# A Longitudinal Study of Pressure Sensing to Infer Real-World Water Usage Events in the Home

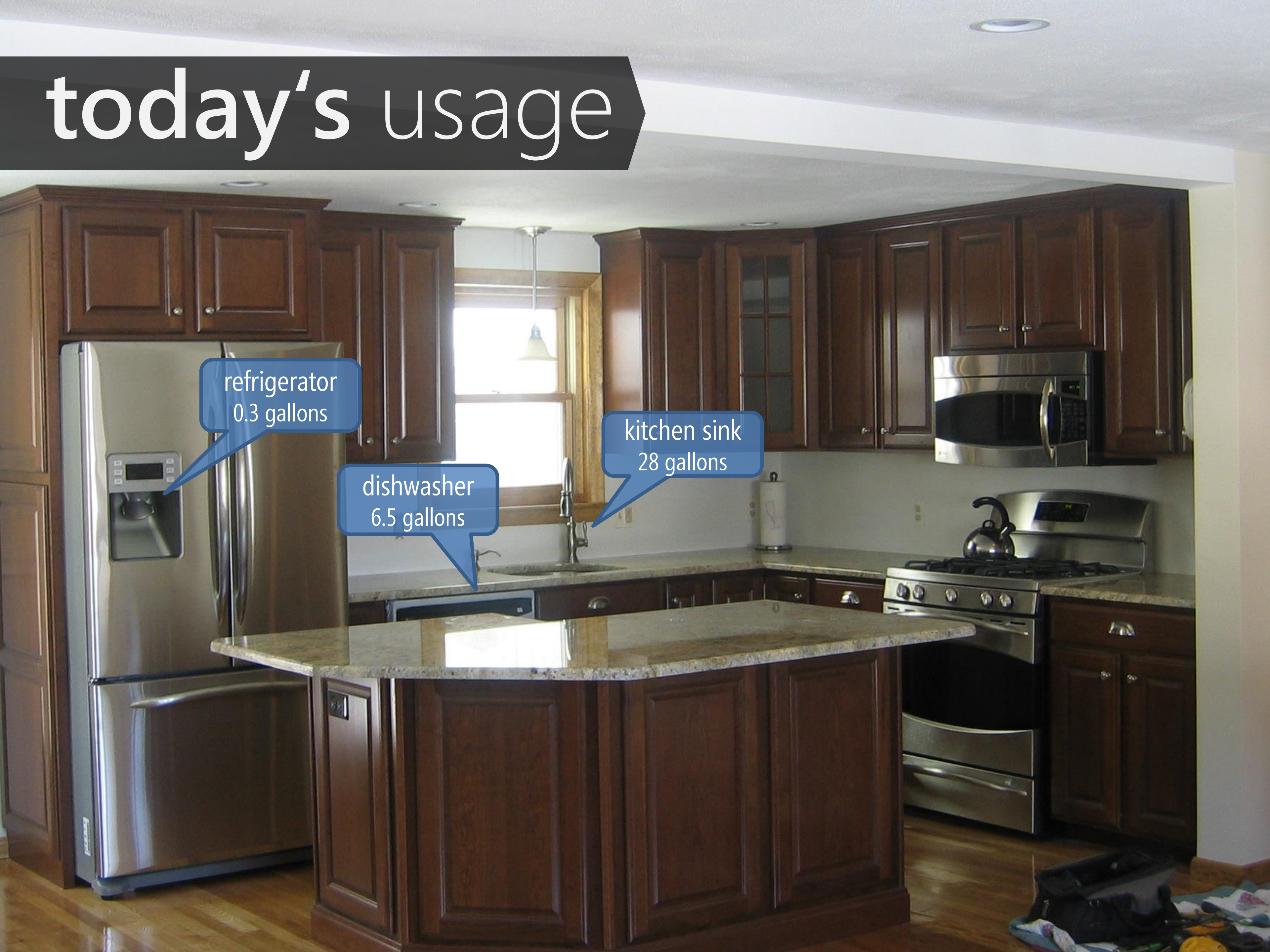
**Eric Larson**, Jon Froehlich, Elliot Saba, Tim Campbell, Les Atlas, James Fogarty and Shwetak Patel


dub design: use: build:
university of washington

ubicomp lab
university of washington

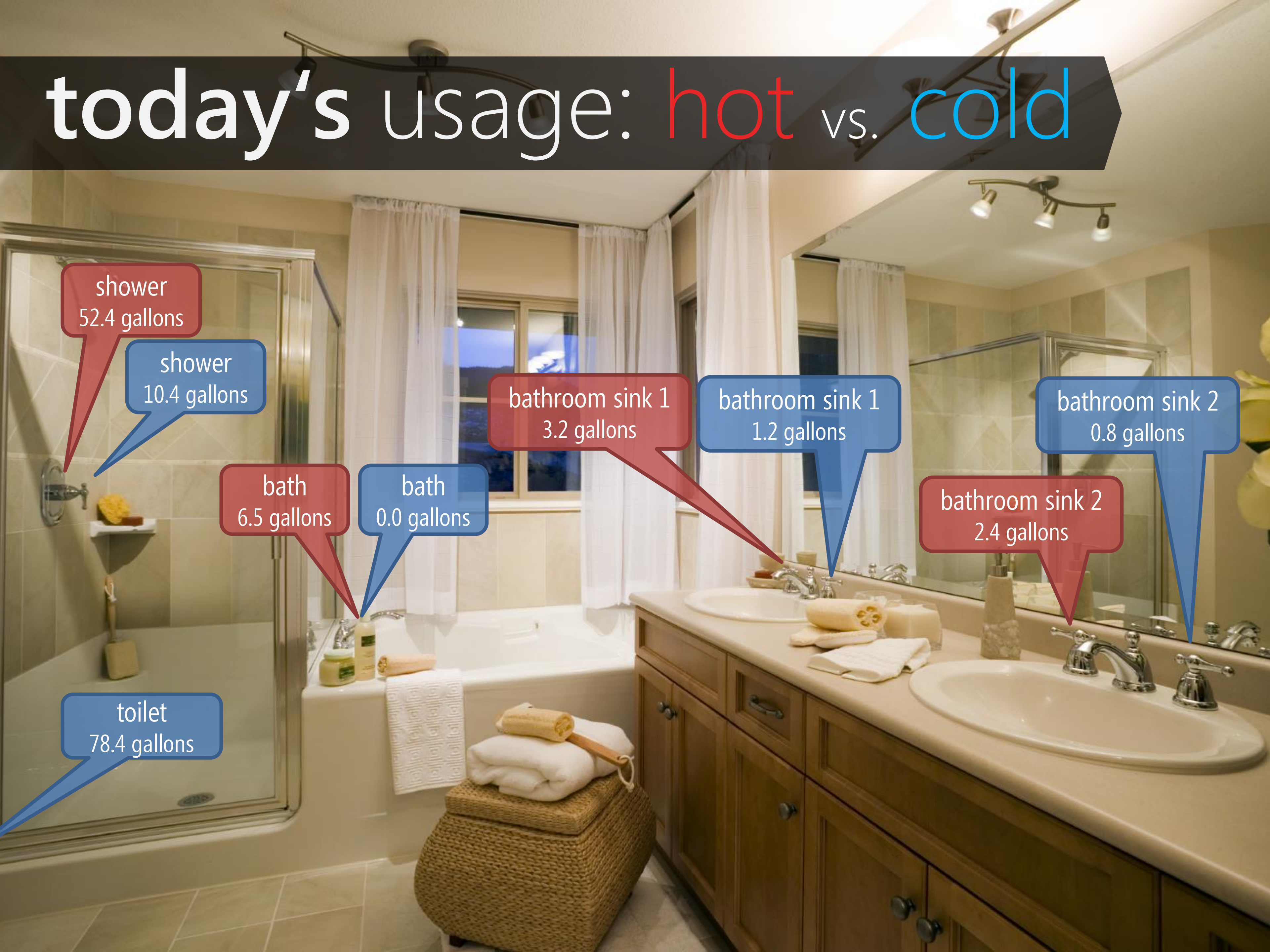
sustain
sustainability research

# today's usage



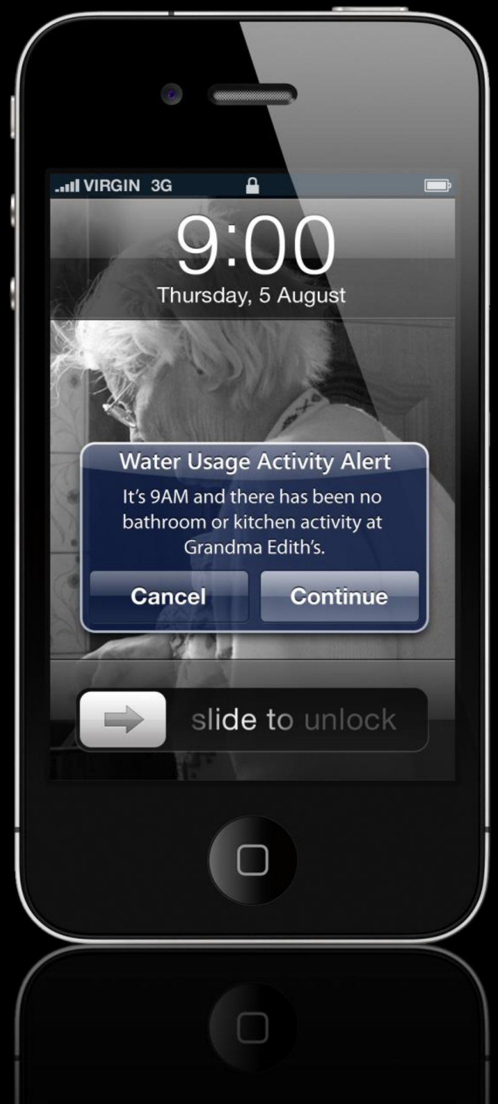
# today's usage

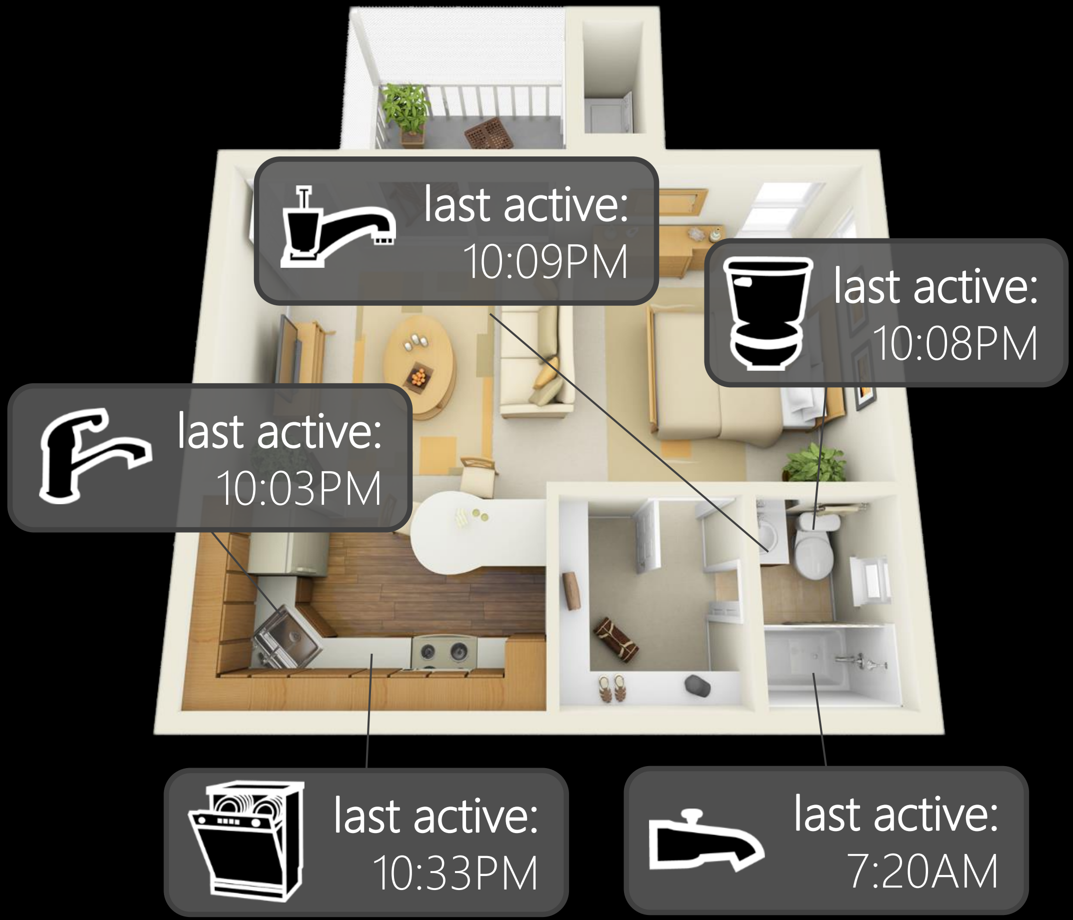
# today's usage: hot vs. cold



# **sustainability** applications

# **assisted living** applications



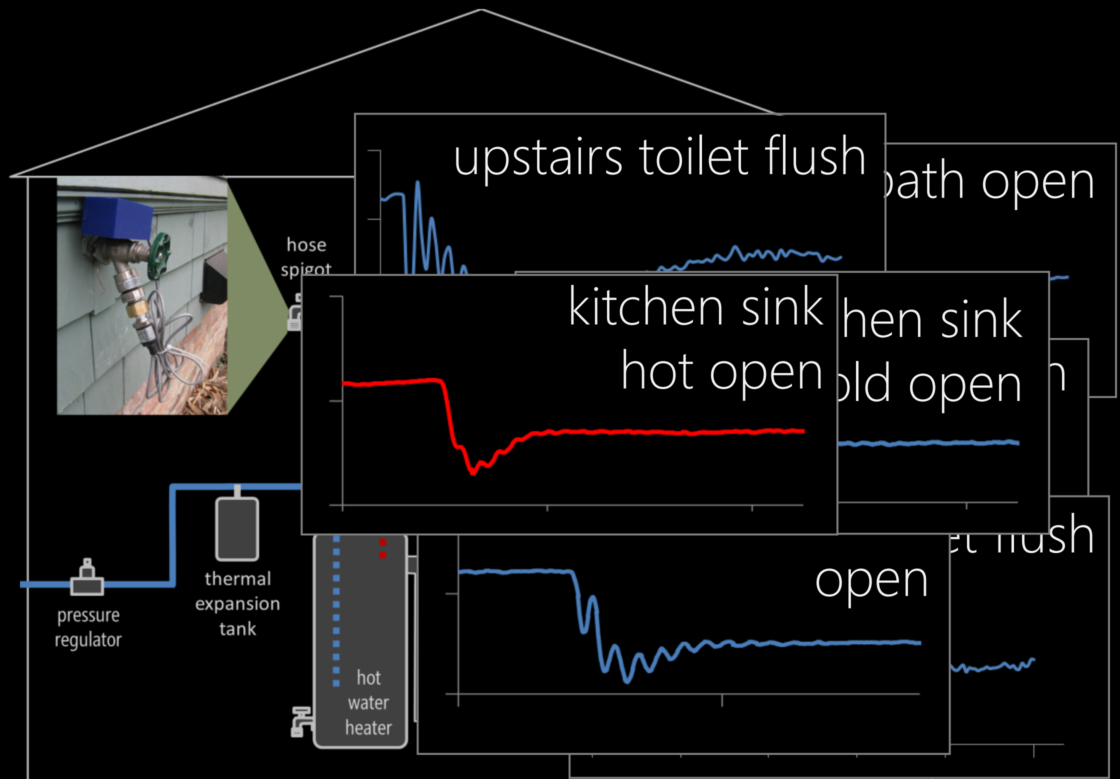



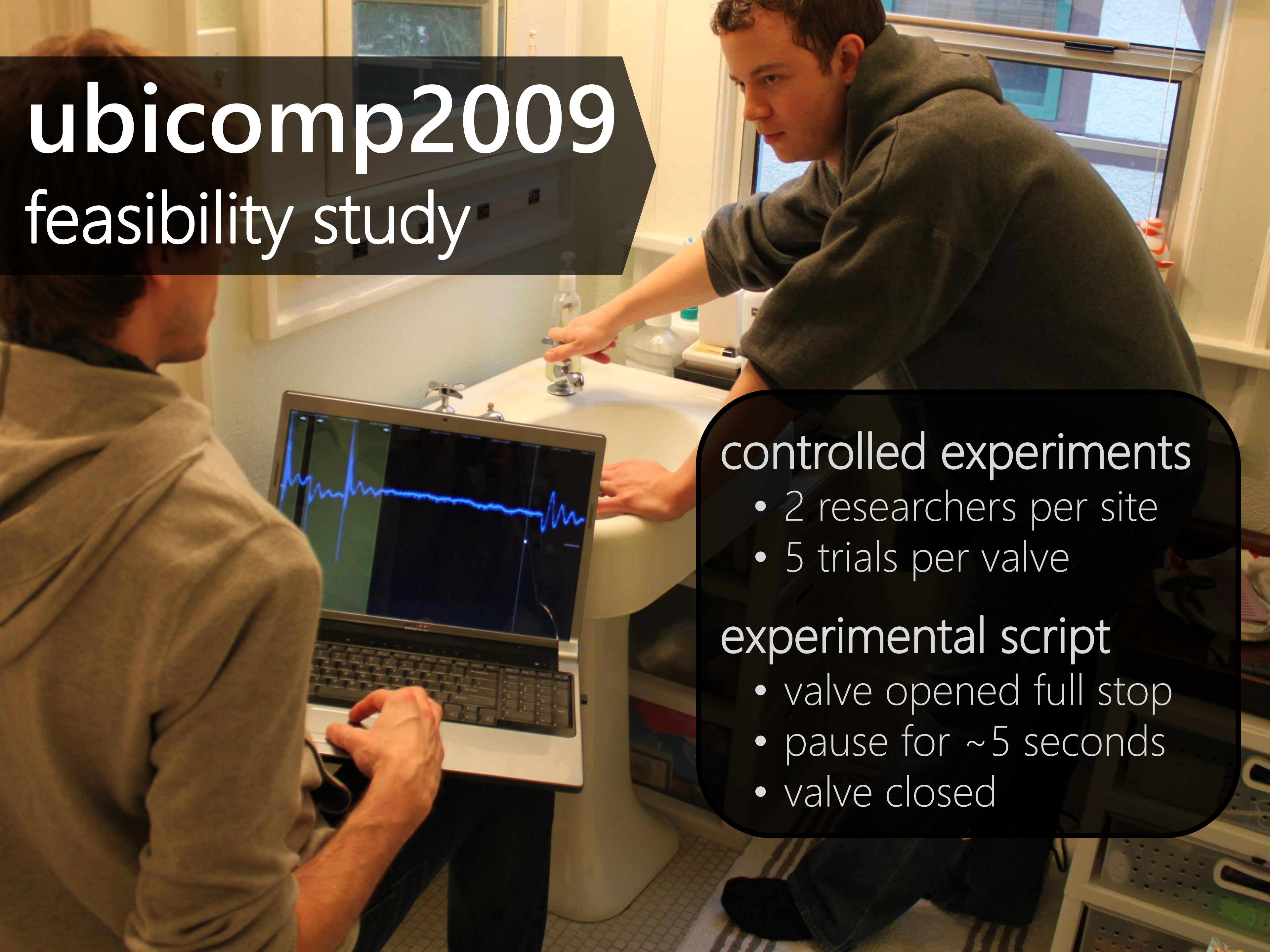
at ubicomp09, we introduced **hydro**sense


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

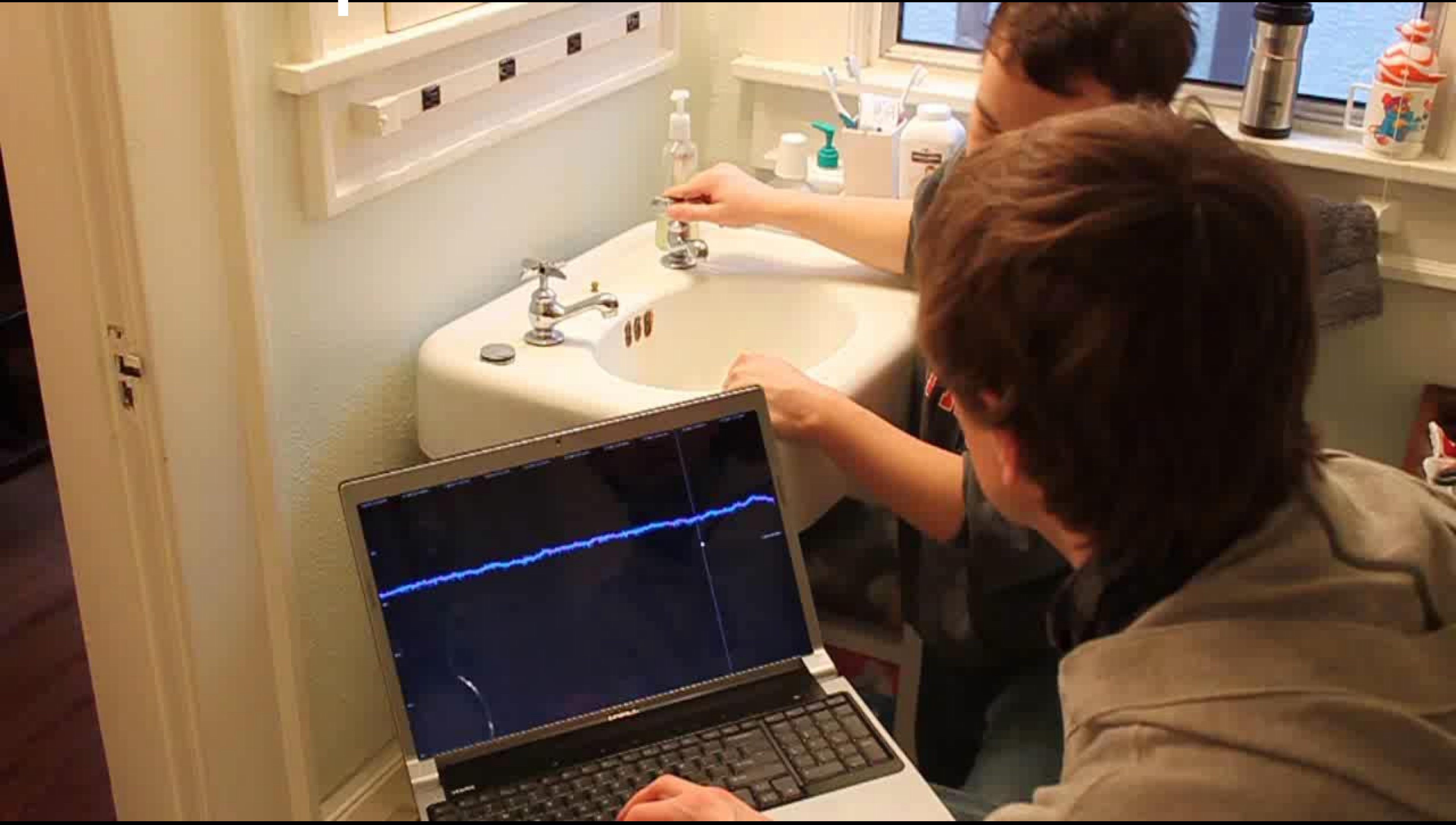
# **hydro**sense

uses pressure waves to identify usage




ubicomp2009
feasibility study
controlled experiments
• 2 researchers per site
• 5 trials per valve
experimental script
• valve opened full stop
• pause for ~5 seconds
• valve closed

# ubicomp2009 data collection



# ubicomp2009 paper

successfully demonstrated the potential of using pressure waves to identify fixture usage

**evaluation method**

staged experiments

all faucet handles were operated at approximately the same flow rates

all fixtures were tested in isolation

**algorithm**

each pressure wave treated independently

did not consider context of usage

was not probabilistic

what we're really interested in...

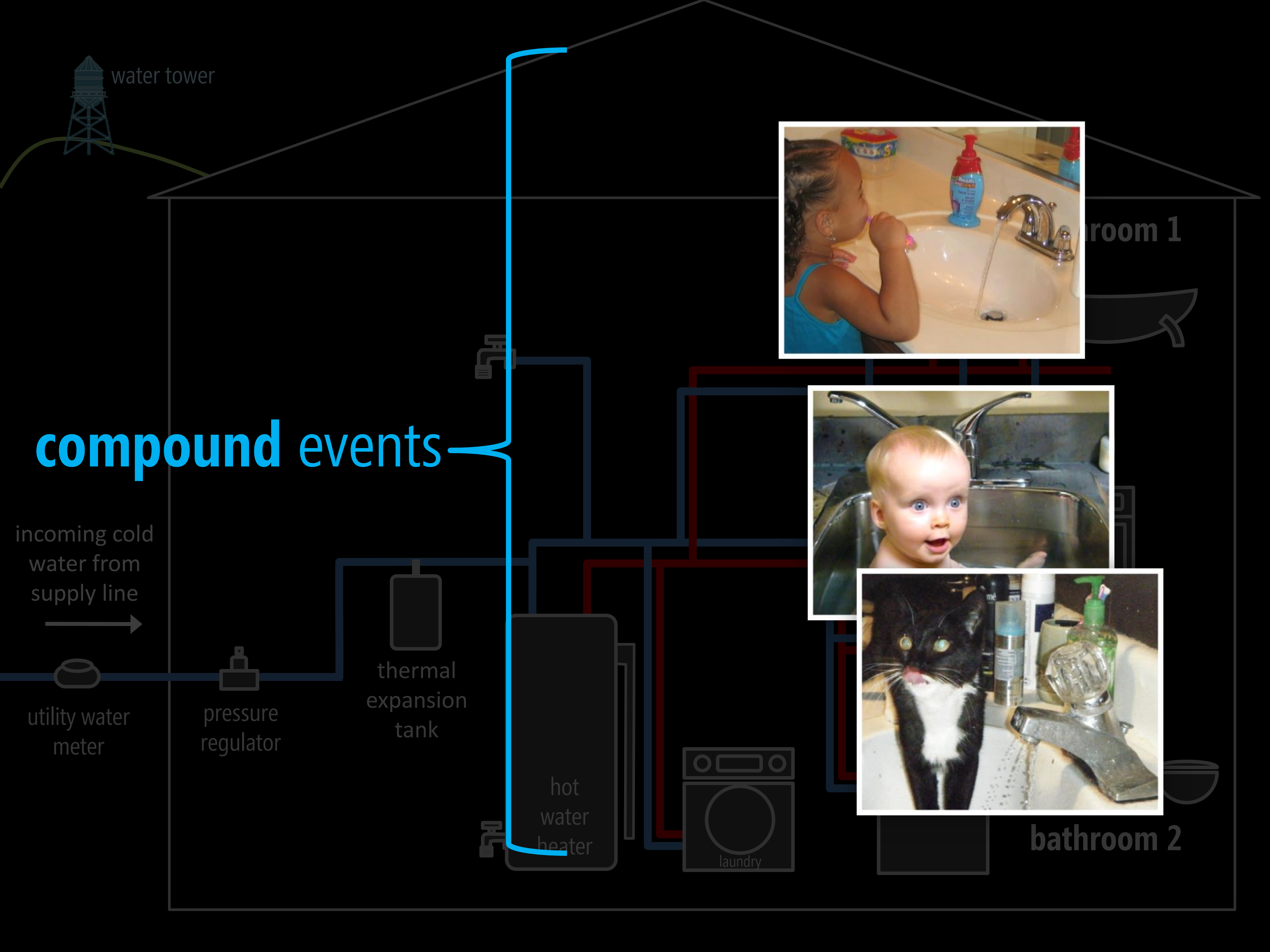
how well will **hydrosense** perform on **real-world water usage** data?

# **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
bathroom 2

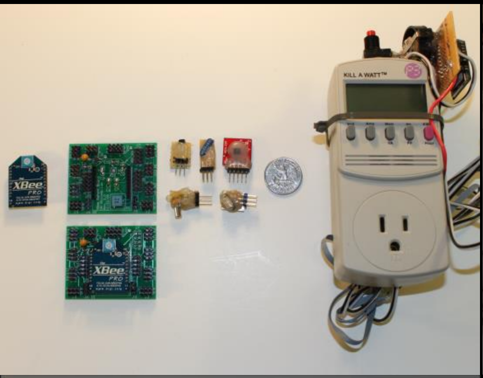
# **pervasive** 2011 contributions

① longitudinal study of real-world water usage and the resulting dataset

② a new probabilistic approach to water usage classification

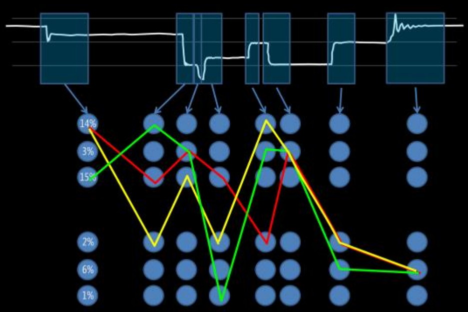
③ demonstrate that this new approach can accurately classify real world data

ground truth sensors

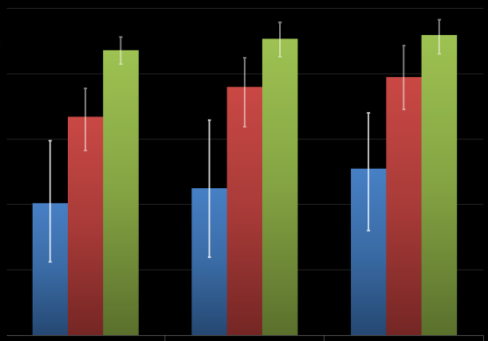


5-week deployment

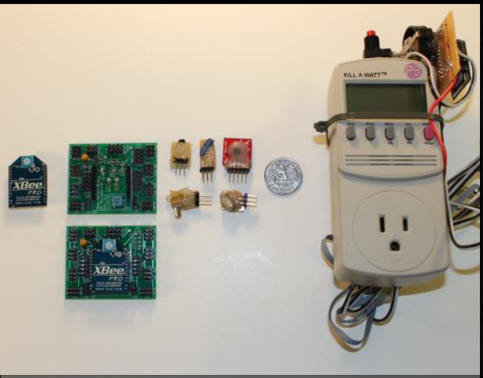
classification algorithm




classification results



ground truth sensors



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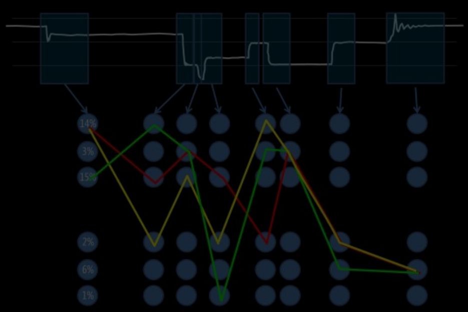
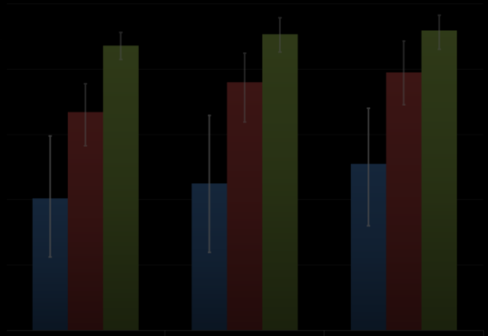
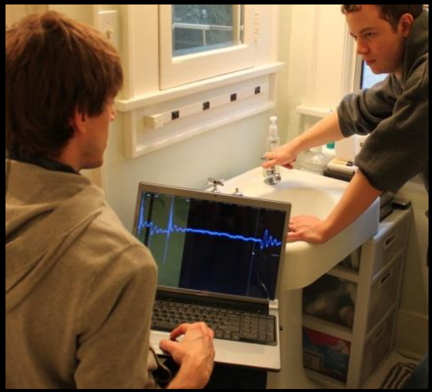


classification results

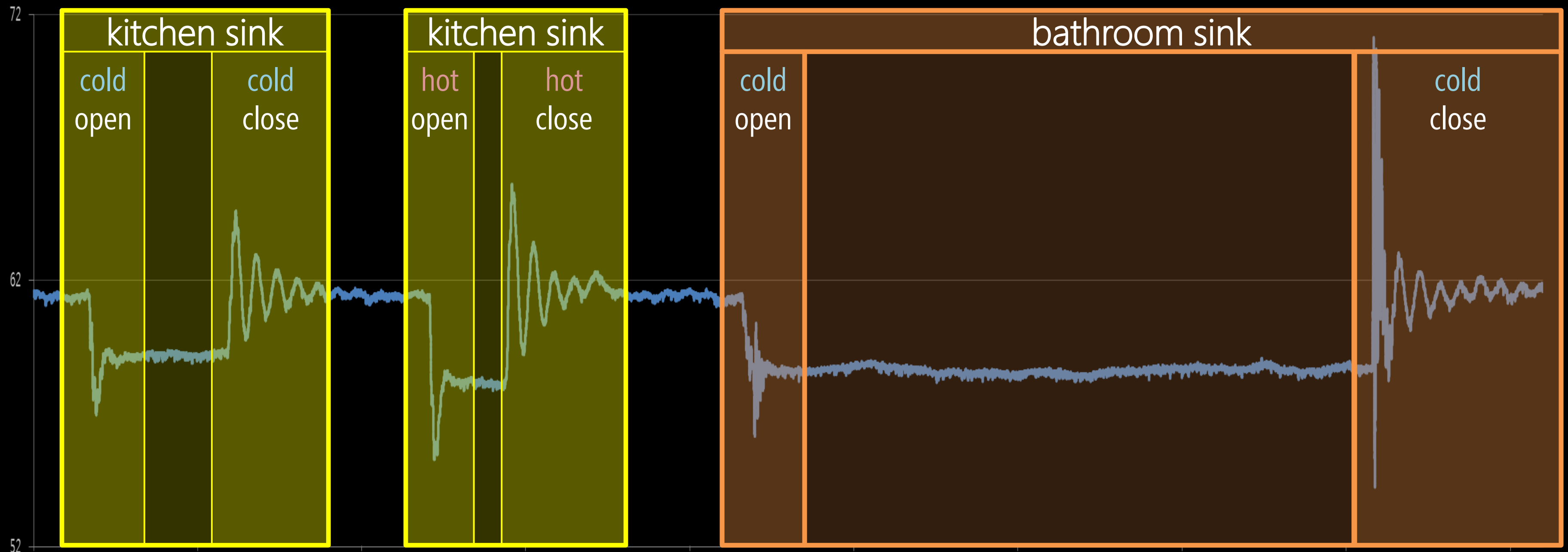


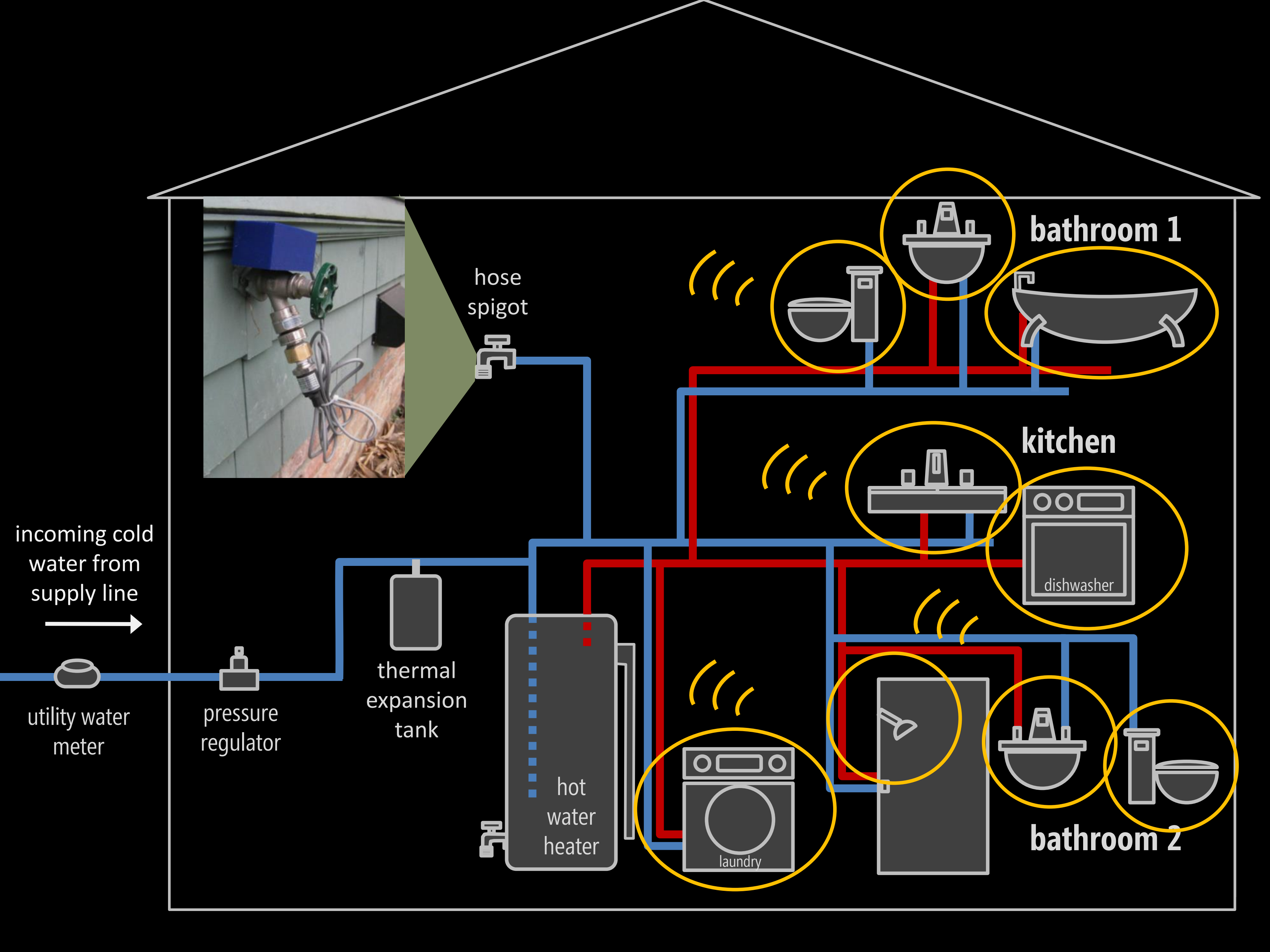
# **ground truth** labels



manual

automatic





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

how can we obtain water usage labels at the **valve-level**?

this is actually a challenging question...

# **function** across fixtures

**kitchen** sink

**bathroom** sink

**bath**

**shower**

**toilet**

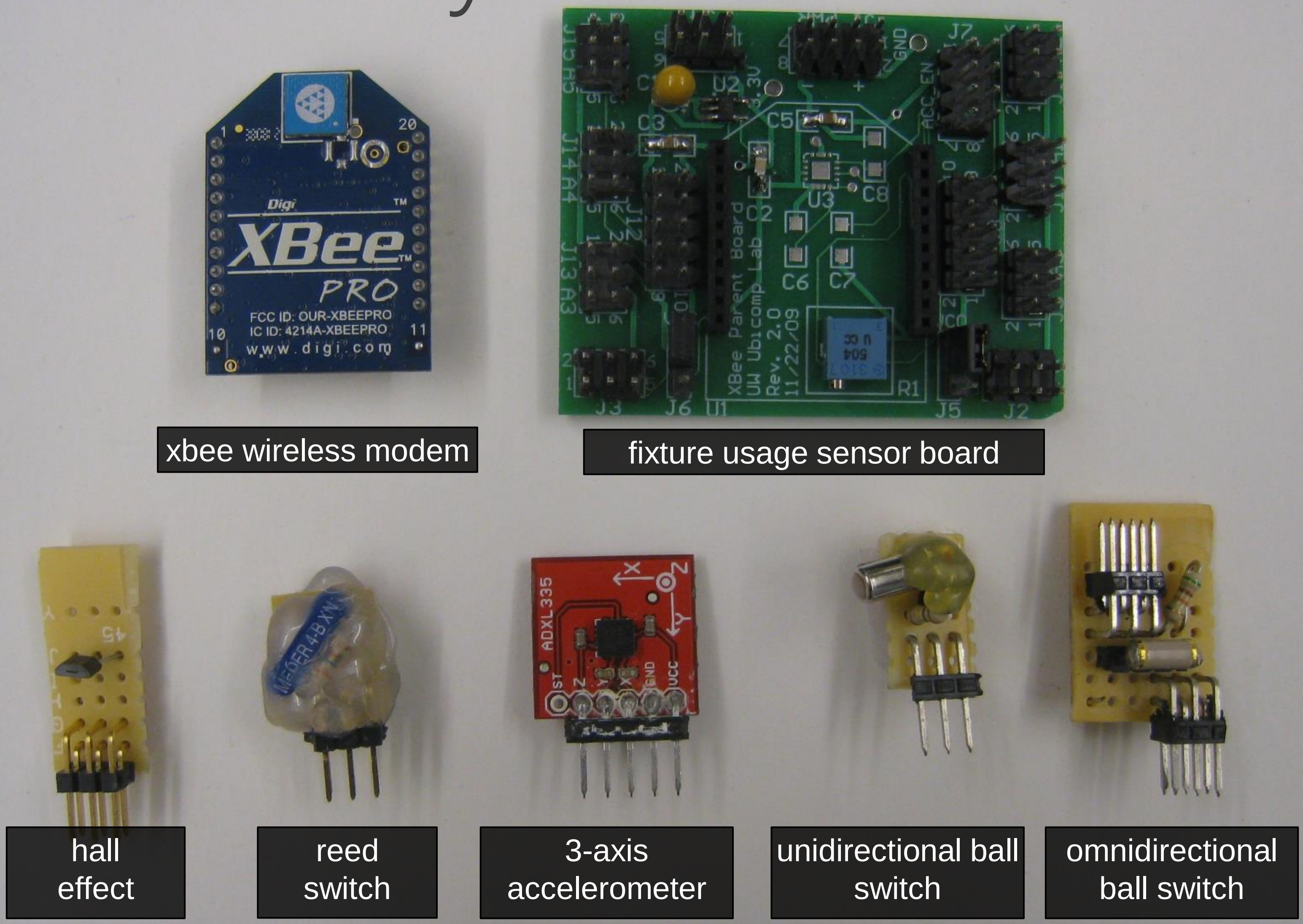
**laundry** basin

**washing** machine

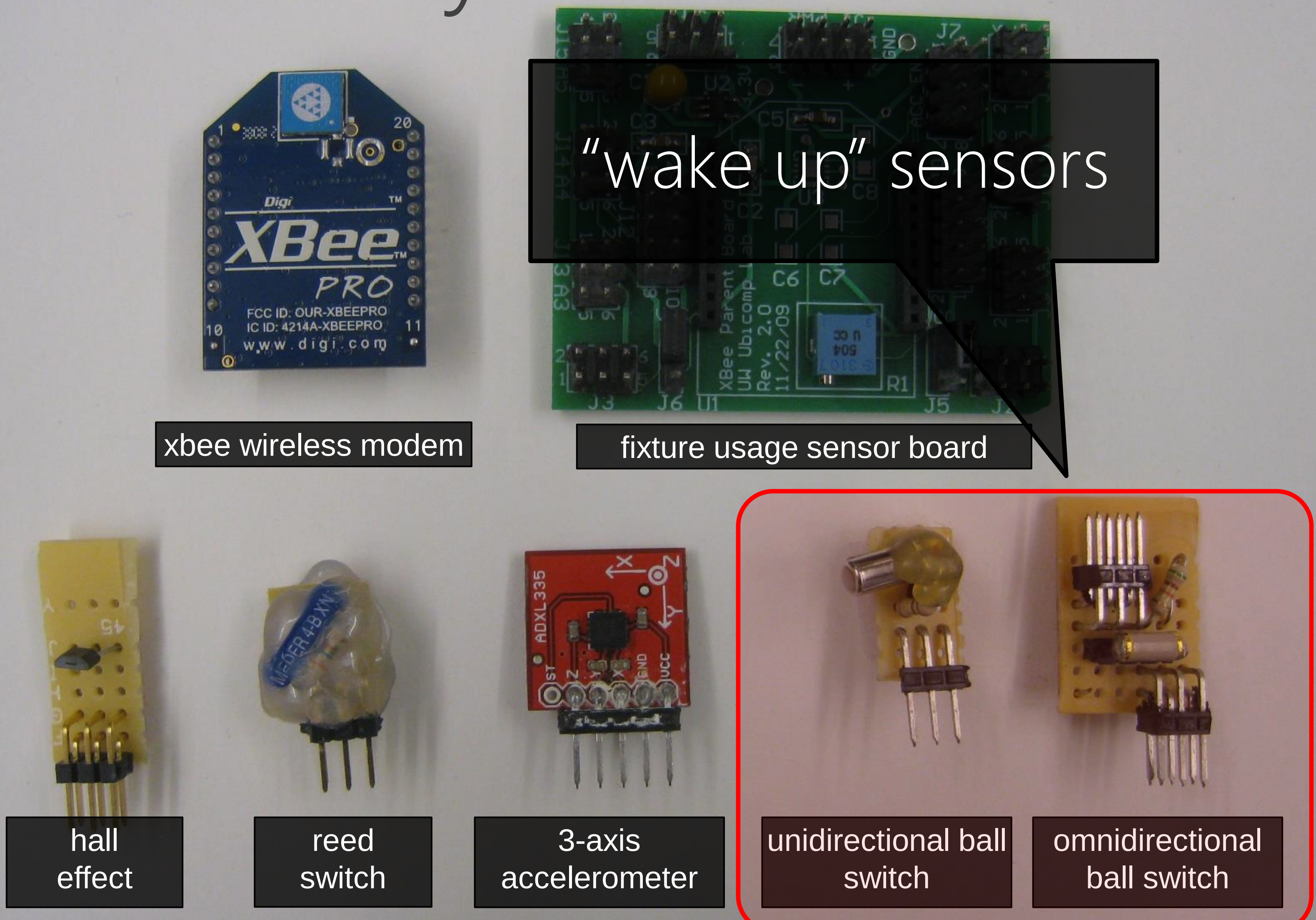
**dish**washer


**after** many failed attempts

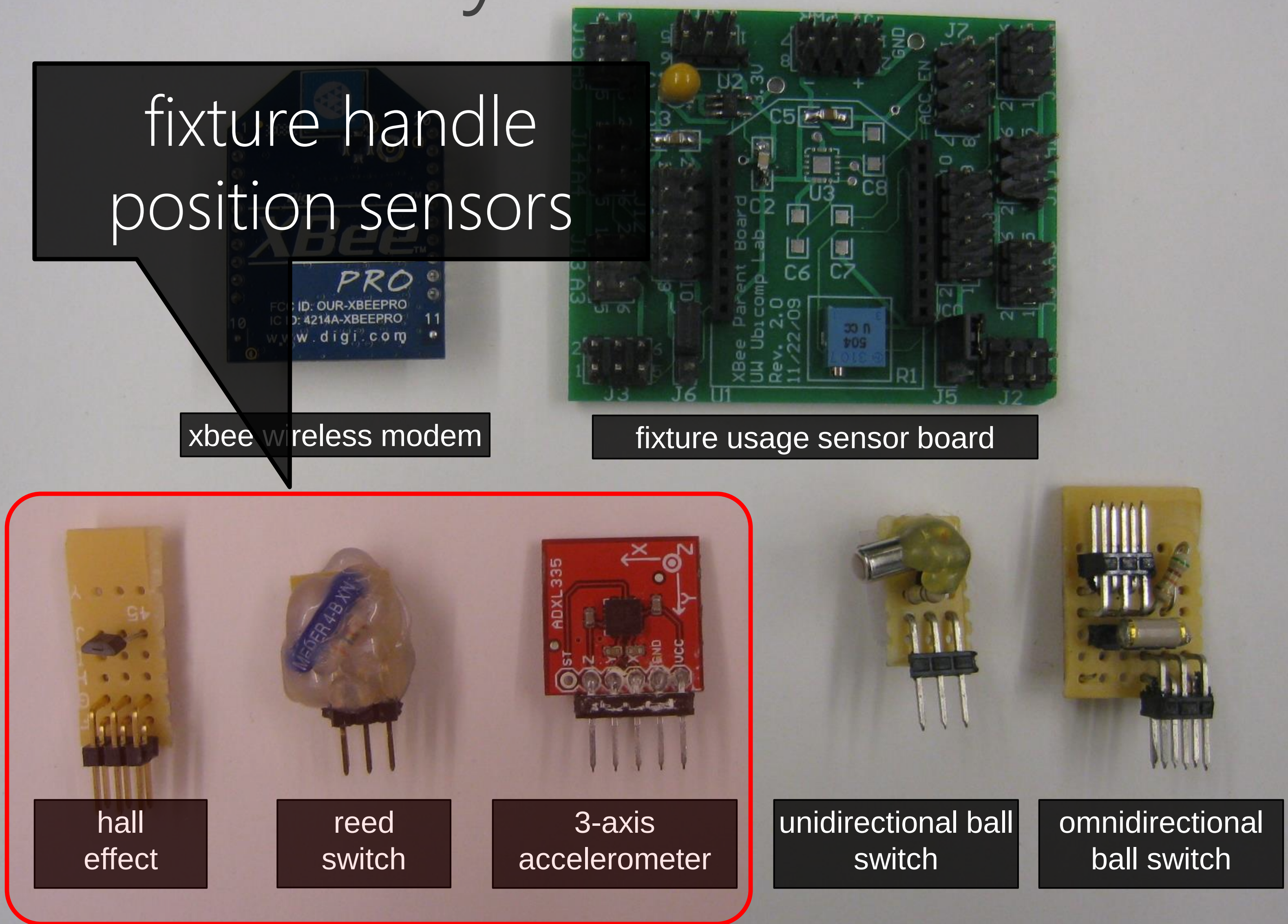
# **custom** ground truth data collection system



# **custom** ground truth data collection system

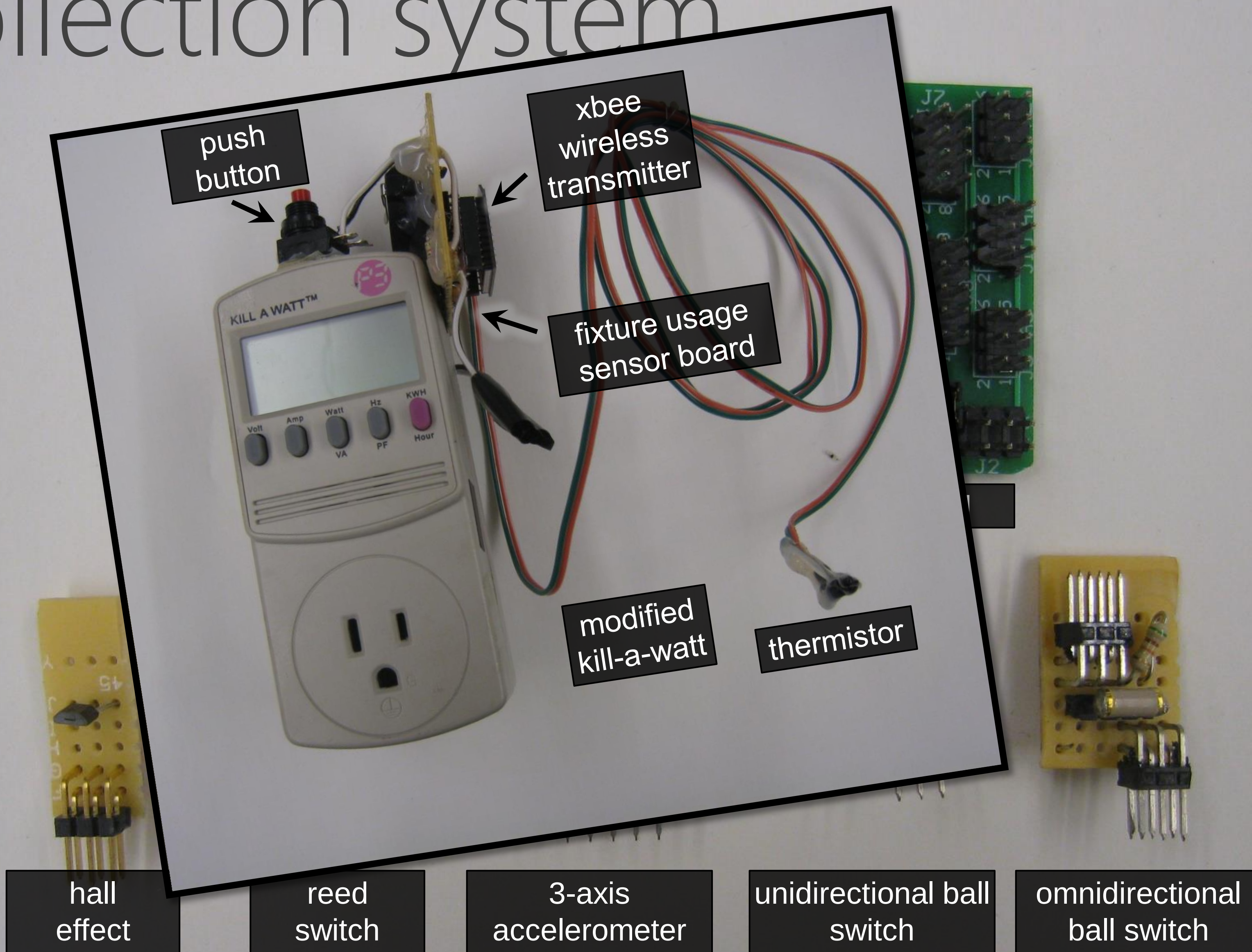


# **custom** ground truth data collection system

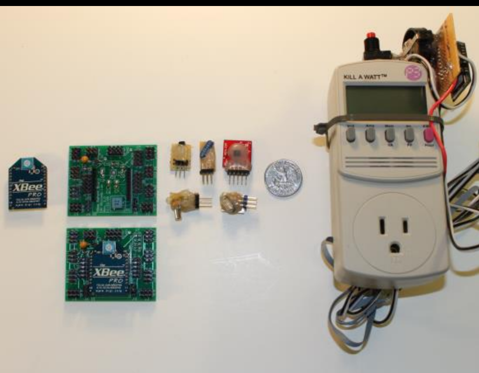



accelerometer

# **custom** ground truth data collection system

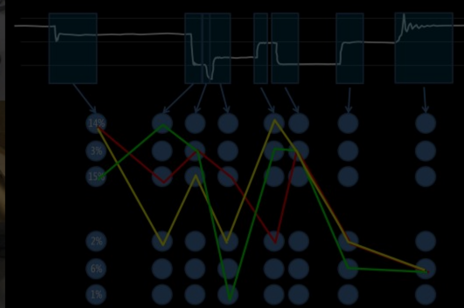


ground truth sensors

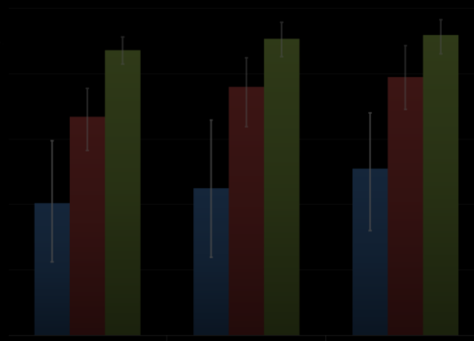


5-week deployment

classification algorithm



classification results



# 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 |

# **deployment** infrastructure

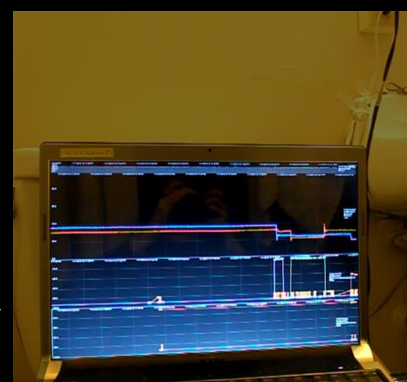
ground truth sensor
on every valve


pressure sensor


xbee

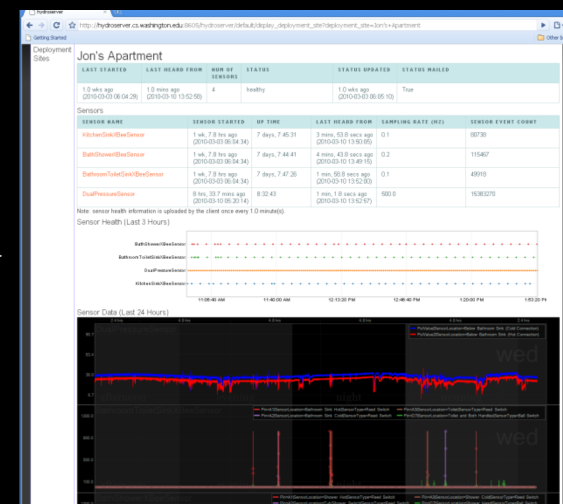
bluetooth

a laptop running
**hydro**logger

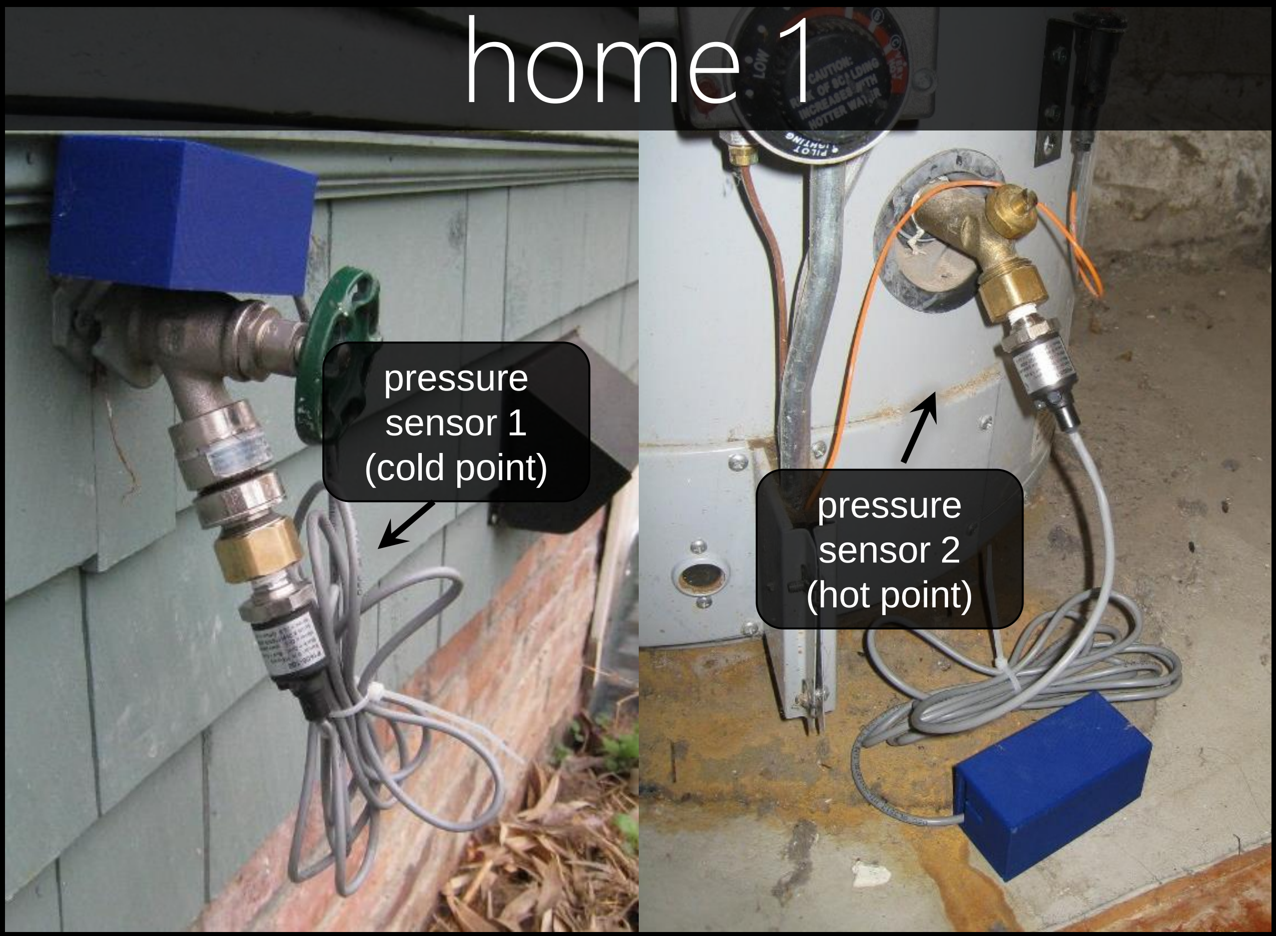


http

backend python
**hydro**server



# **two** pressure sensors per home



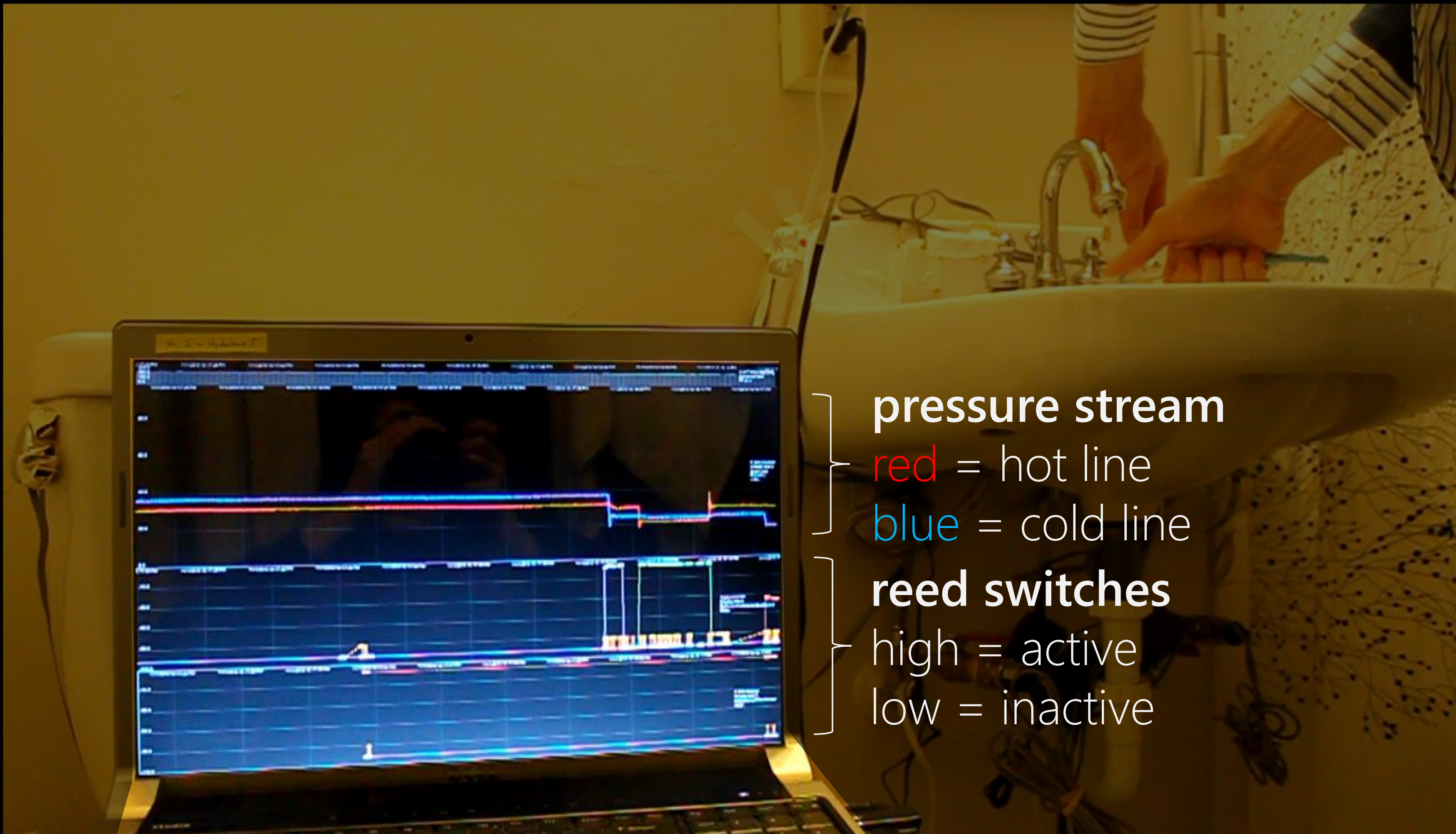

C
H


DELL

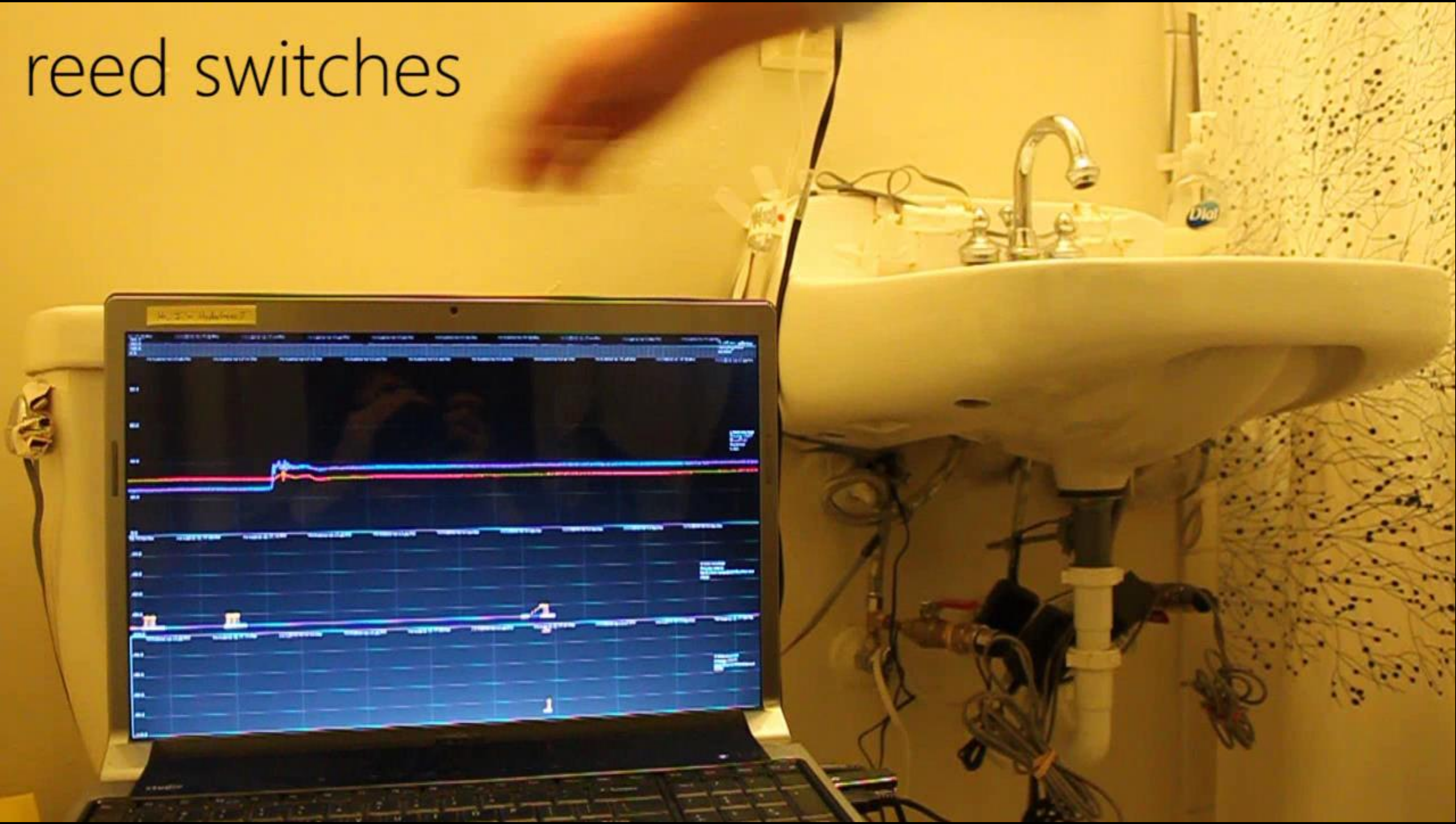

HOT
COLD

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


KitchenAid Superba
ICE
CHILLED WATER

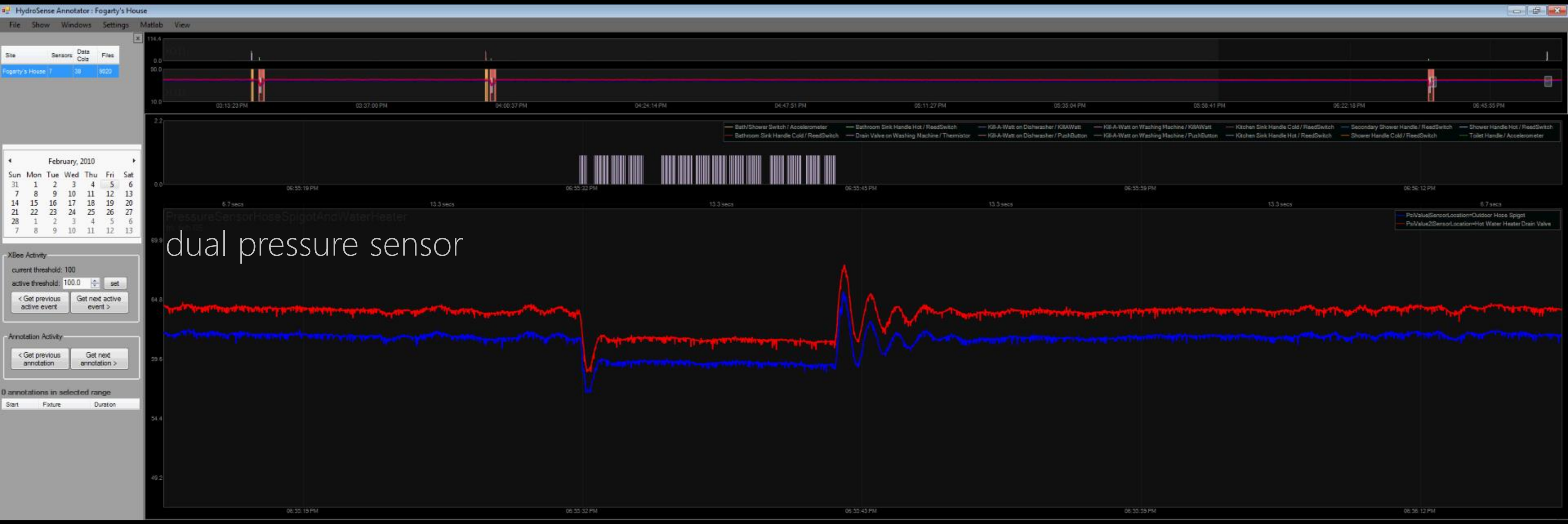

pressure stream
red = hot line
blue = cold line
reed switches
high = active
low = inactive

# reed switches



# **hydro**sense annotations

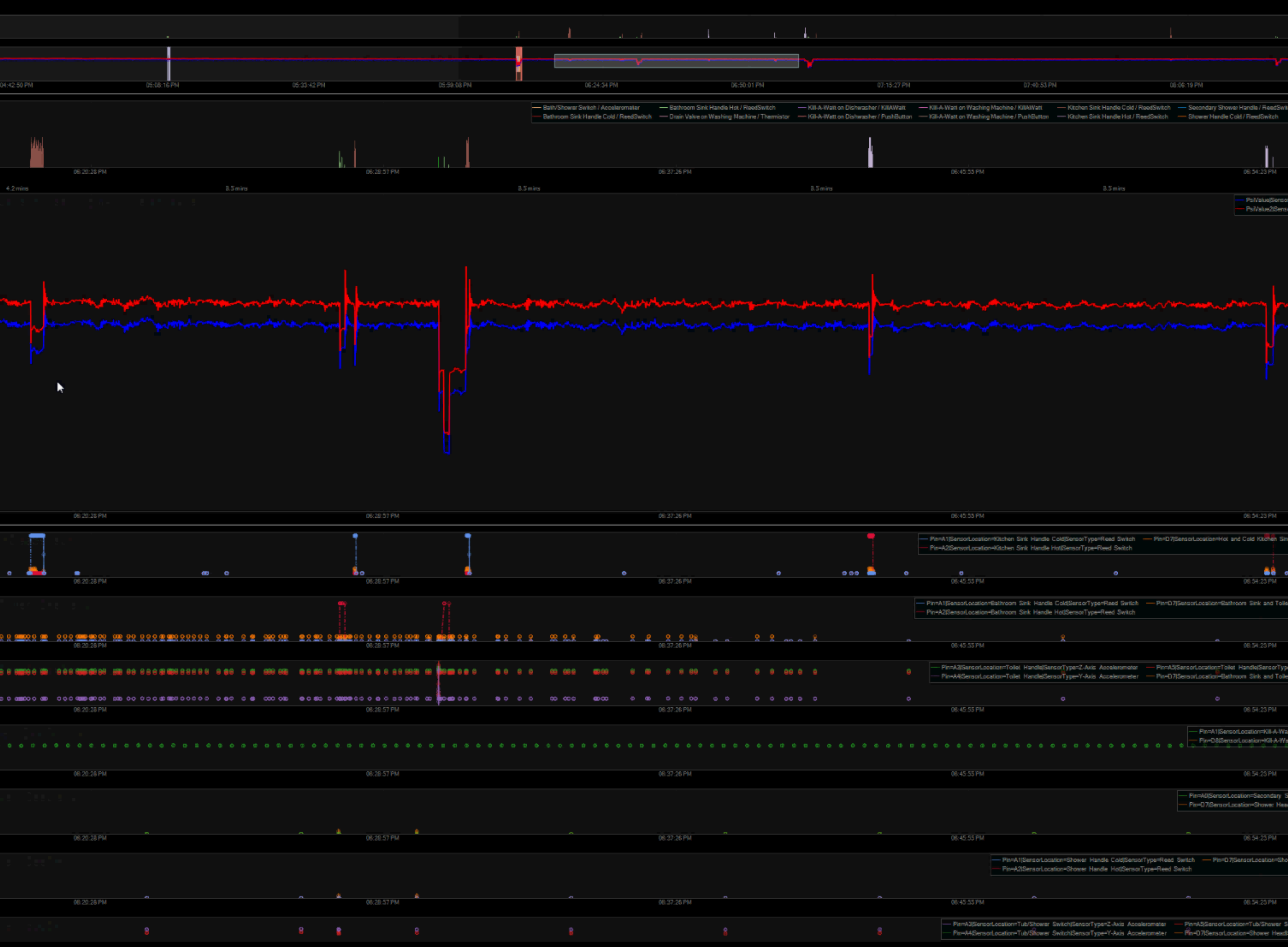
1. **ground truth** sensor
2. **semi-automated** label
3. **review** annotator
4. **verification**
5. **final** label



HydroSense Annotator : Fogarty's House
File
Show
Windows
Settings
Matlab
View
February, 2010
XBee Activity
current threshold: 100
active threshold:
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
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=A1|SensorLocation=Bathroom Sink Handle Cold|Se
Pin=A1|SensorLocation=Kitchen Sink Handle Cold|Se



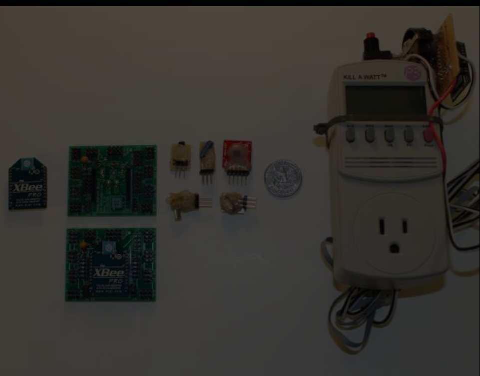
Bath/Shower Switch / Accelerometer
Bathroom Sink Handle Hot / ReedSwitch
Kill-A-Watt on Dishwasher / KillAWatt
Kill-A-Watt on Washing Machine / KillAWatt
Kitchen Sink Handle Cold / ReedSwitch
Bathroom Sink Handle Cold / ReedSwitch
Drain Valve on Washing Machine / Thermistor
Kill-A-Watt on Dishwasher / 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 |
| compound | 22.2% | 21.8% | 16.6% | 32% | 21.3% | 21.9% |

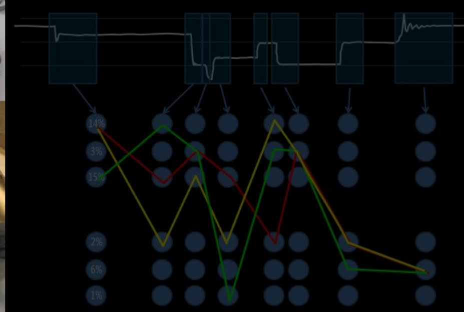
**22% of all events** were compound

ground truth sensors

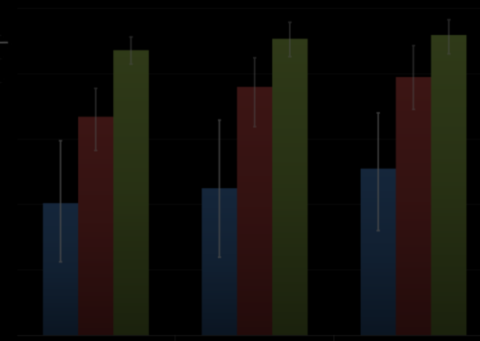


5-week deployment

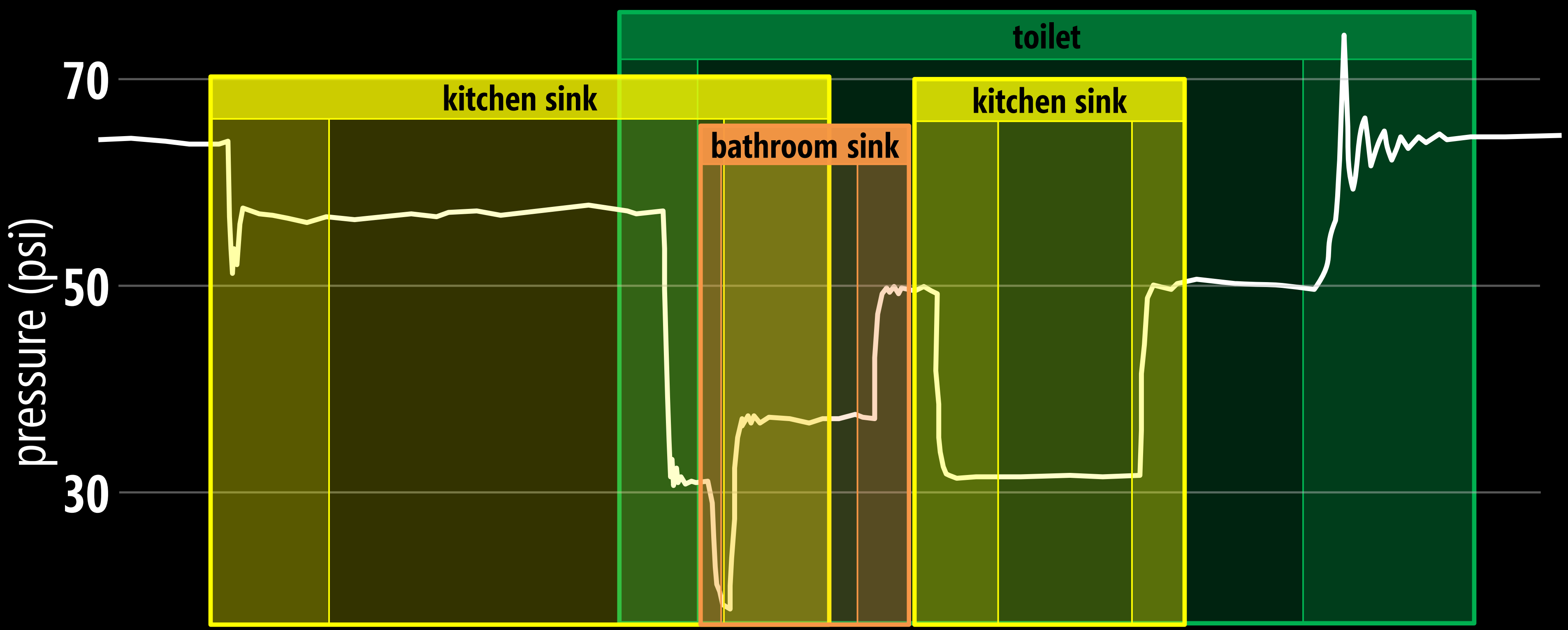
classification algorithm



classification results



# **natural** water use



# **bayesian** inference

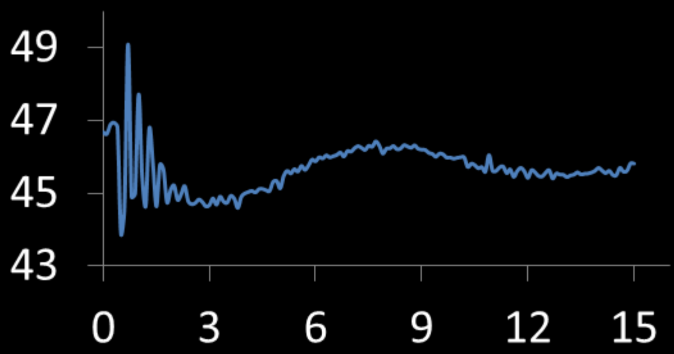
signal

behavior

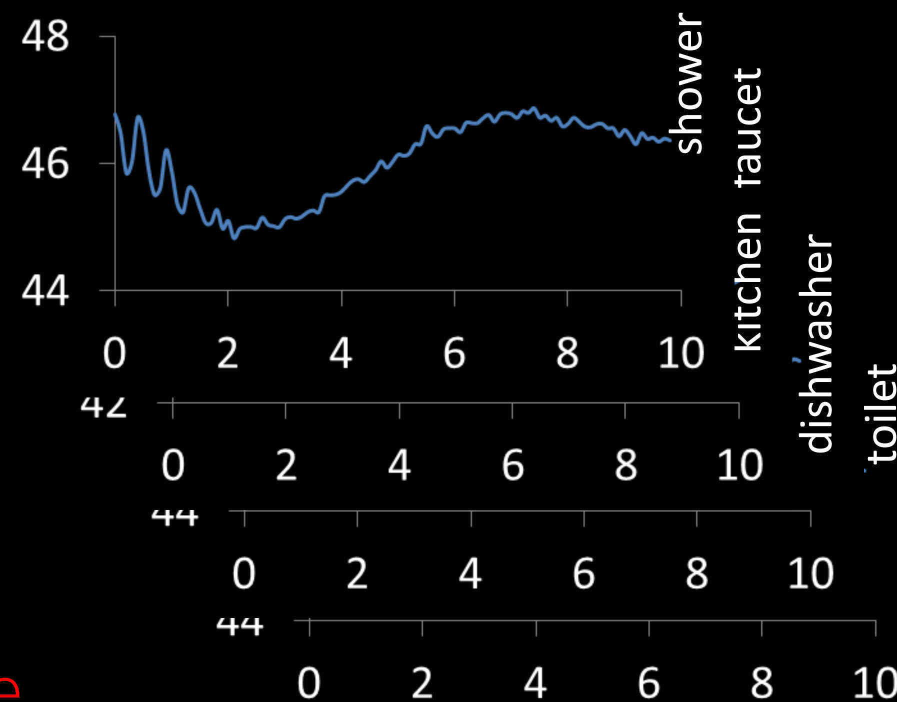
$$\prod_{r=0}^{R-1} f_r(\hat{\boldsymbol{S}}_{\boldsymbol{r}}|\hat{\boldsymbol{V}}_{\boldsymbol{r}}) \prod_{n=0}^{N-1} P(v_n|v_{n-1}) \prod_{i\notin\boldsymbol{\beta}} f_p(v_i) \prod_{k=0}^{K-1} \prod_{\langle a,b\rangle\in\boldsymbol{\beta}} f_k(\langle v_a, v_b\rangle)$$

# **term(i)** template matching

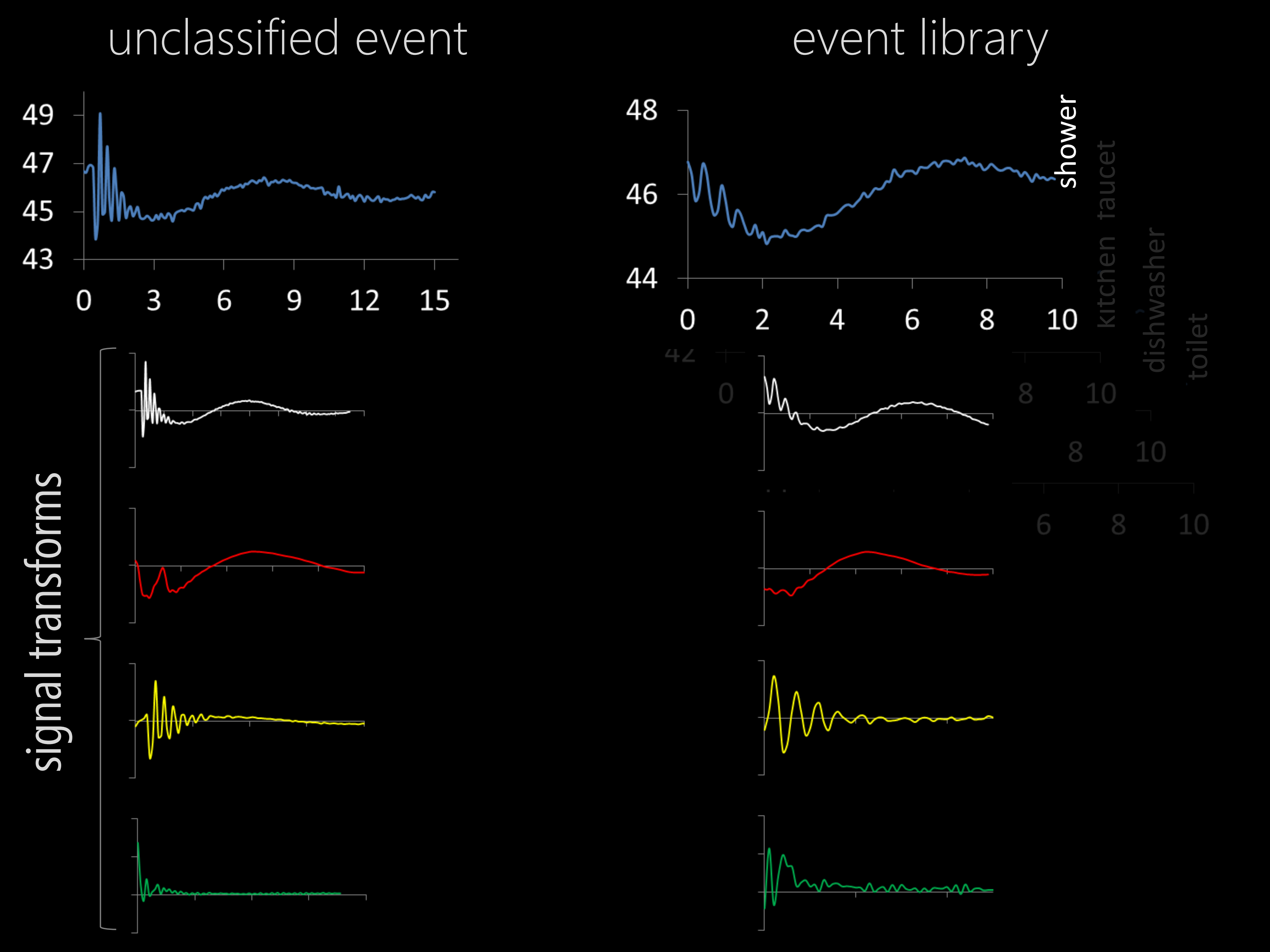
unclassified event

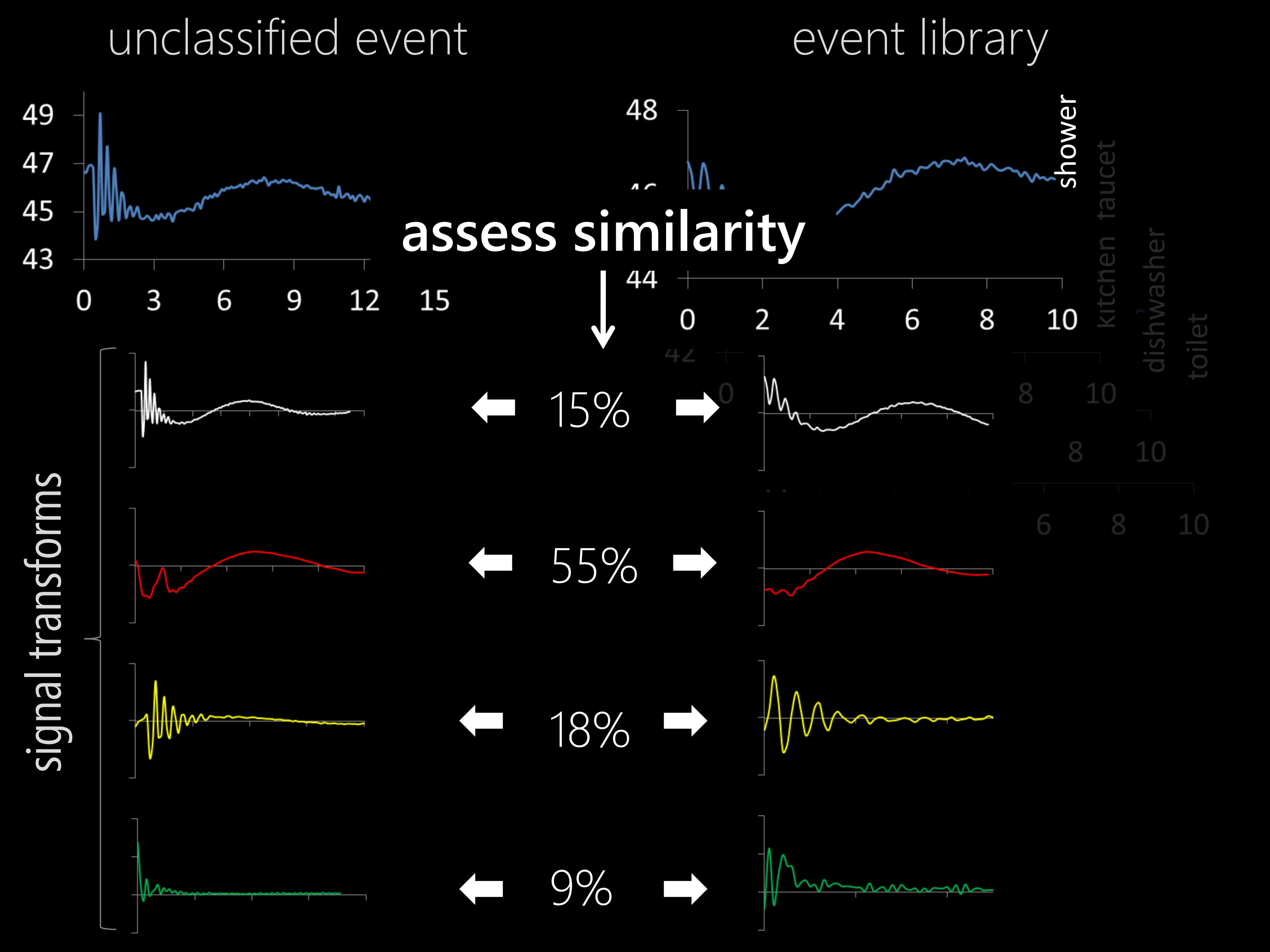



event library



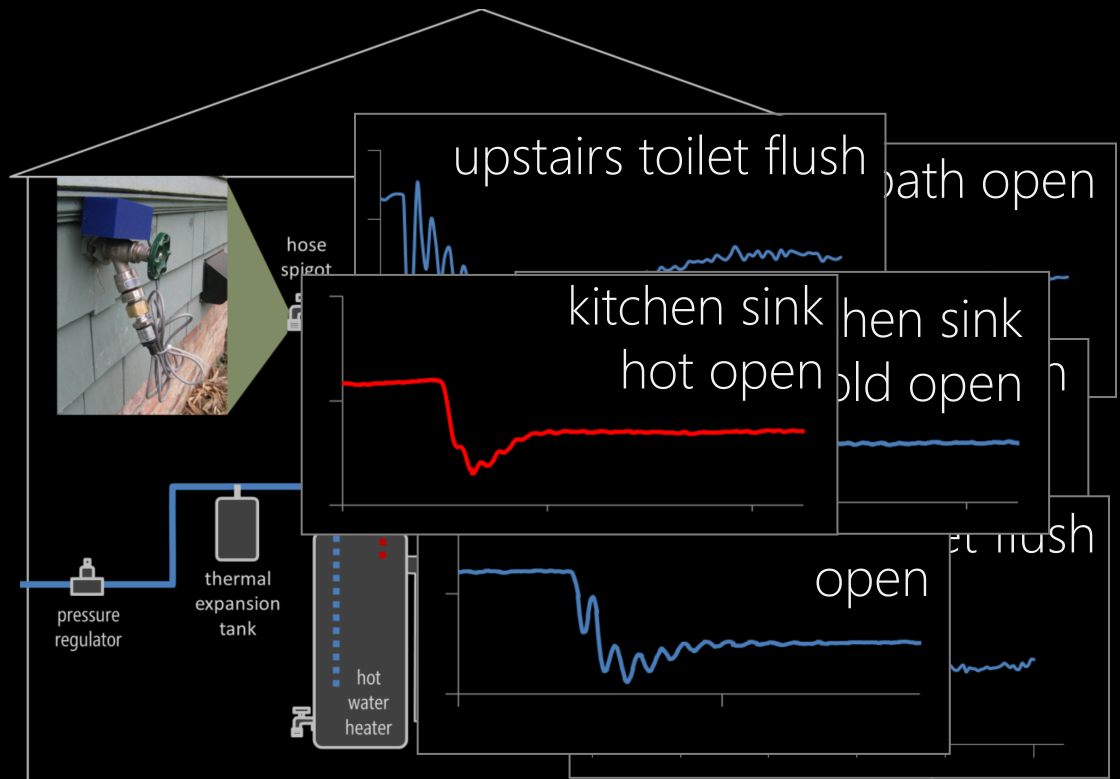

compare across multiple
signal transformations


unclassified event
event library
49
47
45
43
0
3
6
9
12
15
48
46
44
0
2
4
6
8
10
shower
kitchen faucet
dishwasher
toilet
signal transforms


unclassified event
event library
assess similarity
signal transforms
shower
kitchen faucet
dishwasher
toilet
49
47
45
43
0
3
6
9
12
15
48
44
0
2
4
6
8
10
15%
55%
18%
9%

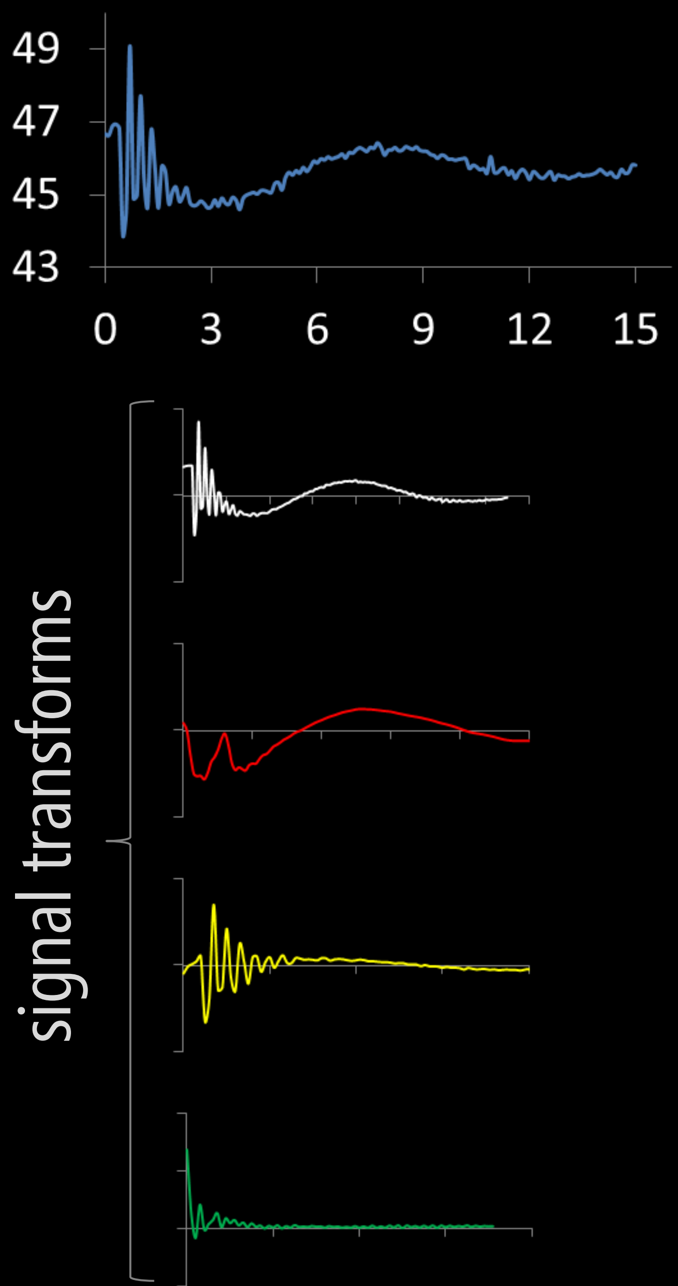
# hydrosense

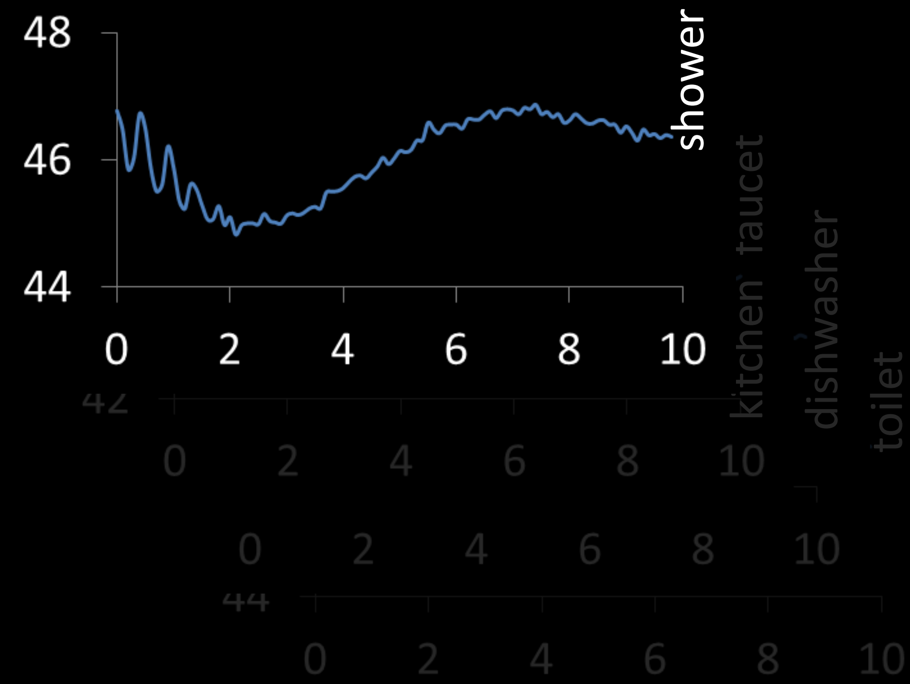
example pressure waves



# unclassified event

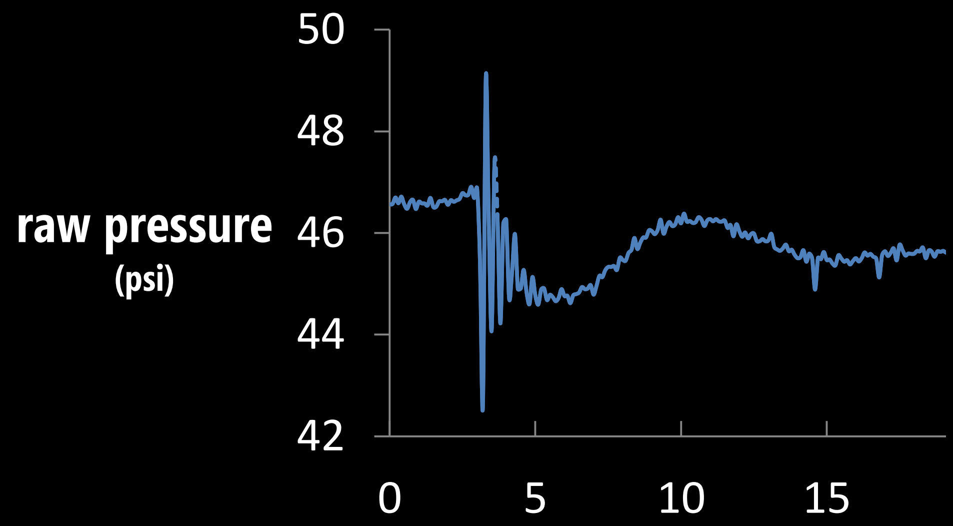
# event library

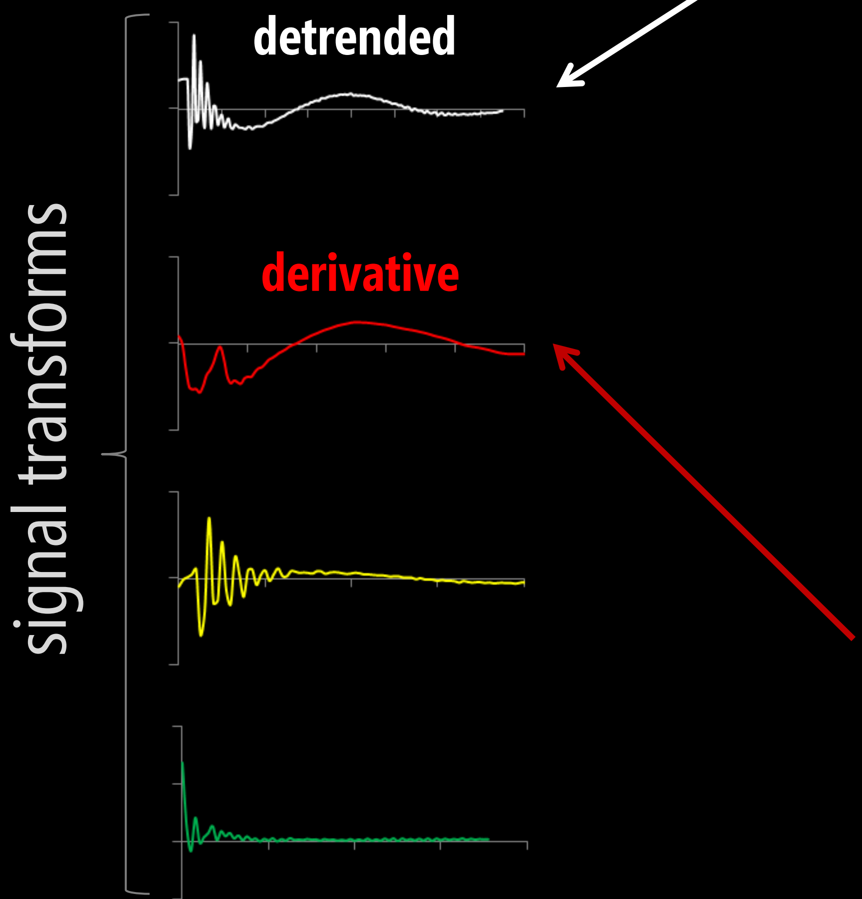


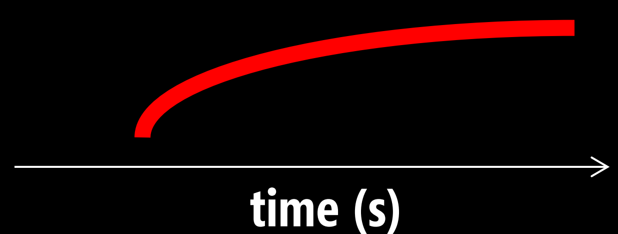



# **term(i)** template matching

## filter transforms



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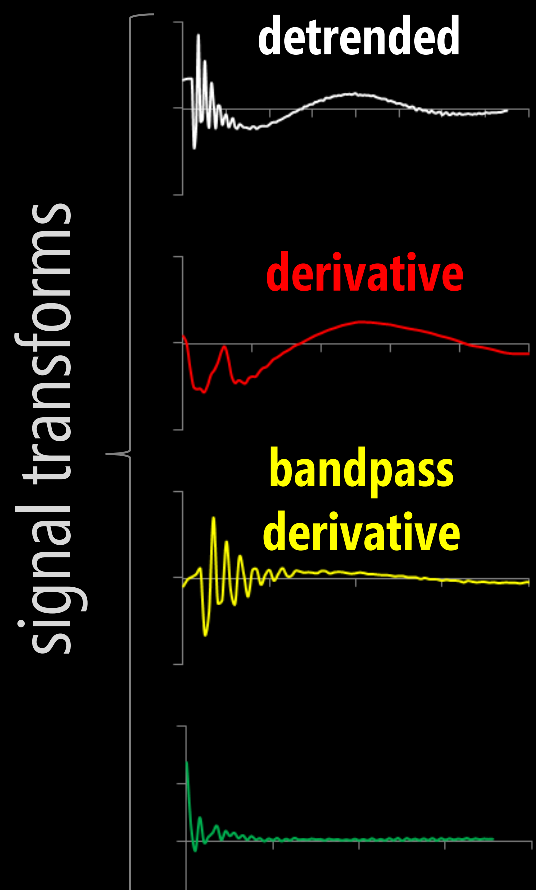
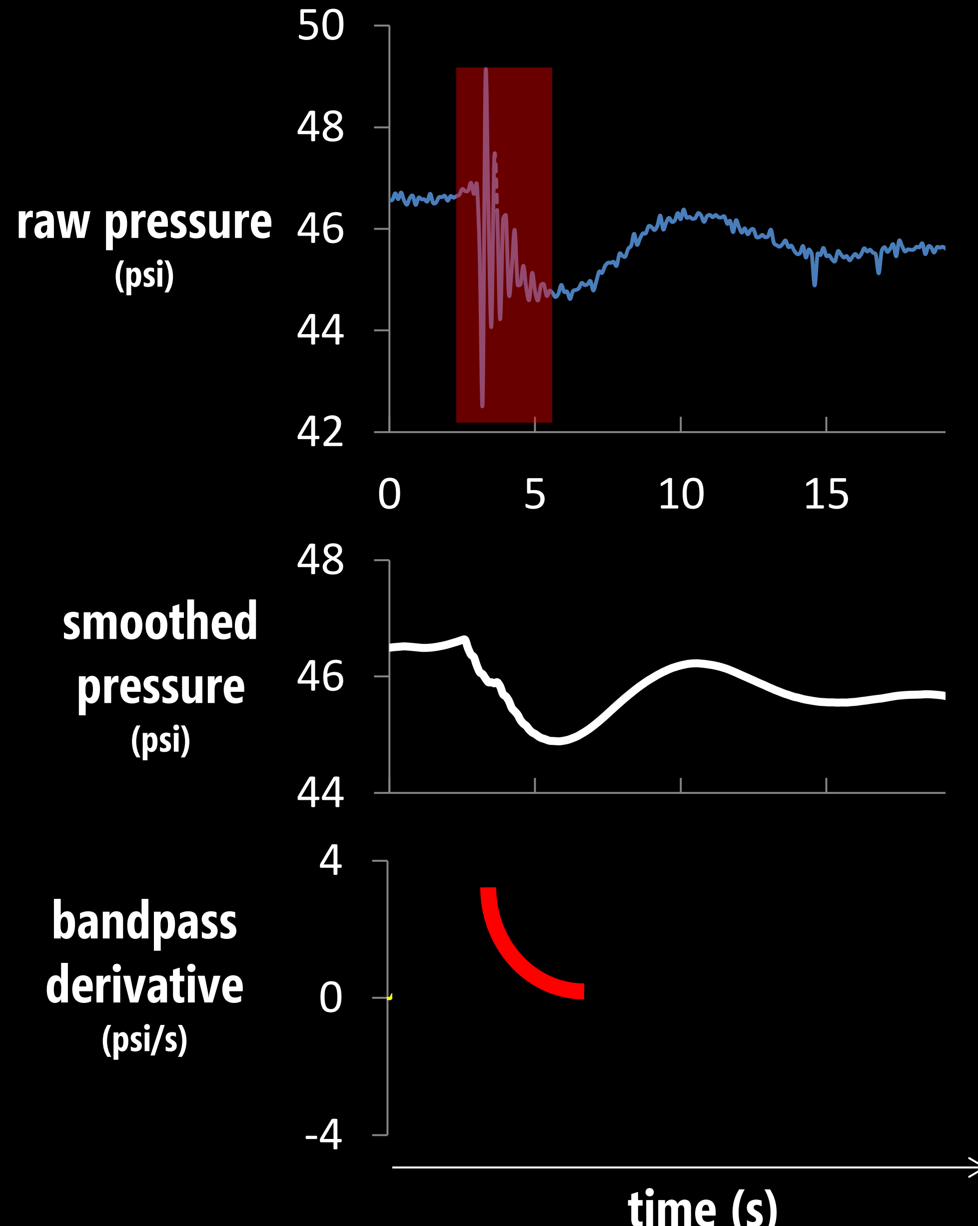
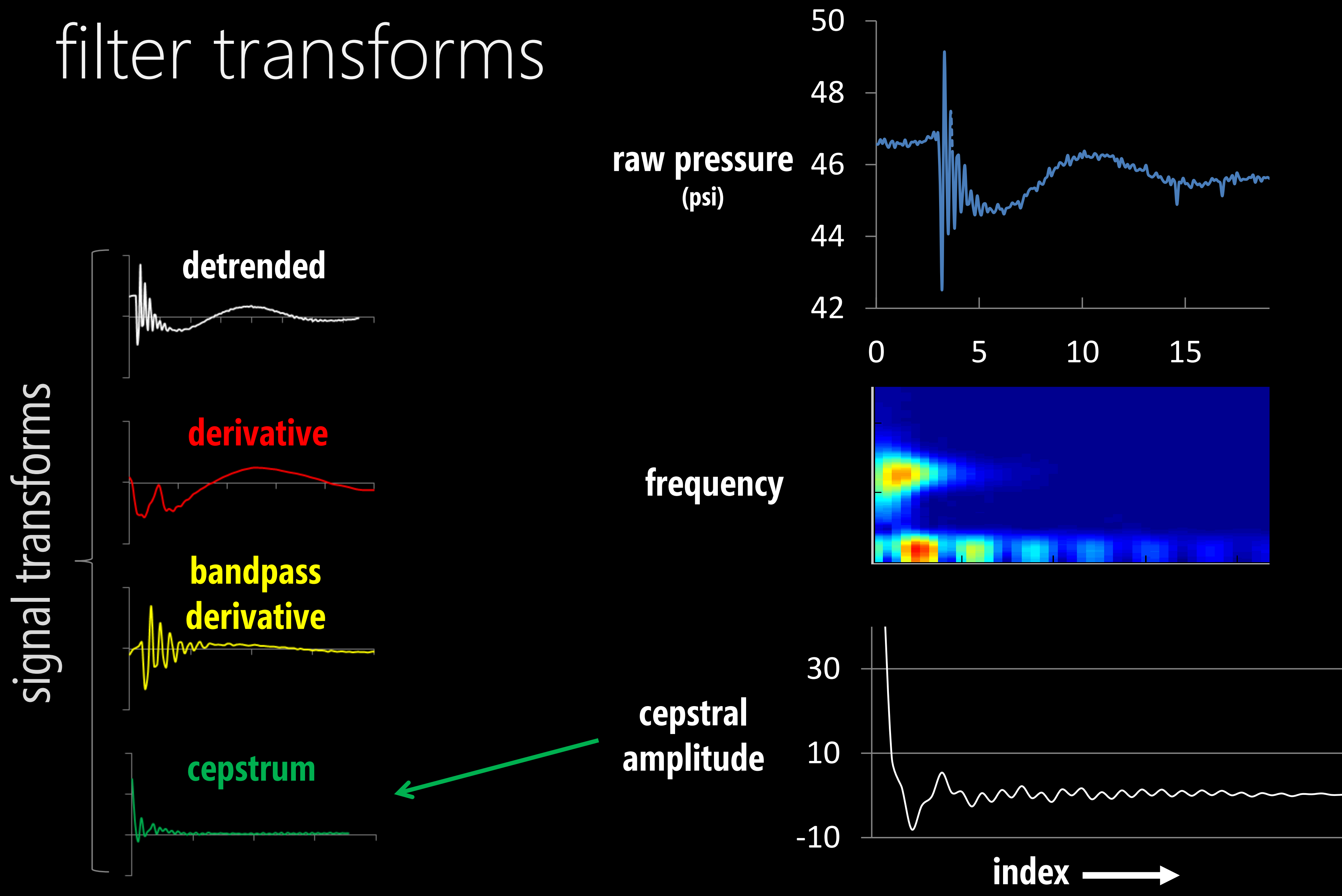
## filter transforms

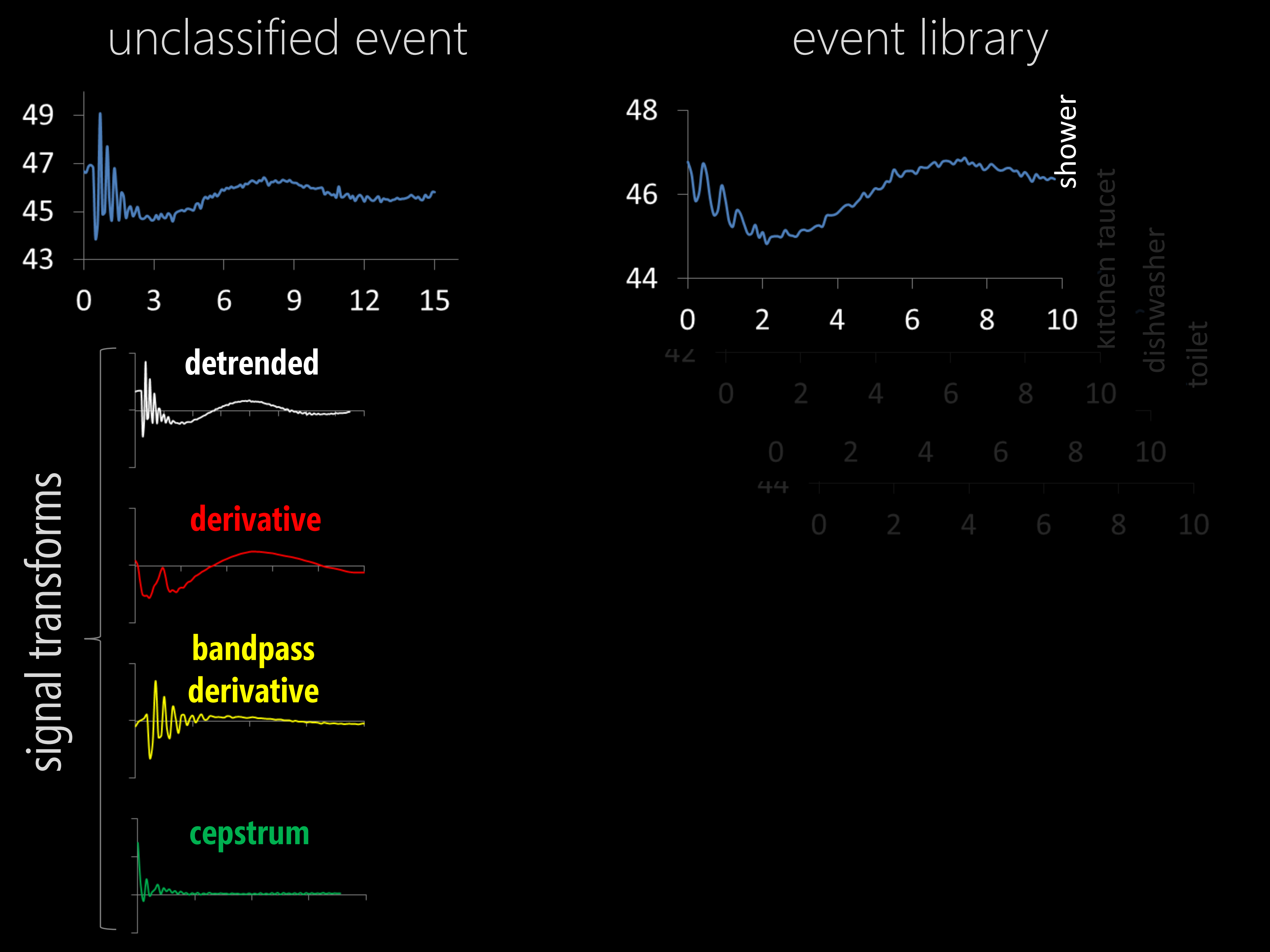


# **term(i)** template matching

## filter transforms

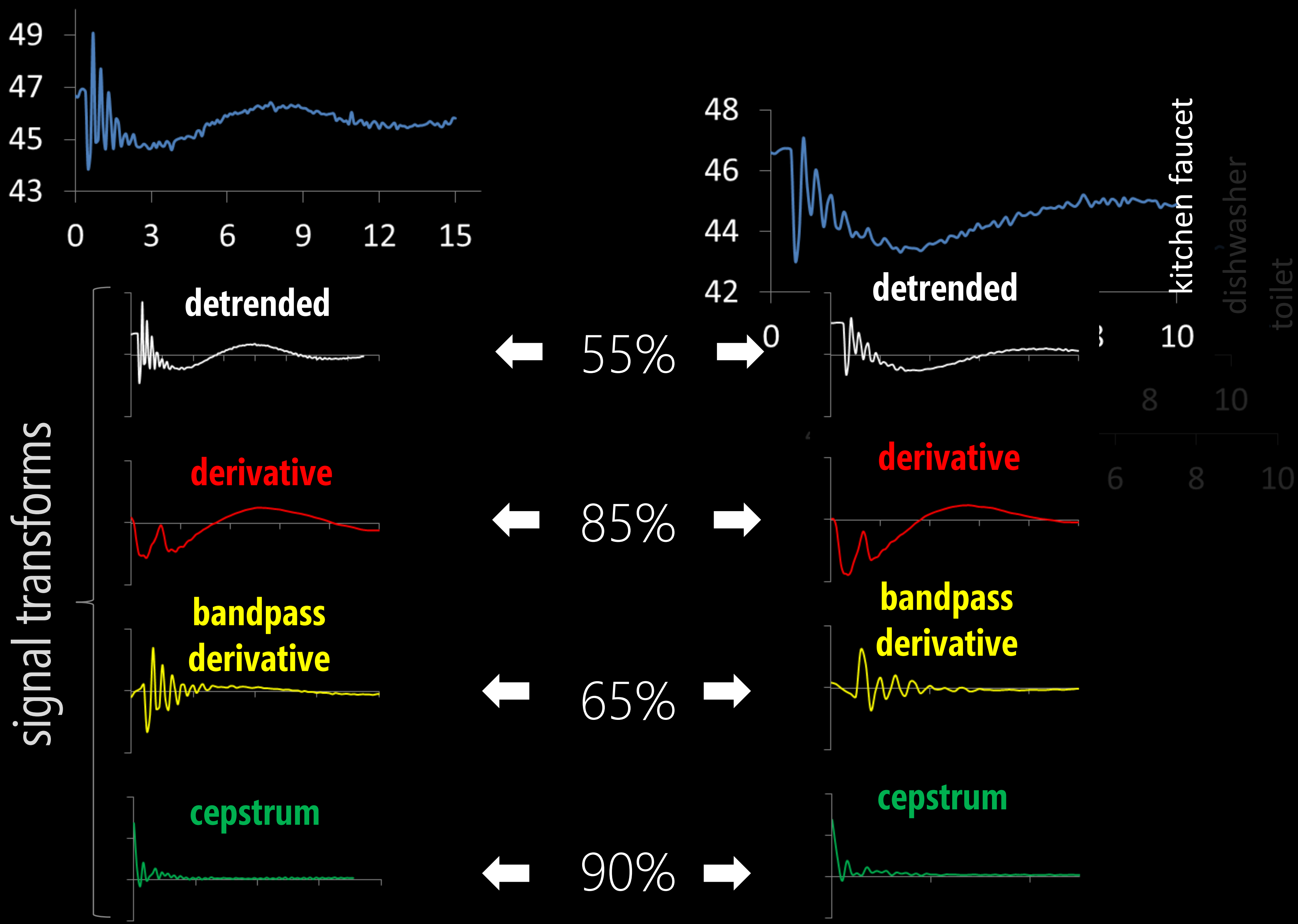


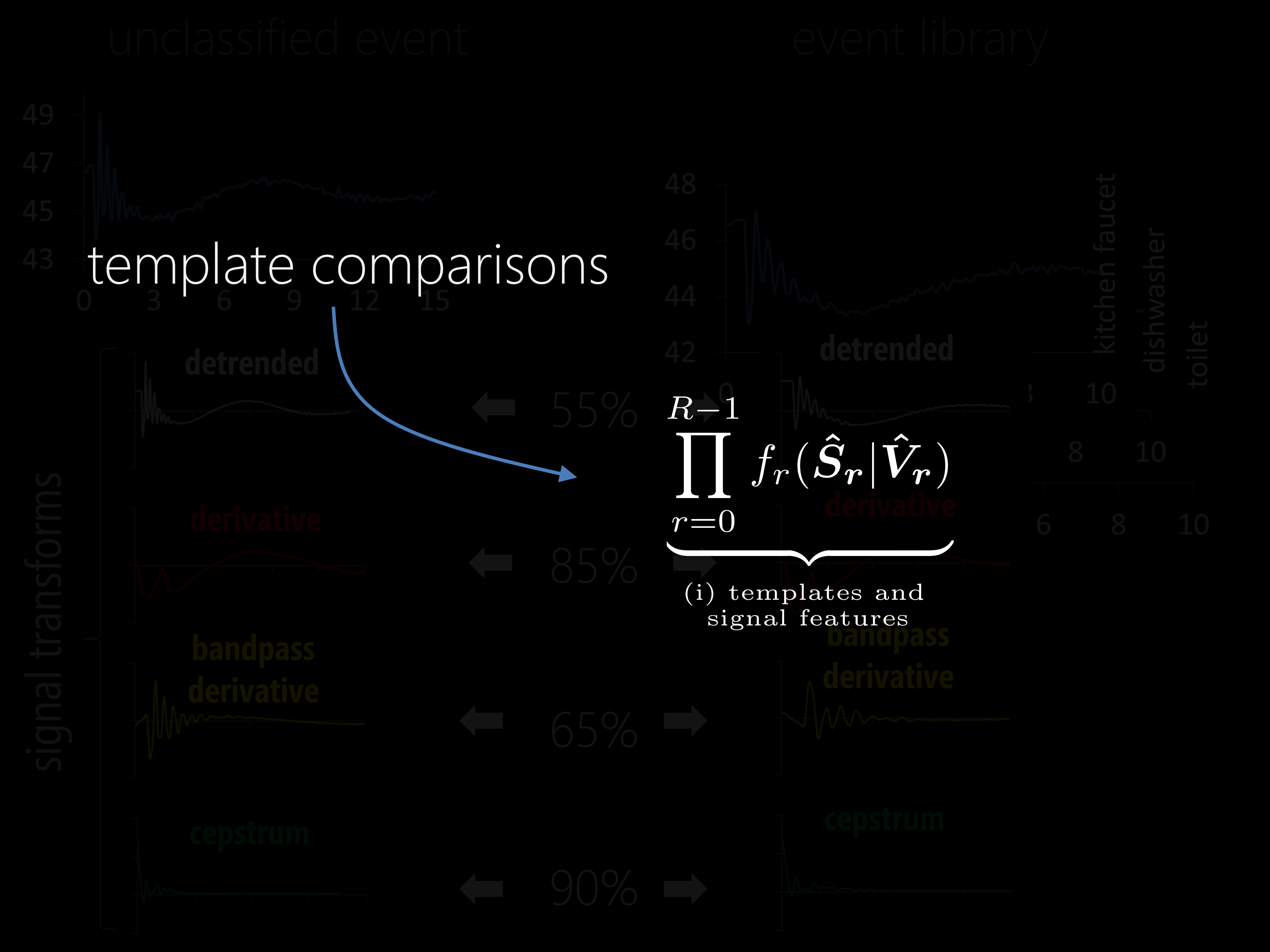


unclassified event
49
47
45
43
0
3
6
9
12
15
event library
48
46
44
0
2
4
6
8
10
shower
kitchen faucet
dishwasher
toilet
signal transforms
detrended
derivative
bandpass
derivative
cepstrum

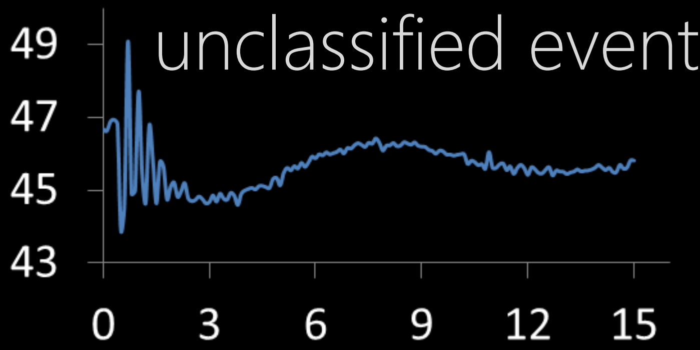
unclassified event

event library

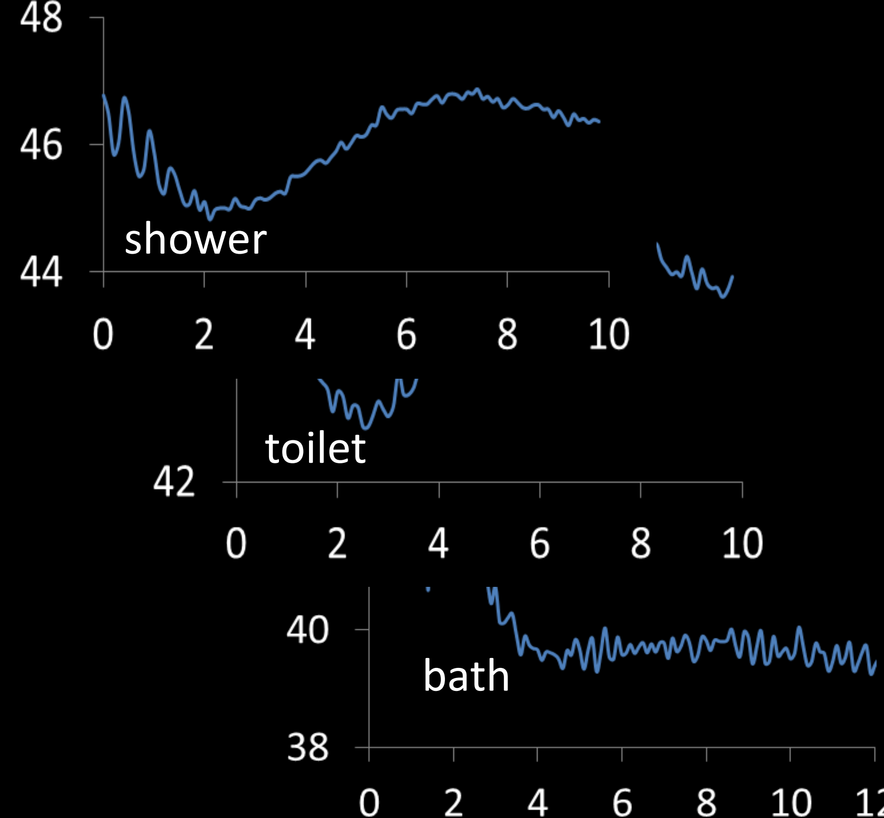



unclassified event
event library
template comparisons
$\underbrace{\prod_{r=0}^{R-1} f_r(\hat{\boldsymbol{S}}_{\boldsymbol{r}} | \hat{\boldsymbol{V}}_{\boldsymbol{r}})}_{\text{(i) templates and signal features}}$
signal transforms
detrended
derivative
bandpass derivative
cepstrum
55%
85%
65%
90%
kitchen faucet
dishwasher
toilet

# **term(i)** signal features

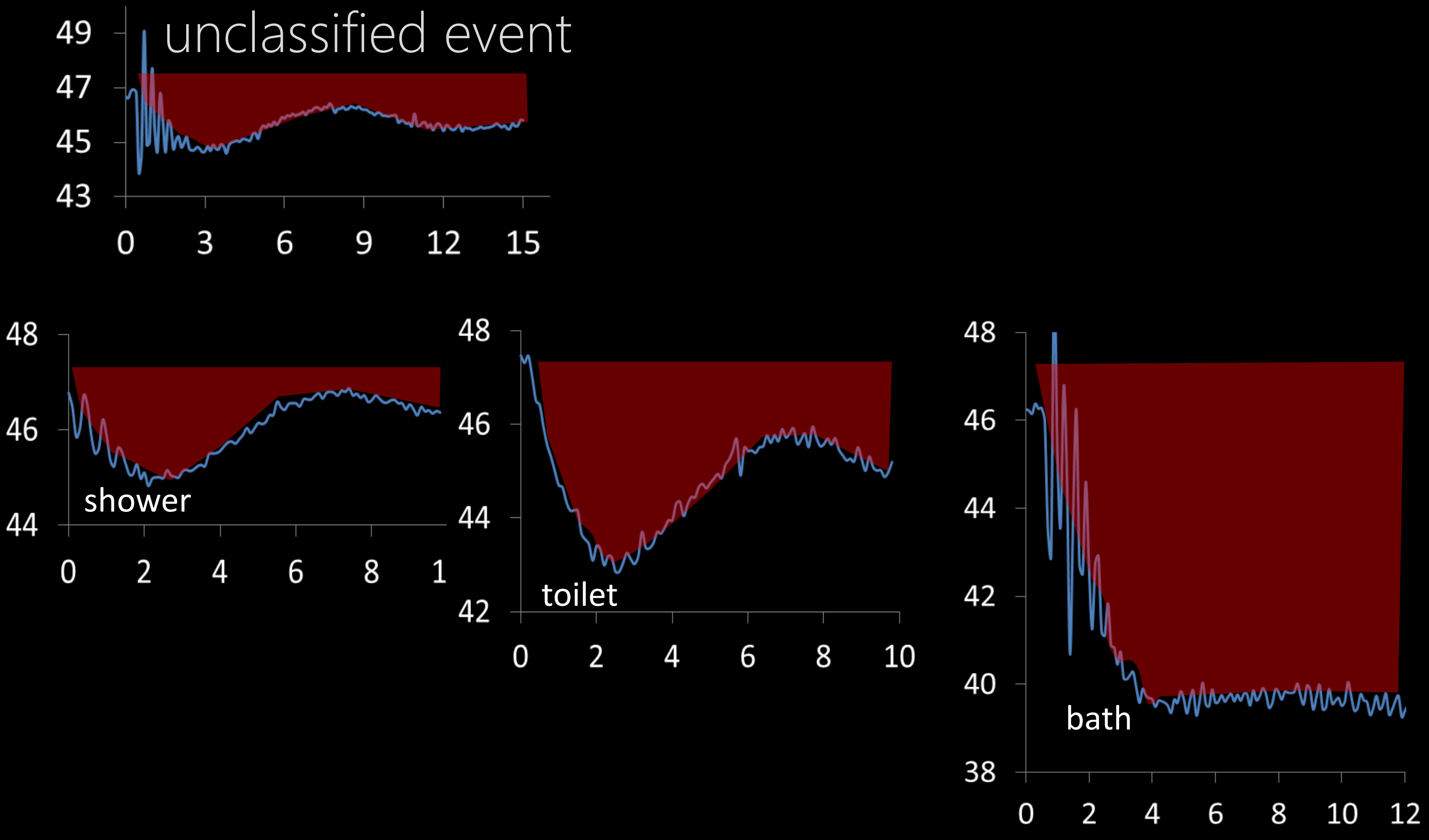



event library



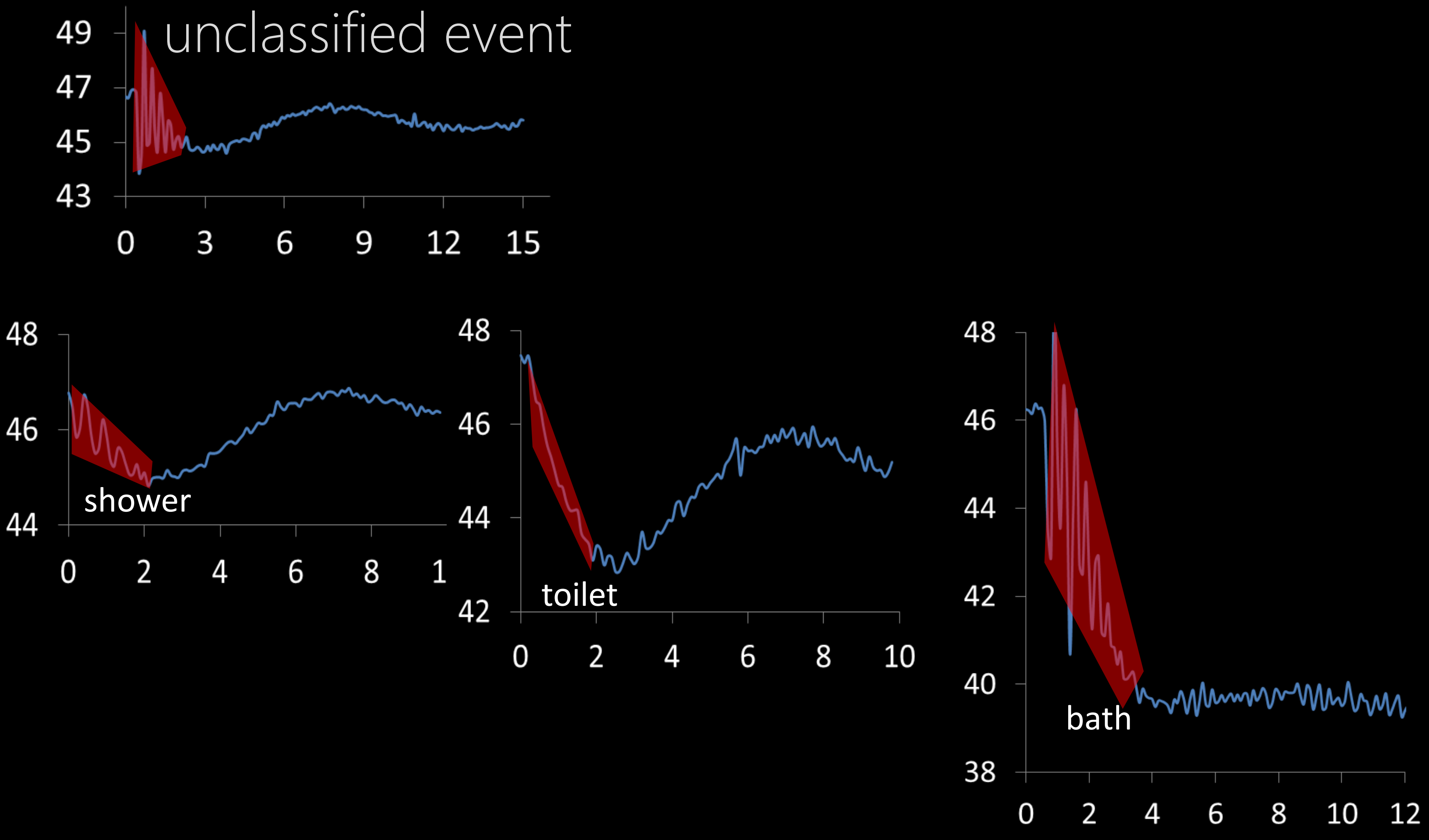
# **term(i)** signal features

pressure drop



# **term(i)** signal features

resonance tracking



# term(i) signal features

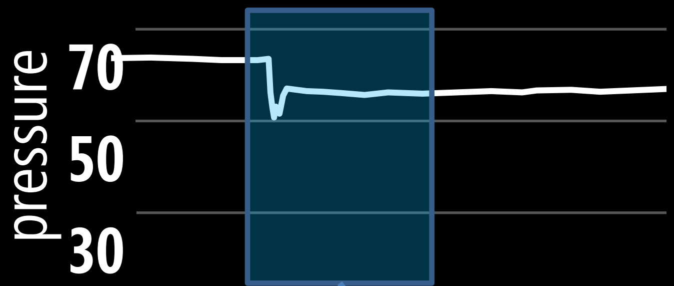
## resonance tracking

template comparisons

$$\underbrace{\prod_{r=0}^{R-1} f_r(\hat{\boldsymbol{S}}_{\boldsymbol{r}} | \hat{\boldsymbol{V}}_{\boldsymbol{r}})}_{\text{(i) templates and signal features}}$$

signal feature comparisons

# **term (i):** templates and signal features




**P(**kitchen sink hot open**)** 14%

**P(**kitchen sink cold open**)** 3%

**P(**toilet open**)** 15%

⋮

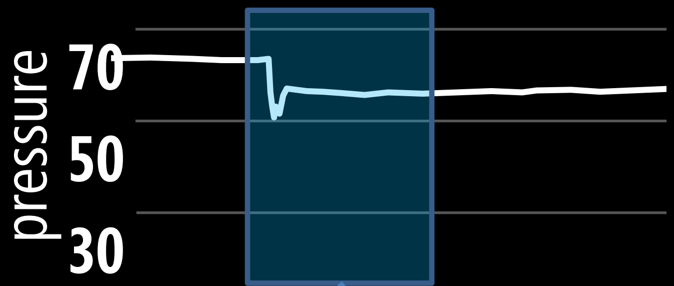
**P(**kitchen hot/cold close**)** 2%

**P(**kitchen hot close**)** 6%

**P(**toilet close**)** 1%

$$\underbrace{\prod_{r=0}^{R-1} f_r(\hat{\boldsymbol{S}}_{\boldsymbol{r}} | \hat{\boldsymbol{V}}_{\boldsymbol{r}})}_{\substack{\text{(i) templates and} \\ \text{signal features}}}$$

# **term (i):** templates and signal features

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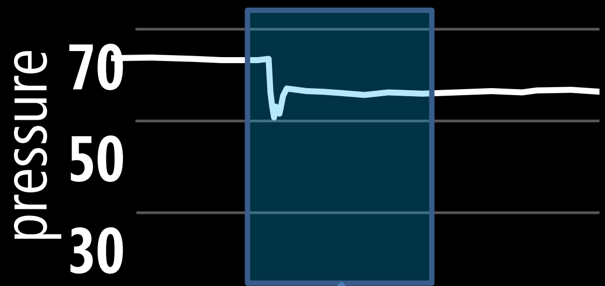
**P(**toilet close**)** 1%

$$\underbrace{\prod_{r=0}^{R-1} f_r(\hat{\boldsymbol{S}}_{\boldsymbol{r}}|\hat{\boldsymbol{V}}_{\boldsymbol{r}})}_{\text{(i) templates and signal features}}$$

# **term (ii):** bigram language model




**P(**kitchen sink hot open**)** 14%

**P(**kitchen sink cold open**)** 3%

**P(**toilet open**)** 15%

•
•
•

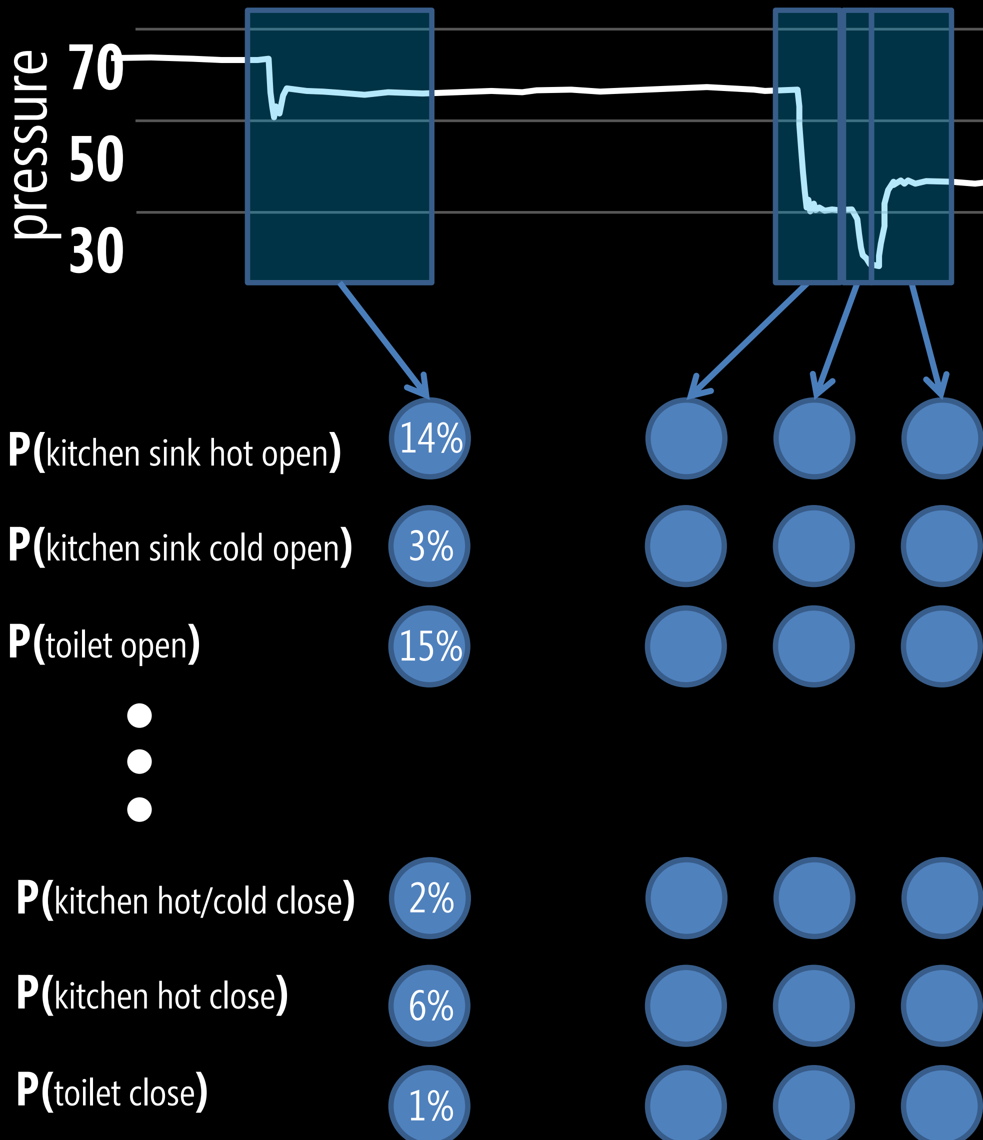
**P(**kitchen hot/cold close**)** 2%

**P(**kitchen hot close**)** 6%

**P(**toilet close**)** 1%

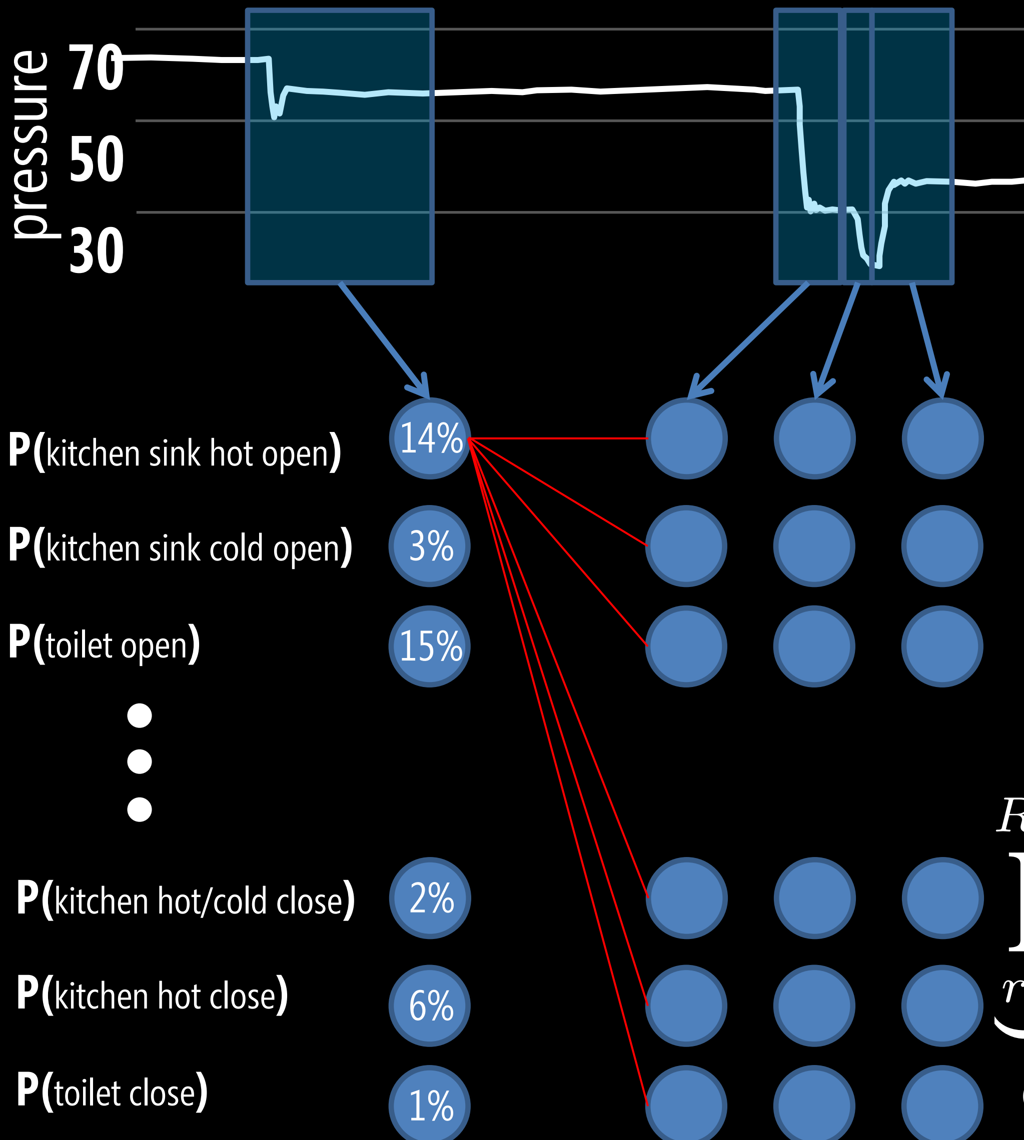
$$\underbrace{\prod_{r=0}^{R-1} f_r(\hat{\boldsymbol{S}}_{\boldsymbol{r}}|\hat{\boldsymbol{V}}_{\boldsymbol{r}})}_{\text{(i) templates and signal features}} \underbrace{\prod_{n=0}^{N-1} P(v_n|v_{n-1})}_{\text{(ii) bigram language model}}$$

# **term (ii):** bigram language model




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

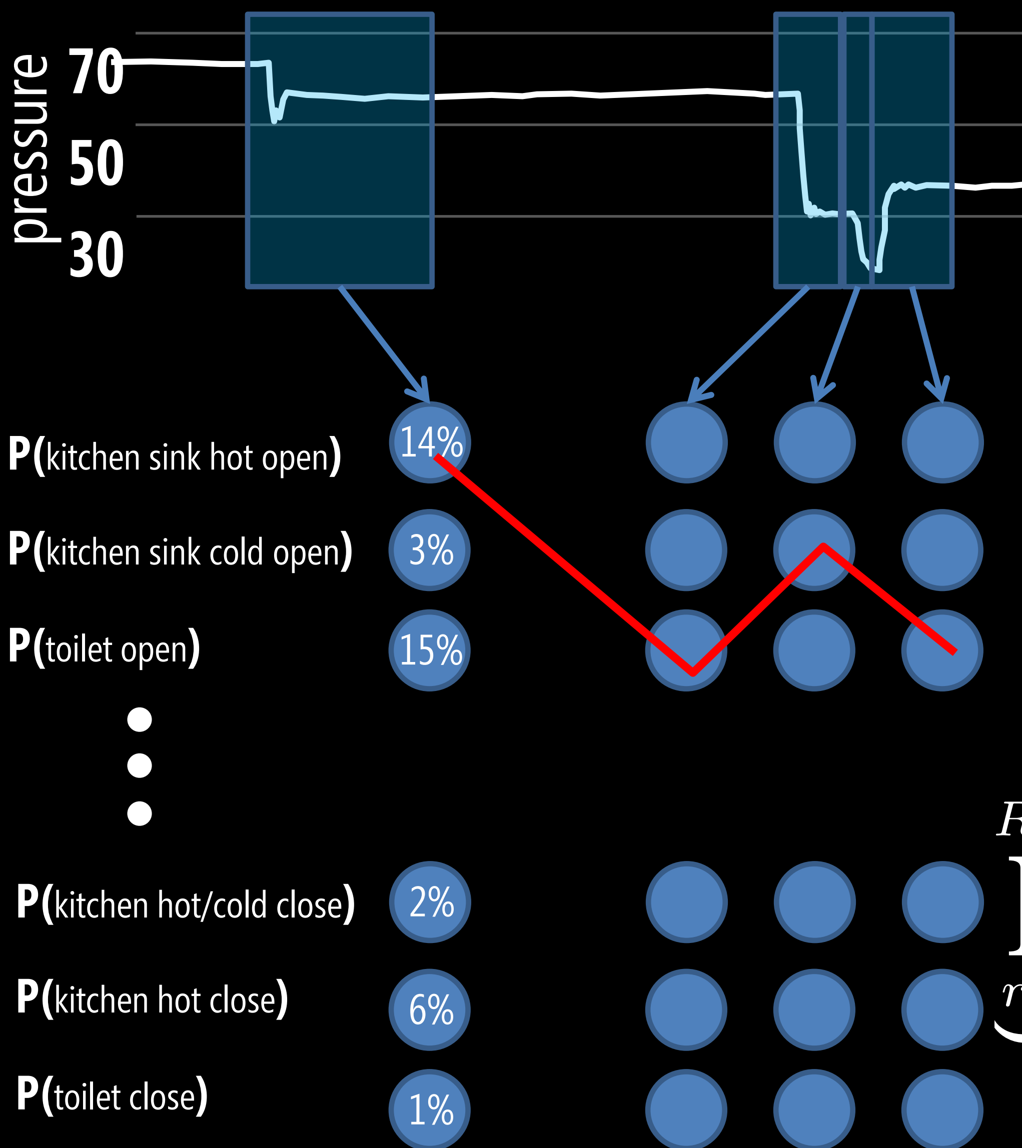
# term (ii): bigram language model




| Toilet | Faucet | Dishwasher | Shower | Bath | Washer | |
|---|---|---|---|---|---|---|
| 0.10 | 0.08 | 0.12 | 0.09 | 0.08 | 0.03 | **Toilet** |
| 0.13 | 0.42 | 0.09 | 0.54 | 0.31 | 0.03 | **Faucet** |
| 0.01 | 0.01 | 0.34 | 0.01 | 0.01 | 0.01 | **Dishwasher** |
| 0.01 | 0.01 | 0.01 | 0.01 | 0.15 | 0.01 | **Shower** |
| 0.04 | 0.03 | 0.01 | 0.01 | 0.25 | 0.01 | **Bath** |
| 0.01 | 0.01 | 0.01 | 0.02 | 0.01 | 0.66 | **Washer** |

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

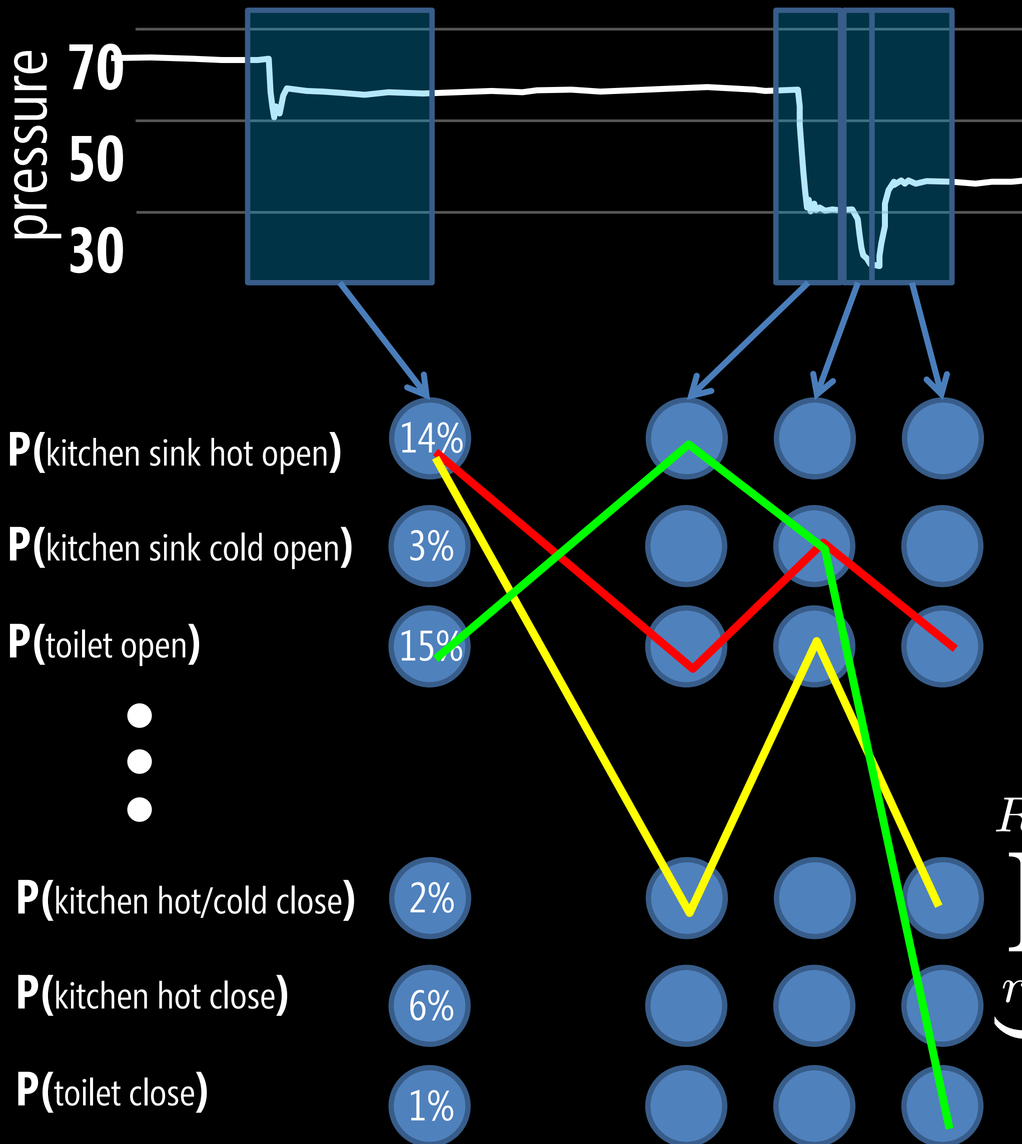
# **term (ii):** bigram language model




| | Toilet | Faucet | Dishwasher | Shower | Bath | Washer |
|---|---|---|---|---|---|---|
| Toilet | 0.10 | 0.08 | 0.12 | 0.09 | 0.08 | 0.03 |
| Faucet | 0.13 | 0.42 | 0.09 | 0.54 | 0.31 | 0.03 |
| Dishwasher | 0.01 | 0.01 | 0.34 | 0.01 | 0.01 | 0.01 |
| Shower | 0.01 | 0.01 | 0.01 | 0.01 | 0.15 | 0.01 |
| Bath | 0.04 | 0.03 | 0.01 | 0.01 | 0.25 | 0.01 |
| Washer | 0.01 | 0.01 | 0.01 | 0.02 | 0.01 | 0.66 |

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

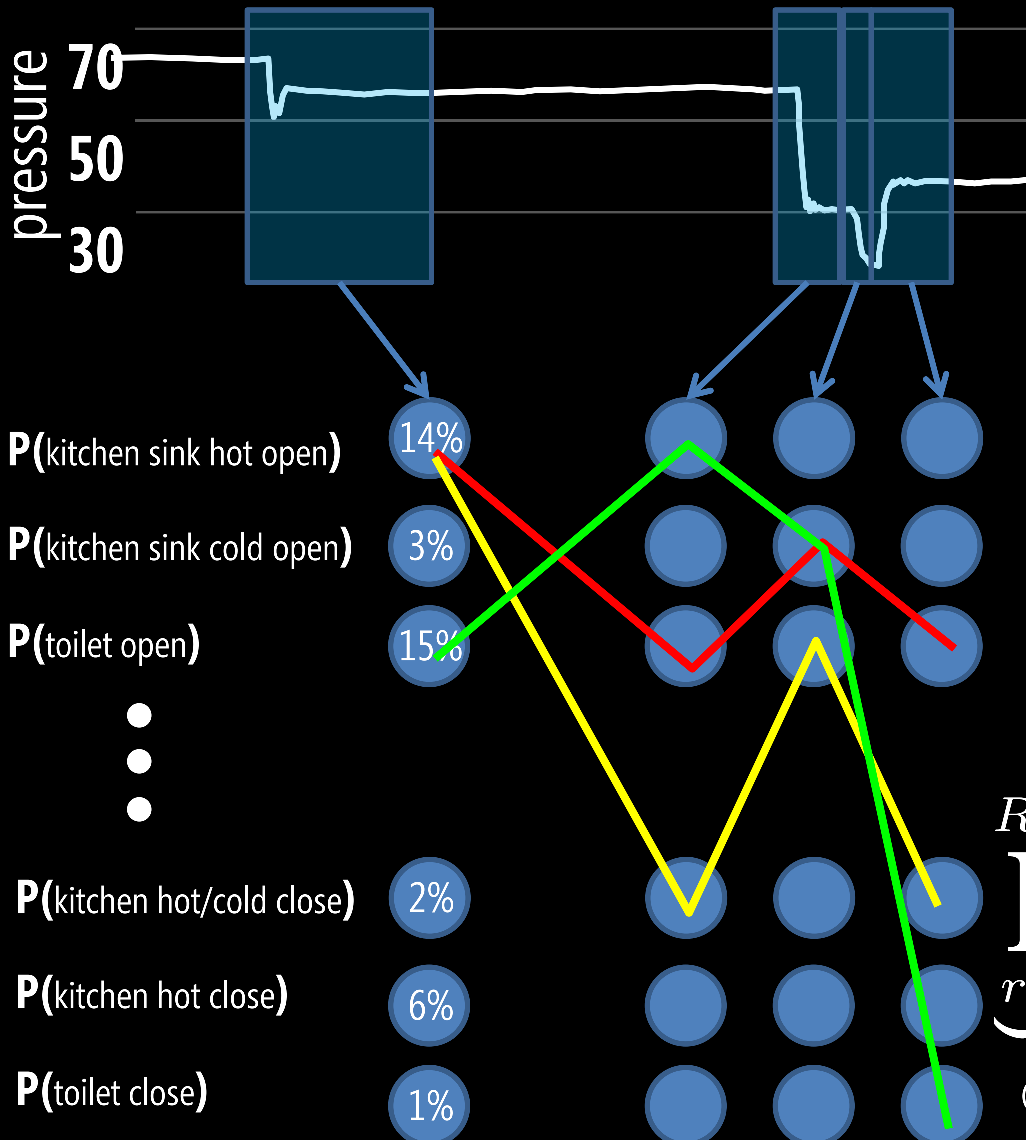
# **term (ii):** bigram language model




| | Toilet | Faucet | Dishwasher | Shower | Bath | Washer |
|---|---|---|---|---|---|---|
| **Toilet** | 0.10 | 0.08 | 0.12 | 0.09 | 0.08 | 0.03 |
| **Faucet** | 0.13 | 0.42 | 0.09 | 0.54 | 0.31 | 0.03 |
| **Dishwasher** | 0.01 | 0.01 | 0.34 | 0.01 | 0.01 | 0.01 |
| **Shower** | 0.01 | 0.01 | 0.01 | 0.01 | 0.15 | 0.01 |
| **Bath** | 0.04 | 0.03 | 0.01 | 0.01 | 0.25 | 0.01 |
| **Washer** | 0.01 | 0.01 | 0.01 | 0.02 | 0.01 | 0.66 |

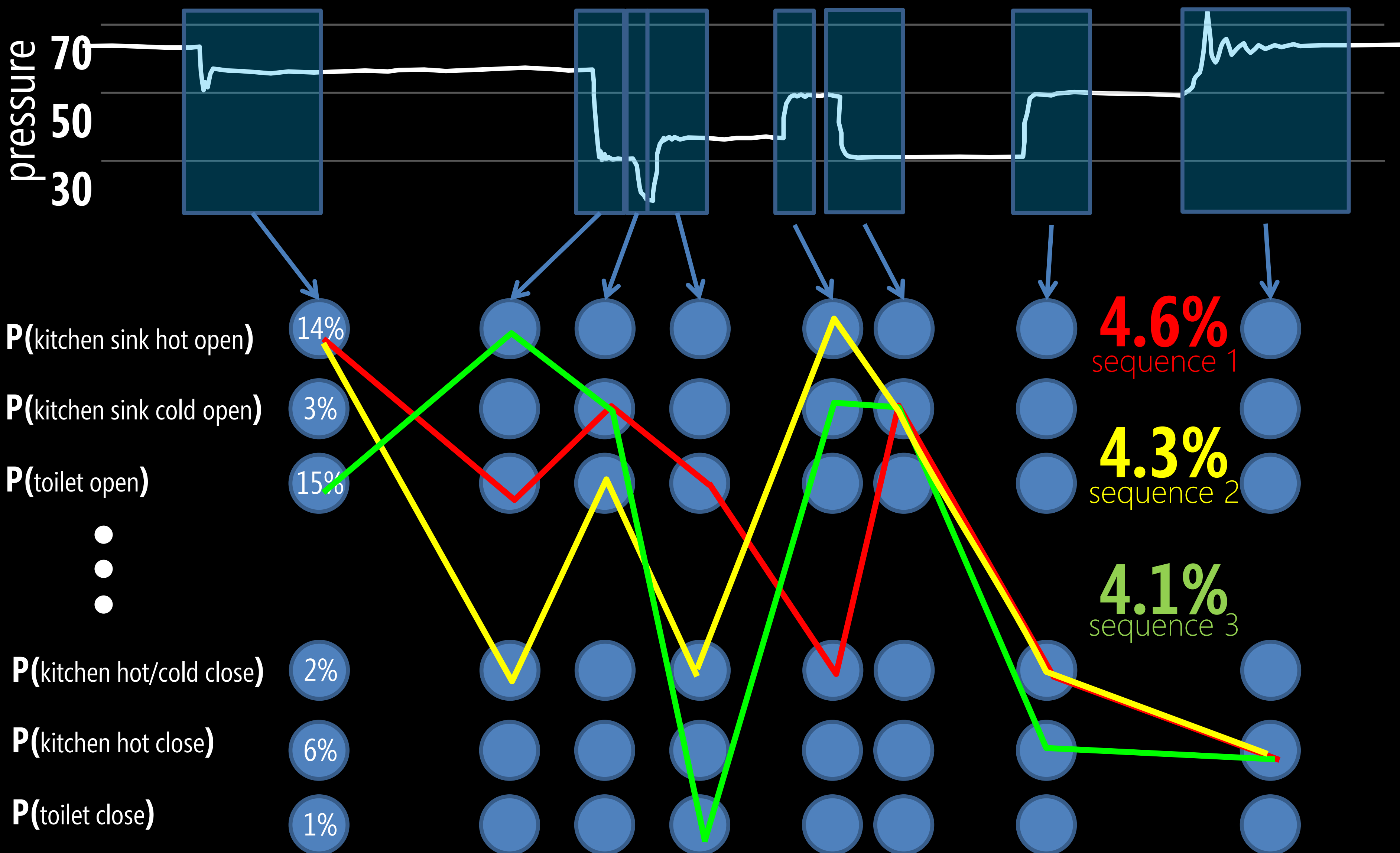
$$\underbrace{\prod_{r=0}^{R-1} f_r(\hat{\boldsymbol{S}}_{\boldsymbol{r}}|\hat{\boldsymbol{V}}_{\boldsymbol{r}})}_{\text{(i) templates and signal features}} \underbrace{\prod_{n=0}^{N-1} P(v_n|v_{n-1})}_{\text{(ii) bigram language model}}$$

# **term (ii):** bigram language model

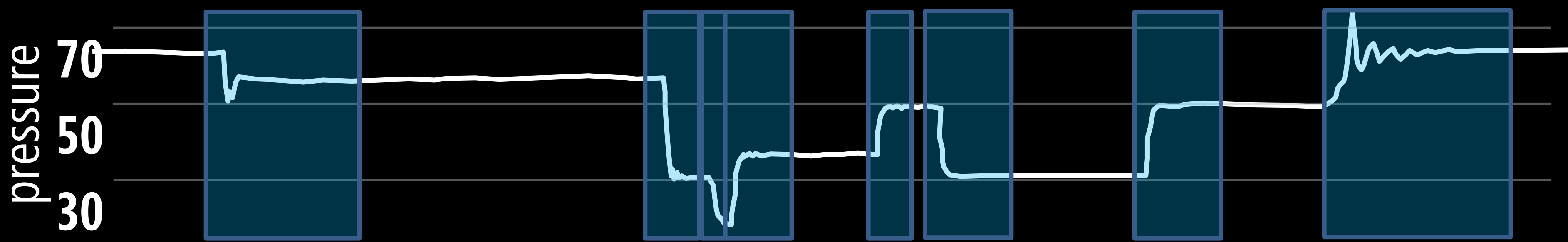



$$\underbrace{\prod_{r=0}^{R-1} f_r(\hat{\boldsymbol{S}}_{\boldsymbol{r}}|\hat{\boldsymbol{V}}_{\boldsymbol{r}})}_{\text{(i) templates and signal features}} \underbrace{\prod_{n=0}^{N-1} P(v_n|v_{n-1})}_{\text{(ii) bigram language model}}$$

# **term (ii):** bigram language model



# term (ii): bigram language model




sequence 1

kitchen sink hot open → kitchen sink cold open → dishwasher open → bathroom sink hot close → kitchen sink hot close → toilet open → toilet close → kitchen sink hot close

sequence 2

kitchen sink hot open → shower cold open → toilet open → bathroom sink hot close → kitchen sink hot close → kitchen sink hot open → kitchen sink hot close → kitchen sink hot close

sequence 3

kitchen sink hot open → toilet open → bathroom sink hot open → bathroom sink hot close → kitchen sink hot close → kitchen sink hot open → kitchen sink hot close → toilet close

⋮

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

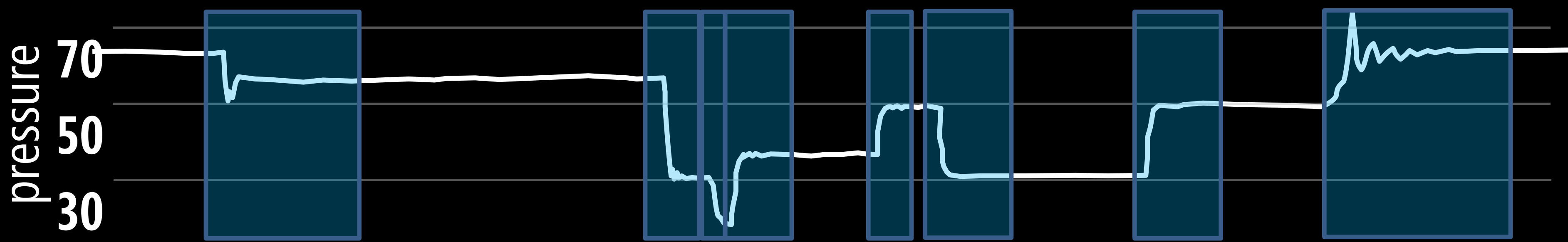
# **term(iii):** grammar

1. opened ⇨ closed
2. opened ⇦ closed
3. temperature consistency

soft penalty

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

# **term(iii):** grammar




sequence 1

kitchen sink hot open → kitchen sink cold open → dishwasher open → bathroom sink hot close → kitchen sink hot close → toilet open → toilet close → kitchen sink hot close

sequence 2

bathroom sink hot open → shower cold open → toilet open → bathroom sink hot close → shower cold close → kitchen sink hot open → toilet close → kitchen sink hot close

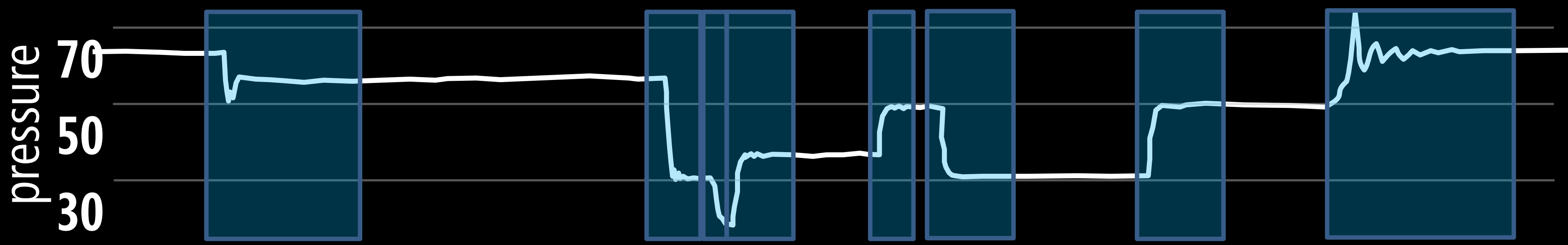
sequence 3

kitchen sink hot open → toilet open → bathroom sink hot open → bathroom sink hot close → kitchen sink hot close → kitchen sink hot open → kitchen sink hot close → toilet close

⋮

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

# **term(iii):** grammar




kitchen sink hot open → kitchen sink cold open → dishwasher open → bathroom sink hot close → kitchen sink hot close → toilet open → toilet close → kitchen sink hot close

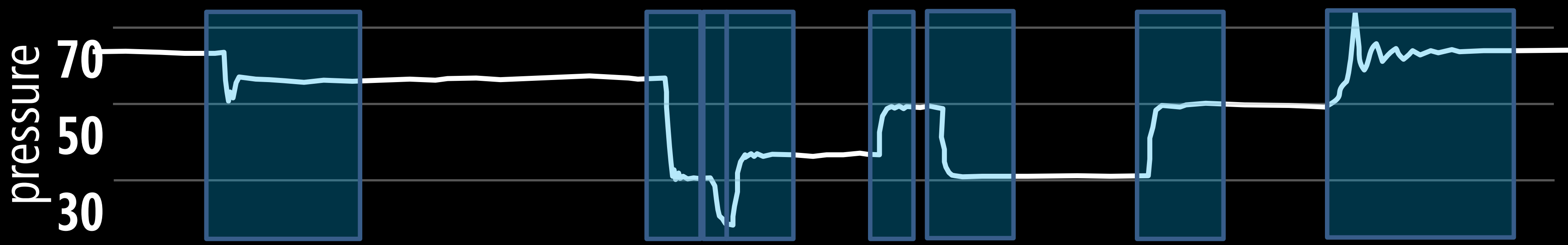
bathroom sink hot open → shower cold open → toilet open → bathroom sink hot close → shower cold close → kitchen sink hot open → toilet close → kitchen sink hot close

kitchen sink hot open → toilet open → bathroom sink hot open → bathroom sink hot close → kitchen sink hot close → kitchen sink hot open → kitchen sink hot close → toilet close

⋮

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

# term(iii): grammar



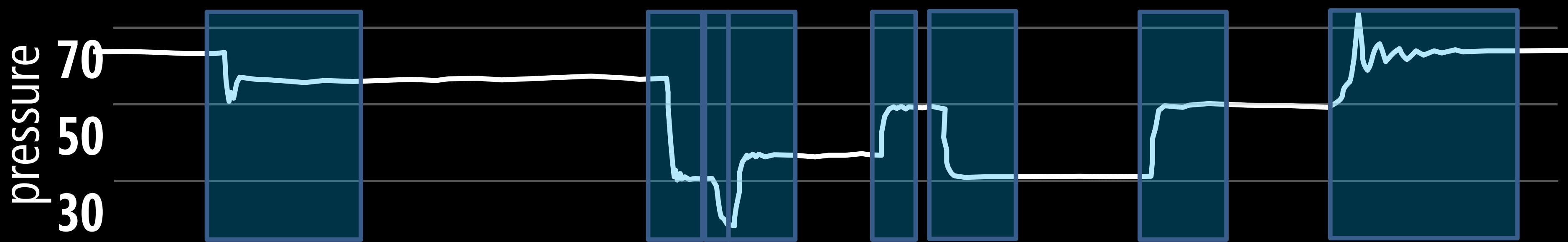

bathroom sink hot open → shower cold open → toilet open → bathroom sink hot close → shower cold close → kitchen sink hot open → toilet close → kitchen sink hot close

kitchen sink hot open → toilet open → bathroom sink hot open → bathroom sink hot close → kitchen sink hot close → kitchen sink hot open → kitchen sink hot close → toilet close

kitchen sink hot open → kitchen sink cold open → dishwasher open → bathroom sink hot close → kitchen sink hot close → toilet open → toilet close → kitchen sink hot close

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

# term(iii): grammar




bathroom sink hot open → shower cold open → toilet open → bathroom sink hot close → shower cold close → kitchen sink hot open → toilet close → kitchen sink hot close

kitchen sink hot open → toilet open → bathroom sink hot open → bathroom sink hot close → kitchen sink hot close → kitchen sink hot open → kitchen sink hot close → toilet close

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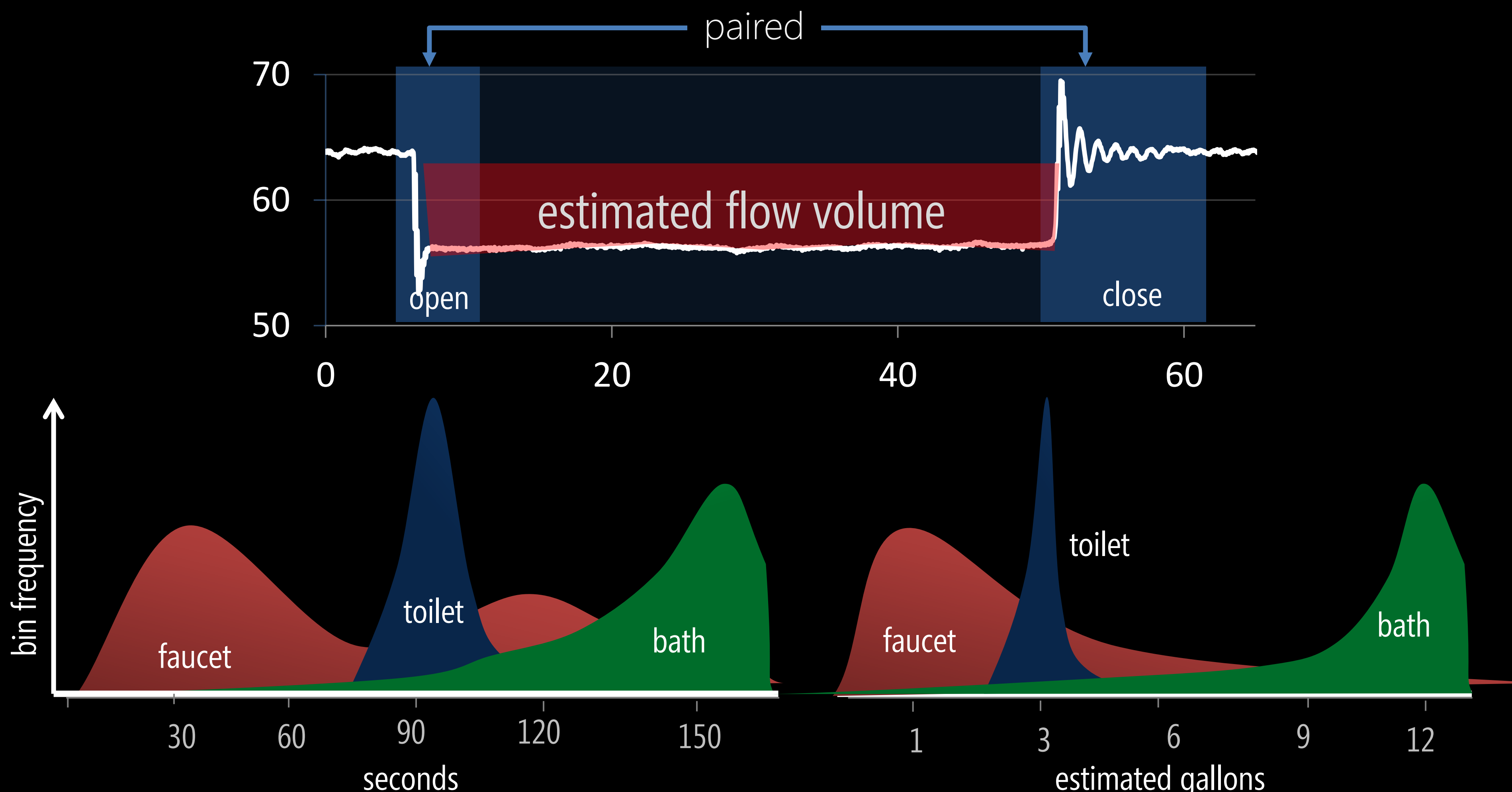
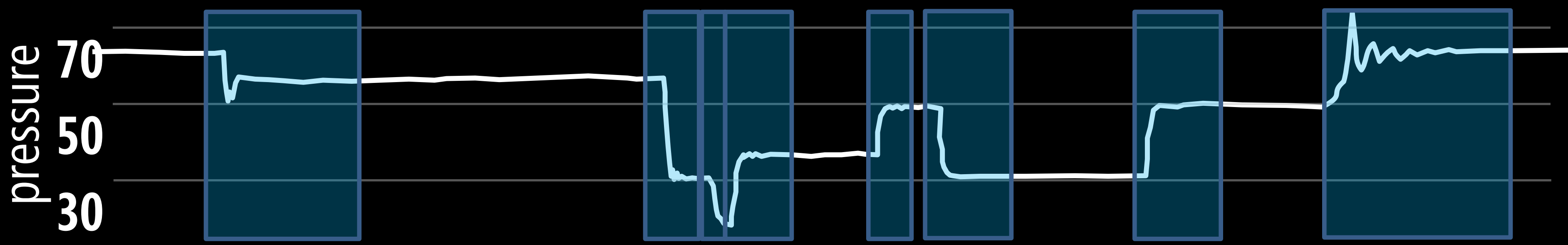
$$\underbrace{\prod_{r=0}^{R-1} f_r(\hat{\boldsymbol{S}}_{\boldsymbol{r}}|\hat{\boldsymbol{V}}_{\boldsymbol{r}})}_{\text{(i) templates and signal features}} \underbrace{\prod_{n=0}^{N-1} P(v_n|v_{n-1})}_{\text{(ii) bigram language model}} \underbrace{\prod_{i\notin\boldsymbol{\beta}} f_p(v_i)}_{\text{(iii)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

# **term(iv):** paired valve priors




**fixture usage duration** **flow volume**

# **term(iv):** paired valve priors




bathroom sink hot open → shower cold open → toilet open → bathroom sink hot close → shower cold close → kitchen sink hot open → toilet close → kitchen sink hot close

kitchen sink hot open → toilet open → bathroom sink hot open → bathroom sink hot close → kitchen sink hot close → kitchen sink hot open → kitchen sink hot close → toilet close

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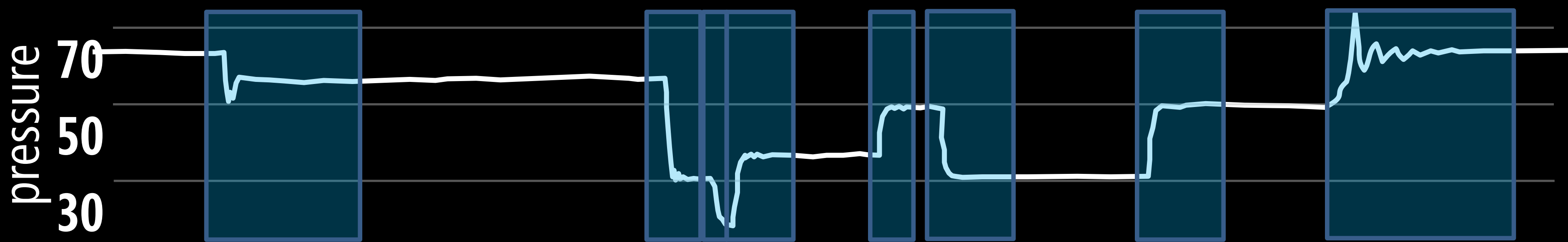
$$\underbrace{\prod_{r=0}^{R-1} f_r(\hat{\boldsymbol{S}}_{\boldsymbol{r}}|\hat{\boldsymbol{V}}_{\boldsymbol{r}})}_{\text{(i) templates and signal features}} \underbrace{\prod_{n=0}^{N-1} P(v_n|v_{n-1})}_{\text{(ii) bigram language model}} \underbrace{\prod_{i \notin \boldsymbol{\beta}} f_p(v_i)}_{\text{(iii)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

# **term(iv):** paired valve priors



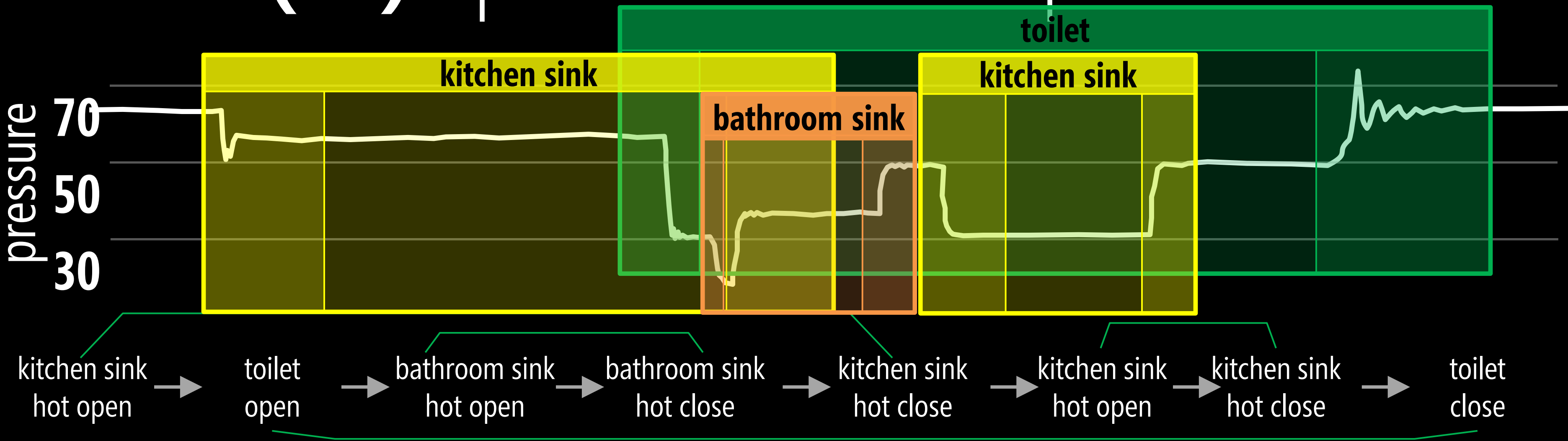

kitchen sink hot open → toilet open → bathroom sink hot open → bathroom sink hot close → kitchen sink hot close → kitchen sink hot open → kitchen sink hot close → toilet close

bathroom sink hot open → shower cold open → toilet open → bathroom sink hot close → shower cold close → kitchen sink hot open → toilet close → kitchen sink hot close

kitchen sink hot open → kitchen sink cold open → dishwasher open → bathroom sink hot close → kitchen sink hot close → toilet open → toilet close → kitchen sink hot close

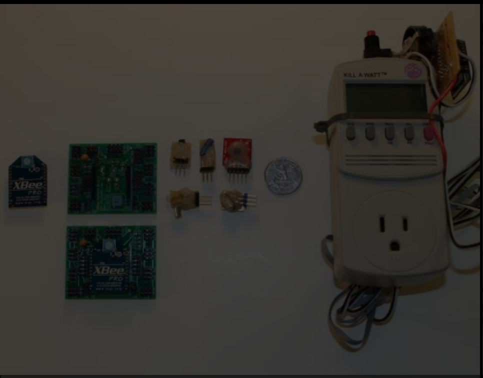
$$\underbrace{\prod_{r=0}^{R-1} f_r(\hat{\boldsymbol{S}}_{\boldsymbol{r}}|\hat{\boldsymbol{V}}_{\boldsymbol{r}})}_{\text{(i) templates and signal features}} \underbrace{\prod_{n=0}^{N-1} P(v_n|v_{n-1})}_{\text{(ii) bigram language model}} \underbrace{\prod_{i\notin\boldsymbol{\beta}} f_p(v_i)}_{\text{(iii)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

# term(iv): paired valve priors



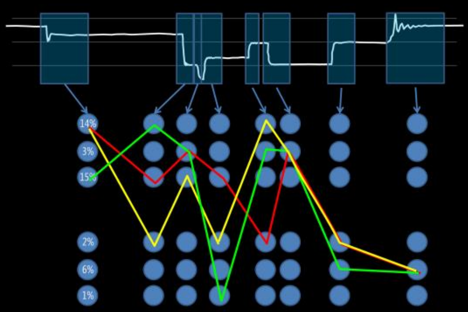

$$\underbrace{\prod_{r=0}^{R-1} f_r(\hat{\boldsymbol{S}}_{\boldsymbol{r}} | \hat{\boldsymbol{V}}_{\boldsymbol{r}})}_{\text{(i) templates and signal features}} \underbrace{\prod_{n=0}^{N-1} P(v_n | v_{n-1})}_{\text{(ii) bigram language model}} \underbrace{\prod_{i \notin \boldsymbol{\beta}} f_p(v_i)}_{\text{(iii)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

ground truth sensors

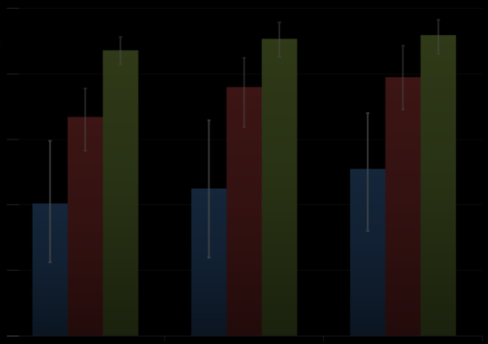


5-week deployment

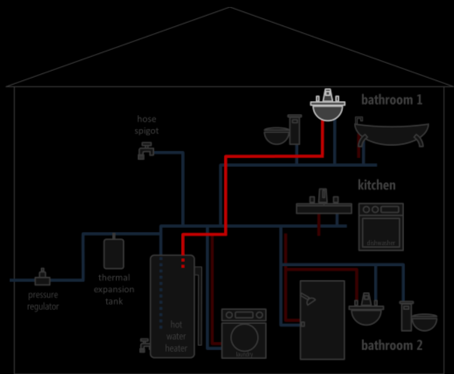
classification algorithm




classification results

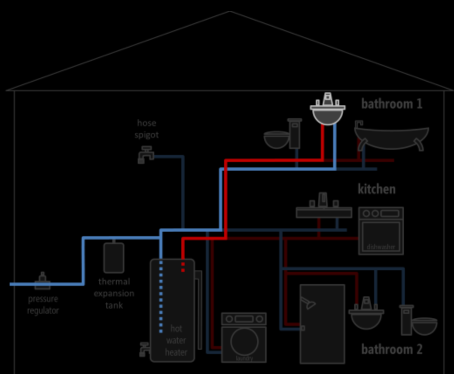


# three levels of granularity



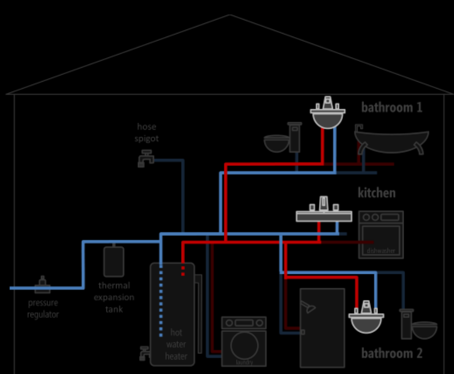

① **valve** level

e.g., upstairs bathroom faucet hot water activated




② **fixture** level

e.g., upstairs bathroom faucet activated

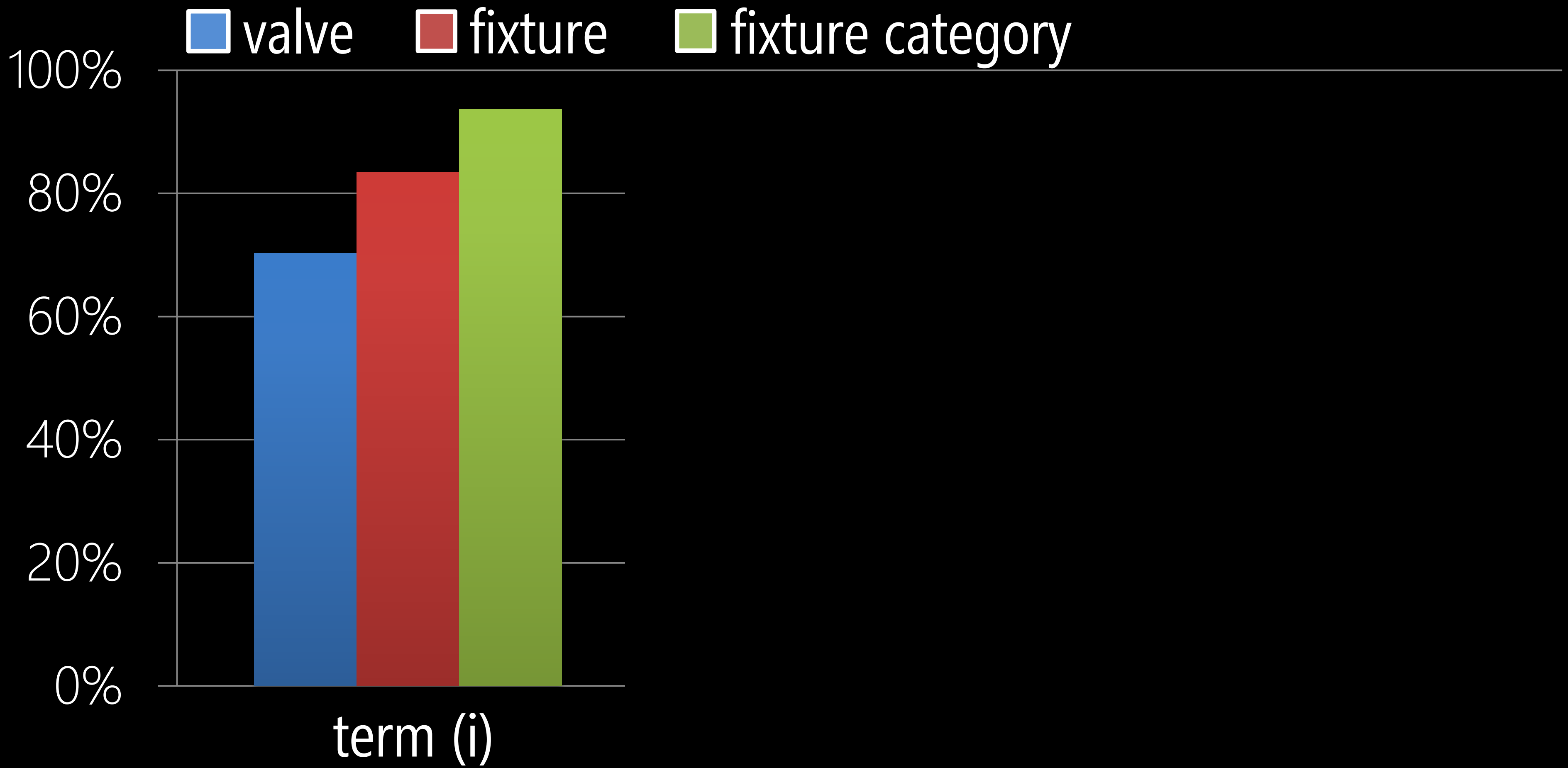



③ **fixture** category level

e.g., faucet activated

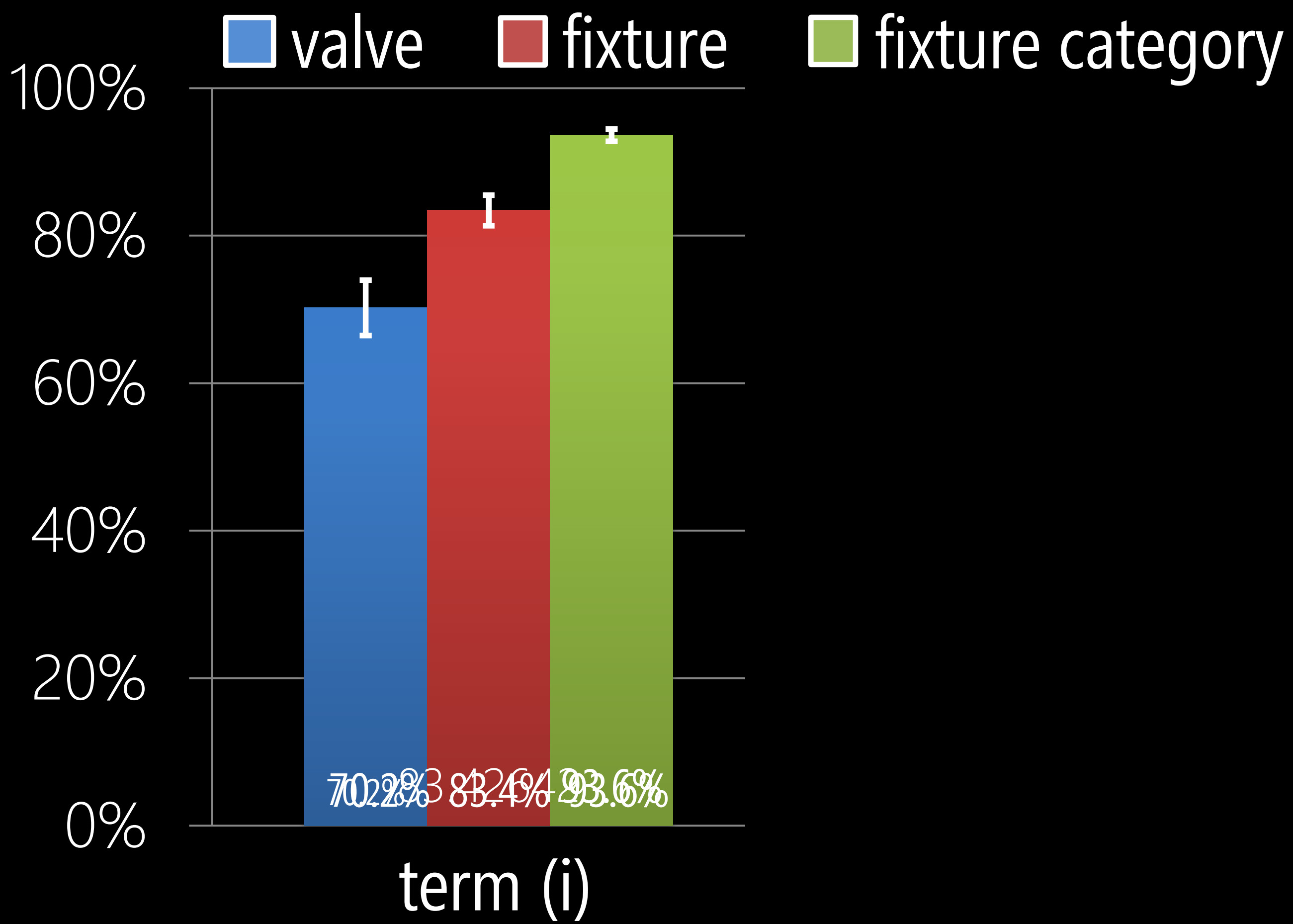
# hydrosense classification results

## real-world water usage data



# hydrosense classification results

## real-world water usage data

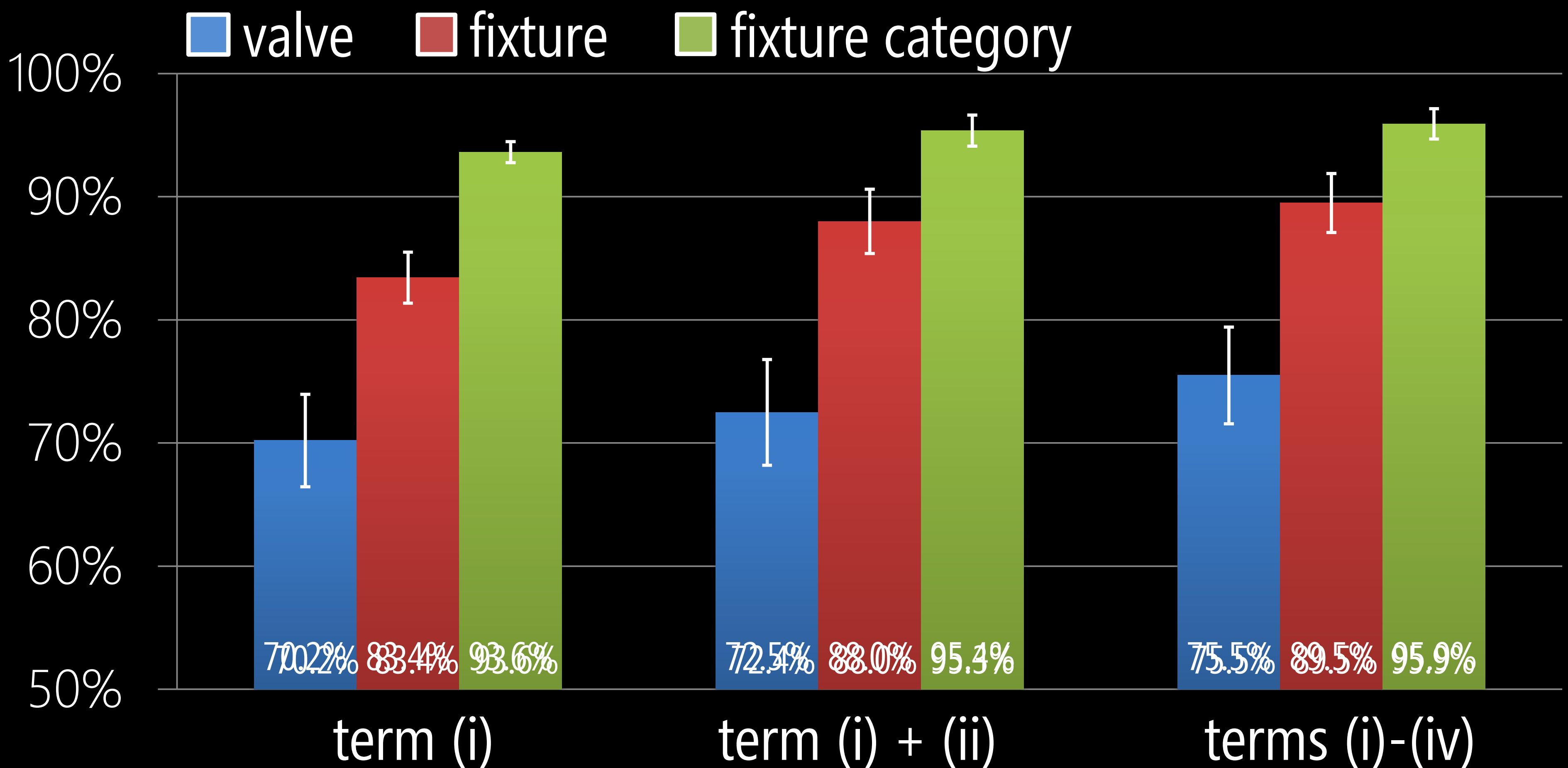



*error bars = std error

*10-fold cross validation

# hydrosense classification results

## real-world water usage data

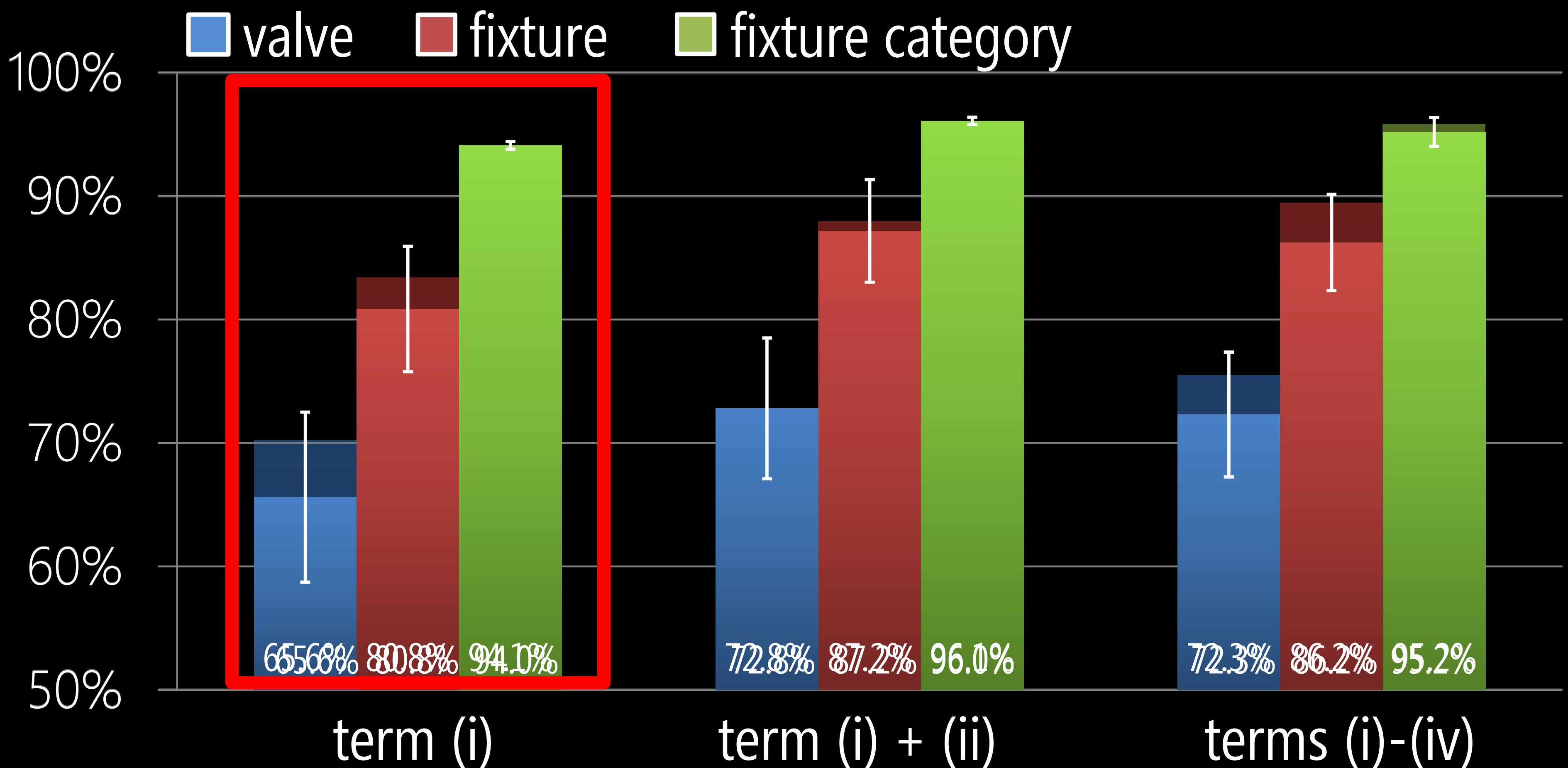



*error bars = std error

*10-fold cross validation

# **compound** events

## real-world water usage data

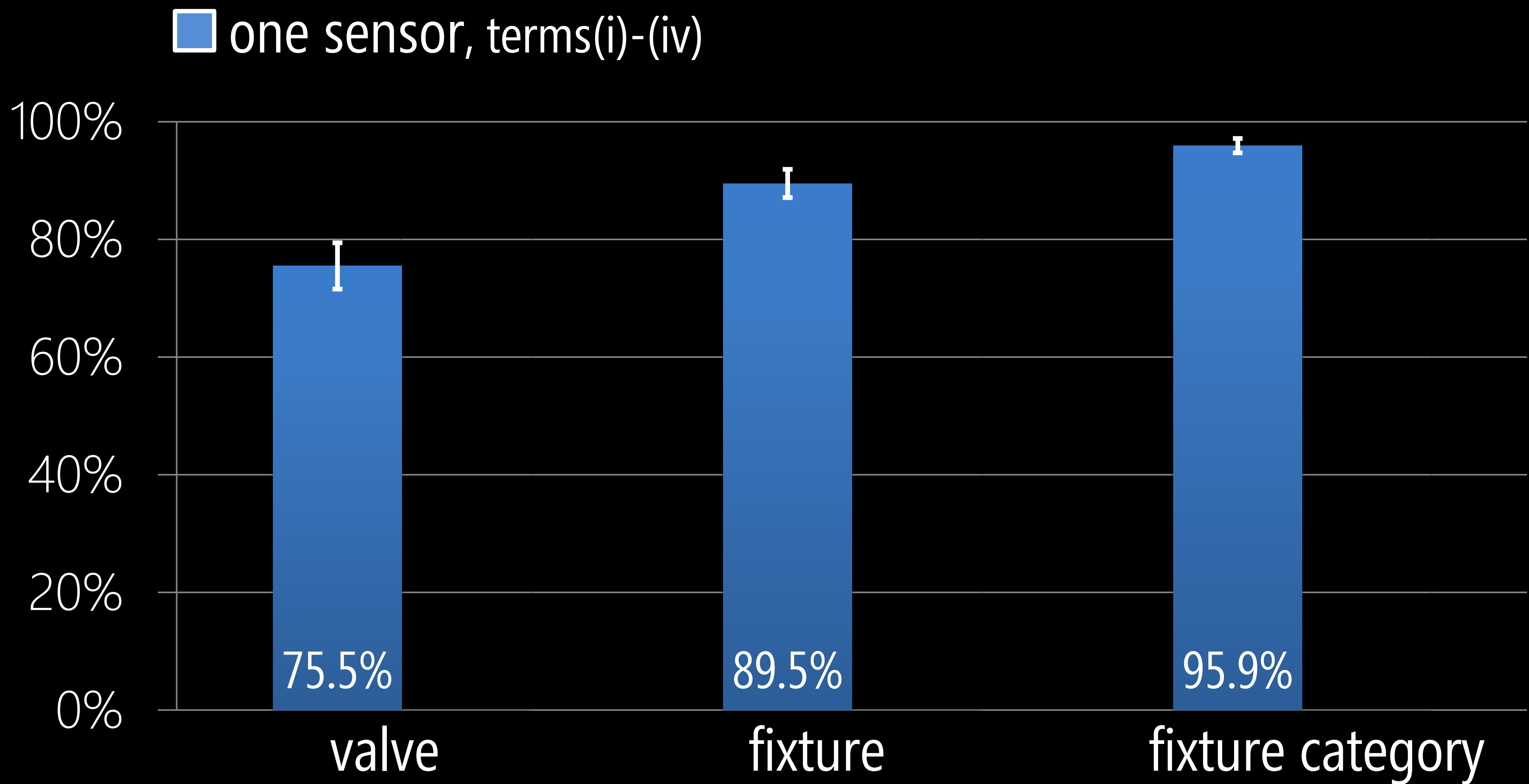



*error bars = std error

*10-fold cross validation

# hydrosense classification results

## real-world water usage data

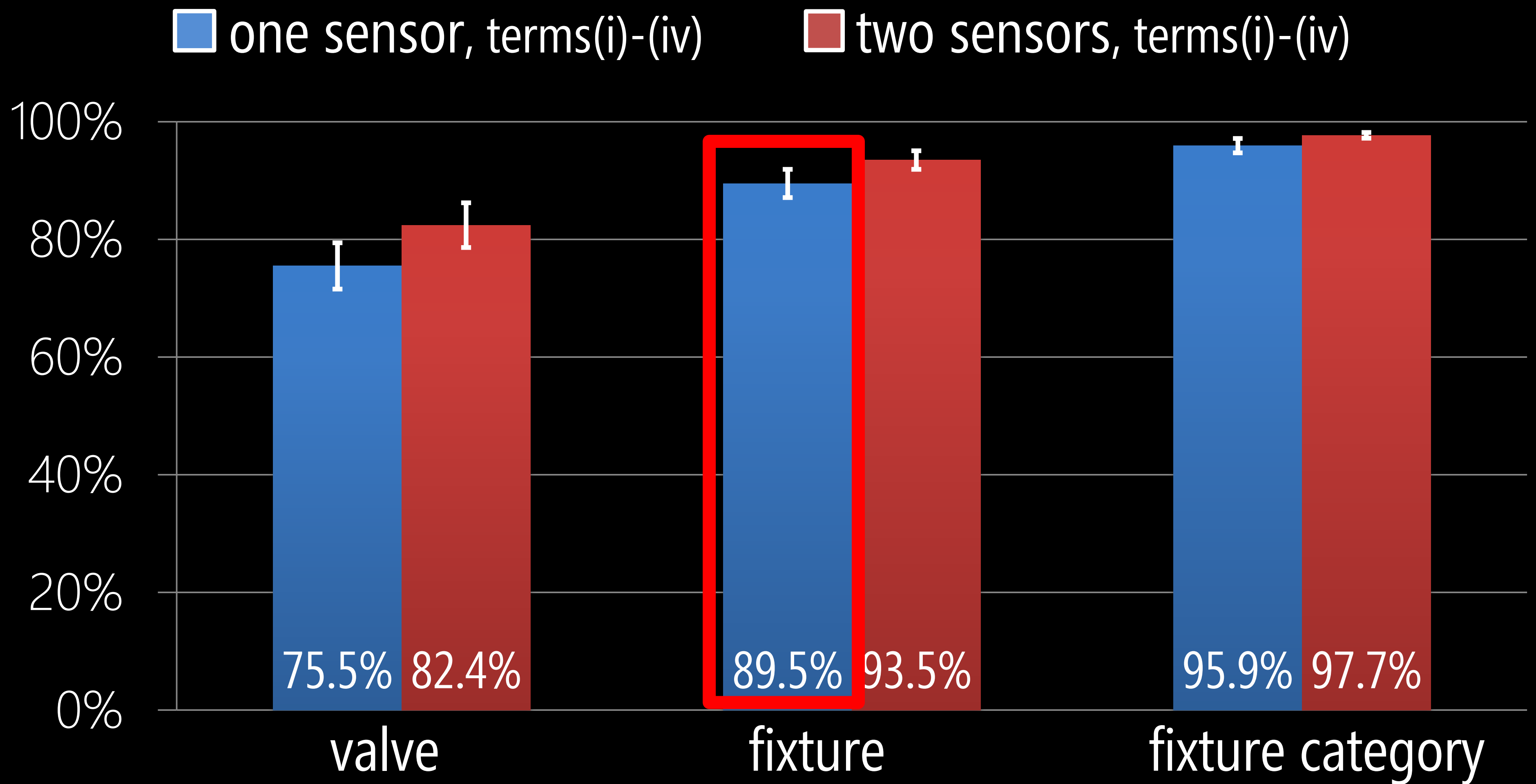



*error bars = std error

*10-fold cross validation

# hydrosense classification results

## real-world water usage data




*error bars = std error

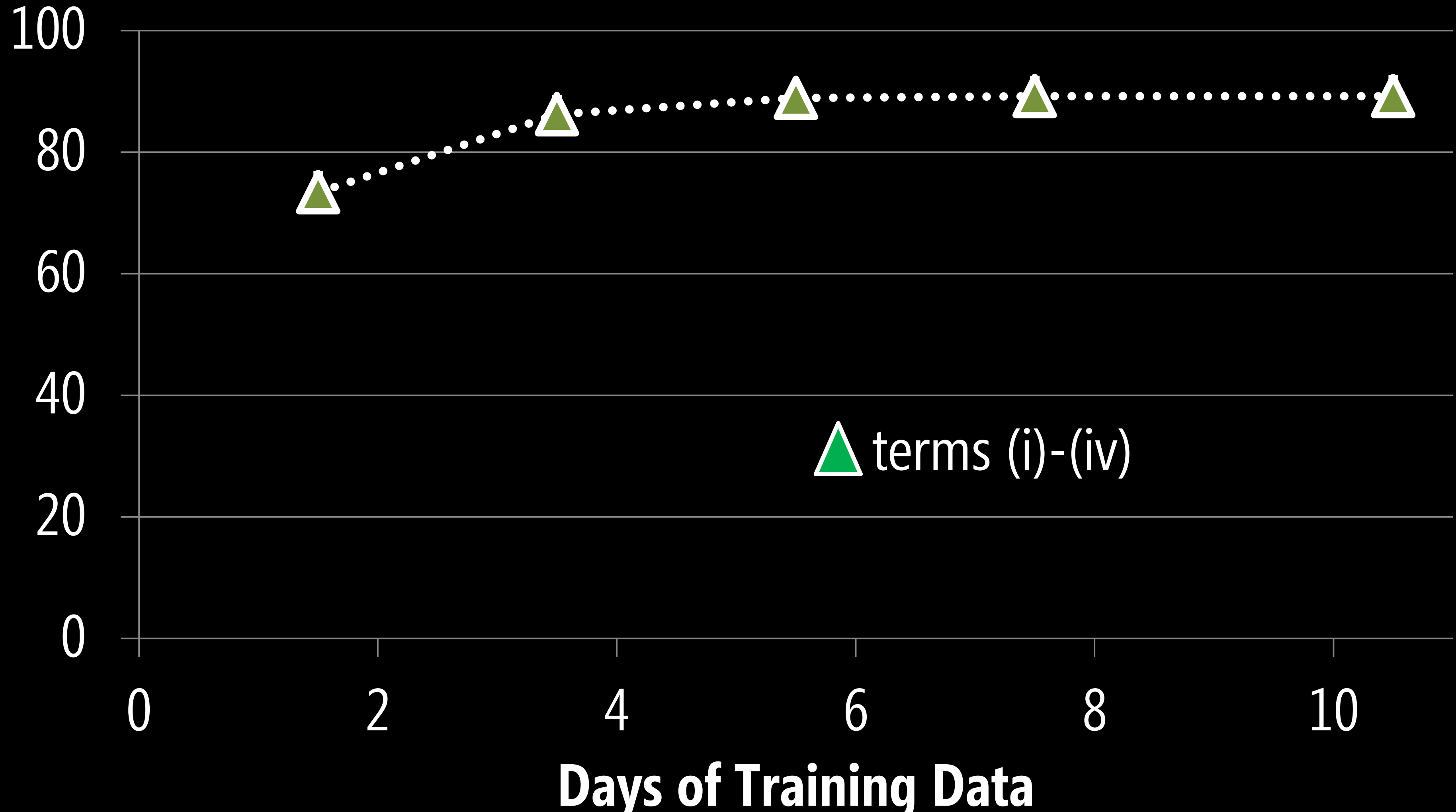
*10-fold cross validation

*terms (i)-(iv)

...what about **training**?

# **hydro**sense training results

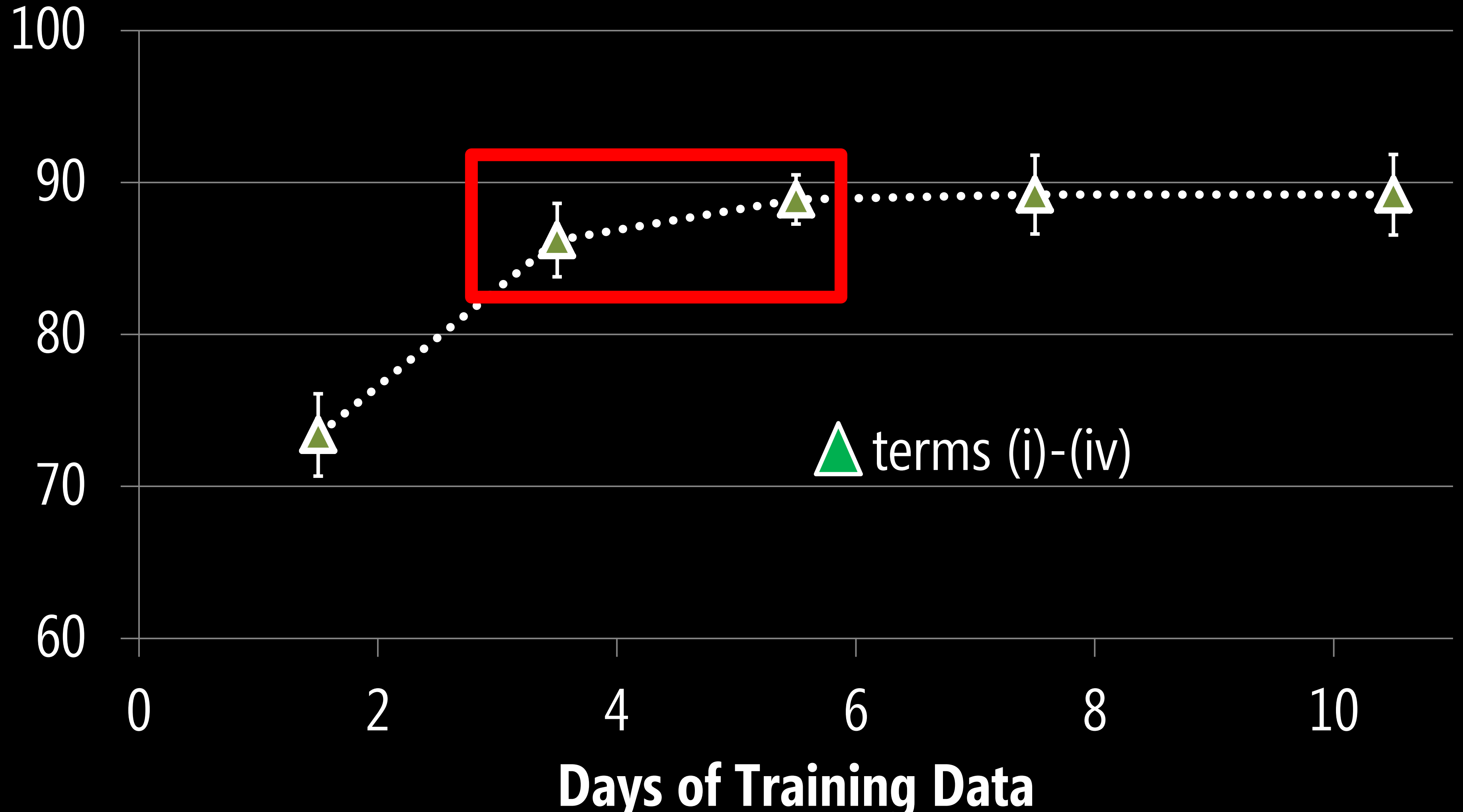
real-world water usage data




*error bars = std error

# **hydro**sense training results

real-world water usage data




*error bars = std error

# **pervasive** 2011 contributions

1. longitudinal study of real-world water usage and the resulting dataset

2. a new probabilistic approach to water usage classification

3. demonstrate that this new approach can accurately classify real world data

# **future** work

① additional features

② segmentation

③ ease of training

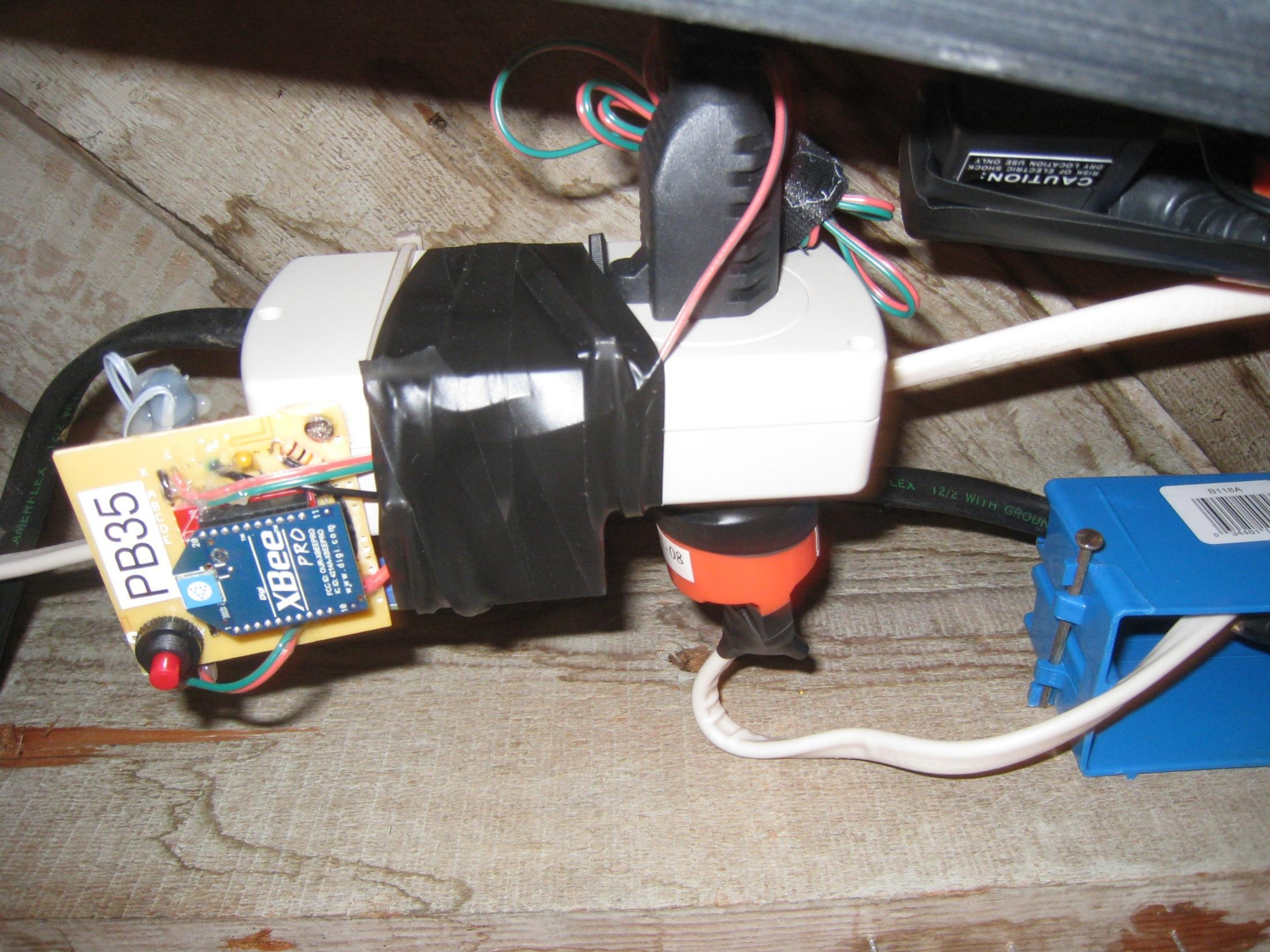
# A Longitudinal Study of Pressure Sensing to Infer Real-World Water Usage Events in the Home

**Eric Larson**
eric.cooper.larson@gmail.com


Jon Froehlich, Elliot Saba, Tim Campbell, Les Atlas, James Fogarty and Shwetak Patel


H
C

BOSCH
On/Off
Menu/ok.
Start
Please also
press button
Made in
finish
Electrasol



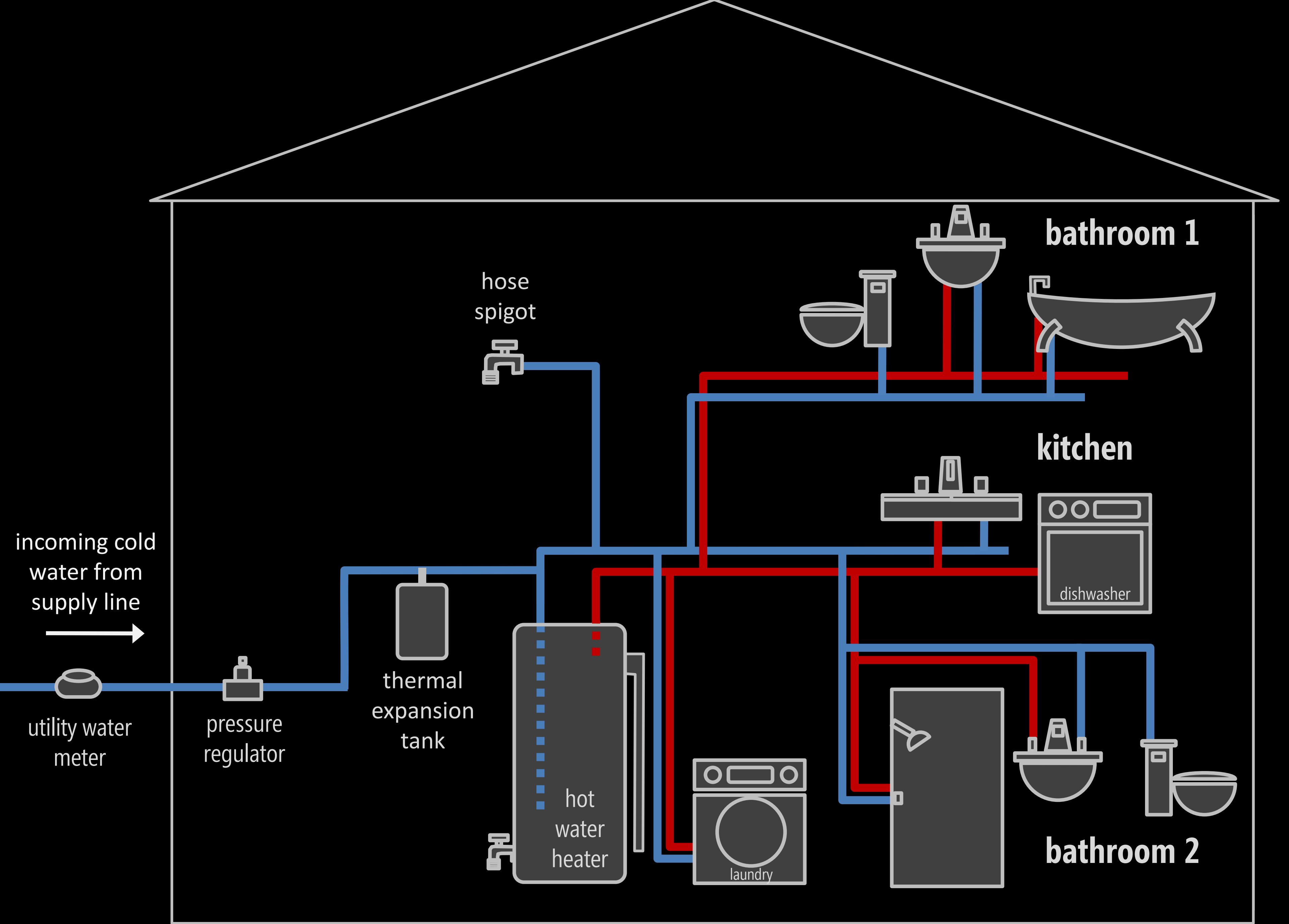
PB35
XBee
PRO
CAUTION:
B118A


LIGHTING INSTRUCTIONS
TO TURN OFF GAS TO APPLIANCE
IGNITER
PILOT

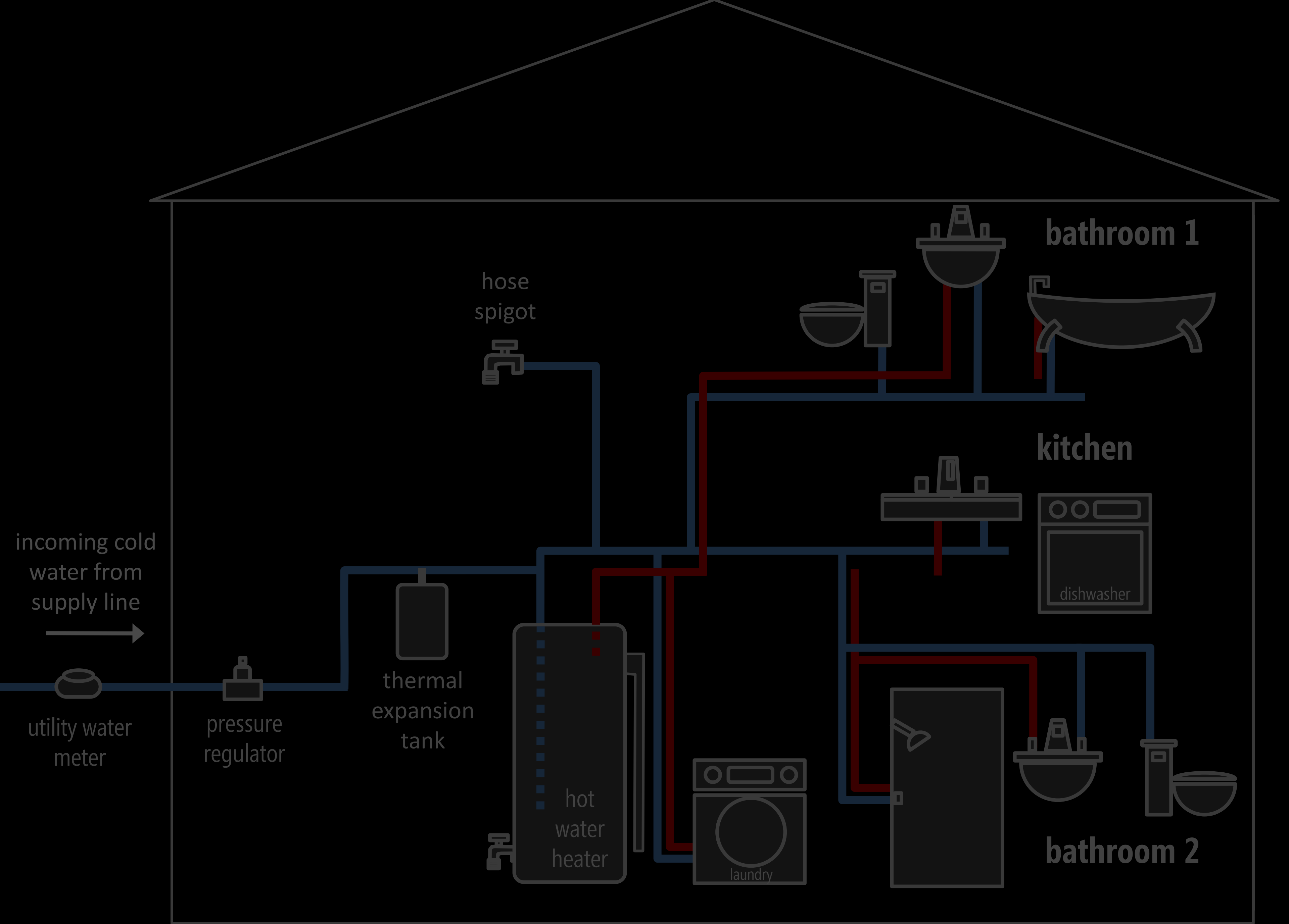

KILL A WATT™
0.00


simplehuman


Daily average consumption by fixture for the month of May
69.3 gallons
Weekly consumption pattern for the month of May
average consumption for this day of the week
average daily consumption
M T W T F S S
M T W T F S S
M T W T F S S
M T W T F S S
M T W T F S S
M T W T F S S
M T W T F S S



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



bathroom 1
hose spigot
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laundry
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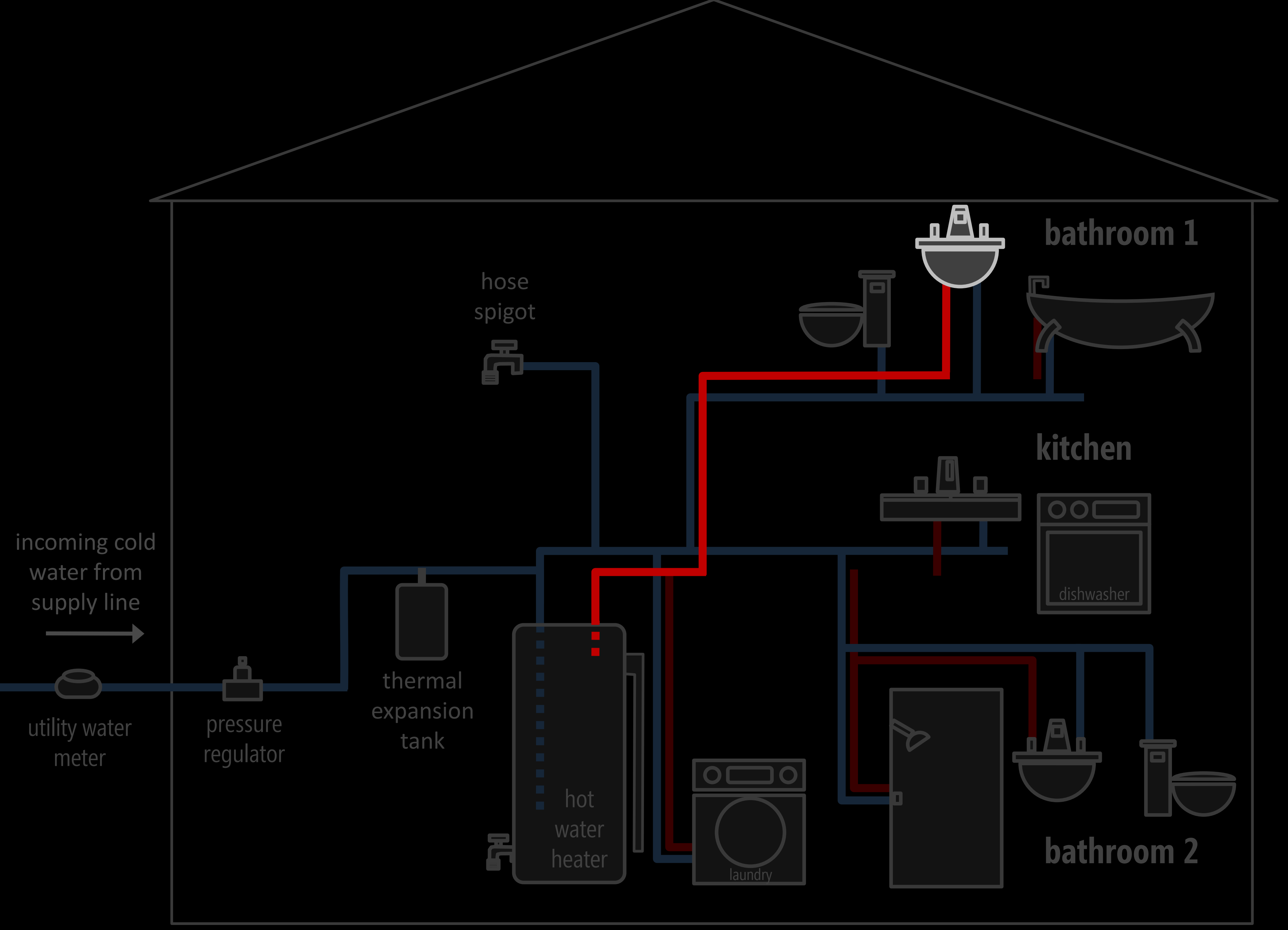

bathroom 1
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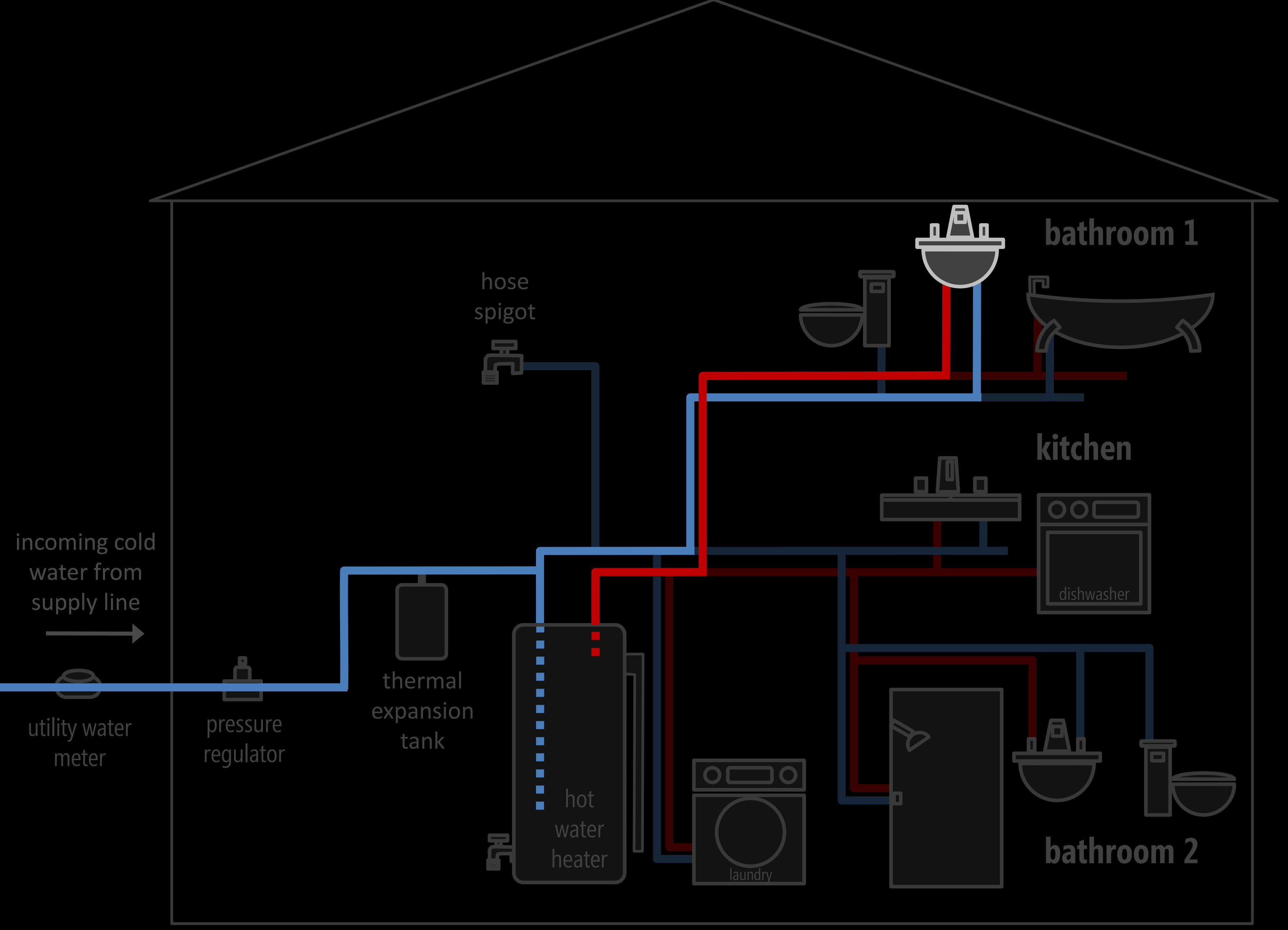
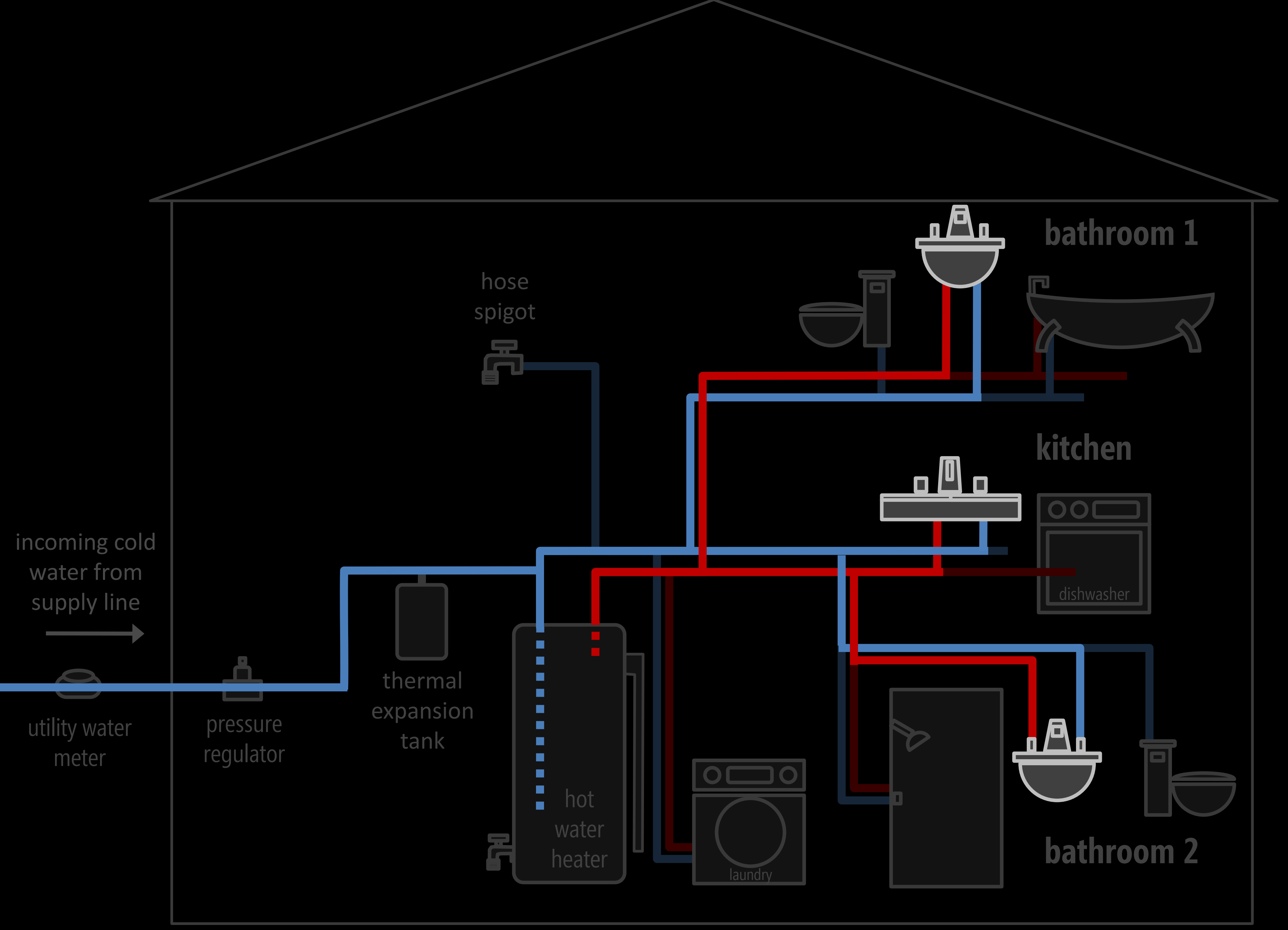

bathroom 1
hose
spigot
kitchen
incoming cold
water from
supply line
dishwasher
thermal
expansion
tank
utility water
meter
pressure
regulator
hot
water
heater
laundry
bathroom 2


bathroom 1
hose
spigot
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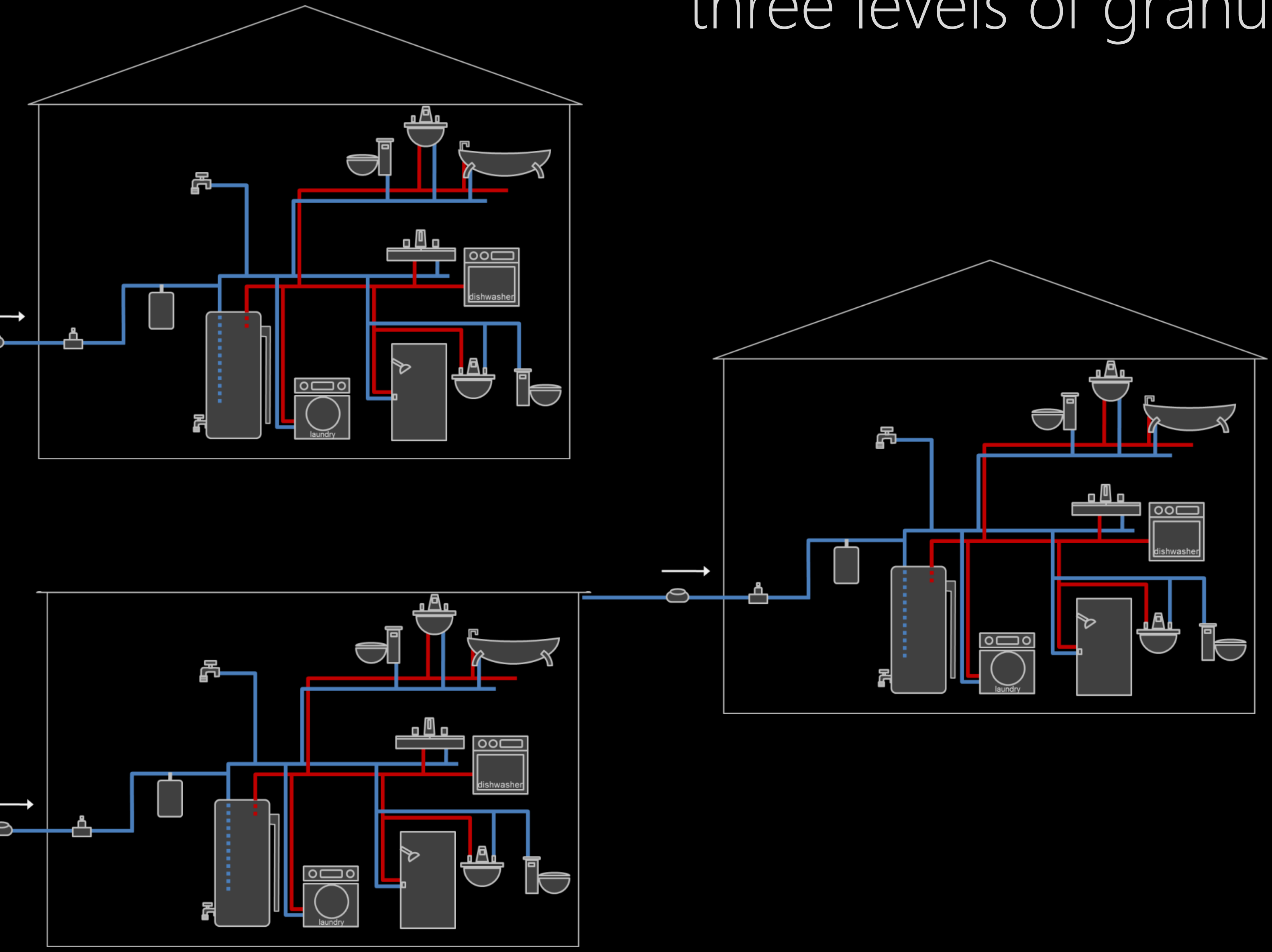
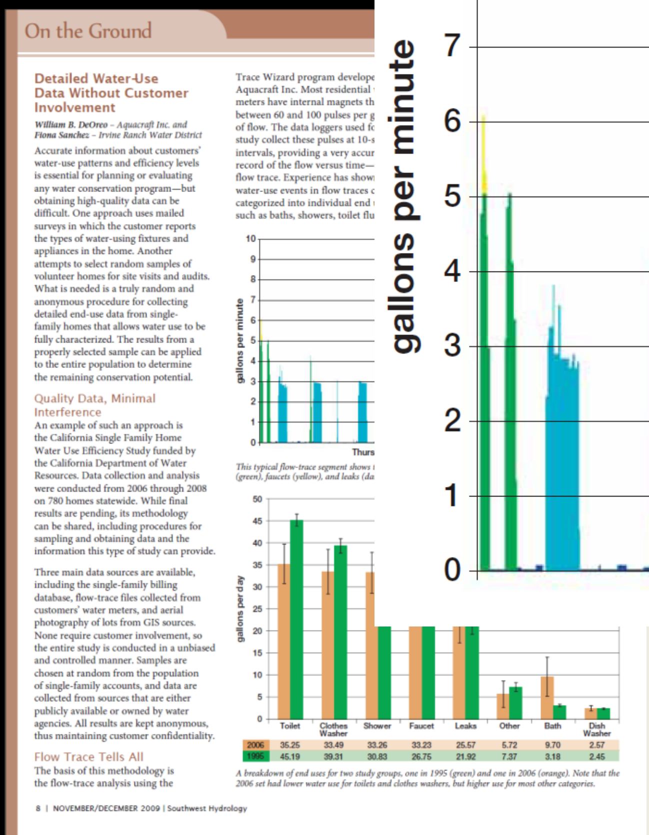
water from
supply line
dishwasher
thermal
expansion
tank
utility water
meter
pressure
regulator
hot
water
heater
laundry
bathroom 2

# three levels of granularity





On the Ground

## Detailed Water-Use Data Without Customer Involvement

*William B. DeOreo – Aquacraft Inc. and Fiona Sanchez – Irvine Ranch Water District*

Accurate information about customers' water-use patterns and efficiency levels is essential for planning or evaluating any water conservation program—but obtaining high-quality data can be difficult. One approach uses mailed surveys in which the customer reports the types of water-using fixtures and appliances in the home. Another attempts to select random samples of volunteer homes for site visits and audits. What is needed is a truly random and anonymous procedure for collecting detailed end-use data from single-family homes that allows water use to be fully characterized. The results from a properly selected sample can be applied to the entire population to determine the remaining conservation potential.

### Quality Data, Minimal Interference

An example of such an approach is the California Single Family Home Water Use Efficiency Study funded by the California Department of Water Resources. Data collection and analysis were conducted from 2006 through 2008 on 780 homes statewide. While final results are pending, its methodology can be shared, including procedures for sampling and obtaining data and the information this type of study can provide.

Three main data sources are available, including the single-family billing database, flow-trace files collected from customers' water meters, and aerial photography of lots from GIS sources. None require customer involvement, so the entire study is conducted in a unbiased and controlled manner. Samples are chosen at random from the population of single-family accounts, and data are collected from sources that are either publicly available or owned by water agencies. All results are kept anonymous, thus maintaining customer confidentiality.

### Flow Trace Tells All

The basis of this methodology is the flow-trace analysis using the

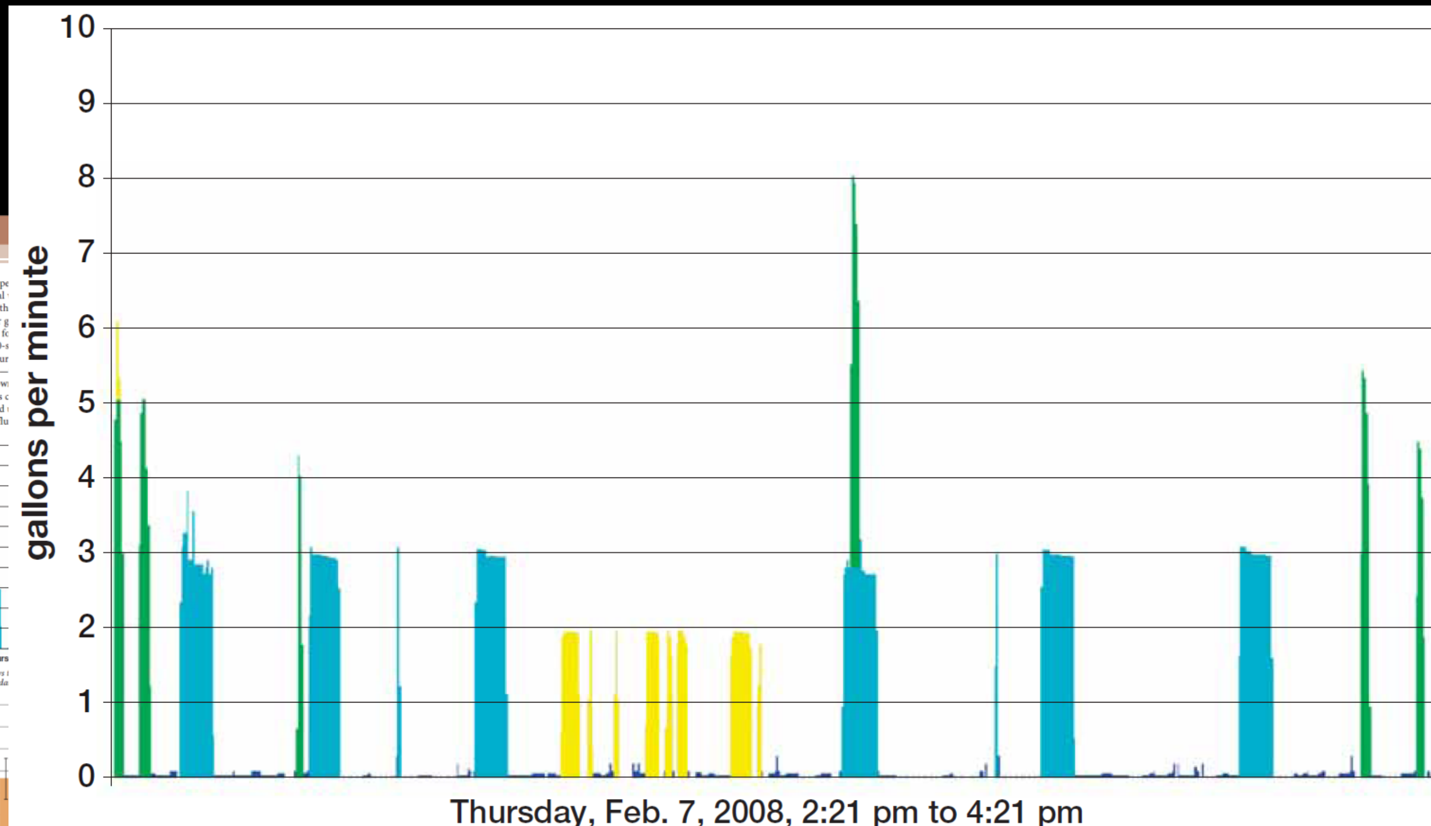
Trace Wizard program develope
Aquacraft Inc. Most residential
meters have internal magnets th
between 60 and 100 pulses per g
of flow. The data loggers used fo
study collect these pulses at 10-s
intervals, providing a very accur
record of the flow versus time—
flow trace. Experience has show
water-use events in flow traces c
categorized into individual end u
such as baths, showers, toilet flu

*This typical flow-trace segment shows t (green), faucets (yellow), and leaks (da*

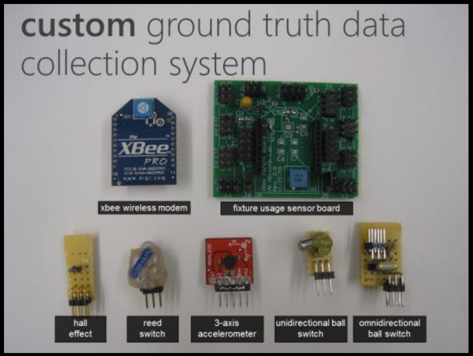
| | Toilet | Clothes Washer | Shower | Faucet | Leaks | Other | Bath | Dish Washer |
|---|---|---|---|---|---|---|---|---|
| 2006 | 35.25 | 33.49 | 33.26 | 33.23 | 25.57 | 5.72 | 9.70 | 2.57 |
| 1995 | 45.19 | 39.31 | 30.83 | 26.75 | 21.92 | 7.37 | 3.18 | 2.45 |

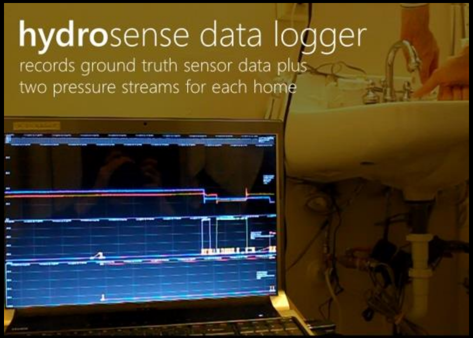
*A breakdown of end uses for two study groups, one in 1995 (green) and one in 2006 (orange). Note that the 2006 set had lower water use for toilets and clothes washers, but higher use for most other categories.*



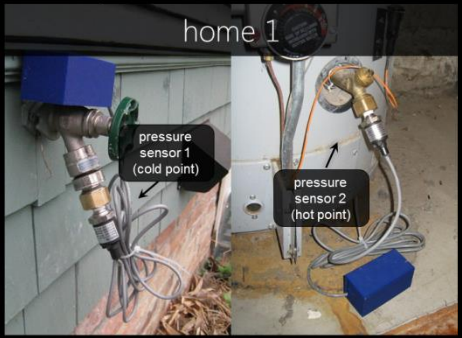


# hydro deployment infrastructure



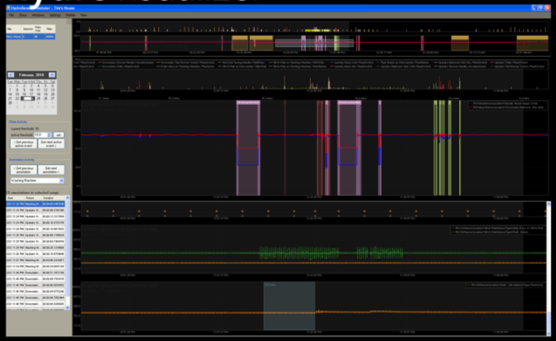

two pressure sensors



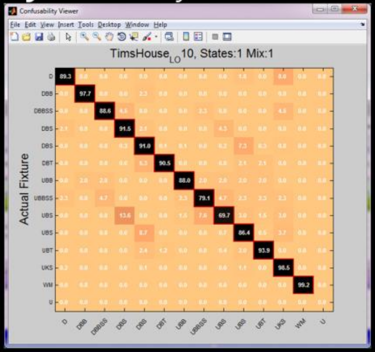

on-site sensing infrastructure


python web backend

hydrovisualizer



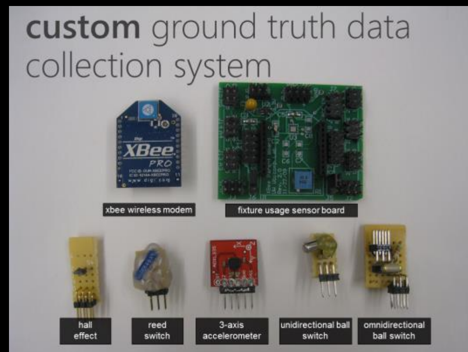
hydroanalyzer

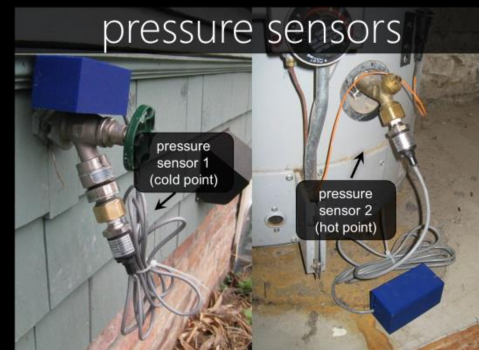


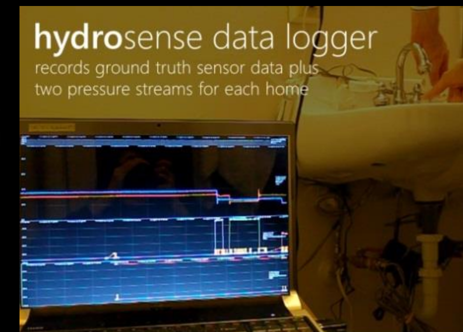

c# and matlab analysis tools

# **hydro** deployment infrastructure

on-site infrastructure



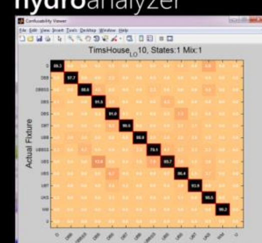




python web backend

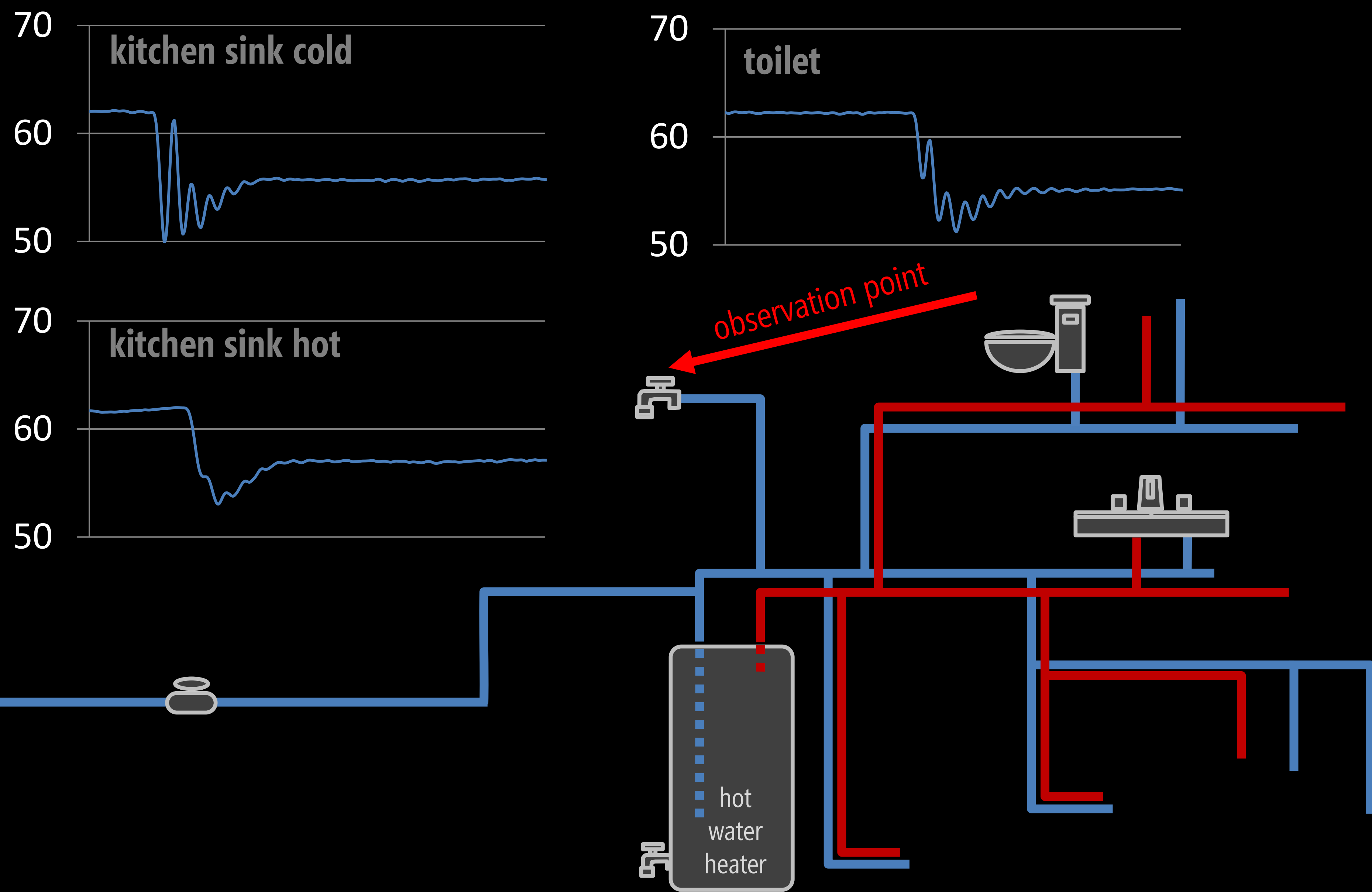

analysis tools & algorithms

**hydro**visualizer

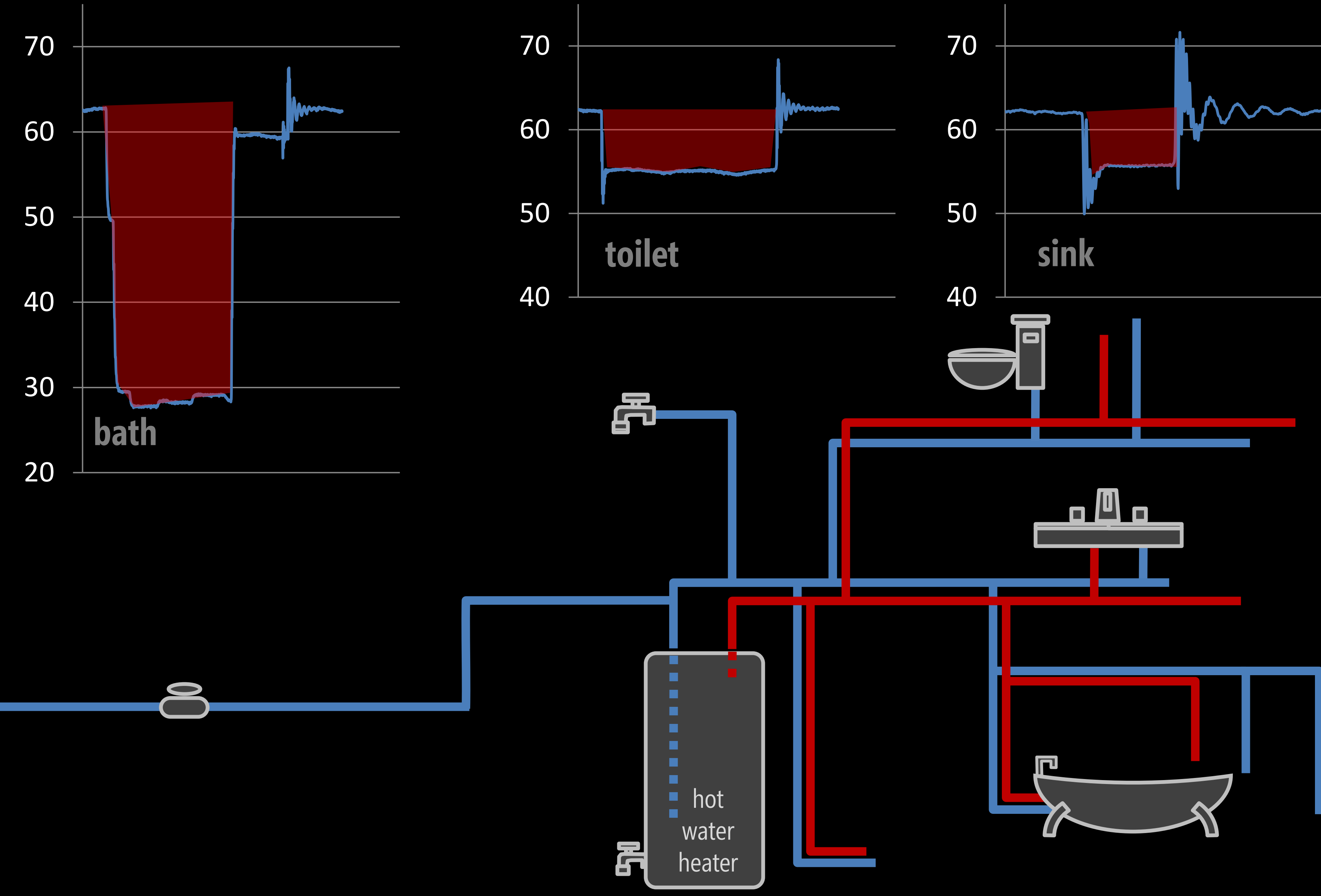
**hydro**analyzer

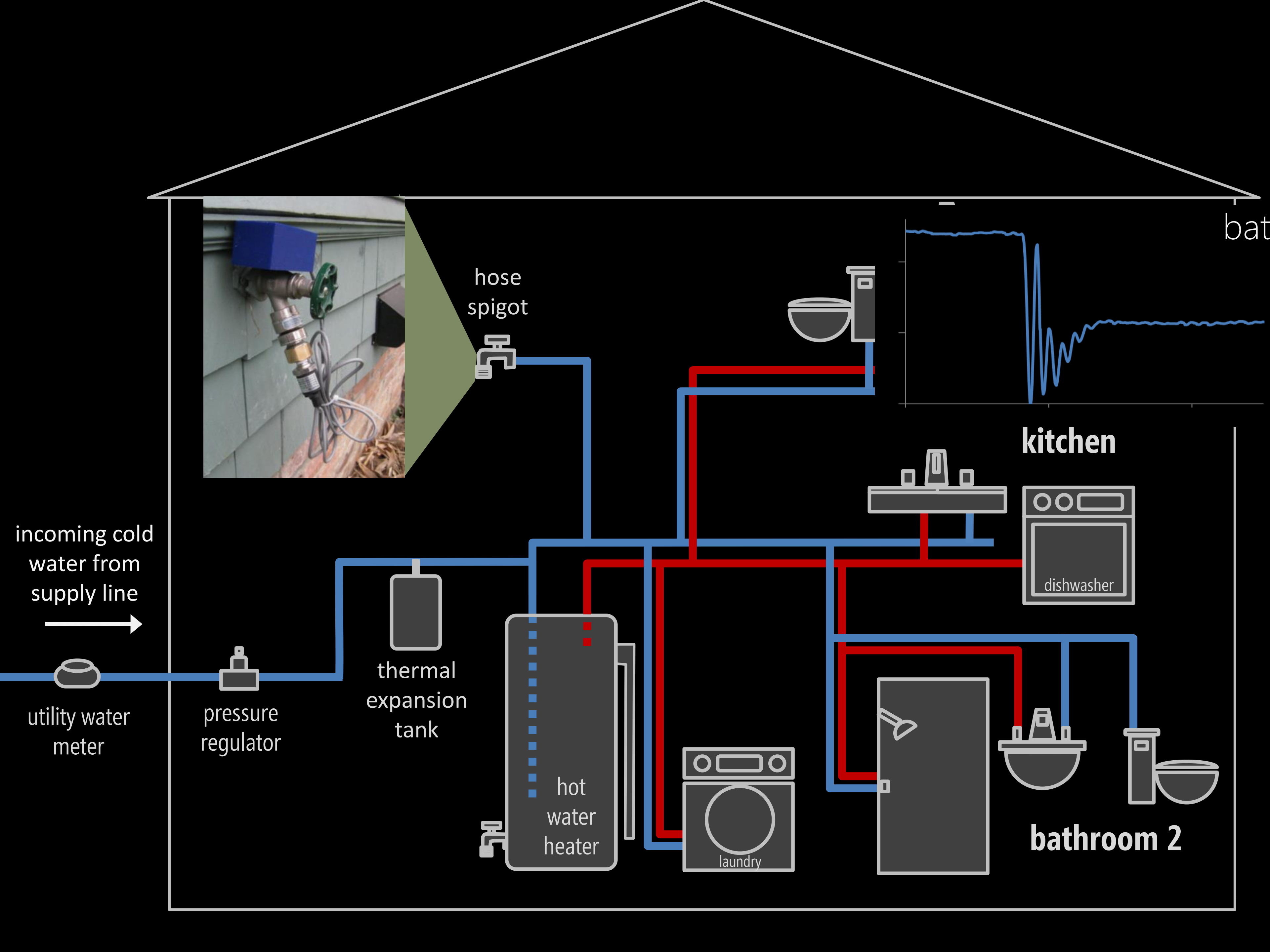


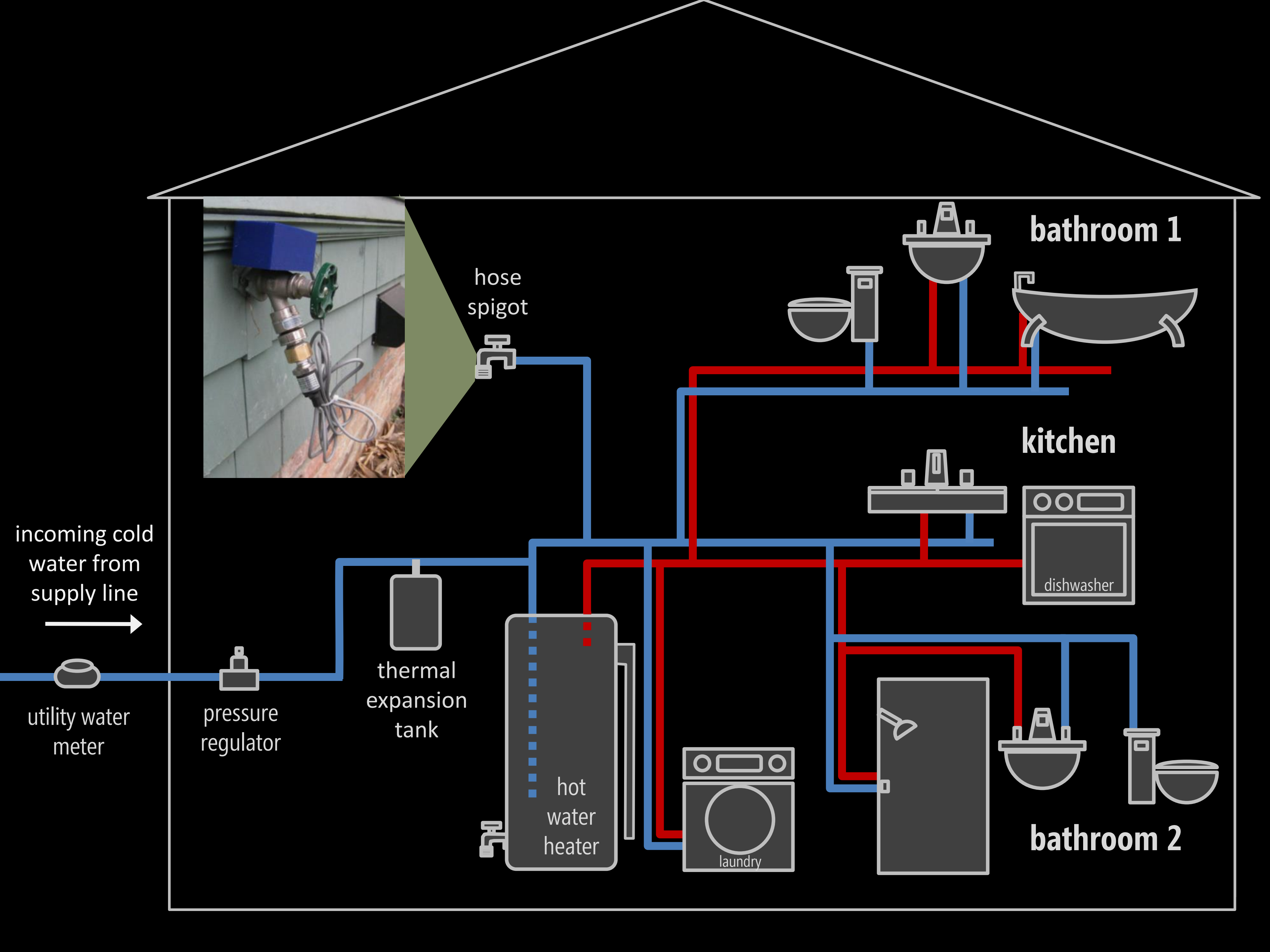
# **valve** mechanics: water tank dampening

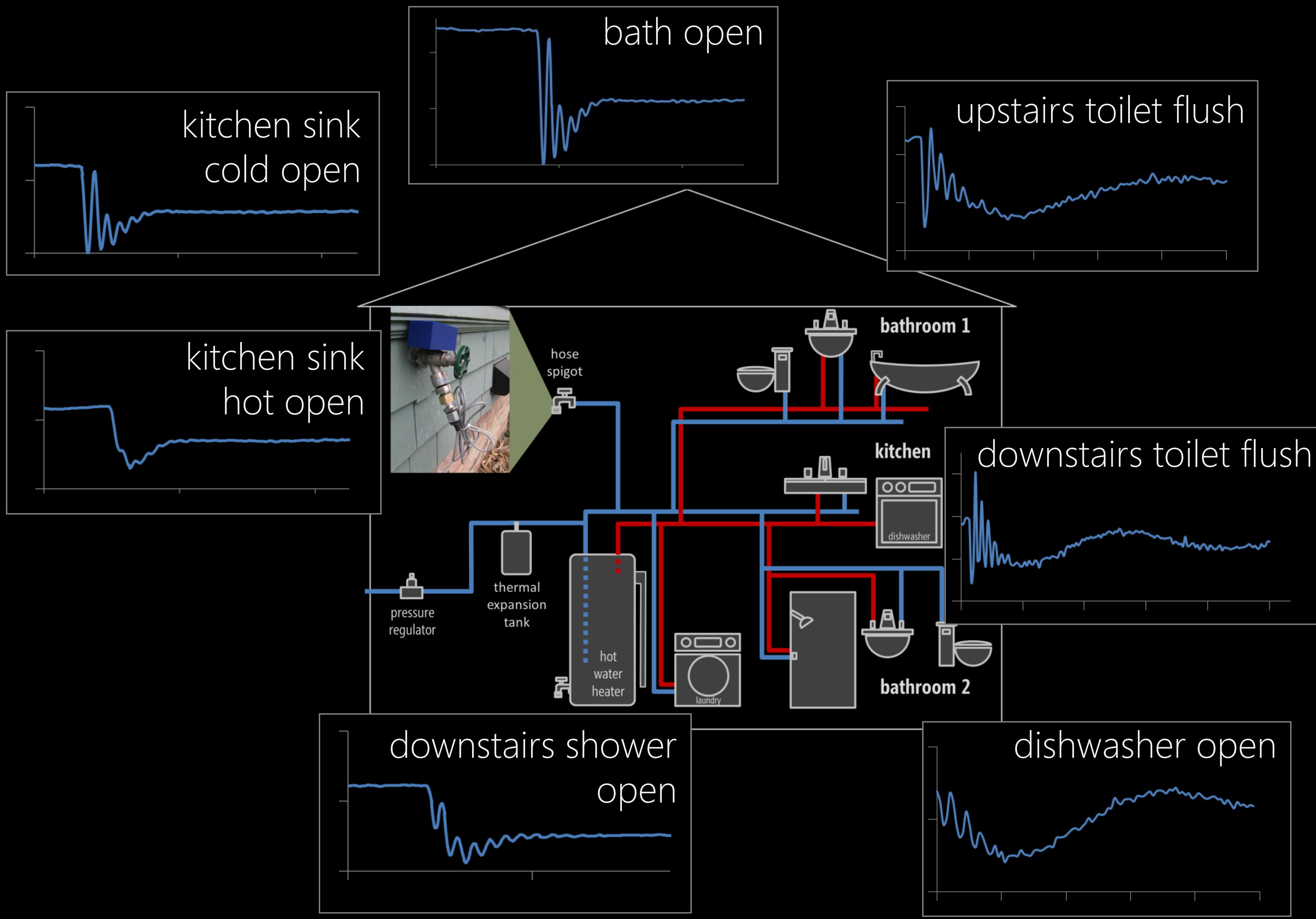


# **valve** mechanics: flow rate

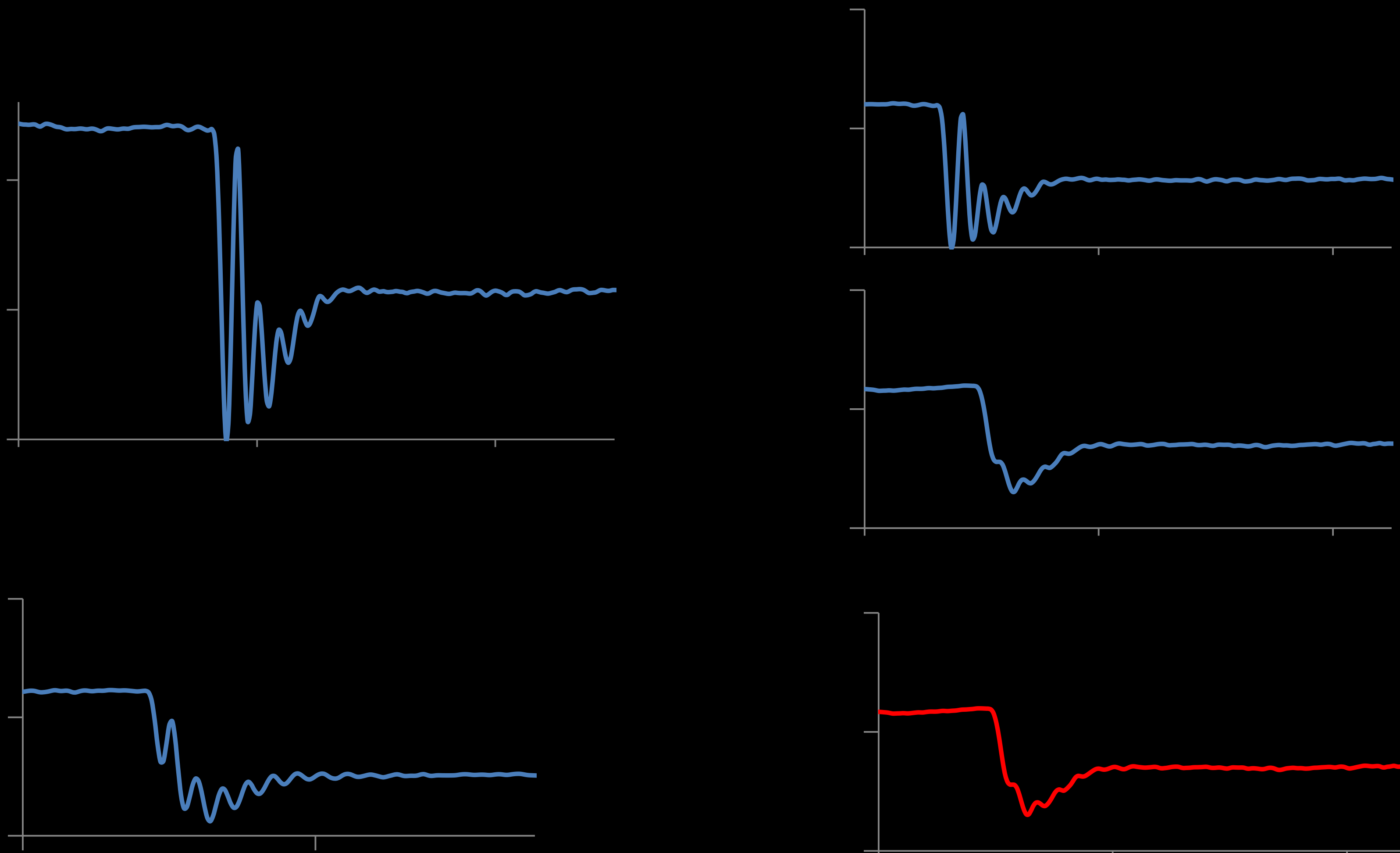


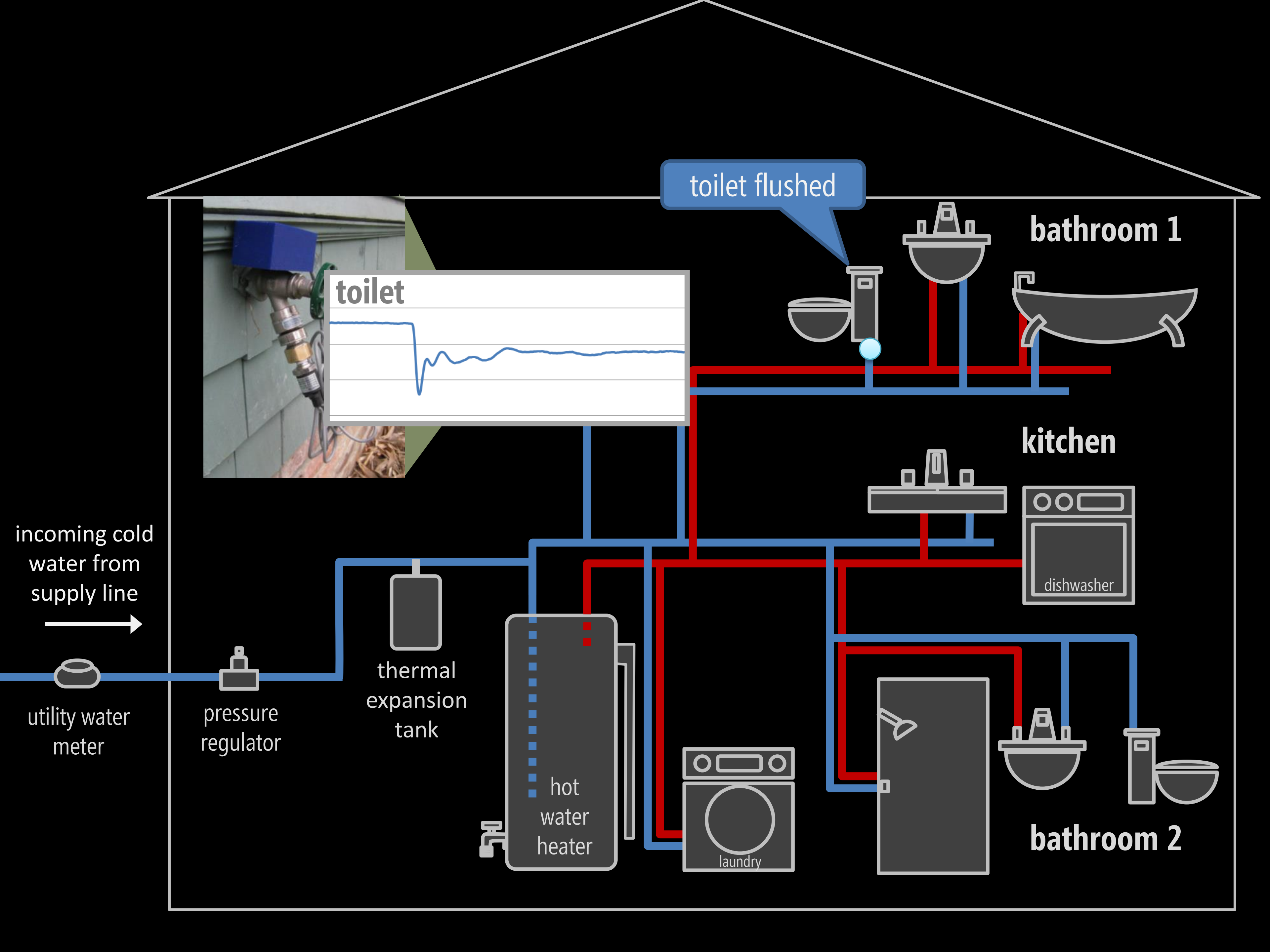

hose spigot
kitchen
dishwasher
incoming cold water from supply line
utility water meter
pressure regulator
thermal expansion tank
hot water heater
laundry
bathroom 2


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



kitchen sink cold open
bath open
upstairs toilet flush
kitchen sink hot open
hose spigot
bathroom 1
kitchen
dishwasher
downstairs toilet flush
thermal expansion tank
pressure regulator
hot water heater
laundry
bathroom 2
downstairs shower open
dishwasher open

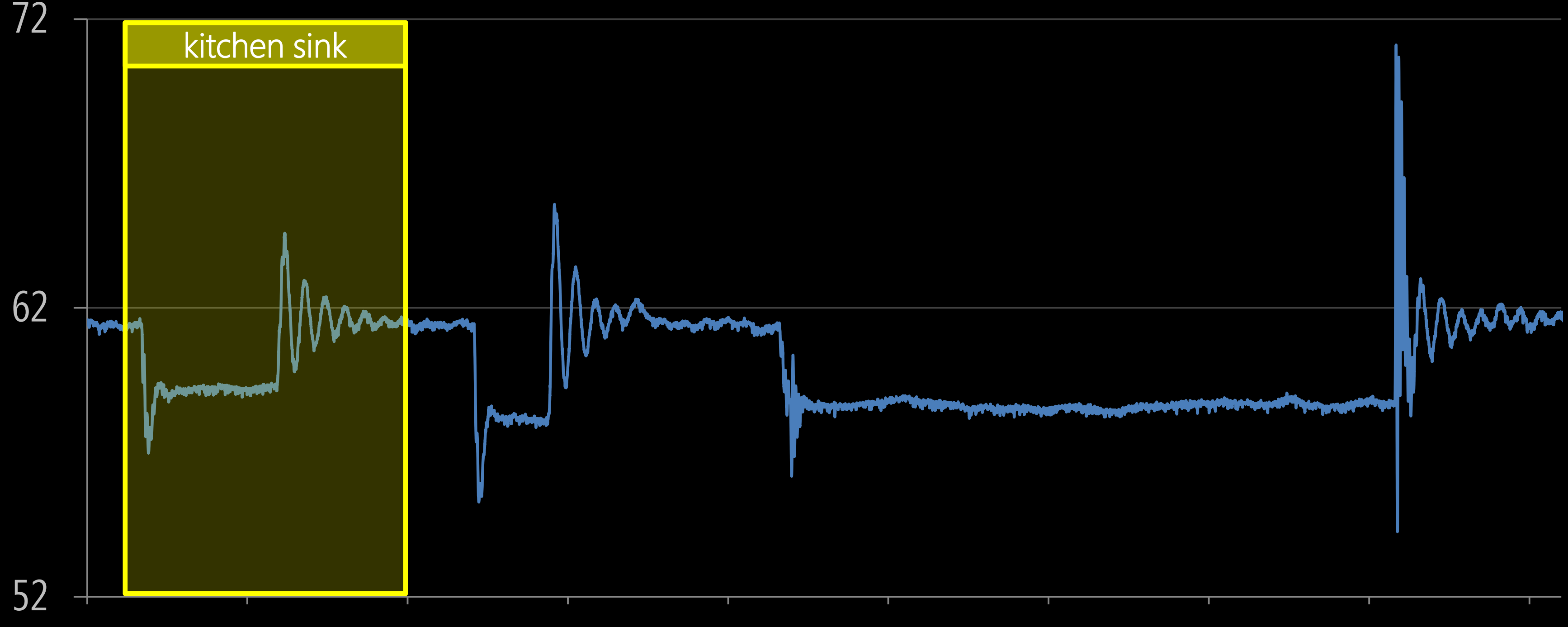




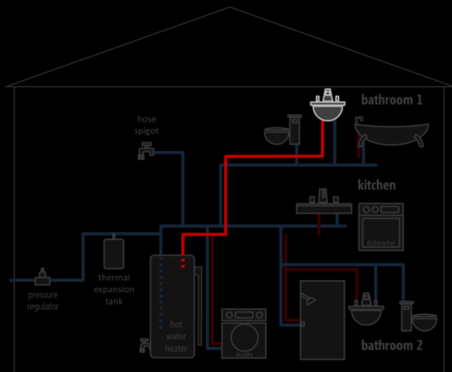
toilet flushed
bathroom 1
toilet
kitchen
incoming cold water from supply line
dishwasher
thermal expansion tank
utility water meter
pressure regulator
hot water heater
laundry
bathroom 2

# **ground truth** labels

for the ubicomp2009 study, we manually provided ground truth labels for the pressure stream during the experiment

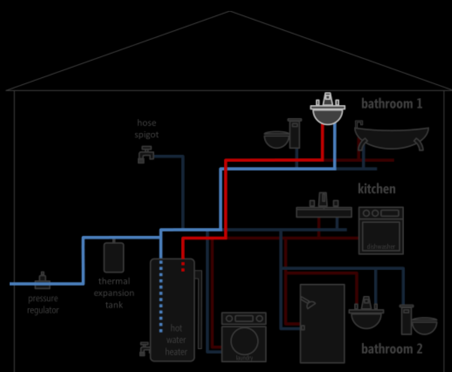


# three levels of granularity



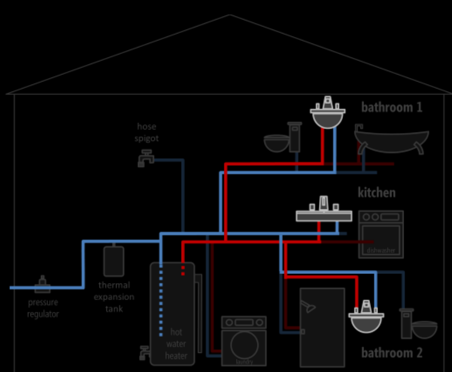

① **valve** level

e.g., upstairs bathroom faucet hot water activated




② **fixture** level

e.g., upstairs bathroom faucet activated




③ **fixture** category level

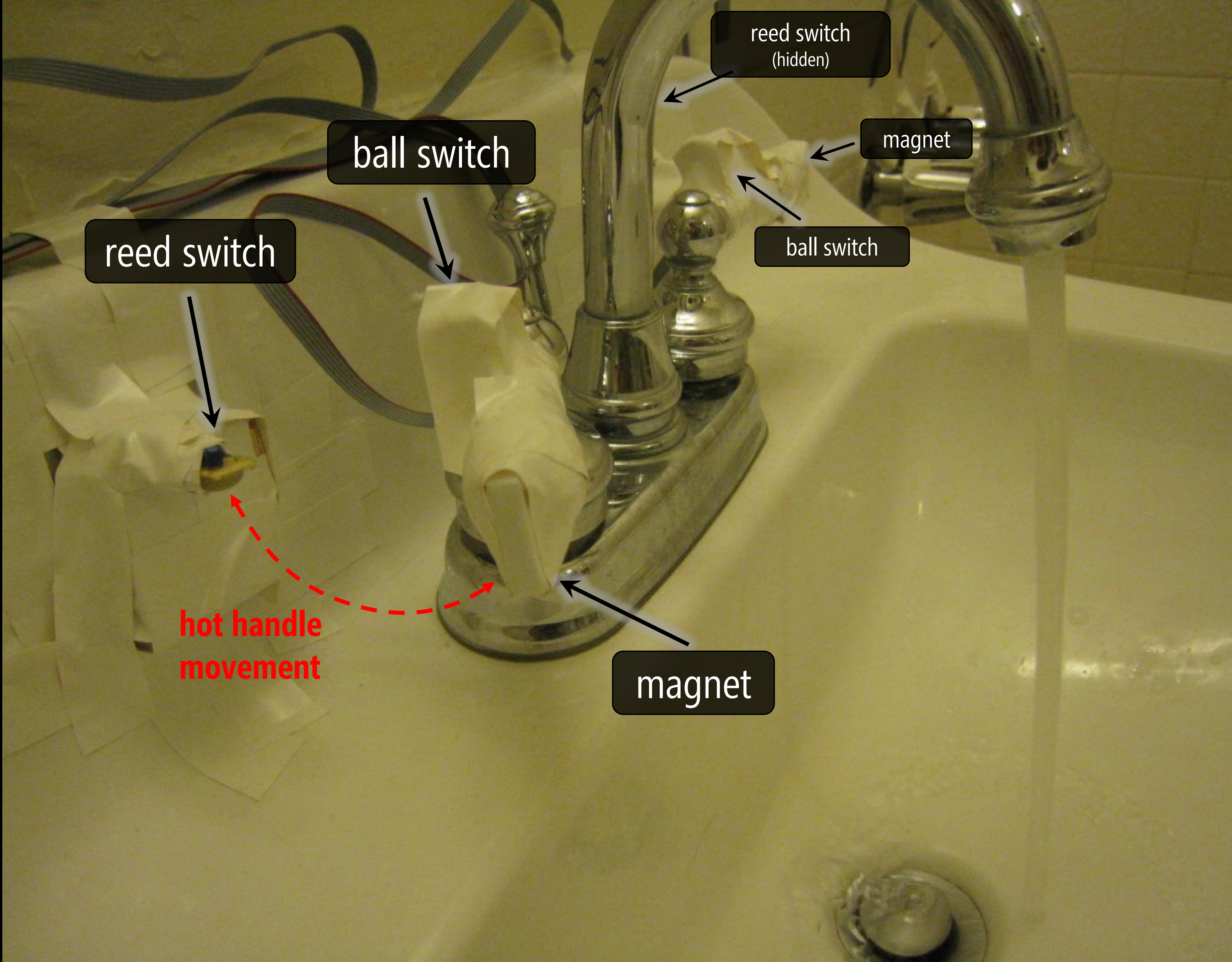
e.g., faucet activated


XBee


XBee


in the first study, pressure waves were **manually** annotated with "ground truth labels" describing:

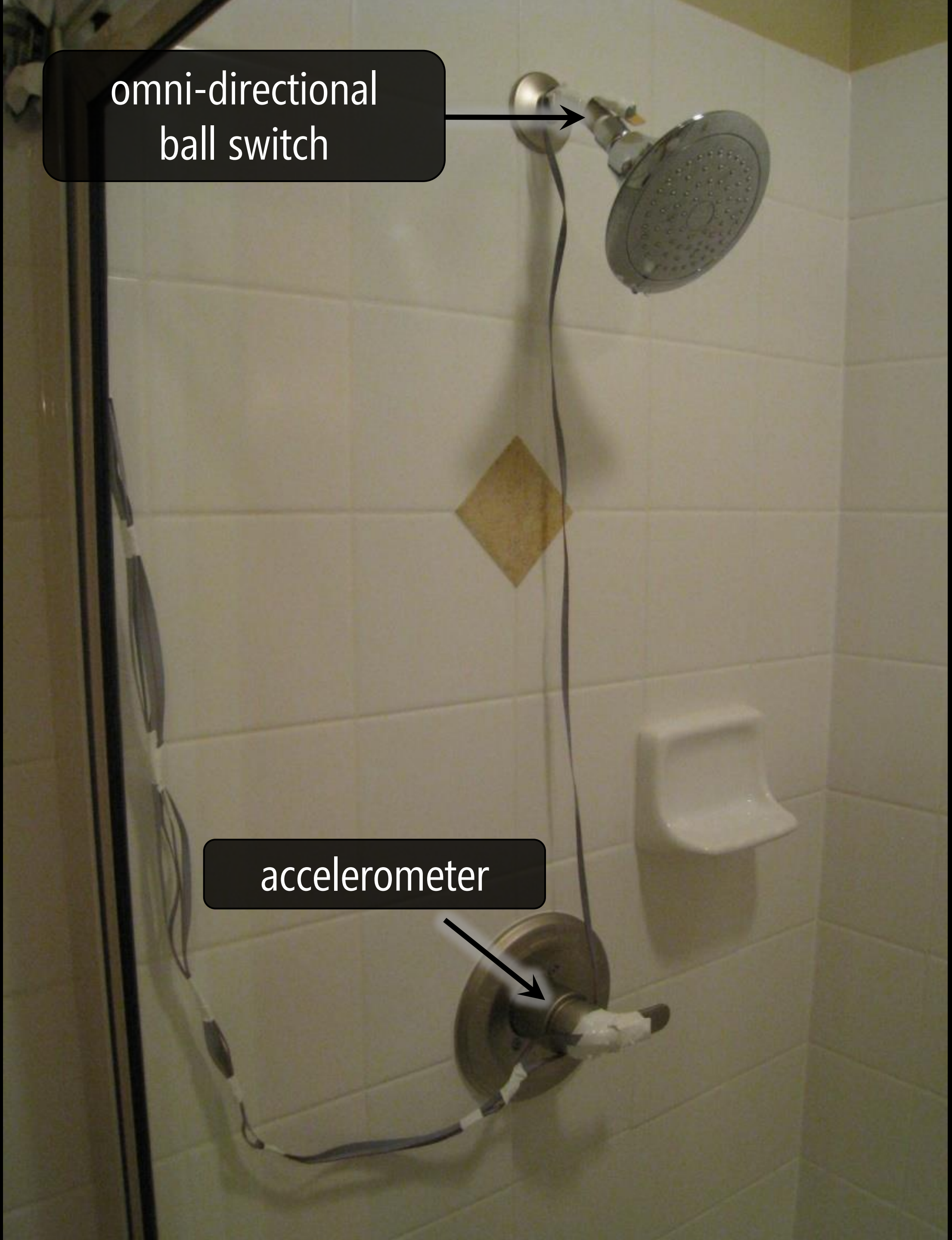
- the fixture used
- the water temperature

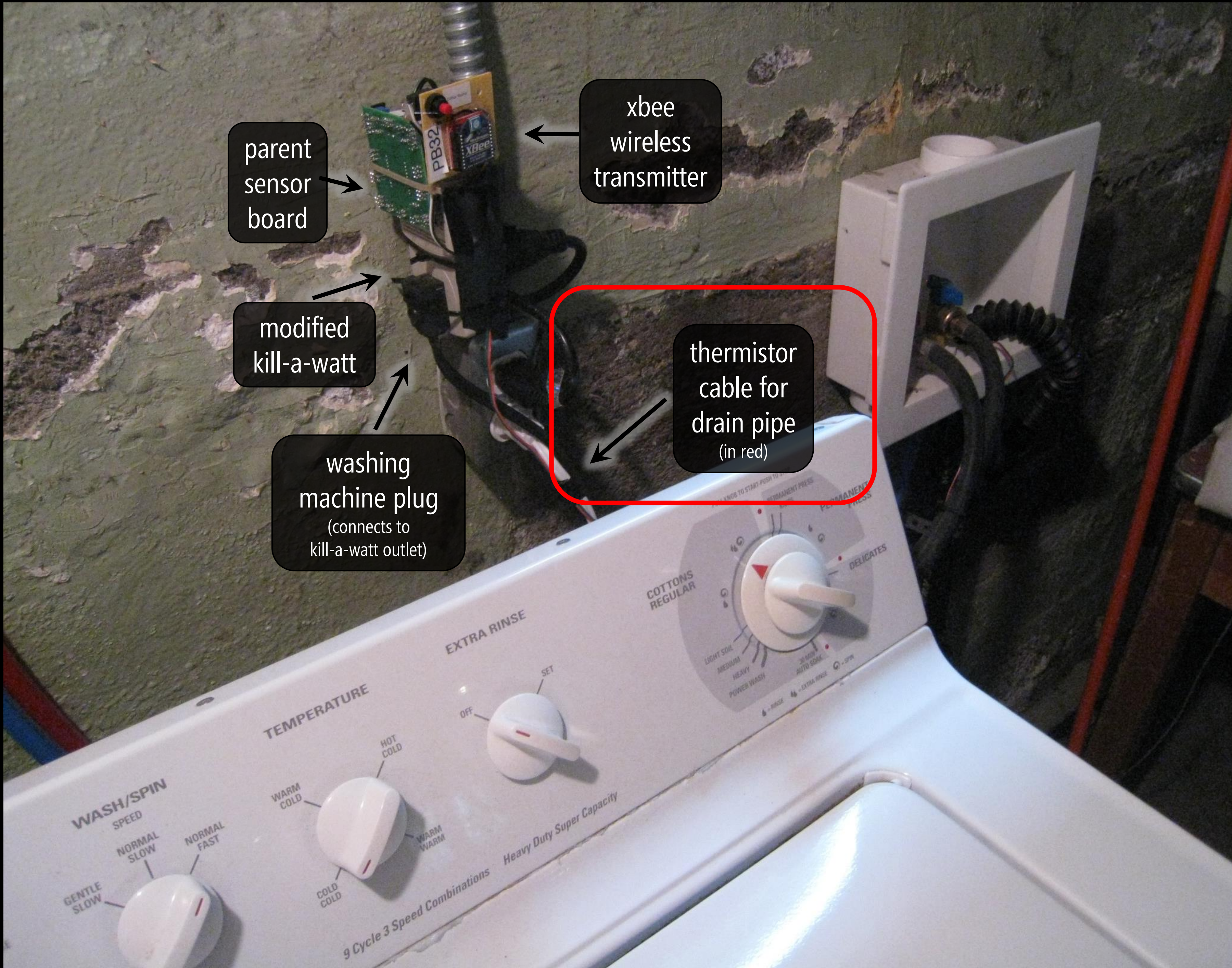

reed switch
(hidden)
magnet
ball switch
ball switch
reed switch
hot handle
movement
magnet

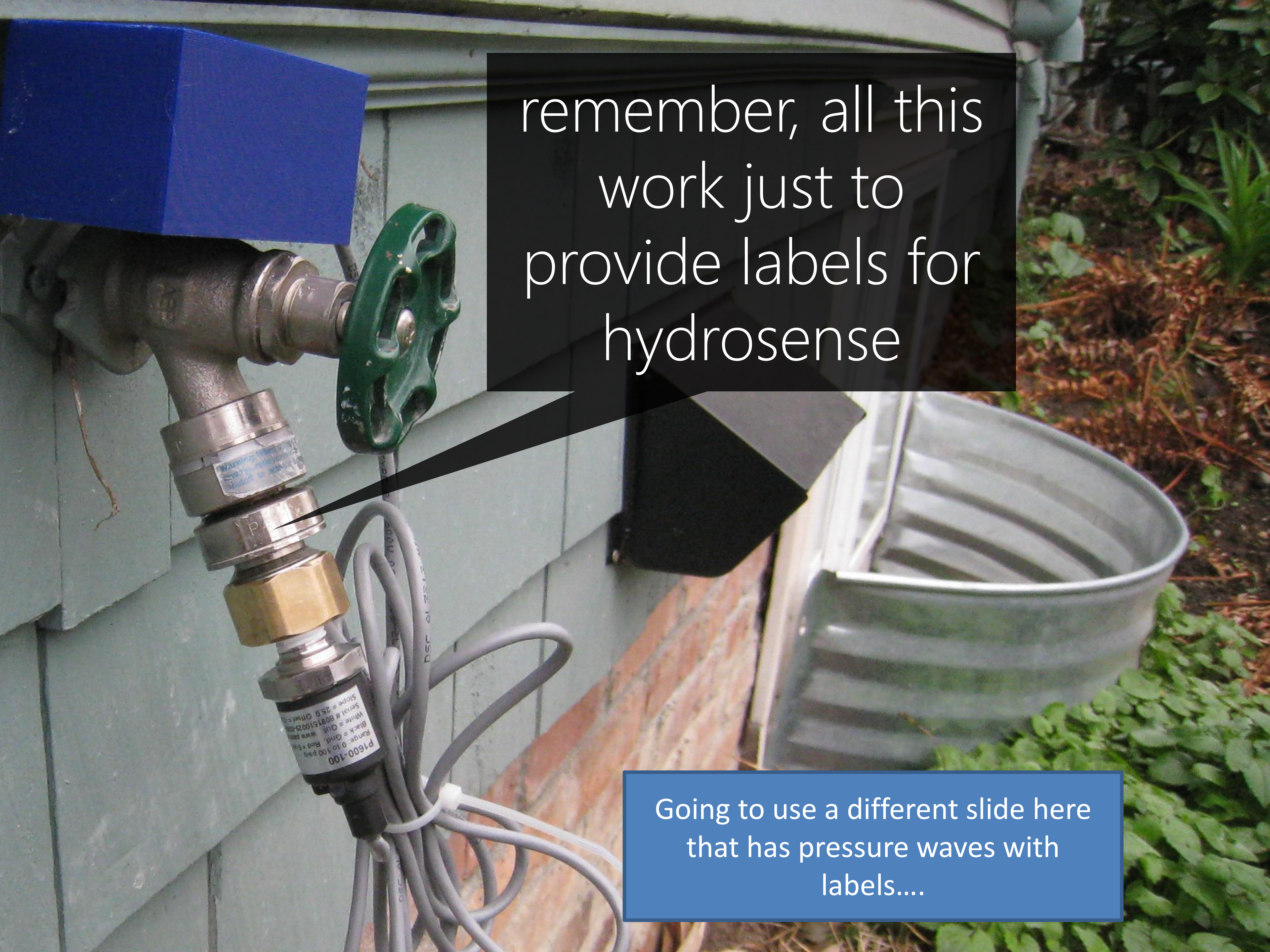

parent sensor board
accelerometer & ball switch


magnet & ball switch
reed switch (cold handle)
magnet & ball switch
reed switch (hot handle)


magnet
reed switch
omni-directional ball switch


omni-directional
ball switch
accelerometer

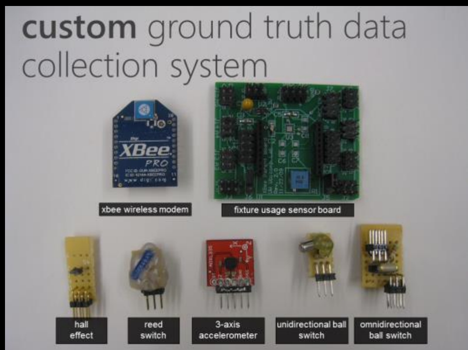

parent sensor board
xbee wireless transmitter
modified kill-a-watt
washing machine plug
(connects to kill-a-watt outlet)
thermistor cable for drain pipe
(in red)
WASH/SPIN
SPEED
GENTLE SLOW
NORMAL SLOW
NORMAL FAST
TEMPERATURE
WARM COLD
HOT COLD
WARM WARM
COLD COLD
EXTRA RINSE
OFF
SET
COTTONS REGULAR
PERMANENT PRESS
DELICATES
9 Cycle 3 Speed Combinations
Heavy Duty Super Capacity


remember, all this work just to provide labels for hydrosense
Going to use a different slide here that has pressure waves with labels….
P1600-100

# on-site sensing & logging

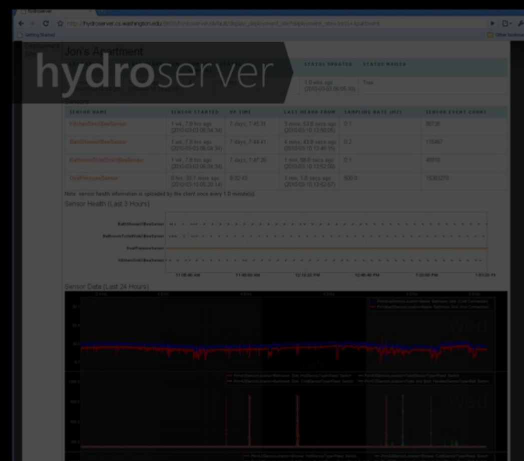
# web backend

# analysis tools & algorithms



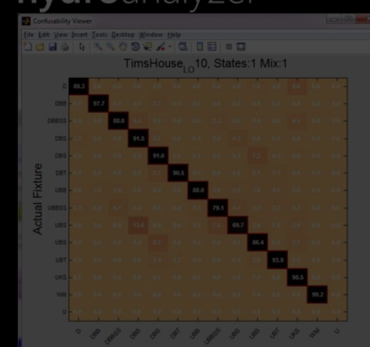

**two** pressure sensors

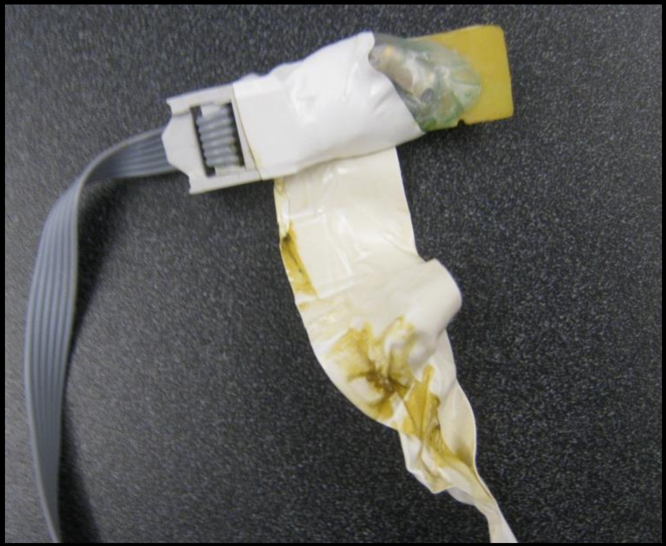


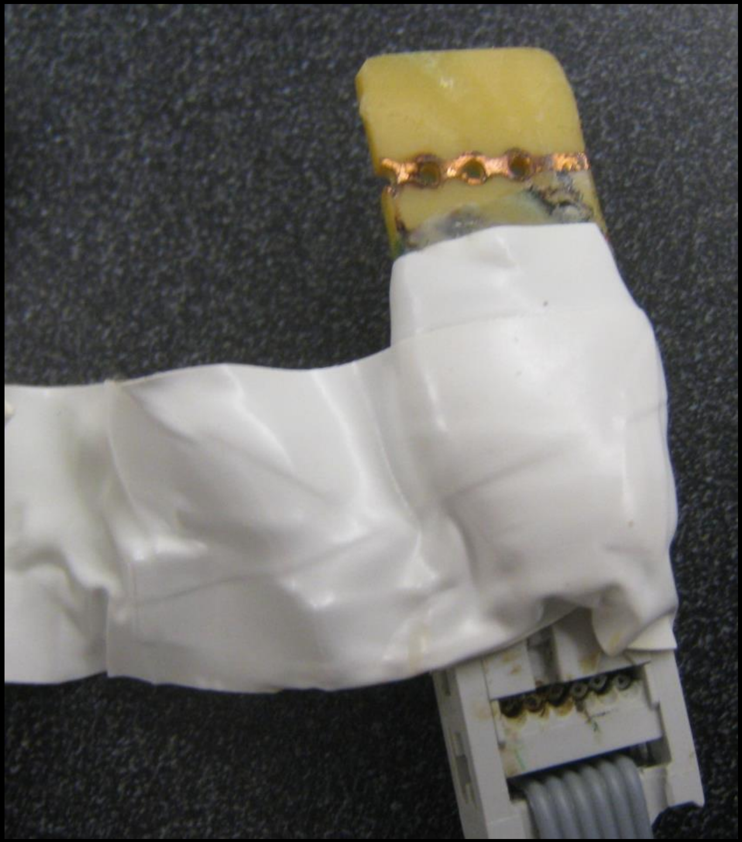


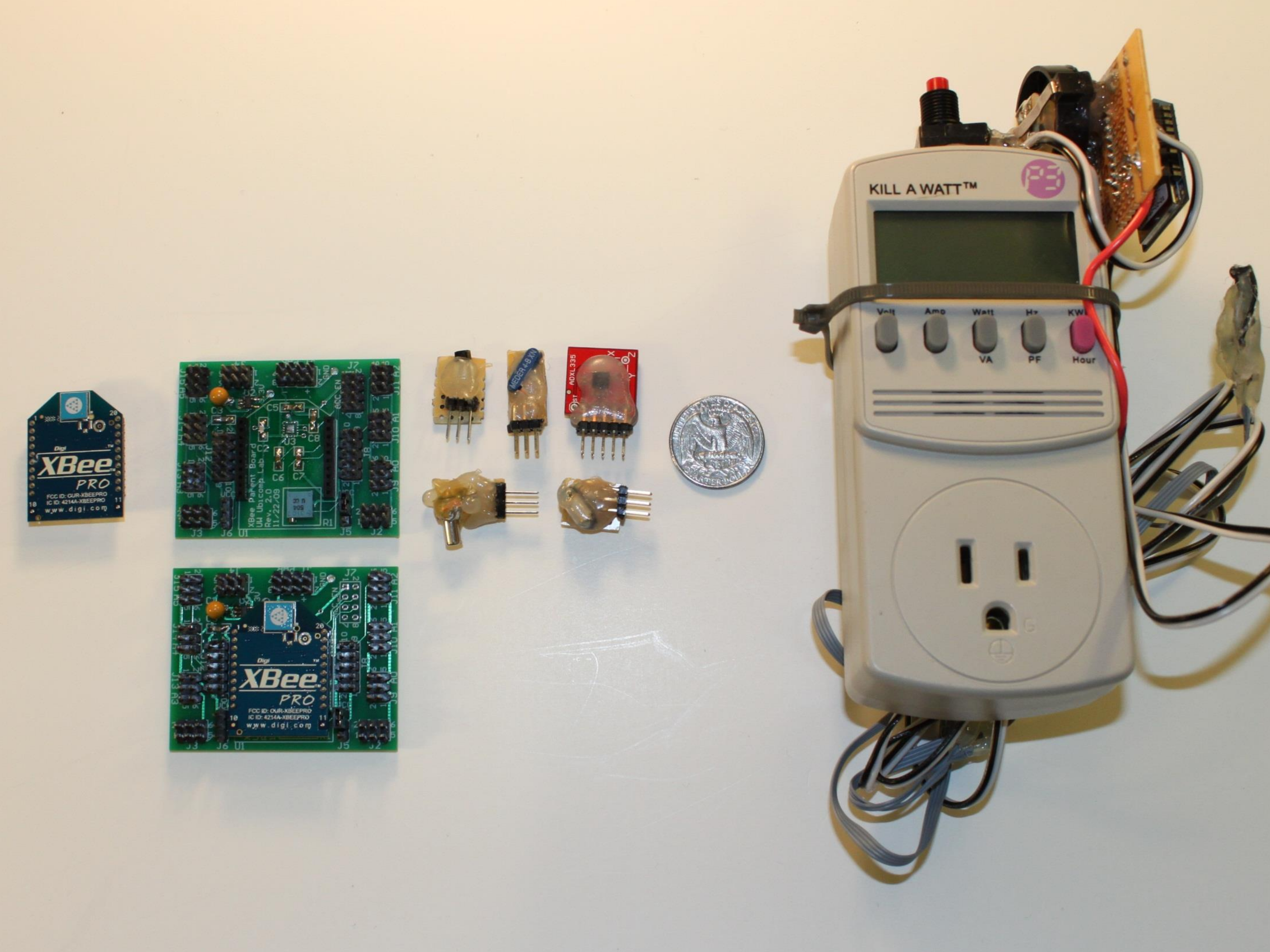

**hydro**visualizer

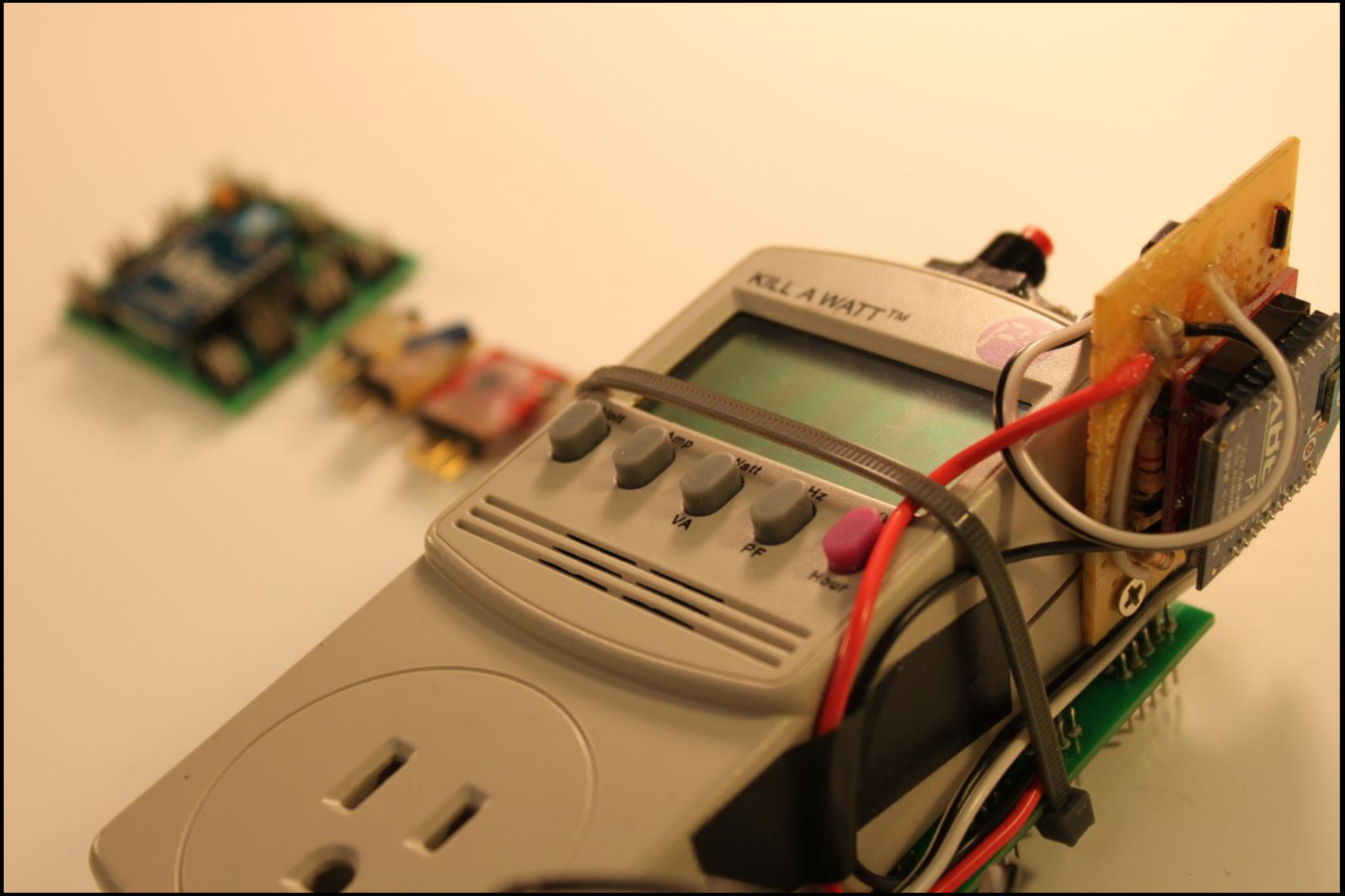
**hydro**analyzer

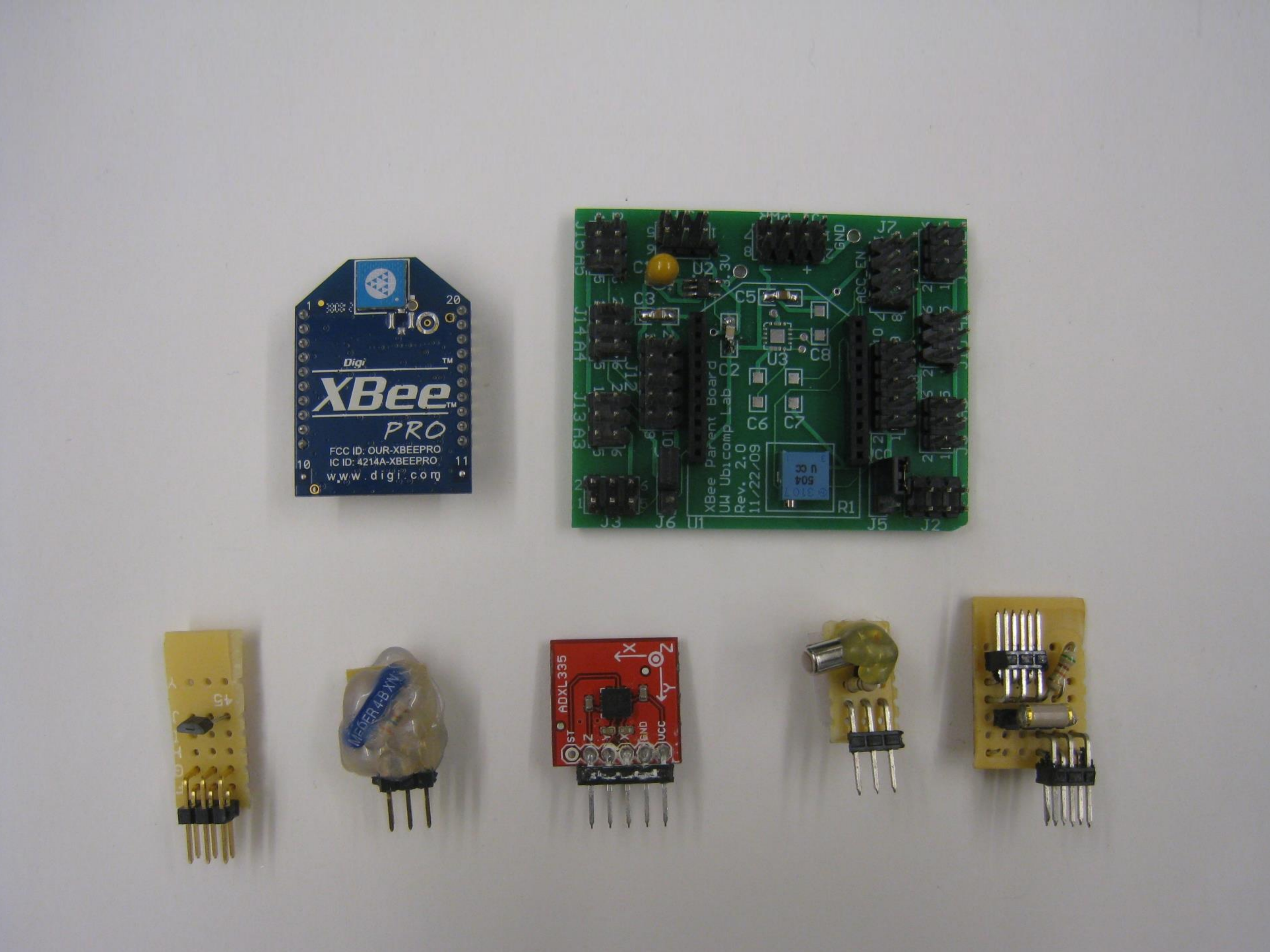




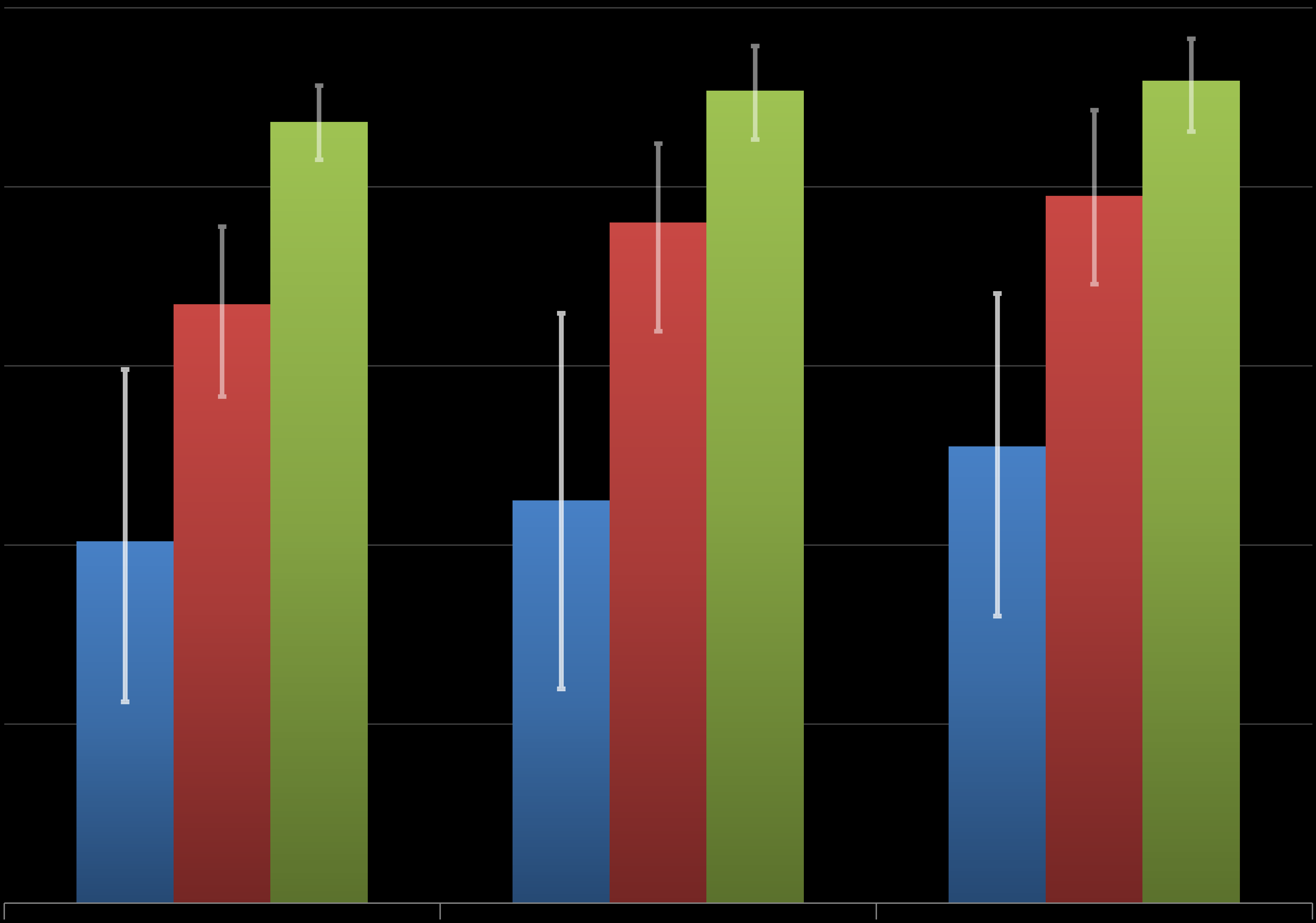



Digi
XBee
PRO
www.digi.com
KILL A WATT™
Volt
Amp
Watt
Hz
VA
PF
Hour
ADXL335
XBee PRO
www.digi.com

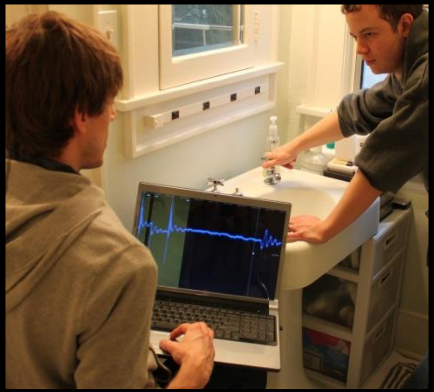

KILL A WATT™
Volt
Amp
Watt
VA
Hz
PF
Hour


Digi
XBee
PRO
FCC ID: OUR-XBEEPRO
IC ID: 4214A-XBEEPRO
www.digi.com
XBee Parent Board
UW Ubicomp Lab
Rev. 2.0
11/22/09
ADXL335

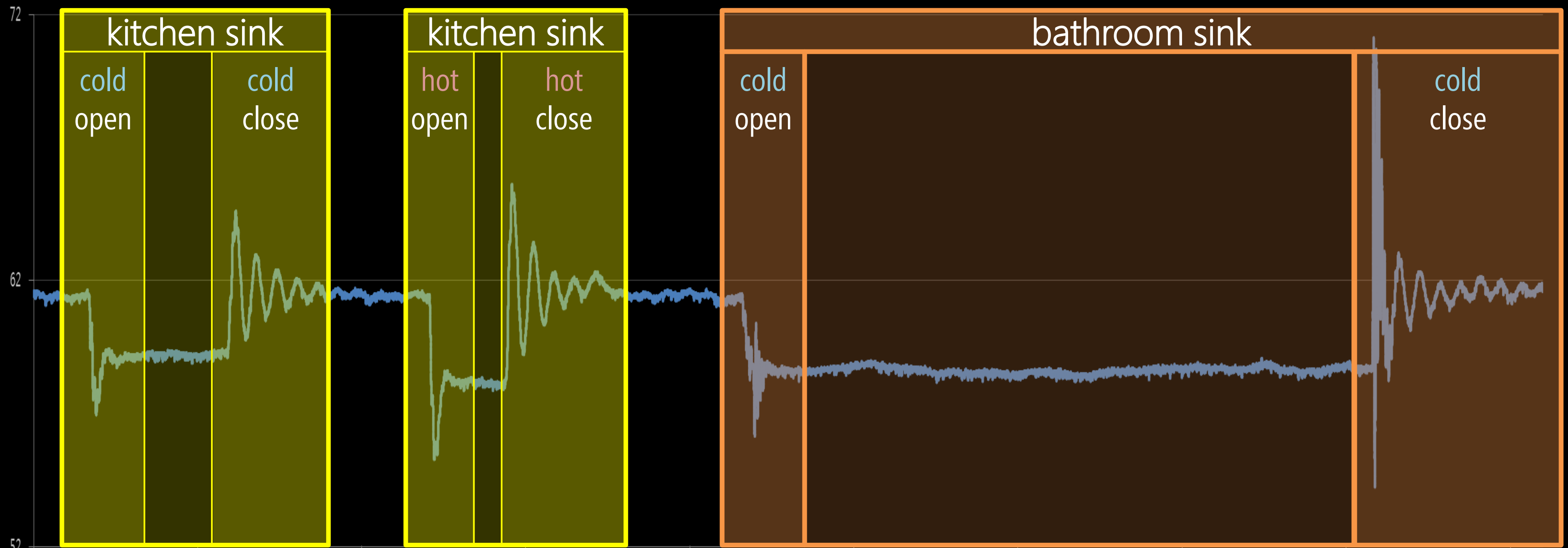

H
C



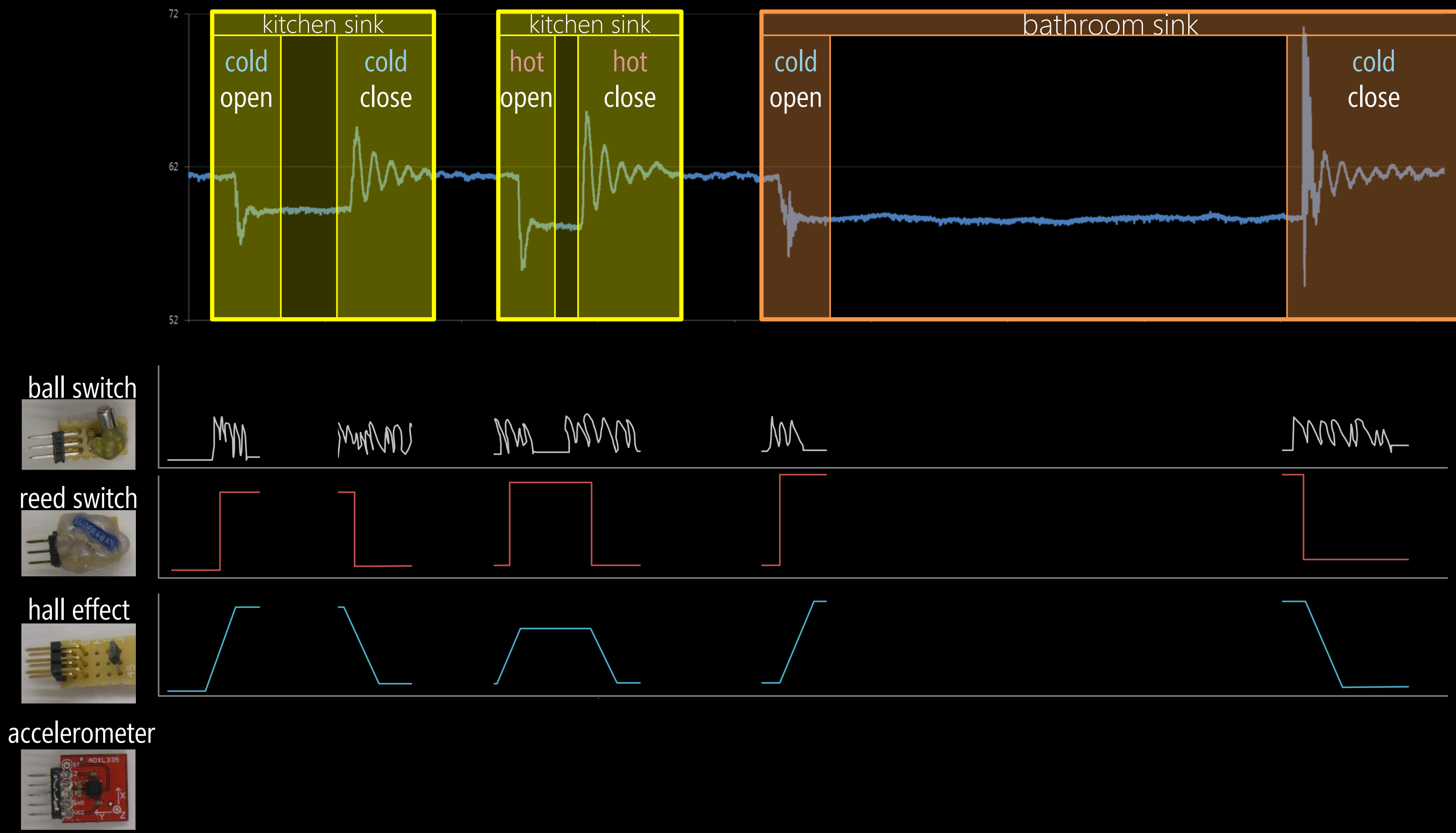
# **ground truth** labels



for the ubicomp2009 study, we manually provided ground truth labels for the pressure stream



# ground truth labels



# **automated** ground truth labeling method

**design** goals

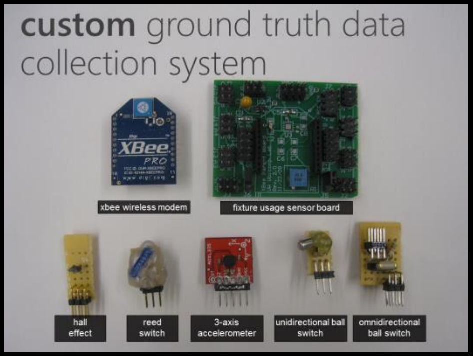
**hardware** capabilities

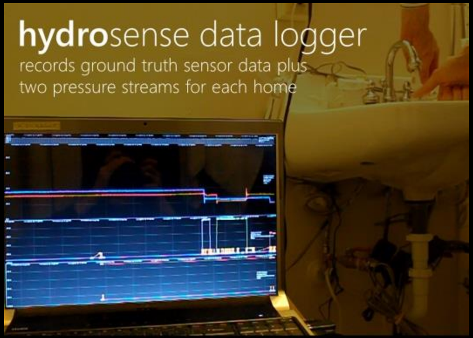
1. wireless communication
2. low-power
3. water resistant

**sensing** capabilities

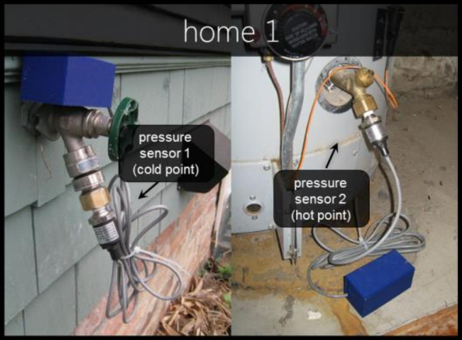
1. work across fixtures/appliances
2. detect opens/closes
3. discriminate hot/cold/mixed

# **hydro** deployment infrastructure

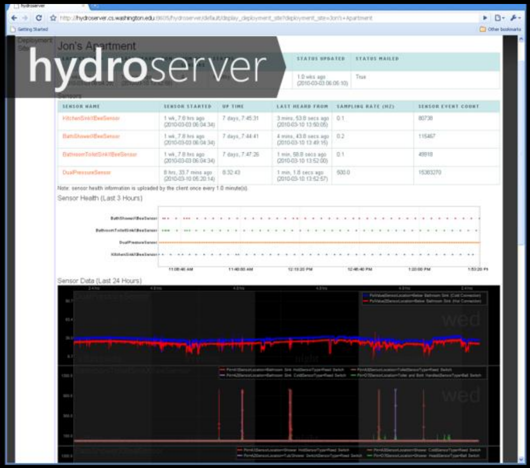



**two** pressure sensors

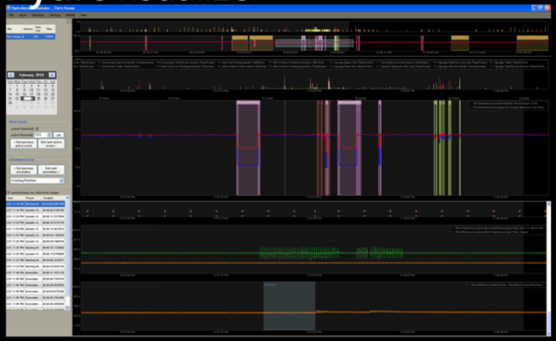



on-site sensing infrastructure

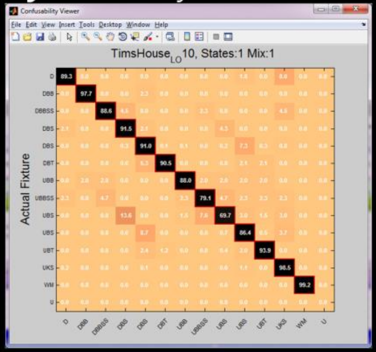



python web backend

**hydro**visualizer



**hydro**analyzer



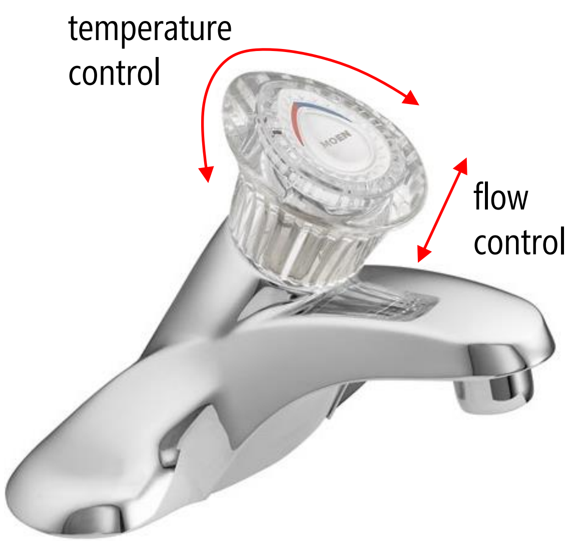

c# and matlab analysis tools


Lots of
tape

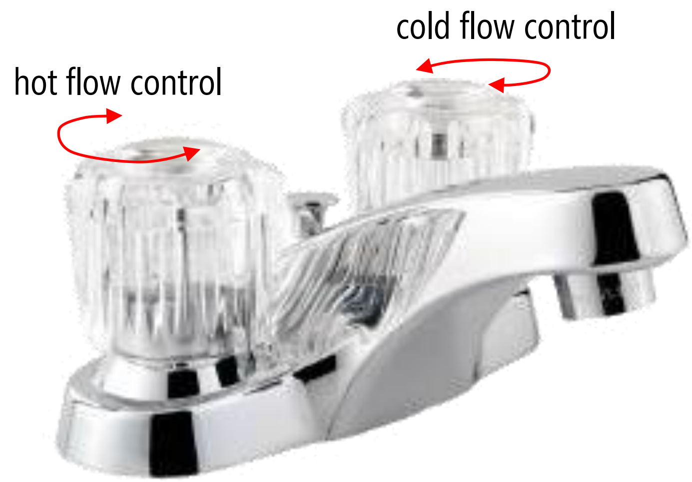
lots of tape
XBee
PRO
XBee
PRO
sparkfun.com
sparkfun.com
sparkfun.com
ADXL335
ADXL335

12
pcbs
14 ball
switches
9 reed
switches
8 acceler-
ometers
lots of
tape

# **challenge:** fixture diversity




single handle faucet




dual handle faucet