# *Cyber-physical systems – linking sensing, networking, computation and people*

Jim Kurose
Department of Computer Science
University of Massachusetts
Amherst MA USA

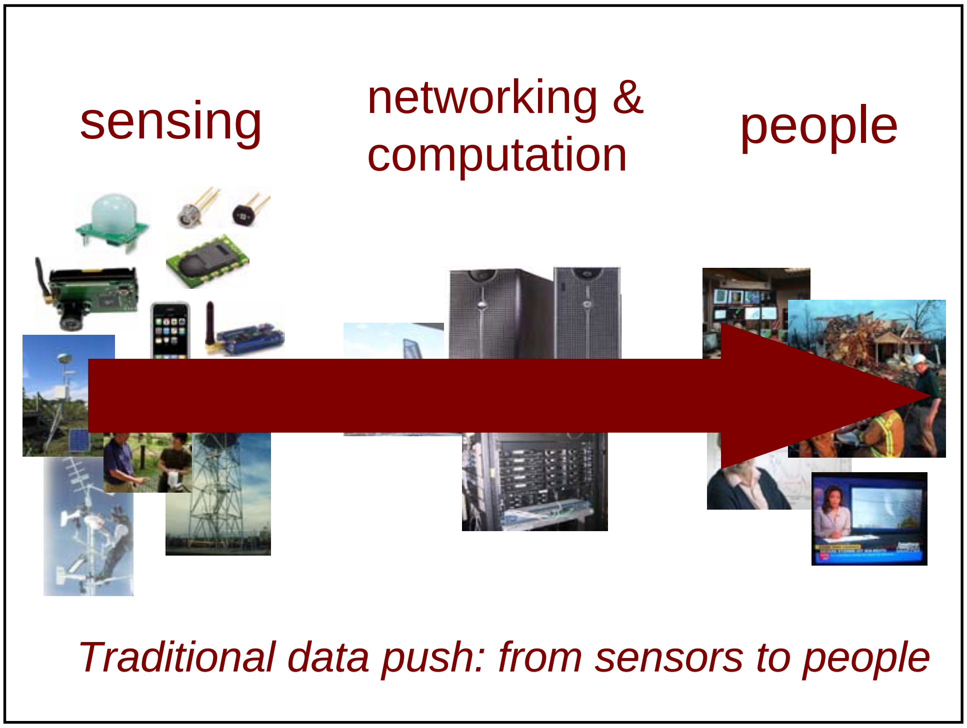
ICCCN 2009, San Francisco

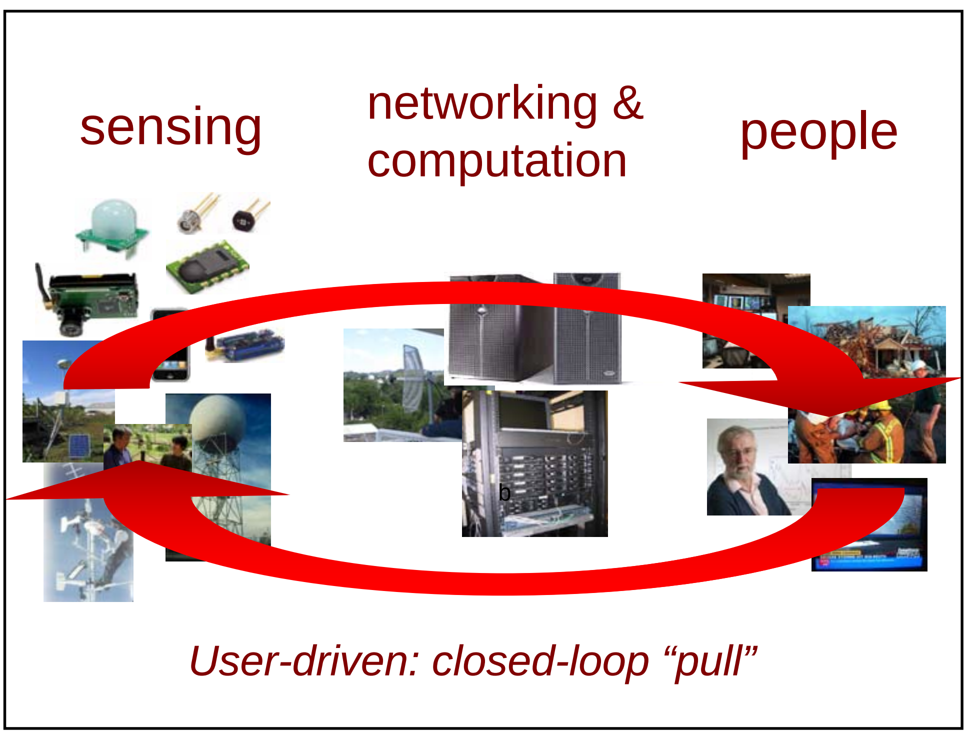
sensing

networking &
computation

people

*Q: How are these "linked" ?*


sensing
networking &
computation
people
Traditional data push: from sensors to people


sensing
networking &
computation
people
User-driven: closed-loop "pull"

## Wide range of "sensors"

habitat monitoring

microclimate monitoring

animal tracking

vehicle tracking in sensor field

auto traffic monitoring

video surveillance

radar/weather

underwater sensing

satellite observation (EODIS)

network traffic monitoring

in spite of differences, commonalities as well!

## Overview

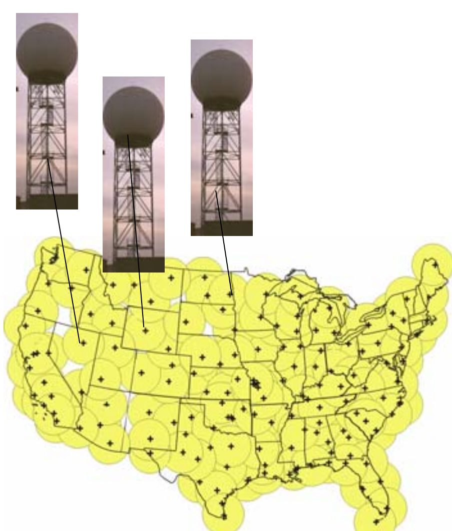
- introduction
- CASA: collaborative adaptive sensing of the atmosphere
  - introduction, motivation
  - testbeds
- research challenges: integrating sensors, networking, computation, people
  - system architecture
  - energy-constrained environments
    - joint sensing/communication
  - incorporating end-user utilities
- discussion: the big picture

## The grand challenge

Revolutionize our ability to *observe, understand, predict* and ... weather hazards, using sensor networks that sample the atmosphere where and when *end-user needs* are greatest.

a challenge for *all* sensor nets


## NEXRAD (current US system)

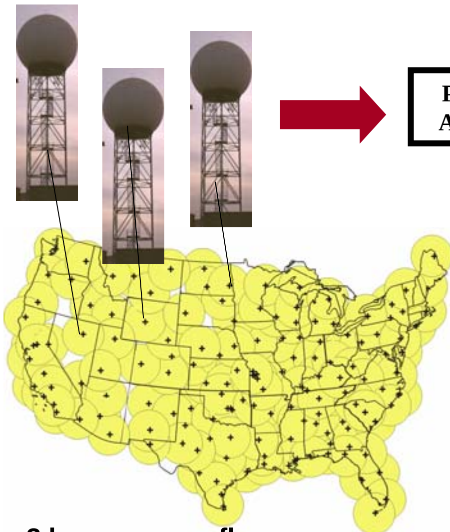


3 km coverage floor

- 158 radars operated by NOAA
- 230 km Doppler mode, 460 km reflectivity-only mode
- “surveillance mode”:
  - sit and spin

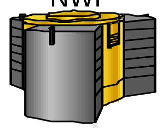
# NEXRAD (current US system)

Observational Data "Push"



**Processing Algorithms**

Nowcasts
NWP

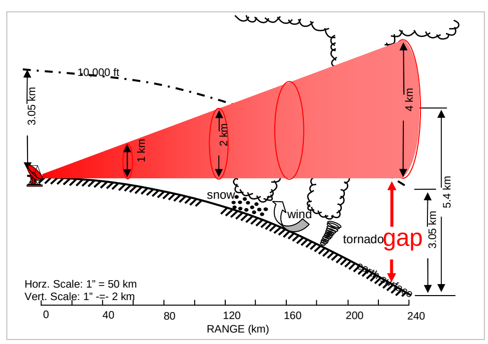


**3 km coverage floor**

# The Sensing Gap

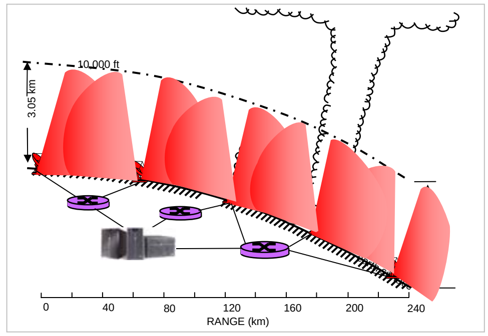
*S*parse, high-power radar

- *sensing gap:* earth curvature effects prevent 72% of the troposphere below 1 km from being observed
- coarse resolution



# CASA: collaborative adaptive sensing of the atmosphere

CASA: dense network of low power radars:
- sense lower 3 km of earth's atmosphere
- *collaborating* radars:
  - improved sensing
  - improved detection, prediction
- finer spatial resolution
- responsive to multiple *end-user needs*

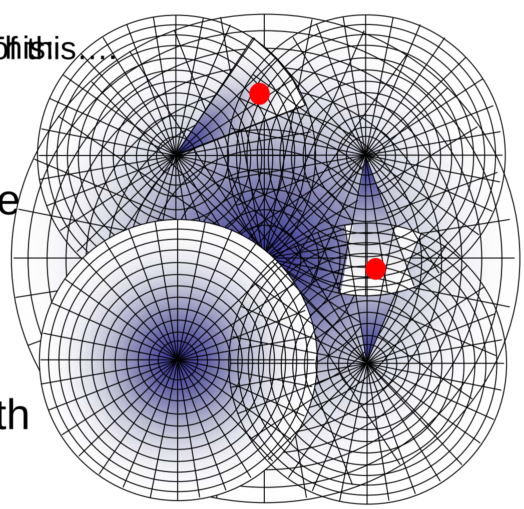



*"Sample atmosphere when and where end-user needs are greatest"*

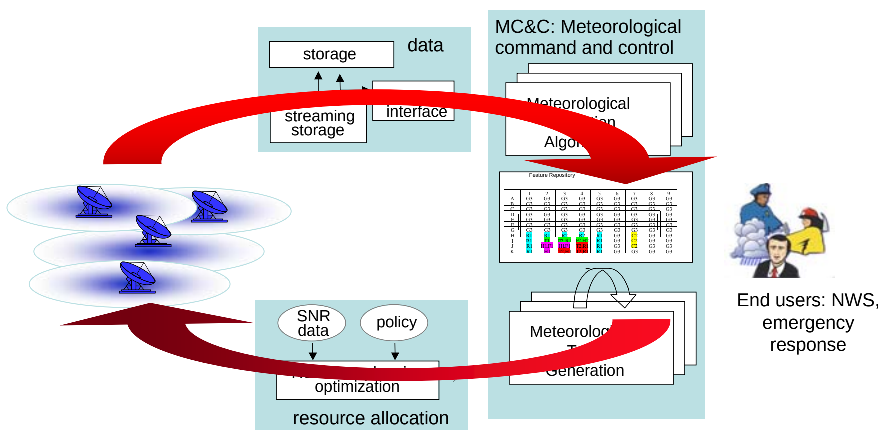
# CASA: dense network of inexpensive, short range radars

instead of this…

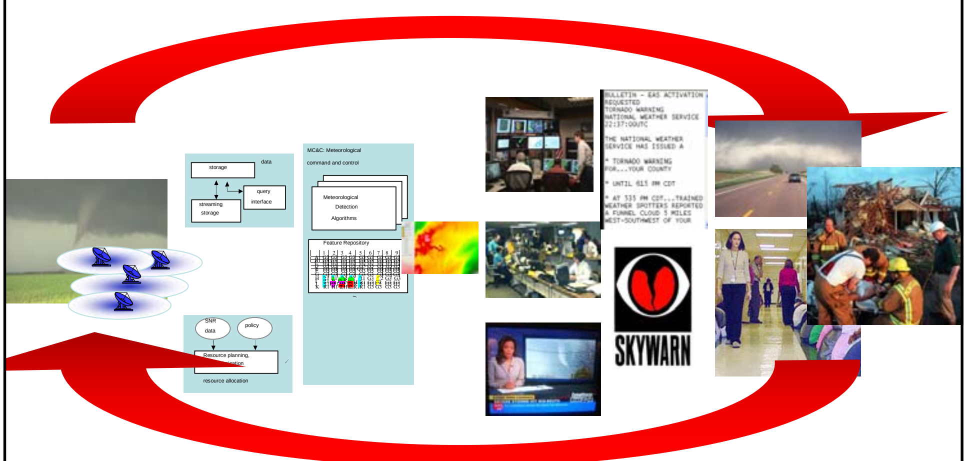
- finer spatial *resolution*
- *beam focus*: more energy into sensed volume
- *multiple looks:* sense volume with most appropriate radars



# CASA: adaptive data pull




# CASA: End Users




(Real) end users: National Weather Service, emergency response managers, researchers

## What's needed to solve this problem?

**CASA**
Collaborative
Adaptive
Sensing
of the Atmosphere

NSF
Engineering Research Center

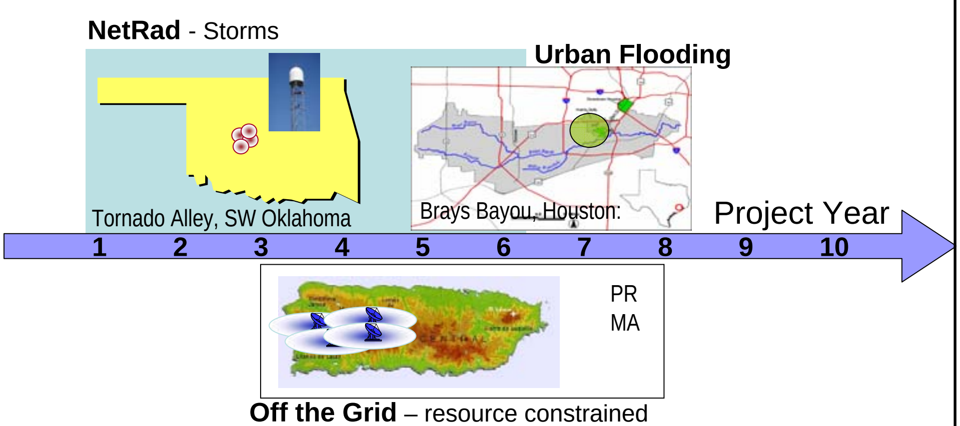
*core partners*

- Remote sensing
- Data-intensive systems
- Networking
- Real-time systems
- Numerical prediction
- Emergency management
- Radar meteorology
- Quantitative inversion
- Climate studies
- Social impact
- Antenna design

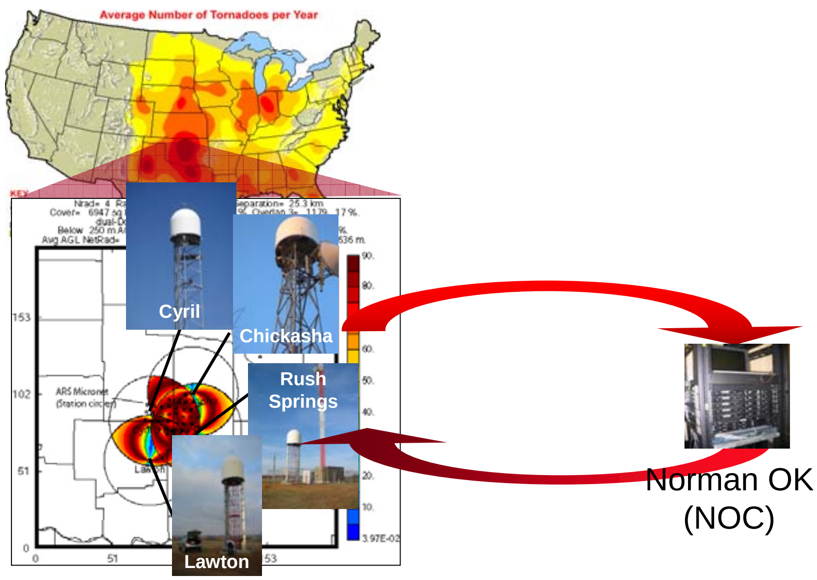
*expertise*

## Integrative, engineered systems

- focus mandated by NSF
- 3 CASA testbeds

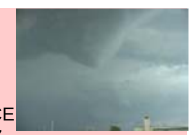


# Oklahoma 4-Node Test Bed




# *Spring 2007 storm season:*

***4/10/07: first CASA data citation by NWS***



FLUS74 KOUN 102343
AWUOUN

AREA WEATHER UPDATE
NATIONAL WEATHER SERVICE
742 PM CDT TUE APR 10 2007

..WARNING DECISION UPDATE

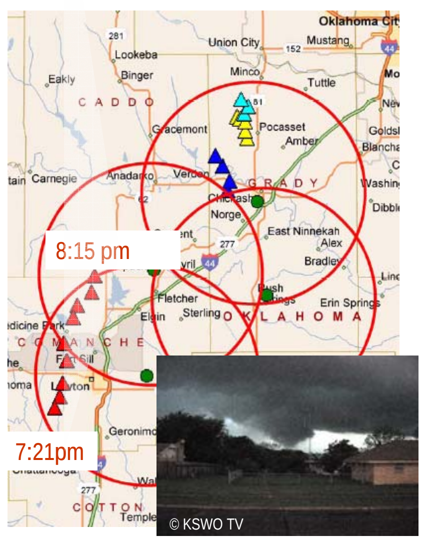
THIS WARNING DECISION UPDATE CONCERNS
COMANCHE AND GRADY COUNTIES.

MESOCYCLONE NEAR STERLING CONTINUES
TO STRENGTHEN PER TWO RADAR VIEWS.
***CASA NETWORK ALSO SHOWING PRONOUNCED HOOK.*** STORM WILL
ENCOUNTER WARM FRONT...WITH POSSIBLE
ENHANCED LOW LEVEL SHEAR JUST EAST OF
STERLING AND WEST OF RUSH SPRINGS.
TORNADO WARNING IS POSSIBLE IF NOT
LIKELY TO BE ISSUED AS STORM REACHES
SOUTHWEST GRADY COUNTY.

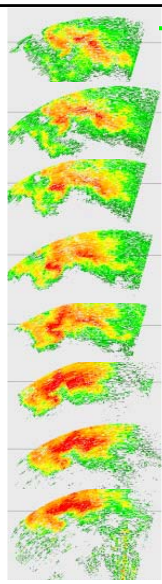
BURKE

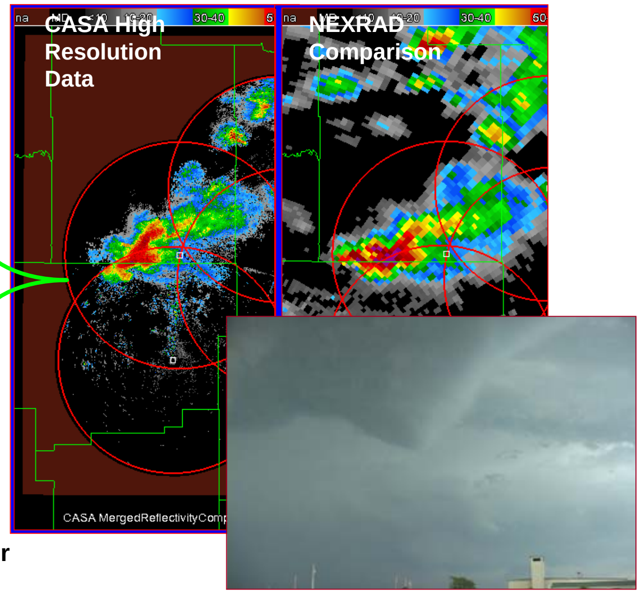
*Note: not policy*

***5/8/07: circulations in testbed***



## April 10, 2007 Elevated Super Cell

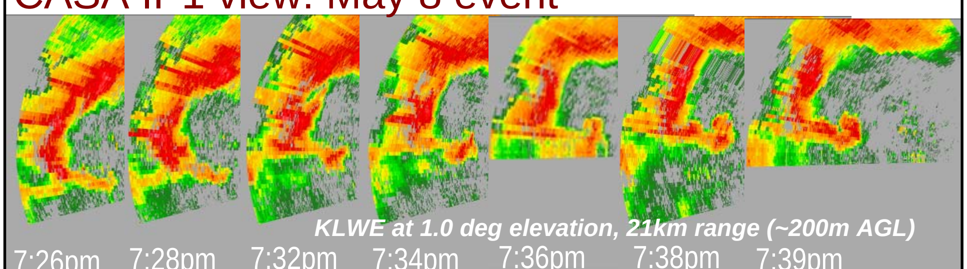




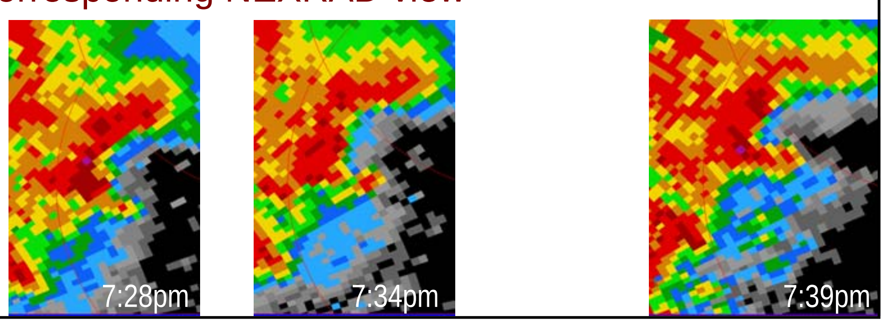

CASA's Adaptive Sector scanning at multiple elevations from 1 to 14 degrees, 40 sec. sector scan

ground truth verification (NEWS9)

## CASA IP1 view: May 8 event

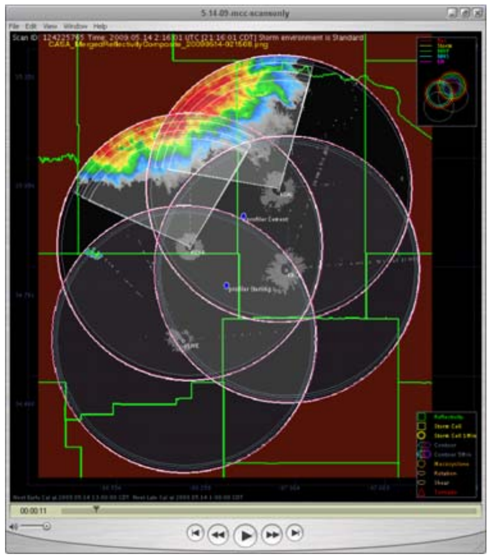



## … corresponding NEXRAD view

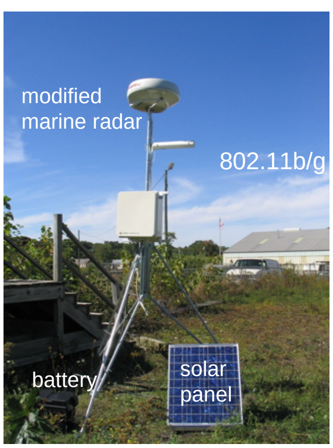


## Movie: NetRad in operation

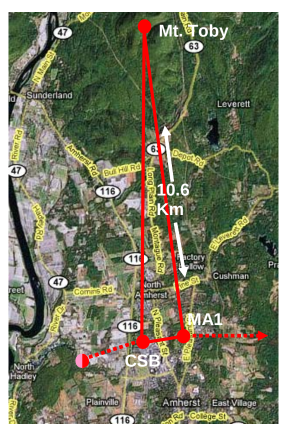
May 14, 2009



## Off-the-Grid Test Bed



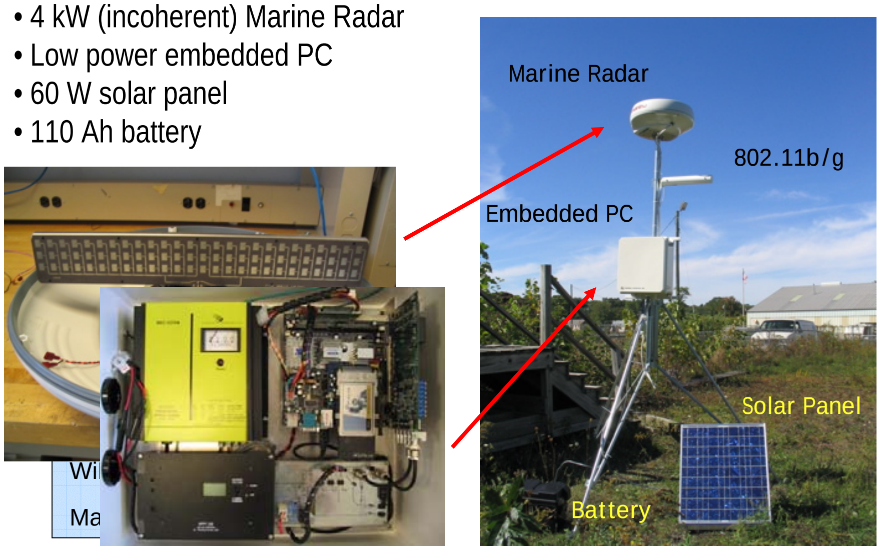

- no reliance on infrastructure
- solar/battery-operated nodes
- multi-antenna multi-hop 802.11 directional antenna




Topology of the MA OTG testbed

# Prototype OTG Node

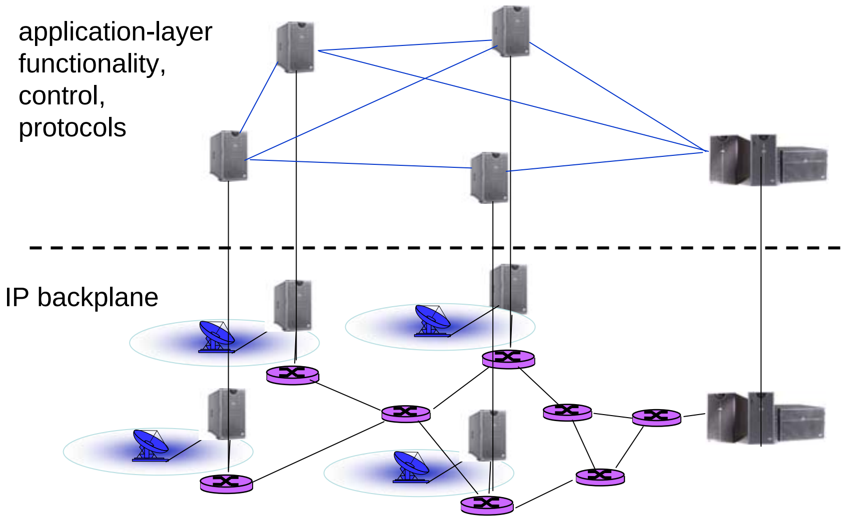
- 4 kW (incoherent) Marine Radar
- Low power embedded PC
- 60 W solar panel
- 110 Ah battery




# Overview

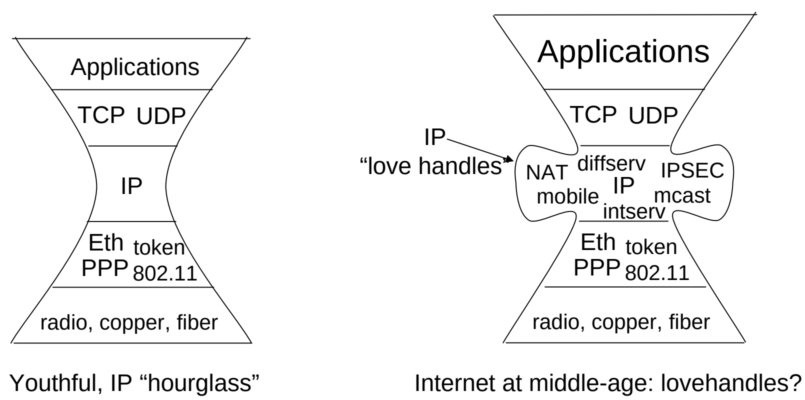
- introduction
- CASA: collaborative adaptive sensing of the atmosphere
  - introduction, motivation
  - testbeds
- research challenges: integrating sensors, networking, computation, people
  - system architecture
  - energy-constrained environments
    - joint sensing/communication
  - incorporating end-user utilities
- discussion: the big picture

## Our architectural worldview



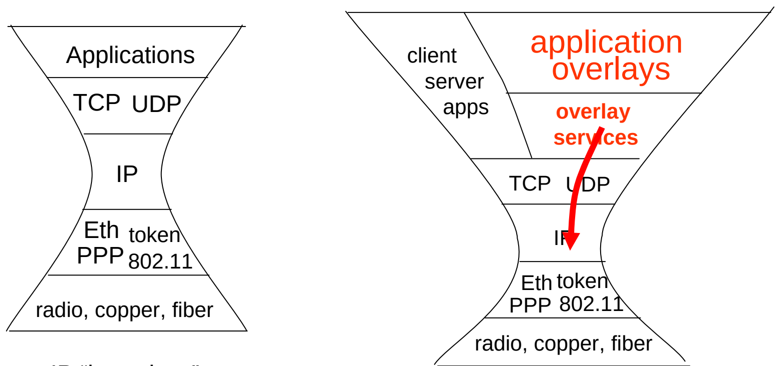

## Middle-aged Internet: losing the hourglass?

middle age: a narrowing mind, a widening waist



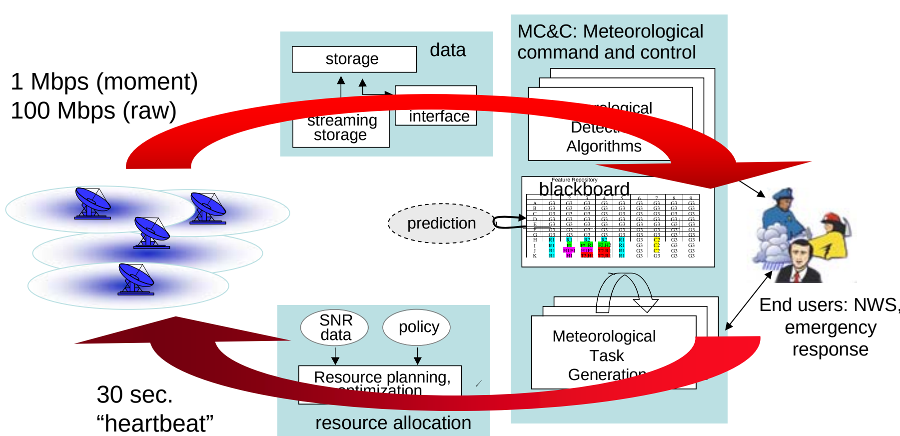
# Middle-aged Internet: *keeping* the hourglass!

middle age: a expanding mind, a slim waist



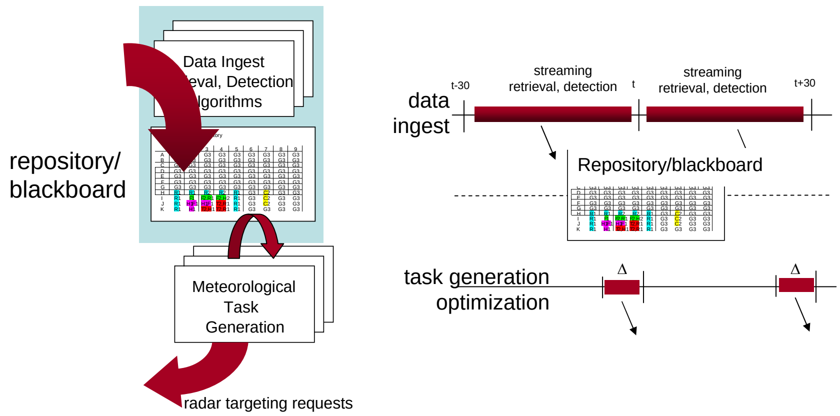

IP “hourglass”

# Architecture overview

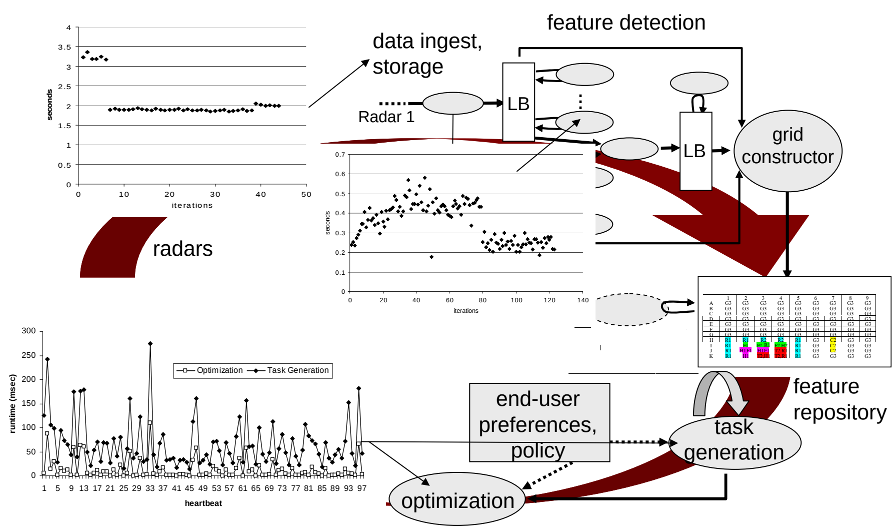


# Meteorological Command and Control (MC&C)

Time sensitive: decouple ingest from command generation




# Meteorological Command and Control

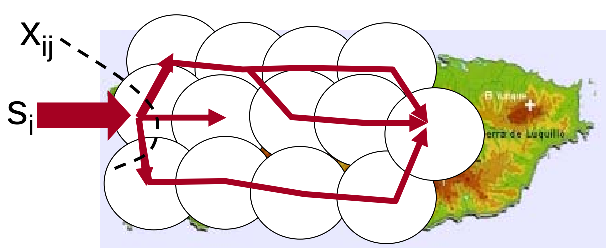



Michael Zink, David Westbrook, Sherief Abdallah, Bryan Horling, Vijay Lakamraju, Eric Lyons, Victoria Manfredi, Jim Kurose, Kurt Hondl, **"Meteorological Command and Control: An End-to-end Architecture for a Hazardous Weather Detection Sensor Network"**

# Overview

- ❑ introduction
- ❑ CASA: collaborative adaptive sensing of the atmosphere
  - ❑ introduction, motivation
  - ❑ testbeds
- ❑ research challenges: integrating sensors, networking, computation, people
  - ❑ system architecture
  - ❑ energy-constrained environments
    - ❑ joint sensing/communication
  - ❑ incorporating end-user utilities
- ❑ discussion: the big picture

## Optimal joint sensing/routing in energy constrained environments



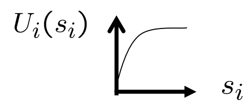

- *energy expenditures:* sensing, send/receive data
- *each node must determine:*
  - ❖ $s_i$: sensing (data generation) rate,
  - ❖ $X_{ij}$: how to route sensed data towards sink,

  subject to power constraints
- *node decision affects others:* sensed data must be sent

# Goal : maximize utility of received data

System-wide utility function $U = \sum_i U_i(s_i)$

- $s_i$: node *i* sensed and delivered data rate
- $U_i(s_i)$ : utility of node *i* data.
  concave, increasing function




# Optimization problem formulation

**S**: sensing rates; **X**: routing

$$\max_{s,X} \text{ network utility } U(s)$$

s.t.

1. $J(s,X) = 0,$
2. $F(s,X) \le C.$
3. $p(s,X) \le P.$

- flow conservation
- routes X satisfying sensing rates s

$$J(s,X) = 0$$

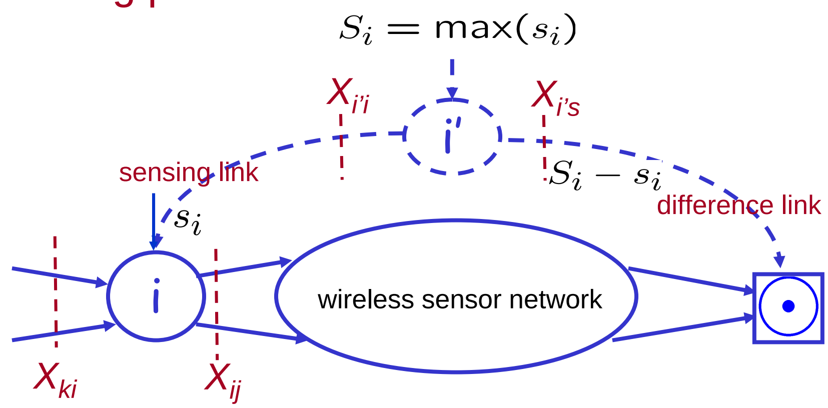
- power usage limited by available power
- power feasibility

$$p(s,X) \le P$$

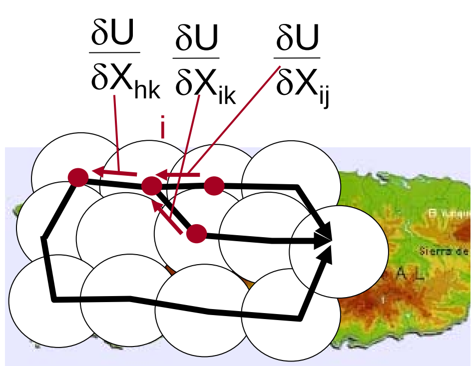
- link rates limited by capacities
- demand feasibility

$$F(s,X) \le C$$

## Mapping from sensing/routing problem to routing problem




## Distributed optimization



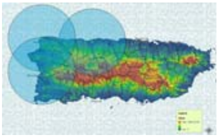

Algorithm:

- receive marginal utility information from downstream nodes
- change flow rates to downstream to balance marginal utility
- compute own marginal utility wrt upstream flow, send upstream

- convergence proof, step-size requirements, evaluation

C. Zhang, J. Kurose, Y. Liu, D. Towsley, M. Zink "An Optimal Distributed Algorithm for Joint Resource Allocation and Routing in Node-based Wireless Networks." IEEE ICNP

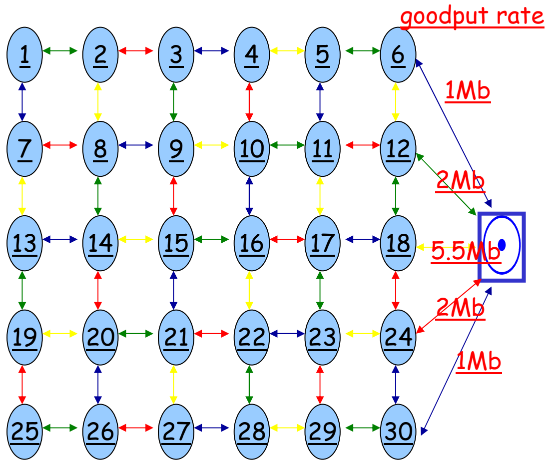
## Simulation scenario



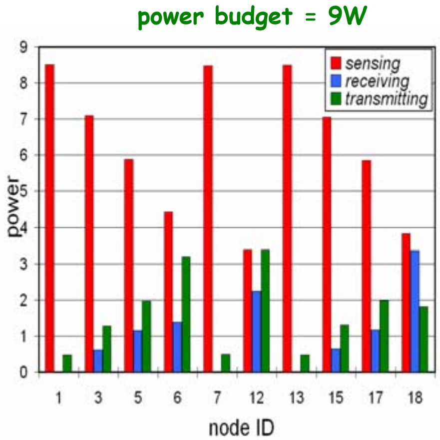
CASA student testbed

- energy collection rate: 7-13W
- X-band radar-on power: 34W
- radar-on rate 1.5Mbps
- link-on trans power: 1.98W
- link-on receive power: 1.39W

$$U_i(s_i) = -w_i s_i^{-0.5}$$
$$U = \sum_i U_i(s_i)$$

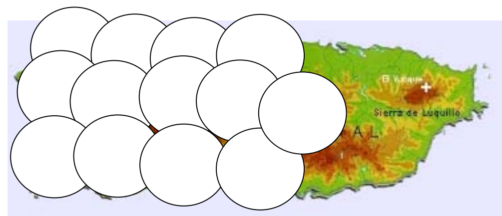



## Energy balance for different energy harvest rates




C. Zhang, J. Kurose, Y. Liu, D. Towsley, "An Optimal Distributed Algorithm for Joint Resource Allocation and Routing in Node-based Wireless Networks,"

## Optimal joint sensing/routing: many open questions!

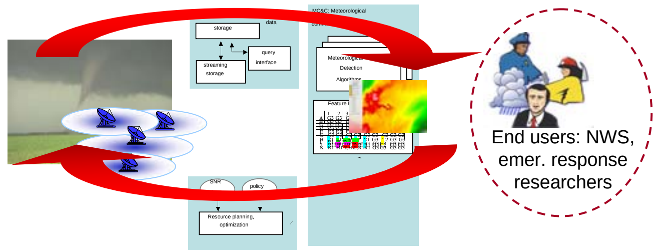


- in-network computation (data fusion)
  - data flow no longer conserved!
- considering battery recharge/drain
- implementation, measurement
  - point-point directional links
  - end-end system

## Overview

- introduction
- CASA: collaborative adaptive sensing of the atmosphere
  - introduction, motivation
  - testbeds
- research challenges: integrating sensors, networking, computation, people
  - system architecture
  - energy-constrained environments
    - joint sensing/communication
  - incorporating end-user utilities
- discussion: the big picture

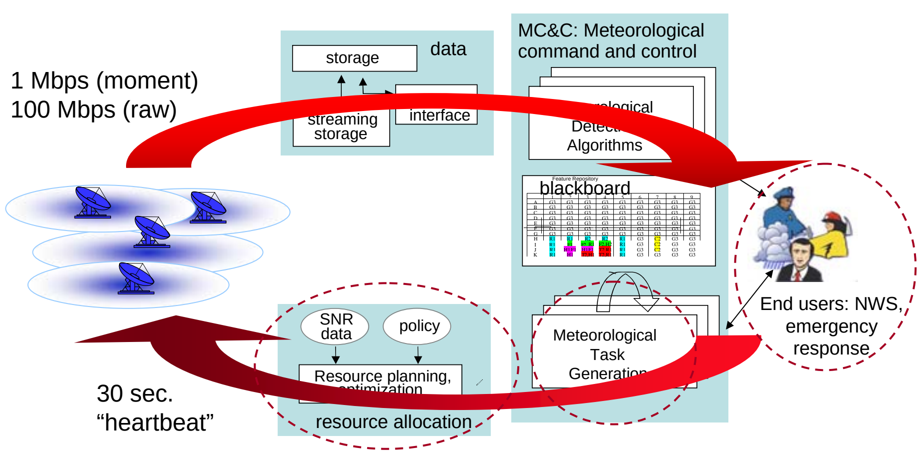
## What do end-users want?




- *understand:* research data
- *predict:* give advance warning
- *respond:* using current/recent data

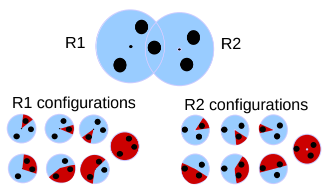
not always achievable simultaneously!

## Incorporating end-user utilities



## Optimizing radar scans: incorporating end user considerations

Where to point?




Find ***configuration*** that optimizes utility at time step k:

$$J = \max_{configurations, C} \sum_{tasks, t} U(t,k) Q(t,C)$$

**Utility** – **"how important"** is task *t* to the users at time k?

$$U(t,k) = \sum_{groups, g} w_g U_g(t,k)$$

**Quality** – **"how good"** is scanning configuration *C (distance, coverage, # radars) for task t?*

## Optimizing radar scans: architecture!

Find ***configuration*** that optimizes utility at time step k:

$$J = \max_{configurations, C} \sum_{tasks, t} U(t,k) Q(t,C)$$

- separation of "how important," *U(t,k),* from "how good',*Q(t,C)*
- *U(t,k,Q(t,C))* would have been possible but:
  - complex to solve
  - complex to specify and update *U(t,k,Q(t,C))*
  - "stovepipe" design

## How to define “how important”: $U_g(t,k)$

- user values for detected weather features

| Event | Location | Prior Information available | NWS utility Wt=0.4 | EM utility Wt=0.3 | Researcher utility Wt=0.2 | Vieux utility Wt=0.1 |
|---|---|---|---|---|---|---|
| TVS detection | AOP | 0 | 5 | 5 | 5 | 1 |
| | | 1 | 4 | 5 | 5 | 1 |
| | Remote | 0 | 5 | 1 | 5 | 1 |
| | | 1 | 4 | 1 | 5 | 1 |
| | | | | | | |
| Mesocyclone | AOP | 0 | 4 | 4 | 4 | 1 |
| | | 1 | 3 | 4 | 4 | 1 |
| | Remote | 0 | 4 | 1 | 4 | 1 |
| | | 1 | 3 | 1 | 4 | 1 |
| | | | | | | |
| Storm cell | AOP | 0 | 4 | 4 | 4 | 4 |

## How to define “how important”: $U_g(t,k)$

- “naturally”: group-sensitive utility for each feature (tornado, wind shear, hail core) scanned
- … and the survey says…..

User feedback:

- NWS: want “mental movie” scanning “areas of interest” at regular intervals
- need context: scan areas around features (storm cell)
- want to joystick system
  (want their own network)

## User Utility Rules (revised)

- *interval-based preferences:* “do X every Y time units”
- utility considers both objects, time

| Rules | Rule trigger | Sector Selection | Elevations | # radars | Contig. | Sampling interval |
|---|---|---|---|---|---|---|
| **NWS** | | | | | | |
| N1 | time | 360 | lowest | 1 | Yes | 1 / min |
| N2 | storm | task size | [illegible] | 1 | Yes | 1 / 2.5 min |
| **EMs** | | | | | | |
| E1 | time | 360 | [illegible] | 1 | Yes | 1 / min |
| E2 | reflectivity over AOI | task size | lowest | 1 | Yes | 1 / min |
| E3 | velocity over AOI | task size | lowest | 2+ | Yes | 1/ 2.5 min |

## How to define “how important”: $U_g(t,k)$

- “naturally”: group-sensitive utility for each feature (tornado, wind shear, hail core) scanned
- … and the survey says…..

User feedback:

- NWS: want “mental movie” scanning “areas of interest” at regular intervals
- need context: scan areas around features (storm cell)
- want to joystick system (want their own network)

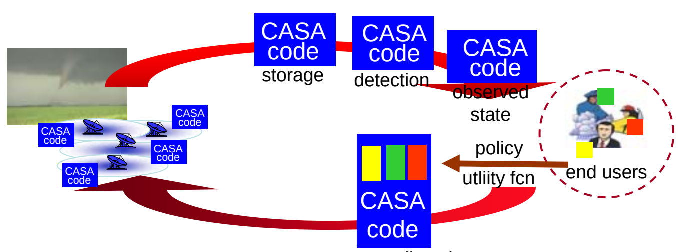
- want to joystick system
  (want their own network)

# Virtualization: enabling the end user

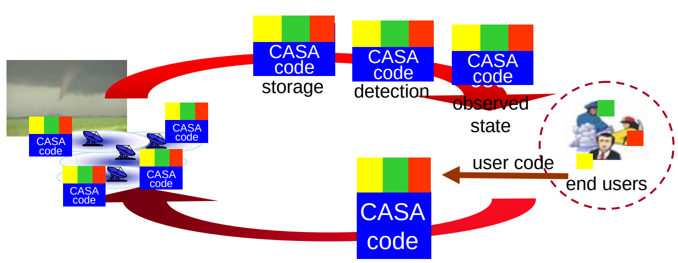
- *virtualization* of computing, communication, *and sensing* resources
- *each* user:
  - sees “standalone” sensor network
  - can modify, download, execute, experiment with own code
  - implements user-specific service outside (architecturally above) infrastructure provider

# Virtualization: making end users happy

instead
of this….

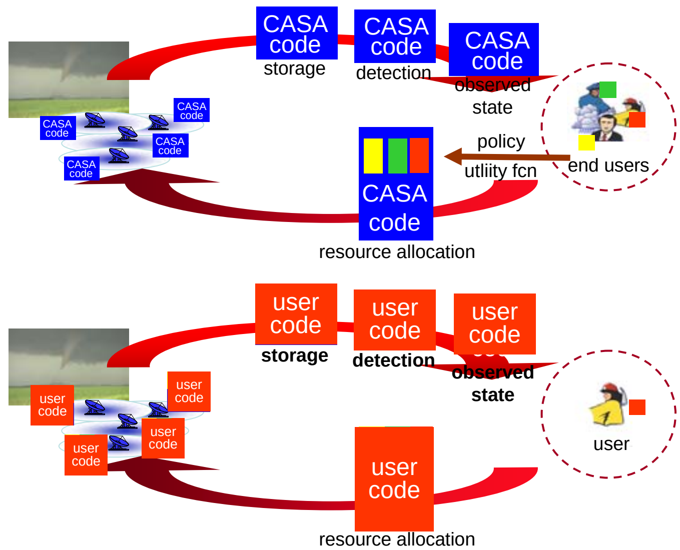



….this
system
view



# Virtualization: enabling end user

instead
of this….



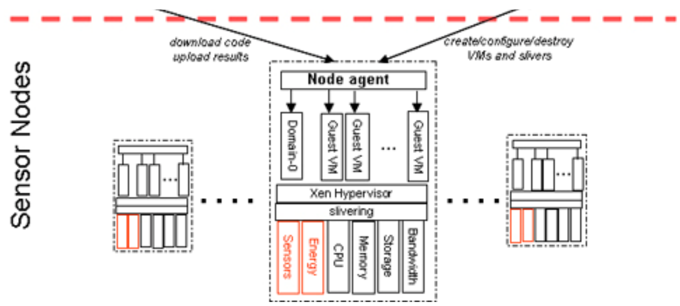

*logical user-view:* dedicated system!

# Why virtualization?

- users want programmability/resources at *in-network* nodes: computing over local data, storage
  - good application: avoid active networking redux
- challenges: virtualizing sensing resources:
  - *sharing:* sensed data from one user usable by another (unlike bandwidth, computing)
  - *admission control:* mediating among different users with different priorities
    - partially satisfiable user requests? (negotiate?)
    - time-vary allocation of resources?
    - priorities among users (policy)?

research challenges

## Sensor Virtualization Architecture




# Overview

- introduction
- CASA: collaborative adaptive sensing of the atmosphere
  - introduction, motivation
  - testbeds
- research challenges: integrating sensors, networking, computation, people
  - system architecture
  - energy-constrained environments
    - joint sensing/communication
  - incorporating end-user utilities
- discussion: the big picture

## sensing

## networking & computation

## people

*Q: How are these “linked” ?*

## The *really* big picture

- importance of the user

“It’s the end-user, stupid”

“It’s the application, stupid”

“It’s the network, stupid”

of course, not everyone agrees ….


Verizon product, 2009

# The *really* big picture

- importance of user requirements

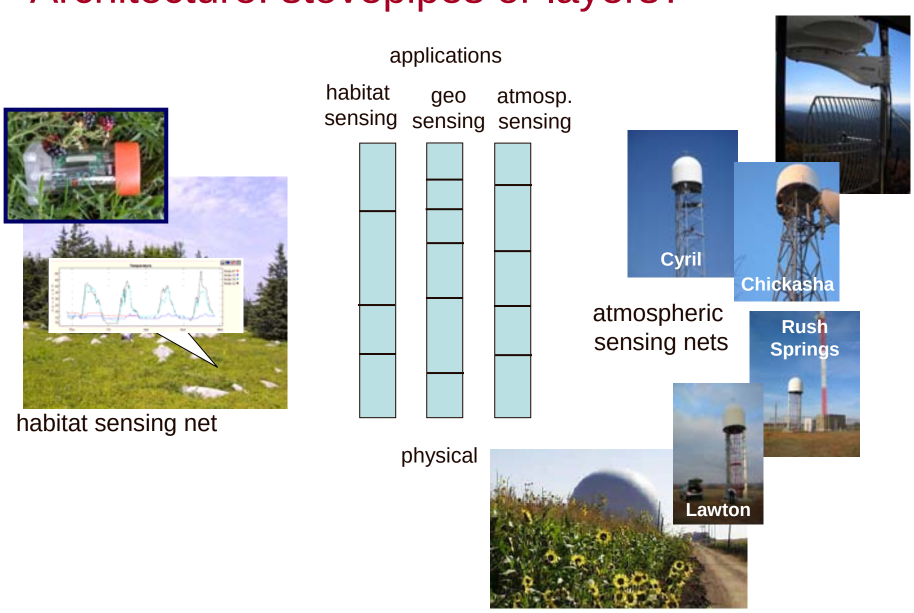
"It's the end-user, stupid"

"It's the application, stupid"

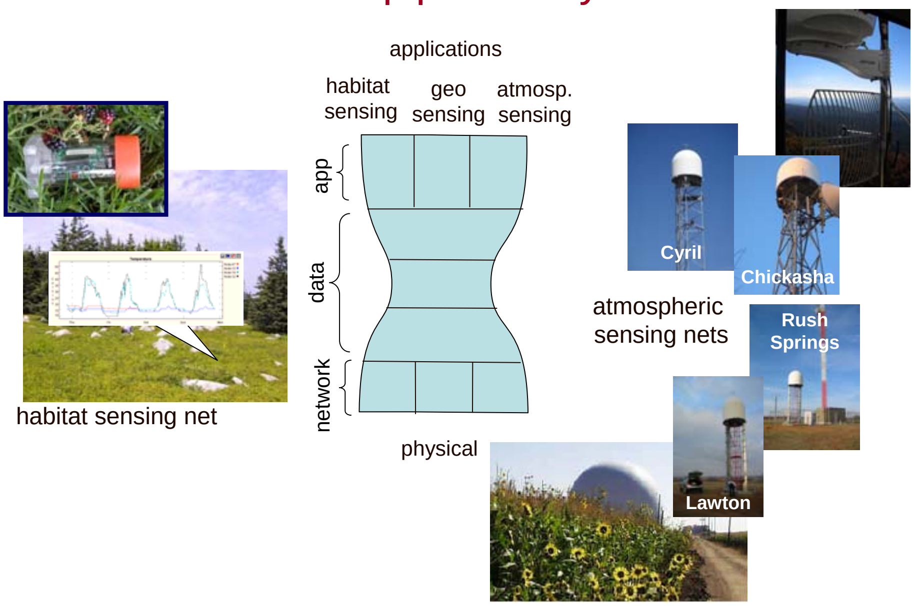
"It's the network, stupid"

- architecture (as opposed to stovepipe) for embedding user requirements?
  - sensor networks
  - content distribution
  - special-purpose overlays

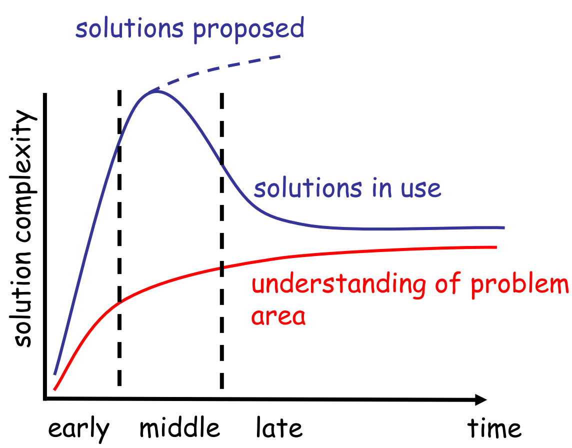
# Architecture: stovepipes or layers?



## Architecture: stovepipes or layers?




## CPS/sensor networking: where are we?




[adapted from Hluchyj 2001]

# The end

thanks!

?? || /* */