Instrumenting the World with Wireless Sensor Networks

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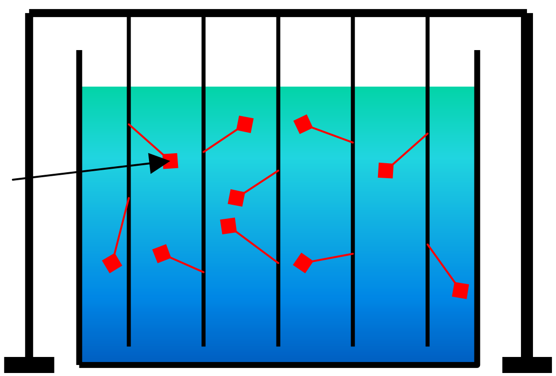
Work summarized here is largely that of students, staff, and other faculty at CENS

We gratefully acknowledge the support of our sponsors, including the National Science Foundation, Intel Corporation, Sun Inc., Crossbow Inc., and the participating campuses.

Embedded Networked Sensing

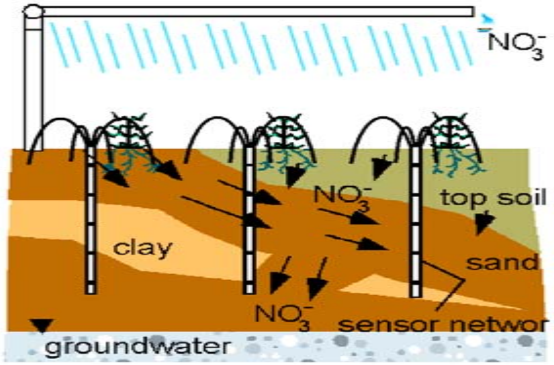
Ecosystems, Biocomplexity

Marine Microorganisms



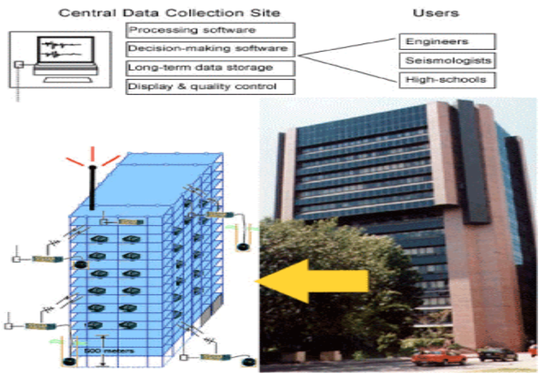
- Micro-sensors, on-board processing, wireless interfaces feasible at very small scale--can monitor phenomena “up close”
- Enables spatially and temporally dense environmental monitoring

Embedded Networked Sensing will reveal previously unobservable phenomena



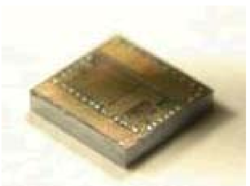
Contaminant Transport

Seismic Structure Response

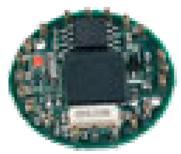


Moore's Law and Microfabrication

Small, cheap, plentiful computing resources

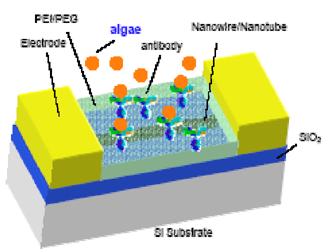


SPEC (J. Hill):
4MHz/8bit, 3K/0K

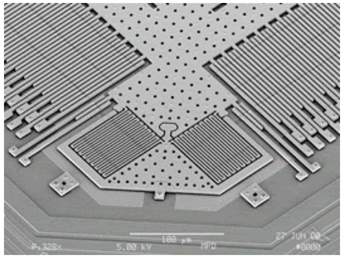


Mica2Dot (Berkeley/Xbow):
8MHz/8bit, 4K/128K

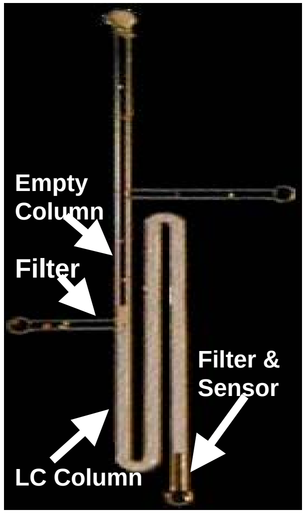
Stargate (Intel/Xbow)
400Mhz/32bit, 64M/32M



Marine Algae Detector
(C Zhao)



iMEMS Accelerometer
(Analog Devices)



Liquid Chromatograph
(YC Tai)

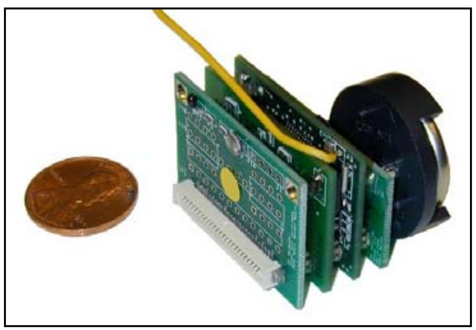
Small, cheap, plentiful sensing technologies

ENS enabled by Integration of Wireless, Computation, Sensing

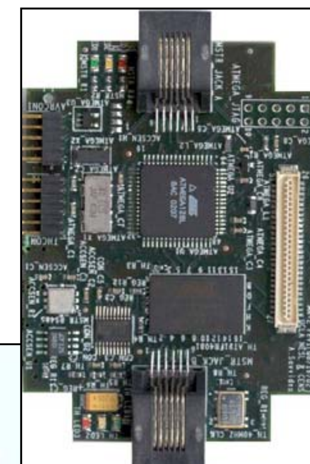
LWIM III
UCLA, 1996
Geophone, RFM radio, PIC, star network

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

Sensor Mote
UCB, 2000
RFM radio, Atmel, TinyOS

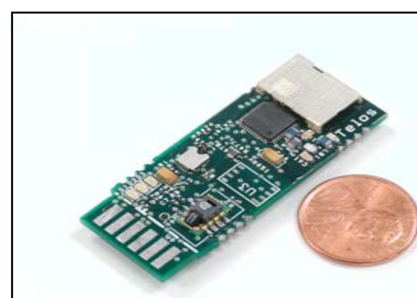


Medusa, MK-2
UCLA NESL
2002



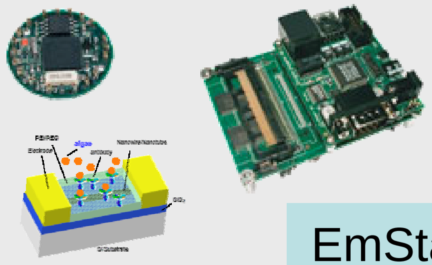
Energy is the primary resource constraint and **communications** is the primary resource consumer

Telos Mote
UCB, 2004
Zigbee radio, Motorolla



Embedded Networked Sensing (ENS)

Technologies:

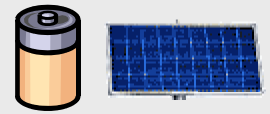


EmStar

TinyOS

Key Constraints:

Energy awareness and conservation



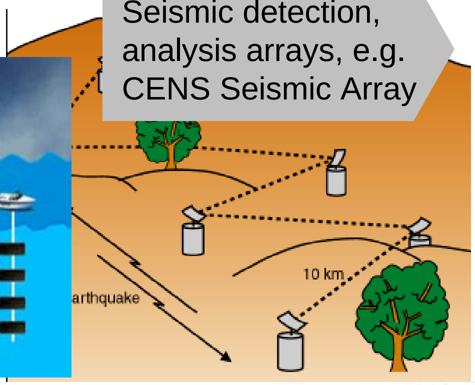
Scaling and adaptation to variable resources and stimuli

Autonomous, disconnected operation

Complexity of Distributed systems

Target Apps:

Habitat investigation, e.g NIMS (Networked Info-Mechanical Systems)



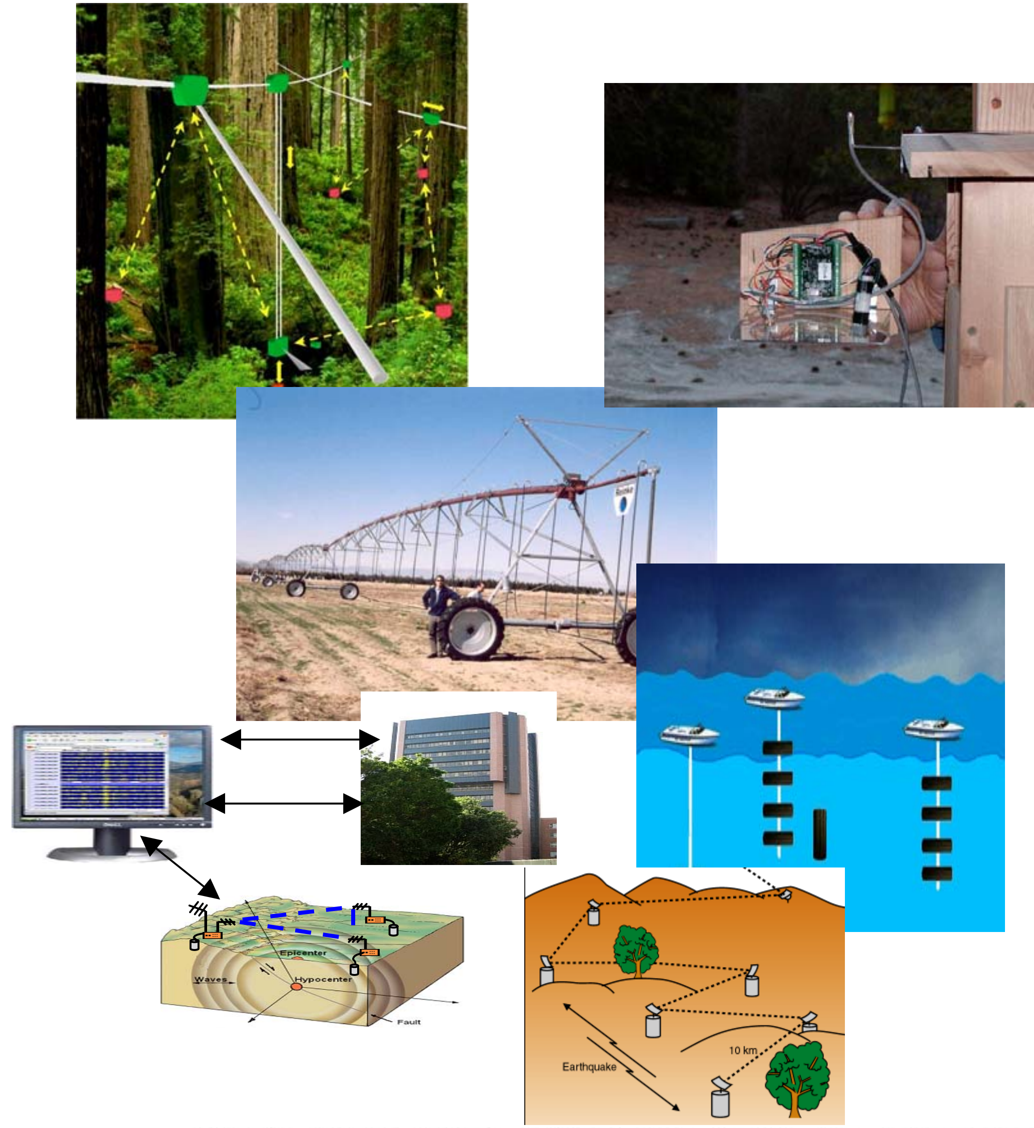
Seismic detection, analysis arrays, e.g. CENS Seismic Array

Technology Research:

- Self configuring systems
- Collaborative signal processing
- Networked Info Mechanical Systems
- Embeddable Micro-Sensors

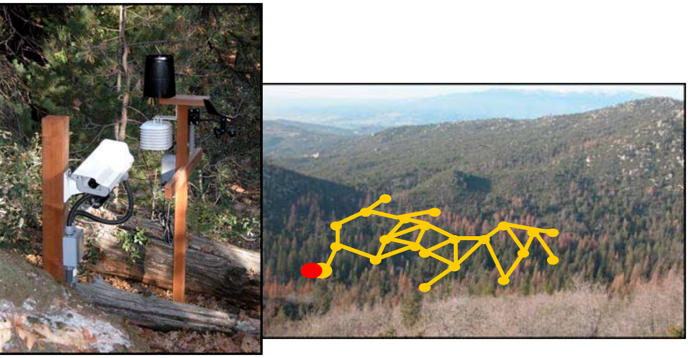
CENS Science Application System Developments

- Biology/Biocomplexity(Hamilton, Rundel)
  - Microclimate monitoring
  - NIMS Adaptive sampling
- Contaminant Transport (Harmon)
  - County of Los Angeles Sanitation Districts (CLASD) wastewater recycling project, Palmdale, CA
- Seismic monitoring(Davis, Wallace)
  - 50 node ad hoc, wireless, multi-hop seismic network
  - Structure response in USGS-instrumented Factor Building
- Marine microorganisms (Caron, Requicha, Sukhatme)
  - Detection of a harmful alga
  - Experimental testbed w/autonously adapting sensor location



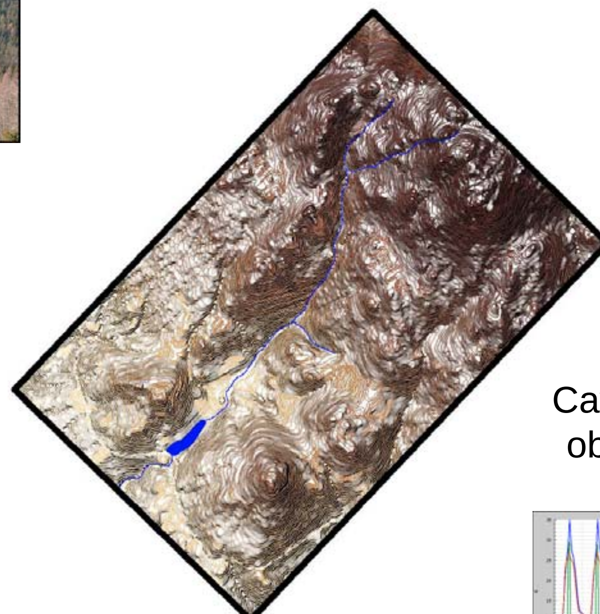
Habitat and Environmental Sensing Applications
(Hamilton, Rundel, Harmon)

UC James Reserve
Habitat Sensing Testbed



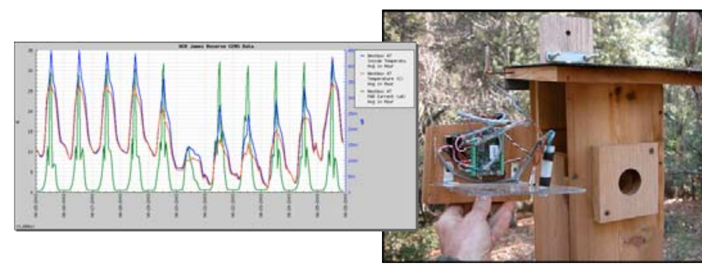
NIMS: mobile ground and canopy climate sensors, data mules, and robotic samplers

Dense micro-climate sensor networks Extensible Sensor System (ESS)

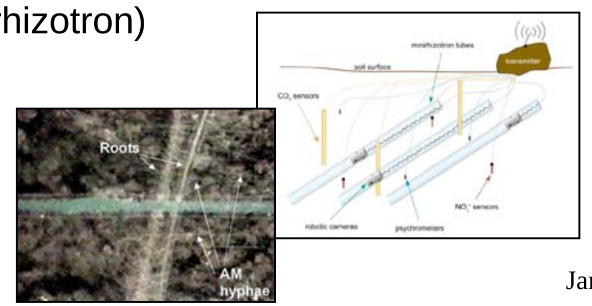


James Reserve and Hall Canyon Research Natural Area

Cavity nest micro-climate, remote observation, bioacoustic sensing

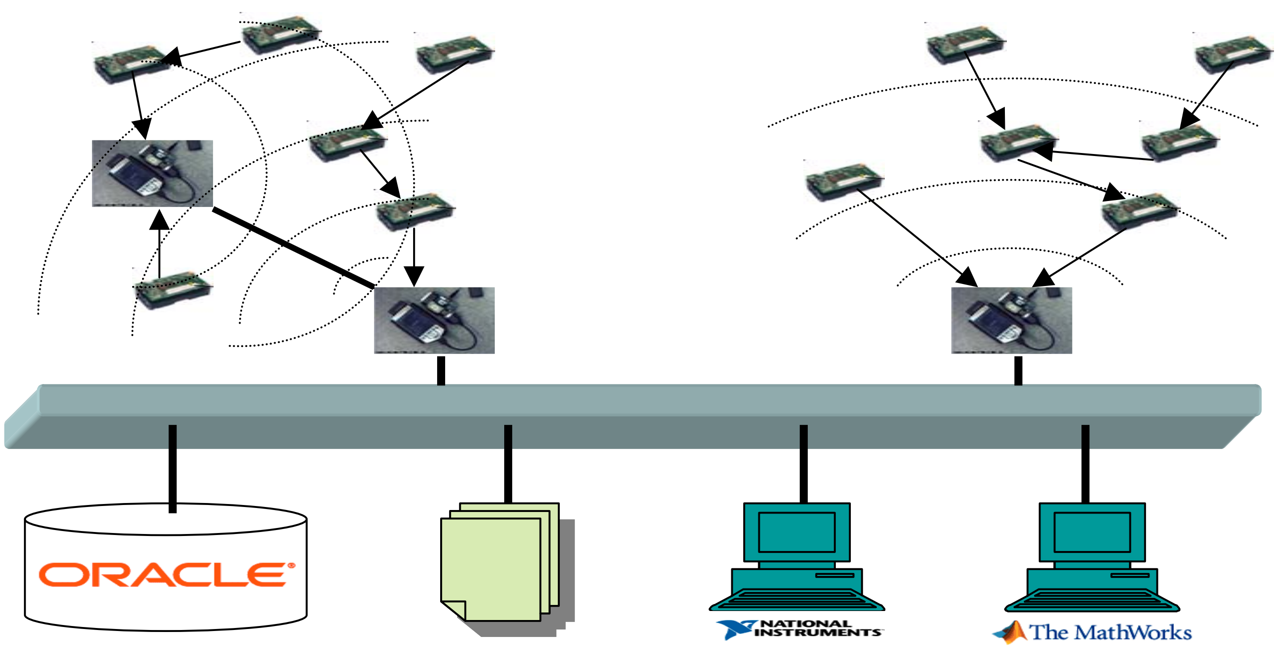


Soil microclimate and chemical sensors, root/fungi imaging systems (mini-rhizotron)



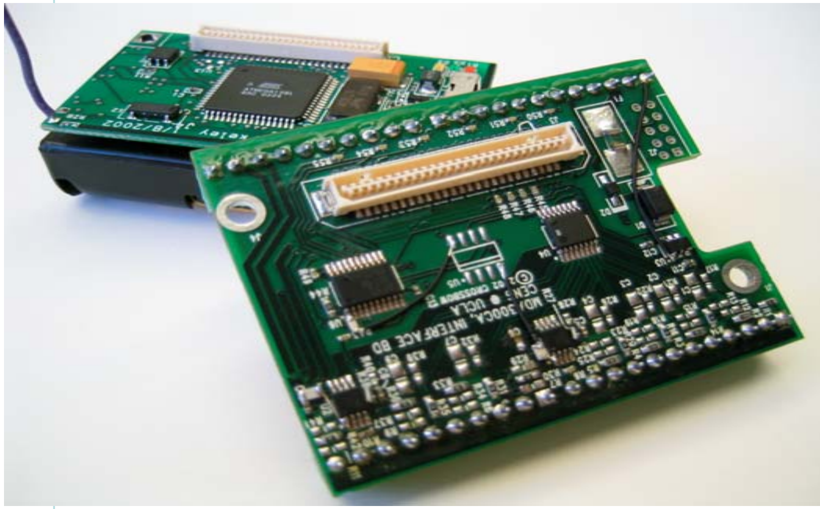
System Support for Dense Monitoring
(CENS Systems Staff)

- Tiered architecture to support taskable, scalable monitoring
  - Mica2 motes (8 bit microcontrollers w/TOS) with Sensor Interface Board hosting in situ sensors
  - Tasking and multihop transport among motes
  - Microservers are solar powered, 32-bit processors, linux OS
  - Pub/sub bus over 802.11 to Databases, visualization and analysis tools, GUI/Web interfaces



Sensor Interface Board: Mote DAQ system
(Rahimi, Wimbrow)

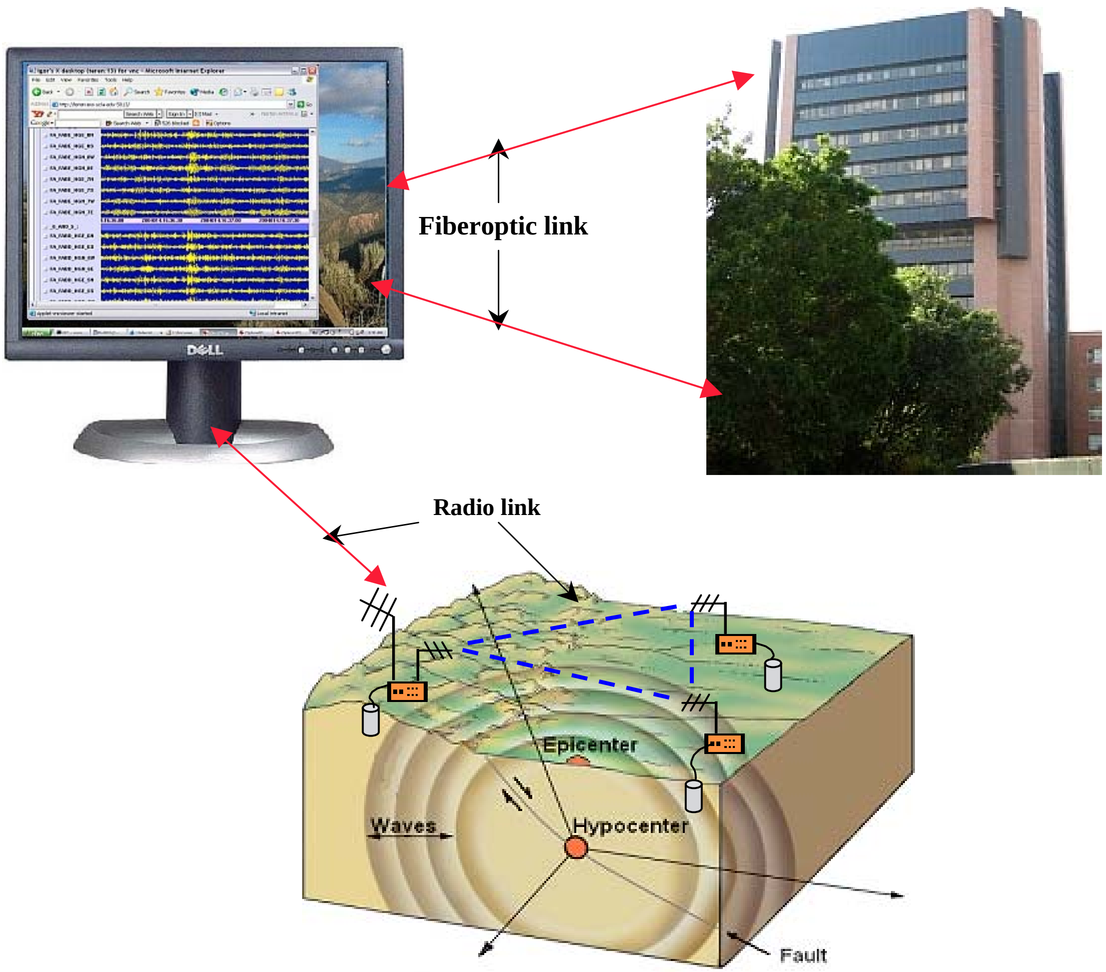
- A general framework for attaching multiple instances and different types of sensors
  - ADC true 12bit
  - High gain differential channels
  - Digital Input (Interrupt driven)
  - Digital Outputs
  - Counter, frequency
  - Relay output
  - On board voltage,temperature and humidity
- *Flexible sampling* rate
- Configurable for different translation functions per channel based on the sensors that has been attached
- Tested with different sensor types.
  - http://www.cens.ucla.edu/~mhr/daq/
  - Now sold by Crossbow



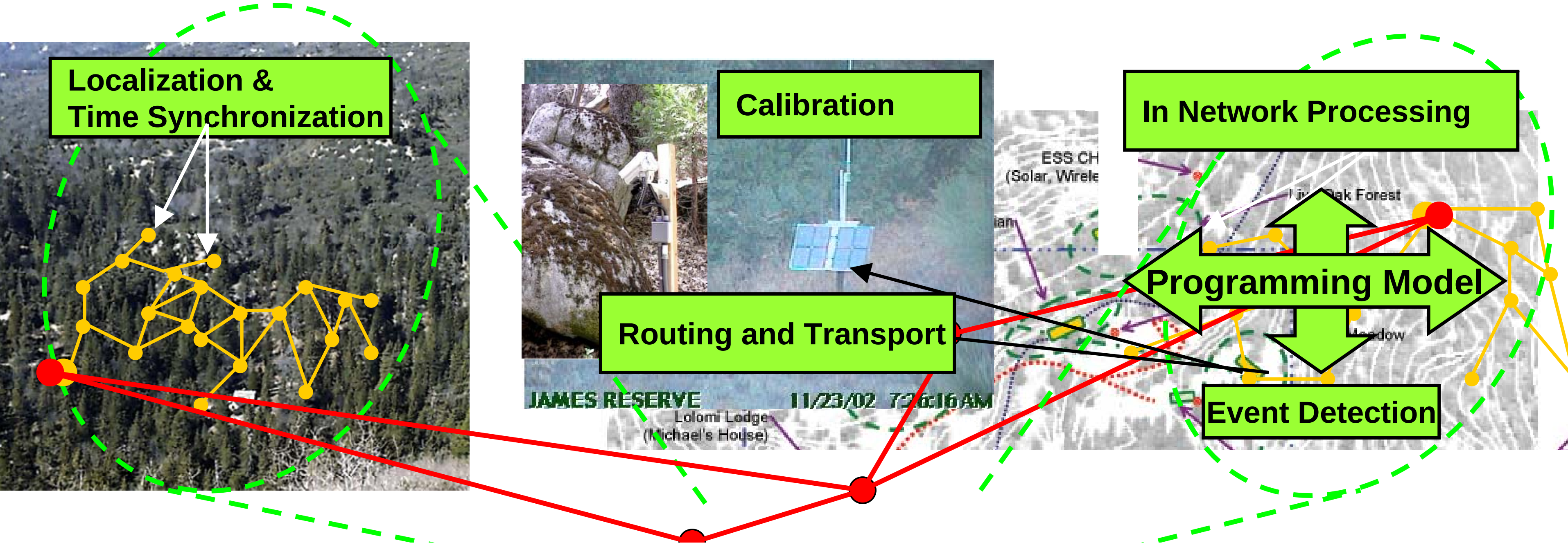
Seismic Applications (P. Davis)

- **Multi-Hopped Radio Linked Array features**
  - Time synchronization
  - Network event detect
  - Sequenced event transmission
  - Deployments planned for UCLA campus and the San Andreas Fault (100m-10 km)
  - Easily reconfigurable
  - Worldwide application

- **Factor Building site**
  - 72 channels of 24-bit data
  - 500 samples per second continuous data recording
  - Internet accessible real time data monitoring
  - Observation of 4 strong earthquakes, including Alaska & Japan



Common system services

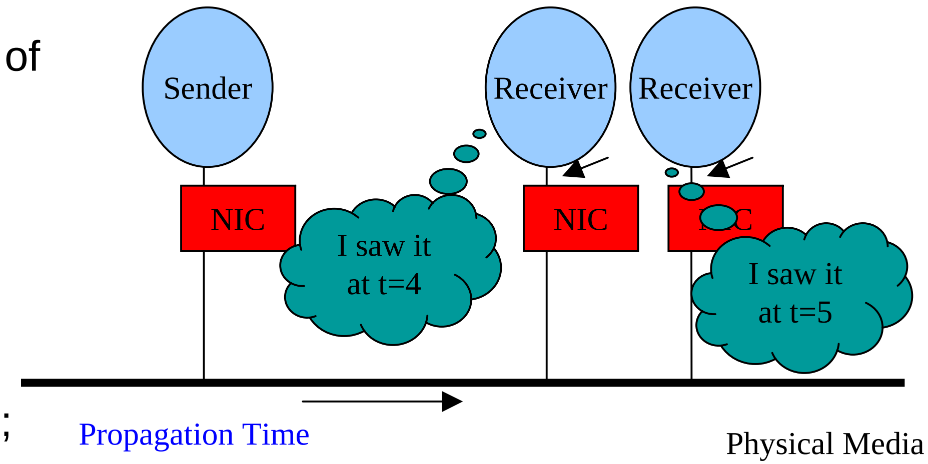


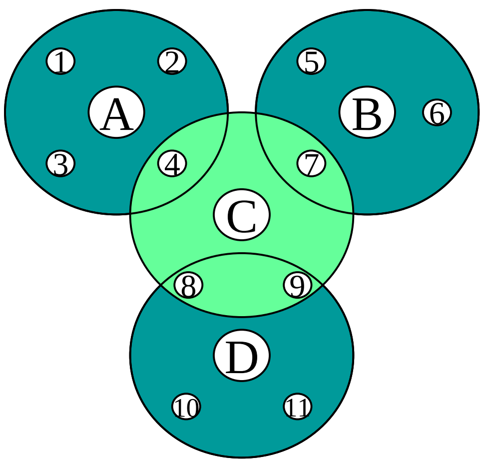
Needed: Reusable, Modular, Flexible, Well-characterized Services/Tools :

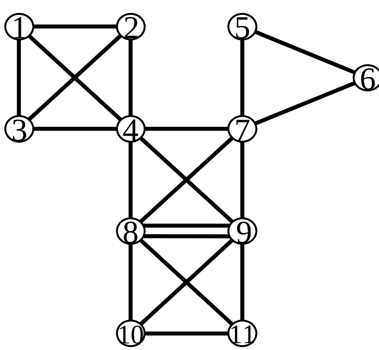
- Routing and transport
- Time synchronization, Localization, Calibration, Energy Harvesting
- In Network Storage, Processing (compression, triggering), Tasking
- Macro-Programming

Time Synchronization Service
(Elson)

- In network processing requires correlation of distributed measurements…and thus time synchronization
- Also crucial in many other contexts
  - Ranging, tracking, beamforming, security, MAC, aggregation etc.
- Global time not always needed
- NTP: often not accurate or flexible enough; diverse requirements!
- New ideas
  - *Local* timescales
  - Receiver-receiver sync
  - Multihop time translation
  - Post-facto sync
- Mote implementation
  - ~10 μs single hop
  - Error grows slowly over hops

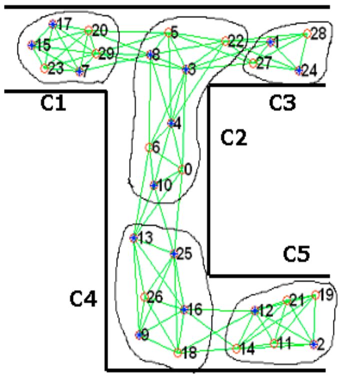


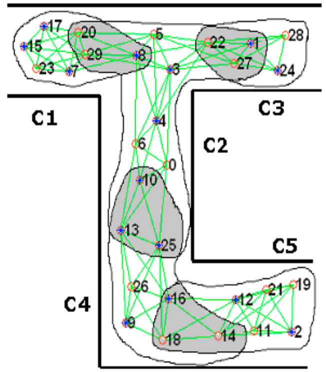


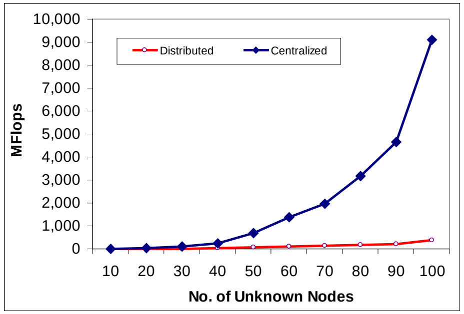


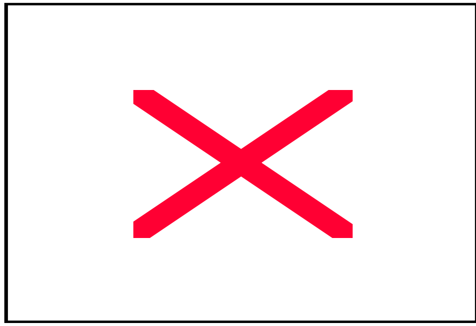
Localization of Sensor Nodes
(M. Srivastava)

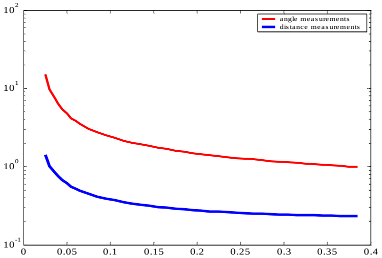
- State of the art networks rely primarily on configured location information where GPS not available
- In situ, infrastructureless, node localization is a very challenging area
  - Robust ranging using wideband acoustics
  - Scalable distributed algorithms
    - Collaborative multilateration (with beacons)
    - Geometry-driven beacon-less
  - Fundamental error analysis
    - Cramer-Rao bounds for multihop
    - Geometry effects
    - Angle vs. distance
  - Implementation
    - MK-II platform with ultrasound ranging
    - IPAQs, Mica2s

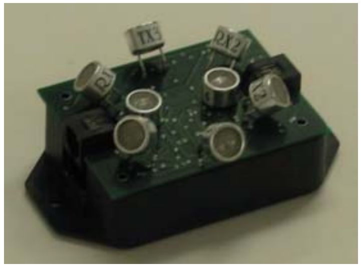








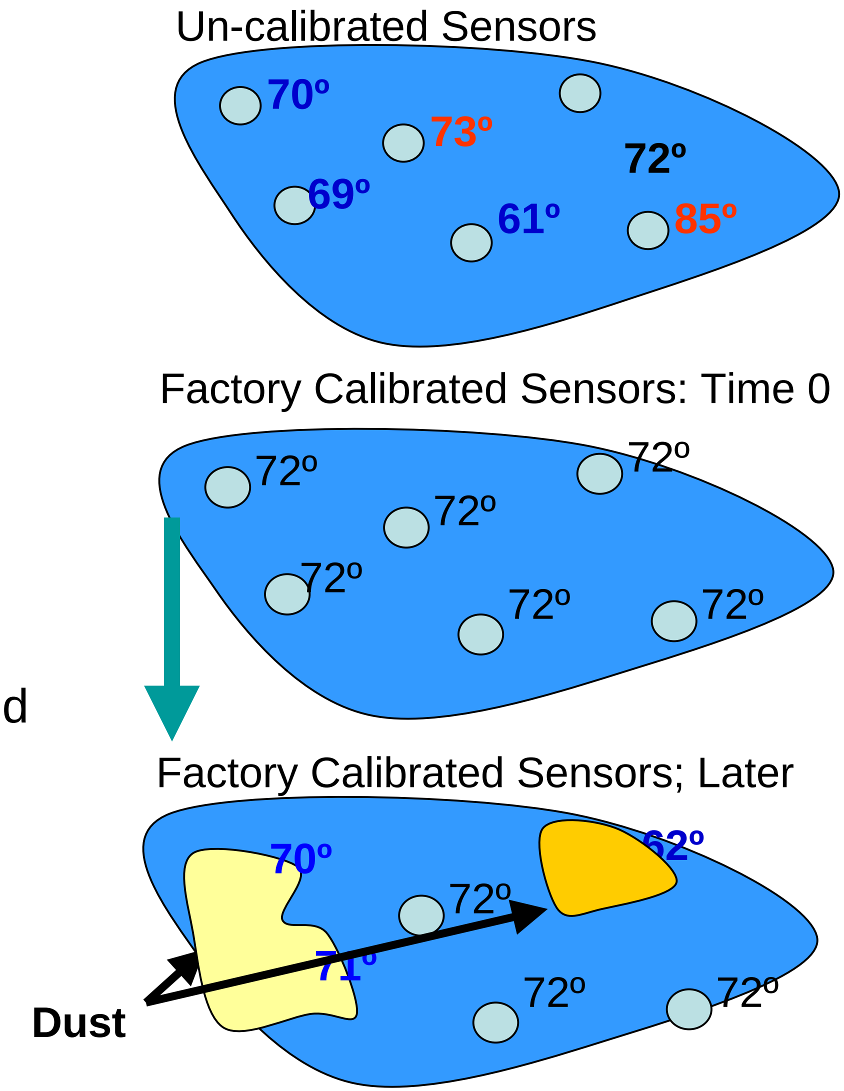




* Srivastava, Saavedes et al

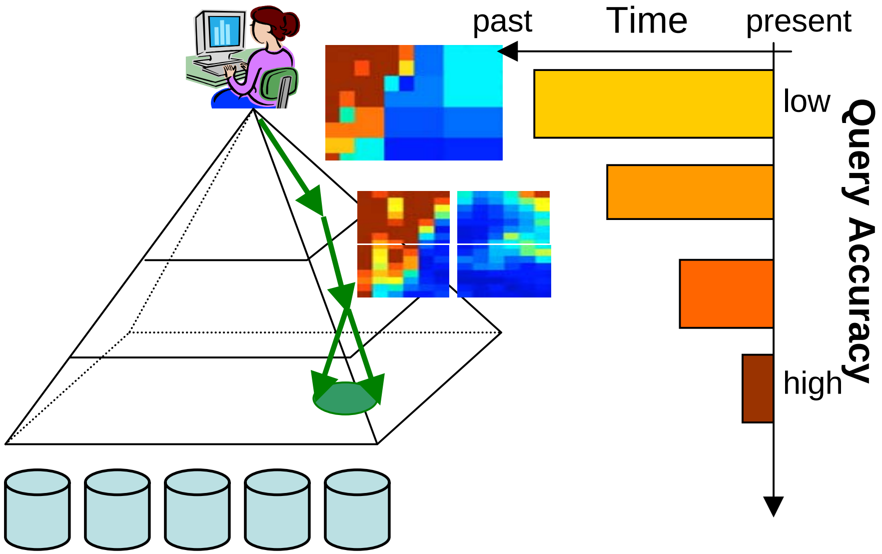
Calibration, or lack thereof
(Harmon, Potkonjak)

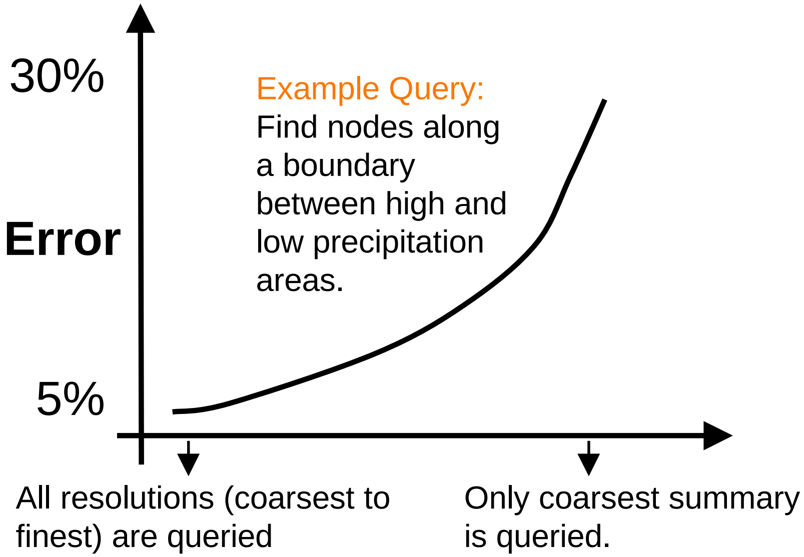
- Storage, forwarding, aggregation, triggering useless unless data values calibrated
- Calibration = correcting systematic errors
  - Sources of error: noise, systematic
  - Causes: manufacturing, environment, age, crud
- Traditional in-factory calibration not sufficient
  - must account for coupling of sensors to environment
- Nearer term: identify faulty sensors and flag data, discard for in-network processing
  - Significant concern that faulty sensors can wreak havoc on in network processing



Systems are also storage-constrained: Lossy Multi-resolution Data Aging (Ganesan)

- When there is too much data to pull it all out….
- Exploit spatio-temporal correlation in sensor data, distributed storage capacity and training datasets to achieve goal.



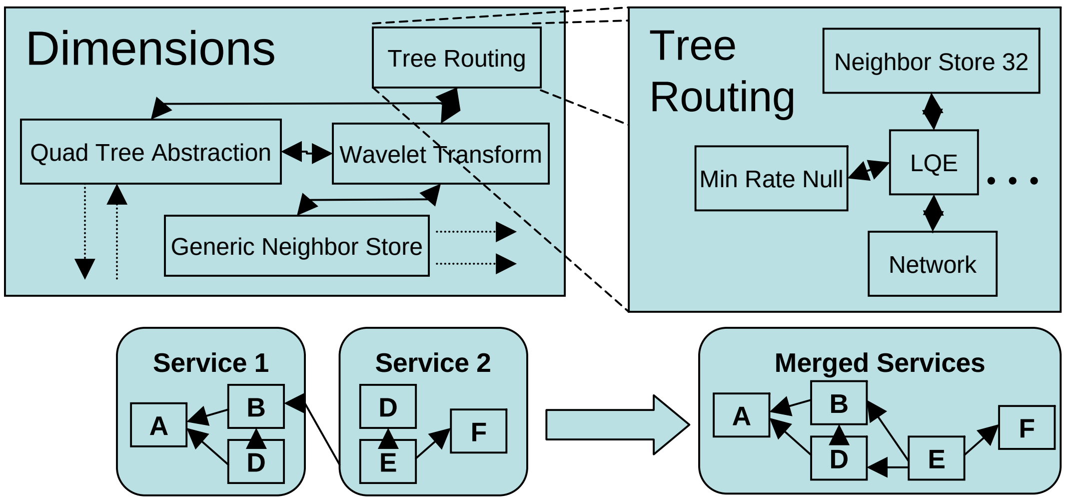


- Construct ***lossy wavelet-compressed summaries*** corresponding to different resolutions and spatio-temporal scales.
- Queries ***drill-down*** from root of hierarchy to focus search on small portions of the network.
- ***Progressively age*** summaries for long-term storage and graceful degradation of query quality over time. Use ***training data*** to determine aging periods.

- Programming problems
  - Codependent components, representing timer interactions, …
- Use a programming language to solve them
- Goal: Smart sensor network service libraries
- System designers build parameterized libraries
  - Examples: temperature sensing, sensor value smoothing, routing tree formation, link quality estimation, query processing, …
  - More flexible application components than conventional nesC
- Scientists plug libraries together to build applications
  - The libraries weave themselves into an efficient program

Programming
(Greenstein, Kohler)

State of the art:
- Components, initializations, and wirings are handcrafted for applications – optimized by eye, not by a compiler
- Complexity has required application development by systems programmers, not end users



Objective:
- Automate the difficult parts of application construction. It's goal is to provide a way for non-programmers to ***easily*** develop ***efficient*** sensor network **Macroprogramming Solutions:**

Macroprogramming Solutions:
- Users describe service requirements
- Compiler:
  - weaves together underlying components to optimize structure
  - merges components with compatible initializations
  - chooses components with superset functionality

Emstar: Development and Deployment Software (J. Elson, L. Girod, T. Stathopoulos)

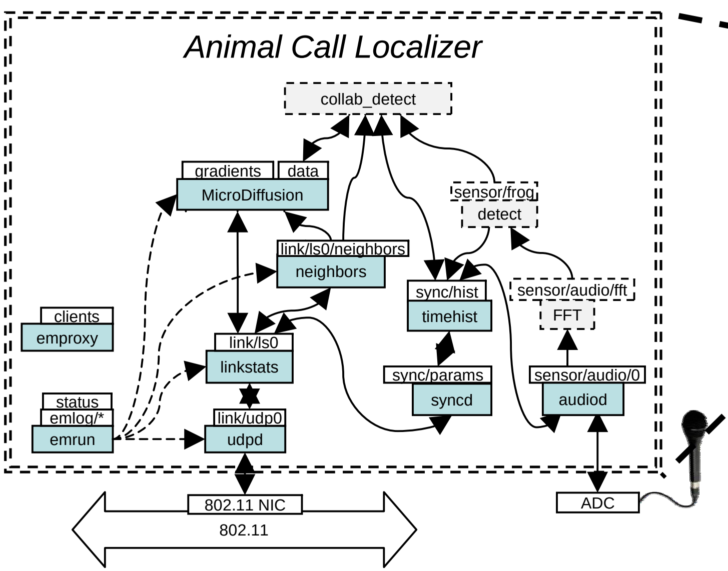
- Allow software to be finely decomposed, modularized
  - Tool chest of "mechanism, not policy" modules
    - Neighbors, link estimation, timesync, routing...
  - Provide rich forms of inter-module communication
  - Isolate as much domain knowledge as possible

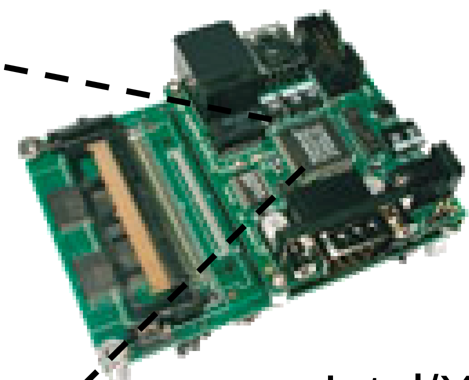
- Provide run-time environments for deep debugging
  - Debug in a transparent context before the necessarily opaque deployment
  - Same code runs in simulation, reality, and hybrids
  - High visibility into the system is key -- status is exposed in both human- and machine-readable form

EmStar is...

- A software system designed to support ENS apps
- Runs on Linux, on PDA-class devices
- Integrates with applications on smaller embedded sensors
- Key Features: Robustness and Transparency

EmStar S/W





Intel/Xbow Stargate
400MHz Xscale
64M RAM/32M Flash
Runs Linux

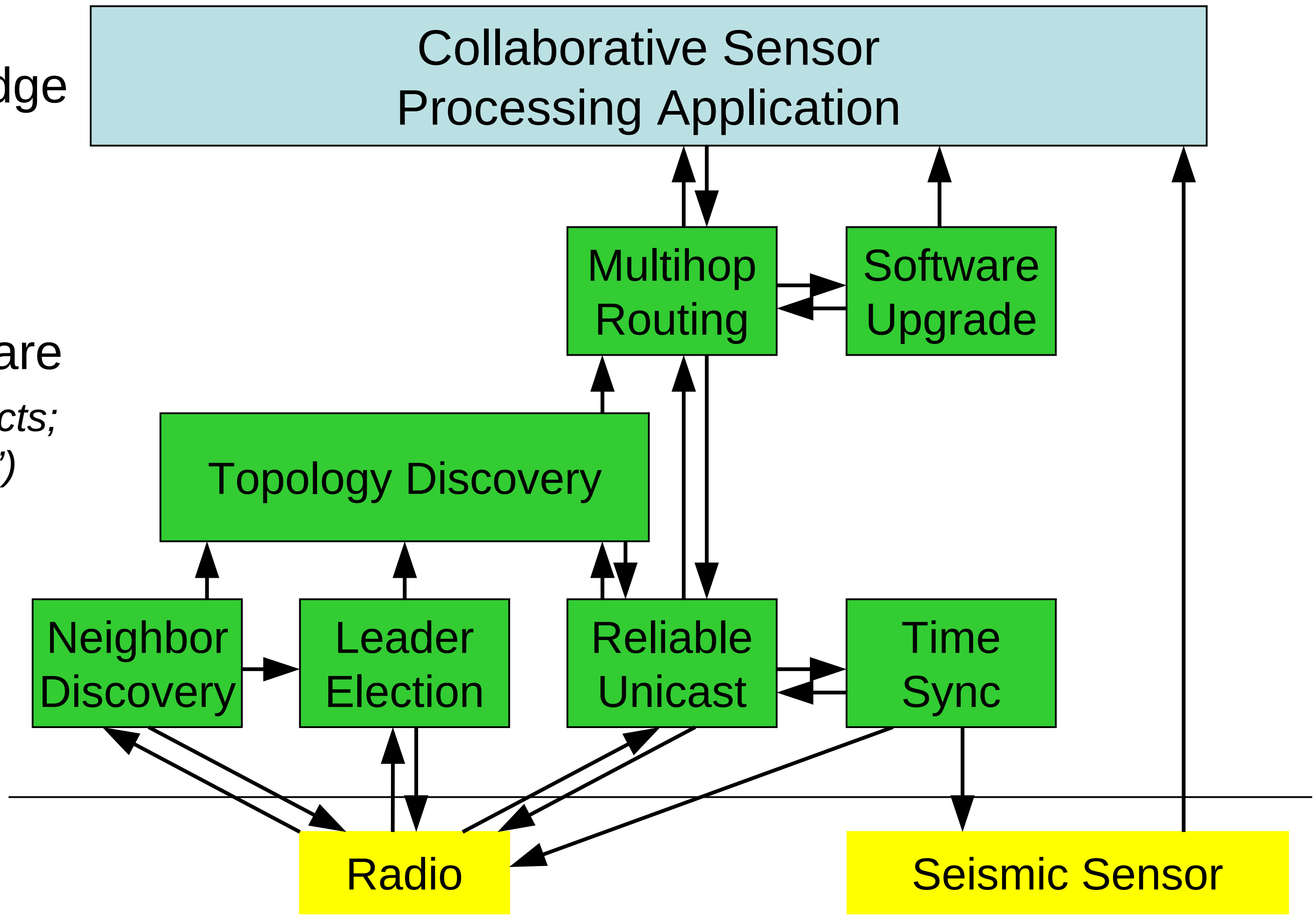
EmStar example: The Seismic Stack

Domain Knowledge

Reusable Software

(Flexible Interconnects; not a strict “stack”)

Hardware



System Ecology: Enabling Sustained and Adaptive Sampling of Ecological Systems

- Spatially distributed static nodes
  - Allows simultaneous sampling across study volume (dense in time, but possibly sparse in space)
  - Limited energy
  - Interesting capabilities in the future such as application specific imaging (cyclops:Agilent)
- Articulated Nodes
  - Provide greater functionality for sensors, communications
- Nodes with constrained mobility
  - Allows dense sampling across transect (dense spatially, but possibly sparse in time)
  - Adaptive provision of resources (sensors, energy, comm.)
  - Surface vehicles and aerial nodes both constrained to 2-D operation