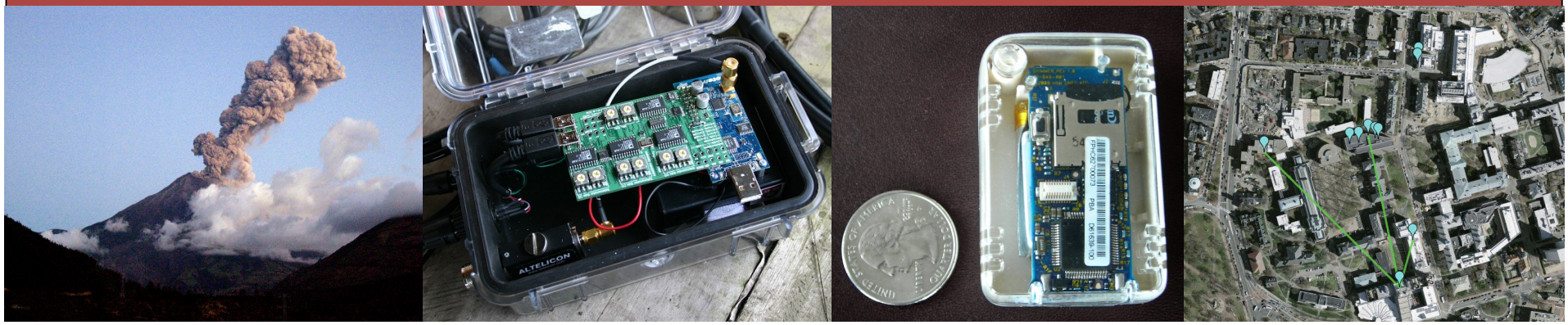
# How to Program a Macroscope



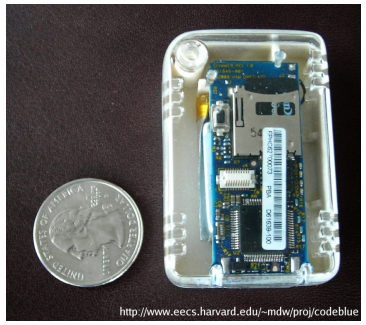

Matt Welsh

Harvard University

# Sensor Networks: A New Computing Platform

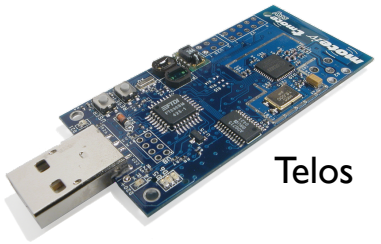
Embedded devices integrating a modest amount of computation, communication, and sensing

SHIMMER




Typical "mote" hardware

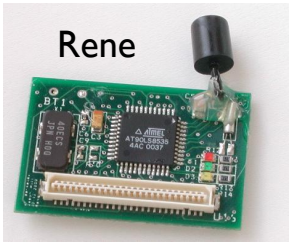
- 8 MHz CPU, 10 KB RAM, 60 KB ROM
- Low-power radio (IEEE 802.15.4 – 250 Kbps PHY rate)
- Various sensors (e.g., light, temp, humidity)
- Cost: Around $75



Telos

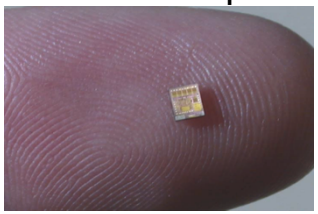
Designed for low power consumption:

- 70 mW active (CPU+radio); 6 uW sleep

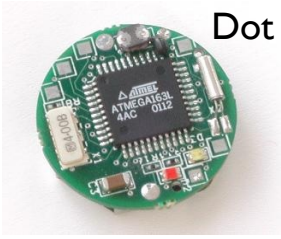


Rene

WeC



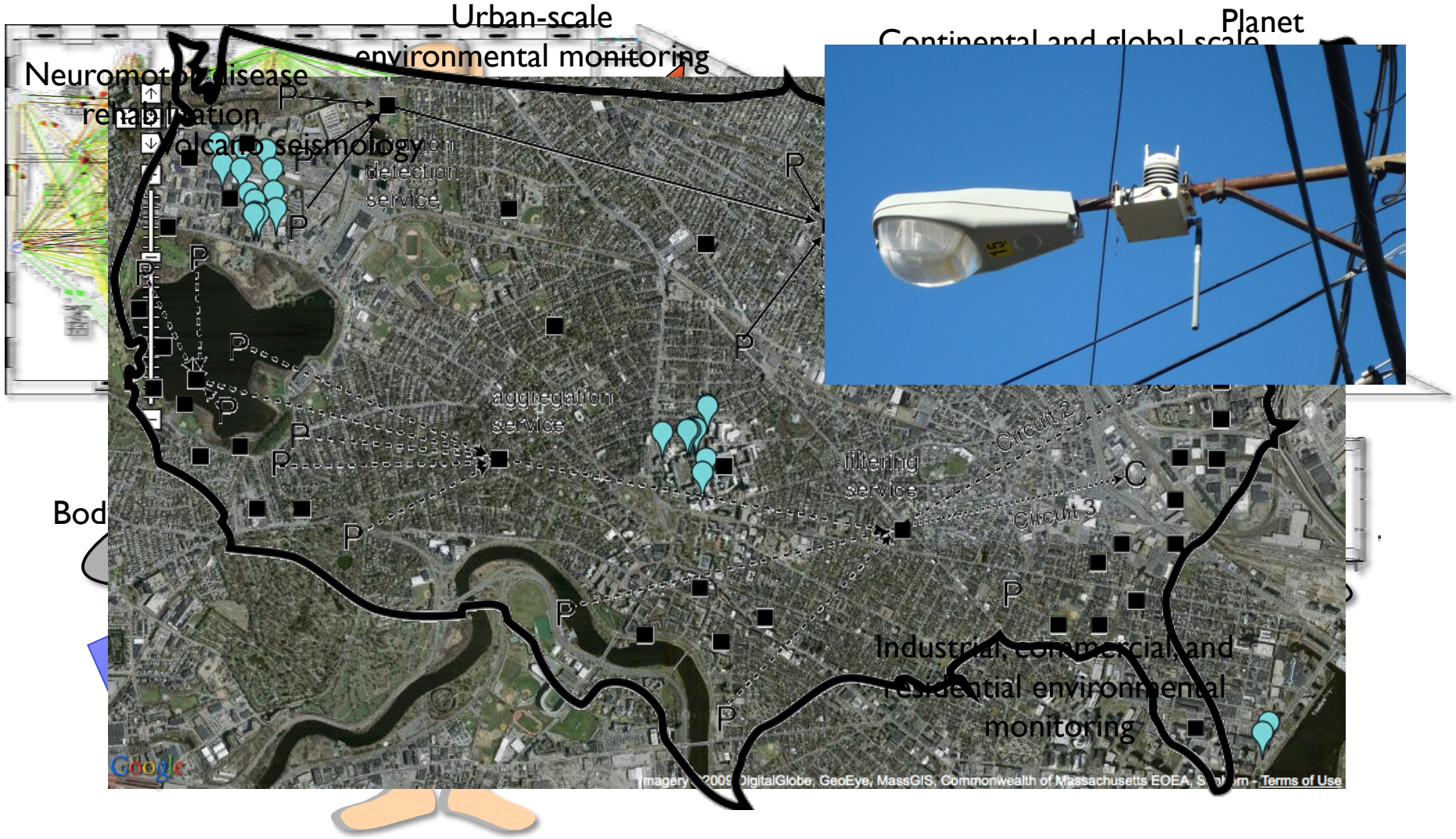
Speck



Dot

MicaZ

# Applications at many scales…



# The Macroscope

*For the first time*, sensor networks allow us to:

1) Observe the world (environment, buildings, people, etc.) at very *high spatial resolutions*;

2) Make these observations *continuously*; and

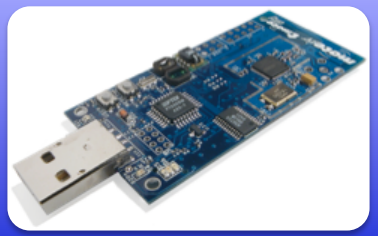
3) Collect the observations in *digital form*.

Some have referred to this concept as a "macroscope" – a scientific instrument that observes entire systems.

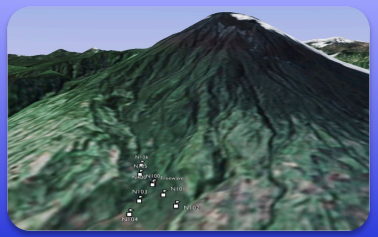



After Joël de Rosnay, *Le Macroscope. Vers une vision globale,* 1975

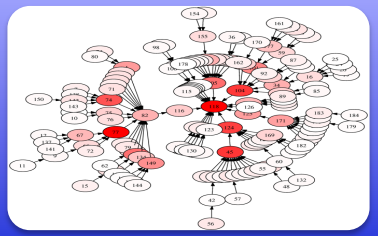
# Key Research Questions



How do we manage scarce resources at the device and network level?

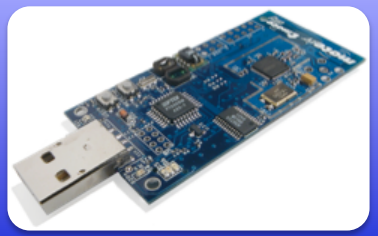


How do we ensure high data fidelity for real-world applications?

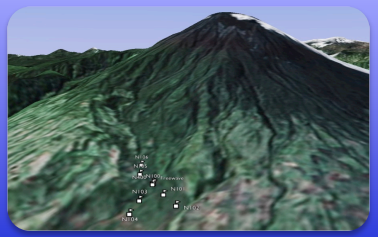


How do we program complex network behavior at a high level?

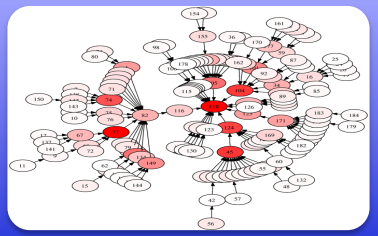
# Our Approach



New OS designs supporting *resource aware programming*:
**Pixie**, **Lance**, and **Mercury**



Extensive field research with domain scientists



New programming models and languages:
**NesC**, **Regiment**, **Flask**, **SORA**, **Abstract Regions**

# Talk Outline

Two application vignettes.

Resource Aware Programming:

- Make resources first class in the programming model.

Macroprogramming:

- Program the network, rather than the individual device.

Wrap-up and conclusions.

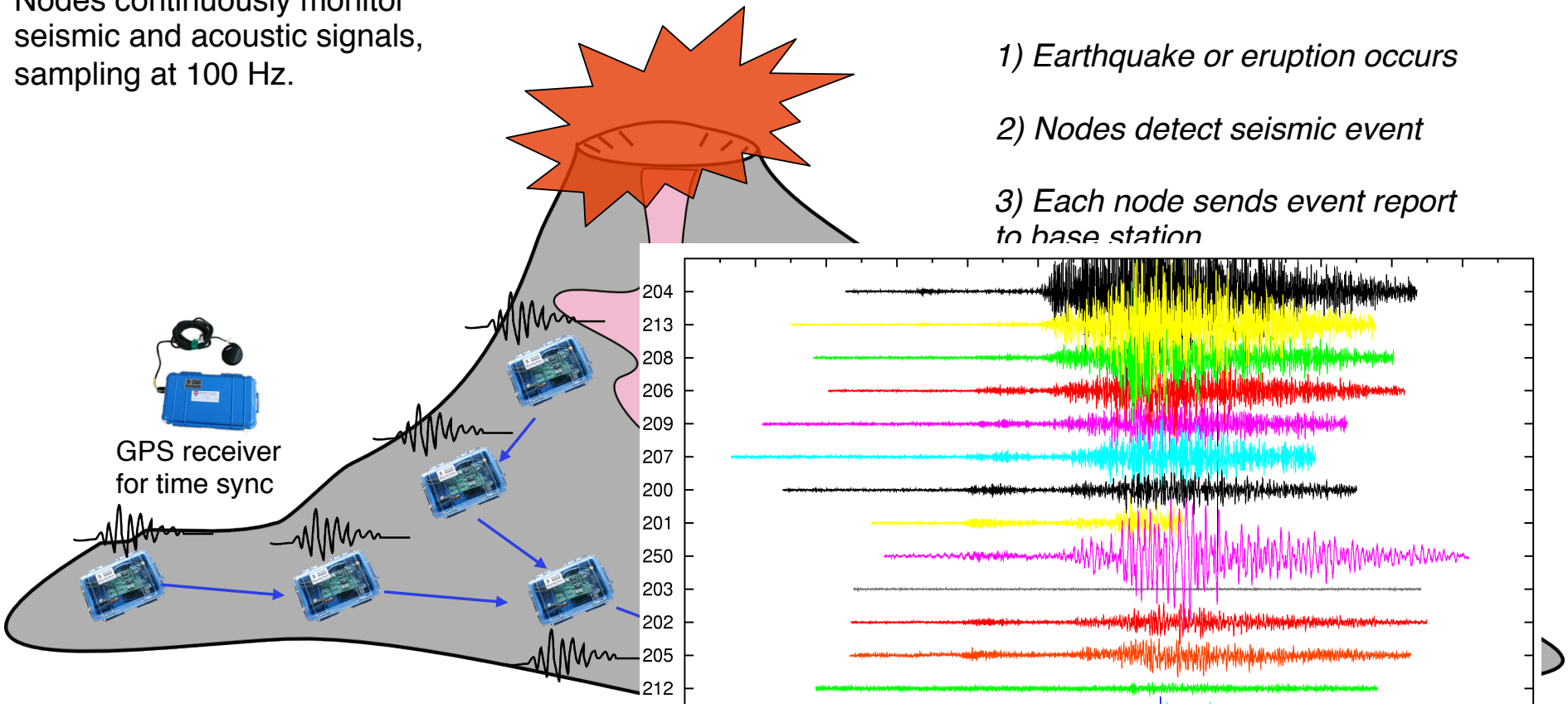
# Application Vignette: Wireless Sensors for Volcanic Monitoring

Nodes continuously monitor seismic and acoustic signals, sampling at 100 Hz.

*1) Earthquake or eruption occurs*

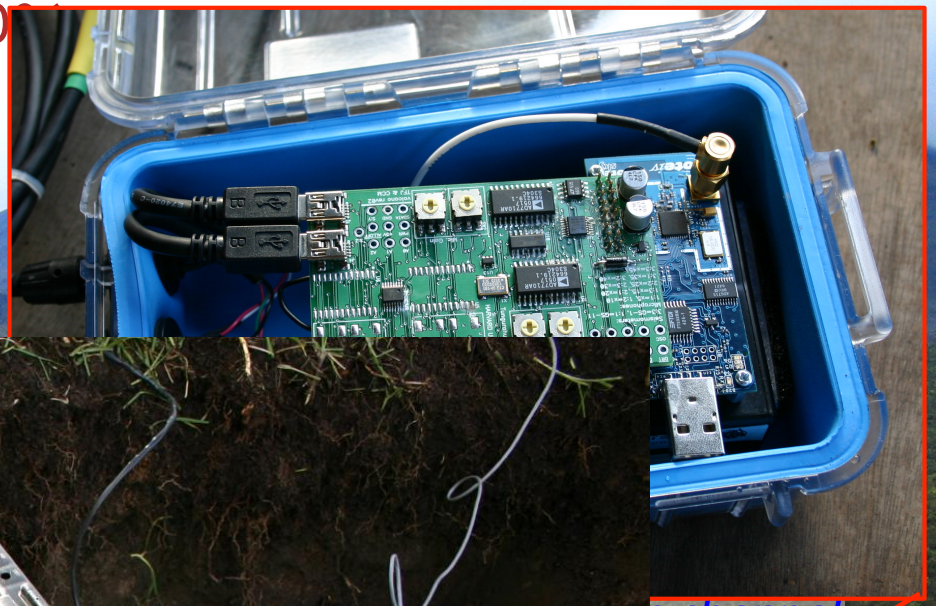
*2) Nodes detect seismic event*

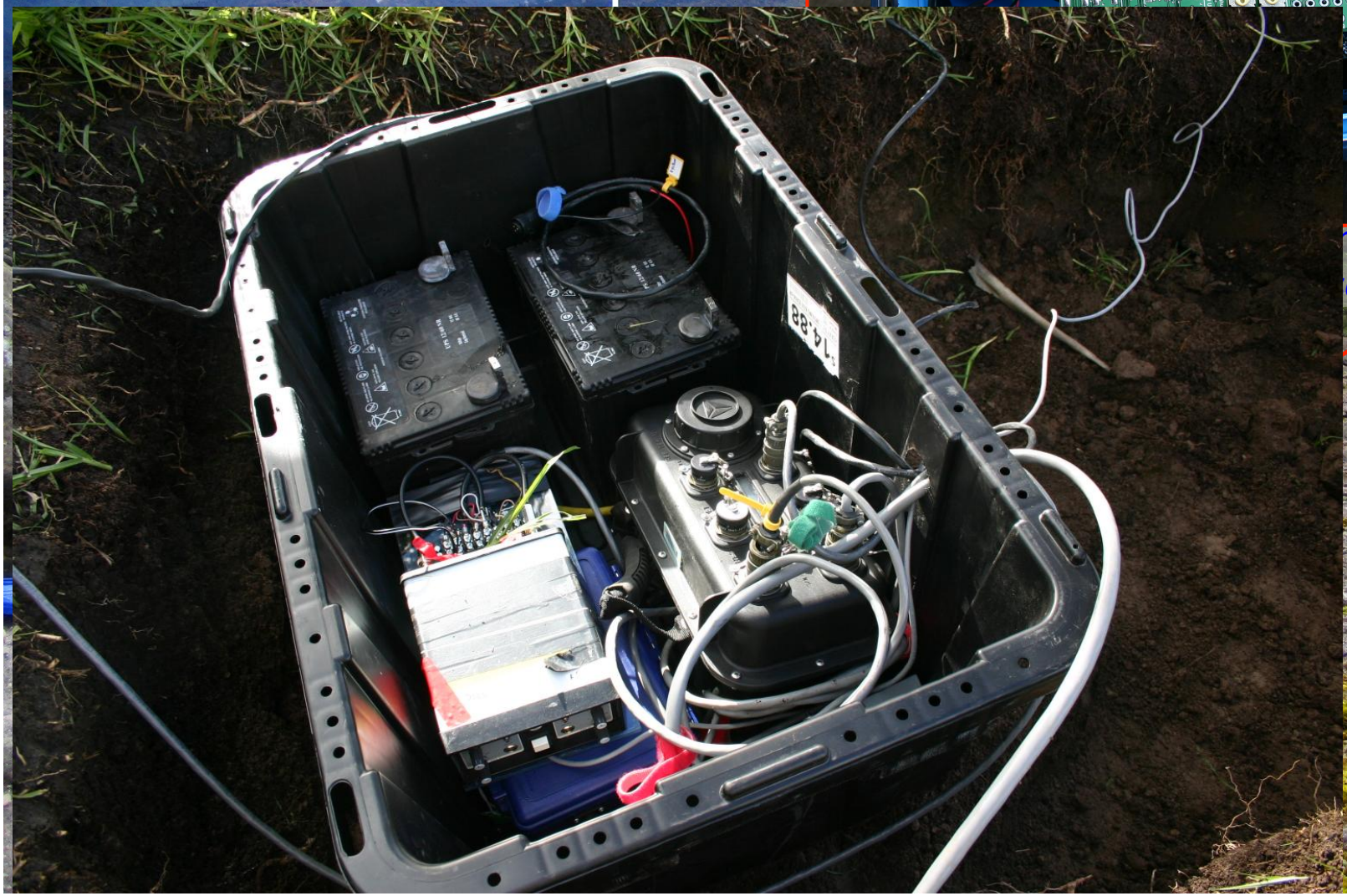
*3) Each node sends event report to base station*



# Reventador Volcano, Ecuador, August 20

with Johnson (NMT) and Lees (UNC)
[OSDI'06, J.Volc. Geo. Res.'06]

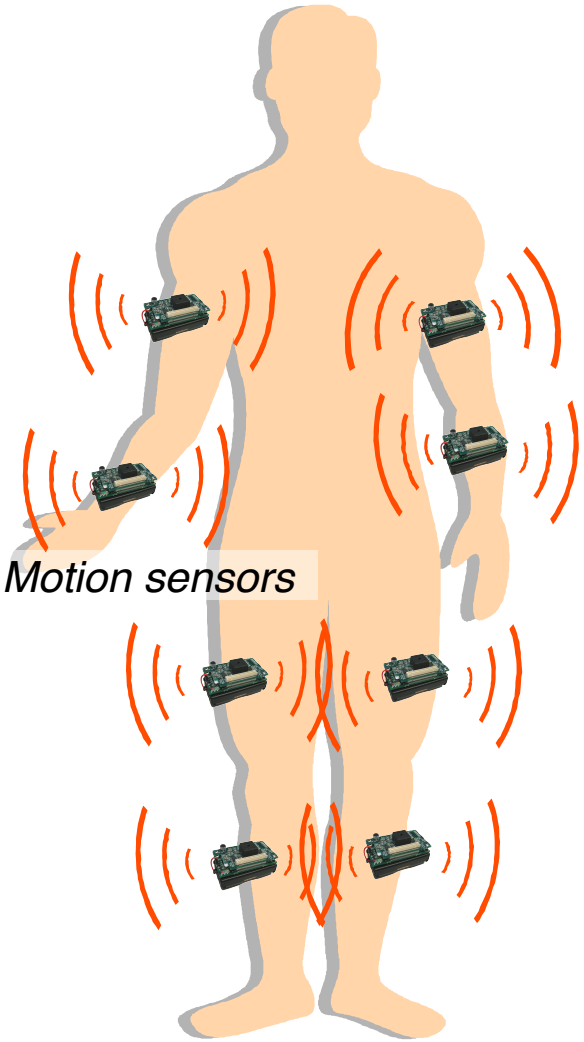




*-channel*
*or node*

# Parkinson's Disease, stroke, and epilepsy monitoring

with P. Bonato, Spaulding Rehabilitation Hospital
[SenSys'09, IEEE Trans. Inf. Technol. Biomed. 2009]



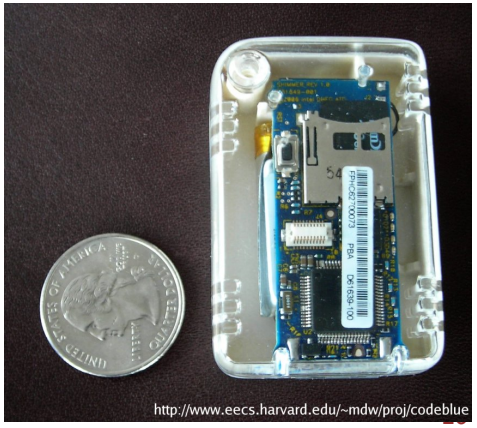

## High-fidelity monitoring of limb motion

- Triaxial accelerometer, triaxial gyroscope
- 6 channels per node, 100 Hz per channel
- Full resolution signal exceeds radio bandwidth
- Store raw data to flash (2 GB MicroSD)

## Nodes perform local feature extraction

- RMS, jerk, dominant frequency, other features...
- Computationally intensive processing
- Requires communication (e.g., time sync, and signal correlation across nodes)

## Offline classification to map features to clinical scores

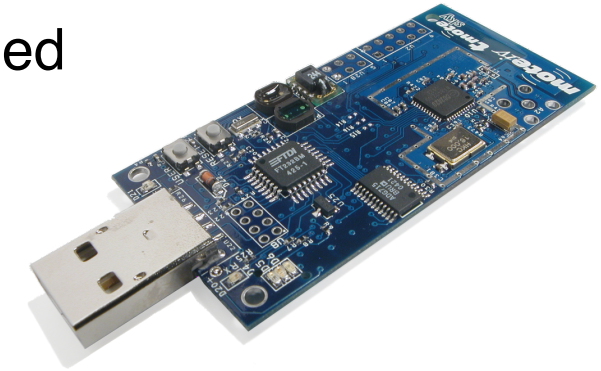



*SHIMMER mote*

# Challenge #1: Resources are extremely limited

Sensor nodes are *severely* resource constrained

- 8 MHz CPU
- 10 KB of memory
- ~100 Kbps of radio link bandwidth (best case)
- 200 mAh – 2000 mAh batteries



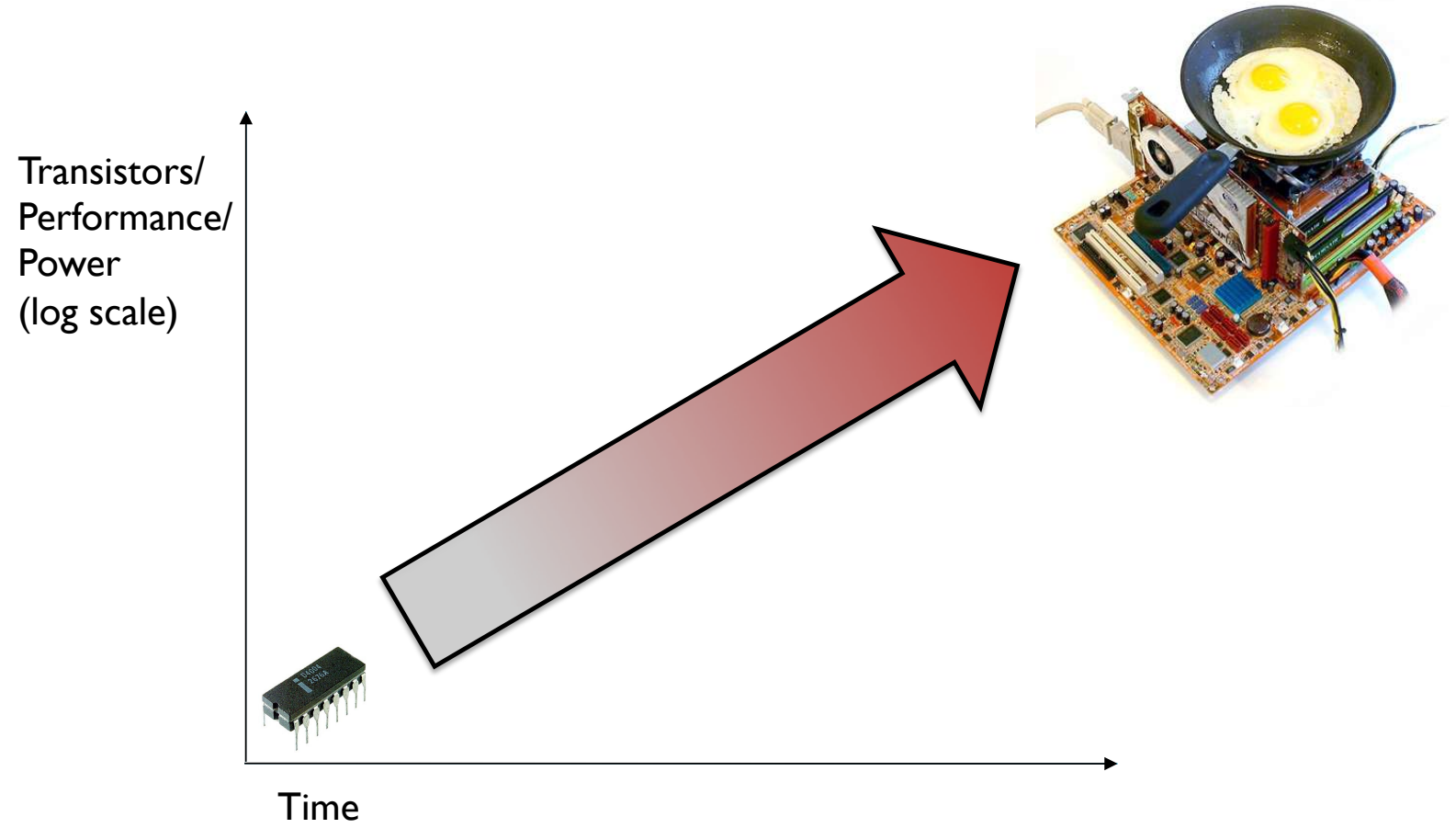
Demands new approach to software design

- Careful management of resources at the **node level**
- **Adaptation** to changing load and resource availability
- Coordination of resource allocation **across the network**

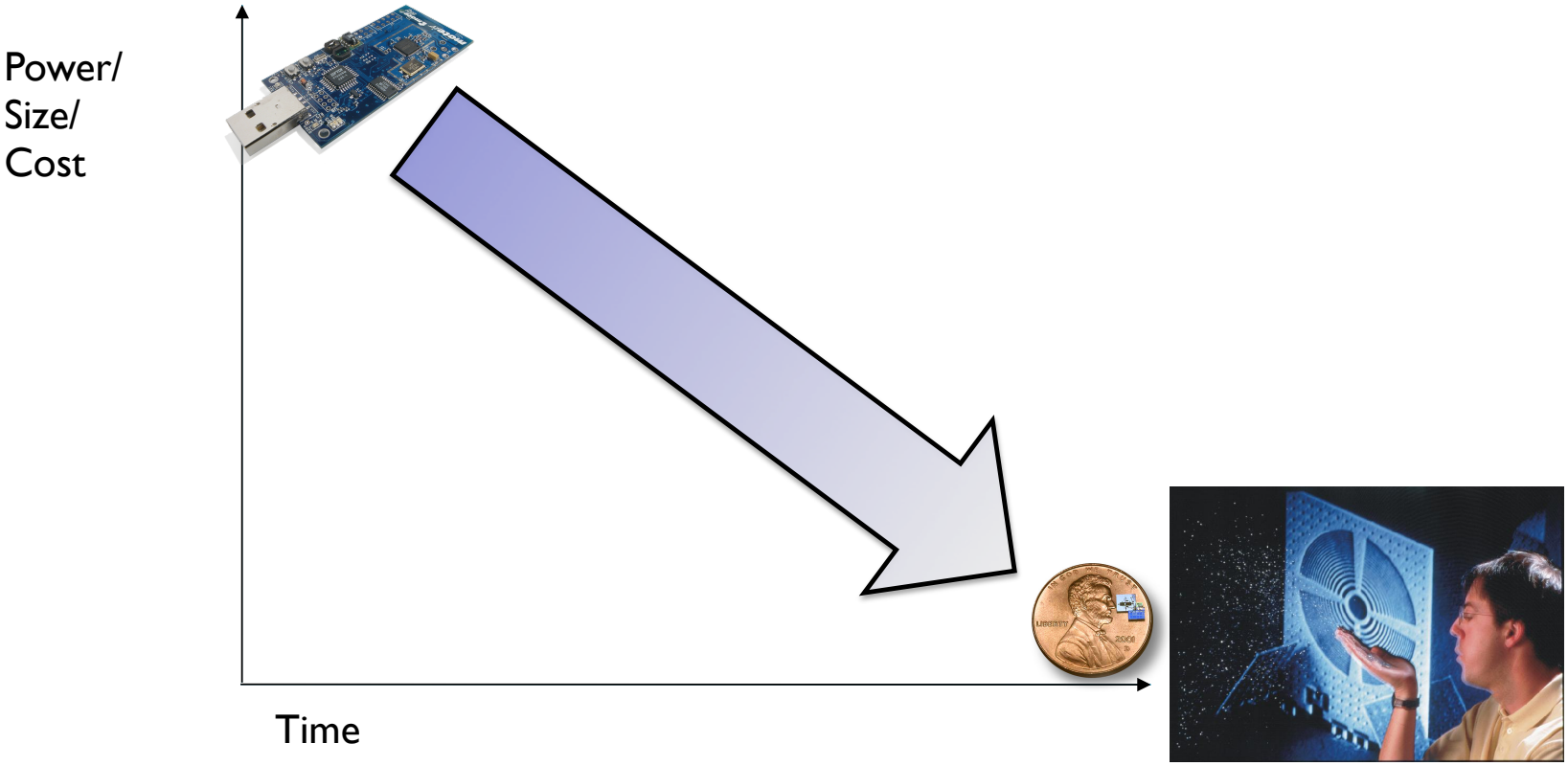
Our mantra: **Resource Aware Programming**

- Make resources a first class primitive in the programming model.

# What about Moore's Law?



# What about Moore's Law?

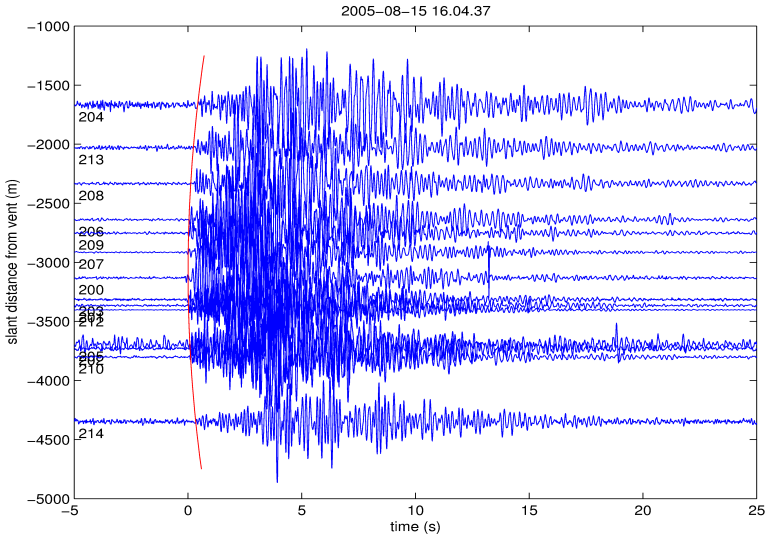


# Challenge #2: Need for high data fidelity

Sensor networks must yield scientifically meaningful data.

Gives rise to many unique challenges:

- Sensor calibration
- Timing precision
- Reasoning about the impact of failures
- Establishing ground truth



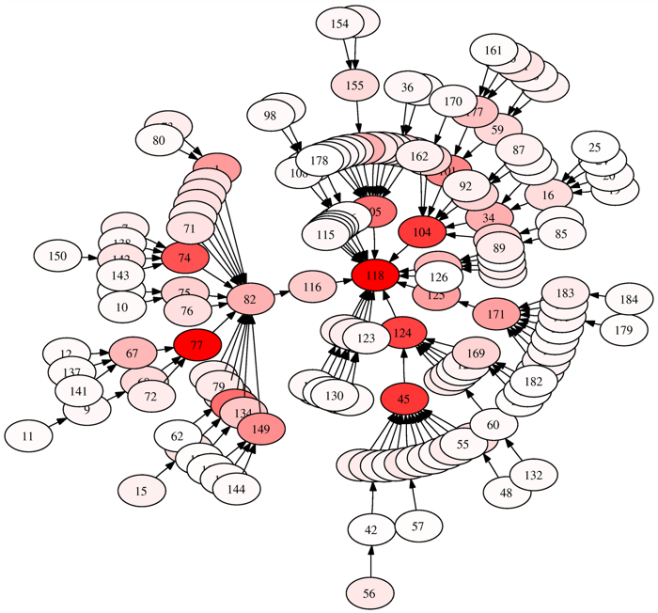

… all coupled with the aforementioned resource limitations.

Many of these challenges are not obvious at first blush.

# Challenge #3: Programming Complex Network Behavior

Current approaches focus on programming individual sensor nodes

- Example: NesC [PLDI'03] – Component oriented variant of C for embedded systems




Extremely low level:

- Radio messaging
- Sensor acquisition
- Hardware duty cycling
- Memory management

Difficult to reason about complex interactions between nodes.

# Talk Outline

Two application vignettes.

Resource Aware Programming:

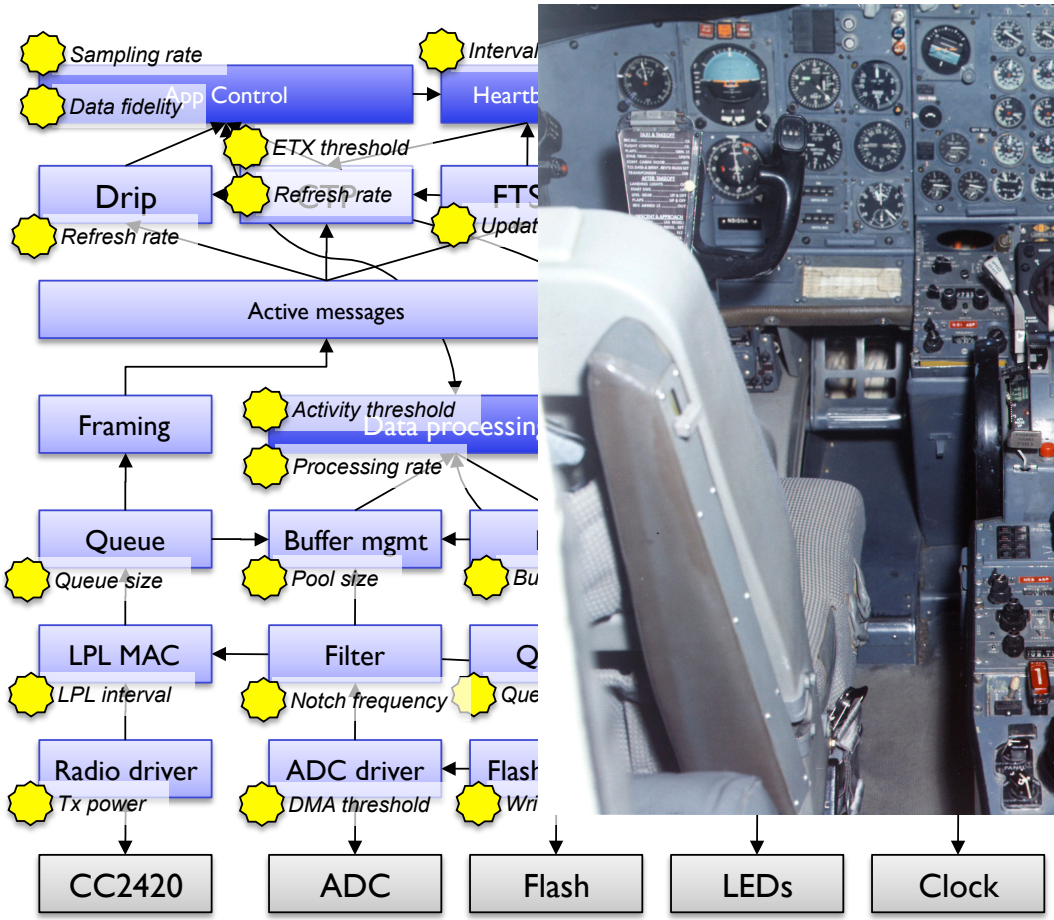
- Make resources first class in the programming model.

Macroprogramming:

- Program the network, rather than the individual device.

Wrap-up and conclusions.

# Resource tuning in sensor networks




# What we really want

# Our Approach: The Pixie Operating System

[SenSys'08, HotEmNets'08]

Pixie is a new operating system for sensor networks that supports:

- Resources as a first-class programming primitive
- Key abstractions: **resource tickets** and **brokers**

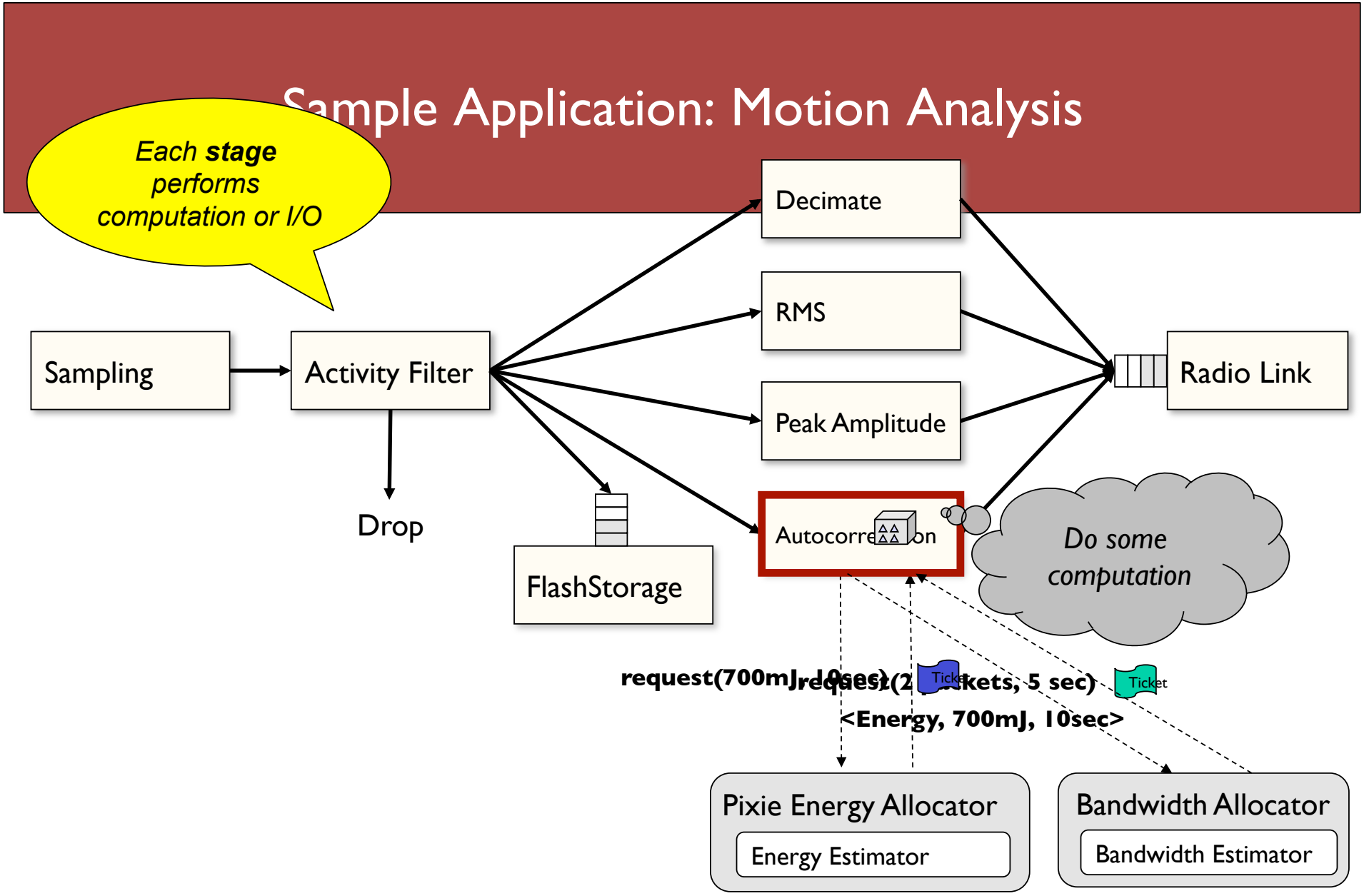
Pixie is intended to make it easy to write adaptive applications

- With such limited sensor node resources, application **must** contend with varying resource conditions!

Fundamental challenge:

- How to enable resource awareness without placing undue burden on the programmer?

# Sample Application: Motion Analysis



# Resource tickets in Pixie

Tickets are / key abstraction for resource management

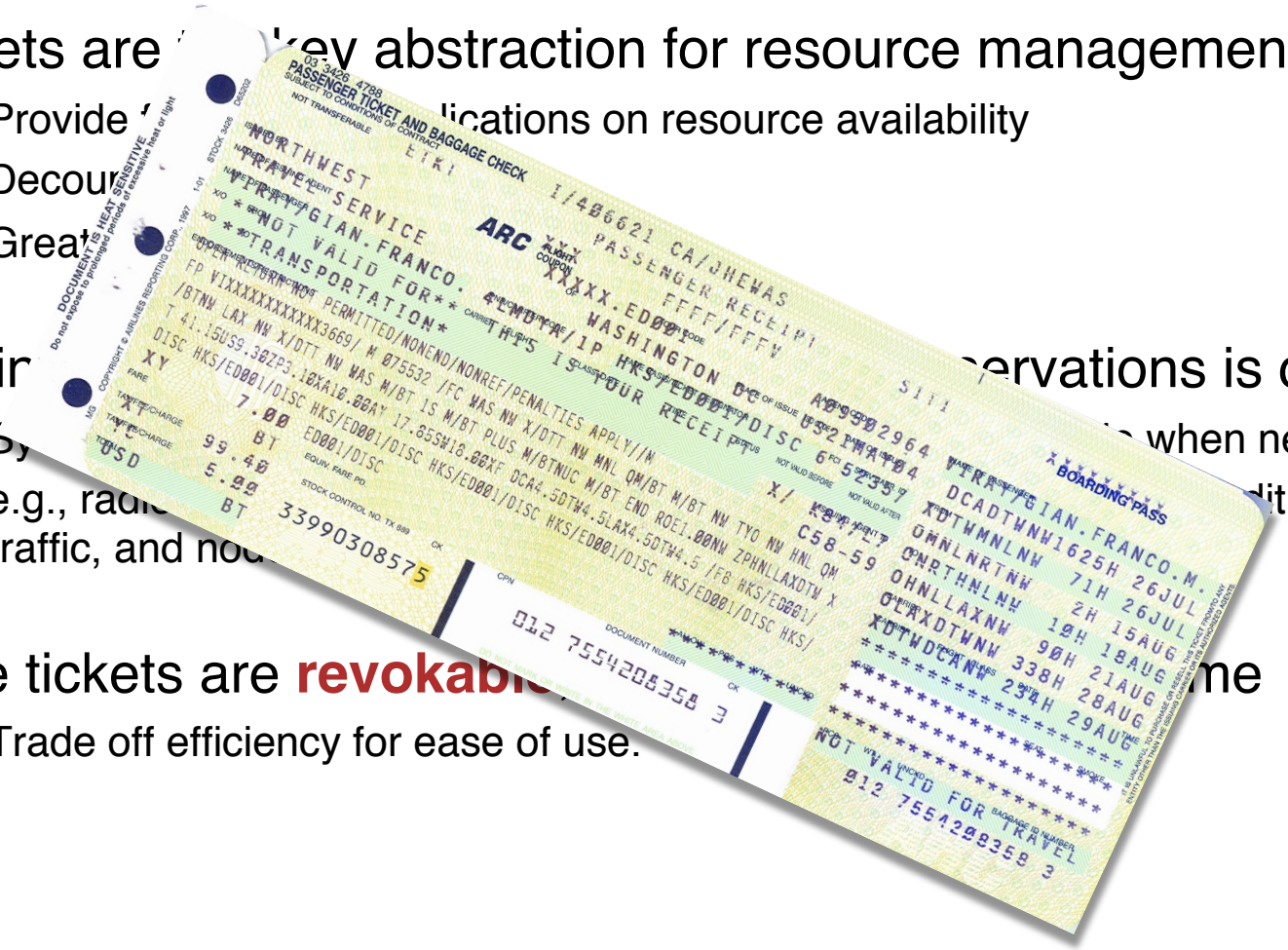
- Provide / lications on resource availability
- Decou
- Grea

Makir servations is difficult:

- S when needed.
- e.g., radi ditions, cross traffic, and no

Pixie tickets are **revokabl** me

- Trade off efficiency for ease of use.



# Resource Brokers

Resource tickets are intended to be low-level and fine-grained

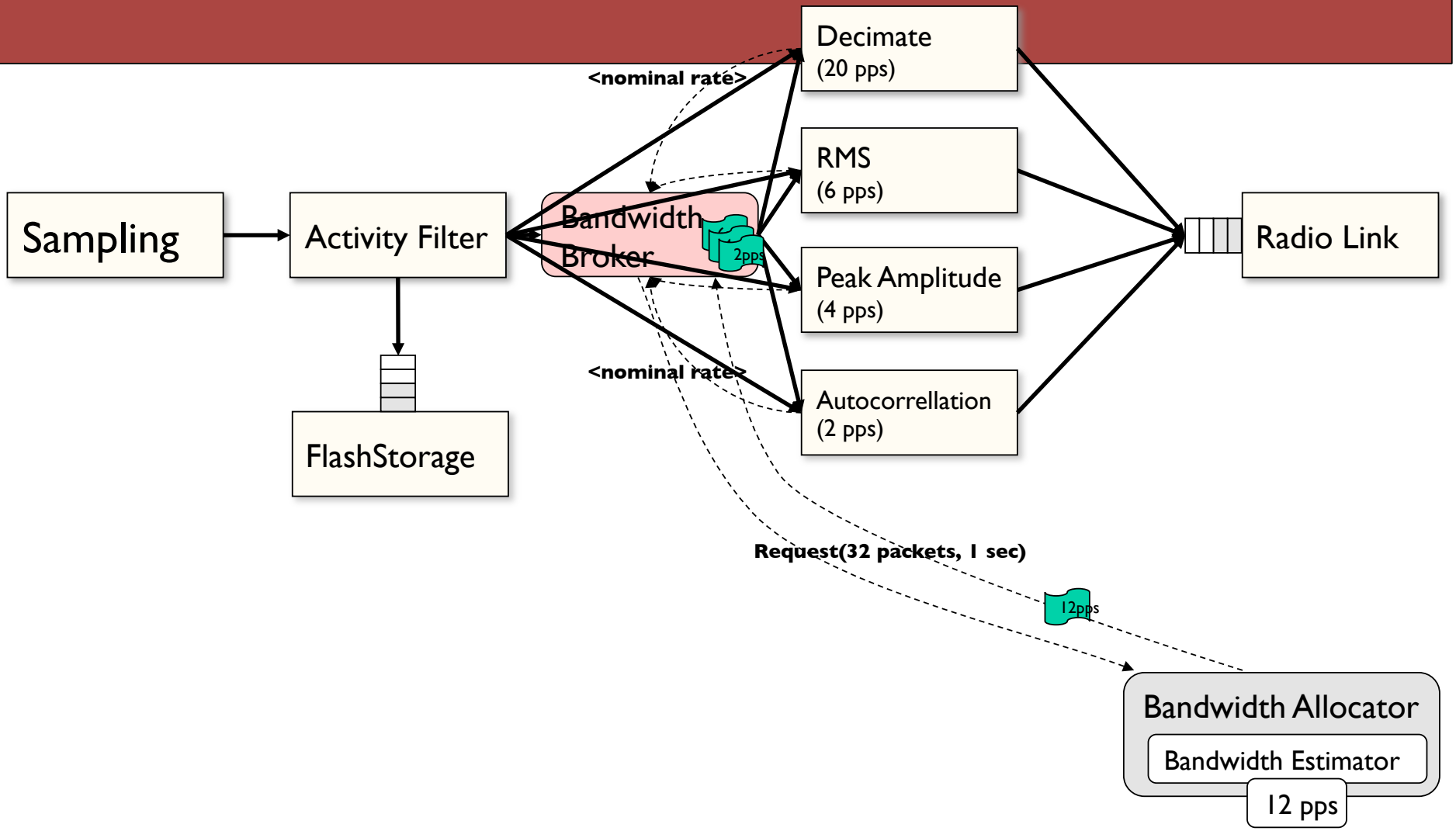
- Very flexible and powerful, but sometimes difficult to use

To simplify app design, we introduce **resource brokers**

- Brokers request and manage resource tickets on behalf of the application
- Each broker implements some policy and provides a high-level API to the app

Tickets provide **mechanism**; brokers implement **policy**.

# Example: Bandwidth Broker



# Evaluation: Bandwidth Adaptation in Motion Analysis

Goal: Adapt type and quantity of data transmitted by each node as link quality varies

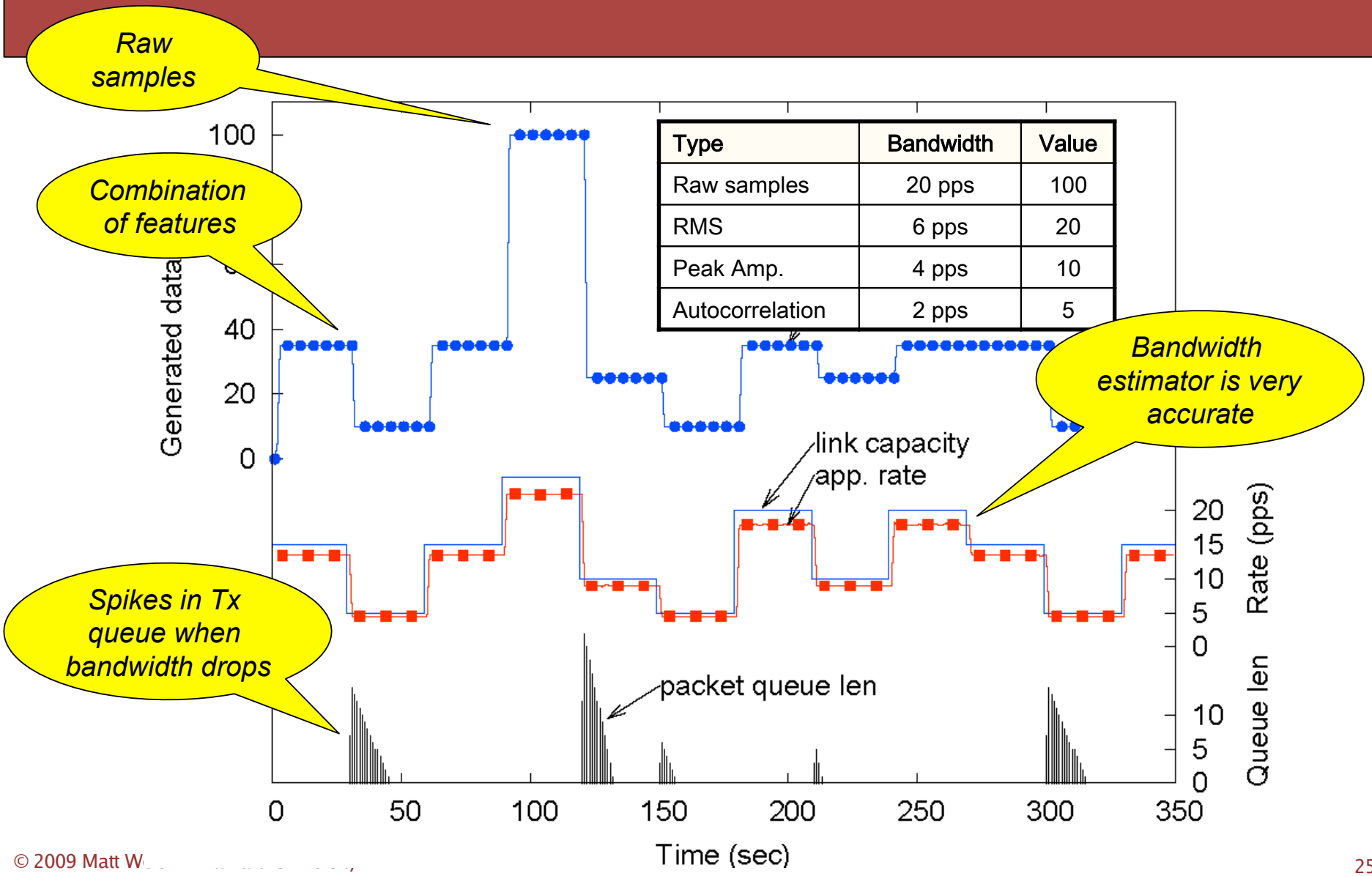
- Don't want to transmit data that won't get to the base station.

Uses Pixie's bandwidth broker

- Multiple data types with associated **cost** and app-assigned **value**
- Estimate available link bandwidth
- Assign bandwidth tickets to maximize value subject to bandwidth limit

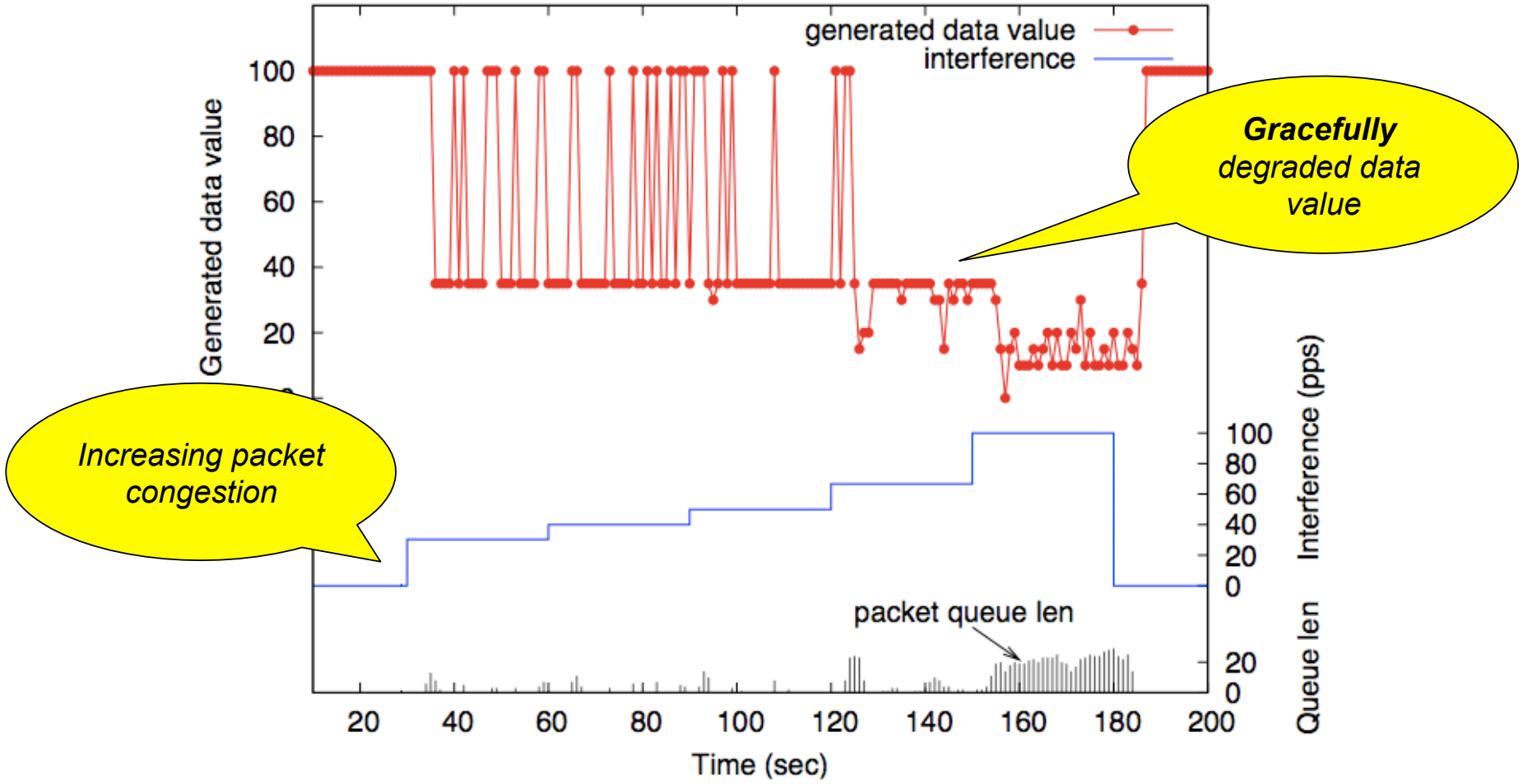
| Type | Bandwidth | Value |
|---|---|---|
| Raw samples | 20 pps | 100 |
| RMS | 6 pps | 20 |
| Peak Amp. | 4 pps | 10 |
| Autocorrelation | 2 pps | 5 |

# Experiment: Bandwidth Adaptation




| Type | Bandwidth | Value |
|---|---|---|
| Raw samples | 20 pps | 100 |
| RMS | 6 pps | 20 |
| Peak Amp. | 4 pps | 10 |
| Autocorrelation | 2 pps | 5 |

# Adaptation to radio channel interference



# Network-Wide Resource Management

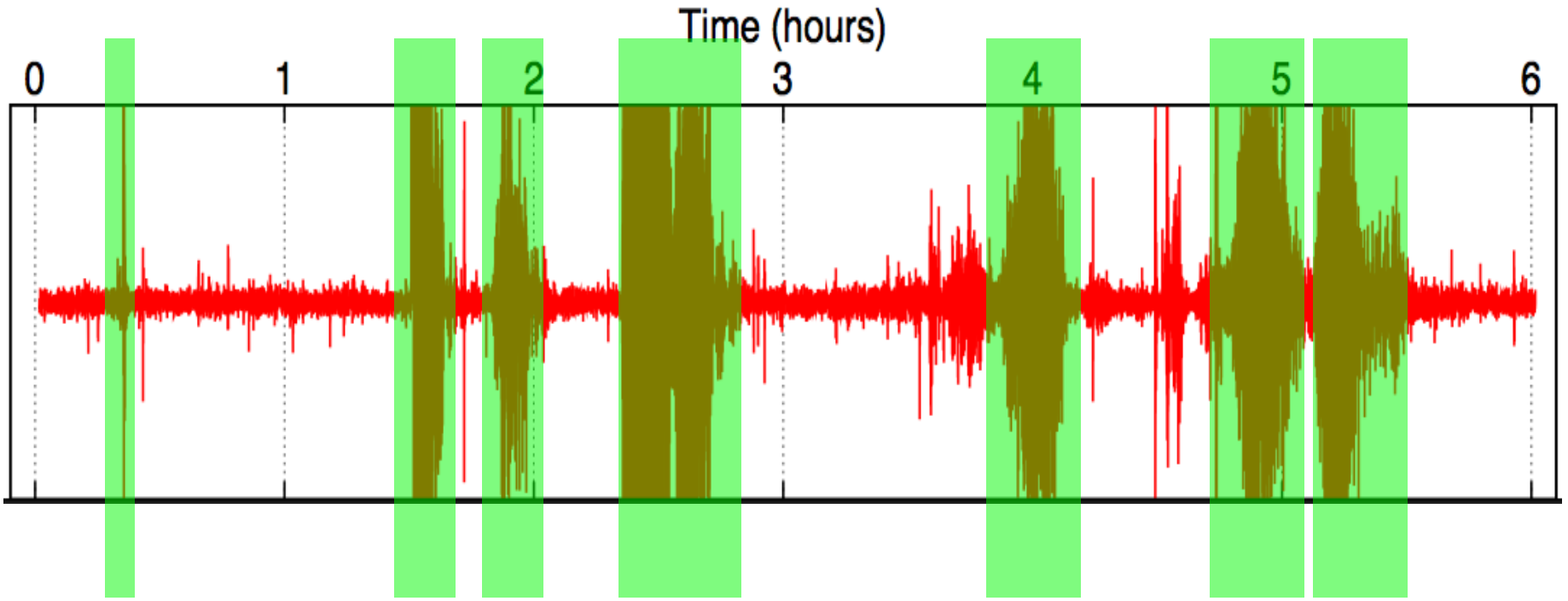
Large sensor networks constrained in two important ways:

- Bandwidth: Reliable data transfer is very slow.
- Energy availability: Even if bandwidth were plentiful, can't run radios all the time.

To optimize data fidelity, need to carefully manage resources **across the network** as a whole.

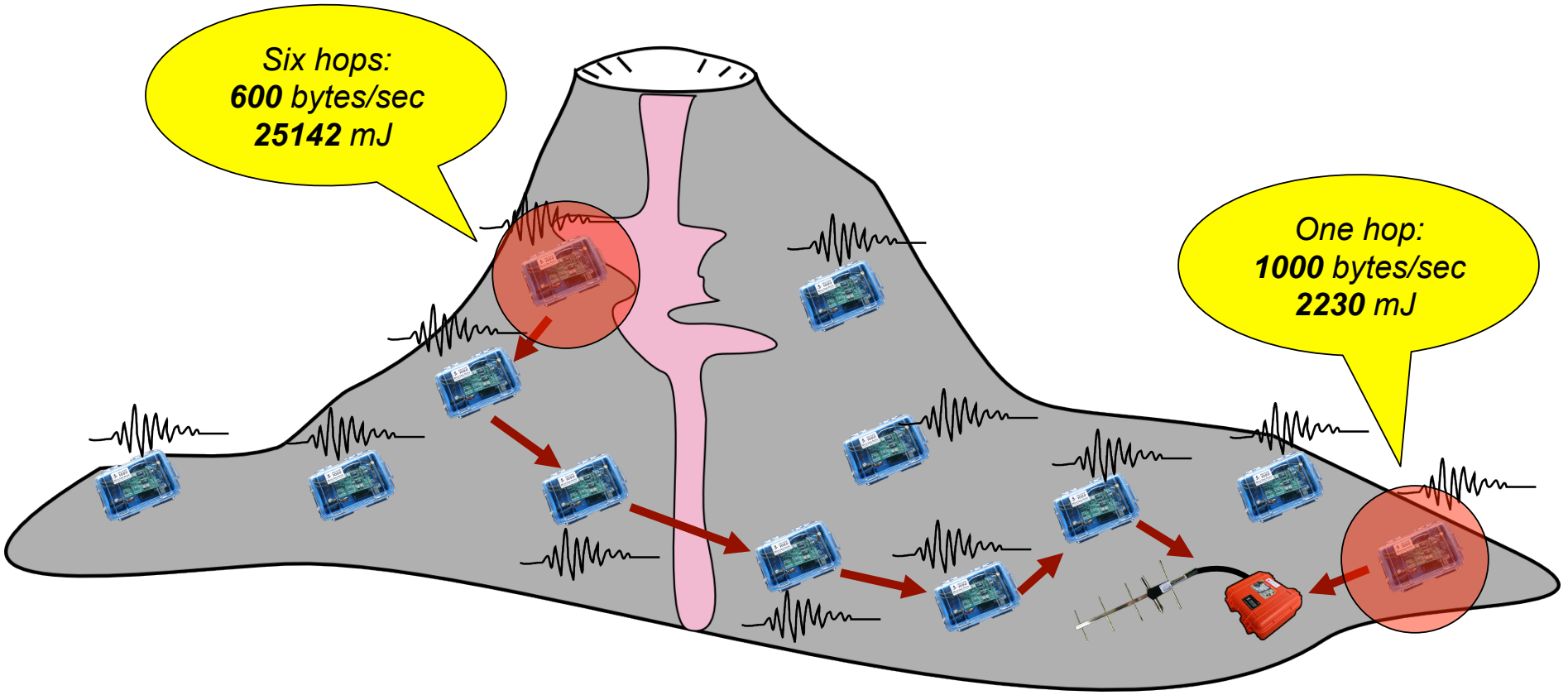
Let's focus on one key problem: Reliable signal collection

# Observation: Data Differs in Value




interesting data

# Observation: Data Differs in Acquisition Cost



# Our Approach: Lance
[SenSys'08]

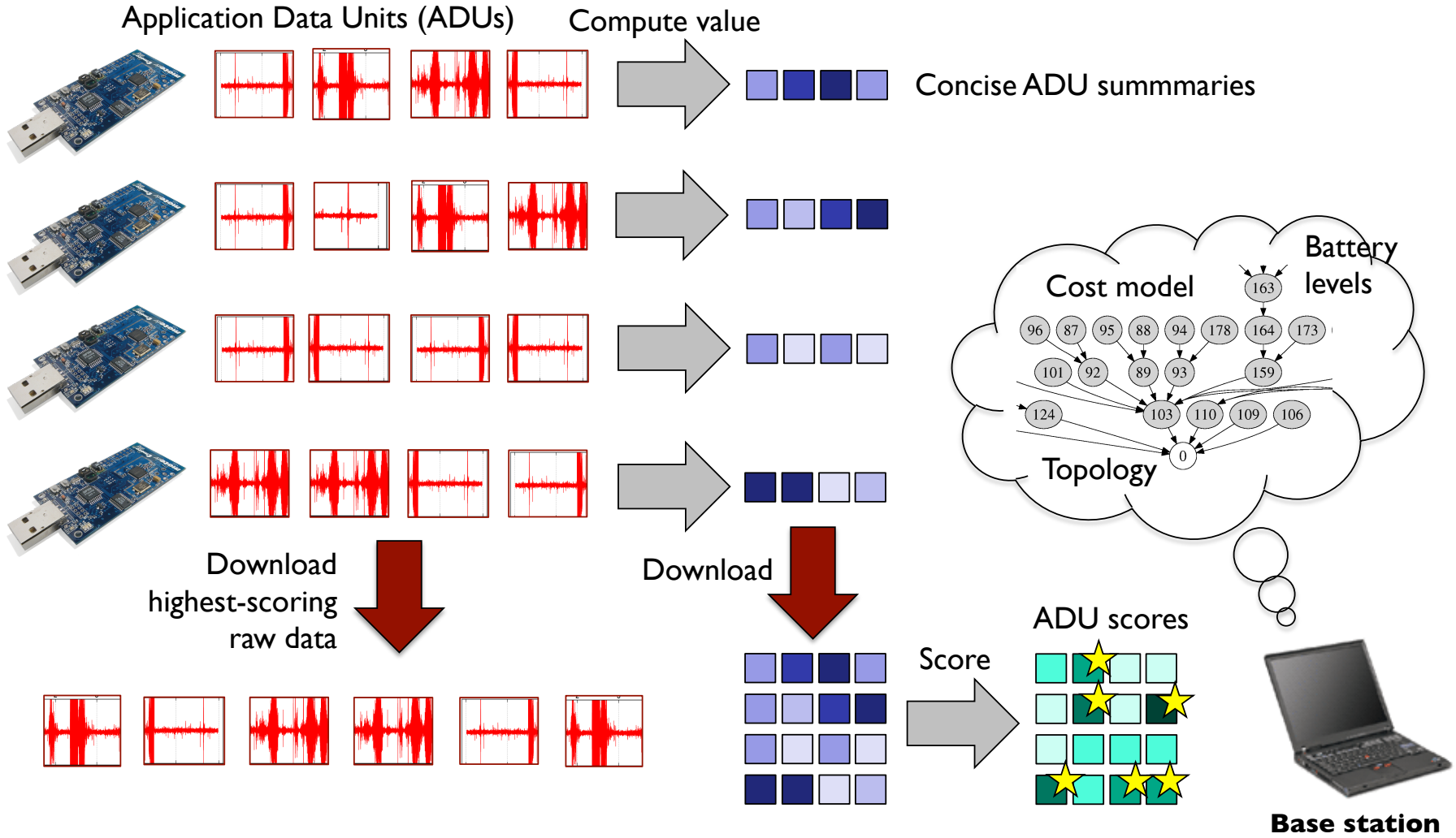
System for priority driven allocation of bandwidth and storage resources within a sensor network

Goal: Optimize data quality subject to energy and bandwidth constraints

Lance decouples mechanisms for resource allocation from app-specific policies

- Can target many optimization metrics
- e.g., fairness, spatial/temporal data distribution, etc.

# Lance Design



# Optimization Goal

***U*** = Set of all possible ADUs

***E*** = Vector of energy capacity of each node

*c(u), v(u)* = cost and value for each ADU *u*

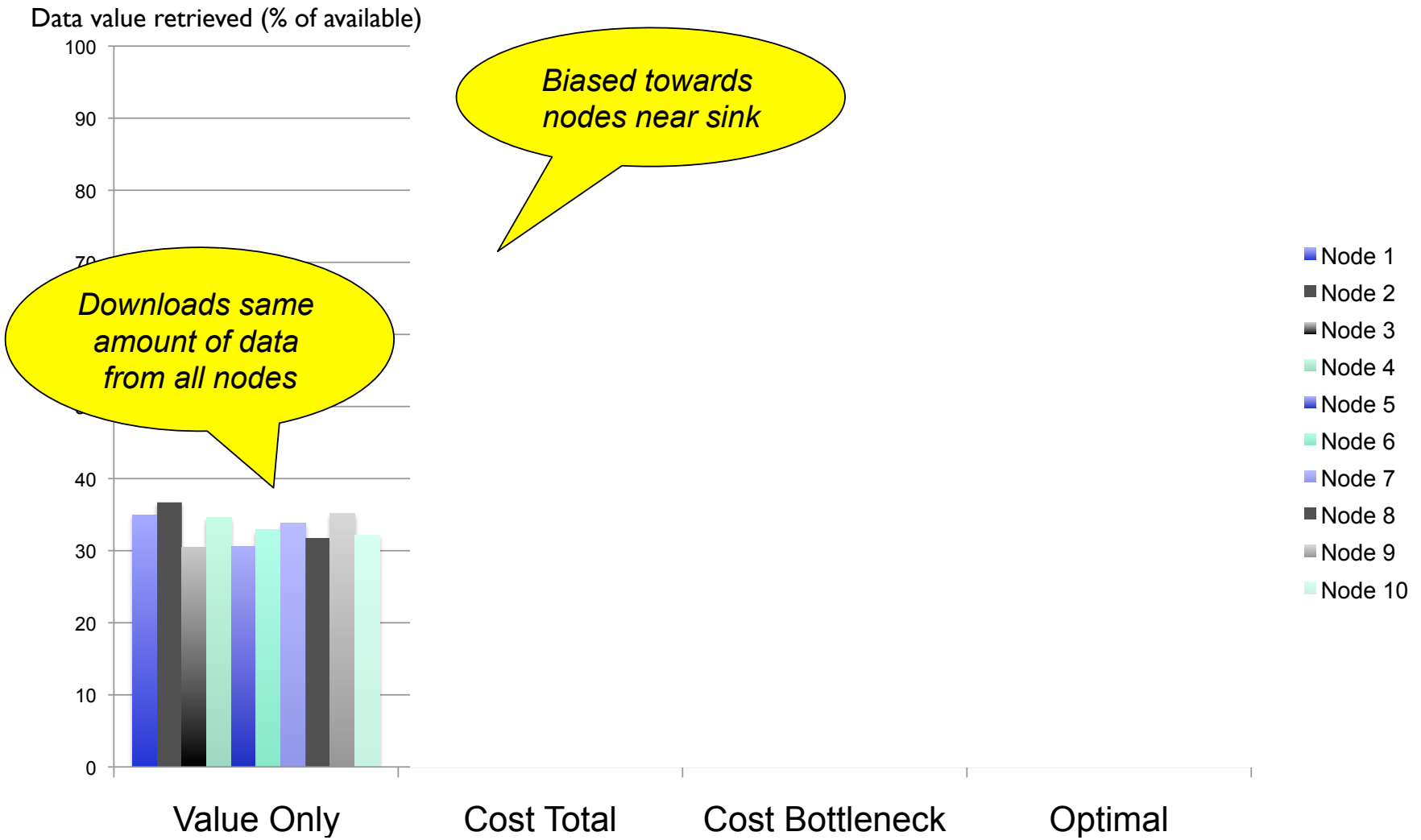
The optimal set $u_o$ is the set of ADUs maximizing

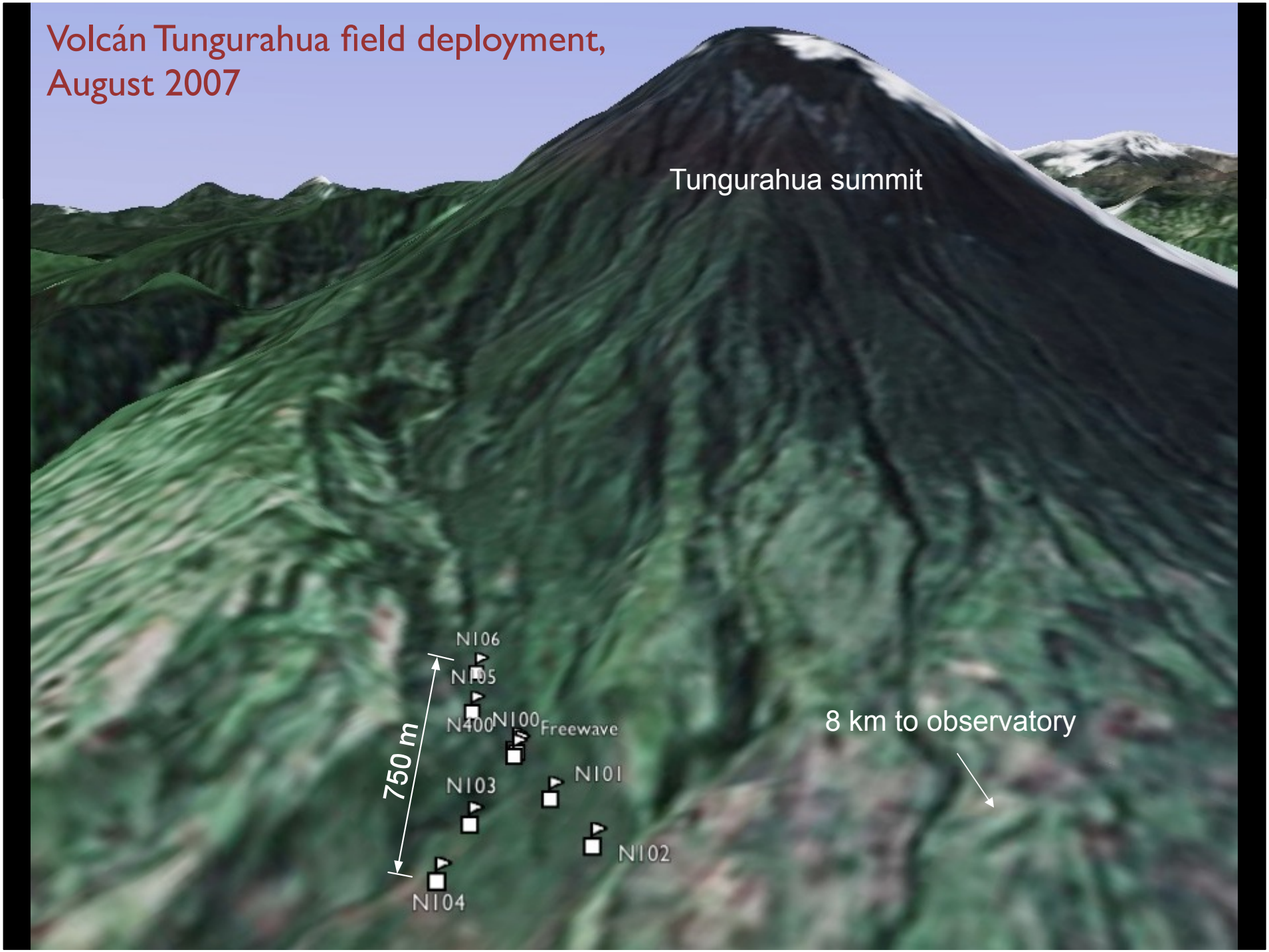
$$\sum \boldsymbol{v(u_o)} \text{ subject to } \sum \boldsymbol{c(u_o)} \leq \boldsymbol{E}$$

Offline Solution: **Multidimensional Knapsack Problem**

But we need an online, greedy approximation.

# Scoring function comparison
## 10-node linear chain




Volcán Tungurahua field deployment,
August 2007
Tungurahua summit
N106
N105
N400
N100
Freewave
N101
N103
N102
N104
750 m
8 km to observatory

# Deployment Results

Deployed 8 sensor nodes for a total of 71 hours

- Lance used to manage storage and bandwidth
- Experimented with different prioritization functions and policy modules

Successfully downloaded 1232 ADUs (77 MB of data)

- 308 downloads failed due to timeouts: success rate 80%

Total storage summaries span 11012 ADUs (688 MB of data)

- Lance downloaded 11% of the data acquired by the network

Lance downloaded **99.5%** of the *optimal* dataset

# Talk Outline

Two application vignettes.

Resource Aware Programming:

- Make resources first class in the programming model.

Macroprogramming:

- Program the network, rather than the individual device.

Wrap-up and conclusions.

# Macroprogramming

I hope I've convinced you that sensor net programming is hard.

- Can we do better?

Key idea: Program the network **as a whole.**

Compile down automatically to node-level programs.

Key challenges:

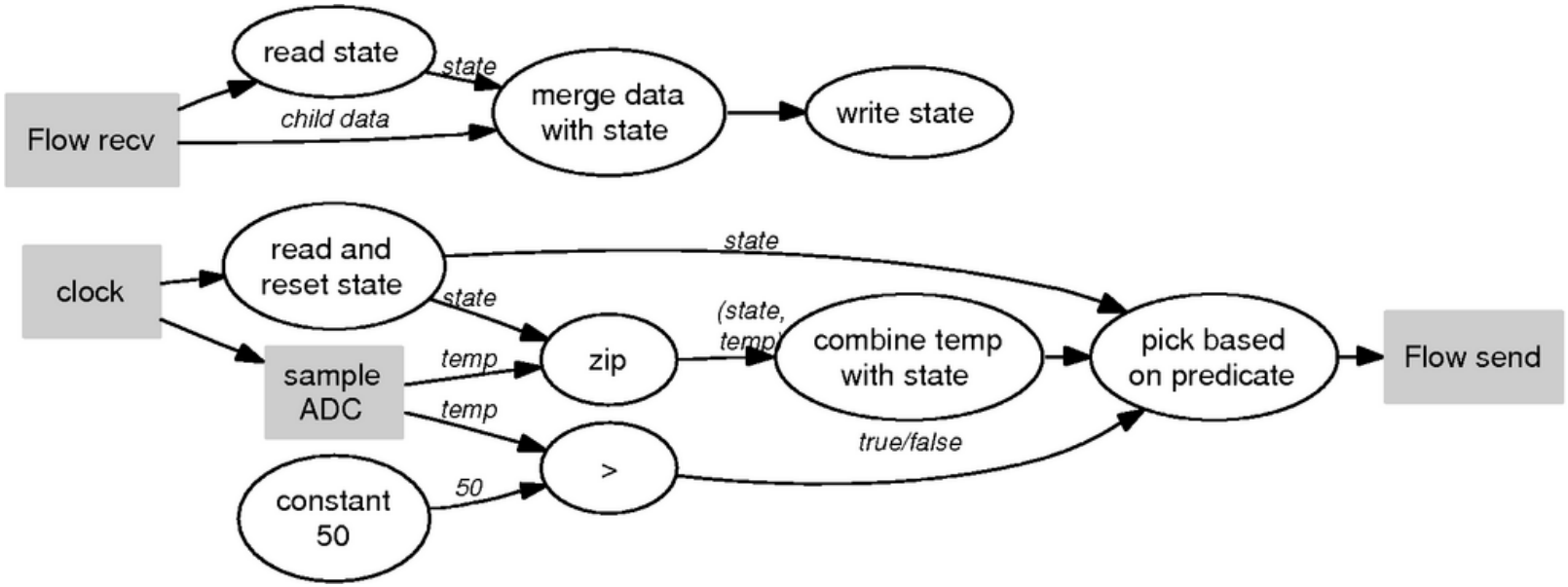
- What are the appropriate programming abstractions?
- How do we retain good resource efficiency?
- How to automate the compilation process?

# Flask: Dataflow Macroprogramming
[ICFP'08]

Synthesize sensor net programs from high-level dataflow

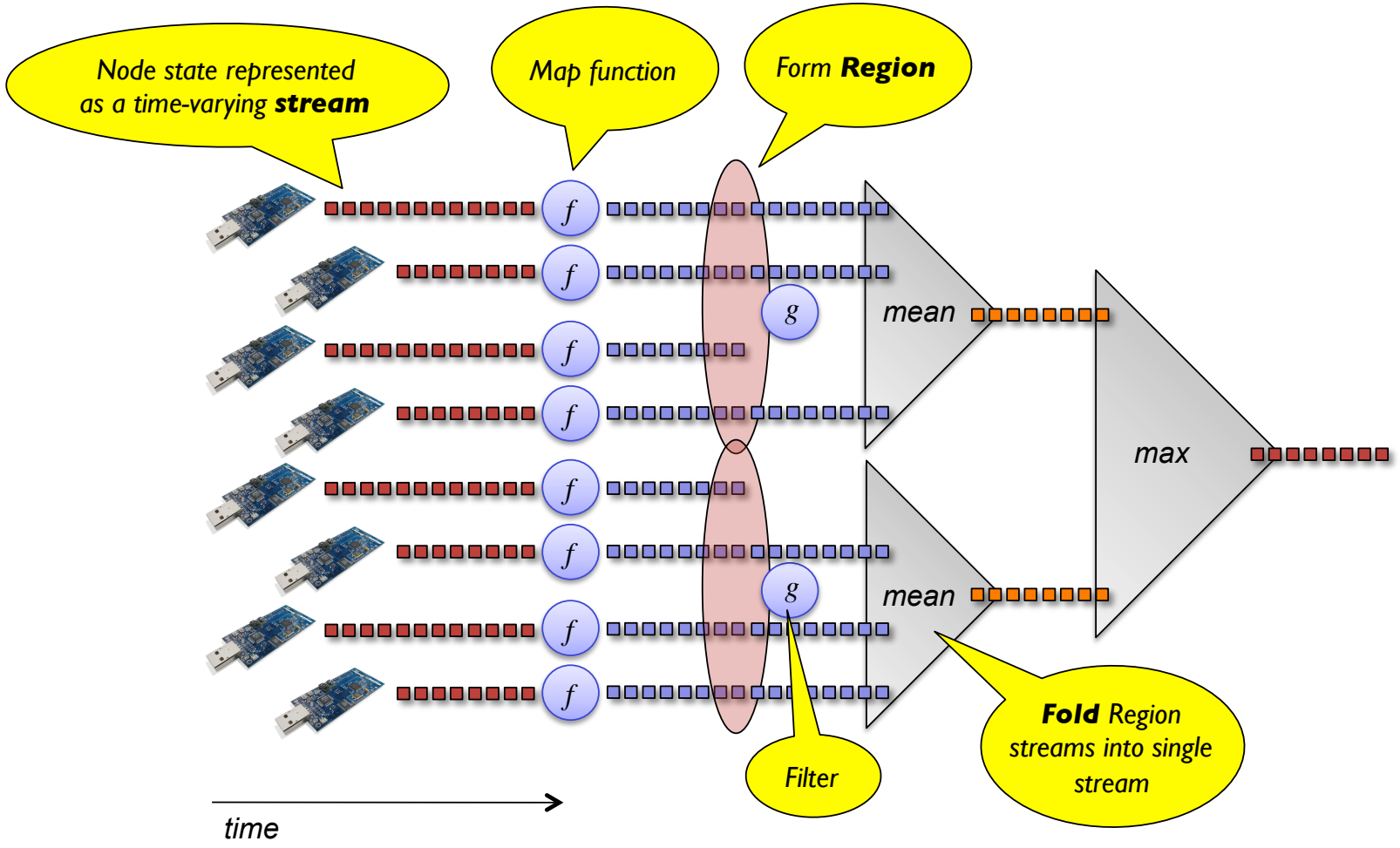
Example: Compiling an SQL query

```
SELECT AVERAGE(temp) WHERE temp > 50 PERIOD 10 s
```

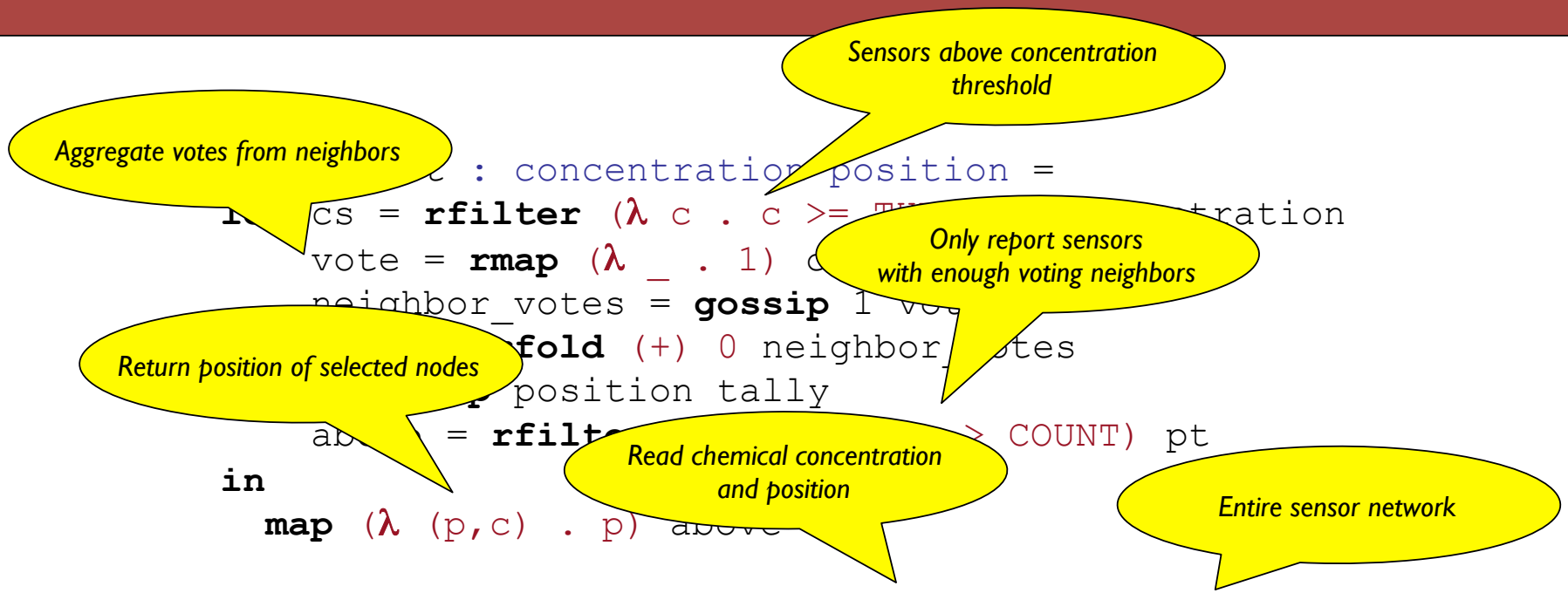


# Regiment: A Stream-Oriented Macroprogramming Language

[IPSN'07, IPSN'05, DMSN'04]



# Regiment Example: Chemical plume "Hotspot" Detection

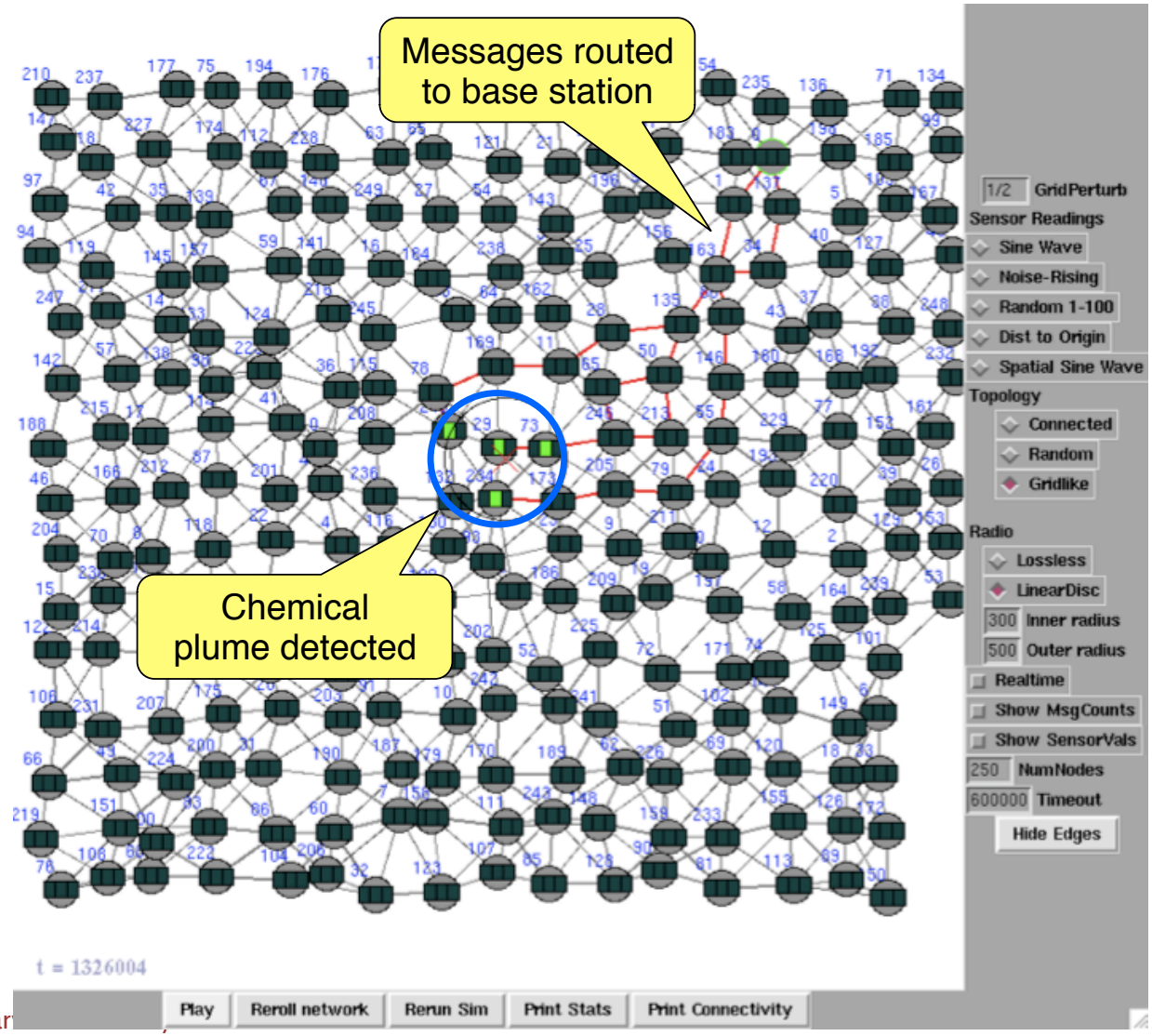



```
                c : concentration*position =
            cs = rfilter (λ c . c >= TH          tration
                vote = rmap (λ _ . 1) c
                neighbor_votes = gossip 1 vo
                fold (+) 0 neighbor_votes
                position tally
                ab      = rfilt                > COUNT) pt
        in
          map (λ (p,c) . p) above

    let conc_stream = rmap (λ n . get_conc(n)) world in
    let pos_stream = rmap (λ n . get_pos(n)) world in
      hot_spot (conc_stream pos_stream)
```

Compare to thousands of lines of C code.

# Regiment Plume Detection at Work



# Overview of Other Projects

## Novel programming models

- **Abstract Regions**: Neighborhood communication model [NSDI'04, HotNets'03]
- **SORA**: Decentralized resource allocation based on machine learning [NSDI'07]

## Planetary-scale data collection and processing

- **COBRA**: RSS and blog search engine [NSDI'06]
- **Hourglass** and **SBONs**: P2P overlay for stream processing [ICDE'06, NetDB'05, IPTPS'05]

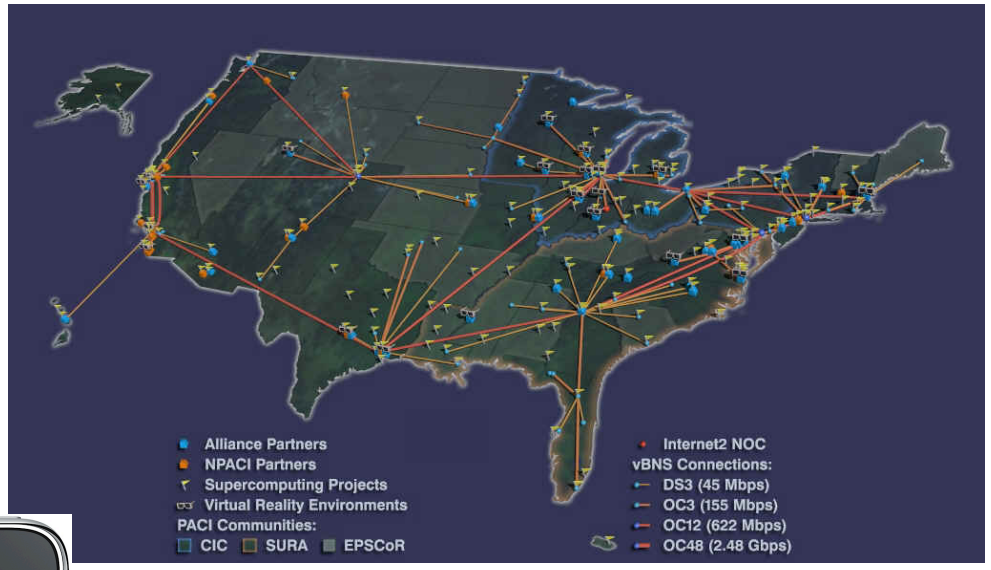
## Testbeds and tools

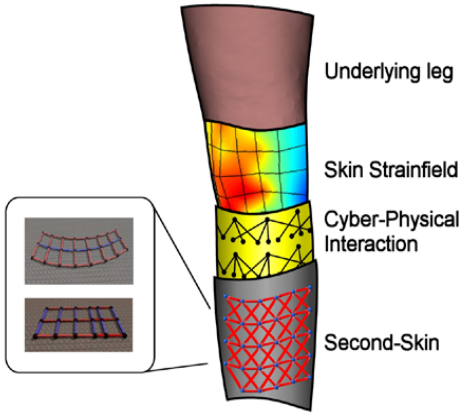
- **MoteLab**: 184 nodes in Maxwell Dworkin [SPOTS'04]
- **CitySense**: Urban-scale open sensor testbed [IEEE HST'08]
- **TOSSIM**: Accurate, energy-aware sensor network simulation [SenSys'03, SenSys'04]

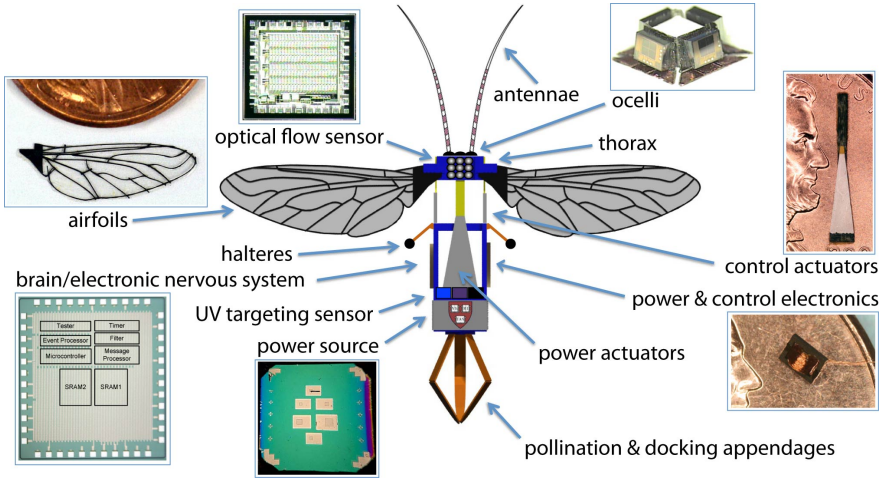
## New architectures for wireless LANs

- **Dyson**: A programmable, evolvable wireless LAN [HotNets'08]

# Implications – Beyond Sensor Networks



# Conclusions

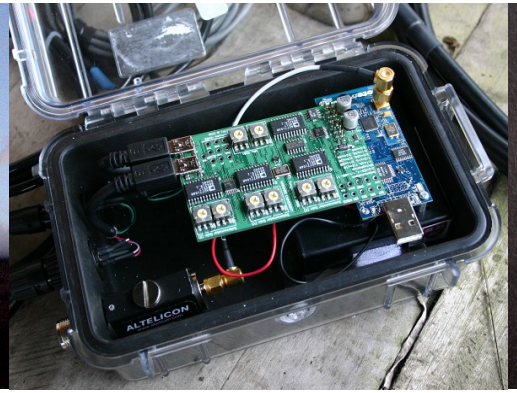
Sensor networks have tremendous potential to impact scientific discovery.

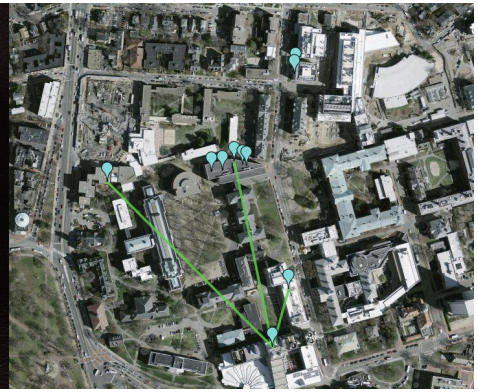
They give rise to several unique programming challenges:

- Achieving good resource efficiency at the node and network level
- Building up complex network behaviors

Our work has focused on OS, programming model, and language techniques to tackle these challenges.

- Real-world scientific applications are the key driver behind this research agenda.



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*fin*

# Related Work

## Resource management primitives in sensor networks

- Large amount of work in energy reduction: MAC protocols, routing, sensor duty cycling
- ICEM, SNACK: Enable cross-component energy reduction
- iCount, Quanto: Energy metering support

## Programming model support for resource management

- Eon, Levels: Tune energy consumption according to set policy
  - *We provide same functionality through Pixie resource brokers*
- TinyDB: Lifetime-targeted queries

## Mobile systems

- Odyssey: Framework allowing applications to adapt to energy, bandwidth, and CPU
- ECOsystem: Tune OS scheduling policy for battery lifetime targets
- Puppeteer: Adaptation to bandwidth variation

# Intelligent Instrumentation

Sensor networks are not just passive instruments!

We can push processing into the network.

Processing can happen at many levels:

- On individual sensor nodes.
- At aggregation points within the network.
- At the base station or gateway.

Sensor networks *fundamentally change* the notion of "scientific observation" from a *passive* process to an *active* one.

- This has a deep impact on many aspects of science.

# Resource Estimation

## Storage and memory are straightforward

- Allocators track total flash/memory consumption

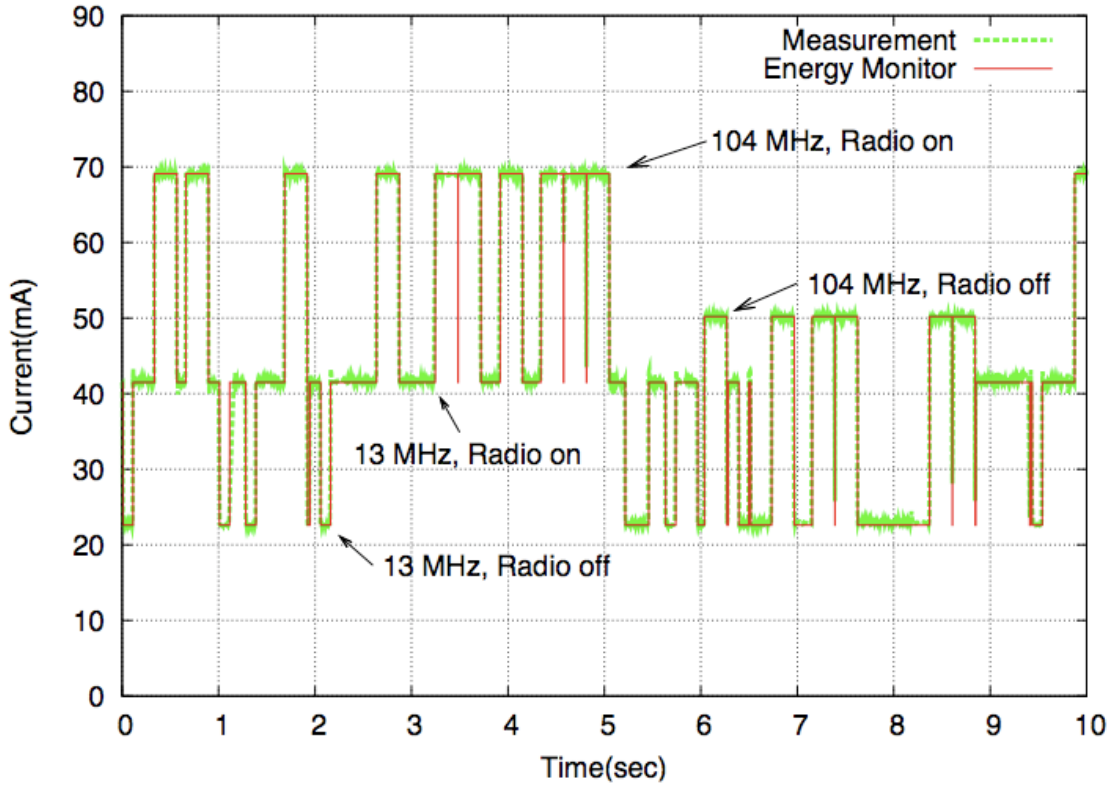
## Bandwidth: Radio link estimates packet transmission delay

- Measure total time for packet transmission plus ARQ (if used)
- Invert transmission delay to estimate instantaneous bandwidth
- Maintain separate estimate for each neighbor
- Currently assumes delay is independent of packet size

# Software energy metering

Energy estimation performed in software

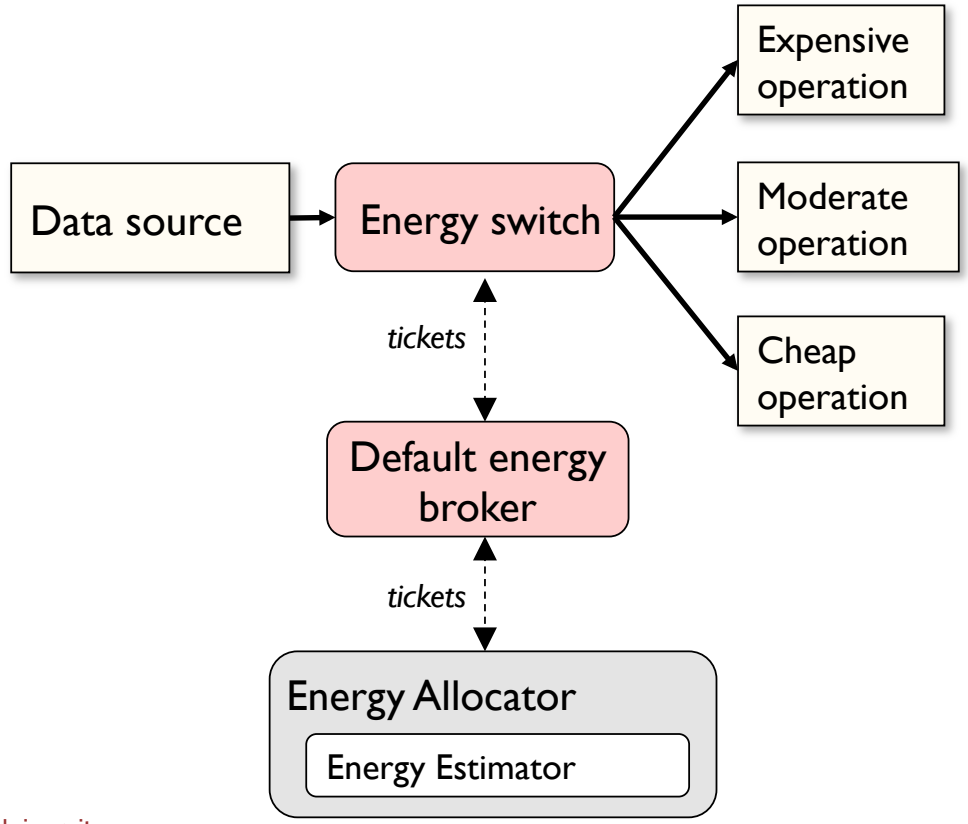
- Tracks state of each hardware device (CPU, radio, flash, sensors) in real time
- Accurate empirical model of hardware energy consumption (about 2-3% error)
- Low overhead, no hardware support required.



# Other Energy Brokers

## Energy-aware switch

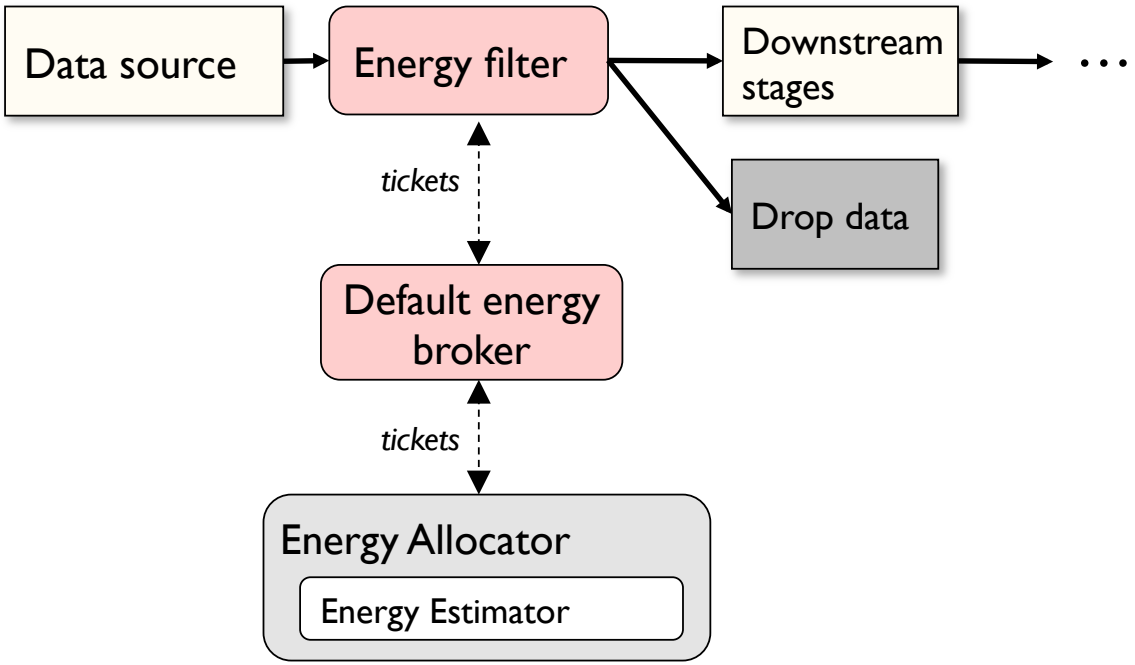
- Sends data down one or more downstream paths based on energy availability
- Mimics policy used by Eon *[Sorber et al., Sensys 2007]*



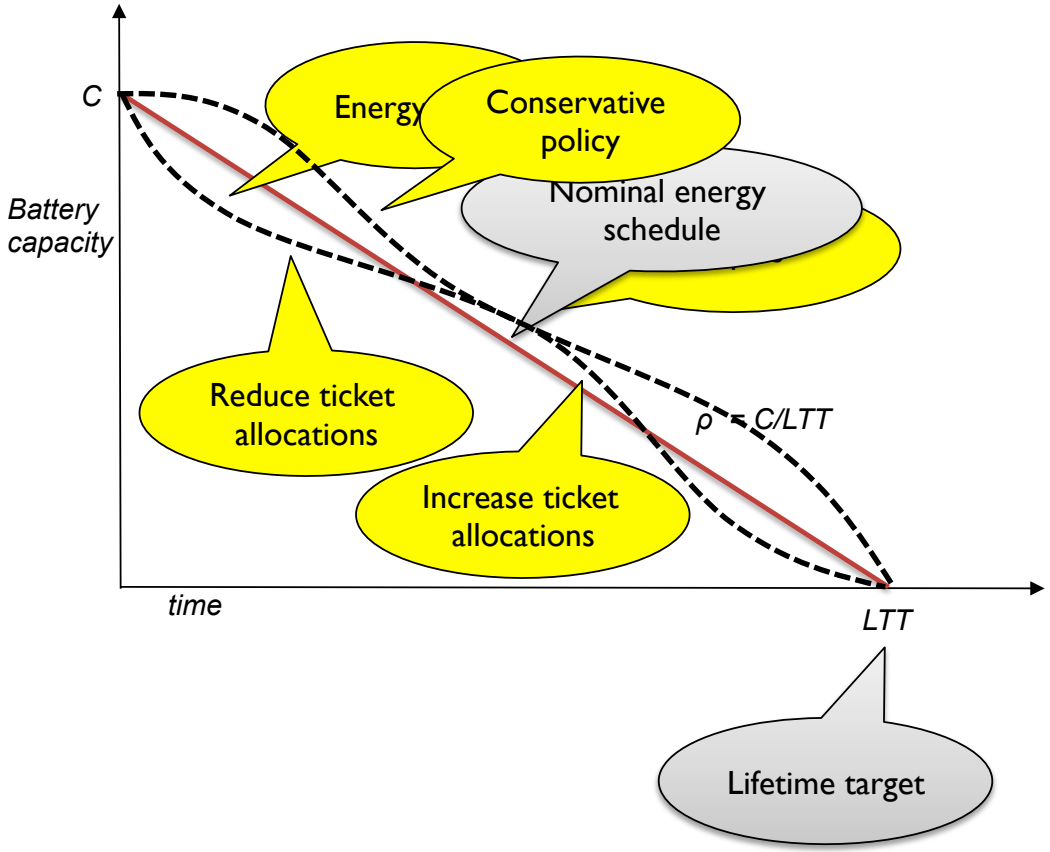
# Other Energy Brokers

## Energy-aware filter

- Selectively drops data to meet energy target
- Effectively controls scheduling and duty-cycling of downstream stages



# Example: Pixie Energy Broker



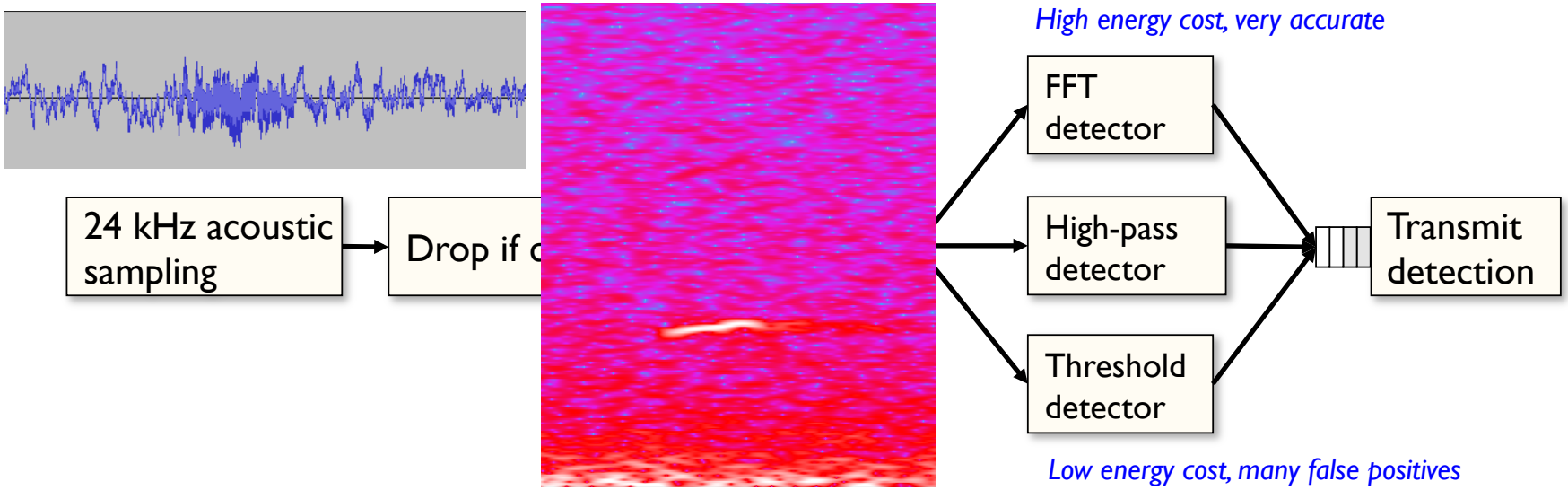
# Evaluation: Acoustic Target Detection

Detect acoustic signature of target (marmot call) in acoustic signal, subject to variable noise.

- *[Girod et al. SenSys'06]*

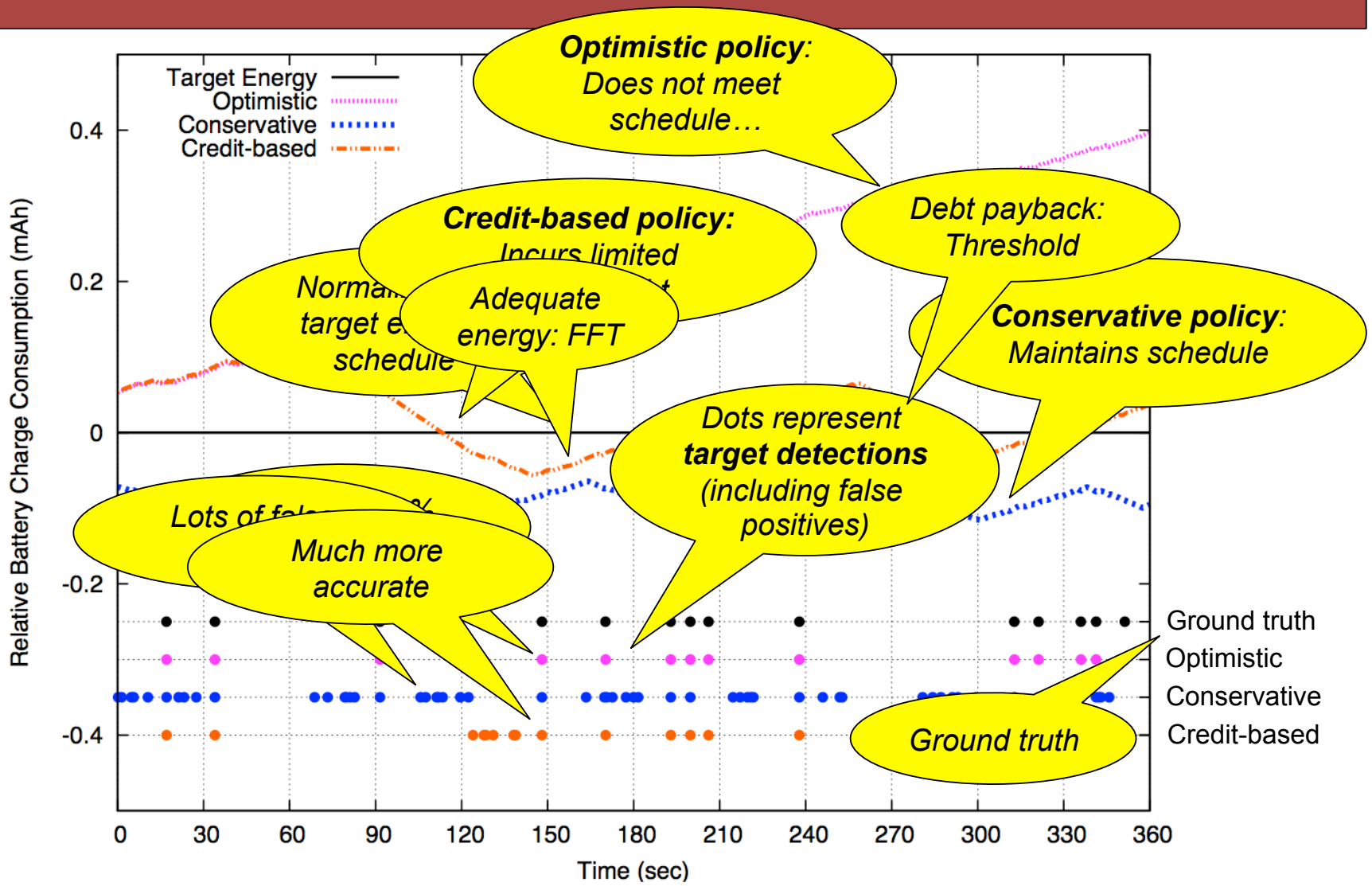
Three detection algorithms with increasing energy cost and accuracy

Goal: Maximize accuracy subject to battery lifetime target



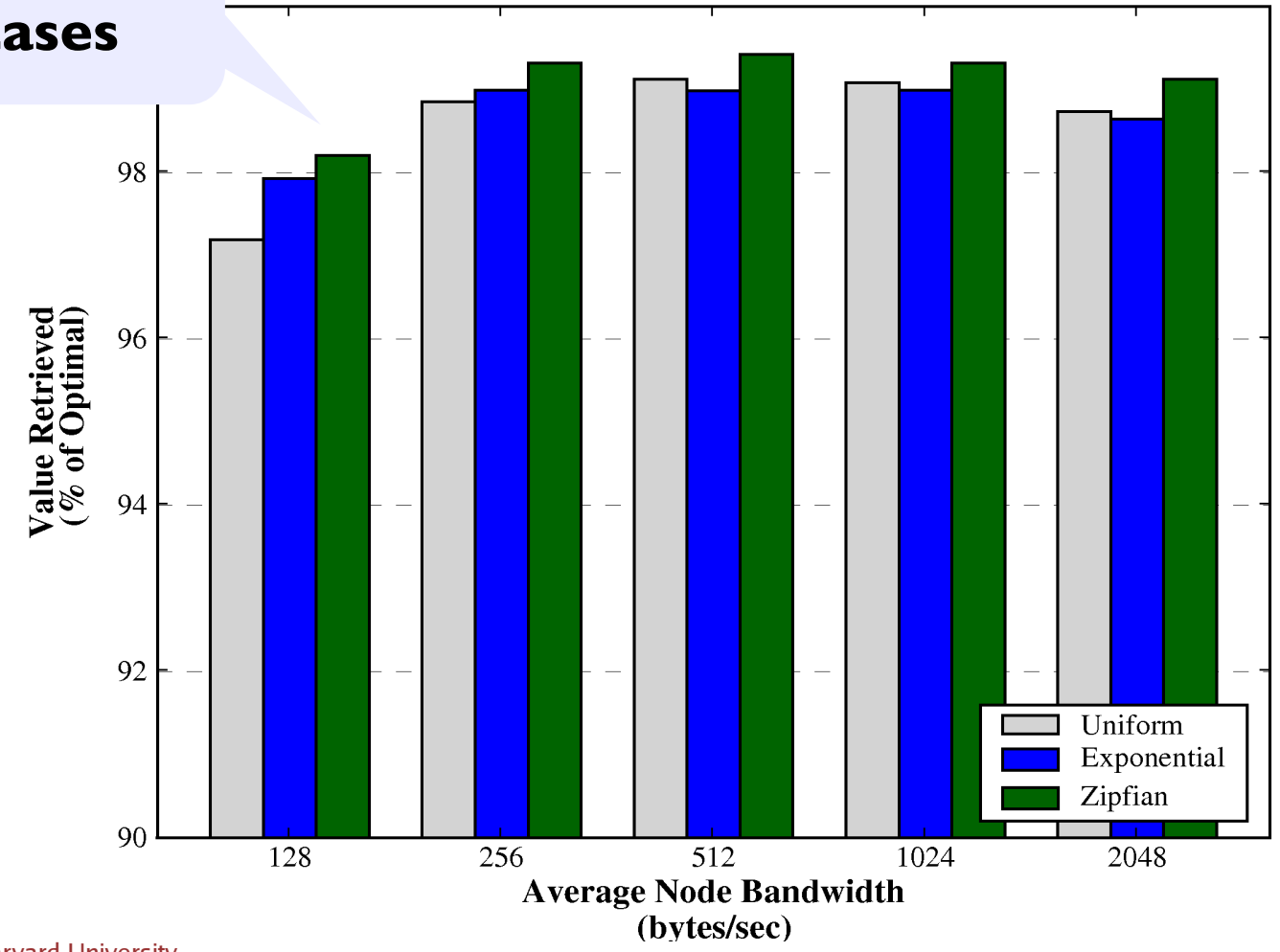
# Energy adaptivity: Varying policies

40-day lifetime target



# Varying Data Value Distribution

**Above 96% in all cases**

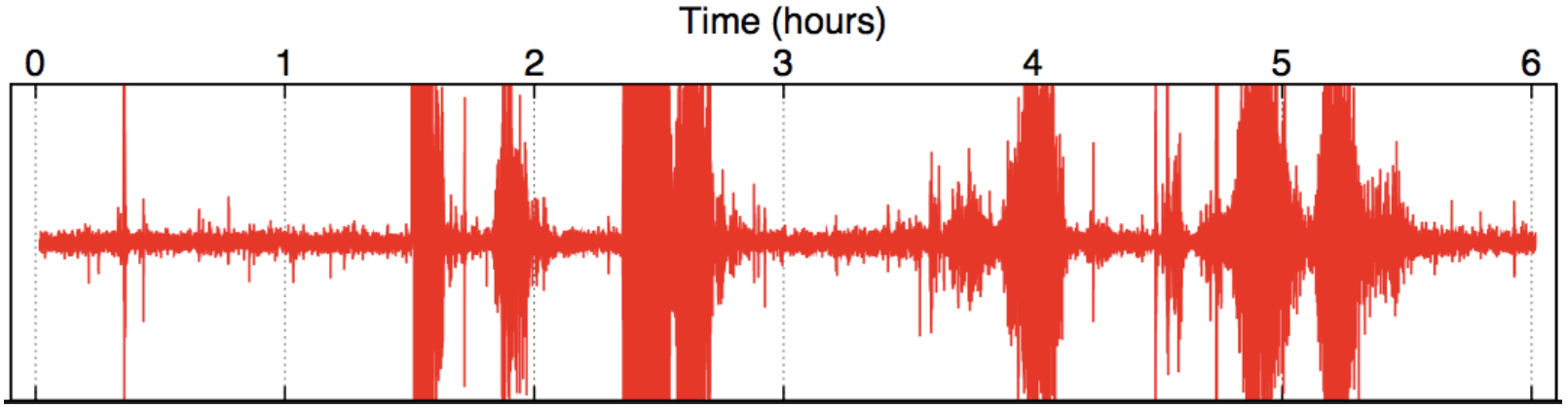


# Defining Data Value

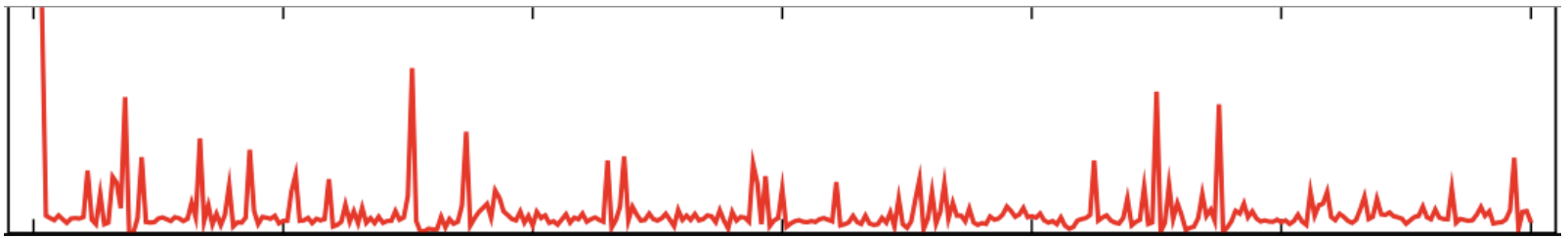
Assumption: nodes compute initial value for each ADU.

- This determination is inherently app-specific

*Raw signal*



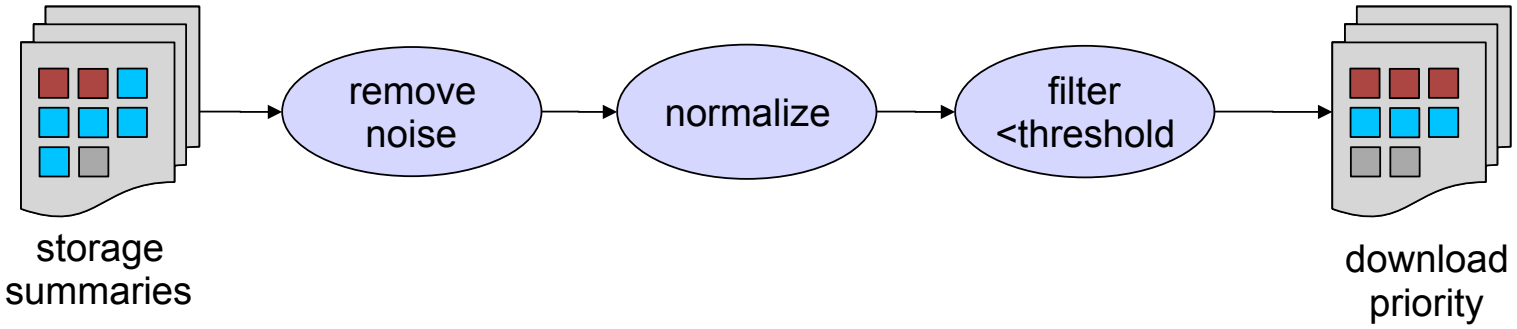

*Short-term average divided by long-term average*



# Lance Policy Modules

User-supplied functions to inspect, filter, or modify raw ADU priorities at the base station.

Composed into a linear chain:




- Take stream of ADU priorities as input, emit (possibly modified) priorities as output
- Can maintain internal state
- Must run efficiently (i.e., keep up with stream of ADU priorities from the network).

# Example Policy Modules

## Priority thresholding

- **filter**: Drop ADU if value below threshold

## Noise removal and calibration

- **adjust**: adjust raw value by adding or subtracting fixed offset
- **debias**: normalize data values across nodes

## Priority dilation

- **timespread**: assign high ADU values to ADUs adjacent in time
- **spacespread**: assign high ADU values to ADUs sampled by different nodes

## Cost weighting

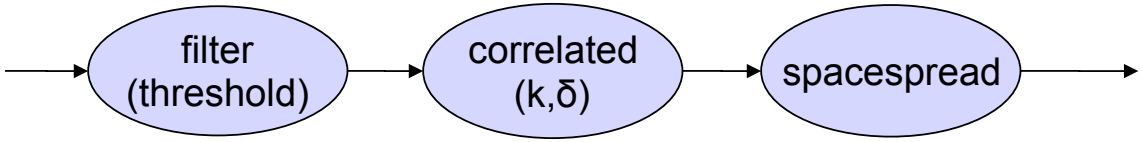
- **costweight**: scale ADU value by cost to download

# Example: Correlated Event Detection

**correlated** policy module W(k,δ)

- counts number of ADUs within a time window δ with a nonzero value
- if at least k ADUs match, retain ADUs in the window
- otherwise, drop this set of ADUs

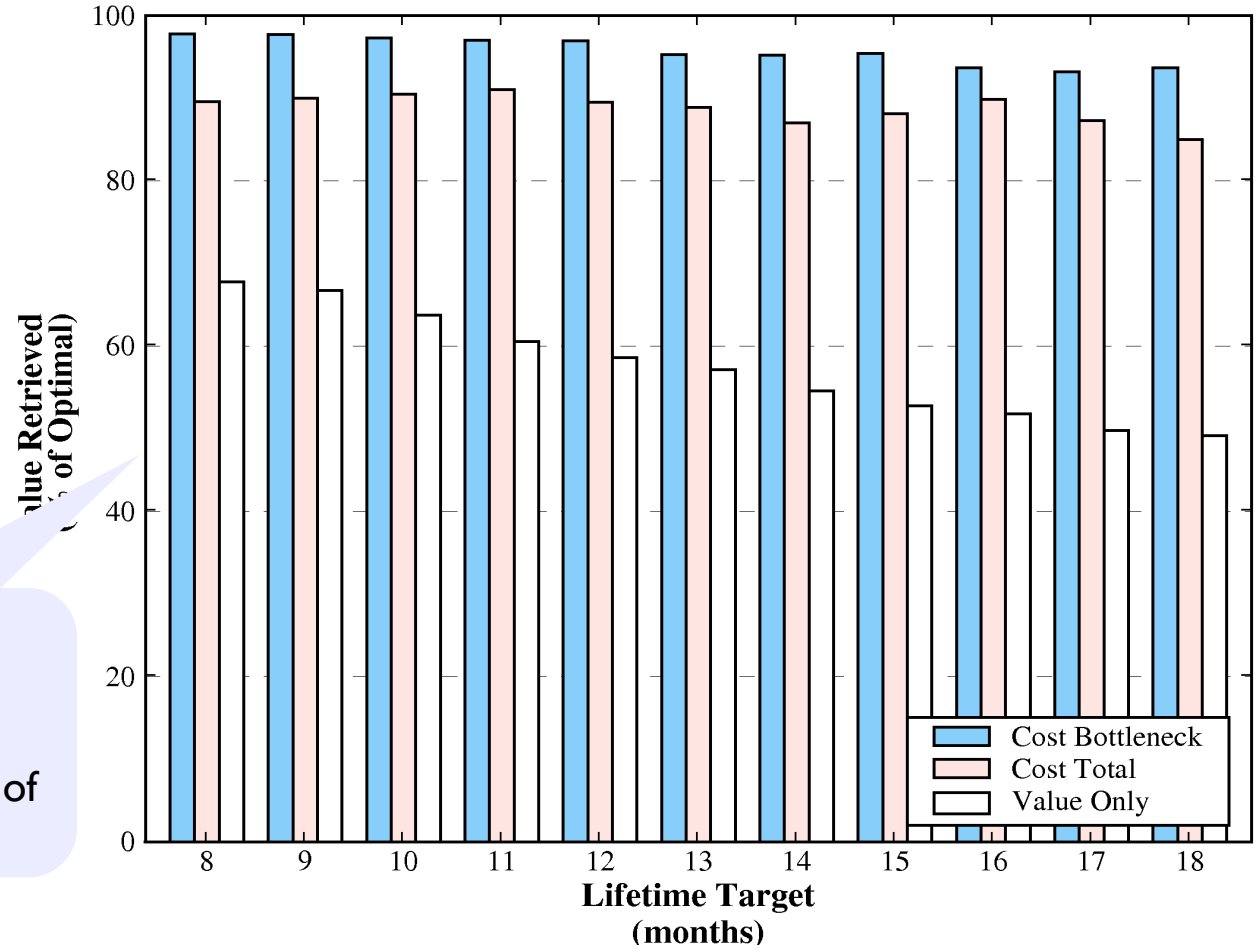
Network-wide earthquake detection in Lance:




- Policy implemented at the base station, rather than on motes.
- Easy to modify behavior of network just by changing policy modules.

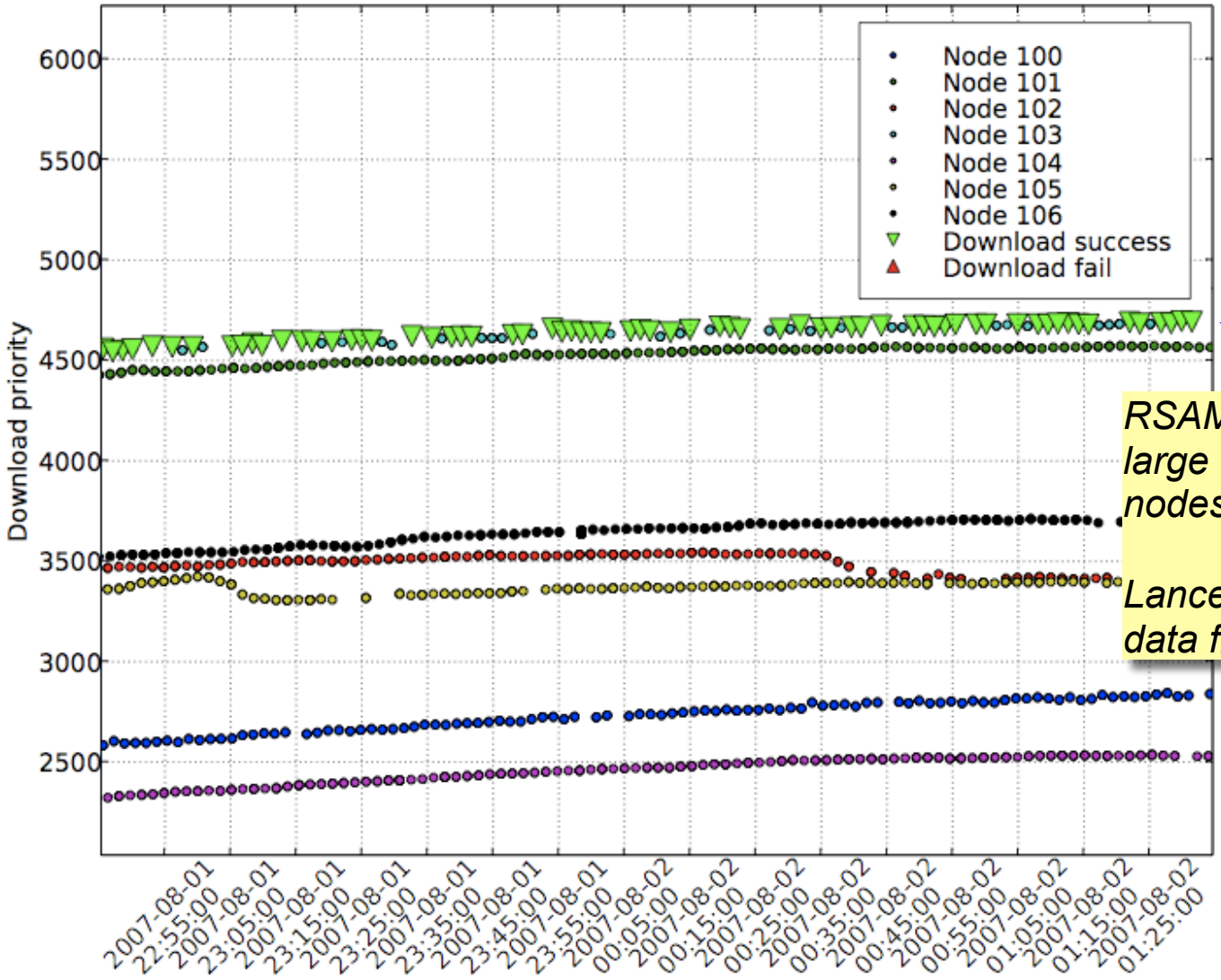
# Results under varying lifetime target

25-node tree, Zipf value distribution




Cost bottleneck achieves > 95% optimality across a wide range of target lifetimes

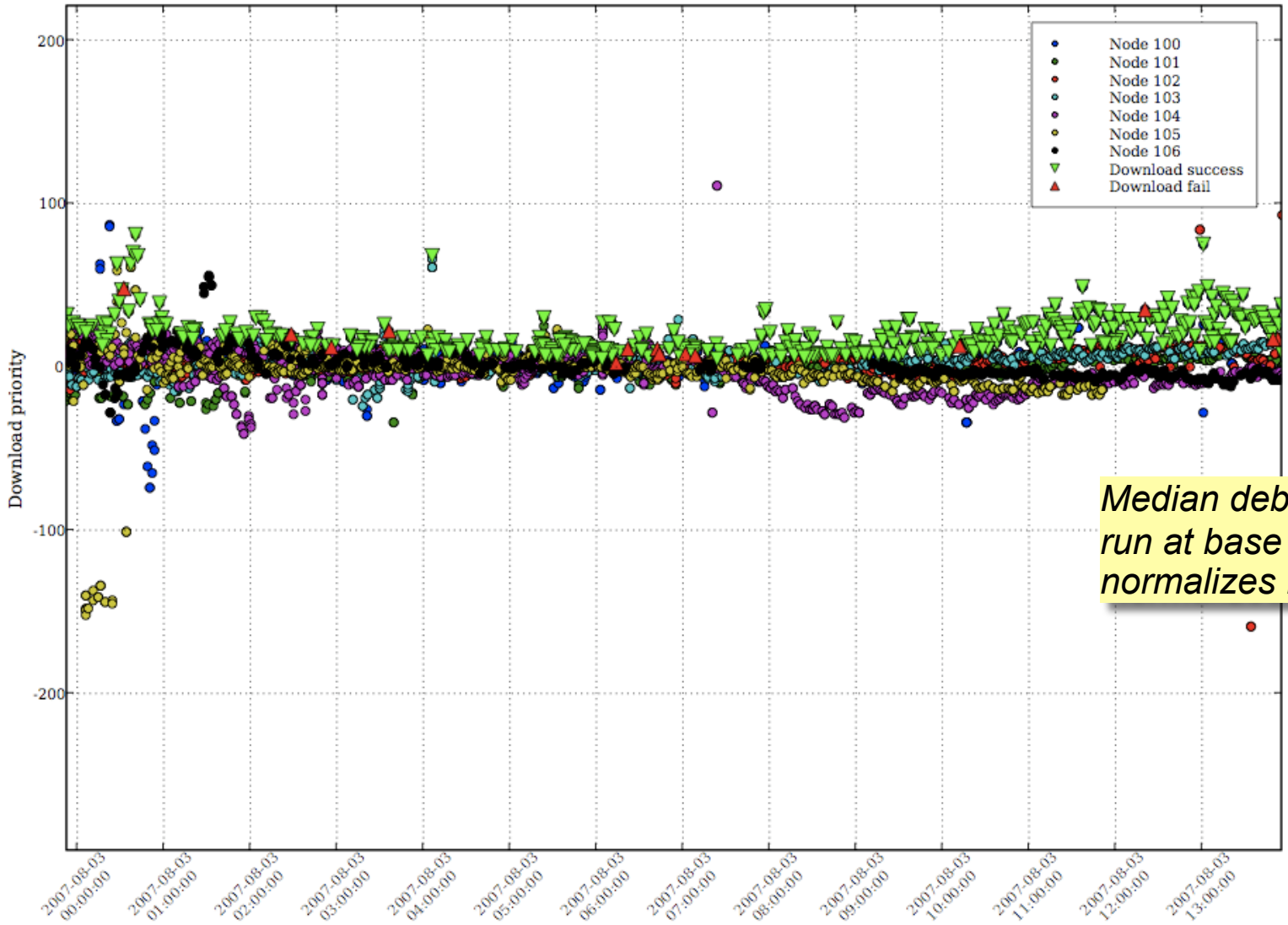
# RSAM prioritization: DC bias




*RSAM values exhibited large DC bias across nodes.*

*Lance only downloaded data from 1 or 2 nodes!*

# The fix: Debiasing policy module




*Median debiasing filter run at base station normalizes RSAM values*

# Programming Benefits

Dataflow programming model maps well onto application structure

- Similar to Eon, Tenet, WaveScope, and Flask

Tickets offer a great deal of flexibility and power

- Fine-grained feedback and control of resource usage at all levels

Brokers decouple resource management policies from mechanisms

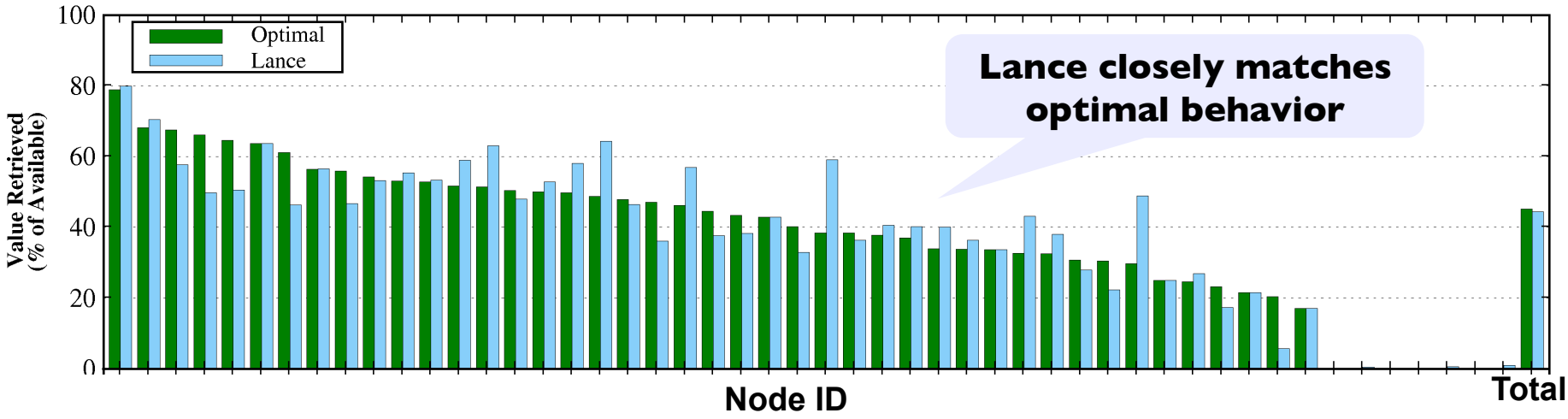
- Enables composable resource adaptations

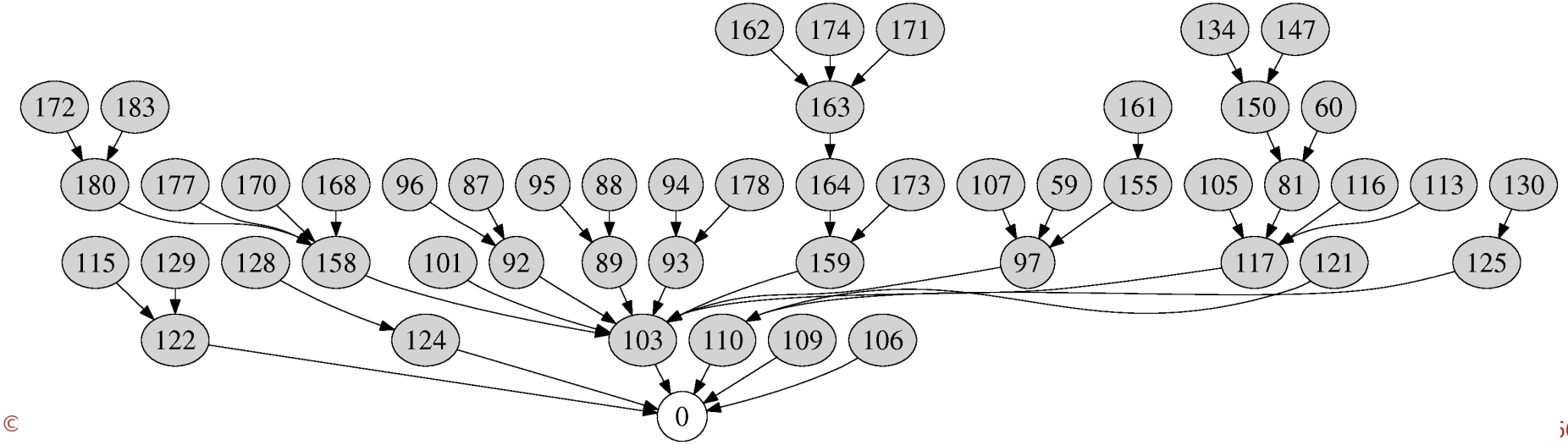
Resource-awareness is pervasive in the programming model

- Not “off to the side”
- Annoying at first, but makes sense when you get used to programming in this way
- Exposes resource dependencies, rather than relying on hidden magic knobs

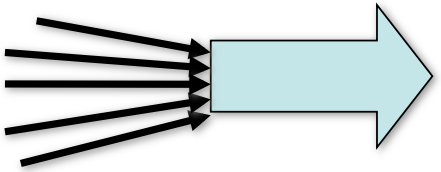
# MoteLab Testbed Experiments

50 node tree topology, Zipf value distribution



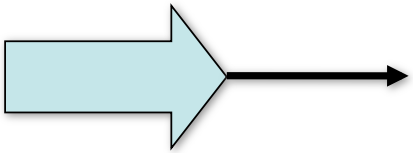
# Some Region Primitives



```
everywhere : α stream → α region
gossip     : int → α stream → α region

rmap : (α → β) exp → α region → β region
rfilter : (α → bool) exp → α region → α region

rfold   : (α *β → β) exp * β exp →
            α region → β stream
rfunnel : α region → α stream
```



# Future Directions: Peloton

What about coordinated resource management within the network?

- Example: Group of nodes detect an event, elect leader to collect signals, process data, deliver results to the base station.
- Nodes need to **share** information on resource availability, **coordinate** resource allocation decisions, and represent **cross-node allocations**

*Peloton* – A Distributed OS for resource-aware programming

- Decentralizes resource management within the network
- Extend Pixie's abstractions to span allocations on multiple nodes.
- [HotOS 2009]

# Future Directions: RoboBees

NSF Expeditions in Computing

My group: Swarm OS for distributed resource management and programming models