The Princeton ZebraNet Project:

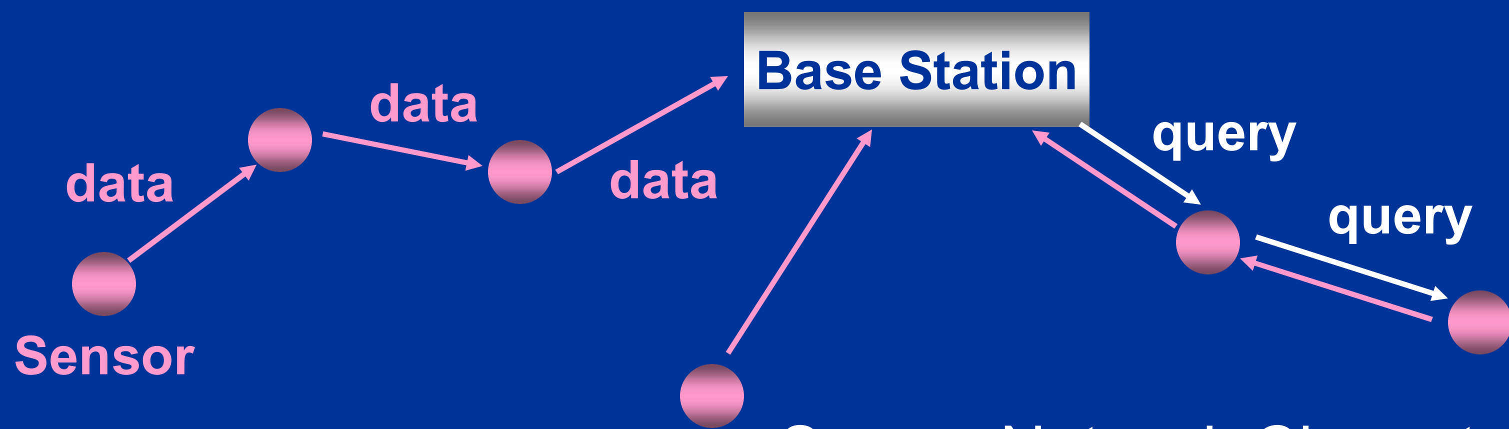
Mobile Sensors for Wildlife Tracking and Beyond

Prof. Margaret Martonosi
Dept. of Electrical Engineering
Princeton University

Sensor Networks:
Emerging Research and Societal Impact

Photo credits: UCLA, Harvard, Princeton, Lehigh

Diverse Applications, But Common Characteristics



Applications:
- Science: environmental, habitat monitoring, …
- Commercial: Traffic monitoring, social networks, manufacturing control, …
- Other: Aging-in-place, telemedicine, hazardous waste detection, …
- Homeland Security

Sensor Network Characteristics:
- Many distributed sensing nodes
- Size-constrained, energy-constrained, Bandwidth-constrained,
- Usage: Data aggregation & distributed queries
- Long-running hw, software
- Often: Mobile systems, LARGE areas to cover

Abstraction Layers and Research Questions

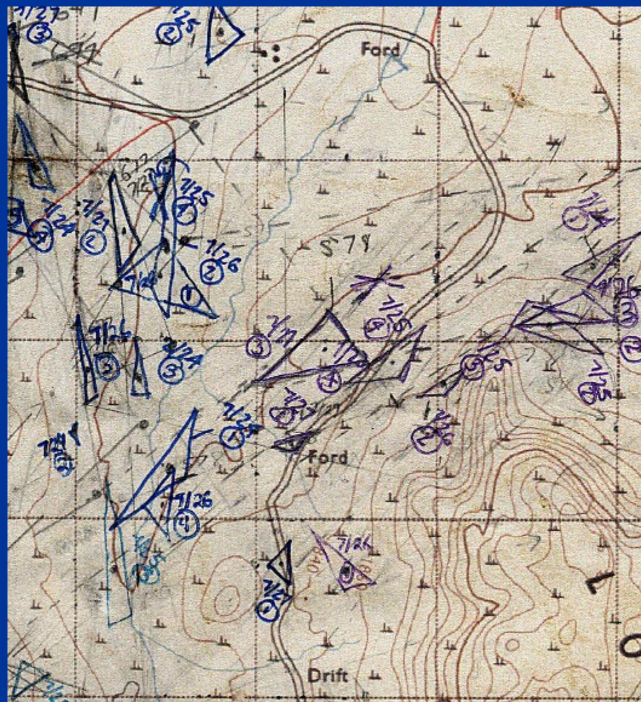
Application
Protocols & Data Collection
Middleware/OS
Hardware
Physical Design, Circuits, Antennas, …

- Portability across apps?
- Impact of app constraints and needs on design?
  - energy, weight, lifetime, datarate
  - latencies, data rates, accuracy
- Info passing between interface layers?

Talk Outline

- ZebraNet: Application Motivation & Overview
- System design Issues:
  - Protocols
  - Impala Middleware/OS
  - Hardware
- Deployment experiences and plans
- Broader applications view
- Conclusions
- More photos (time permitting)

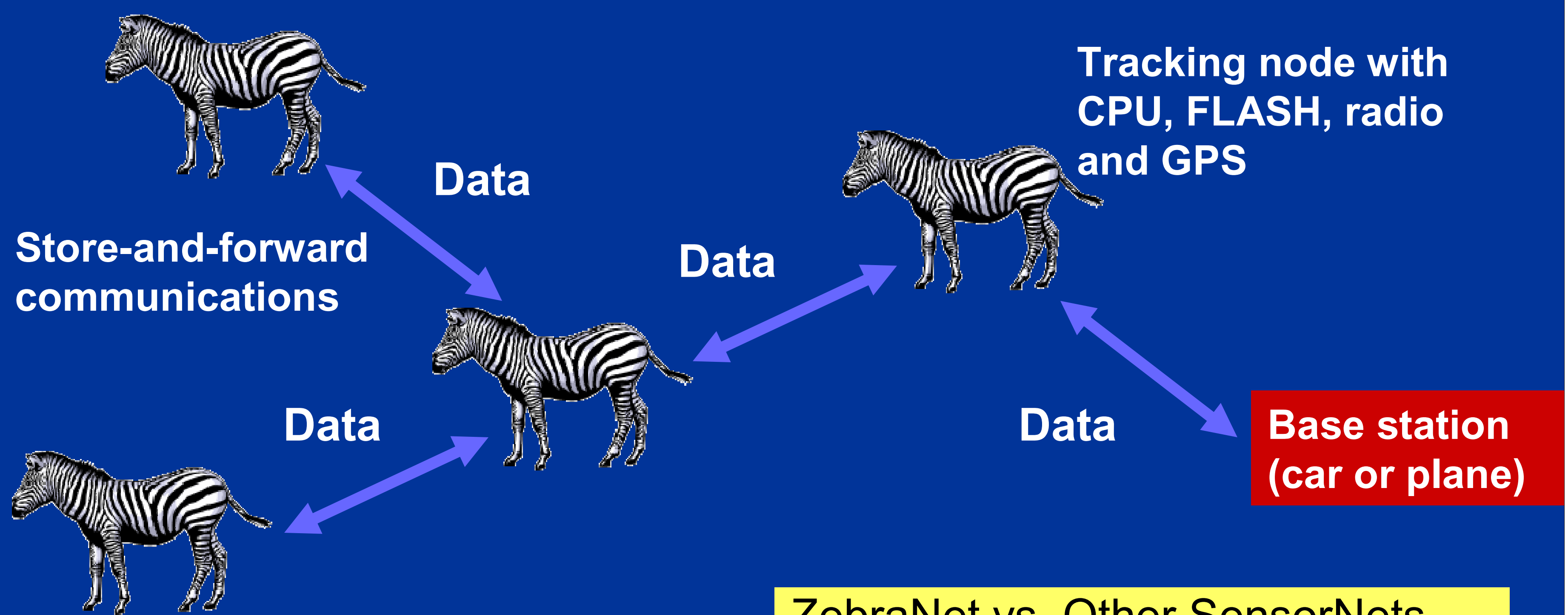
ZebraNet as Biology Research



- Goal: Biologists want to track animals long-term, over long distances
  – Interactions within a species?
  – Interactions between species?
  – Impact of human development?

- Current technology is limited:
  – VHF Triangulation is difficult & error-prone
  – GPS trackers limit data to coarse sampling and require collar retrieval
- Overall, energy and info retrieval are key limiters
- Peer-to-peer offers opportunity to improve

ZebraNet as Computing Research



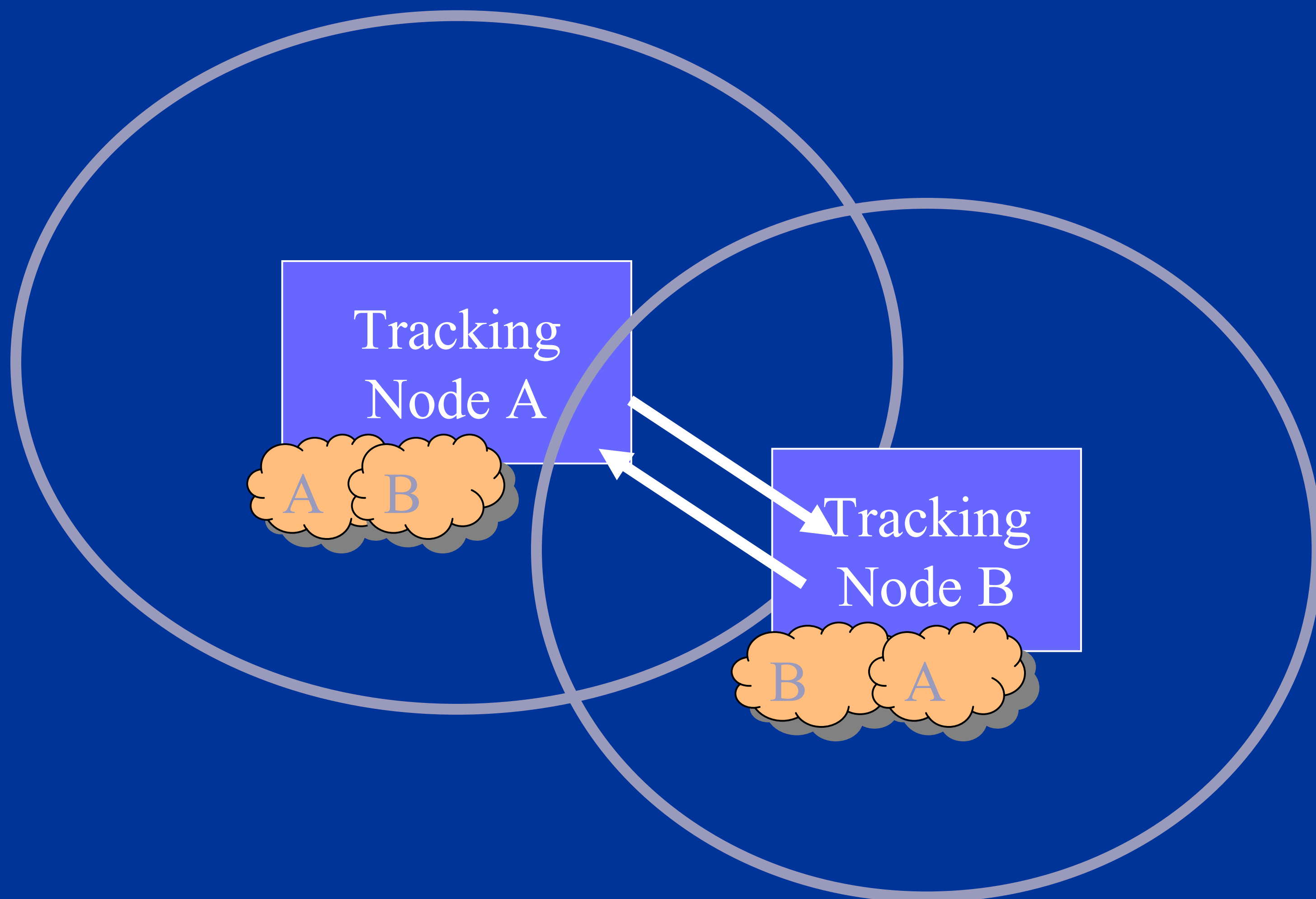
Research Questions

- Protocols and mobility?
- Energy-efficiency?
- Software layering design?

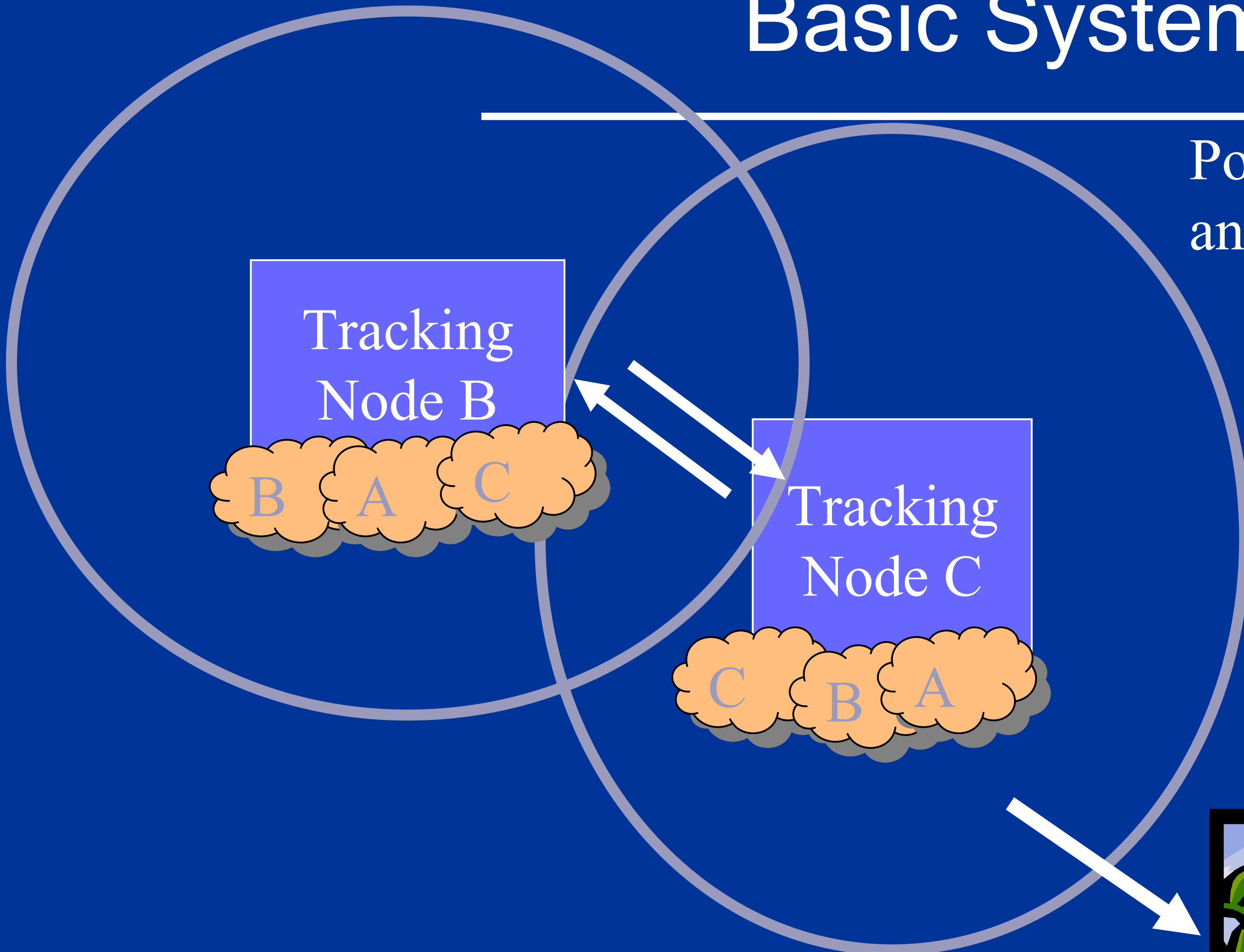
ZebraNet vs. Other SensorNets

- All sensing nodes are mobile
- Large area: 100's-1000s sq. kilometers
- "Coarse-Grained" nodes
- GPS on-board
- Long-running and autonomous

Basic System Operation

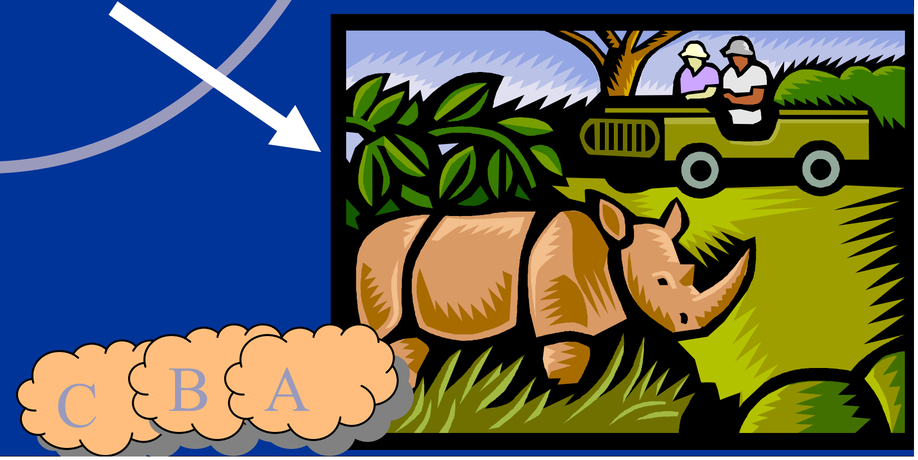


Basic System Operation



Potentially much later and far from node A…

Daily/weekly;
Car or Plane



What data to track?

Current:

- GPS Position sample every 8 minutes
- Sun/Shade indication

- ~256 bytes per hour
- 1 “collar-day of info” ~ 6KB
- ~78 collar-days in 8Mbit FLASH chip
- XYZ accelerometer data for head motions

Future:

- Ambient temperature, Body temperature, Heart rate, Low res digital images, …
- Bit rate & storage needs could increase arbitrarily…

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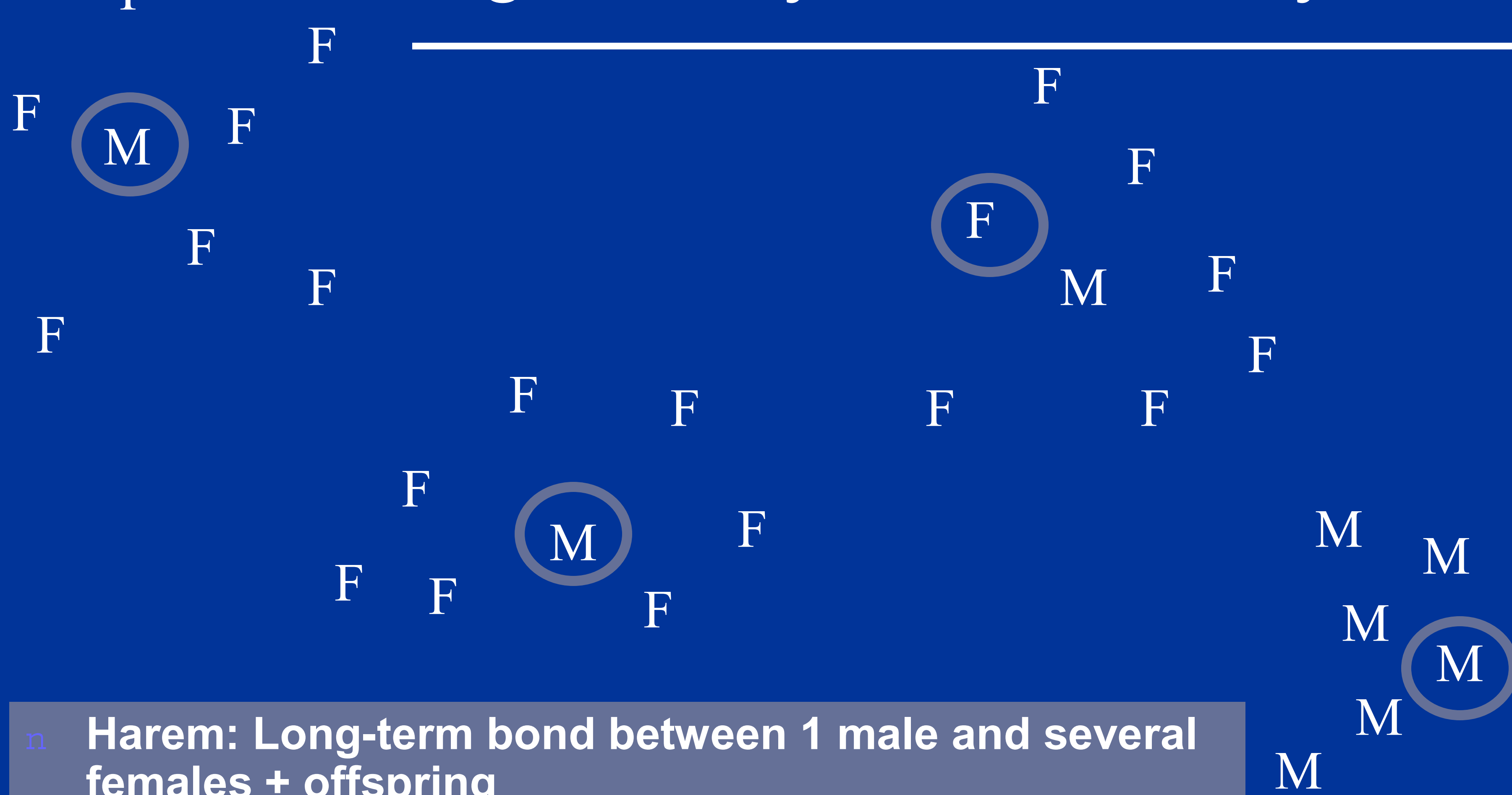
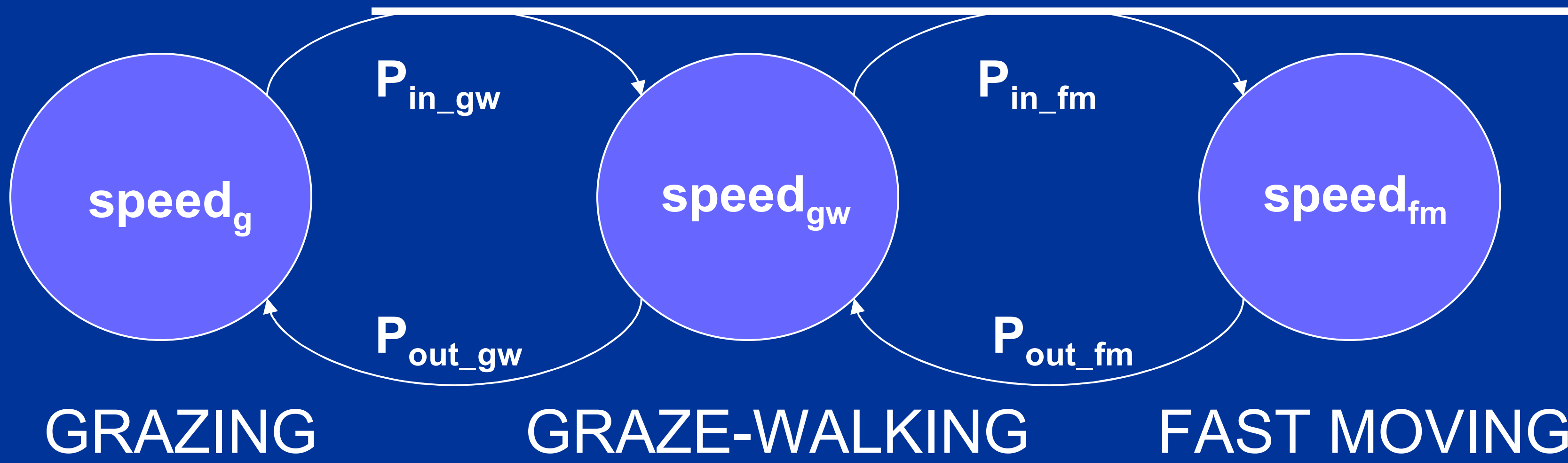
Modeling Mobility: Zebra Lifestyles…



- Harem: Long-term bond between 1 male and several females + offspring
- Herd: Looser coalition of several harems

➨ Track 30-50 samples from several harems + bachelors

Modeling Mobility: Zebra Lifestyles II

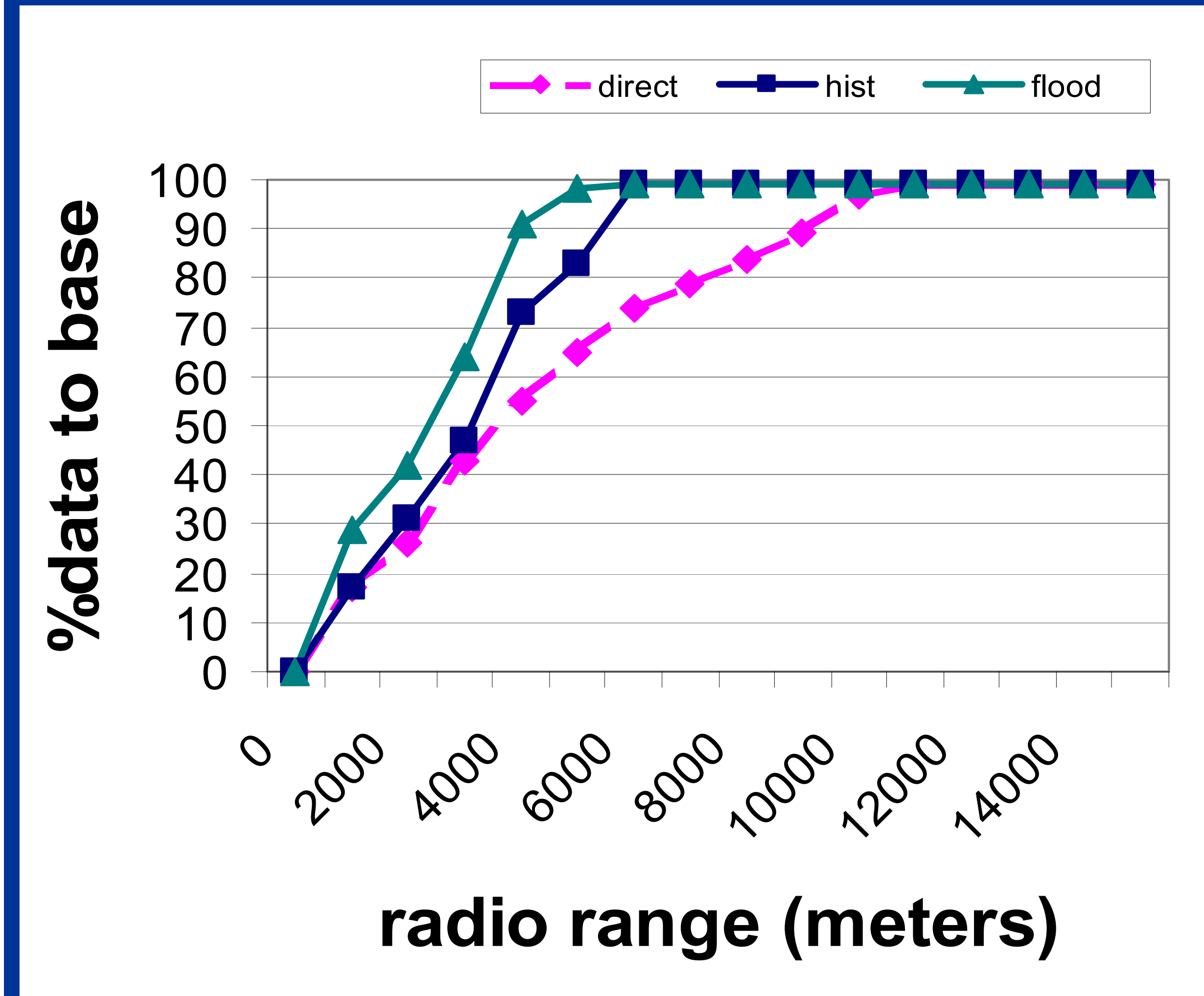


- Mostly: herbivores graze
- Sometimes: graze-walk while looking for greener pastures.
- Rare: run to/away from something

Water

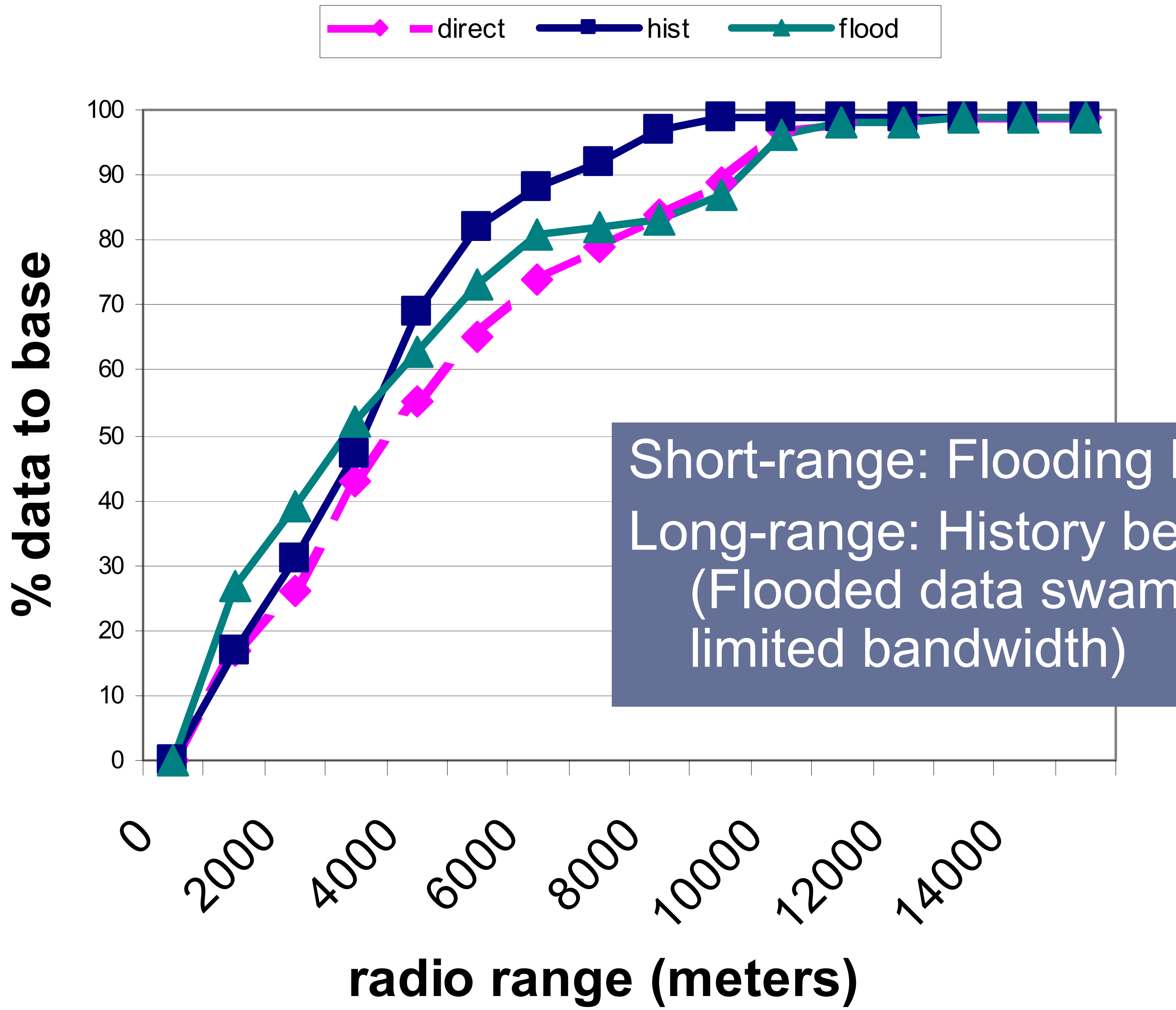
- "thirsty" ~once a day
- Model at random time
- Walk to nearest water
- After drink, resume ambient motion

Protocol Success Rate: Ideal



- Radio range for 100% delivery:
  - No peer-to-peer: ~12km
  - With Peer-to-peer: ~6km

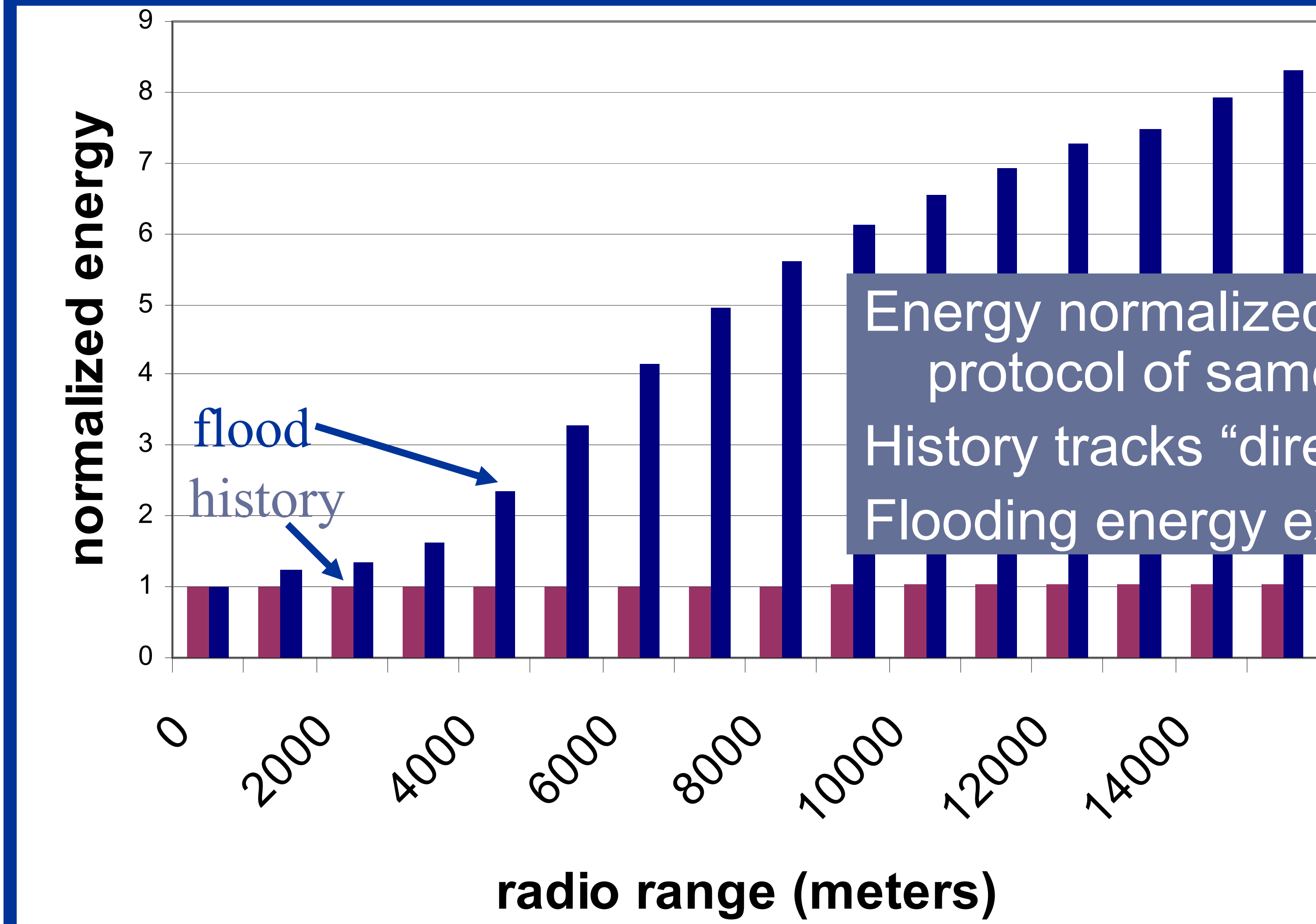
Protocol Success Rate: Constrained Bandwidth



Short-range: Flooding best

Long-range: History best. (Flooded data swamps limited bandwidth)

Protocol Energy Dissipation



- Energy normalized to “direct” protocol of same radio range.
- History tracks “direct”
- Flooding energy explodes

Mobility & Protocol Summary

- Radio range key to data homing success: ~3-4km for 50 collars in 20kmx20km area
- Success rate:
  - Ideal: flooding best
  - Constrained bandwidth: history best
- Energy trends make selective protocols best
- Mobility model key to protocol evaluations
  - Fast random moves hurt history
  - Chicken and Egg: mobility model is the biology research goal

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Applications…

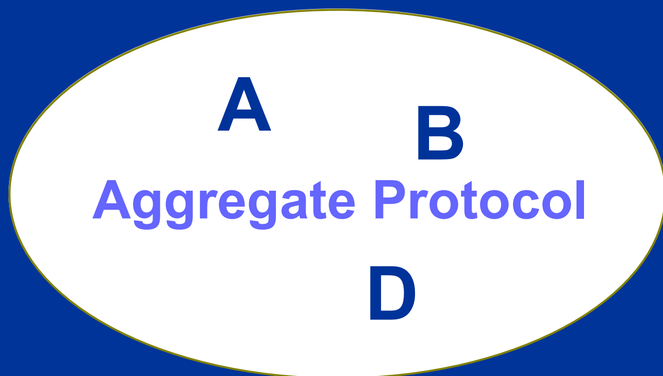
Protocols & Data Collection

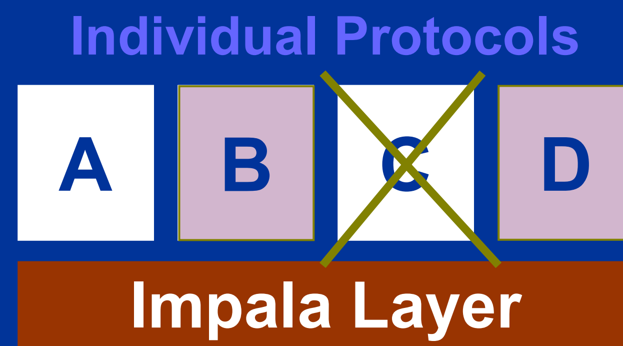
Middleware/OS

Hardware

Physical Design, Circuits, Antennas, …

Impala: Middleware/OS Support for Application/Protocol Modularity





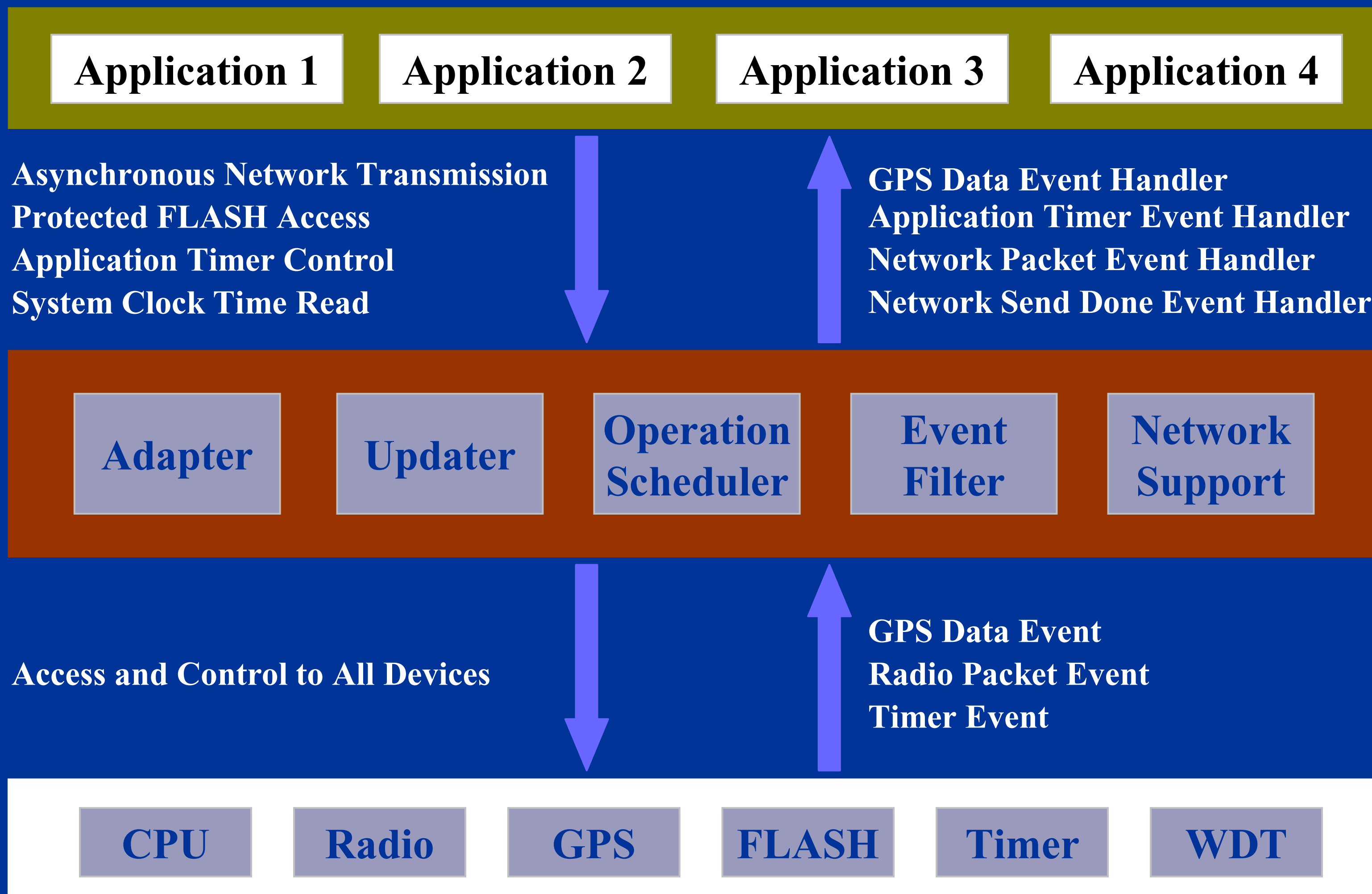
Monolithic Approach:

- Source code hardwired to particular situations
- App responsible for adapting situation/version choices
- Difficult to debug, maintain
- Difficult to update on the fly
- Difficult for other apps to reuse

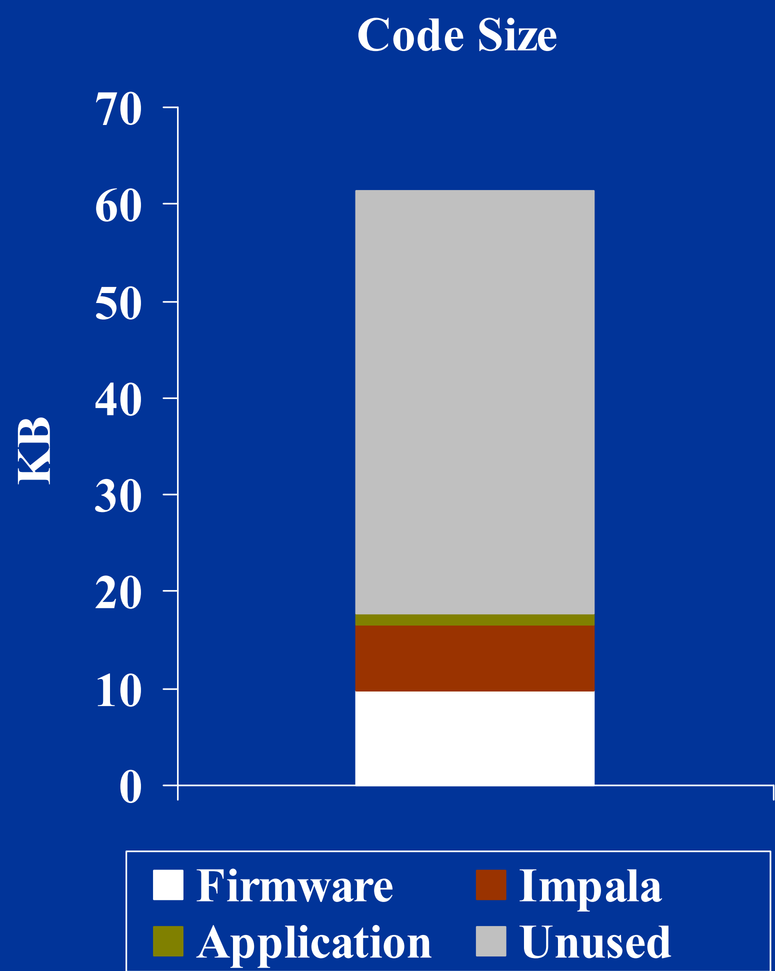
Layered Approach:

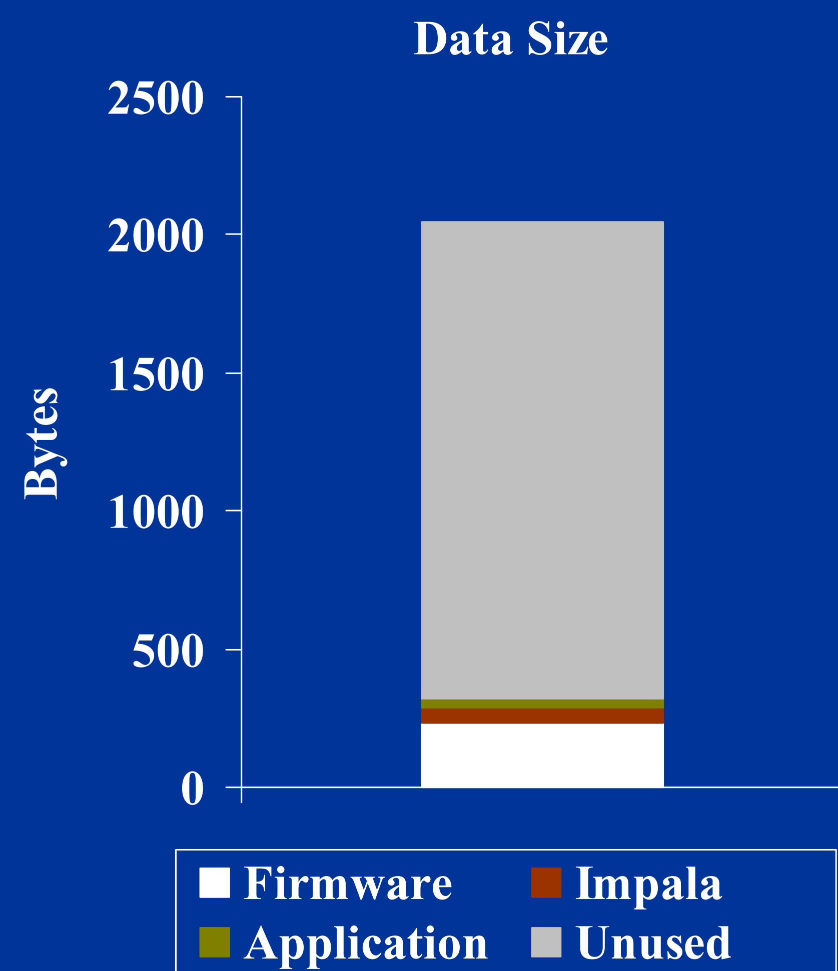
- OS provides network and event-handling services
- Middleware adapts, updates apps, protocols dynamically
- New protocols can be plugged in at any time

Impala Middleware/OS Layers

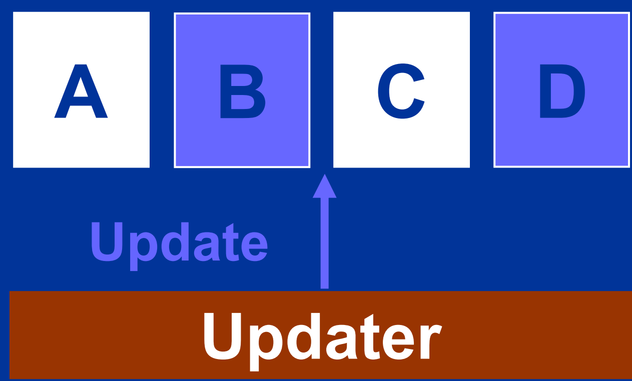


Code and Data Size: Memory Footprint of Impala Layers

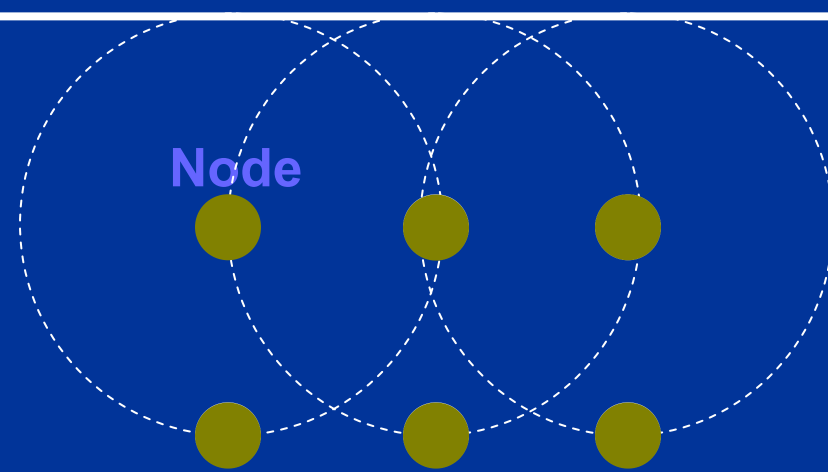




Impala Code Updates



On a single sensor node



Full network

ZebraNet Characteristics
High Node Mobility
Constrained Bandwidth
Wide Range of Updates

→

Design Implications
Incomplete Updates
Updates vs. Execution
Out of order Updates

Impala Status and Summary

- Sensor networks need modular, adaptable, repairable software
- Impala OS:
  - lightweight common support for sensor services & networking
  - Event handler & low-level services
- Impala middleware
  - Adaptive application management
  - Remote software update
- Prototype implementations and simulations demonstrate:
  - Low overhead
  - Efficient network reprogramming
  - Code updates

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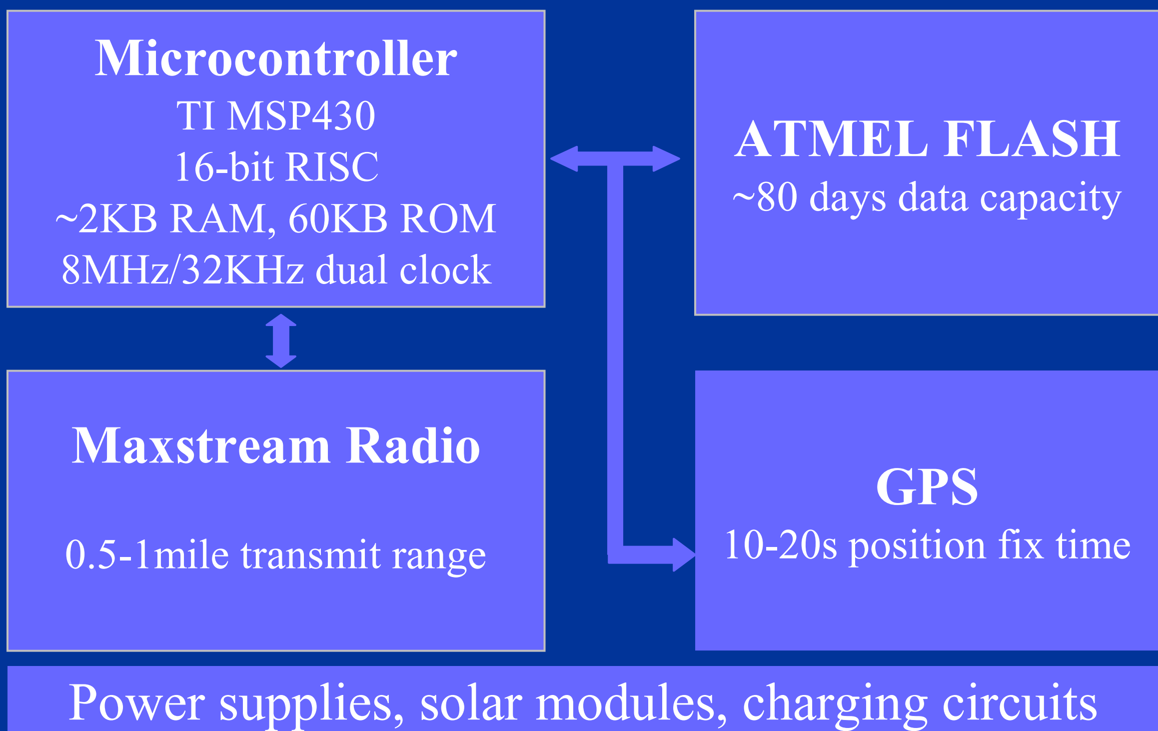
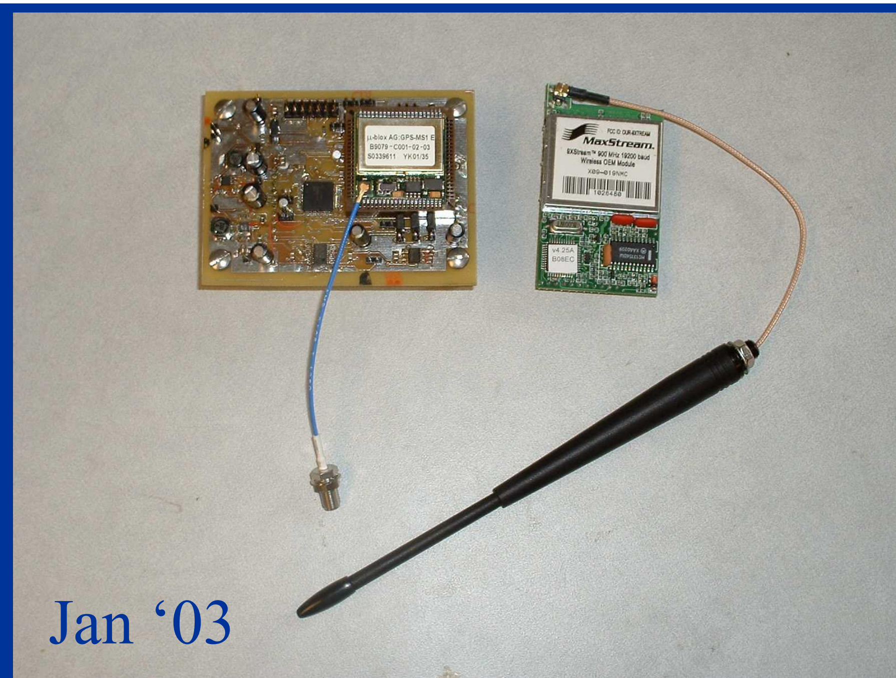
ZebraNet Hardware Design



Mode	Power
32Khz CPU	9.6 mW
8MHz CPU	19.32 mW
8MHz w/ GPS	568 mW
8MHz + radio xmit	780 mW
8MHz + radio rcv	312 mW

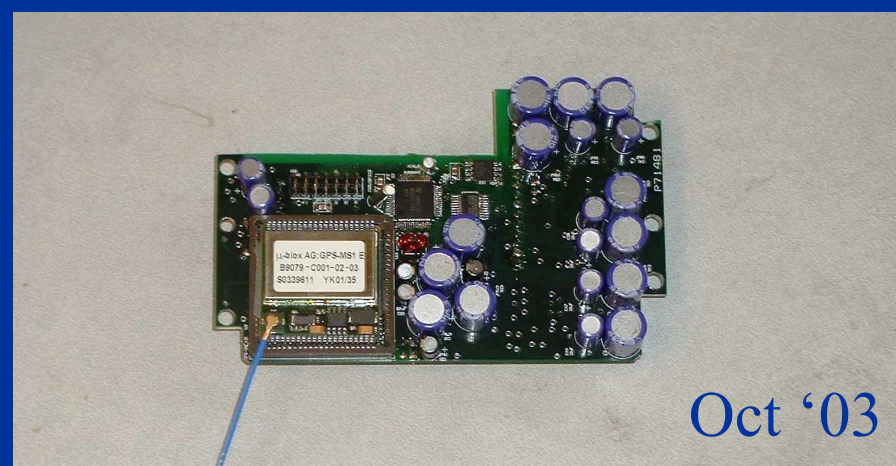
ZebraNet Hardware: Time-Lapse View…

Aug ‘02

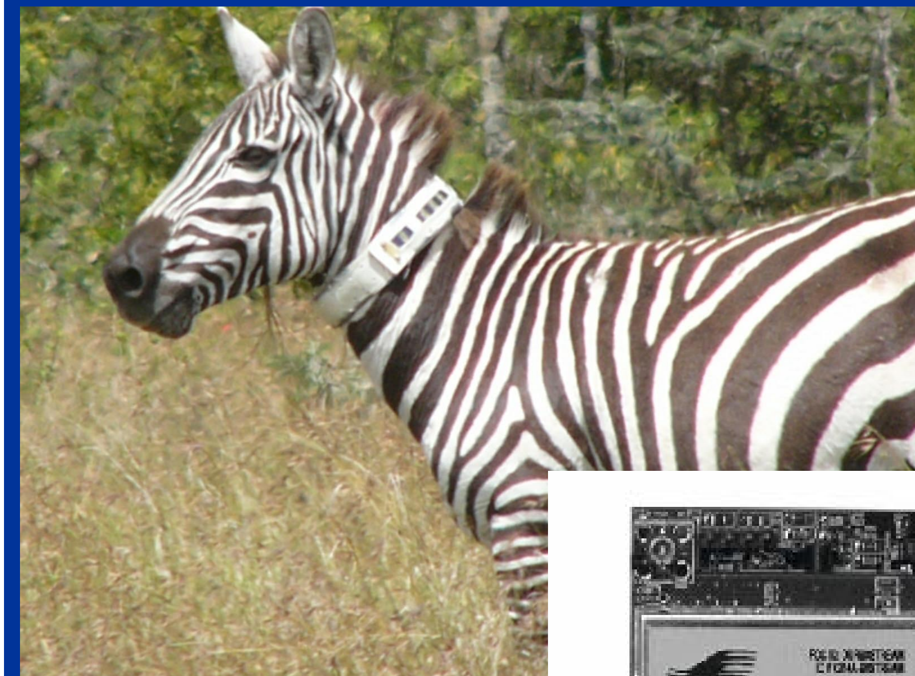


Jan ‘03


Aug ‘03


Oct ‘03

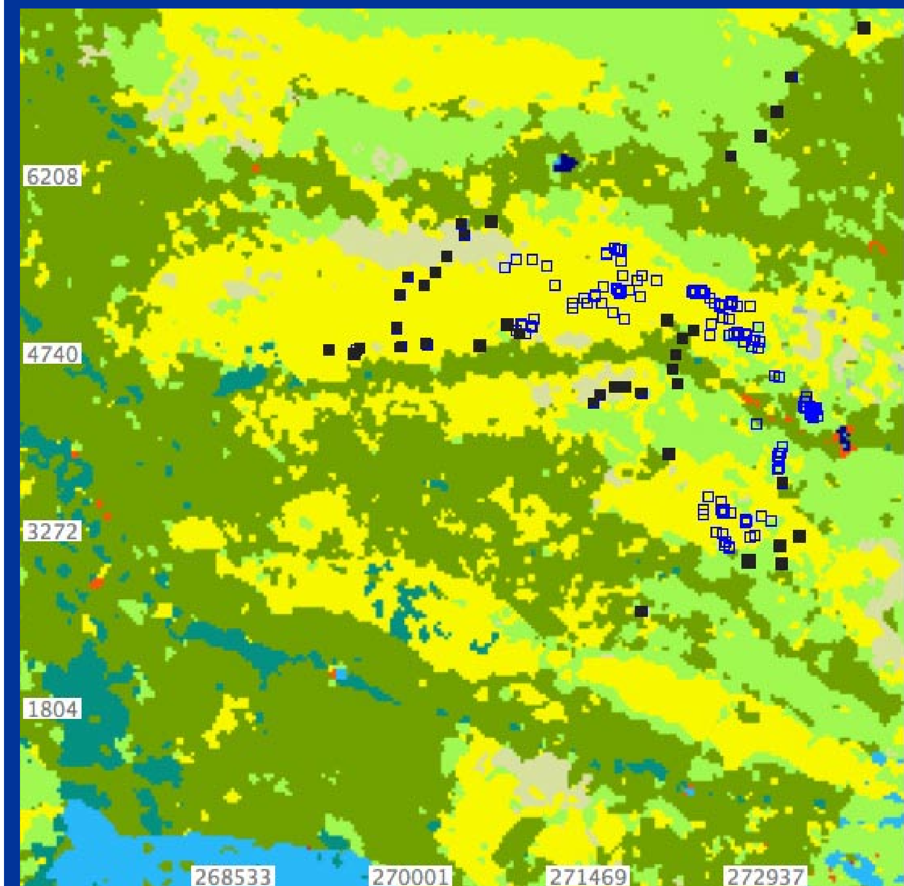
January, 2004 ZebraNet Hardware



January, 2004: Initial test deployment

- Ate/slept/worked at Mpala Research Centre near Nanyuki Kenya
- Deployed collars at Sweetwaters Preserve, also near Nanyuki Kenya

Deployment Results



Biology

- Zebras affected by collar first day (head shaking) but little thereafter
- First night-time zebra movement data: animals appear to explore more wooded areas and gullies at night

Engineering

- Radio range: <1km in final collar packaging,
  - Disappointing vs. NJ tests
  - Even more attention needed on ground plane and noise effects
- Communication protocols: generally worked as plans, although duplicated ACK packets improved their performance

15 months later…

- Collar on Zebra for roughly 1.25 years
  - Hot sun, tough weather.
- Zebra attacked/killed by a lion (not unusual, probably not related to collar)
- How did the collar do?

Next Steps

Second Deployment: June/July, 2005

- Amorphous silicon solar cells with Tefzel coating
- Leather rather than butyl rubber collar
- New version of msp processor
- New radio
- New GPS
- New collar design
- Improved code (latencies, interrupt handling….)

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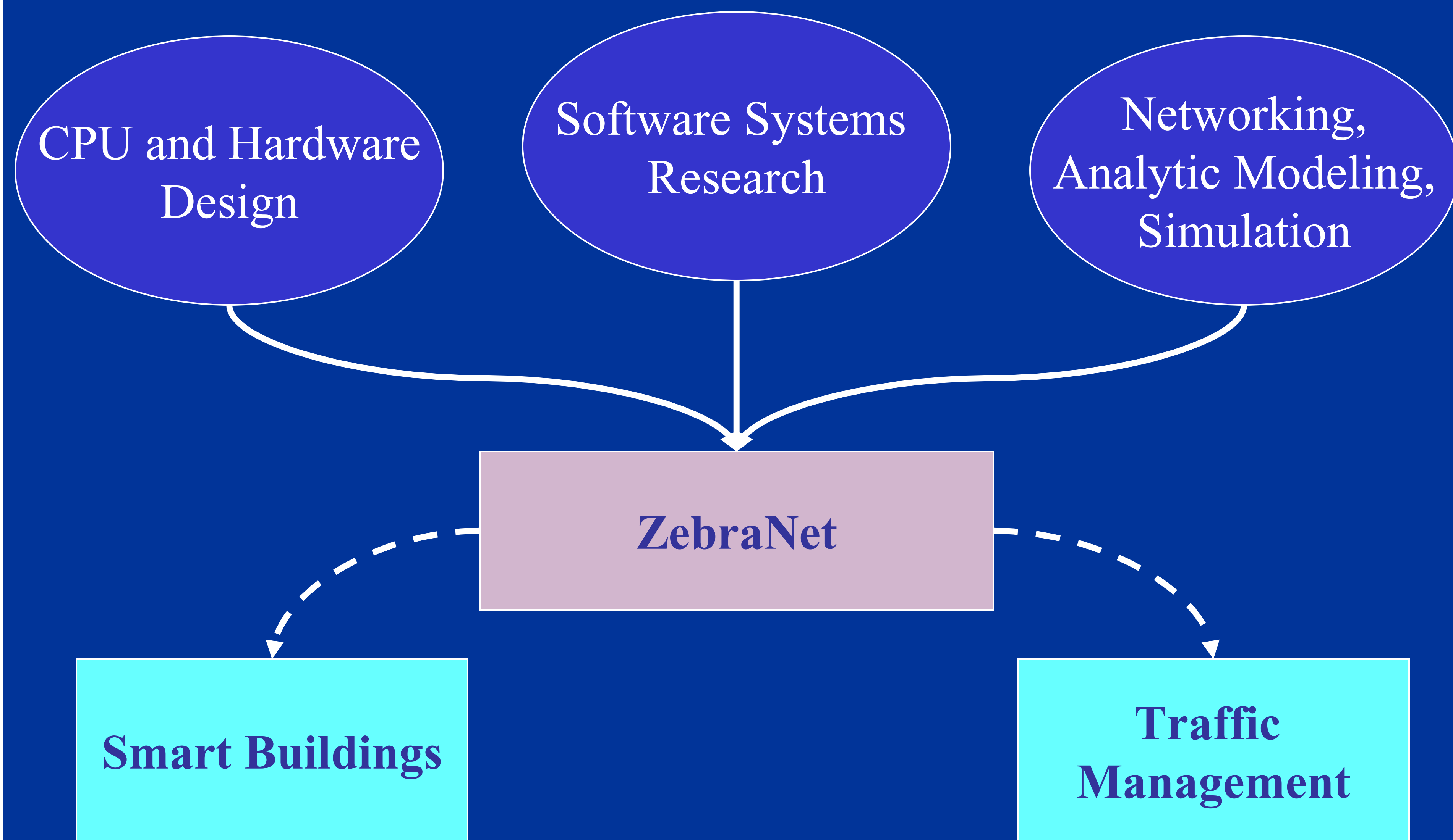
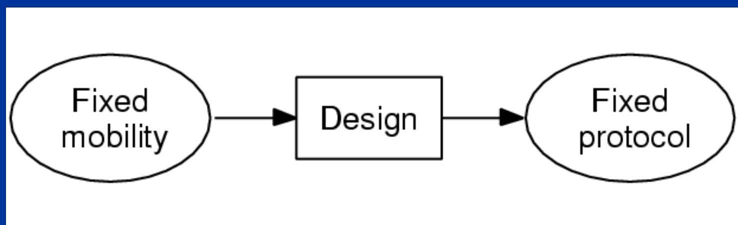
Applications…
Protocols & Data Collection
Middleware/OS
Hardware
Physical Design, Circuits, Antennas, …

More than just zebras…



Model-based Mobility-Adaptive Protocols



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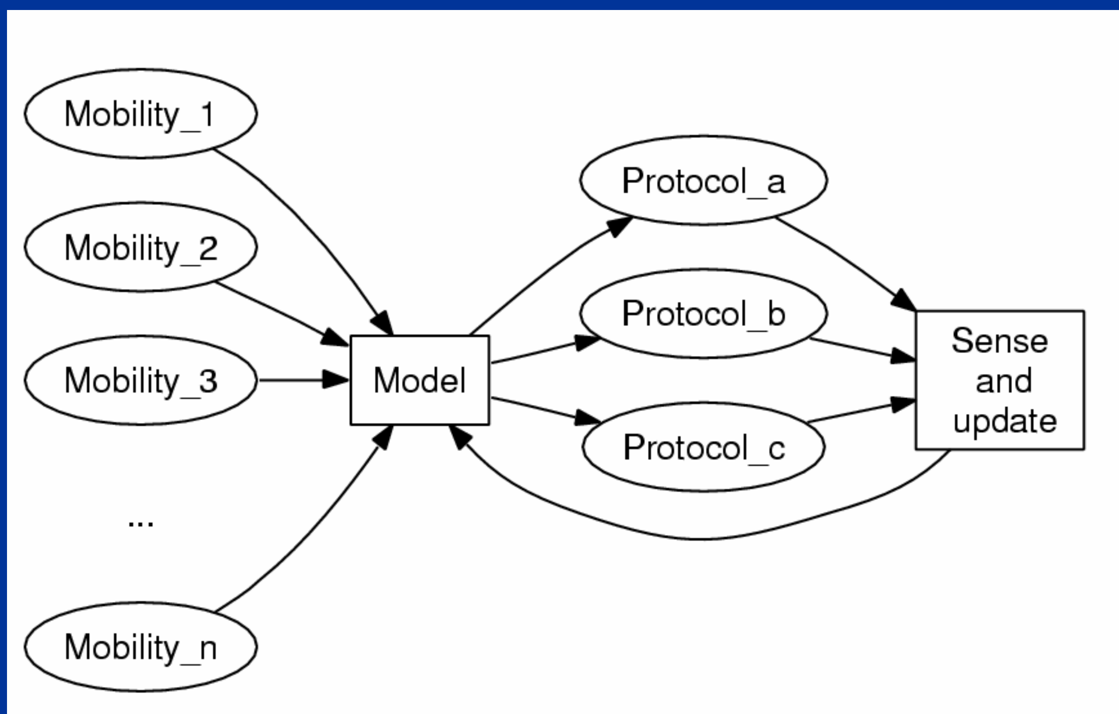
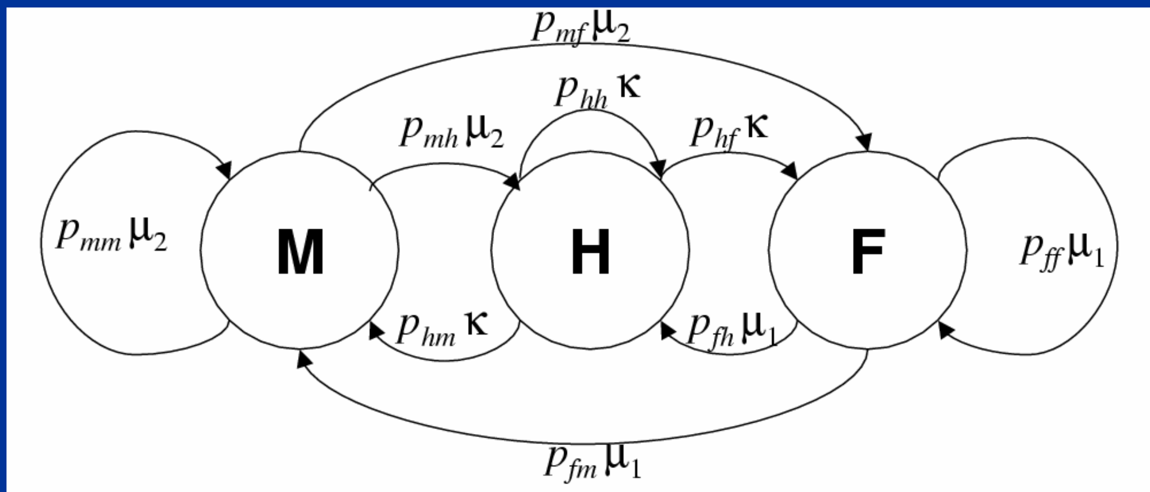


[Model-based]

With Yong Wang, LS Peh, Mobihoc 2004

Example: Markov Model based on route cache lifetimes



Markov route cache model

Traffic Rate	Original (DSR)	Markov approach	% latency improvement
2 pkts/s	6.2	5.2	16%
4 pkts/s	4.1	3	27%
8 pkts/s	2.7	2.1	22%

Erasure-Coding Based Routing for Disruption-Tolerant Networks

- In sparse, disrupted networks like ZebraNet, inter-contact duration (link-off time) is heavy-tailed
  - Flooding to all nodes will work but with heavy energy/storage cost
  - Reducing flooding risks choosing “loner” or unreliable nodes.
- Erasure-coding approach
  - Replicate via erasure-coded packets, rather than strict redundancy.
  - Partial packet delivery can be used to reconstruct original message
- Results depend on mobility/connectivity model, but overall:
  - Erasure-coded replication tends to increase success rate
  - With slight degradation in “best-case” latency

Summary

- ZebraNet as Biology Research:
  - Enabling technology for long-range migration research
  - Good view of key inter-species interactions
- ZebraNet as Engineering Research:
  - Early detailed look at mobile sensor net with mobile base stations
  - Demonstrates promise of large-extent, long-life sensor networks with GPS
  - Detailed look at power/energy concerns
  - Novel protocol, middleware, and hardware designs to support research goals
- Sensor Networks Overall
  - Unique characteristics and challenges: Energy-constraints, Mobility, Long-lived hardware/software

The Princeton ZebraNet Project: Mobile Sensor Networks for Wildlife Tracking

ZebraNet Folks at Mpala Research Centre, near Nanyuki, Kenya. January 2004.

- *Grads: Pei Zhang, Chris Sadler, Ting Liu, Ilya Fischoff,* Yong Wang, Philo Juang.
- Profs: *me, Dan Rubenstein, Steve Lyon,* Li-Shiuan Peh, Vince Poor.
- Undergrads: Julie Buechner, Chido Enyinna, Brad Hill, Kinari Patel, Karen Tang, Jeremy Wall
- Departments of EE, CS, and Biology at Princeton
- Funded by NSF ITR since 9/2002

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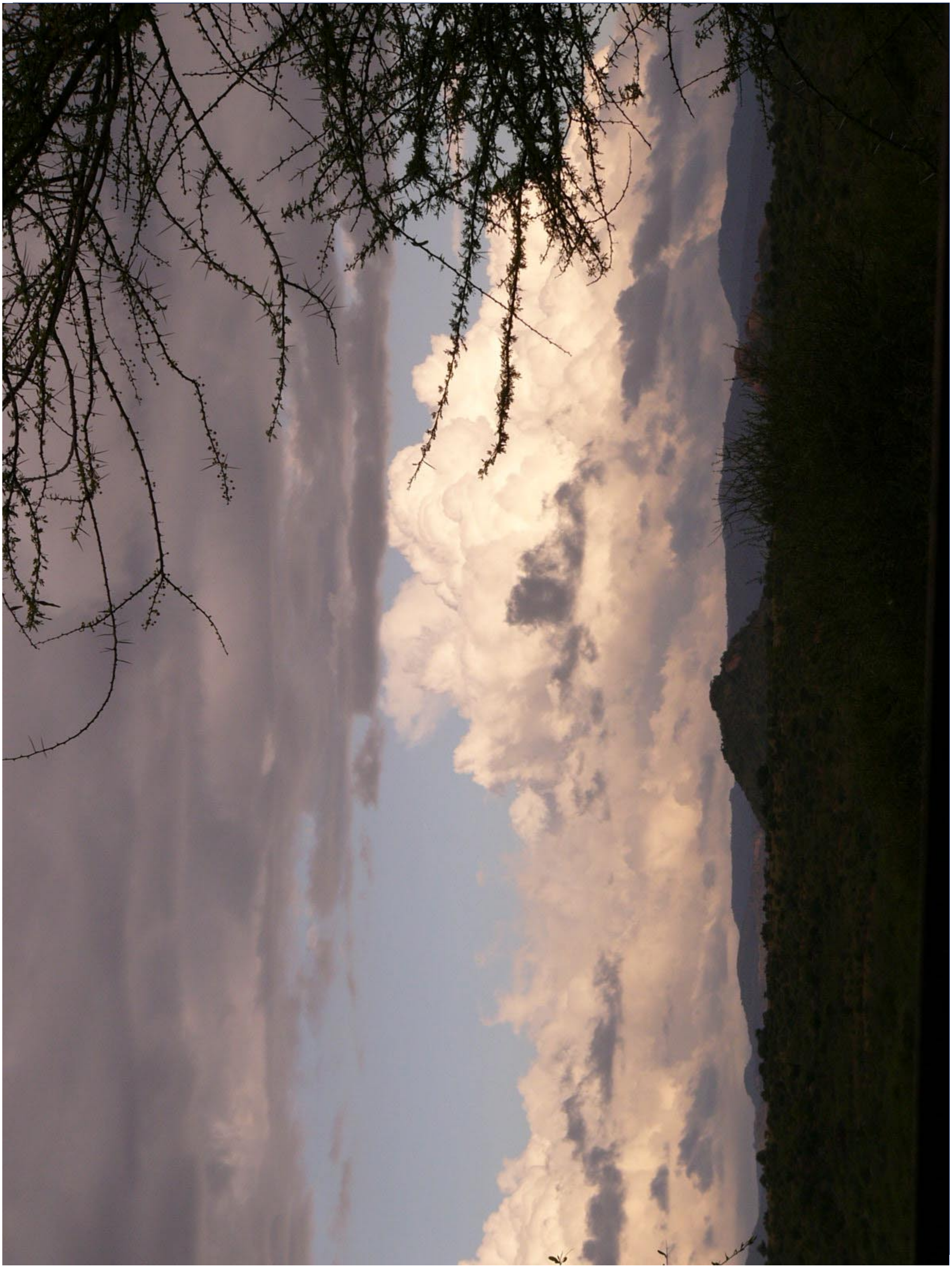
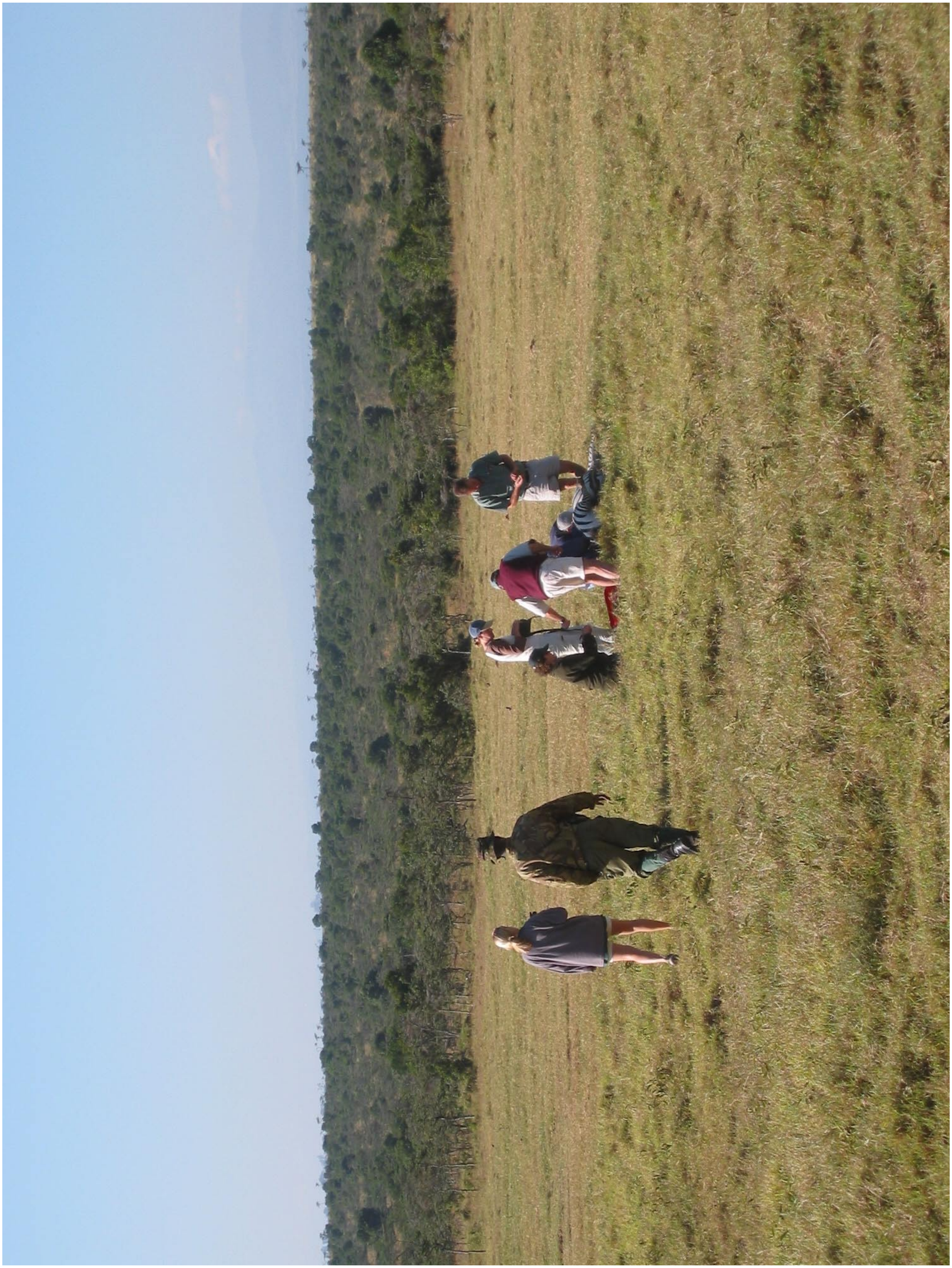



VISITORS INFORMATION CENTRE




LOCAL CRAFTS

More questions?

For more info, see papers:
ASPLOS02, PPOPP03, Mobisys04,SenSys04

… and my webpage
www.princeton.edu/~mrm