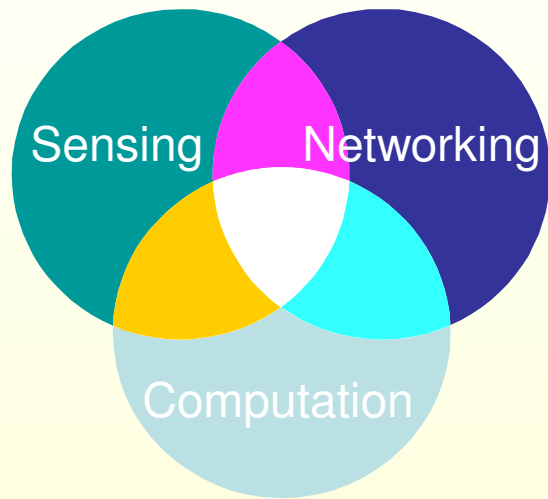
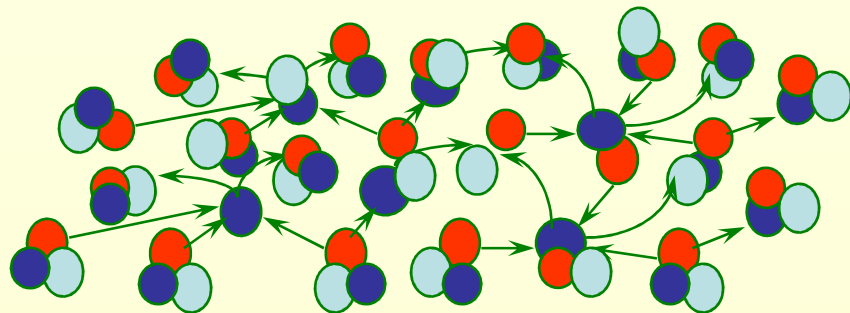


CS321: Information Processing for Sensor Networks

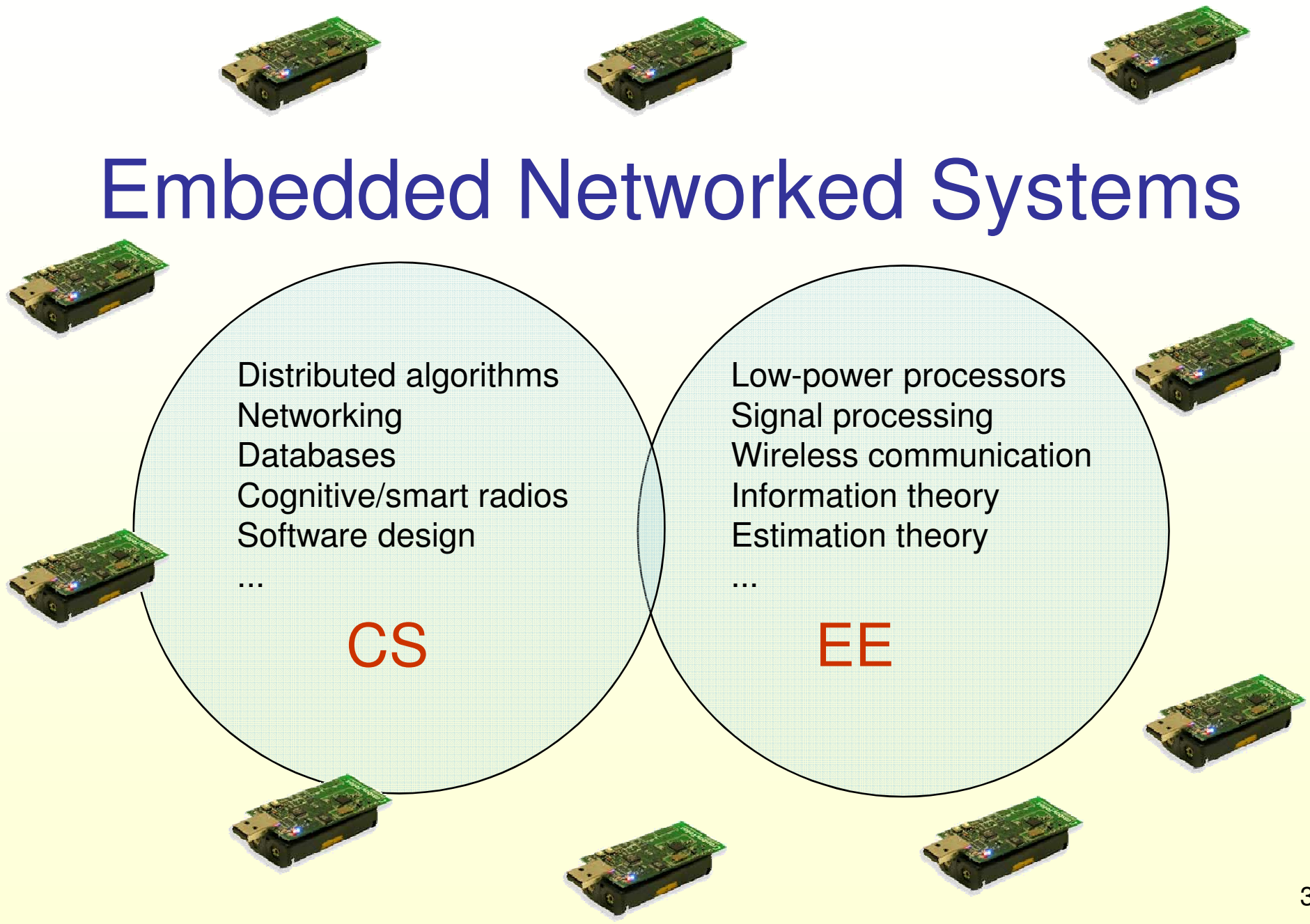


Leonidas Guibas
Computer Science Dept.
Stanford University

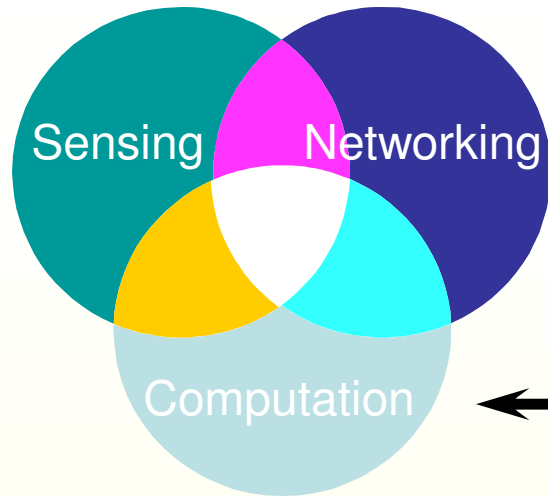


Wireless Sensor Networks

Embedded Networked Systems



Smart Sensors and Sensor Networks



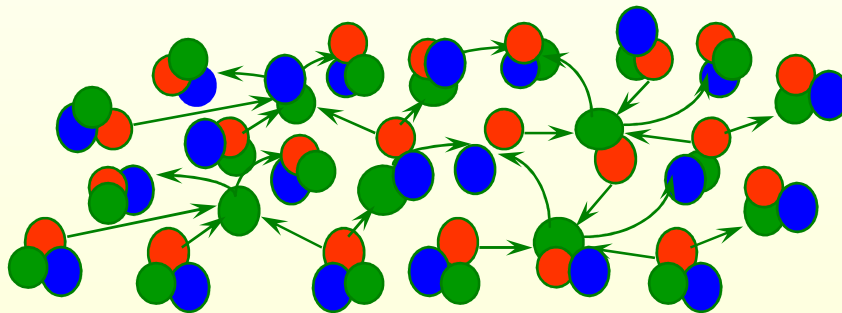
Berkeley/Crossbow Motes



Rockwell HiDRA



UCLA WINS

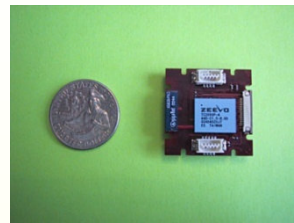


Untethered micro sensors will go anywhere and measure anything -- traffic flow, water level, number of people walking by, temperature. This is developing into something like a nervous system for the earth. -- Horst Stormer in *Business Week*, 8/23-30, 1999.

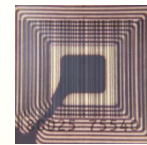
- **Environmental sensing**
 - Traffic, habitats, pollution, hazards, security
- **Industrial sensing**
 - Machine monitoring and diagnostics (IC fab)
 - Power/telecom grid monitoring
- **Human-centered computing**
 - Smart, human-aware spaces and environments

Wireless Sensor Networks

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



Intel imote



RFID



DOT



MICA



Ember transceiver



MS Spot Watch



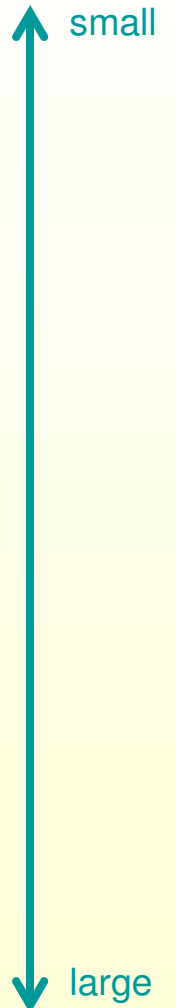
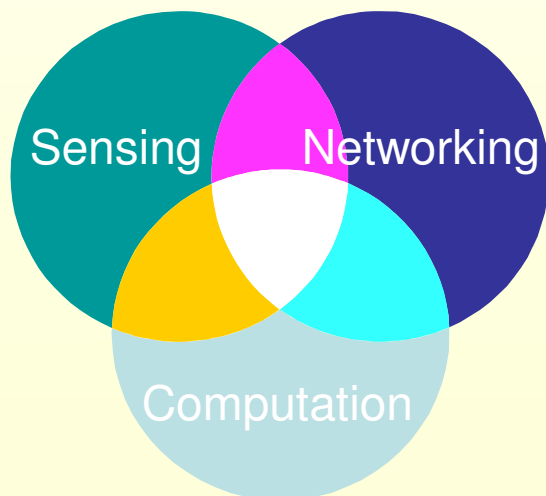
Crossbow MicaZ



PDA

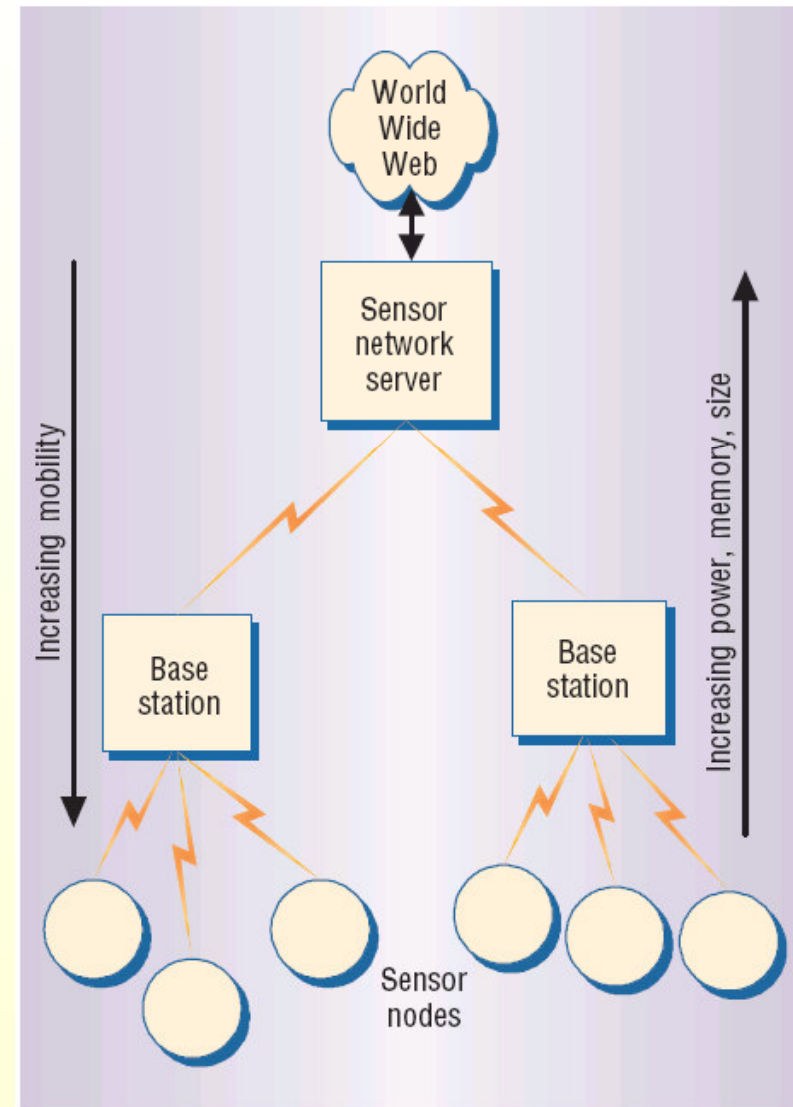


Sensoria Node



Monitoring the World

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



Wireless Sensor Network Deployment

- **Advantages:**

- sensors can be close to signal sources, yielding high SNR
- phenomena can be monitored that are widely distributed across space and time
 - a `macroscope' [D. Culler]
- a distributed architecture provides for scalable, robust and self-repairing systems
- significant installation advantages: deployment speed, savings on cabling, etc.

British Columbia winery with networked temperature sensors



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

BP Shipboard Vibration Monitoring



[From Ganesan]

Petrel Nesting Behavior at Great Duck Island (2002)



Great Duck Island Deployment



[From Ganesan]

Storm Petrel Monitoring

Questions

- What environmental factors make for a good nest? How much can they vary?
- What are the occupancy patterns during incubation?
- What environmental changes occurs in the burrows and their vicinity during the breeding season?

Methodology

- Characterize the climate inside and outside the burrow
- Collect detailed occupancy data from a number of occupied and empty nest
- Spatial sampling of habitat – sampling rate driven by biologically interesting phenomena
- Validate a sample of sensor data with a different sensing modality
- Augmented the sensor data with deployment notes (e.g. burrow depth, soil consistency, vegetation data)
- Try to answer the questions based on analysis of the entire data set



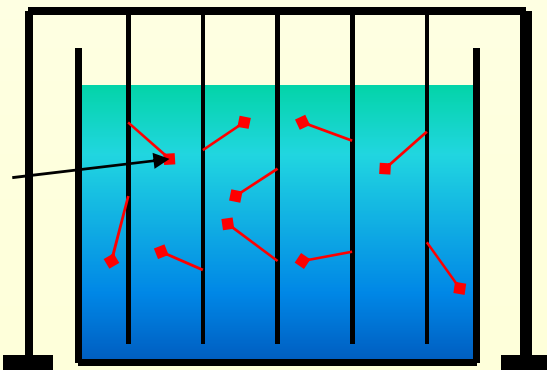
[From Ganesan]

Embedded Networked Sensing



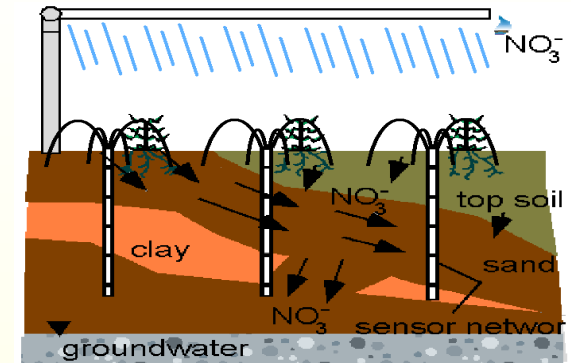
Ecosystems, Biocomplexity

Marine Microorganisms



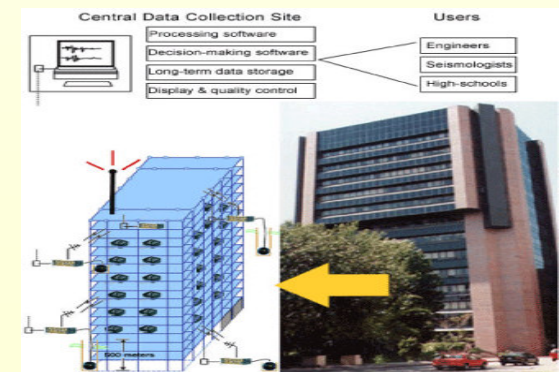
- Micro-sensors, on-board processing, wireless interfaces feasible at very small scale--can monitor phenomena “up close”
- Enables spatially and temporally dense environmental monitoring

Embedded Networked Sensing will reveal previously unobservable phenomena



Contaminant Transport

Seismic Structure Response



[From Estrin]

NIMS: Networked InfoMechanical Systems



- ◆ NIMS Architecture: Robotic, aerial access to full 3-D environment
 - Enable sample acquisition
- ◆ Coordinated Mobility
 - Enables self-awareness of Sensing Uncertainty
- ◆ Sensor Diversity
 - Diversity in sensing resources, locations, perspectives, topologies
 - Enable reconfiguration to reduce uncertainty and calibrate
- ◆ NIMS Infrastructure
 - Enables speed, efficiency
 - Low-uncertainty mobility
 - Provides resource transport for sustainable presence

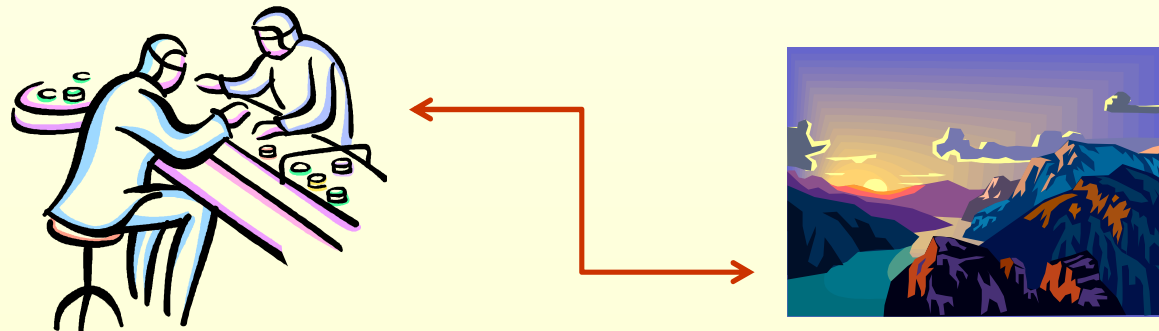
(Kaiser, Pottie, Estrin, Srivastava, Sukhatme, Villasenor)

More Data Extraction Applications

- Industrial automation (conditional maintenance)
 - Sensors on assembly lines, machines
 - Early failure detection
- Asset tracking
- Building security
- Automated meter reading
- Homeland defense

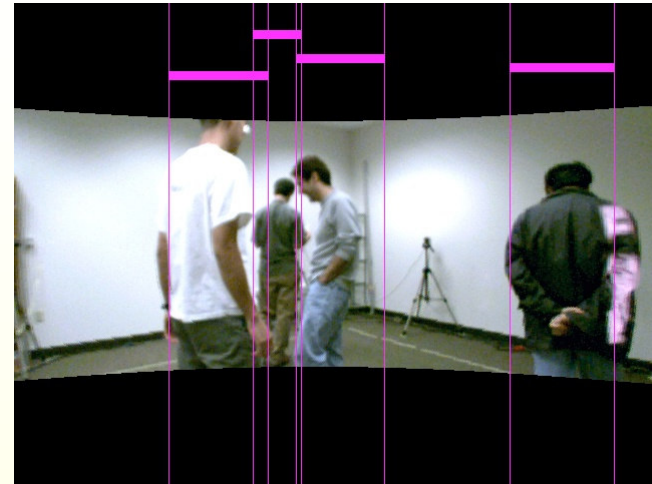
Networks for Data Extraction

- Data collection
 - from untethered networked sensor devices
 - without hard latency constraints
- For users generally remote from the observation site



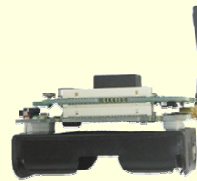
More Demanding Sensor Network Applications

- 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.

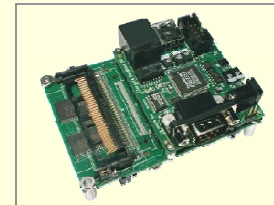


Sensor Networks in Human Spaces

- A sensor network is deployed to provide situational awareness
- Users are embedded and operate in the same space as the network
- Both event capture by the network and the users' need for information arise in a distributed fashion
- Users also act as sensors and provide both information as well as data interpretation to the network



mote



stargate

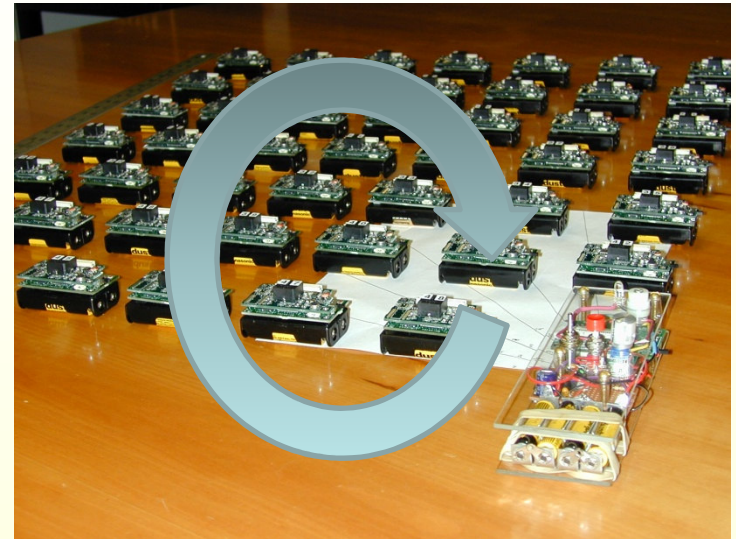


nokia N800

Multiple device classes

Action Webs: A New Setting

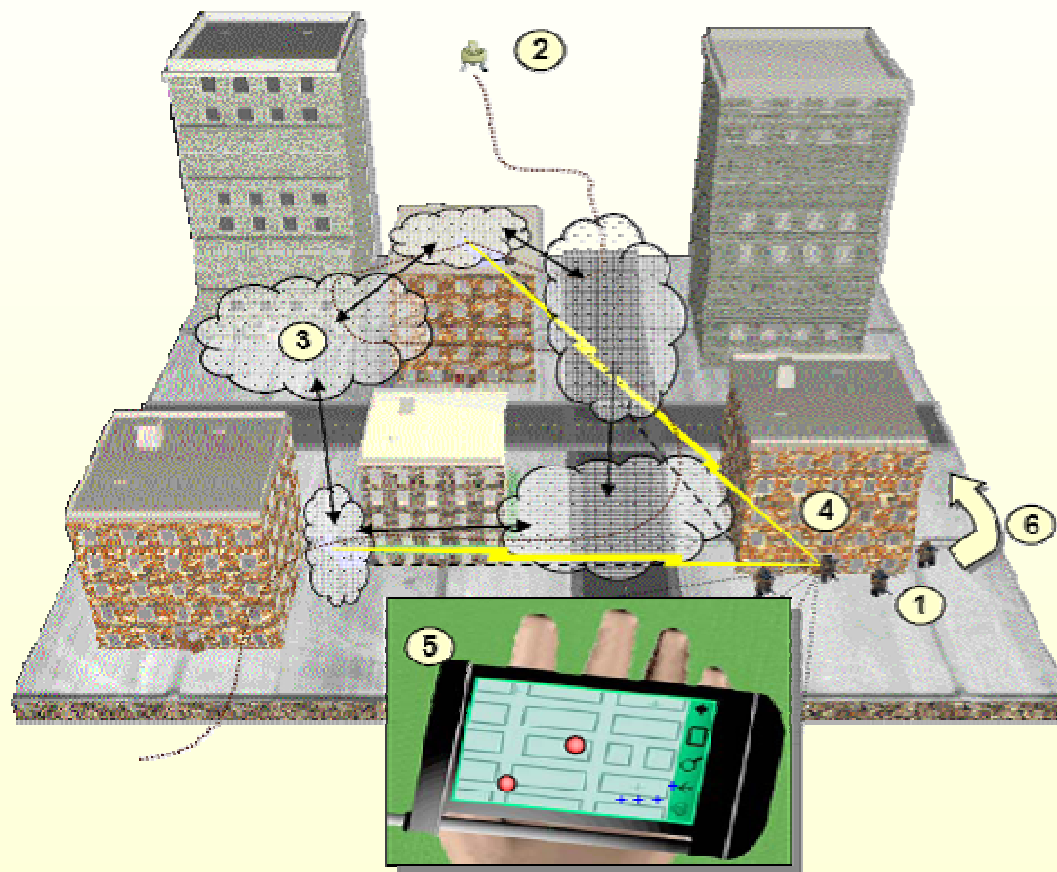
- Closing the loop around sensor networks by providing real-time information to users, so as to enable timely action
- Enabling multi-user collaboration in deriving value from sensor data



Shooter Localization (Vanderbilt)

[From Arora]

Objective: Locate shooters within an urban environment via weapon muzzle blast and shockwave data

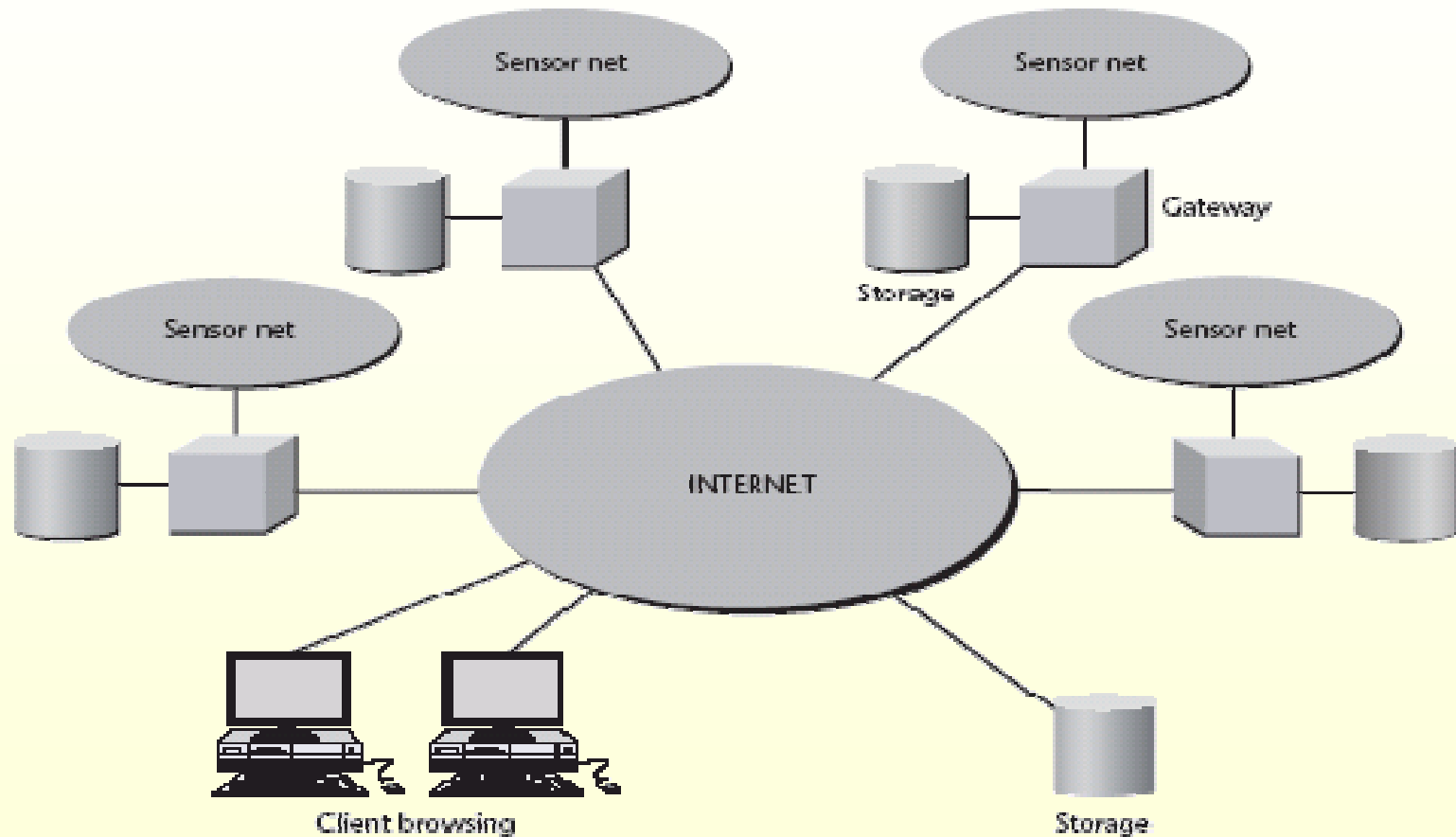


Operational Scenario

- 1 Soldiers move within an urban environment with limited situational awareness
- 2 Prior to advancing, Sensor Network is deployed (e.g., via UAV)
- 3 Sensor Network nodes self-configure and initialize
- 4 When a shot is detected, Sensor Network gathers data and transmit that to soldiers
- 5 Sensor Network data provides soldiers with exact location of shooter(s)
- 6 Soldiers adjust tactics based on enhanced situational awareness provided by the Sensor Network

Enhanced Situational Awareness and Greater Ability to Neutralize OPFOR Assets

Integration with Current Networks



Access to unfiltered information, highly localized in time and space

The Commercial Space: Some Sensor Net Companies

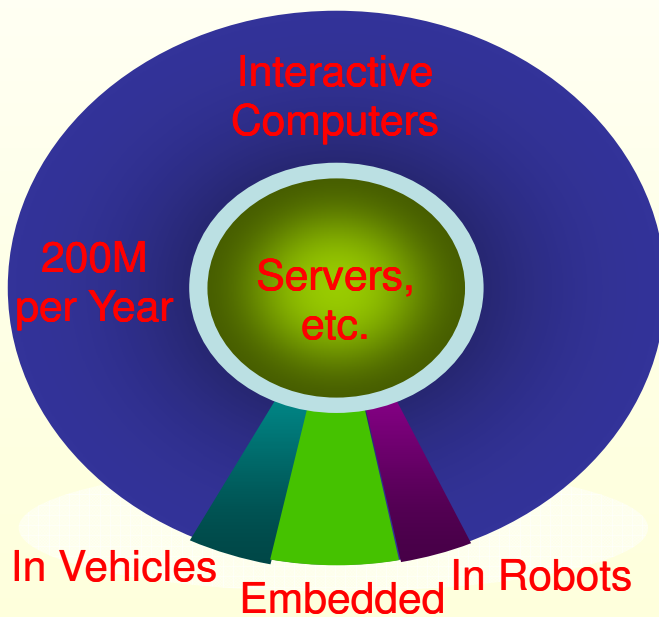
- Crossbow (<http://www.xbow.com/>)
- Dust Networks
(<http://www.dustnetworks.com/>)
- Ember (<http://www.ember.com/>)
- Arch Rock (<http://www.archrock.com/>)
- Millennial Net (<http://www.millennial.net/>)

Sensor Network Hardware

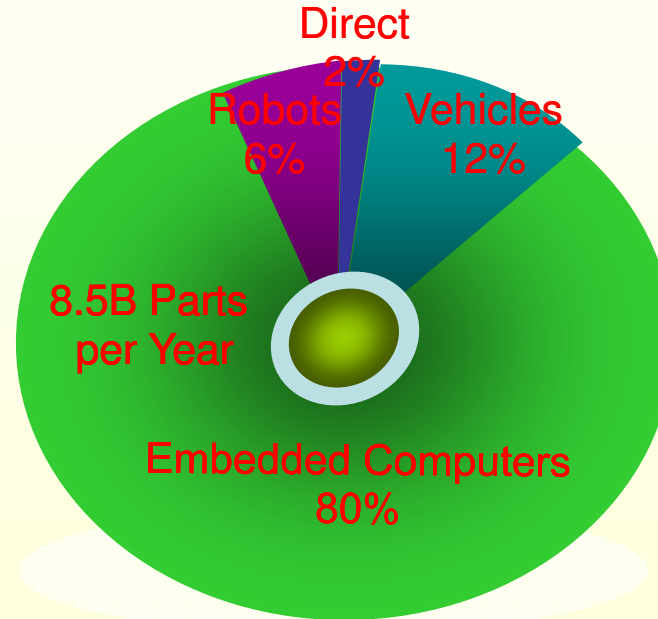
Where are the CPUs?

An estimated 98% of 8 Billion CPUs produced in 2000 were used for embedded apps

Where Has CS Focused?

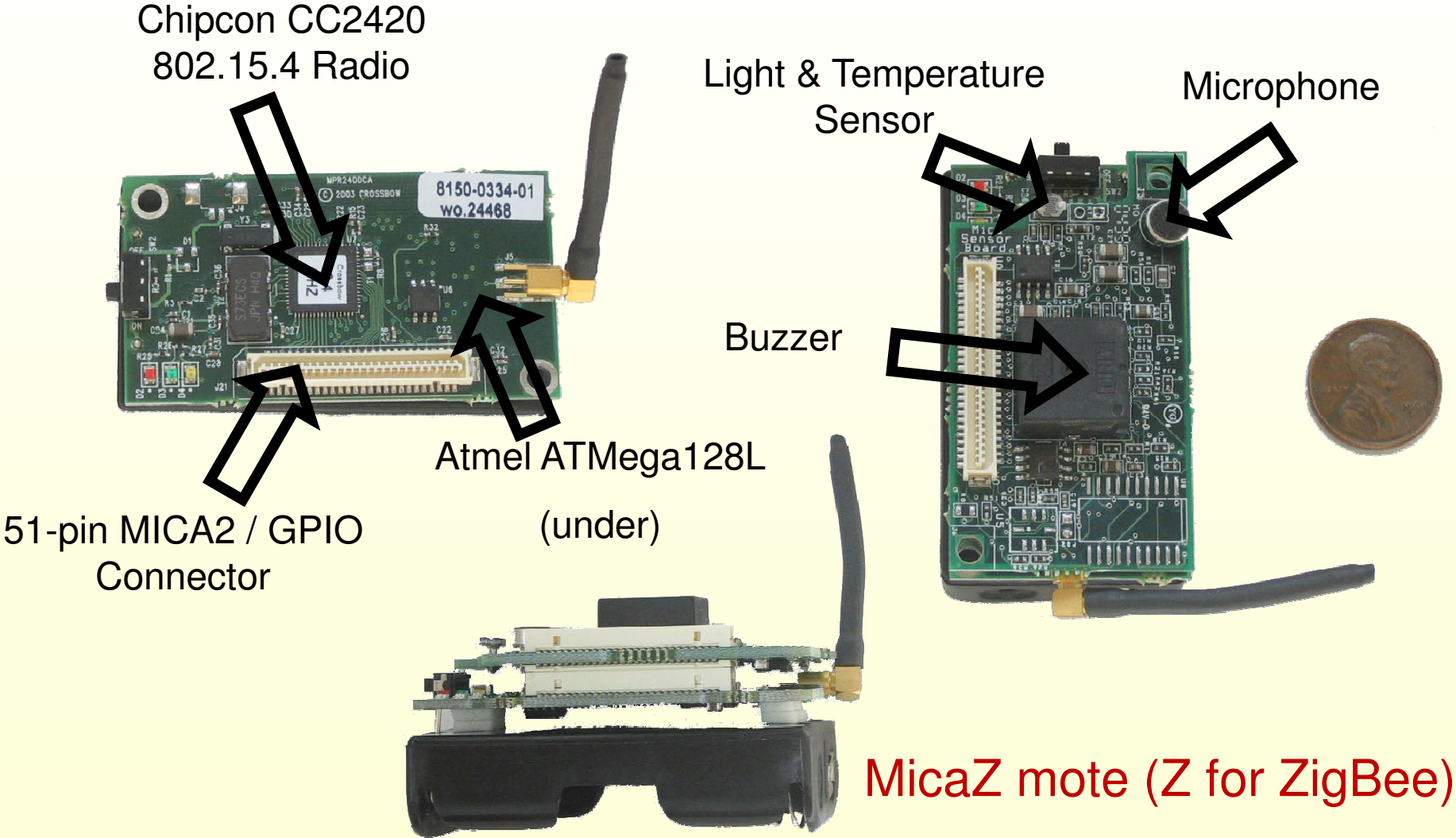


Where Are the Processors?

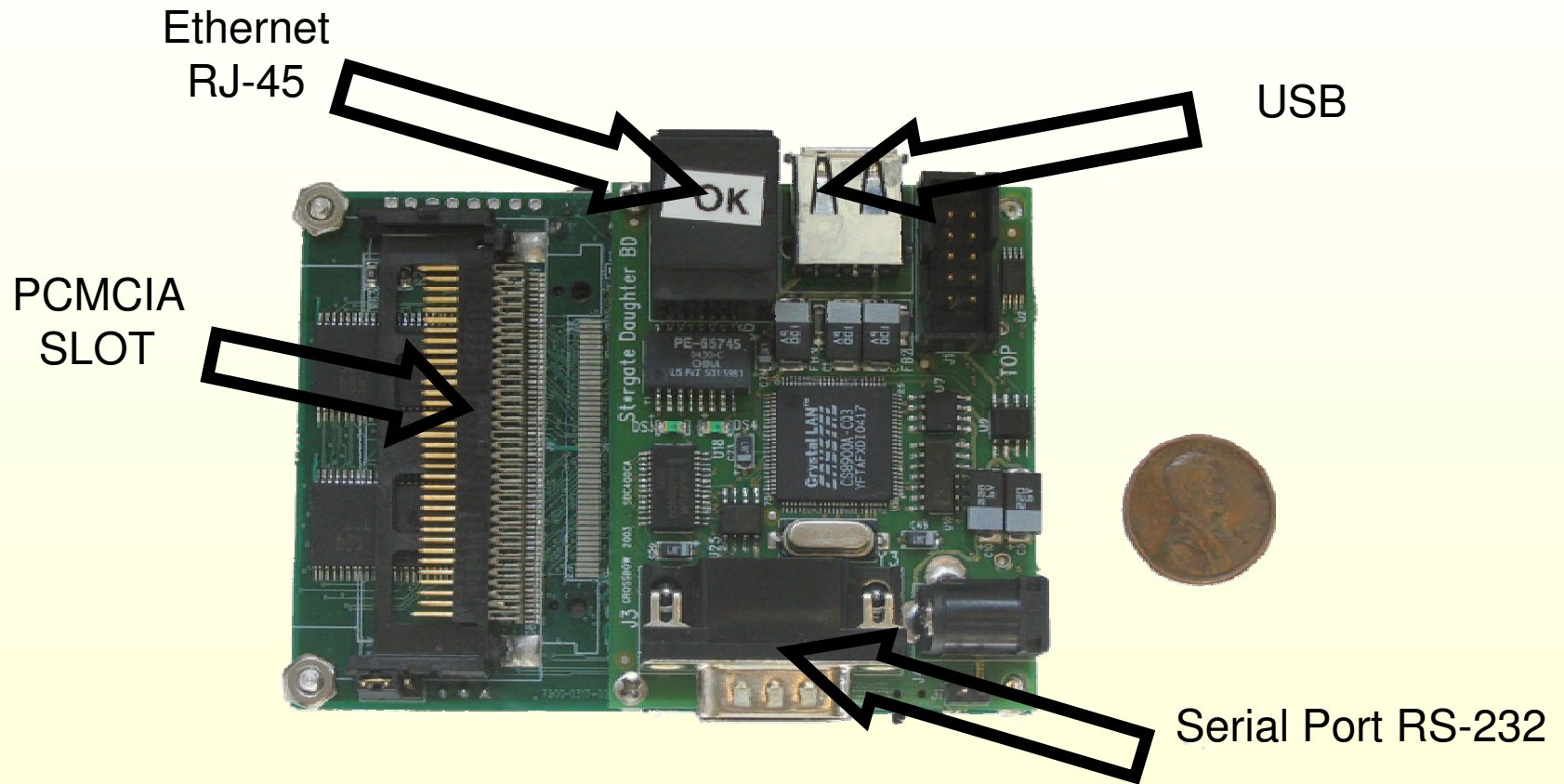


Look for the CPUs...the Opportunities Will Follow!

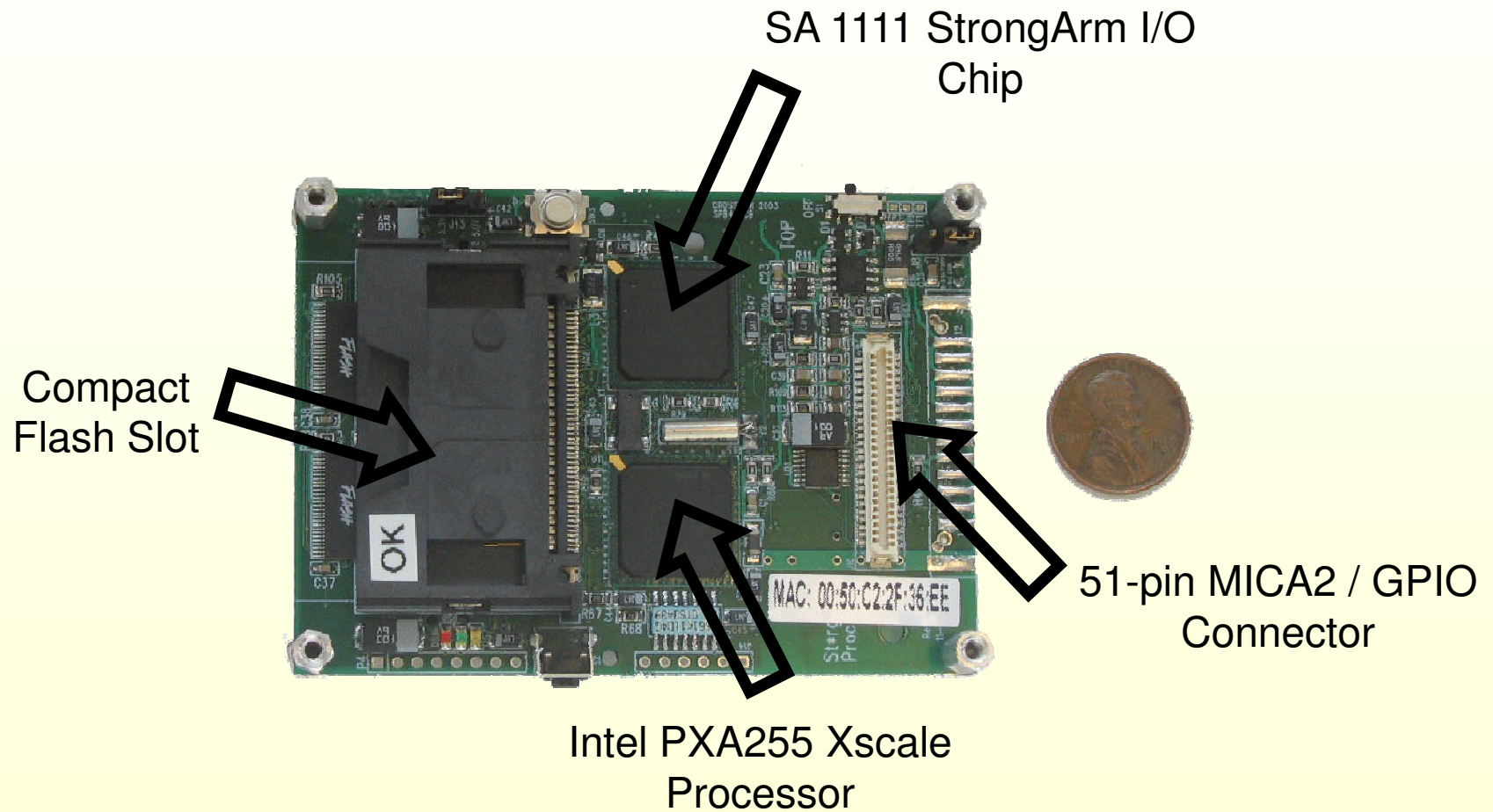
Most Popular: Crossbow Motes



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
 - 50 m range

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>

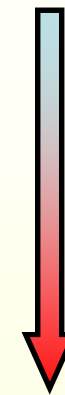
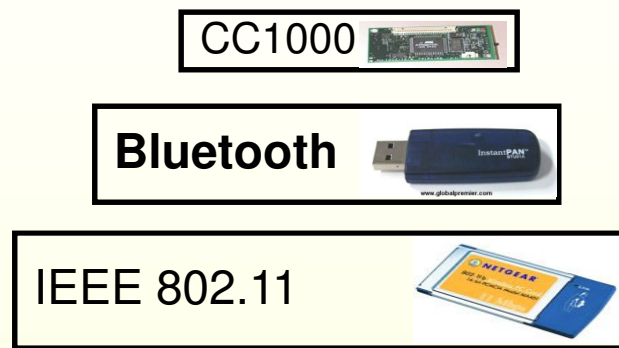
More Comparisons

[From Arora]

Node Type	Sample "Name" and Size	Typical Application Sensors	Radio Bandwidth (Kbps)	MIPS Flash RAM	Typical Active Energy (mW)	Typical Sleep Energy (uW)	Typical Duty Cycle (%)
Specialized sensing platform	Spec mm ³	Specialized low-bandwidth sensor or advanced RF tag	<50Kbps	<5	1.8V*10–15mA	1.8V *1uA	0.1–0.5%
				<0.1Mb			
				<4Kb			
Generic sensing platform	Mote 1-10cm ³	General-purpose sensing and communications relay	<100Kbps	<10	3V*10–15mA	3V *10uA	1–2%
				<0.5Mb			
				<10Kb			
High-bandwidth sensing	Imote 1-10cm ³	High-bandwidth sensing (video, acoustic, and vibration)	~500Kbps	<50	3V*60mA	3V *100uA	5–10%
				<10Mb			
				<128Kb			
Gateway	Stargate >10cm ³	High-bandwidth sensing and communications aggregation Gateway node	>500Kbs–10 Mbps	<100	3V*200mA	3V *10mA	>50%
				<32Mb			
				<512Kb			

Radio Comparison

[From Arora]



Technology	Data Rate	Tx Current	Energy per bit	Idle Current	Startup time
CC1000	76.8 Kbps	10 mA	430 nJ/bit	7 mA	Low
Bluetooth	1 Mbps	45 mA	149 nJ/bit	22 mA	Medium
802.11	11 Mbps	300 mA	90 nJ/bit	160 mA	High

Communication is Expensive

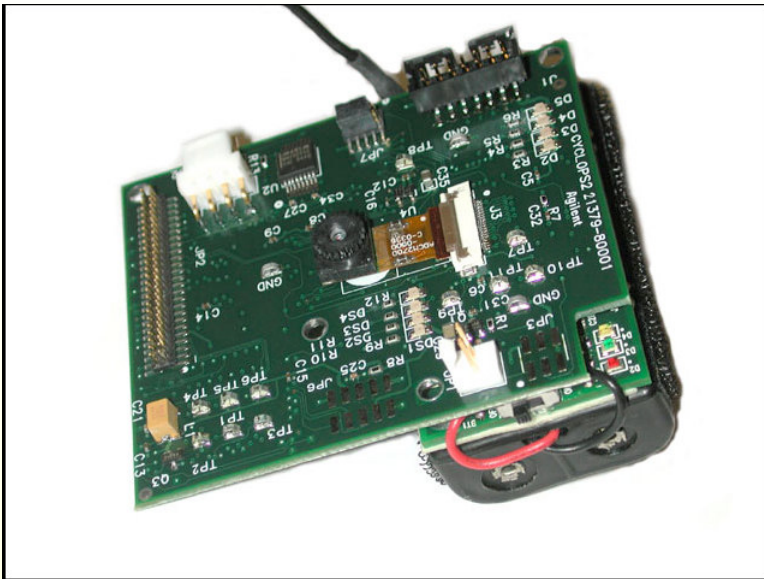
	1999 (Bluetooth Technology)	2004
Communication	(150nJ/bit)	(5nJ/bit)
	1.5mW*	50uW
Computation		~ 190 MOPS
		(5pJ/OP)

Assume: 10kbit/sec. Radio, 10 m range.

Large cost of communications relative to computation continues

Source: ISI & DARPA PAC/C Program

High Data Rate Sensors



- Agilent cyclops imager
 - CMOS, medium quality
 - 128 x 128 and low power
 - 46mw active, 100nW standby
- CPLD
 - Low power frame grabber w. controlled clocking
- External SRAM
 - Image capture and manipulation buffer
 - Auto sleep
- External FLASH
 - Permanent storage for temple matching

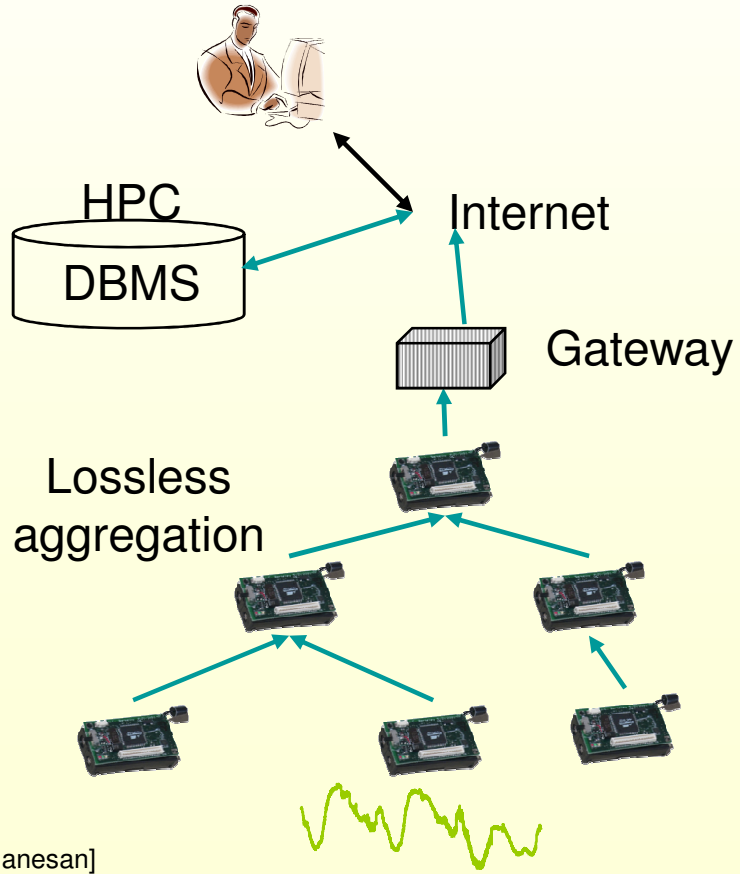


128 x 128 image

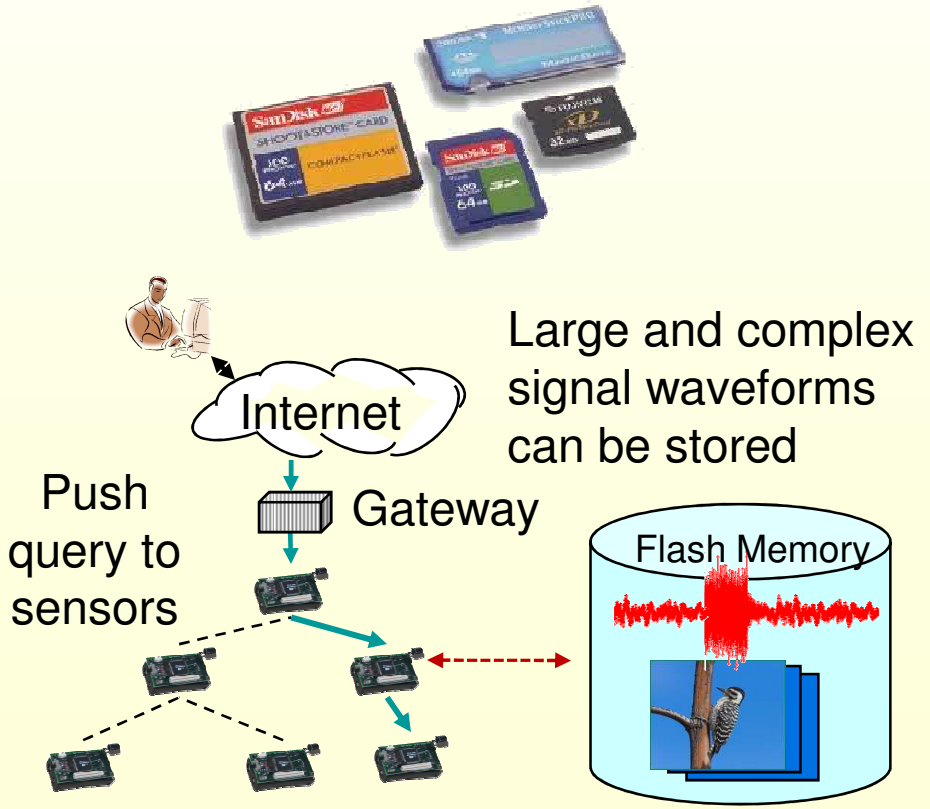
Using imagers as higher-level sensors

A Technology Driver: Distributed Storage in Sensor Networks

Centralized Repository



On-Node Storage: Flash Memory 2-8Gb



[From Ganesan]

Data Overload

- A lot more data will be captured than can or will ever be looked at
 - Classical data indexing methods do not apply
- Most data must stay on the nodes

on a mote-class device, transmitting the entire contents of a single 4GB flash chip takes approximately 110 hours of uninterrupted communication: just under five days, twice the expected lifetime of a node with 2 AA batteries [P. Levis]

- We must be highly selective on what data is sent to users

Architectural Challenges

High-level Research Questions

- What element and system behaviors must we design into these large-scale, physically coupled, inherently distributed, autonomous systems?
- How can we program large aggregates of physically distributed and dynamic elements?
- What forms of spatio-temporal processing can take advantage of the spatial distribution and organization of ENS systems?
- What are the tradeoffs between actuation and sensing in hybrid systems and what distributed control techniques apply to sensor rich environments?
- What are the fundamental design principles relevant to ENS?

Distributed Sensor Communication: Multi-Hop RF Advantage

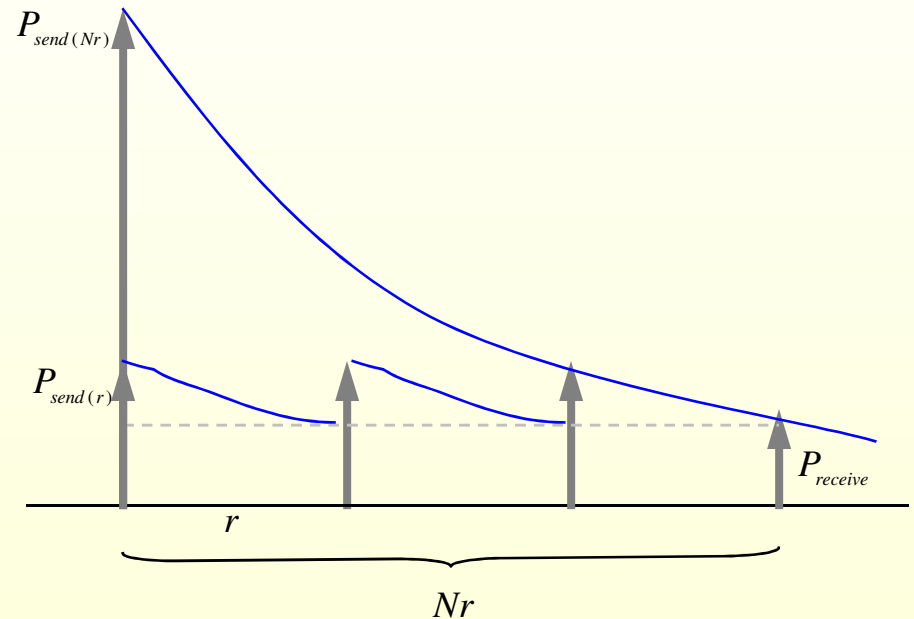
RF power attenuation near ground:

$$P_{receive} \propto \frac{P_{send}}{r^\alpha}, \quad \alpha: 2-5$$

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

Power advantage:

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



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 $10\log N$ 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:

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

Scaling Laws

- Structuring communication is very important:

In a setting where each node wishes to communicate some arbitrary data to another node at random, interference hinders spatial reuse, and therefore limits throughput scaling:

the per node capacity scales as $\frac{1}{\sqrt{N}}$ (Gupta & Kumar '99)

Because short communications are optimal in reducing interference -- effectively each node is using most 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.

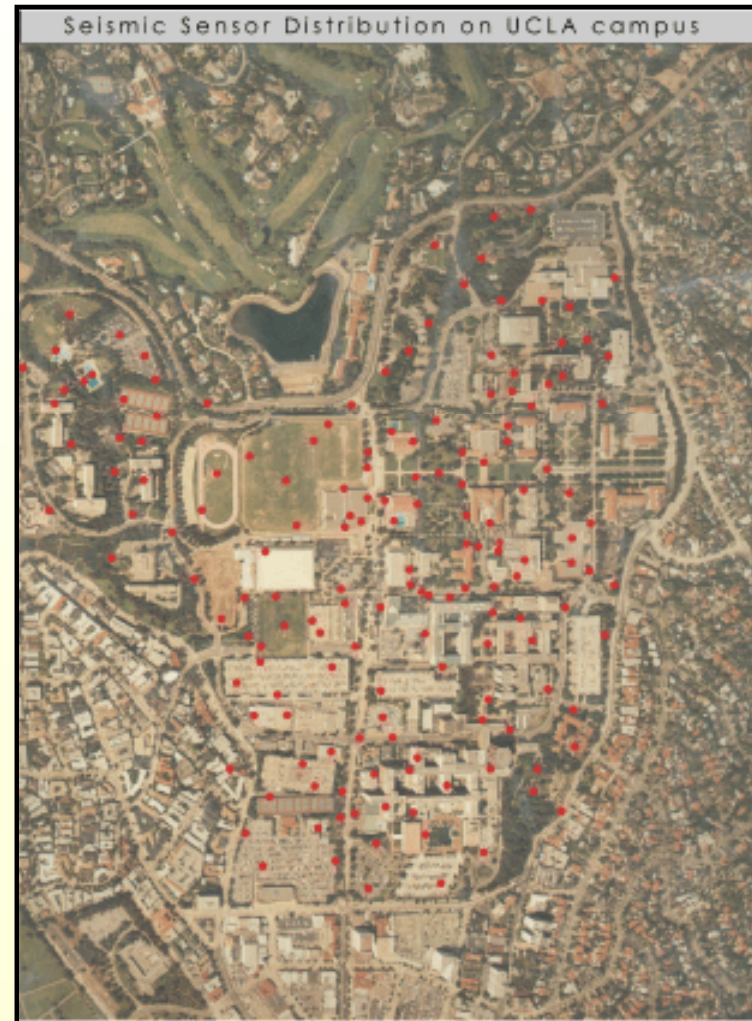
Sensor Network Challenges

- 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



Structure Discovery

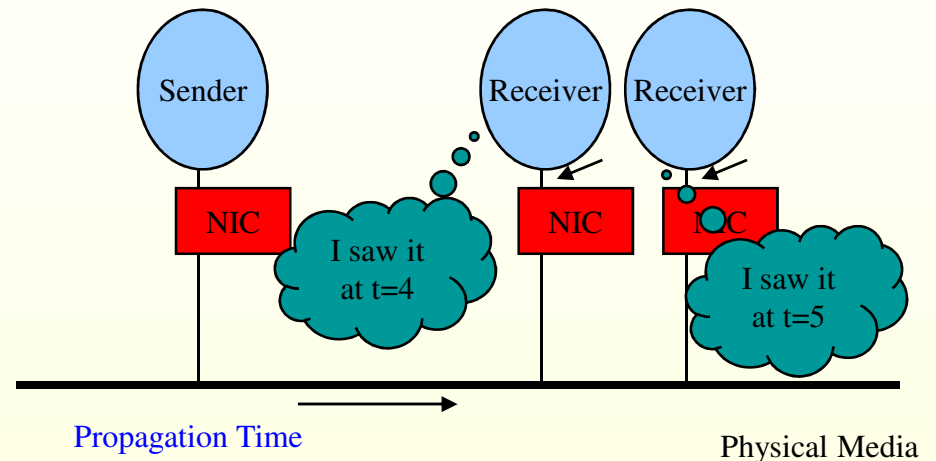
- A sensor network is a novel type of computing device -- **a sensor computer**
- One of its first tasks is to discover its own structure and establish
 - information highways
 - sensor collaboration groups
- as well as adapt to its signal landscape



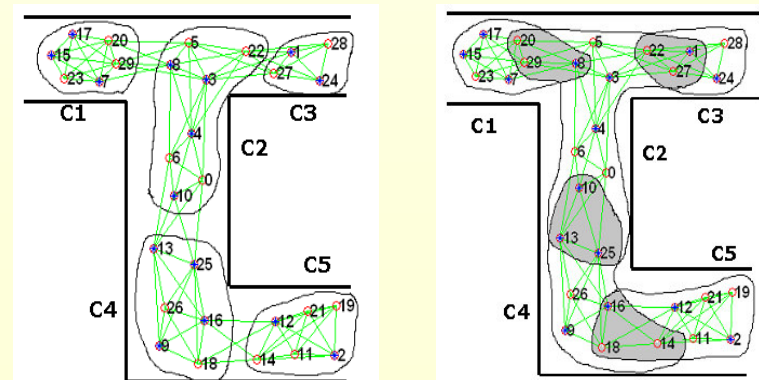
Self-Configuration for Ad-Hoc Deployment

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

• Time Synchronization



• Localization

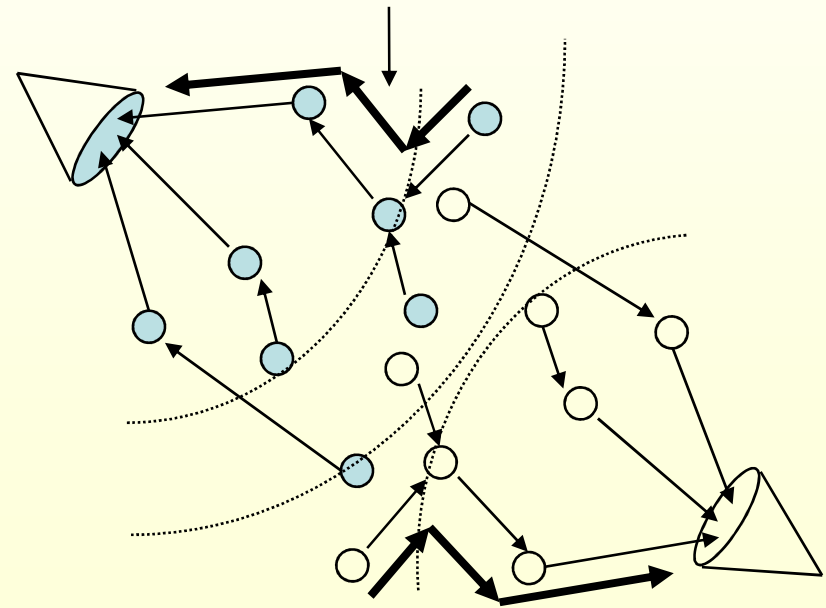


[From Estrin]

Semantic Routing and Networking

- We want to address sensor data that carry useful information, not individual nodes
- Content and address in a message get intermixed
- How do we help information providers and clients find each other?

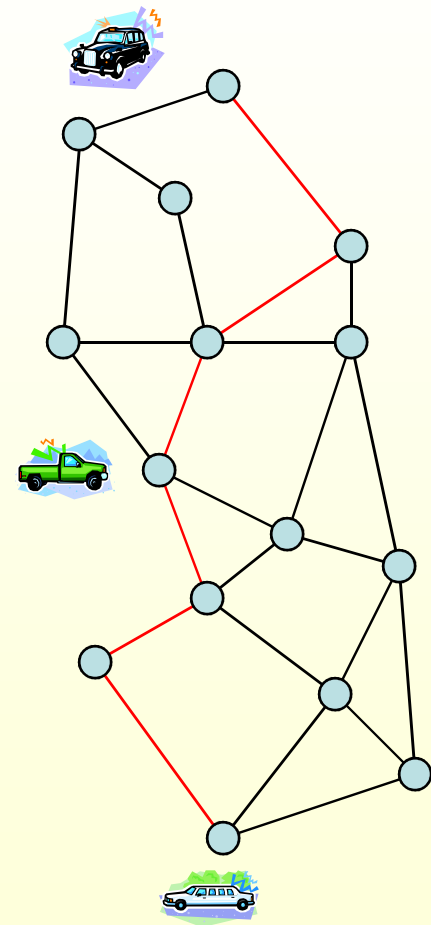
Directed diffusion
Geo-routing



[From Estrin]

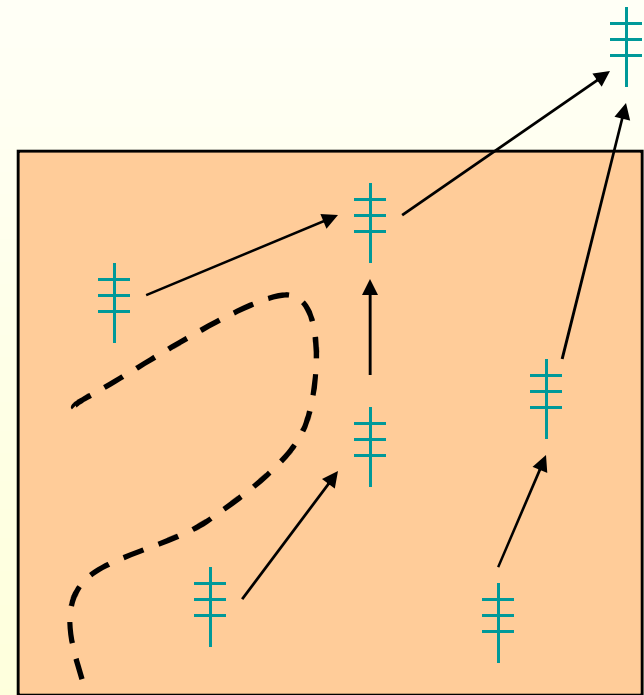
Networking Sensor Networks

- 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**.



Data Aggregation and In-Network Processing

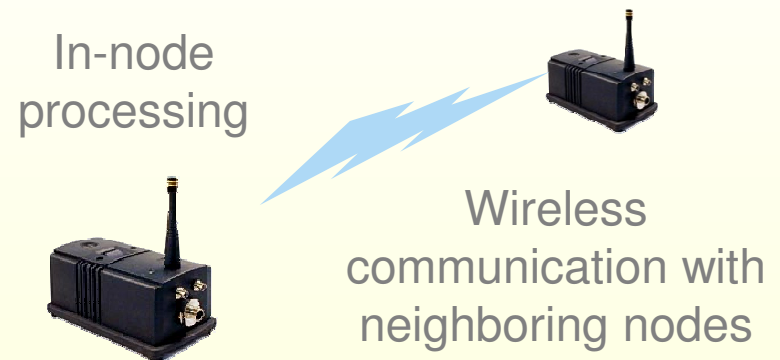
- Information aggregation can happen on the way to a destination, thus saving communication energy
- Need to balance quality of paths with quality of information collected
- Are there “application-independent” paradigms of information aggregation?



Temperature aggregation

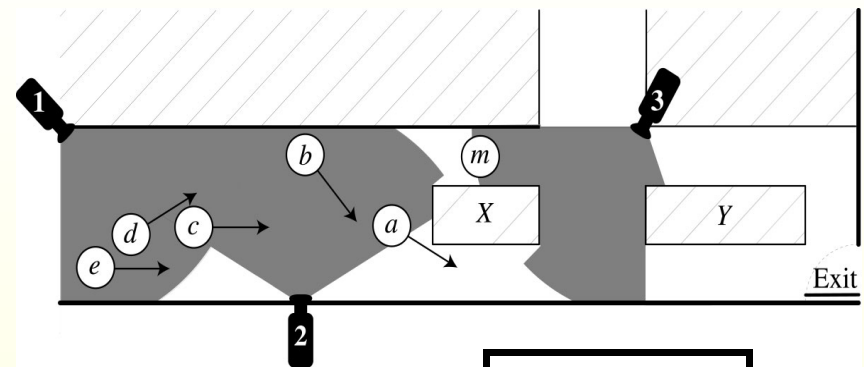
Power-Aware Sensing and Communication

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



Sensor Tasking and Control

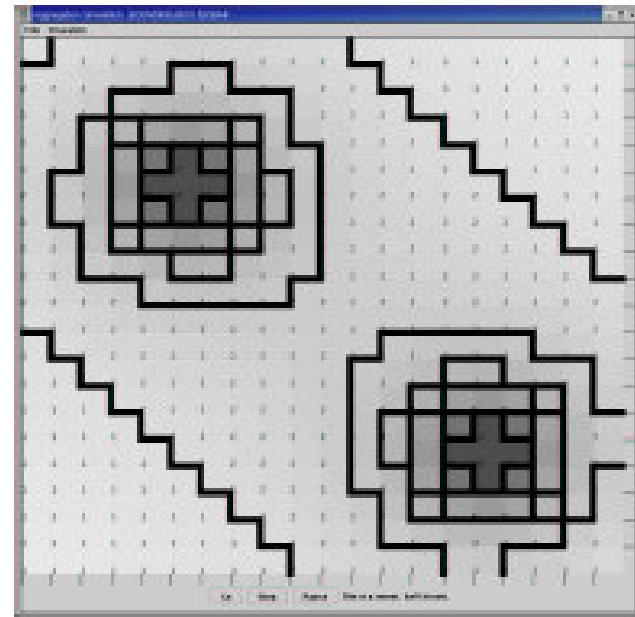
- Decide which sensors should sense and communicate, according to the high-level task – a non-trivial algorithmic problem
- Direct sensing of relations relevant to the task – do not estimate full world state



<i>a</i> ahead-of <i>b</i>
<i>b</i> ahead-of <i>c</i>
<i>c</i> ahead-of <i>d</i>
<i>d</i> ahead-of <i>e</i>

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?”



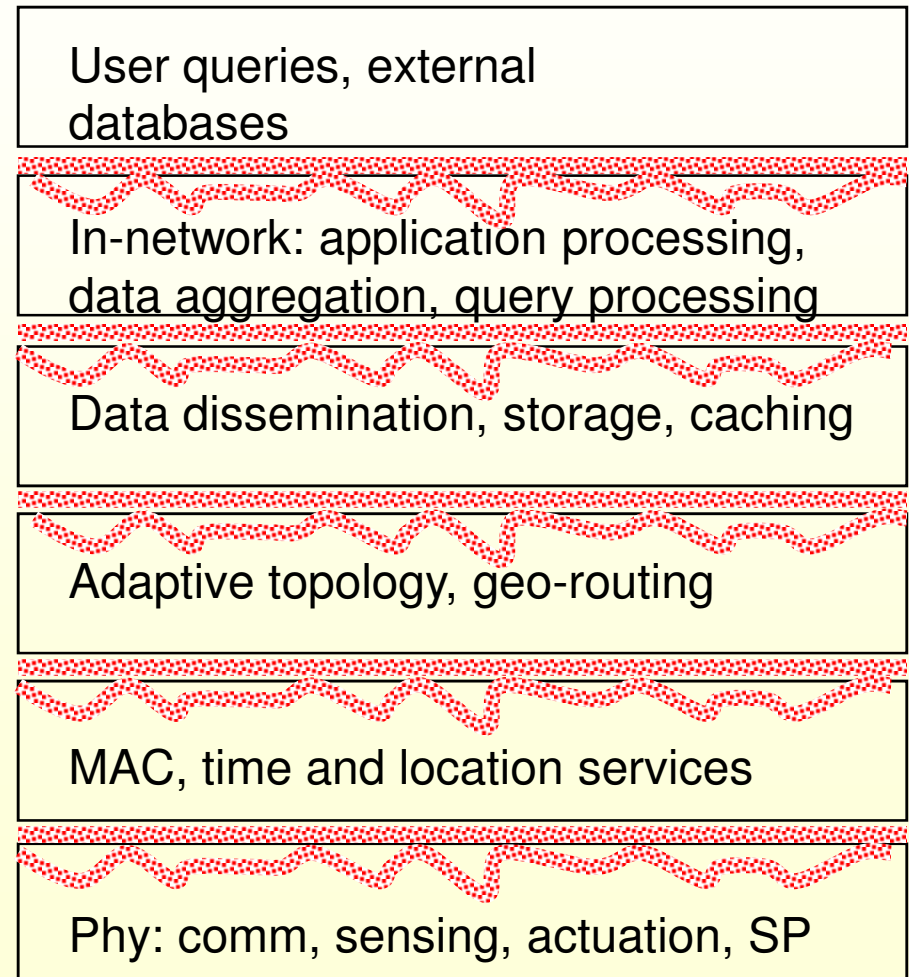
(a) Lossless Isobars

Field isolines

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?



Various Issues

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



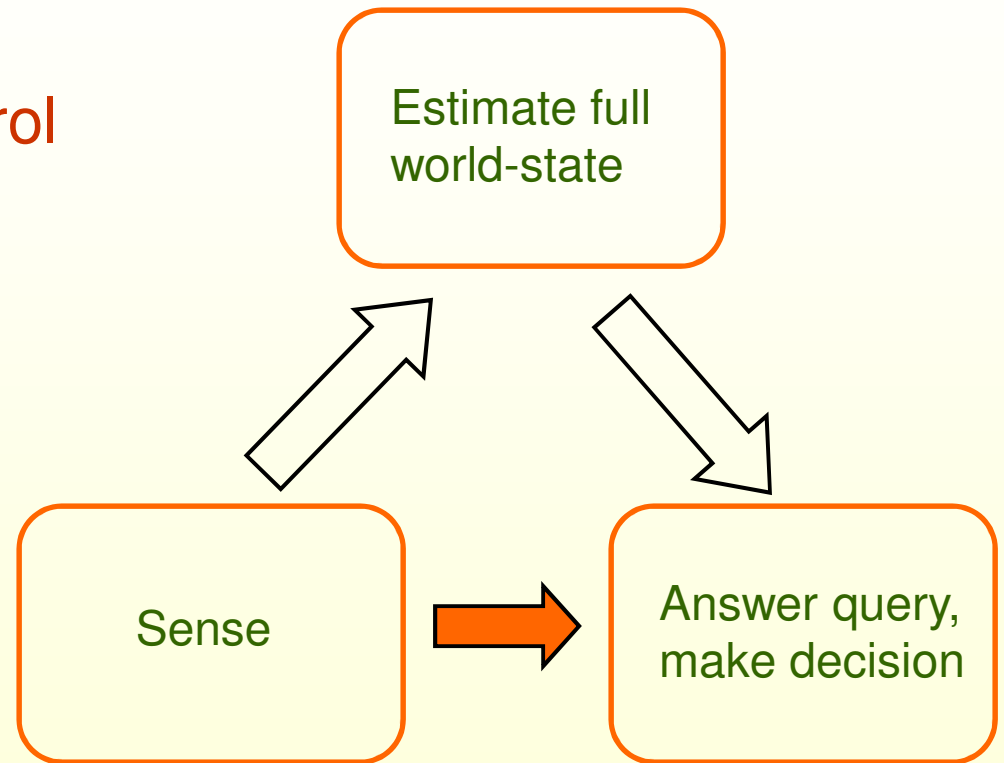
Distributed robotics

What Defines Sensor Networks?

- Multi-hop communication
 - Many nodes act as routers
 - Multiple paths exist and must be considered
- Bandwidth limitations
 - Volume of data sensed exceeds to capacity of the network to transport
- Power limitations
 - (At least some) nodes operate untethered and energy conservation must be considered in all of sensing, processing, and communication
- A cooperative system
 - All nodes serve one, or a small number of tasks

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.

CS321: The Course

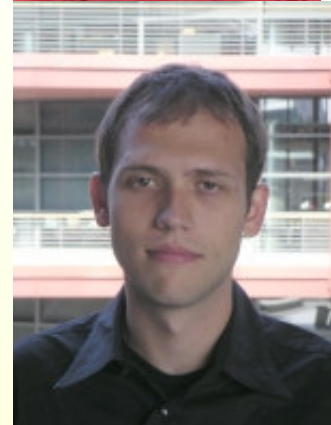
Course Personnel

- Instructor: **Leonidas J. Guibas**
- Course Assistant: **Primož Skraba**
- Senior Assistant: **Branco Kusy**

Course web page:

<http://graphics.stanford.edu/courses/cs321-07-fall>

<http://www.stanford.edu/class/cs321>

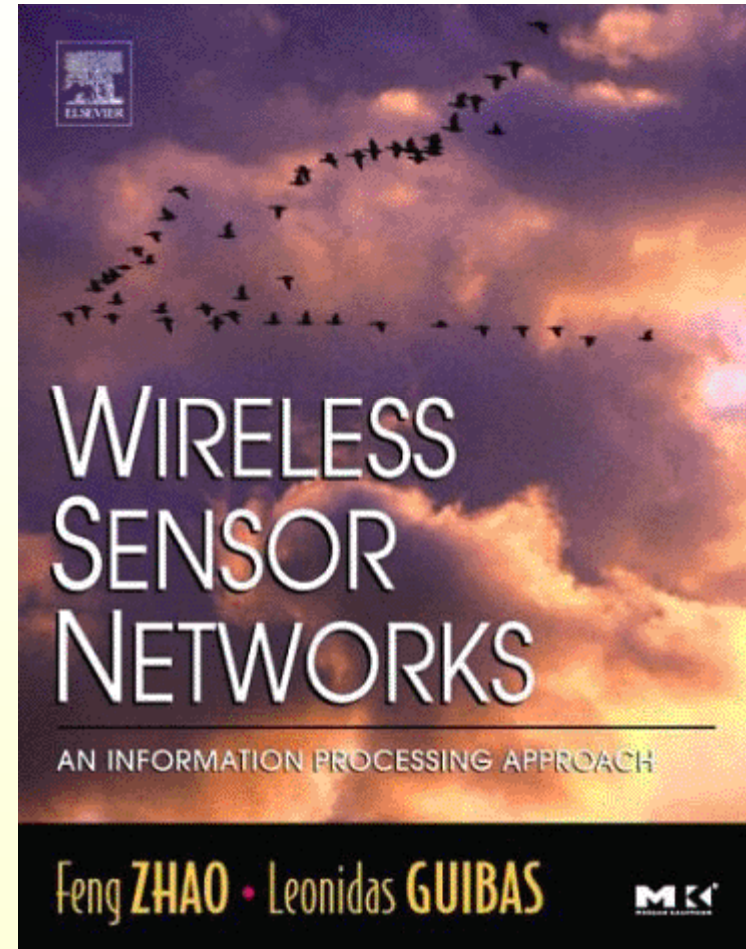


Course TextBook

Wireless Sensor
Networks: An
Information
Processing Approach

Feng Zhao and
Leonidas Guibas

Morgan-Kaufmann 2004



Course Outline, I

- Basics of embedded systems; sensor node hardware and software; simulators
- Wireless links and topology control; unicast and multicast multi-hop routing; broadcasting
- Power conservation and duty cycling
- Infrastructure establishment: time synchronization
- Infrastructure establishment: localization
- Information aggregation and in-network processing
- Information discovery and query processing
- Gossiping, bloom filters, network coding
- Distributed storage
- Sensor tasking and control, collaborative processing

Course Outline, II

- Applications:
 - Environmental monitoring
 - Tracking localized and non-localized phenomena

The course emphasizes the algorithmic, protocol design, and analytical aspects of sensor networks. Many other important aspects will not be fully addressed:

- hardware design
- physical layer issues
- low-level system software
- sensor-specific issues
- application-specific issues

Some Related Stanford Courses

- Prof. Phil Levis (CS & EE)
 - CS344E: Sensor Network Systems, Spring 2008
- Prof. Hamid Aghajan (EE)
 - EE392Y: Vision Sensor Networks Lab
- Other faculty: Abbas El Gamal (EE), Andrea Goldsmith (EE), Teresa Meng (EE), Ashish Goel (MS&E), ...

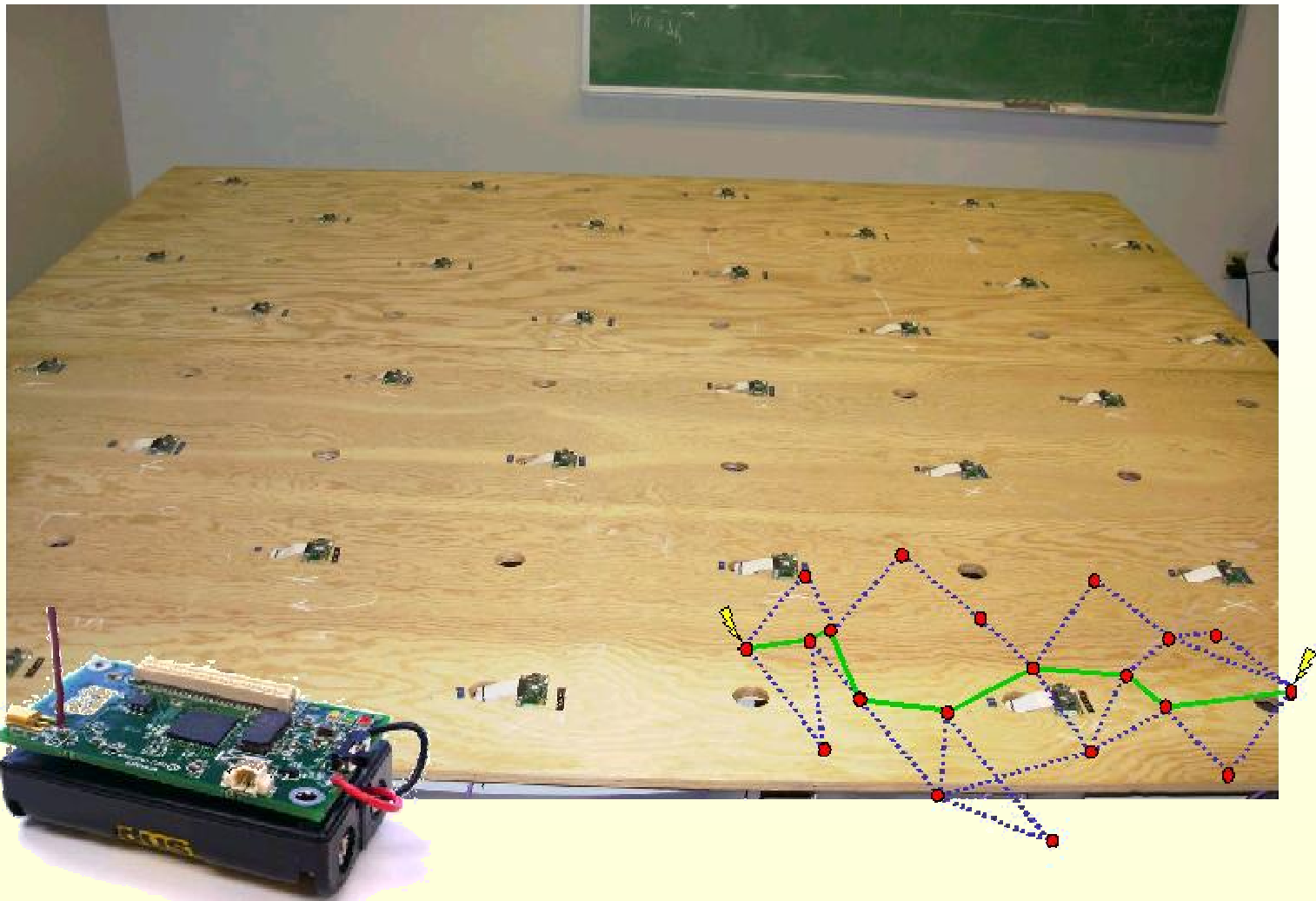
Course Format

- Lectures by the instructor, or the assistants
- Student presentations of current research papers
- A course project is required. We will provide guidance and support for a specific implementation project on actual mote hardware. However, other projects of your own design are also OK. These can be
 - an implementation on actual mote hardware, supported by simulations
 - a more theoretical/analytical investigation, supported by simulations
 - a simulation only project is not OK

Course Grading

- 20% class participation
- 5% warm-up project
- 25% oral presentation or 5% in class midterm
- 50% course project
- no final

We Plan to Have Fun!



[From Agrawal]

The End