Interoperability in CyberPhysical Systems

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The Team (over the years)

- **UC Irvine**
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- **Emergency Response Agencies**
  - **County of LA Fire Dept.**
  - **Newport Beach Fire**
  - **Orange County Fire Authority**
  - **City of Ontario**
  - **City of Los Angeles**
  - **State of CA OES**
  - **Department of Homeland Security**
  - **Federal Emergency Management Agency**

responsphere

rescue

SAFIRE: Situational Awareness for Firefighters

CYPRESS
Cyber Physical RESilience & Sustainability

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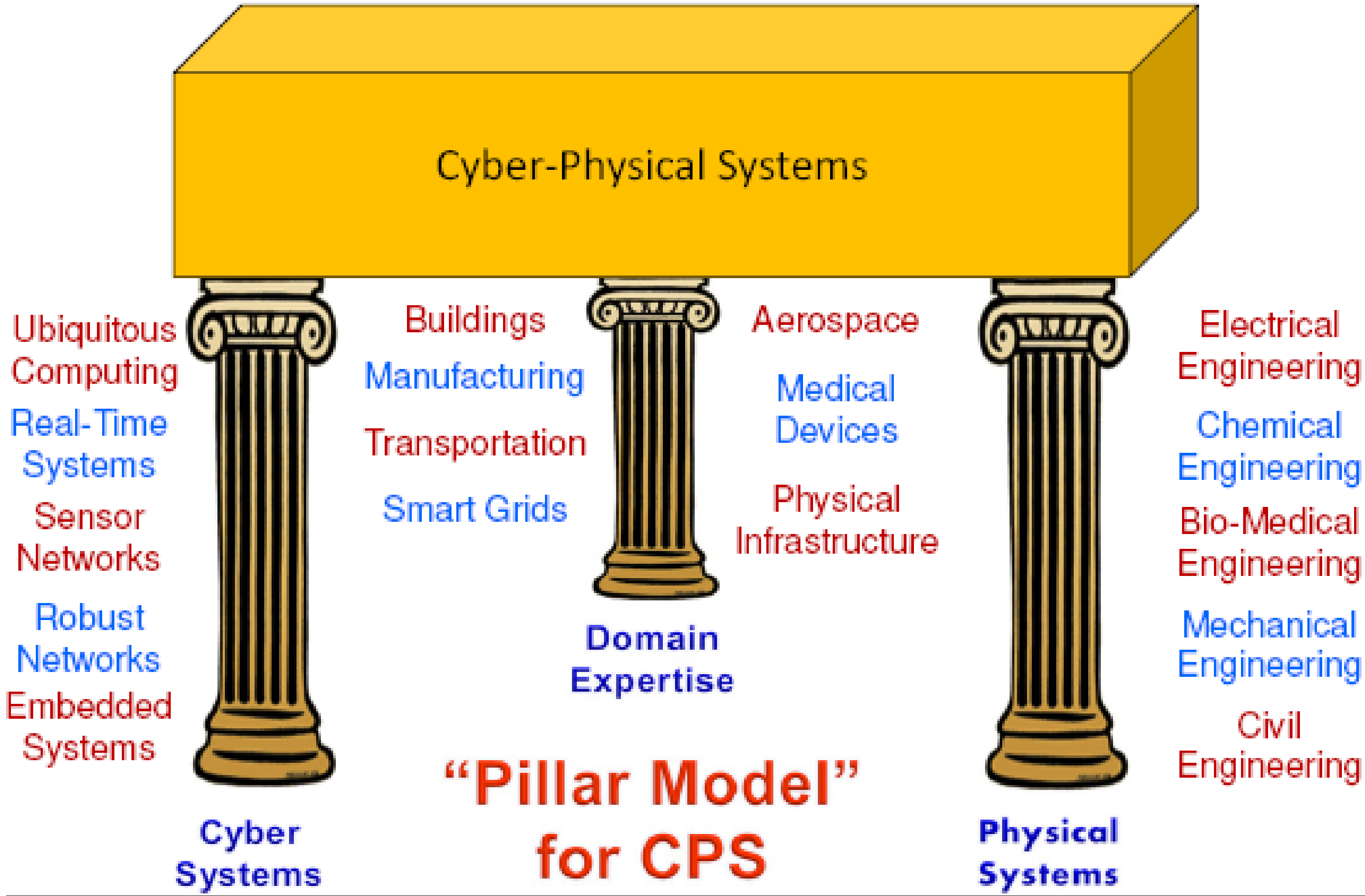
Outline

- Introduction to CyberPhysical Systems
- Instrumented CyberPhysical Spaces
- Related projects at UCI
  - SATWARE, SAFIRE, CYPRESS
- Interoperability challenges
  - A Multi-layer perspective
- Formal methods for interoperable networked CPS

What is a Cyber-physical System?

- A *cyber-physical system integrates computing and* communication capabilities with the monitoring and/or control of entities in the physical world
  - dependably, safely, securely, efficiently and in real-time.
- Long-term goal: Cyber-physical systems transform how we interact with the physical world just like the internet transformed how we interact with one another.
- Multiple Real World Applications
  - Intelligent transportation, healthcare, assisted living, civil structure monitoring, smart buildings

A Model for CPS (Raj Rajkumar @CMU)



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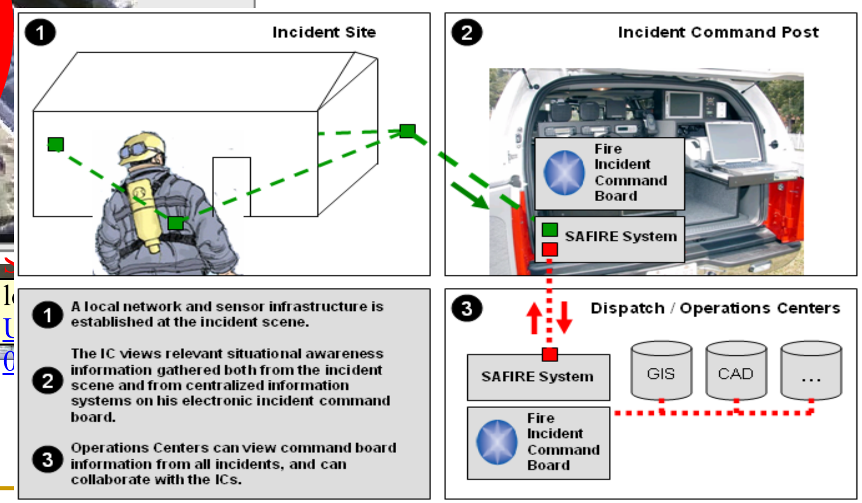
Instrumented CyberPhysical Spaces (ICPS)

Create a digital representation of an evolving physical world

Applications: surveillance & monitoring

Applications: Situation Awareness



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Responsphere (I-Sensorium) – A Sample ICPS

Campus-wide infrastructure to instrument, experiments, monitor, disaster drills & to validate technologies

sensing, communicating, storage & computing infrastructure

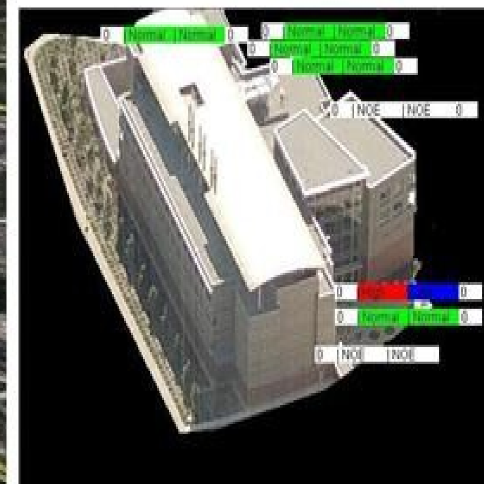
Software for real-time collection, analysis, and processing of sensor information

used to create real time information awareness & post-drill analysis

Responsphere Enables Drills & Technology Evaluation

- Technology Testing Exercise: 16 SEP 08
  - Bren Hall Evacuation w/Campus Police Department & UCI Zone Crew 3
- Live Burn with OCFA,LA Fire and Anaheim Fire
  - Testing Sensing (human bio-sensing) data collection & 2nd generation Fire Incident Command Board (FICB)
- SAFIRE / FICB Usability Study – 15 MAY 09
  - Freeze points identified as critical junction / decision points to assess SA with and without FICB

Observation Systems – Office Monitor, Building Security, Green Buildings



Calit2 Building

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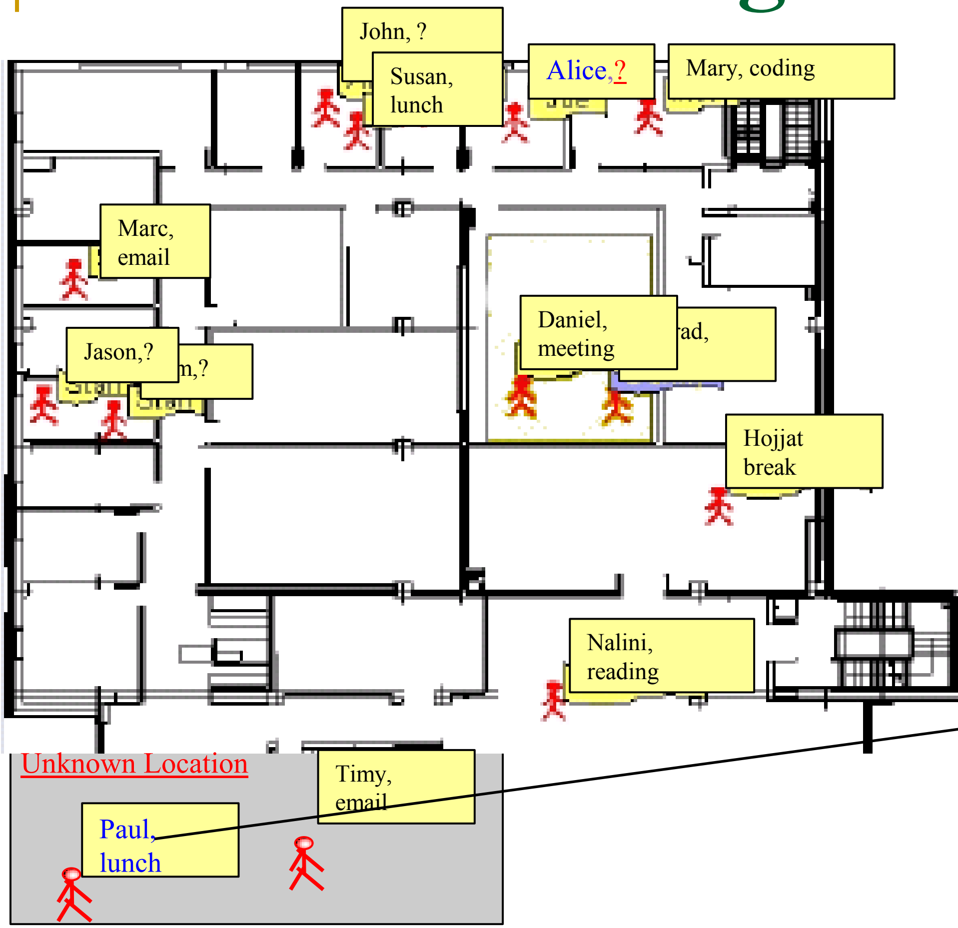
Office Monitoring



Office monitor

Privacy challenges:

1.- Inference

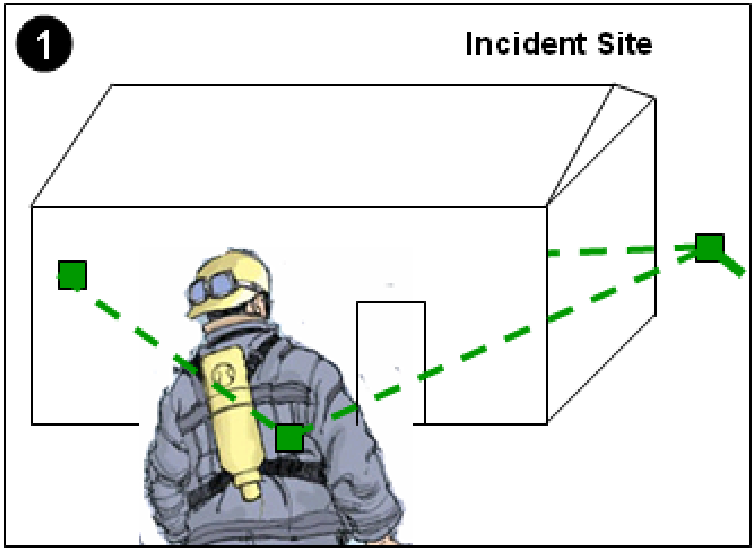
Public knowledge:
"Alice and Paul always have lunch together."

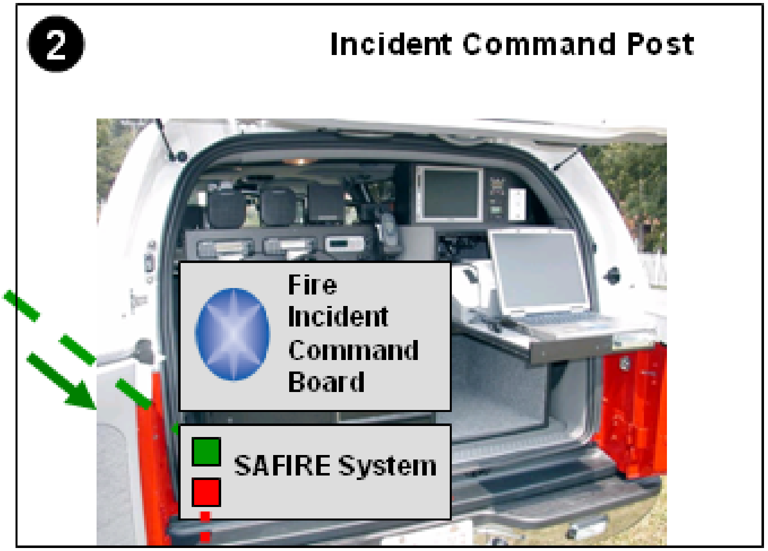
+

→ *Alice is having lunch*
→ *Paul is at Alice's office*

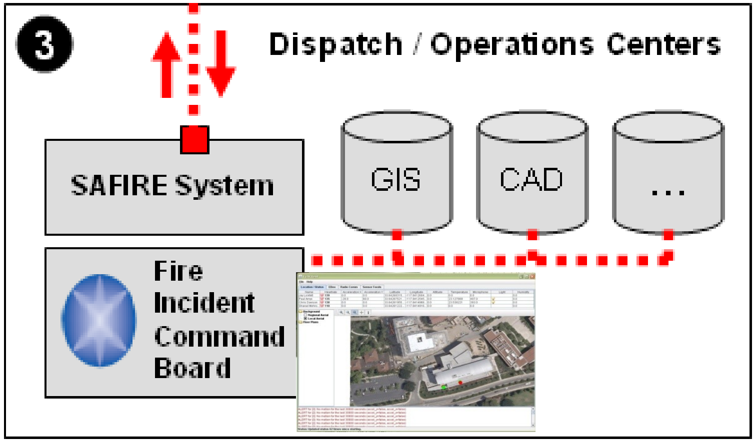
2.- What is privacy and how do users express it?

SAFIRE (Situational Awareness for Firefighters)





1. A local network and sensor infrastructure is established at the incident scene.
2. The IC views relevant situational awareness information gathered both from the incident scene and from centralized information systems on his electronic incident command board.
3. Operations Centers can view command board information from all incidents, and can collaborate with the ICs.



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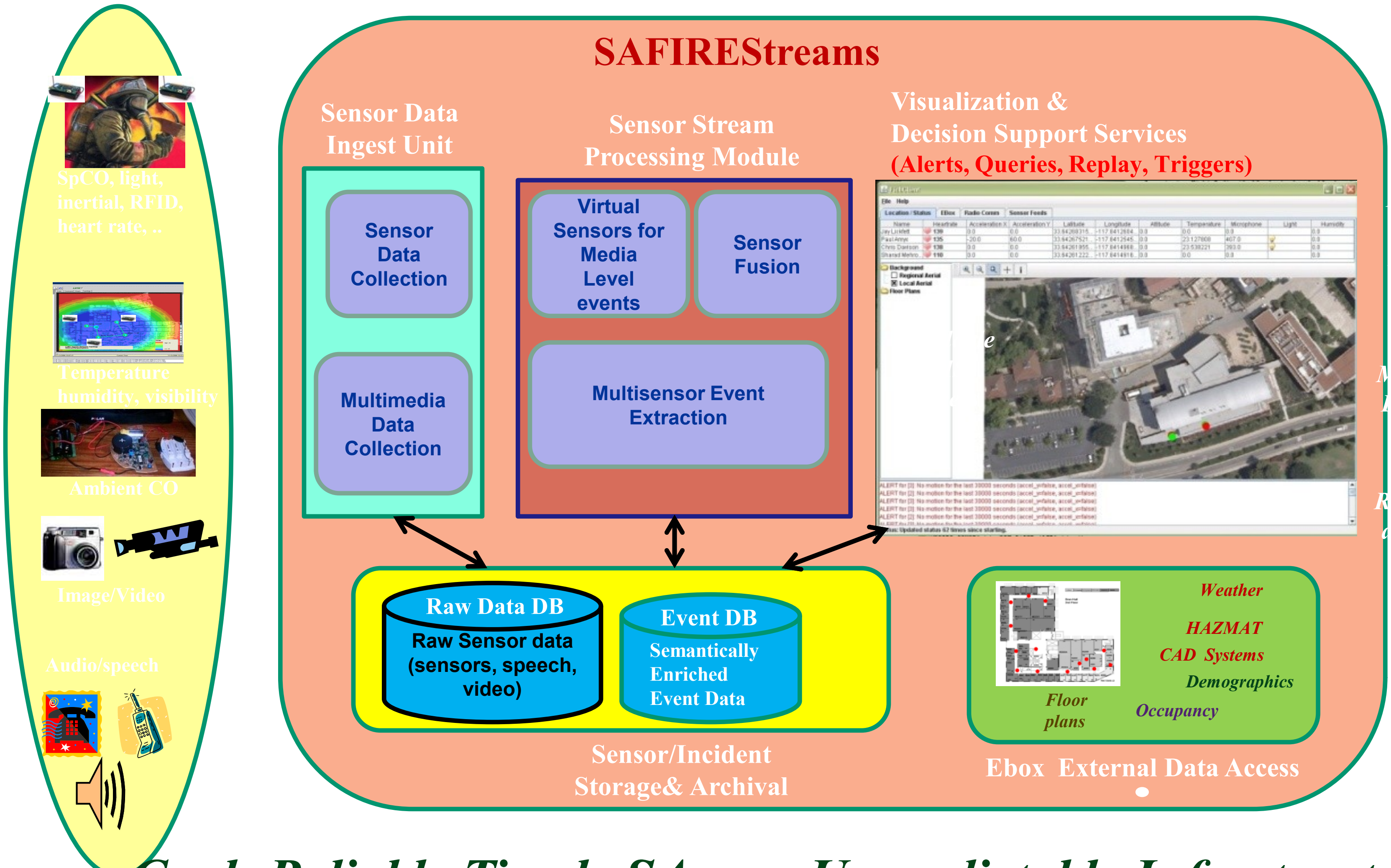
SAFIRE : An End-to-end SA Tool for ICs



Goal: Reliable Timely SA over Unpredictable Infrastructure

CYPRESS

Cyber Physical RESilience & Sustainability

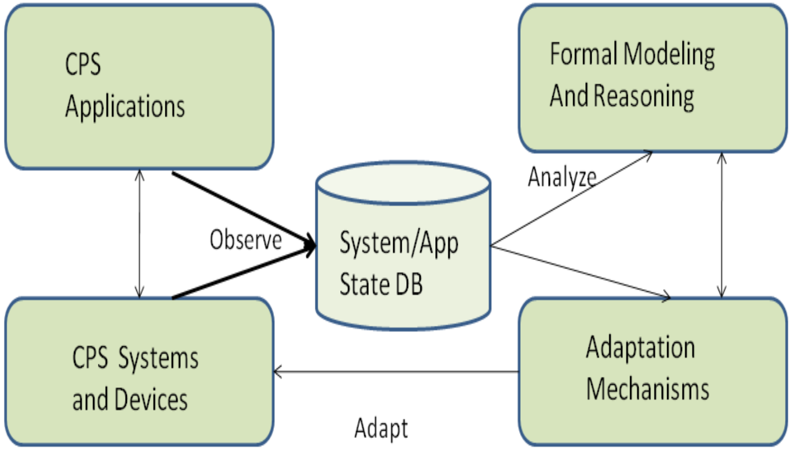
- Explores techniques for dependability, resilience and sustainability in cyber-physical spaces.
- Semantic foundations, cross-layer system architecture and adaptation services to improve dependability in ICPS.
- Based on a Reflective (observe-analyze-adapt) Architecture
  - ICPS has a model of itself, its objectives, and its effects on the environment; the ICPS achieves dependability objectives through adaptation using runtime application of formal analysis methods.

CYPRESS: Safe adaptations for dependability in CPS

What can go wrong?

- Infrastructure component errors/failures
  - Device Failures, Network Failures,Congestion and Overloads
- Data Interpretation errors/failures
  - Uncertainty in Processing (e.g. speech/image processing)
  - Contextual errors (e.g occlusions to a light sensor)

- CYPRESS goal
  - Digital state representation of ICPS guides a range of “safe” adaptations to achieve end-to-end ***infrastructure*** and ***information*** dependability.



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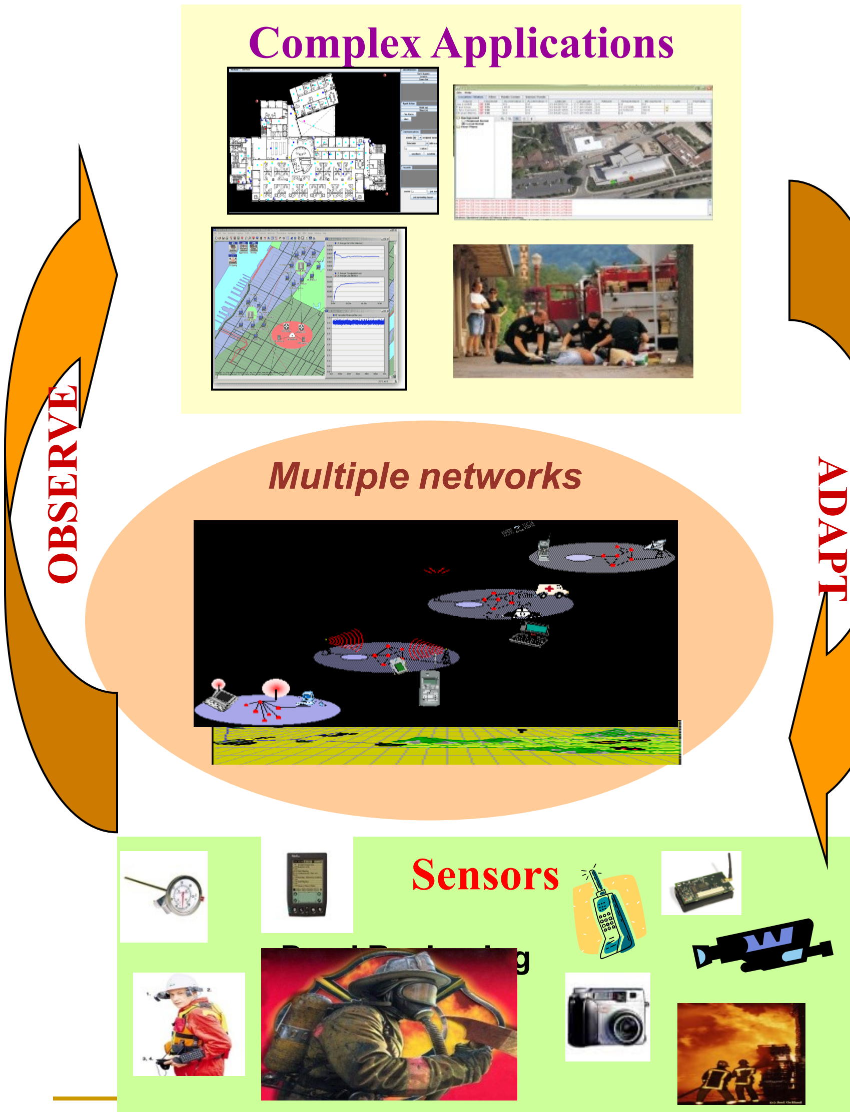
Interoperability Challenges



Interoperability Challenge 3
Heterogeneous Applications

Interoperability Challenge 2
Heterogeneous Networks

Interoperability Challenge 1
Heterogeneous Sensor Platforms

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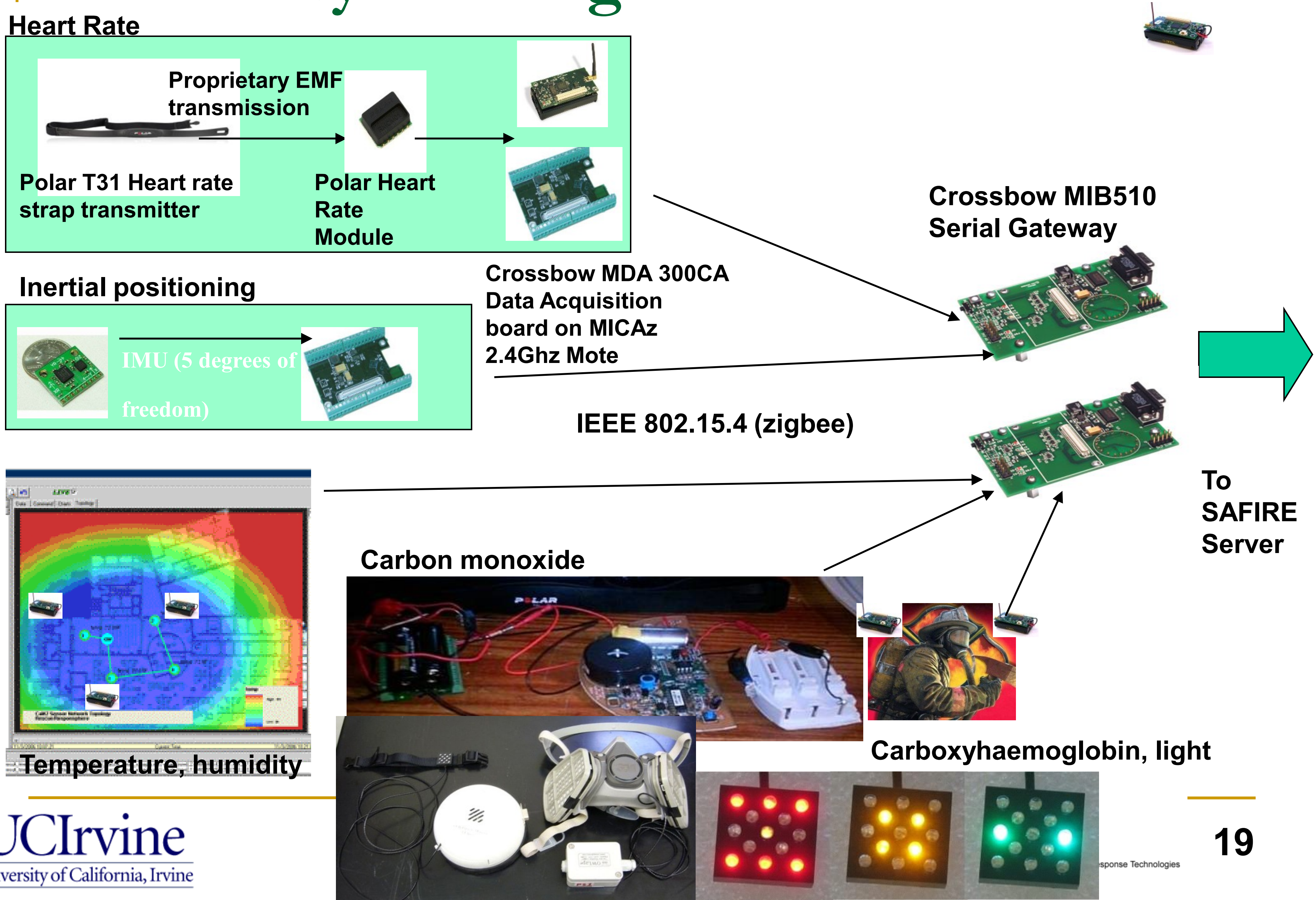
Interoperability challenge 1

Heterogeneous Sensor Platforms

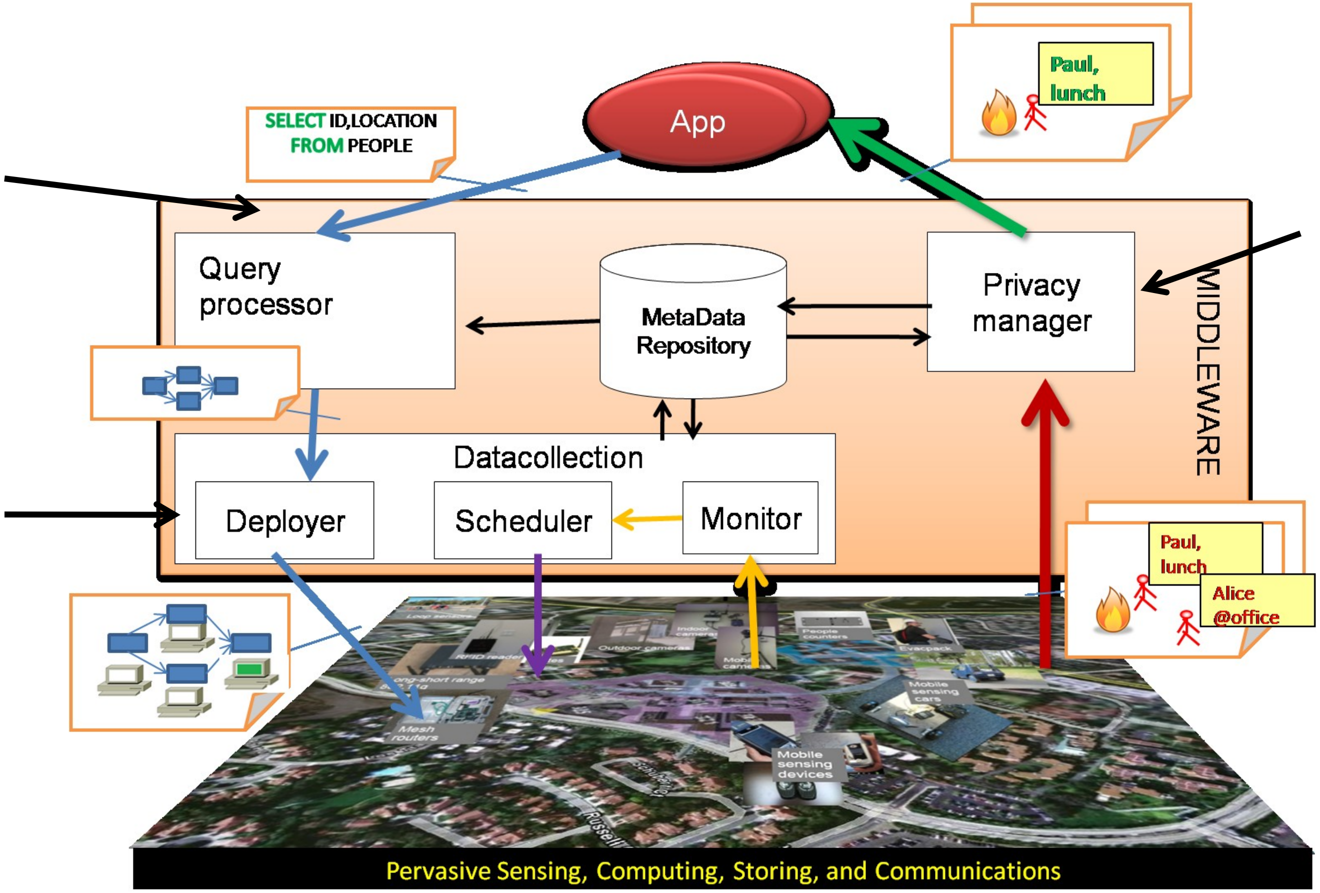
Case Study: Sensing for the Fire Practice



Sensors and Infrastructure

- **Sensor & Platform diversity makes programming complex.**
- **Multimodal Sensors (image/audio/video) – both opportunity and challenge**
  - **Resource demands -** Increasing sensor complexity → increasing network bandwidth
  - **Application-driven constraints** on quality, timeliness properties – real-time A/V
  - **Battery based power supply** impose significant restrictions
    - limits the transmission protocols that can be used by sensors
- **Semantic Sensing** untapped potential despite benefits
  - E.g., human speech, observations, blogs
- **Robustness of sensors remains elusive**
  - Indoor localization still unsolved
  - Calibration, sensitivity to ambient conditions, resilience in extreme situations

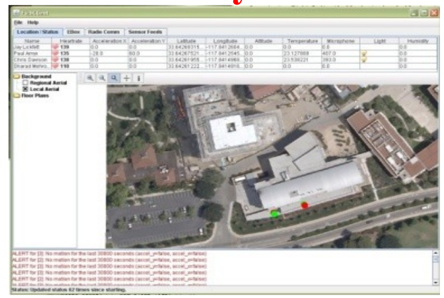
SATWARE – Semantic Middleware for Sentient Spaces



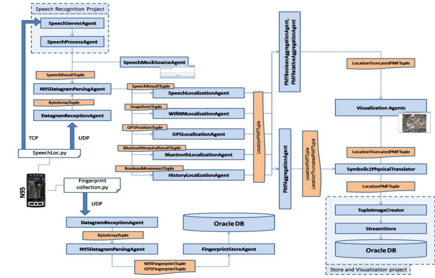
SATWARE applications

Human as Sensor System

SAFIRE- situational awareness System

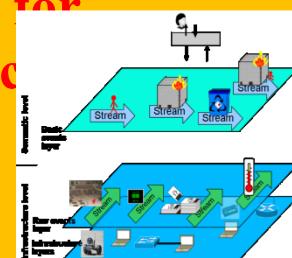


Indoor Localization Framework

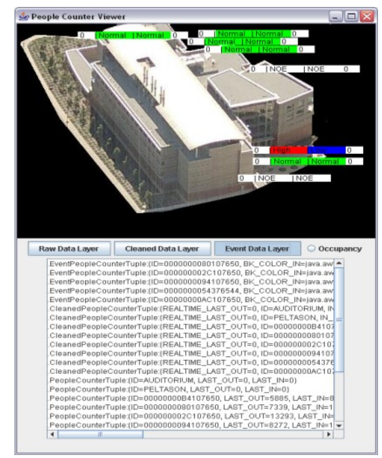


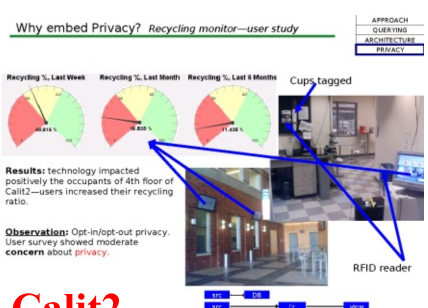
Privacy Preserving Surveillance System

SATWARE: semantic middleware for sentient spac

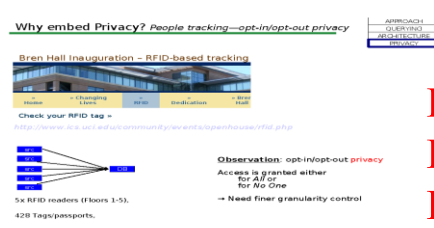


Occupancy Forecasting System





Calit2 Recycling Monitor



Bren Hall Inauguration RF-ID tracking

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Related Previous Work

SATware builds on top of from a large body of previous research

Streams

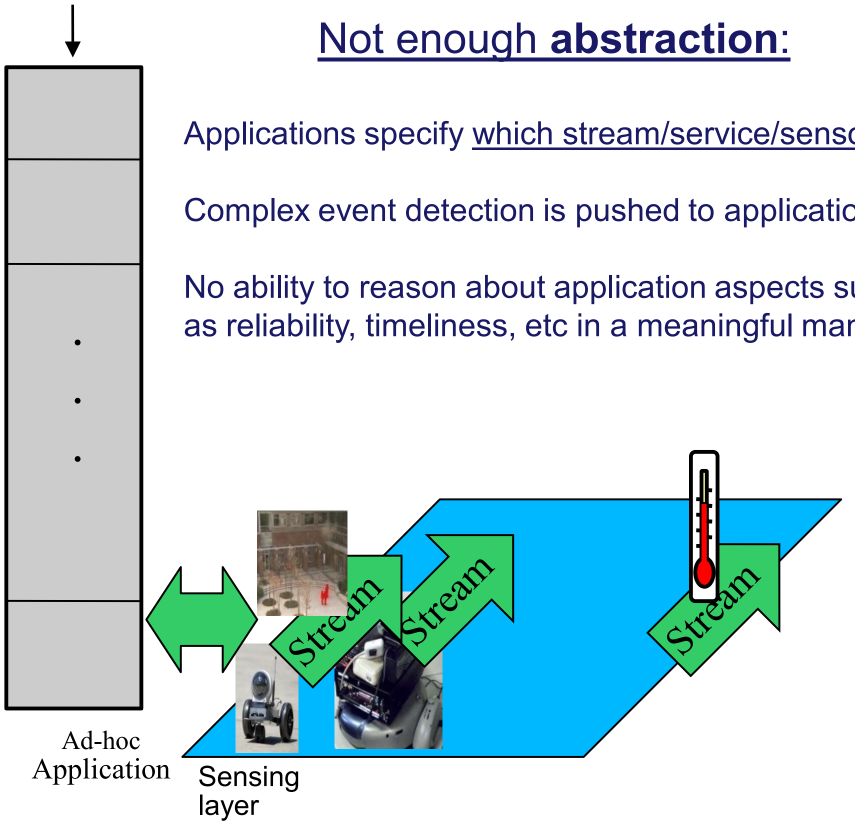
Centralized Server where stream queries are resolved

Sensor networks

In-network processor WSN as a DB

Middleware Perv. spaces

SOC: Applications as graphs of services



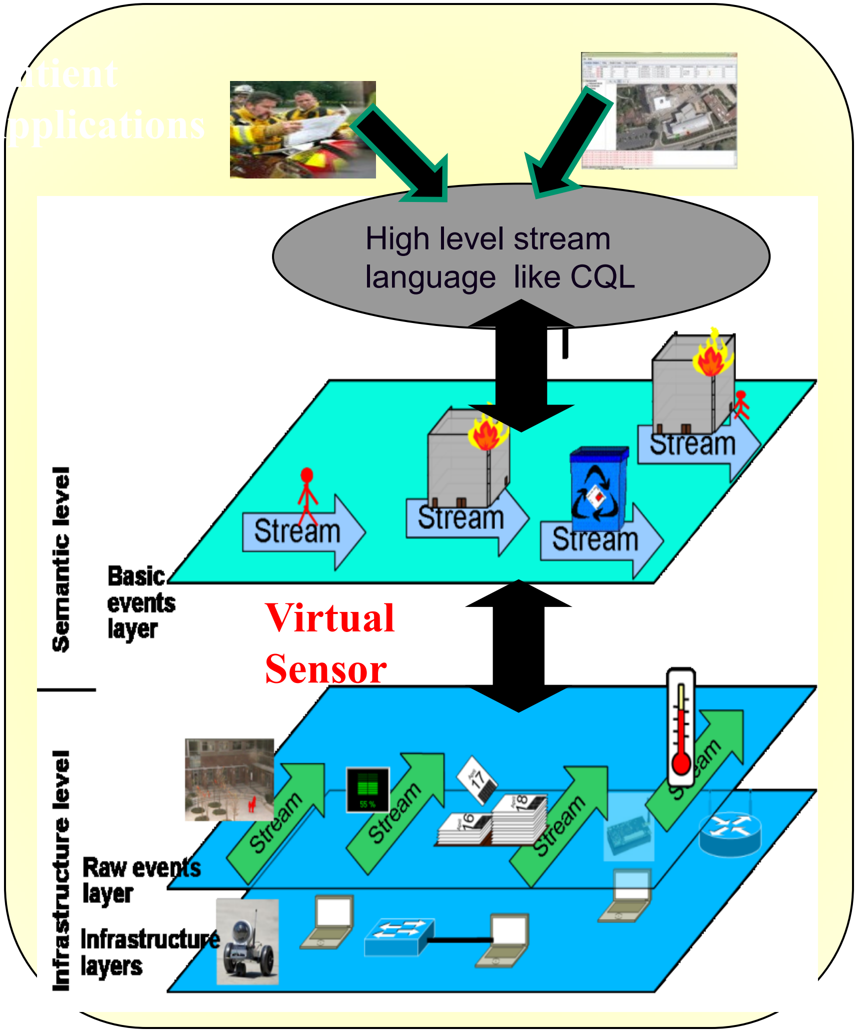
Not enough **abstraction**:

Applications specify which stream/service/sensor

Complex event detection is pushed to application,

No ability to reason about application aspects such as reliability, timeliness, etc in a meaningful manner.

SATWARE Approach



Semantic Level:

- Entities -- people, appliances, and buildings, rooms; Relationships – interactions.

Infrastructure Level:

- sensing devices, computing devices, network devices.

Virtual Sensors:

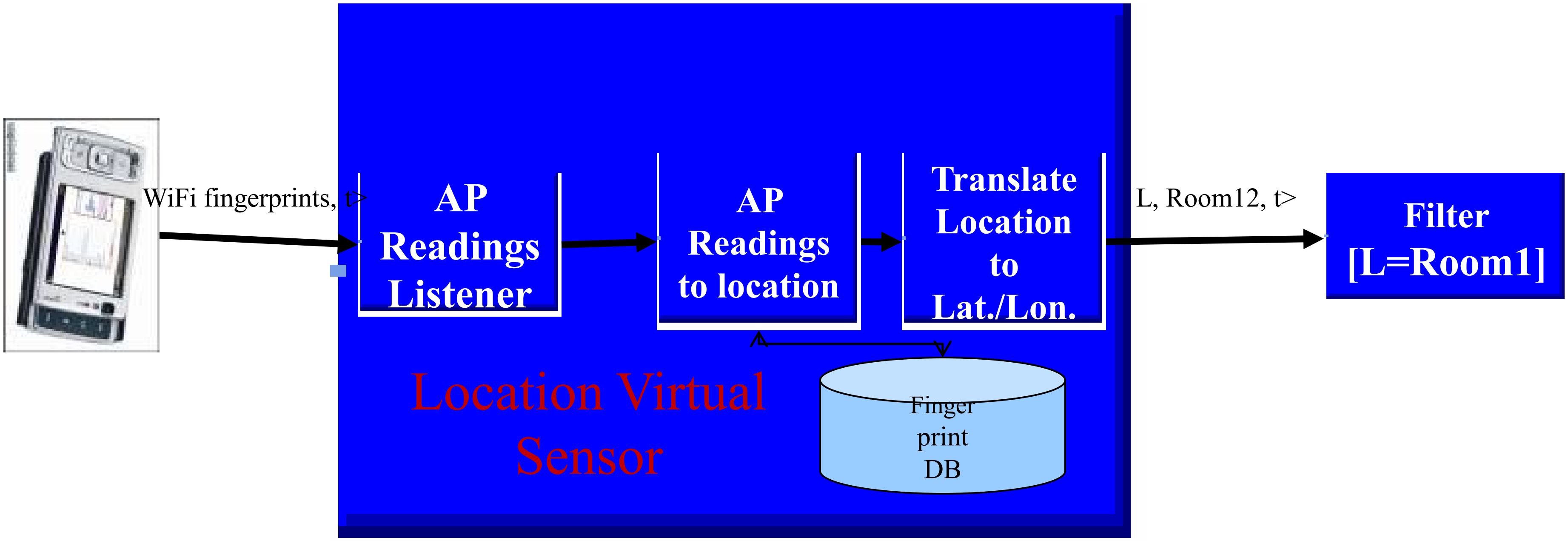
- maps data captured by sensors into **events** in the semantic world.

Event Logs:

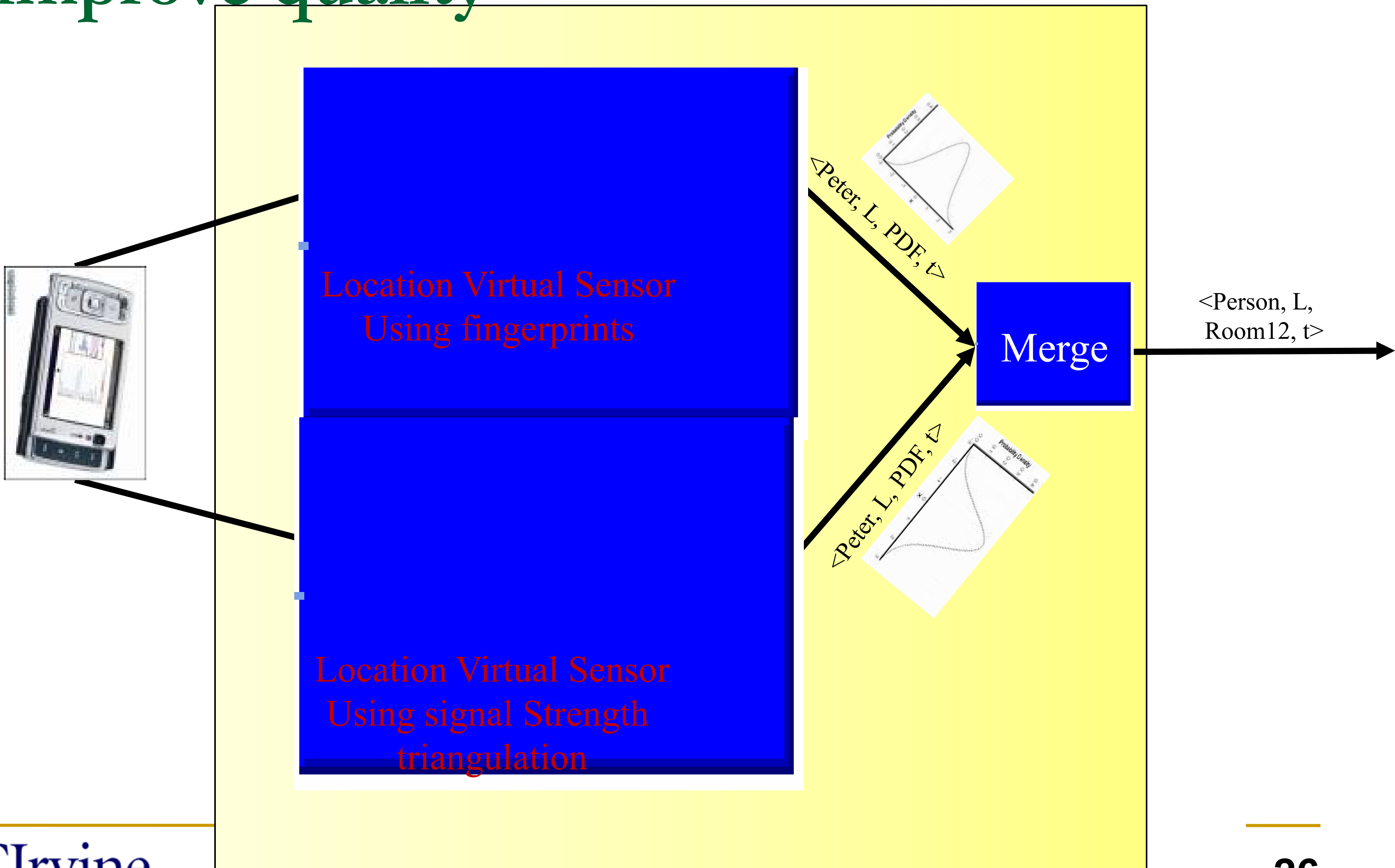
- evolution of physical world as observed by the sentient system

Key Concept: Virtual Sensors

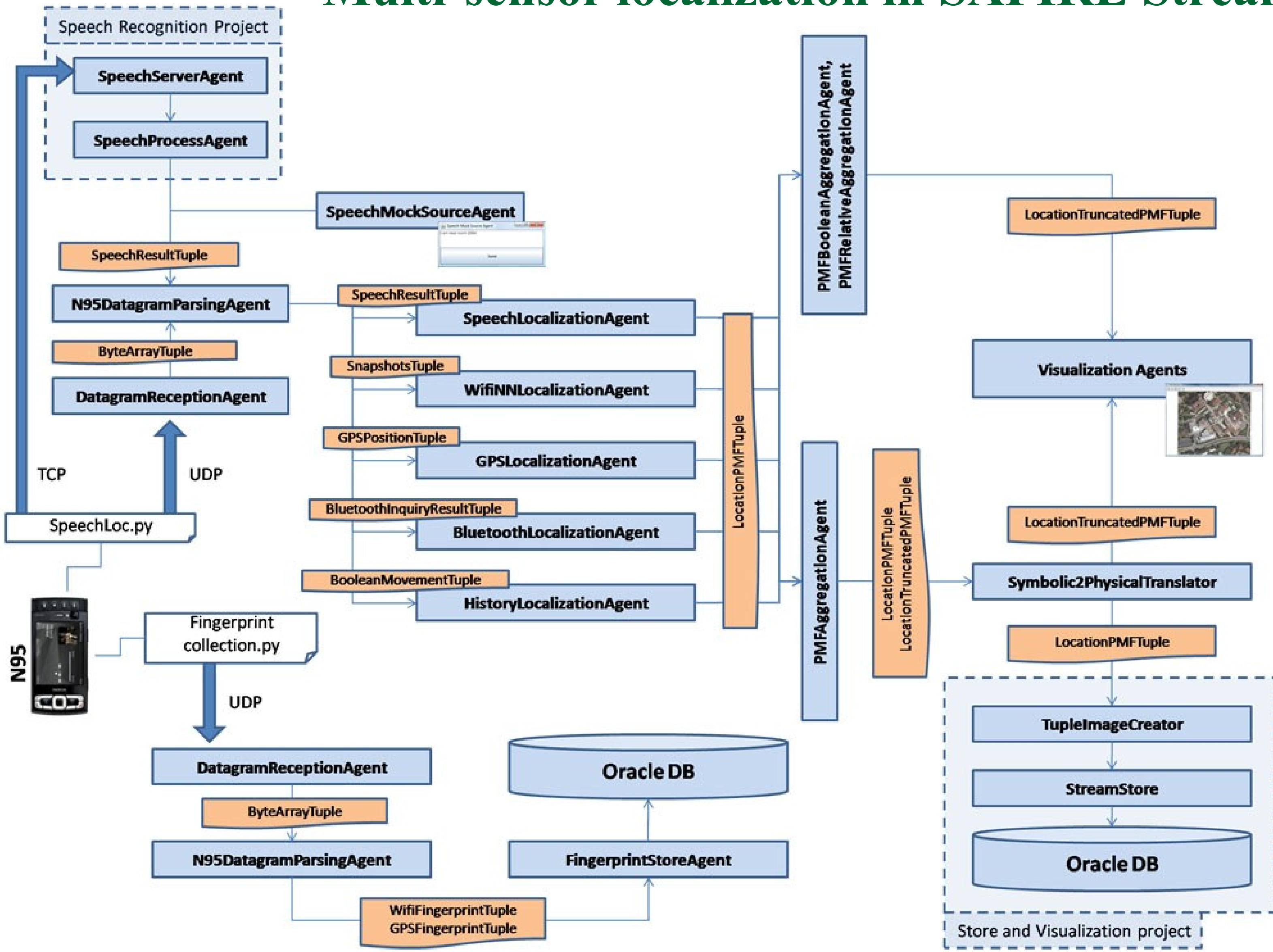
- A set of transformations applied to raw sensor streams to produce a semantically meaningful stream
- Provide the "bridge" between sensors & the semantic "real" world concepts.



Virtual Sensors: Multi-Sensor Fusion to improve quality

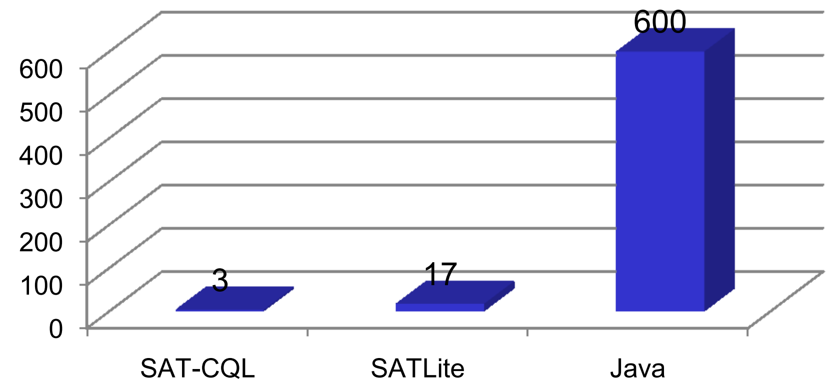


Multi-sensor localization in SAFIRE Streams



SAT-CQL

Lines of code
to implement Q1



Similar to that of SQL

- Declarative
- Concise
- Can be optimized
- Hides sensor heterogeneity and complexity

- *Return RoomID when occupancy > capacity*

```
SELECT RoomID
FROM Rooms
WHERE occupancy > capacity
```

- *Return RoomID when Eli holds a meeting with > 4 people*

```
SELECT RoomID
FROM Rooms
WHERE (occupancy  @ t > 5 )  AND (RoomID IN SELECT location @ t
                                          FROM People
                                          WHERE name = "ELI")
```

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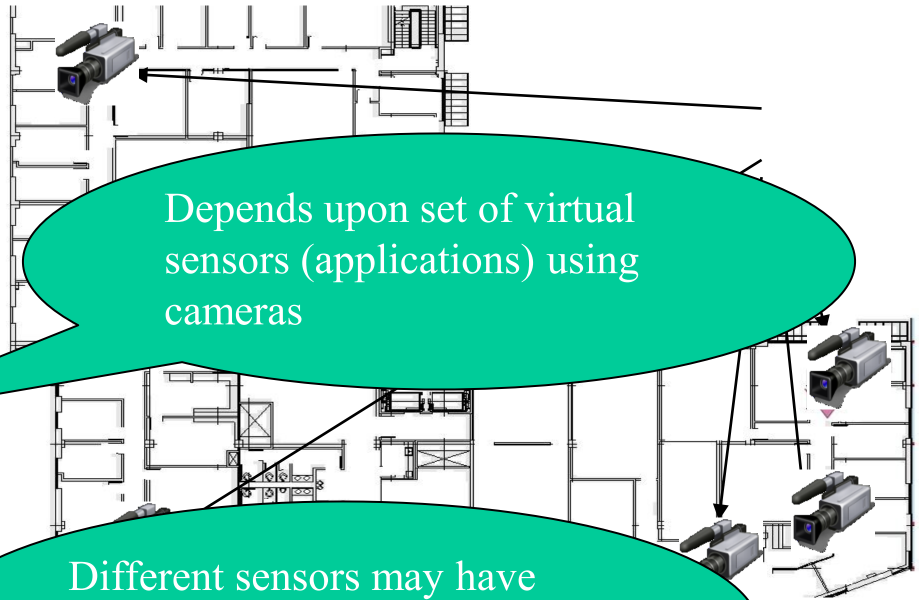
Application Needs → Sensor Plans

C →Set of *n* Cameras.

Plan(t) → {0,1} vector <b1,..,bn> (Indicating Which Cameras to Probe)

Benefit(Plan(t)) → expected benefit from executing this plan.

Cost(Plan(t)) → cost associated with that plan.



Depends upon set of virtual sensors (applications) using cameras

Different sensors may have different costs associated

...that:

- Benefit($Plan_{(t)}$) is ***maximized***.
- Cost($Plan_{(t)}$) is ***minimized***.
- Under the ***constraint***: $\Sigma b_i \leq k$

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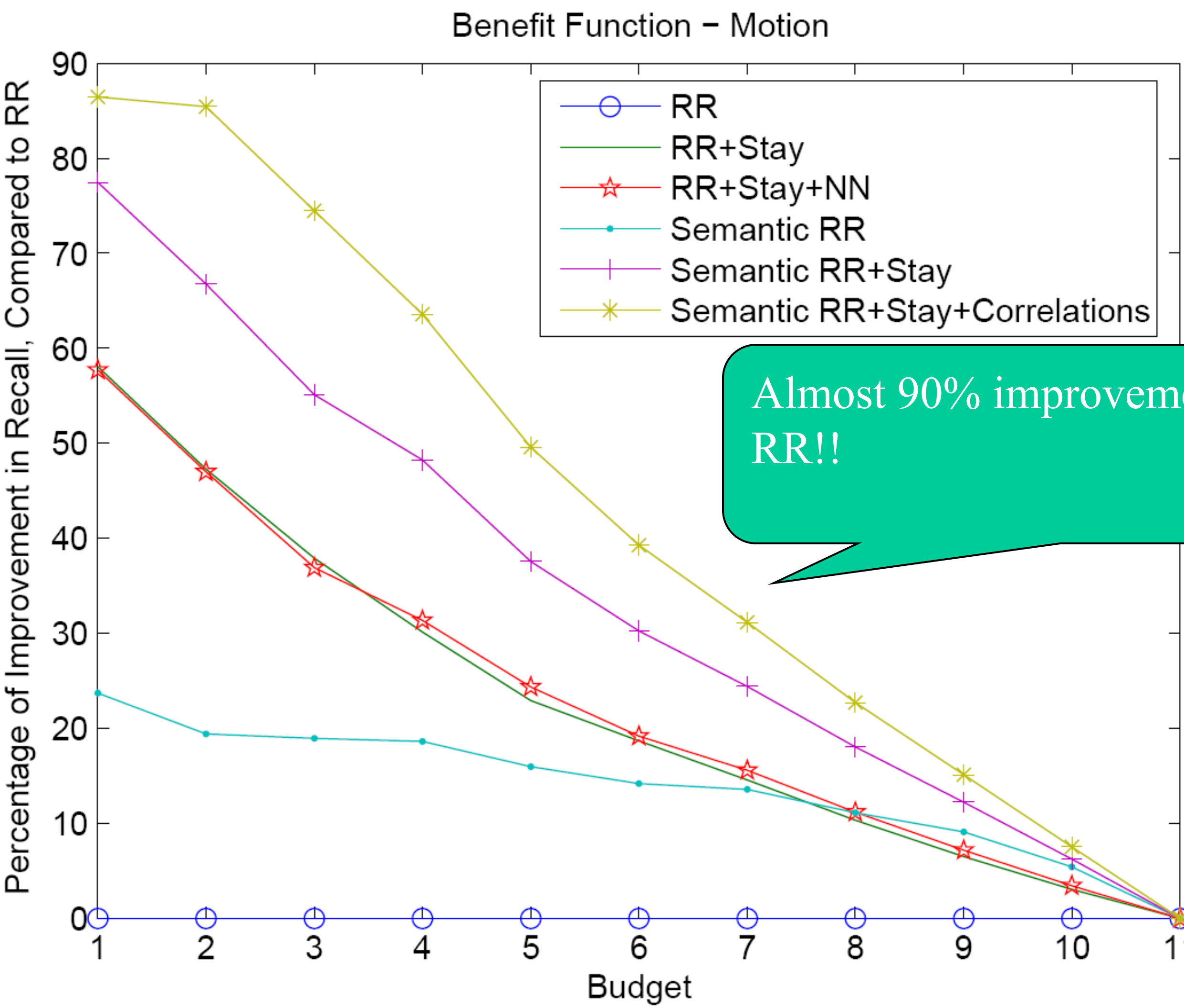
Semantics Based Task Scheduling

- ***A priori:***
  - What are the cameras that we should probe, when nothing else is known.
- ***Self Correlation:***
  - If we've seen someone walking in camera A, how likely is it to see more motion in A.
- ***Cross Correlation:***
  - If this is the state of the system we are aware of:
    - We've seen motion in camera B 5 seconds ago.
    - And motion in camera C 2 seconds ago.
  - How likely is it to see motion in camera A.

Improvements by Exploiting Semantics in Scheduling



Almost 90% improvement compared to RR!!

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Benefits of SATware ..

- Application writers (primarily) deal with semantic level
  - Hides complexity of programming sensors, heterogeneity, errors, uncertainty
  - Similar to SQL, SATQL is declarative, concise, and can be optimized
- exposes the characteristics of the environment providing significant opportunities for adaptive data collection
- enables specification of privacy policies and reasoning with such policies in sentient spaces

A **powerful programming environment** for sentient space applications

Adaptivity to different loads
Robustness to physical changes in the environment

Native support for implementing **privacy**

Interoperability challenge 2

Heterogeneous Networks

Experiences in deploying WiFi Mesh

Commercial mesh routers not good enough

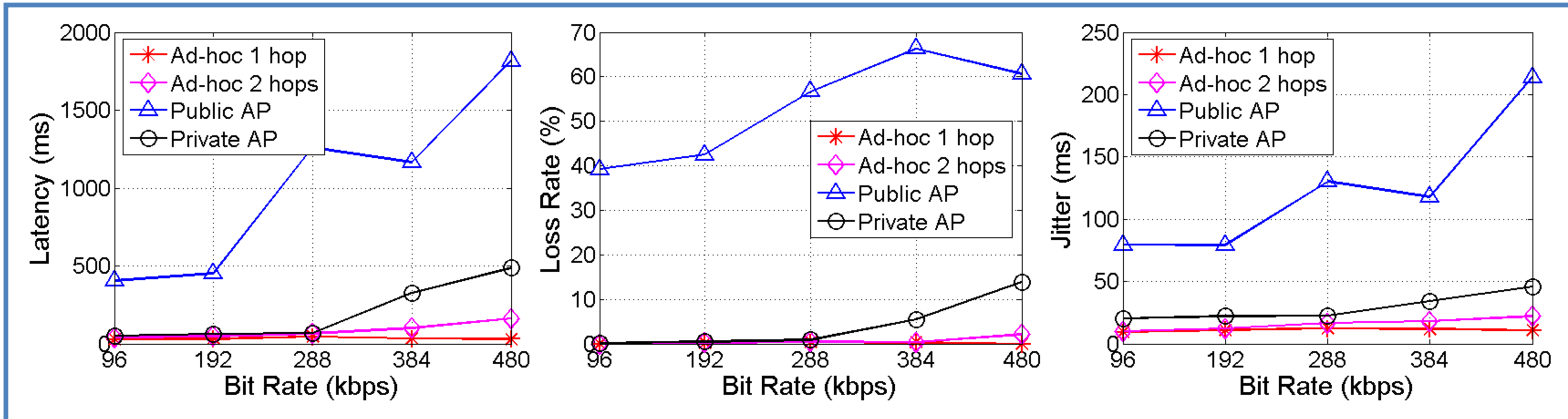
5X improvement with new antenna technology

Better signal coverage better building penetration

- Some Setup effort required
- Not always feasible
- Vulnerable to hardware failures

(Un) Reliability of Wi-Fi Networks

- Varying traffic load
- Varying level of contentions and congestions
- Varying inter-device distance



Ad-hoc 1hop > Ad-hoc 2 hops > Private AP >>> Public AP

- Increased bandwidth share
- Reduced contentions/collisions

- Less interferences
- Distributed Beaconing

- No background traffic
- Controllable configuration

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Wi-Fi (Speech)

Acoustic Capture | **Acoustic Analysis** | **SA**

Speech → Voice → Amb. Noise → **Processing**

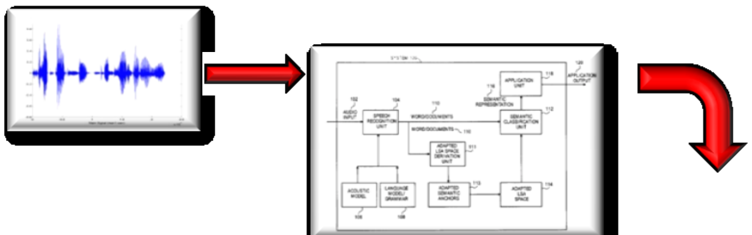
- Alerts
- Conversation Monitoring & Playback
- Image & Video Tagging
- Spatial Messaging
- Localization via Speech

Type of Acoustic Analysis

- **Human Speech:** Who spoke to whom about what from where and when
- **Ambient Sounds:** explosions, loud sounds, screaming, etc
- **Physiological Events:** cough, gag, excited state of speaker, slurring, …
- **Other features:** too loud, too quiet for too long, …

Different Goals of ASR & SA Applications

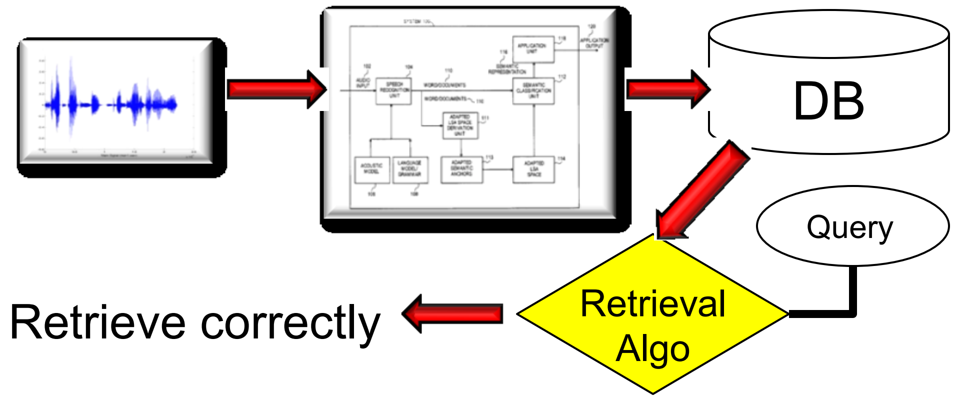
Recognition



This is a *bed sun tan*

This is a bad sentence

Acoustic Tagging & Retrieval



Result for Audio Transmission over WiFi:

	Noise: Network	Noise: Ambient	Text to Speech Ratio	Quality
Stationary	No	No	0.767	Very Clear
		Yes	0.589	Understandable
	Yes	No	0.533	Not Clear
		Yes	0.483	Not Clear
Mobile	No	No	0.739	Very Clear
		Yes	0.611	Understandable
	Yes	No	0.522	Not Clear
		Yes	0.467	Not Clear

Quality Metric :

Precision, recall, F-measure of

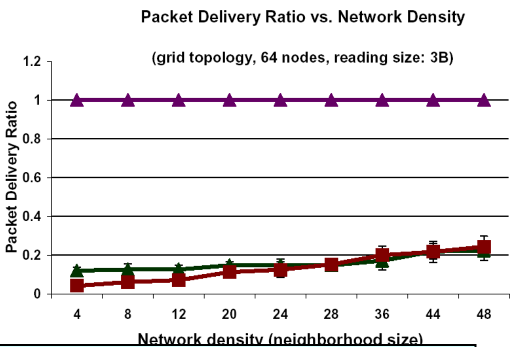
- returned images
- activated triggers

It can be possible to build a good retrieval system on uncertain data.

Low WER does not imply low retrieval & SA quality. *Observe: Errors in words that are not in triggers do not matter*

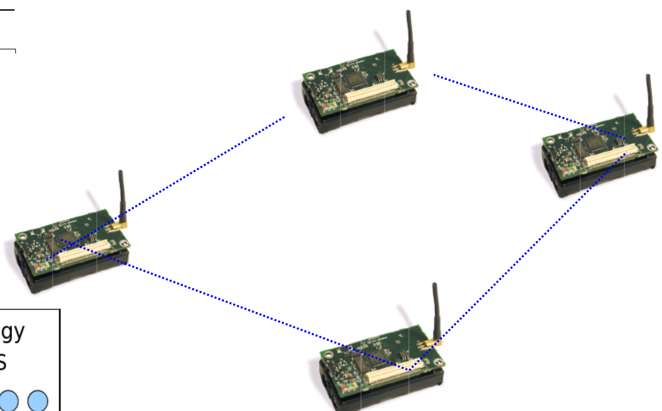
Experiences in deploying mote sensors and Zigbee networks

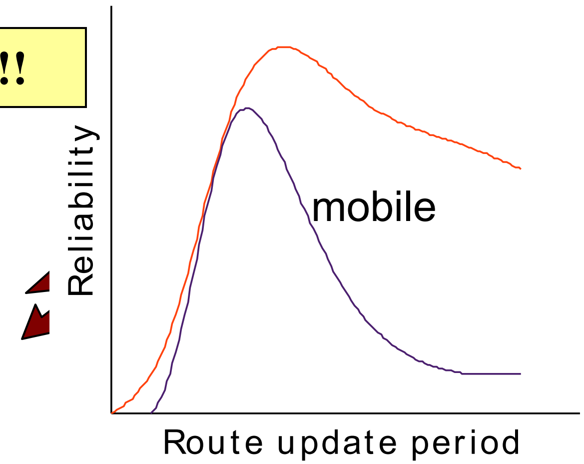
↑Mobility↓Reliability
Network convergence, gateway availability

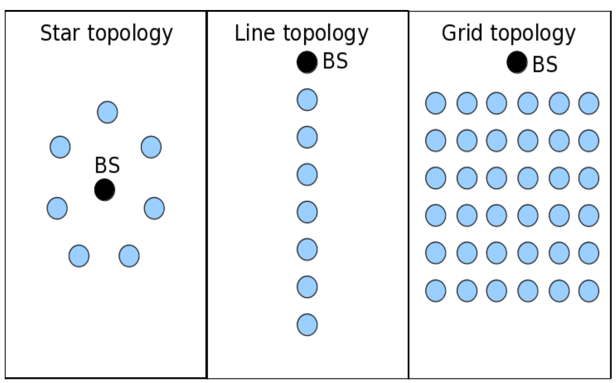


↑Density↑Reliability

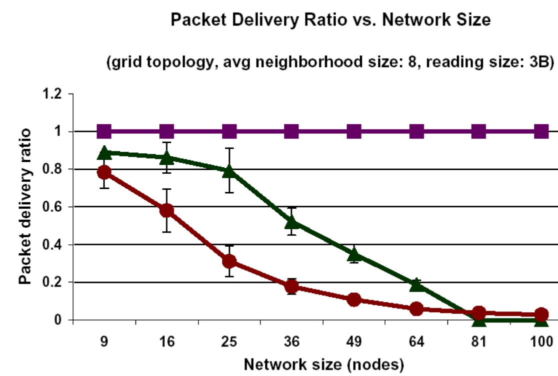
Frequency matters!!







Topology matters!!



↑Size↓Reliability

Lessons Learned using multiple networking technologies

- Despite multitudes of technologies, rapidly deployable, self-configuring networks that provide end-to-end & continuous connectivity are hard to create!!!
- Need Multinetwork State to choose proper access technologies, links, nodes
  - Links/Node State of different networks, access network topologies, their interactions
- Existing efforts – single network, lower layers (MAC, Network)

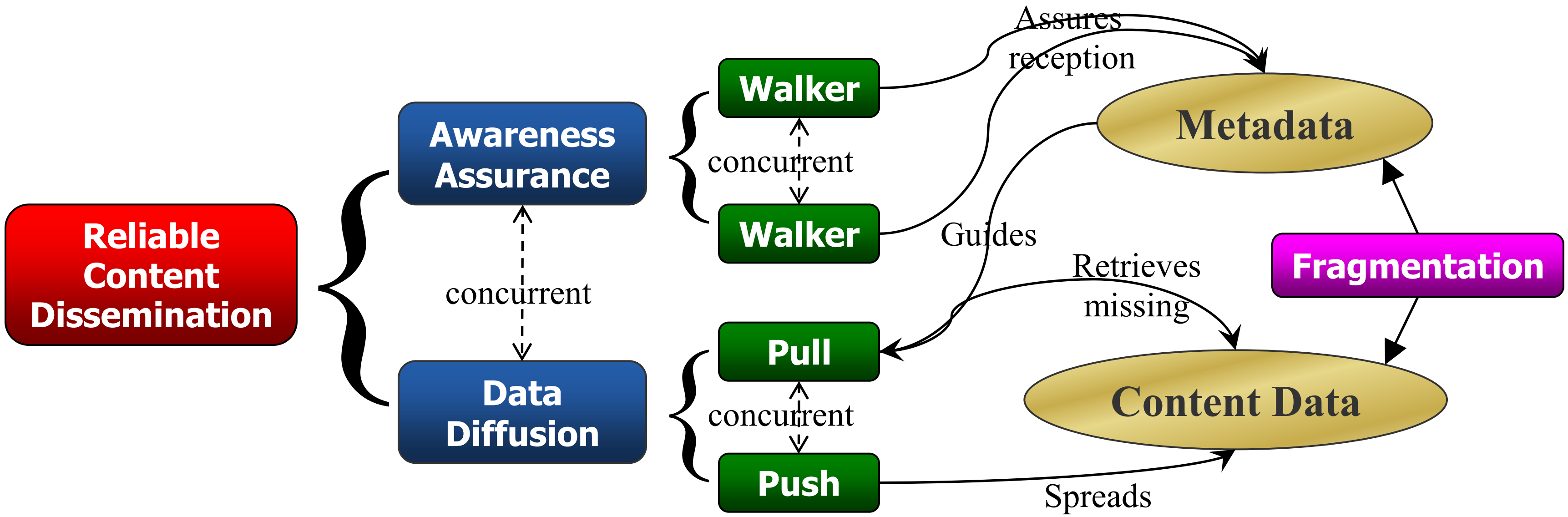
Techniques to enable network interoperability in CPS

- **Exploit application awareness in designing reliable communication protocols.**
- **Exploit multiple networks that together provide connectivity *(Mobiquitous 2005, WCNC 2007, INFOCOM 2009)***
    - WiFi mesh – direct connectivity to a mesh router
    - MANETS – hop by hop connectivity to gateway nodes
    - Infrastructure networks (3G cellular, 802.11 access point)
    - Zigbee adhoc – connect to WiFi backbone through gateway node
- **Exploit mobility when disconnected (SECON 2010)**
    - Store-and-forward networks (Delay Tolerant Networking)
        - mobile nodes ferry data to gateway node
- **Combine connected clouds and disconnected networks**
- **Customize messaging strategy – unicast,broadcast, multicast, anycast based on size, location/density, link availability**

Technique 1: Application aware reliable communication

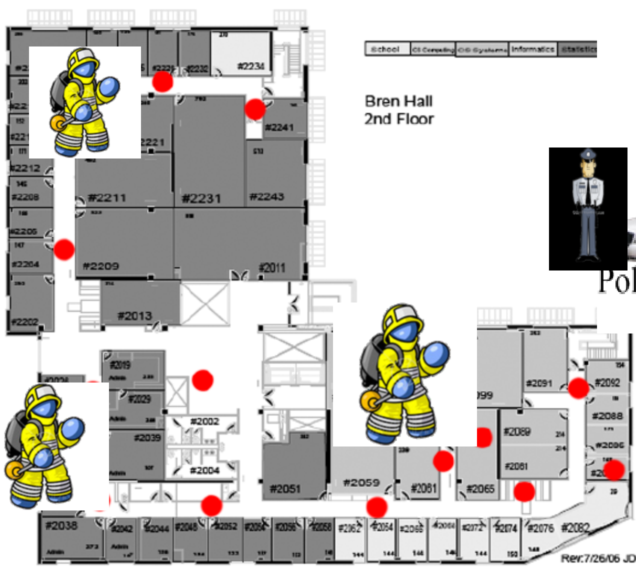
RADCAST: Flash Broadcast in MANETS *(Infocom 2009, Percom 2009)*

- Concurrent dissemination of awareness and content
  - Data diffusion: based on a mix of push/pull (Pryer)
  - Awareness assurance: network traversal using walkers (Peddler)
- Problem: fast network traversal (NP-hard)
  - Minimizing cover time, termination time and transmission overhead



Technique 2: Exploiting Multiple Access Networks

The Problem : Deliver contextual data to/from onsite responder to onsite incident commander and external entities



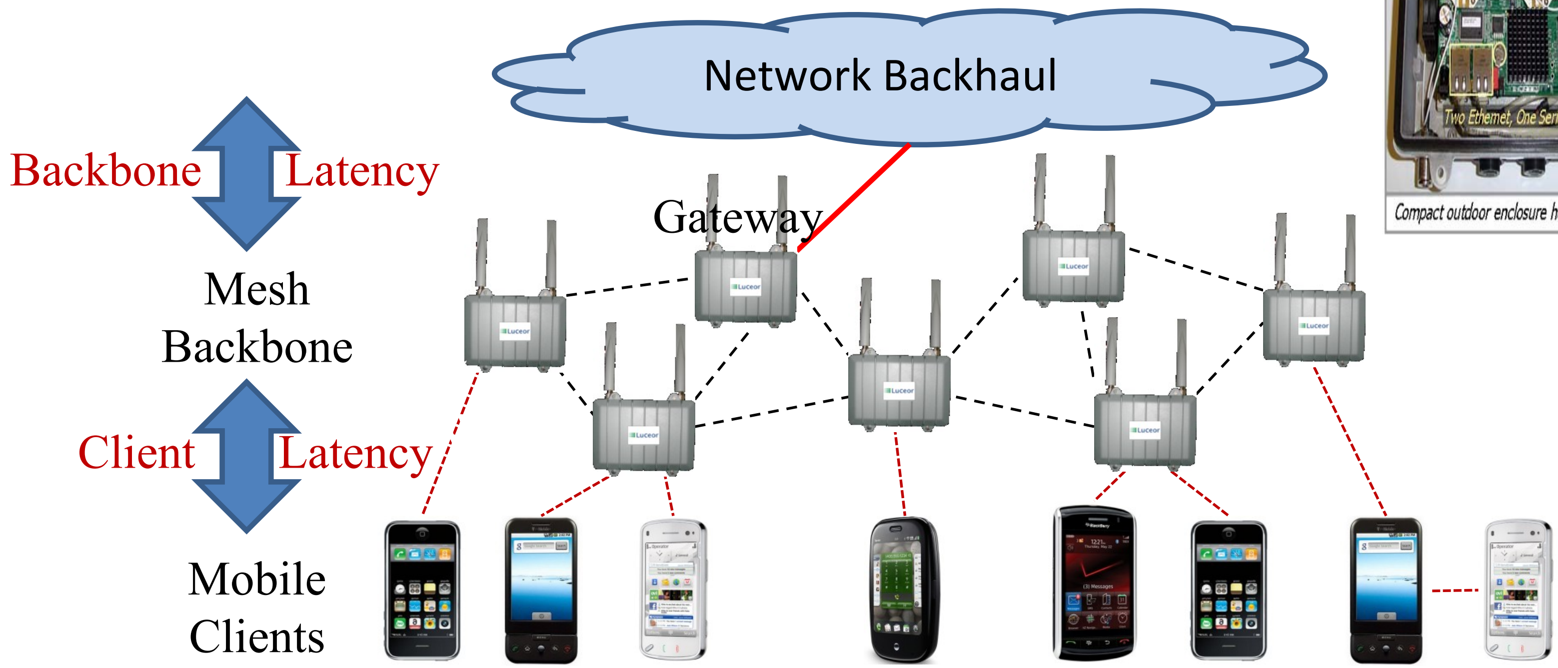
Goals

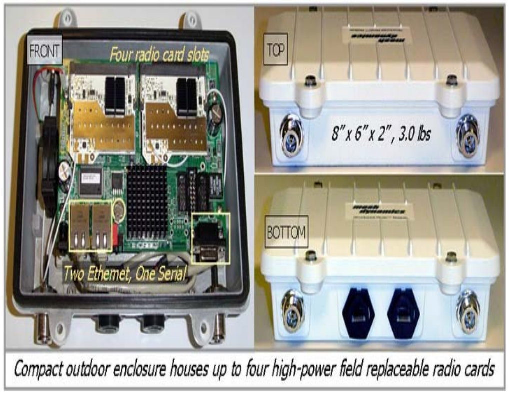
- **Reliability**
- Timeliness
- Message Efficiency

Challenges

- Limited infrastructure access
- High network deployment cost

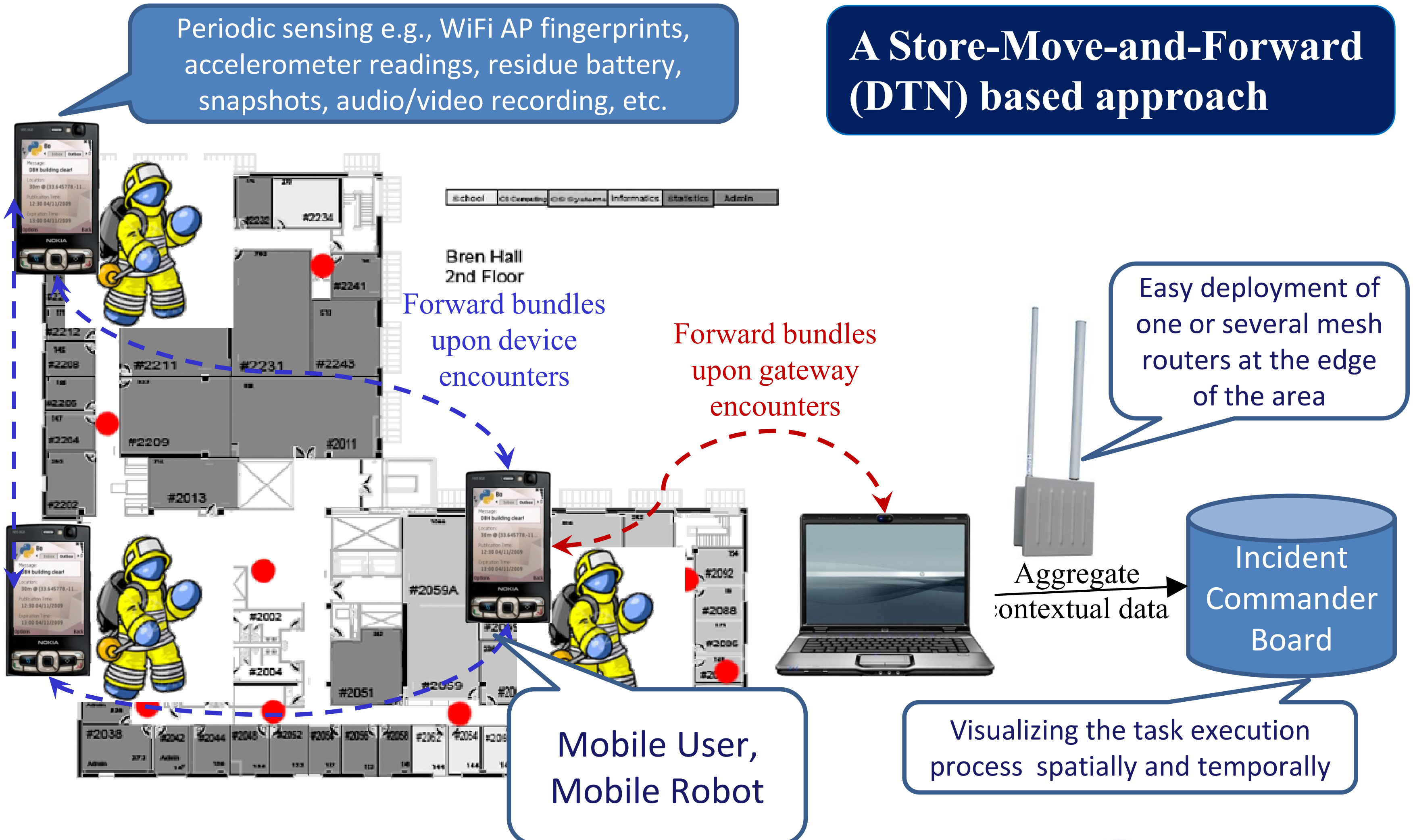
A Sample Problem: Gateway Designation Problem in Instant Mesh MultiNetworks





The Problem:
To determine which mesh router in a given mesh backbone should serve as the gateway, so that backbone latency is minimized.
Solution: **Use concepts from network centrality to find best gateways**

Technique 3: Use Mobility to Enhance Reliability in Disconnected Networks



The Store-and-Forward Data Transfer Problem

System Model

- Each device maintains a cache storing bundles from itself and others
- Devices exchange certain bundles in cache upon encounters

Goals

- High reliability
- Low storage cost
- Low transmission cost
- Short latency

Sub-Problems

Replication	• How many copies should be generated for each bundle?
Forwarding	• Which bundles should be forwarded upon device encounters, and in what order?
Purging	• Which bundles should be removed to accommodate incoming bundles upon cache overflow?

Hierarchical Approach to Multinetwork State Management

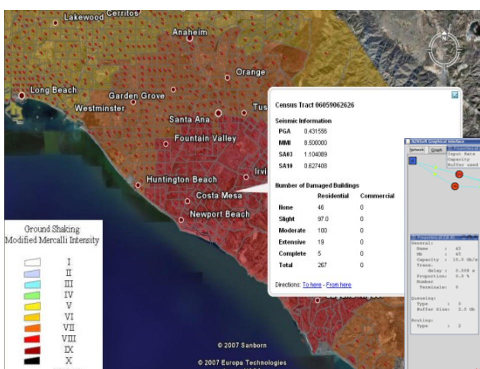
- Need Multinetwork State to choose proper access technologies, links, nodes
  - Links/Node State of different networks, access network topologies, their interactions
- A multilevel approach to organizing networks based on
  - Node Stability (fixed, mostly stationary, mobile)
  - Connectivity features
- Devise techniques to collect and maintain multinetwork state efficiently.

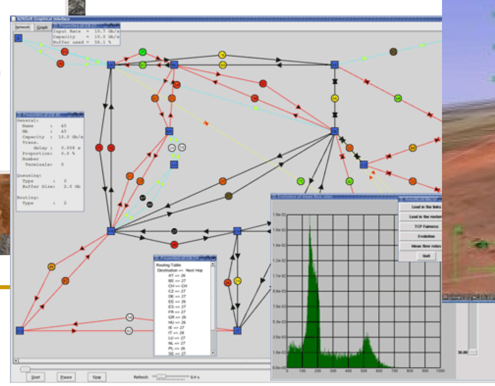
Interoperability challenge 3

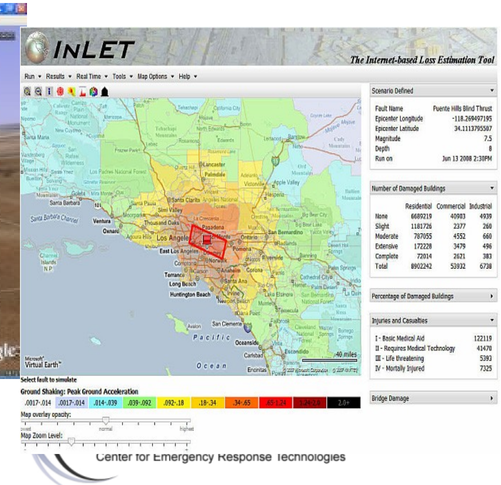
Heterogeneous Applications

Heterogeneous applications

- **Multisimulations-** Integrated Simulation Environments
- Many available simulators
  - Operate on **specific domains**
    - Planning and decision support- defence simulations, emergency response simulations e.g fire simulators
    - Domain specific Testing and Analysis - traffic analysis, human behaviour study: crowd dynamics or evacuation simulators, network simulators, , transportation simulators.
    - Immersive synthetic platforms for training







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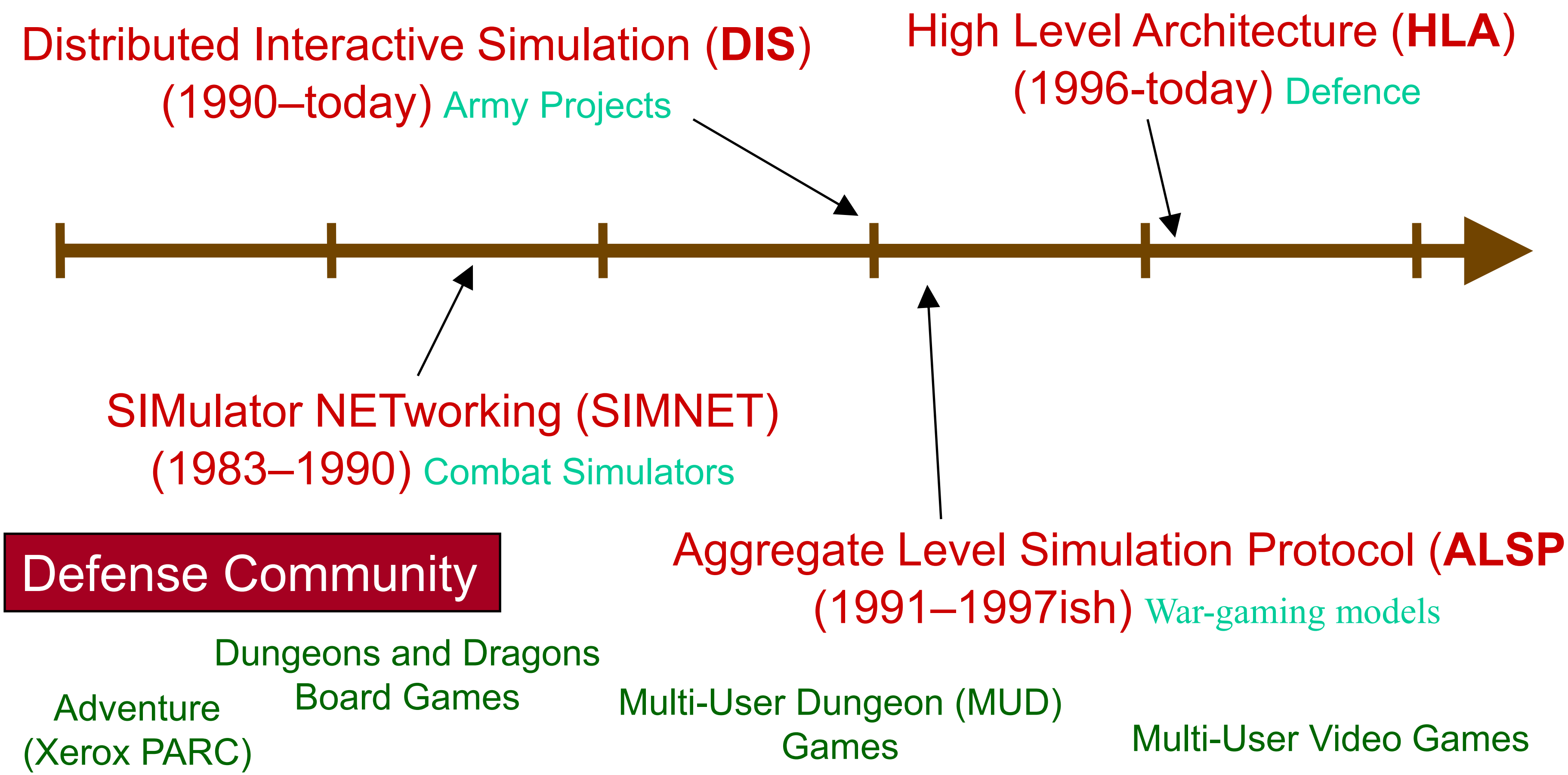
Motivation for Multisimulations

- Interoperability of heterogeneous applications: s***imulation models***
  - Many available simulators that operate on specific domains- e.g fire simulators, transportation simulators
- Infeasible to build complex simulations entirely from scratch
- Need ability to build ***Multisimulations***
  - The ***reuse*** mechanism to build new simulation platform from the existing ones
  - The ***interoperability*** mechanisms to bring together simulators from various modeling domains
  - Model and test larger and more complex scenarios
  - Study cause- effect relationships to integrate simulators

Simulation Integration- *historical view*



Limitations of current approaches

- Existing Integrated platforms, define a standard model and require the individual simulators to conform to the standard
  - It might not be always possible
  - The standard may not have designed to handle the new simulator needs
  - Current model registration needs a lot of manual work
  - The approaches are costly, time consuming, easily fail, difficult to maintain, difficult to scale

HLA:

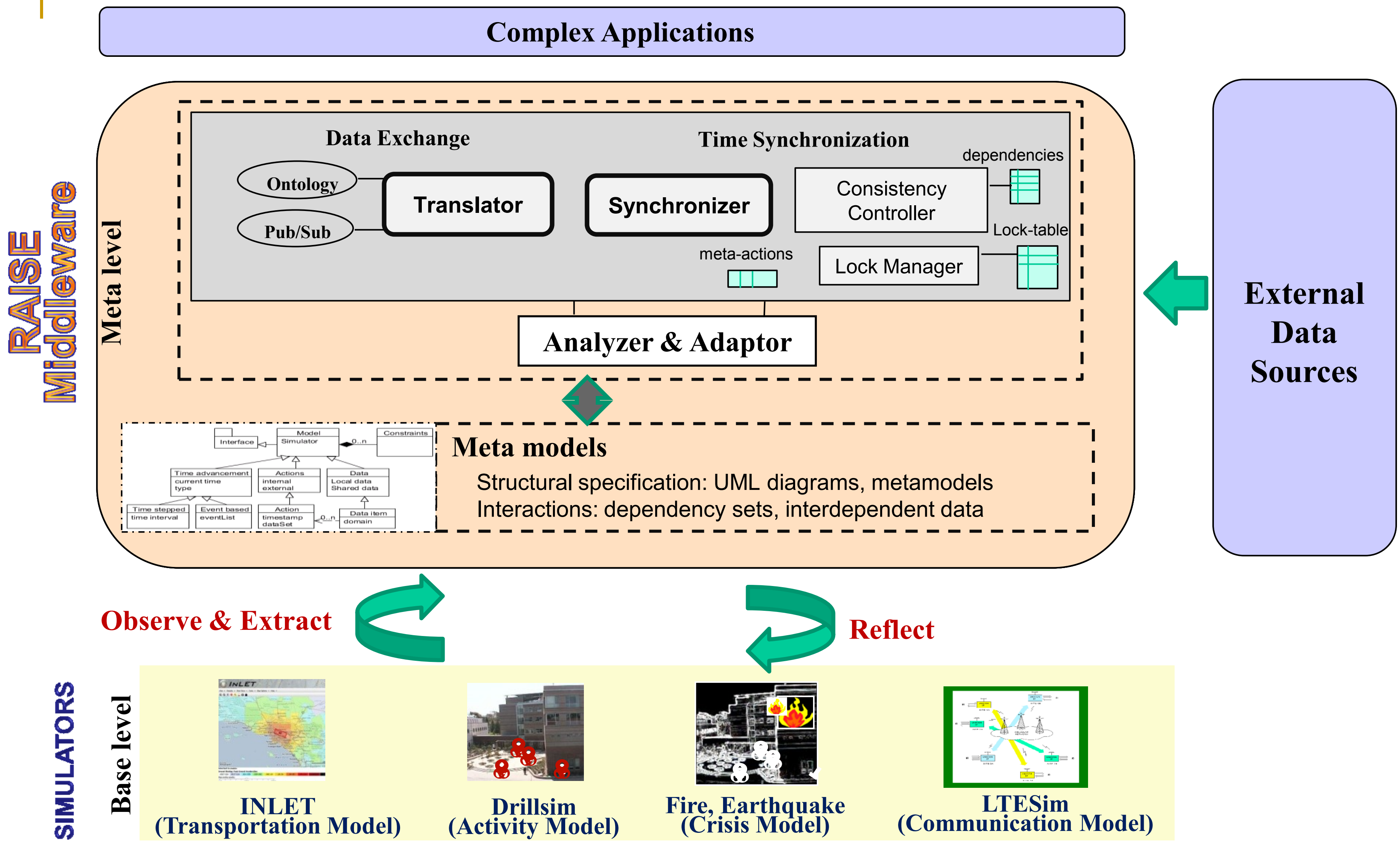
- **Low level knowledge needed from the practitioner**
- **Cost issues**
- **Complexity**
- **No support for semantic interoperability**
- **Transparency**
- **HLA is too big and mainly applied in defense**

Most of other works on simulation integration provided specific services for interoperability in a small range of cases

RAISE- reflective system for multisimulations

- Research project aimed at **building a framework that supports the integration of multiple existing simulation models**
- Goal is to create a platform that takes expert simulation models of constituent real-world systems related to emergency response domain, integrating those models, **resulting in an interoperating complex composite simulation** with which policy-makers can try out alternatives in a low-cost, highly responsive way.
- Using Reflective architecture to support:
  - ***Reusability***: to reuse finer-grained simulators that are available, rapid simulation development , cost effective
  - ***Scalability***: to design and implement scalable simulation engines
  - ***Composability***: to provide capability to select and assemble simulation components in various combinations into simulation systems

RAISE- architecture overview

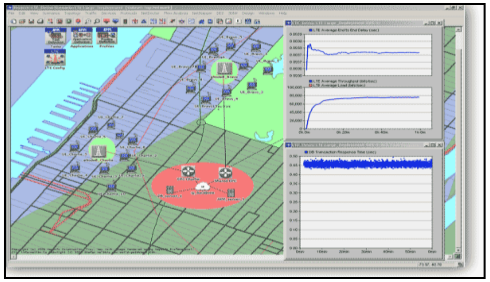


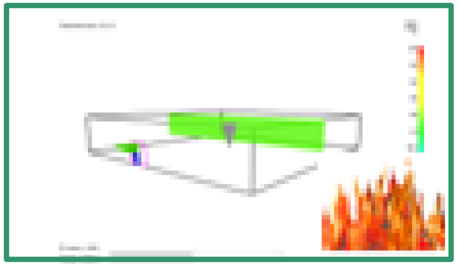
General Challenges in RAISE

- ***Managing Complexity of Interoperating Systems***
  - Analysis of cause- effect relationships
  - Reusability: e.g. components, models
  - We use meta models to describe simulator-related meta-data
    - Make the underlying simulator more understandable
    - Abstract of lower-level details of integration and interoperability
- ***Correctness***
  - Ensure the correctness of integrated simulation environments
    - Time synchronization: timing issues and causality correctness
    - Data exchange: data transformations
- ***Scalability***
  - e.g multiple geographies

A Case study for Simulation Integration

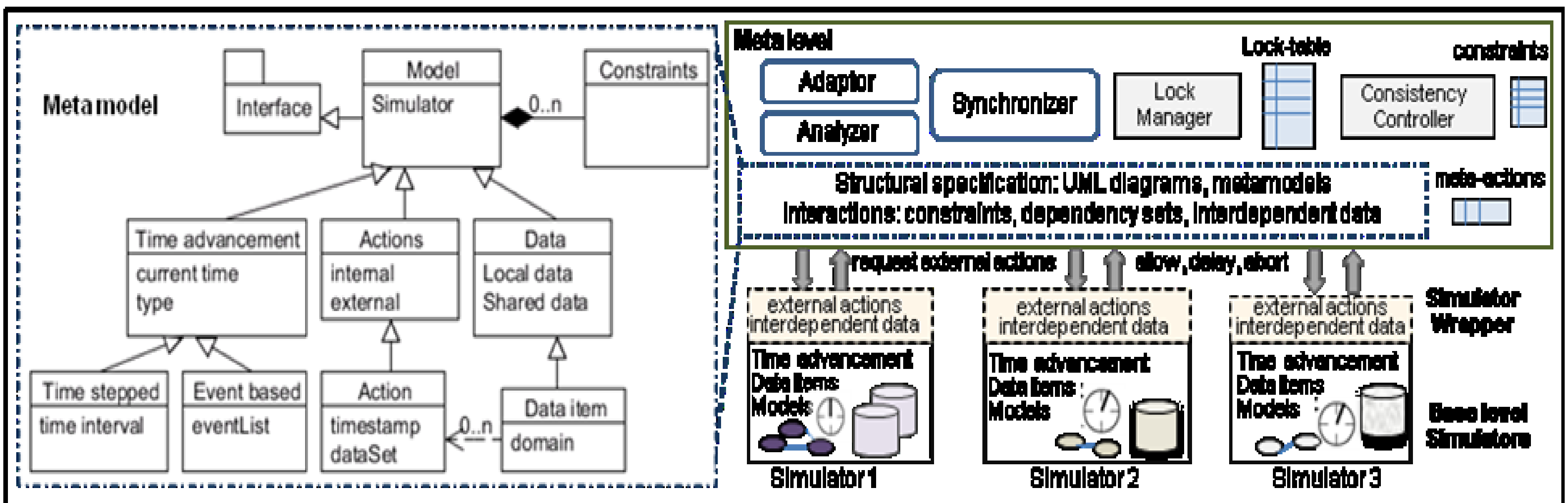
Evacuation Simulator	Communication Simulator	Fire Simulator
❖DrillSim [9] ❖ Simulates a response activity evacuation ❖Time stepped ❖Open source (in Java) ❖Agent based ❖Parameters: health profile, visual distance, speed of walking, num. of ongoing call, etc. ❖Output: num. of evacuees, injuries, etc	❖LTESim [31] ❖Performs network level simulations of 3GPP LTE ❖Event based ❖Open source (in Matlab) ❖Parameters: num. of transmit and receive antennas, uplink delay, network layout, channel model, bandwidth, frequency, receiver noise, etc. ❖Output: pathloss, throughput, etc.	❖CFAST [10] ❖Simulates the effects of fire and smoke inside a building ❖Time stepped ❖Black-box (no access to source) ❖Parameters: building geometry, materials of construction, fire properties. ❖Output: temperatures, pressure, gas concentrations: CO_2, etc.





Prototype System Implementation

- **Analyzer and Adaptor**: to provide data transfer between simulators using data translators
  - e.g. update an agent's health in Drillsim based on the harmful condition in CFAST
  - Geometry Transformer: different representation of coordinate systems and resolutions, Using a set of guide points in multiple geographies and determine a coordinate transform matrix
- **Synchronizer:** to monitor and control concurrent execution of multiple simulations
  - Using concepts from serializability theory in transaction processing
  - Developed three techniques: conservative, optimistic, hybrid



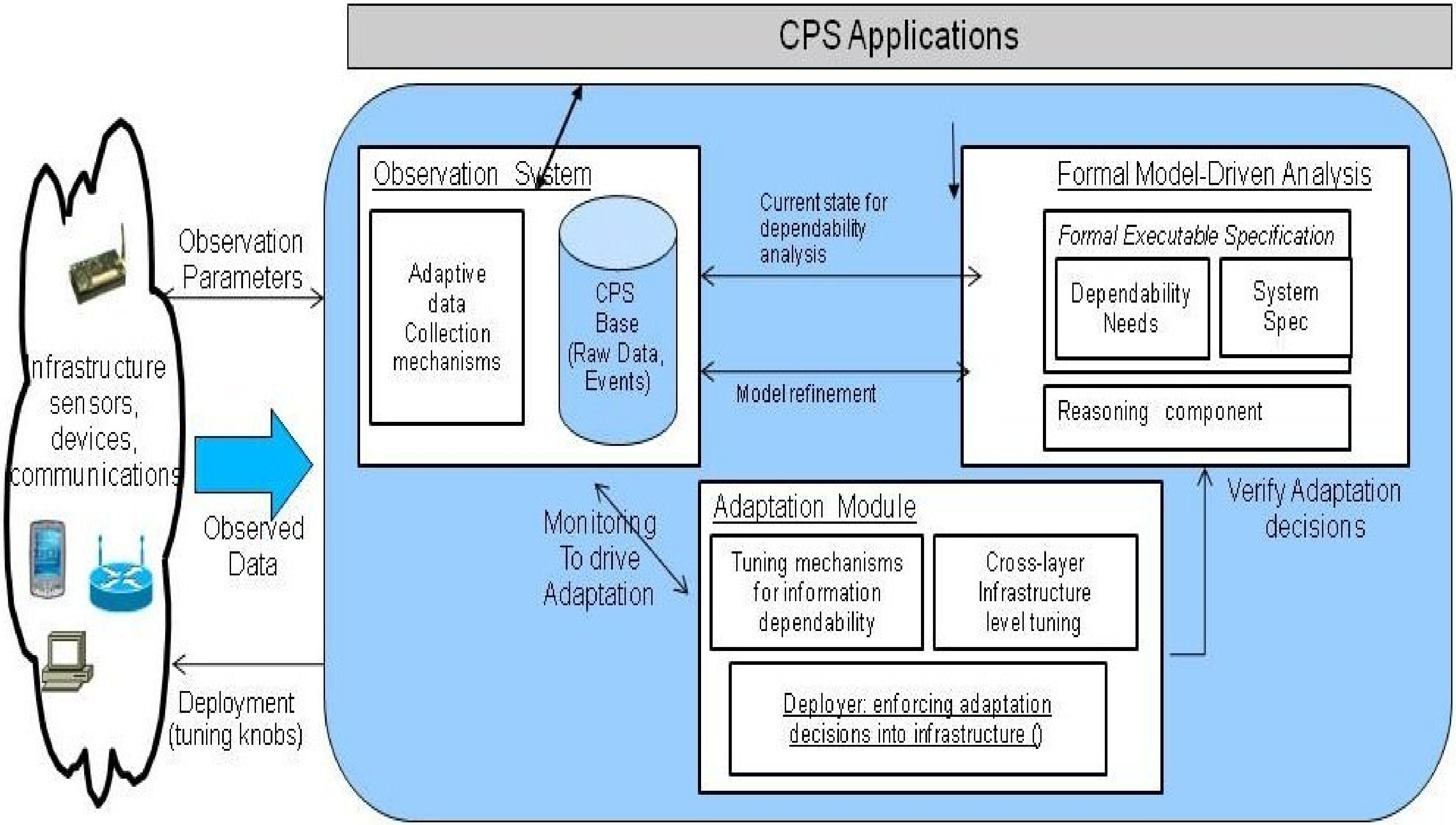
Outline

- Introduction of Cyber Physical System
- Instrumented Cyber Physical Space
- Related projects at UCI
  - SATWARE, SAFIRE, Responsphere
- Interoperability challenges
  - Multi-layer perspective
- Formal methods for interoperable networked CPS

Formal methods for interoperable networked CPS – thoughts

- Formal methods and tools must work with
  - Dynamic topologies, network partitions, and mobile nodes
  - Heterogeneous nodes and networking technologies
- Key Problem
  - Traditional logics are not designed for distributed reasoning
  - Logics are traditionally closed systems, i.e. not interactive
- Potential principles
  - A New Partially ordered knowledge-sharing model for loosely coupled distributed computing
  - Distributed logic for declarative control
  - Lightweight on-the-fly formal reasoning

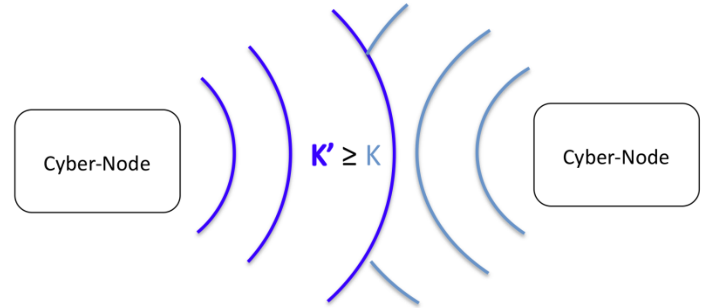
Lightweight Formal Methods for Adaptation in CPS

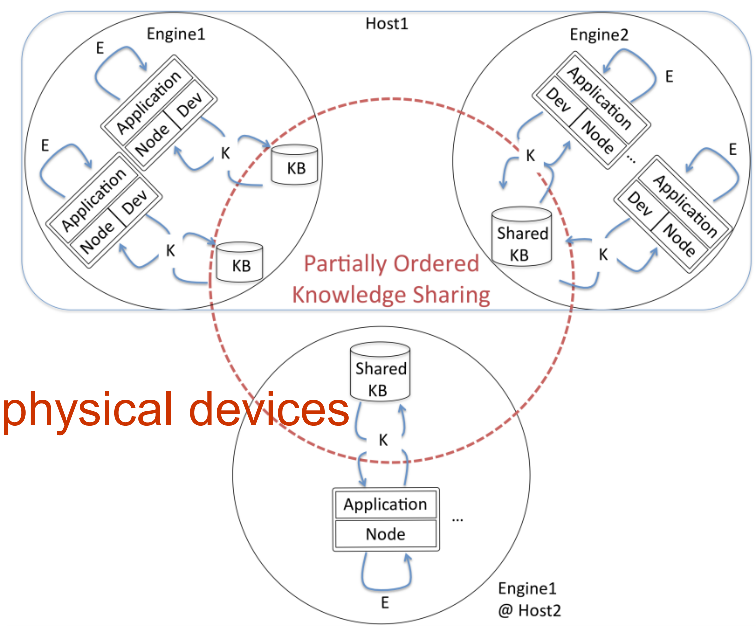


Partially Ordered Knowledge Sharing

New Loosely Coupled Distributed Computing Model

- Inspired by our earlier work on delay-/disruption-tolerant networking (DTN)
- Minimal assumptions on network connectivity (can be very unreliable)
- Partial order allows the network to replace obsolete or subsumed knowledge
- Global consistency is not enforced (impossible in disruptive environments)
- Avoids strong non-implementable primitives, e.g. transactions
- Locally each cyber-node uses an event-based model with local time
- Each cyber-node can have attached cyber-physical devices





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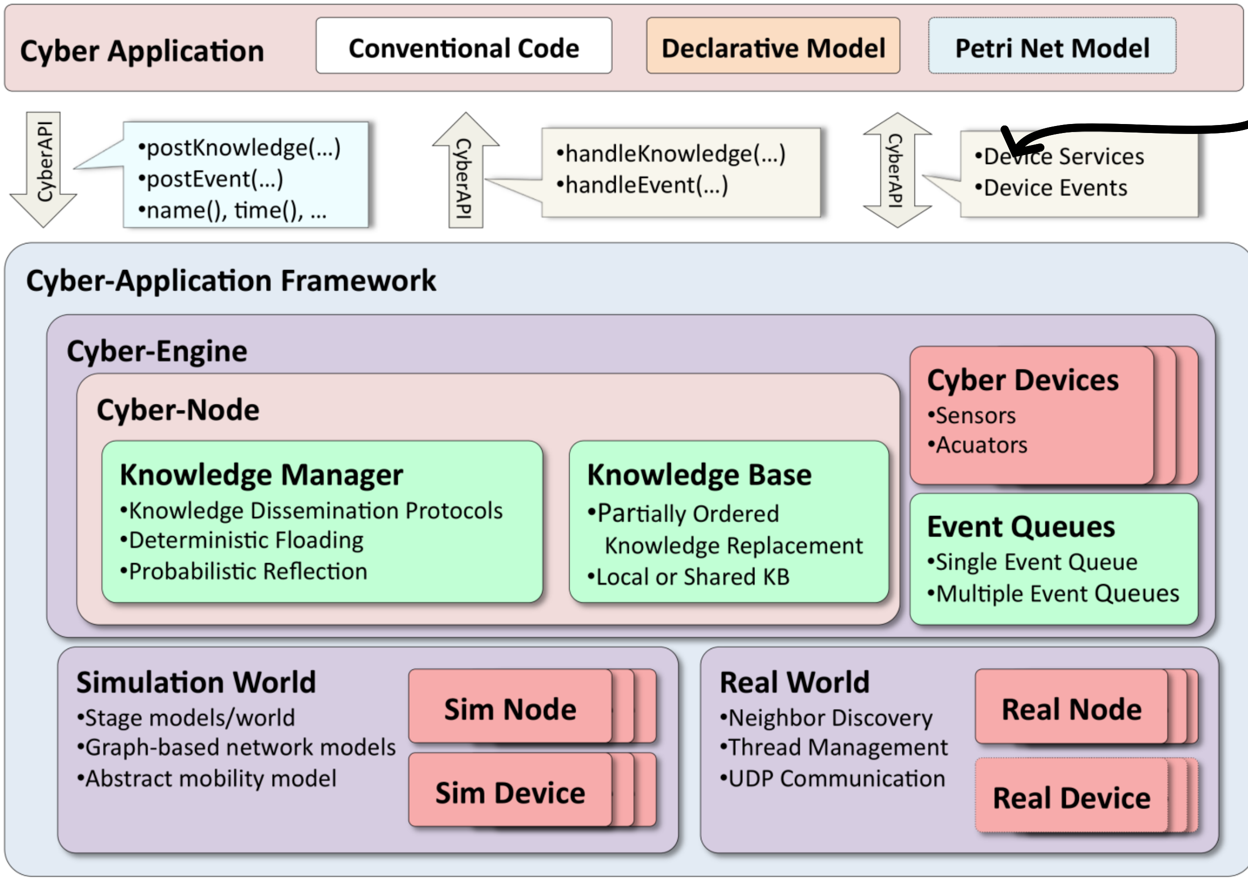
Cyber-Application Framework

- Cyber-framework implements partially ordered knowledge-sharing model
- Logical framework is implemented as a cyber-application
- Can coexist and interoperate with conventional code



Mechanisms to allow same application code to be used for simulation and deployment.

Other challenges

- Sustainability and Efficiency
- Privacy, Security, Trust
- Resilience and Dependability