CS 194: Distributed Systems
OpenDHT
and
Introduction to SensorNets

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Announcements

- My office hours this week: not today, but Th 10-11
- HW #4 will be out shortly....

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Why OpenDHT?

Consider FreeDB (the CD metadata database)

- Two options to implement large-scale FreeDB

1. Implement your own DHT:
   - Find 500 nodes you can use
   - Run DHT 24/7
   - Debug DHT problems when they occur
2. Use OpenDHT:
   - 58 lines of Perl

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Challenges

- Interface
- Security (securing interface)
- Resource allocation
- Beyond rendezvous
  - ReDiR
  - Range queries

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Three Classes of DHT Interfaces

- Routing: app-specific code at each hop
- Lookup: app-specific code at endpoint
- Storage: put/get

For a shared infrastructure that can't incorporate app-specific code, the only choice is put/get

- Limited flexibility
- Does convenience outweigh constraints?

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Basic Interface

- put(k,v,t): write (k,v) for TTL t
- Why TTL? No garbage collection...

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Security Worries

- Modifying: changing data stored by someone else
- Squatting: getting key first and not allowing others to use it
- Drowning: storing many values at certain key, so that client can't get data they want without sifting through huge pile

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Put/Get Interface w/Authentication

- put-unauth(k,v,t): append-only (no remove), no auth
  - *no modifying, no squatting, but drowning*
  - for easy use
- put-immutable(k,v,t): k=H(v)
  - *no modifying, squatting or drowning, but no flexibility in key choice*
- put-auth(k,v,t;n,K,s): removable, authenticated
  - n is sequence number
  - Public key K
  - s=H(k,v,n) signed with private key
  - get-auth(k,H(K)) retrieves only entries with that public key
  - *no modifying, squatting, or drowning, and flexibility of key choice*

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Resource Allocation

- Consider a put of size B and TTL T
- The resource consumed by that put is BT
- Resource allocation strategy:
  - At any one time, allocate resources to keep instantaneous rate of resource allocation even
  - Leave enough room for future puts

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Storage Constraint Equation

- Baseline rate: r_{min}
- Disk capacity C
- Let S(t) be total number of current bytes that will still be on disk at time t
- A put of size b can be accepted iff

$$S(t)+b + t\cdot r_{min} \leq C \text{ for } 0 \leq t \leq T$$

different notation than Sean's

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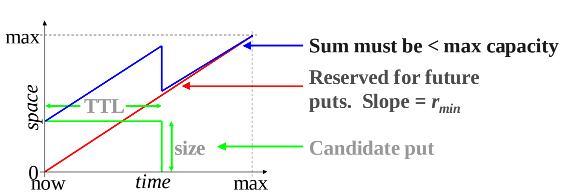
Does it Fit?



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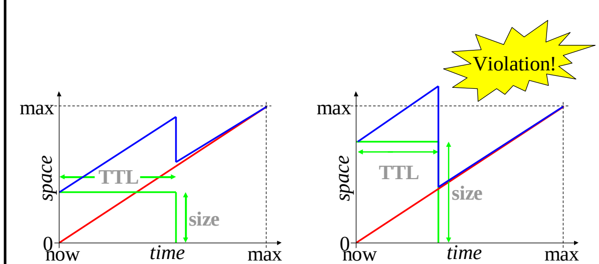
Does it Fit?



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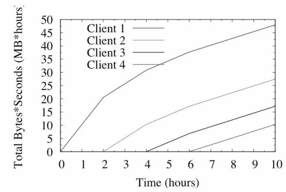
Performance



Key point: slopes of all lines the same at all times!

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Beyond Rendezvous

- More complicated queries
- Application-specific processing

without changing interface!

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Range Queries

- Useful for many applications like databases and publish-subscribe systems
  - but not directly supported by a DHT
- Existing approaches require changes to DHT implementation
  - Skip Graphs [Shah et al, SODA 2003]
  - Load Balancing [Karger et al, SPAA 2004]
- How can range queries be supported on top of a generic put/get interface?

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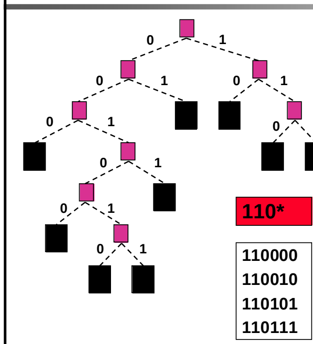
Prefix Hash Tree



Trie data structure

Data items are stored at leaf nodes with matching prefixes

Logical structure mapped to DHT nodes by hashing prefix labels

HASH(110*) ⇒ key

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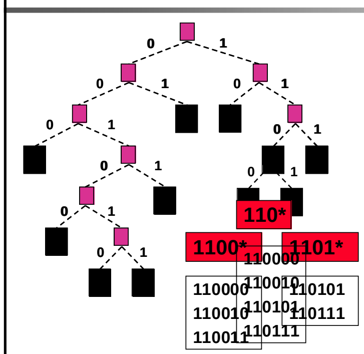
Insertion / Deletion



Leaf nodes have a capacity constraint *B*

Insertion could result in the splitting of a leaf node

For example, Insert(110011) (*B* = 4)

Conversely, deletion could result in the merging of two sibling leaf nodes

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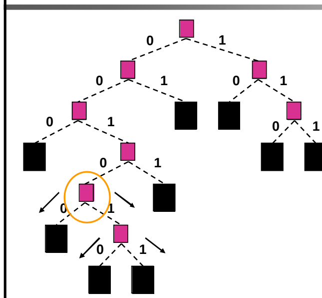
Range Queries



Parallel traversal of smallest sub-trie completely covering range query

Root of this sub-trie can be directly accessed instead of top-down traversal

For example, Query(9,11)

HASH(0010*)

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PHT Properties

- Efficient: Operations are doubly logarithmic in domain size due to direct access
- Load Balanced: Top-down traversal is not required, reducing load in upper levels of the trie
- Fault-tolerant: Node failure does not affect the ability to access data available at other nodes

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Application-Specific Functionality

- How can you apply application-specific functionality to OpenDHT applications?
- Approach: use OpenDHT for routing, use external nodes nodes for application-specific processing
  - Application owner doesn't need to understand DHTs
  - Can write application assuming a lookup(key) operation just works
- Accomplished through a client library called ReDiR
  - takes application lookup(key) calls and returns with proper IP address (of external node) using put/get interface on OpenDHT

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ReDiR

- Each set of app-specific nodes is assigned a namespace
- Each node has a key in that namespace
- ReDiR supports:
  - join(namespace, key, ip)
  - lookup(namespace, key)

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ReDiR

- Consider multiple "levels" of the key space
- The l'th level has 2^l partitions
- The namespace is assigned a key in each partition
  - mirror elements

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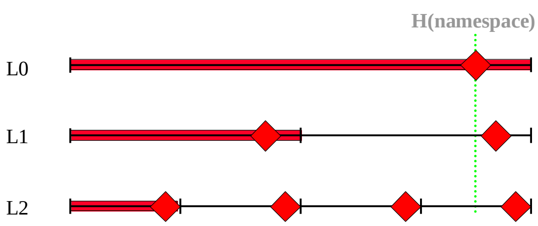
ReDiR "Homes"



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ReDiR Join Rule

- Store your (key, IP) at the namespace key in the lowest partition and continue to higher levels, stopping only after you've stored at a level where you aren't the lowest key
  - There's a more sophisticated method using both highest or lower
- When you are the highest or lowest, "kick out" the previous lowest
  - not necessary with soft state, but for the sake of the presentation

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ReDiR Lookup Rule

- Keep going up levels until you find a successor
- You are guaranteed that that's your successor (aside from the lowest level)
  - Why?

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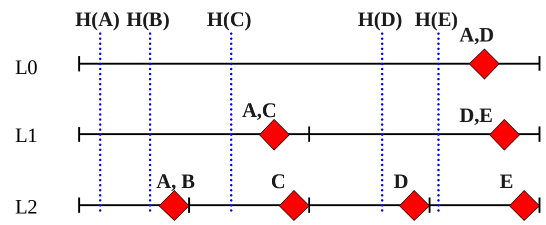
ReDiR Join

- Join cost:
  - Worst case: O(log *n*) puts and gets
  - Average case: O(1) puts and gets



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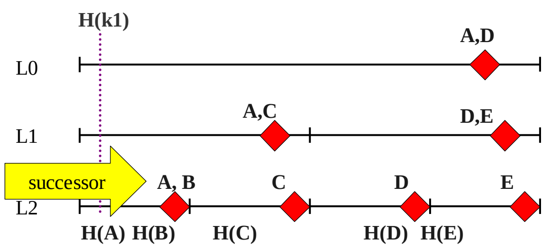
ReDiR Lookup



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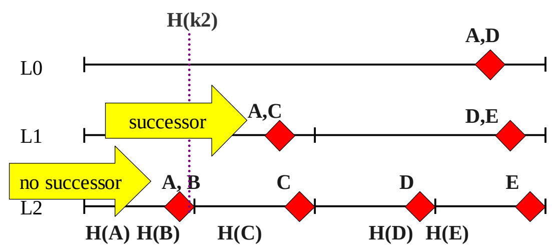
ReDiR Lookup



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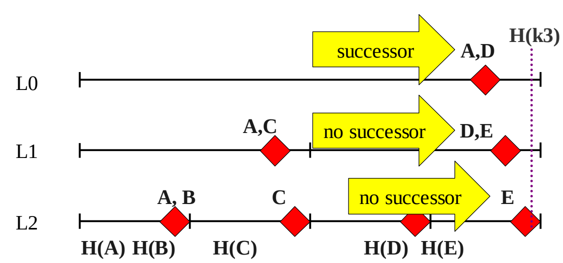
ReDiR Lookup



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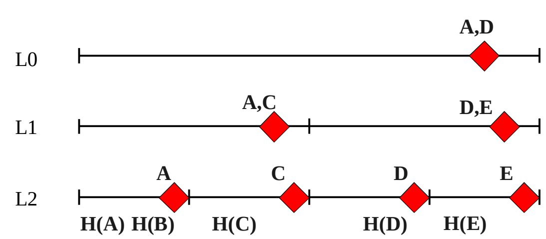
ReDiR Lookup

- Lookup cost:
  - Worst case: O(log *n*) gets
  - Average case: O(1) gets



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Wireless Sensor Networks

based on a tutorial by Ramesh Govindan

All Three Words Count

- Wireless: no lines (network or power)
- Sensors: tied to real world
- Networks: not just a single hop

Sensing

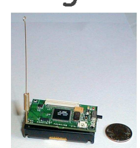
Remote Sensing

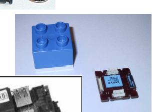
In-situ Sensing

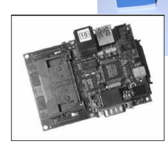
Networked Sensing

Networked Sensing Enabler

- Small (coin, matchbox sized) nodes with
  - Processor
    - 8-bit processors to x86 class processors
  - Memory
    - Kbytes – Mbytes range
  - Radio
    - 20-100 Kbps initially
- Battery powered
- Built-in sensors!

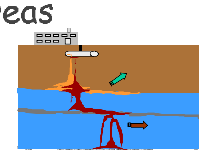






Application Areas

Seismic Structure response

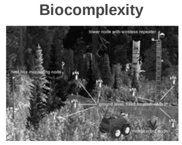


Contaminant Transport

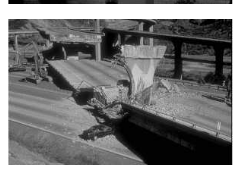
Structural Condition Assessment

Marine Microorganisms

Ecosystems, Biocomplexity

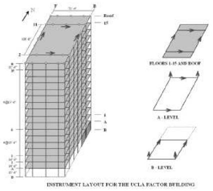


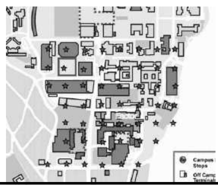
Seismic Structure Response

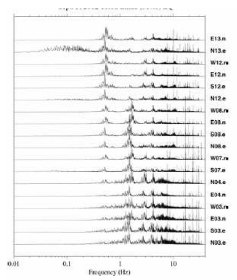


- Interaction between ground motions and structure/foundation response not well understood.
- Current seismic networks not spatially dense enough
  - to monitor structure deformation in response to ground motion.
  - to sample wavefield without spatial aliasing.

A Wired Seismic Array







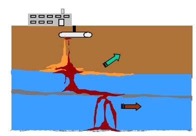
A Wireless Seismic Array

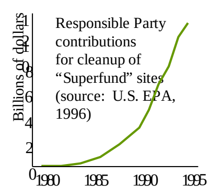
- Use motes for seismic data collection
  - Small scale (10 or so)
  - Opportunity: validate with existing wired infrastructure
- Two on-going experiments
  - Factor building
  - Four Seasons building

Condition Assessment

- Longer-term
- Challenges:
  - Detection of damage (cracks) in structures
  - Analysis of stress histories for damage prediction
- Applicable not just to buildings
  - Bridges, aircraft

Contaminant Transport



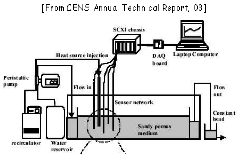


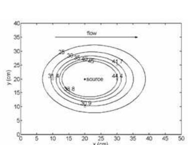
- Industrial effluent dispersal can be enormously damaging to the environment
  - marine contaminants
  - groundwater contaminants
- Study of contaminant transport involves
  - Understanding the physical (soil structure), chemical (interaction with and impact on nutrients), and biological (effect on plants and marine life) aspects of contaminants
  - Modeling their transports
- Mature field!
- Fine-grain sensing can help

Lab-Scale Experiments

- Use surrogates (e.g. heat transfer) to study contaminant transport
- Testbed
  - Tank with heat source and embedded thermistors
  - Measure and model heat flow

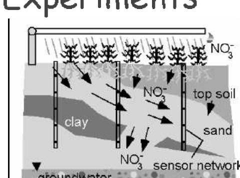
[From CENS Annual Technical Report, 03]





Field-Level Experiments

- Nitrates in groundwater
- Application
  - Wastewater used for irrigating alfalfa
  - Wastewater has nitrates, nutrients for alfalfa
  - Over-irrigation can lead to nitrates in ground-water
  - Need monitoring system, wells can be expensive
- Pilot study of sensor network to monitoring nitrate levels

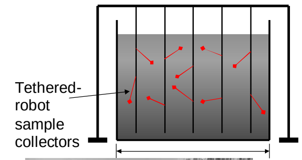


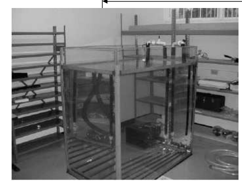
Marine Micro-organism Monitoring

- Algal Blooms (red, brown, green tides) impact
  - Human life
  - Industries (fisheries and tourism)
- Causes poorly understood, mostly because
  - Measurement of these phenomena can be complex and time consuming
- Sensor networks can help
  - Measure, predict, mitigate

Lab-Scale Experimentation

- Build a tank testbed in which to study the factors that affect micro-organism growth
- Actuation is a central part of this
  - Can't expect to deploy at density we need
  - Mobile sensors can help sample at high frequency
- Initial study:
  - thermocline detection

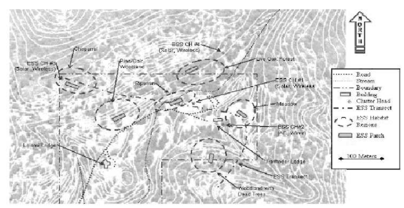




Ecosystem Monitoring

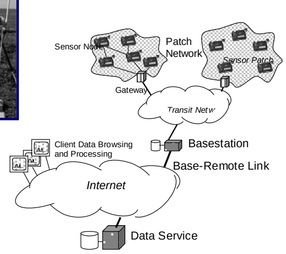
- Remote sensing can enable global assessment of ecosystem
- But, ecosystem evolution is often decided by local variations
  - Development of canopy, nesting patterns often decided by small local variations in temperature
- In-situ networked sensing can help us understand some of these processes

James Reserve



- Clustered architecture
- Weather-resistant housing design
- Sensors: Light, temperature, pressure, humidity

Great Duck Island



- Study nesting behavior of Leach's storm petrels
- Clustered architecture:
  - 802.11 backbone
  - multihop sensor cluster

Challenges

Energy

- Nodes are untethered, must rely on batteries
- Network lifetime now becomes a performance metric

Communication is Expensive

- The Communication/Computation Tradeoff
  - Received power drops off as the fourth power of distance
  - 10 m: 5000 ops/transmitted bit
  - 100 m: 50,000,000 ops/transmitted bit
- Implications
  - Avoid communication over long distances
  - Cannot assume global knowledge, or centralized solutions
  - Can leverage data processing/aggregation inside the network

Can't Ignore Physical World

- Can't hide in the machine room!
- Conditions variable and sometimes challenging

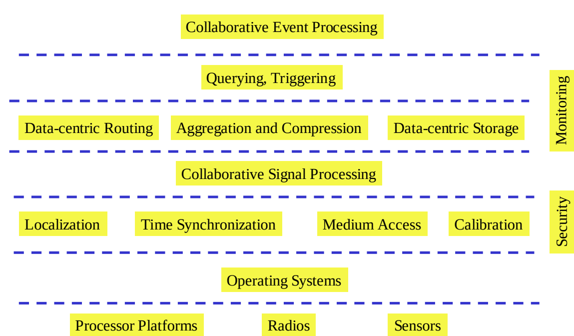
No Configuration

- System must be self-organizing

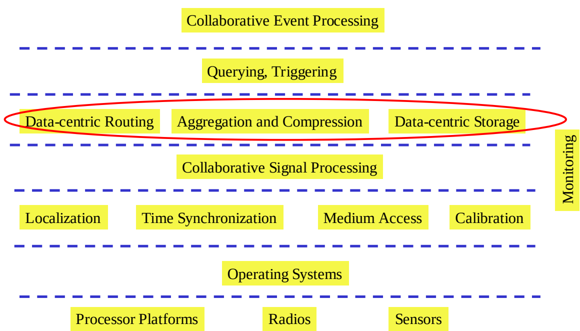
Generality vs Specificity

- Internet: single infrastructure capable of supporting many apps
- Sensornets: each deployment will have limited number of users and limited number of apps
- But basic technology should be general

Components of Infrastructure



Components of Infrastructure



How to Access Data

- Sensornet is useless if one can't access the required data
- Can't send it all to external storage:
  - limited bandwidth
  - limited energy
- How can you get only the data you need?

Name the Data!

- Don't know which nodes have data
- Don't think in terms of point-to-point protocols (as in Internet)
- Think in terms of data

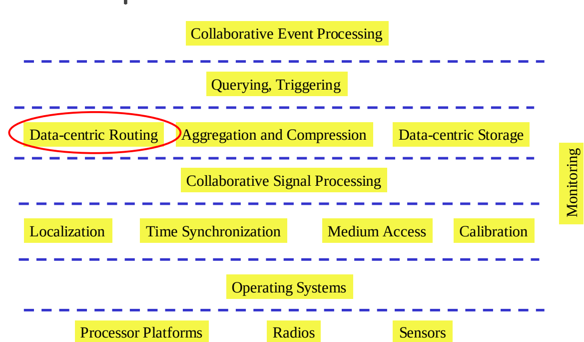
Ask for Data!

- Send out requests for data by name
- If nodes have the relevant data, they respond

Three Communication Patterns

- Data-centric routing
- Tree-based aggregation/collection
- Data-centric storage

Components of Infrastructure

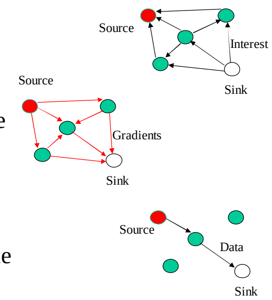


Diffusion messages

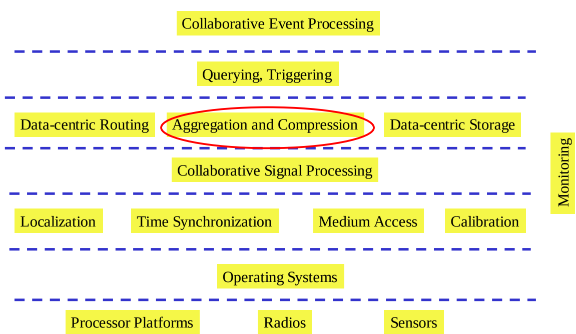
- Messages are sets of attribute-value pairs
- Message types
  - Interest (from sinks)
  - Data (from sources)
  - Control (reinforcement)

Diffusion Routing: Two phase pull

- Flood interest
- Flood data in response
- Sink reinforces
- Forward data along the reinforced paths



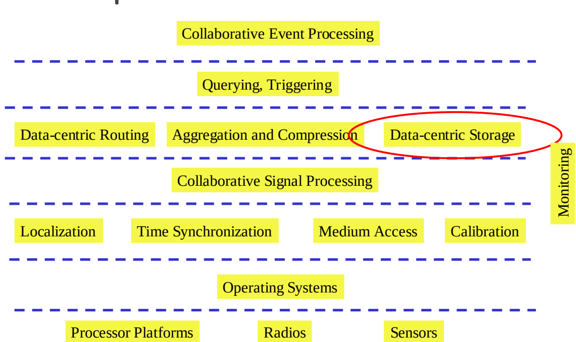
Components of Infrastructure



TinyDB/TAG

- Set up spanning tree from source
  - not as easy as it sounds!
- Flood query down tree
- Data sent back along reverse path
- Apply various aggregation operators

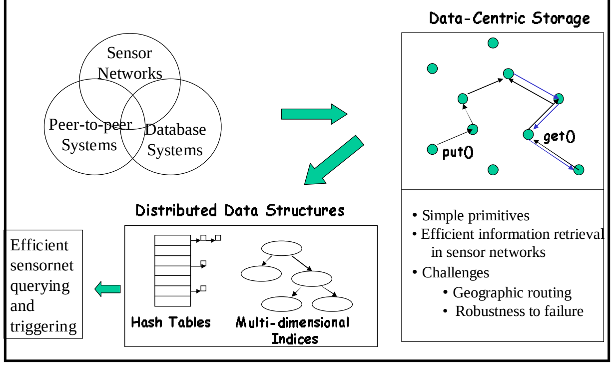
Components of Infrastructure



So Far....

- Data access methods are flood-response
- Good for long-lived queries
- What about one-shot queries?

Data-Centric Storage

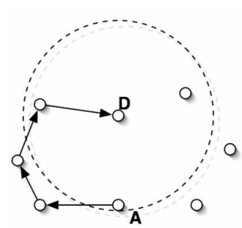


An Instance of Data-Centric Storage

- Geographic Hash Tables (GHTs)
- *Hash* the name of the data to a geographic location
- Store data at the node closest to that locations
  - Use a geographic routing protocol (e.g., GPSR)
- Can retrieve data the same way

GPSR Internals

- Nodes are named by their geographic locations
- Greedy routing as far as possible
- Perimeter routing when greedy fails
  - Fundamentals: Right-hand rule
  - Planarization removes crossing links
- Recover to greedy whenever possible
- Drop a packet when it is going to enter a perimeter along the same route again!



GHT = GPSR + DHT

- Answer queries for exact matched data, just like any other hash tables.

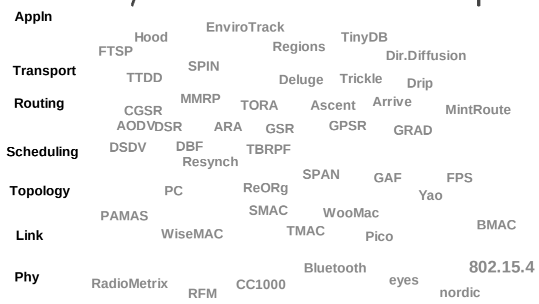
More Sophisticated Queries

- Spatio-temporal aggregates
- Multi-dimensional range queries
- Approach
  - Use hashing and spatial decomposition
- Data-centric storage not yet deployed

Current UCB Project

- Defining a sensornet architecture (SNA)

Today's Sensornet Landscape



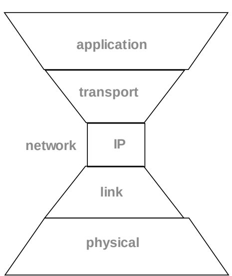
Not Just a Messy Picture

- Many components developed in isolation
  - Differing assumptions about overall structure…
- Some vertically integrated systems
  - Not much interoperability between them

Our Conjecture

- The biggest impediment to progress is *not* any single technical challenge
- It is the lack of an overall architecture that would increase composability and interoperability

The "Internet Architecture"



Internet Architecture

- Goal 1: universal connectivity
  - Problem: diversity of network technologies
  - Solution: universal and opaque IP protocol
- Goal 2: application flexibility
  - Problem: application-aware networks limit flexibility *(because network is static)*
  - Solution: end-to-end principle
  - *Put app. functionality in hosts, not network*
  - *Hosts under our control, and can be changed*

The Internet Architecture

- Shields applications from hardware diversity
- Shields network from application diversity
- Speeds development and deployment of both

How Do Sensornets Differ?

- Apps: data-centric, not host-centric
  - Endpoints not explicitly addressed by apps

  ⇒ Can't organize around end-to-end abstractions

- Goal: code portability and reuse
  - Not universal connectivity
  - Not application flexibility for static network

  ⇒ End-to-end principle not (automatically) applicable
  In-network processing is often much more efficient

How Do Sensornets Differ?

- Constraints: scarce resources (energy)
- Internet: opaque layers as easy abstraction
  - Willing to tolerate significant efficiency loss
- Sensornets: need *translucent* layers
  - Hide details of hardware underneath
  - But expose abstractions for control
- Goal: trade (small) efficiency loss for (much) less reprogramming

Where is the Narrow Waist?

- Internet: best-effort end-to-end packet delivery (IP)
- Sensornets: best-effort single-hop broadcast (SP)?
- Expressive abstraction of a universal link layer
  - Single abstraction for all lower layer technologies
- Abstraction should allow higher-layers to optimize without knowing the underlying technology

The Sensornet "Hourglass"