G 364: Mobile and Wireless Networking

CLASS 11, Wed. Feb. 11 2004

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Spring 2004

M-W, 11:40am-1:20pm, 109 Rob

Wireless Sensor Networks (WSNs)

- Motivating applications
- Enabling technologies
- Unique constraints
- Application and architecture taxonomy

(Based on Mani Srivastava tutorial)

Wireless Networking & Computing Technology

Until Now

- People and human-mediated data sources interaction (other people, web services)
- # of users ~ # of networked nodes
- Resource-rich nodes
- Facilitate human-centered decision making
- Communicate bits among geographically distributed nodes

Focus on networking interactive computers

The Future

- Interaction between people and the instrumented physical world (sensors, actuators)
- # of users << # of networked nodes
- Resource-constrained nodes
- Facilitate human-supervised autonomous decision making

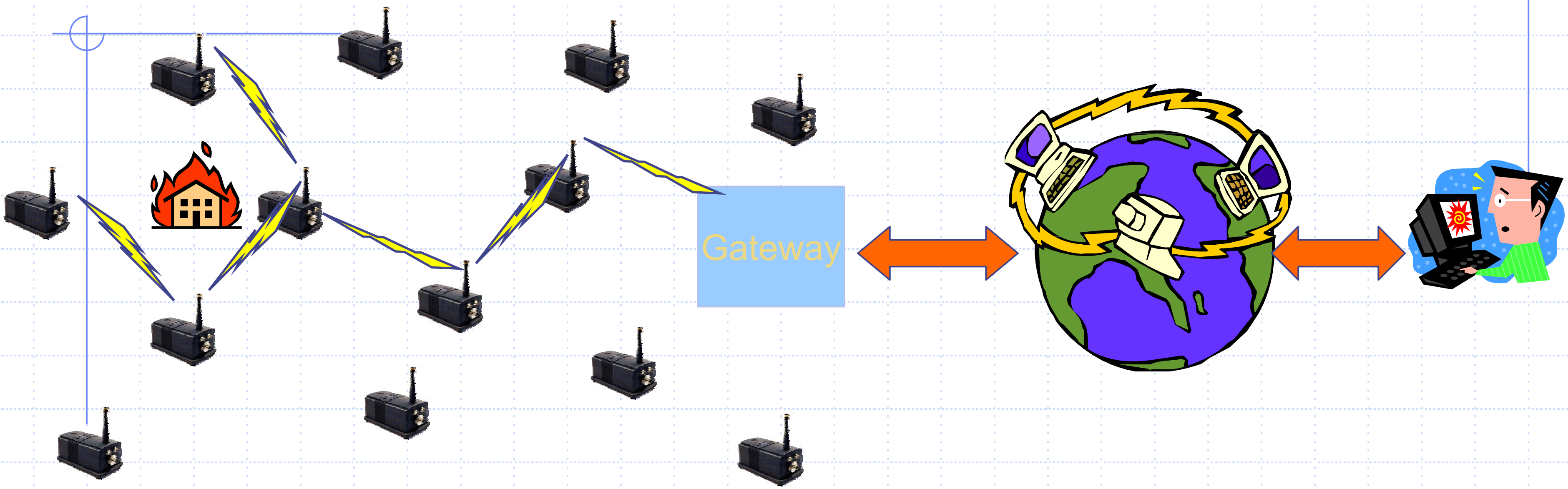
Focus on distributed embedded computation

Networked Sensing & Actuation

- "Communication" between people and their physical environment
  - Allow users to query, sense, and manipulate the state of the physical world
- Technology enablers
  - Cheap, ubiquitous, high-performance, low-power embedded processing
    - e.g. low-power processor cores
  - Cheap, ubiquitous (wireless) networking
    - e.g. single-chip CMOS radios
  - Cheap, ubiquitous, high-performance sensors and actuators
    - e.g. MEMS devices

Soon, all on a single system-on-chip!

"The Network is the Sensor"



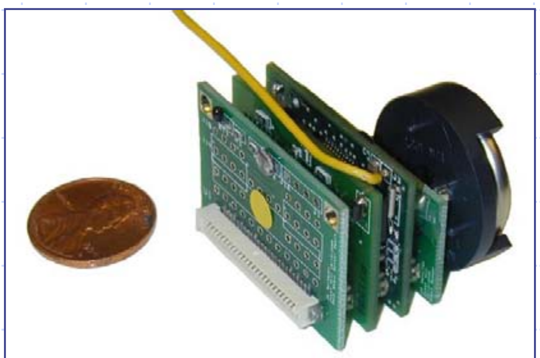
- Distributed and large-scale like the current Internet
- But:
  - physical instead of virtual
  - resource constrained
  - real-time control loops instead of interactive human loops

Wirelessly Networked Sensor Nodes

LWIM III
UCLA, 1996
Geophone, RFM radio, PIC, star network

AWAIRS I
UCLA/RSC 1998
Geophone, DS/SS Radio, strongARM, Multi-hop networks

Sensor Mote
UCB, 2000
RFM radio, PIC

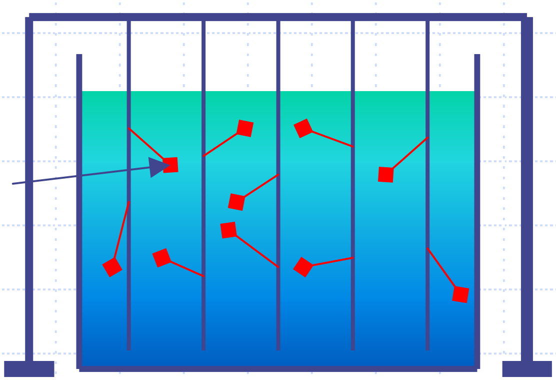


Medusa, MK-2
UCLA NESL
2002

WSNs in the Environment

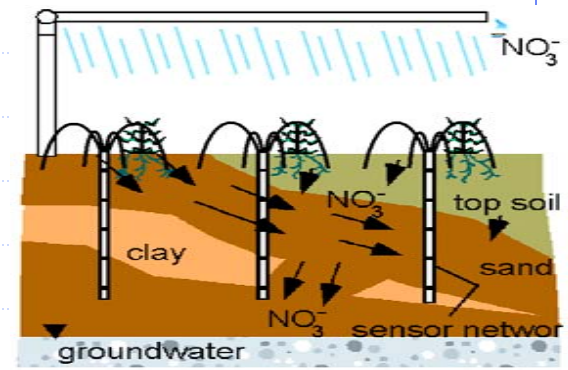
Ecosystems, Biocomplexity

Marine Microorganisms



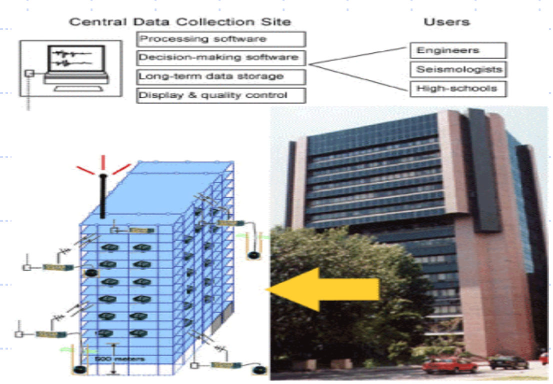
- Micro-sensors, on-board processing, wireless interfaces feasible at very small scale--can monitor phenomena "up close"
- Enables spatially and temporally dense environmental monitoring

Embedded Networked Sensing will reveal previously unobservable phenomena



Contaminant Transport

Seismic Structure Response



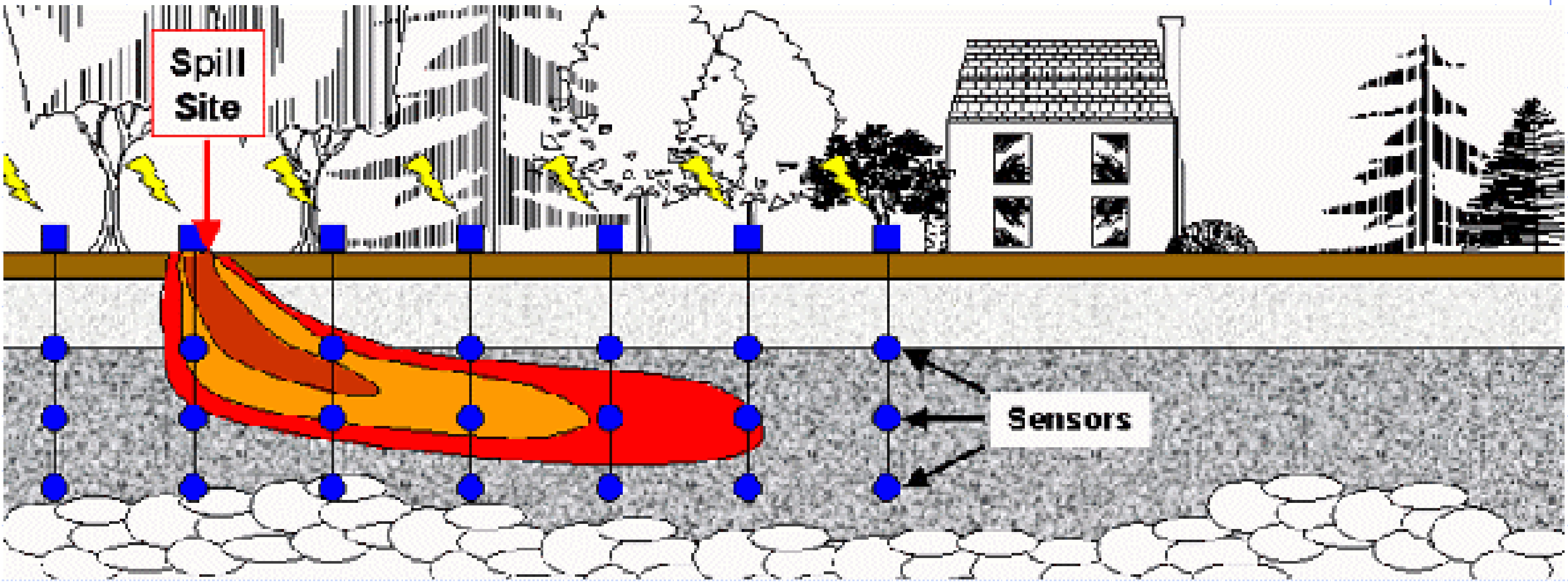
Example Application: Seismic

- 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.

Research Challenges

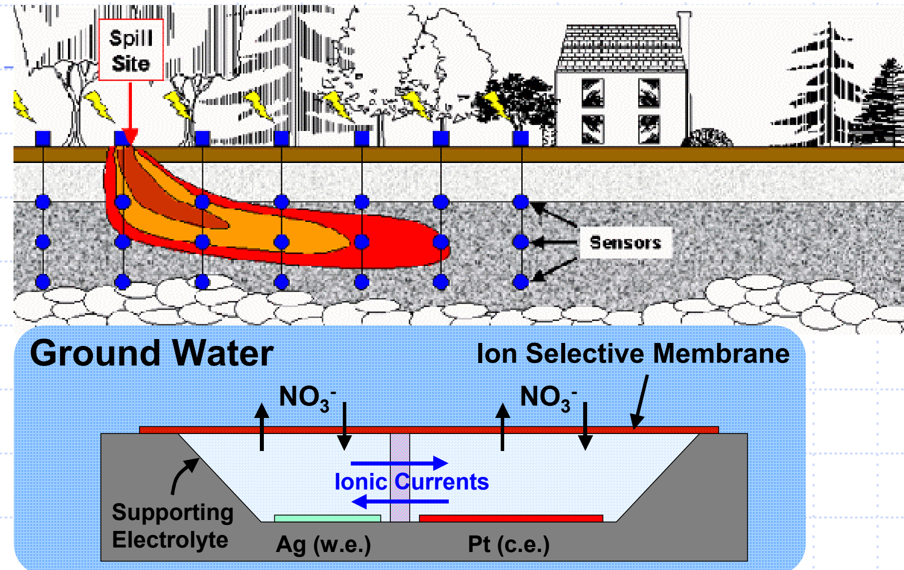
- Real-time analysis for rapid response
- Massive amount of data $\rightarrow$ Smart, efficient, innovative data management and analysis tools
- Poor signal-to-noise ratio due to traffic, construction, explosions
- Insufficient data for large earthquakes $\rightarrow$ Structure response must be extrapolated from small and moderate-size earthquakes, and force-vibration testing

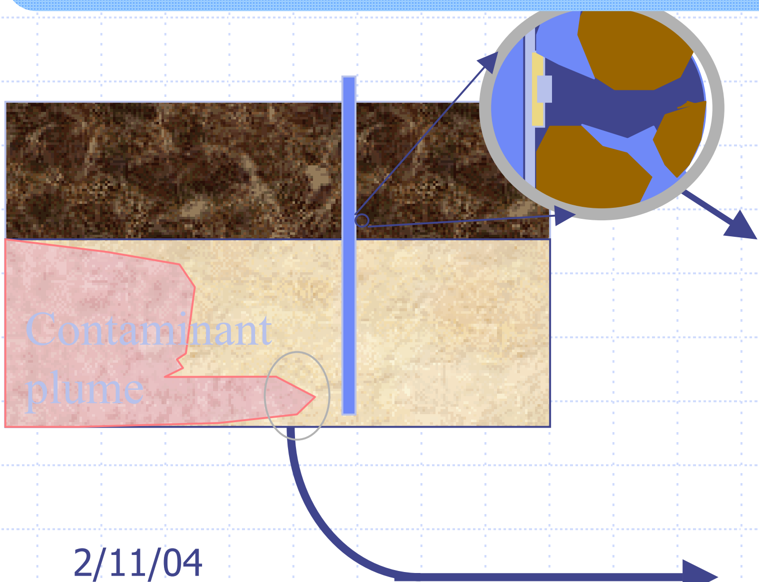
Application Scenario



- Ecological/Health: Contaminant monitoring/mapping
- Agricultural: Precision farming

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.**
- Calibration

Ecosystem Monitoring

Science: Response of wild populations (plants and animals) to habitats over time.

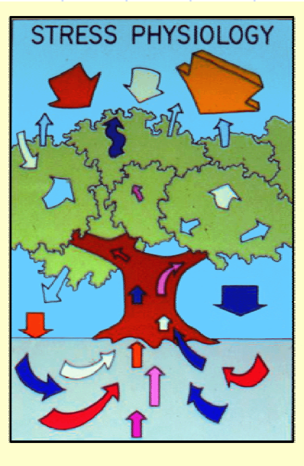
- Develop in situ observation of species and ecosystem dynamics

Techniques: Data acquisition of physical and chemical properties, at various spatial and temporal scales

- 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, ...

Field Experiments

- **Monitoring ecosystem processes**
  - **Imaging, ecophysiology, and environmental sensors**
  - **Study vegetation response to climatic trends and diseases**
- Species Monitoring
  - Visual identification, tracking, and population measurement of birds and other vertebrates
  - Acoustical sensing for identification, spatial position, population estimation
- Education outreach
  - Bird studies by High School Science classes



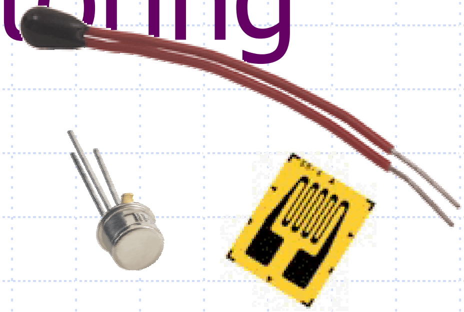
Vegetation change detection

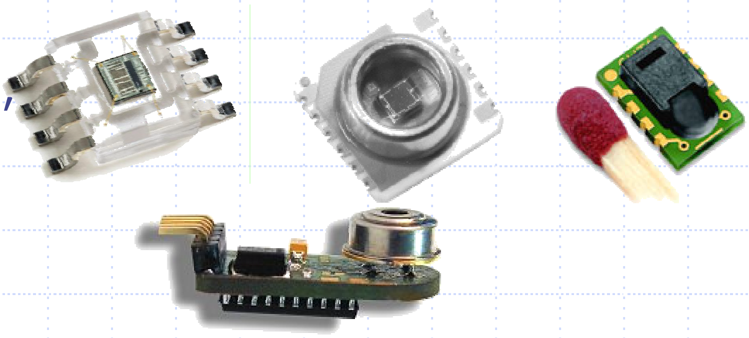
Avian monitoring

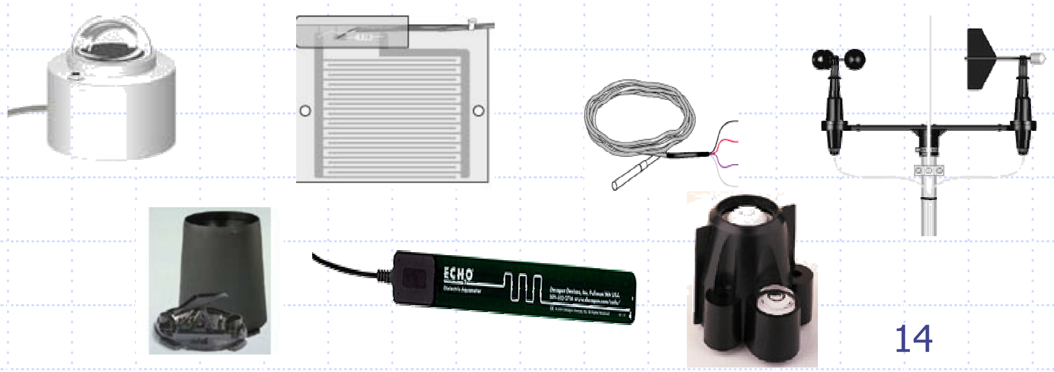
Virtual field observations

Micro-Climate Monitoring

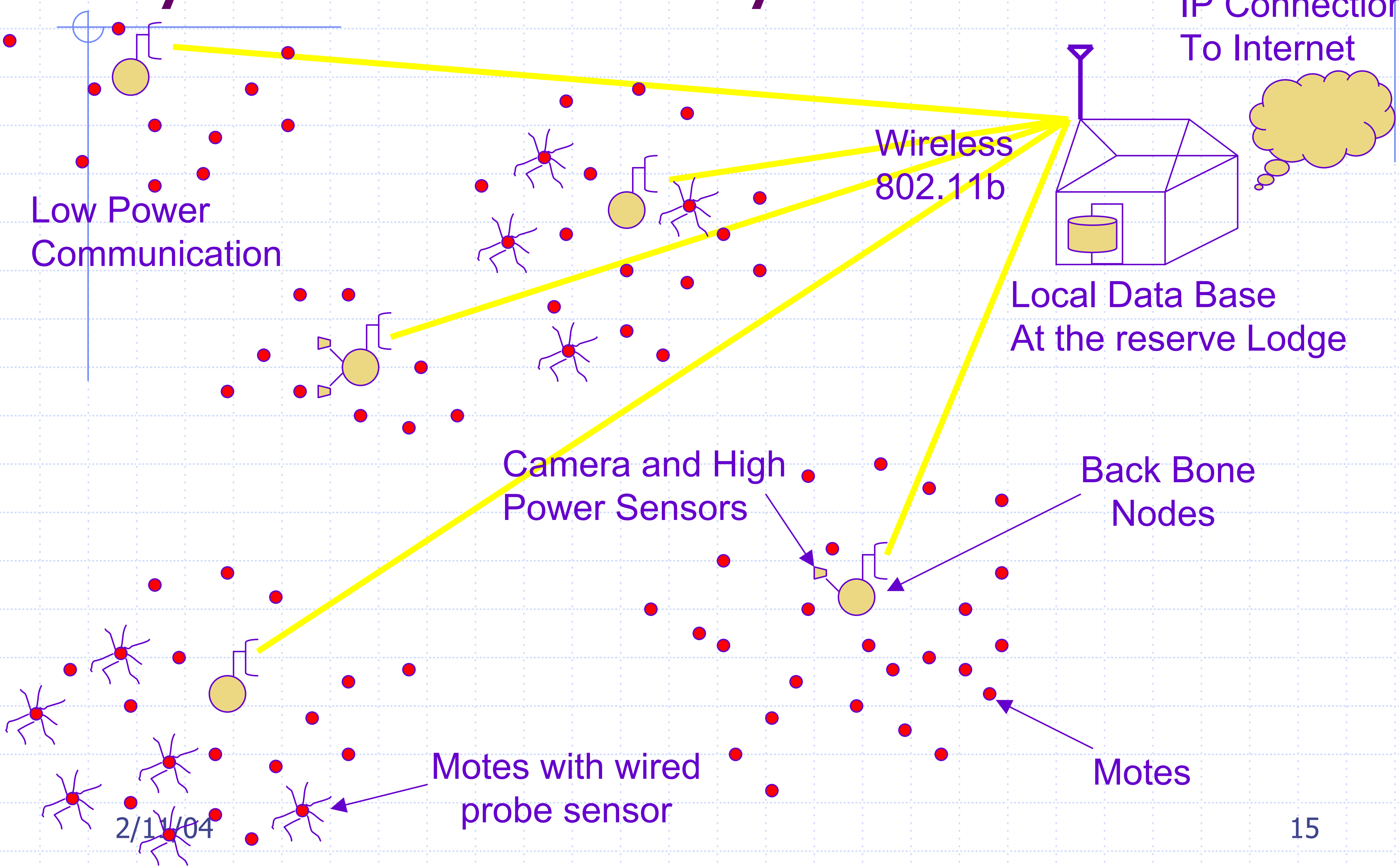
- Weather-motes
  (Berkeley Intel Lab and UCLA)
  - Miniature wired probes to off-board sensors
    - Leaf wetness
    - Light: PAR, UV, Solar radiation, Visible light
    - Rain fall
    - Wind speed and direction
    - Soil moisture
    - Temperature probes
  - Onboard
    - Temp
    - Humidity
    - Pressure
    - Thermopile
    - Light







System Hierarchy



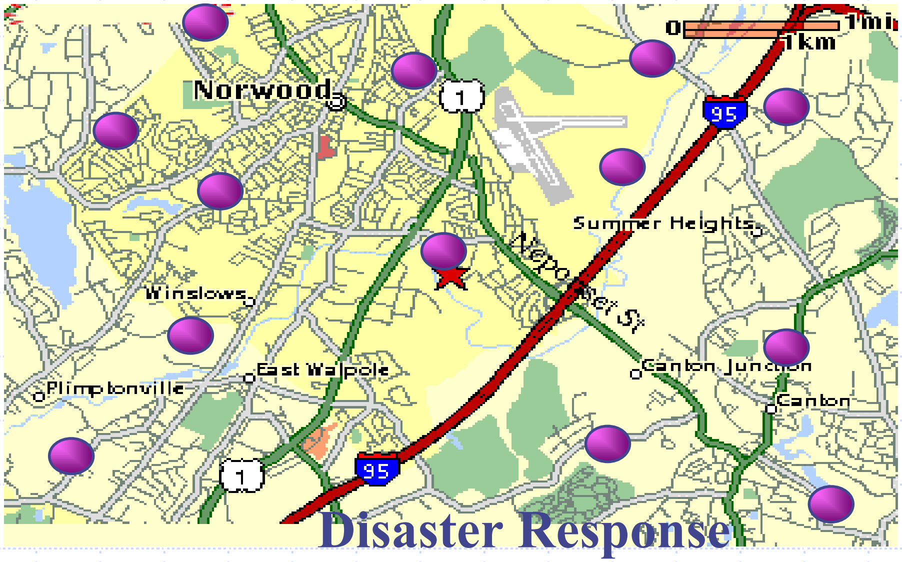
Requirements for Habitat Applications, 1

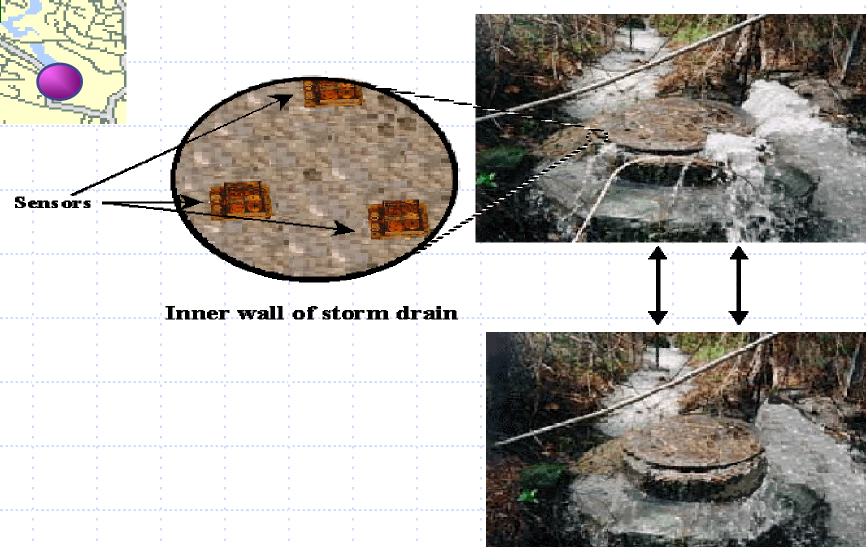
- Diverse sensor sizes (1-10 cm), sampling intervals (1cm to 100m), and temporal sampling intervals (1μs to days), depending on habitats and organisms
- Naive approach → Too many sensors →Too many data

Requirements for Habitat, 2

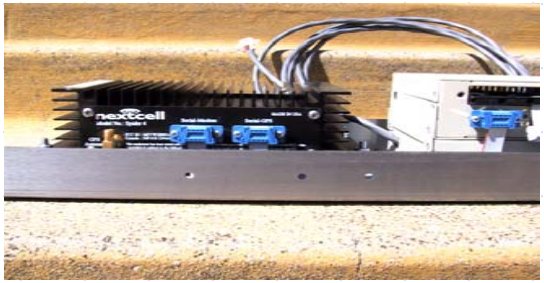
- Wireless communication due to climate, terrain, thick vegetation
- Adaptive Self-Organization to achieve reliable, long-lived, operation in dynamic, resource-limited, harsh environment
- Mobility for deploying scarce resources (e.g., high resolution sensors)

Transportation and Urban Monitoring





Intelligent Transportation Project



Smart Kindergartens: Physical and the Cognitive, 1

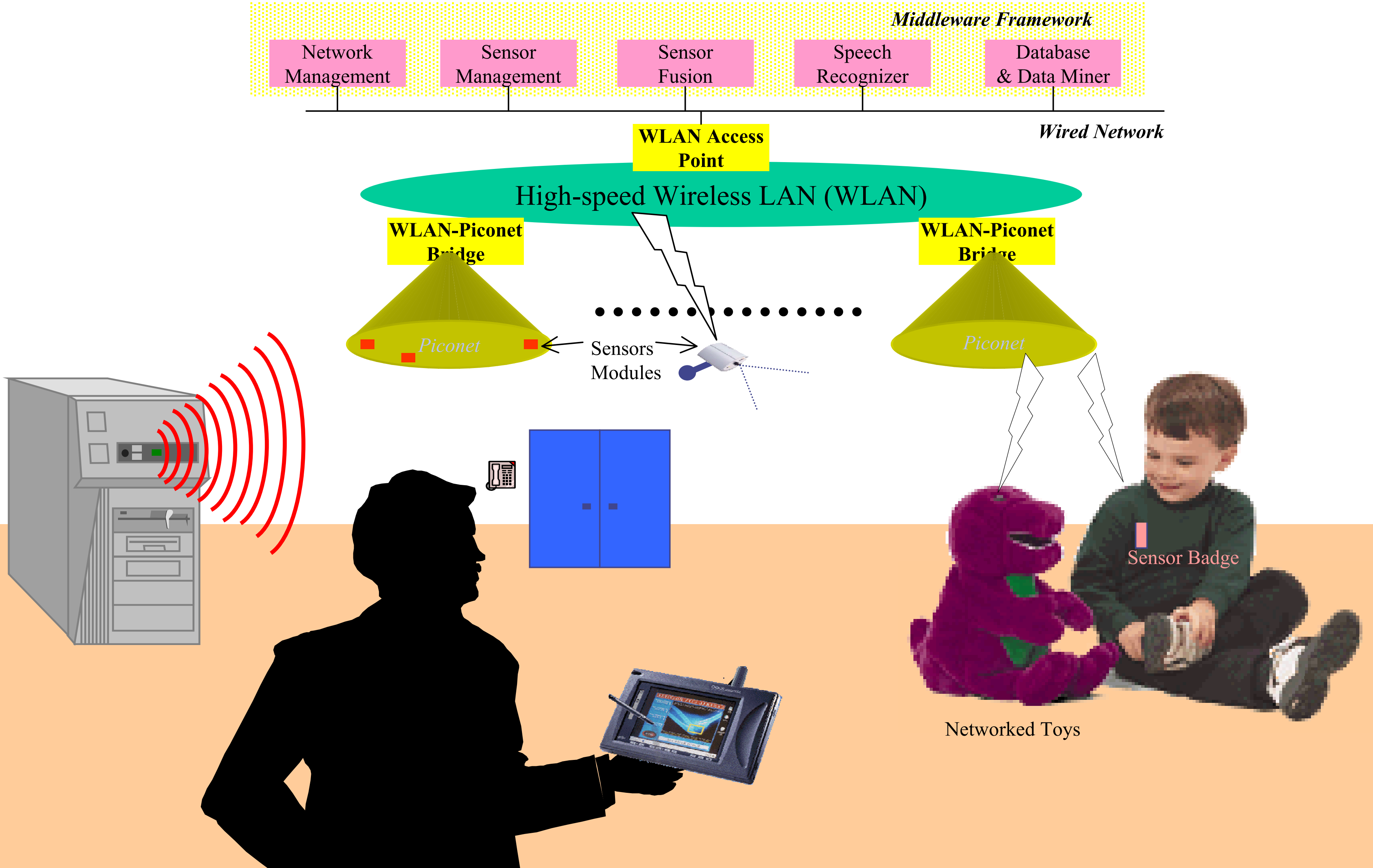
- Wireless networked sensors densely embedded in a kindergarten room
  - create a problem solving environment that can is continually sensed in detail
  - kids, toys, blocks, playthings, classroom "woodwork"
- Background computing & data management infrastructure for on-line and off-line sensor data processing and mining

Smart Kindergartens, 2

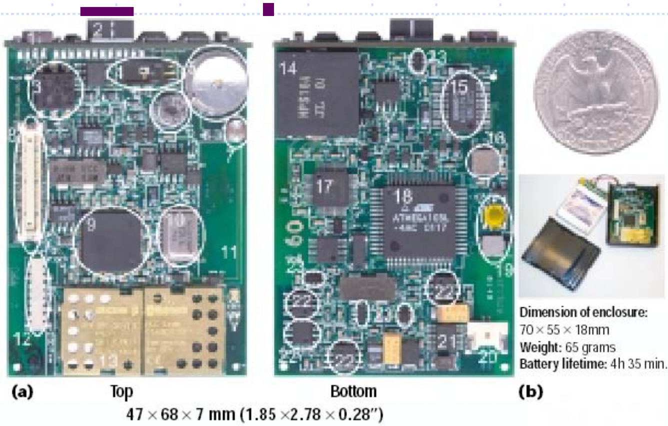
- Sensor information used for
  - assessment of student learning and group dynamics
  - problem solving tasks that are adaptive and reactive
  - services beneficial to teacher and students

Smart Kindergarten Project:

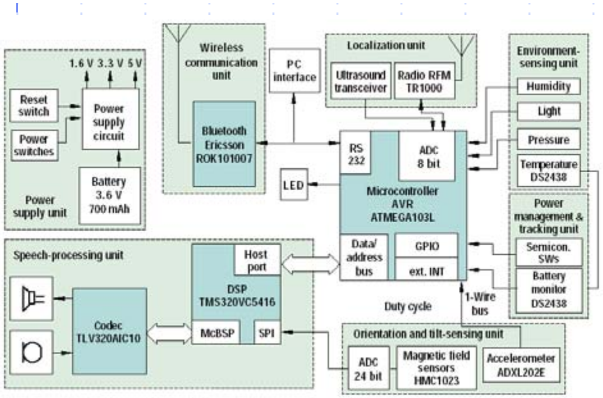
Sensor-based Wireless Networks of Toys for Smart Developmental Problem-solving Environments



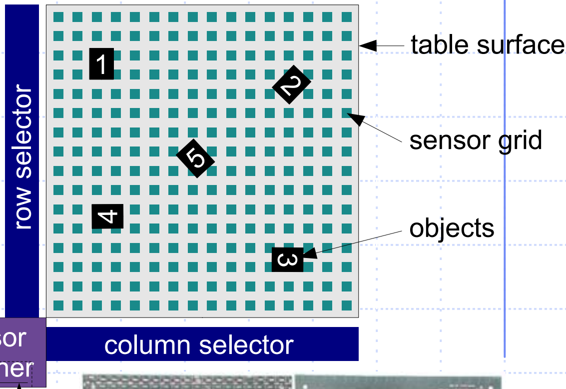
The Smart Kindergarten

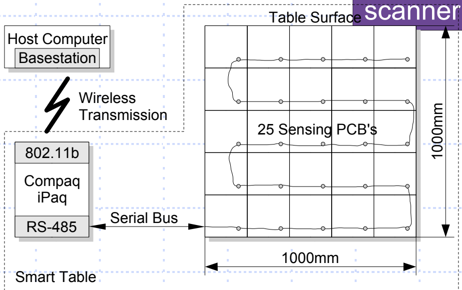


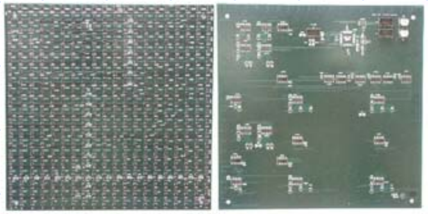
1. Accelerometer forx, y-axis
2. Magnetic field sensor
3. Pressure sensor
4. Humidity sensor
5. Ultrasound tranceiver
6. Microphone
7. Light sensor
8. Connector (SW download)
9. DSP
10. RFM radio (for localization)
11. PCB antenna for RFM radio
12. Blue tooth antenna
13. Blue tooth module
14. Loudspeaker
15. ADC magnetic field sensor
16. Accelerometer for x-axis
17. Codec chip
18. Microcontroller
19. Switches (Power, Reset)
20. Battery connector
21. Power supply
22. Battery monitors
23. Switches to functional units



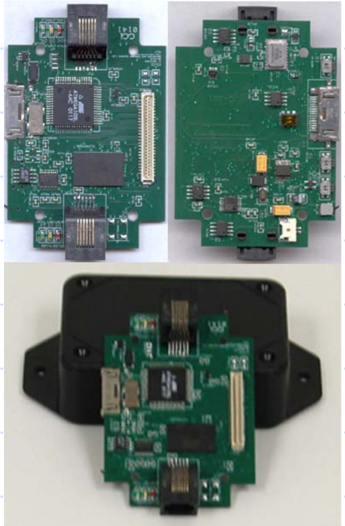
iBadge: *Wearable Sensor Node*

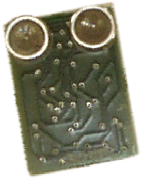






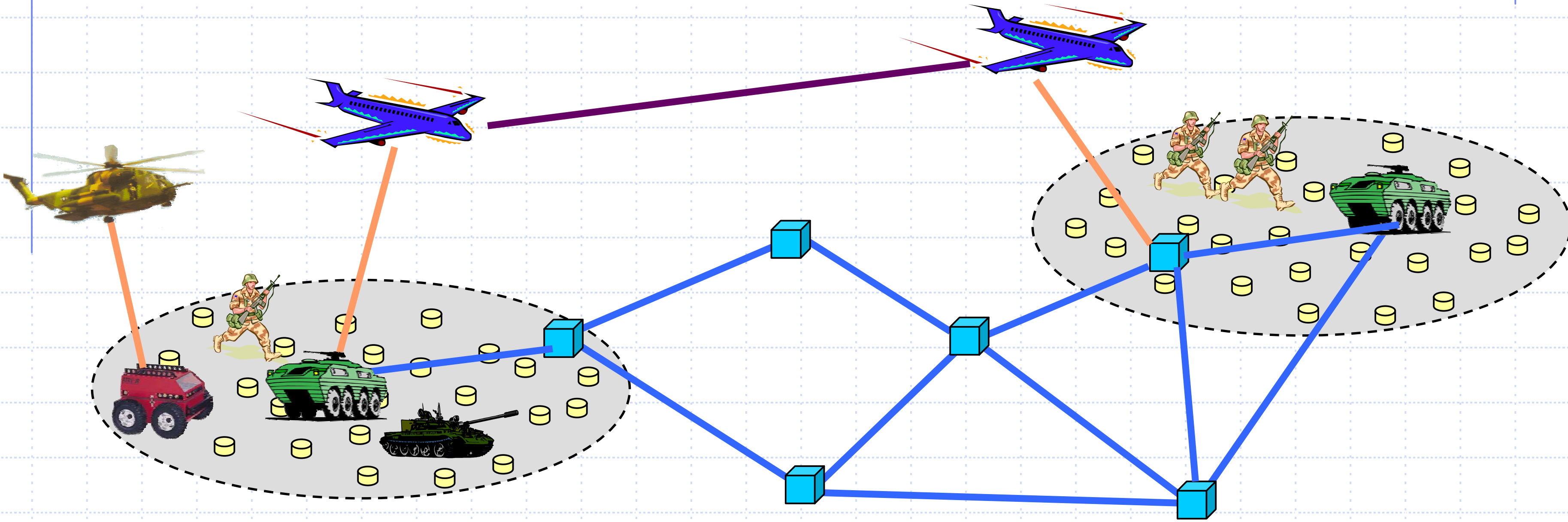
Smart Table: *Sensor-instrumented Surface for Object Id and Localization*





Medusa MK-2 == *Motes + StrongThumb + Ultrasound*

WSNs and the Battlefield, 1



WSNs and the Battlefield, 2

- Mobile ‘users’ query and track mobile targets in a battle space instrumented with a number of ‘sensor networks’ composed of a large number of energy limited air-borne and ground-based ‘sensor nodes’ (e.g. cameras)
  - Users: rovers, UAVs, soldiers
  - Sensors: rovers & UAVs carrying sensors, static sensor nodes
  - Targets: vehicles, soldiers
- UCLA Minuteman Project

Existing Systems Inadequate in Understanding WSN

- Large-scale
- Distributed
- Real-time (control loops and events)
- Physically-coupled
- Resource-constrained
- Wireless
- Computation, and not just communication

Combines the hard problems of the Internet, Embedded Systems, Wireless Networks, and Distributed Computing!

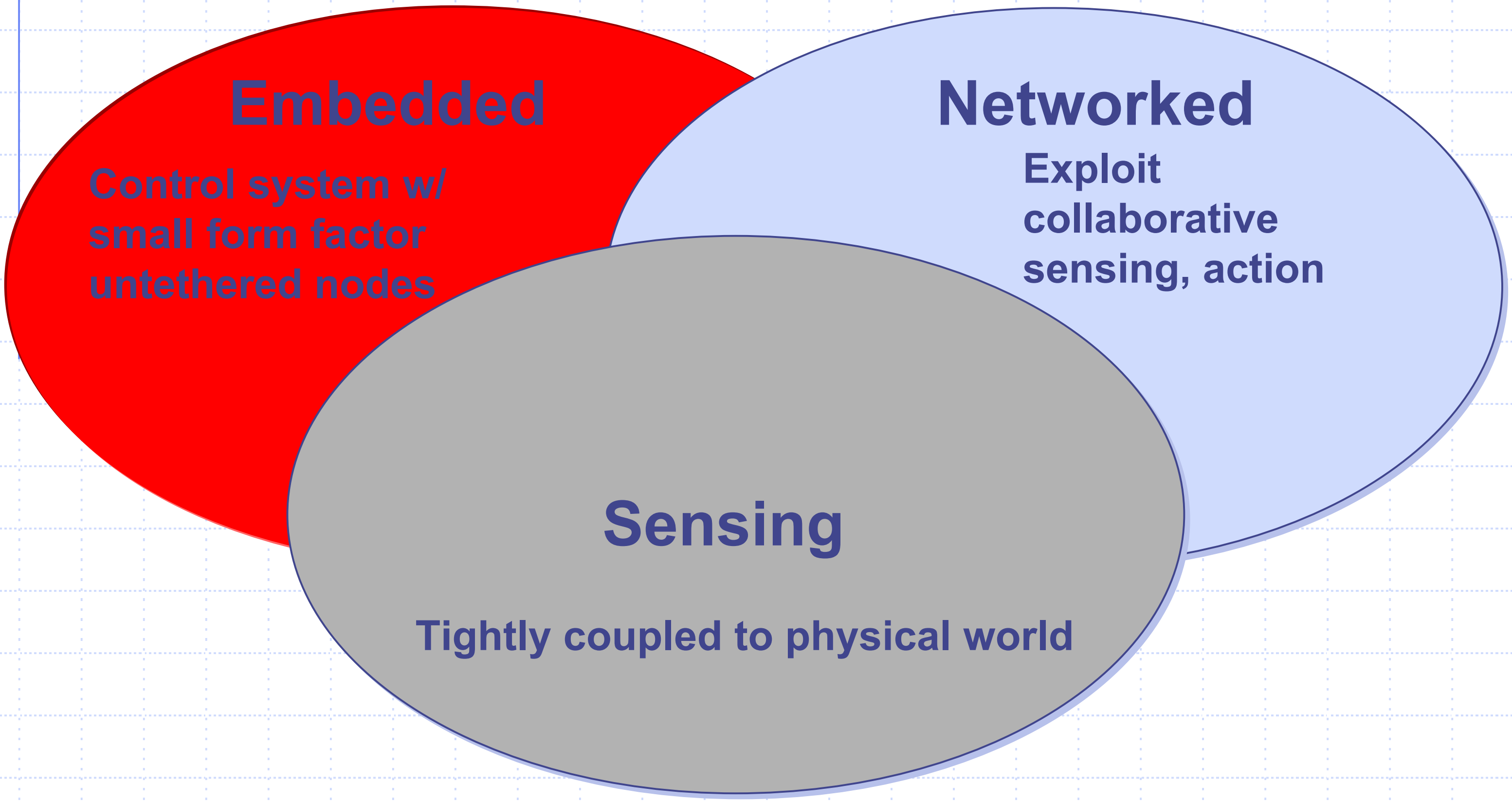
New Design Themes for WSNs

- Long-lived systems that can be untethered (wireless) and unattended
  - Communication is the primary consumer of scarce energy resources
  - "Every bit transmitted brings a sensor node one moment closer to death" (G. Pottie)
- Leverage data processing inside the network
  - Exploit computation near data to reduce communication
  - Achieve desired global behavior with localized algorithms (distributed control)
- "The network is the sensor" (Manges&Smith, Oakridge Natl Labs, 10/98)
  - Requires robust distributed systems of thousands of physically-embedded, unattended, and often untethered, devices

Enabling Technologies

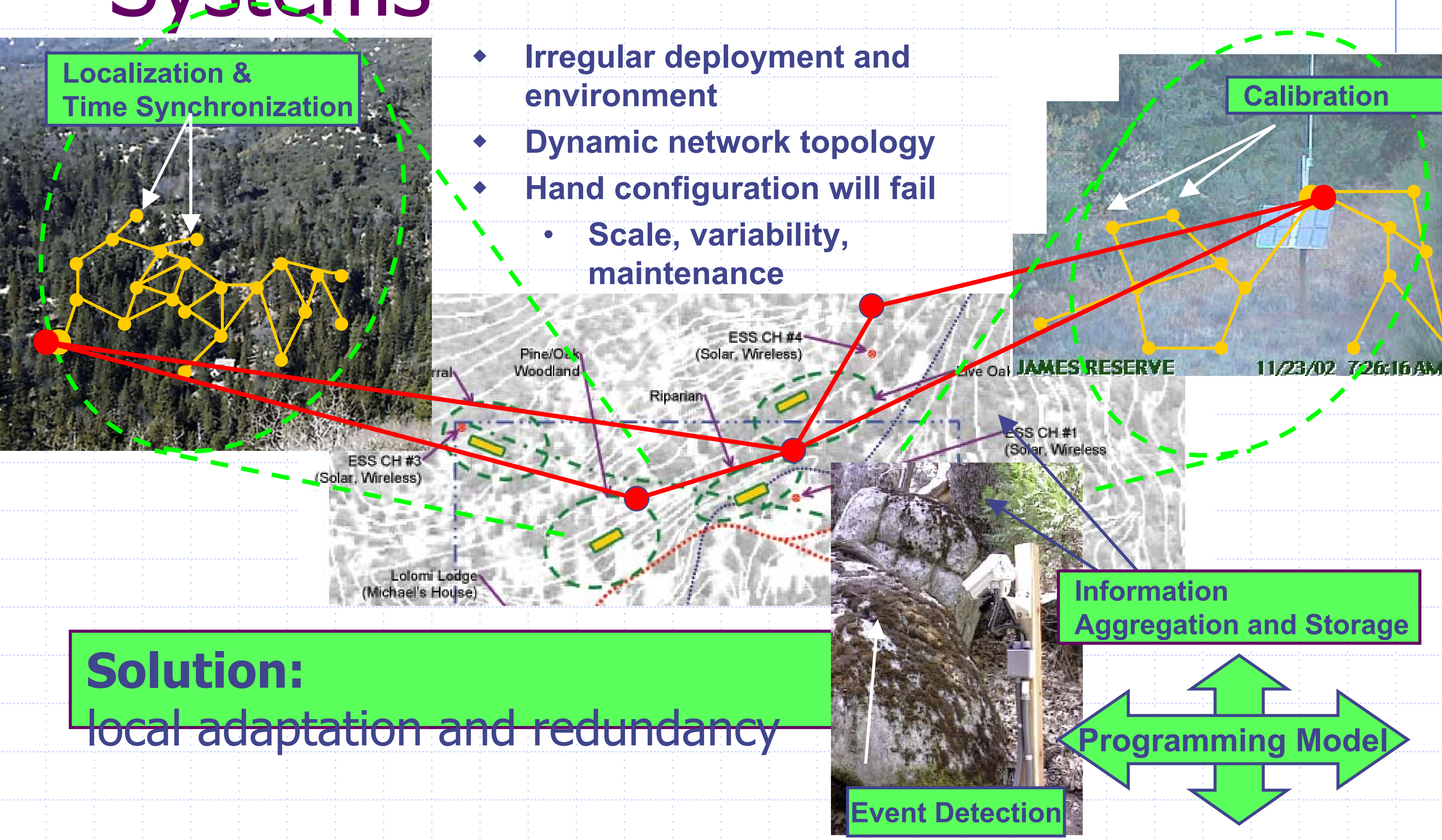
Embed numerous distributed devices to monitor and interact with physical world

Network devices to coordinate and perform higher-level tasks



Exploit spatially and temporally dense, in situ, sensing and actuation

Long-lived Self-Configuring Systems

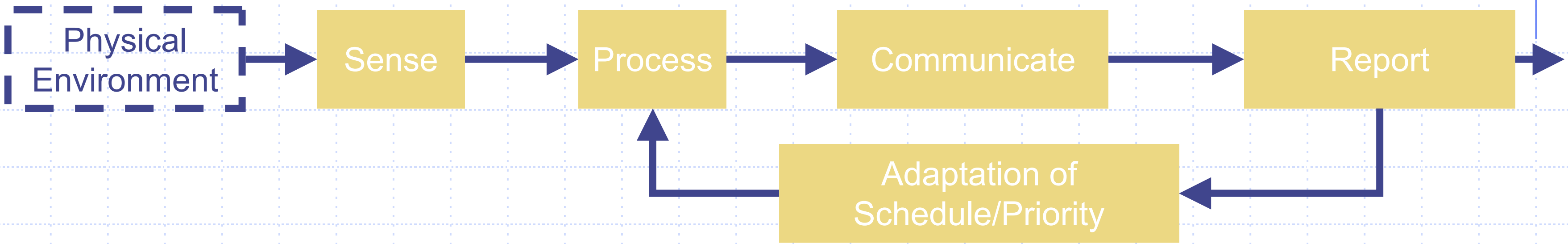


- Irregular deployment and environment
- Dynamic network topology
- Hand configuration will fail
  - Scale, variability, maintenance

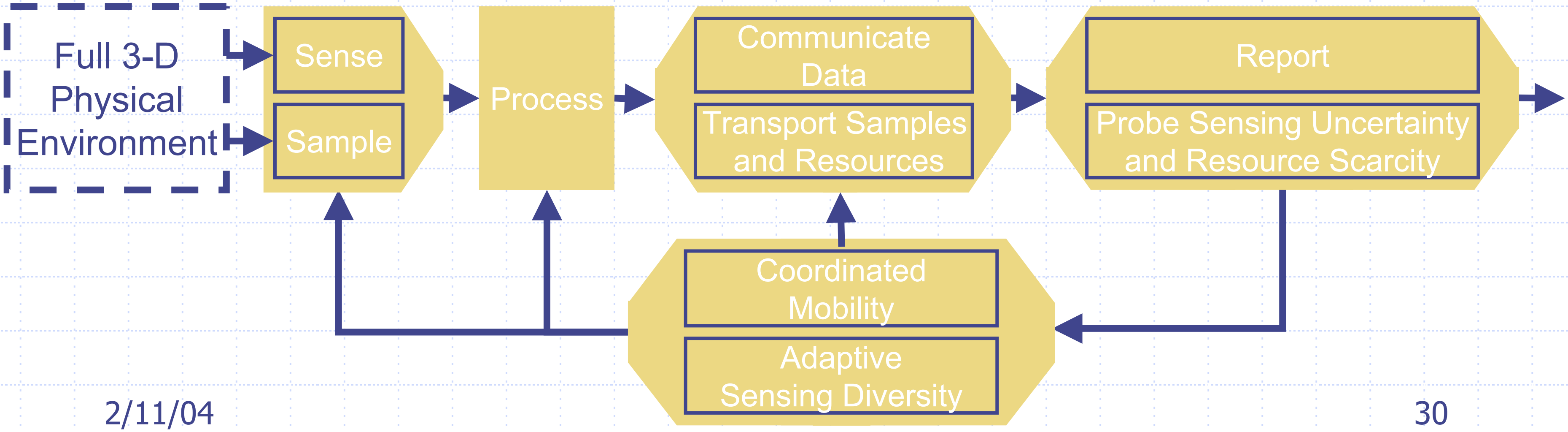
Solution:
local adaptation and redundancy

NIMS vs. Static WSNs

- Static Sensor Network



Networked InfoMechanical Systems (NIMS)



From Embedded Sensing to Embedded Control

- Embedded in unattended "control systems"
  - Different from traditional Internet, PDA, Mobility applications
  - More than control of the sensor network itself
- Critical applications extend beyond sensing to control and actuation
  - Transportation, Precision Agriculture, Medical monitoring and drug delivery, Battlefied applications
  - Concerns extend beyond traditional networked systems: Usability, Reliability, Safety

Sample Layered Architecture

User Queries, External Database

In-network: Application processing, Data aggregation, Query processing

Data dissemination, storage, caching

Adaptive topology, Geo-Routing

MAC, Time, Location

Phy: comm, sensing, actuation, SP

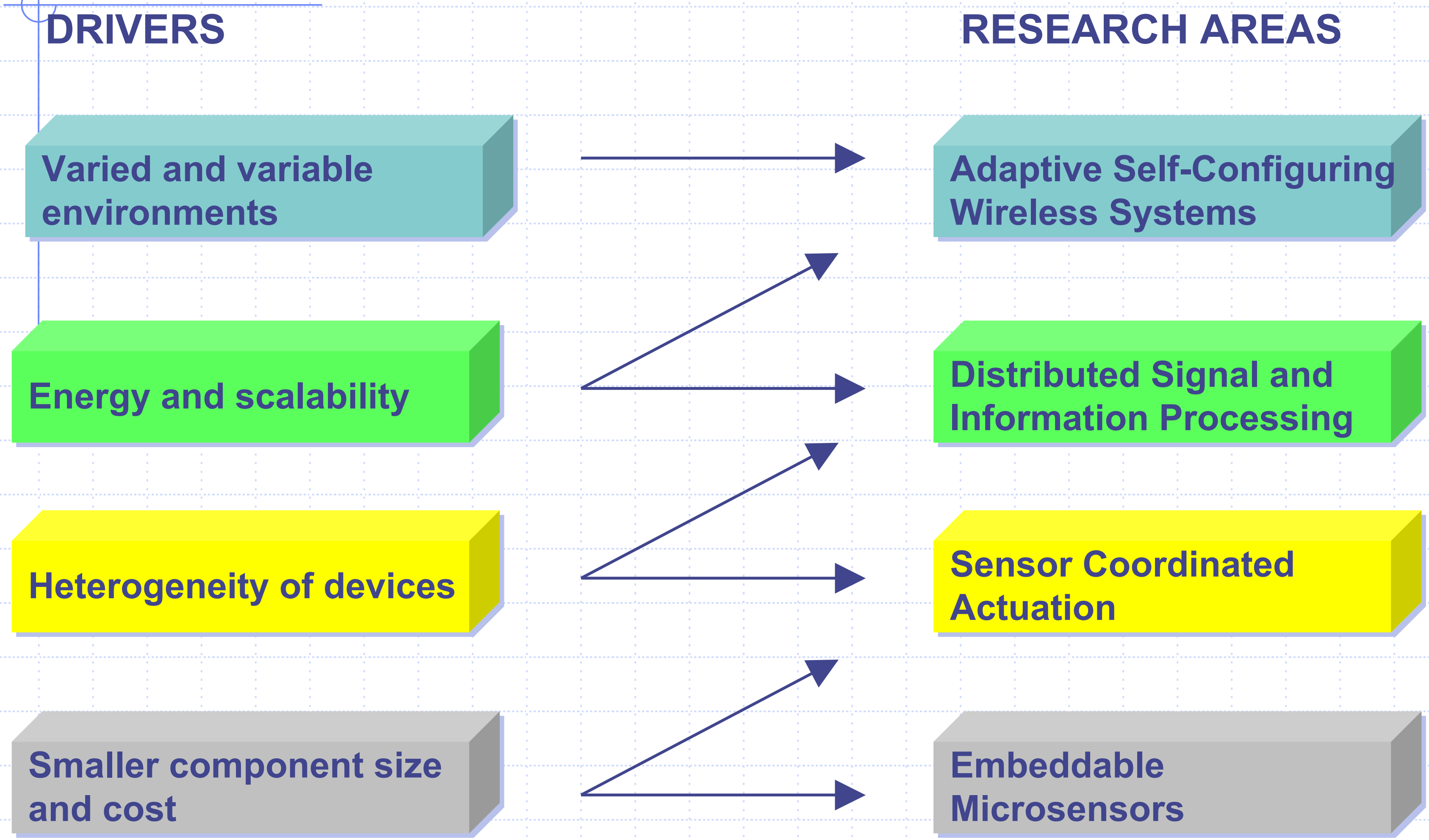
Resource constraints call for more tightly integrated layers

Open Question:

Can we define an Internet-like architecture for such application-specific systems?

Systems Taxonomy	Load/Event Models	Metrics
◆ Spatial and Temporal Scale ▪ Extent ▪ Spatial Density (of sensors relative to stimulus) ▪ Data rate of stimuli ◆ Variability ▪ Ad hoc vs. engineered system structure ▪ System task variability ▪ Mobility (variability in space) ◆ Autonomy ▪ Multiple sensor modalities ▪ Computational model complexity ◆ Resource constraints ▪ Energy, BW ▪ Storage, Computation	◆ Frequency ▪ spatial and temporal density of events ◆ Locality ▪ spatial, temporal correlation ◆ Mobility ▪ Rate and pattern	◆ Efficiency ▪ System lifetime/System resources ◆ Resolution/Fidelity ▪ Detection, Identification ◆ Latency ▪ Response time ◆ Robustness ▪ Vulnerability to node failure and environmental dynamics ◆ Scalability ▪ Over space and time

Architecture Drivers



Research Opportunities, 1

- Self-configuration and Resource Management
  - Timing Synchronization, Node Localization, Sensor Calibration
  - Topology Management, Coverage and Deployment, Exploiting Hierarchy
  - Sensor Network Management
  - Controlled mobility
- Programming the Aggregate
  - Storage Framework
  - Programming Framework
  - Runtime Mechanisms for Macroprogramming

Research Opportunities, 2

- Signal Processing & Information Theory
  - Distributed detection, identification, tracking
  - Information theoretic limits and trade-offs
- Technology
  - Advanced node platforms (energy scavenging, mobile etc.)
  - Advanced sensors (biochemical, genetic, self-calibrating etc.)
- Tools
  - Simulation, Emulation, Analysis, and Optimization, Tools

Summary, 1

- Wireless technology focus is moving towards improving the interaction between people & their physical world
- Distributed embedded systems (cheap low power processors and sensors, all cooperatively networked) are the key enabling technology
- Requires combination of wireless, networking, embedded systems, and energy-aware
  - Distributed embedded computation in ad hoc, resource constrained environments

Summary, 2

- Limitations of analysis and simulations in physically-coupled resource-constrained embedded systems
- Important to
  - build real embedded system hardware and software in the context of real applications
  - do all of: algorithms, protocols, systems, tools, & applications
  - have a multidisciplinary team: embedded systems, networking, signal processing, distributed computing etc.

Assignments

- Download the survey on sensor nets
- Updated information on the class web page: www.ece.neu.edu/courses/eceg364/2004sp