CYBER-PHYSICAL SYSTEMS:
IOT MEETS CLOUDS

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MESL
Microelectronic Embedded
Systems Laboratory

CPS: Societal Scale *Embedded* Systems

CPS

Transportation

Health

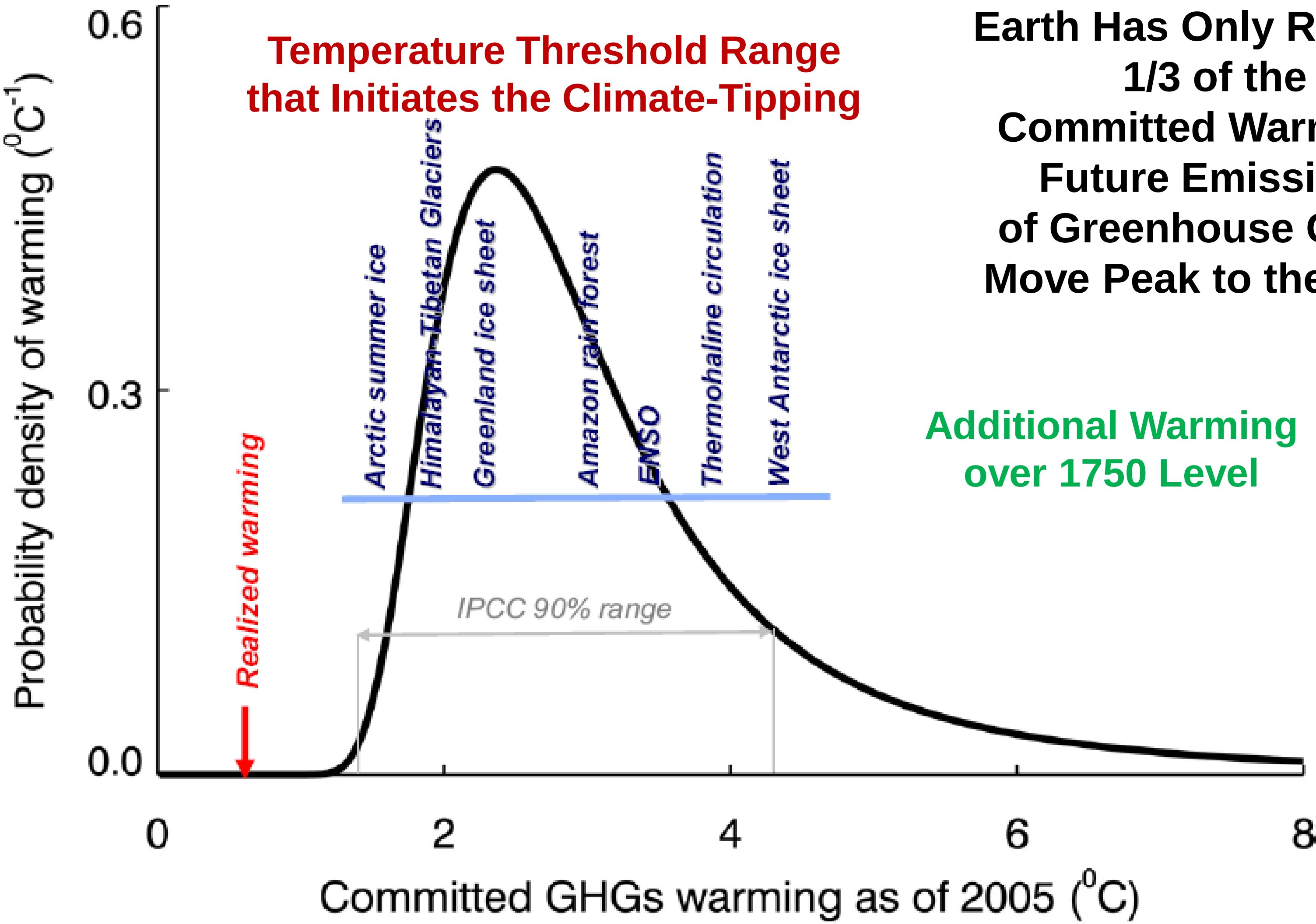
Smart Grid

Smart Home

The Story Of

A WEEKEND IN APRIL 2009

The Planet is Already Committed to a Dangerous Level of Warming



Earth Has Only Realized 1/3 of the Committed Warming - Future Emissions of Greenhouse Gases Move Peak to the Right

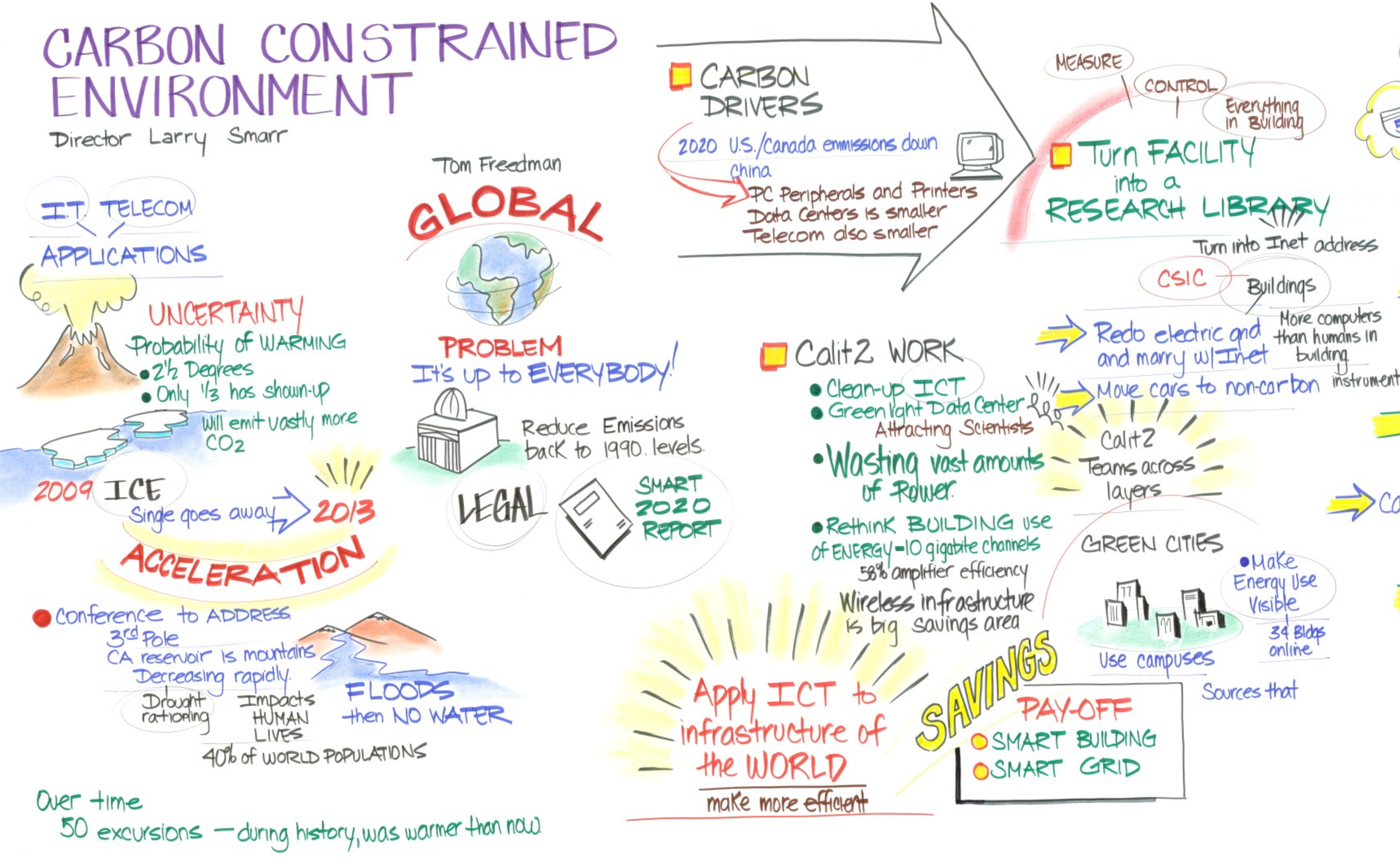
Additional Warming over 1750 Level

V. Ramanathan and Y. Feng, Scripps Institution of Oceanography, UCSD

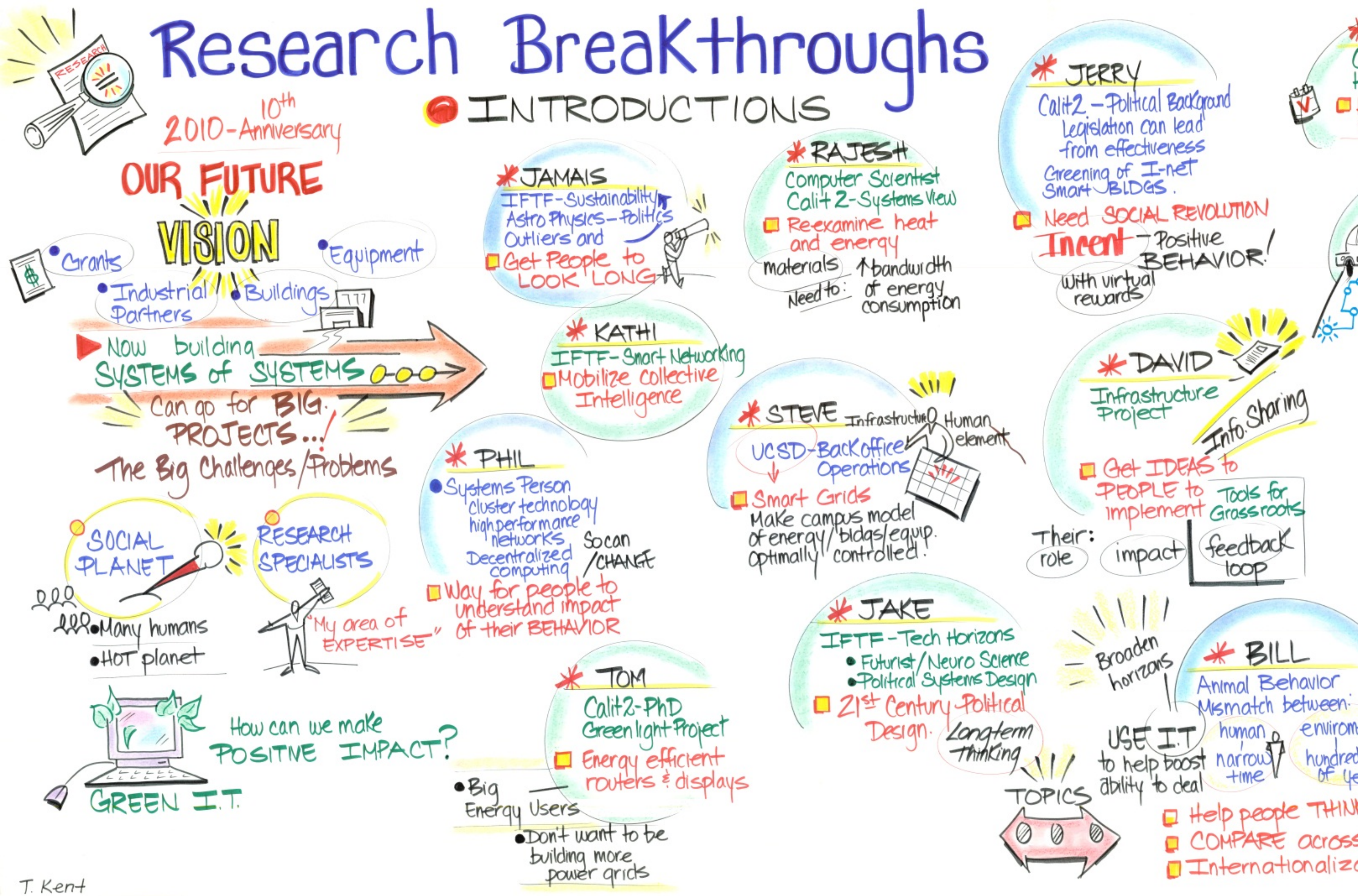
September 23, 2008
www.pnas.orgcgidoi10.1073pnas.0803838105

UCSD UCIrvine

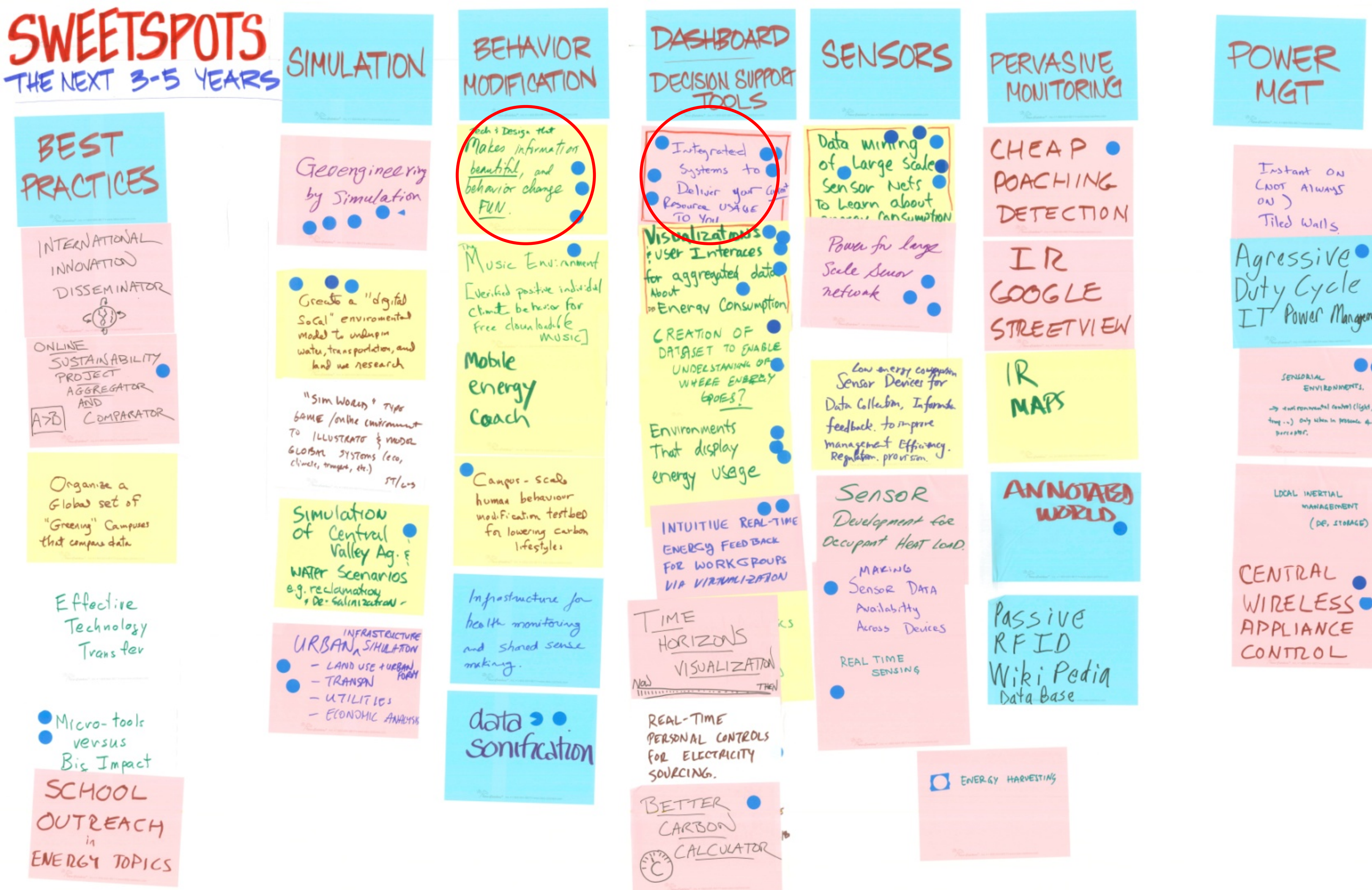
it2



Universities enable Learning & Living in Future



Listen carefully from a diverse group…


SWEETSPOTS
THE NEXT 3-5 YEARS
SIMULATION
BEHAVIOR MODIFICATION
DASHBOARD
DECISION SUPPORT TOOLS
SENSORS
PERVASIVE MONITORING
POWER MGT
BEST PRACTICES
INTERNATIONAL INNOVATION DISSEMINATOR
ONLINE SUSTAINABILITY PROJECT AGGREGATOR AND COMPARATOR
A>B
Organize a Global set of "Greening" Campuses that compare data
Effective Technology Transfer
Micro-tools versus Big Impact
SCHOOL OUTREACH in ENERGY TOPICS
Geoengineering by Simulation
Create a "digital social" environmental model to underpin water, transportation, and land use research
"Sim World" type GAME / online environment To ILLUSTRATE & MODEL GLOBAL SYSTEMS (eco, climate, transport, etc.)
Simulation of Central Valley Ag. & WATER Scenarios e.g. reclamation & De-salinization
URBAN INFRASTRUCTURE SIMULATION
– LAND USE + URBAN FORM
– TRANSPN
– UTILITIES
– ECONOMIC ANALYSIS
Tech & Design that Makes information beautiful, and behavior change FUN.
Music Environment
[Verified positive individual climate behavior for free downloadable music]
Mobile energy Coach
Campus-scale human behaviour modification testbed for lowering carbon lifestyles
Infrastructure for health monitoring and shared sense making.
data sonification
Integrated Systems to Deliver your Resource USAGE TO YOU
Visualizations & User Interfaces for aggregated data About Energy Consumption
CREATION OF DATASET TO ENABLE UNDERSTANDING OF WHERE ENERGY GOES?
Environments That display energy usage
INTUITIVE REAL-TIME ENERGY FEEDBACK FOR WORKGROUPS VIA VIRTUALIZATION
TIME HORIZONS VISUALIZATION
NOW
THEN
REAL-TIME PERSONAL CONTROLS FOR ELECTRICITY SOURCING.
BETTER CARBON CALCULATOR
Data mining of Large Scale Sensor Nets To Learn about energy consumption
Power for large Scale Sensor network
Low energy computation Sensor Devices for Data Collection, Information feedback to improve management Efficiency. Regulation provision.
SENSOR Development for Occupant Heat Load.
MAKING SENSOR DATA Availability Across Devices
REAL TIME SENSING
ENERGY HARVESTING
CHEAP POACHING DETECTION
IR GOOGLE STREETVIEW
IR MAPS
ANNOTATED WORLD
Passive RFID
WikiPedia Data Base
Instant ON (NOT ALWAYS ON)
Tiled Walls
Agressive Duty Cycle IT Power Management
SENSORIAL ENVIRONMENTS.
LOCAL INERTIAL MANAGEMENT (OR. STORAGE)
CENTRAL WIRELESS APPLIANCE CONTROL

Making Buildings Energy Efficient

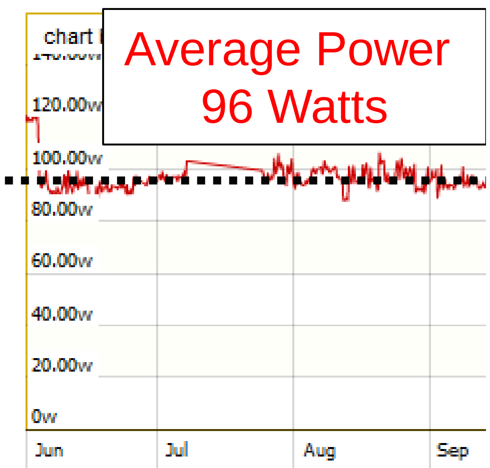
Increasing bandwidth of use, decreasing granularity of response.

1. Reduce energy consumption by IT equipment
   - Servers and PCs left on to maintain network presence
   - Key: "Duty-Cycle" computers aggressively maintaining availability
   - *Somniloquy [NSDI '09]* and *SleepServer [USENIX '10]*
2. Reduce energy consumption by the HVAC system
   - Energy use is not proportional to number of occupants
   - Key: Use real-time occupancy to drive HVAC at fine spatial scales
   - *Synergy occupancy* node *[BuildSys '10], HVAC Control [IPSN '11]*
3. Reduce energy consumption by Plug-Loads
   - "Dark-loads" distributed over a building, diverse types
   - Key Idea: Measure and actuate based on "policies" at fine temporal scales *[BuildSys'11].*

UC San Diego | Energy Dashboard

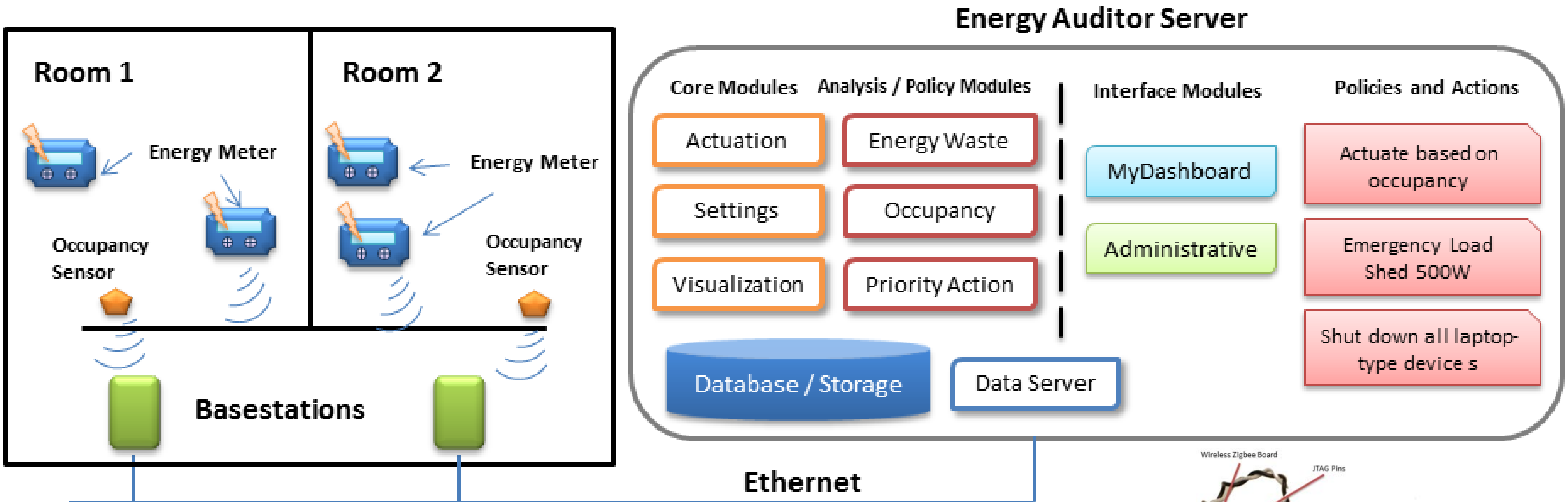
1. IT

SleepServers: Enable Aggressive Duty Cycling



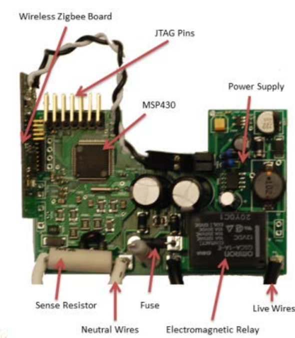
68% energy savings since *SleepServer* deployment

ent:
5 buildings
1M sq. feet
50% PC penetration
Target: 40% savings
$800K off $2M



2. HVAC

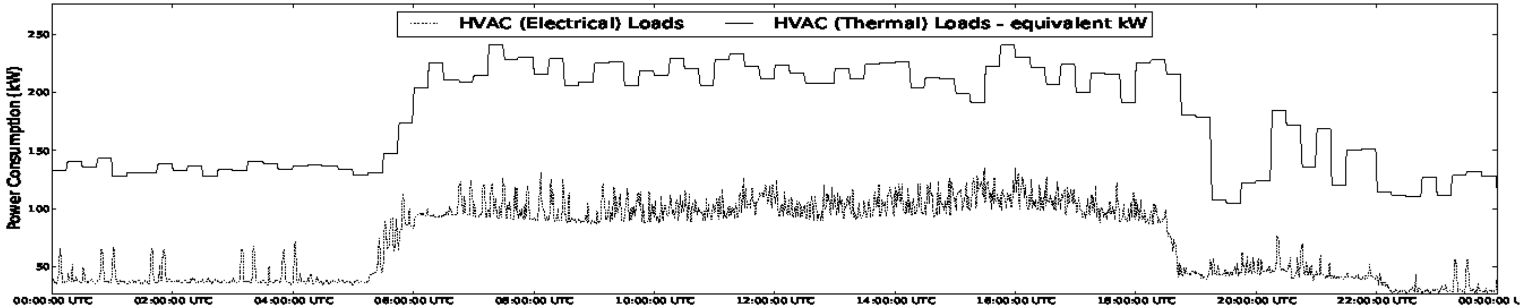
Occupancy-driven HVAC



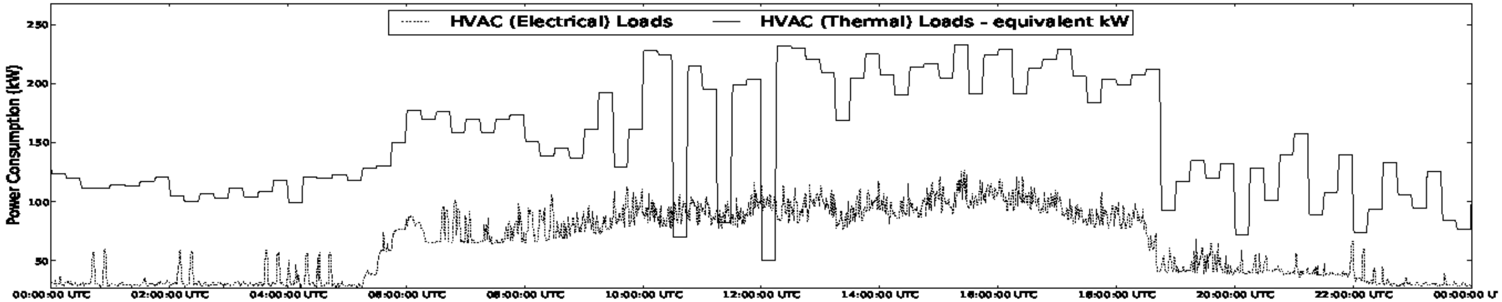
(a) (b) (c) (d)

Figure 4. Picture of our energy meter (a, b) along with our SheevaPlug base station (c) that is deployed in the hallways. The CC2530 based wireless module that are in both the base station and the energy meters is also shown (d).

2. HVAC Energy Savings



HVAC Energy Consumption (Electrical and Thermal) during the baseline day.



HVAC Energy Consumption (Electrical and Thermal) for a test day with a similar weather profile. HVAC energy savings are significant: over 13% (HVAC-Electrical) and 15.6% (HVAC-Thermal) for just the 2nd floor

Estimated 40% savings across entire building. Detailed occupancy can be used to drive other systems.

Demand Response

3. Plug Loads

- 54 HVAC zones including 1 kW corridor each floor
  - 15-20 kW per floor, 260-358 W per zone
  - DREM for plug loads with device type and priority levels
  - Actuation classes: Off (PL 1), Occ_low (PL 2), Occ_hi (PL 3), On (PL 10).

	Subsystem Type	DR Priority-1 (P1)	DR Priority-2 (P2)
		Plug Load Devices	
1	Class: `always-off` Space heater, fans Laptops, Chargers	Occ: Load=OFF | NotOcc: Load=OFF Inconvenience=1pt/10min Savings -> Device Load(Occ) Savings -> Device Load(NotOcc)	Occ: Load=OFF | NotOcc: Load=OFF Inconvenience=1pt/10min Savings -> Device Load(Occ) Savings -> Device Load(NotOcc)
2	Class: `Occupancy-Based-Low` PC Speakers, Room Printers	Occ: Load=ON | NotOcc: Load=OFF Inconvenience=0pt Savings -> Device Load(Occ) Savings -> No Savings (NotOcc)	Occ: Load=OFF | NotOcc: Load=OFF Inconvenie[illegible]pt/10min Savings [illegible]e Load Savin[illegible]oad (NotOcc)
3	Class: `Occupancy-Based-High` Lamps	Occ: Load=ON | NotOcc: Load=OFF Inconvenience=0pt Savings -> No Savings (Occ) Savings -> Device Load (NotOcc)	Occ[illegible] NotOcc: Load=OFF [illegible]onvenience=0pt [illegible]ngs -> No Savings (Occ) [illegible]ings -> Device Load (NotOcc)
		[illegible]esktop Computers and [illegible]ns	
4	[illegible]	[illegible]ctive | NotOcc: Sleep if CPU < [illegible] Inconvenience=0pt Savings -> No Savings(Occ) Savings -> Desktop + LCD (NotOcc)	Occ: Sleep if no input for 5mins | NotOcc: Sleep Inconvenience=1pt Savings -> Desktop+LCD if allowed to sleep(Occ) Savings -> Desktop+LCD (NotOcc)
		Heating Ventilation and Air Conditioning (HVAC) System	
5		Occ: ON | NotOcc(all rooms in zone): OFF Inconvenience=1pt/room, 3pt/shared zone* Savings -> 260W-358W per zone shutdown	Occ: ON | NotOcc(at least 1 room in zone): OFF Inconvenience=2pt/10min room, 6pt/10min shared Savings -> 260W-358W per zone shutdown

Building OS?

OpenBuildings

30 Room Deployment

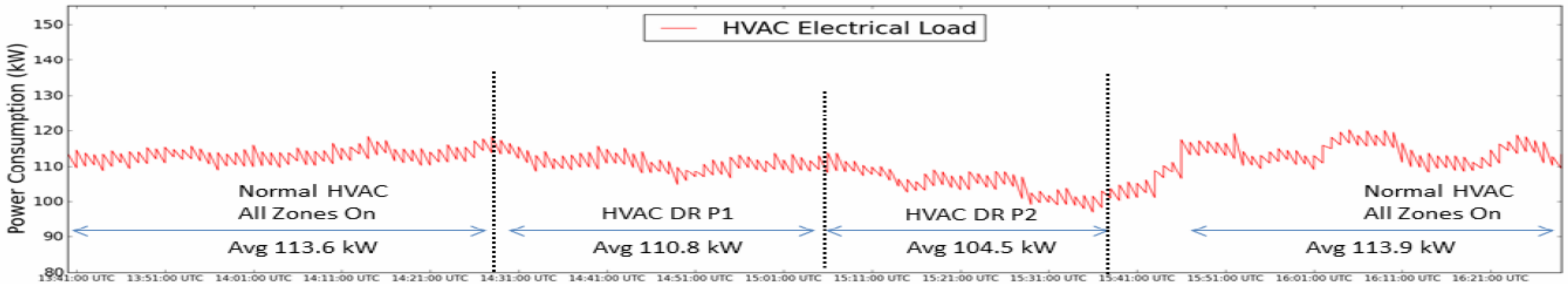


Figure 8: The energy consumption of our HVAC experiment. Occupancy information is gotten prior to DR P1, and held constant for the duration of the DR event.

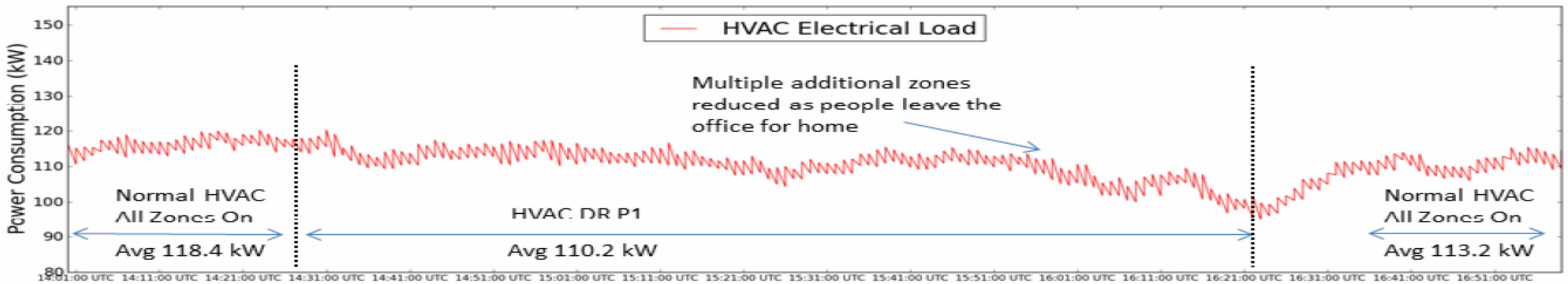
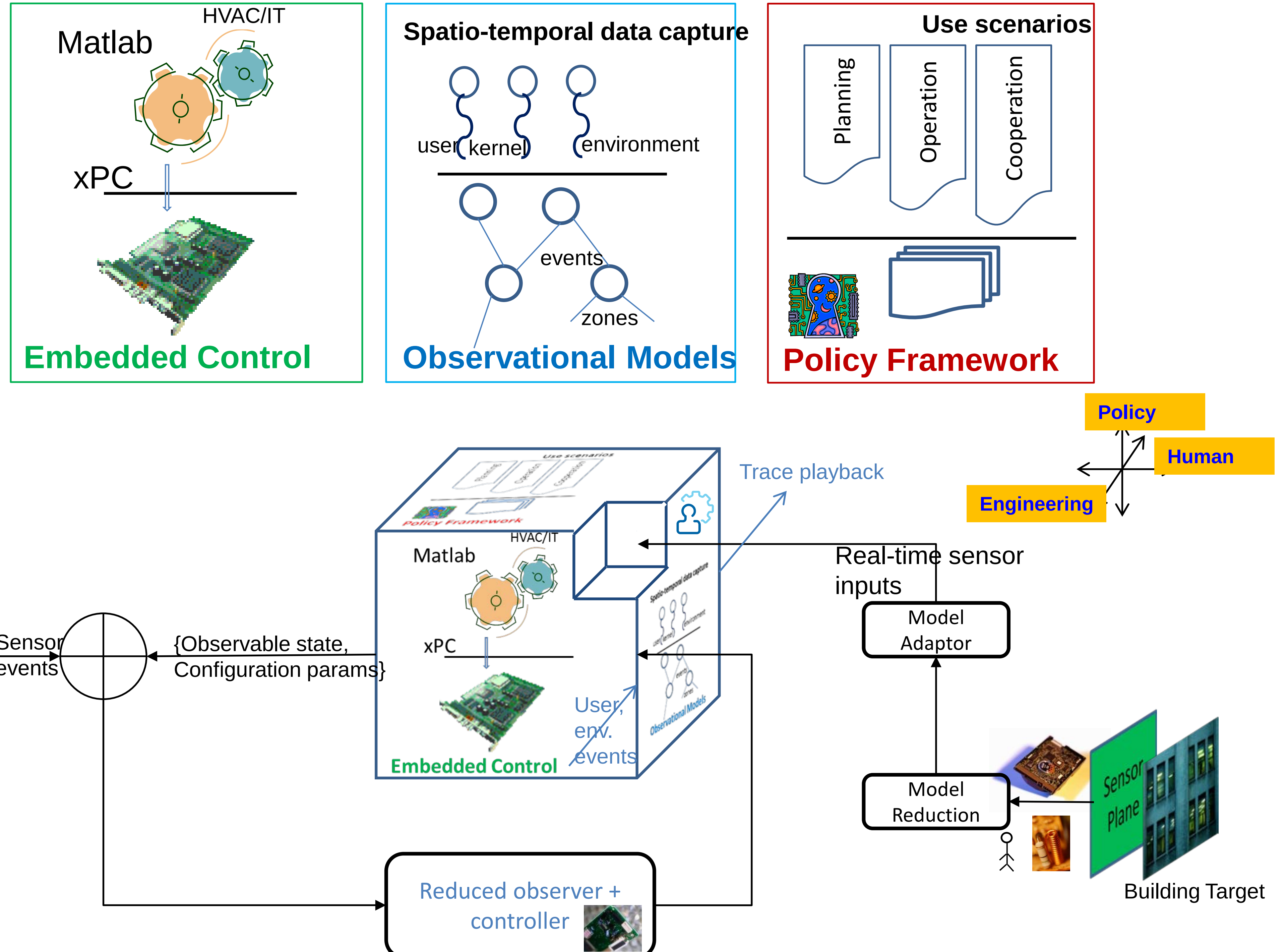


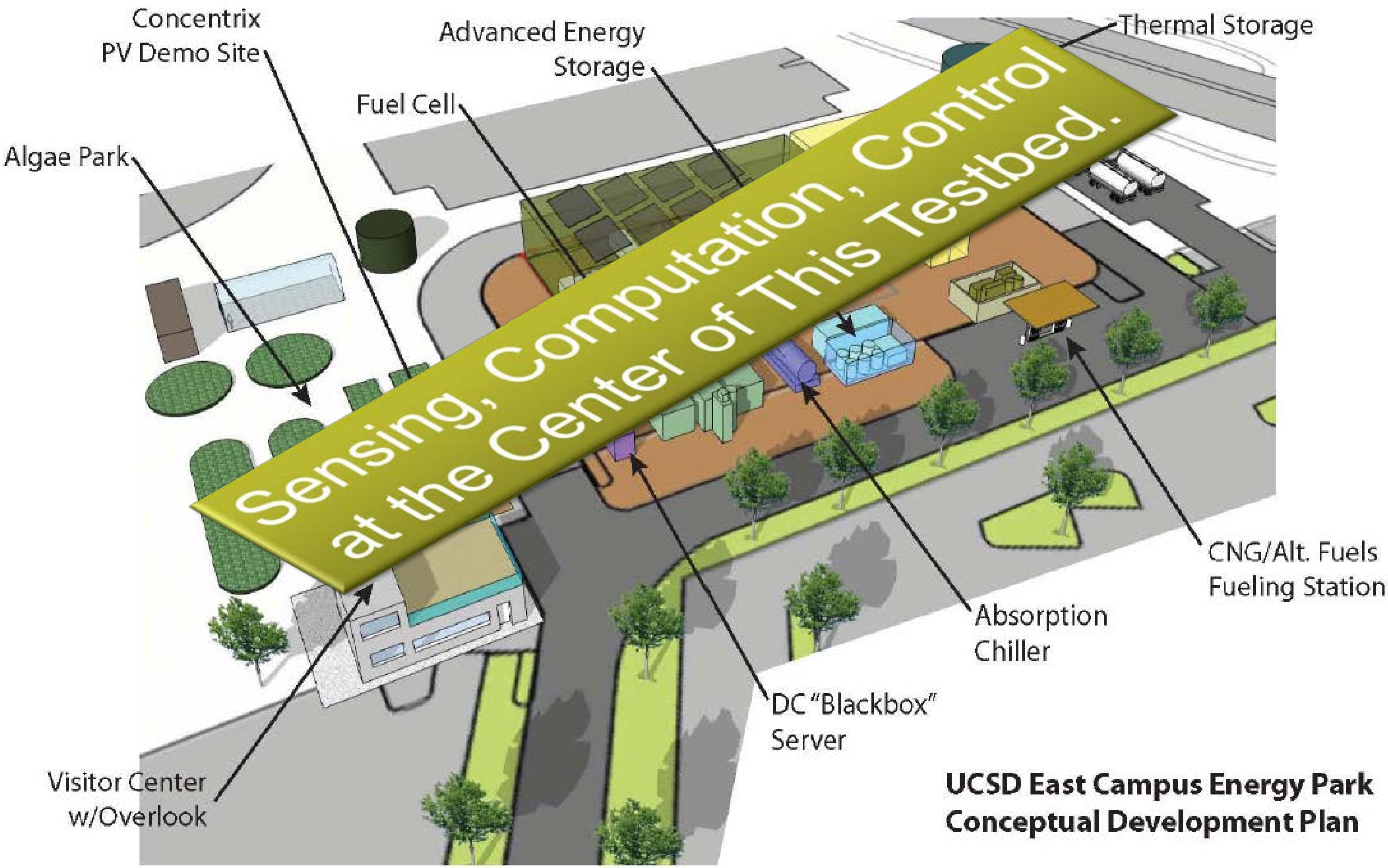
Figure 9: The energy consumption of HVAC for the actual occupancy-based deployment. HVAC zones controlled as occupancy changes.

36.9% lower energy use over 8-hour work day. DR response in minutes.



Matlab
HVAC/IT
xPC
Embedded Control
Spatio-temporal data capture
user
kernel
environment
events
zones
Observational Models
Use scenarios
Planning
Operation
Cooperation
Policy Framework
Policy
Human
Engineering
Trace playback
Real-time sensor inputs
Model Adaptor
Model Reduction
Sensor Plane
Building Target
Sensor events
{Observable state, Configuration params}
User, env. events
Embedded Control
Reduced observer + controller

Campus As A Living Laboratory of Localized Co-Generation and Storage



Import/Production

Meter Reads

Vista

UCSD MAP

HOUSING

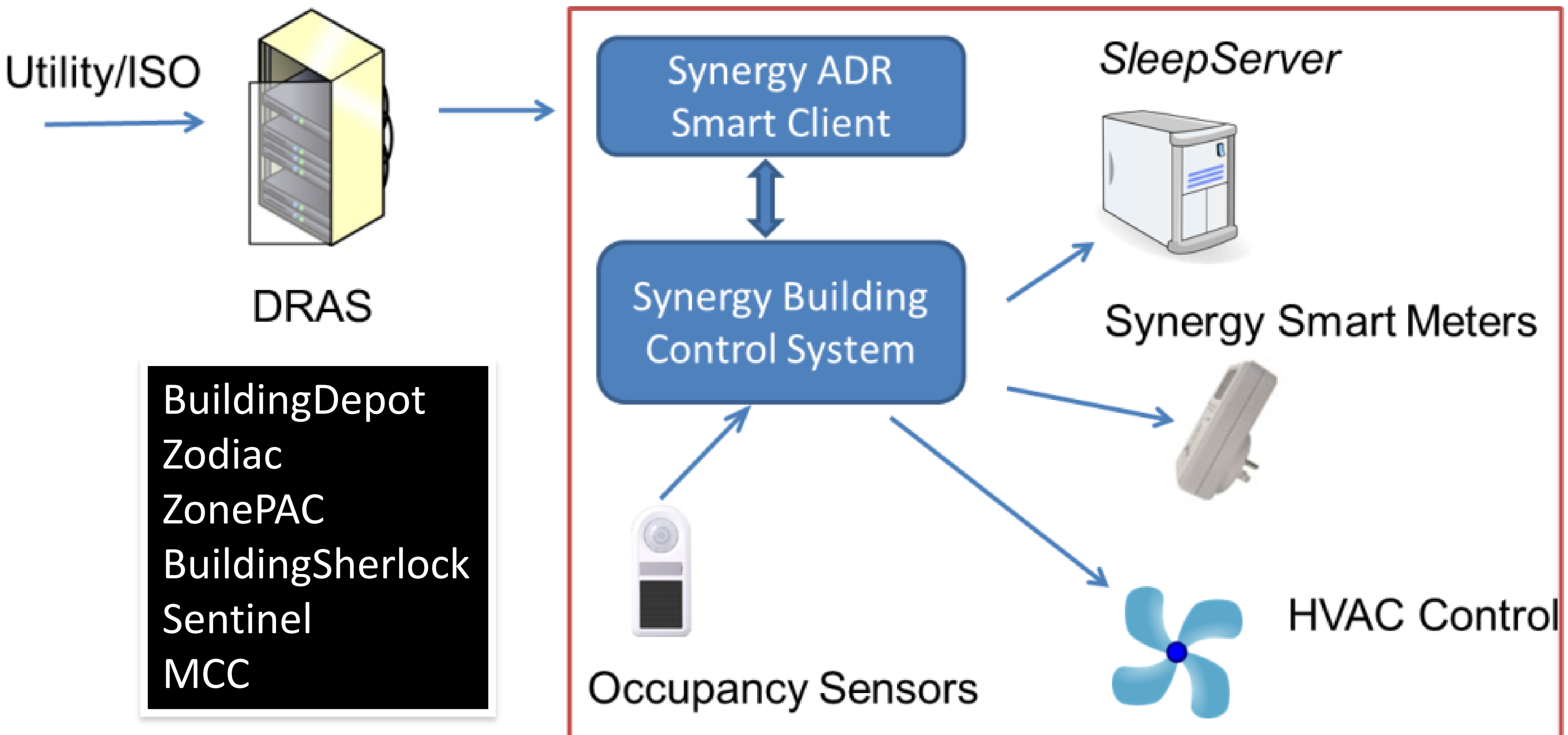
Real Time Cost Per Hour $ 2,570

Real Time kW Usage 30,238 kW

	SIO	UCSD Medical Center La Jolla	Warren Campus University Center	East Campus	Muir Campus
Current Month:					
Monthly Cost ($)	66,121	64,277	138,097	18,564	67,143
kWh del	777,893 kWh	756,204 kWh	1,624,674 kWh	218,400 kWh	789,923 kWh
Previous Month:					
Monthly Cost ($)	149,881	148,692	320,149	42,478	157,613
kWh del	1,763,309 kWh	1,749,312 kWh	3,766,459 kWh	499,744 kWh	1,854,266 kWh
Realtime Values:					
kW inst	2,546 kW	2,665 kW	5,475 kW	638 kW	2,404 kW

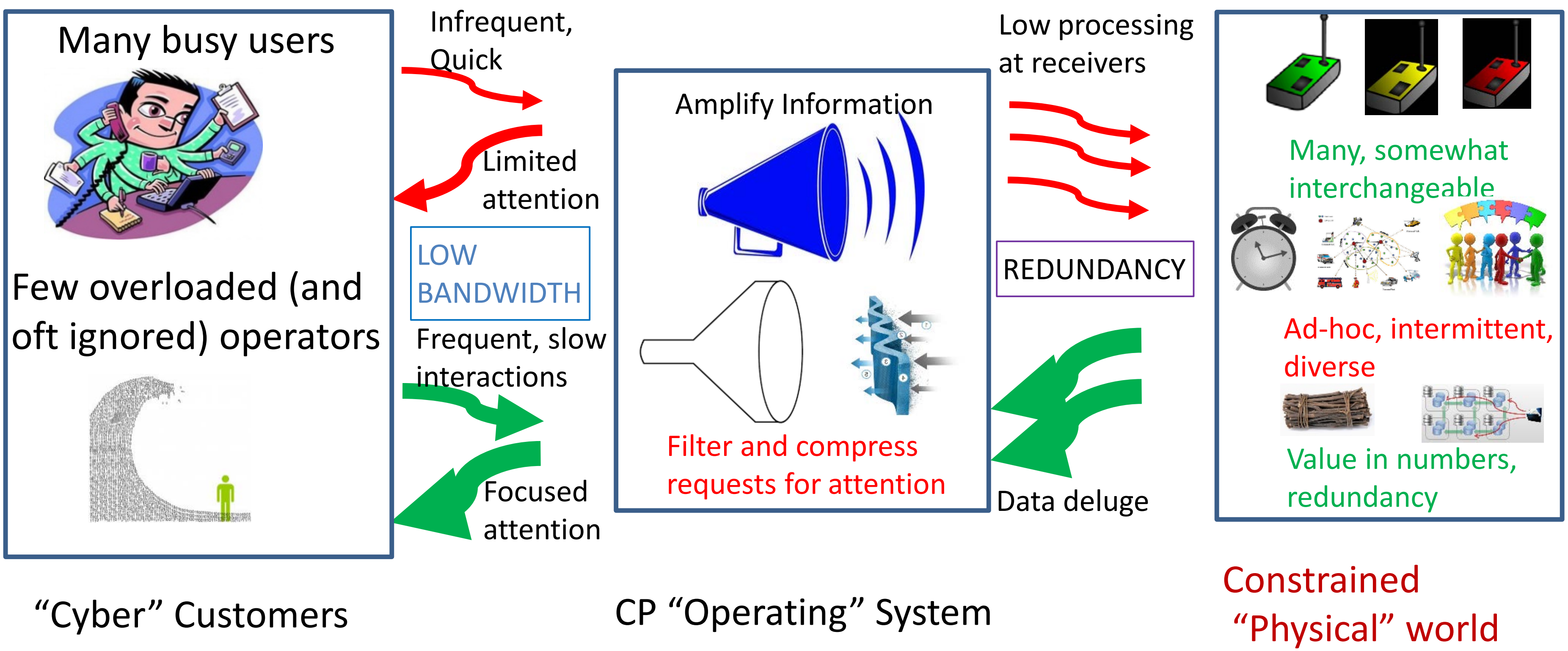
	SOM	North Campus	Revelle Campus	Central Plant	UCSD Total
Current Month:					
Monthly Cost ($)	19,075	30,163	236,794	93,913	734,148
kWh del	224,414 kWh	354,860 kWh	2,785,807 kWh	1,104,854 kWh	8,637,030 kWh
Previous Month:					
Monthly Cost ($)	45,133	67,085	557,638	184,830	1,673,499
kWh del	530,982 kWh	789,230 kWh	6,560,443 kWh	2,174,474 kWh	19,688,219 kWh
Realtime Values:					
kW inst	715 kW	1,022 kW	8,777 kW	3,947 kW	30,238 kW

A NEW Computing Platform: Instrumented Buildings for measuring occupancy, energy use



Built in 2004, 145,000 sq ft, 5 floors
HVAC : VAV with reheat coil, 237 zones
Occupants : Faculty, staff and students
more than 1 year data, 17+ sensors per zone
100s of Air Handler (AHU) sensors
every ~5 minutes

Complicated Information Flows in CP Systems



"Wealth of data, poverty of attention," Herb Simon

Find Architectural Support To Structure Information Flows

HVAC
- Control based on weather
- Use of solar panels and solar heaters
- Adapt to user comfort

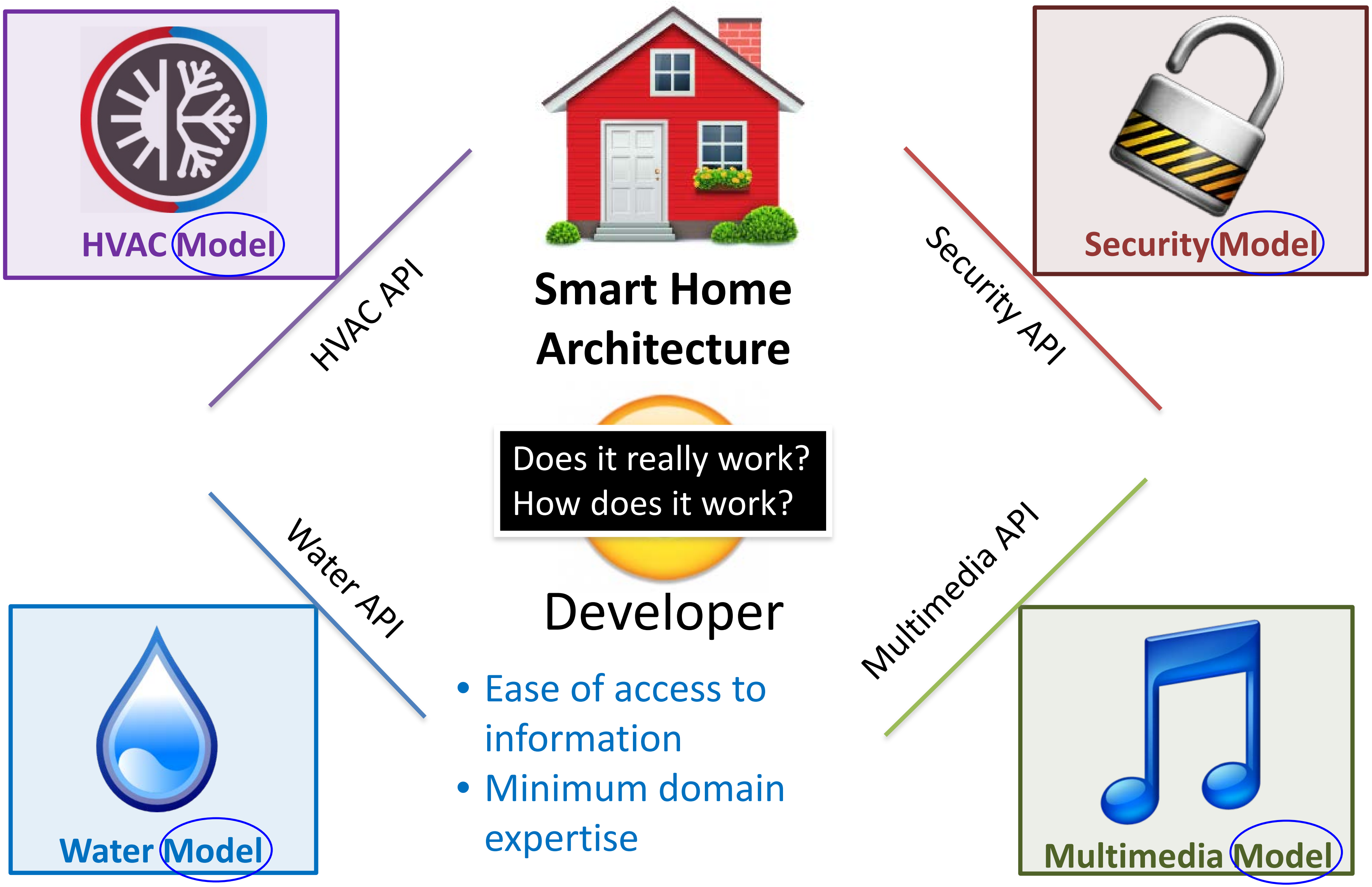
Security
- Biometric locking system
- Video surveillance
- Smoke detector
- Alarm system

Smart Home as an example CPS

Water
- Cooking, drinking & washing
- Lawn irrigation system
- Solar heating system
- Pool filtration & heating

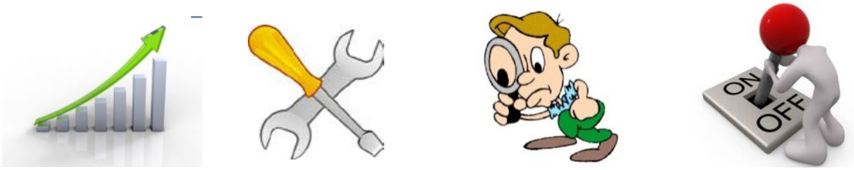
Multimedia
- Television & Radio
- Video Games
- Internet
- Recording systems

Putting Things Together



BRICK: Exciting New Platform with new “Apps”

Apps



Visualize Maintain Analyze Control

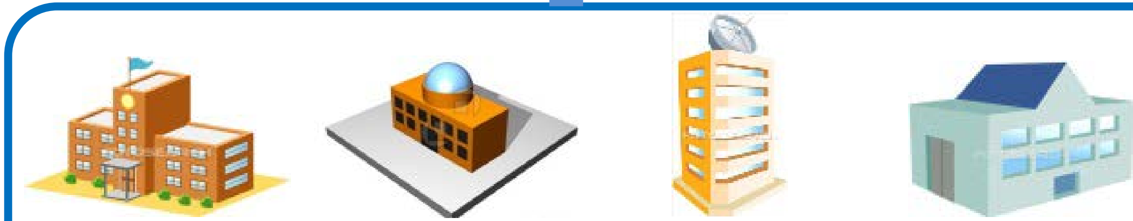
Next generation building applications via standardized API

REST/ Native API

- Scalable, distributed data storage
- Metadata and contextual tagging
- Access control across users
- REST API for app development

Data management system for sensors and actuators

Data Connectors



Building A Building B Building C Building D

Large amount of data generated in modern buildings

http://brickschema.org/

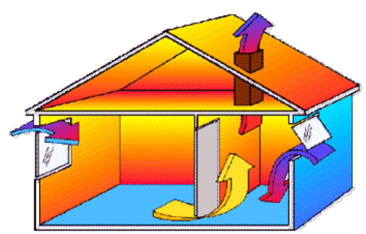
[1] Agarwal, Yuvraj, et al. "BuildingDepot: An extensible and distributed architecture for building data storage, access and sharing." Proceedings of the Fourth ACM Workshop on Embedded Sensing Systems for Energy-Efficiency in Buildings. ACM, 2012.

Models can extend reasoning methods

Rule based

If  but still  then 

Model based

If  then I expect  but I got  so 

Change based

The last time I did  sensors told me I got  but this time  so 

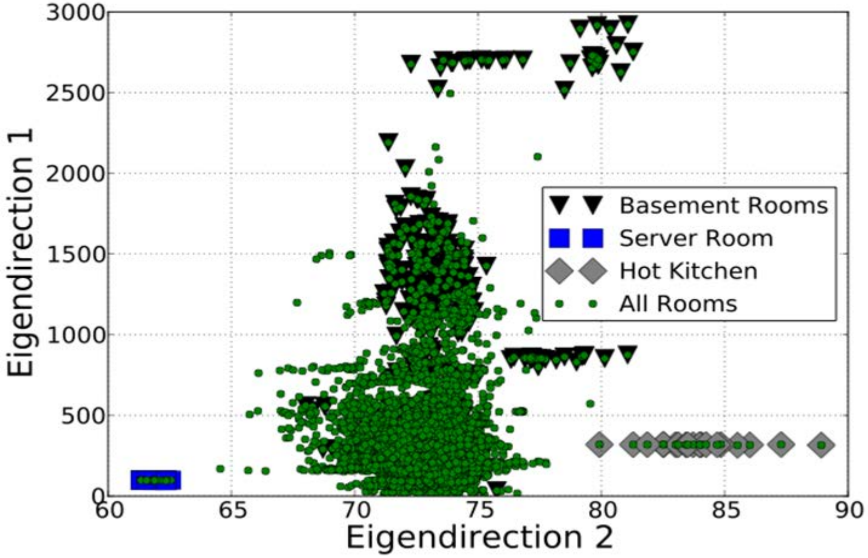
Building Data Models and Comparative Data Mining

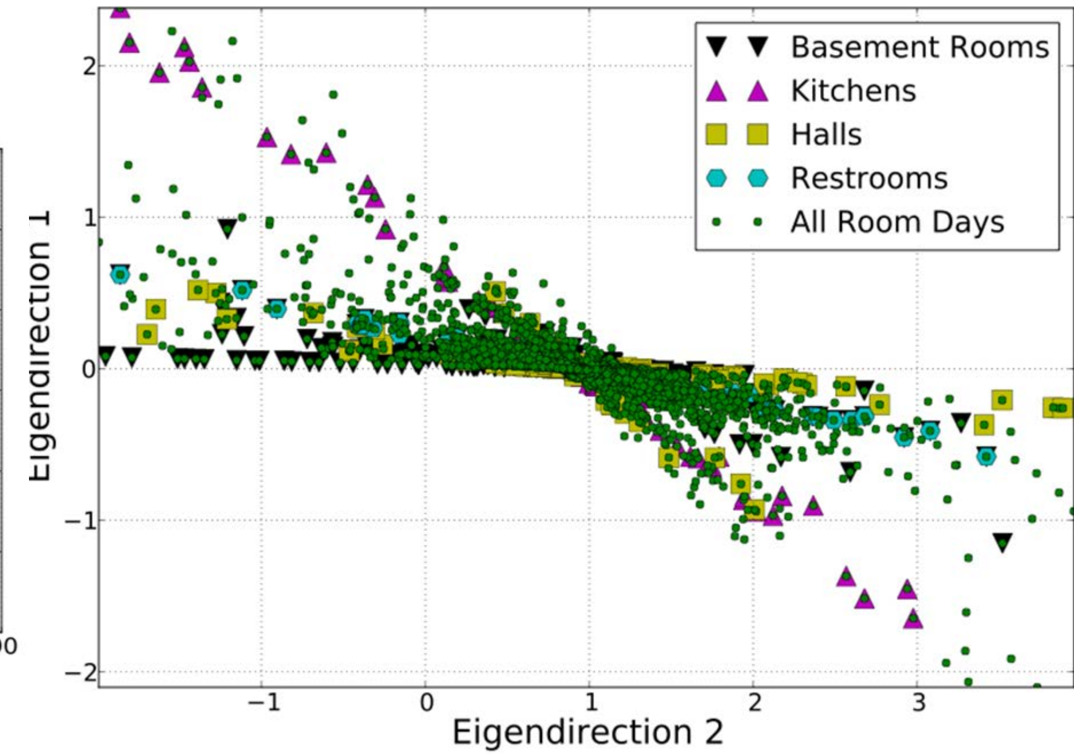
- Working directly with sensor readings tends to find extremes in sensor readings
  - Models that capture on the inter-relationships between sensors and parameters of interest
- Large differences between zones even on the same day
  - Cluster rooms with the same characteristics
- Sensitivity to confounding parameters (human actions)
  - Compare rooms that have the same confounding parameters

Misconfigurations are common, in 40% of buildings we examined.

[1]. Narayanaswamy, Balakrishnan, et al. "Data driven investigation of faults in HVAC systems with model, cluster and compare (MCC)." Proceedings of the 1st ACM Conference on Embedded Systems for Energy-Efficient Buildings. ACM, 2014.

Better Models, Improved Diagnosis



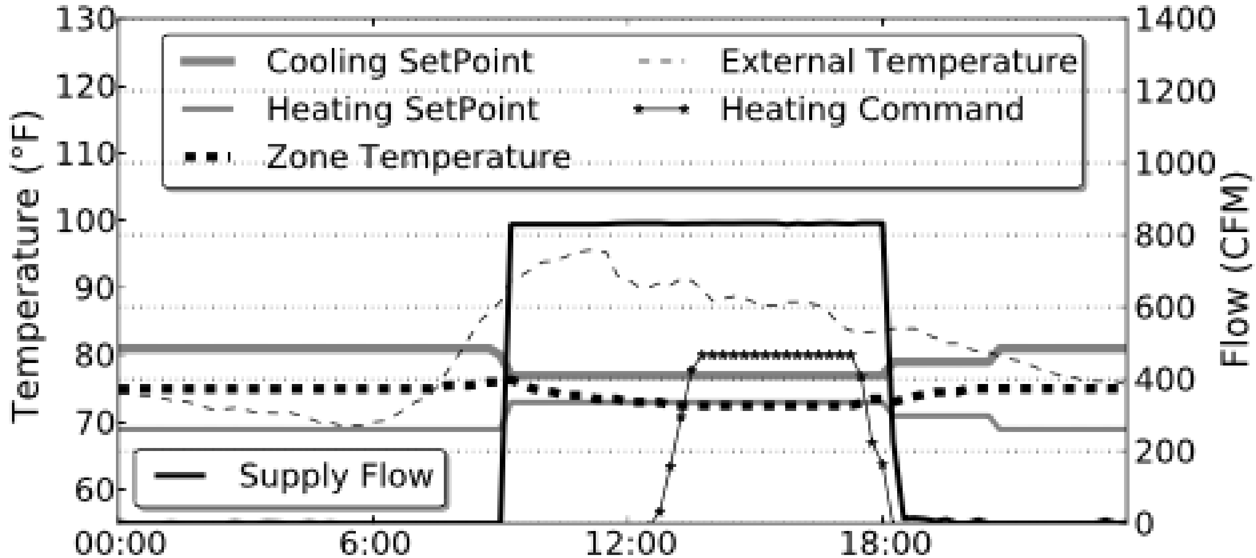


Build learning models from sensor data

Cluster model parameters

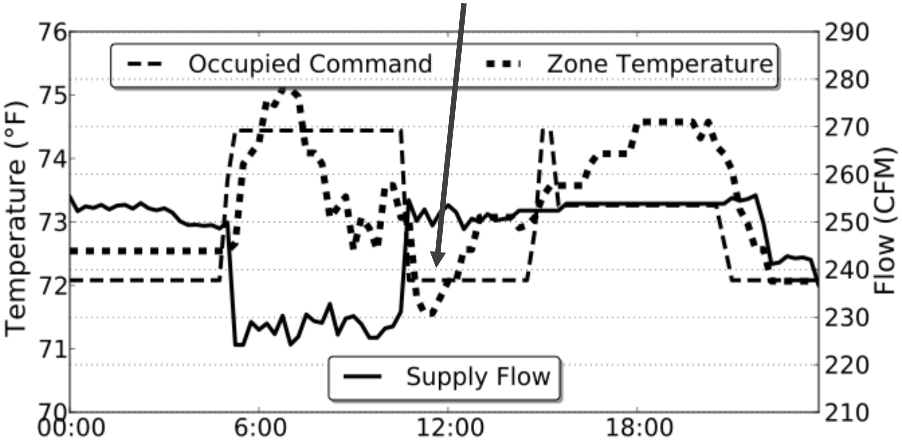
Compare groups

Design Rules for fault detection and diagnosis.



Model, Cluster, Compare: Enables us to detect and use relationships

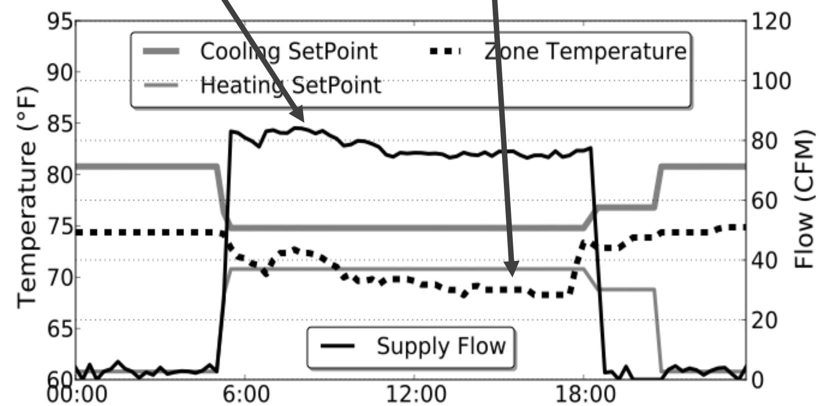
Conditioning more when unoccupied



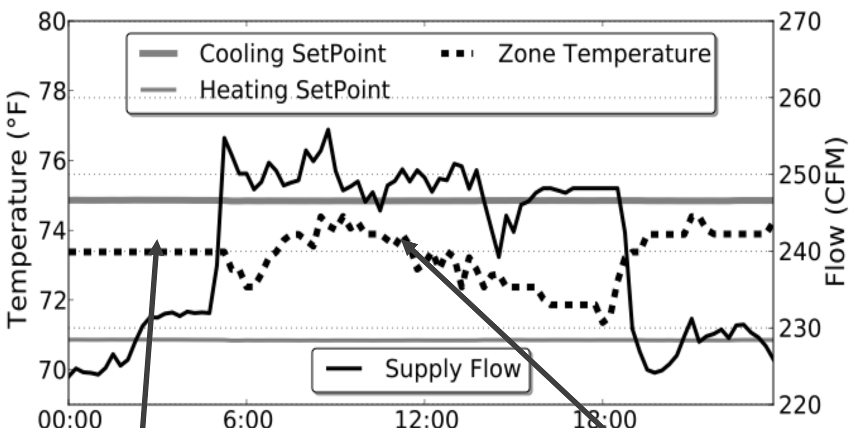
Actuation and Sensing not in sync

High Airflow

Causes overcooling



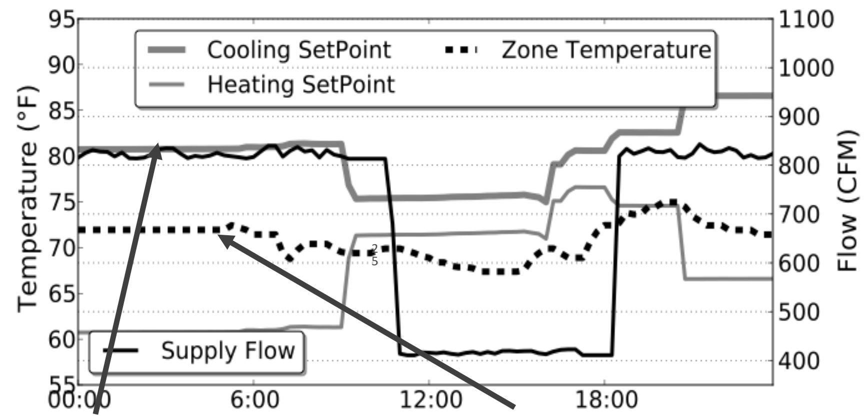
High set point causes over-cooling



Setpoints never change

High Airflow all the time

Set points and actuation not in sync



High Airflow

Even when temperature within setpoints

(Unnecessary) high flow when within setpoints

CPS/IOT Needs, Requirements

Models

- Encapsulate domain knowledge
- Standardize representation of disparate systems

Abstractions

- Simplify access to domain expertise
- Facilitate communication across systems

Architecture

- Allow models to co-exist to create a system of models
- Provide mechanisms for protection, communication and consistency

UCSD and CPS

Across several engineering disciplines: EE, CS, SE, MAE, NE.

CALIT2 @ UCSD

UCSD @ LANL