Recent Progress on Sensor Networks and Embedded Computing

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Acknowledgment

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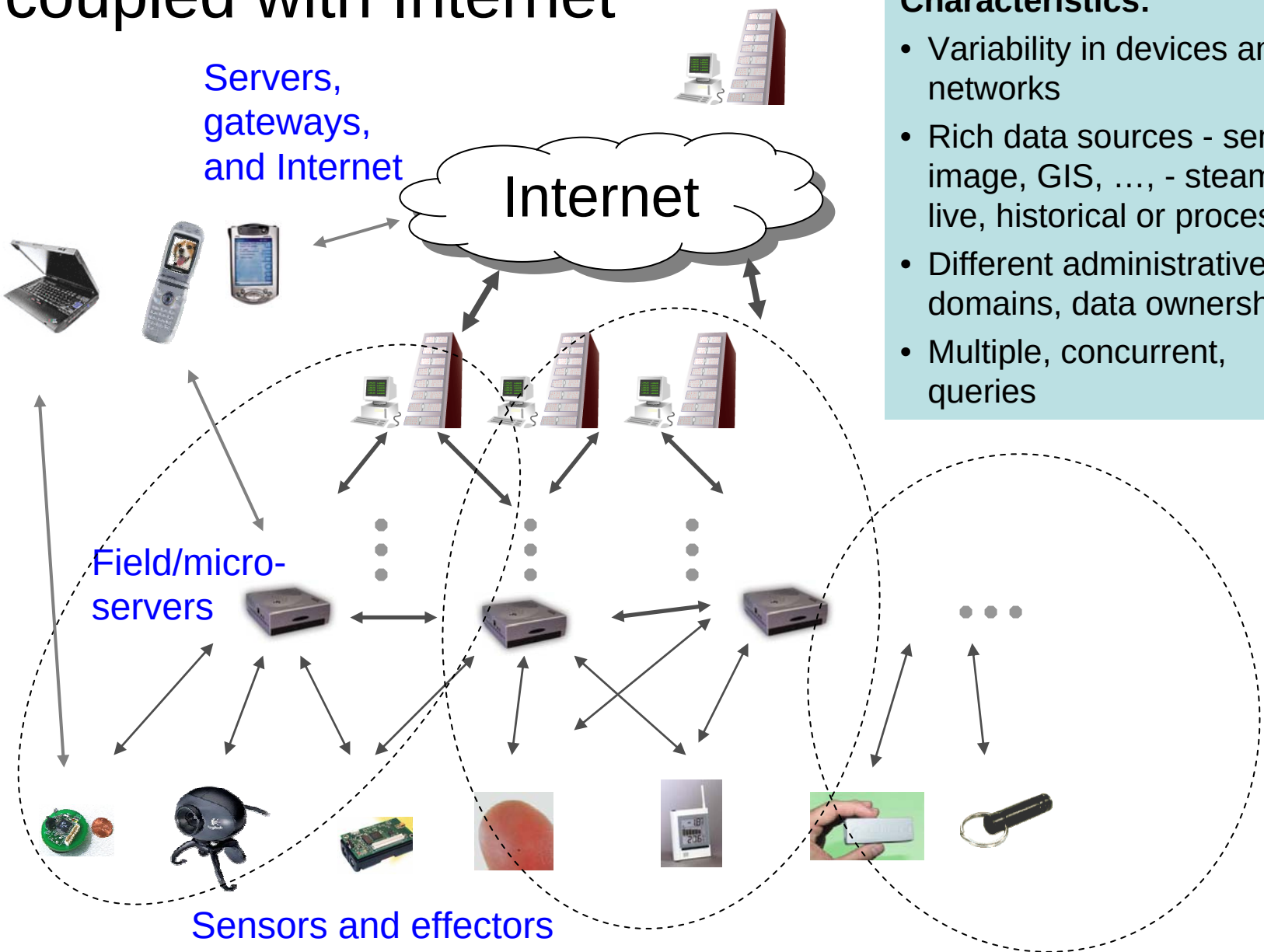
- Collaborations with Johannes Helander, Tom Blank, Mike Sinclair, Ray Bittner
- Engineering help from Jessica Miller, Darren Gehring, Piali Choudhury and MSRSUPP
- Partnership with Stewart Tansley of MSR ERP

Highlights

- The MSR Networked Embedded Computing Group inaugurated 3/04
- Focused on programming, tools, sensor/Web mash-up, and platforms. Published 8 papers on the new results.
- MSRSense **Toolkit** source code released 12/14/05, with 7000+ downloads since, and on MSR Home Page popular download list in 4/06. DVD kit ready for 7/06 Faculty Summit
- MSR Sensornet **Workshop** successfully held 10/10-11/05, with 50 people attending, including many leading researchers in the field. Keynotes by Kris Pister and Tony Hey. All presentation materials online.
- **SenseWeb** prototype demoed 5/06, with coverage in *Technology Review*, *EE Times*, *InternetNews* etc., hundreds of blogs, and over 130,000 hits on Google search within weeks. Portal ready for Faculty Summit.

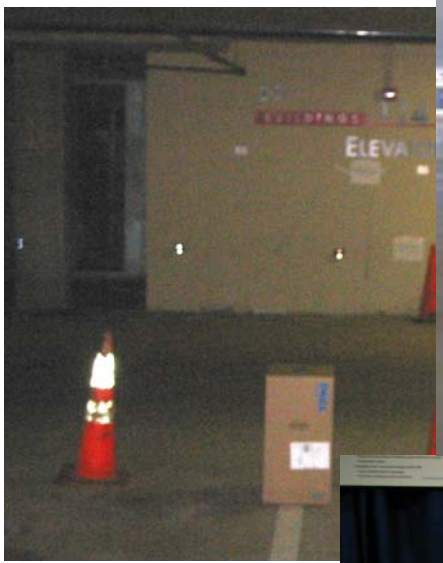
Multi-tier net of sensornets, coupled with Internet



Characteristics:

- Variability in devices and networks
- Rich data sources - sensor, image, GIS, …, - steaming, live, historical or processed
- Different administrative domains, data ownership
- Multiple, concurrent, queries

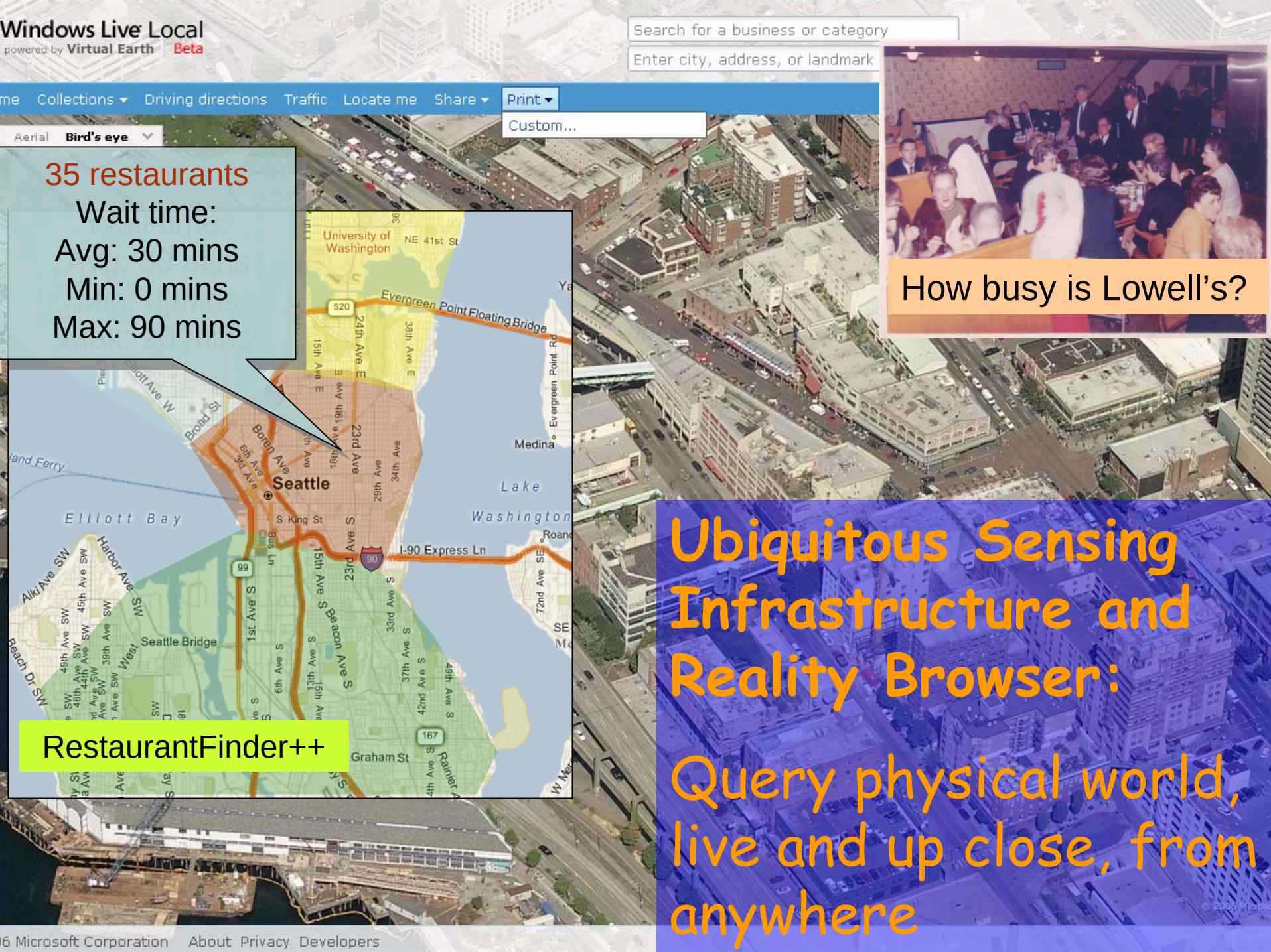
Space Monitoring Apps




N
Okanogan National Forest
Anacortes
Saanich
Winthrop
UNITED STATES
Omak
Okanogan
Strait of Juan de Fuca
Port Townsend
Port Angeles
Glacier Peak Wilderness
Bridgeport
Forks
Everett
104
Olympic National Park
Olympic Peninsula
Wenatchee National Fores
2
Shoreline
Kirkland
Redmond
Seattle
Bellevue
Mount Baker-Snoqualmie National Forest
Waterville
Bremerton
Renton
Quinault Indian Reservation
Olympic National Forest
Wenatchee
Federal Way
Ephrata
28
Quincy
University Place
Tacoma
Lakewood
Cascade Range
8
Lacey
Olympia
Montesano
Hoquiam
Aberdeen
Ellensburg
Royal City
Mt. Rainier National Park
WASHINGTON
Othello
Centralia
Chehalis
South Bend
Yakima
12
Goat Rocks Wilderness
Sunnyside
Grandview
Richland
Astoria
Cathlamet
Gifford Pinchot National Forest
Prosser
82
Yakama Indian Reservation
Seaside
40 mi
© 2005 Microsoft Corp
Goldendale

Projects

- SenseWeb
  - Sensors meet World-Wide Web: platforms for organizing and browsing live data
    - http://research.microsoft.com/nec/senseweb
- MSR Sense Toolkit
  - .NET/PC/mote tools for collecting, processing, visualizing, and archiving sensor data
    - http://research.microsoft.com/nec/msrsense
- SONGS
  - Service-oriented approach to programming and managing federated devices such as sensors
- mPlatform
  - A ref platform design for mobile/embedded apps: reconfigurable hw/sw for power-aware processing/communication


Windows Live Local
powered by Virtual Earth Beta
Search for a business or category
Enter city, address, or landmark
Collections
Driving directions
Traffic
Locate me
Share
Print
Custom...
Aerial
Bird's eye
35 restaurants
Wait time:
Avg: 30 mins
Min: 0 mins
Max: 90 mins
University of Washington
NE 41st St
Evergreen Point Floating Bridge
520
24th Ave E
23rd Ave
Medina
Lake Washington
Seattle
Elliott Bay
S King St
I-90 Express Ln
90
99
Seattle Bridge
Beacon Ave S
167
Graham St
RestaurantFinder++
How busy is Lowell's?
Ubiquitous Sensing Infrastructure and Reality Browser:
Query physical world, live and up close, from anywhere
© 2006 Microsoft Corporation
About
Privacy
Developers

Potential Apps

- Environment
  - Volcano, underwater, rainforest
- Education
  - K-12 interactive learning, virtual laboratory
- Leisure
  - Virtual travel, sunny spot tracker (for Seattle!), what is the temperature at my favorite beach? what is the water algae level?
- Getting around
  - Where is the nearest available parking space? What is the traffic like on the bridge? How long is the queue at the gas station? Where is the bus?

SenseWeb

- Goal: Simplifying <u>publishing</u> live data on Web and <u>querying</u> that data (from sensors)

Indexing live data
Processing queries on the data

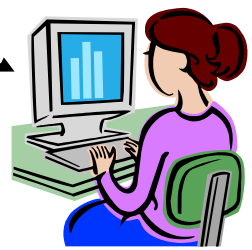
SenseWeb

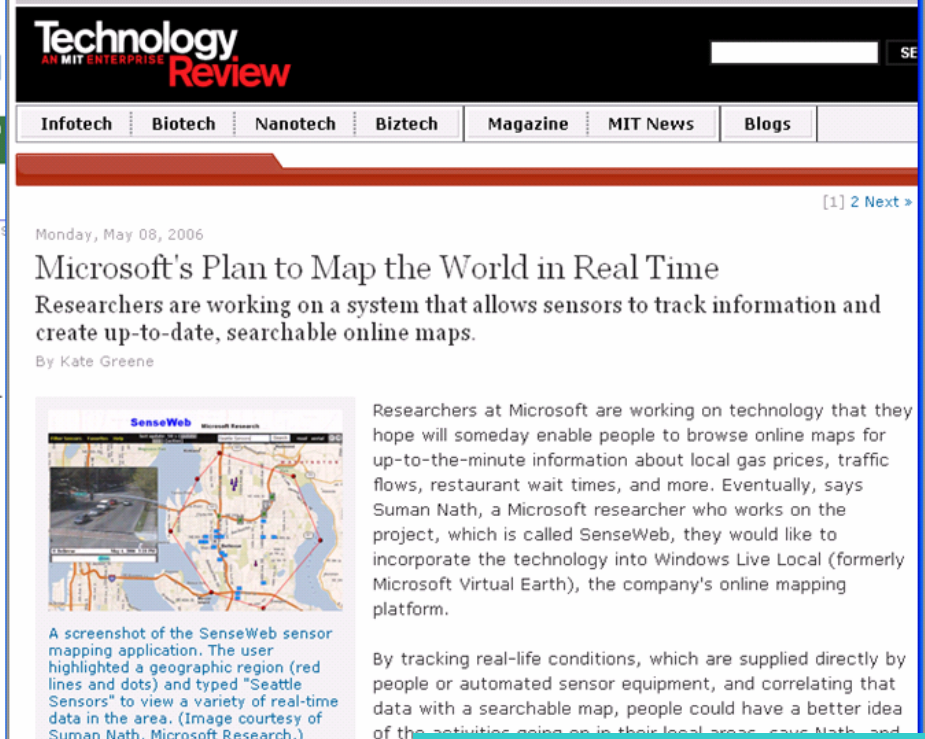
(Indexing, query processing, caching, scalability, etc.)

Query response

Data publishing

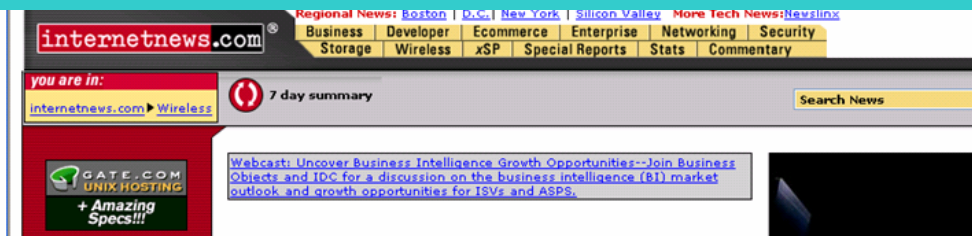
- Generic functionalities implemented
- Programmable



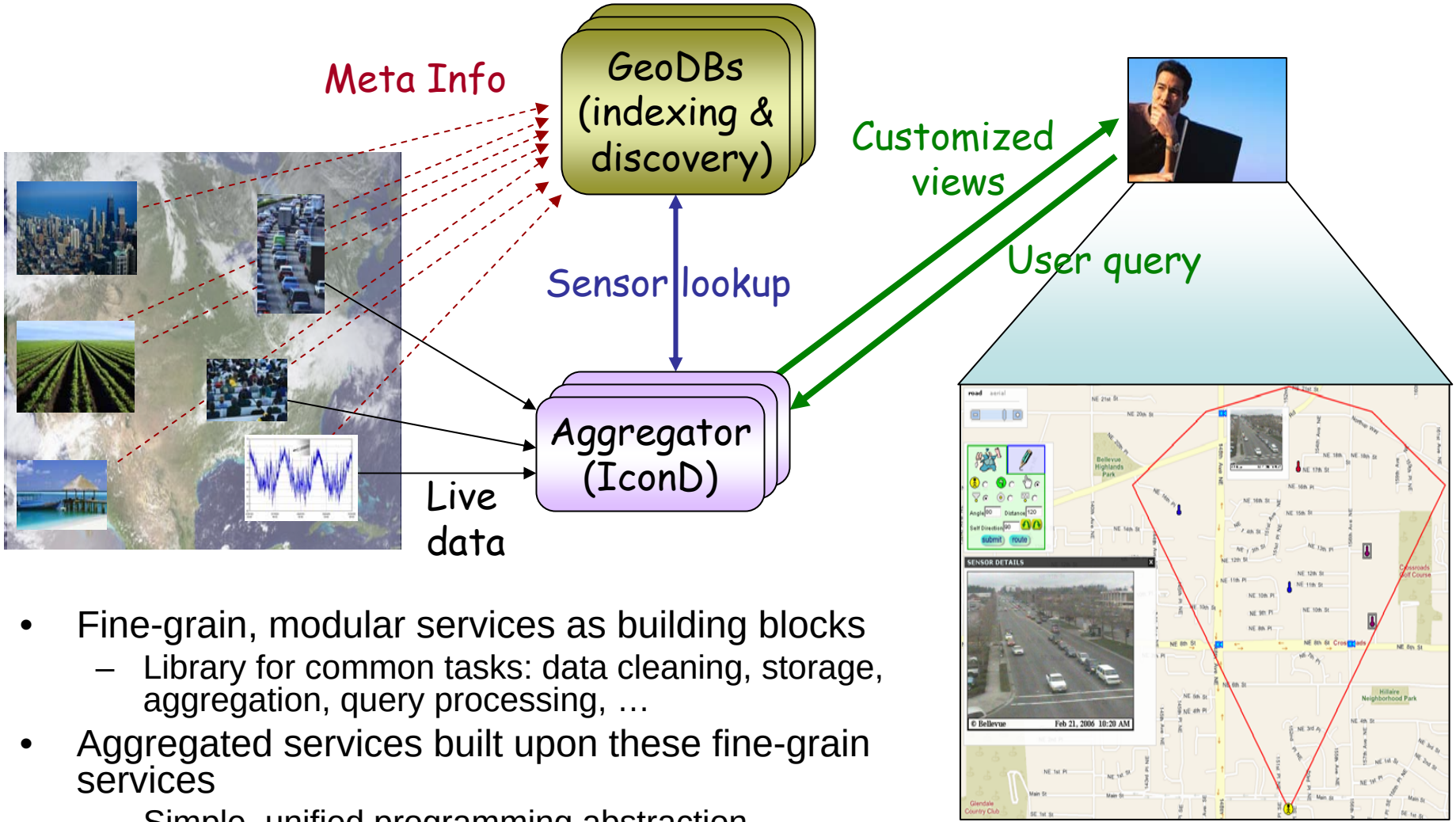


News articles on SenseWeb:

- Microsoft's Plan to Map the World in Real Time, *Technology Review*, 5/8/06
- Adding Real-Time Info to Local Searchers, *InternewNews.com*, 5/11/06
- Microsoft Research showcases future technology, *EETimes, InformationWeek, CRN*, 5/3/06
- Microsoft Keeping Web Arsenal Well-Stocked, *TheStreet.com*, 5/3/06
- Over 130,000 hits on “SenseWeb” and “Microsoft” using Google search within weeks



SenseWeb Architecture

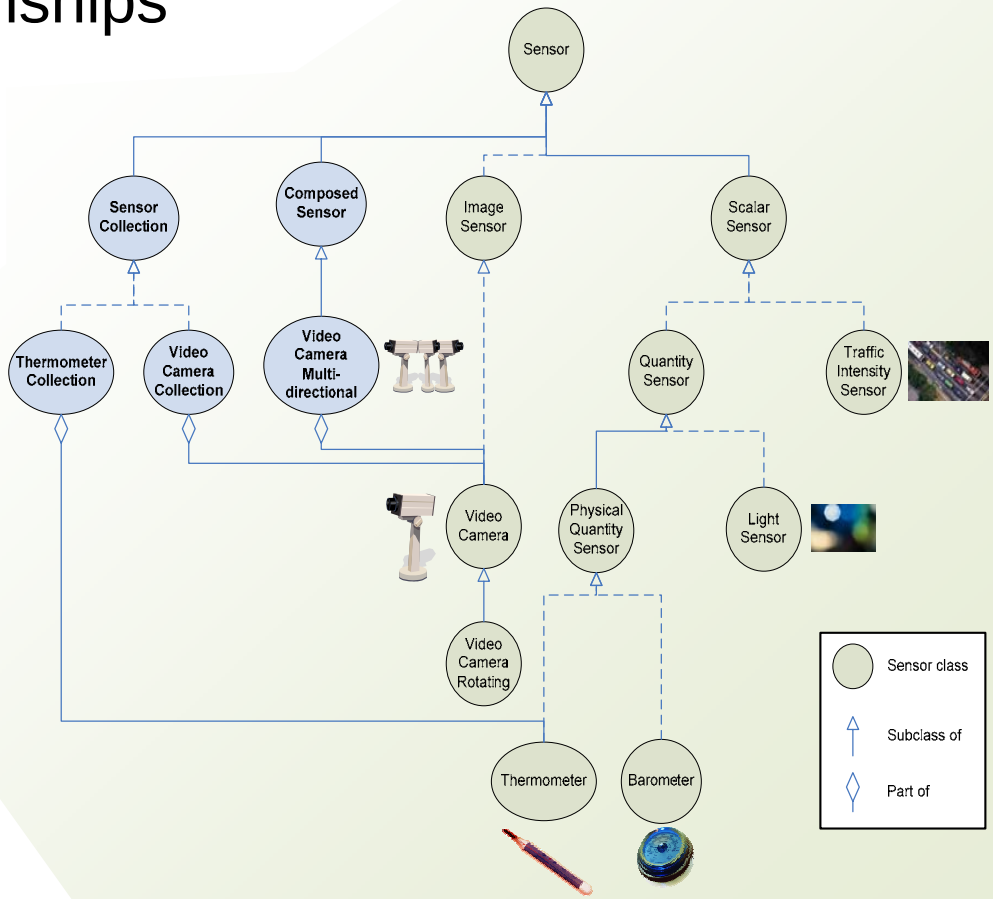


- Fine-grain, modular services as building blocks
  - Library for common tasks: data cleaning, storage, aggregation, query processing, …
- Aggregated services built upon these fine-grain services
  - Simple, unified programming abstraction
- Extensible, friendly to 3rd party services

Sensor Ontology

- OWL sensor ontology exposes the semantics associated with sensor types, groups and relationships

- The ontology provides high-level interoperability at syntactic and semantic levels



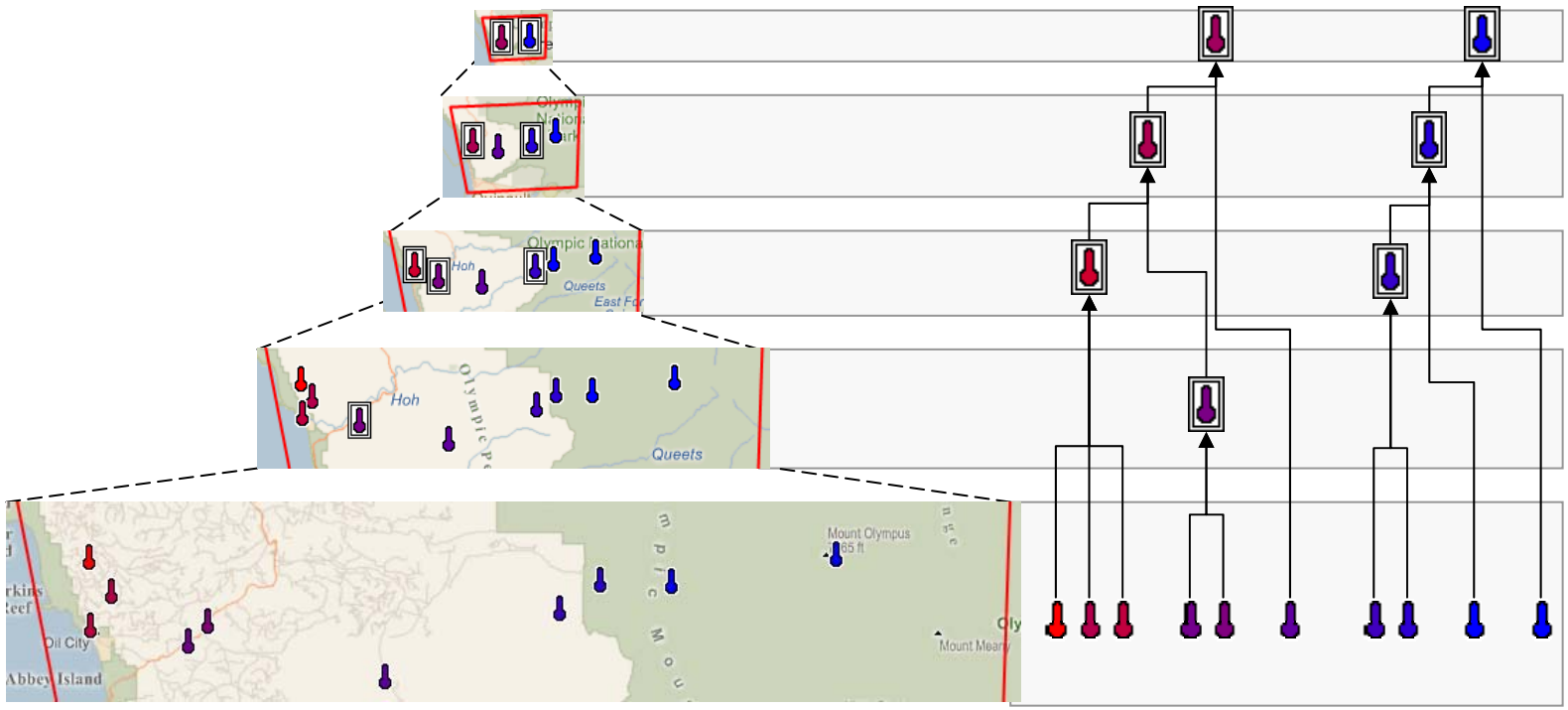
GeoDB

- Processes queries on geographic data
  - E.g., cameras inside a region, near a route
- Sensors register themselves
  - Single rendezvous point for sensors and users
- Data indexed with Hierarchical Triangular Mesh (HTM)

  - Proximity-preserving 1D mapping of Lat/Long
  - Implemented as table valued functions in SQL Server 2005 + external library
- Simple APIs and Web Service interface to store, modify, and query the database

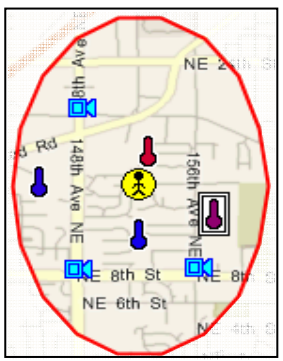
Aggregator (IconD)

- Aggregates sensor data, produces icons
- Aggregation at different granularities
  - Dynamically, e.g., based on zoom levels

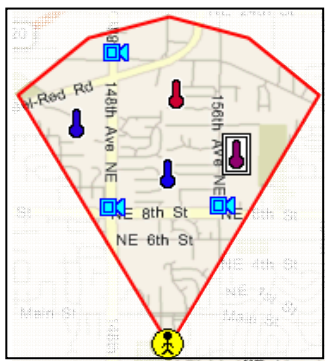


Client-side GUI library

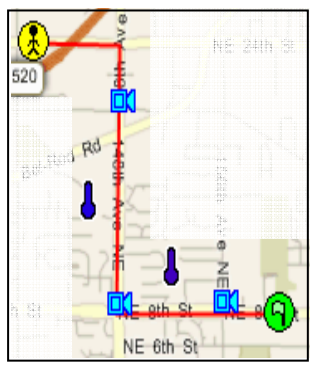
Java-script library to develop web-based GUI with more controls to interact with data



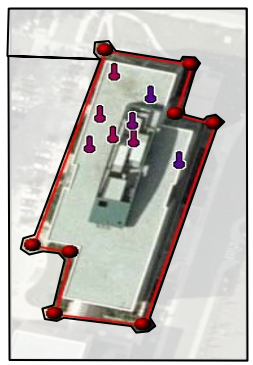
region

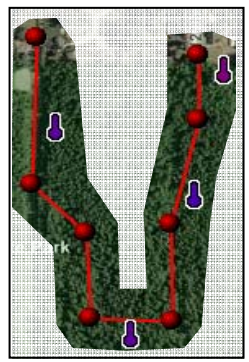


orientation



path

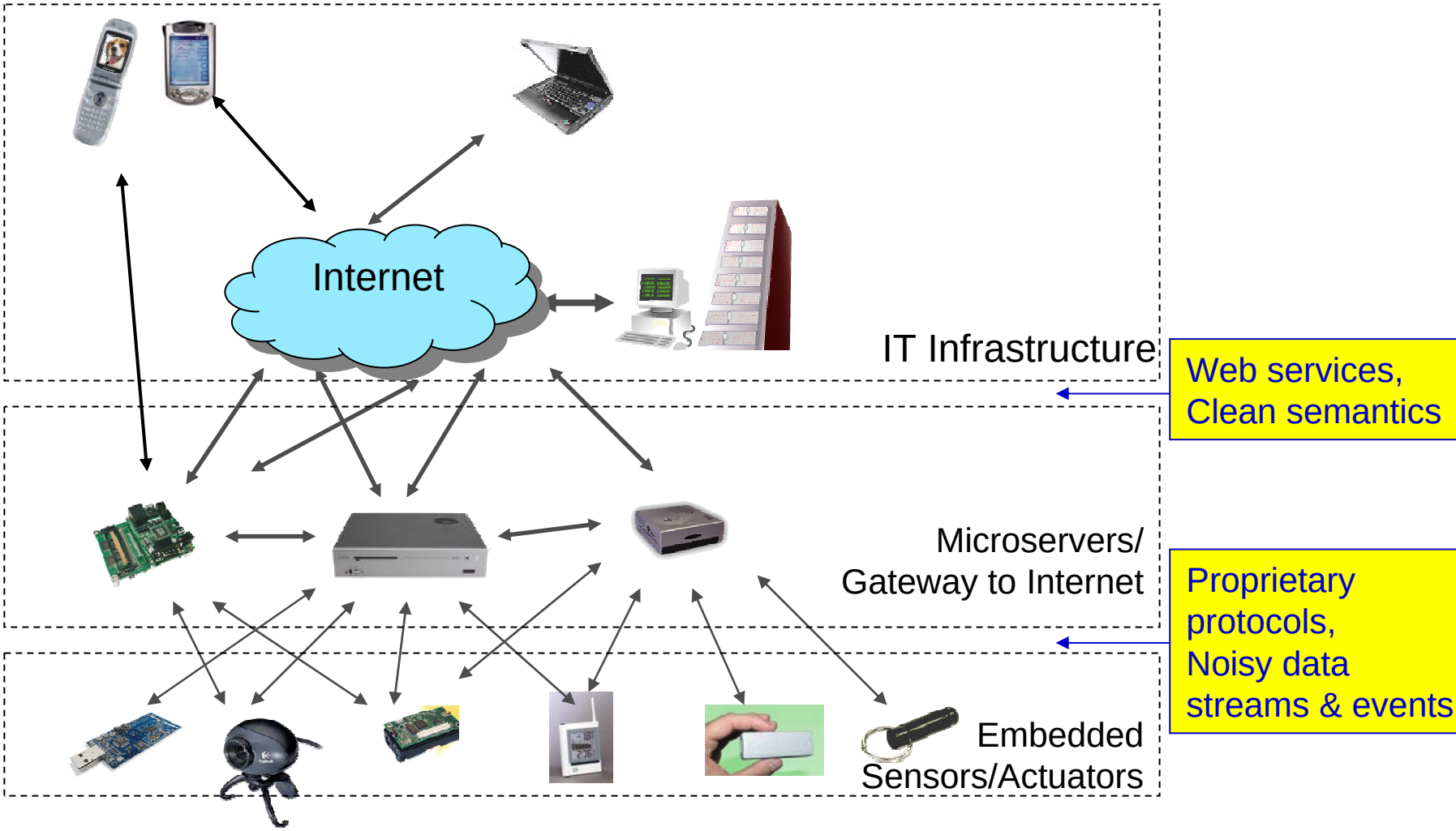




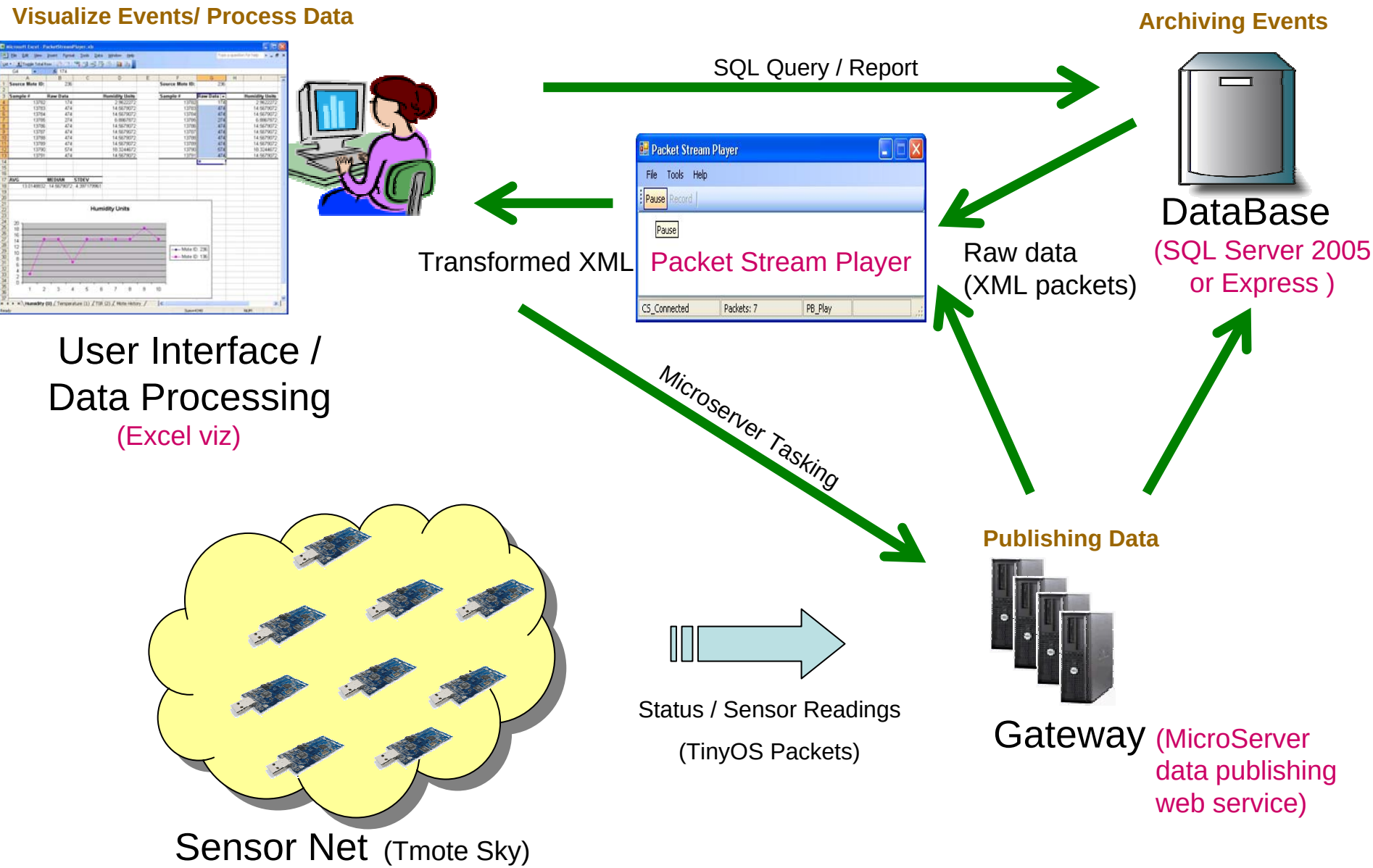

SenseWeb
Microsoft Research
road aerial
Show labels
submit
clear
filter
favorites
Filter Sen
Help
last update: 58 s (update now) [active]
Seattle Sensors
Search
road aerial
Magnuson Park
Kirkland
Redmond
Redmond Way
WASHINGTON
Marymoor Park
Yarrow Point
Hunts Point
Clyde Hill
NE 24th St
Bel-Red Rd
NE 8th St
Main St
Medina
Bellevue Way SE
Roanoke
Beaux Arts
Mercer Island
SE 40th St
W Mercer
S Jackson St
Adelaide
count 4
average 15.5
minimum 12
maximum 20
© Bellevue
May 4, 2006 3:18 PM
close
NEW SENSOR
Sensor name: Thermometer_112_3347
Sensor type: thermometer
Latitude: 47.640750056505716
Longitude: -122.14115919289585
Description: A thermometer in the 112/3347 room.
URI: http://necomp4/SensingService/Service.asmx
Insert
Cancel

SensorMap demo

Publish data to the Web



MSRSense: A toolkit for data publishing, archiving, visualization



Toolkit Release

- Released on 12/15/05; Latest (v0.1.4) on 6/30/06. Available from http://research.microsoft.com/nec/msrsense
  - Key components:
    - **mSEE**: The microServer Execution Environment is a component-based runtime system that can be dynamically tasked to collect and process sensor data
    - **mSIC**: The microServer Interaction Console is a user interface for tasking microservers and receiving data
    - **MoteForwarder**: This is a .NET solution for SerialForwarder found in TinyOS. MoteForwarder converts USB connections from PC to motes (base stations) into TCP socket interfaces that can be used by multiple consumers.
    - **Senscel**: The Excel extension allows users to visualize and archive streaming data from microservers through an Excel spreadsheet interface.
    - **Web service interfaces** for microservers and integrate with SenseWeb data hub.
- Very positive response from the community. On MSR Home Page popular download list in 4/06
- CD kit ready for the Faculty Summit ’06 release
- Publication
  - Spreadsheet programming and interface (IPSN/SPOTS’06)

Mote Programming

Microsoft Excel - bldg112demo.xls

Mote Deployment in Building 112

Live Refresh	Location	IP	Control Port	Data Port	MoteID	Programs: Browse Directory... / Program Selected Motes!
1	112/3312	172.31.47.101	10005	9001	1	C:\Program Files\UCB\cygwin\opt\tinyos-1.x\apps\TOSBase
1	112/3314	172.31.47.102	10005	9001	2	C:\Program Files\UCB\cygwin\opt\tinyos-1.x\apps\TOSBase
1	112/3316	172.31.47.103	10005	9001	3	C:\Program Files\UCB\cygwin\opt\tinyos-1.x\apps\TOSBase
1	112/3318	172.31.47.104	10005	9001	4	C:\Program Files\UCB\cygwin\opt\tinyos-1.x\apps\TOSBase
0	112/3320	172.31.47.105	10005	9001	5	C:\Program Files\UCB\cygwin\opt\tinyos-1.x\apps\TOSBase
0	112/3334	172.31.47.106	10005	9001	6	C:\Program Files\UCB\cygwin\opt\tinyos-1.x\apps\TOSBase
1	112/3336	172.31.47.107	10005	9001	7	C:\Program Files\UCB\cygwin\opt\tinyos-1.x\apps\TOSBase
0	112/3338	172.31.47.108	10005	9001	8	C:\Program Files\UCB\cygwin\opt\tinyos-1.x\apps\TOSBase
1	112/3354	172.31.47.109	10005	9001	9	C:\Program Files\UCB\cygwin\opt\tinyos-1.x\apps\TOSBase
1	112/3356	172.31.47.110	10005	9001	10	C:\Program Files\UCB\cygwin\opt\tinyos-1.x\apps\TOSBase
1	112/3372	172.31.47.111	10005	9001	11	C:\Program Files\UCB\cygwin\opt\tinyos-1.x\apps\TOSBase
1	112/3374	172.31.47.112	10005	9001	12	C:\Program Files\UCB\cygwin\opt\tinyos-1.x\apps\Blink
1	112/3376	172.31.47.113	10005	9001	13	C:\Program Files\UCB\cygwin\opt\tinyos-1.x\apps\Blink
1	112/3378	172.31.47.114	10005	9001	14	C:\Program Files\UCB\cygwin\opt\tinyos-1.x\apps\Blink
0	112/3308	172.31.47.115	10005	9001	15	C:\Program Files\UCB\cygwin\opt\tinyos-1.x\apps\Blink
0	112/3309	172.31.47.116	10005	9001	16	C:\Program Files\UCB\cygwin\opt\tinyos-1.x\apps\Blink
1	112/3321	172.31.47.117	10005	9001	17	C:\Program Files\UCB\cygwin\opt\tinyos-1.x\apps\Blink
0	112/3323	172.31.47.118	10005	9001	18	C:\Program Files\UCB\cygwin\opt\tinyos-1.x\apps\Blink
0	112/3339	172.31.47.119	10005	9001	19	C:\Program Files\UCB\cygwin\opt\tinyos-1.x\apps\Blink
0	112/3341(A)	172.31.47.120	10005	9001	20	C:\Program Files\UCB\cygwin\opt\tinyos-1.x\apps\Blink
0	112/3359	172.31.47.121	10005	9001	21	C:\Program Files\UCB\cygwin\opt\tinyos-1.x\apps\Blink
0	112/3306	172.31.47.122	10005	9001	22	C:\Program Files\UCB\cygwin\opt\tinyos-1.x\apps\Blink
0	112/3307	172.31.47.123	10005	9001	23	C:\Program Files\UCB\cygwin\opt\tinyos-1.x\apps\Blink
1	112/3325	172.31.47.124	10005	9001	24	C:\Program Files\UCB\cygwin\opt\tinyos-1.x\apps\Blink
0	112/3343	172.31.47.125	10005	9001	25	

Sheet1 / Sheet2 / Sheet3

Ready Sum=57027 NUM

Data Streaming Worksheet

= -39.60 + 0.01 * Raw Data

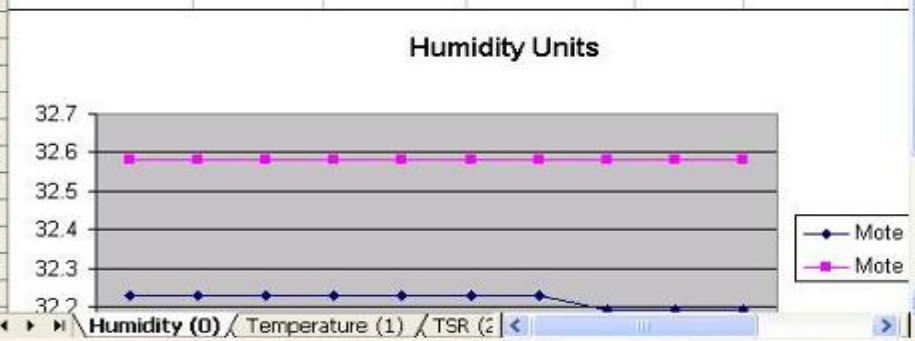
Microsoft Excel - PacketStreamPlayer.xls

File Edit View Insert Format Tools Data Wind

List | Σ Toggle Total Row

G4 | fx 968

	A	B	C	D	F
1	Source Mote ID:	236			Source Mote ID
2					
3	Sample #	Raw Data		Humidity Units	Sample #
4	48348	958		32.2292608	601E
5	48349	958		32.2292608	601E
6	48350	958		32.2292608	601E
7	48351	958		32.2292608	601E
8	48352	958		32.2292608	601E
9	48353	958		32.2292608	601E
10	48354	958		32.2292608	6017
11	48355	957		32.1941228	6017
12	48356	957		32.1941228	6017
13	48357	957		32.1941228	6017
14					
15					
16					
17	AVG	MEDIAN	STDEV		
18	32.3995261	32.4047968	0.185871218		
19					
20					



Humidity (0) / Temperature (1) / TSR (2

Ready Sum=9680

XML Source

XML maps in this workbook:

m136_0

ns4:ArrayOscopeMsg

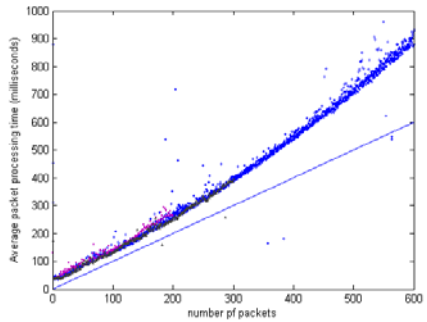
To map repeati
from the tree o
want the data

To import data
on the List tool

Options

Verify Map for

Tips for ma




```
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http://www.w3.org/2001/XMLSchema
xmlns:xsi=
"http://www.w3.org/2001/XMLSchema-instance">
  <sourceMoteID>30</sourceMoteID>
  <lastSampleNumber>40550
                  </lastSampleNumber>
  <channel>1</channel>
  <data1>6091</data1>
  <data2>6090</data2>
  <data3>6090</data3>
  <data4>6088</data4>
  <data5>6086</data5>
  <data6>6086</data6>
  <data7>6084</data7>
  <data8>6084</data8>
  <data9>6081</data9>
  <data10>6081</data10>
</OscopeMsg>
```

Software release

- MSRSense toolkit available (in source code)
  - http://research.microsoft.com/nec/msrsense
  - 12/14/05 announcement on TinyOS mailing list
- SenseWeb portal is available now
  - http://research.microsoft.com/senseweb
  - For browsing and data publishing
  - Available data from traffic webcams, weather, city street parking, soil, lake ecosystem

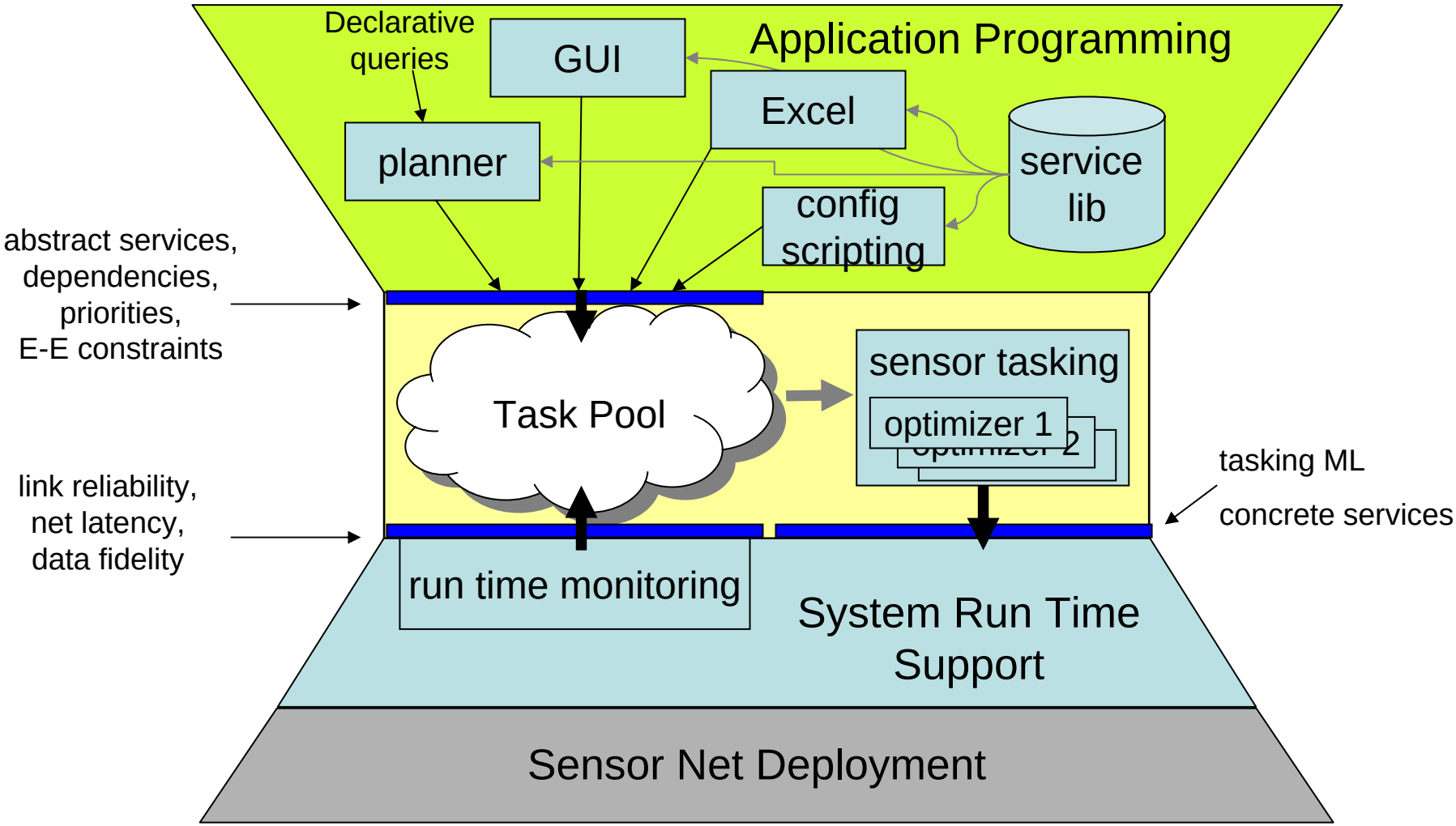
Challenges that come with the real world

- A great deal of variability
  - Variability in app requirements
    - Use scenarios (data collection, control in the loop, or in-network compression), sensing modality, data rate
  - System dynamism and heterogeneity
    - Nodes/links come and go; possibly non-replenishable resources
    - Hw heterogeneity; incremental deployment by multiple vendors with different technologies (e.g., network protocols)
  - Unreliable data
    - Uncertainty due to packet loss, sensor noise, partial observability
  - Mismatch between user queries and imperative mote programs
    - Semantic user queries such as “Tell me if you see a red car”
- As a result
  - Phil Buonadonna: “Every sensor net experiment needs 2 PhDs and 5 grad students”, or something like that

Issues to address

- Real time response
  - Handling of time-critical events
- Resource sharing and management
  - Resource (energy, bandwidth, processing, storage) models and monitoring
  - Task prioritization and scheduling
- Programming the networks as a whole
  - Interfaces between various components (e.g., SP link layer abstraction, SensorML)
  - Programming model; event driven vs. threaded
- System management
  - Tools for sys config/mgmt, for data collection and vis, for in-situ debugging

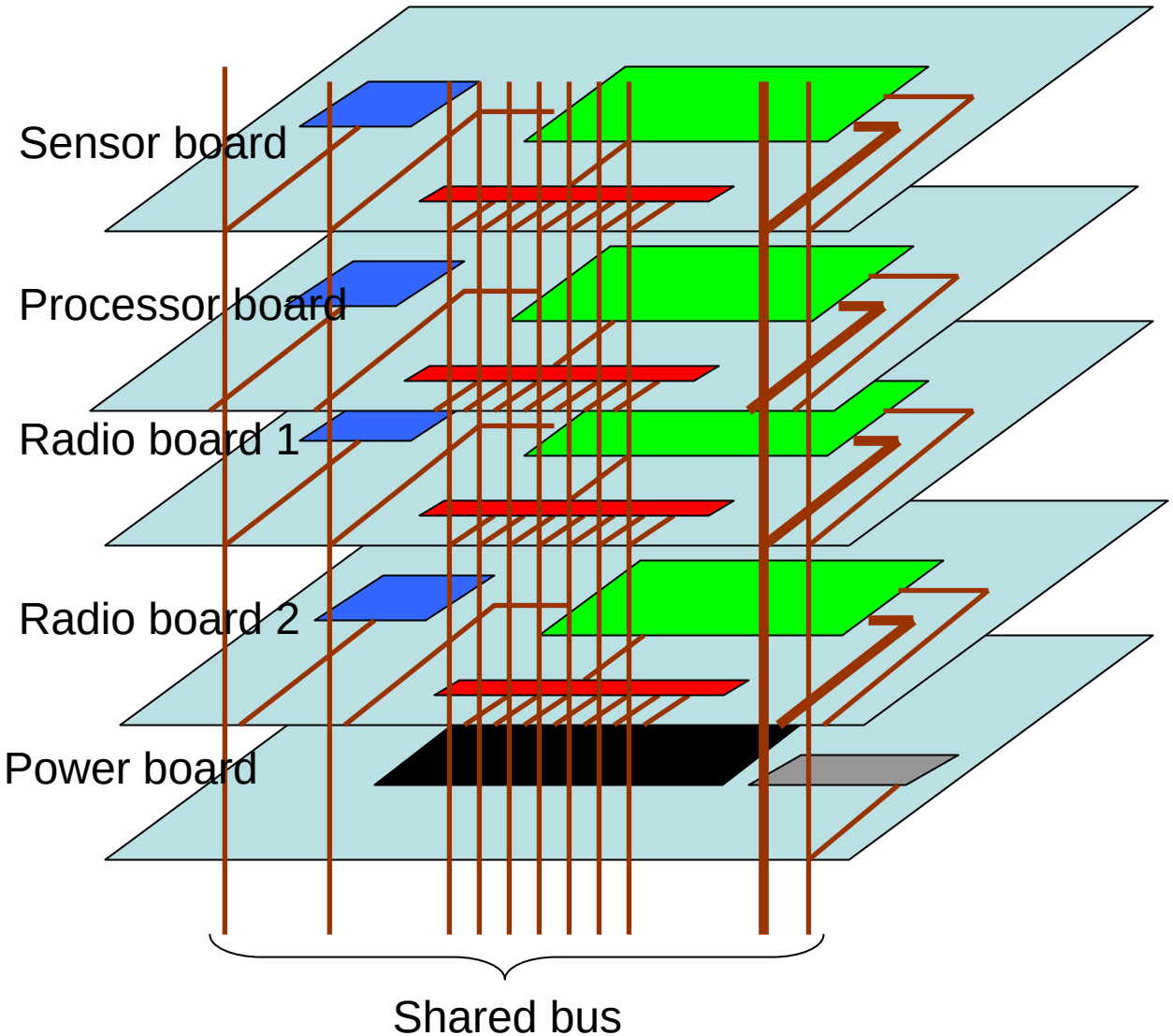
A Tasking Architecture



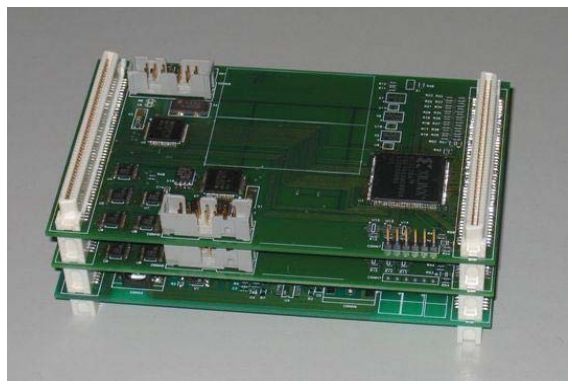
mPlatform: A clean-slate approach to reconfigurable networked embedded computing

- Goal
  - Re-think how hw/sw for small devices are organized, using a flexible and yet constrained platform
  - Motivated by concrete apps
- Lego-like, extensible multi-board hardware
  - Multiple radios (Zigbee/BlueTooth/WiFi/GPRS) and processors (MSP430/ARM7/PXA), add-ons (sensors)
  - Real-time handling of time-critical events
  - Programmable inter-connects between boards
- Reconfigurable, modular software platform
  - Uniformity in on/off node messaging
  - Dynamic tasking
  - Power-aware scheduling

A reconfigurable, extensible multi-board design

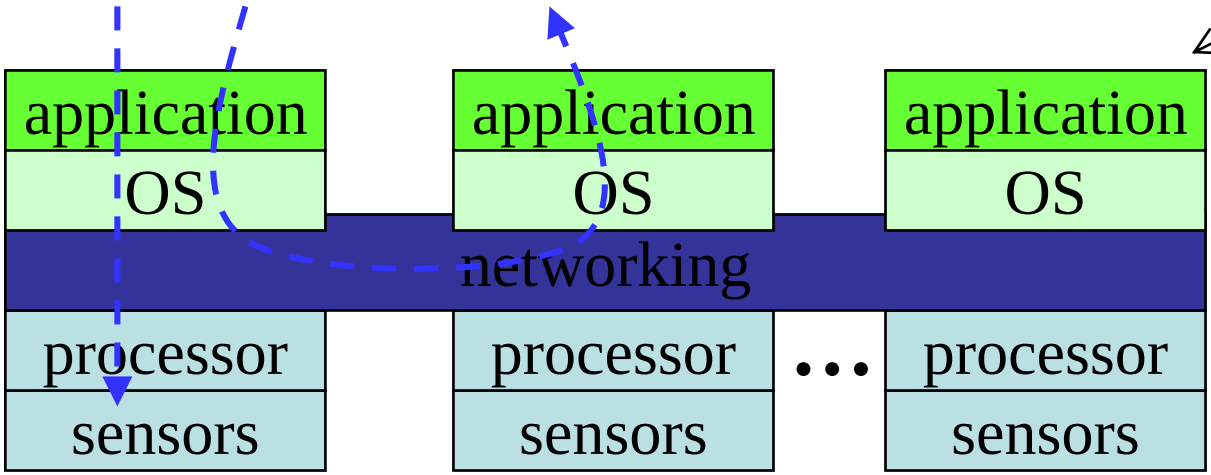


- A collection of stackable boards
- Each board has enough buffer storage and processing power to handle time critical events
- A shared clock signal enables system-wide synchronization
- Advantages:
  - Can deign, build, and test independently
  - Flexible hardware configuration



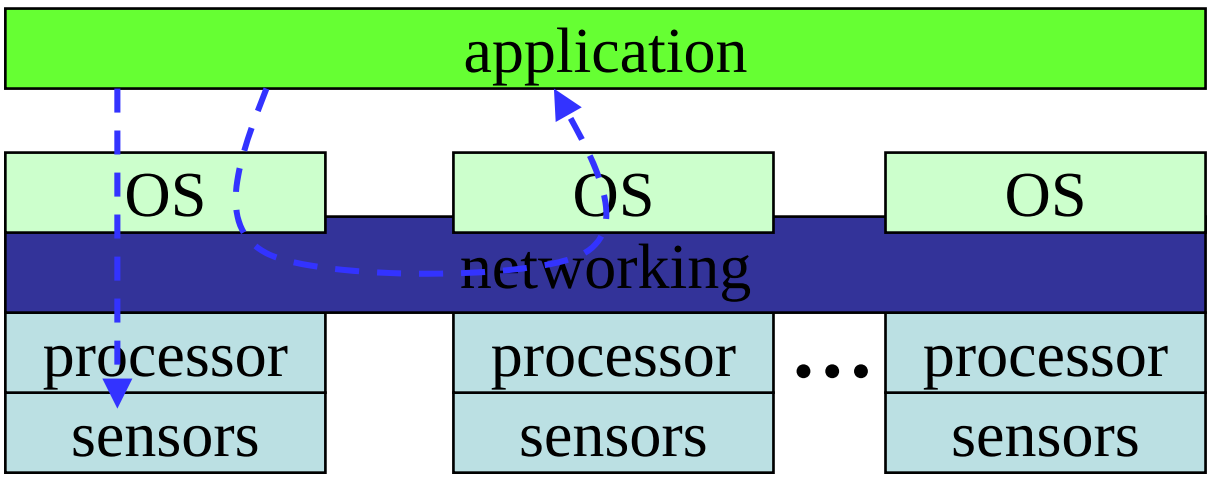
Prototype boards for mPlatform

Programming the ensemble



React to events/messages

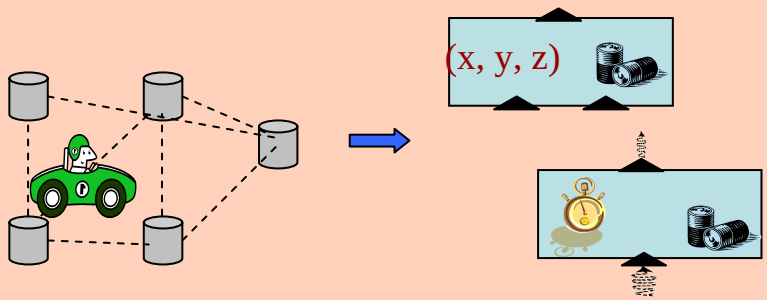
- handshaking
- locks and monitors
- interrupt services
- pulling sensors



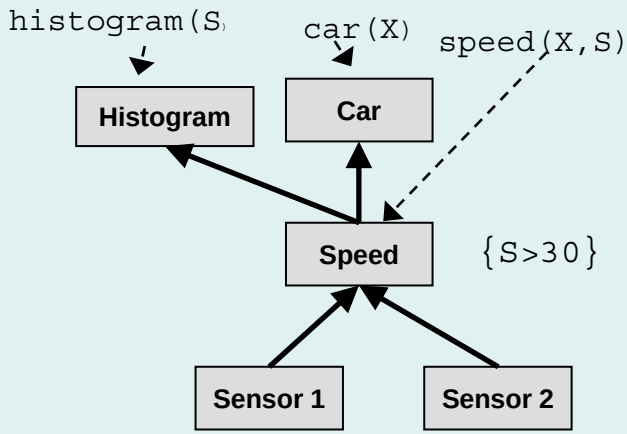
Cross-board and cross-node programming

SONGS: Service Oriented Networked ProGramming of Sensors

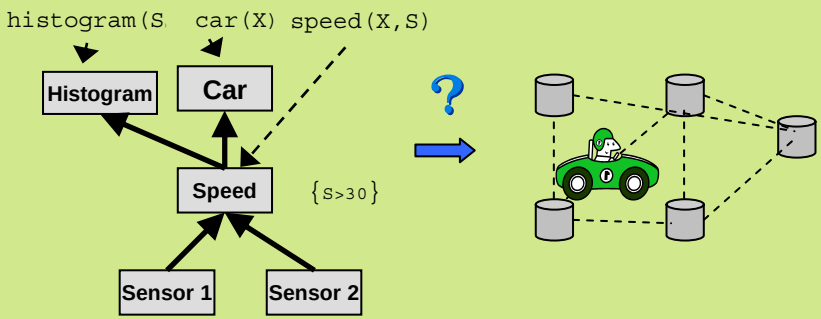
Service Abstraction and Interface



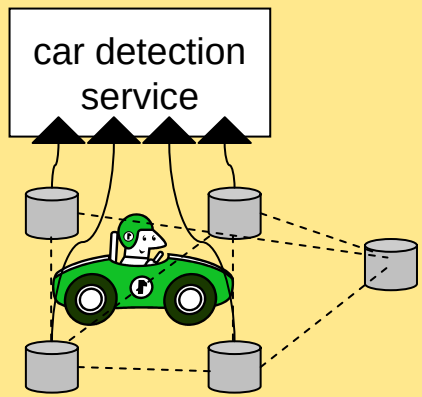
Service Planning



Service Embedding



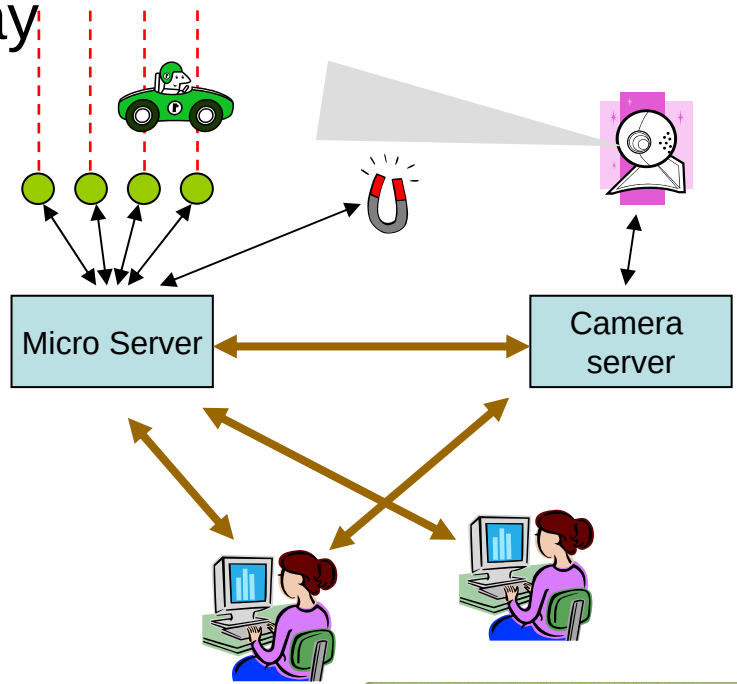
Service Scheduling and Execution

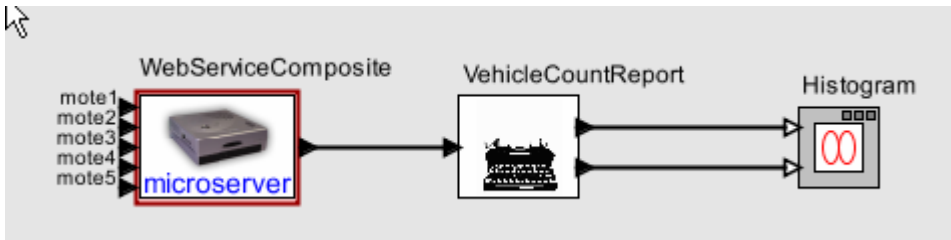


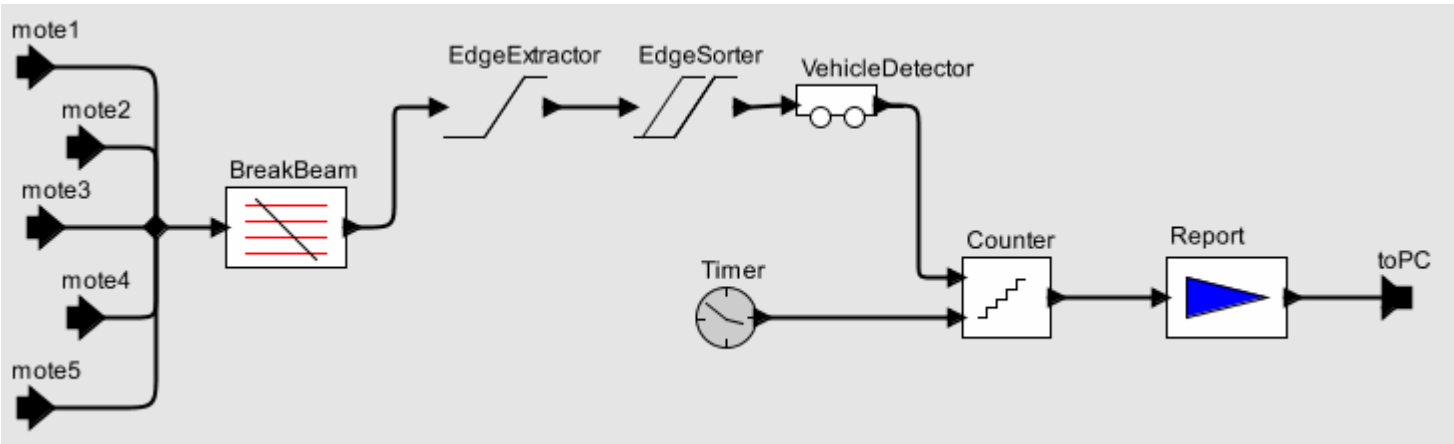
Example of services and their composition

Counting vehicles with a sensor array

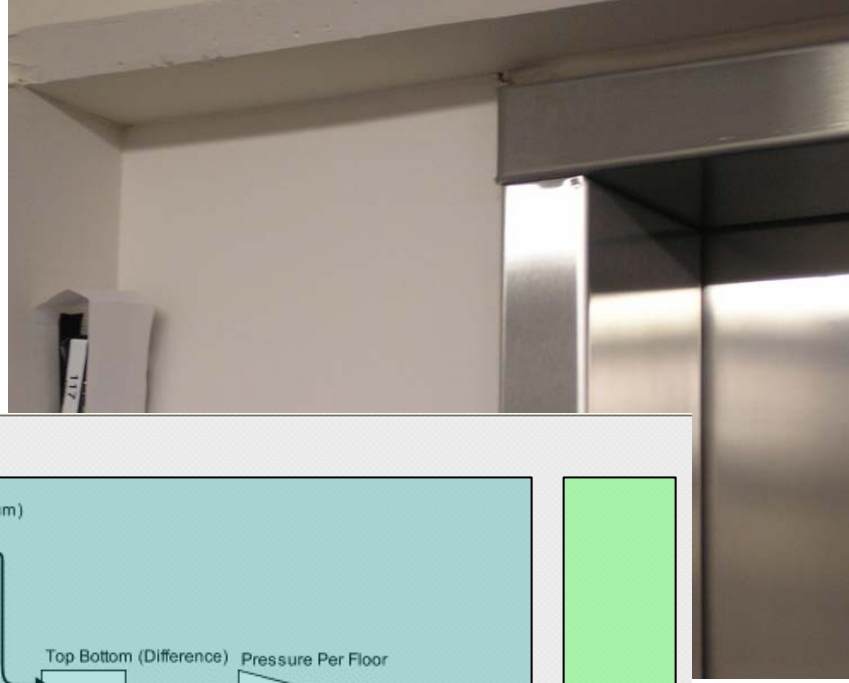
- Extract edges from break beam detections
- Sort edges into consecutive detections
- Detect vehicles based on timing relations among detections
- Count vehicles
- Generate an arrival histogram report

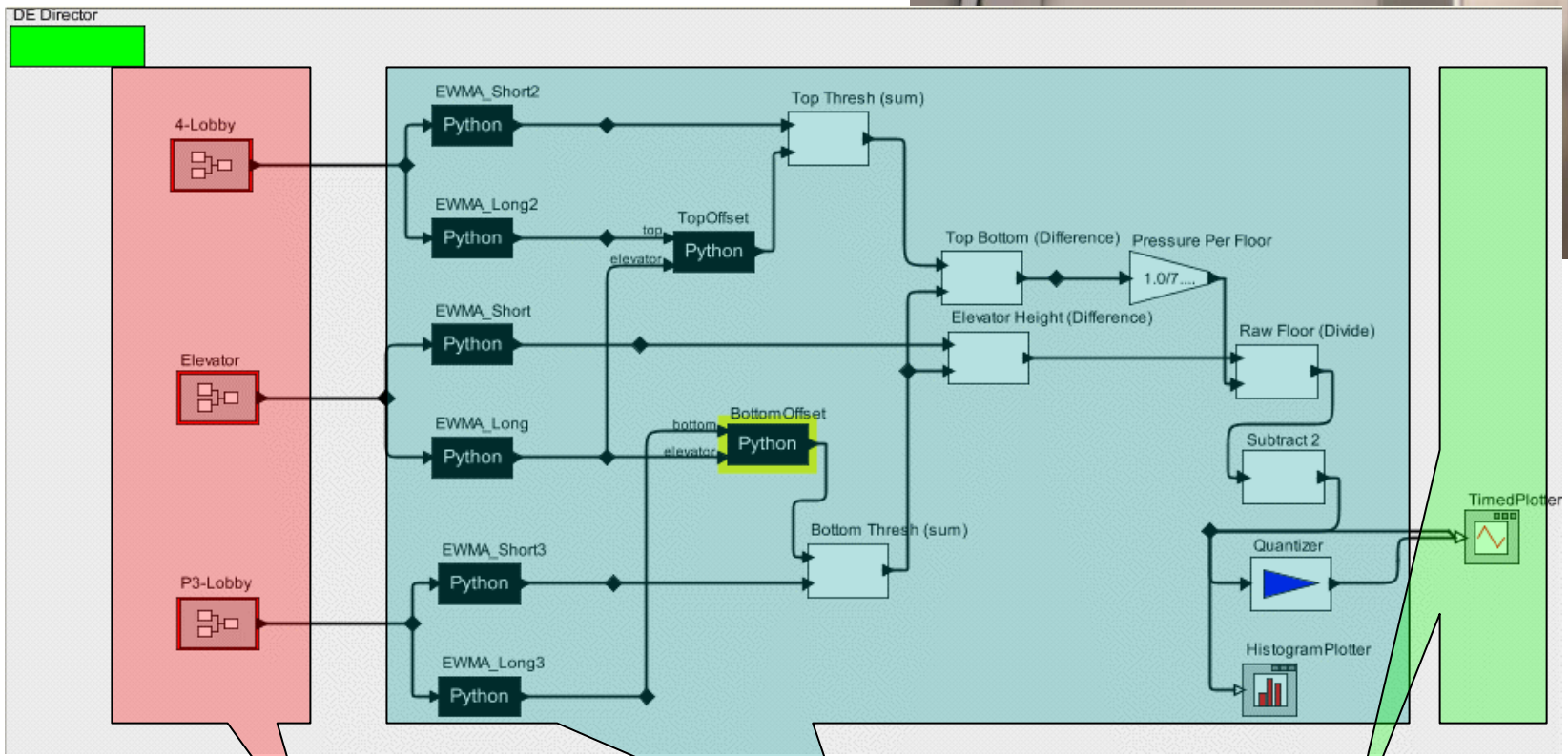






Another Example: where is the elevator?





Data Sources

Intermediate Processing

Output

Automatic Service Planning

- Declarative specification
- Automatic resource sharing and reuse
- Reasoning about space/time constraints
- Execution monitoring and re-planning
- Constraint-based trade-offs

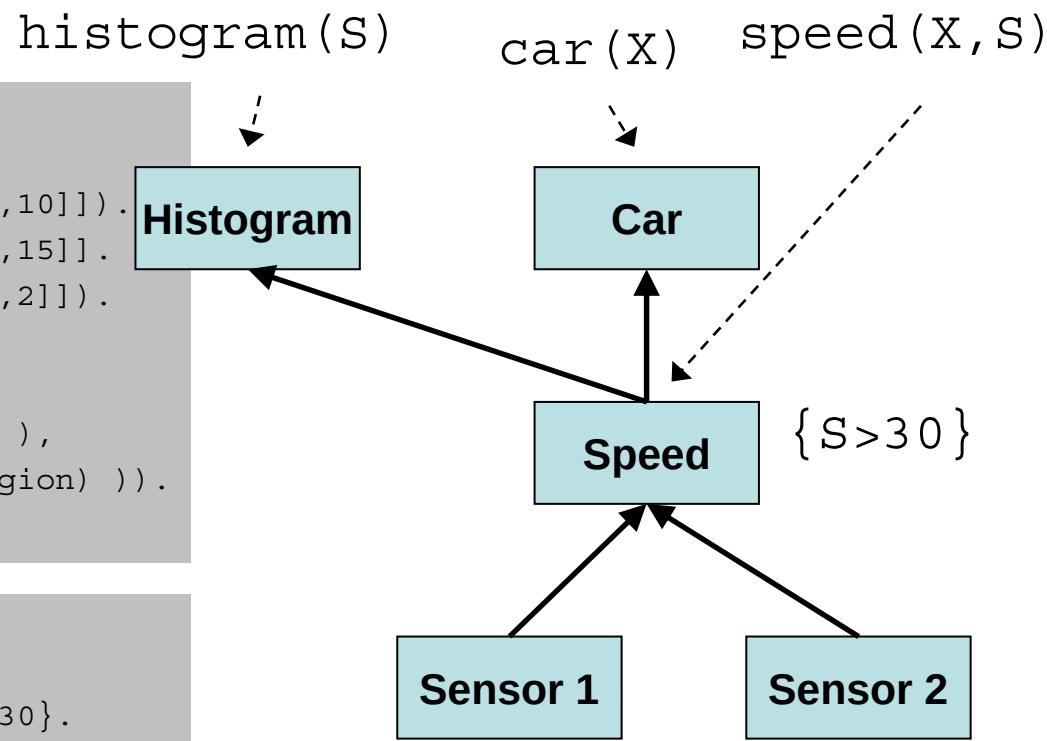
Service Description

```
sensor( magSensor,    [[60,0,0],[70,10,10]]).
sensor( camera,       [[40,0,0],[55,15,15]].
sensor( breakSensor,  [[10,0,0],[12,10,2]]).

service(  breakService (Region),
needs(    sensor (breakSensor,Region) ),
creates(  break (X), detected (X,T,Region) )).
```

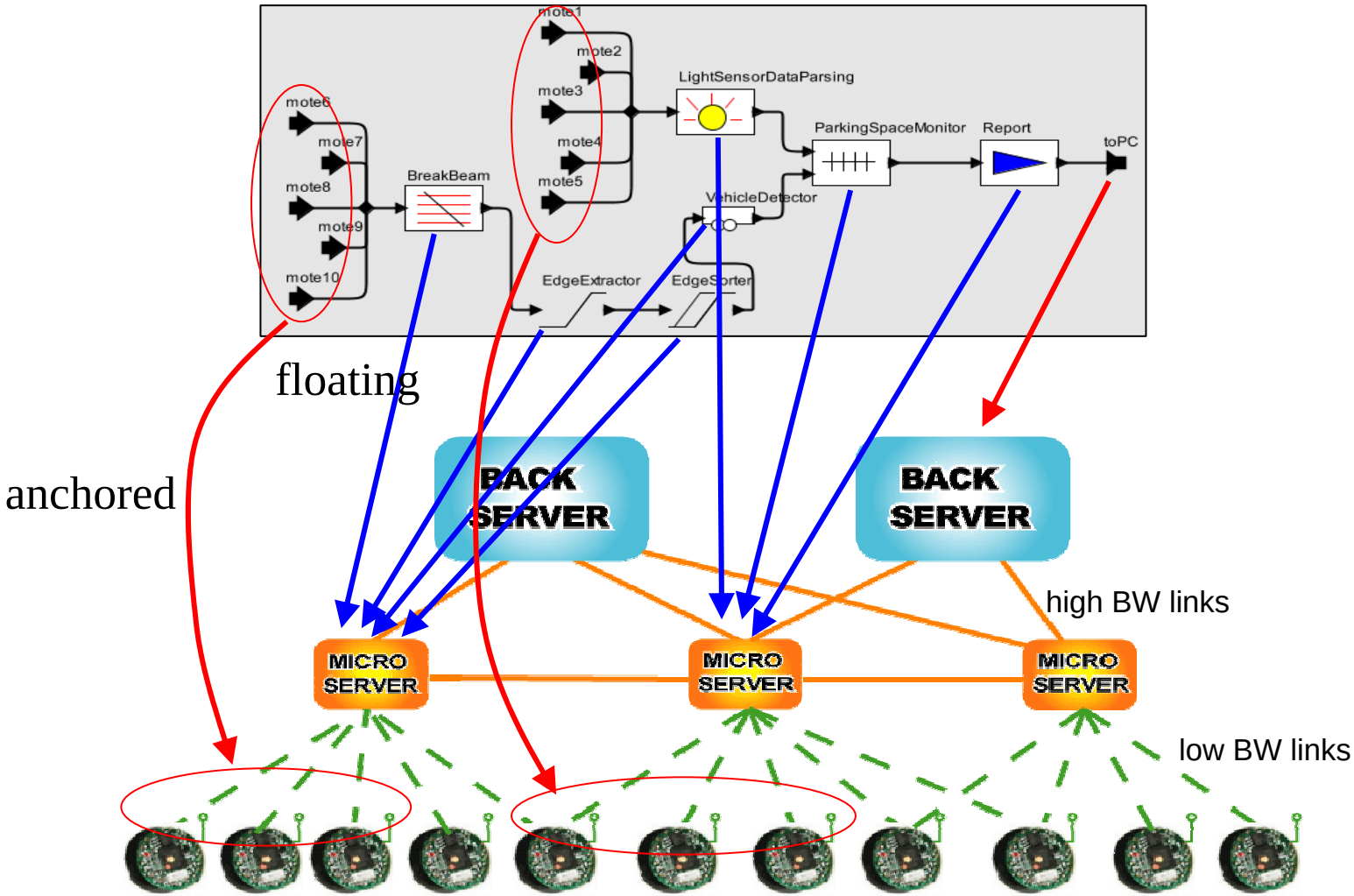
User Query

```
car(X), speed(X,S), histogram(S), {S>30}.
```



"Semantic Streams: a Framework for Composable Semantic Interpretation of Sensor Data." *EWSN'06*.

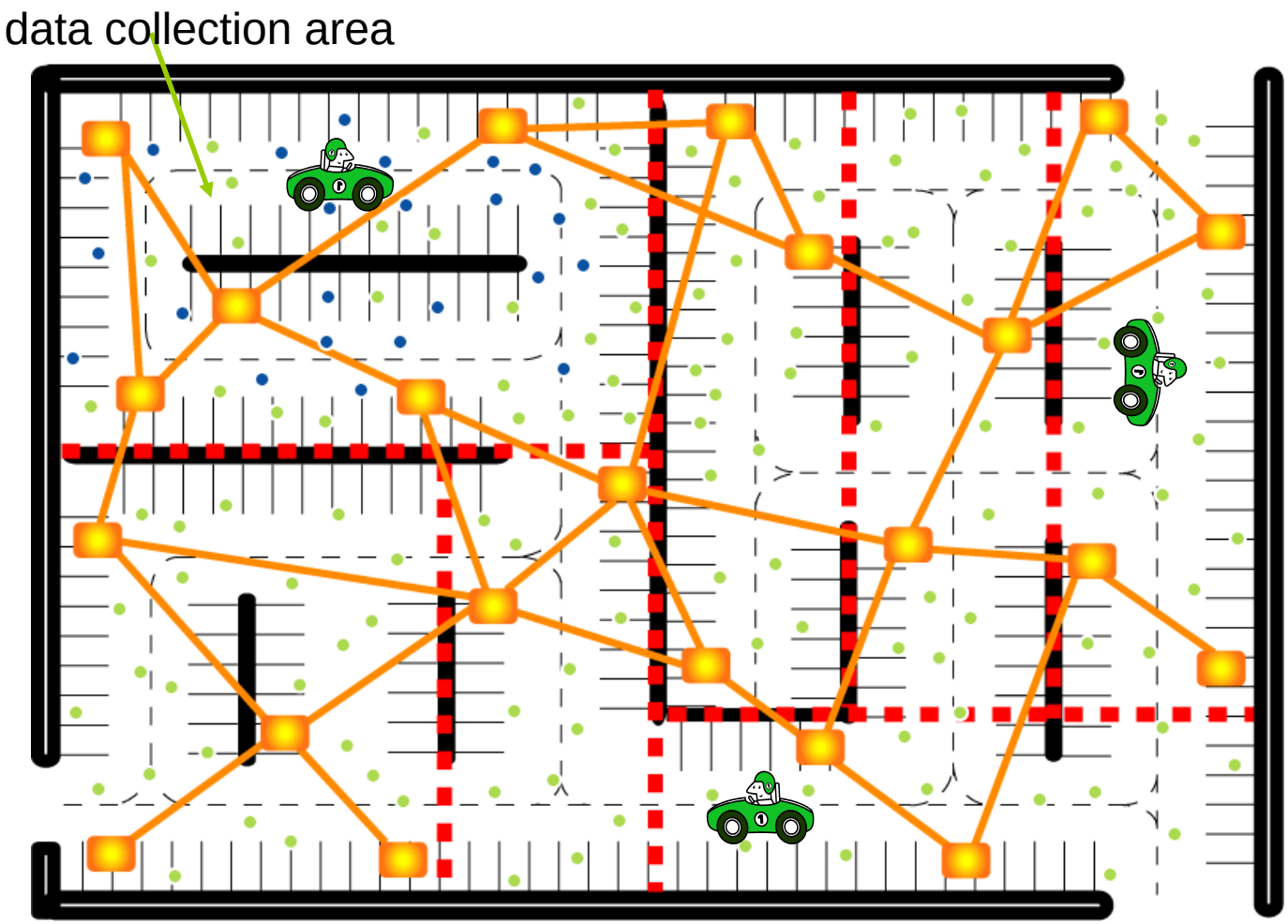
Task Assignment



Given a *service composition tree* (workflow) and a *physical network* of nodes, how to map logical services onto the devices?

Example: Monitoring a Garage

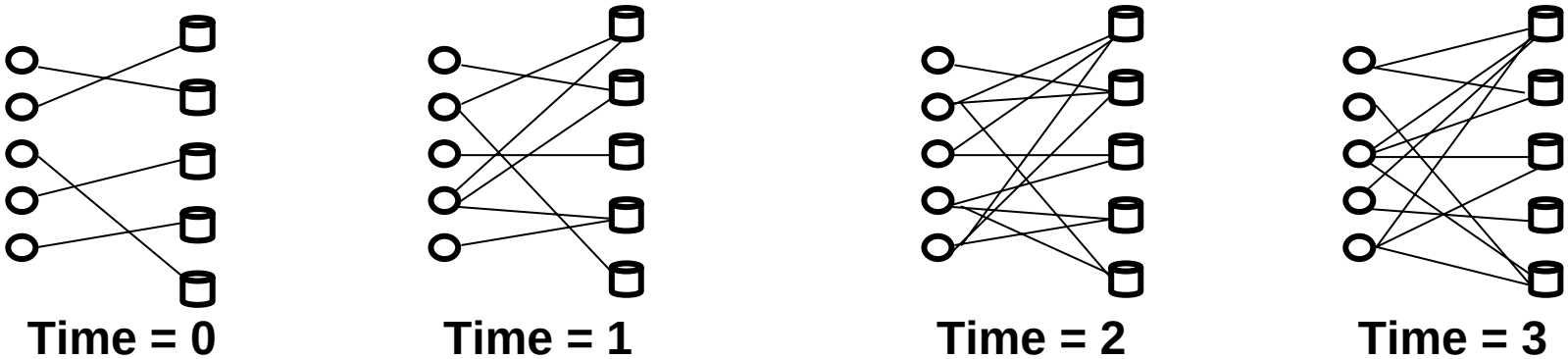
Kinetically Stable Assignment: Assign data collection tasks to microservers, to minimize overall cost of task migration for all future steps of interest



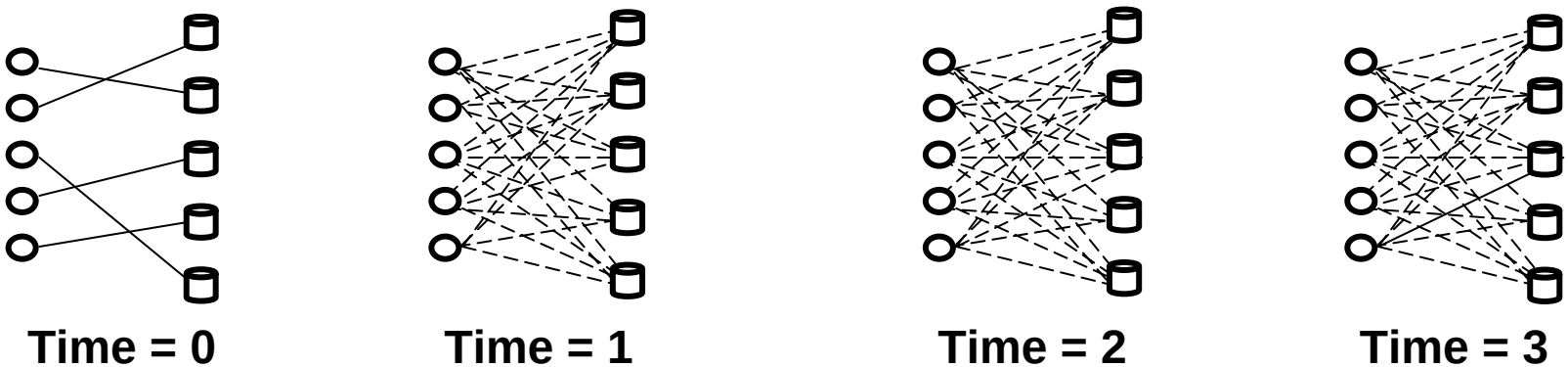
- K tasks,
  N uServers,
  T time window
- Server capacity limit
- Cost of task migration
- Uncertainty in environment

Kinetically Stable Assignment (KSA)

Deterministic Bipartite Graph per Time Step



Probabilistic Bipartite Graph per Time Step



"Kinetically Stable Task Assignment for Networks of Microservers." *IPSN'06*.

Working with the research community

Microsoft® Research

Networked Embedded Computing & External Research and Programs

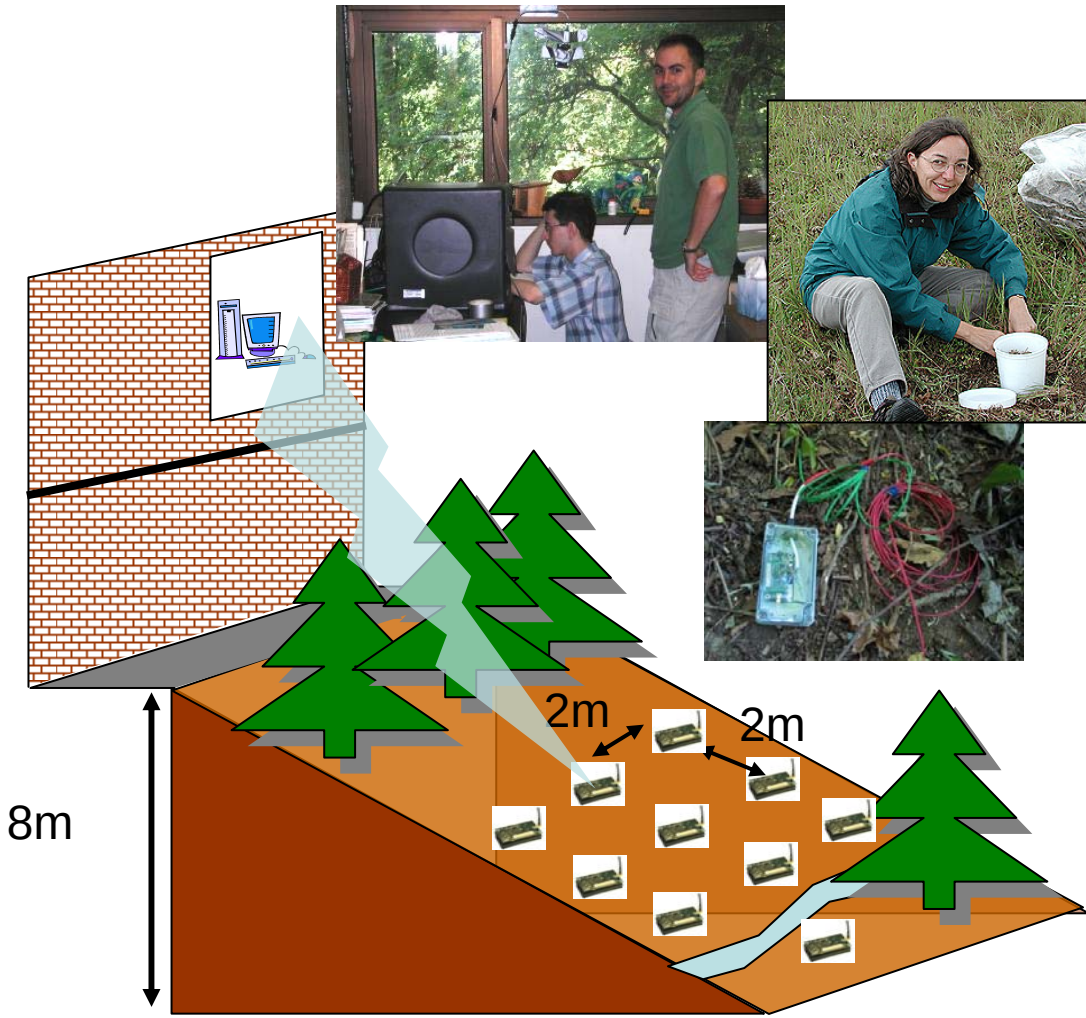
Sensor Networks Workshop 2005

Woodinville, Washington, USA
Willows Lodge

http://research.microsoft.com/workshops/sensorws2005

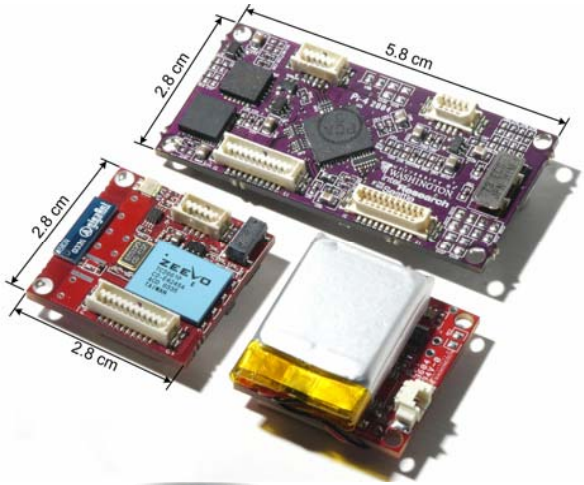
Wireless Sensor Networks for Soil Ecosystem Studies

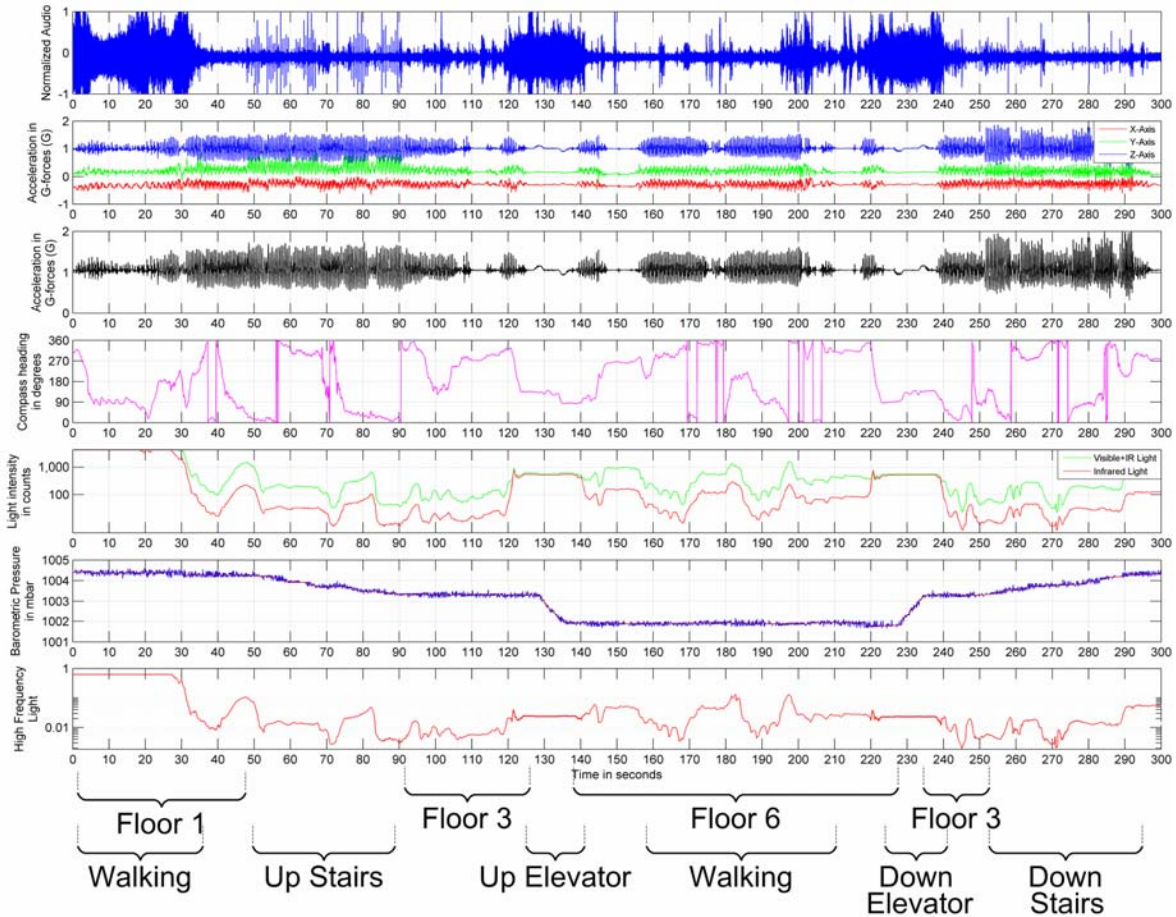
Katalin Szlavecz, Earth and Planetary Sciences,
Johns Hopkins University



Sensor Networks for Human Activity Inferencing

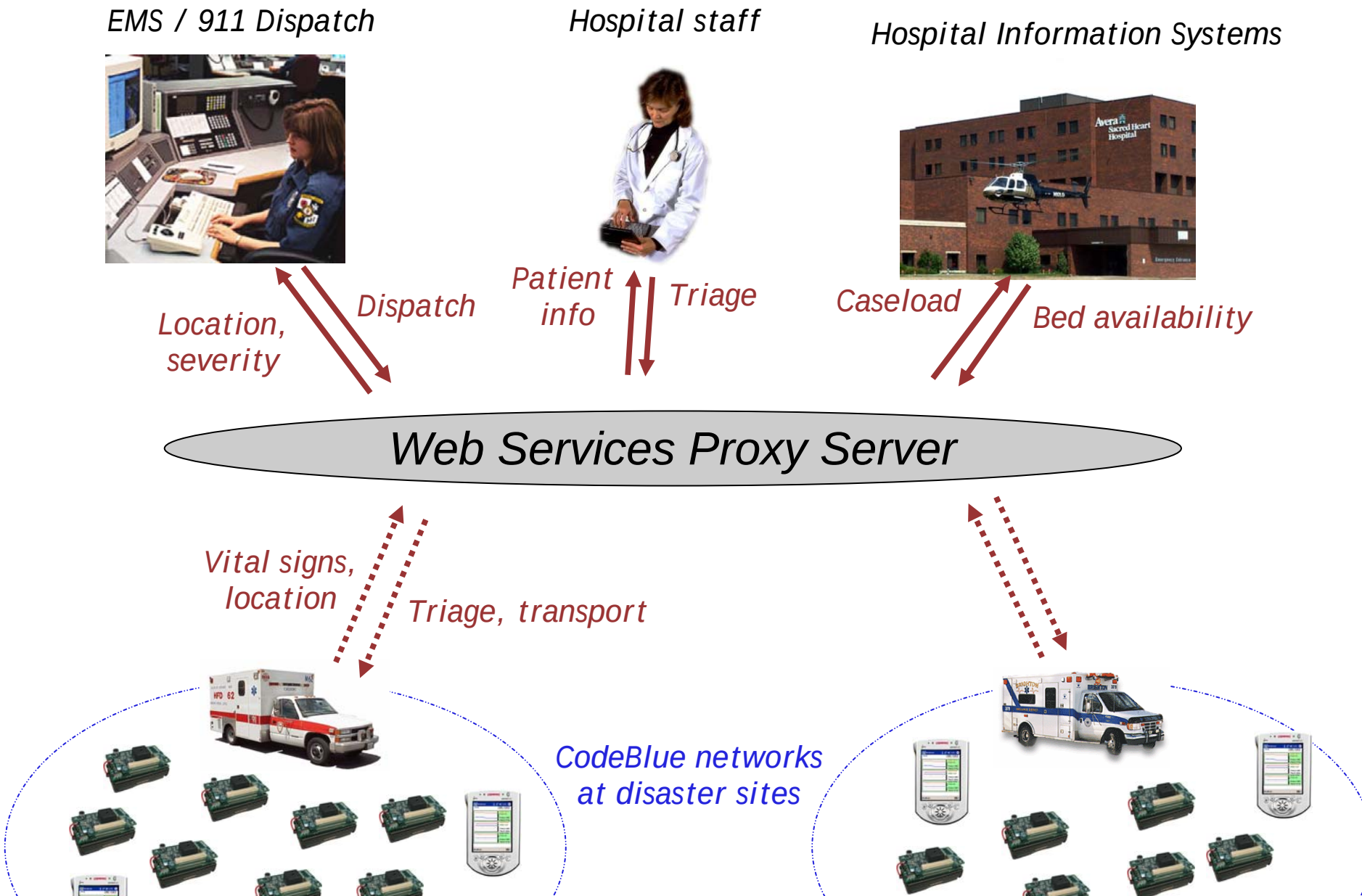
Gaetano Borriello, University of Washington





Integrating Sensor Networks into Medical Care Using Web Services

Matt Welsh, Harvard



SensorMap RFP (provisional)

- The goal is to build an open sensor data repository and interesting scientific applications on top of that, leveraging the SensorMap platform as well as other tools developed by the community.

- We expect this RFP (Request for Proposals) will result in a broad selection of supported university research projects whose purpose will be to explore the next-generation sensor networks that interface with the internet and enterprise networks.

- We anticipate accepting proposals in the Fall – please await our formal announcement before submitting proposals! Thank you for your patience. ☺

- Questions: Stewart Tansley (stansley@microsoft.com)

Summary

- We have focused on programming models, system tools, and web and query interfaces. **Research results** presented in:
  - "SenseWeb: Browsing the Physical World in Real Time", Demo Abstract, IPSN'06.
  - "Kinetically Stable Task Assignment for Networks of Microservers." IPSN'06.
  - "Greedy is Good: On Service Tree Placement for In-Network Stream Processing." ICDCS'06.
  - "A Spreadsheet Approach to Programming and Managing Sensor Networks." SPOTS'06.
  - "Tinker: A Tool for Designing Data-Centric Sensor Networks." SPOTS'06.
  - "Semantic Streams: A Framework for Composable Semantic Interpretation of Sensor Data." EWSN'06.
  - "Towards Semantic Services for Sensor-Rich Information Systems," Basenets'05.
  - "Semantics-Based Optimization Across Uncoordinated Tasks in Networked Embedded Systems," EMSOFT'05.

- **SenseWeb** prototype demoed 5/06, with articles in *Technology Review*, *EE Times*, *InternetNews* etc., hundreds of blogs, and over 130,000 hits on Google search within two weeks.

- MSRSense **Toolkit** released 12/14/05, with 7000+ downloads since. DVD kit available at Faculty Summit

- MSR Sensornet **Workshop** successfully held 10/05, with 50 people attending. Keynotes by Kris Pister and Tony Hey. All presentation materials online.