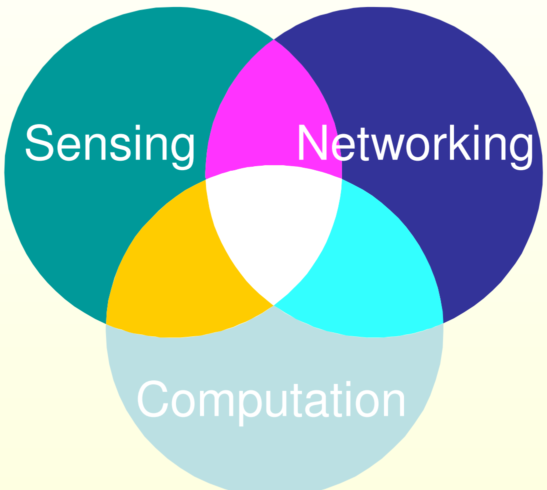
# CS428: Information Processing for Sensor Networks




Leonidas Guibas
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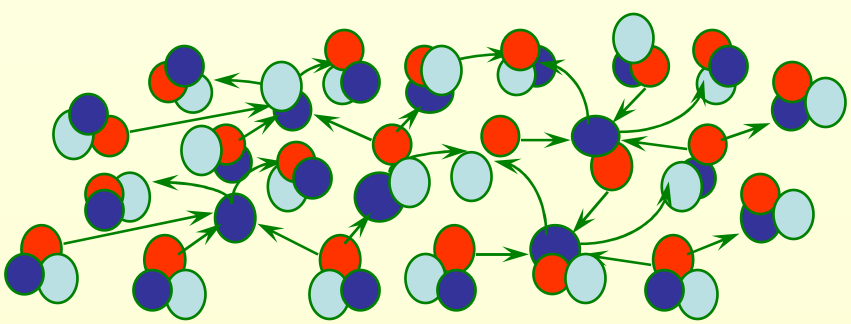
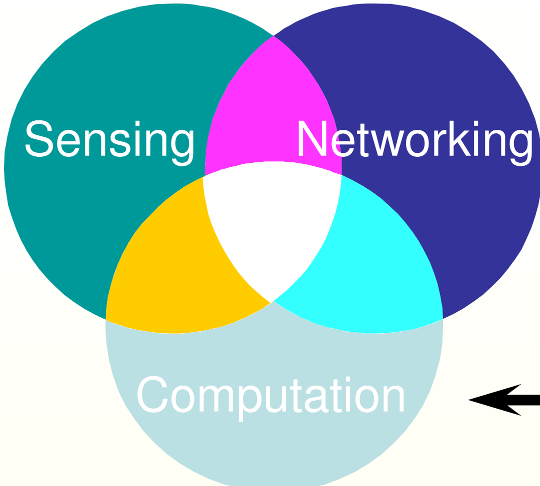
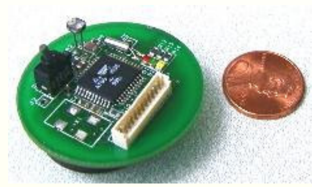


# Introduction

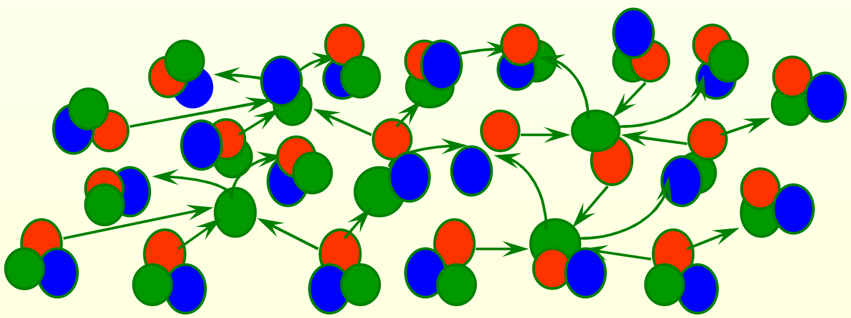
# Smart Sensors and Sensor Networks





Berkeley/Crossbow Motes


Rockwell HiDRA


UCLA WINS

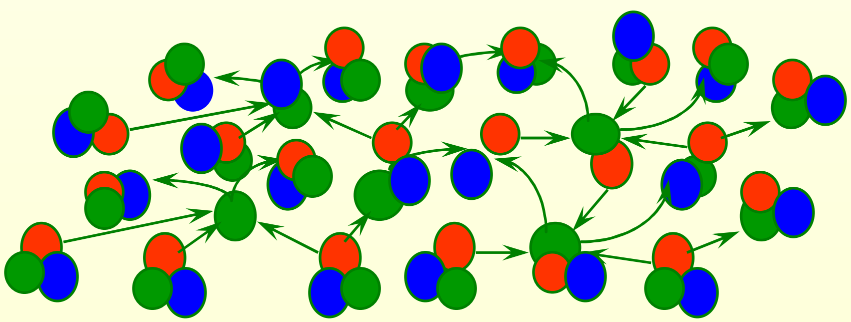


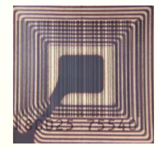
- **Environmental sensing**
  - Traffic, habitats, pollution, hazards, security
- **Industrial sensing**
  - Machine monitoring and diagnostics (IC fab)
  - Power/telecom grid monitoring
- **Human-centered computing**
  - Smart, human-aware spaces and environments

**Untethered micro sensors will go anywhere and measure anything -- traffic flow, water level, number of people walking by, temperature. This is developing into something like a nervous system for the earth. -- Horst Stormer in *Business Week, 8/23-30, 1999*.**

# Wireless Sensor Networks

- Distributed systems consisting of small, untethered, low-power nodes capable of sensing, processing, and wireless communication





RFID

DOT

MICA


MS Spot Watch

PDA

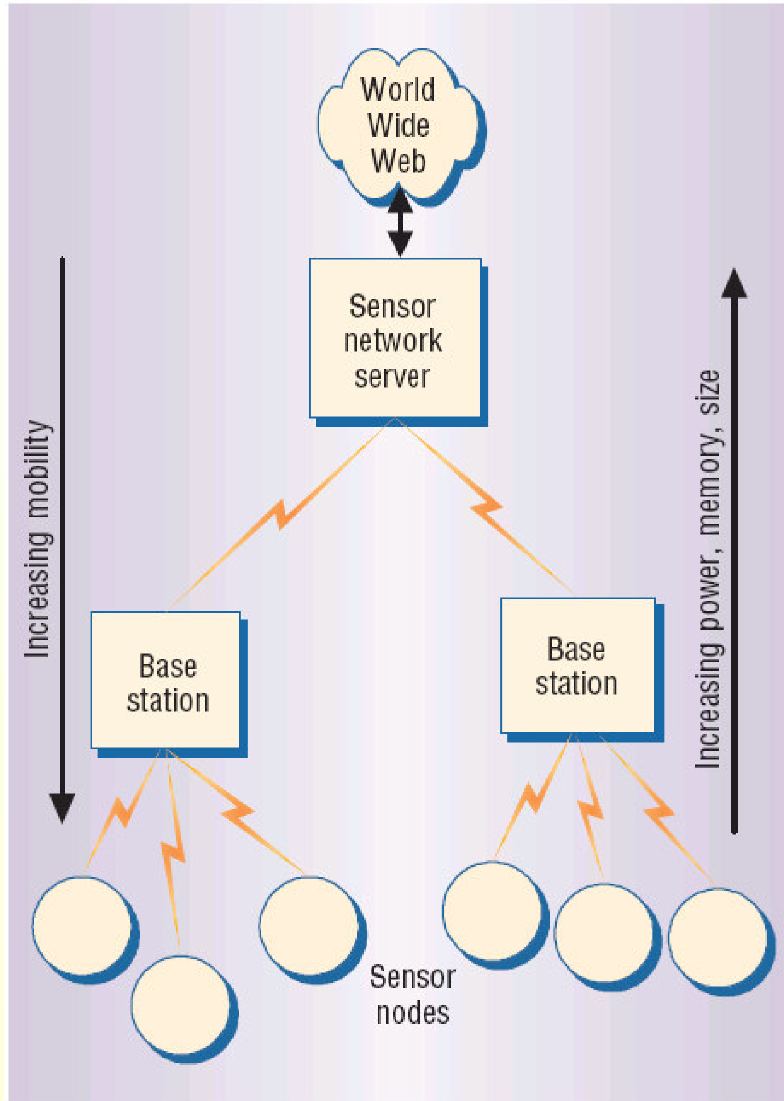
Sensoria Node

small

large

# Monitoring the World

- Monitoring the environment and other spaces
- Monitoring objects
- Monitoring interactions between objects, or between objects and their environment



# Petrel Nesting Behavior at Great Duck Island

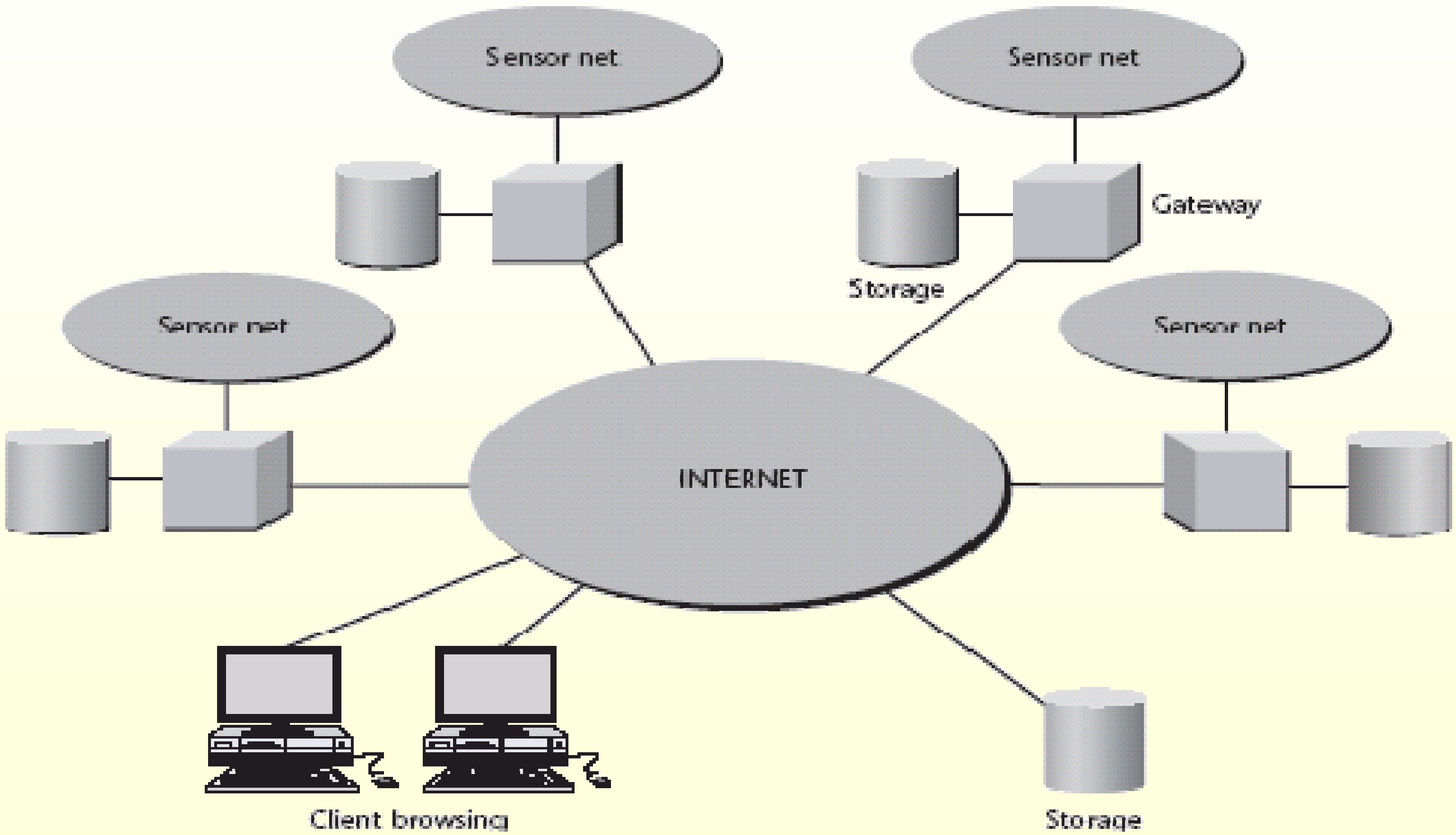
# Wireless Sensor Network Deployment

- Advantages:
  - sensors can be close to signal sources, yielding high SNR
  - can monitor phenomena widely distributed across space and time
  - distributed architecture provides for scalable, robust and self-repairing systems
  - significant savings on cabling, etc are possible

British Columbia winery with networked temperature sensors

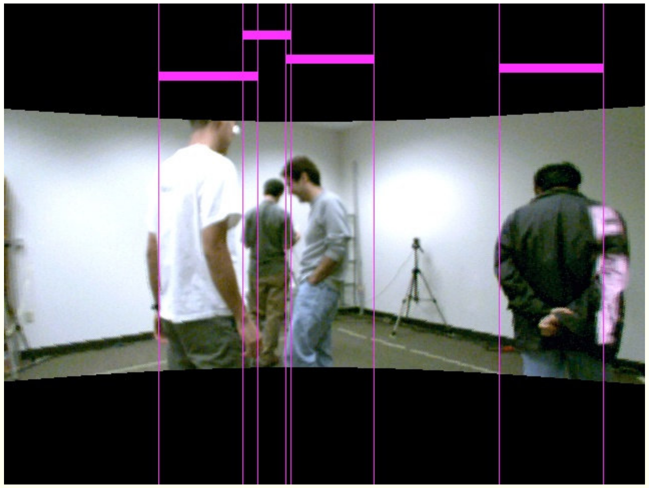
Other data collection and monitoring: temperature in data centers (HP), oil tanker vibrations (Exxon), soil contaminants, etc.

# Integration with Current Networks

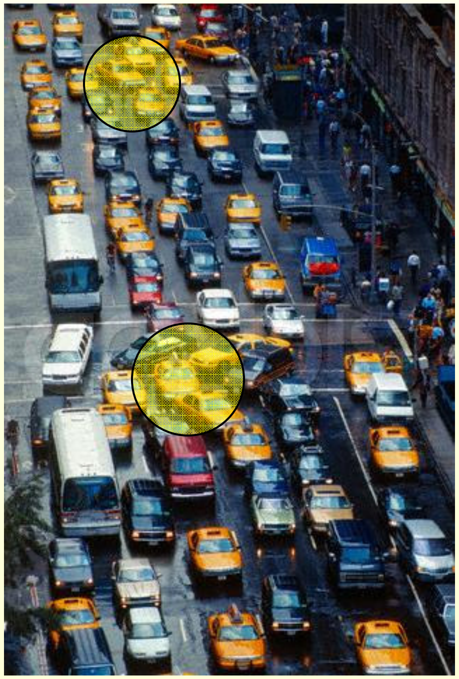



Access to unfiltered information, highly localized in time and space

# More Demanding Sensor Network Applications

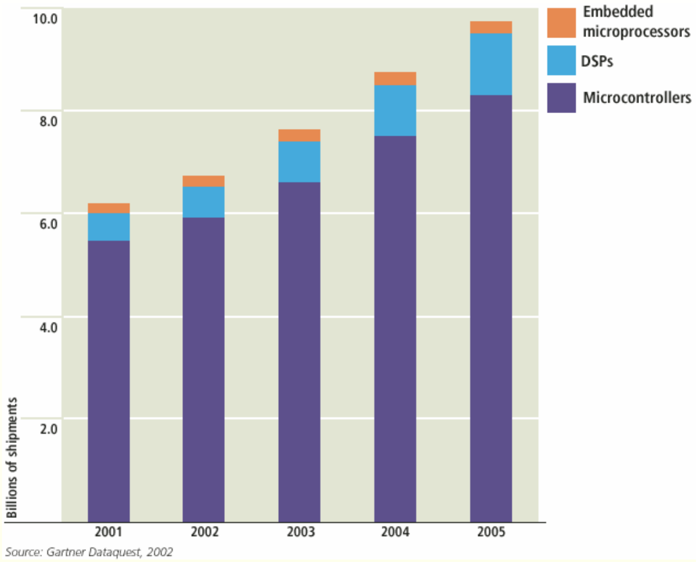


- Beyond simple data collection and aggregation
  - acting on the world
  - simultaneous tracking of multiple objects
  - distributed, wide-area phenomena
  - distributed attention: focus and context
- Network must adapt to highly dynamic foci of activity
- Sensing and communication tasks must be allocated
- Resources must be apportioned between detection, tracking, etc.



# Sensor Network Hardware

# Wireless Sensor Trends




- Of 9.6 billion µP's to be shipped in 2005, 98% will be embedded processors!

- Riding on Moore's law, smart sensors get:

**More powerful**

Sensoria WINSNG 2.0
CPU: 300 MIPS
1.1 GFLOP FPU
32MB Flash
32MB RAM
Sensors: external

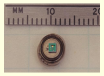
**Easy to use**

HP iPAQ w/802.11
CPU: 240 MIPS
32MB Flash
64MB RAM
Both integrated and off-board sensors

**Inexpensive & simple**

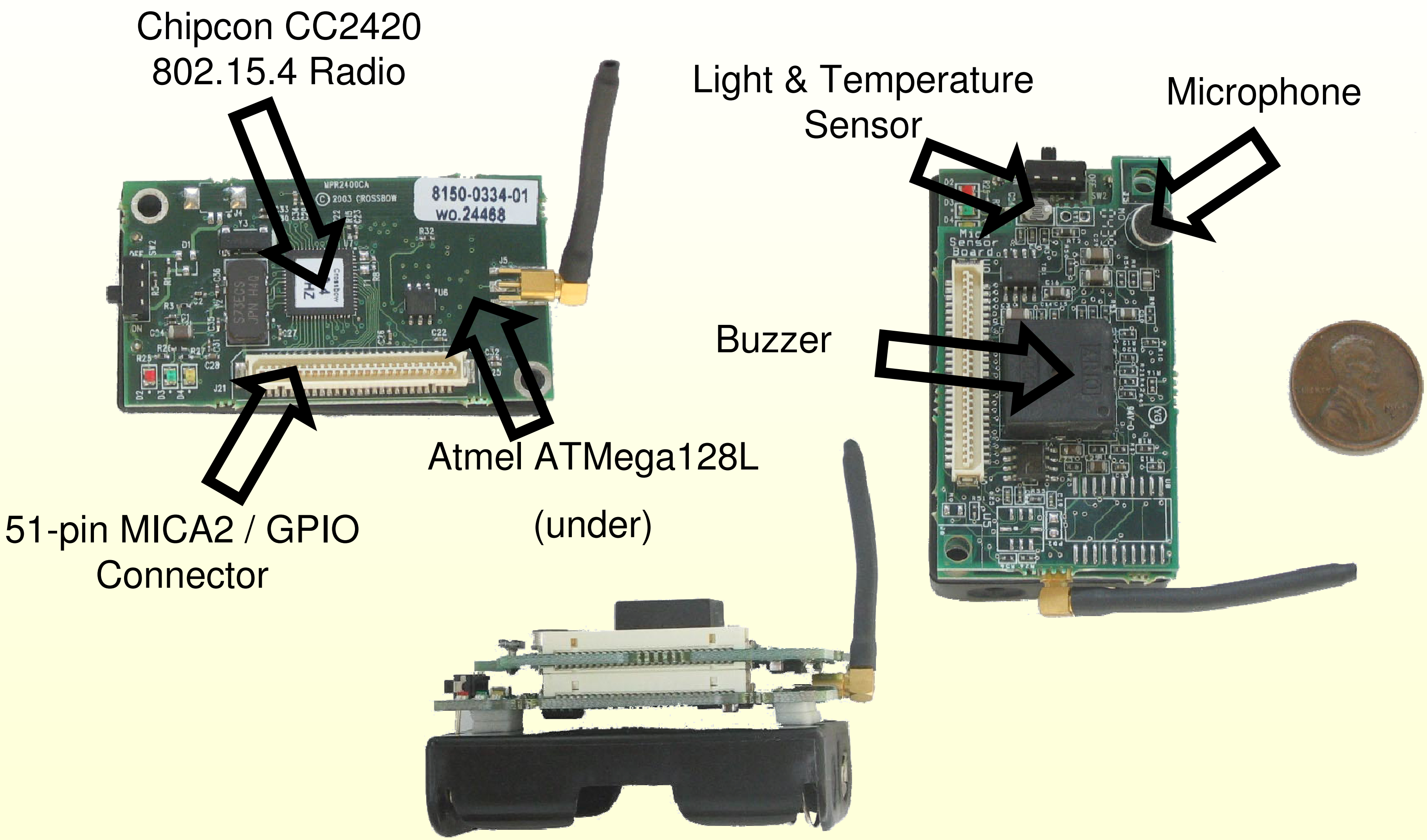
Crossbow MICA mote
4 MIPS CPU (integer only)
8KB Flash
512B RAM
Sensors: on board stack

**Supercheap & tiny**

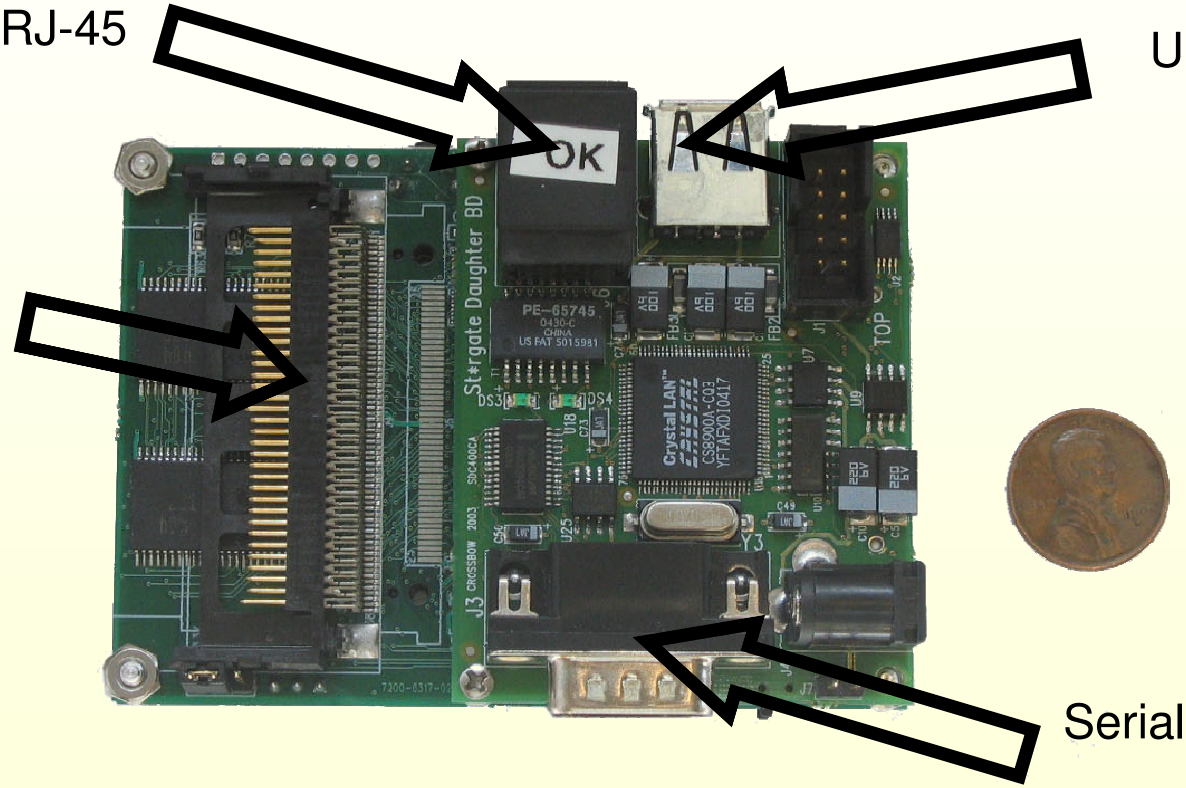


Smart Dust (in progress)
CPU, Memory: TBD (LESS!)
Sensors: integrated

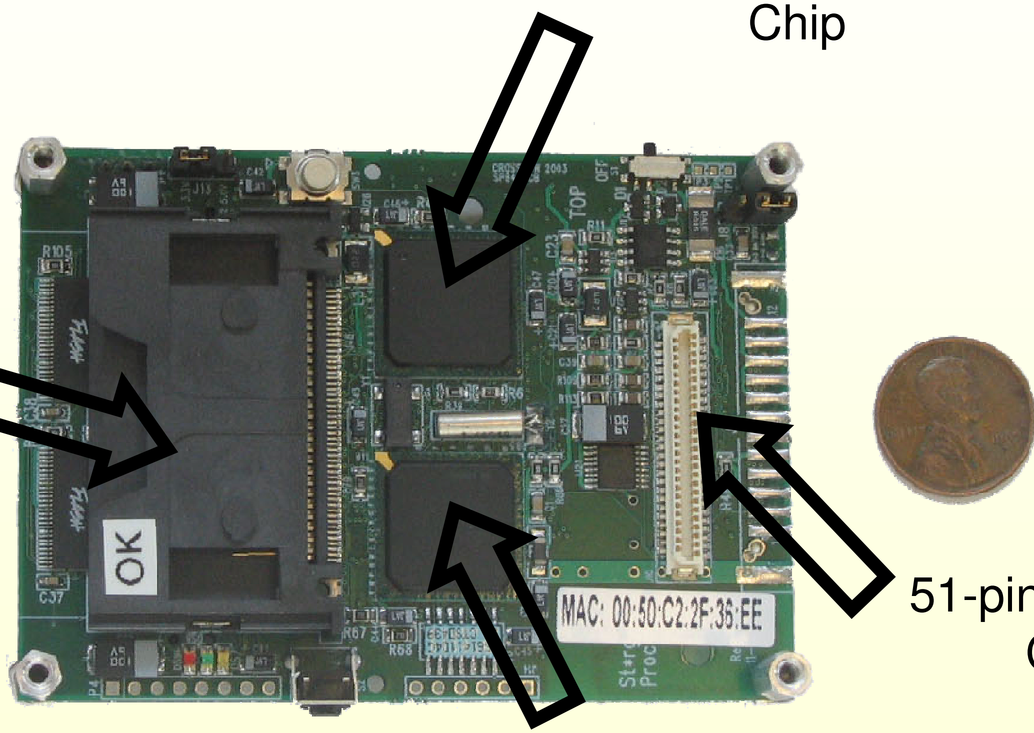
# Most Popular: Crossbow Motes



# Crossbow Stargate - Top View



# Crossbow Stargate - Bottom View



# Specifications

## MicaZ Mote

- TinyOS
- 16 Mhz Atmel ATMega128L
- 128 kB Program FLASH
- 512 kB Serial FLASH
- Current Draw
  - 8 mA – Active Mode
  - <15 uA – Sleep Mode
- Chipcon CC2420 802.15.4 Radio
  - 250 kbps
  - 26 Channels – 2.4 Ghz
  - Current Draw – 15 mA

## Stargate

- Embedded Linux OS
- 400 Mhz Intel Xscale
- 64 MB SDRAM
- 32 MB FLASH
- Many different interfaces
  - RS-232, Ethernet, USB,…

www.xbow.com
http://computer.howstuffworks.com/mote4.htm

# Power Breakdown …

| | Active | Idle | Sleep |
|---|---|---|---|
| CPU | 5 mA | 2 mA | 5 μA |
| Radio | 7 mA (TX) | 4.5 mA (RX) | 5 μA |
| EE-Prom | 3 mA | 0 | 0 |
| LED's | 4 mA | 0 | 0 |
| Photo Diode | 200 μA | 0 | 0 |
| Temperature | 200 μA | 0 | 0 |

Rene motes data, Jason Hill

Panasonic CR2354
560 mAh

Computation/communication ratio:

- Rene motes:
  - Comm: (7mA*3V/10e3)*8=16.8μJ per 8bit
  - Comp: 5mA*3V/4e6=3.8 nJ per instruction
  - Ratio: 4,400 instructions/hop
- Sensoria nodes:
  - Comm: (100mW/56e3)*32=58μJ per 32bit
  - Comp: 750mW/1.1e9=0.7nJ per instruction
  - Ratio: 82,000 instructions/hop

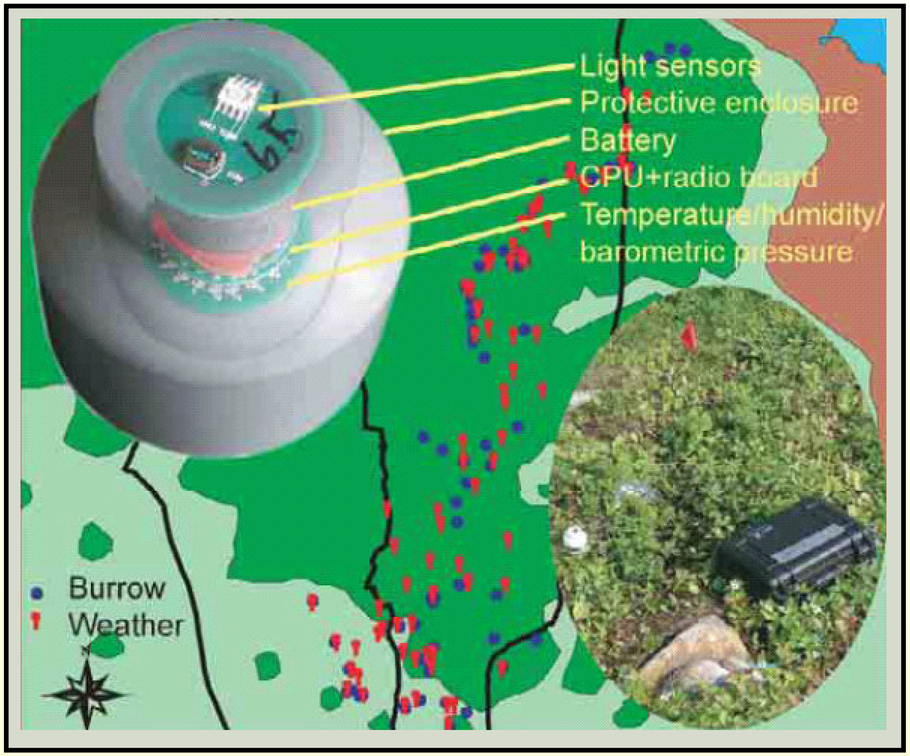
This means

– Lithium Battery runs for 35 hours at peak load and years at minimum load, a three orders of magnitude difference!

# Architectural Challenges

# Sensor Network Challenges

- Power management
  - communication 1000s of times more expensive than computation
  - load balancing
  - coordinated sleeping schedules
  - correlated sensor data
- In-network processing
  - data aggregation
  - overcounting of evidence
- Difficult calibration
  - localization
  - time-synchronization
- Constant variability
  - networking
  - sensing



# Distributed Sensor Communication: Multi-Hop RF Advantage

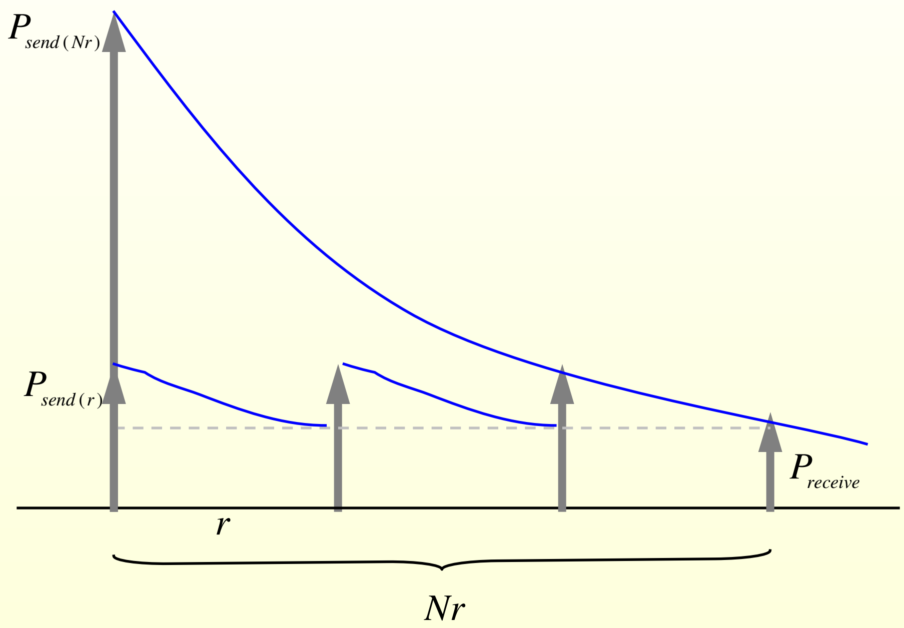
RF power attenuation near ground:

$$P_{receive} \propto \frac{P_{send}}{r^{\alpha}}, \qquad \alpha : 3-5$$

Or equivalently, $P_{send} \propto r^{\alpha} P_{receive}$

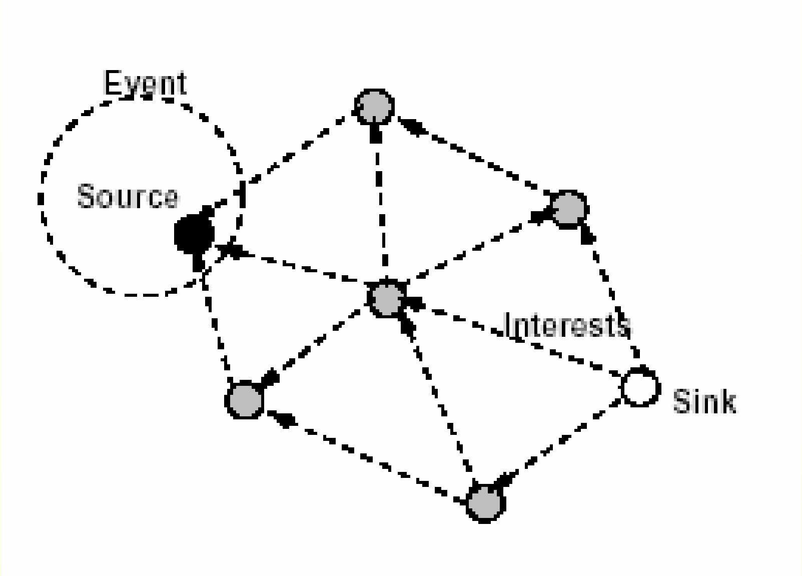
Power advantage:

$$\frac{P_{send(Nr)}}{N \cdot P_{send(r)}} = \frac{(Nr)^{\alpha} P_{receive}}{N \cdot r^{\alpha} P_{receive}} = N^{\alpha-1}$$



# Semantic Routing and Networking

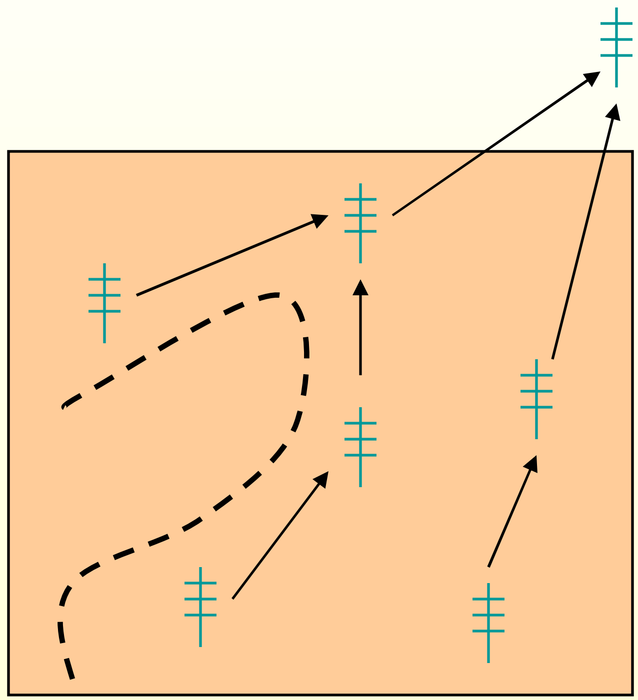
- We want to address spatial locations or information, not individual nodes
- Content and address in a message get intermixed
- How do we help information providers and clients find each other?




Directed diffusion
Geo-routing

# In-Network Processing

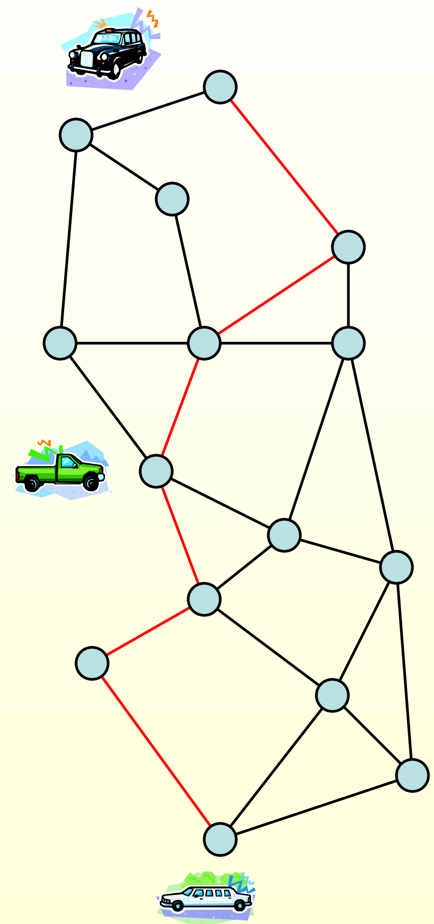
- Information aggregation can happen on the way to a destination
- Need to balance quality of paths with quality of information collected
- Are there “application-independent” paradigms of information aggregation?



Temperature aggregation

# Networking Sensor Networks

- Network support for a small number of collaborative tasks.
- Data-centric, (as opposed to a node-centric) view of the world.
- Monitoring processes may migrate from node to node, as the phenomena of interest move or evolve.
- Communication flow and structure is dictated by the geography of signal landscapes and the overall network task.



# Distributed Sensor Networks: Detection and SNR Advantage

Sensors have a finite sensing range. A denser sensor field improves the odds of detecting a target within the range. Once inside the range, further increasing sensor density by *N* improves the SNR by 10log*N* db (in 2D). Consider the acoustic sensing case:

Acoustic power received at distance *r*:

$$P_{receive} \propto \frac{P_{source}}{r^2}$$

Signal-noise ratio (SNR):

$$SNR_r = 10\log P_{source} - 10\log P_{noise} - 20\log r$$

Increasing the sensor density by a factor of *N* gives a SNR advantage of:

$$SNR_{\frac{r}{\sqrt{N}}} - SNR_r = 20\log \frac{r}{\frac{r}{\sqrt{N}}} = 10\log N$$

# Collaborative Estimation

- Structuring communication is very important:

  In a setting where each node wishes to communicate some data to another node at random, interference hinders scaling:

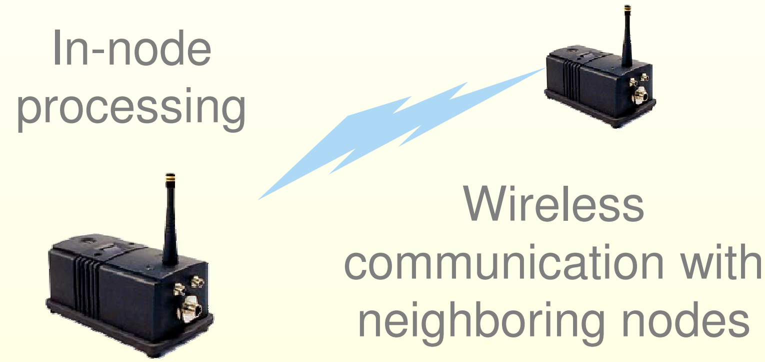
  the per node throughput scales as $\frac{1}{\sqrt{N}}$

  Effectively each node is using all of its energy to route messages for other nodes.

  In a sensor network, however, because data from nearby sensors are highly correlated and more intelligent information dissemination strategies are possible.

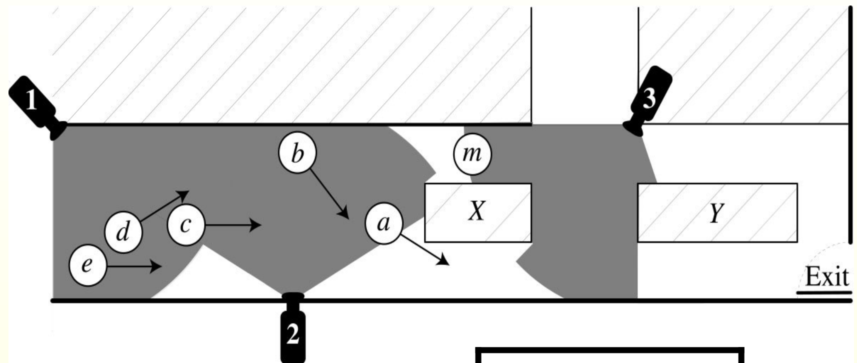
# Power-Aware Sensing and Communication

- Variable power systems
- Let most sensors sleep most of the time; paging channels
- Exploit correlation in readings between nearby sensors
- Load-balance, to avoid depleting critical nodes



# Sensor Tasking and Control

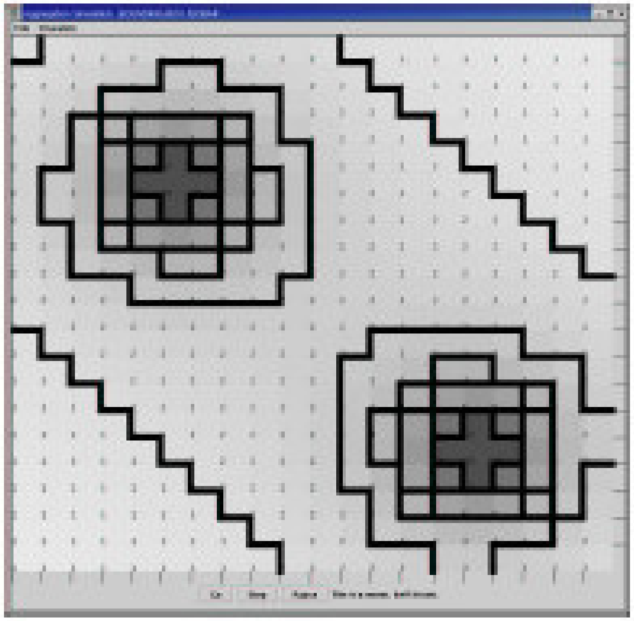
- Decide which sensors should sense and communicate, according to the high-level task – a non-trivial algorithmic problem
- Direct sensing of relations relevant to the task – do not estimate full world state




| |
|---|
| *a* ahead-of *b* |
| *b* ahead-of *c* |
| *c* ahead-of *d* |
| *d* ahead-of *e* |

# Enable Data-Base Like Operations

- Data only available right after sensing operation
- Dense data streams must be sampled, or otherwise summarized
- Must deal with distributed information storage – "where is the data?"

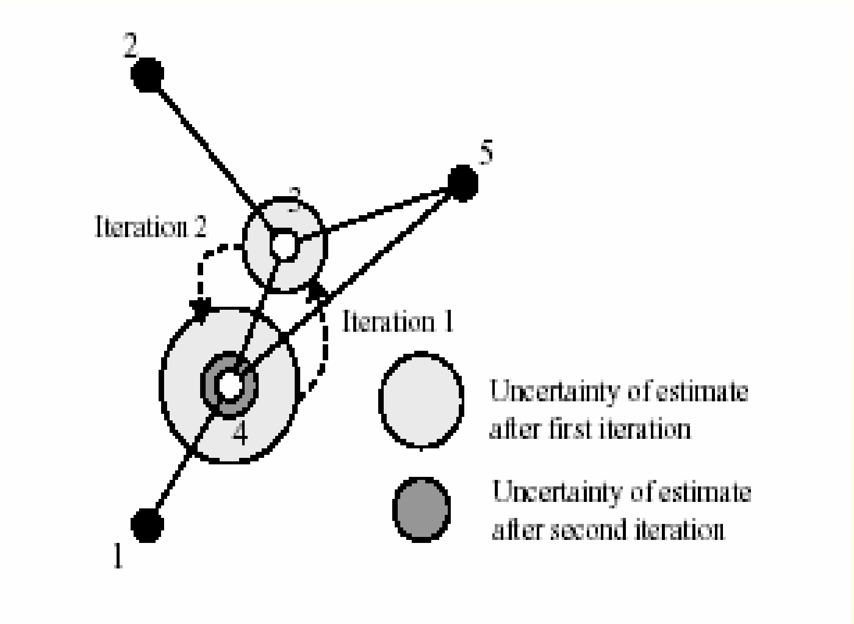


(a) Lossless Isobars

Field isolines

# Self-Configuration for Ad-Hoc Deployment

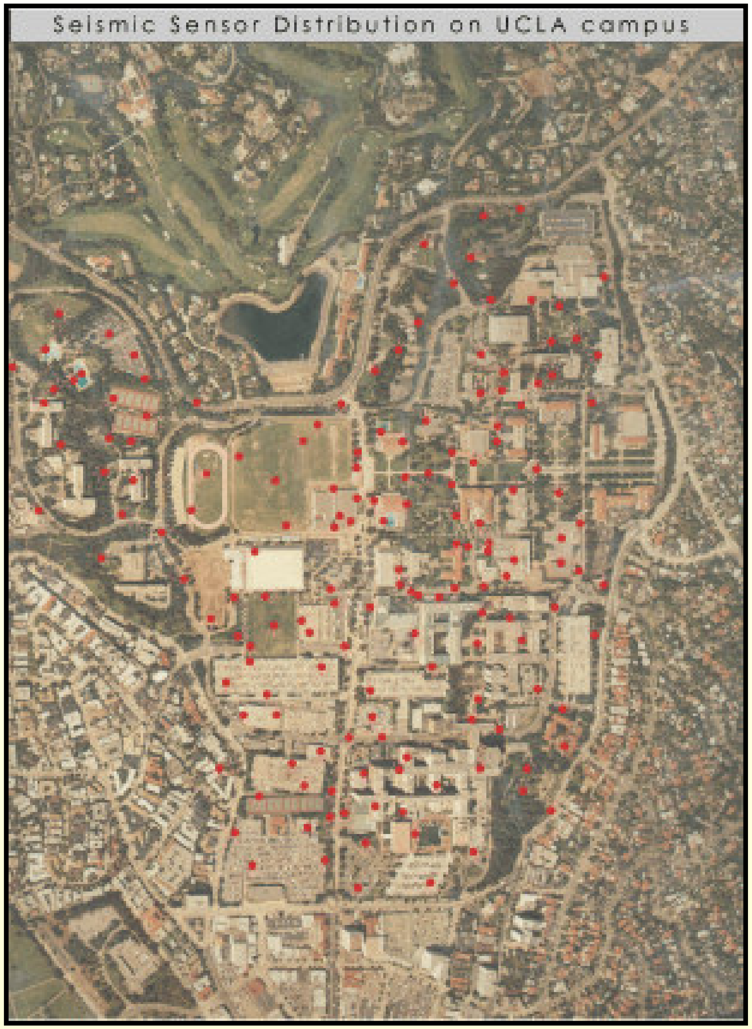
- Network size makes it impossible to configure each node individually
- Environmental changes may require frequent re-calibration
- Network must recover after node failures




Iterative localization

# Structure Discovery

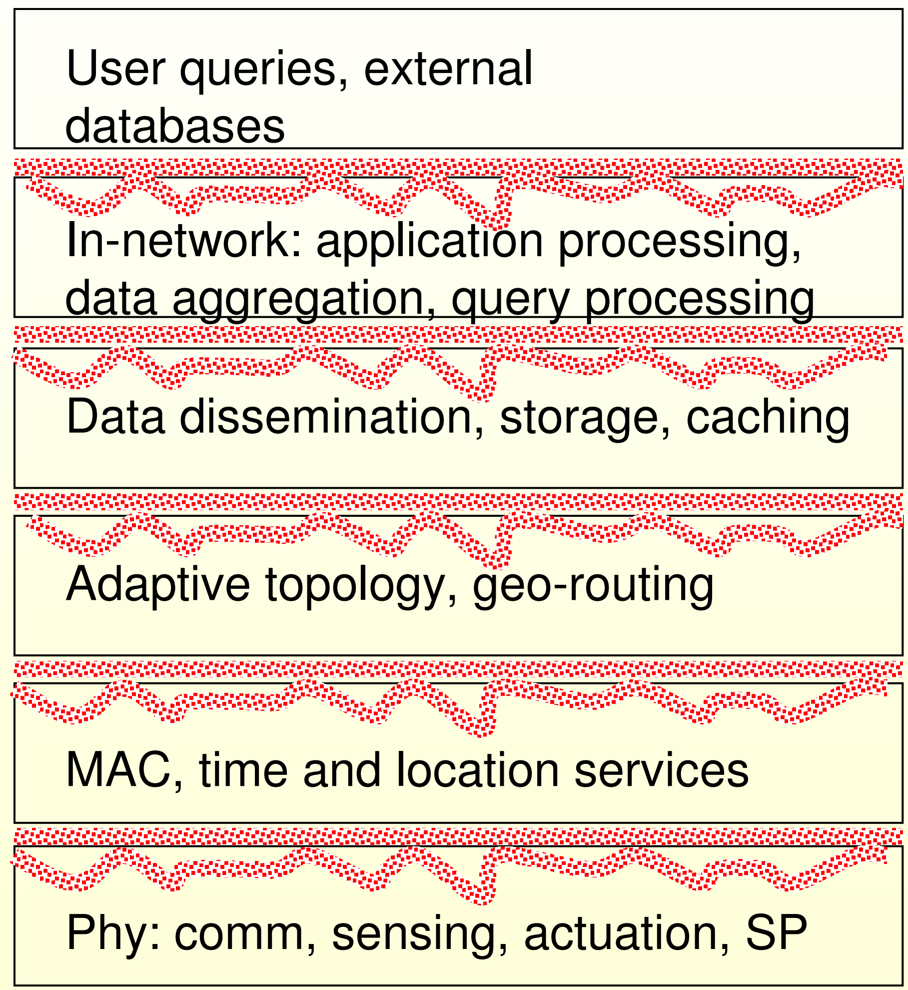
- A sensor network is a novel type of computing device -- a sensor computer
- One of its first tasks is to discover its own structure and establish
  - information highways
  - sensor collaboration groups
- as well as adapt to its signal landscape



# New System Architectures

- Resource constraints require close coupling between the networking application layers
- Can we define *application-independent* programming abstractions for sensor networks?

A sensor net stack?



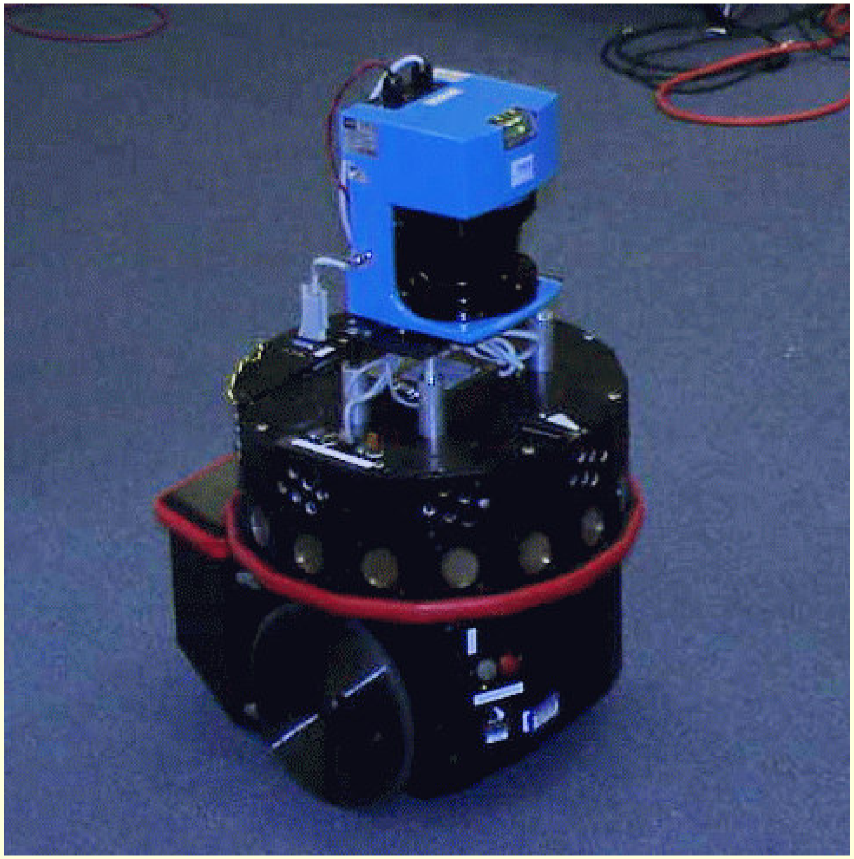
# Challenges at the Node and System Levels

The setting:

- power conservation is important:
  - untethered node operation
  - communication far more expensive than computation (sensing, too)
- *ad hoc* deployment in noisy, adverse environments
  - self-initialization, self-configuration
  - robustness to individual node failure

# Various Issues

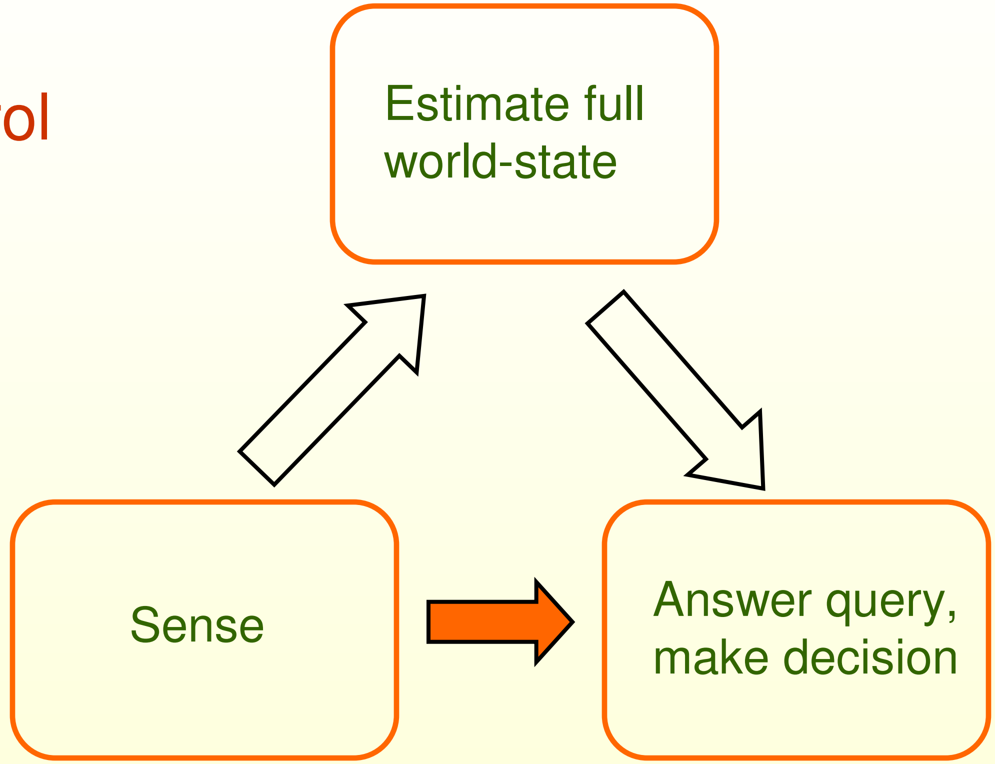
- Integration of sensors with widely different modalities
  - High data-rate sensors (cameras, laser scanners)
- Sensor mobility
- Actuation



Distributed robotics

# Sensor Network Research

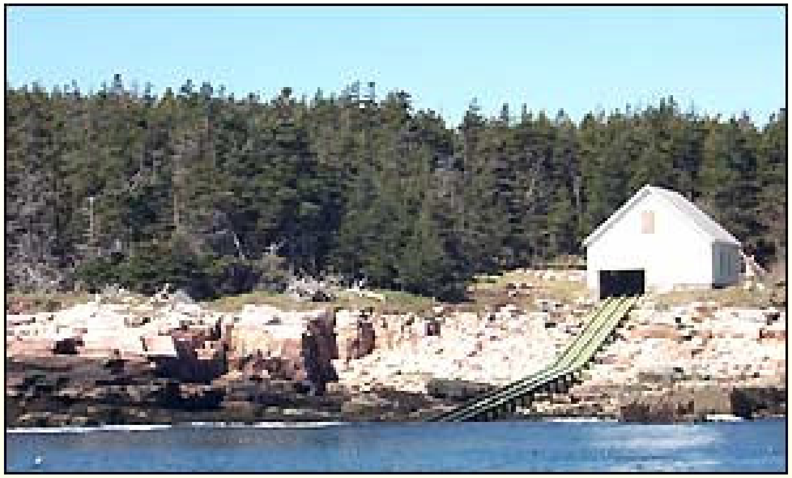
- power awareness
- sensor tasking and control
- formation of sensor collaboration groups
- in-network, distributed processing
- node management, service establishment, software layers
- coping with noise and uncertainty in the environment




A key algorithmic problem is how to sense and aggregate only the portions of the world-state relevant to the task at hand, in a lightweight, energy-efficient manner.

# Applications

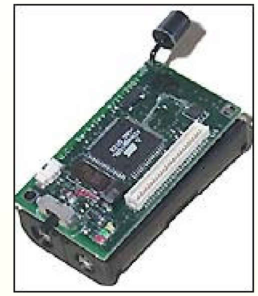
# Habitat monitoring: www.greatduckisland.net



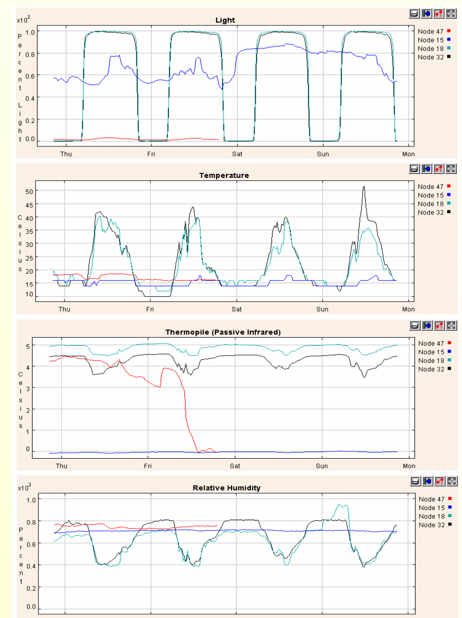
Great Duck Island, 10 miles off the coast of Maine:

Remote wireless sensors are being used to find out more about birds in their natural habitat.

Petrel: Rarely seen by birdwatchers



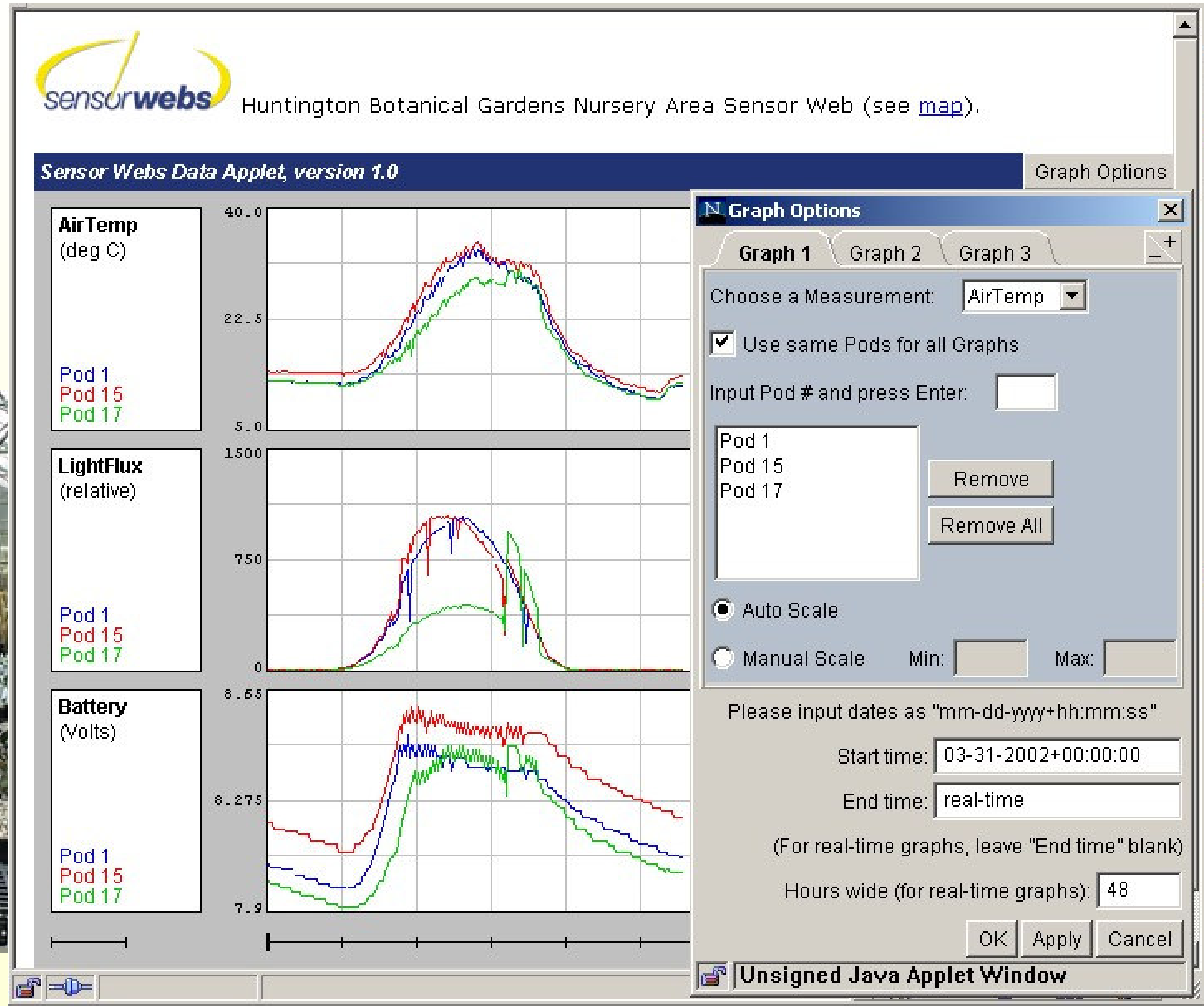
Wireless biological sensors placed in nests




"It will enable us to study ecosystems at a level that has not been conceived."
Steve Katona, College of the Atlantic biologist and president

BBC News, October 10, 2002

# Monitoring Plants at Huntington Botanical Garden



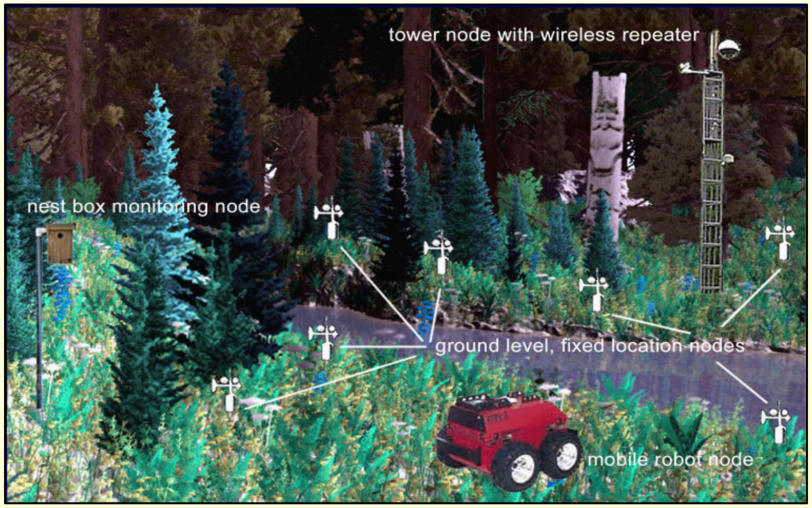
# Ecosystem Monitoring

**Science**

- Understand response of wild populations (plants and animals) to habitats over time.
- Develop in situ observation of species and ecosystem dynamics.

**Techniques**

- **Data acquisition of physical and chemical properties, at various spatial and temporal scales, appropriate to the ecosystem, species and habitat.**
- Automatic identification of organisms (current techniques involve close-range human observation).
- Measurements over long period of time, taken *in-situ*.
- Harsh environments with extremes in temperature, moisture, obstructions, ...



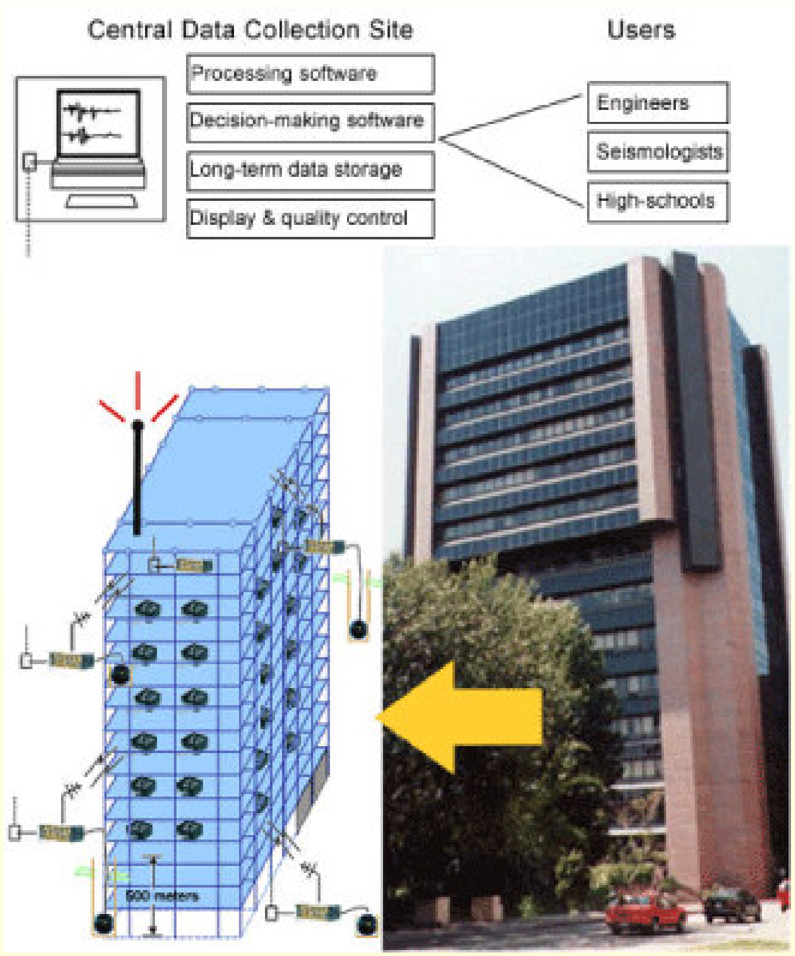

[From D. Estrin, UCLA]

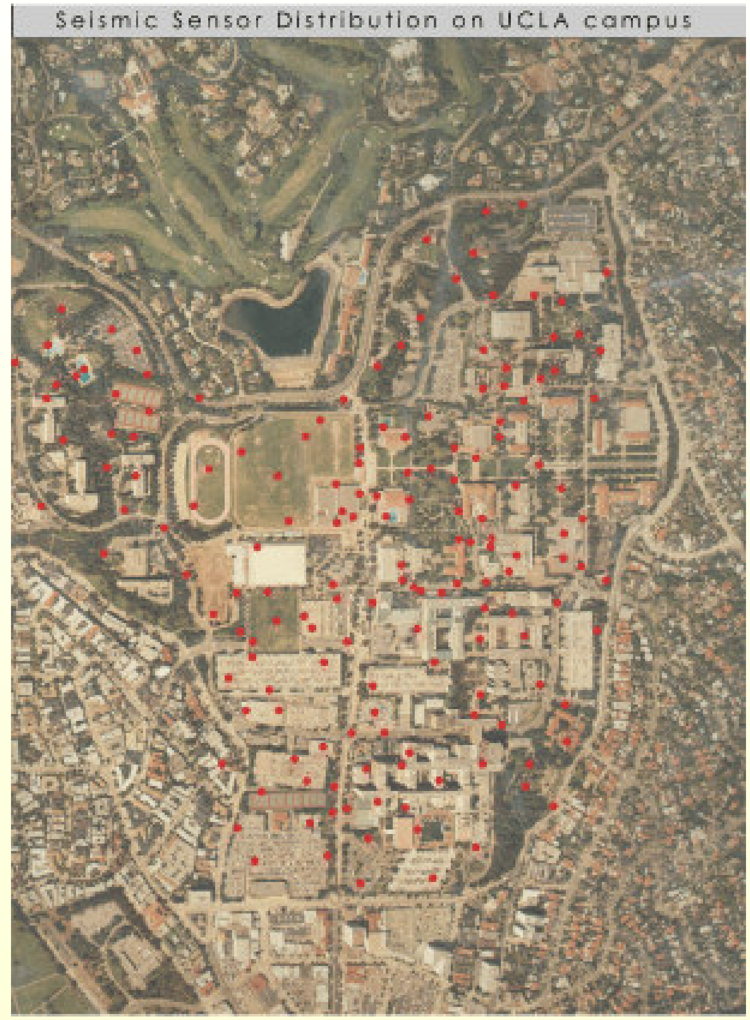
# Seismic Monitoring

- Interaction between ground motions and structure/foundation response not well understood.
  - **Current seismic networks not spatially dense enough** to monitor structure deformation in response to ground motion, to sample wavefield without spatial aliasing.
- Science
  - Understand response of buildings and underlying soil to ground shaking
  - Develop models to predict structure response for earthquake scenarios.
- Technology/Applications
  - Identification of seismic events that cause significant structure shaking.
  - Local, at-node processing of waveforms.
  - Dense structure monitoring systems.

[From D. Estrin, UCLA]

- 38 strong-motion seismometers in 17-story steel-frame Factor Building.
- 100 free-field seismometers in UCLA campus ground at 100-m spacing




1 km

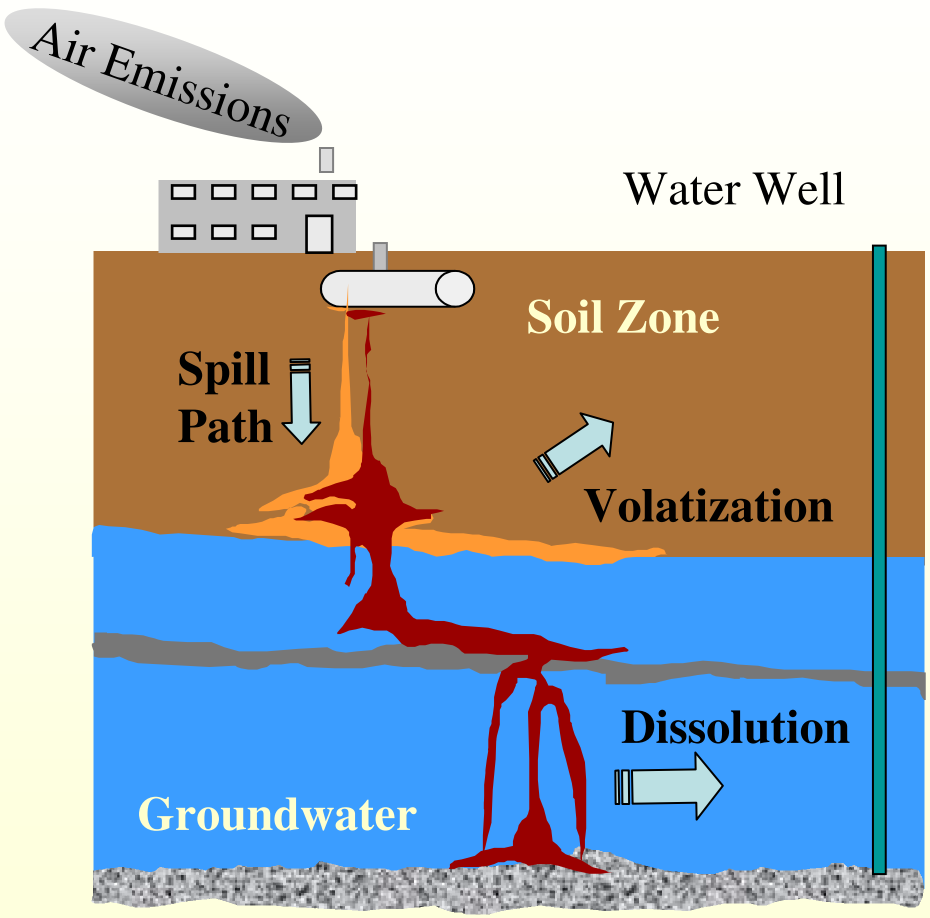
[From D. Estrin, UCLA]

# Research Challenges

- Real-time analysis for rapid response.
- Massive amount of data → Smart, efficient, innovative data management and analysis tools.
- Poor signal-to-noise ratio due to traffic, construction, explosions, ….
- Insufficient data for large earthquakes → Structure response must be extrapolated from small and moderate-size earthquakes, and force-vibration testing.
- First steps
  - Monitor building motion
  - Develop algorithm for network to recognize significant seismic events using real-time monitoring.
  - Develop theoretical model of building motion and soil structure by numerical simulation and inversion.
  - Apply dense sensing of building and infrastructure (plumbing, ducts) with experimental nodes.

[From D. Estrin, UCLA]

# Contaminant Transport

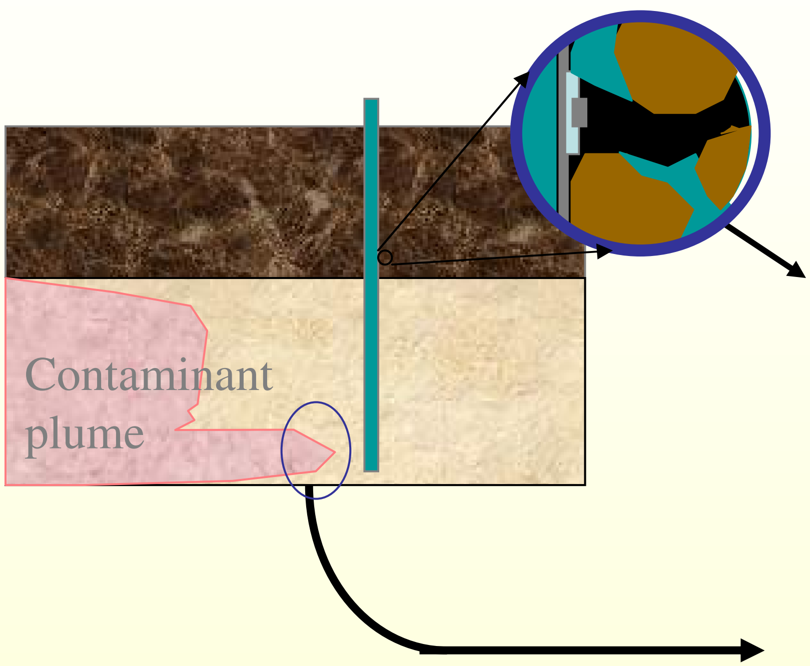



- Science
  - Understand intermedia contaminant transport and fate in real systems.
  - Identify risky situations before they become exposures.

  Subterranean deployment.
- Multiple modalities (e.g., pH, redox conditions, etc.)
- Micro sizes for some applications (e.g., pesticide transport in plant roots).
- Tracking contaminant “fronts”.
- At-node interpretation of potential for risk (in field deployment).

[From D. Estrin, UCLA]

# Research Implications

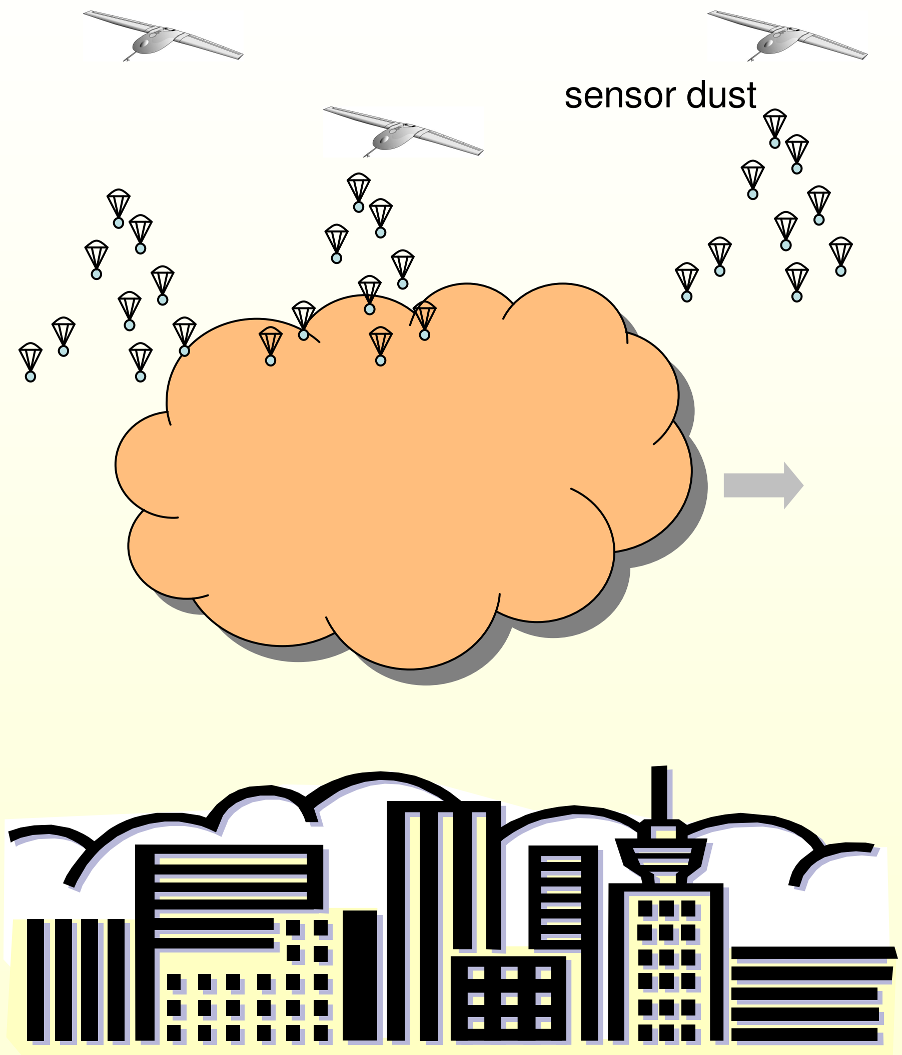



- Environmental Micro-Sensors
  - Sensors capable of recognizing phases in air/water/soil mixtures.
  - Sensors that withstand physically and chemically harsh conditions.
  - Microsensors.
- Signal Processing
  - Nodes capable of real-time analysis of signals.
  - **Collaborative signal processing to expend energy only where there is risk.**

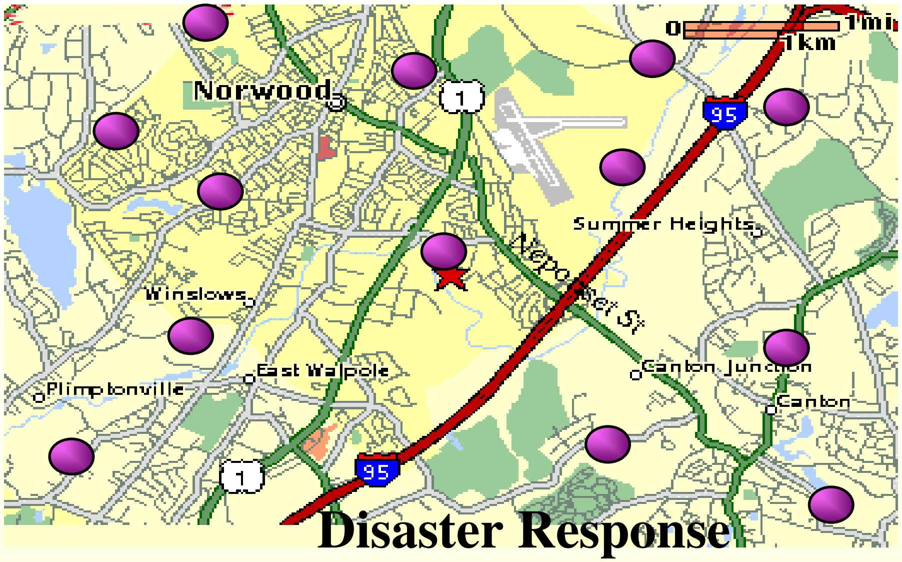
[From D. Estrin, UCLA]

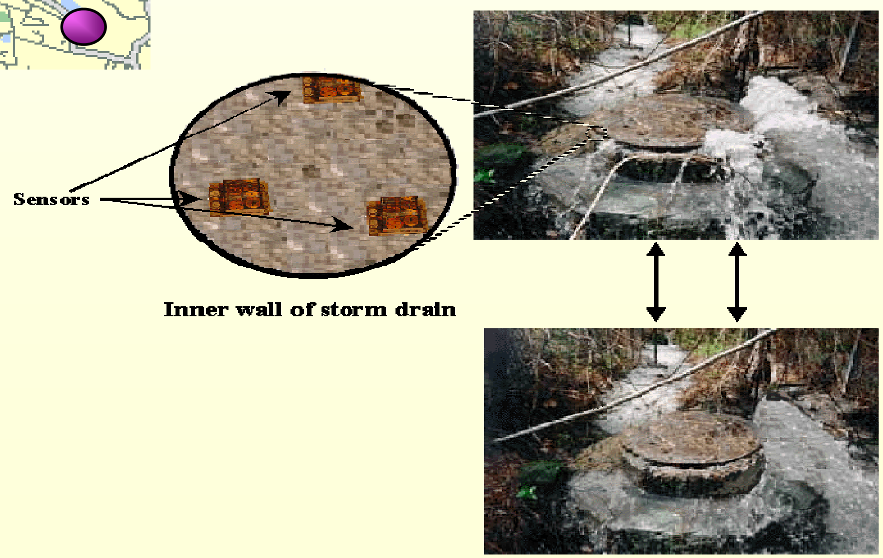
# A Chemical Disaster Tracking Scenario

- A large-scale chemical gas leak has been detected at a plant 20 minutes ago
- The national guard has been activated to evacuate nearby towns, and to close roads/bridges
- To get a real-time situational assessment of the extent and movement of the gas release and inform the evacuation, a *SWAT Team* is called in
- Three small UAVs are immediately launched from an open field 15 miles south of the attack site, each equipped with 1000 tiny chemical sensing nodes
- Upon flying over the vicinity of the attack site, the sensor nodes are released
- The nodes self-organize into an ad hoc network, while airborne, and relay the tracking result back to the emergency response command center
  - Where is the plume, how big, how fast, which direction?



# Transportation and Urban Monitoring

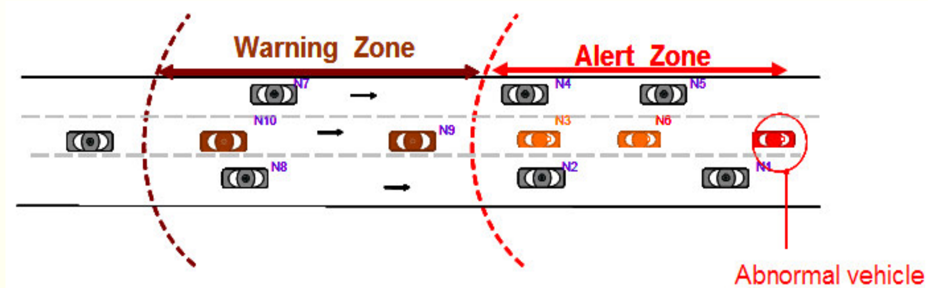



[From D. Estrin, UCLA]

# Traffic and Collision Control

- V2V communication of Emergency Alert Messages. Early collision awareness and avoidance.

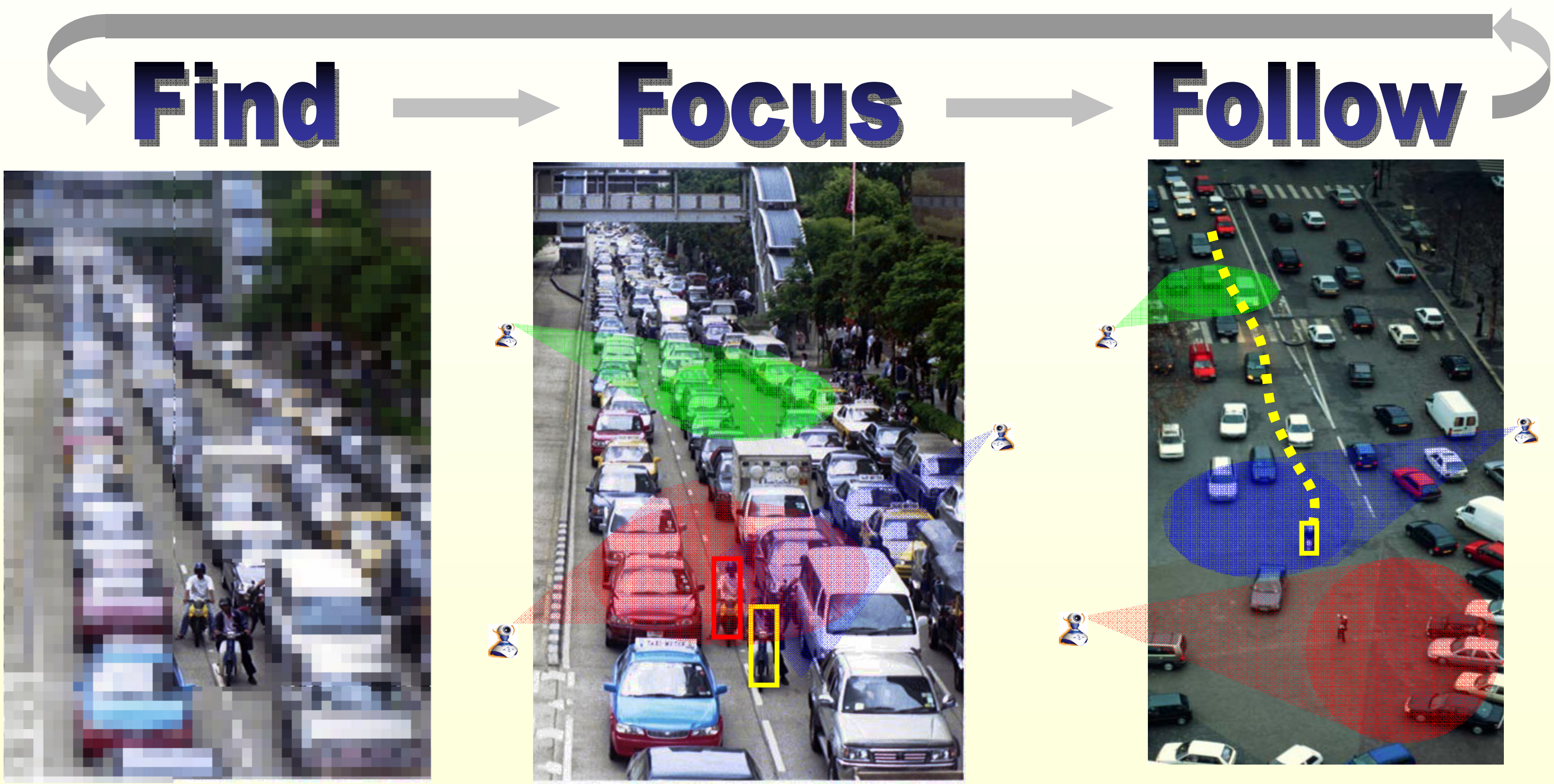



- Traffic jam information collection and propagation.


[From J. Reich, PARC]

# Distributed Attention

**Sensor Networks in Complex, Urban Environments**




[From J. Reich, PARC]

# What is Unique about Sensor Networks?

- Unique characteristics
  - **Coverage**: Distance/area covered, number of events, number of active queries
  - **Spatial diversity**: Dense spatial sampling, multi-aspect sensing, multiple sensing modalities
  - **Survivability**: Robust against node/link failures
  - **Ubiquity**: Quick/flexible deployment, ubiquitous access, info timeliness
- Particularly suited for detecting, classifying, tracking
  - Non-local spatio-temporal events/objects
    - **Simultaneous dense spatial sampling** to identify and track large, spatially extended event
    - **Continuous spatio-temporal sampling** to track moving objects
  - Low-observable events
    - **Distributed information aggregation**
    - **Non-local information validation**

# Conclusion

- Ubiquitous networked sensors provide a dense spatial and temporal sensing of the physical world
- They potentially provide low-latency access to information that is highly localized in time and space, and thus provide a way to sense and act on the physical world beyond what has been possible up to now
- Sensor networks raise many research issues at the physical node level, the system architecture level, and the algorithm deployment level

# CS428: The Course

# Course Outline, I

- Networking sensor networks (topology discovery, MAC layer issues, routing, energy considerations)
- Information brokerage (directed diffusion, distributed hash tables)
- Infrastructure establishment (time-synch, localization)
- Sensor network hardware (Motes/Stargates and other common node types, power issues)

# Course Outline, II

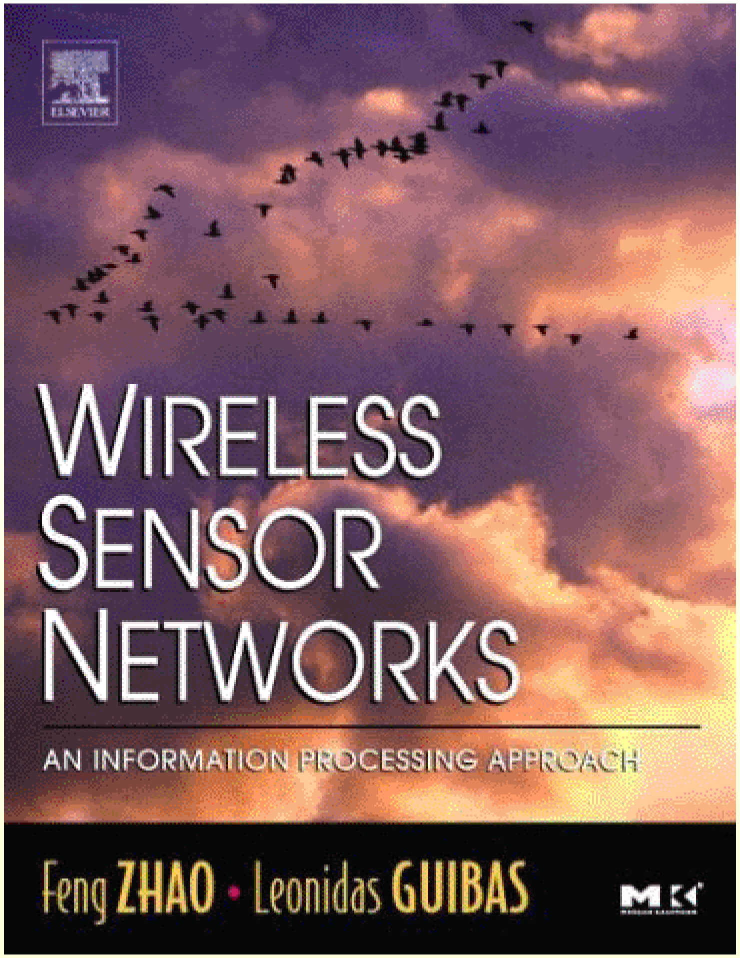
- Sensor network software (TinyOS, programming abstractions)
- Probabilistic state estimation with sensor data (Kalman and particle filters)
- Sensor tasking and control (value of information, collaborative signal processing)
- Distributed data processing and storage (in-network data aggregation, range searching)
- Applications (camera networks)

# Course TextBook

Wireless Sensor Networks: An Information Processing Approach

Geng Zhao and Leonidas Guibas

Morgan-Kaufmann 2004



# Course Format

- Lectures by the instructor, plus student presentations of current research papers
- Possible to do a course project

- Grading:
  - 2 units: P/NP, paper presentation required
  - 3 units: letter grade, project required

# Course Personnel

- Instructor:

  Leonidas J. Guibas

- TA:

  Primoz Skraba

Course web page:

http://graphics.stanford.edu/courses/cs428-05-spring

http://www.stanford.edu/class/cs428

*The End*