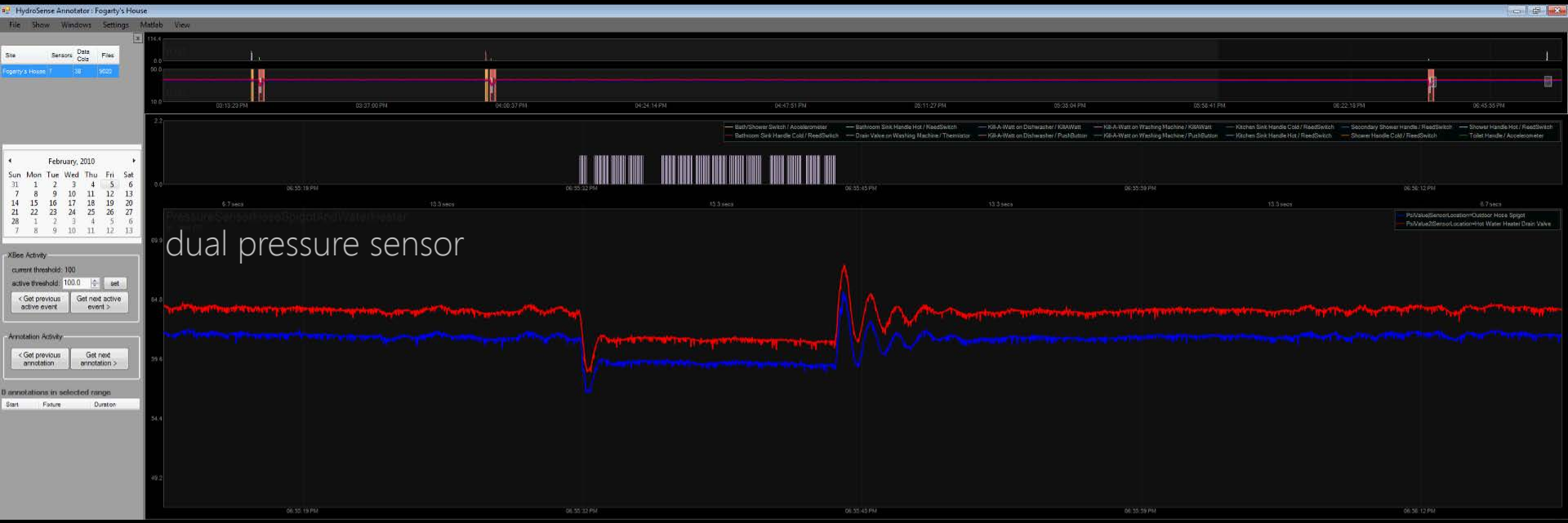
2. **semi-automated** label

3. **review** annotator

4. **verification**

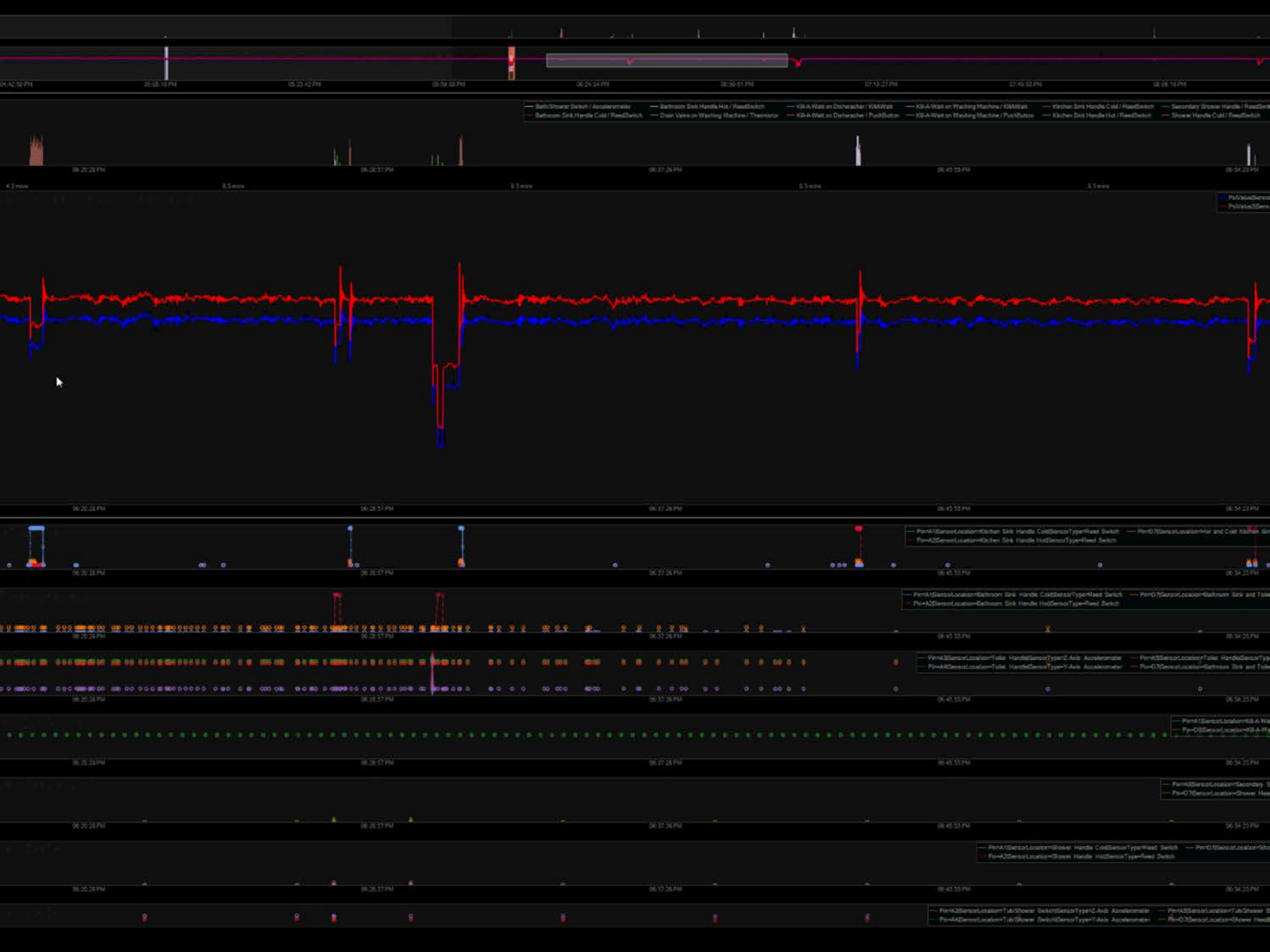
5. **final** label




HydroSense Annotator : Fogarty's House
File
Show
Windows
Settings
Matlab
View
Site
Sensors
Data Cols
Files
Fogarty's House, T
38
9020
February, 2010
Sun Mon Tue Wed Thu Fri Sat
XBee Activity
current threshold: 100
active threshold: 100.0
set
< Get previous active event
Get next active event >
Annotation Activity
< Get previous annotation
Get next annotation >
0 annotations in selected range
Start
Fixture
Duration
dual pressure sensor


HydroSense Annotator : Fogarty's House
File
Show
Windows
Settings
Matlab
View
February, 2010
dual pressure sensor
toilet
bathroom faucet
kitchen faucet
dishwasher
washing machine
bath/shower
bath/shower diverter

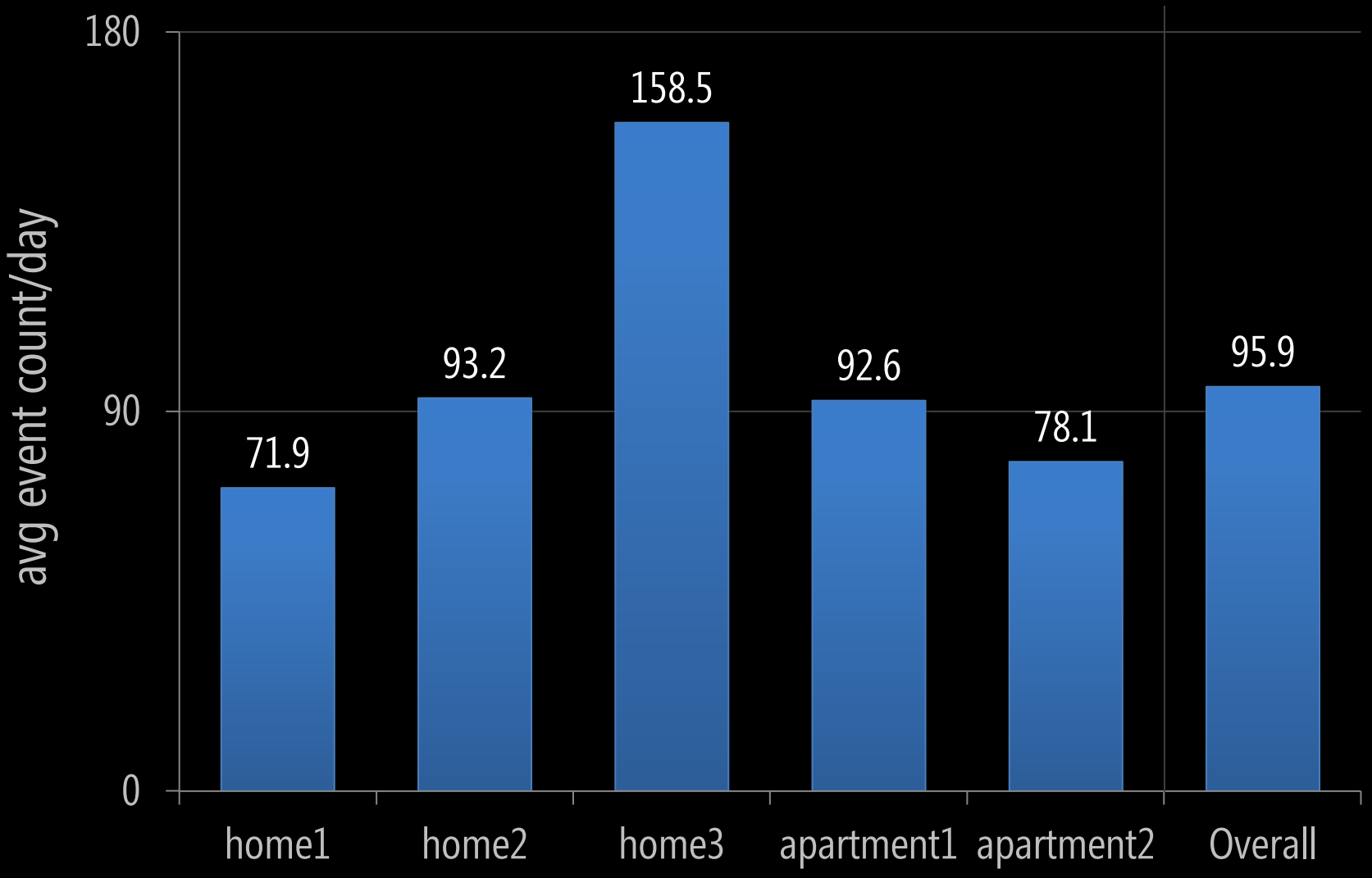

06:55:32 PM
06:55:45 PM
06:55:59 PM
13.3 secs
13.3 secs
13.3 secs
WaterHeater
Pin=A3|SensorLocation=Toilet Handle|SensorTyp
Pin=A4|SensorLocation=Toilet Handle|SensorTyp
Pin=A1|SensorLocation=Bathroom Sink Handle Cold|S
Pin=A2|SensorLocation=Bathroom Sink Handle Hot|Se
Pin=A1|SensorLocation=Kitchen Sink Handle Cold|Se
Pin=A2|SensorLocation=Kitchen Sink Handle Hot|Sen



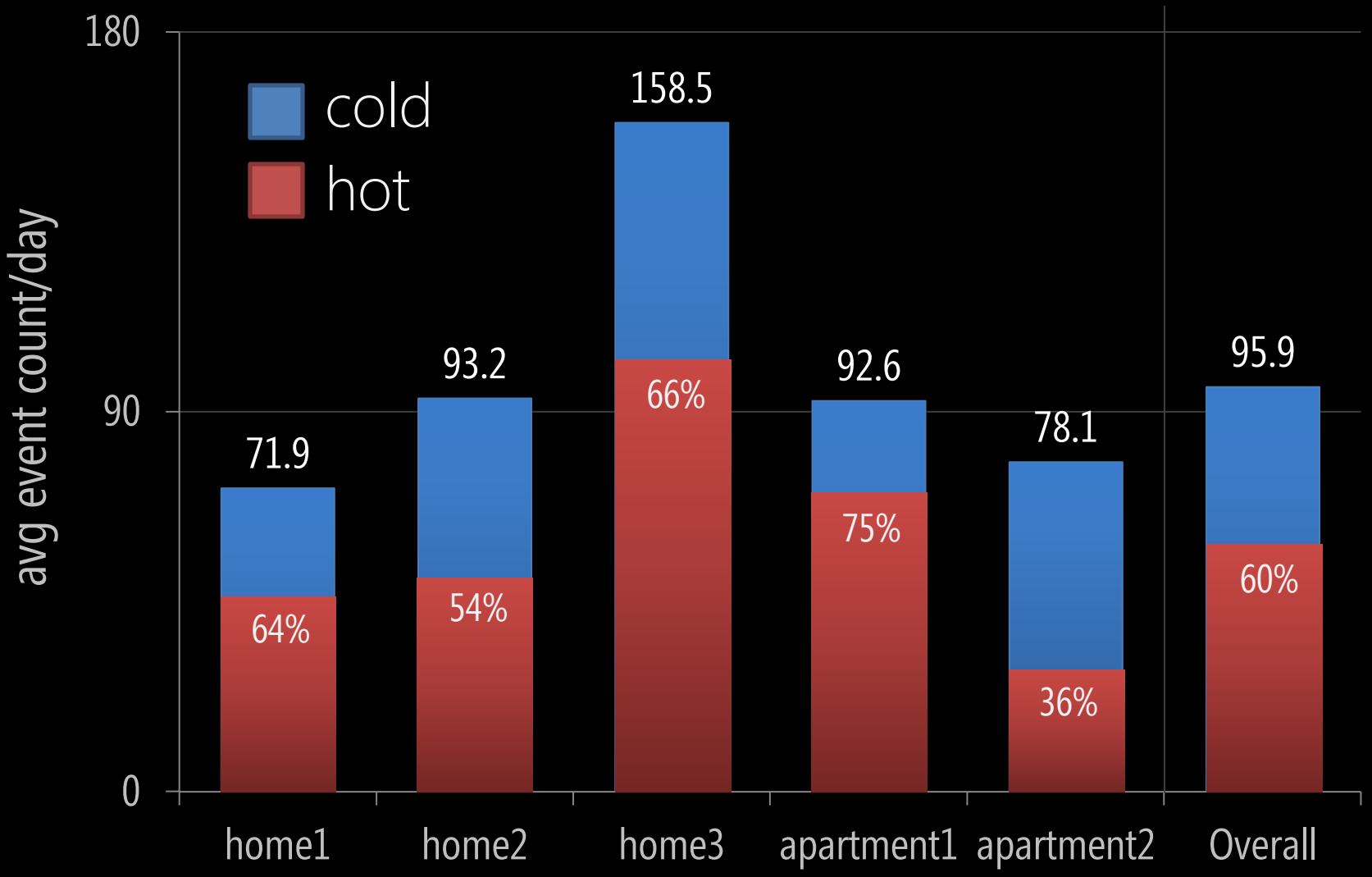
5-week dataset

						totals
days	33	33	30	27	33	156
events	2374	3075	4754	2499	2578	14,960
events/day	71.9	93.2	158.5	92.6	78.1	95.9

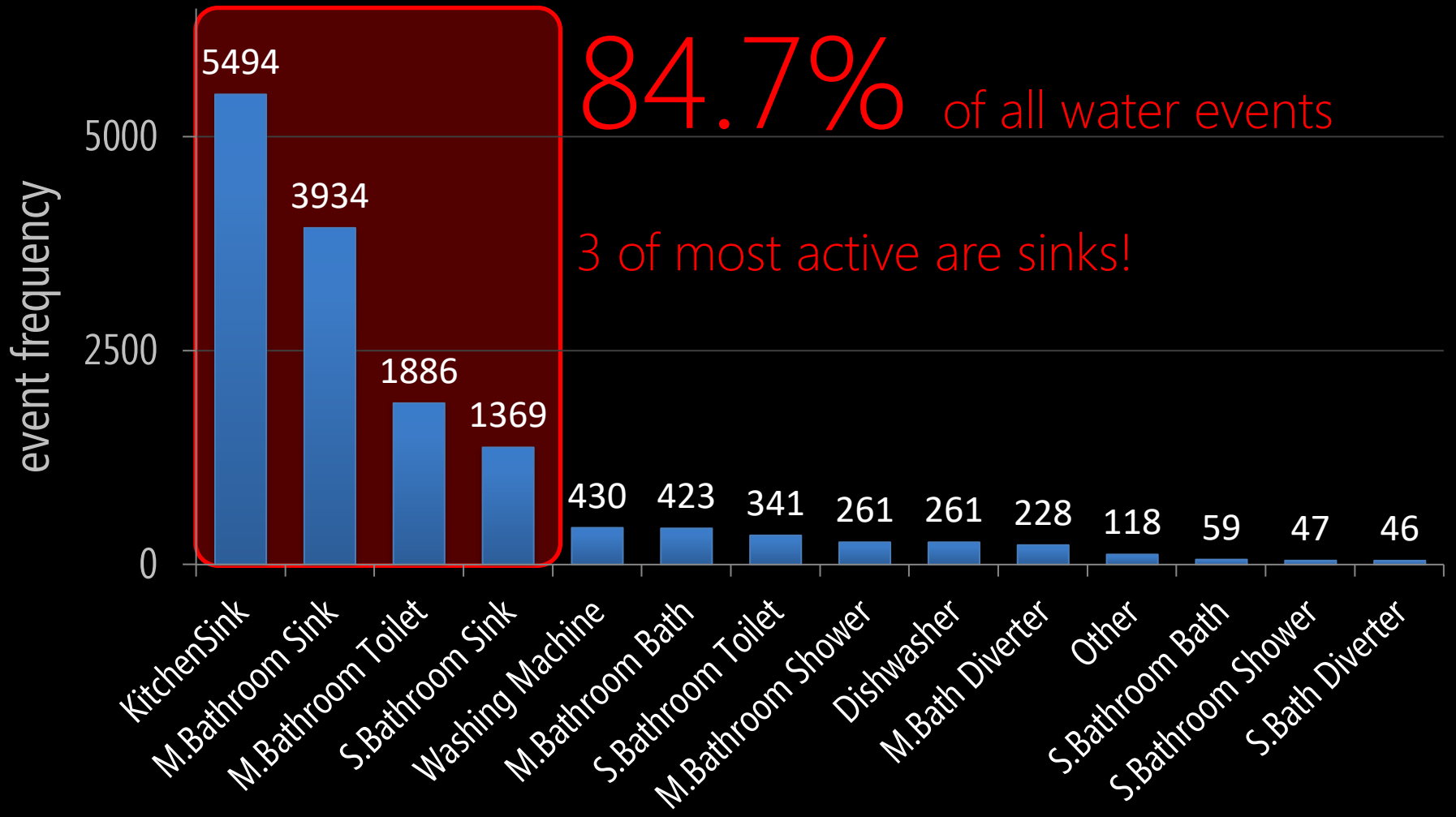
avg num water events/day

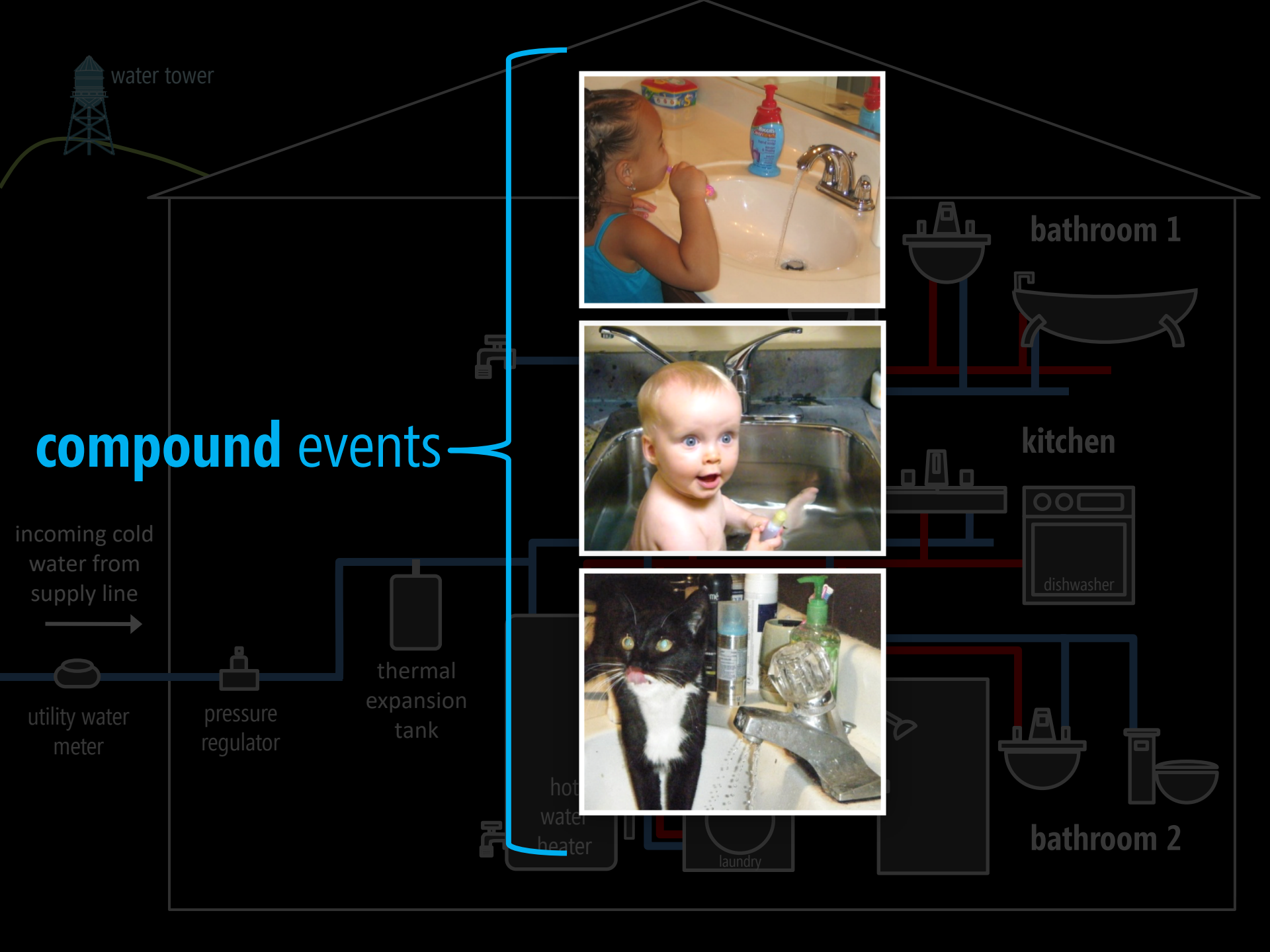


avg num water events/day



fixture activity frequency




water tower
compound events
incoming cold water from supply line
utility water meter
pressure regulator
thermal expansion tank
hot water heater
laundry
bathroom 1
kitchen
dishwasher
bathroom 2

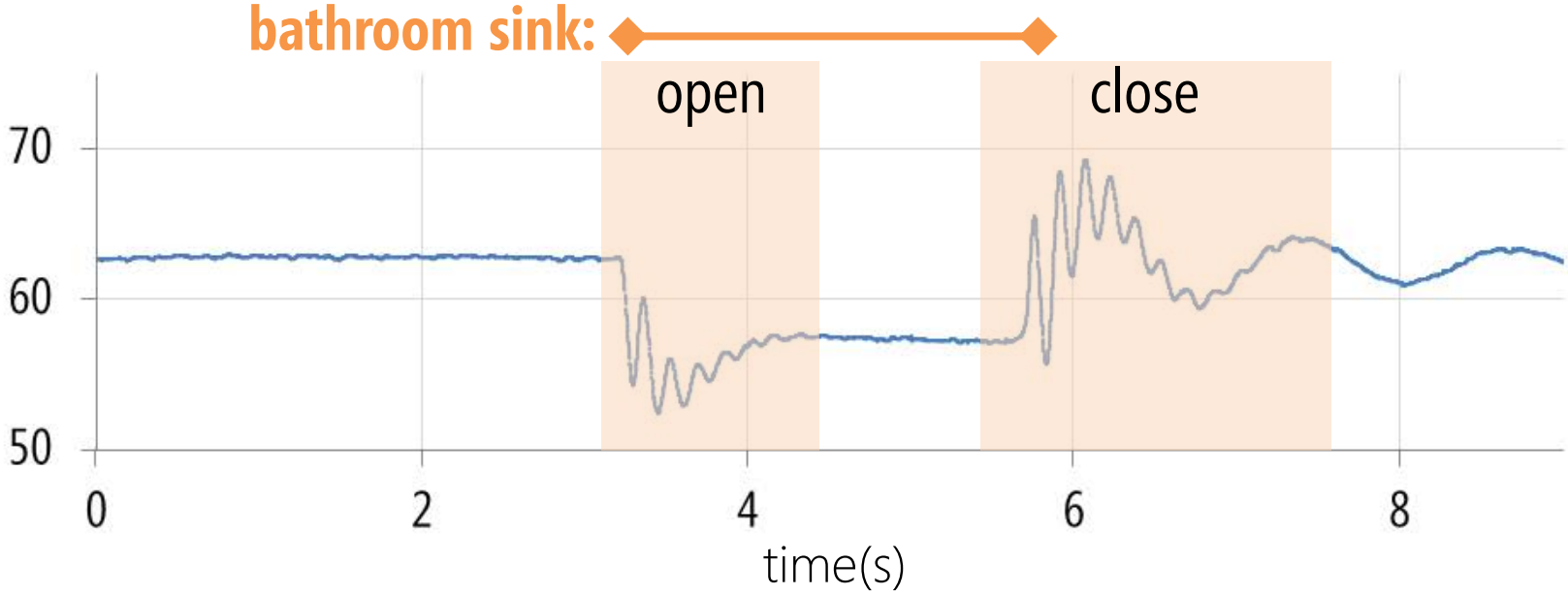
22%

of all water events were compound

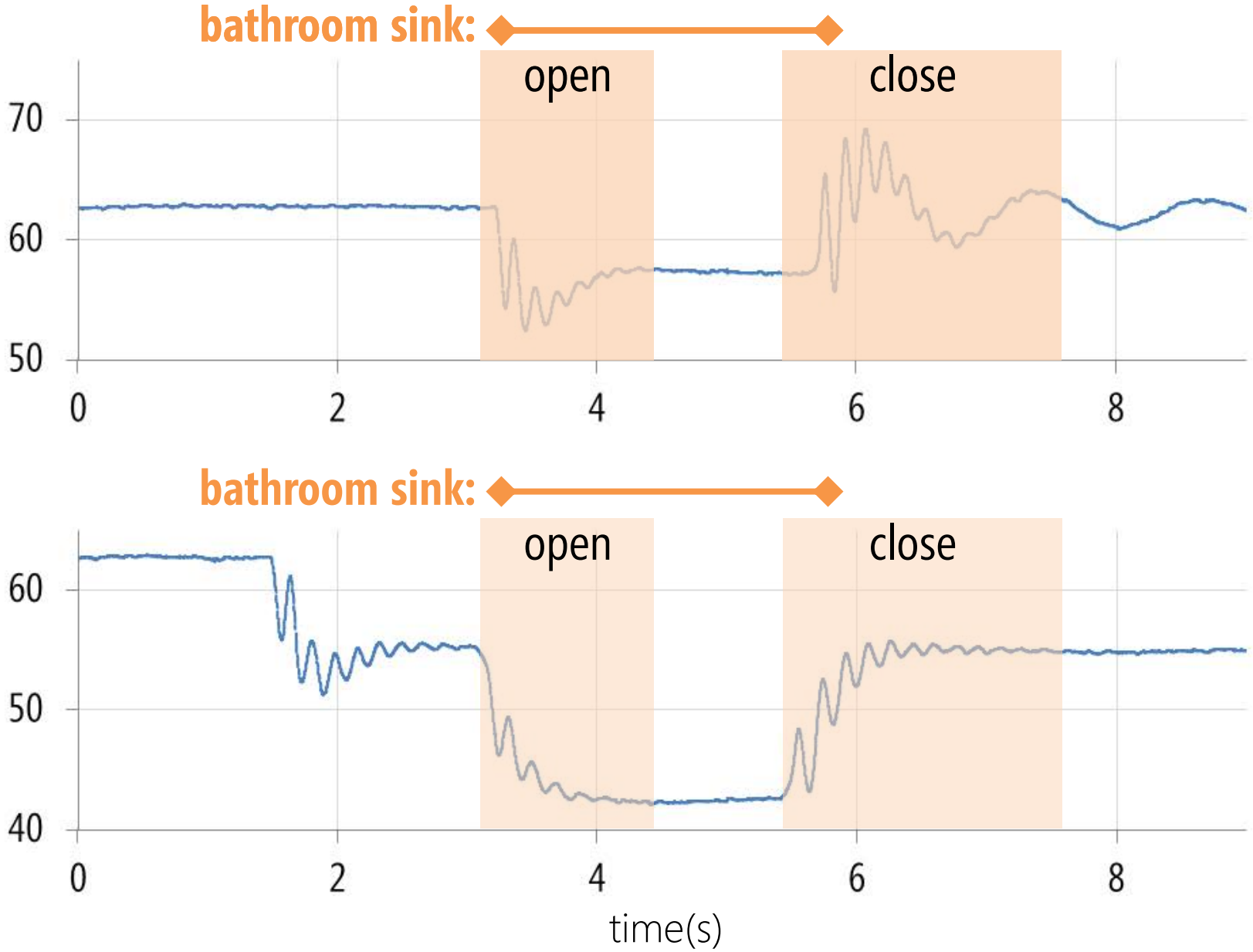
41.8%

of all bathroom sink events were compound

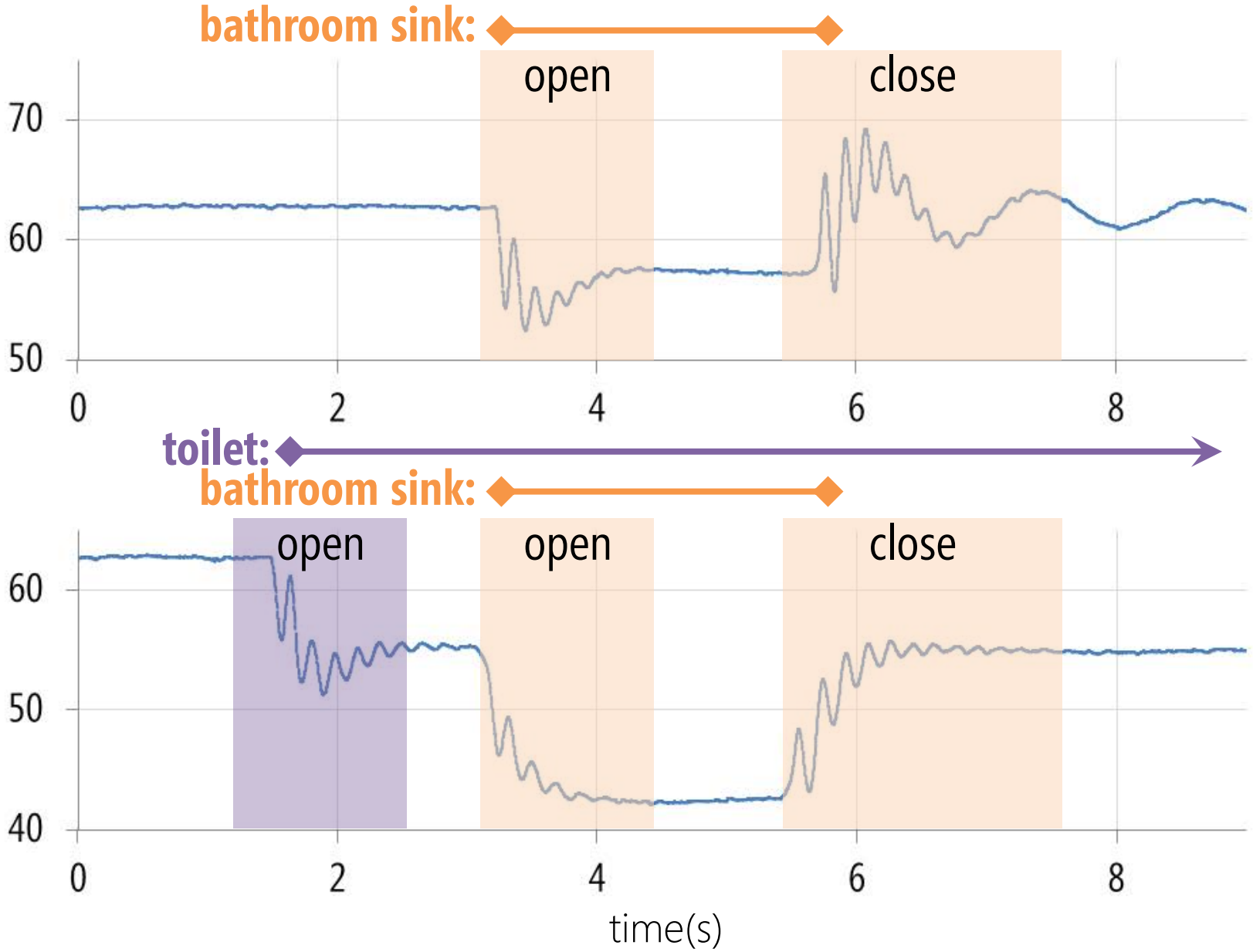
compound event example



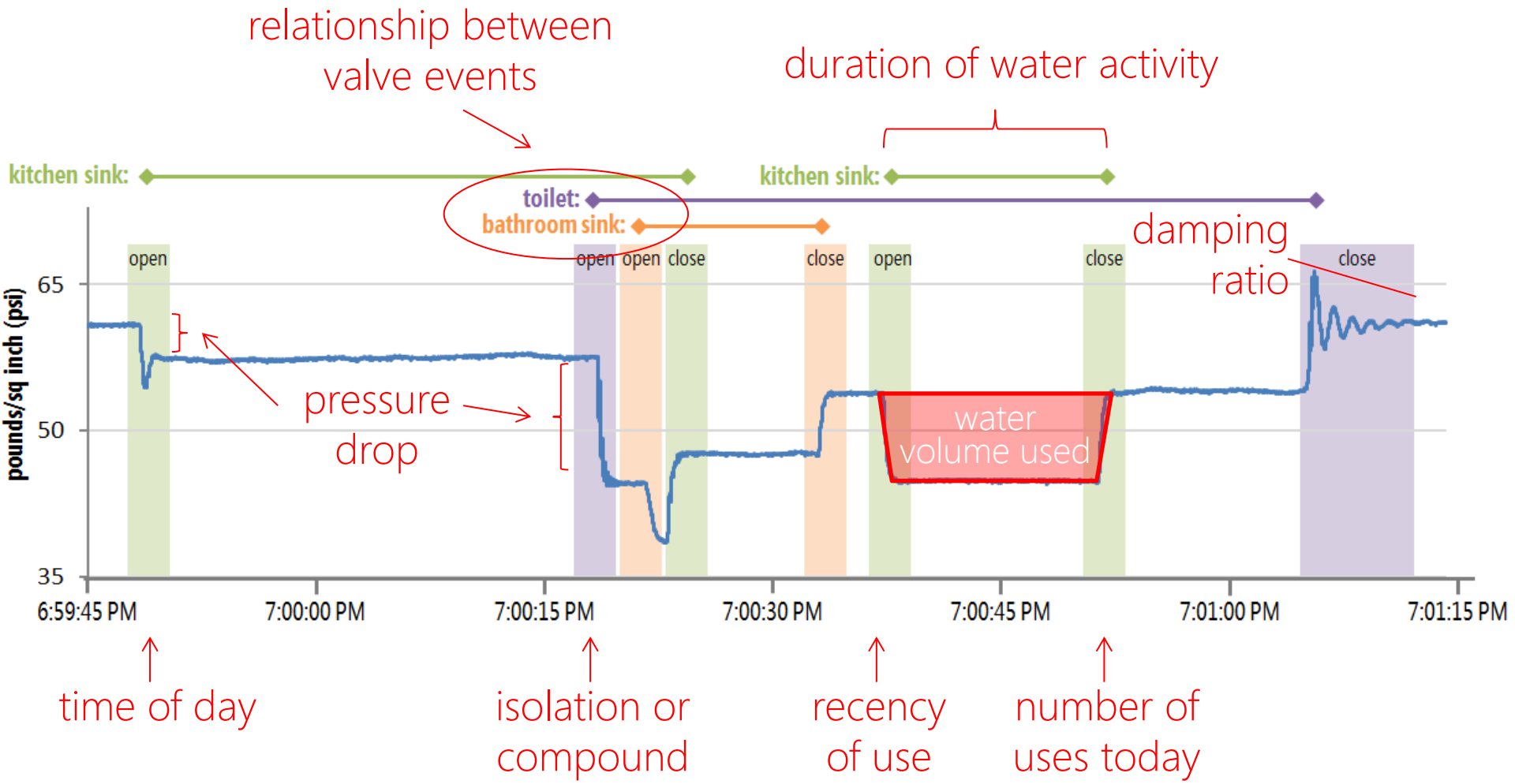
compound event example



compound event example



beyond **template matching**



bayesian approach

New algorithm borrows from Bayesian inference in speech recognition

signal

behavior

$$P(\mathbf{S}|\mathbf{V}) \quad P(\mathbf{V})$$

$$\underbrace{\prod_{r=0}^{R-1} f_r(\hat{\mathbf{S}}_r \mid \hat{\mathbf{V}}_r)}_{\text{(i) templates and signal features}} \underbrace{\prod_{n=0}^{N-1} P(v_n \mid v_{n-1})}_{\text{(ii) bigram language model}} \underbrace{\prod_{i \notin \beta} f_p(v_i)}_{\text{(iii) grammar}} \underbrace{\prod_{k=0}^{K-1} \prod_{\langle a,b \rangle \in \beta} f_k(\langle v_a, v_b \rangle)}_{\text{(iv) paired valve priors}}$$

bayesian approach

V = pressure signature library

S = sequence of unknown pressure transients

most likely valve sequence

$$\hat{V} = \arg\max P(\mathbf{V} \mid \mathbf{S}) = \arg\max \frac{P(\mathbf{S} \mid \mathbf{V})P(\mathbf{V})}{P(\mathbf{S})}$$

bayesian approach

V = pressure signature library

S = sequence of unknown pressure transients

conditional probability term

$$\hat{V} = \arg\max P(\mathbf{V} \mid \mathbf{S}) = \arg\max \frac{P(\mathbf{S} \mid \mathbf{V}) P(\mathbf{V})}{P(\mathbf{S})}$$

$$\overbrace{\prod_{r=0}^{R-1} f_r(\hat{\mathbf{S}}_r \mid \hat{\mathbf{V}}_r)}^{P(\mathbf{S}|\mathbf{V})}$$

(i) templates and signal features

e.g., matched filtering and stabilized pressure drop

bayesian approach

V = pressure signature library

S = sequence of unknown pressure transients

prior probability term

$$\hat{V} = \arg\max P(\mathbf{V} \mid \mathbf{S}) = \arg\max \frac{P(\mathbf{S} \mid \mathbf{V}) P(\mathbf{V})}{P(\mathbf{S})}$$

$$\overbrace{\underbrace{\prod_{r=0}^{R-1} f_r(\hat{\mathbf{S}}_r \mid \hat{\mathbf{V}}_r)}_{\text{(i) templates and signal features}} \underbrace{\prod_{n=0}^{N-1} P(v_n \mid v_{n-1})}_{\text{(ii) bigram language model}}}^{P(\mathbf{S}|\mathbf{V})}$$

e.g., transition probability for toilet open->bathroom sink open

bayesian approach

V = pressure signature library

S = sequence of unknown pressure transients

prior probability term

$$\hat{V} = \arg\max P(\mathbf{V} \mid \mathbf{S}) = \arg\max \frac{P(\mathbf{S} \mid \mathbf{V}) P(\mathbf{V})}{P(\mathbf{S})}$$

$$\overbrace{\underbrace{\prod_{r=0}^{R-1} f_r(\hat{\mathbf{S}}_r \mid \hat{\mathbf{V}}_r)}_{\text{(i) templates and signal features}} \underbrace{\prod_{n=0}^{N-1} P(v_n \mid v_{n-1})}_{\text{(ii) bigram language model}} \underbrace{\prod_{i \notin \beta} f_p(v_i)}_{\text{(iii) grammar}}}^{P(\mathbf{S}|\mathbf{V})}$$

e.g., opening of valve v_x must be followed by closing of v_x

bayesian approach

V = pressure signature library

S = sequence of unknown pressure transients

prior probability term

$$\hat{V} = \arg\max P(\mathbf{V} \mid \mathbf{S}) = \arg\max \frac{P(\mathbf{S} \mid \mathbf{V}) P(\mathbf{V})}{P(\mathbf{S})}$$

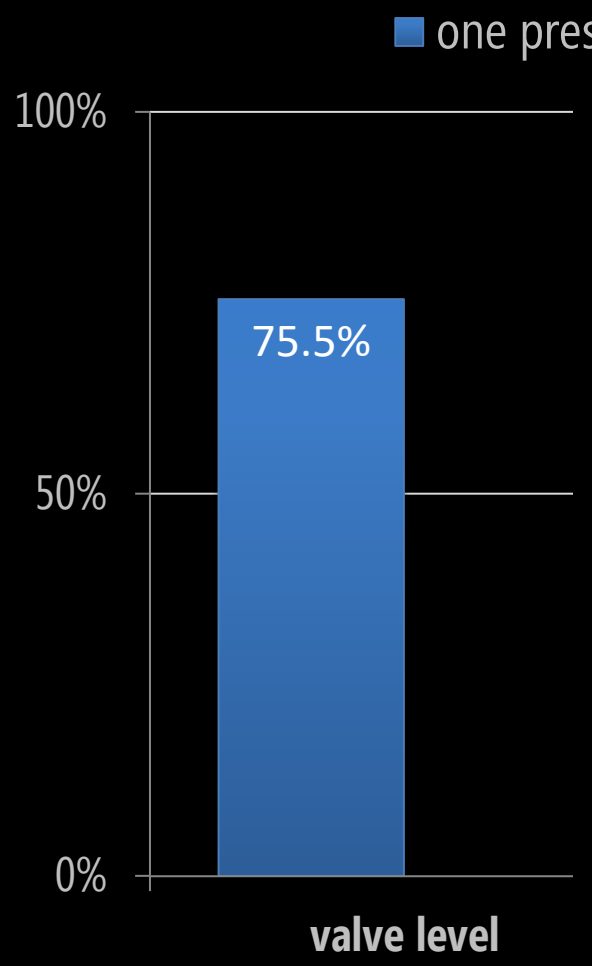
$P(\mathbf{S}|\mathbf{V})$ $P(\mathbf{V})$

$$\underbrace{\prod_{r=0}^{R-1} f_r(\hat{\mathbf{S}}_r \mid \hat{\mathbf{V}}_r)}_{\text{(i) templates and signal features}} \underbrace{\prod_{n=0}^{N-1} P(v_n \mid v_{n-1})}_{\text{(ii) bigram language model}} \underbrace{\prod_{i \notin \beta} f_p(v_i)}_{\text{(iii) grammar}} \underbrace{\prod_{k=0}^{K-1} \prod_{\langle a,b \rangle \in \beta} f_k(\langle v_a, v_b \rangle)}_{\text{(iv) paired valve priors}}$$

e.g., water usage duration

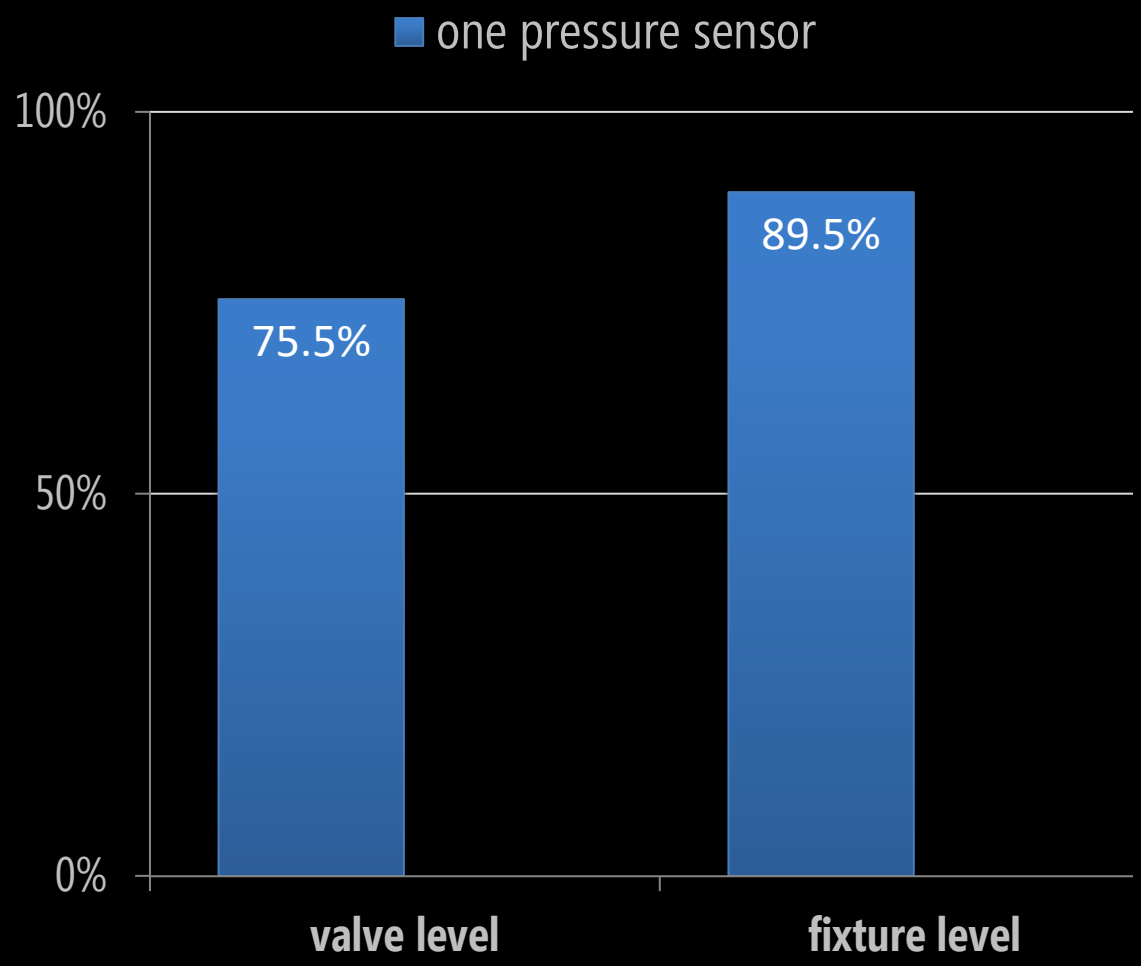
hydrosense classification results

real-world water usage data



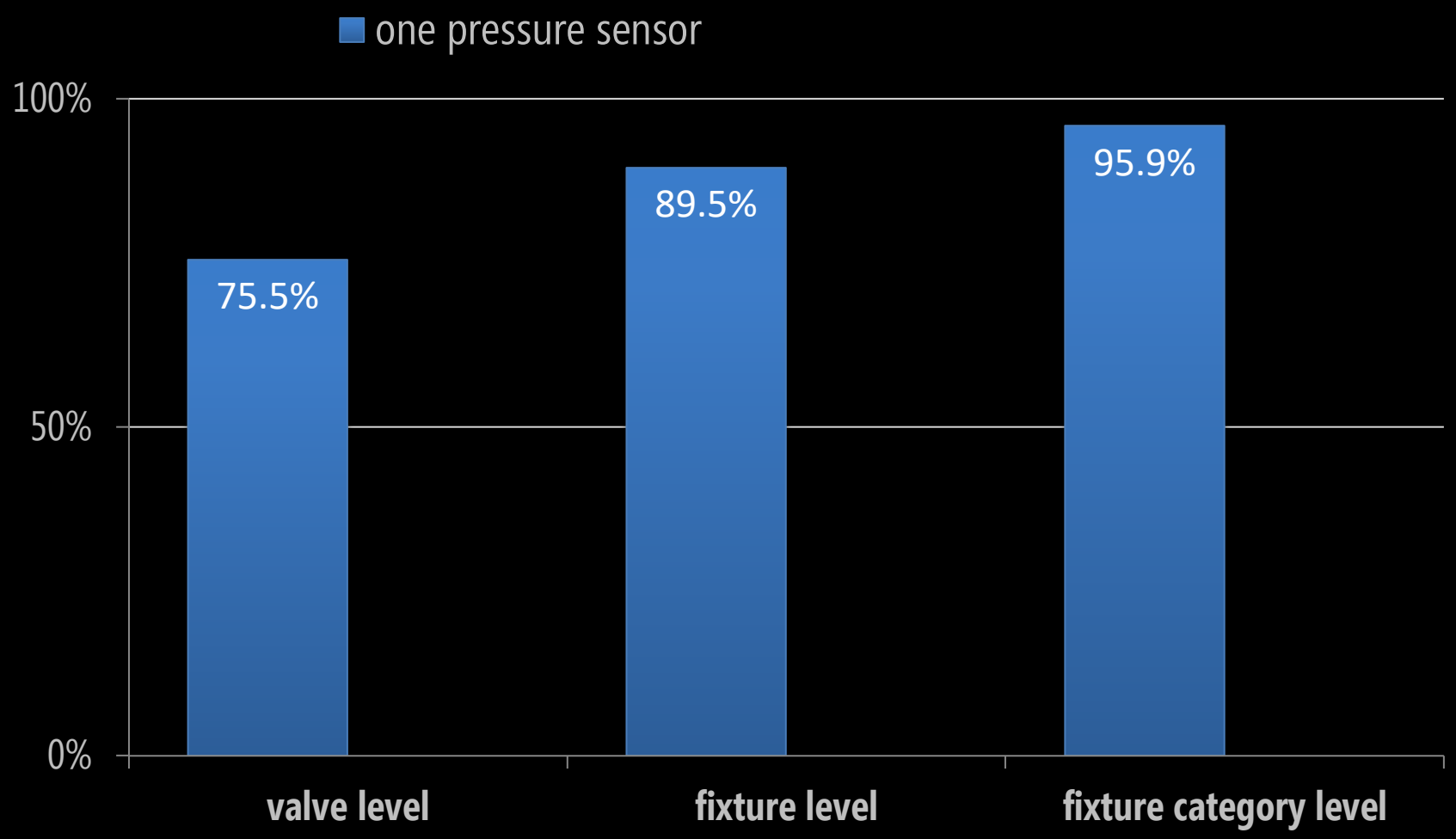
hydrosense classification results

real-world water usage data



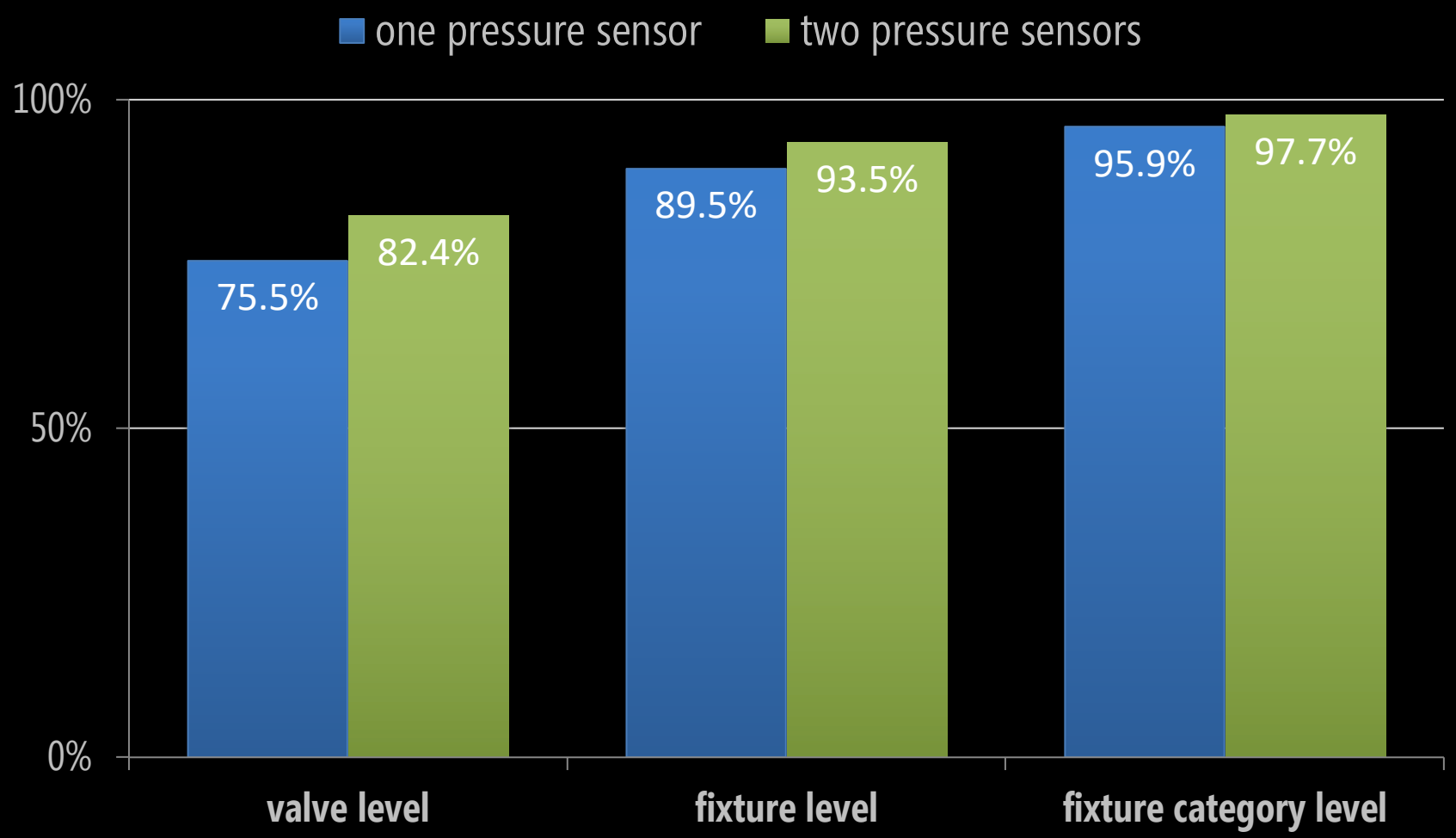
hydrosense classification results

real-world water usage data



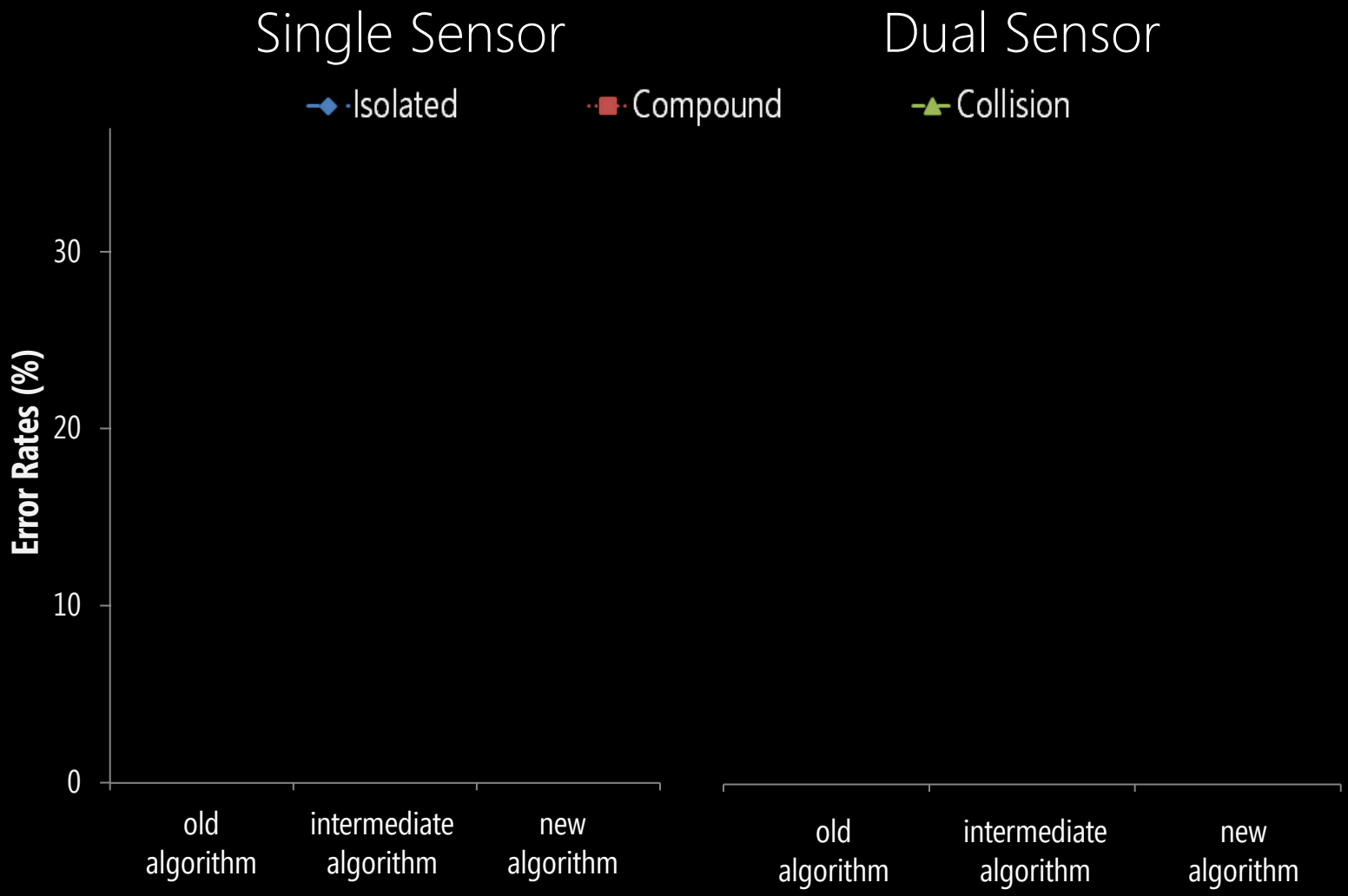
hydrosense classification results

real-world water usage data



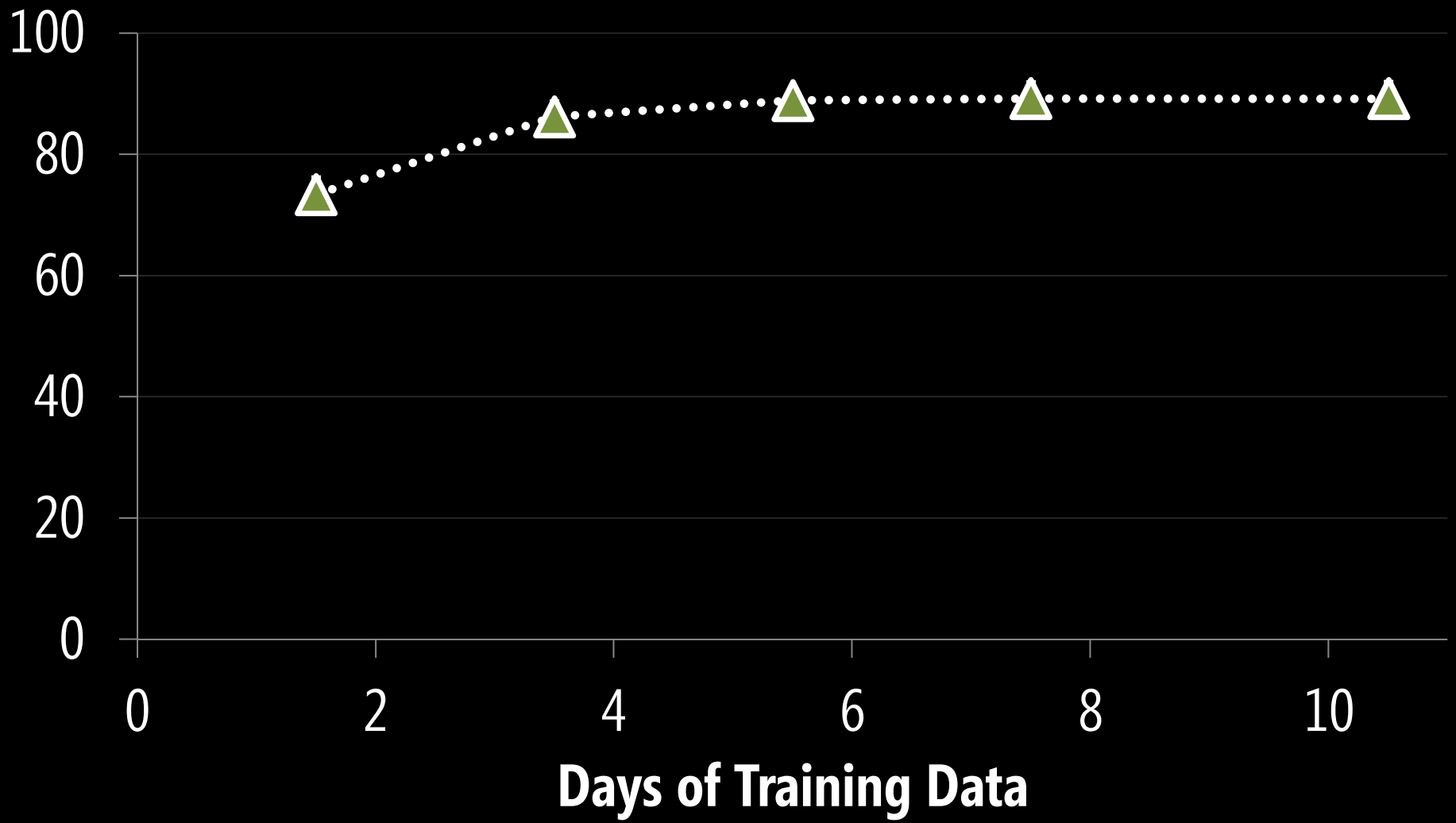
compound events results

real-world water usage data



hydrosense training results

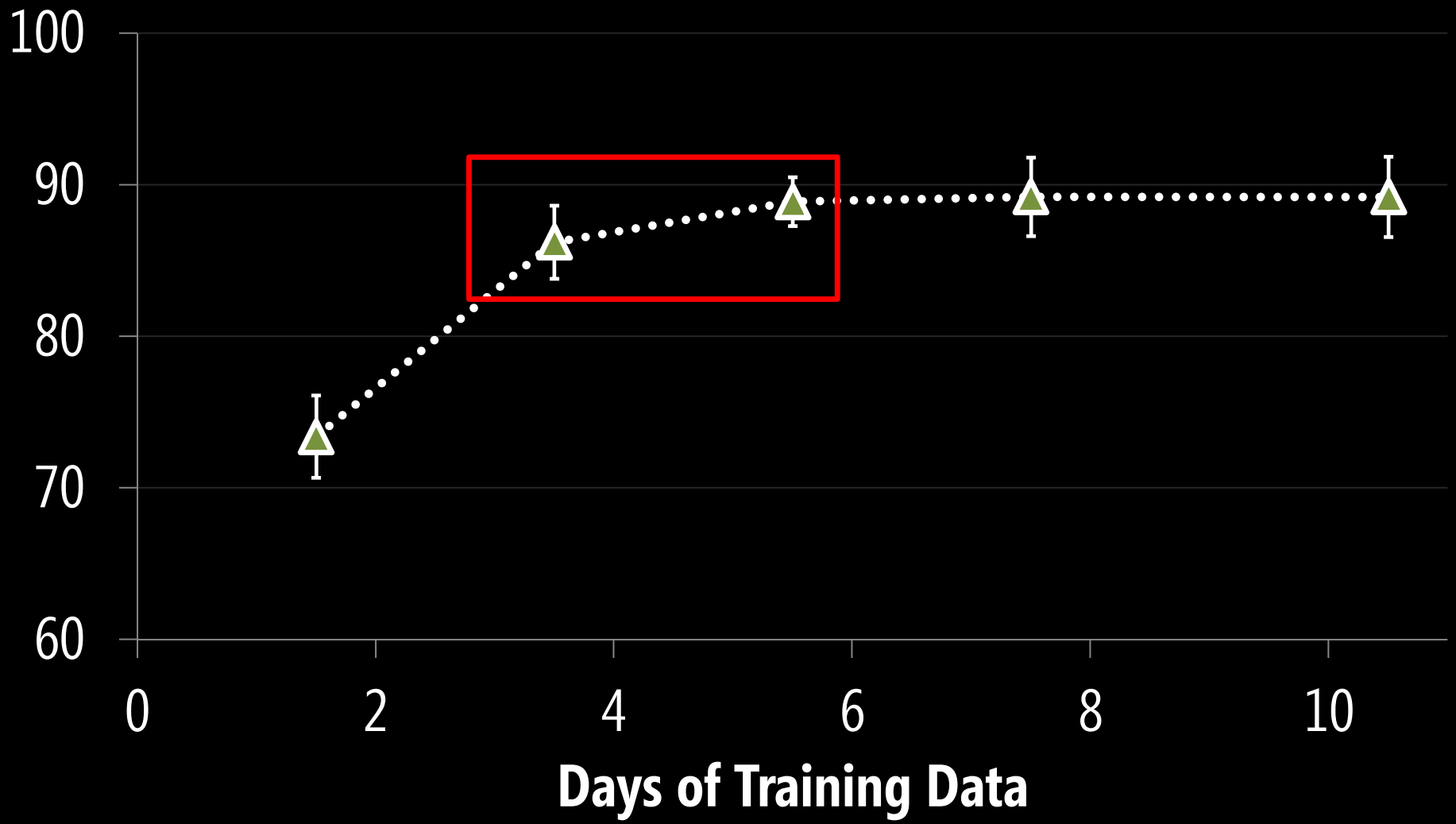
real-world water usage data



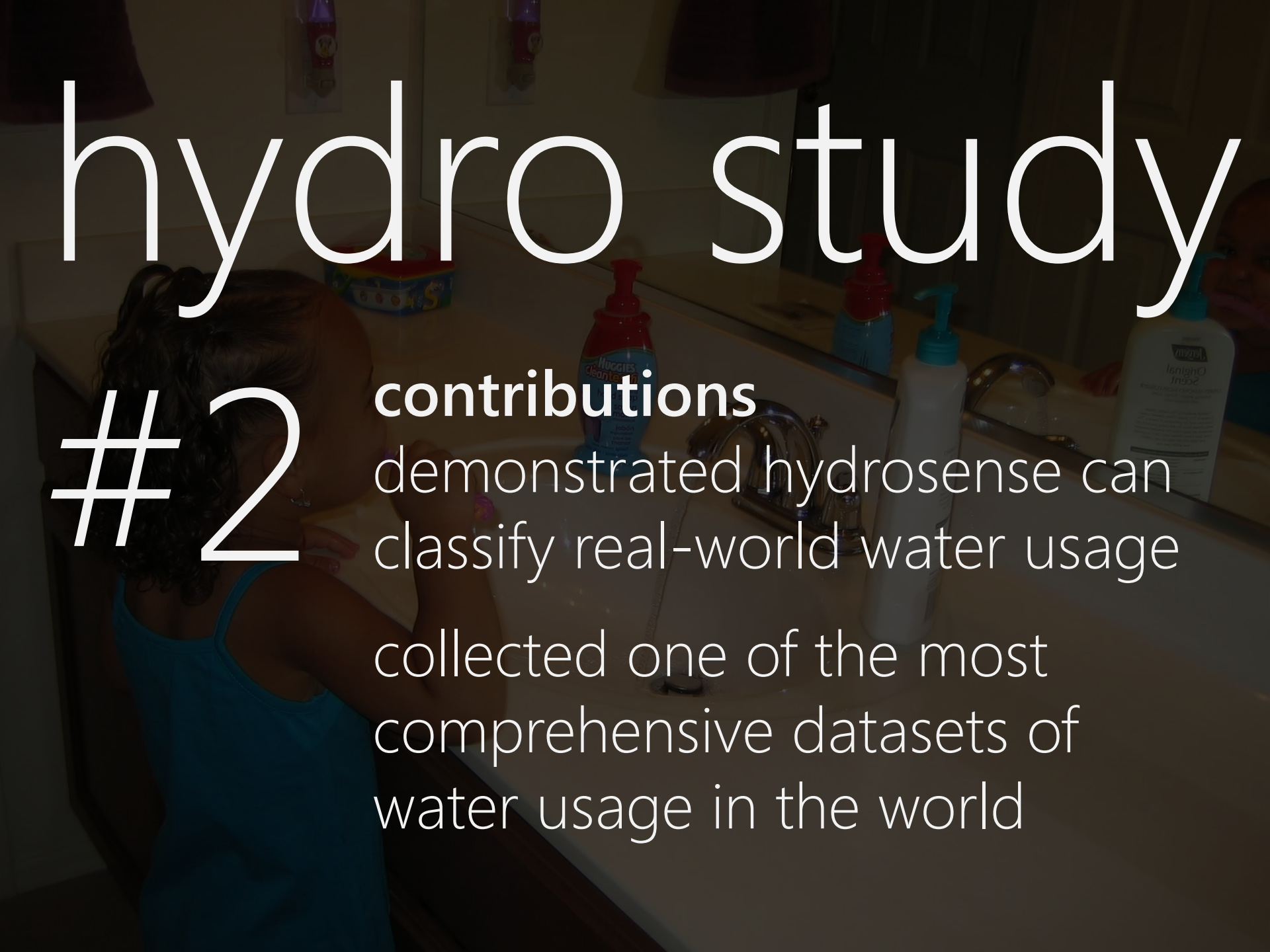
*error bars = std error

hydrosense training results

real-world water usage data



*error bars = std error



hydro study #2

contributions

demonstrated hydrosense can classify real-world water usage

collected one of the most comprehensive datasets of water usage in the world