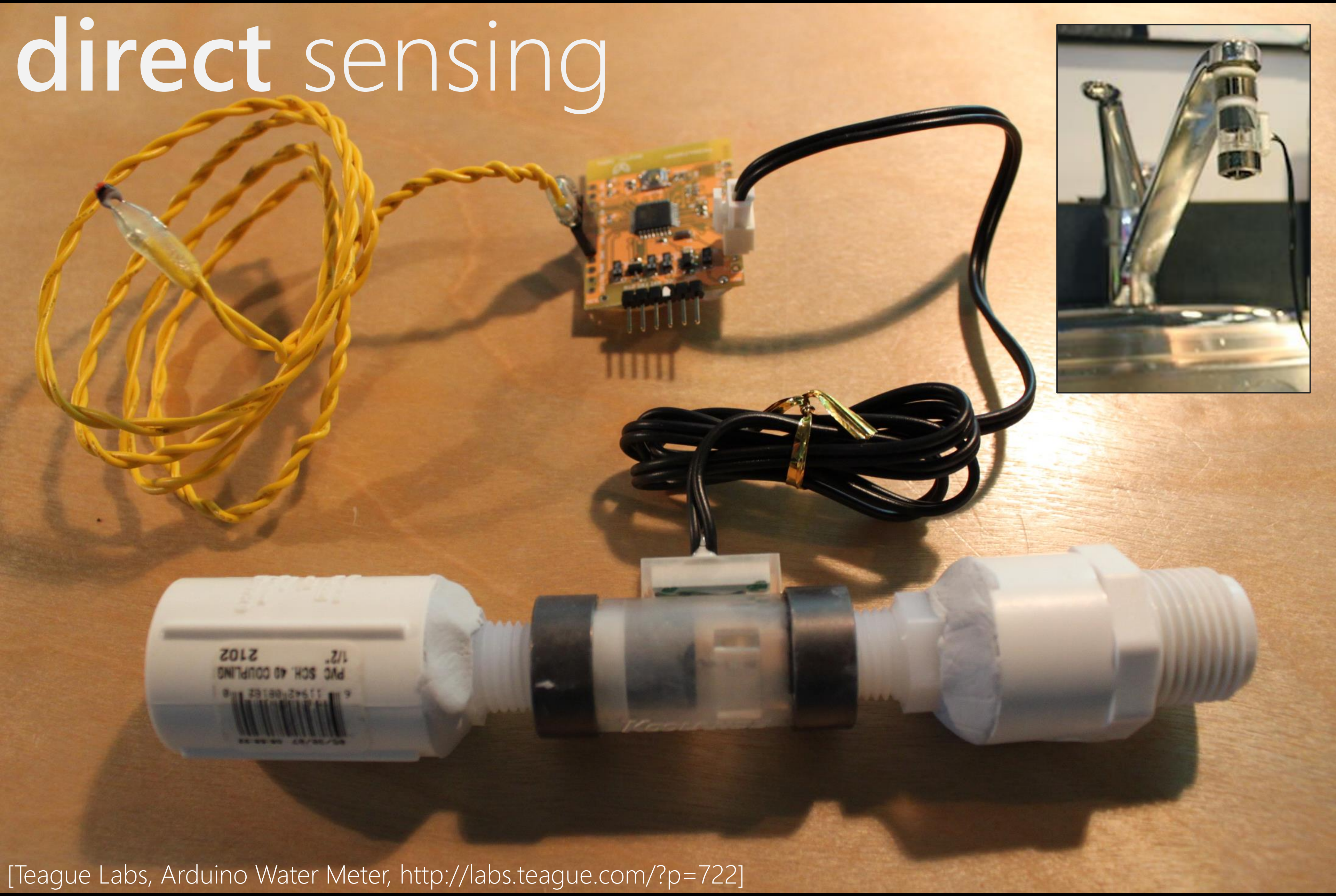
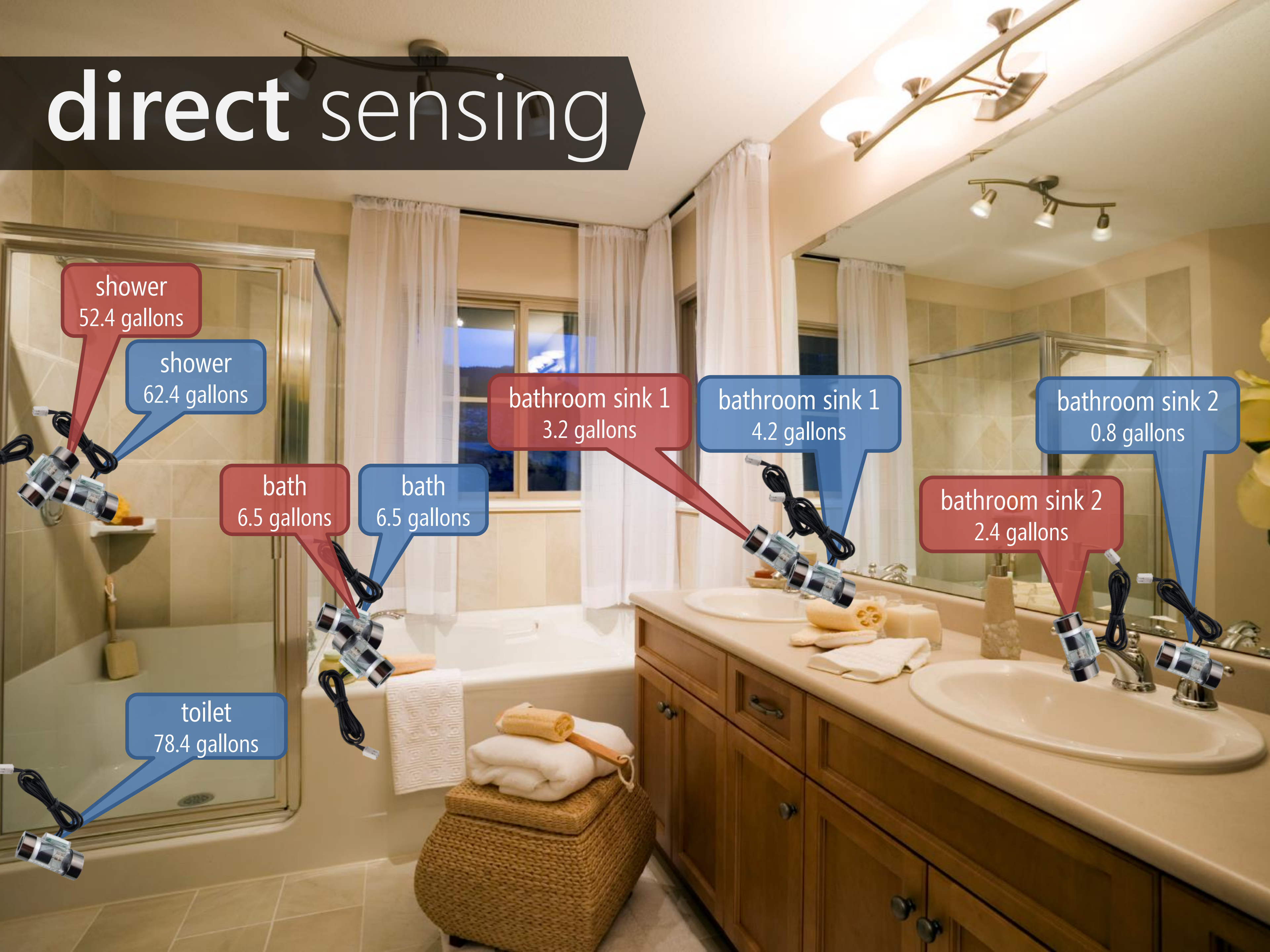
direct sensing

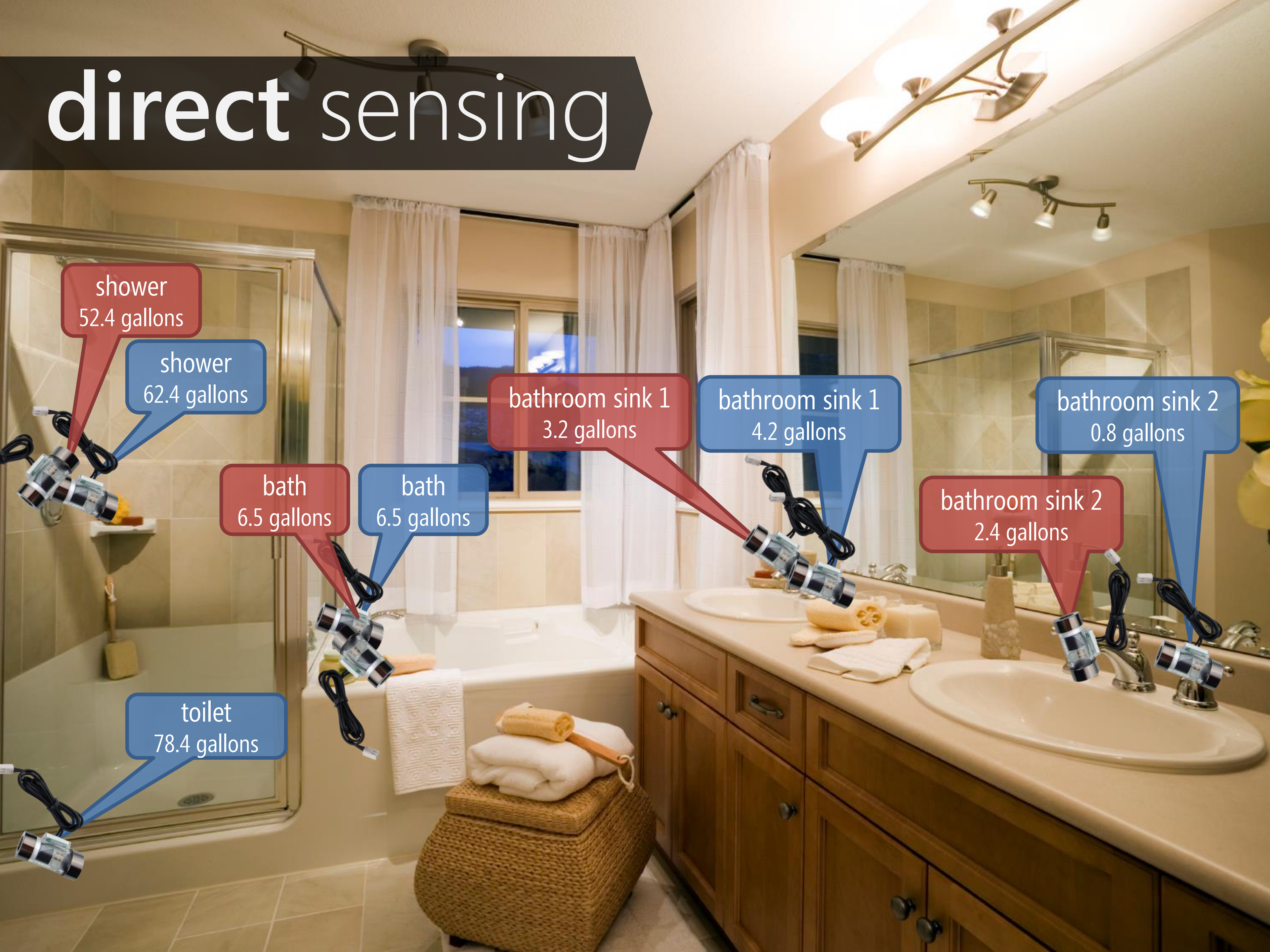


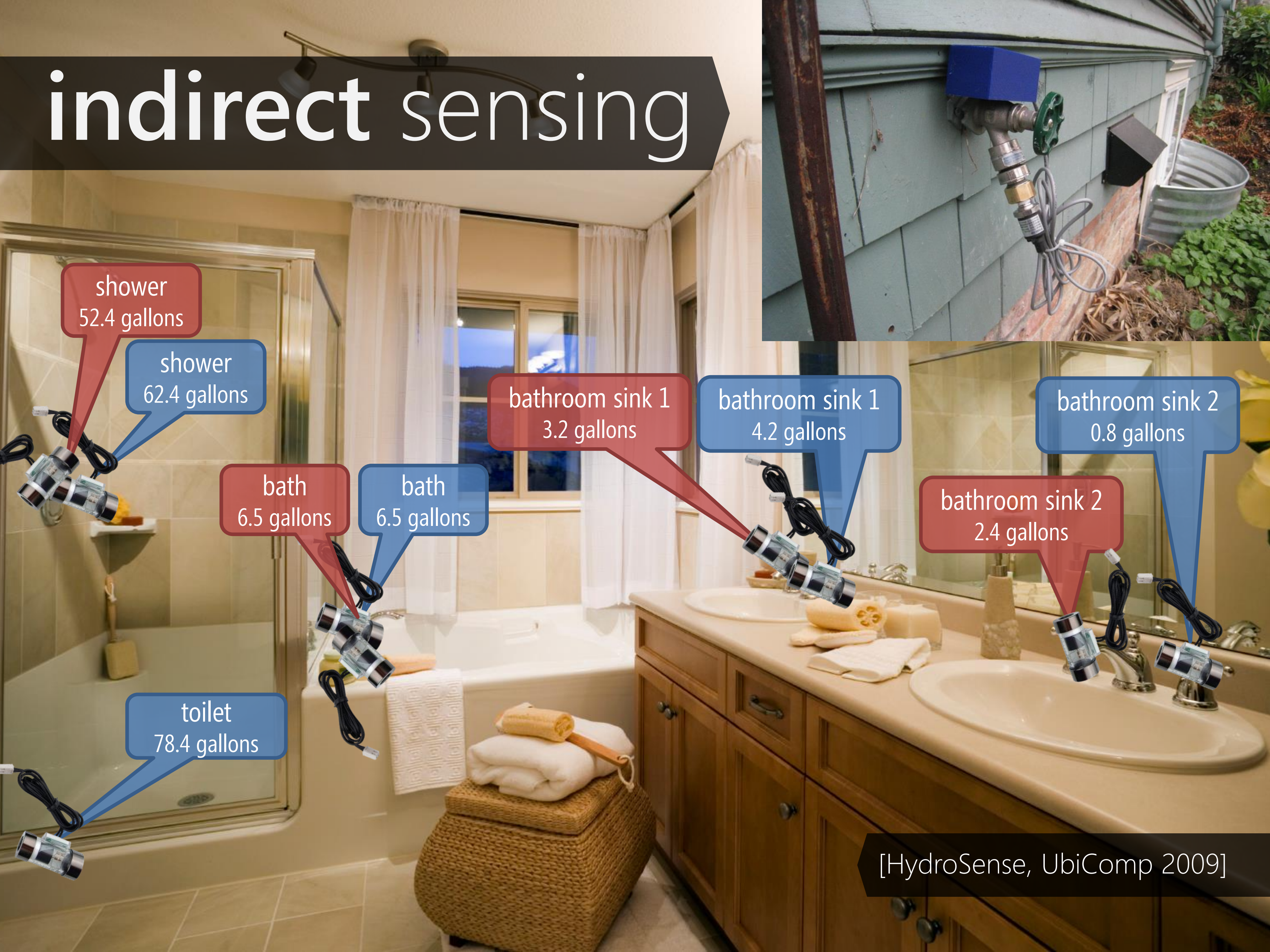
[Teague Labs, Arduino Water Meter, http://labs.teague.com/?p=722]

direct sensing


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

direct sensing



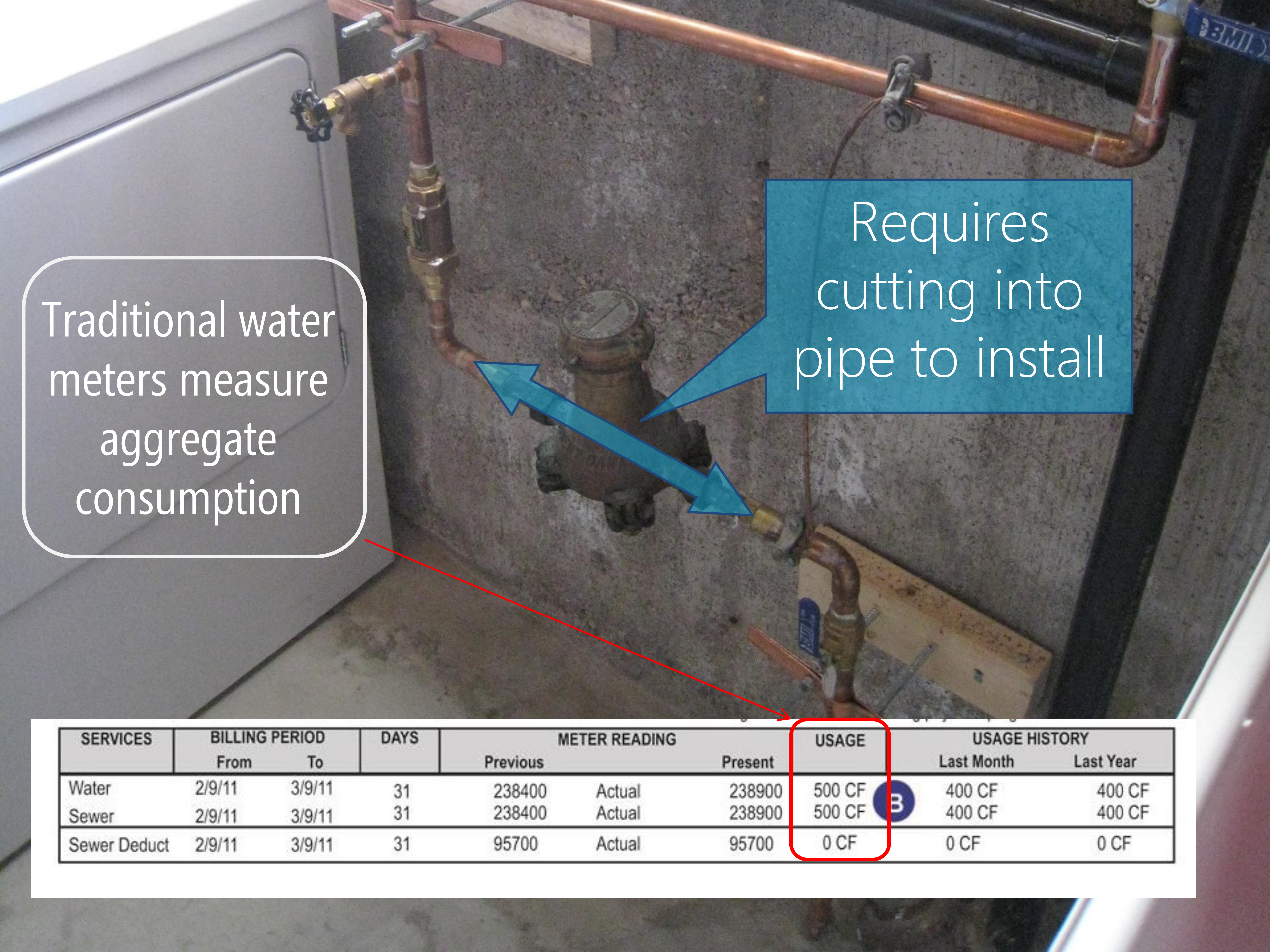

indirect sensing
shower
52.4 gallons
shower
62.4 gallons
bath
6.5 gallons
bath
6.5 gallons
bathroom sink 1
3.2 gallons
bathroom sink 1
4.2 gallons
bathroom sink 2
0.8 gallons
bathroom sink 2
2.4 gallons
toilet
78.4 gallons
[HydroSense, UbiComp 2009]

indirect sensing

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

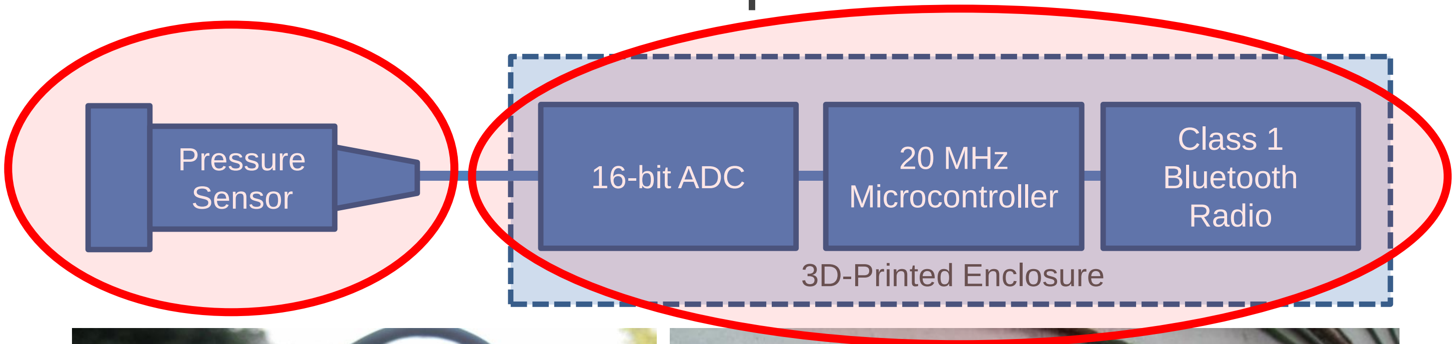
[HydroSense, UbiComp 2009]

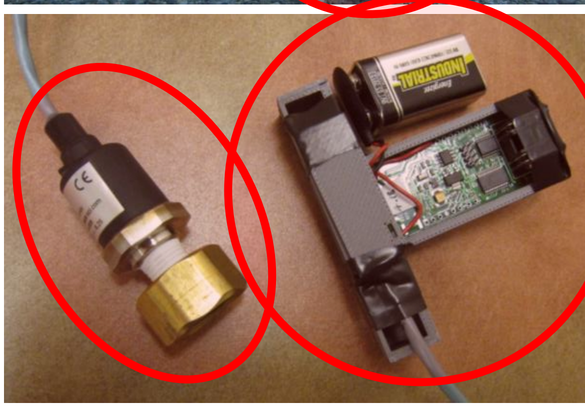

hydrosense
• single, screw-on sensor
• identifies fixture usage
• estimates flow
Froehlich et al., UbiComp2009; Larson et al., PMC2010

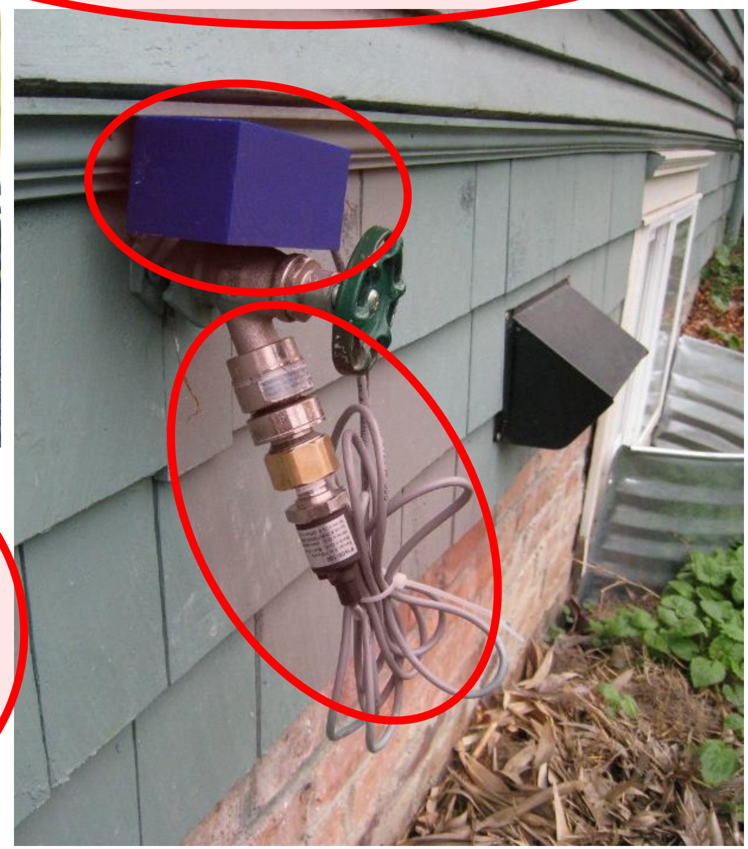


SERVICES	BILLING PERIOD From	BILLING PERIOD To	DAYS	METER READING Previous		METER READING Present	USAGE	USAGE HISTORY Last Month	USAGE HISTORY Last Year
Water	2/9/11	3/9/11	31	238400	Actual	238900	500 CF	400 CF	400 CF
Sewer	2/9/11	3/9/11	31	238400	Actual	238900	500 CF	400 CF	400 CF
Sewer Deduct	2/9/11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

hydrosense implementation



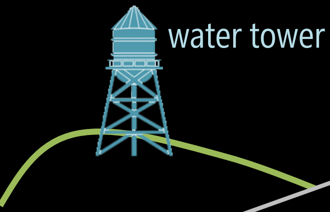




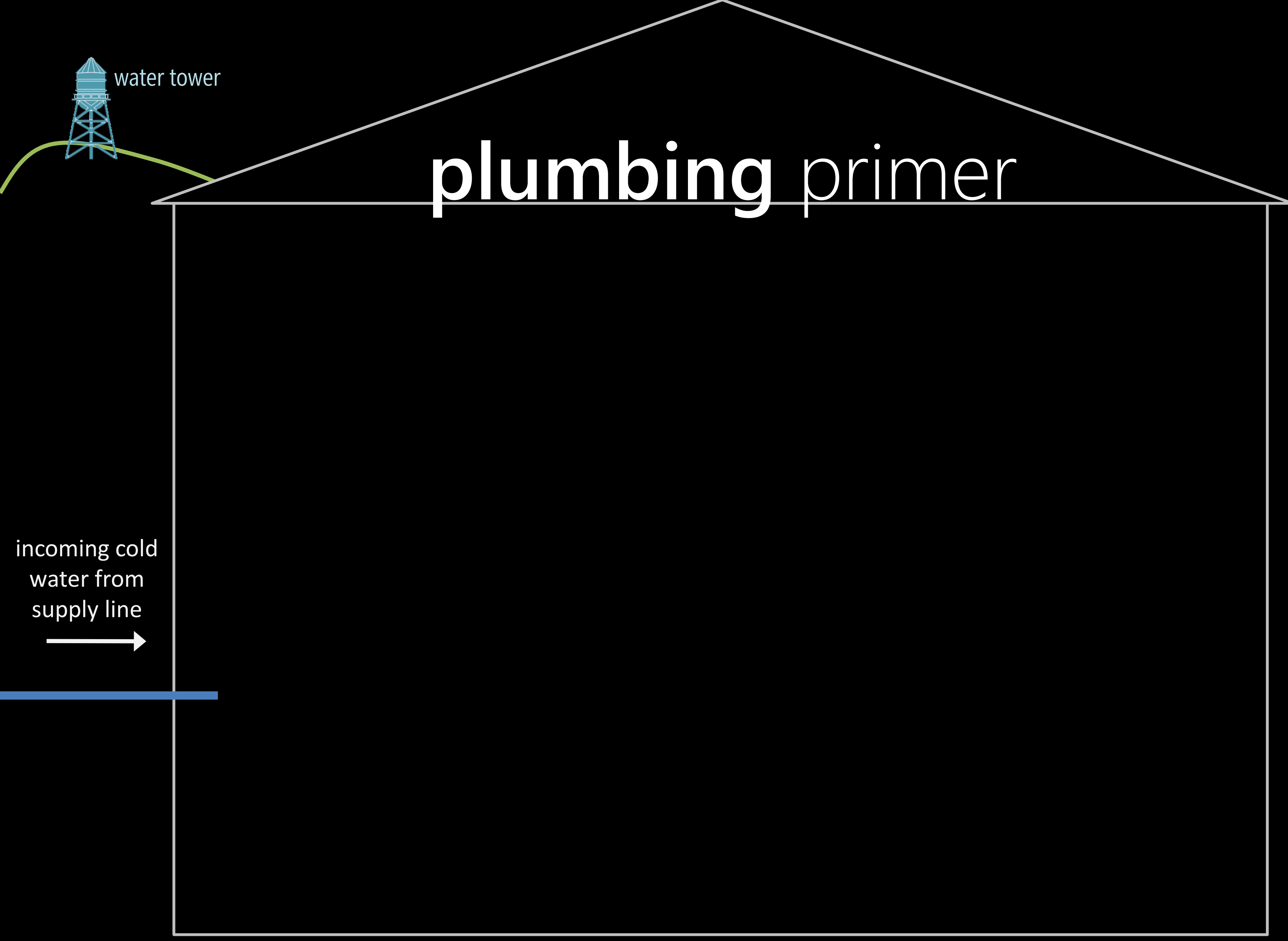
brief plumbing primer

brief plumbing primer

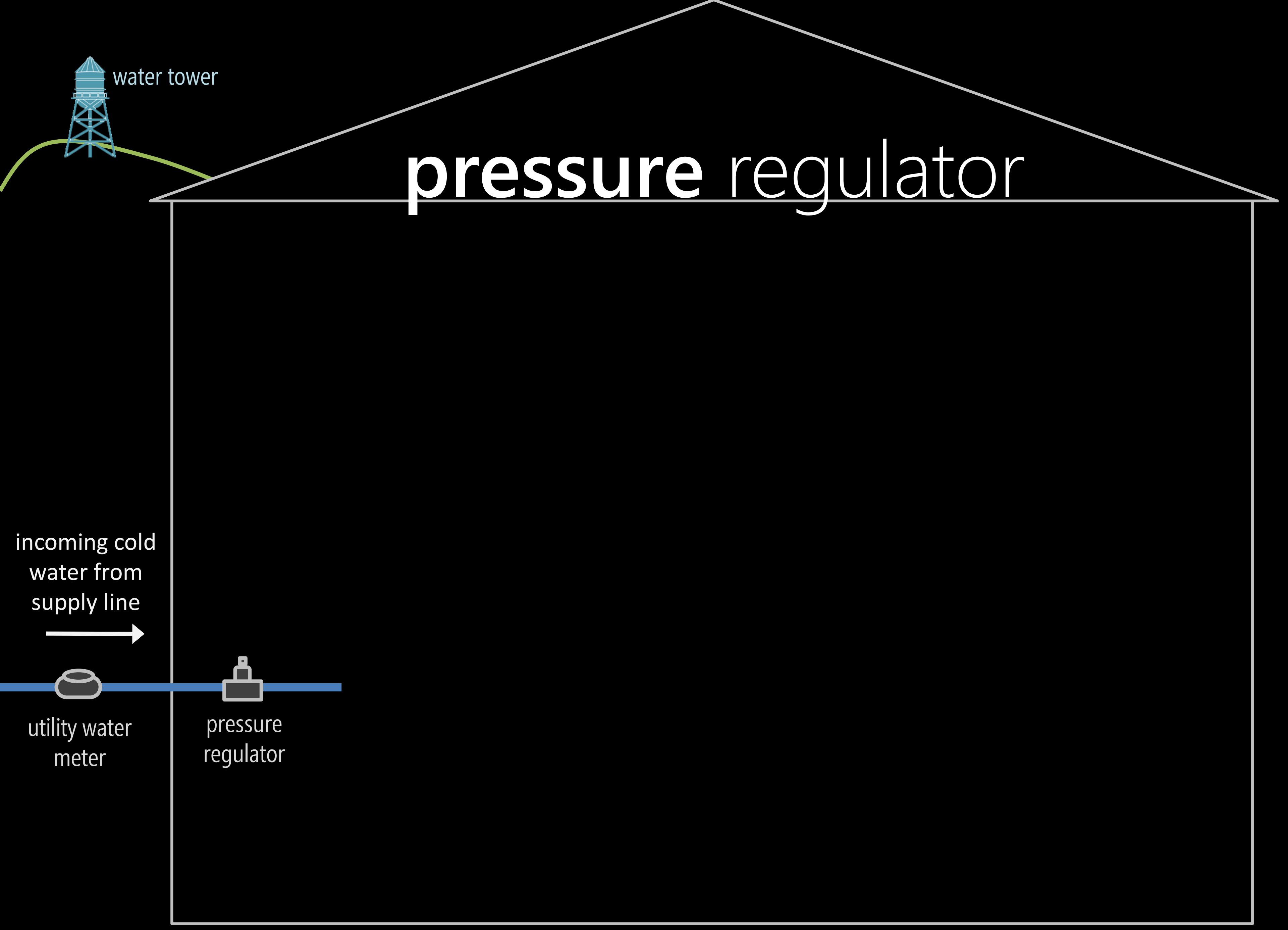
plumbing primer

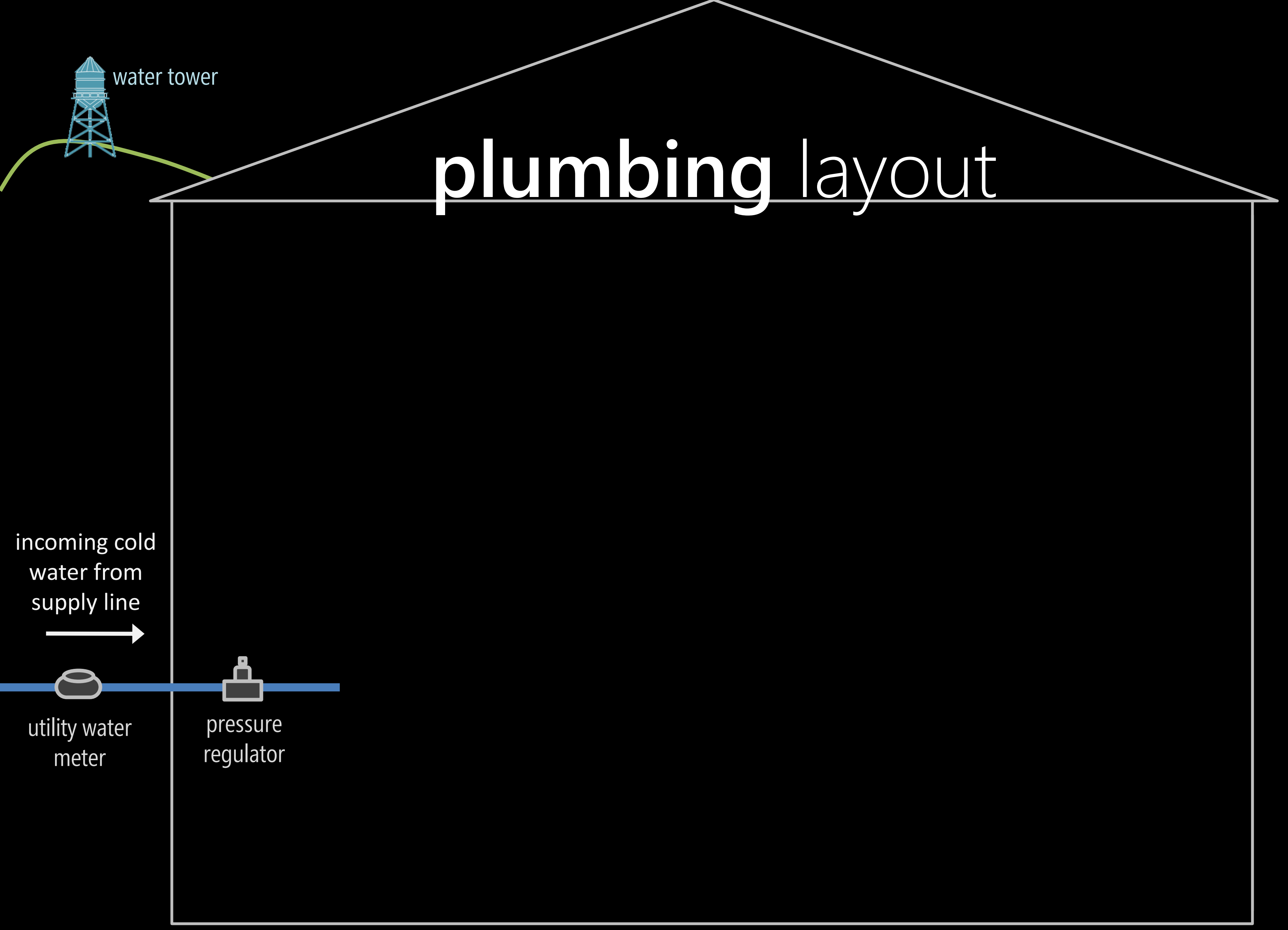


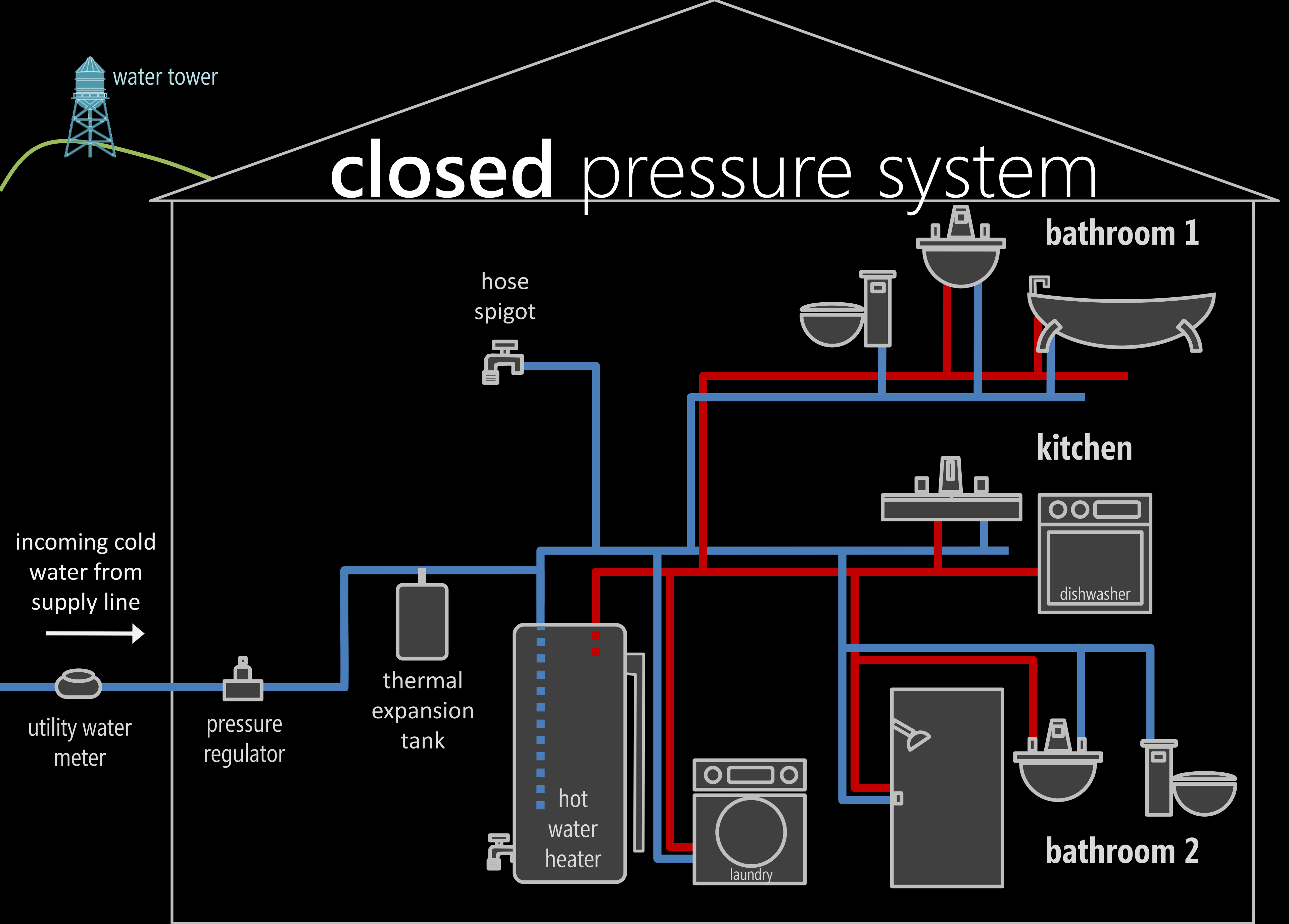
plumbing primer



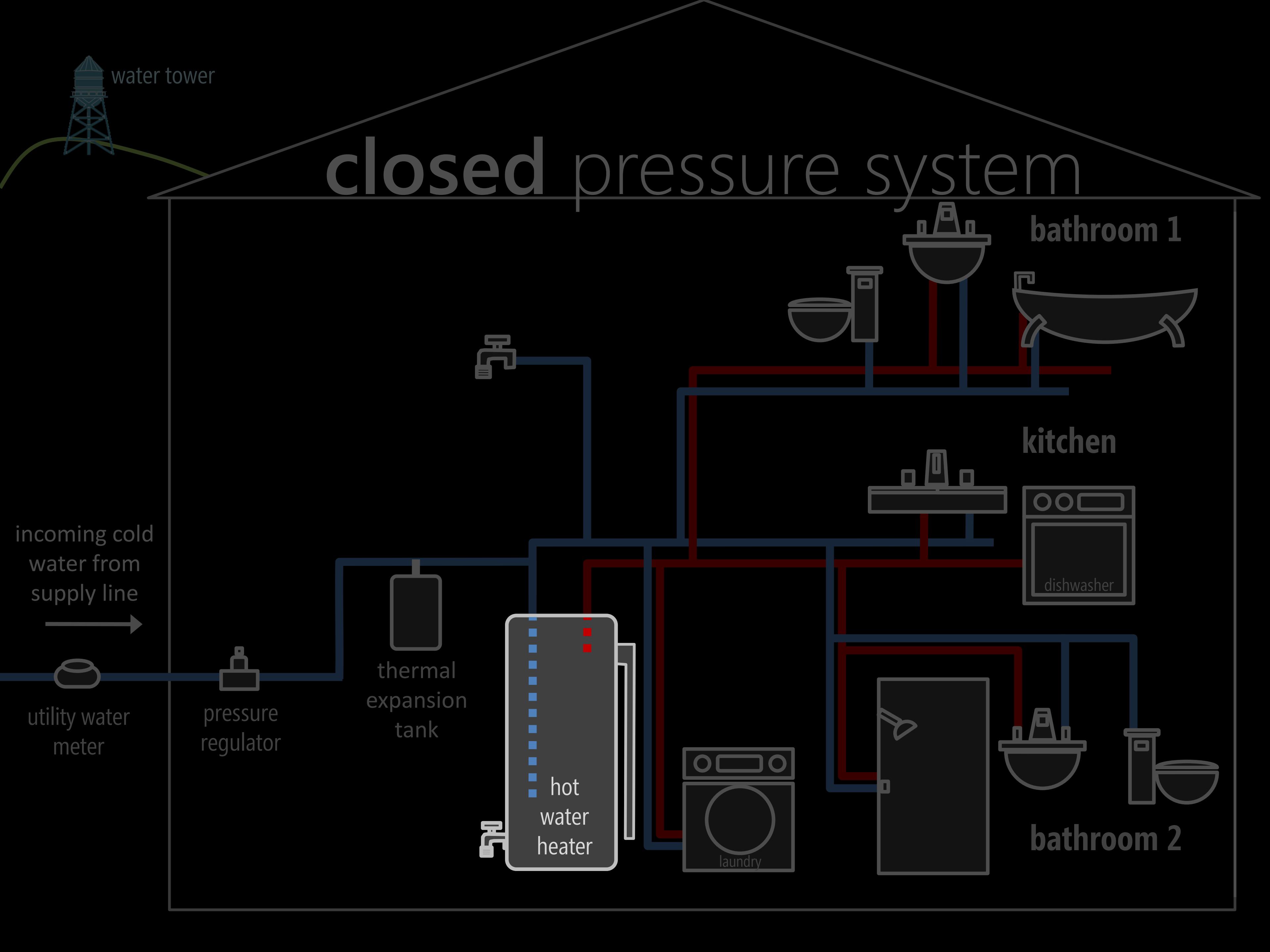
pressure regulator



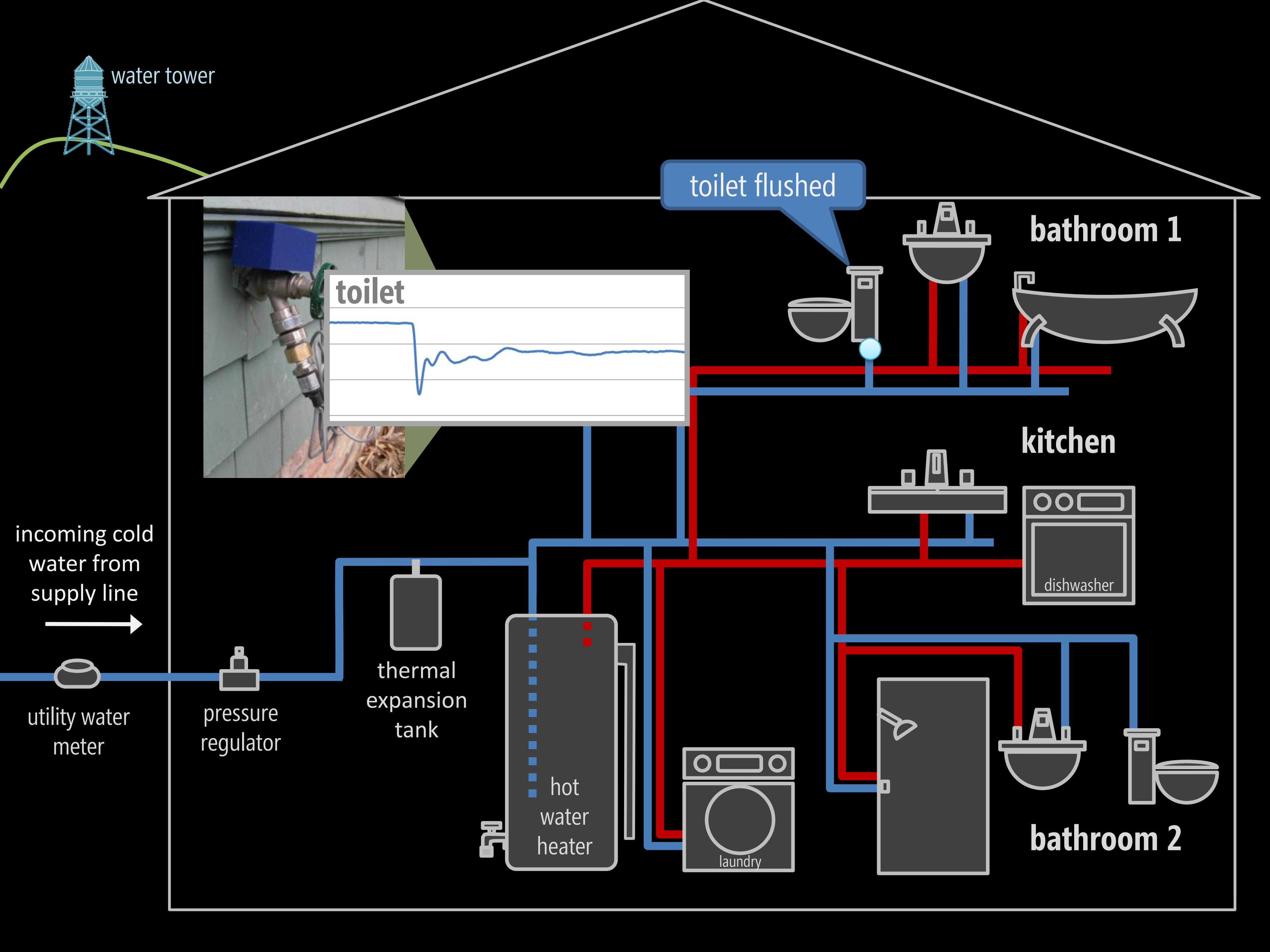

water tower
plumbing layout
incoming cold water from supply line
utility water meter
pressure regulator



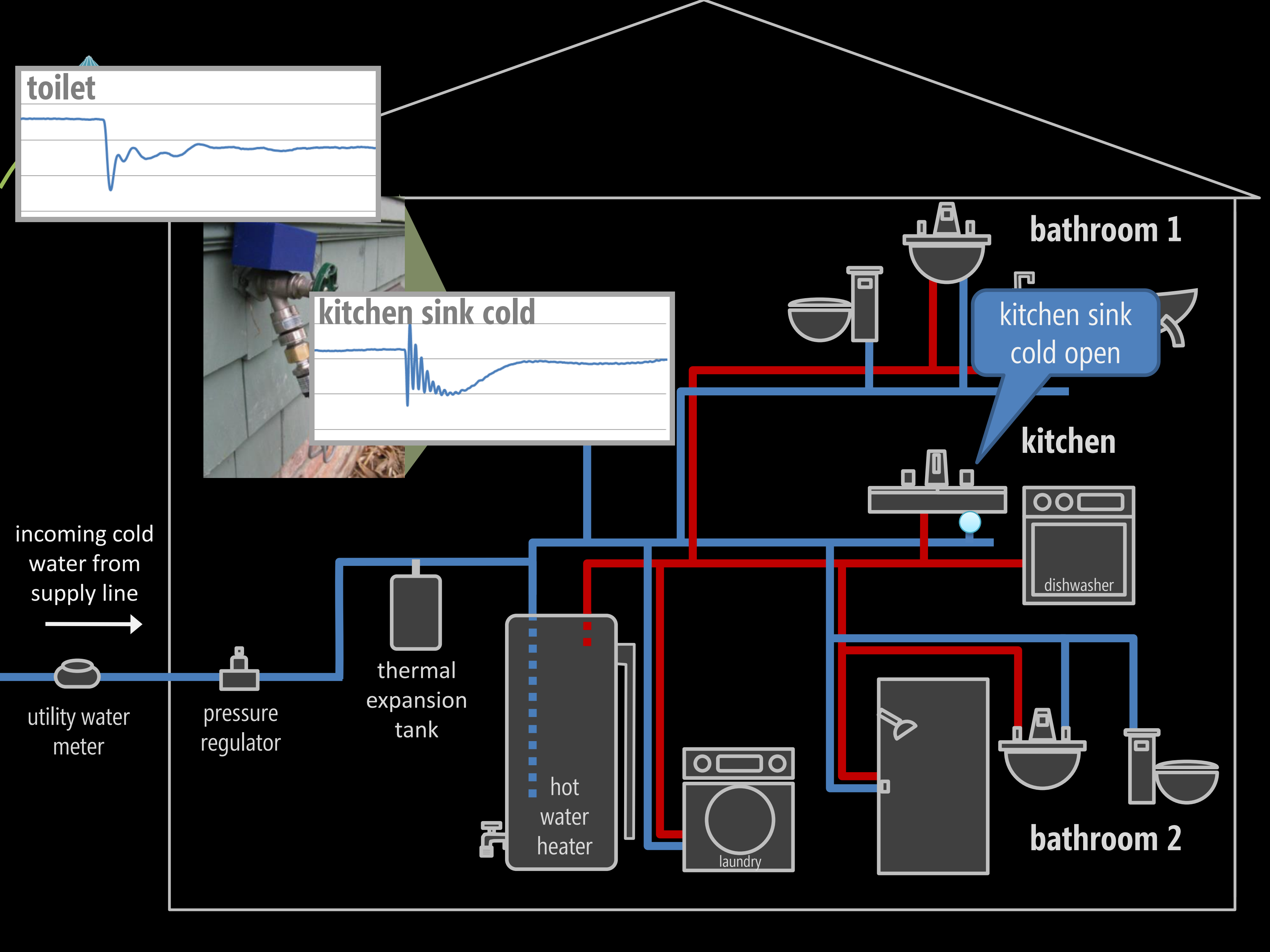
water tower
closed pressure system
bathroom 1
hose spigot
kitchen
dishwasher
incoming cold water from supply line
utility water meter
pressure regulator
thermal expansion tank
hot water heater
laundry
bathroom 2

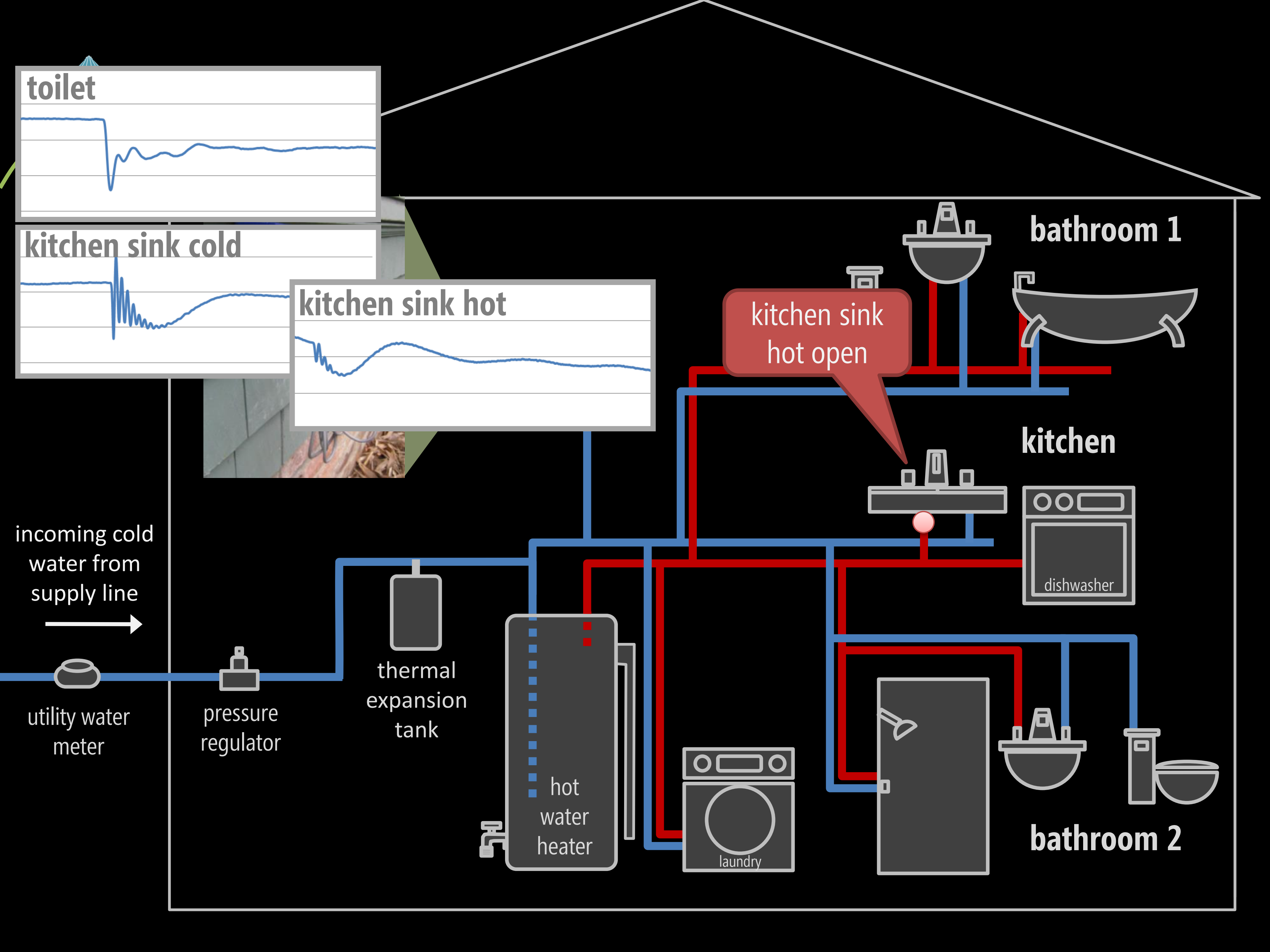


closed pressure system
water tower
bathroom 1
kitchen
dishwasher
incoming cold water from supply line
utility water meter
pressure regulator
thermal expansion tank
hot water heater
laundry
bathroom 2

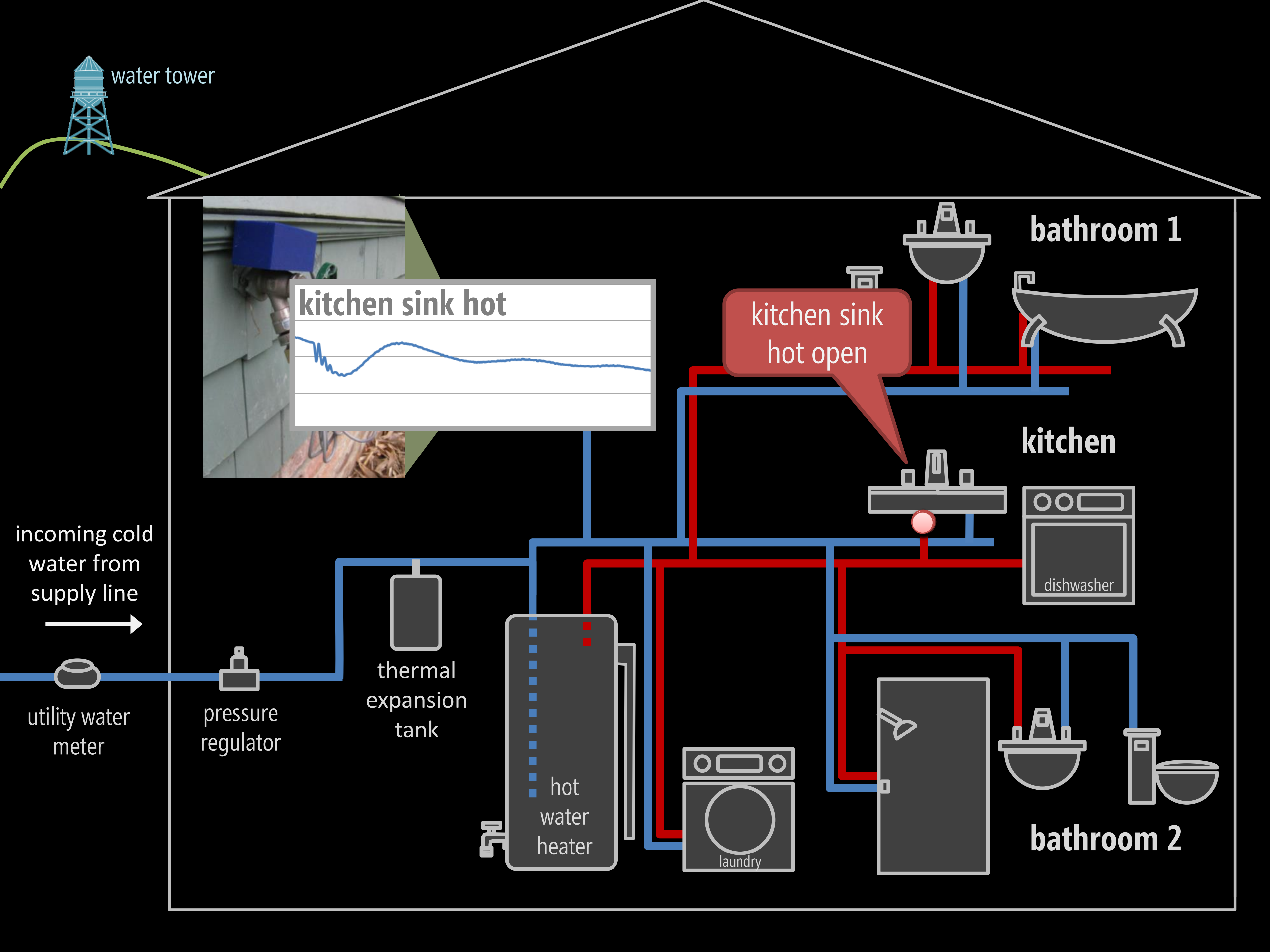


water tower
toilet flushed
toilet
bathroom 1
kitchen
dishwasher
incoming cold water from supply line
utility water meter
pressure regulator
thermal expansion tank
hot water heater
laundry
bathroom 2

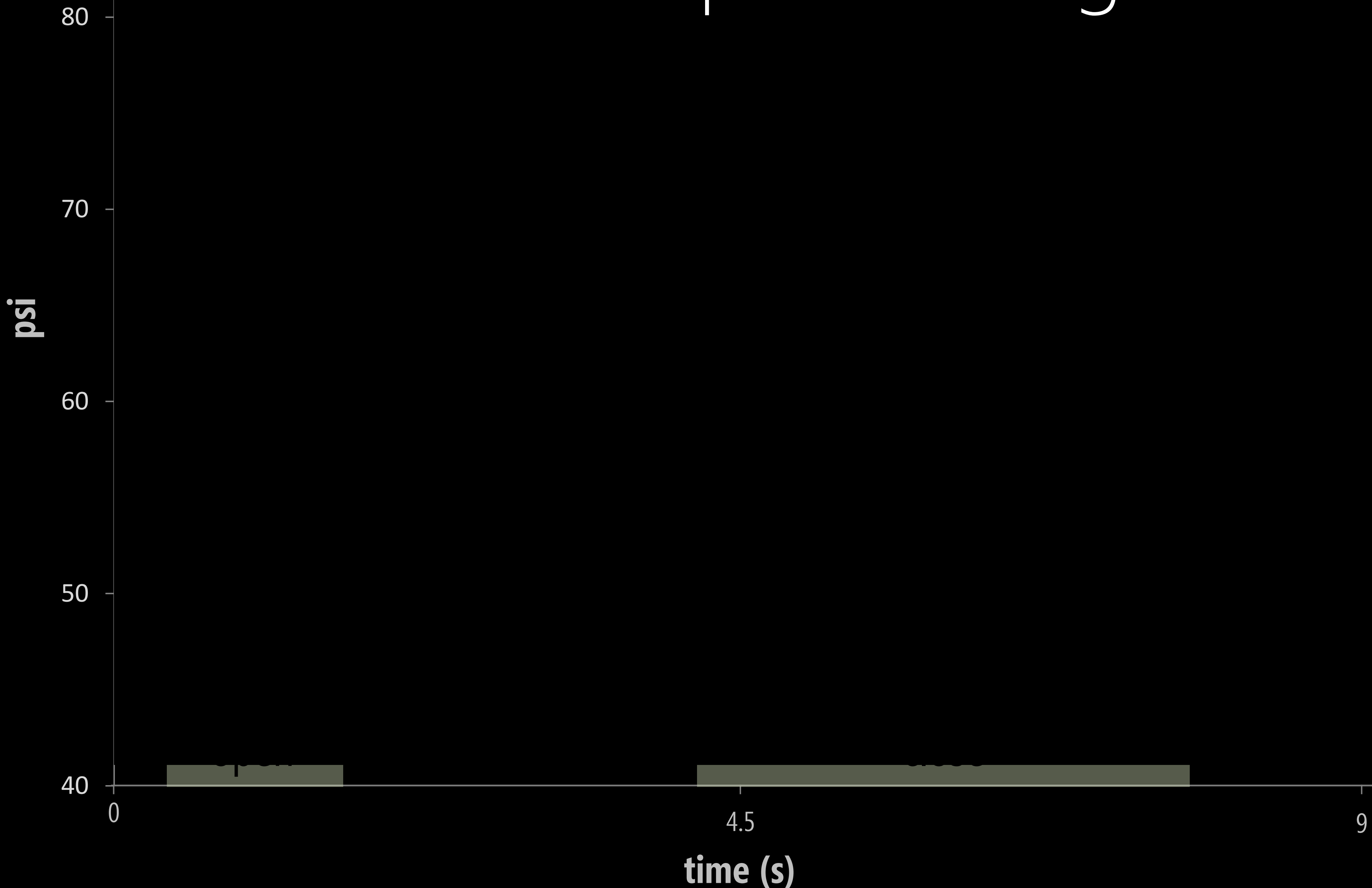

toilet
kitchen sink cold
bathroom 1
kitchen sink
cold open
kitchen
dishwasher
incoming cold
water from
supply line
utility water
meter
pressure
regulator
thermal
expansion
tank
hot
water
heater
laundry
bathroom 2



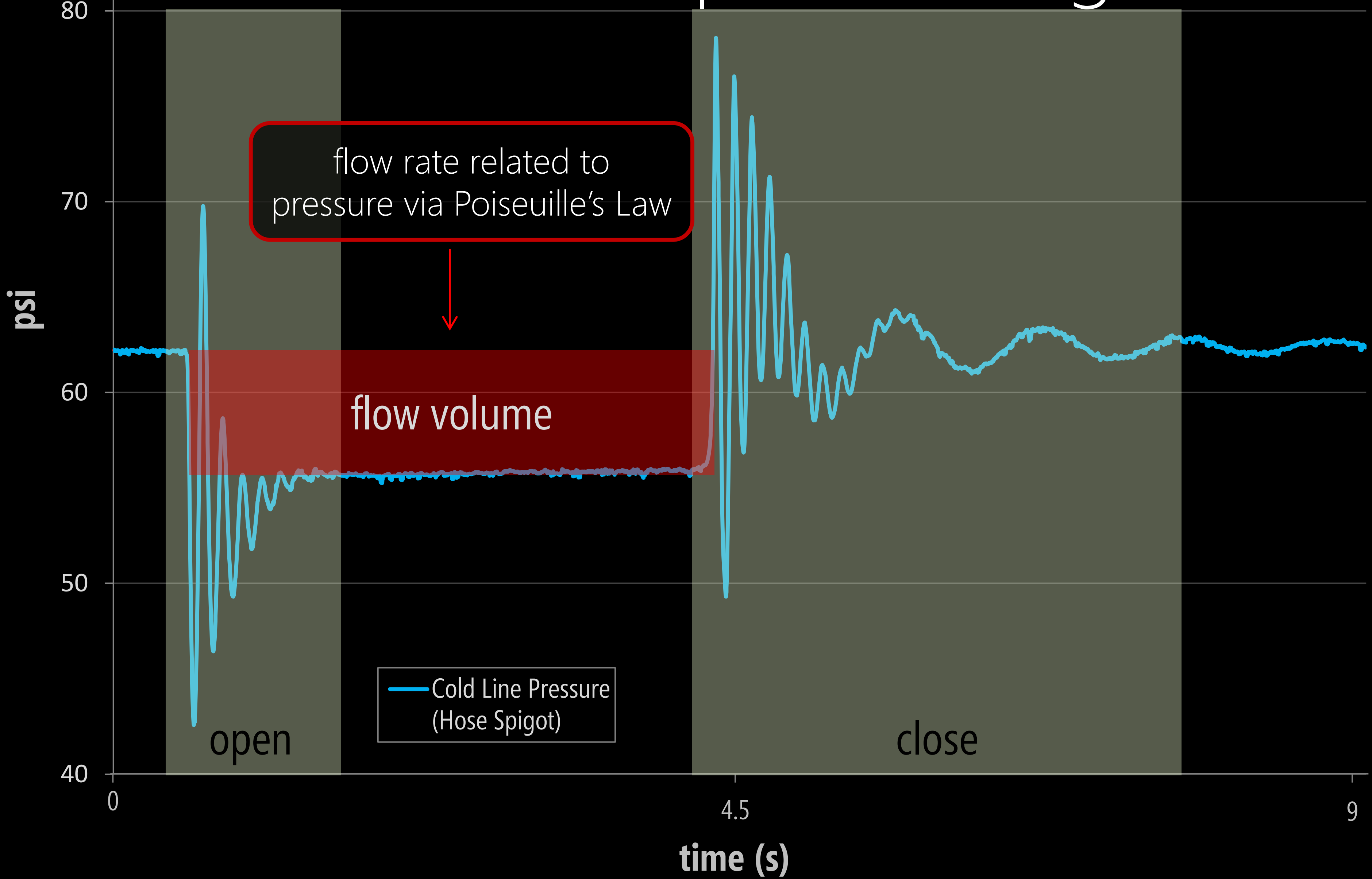
toilet
kitchen sink cold
kitchen sink hot
bathroom 1
kitchen sink
hot open
kitchen
incoming cold
water from
supply line
dishwasher
thermal
expansion
tank
utility water
meter
pressure
regulator
hot
water
heater
laundry
bathroom 2

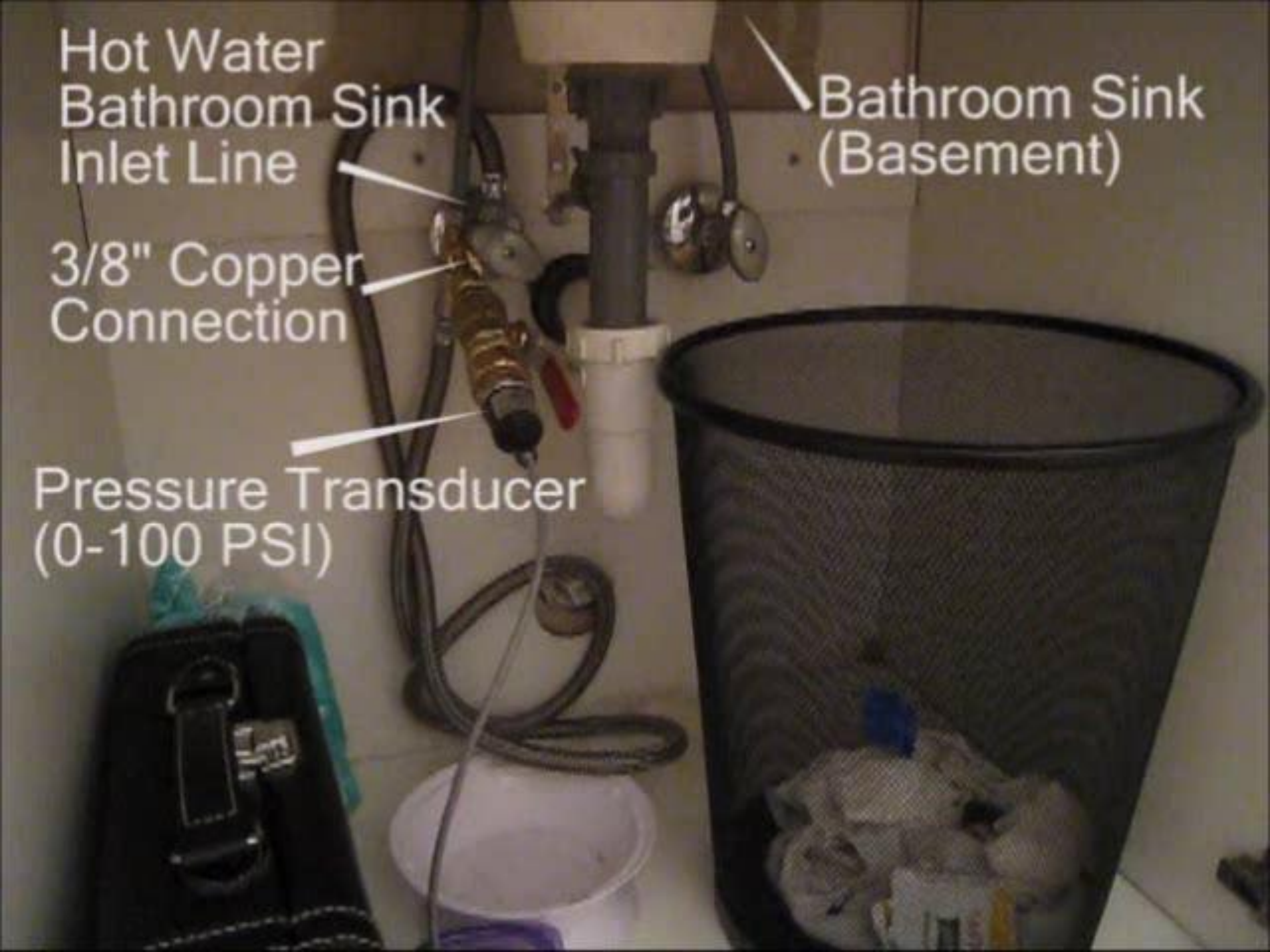

water tower
kitchen sink hot
kitchen sink
hot open
bathroom 1
kitchen
dishwasher
incoming cold
water from
supply line
utility water
meter
pressure
regulator
thermal
expansion
tank
hot
water
heater
laundry
bathroom 2

bathroom sink pressure signal

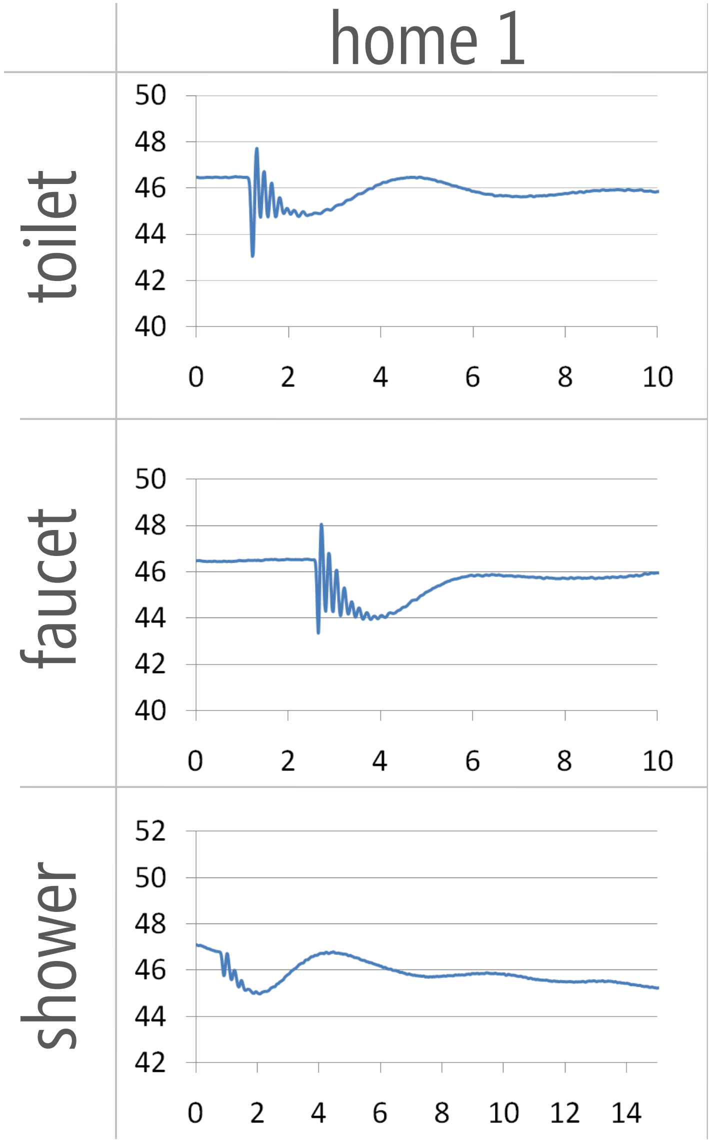


bathroom sink pressure signal




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

example open events



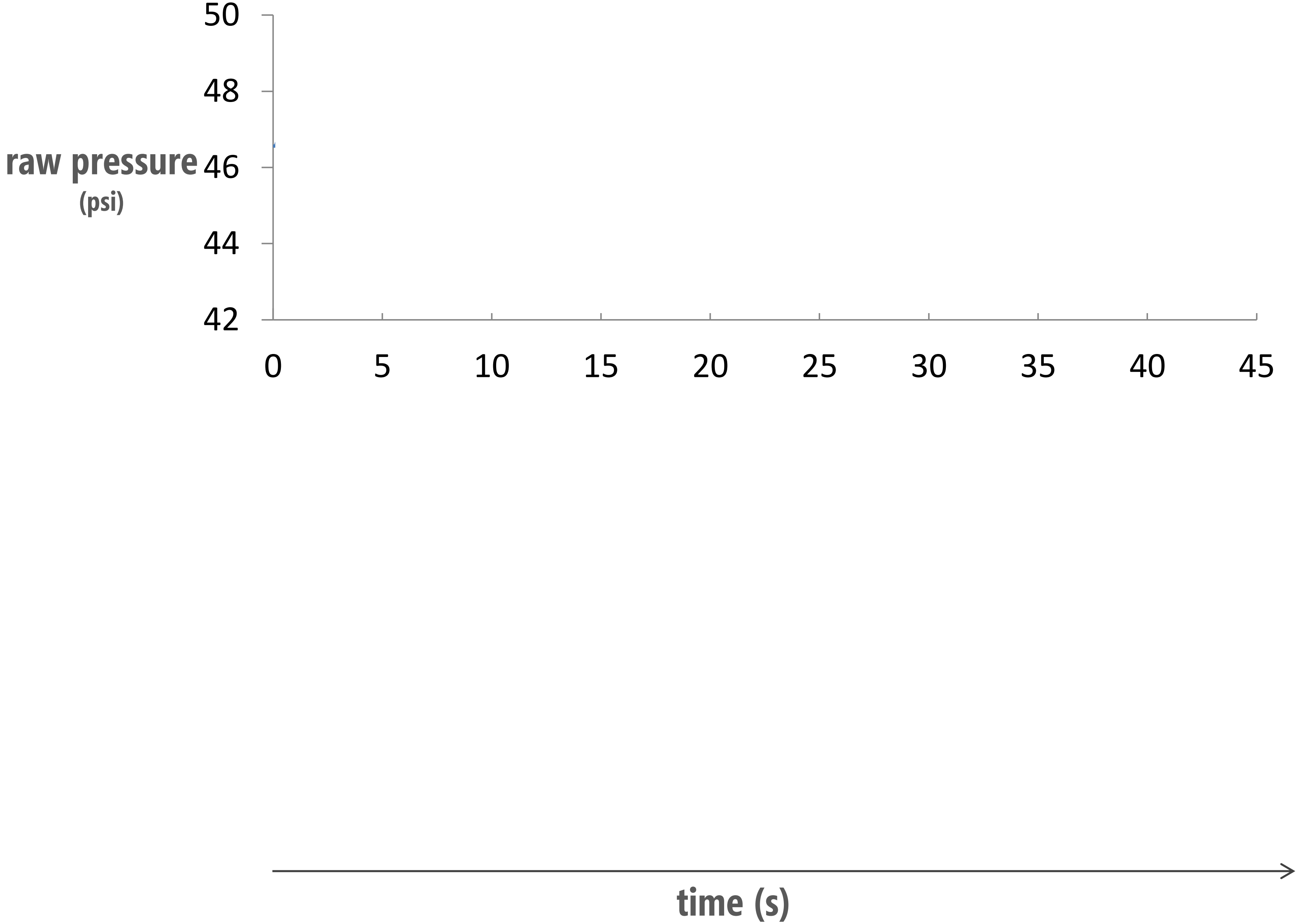
signature dependent on:

- fixture type
- valve type
- valve location in home

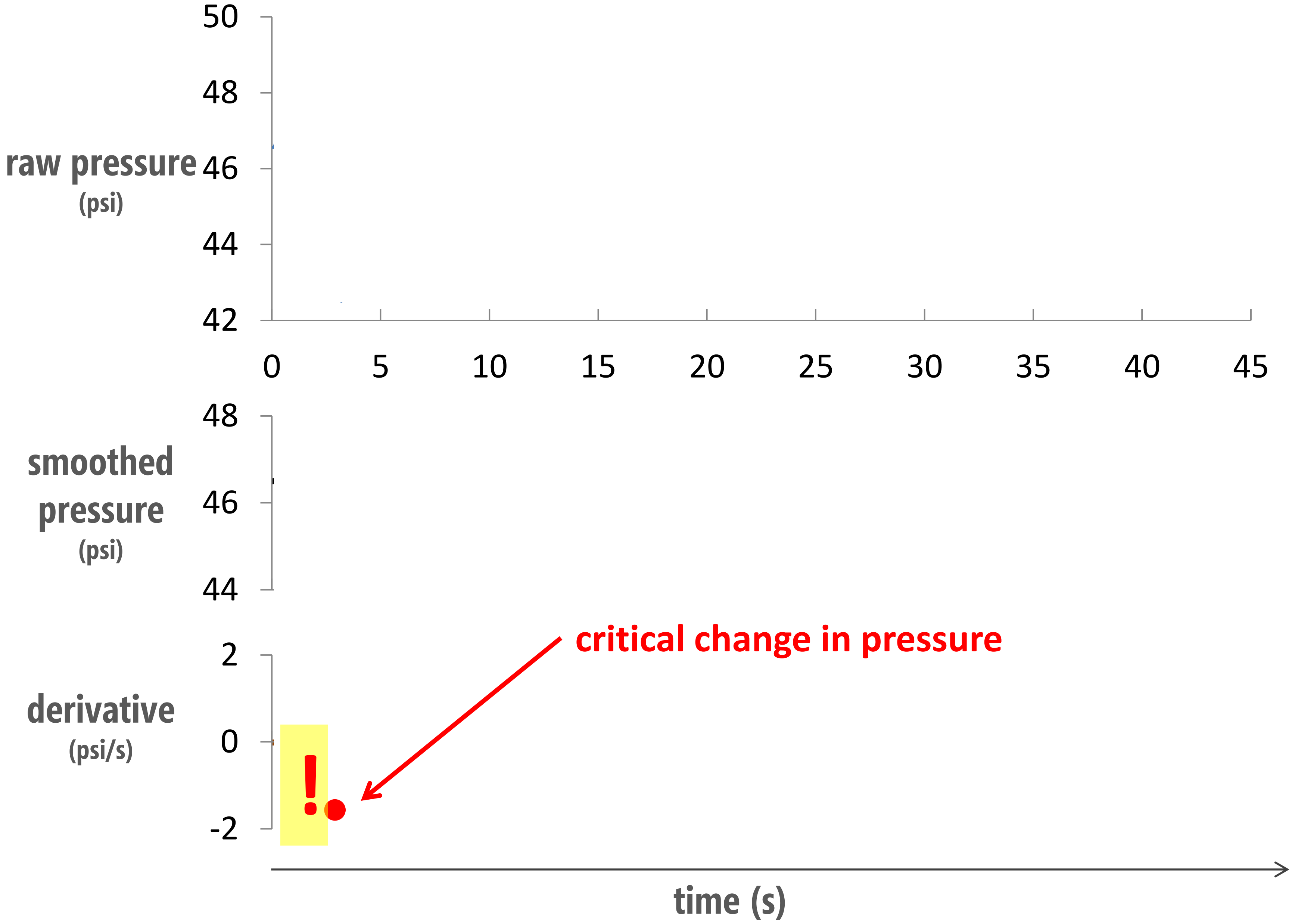
hydro algorithm

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

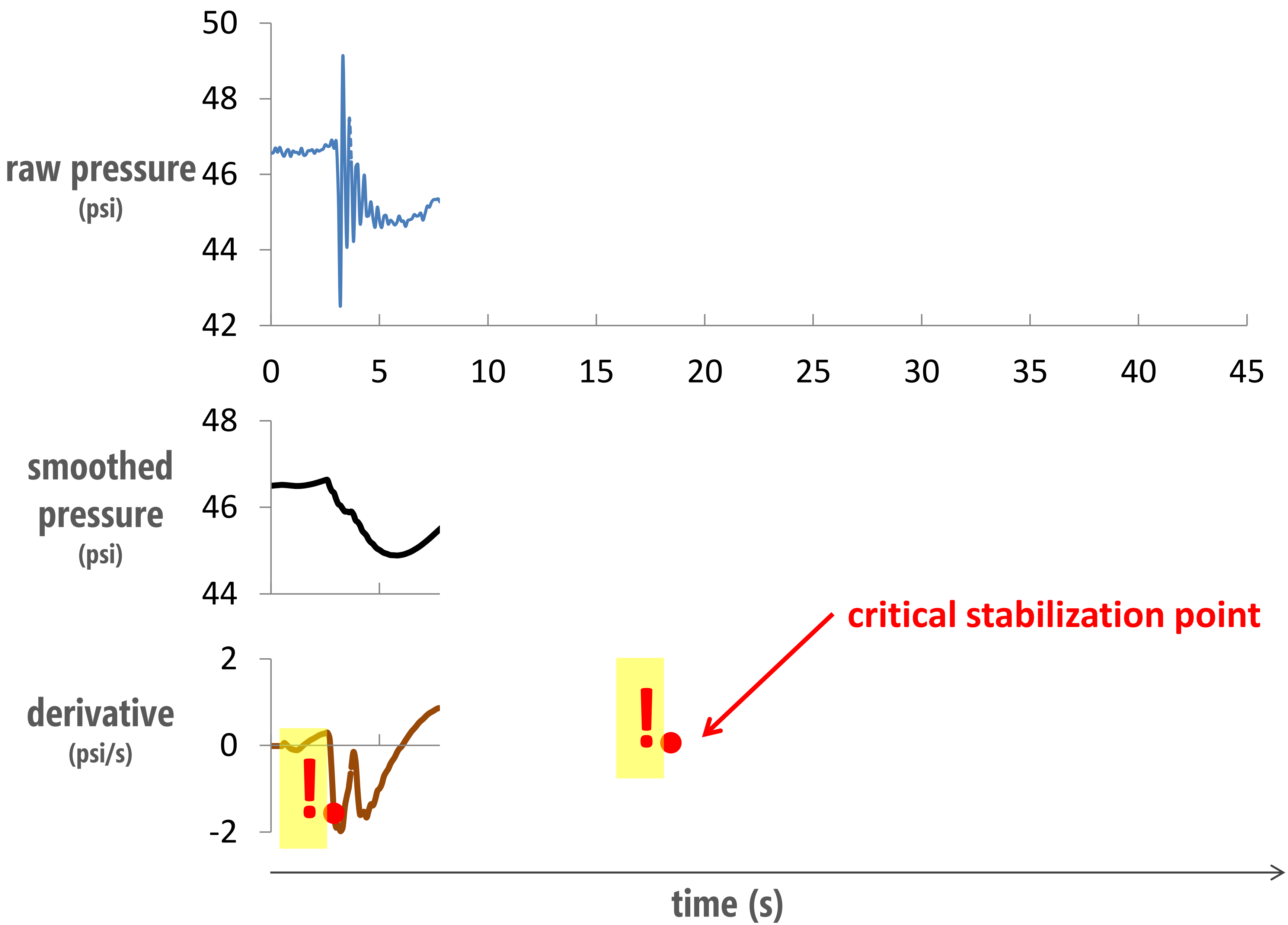
event detection/segmentation



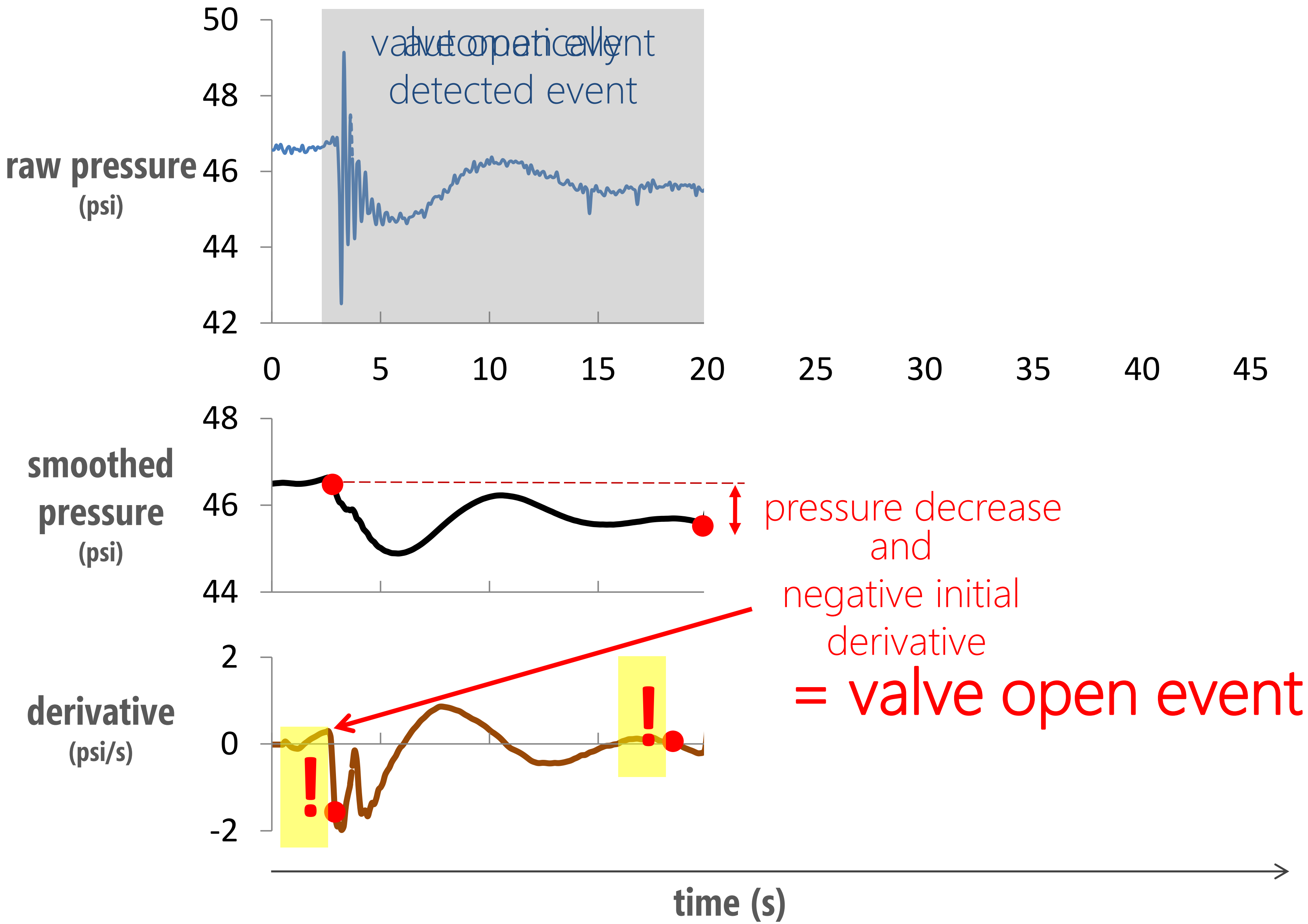
event detection/segmentation



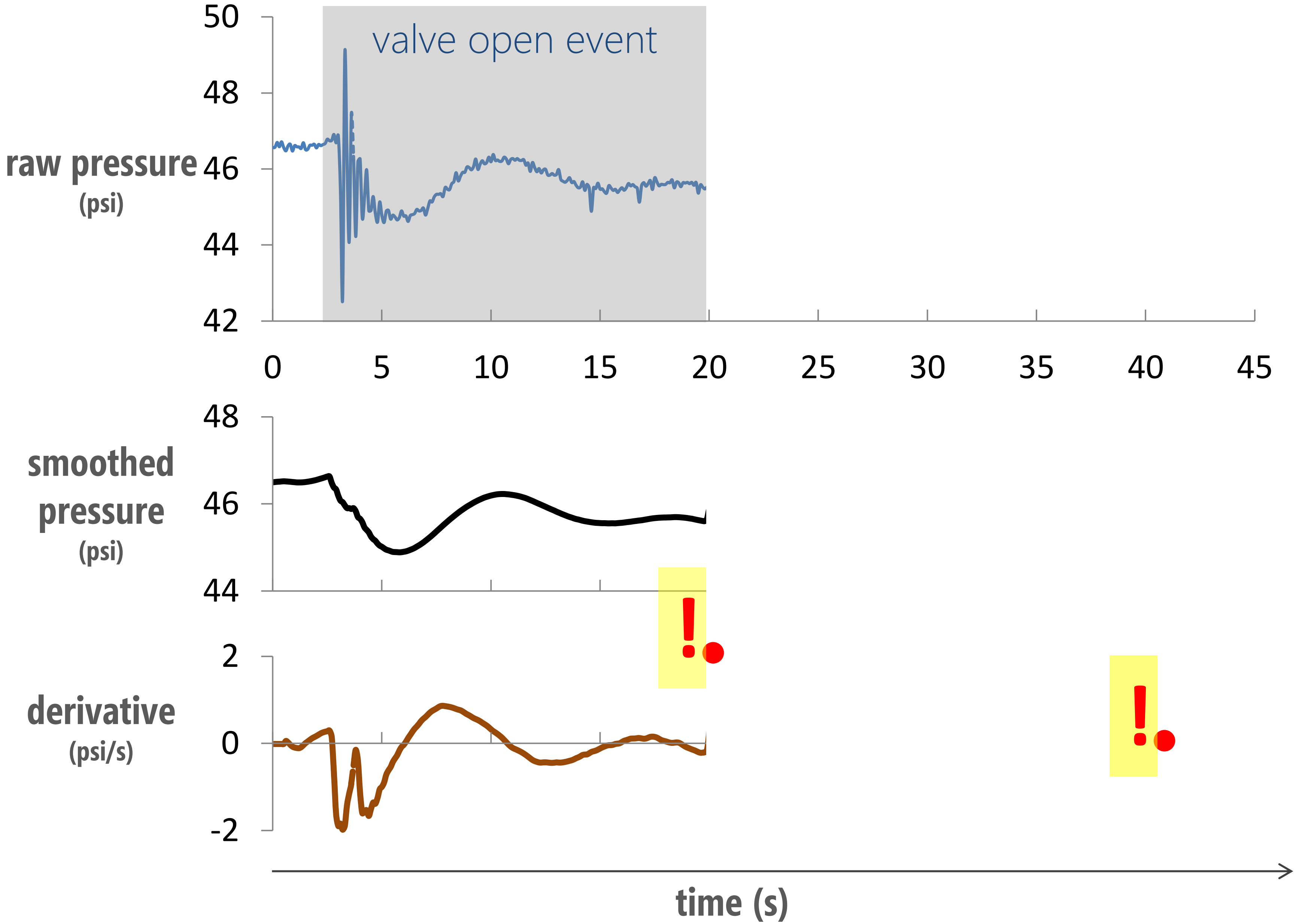
event detection/segmentation



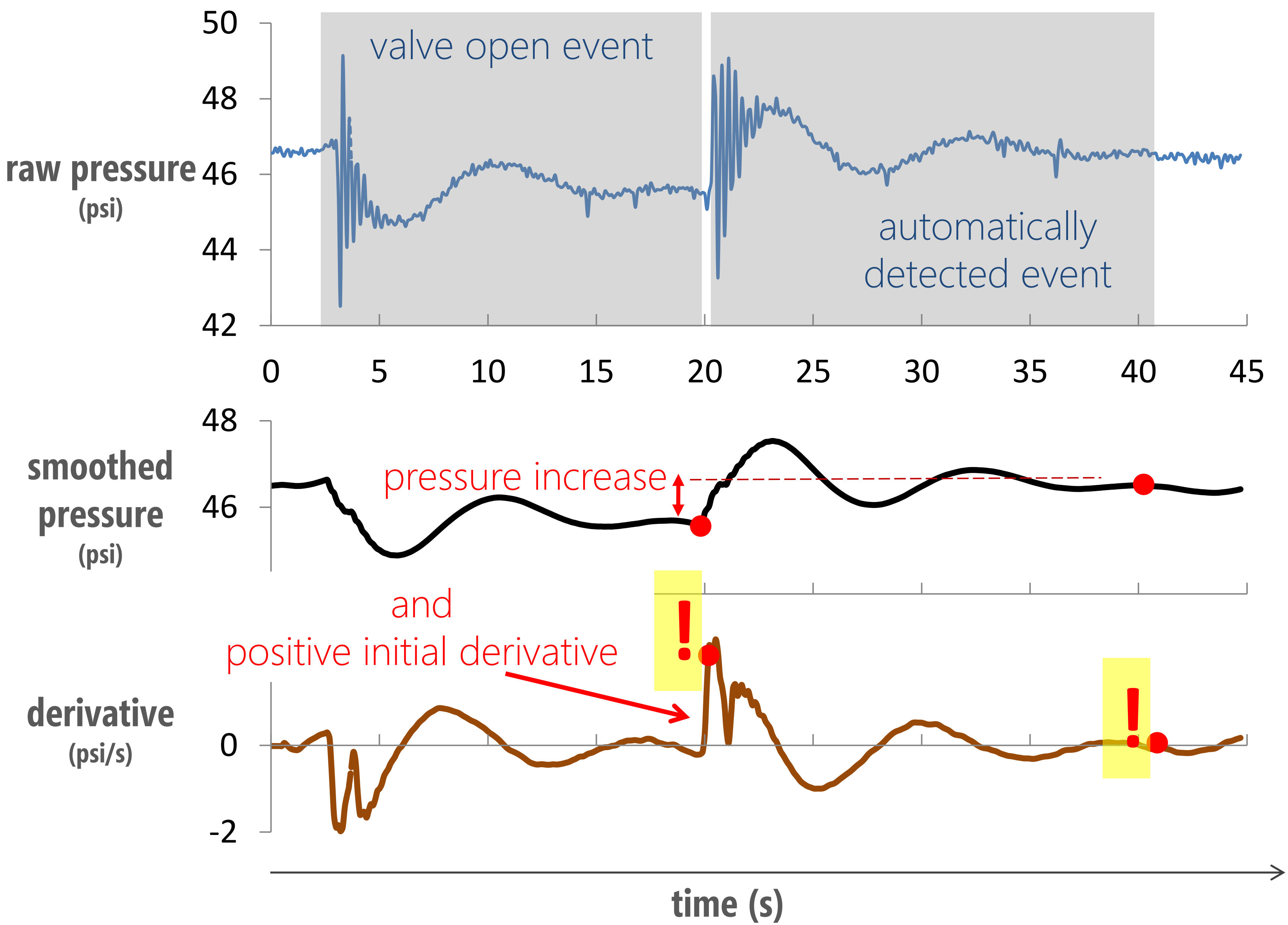
event detection/segmentation



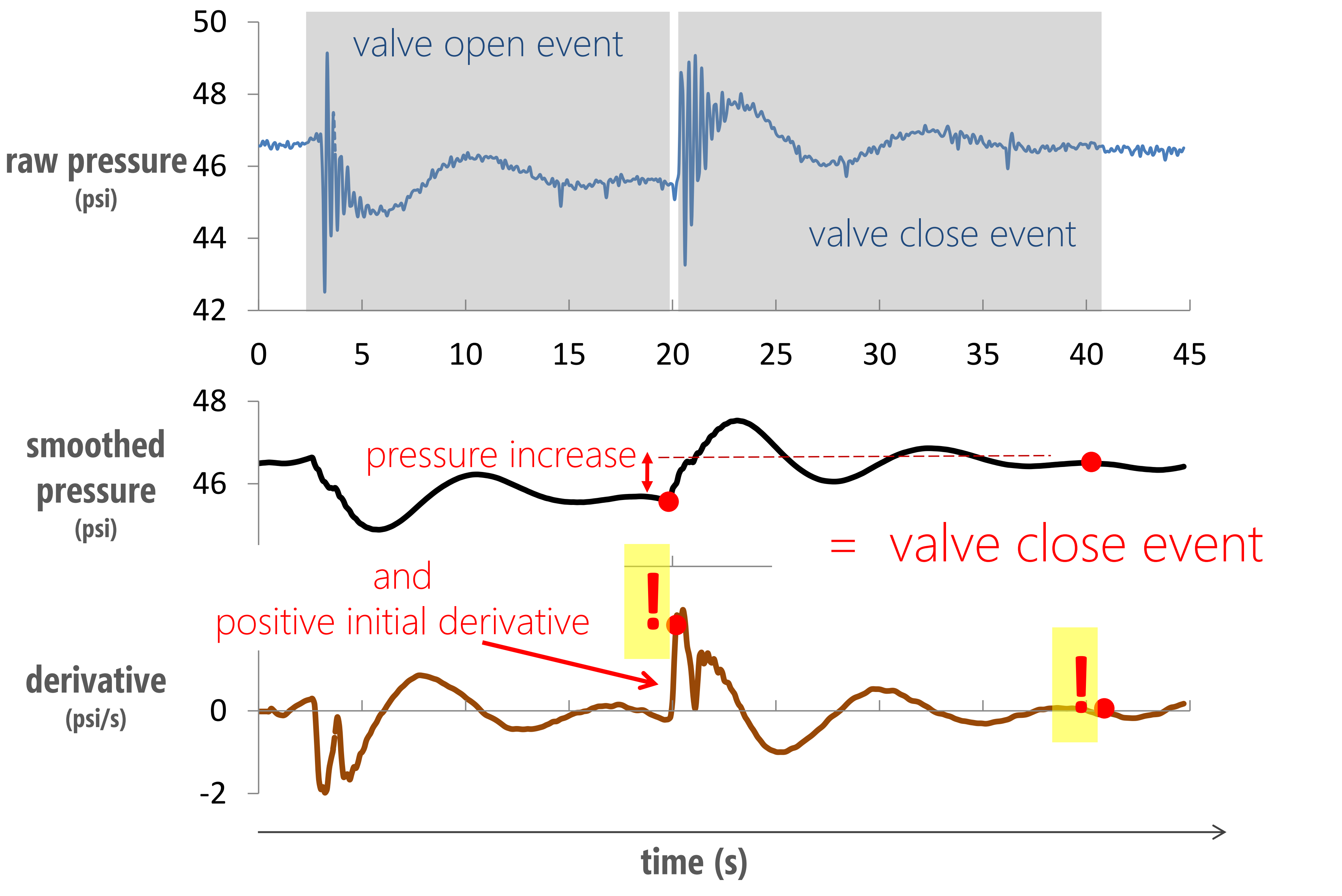
event detection/segmentation



event detection/segmentation

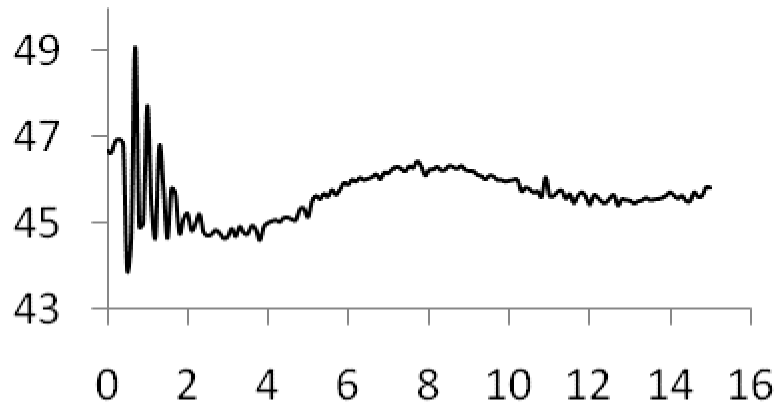


event detection/segmentation

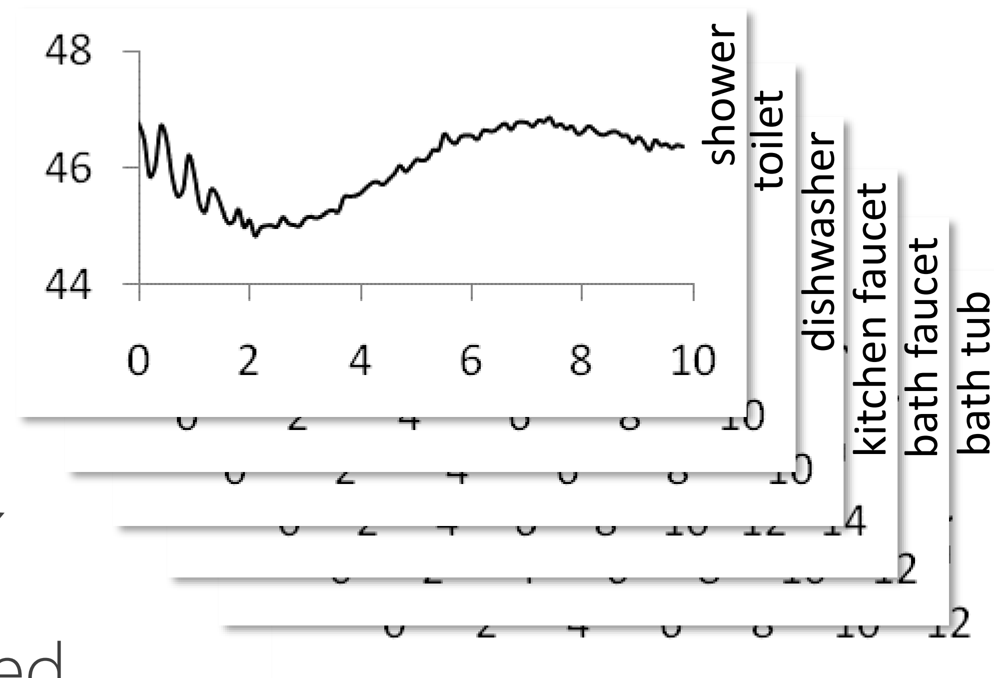


fixture classification

unclassified open event



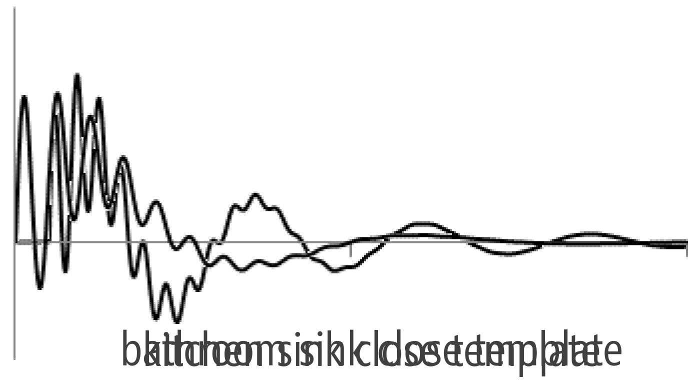
open event library

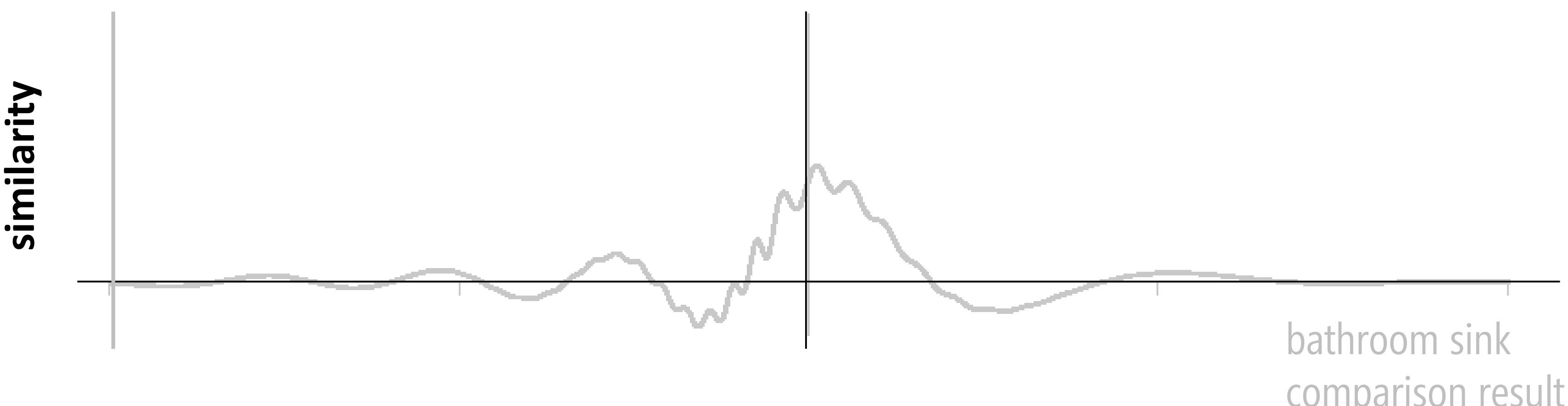


compare via matched filtering across multiple signal transformations

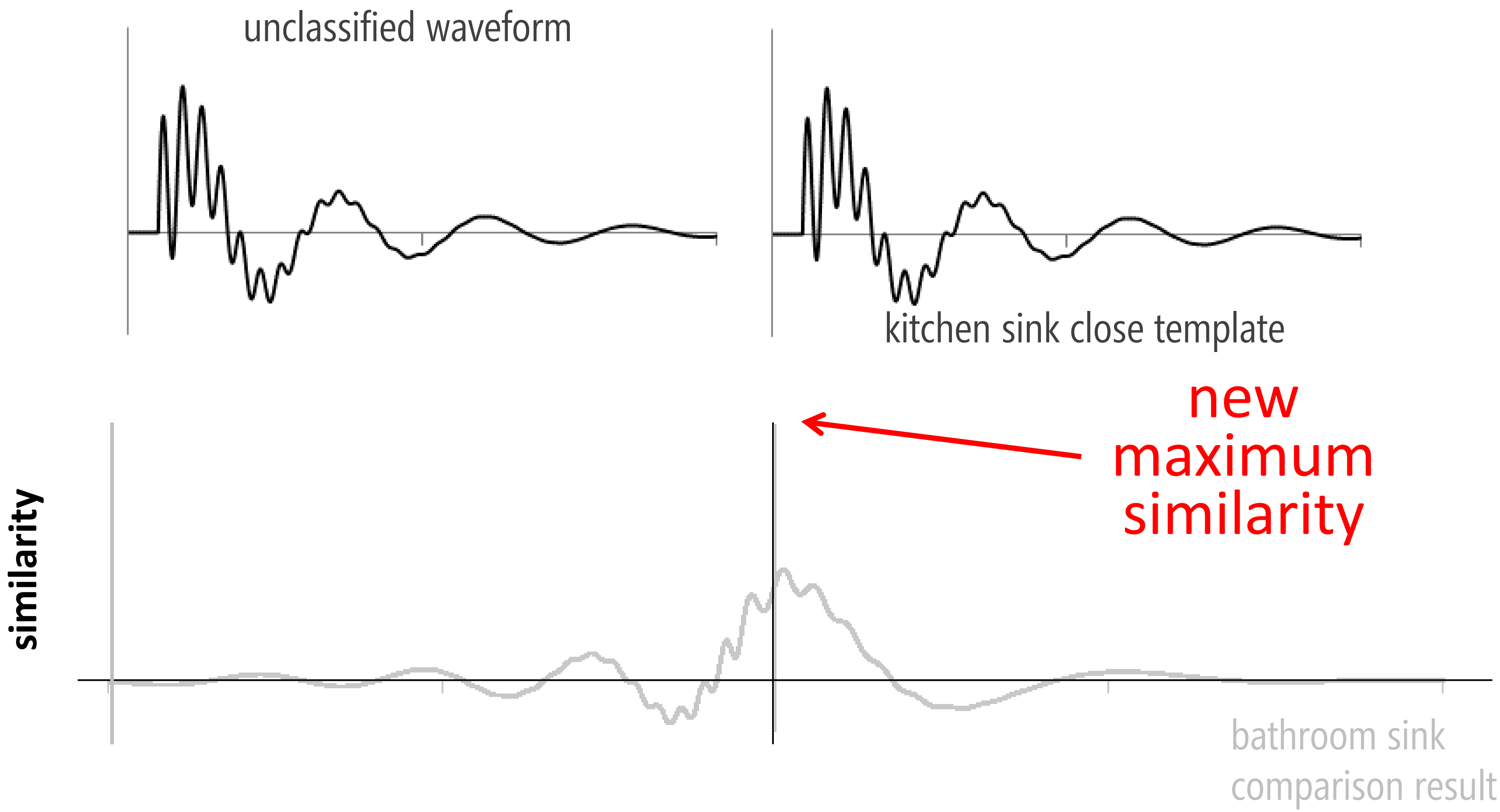
matched filtering

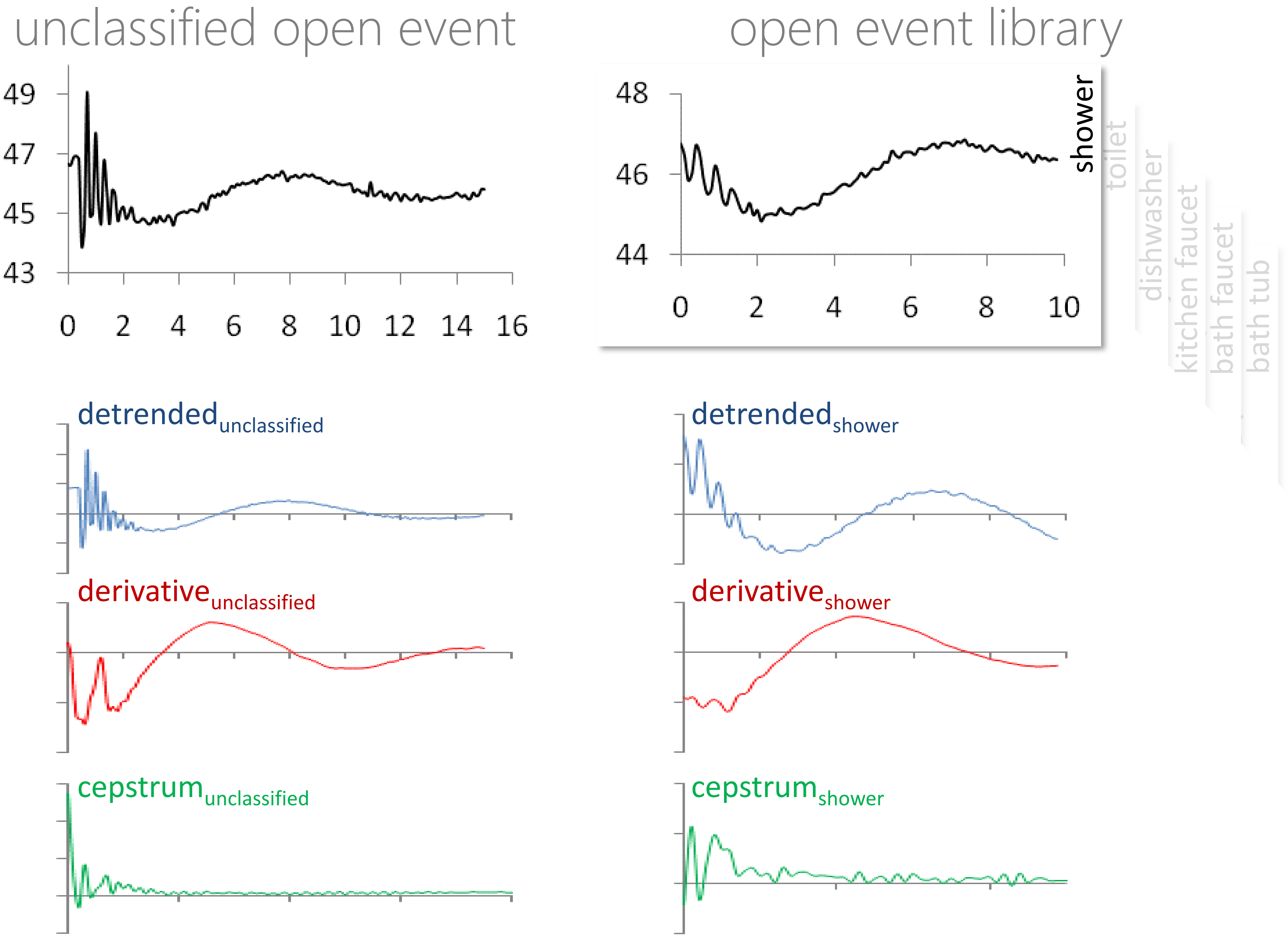
matched filtering

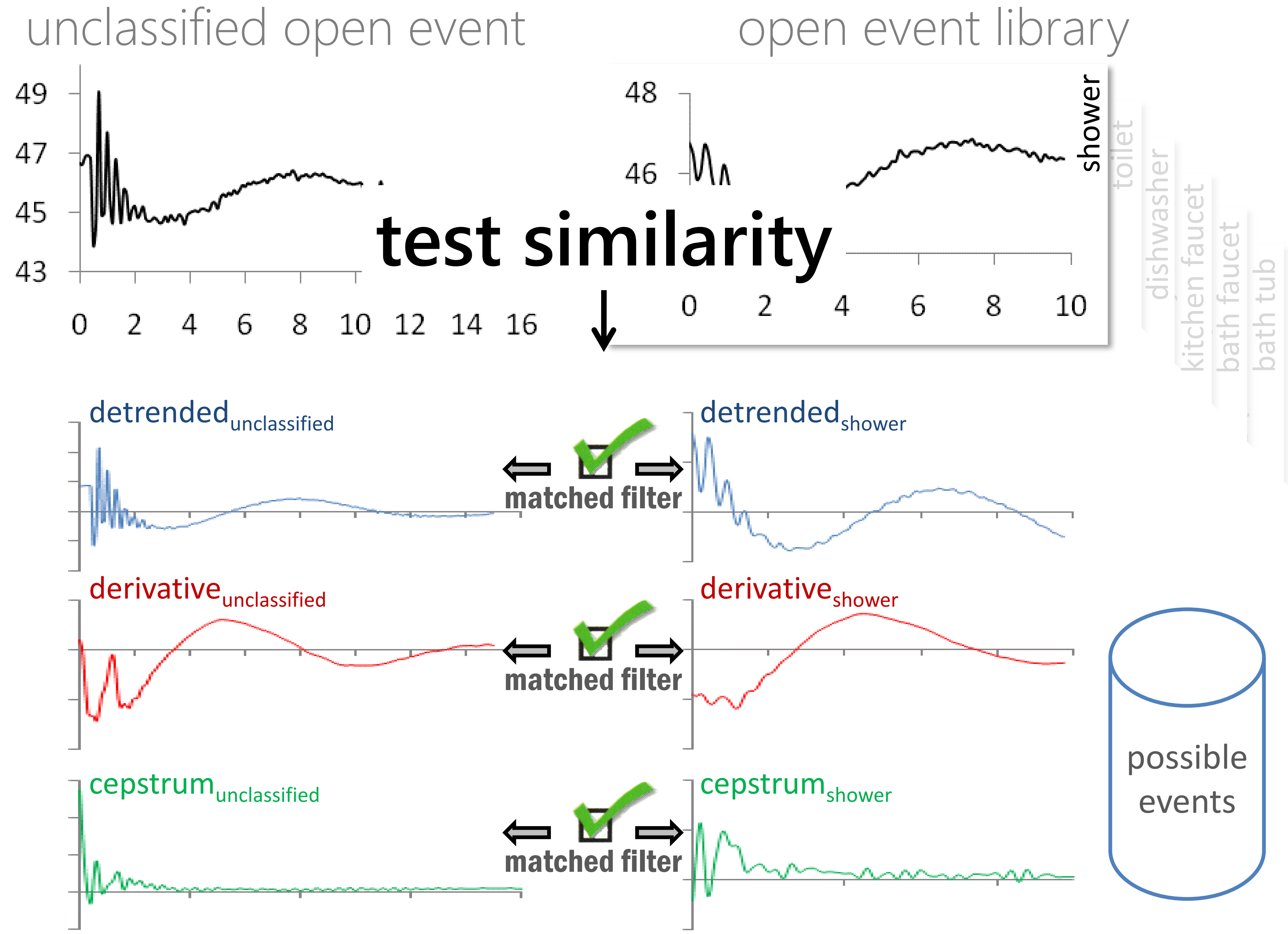




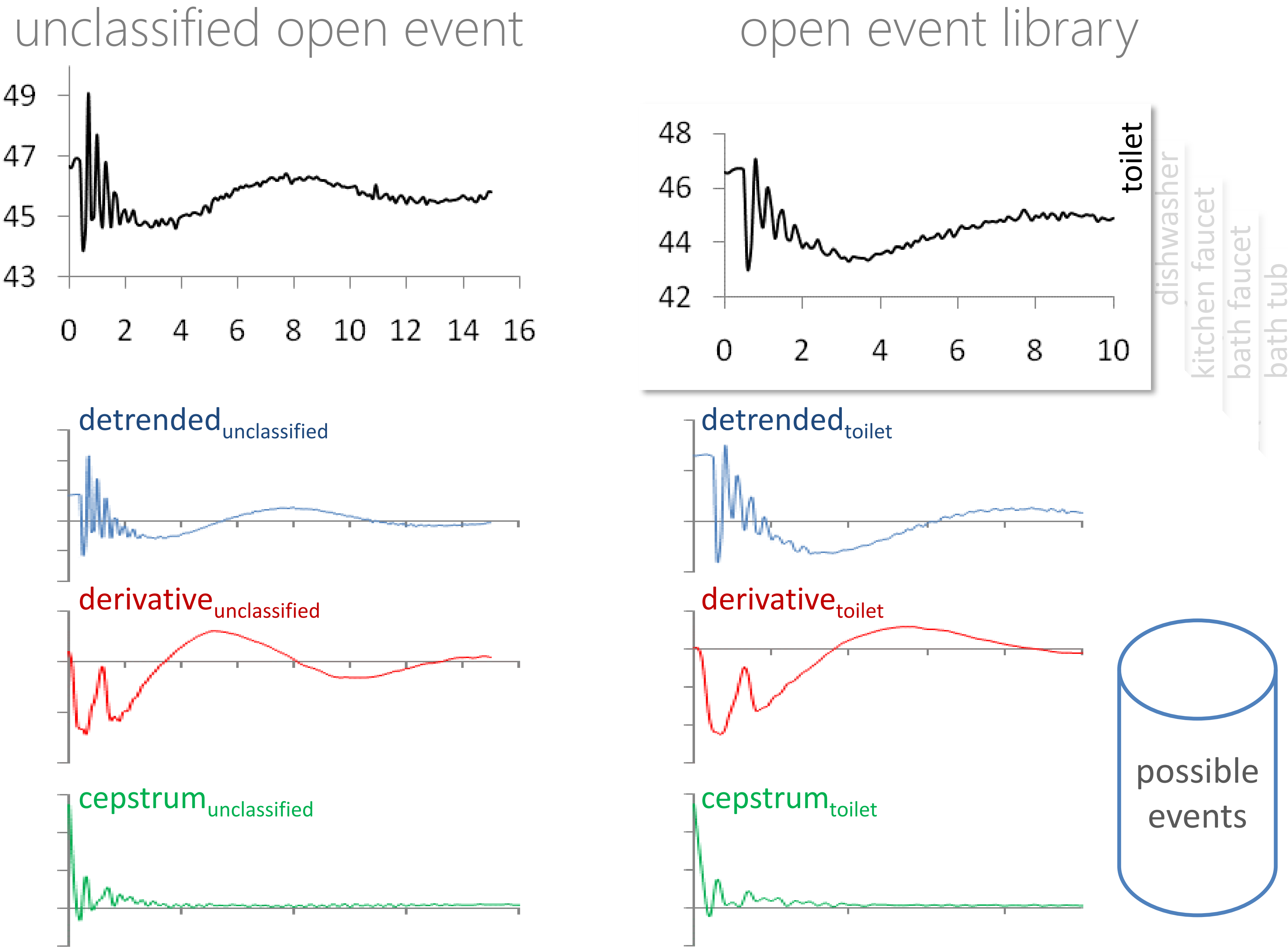
matched filtering



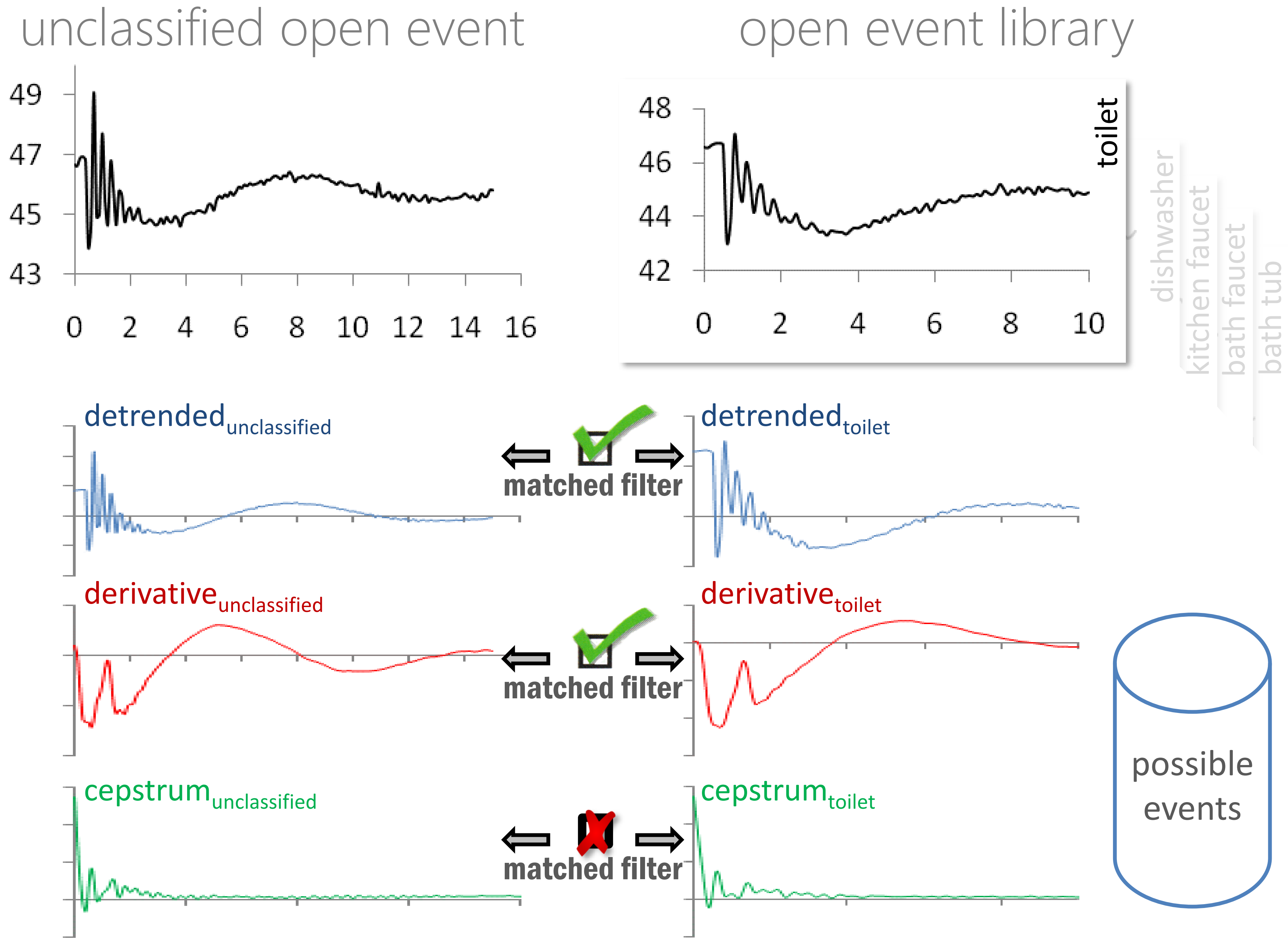

unclassified open event
open event library
49
47
45
43
0 2 4 6 8 10 12 14 16
48
46
44
0 2 4 6 8 10
shower
toilet
dishwasher
kitchen faucet
bath faucet
bath tub
detrended unclassified
detrended shower
derivative unclassified
derivative shower
cepstrum unclassified
cepstrum shower



unclassified open event
open event library
49
47
45
43
0 2 4 6 8 10 12 14 16
48
46
0 2 4 6 8 10
shower
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

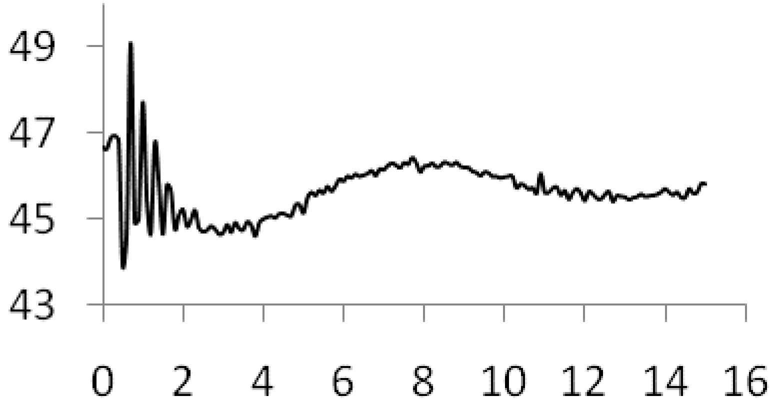


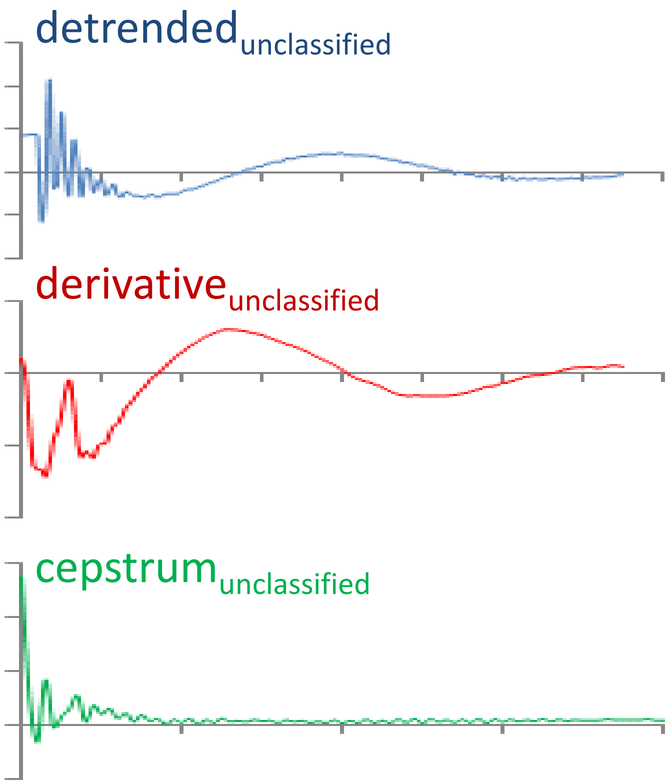
unclassified open event
open event library
49
47
45
43
0 2 4 6 8 10 12 14 16
48
46
44
42
0 2 4 6 8 10
toilet
dishwasher
kitchen faucet
bath faucet
bath tub
detrended unclassified
derivative unclassified
cepstrum unclassified
detrended toilet
derivative toilet
cepstrum toilet
possible events



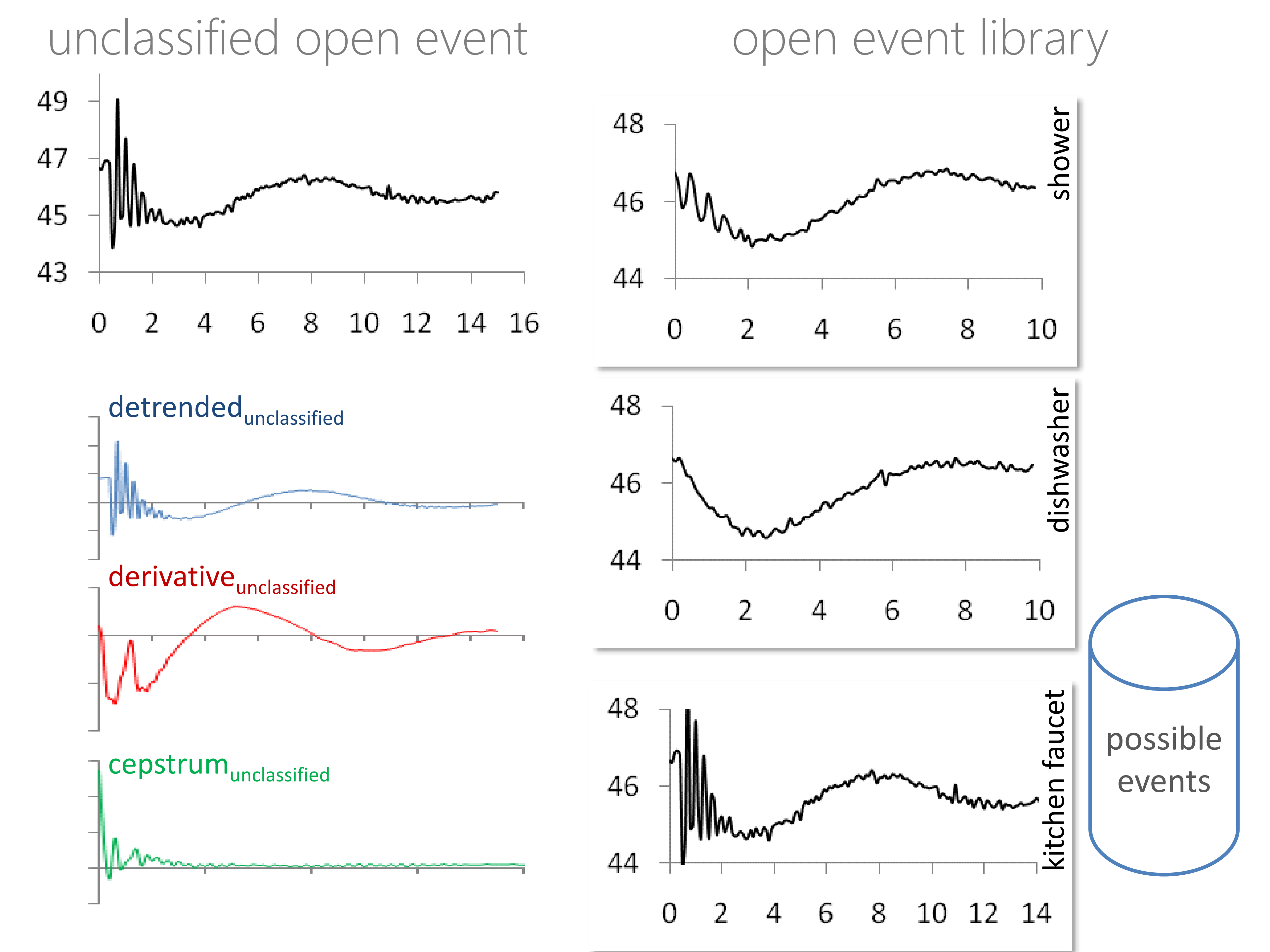
unclassified open event
open event library
49
47
45
43
0
2
4
6
8
10
12
14
16
toilet
48
46
44
42
0
2
4
6
8
10
dishwasher
kitchen faucet
bath faucet
bath tub
detrended unclassified
detrended toilet
matched filter
derivative unclassified
derivative toilet
matched filter
cepstrum unclassified
cepstrum toilet
matched filter
possible events

unclassified open event

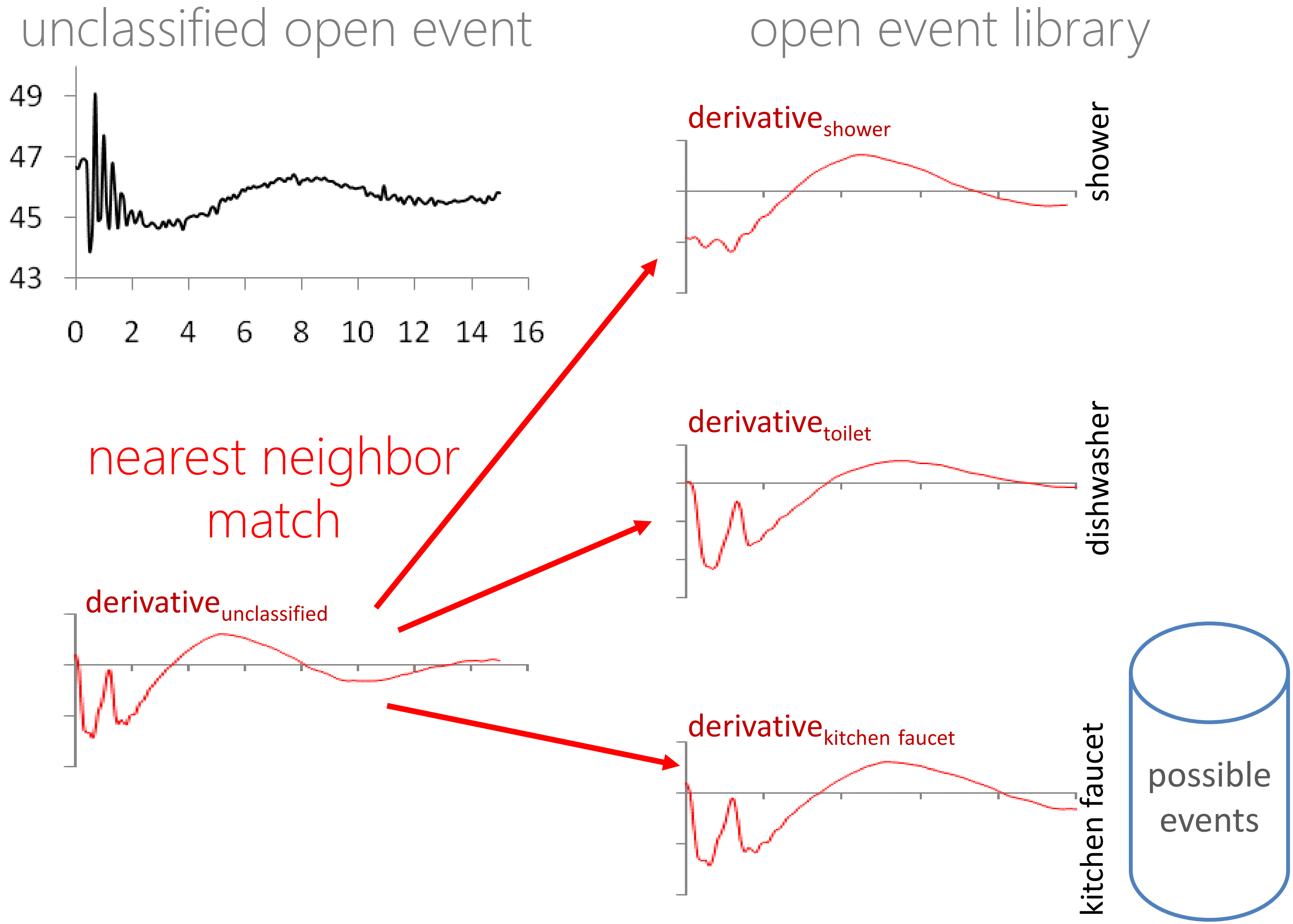




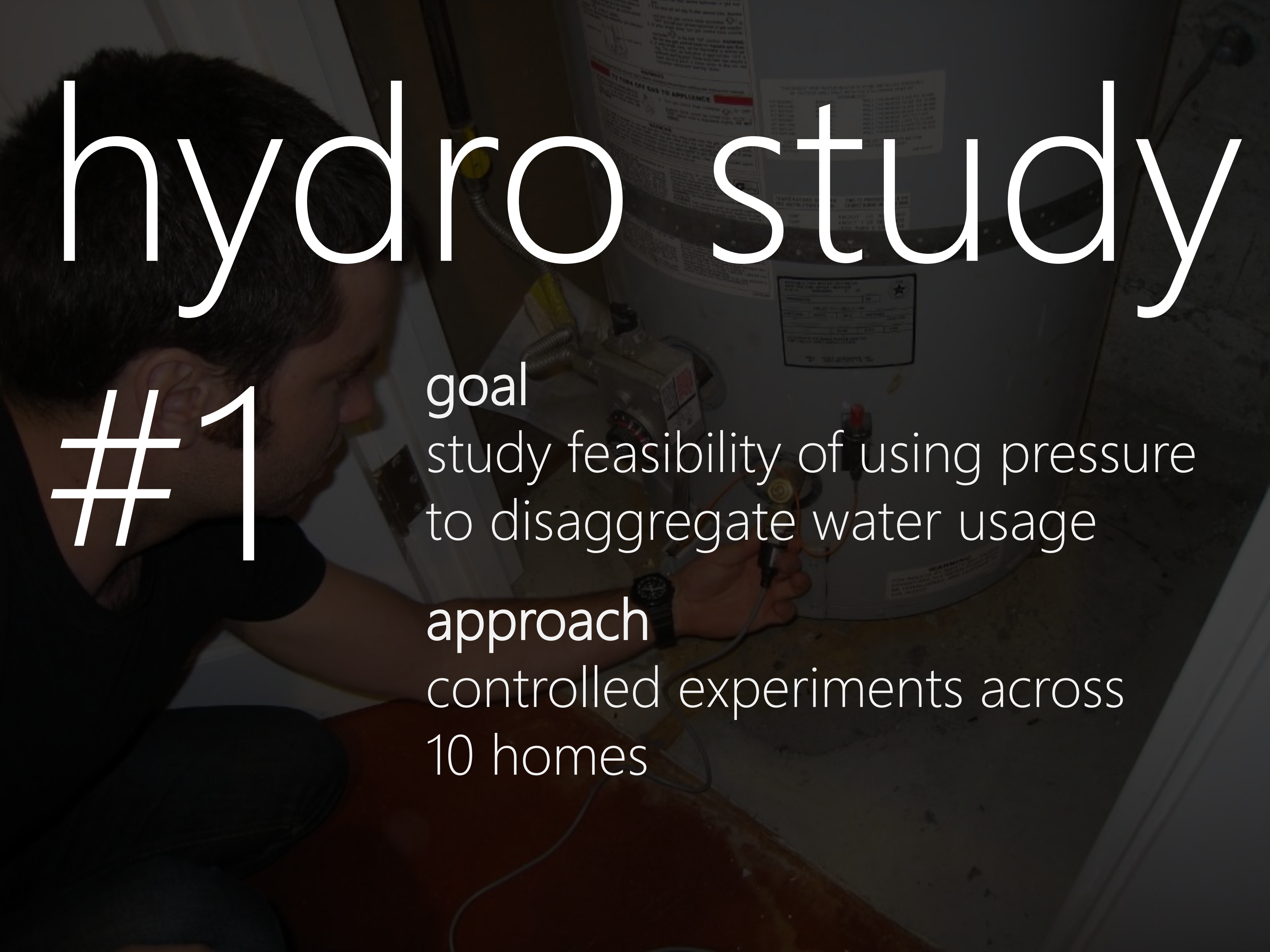
open event library

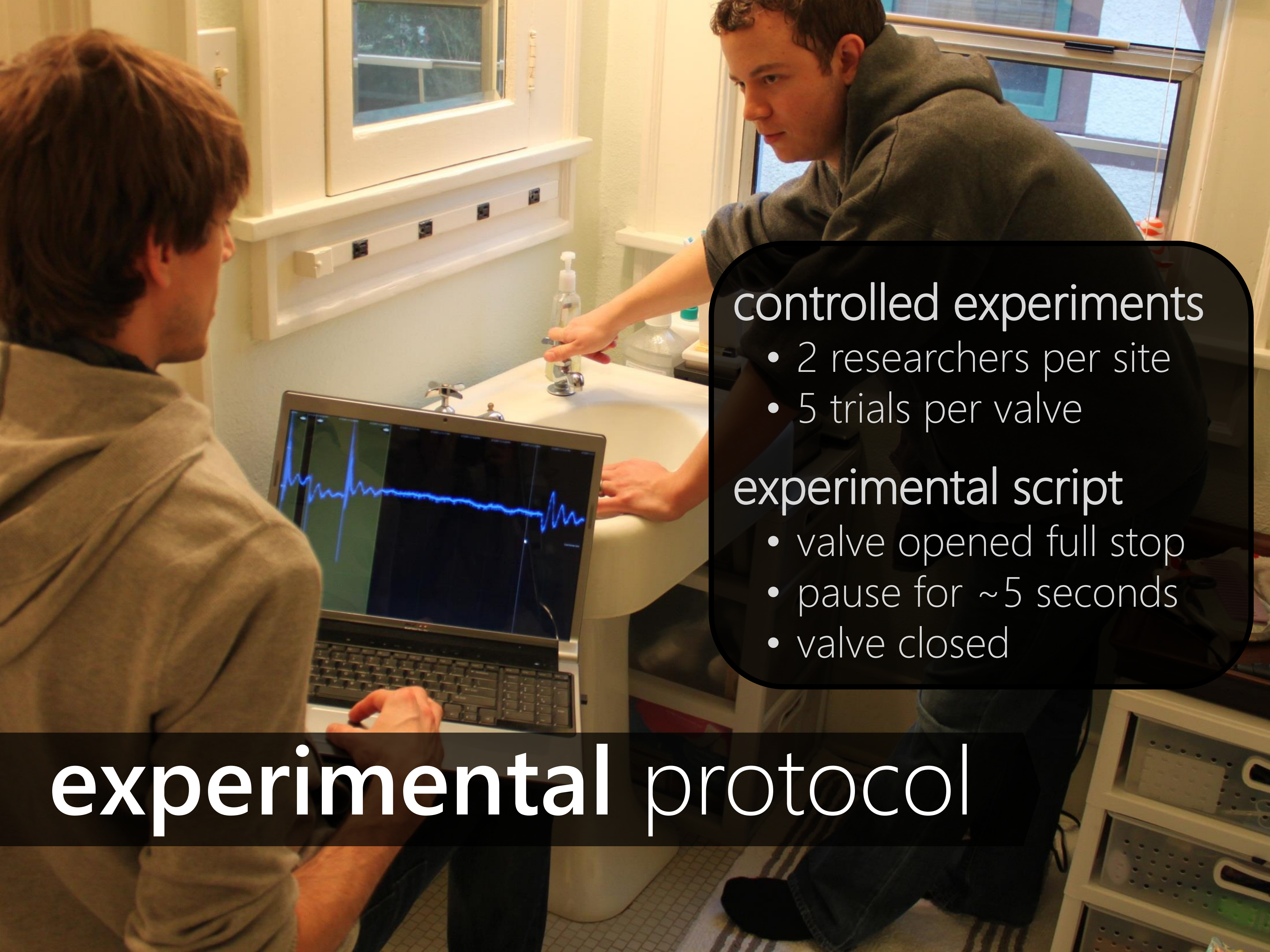

unclassified open event
open event library
49
47
45
43
0 2 4 6 8 10 12 14 16
detrended$_{unclassified}$
derivative$_{unclassified}$
cepstrum$_{unclassified}$
48
46
44
0 2 4 6 8 10
shower
48
46
44
0 2 4 6 8 10
dishwasher
48
46
44
0 2 4 6 8 10 12 14
kitchen faucet
possible events

unclassified open event
open event library
49
47
45
43
0 2 4 6 8 10 12 14 16
detrended unclassified
derivative unclassified
cepstrum unclassified
derivative shower
shower
48
46
44
0 2 4 6 8 10
derivative toilet
dishwasher
48
46
44
0 2 4 6 8 10
derivative kitchen faucet
kitchen faucet
48
46
44
0 2 4 6 8 10 12 14
possible events



unclassified open event
open event library
49
47
45
43
0
2
4
6
8
10
12
14
16
derivative$_{shower}$
shower
derivative$_{toilet}$
dishwasher
nearest neighbor match
derivative$_{unclassified}$
derivative$_{kitchen\ faucet}$
kitchen faucet
possible events


hydro study
#1
goal
study feasibility of using pressure
to disaggregate water usage
approach
controlled experiments across
10 homes

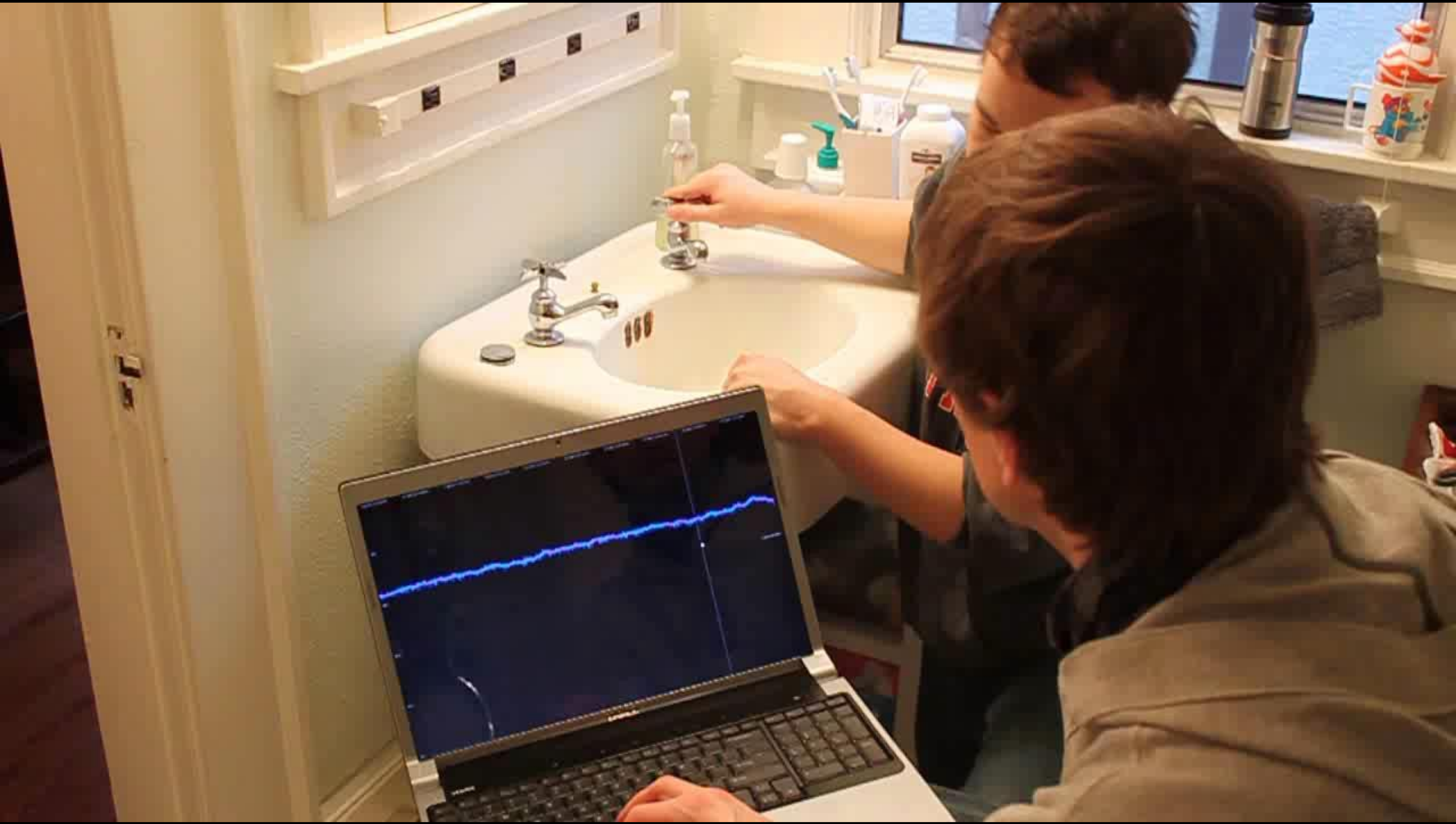


experimental protocol

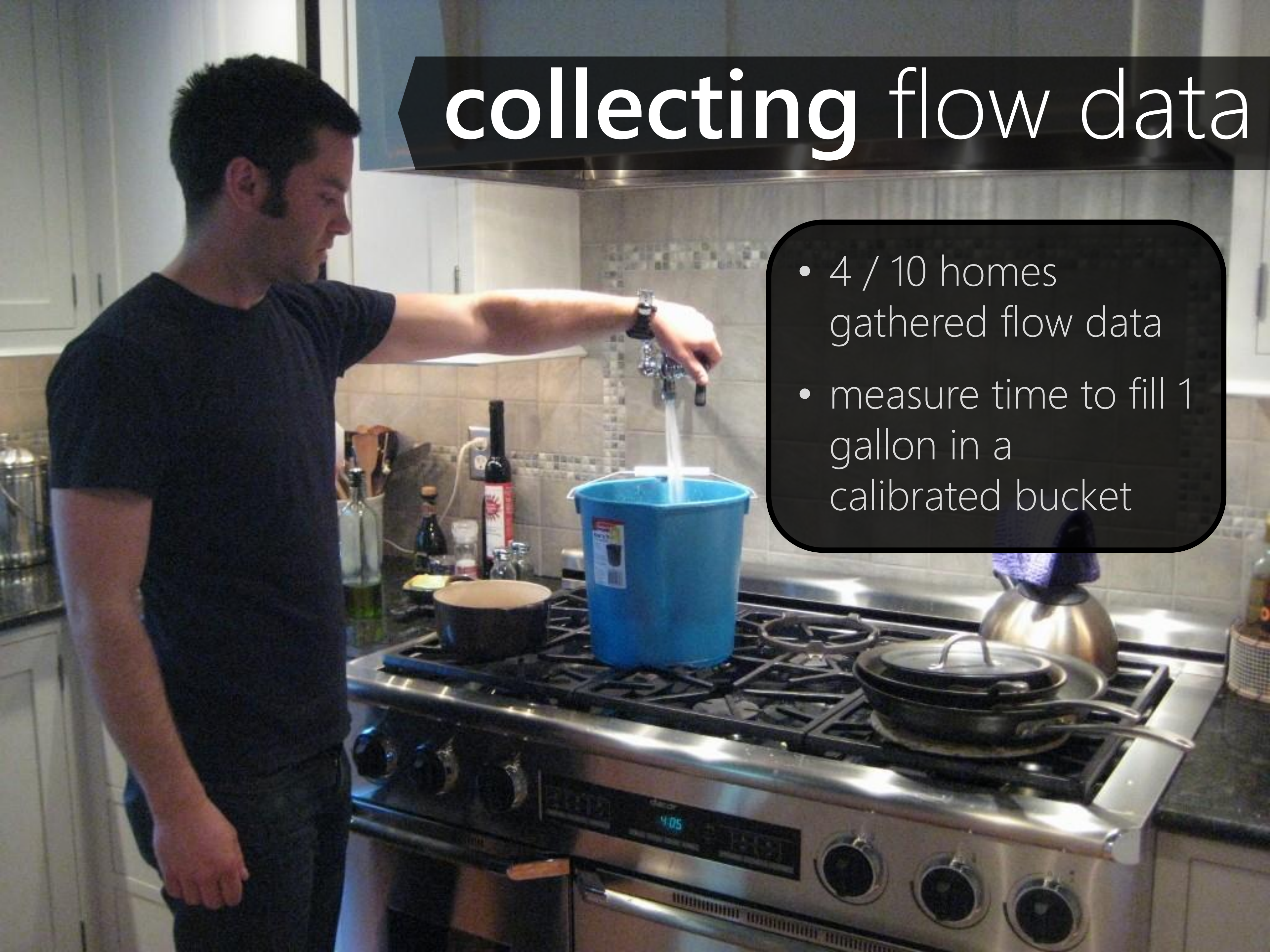
controlled experiments
- 2 researchers per site
- 5 trials per valve

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

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

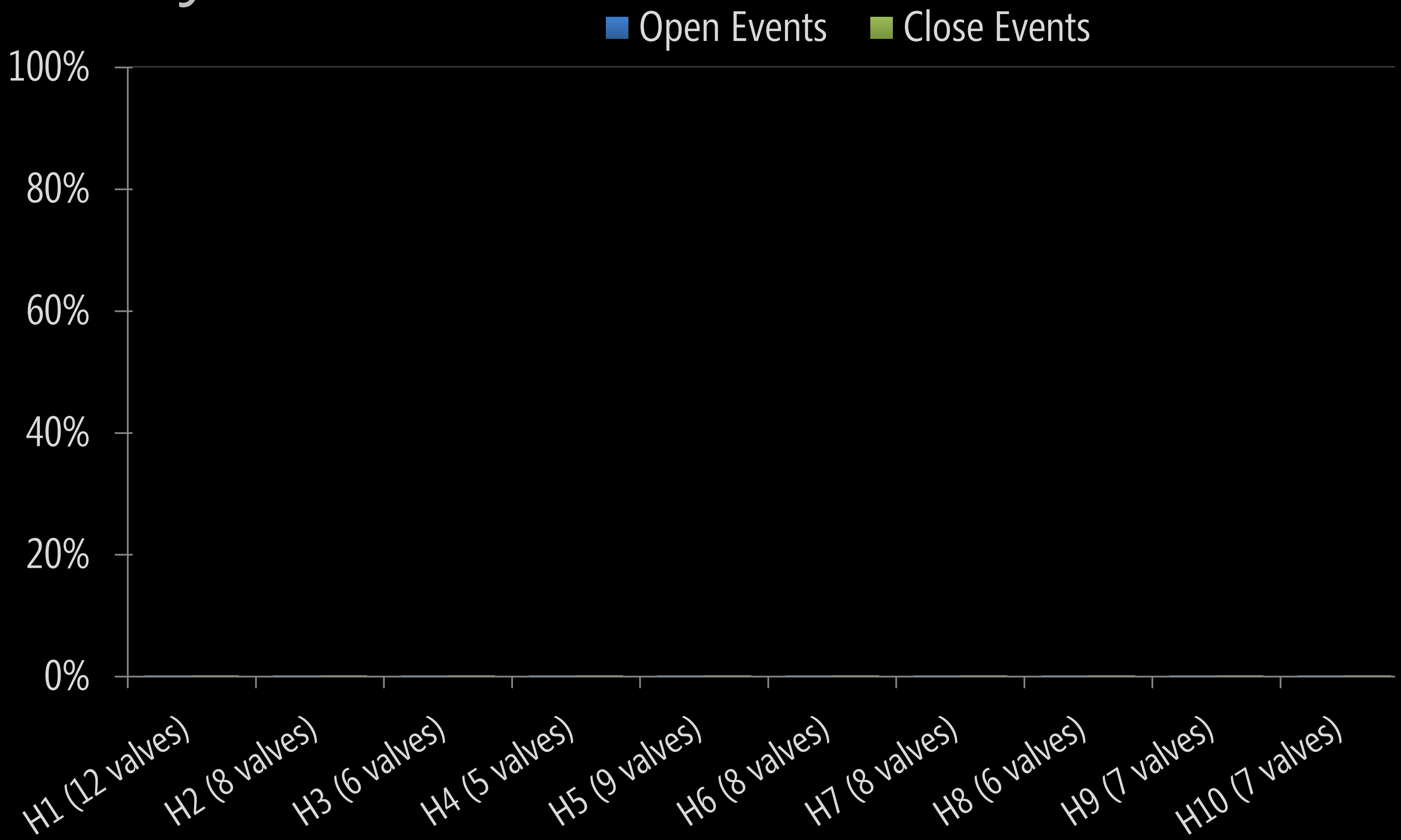
- 706 trials
- 155 flow trials
- 84 total fixtures tested

classification experiments

10-fold cross validation

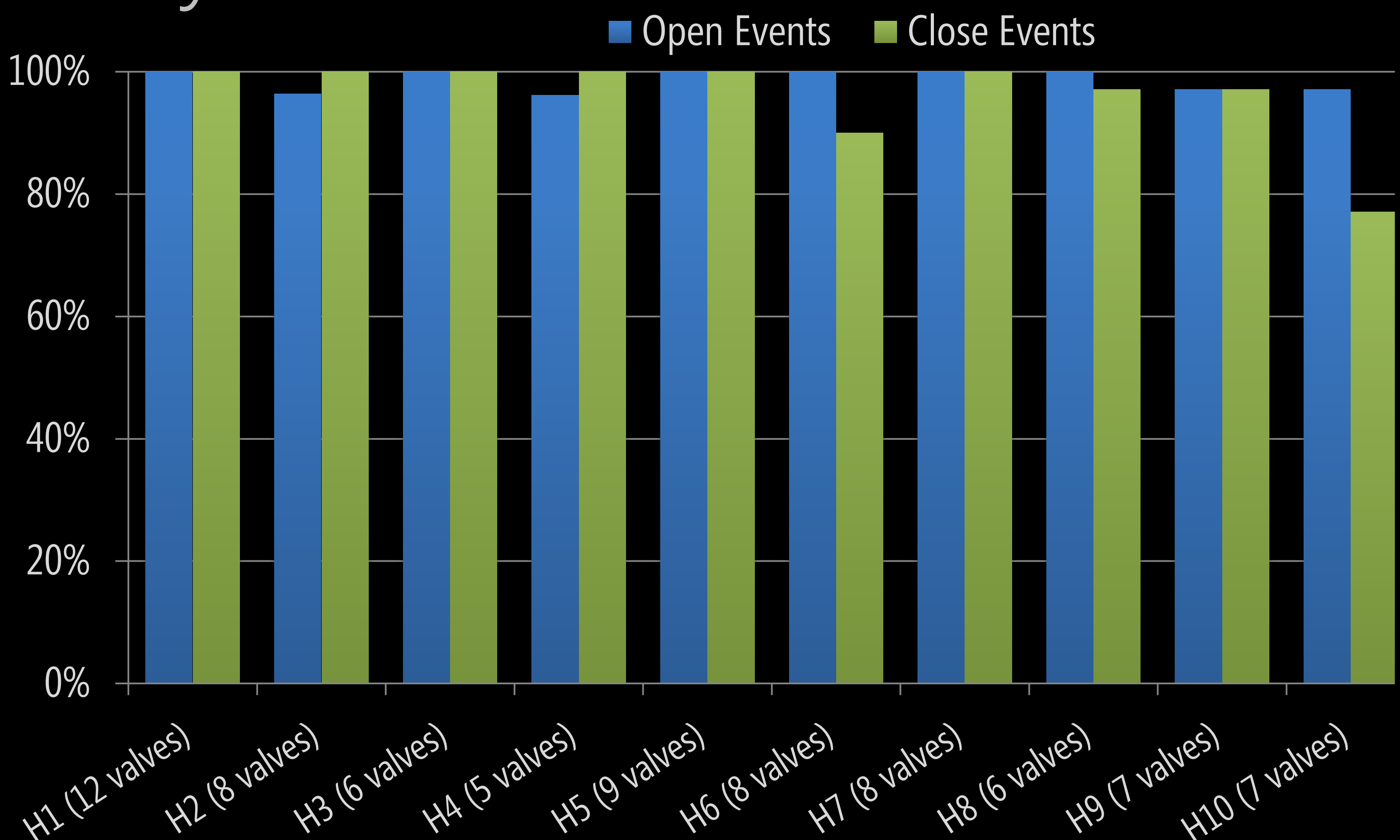
1. break data into 10 sets of size n/10
2. train on 9 datasets and test on 1
3. repeat for each combination of datasets
4. take mean accuracy

fixture classification results
by home



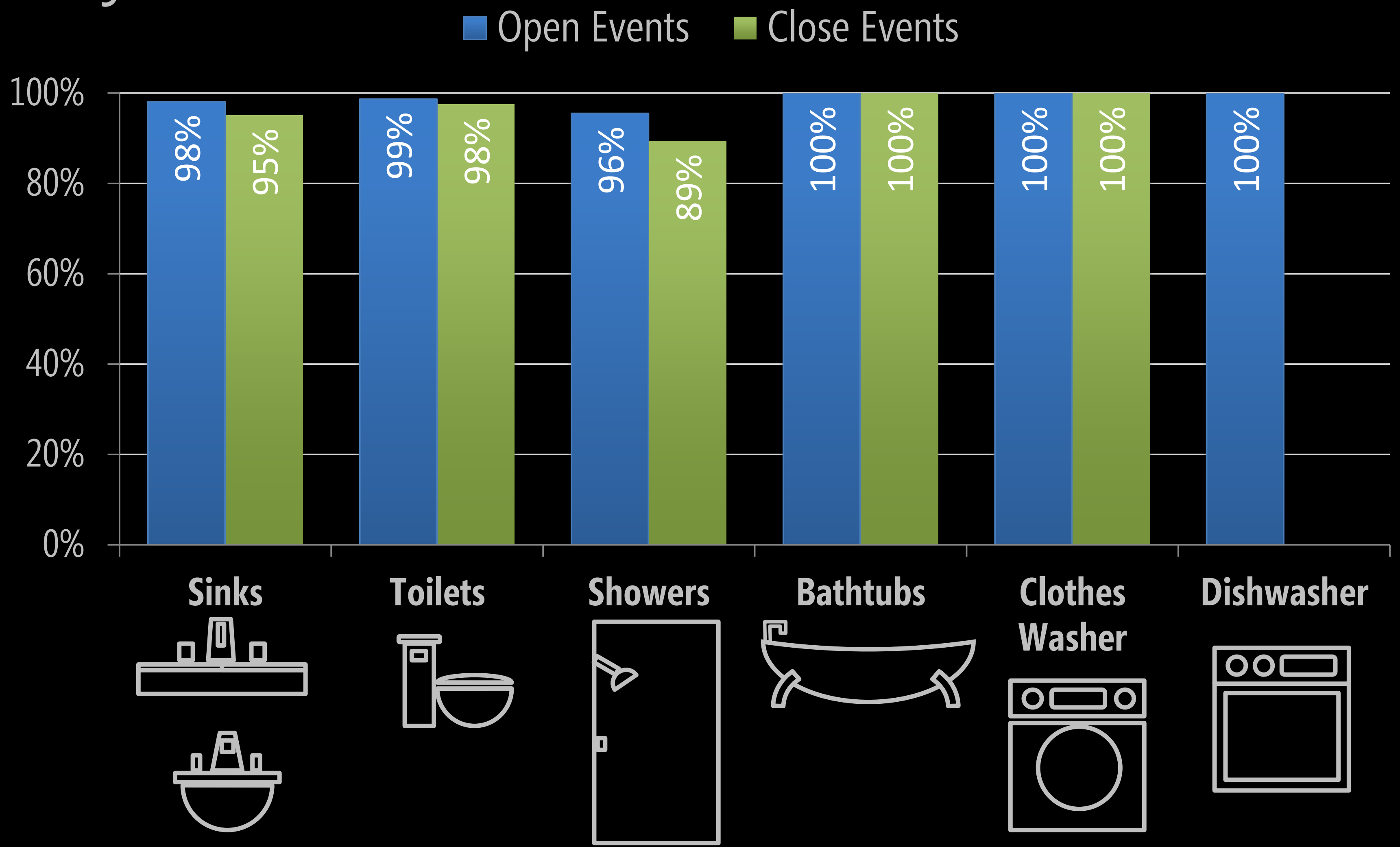
10-fold cross validation

fixture classification results
by home

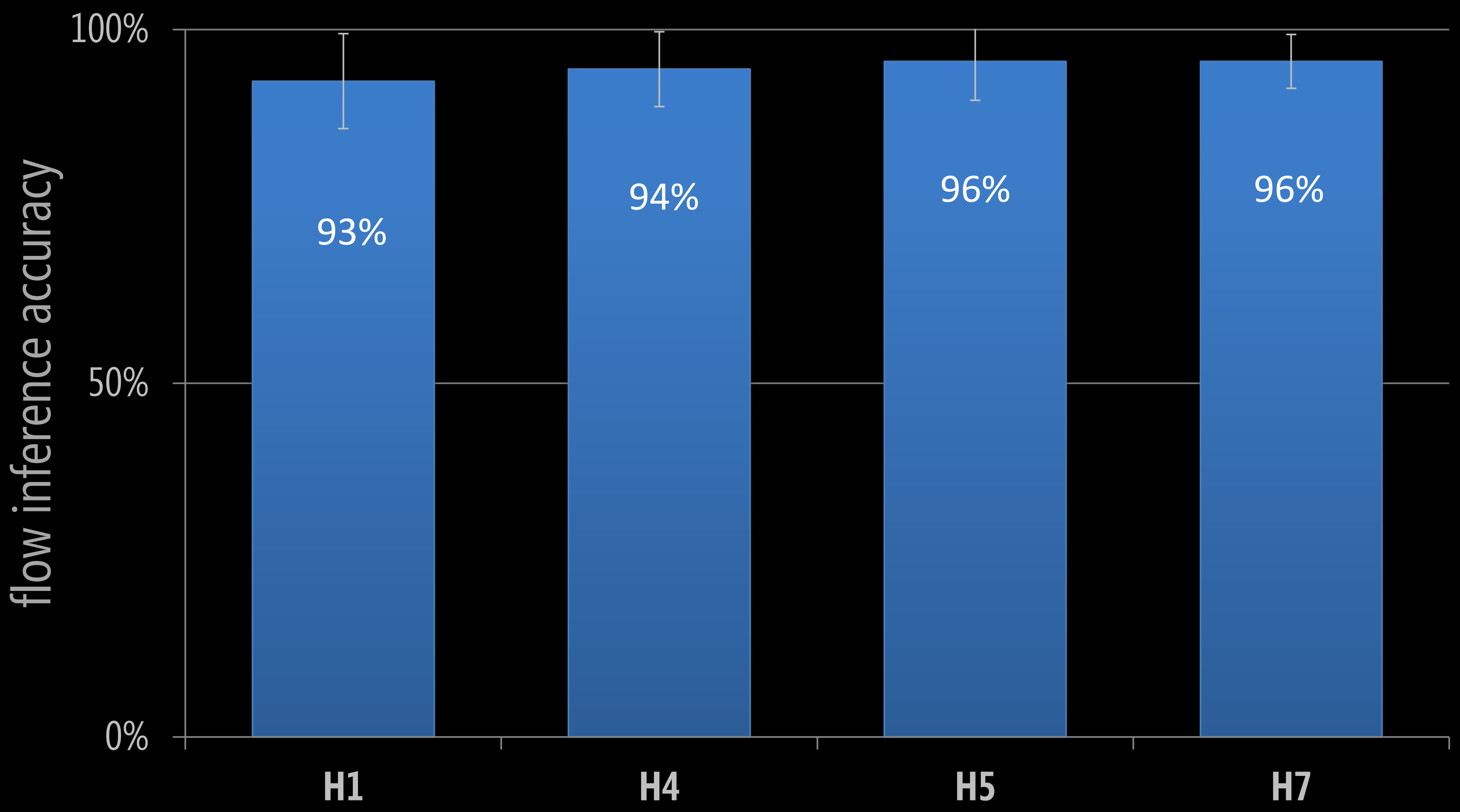


10-fold cross validation

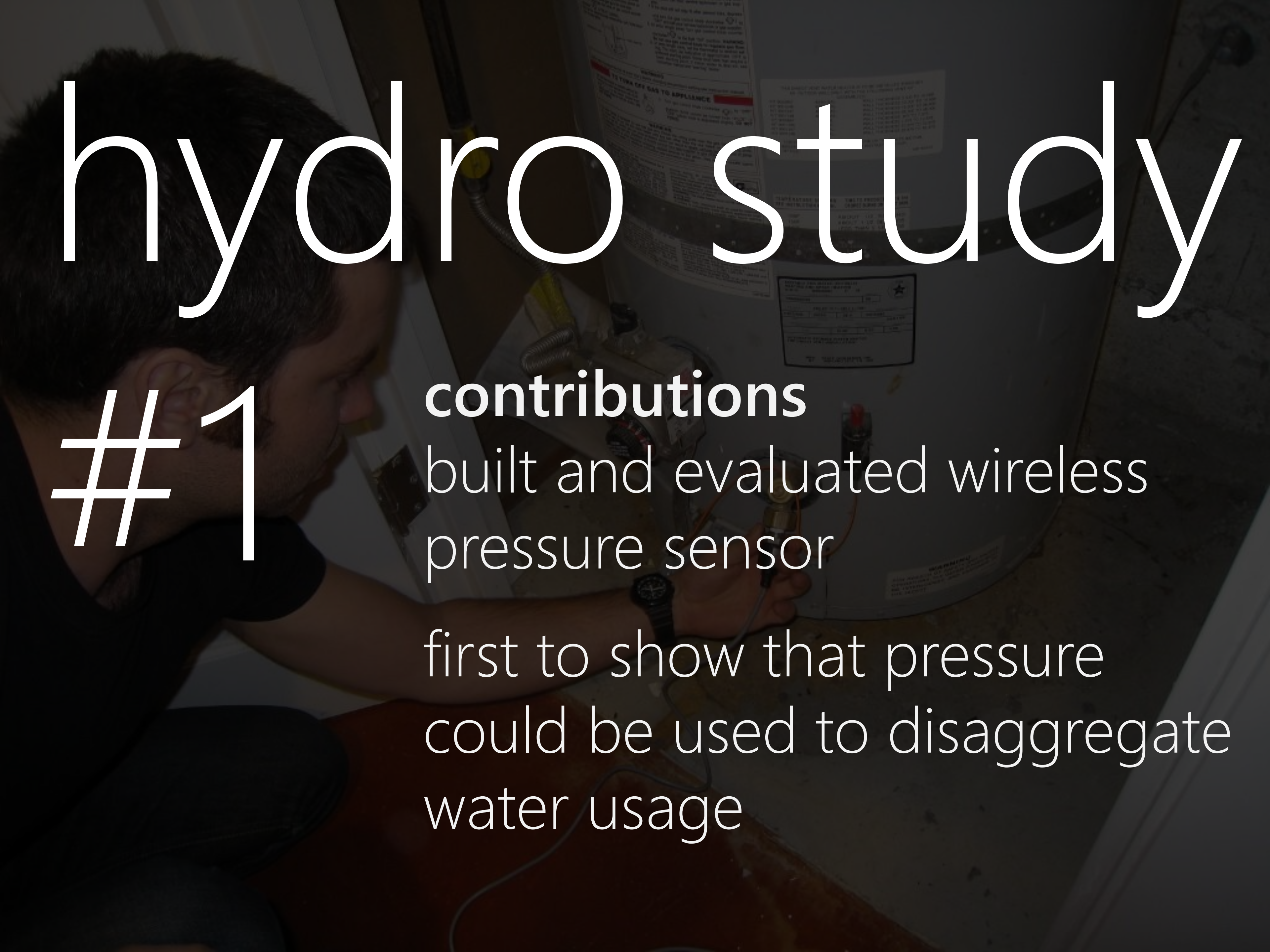
fixture classification results
by fixture



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

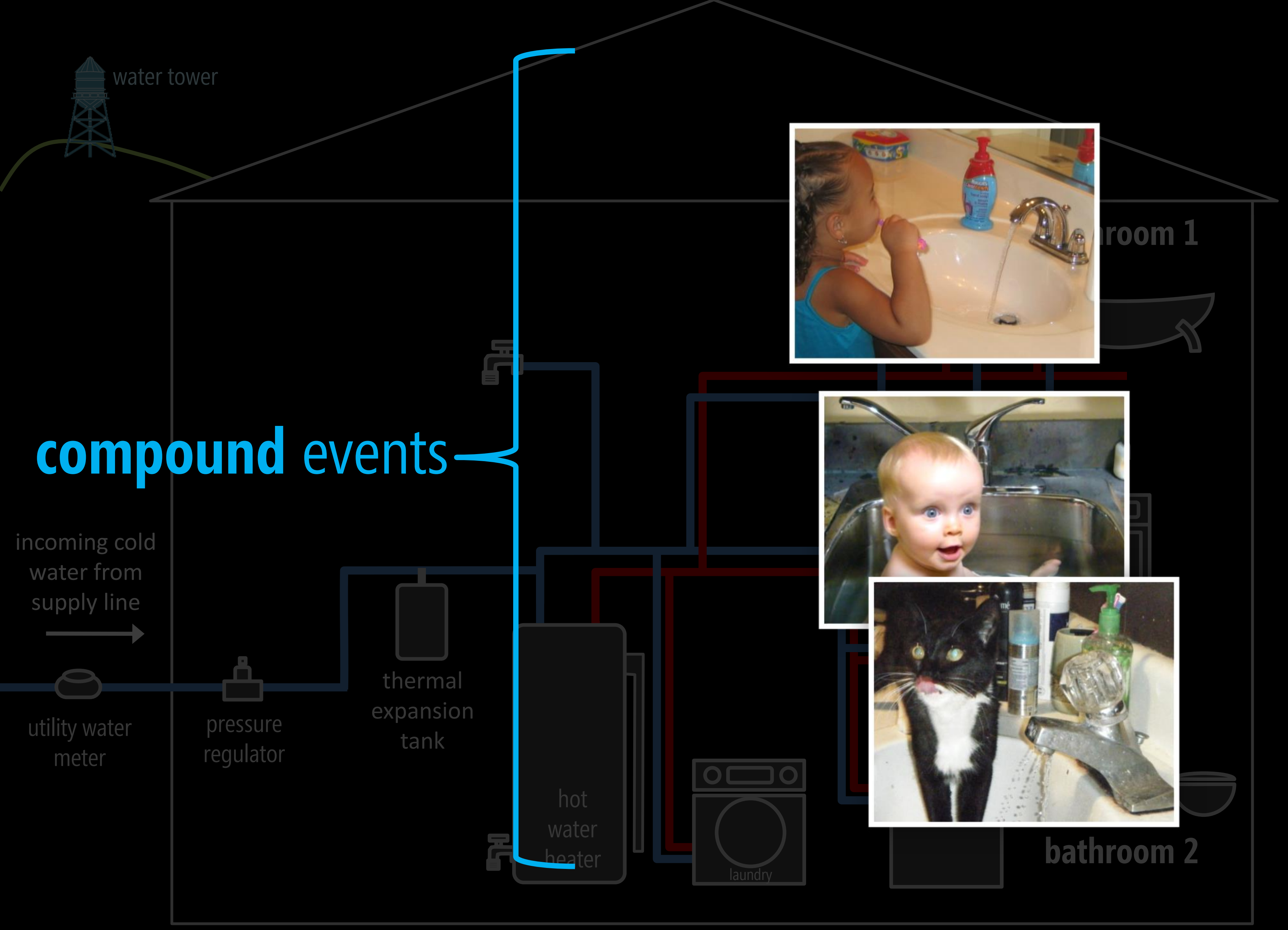
first to show that pressure could be used to disaggregate water usage

brushing teeth

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
room 1
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

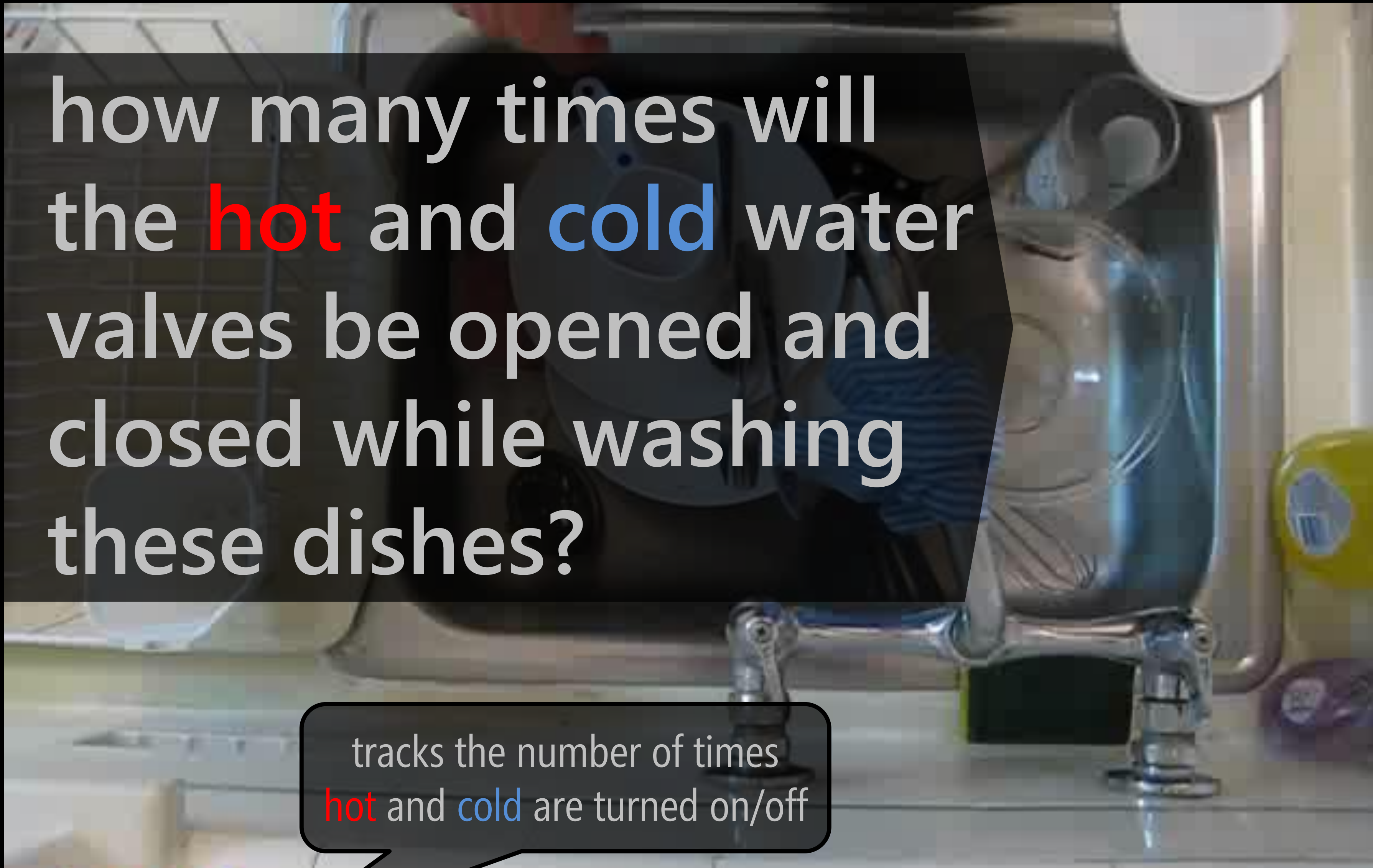
I'm about to flush the toilet!
Awesome! Marked it. Thanks Mr. Johnson

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

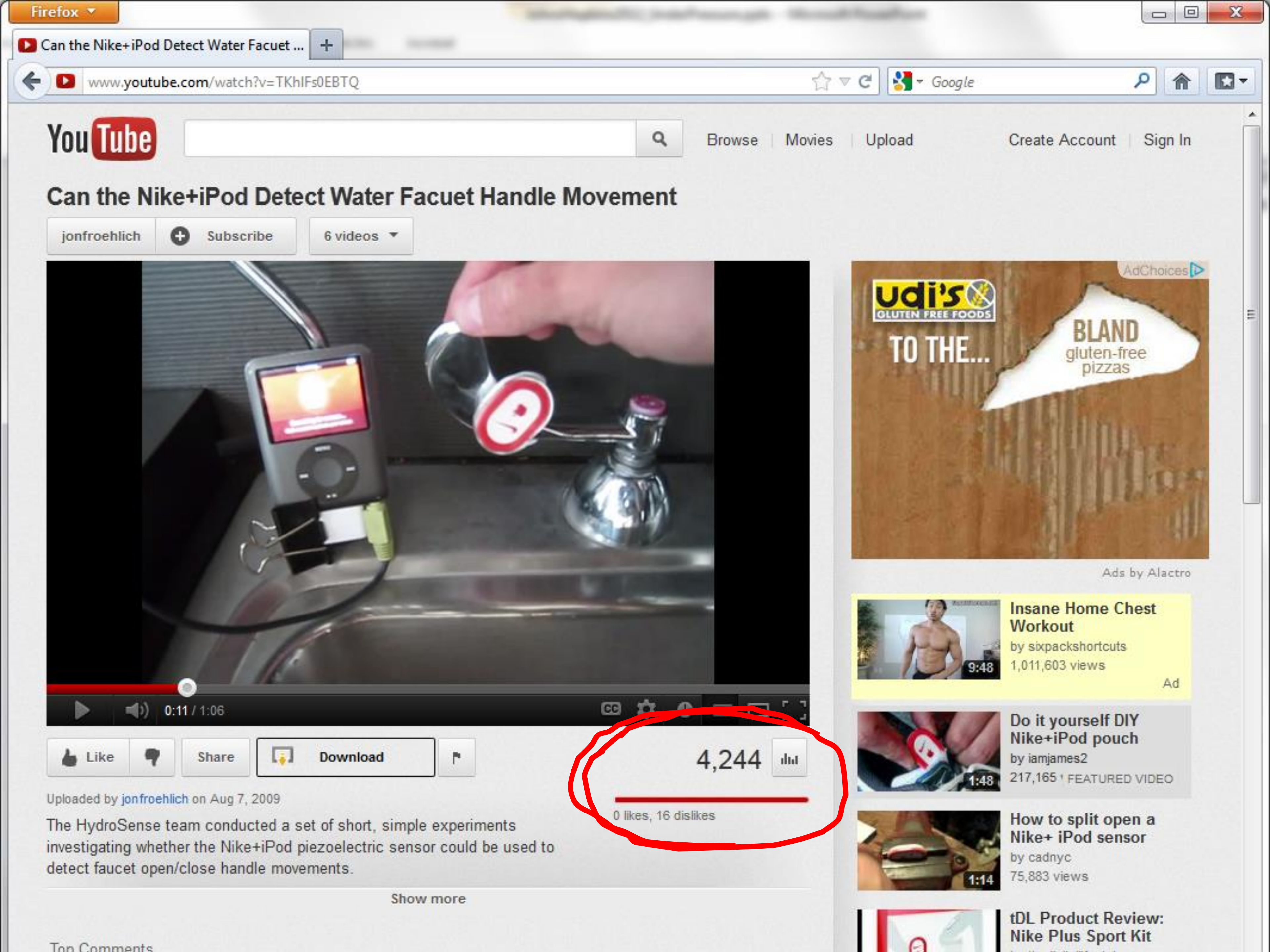

wireless buttons
HOT ON
HOT OFF
COLD ON
COLD OFF
FAIL #1

other failed solutions

intel labs shake sensors

FAIL #3


nike+ piezo sensor
FAIL #4
MENU


Firefox
Can the Nike+iPod Detect Water Facuet ...
www.youtube.com/watch?v=TKhIFs0EBTQ
Google
YouTube
Browse
Movies
Upload
Create Account
Sign In
Can the Nike+iPod Detect Water Facuet Handle Movement
jonfroehlich
Subscribe
6 videos
0:11 / 1:06
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.
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Top Comments
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GLUTEN FREE FOODS
TO THE...
BLAND
gluten-free pizzas
Ads by Alactro
Insane Home Chest Workout
by sixpackshortcuts
1,011,603 views
9:48
Ad
Do it yourself DIY Nike+iPod pouch
by iamjames2
217,165 FEATURED VIDEO
1:48
How to split open a Nike+ iPod sensor
by cadnyc
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1:14
tDL Product Review: Nike Plus Sport Kit

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

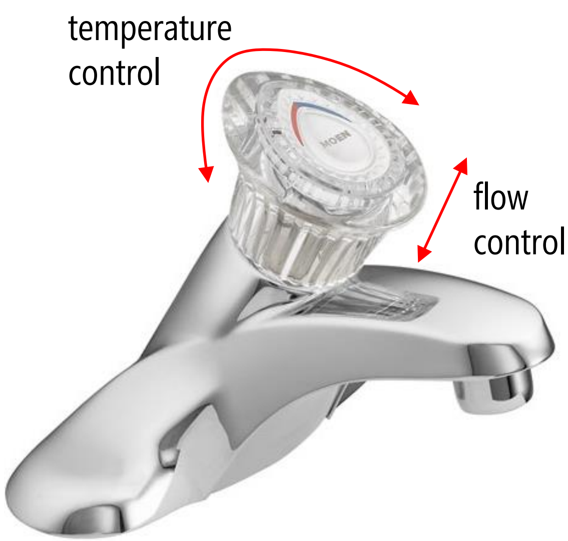
toilet

laundry basin

washing machine

dishwasher

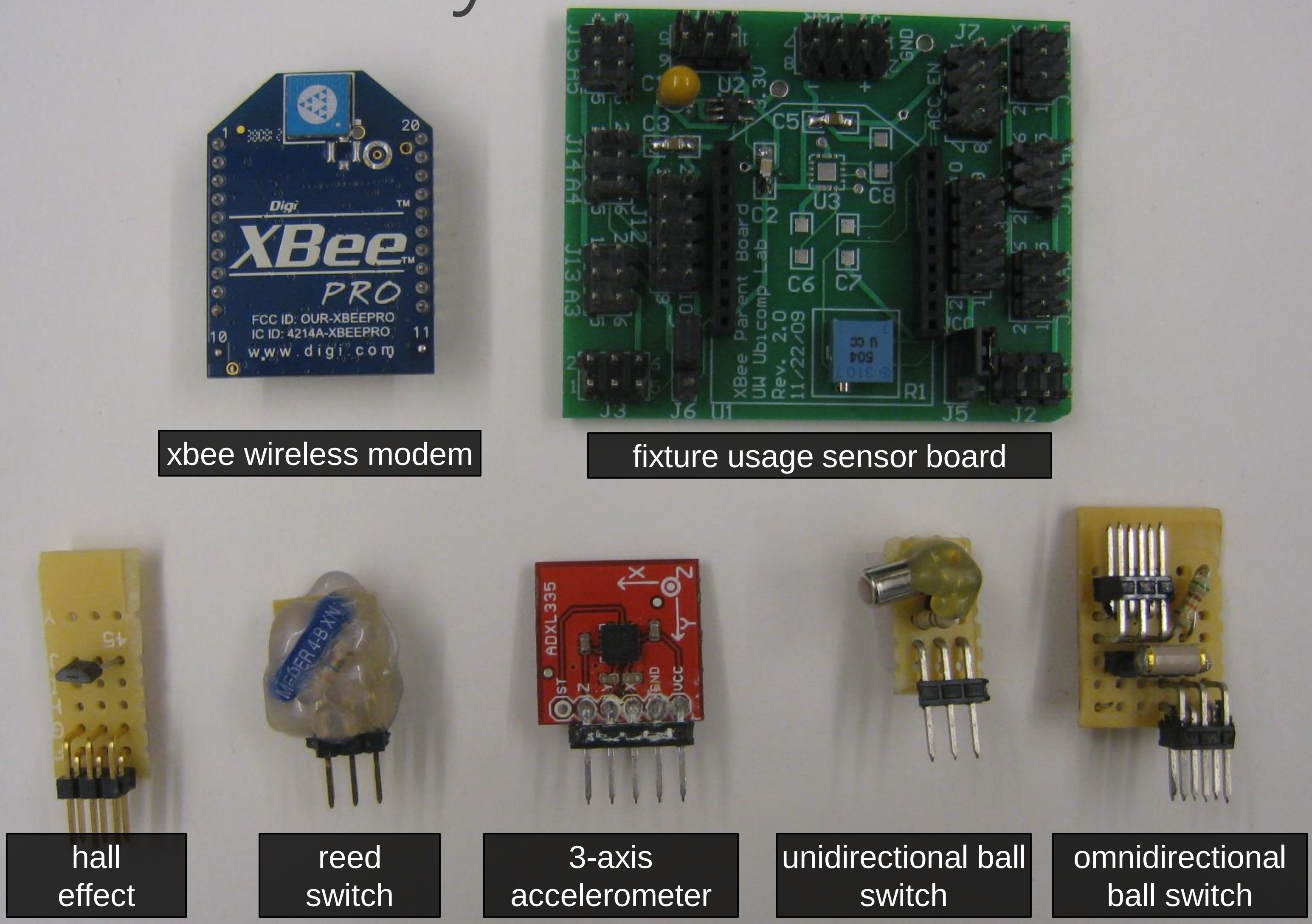
challenge: fixture diversity



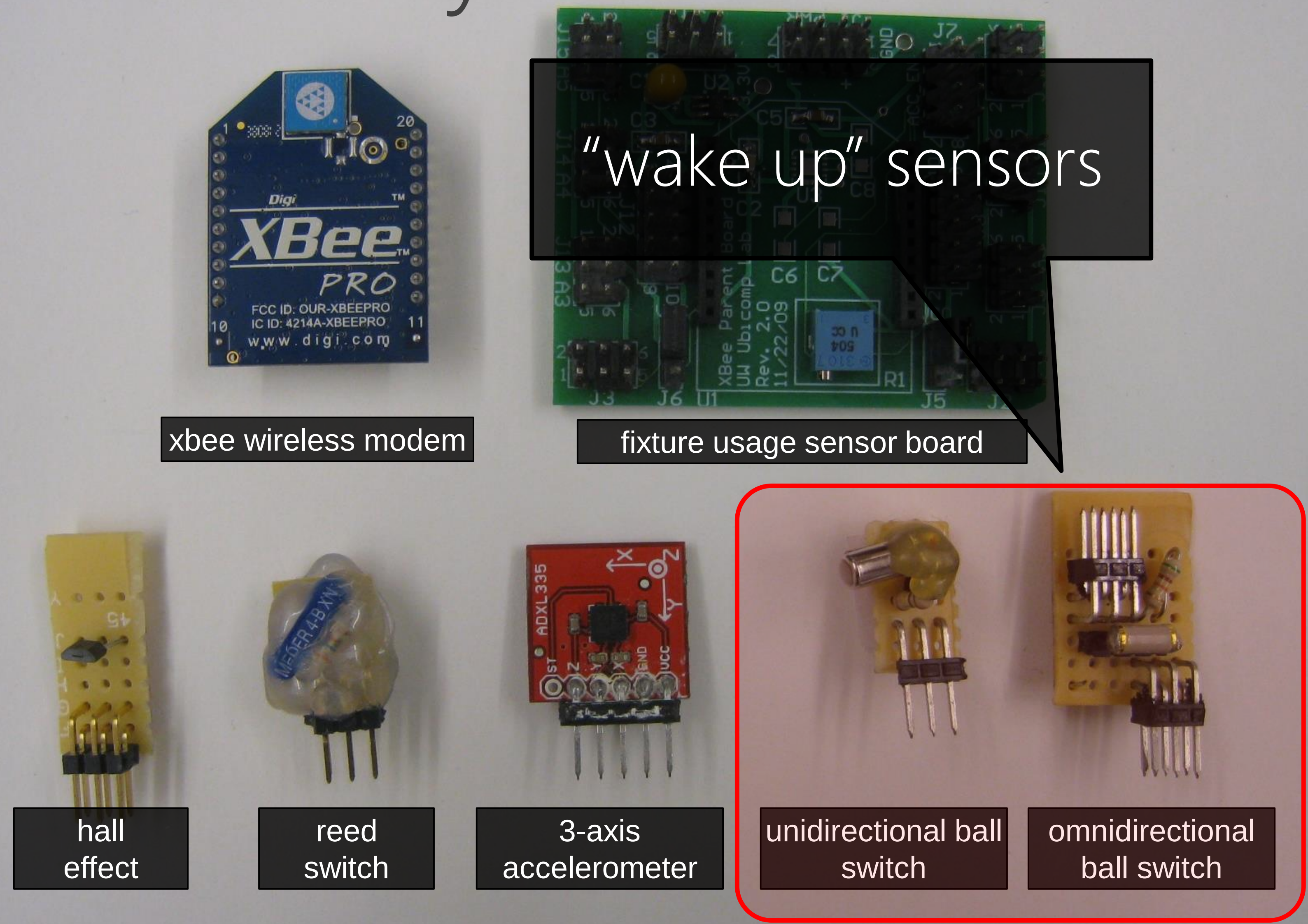
single handle faucet

dual handle faucet

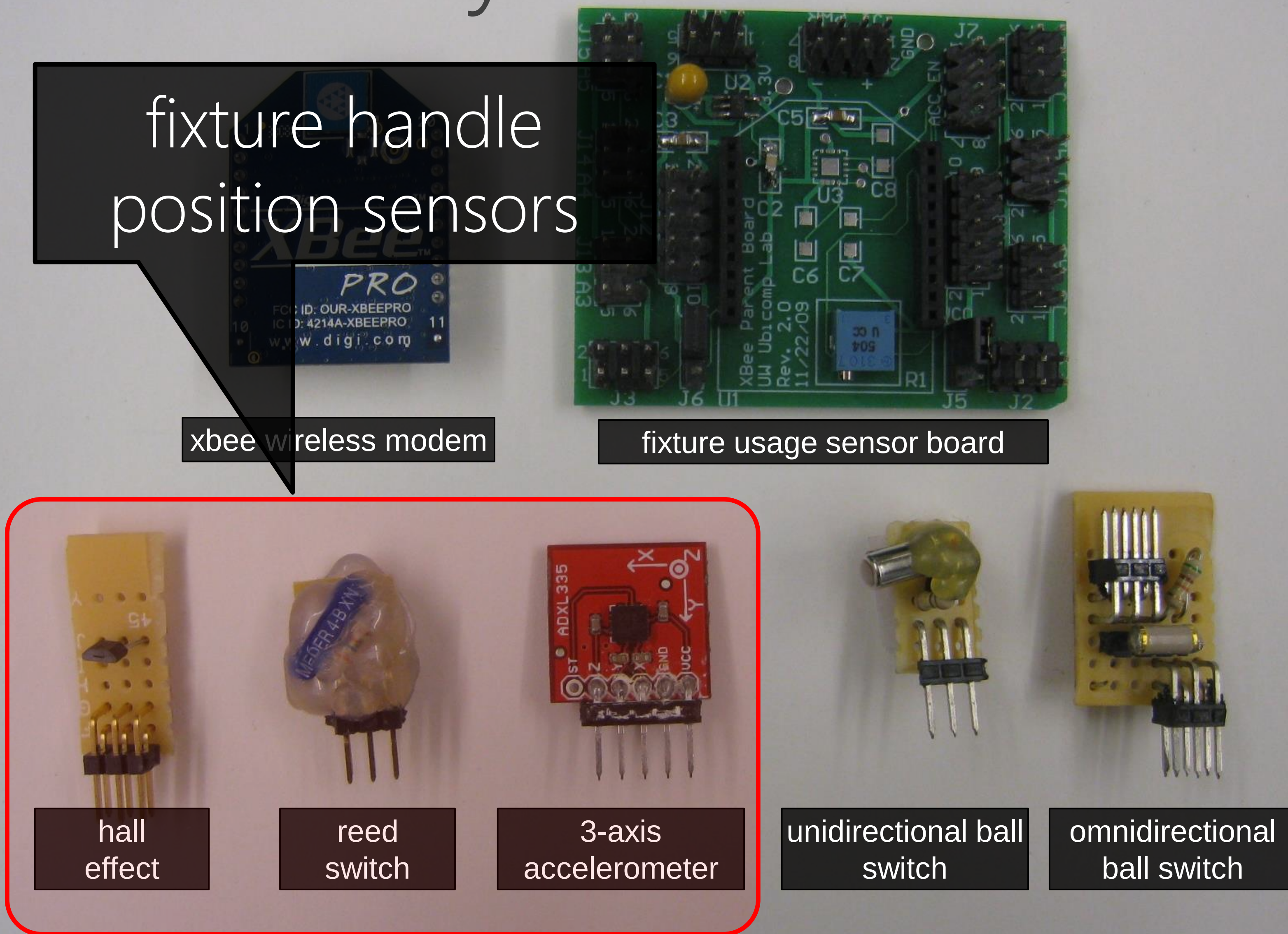
custom ground truth data collection system



custom ground truth data collection system

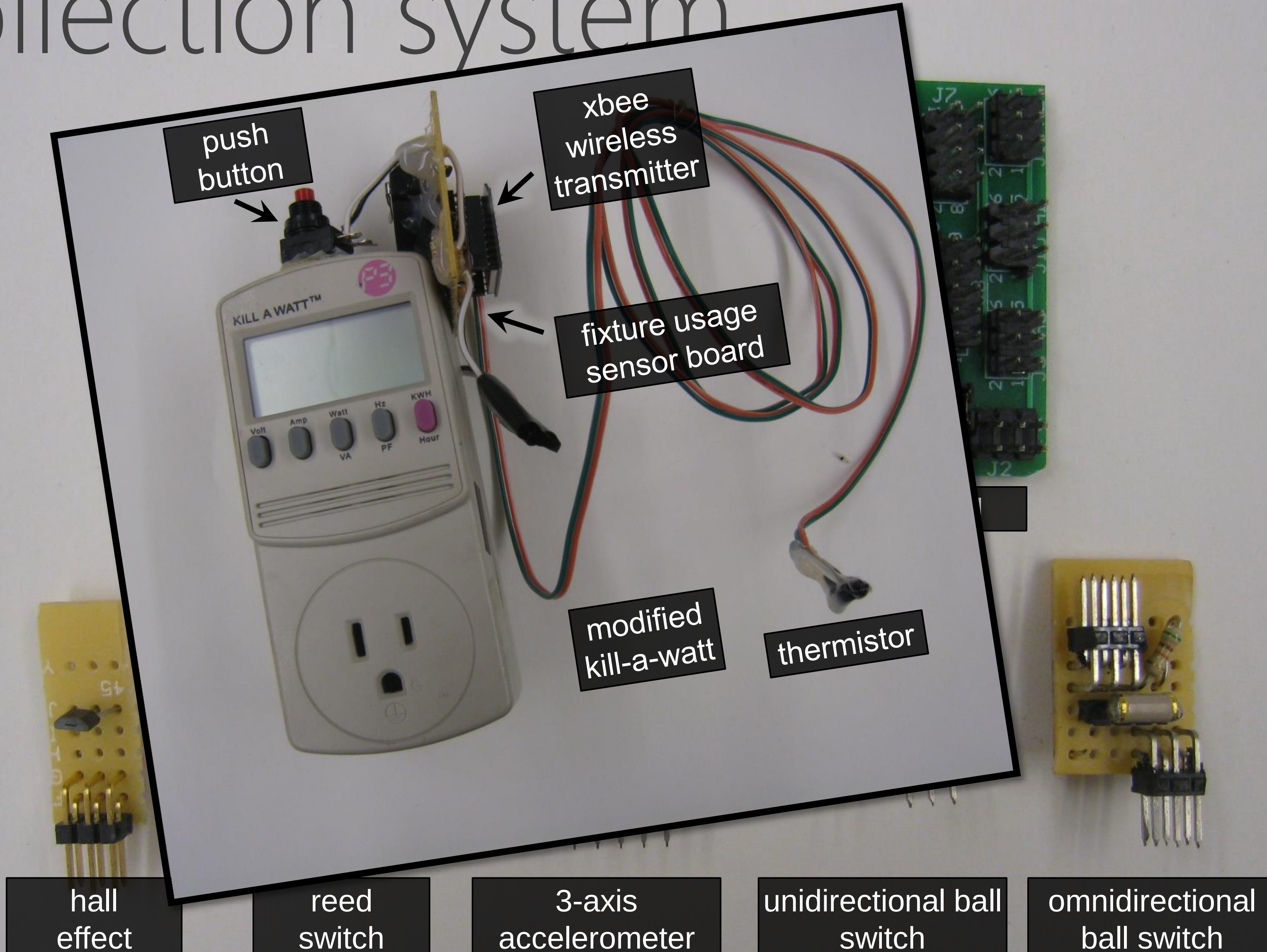


custom ground truth data collection system




accelerometer
Accelerometer
& Ball Switch
Taped on

custom ground truth data collection system



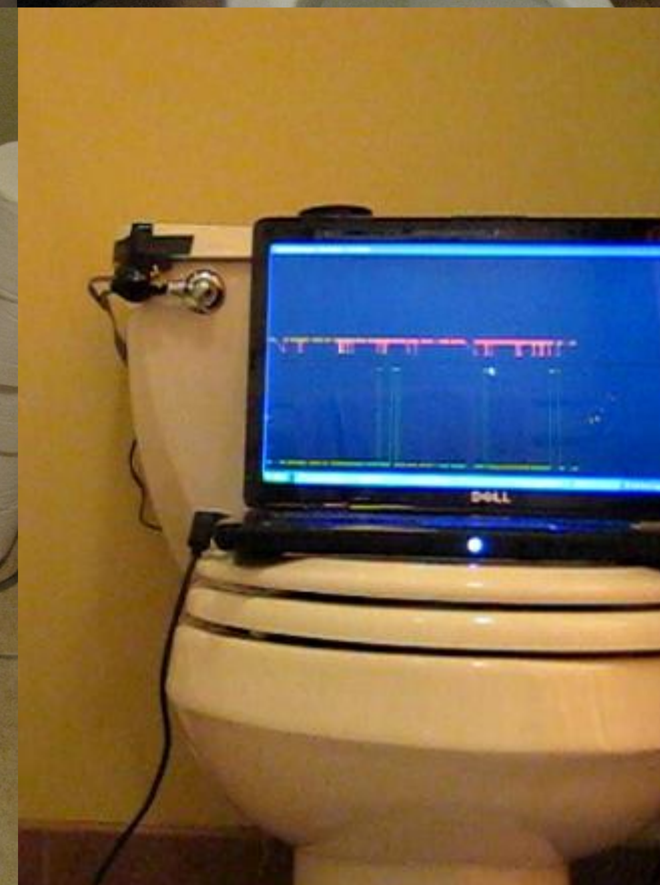
deployment sites

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


C
H





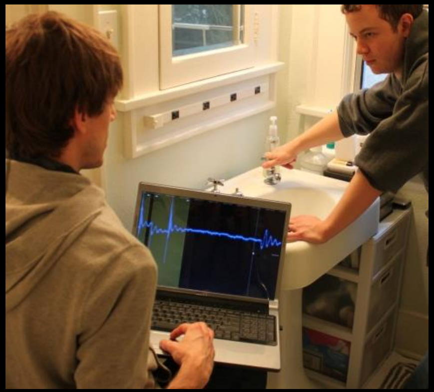


DELL


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
y Duty Super Capacity
= RINSE
= EXTRA RINSE
= SPIN

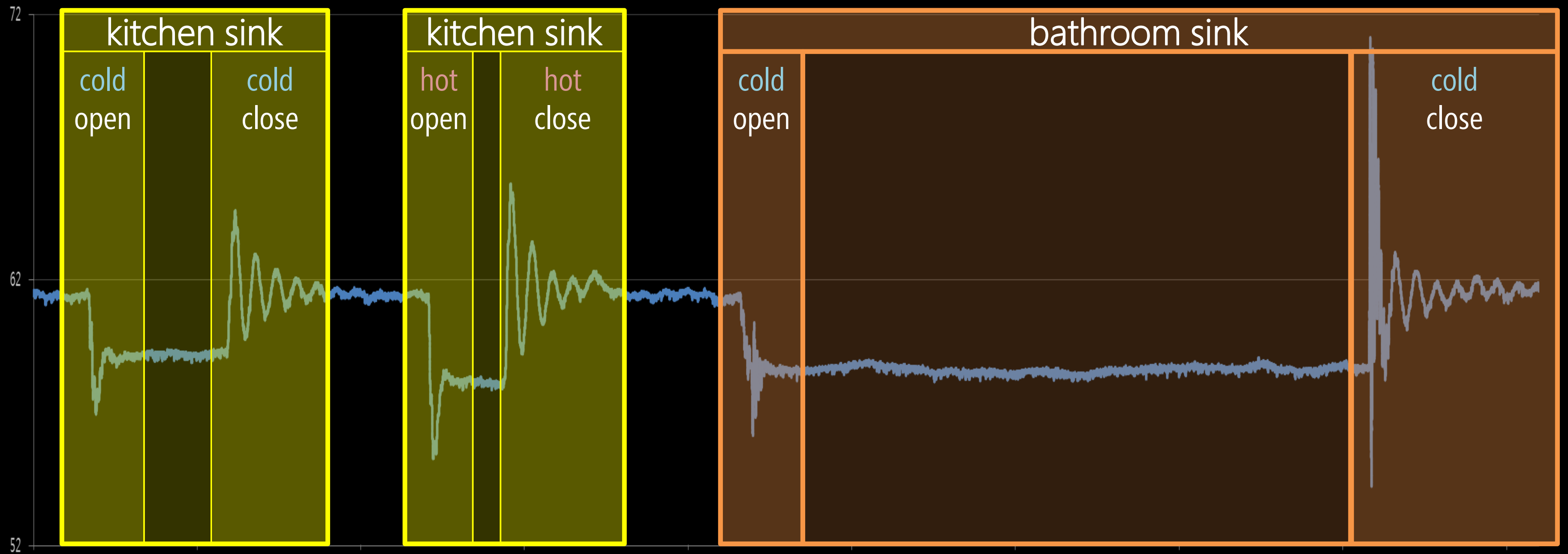

KitchenAid Superba
ICE
CHILLED WATER

ground truth labels

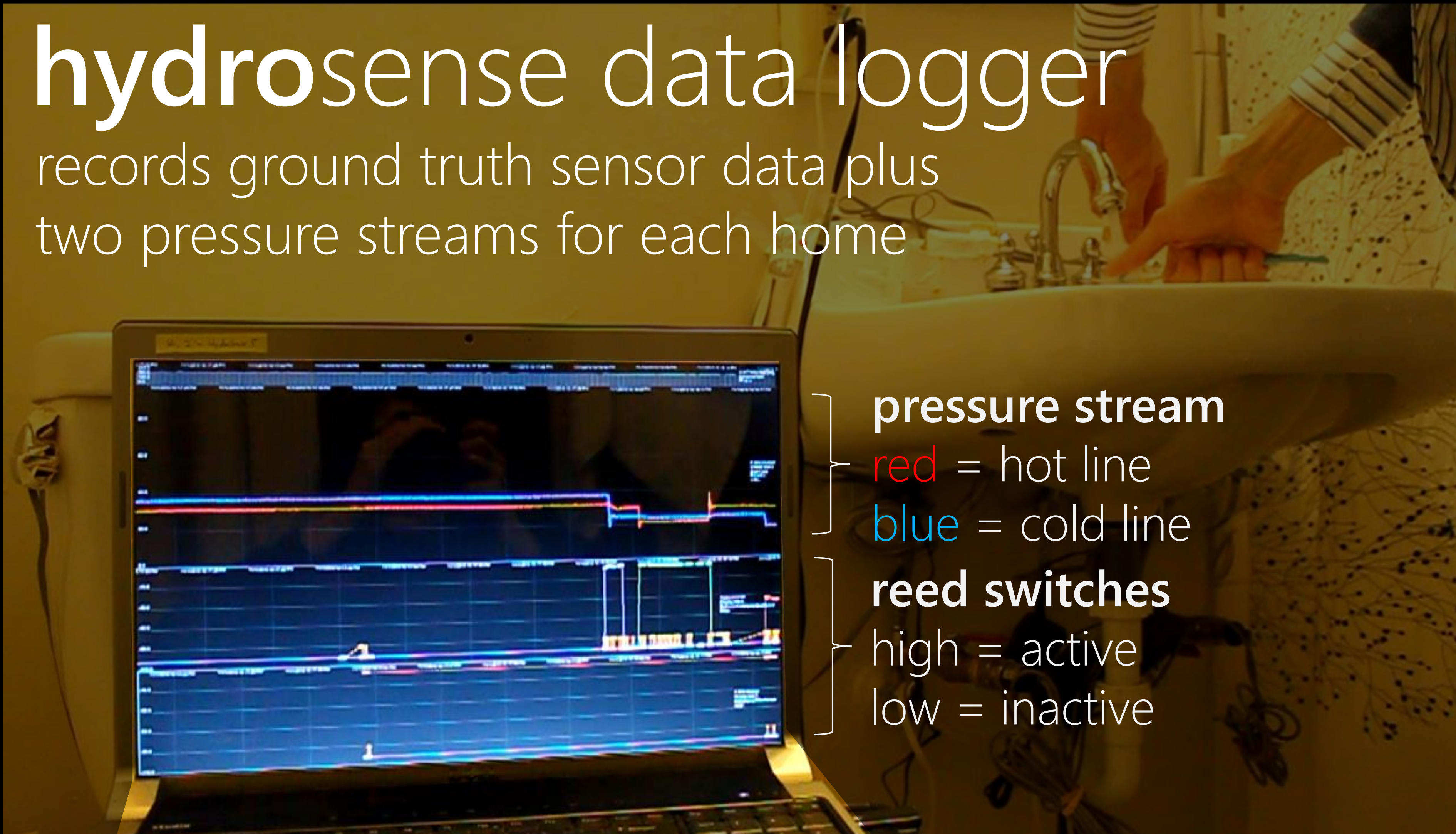


manual

automatic

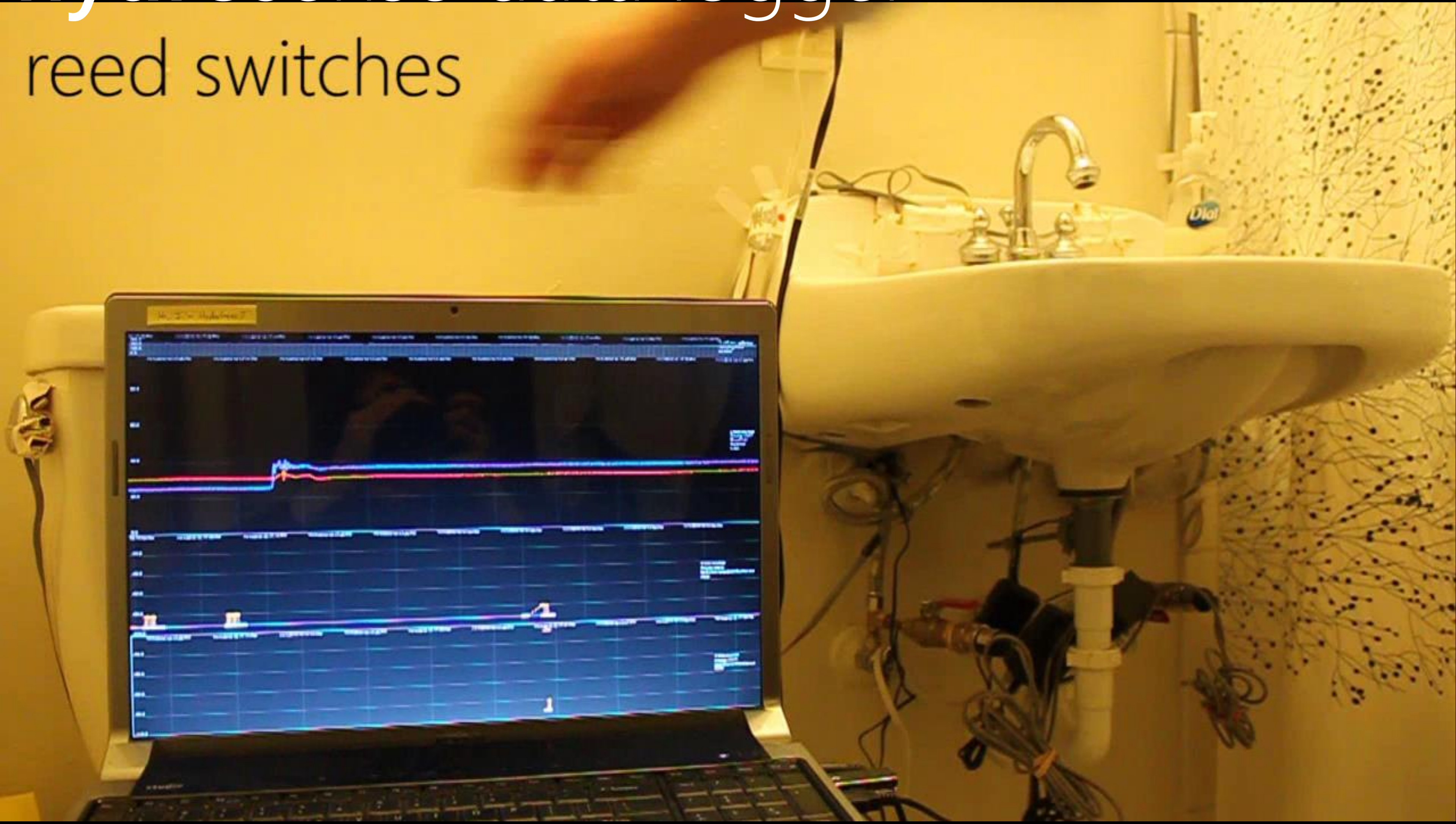


two pressure sensors per home

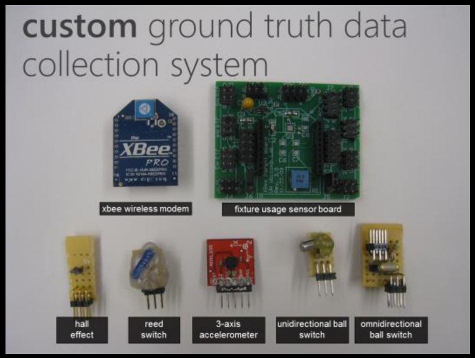

hydrosense data logger
records ground truth sensor data plus
two pressure streams for each home
pressure stream
red = hot line
blue = cold line
reed switches
high = active
low = inactive

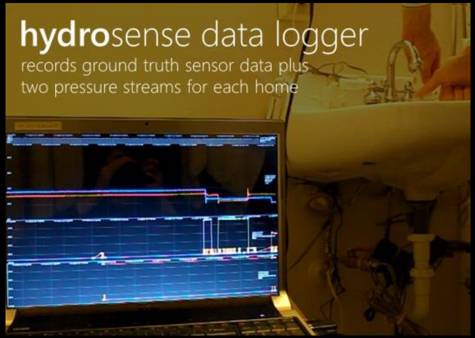
hydrosense data logger

reed switches

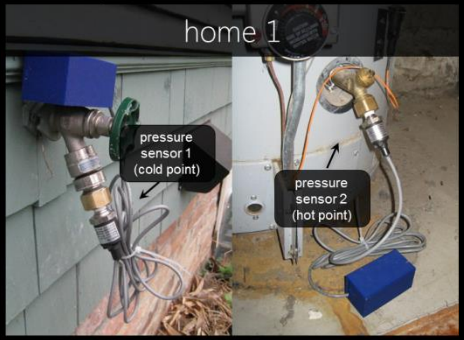


hydro deployment infrastructure

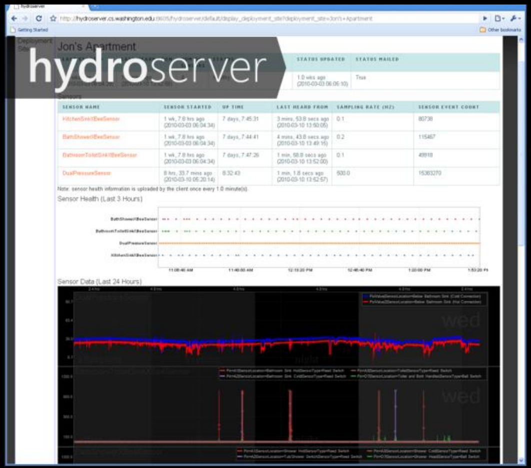




two pressure sensors

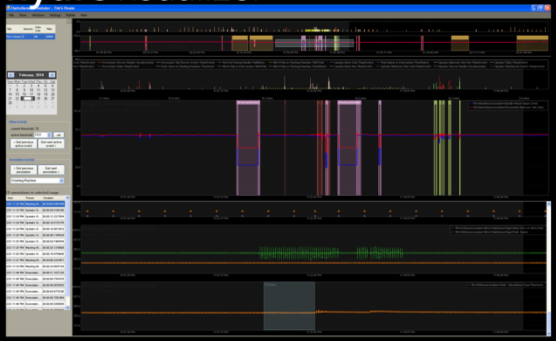


on-site sensing infrastructure

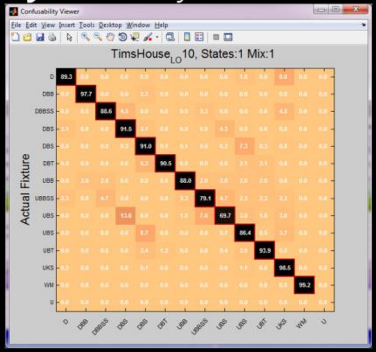


python web backend

hydrovisualizer



hydroanalyzer



c# and matlab analysis tools

hydrosense annotations

1. **ground truth** sensor

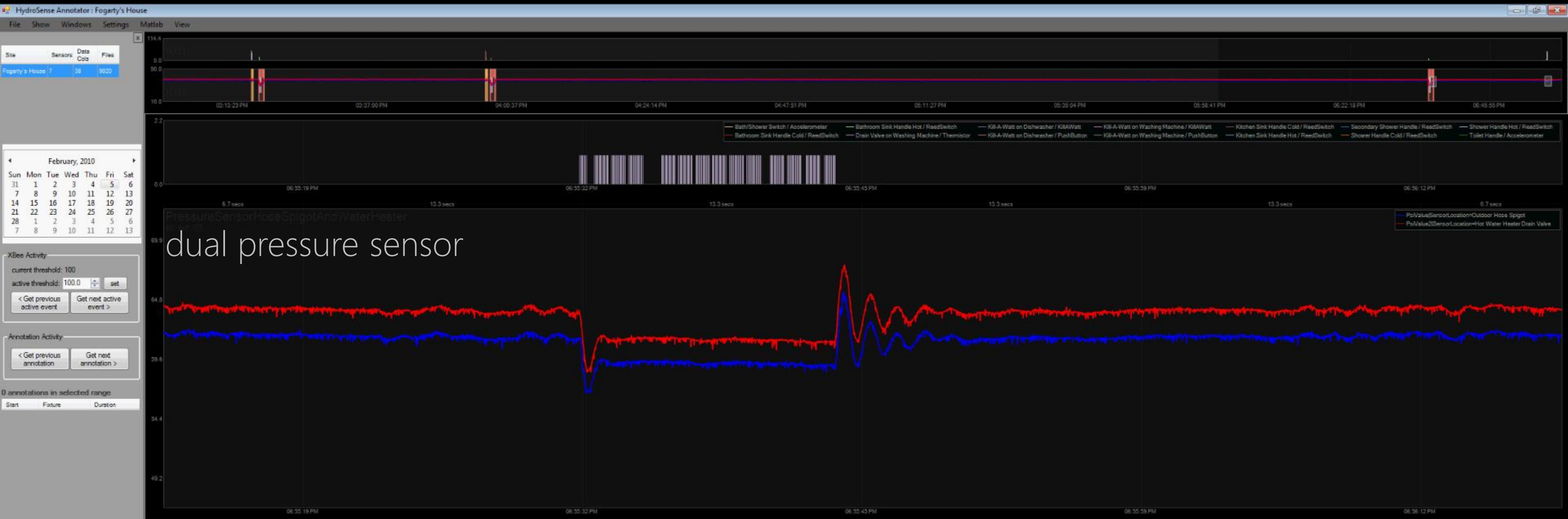
2. **semi-automated** label

3. **review** annotator

4. **verification**

5. **final** label

dual pressure sensor

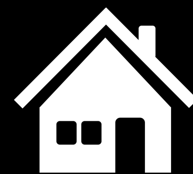



HydroSense Annotator : Fogarty's House
File Show Windows Settings Matlab View
February, 2010
XBee Activity
current threshold: 100
active threshold: 100.0
set
< Get previous active event
Get next active event >
Annotation Activity
< Get previous annotation
Get next annotation >
0 annotations in selected range
Start Fixture Duration
dual pressure sensor
toilet
bathroom faucet
kitchen faucet
dishwasher
washing machine
bath/shower
bath/shower diverter

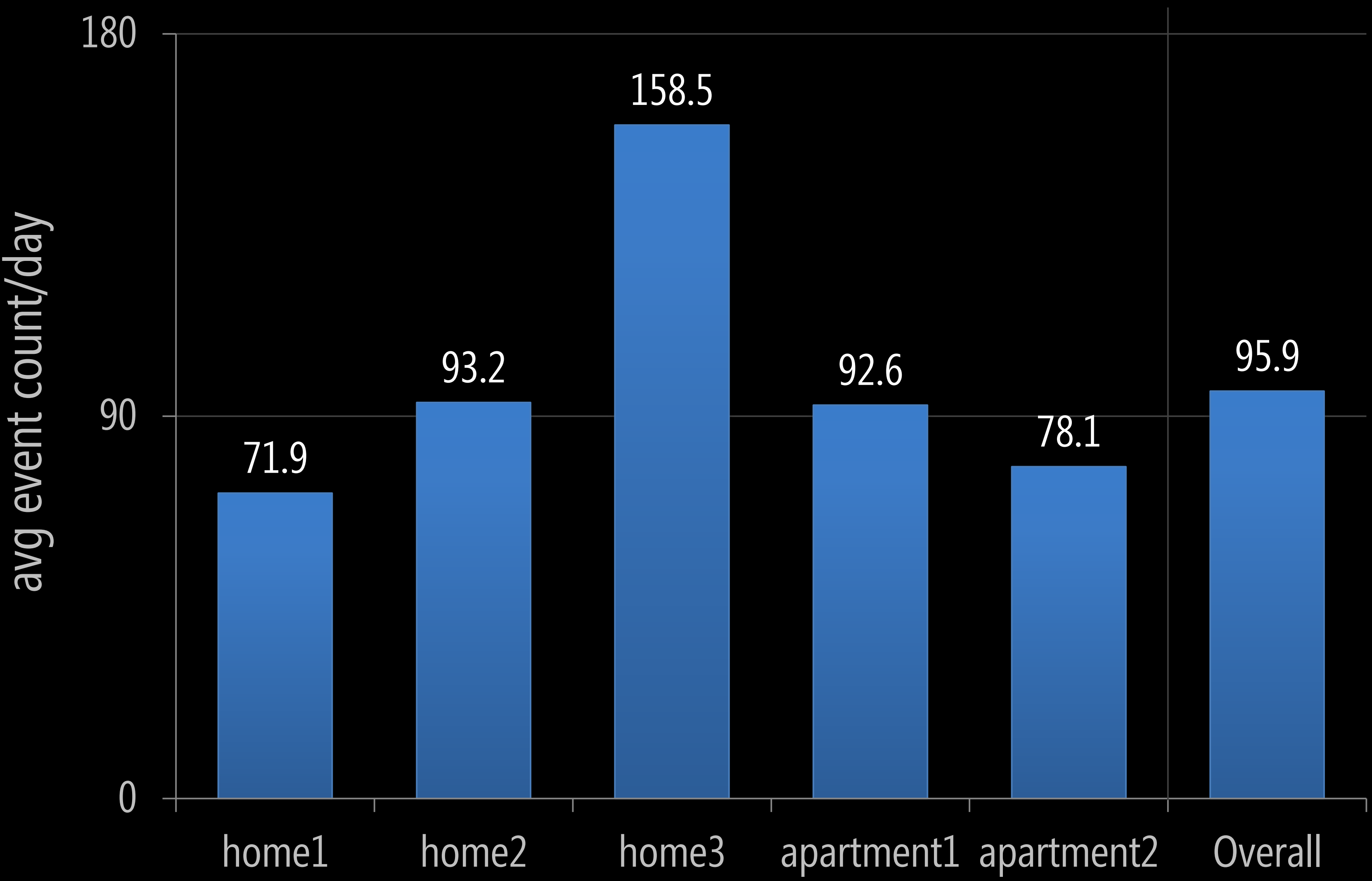

06:55:32 PM
06:55:45 PM
06:55:59 PM
13.3 secs
13.3 secs
13.3 secs
Pin=A3|SensorLocation=Toilet Handle|SensorTyp
Pin=A4|SensorLocation=Toilet Handle|SensorTyp
Pin=A1|SensorLocation=Bathroom Sink Handle Cold|S
Pin=A2|SensorLocation=Bathroom Sink Handle Hot|Se
Pin=A1|SensorLocation=Kitchen Sink Handle Cold|Se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

04:42:50 PM
05:08:16 PM
05:33:42 PM
05:59:08 PM
06:24:34 PM
06:50:01 PM
07:15:27 PM
07:40:53 PM
08:06:19 PM
Bath/Shower Switch / Accelerometer
Bathroom Sink Handle Hot / ReedSwitch
Kill-A-Watt on Dishwasher / KillAWatt
Kill-A-Watt on Washing Machine / KillAWatt
Kitchen Sink Handle Cold / ReedSwitch
Bathroom Sink Handle Cold / ReedSwitch
Drain Valve on Washing Machine / Thermistor
Kill-A-Watt on Dishwasher / PushButton
Kill-A-Watt on Washing Machine / PushButton
Kitchen Sink Handle Hot / ReedSwitch
Shower Handle Cold / ReedSwitch
06:20:28 PM
06:28:57 PM
06:37:26 PM
06:45:55 PM
06:54:23 PM

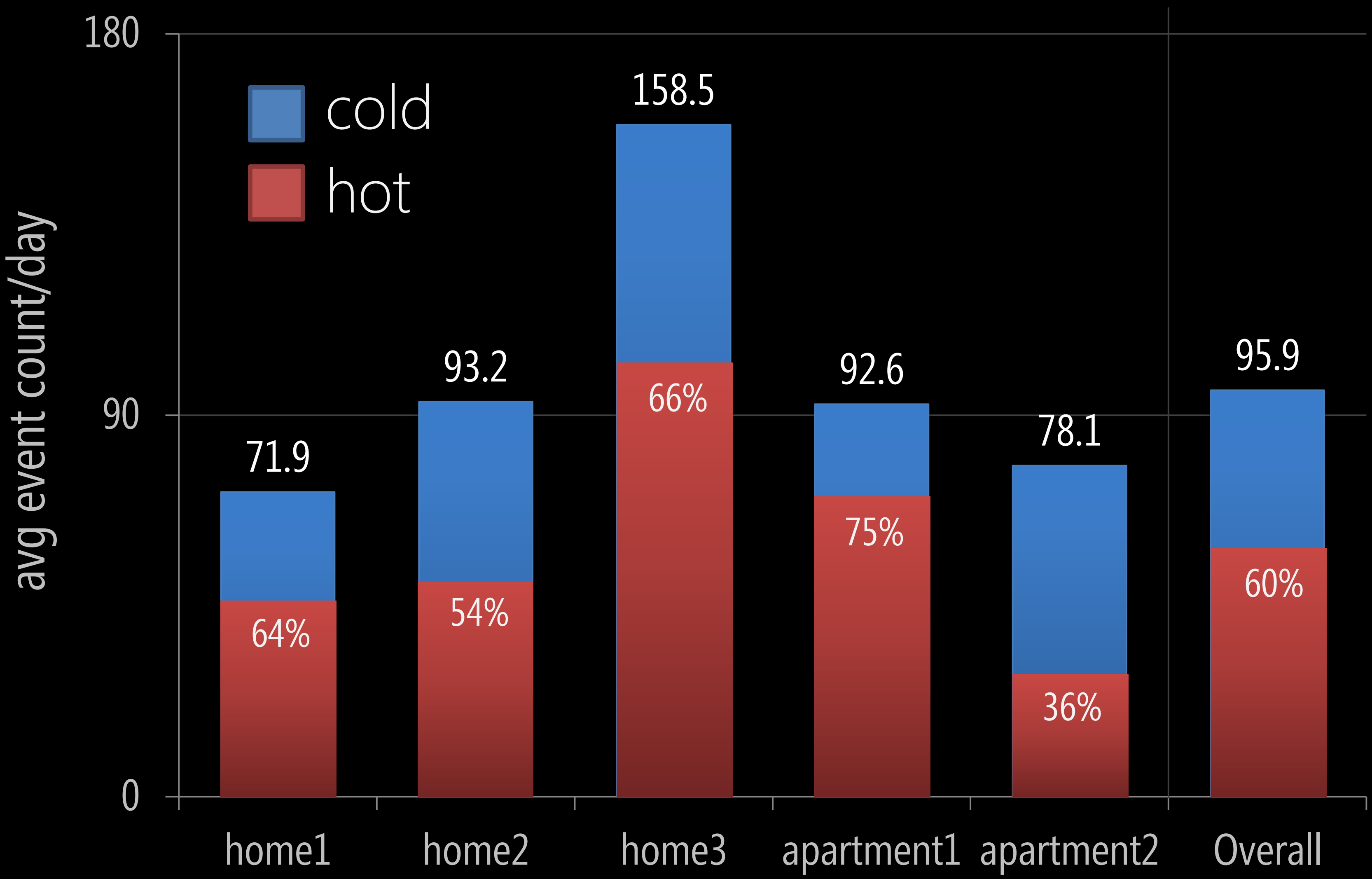
5-week dataset

						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

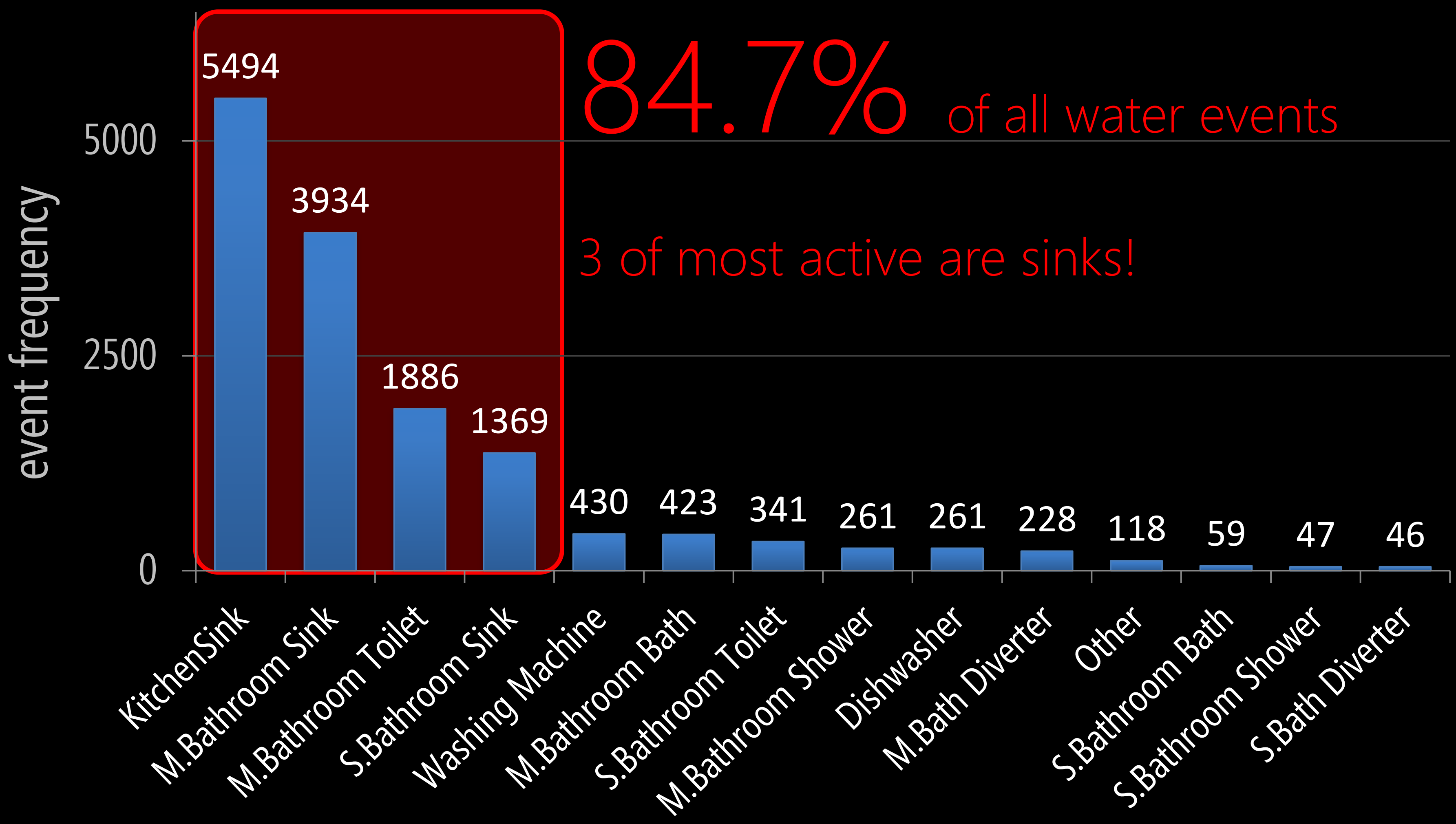
avg num water events/day

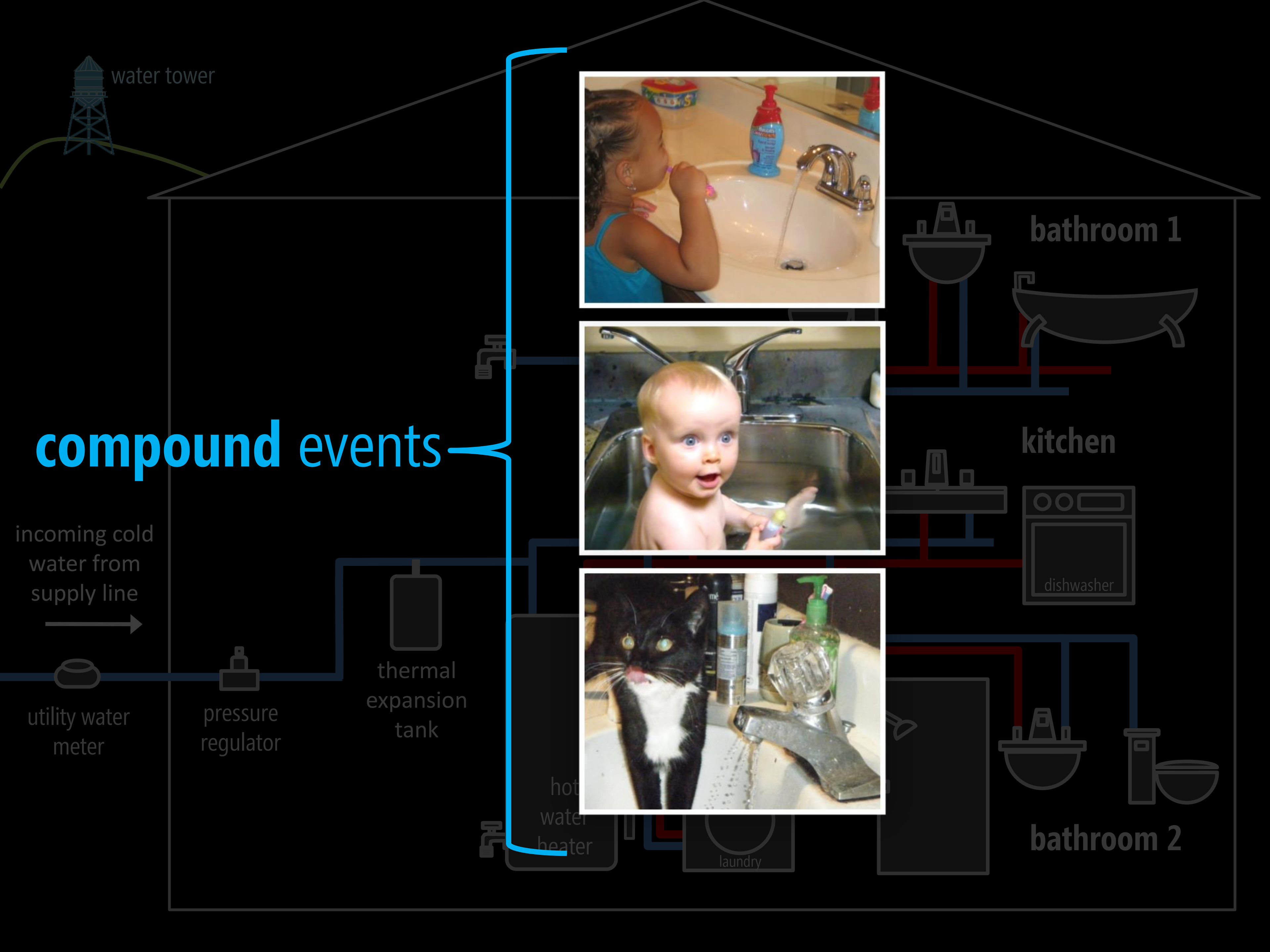


avg num water events/day



fixture activity frequency




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

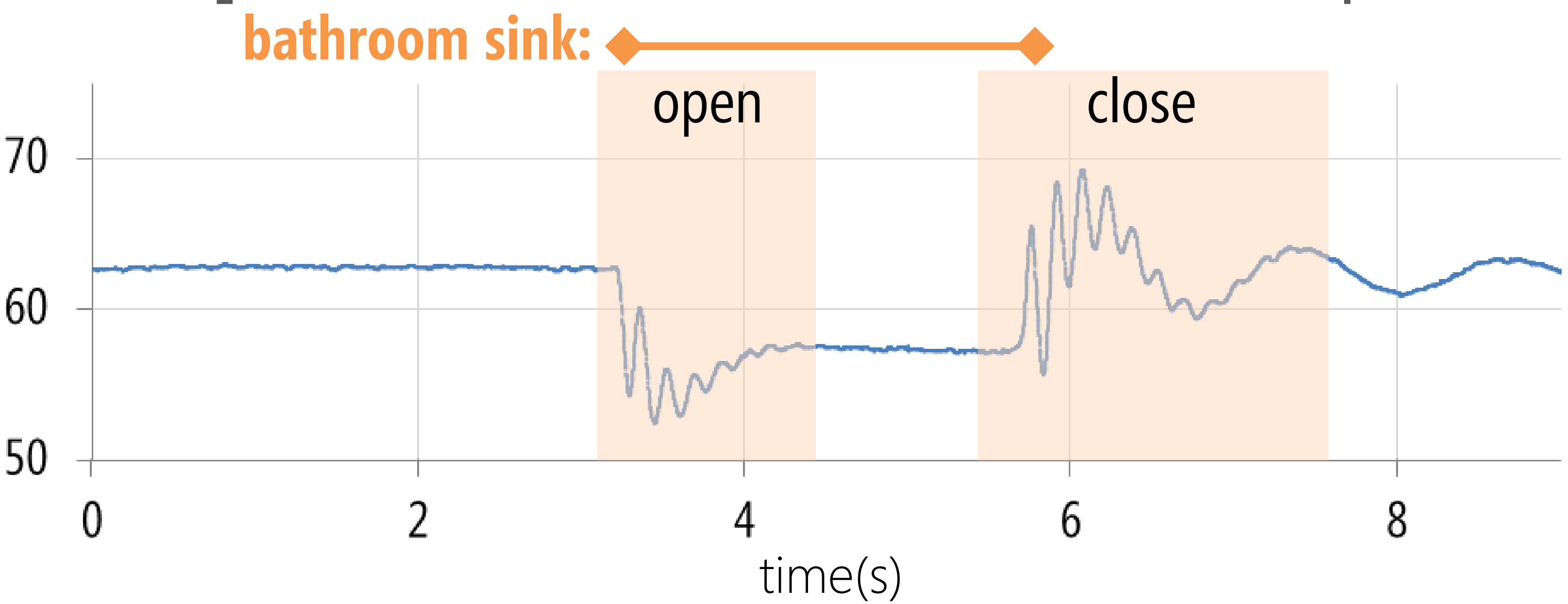
22%

of all water events were compound

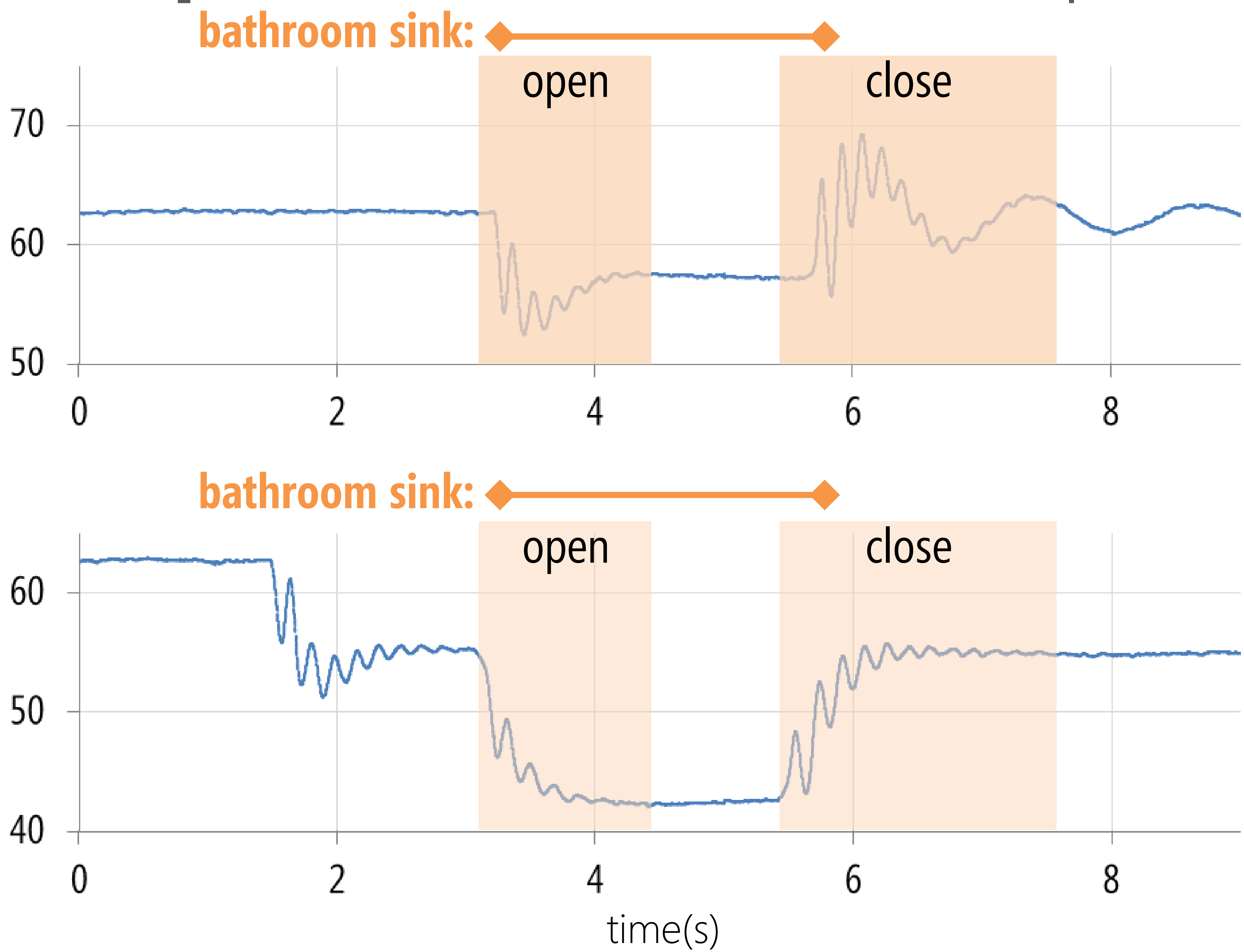
41.8%

of all bathroom sink events were compound

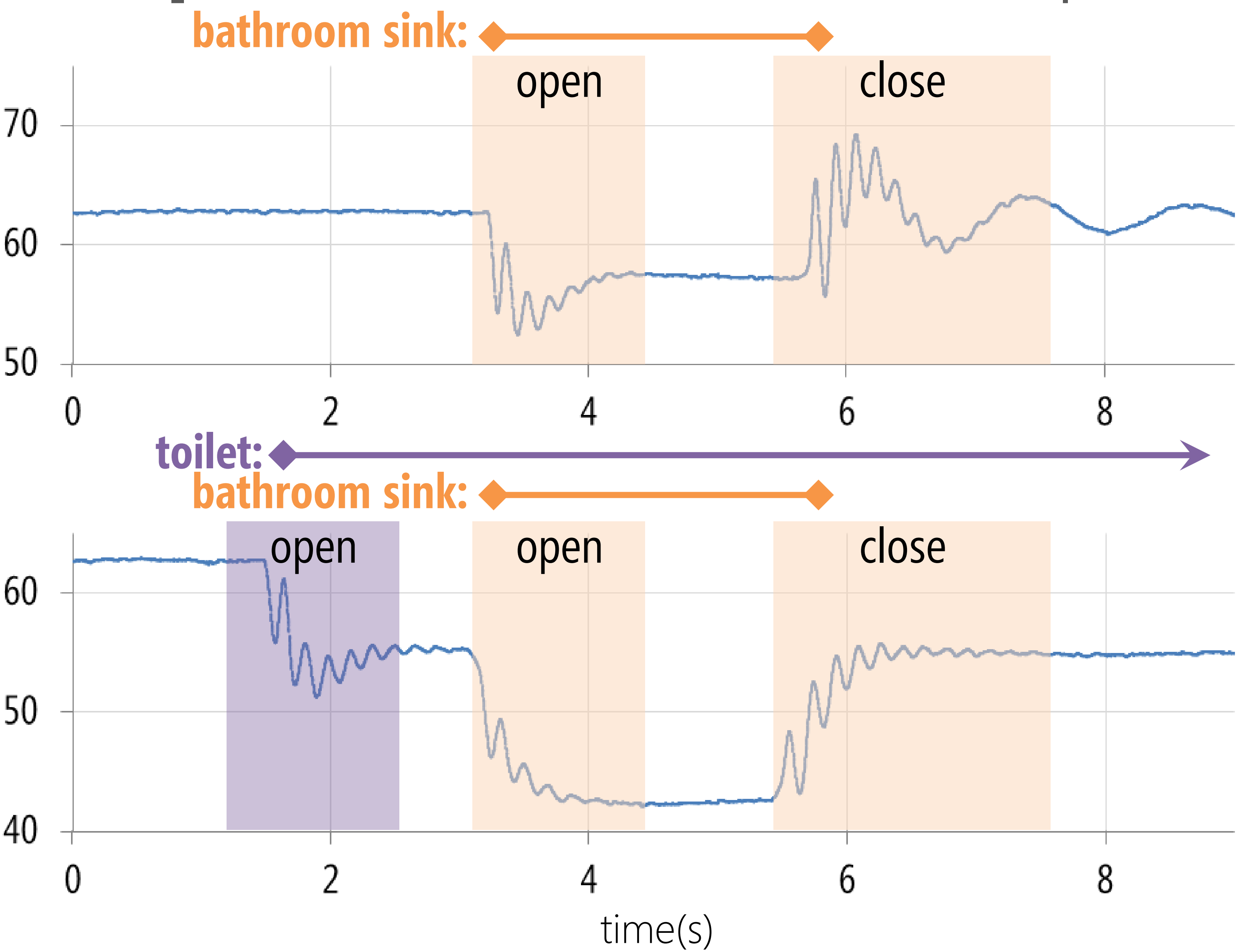
compound event example



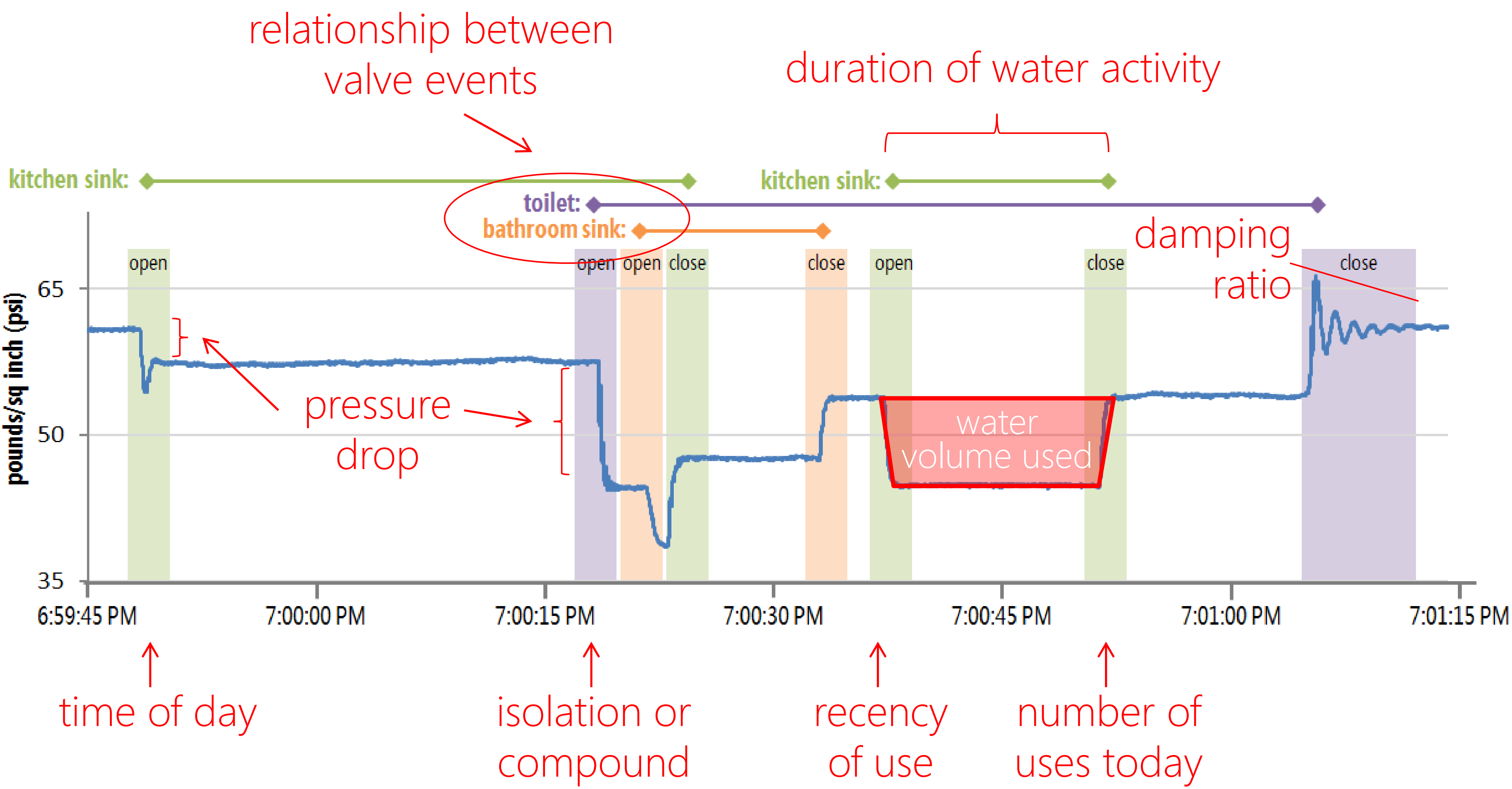
compound event example



compound event example



beyond **template matching**



bayesian approach

New algorithm borrows from Bayesian inference in speech recognition

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

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

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

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

(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

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

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

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

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

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

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

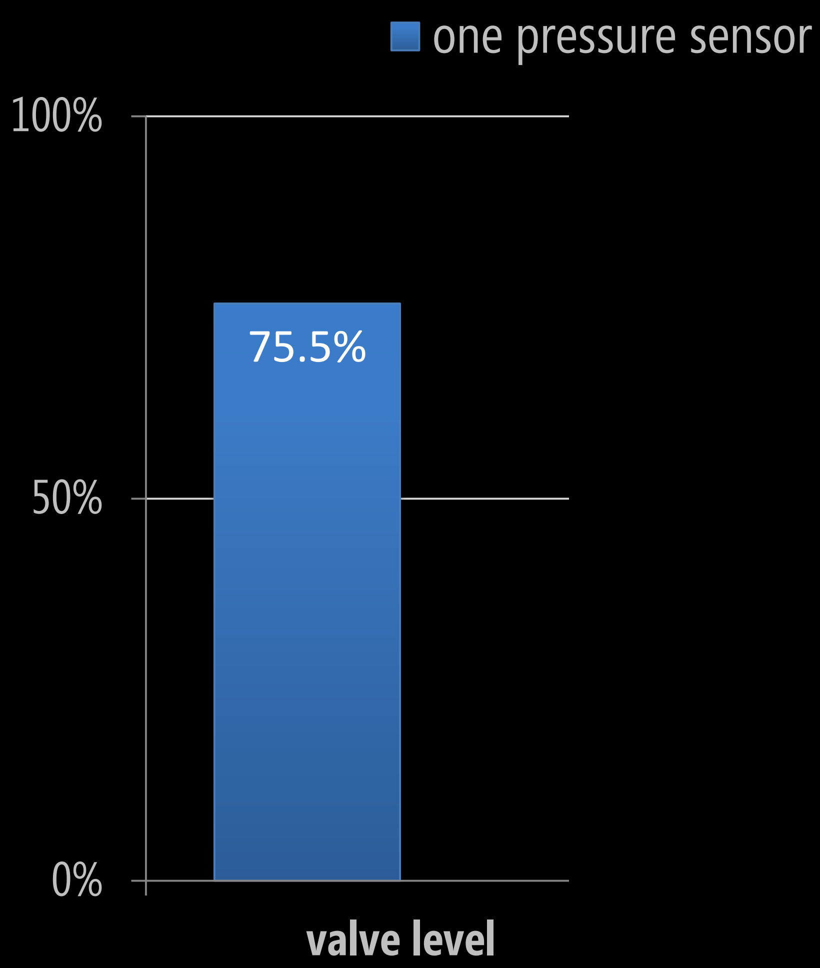
$$\hat{V} = \arg\max P(\mathbf{V} \mid \mathbf{S}) = \arg\max \frac{P(\mathbf{S} \mid \mathbf{V})\boxed{P(\mathbf{V})}}{P(\mathbf{S})}$$

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

e.g., water usage duration

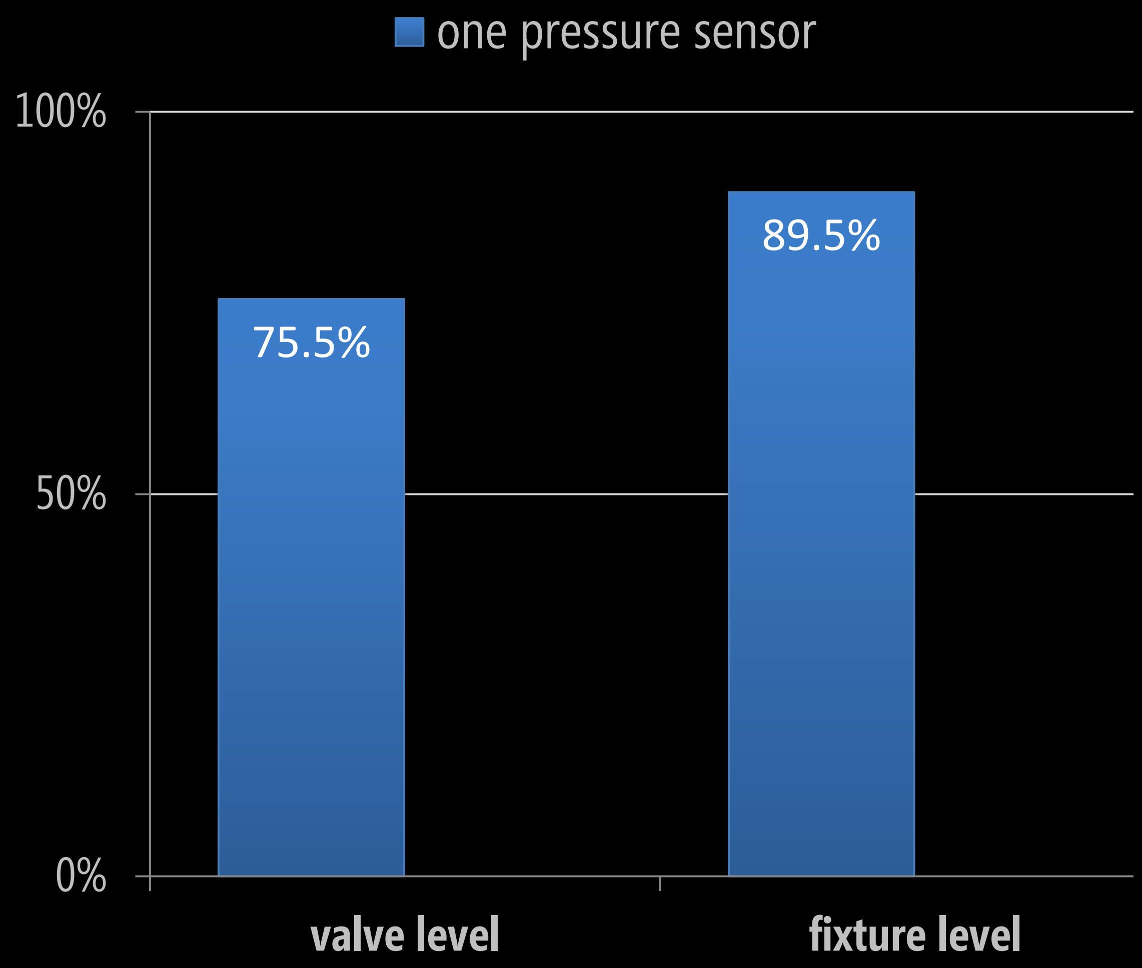
hydrosense classification results

real-world water usage data



hydrosense classification results

real-world water usage data



hydrosense classification results

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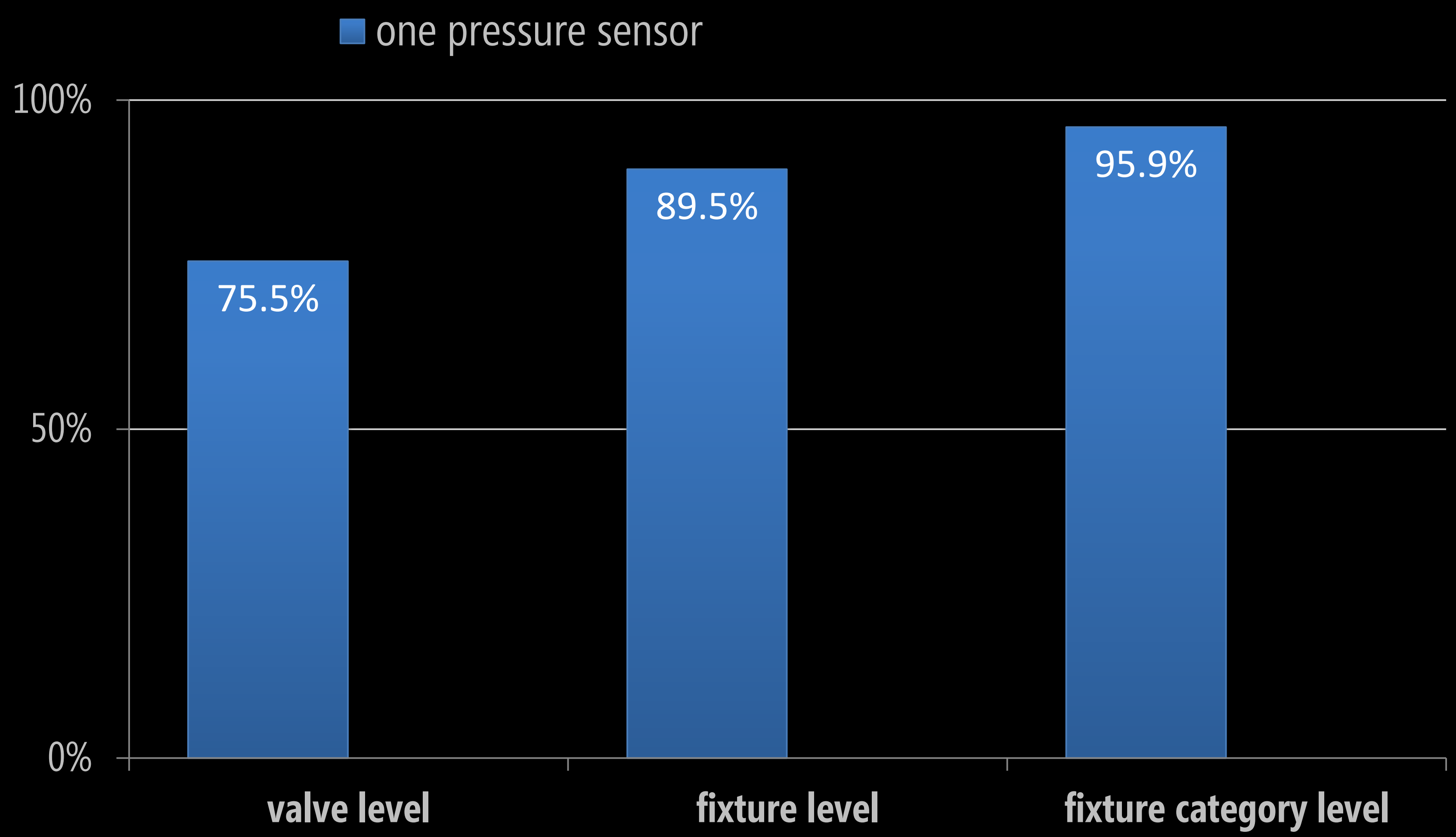
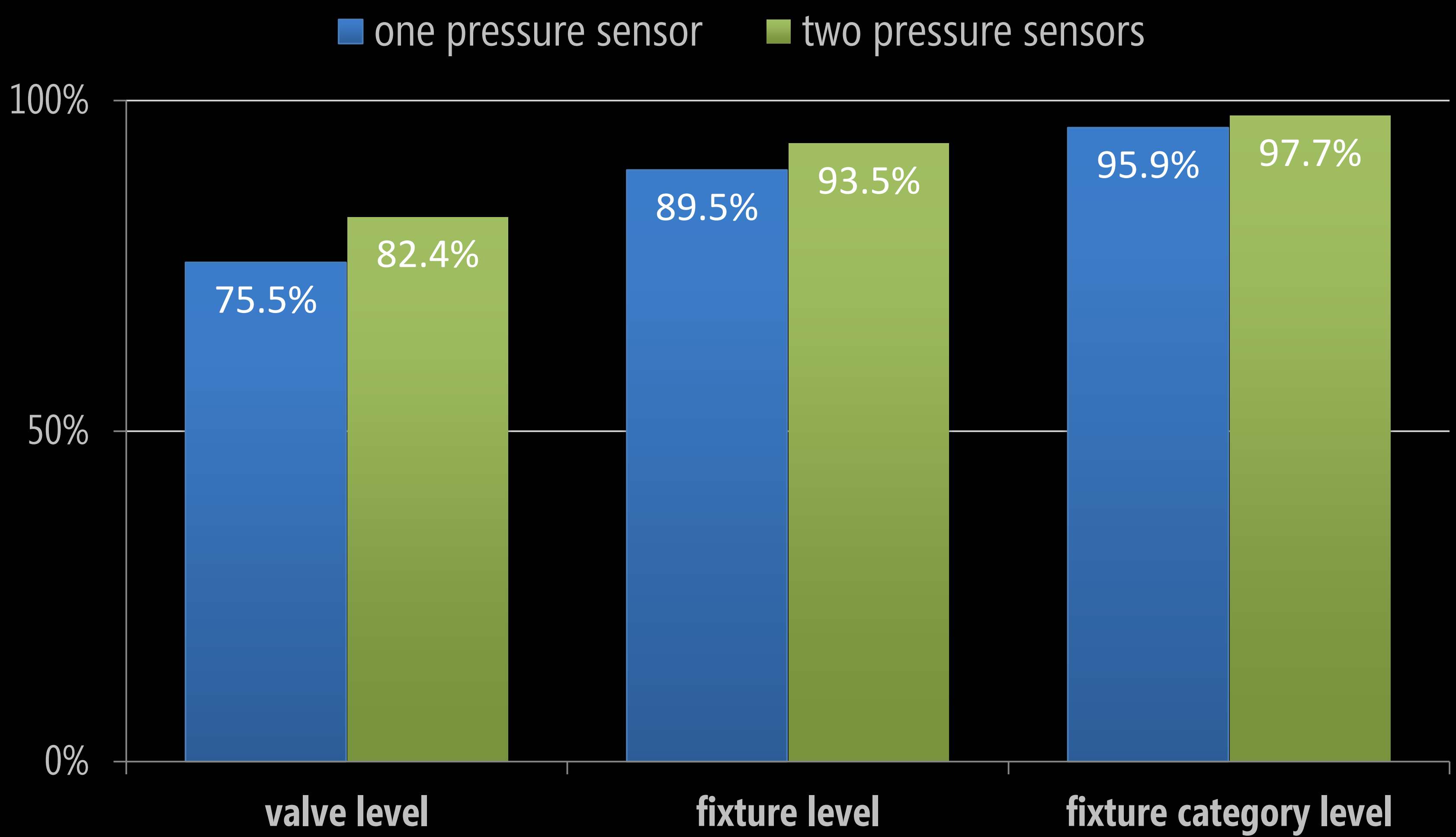


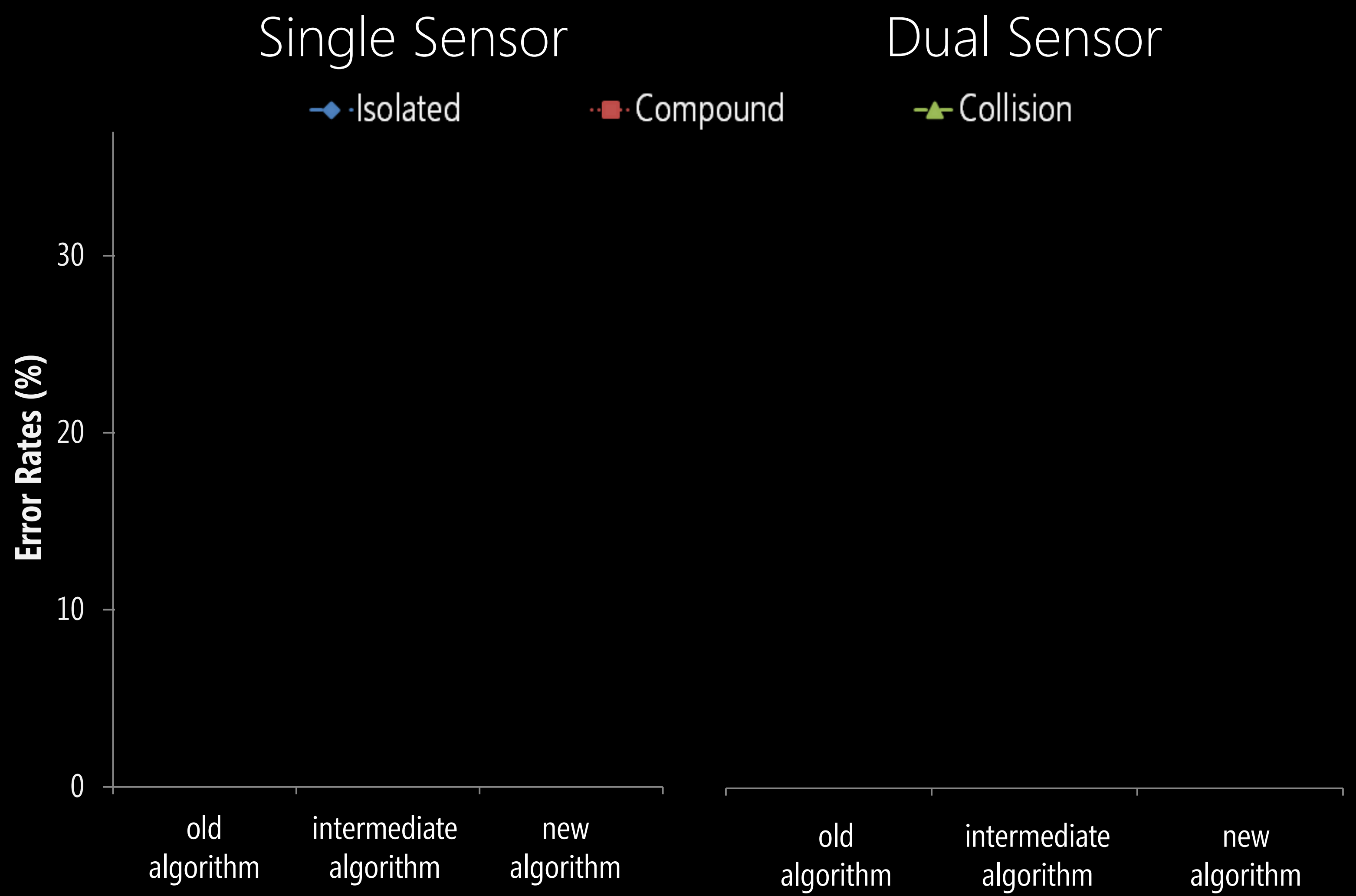
hydrosense classification results

real-world water usage data



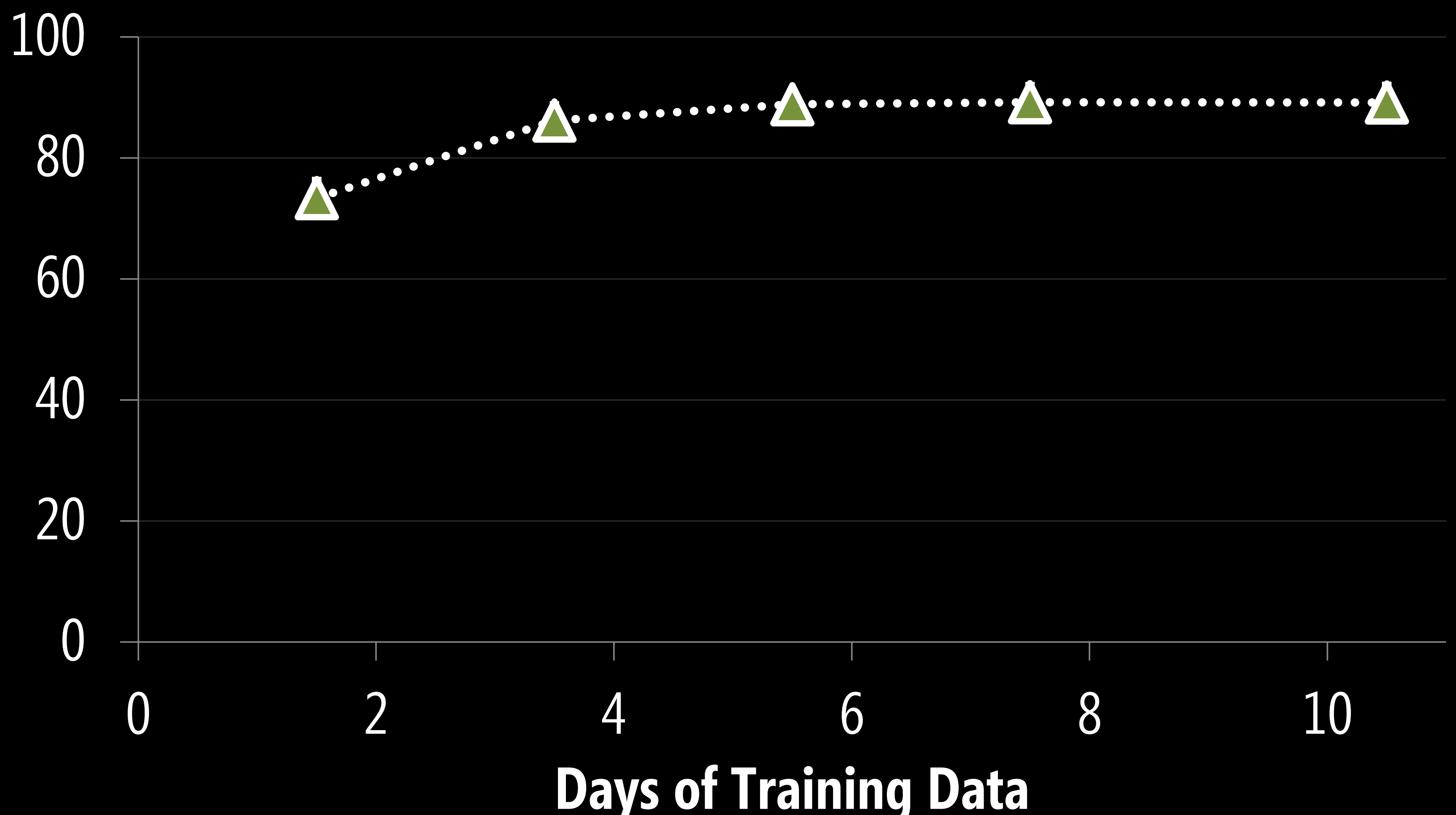
compound events results

real-world water usage data



hydrosense training results

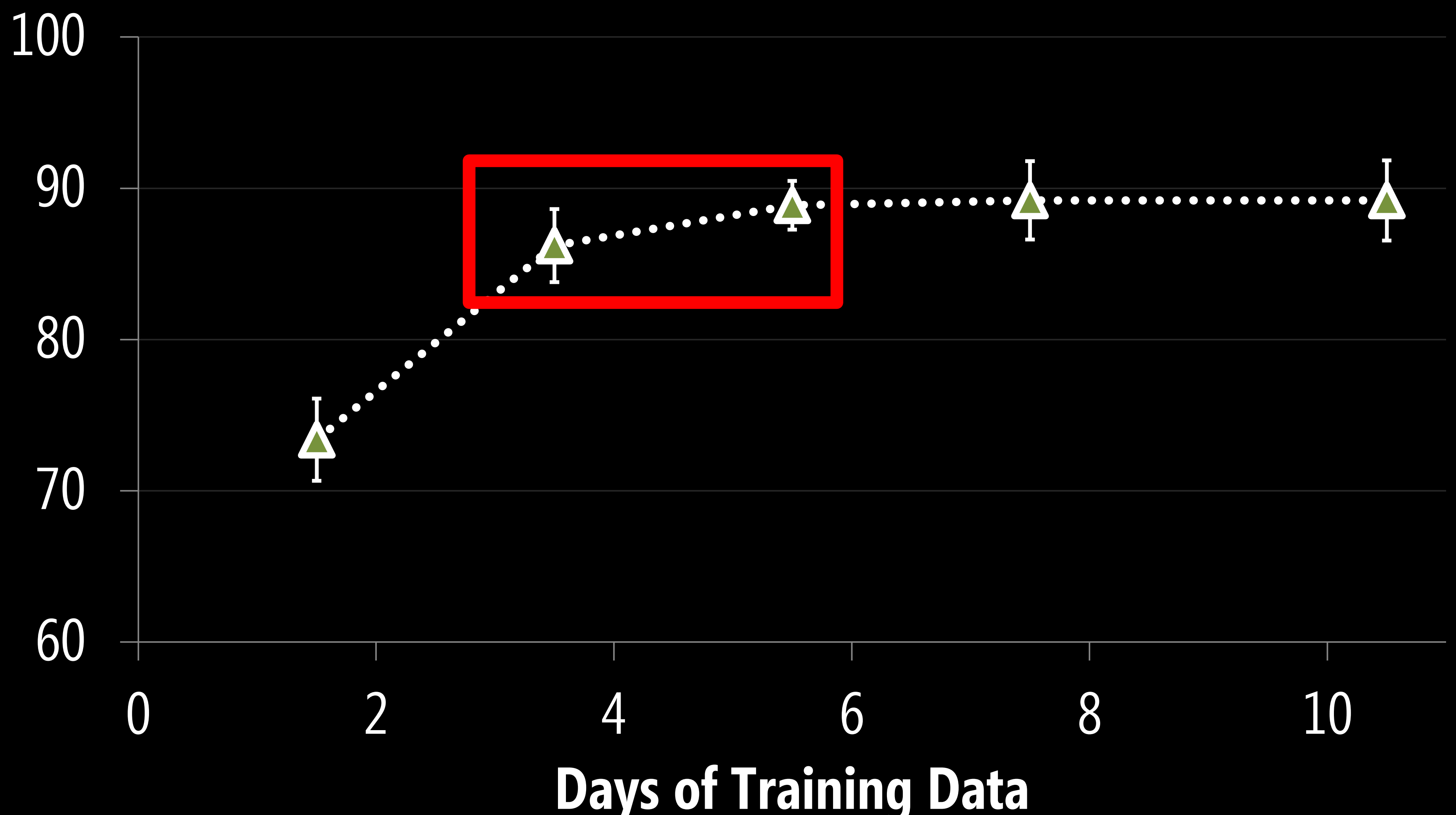
real-world water usage data



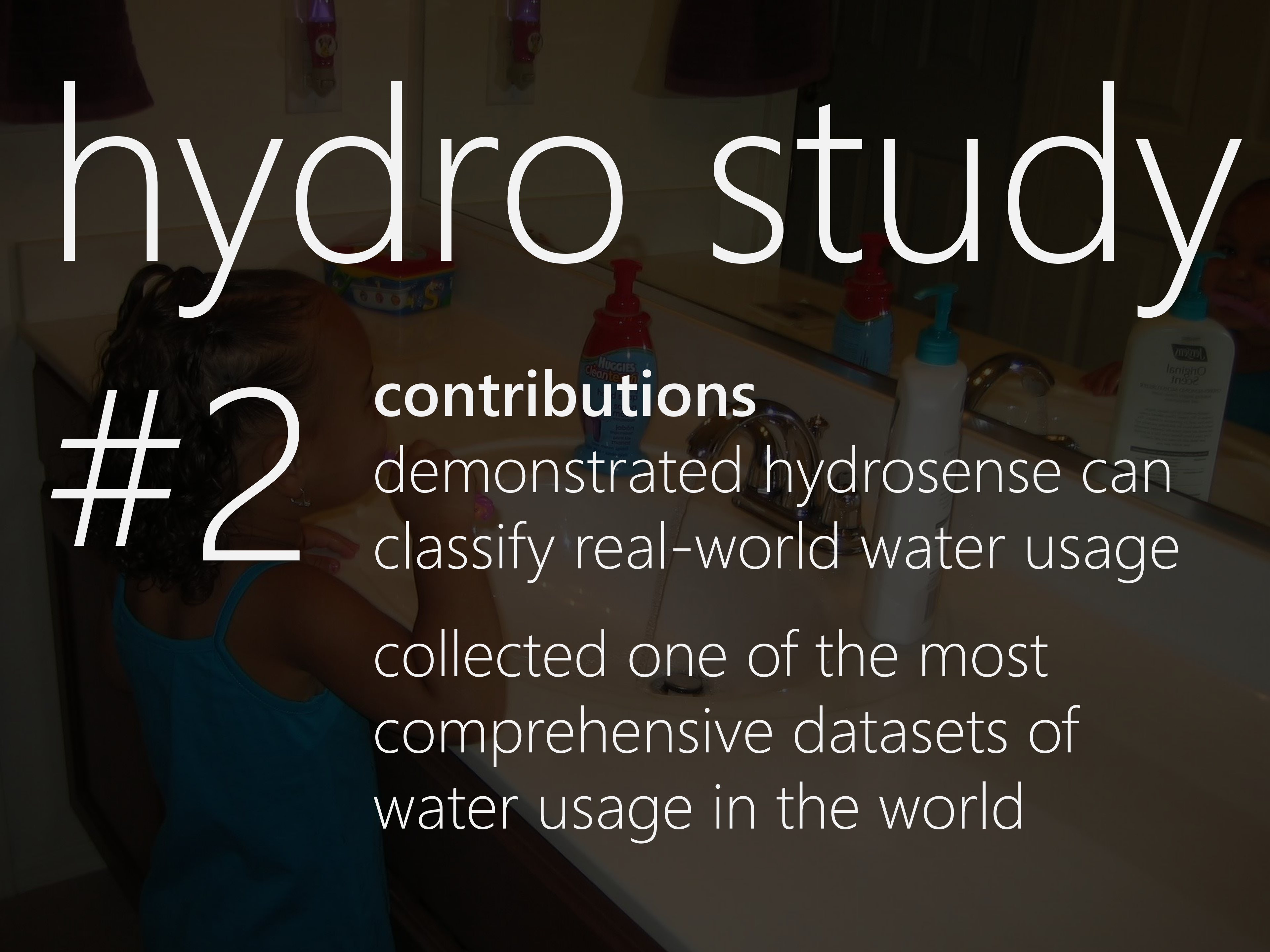
*error bars = std error

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