Architectures and Algorithms for Internet-Scale (P2P) Data Management

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Powerpoint Compatibility Note

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Overview

- Preliminaries
  - What, Why
  - The Platform
- "Upleveling"
  - Network Data Independence
- Early P2P architectures
  - Client-Server
  - Floodsast
  - Hierarchies
  - A Little Gossip
  - Commercial Offerings
  - Lessons and Limitations
- Ongoing Research
  - Structured Overlays: DHTs
  - Query Processing on Overlays
  - Storage Models & Systems
  - Security and Trust
- Joining the fun
  - Tools and Platforms
  - Closing thoughts

Acknowledgments

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Preliminaries

Outline

- Scoping the tutorial
- Behind the "P2P" Moniker
  - Internet-Scale systems
- Why bother with them?
- Some guiding applications

Scoping the Tutorial

- Architectures and Algorithms for Data Management
- The perils of overviews
  - Can't cover everything. So much here!
- Some interesting things we'll skip
  - Semantic Mediation: data integration on steroids
    - E.g., Hyperion (Toronto), Piazza (UWash), etc.
  - High-Throughput Computing
    - I.e. The Grid
  - Complex data analysis/reduction/mining
    - E.g. p2p distributed inference, wavelets, regression, matrix computations, etc.

Moving Past the "P2P" Moniker: The Platform

- The "P2P" name has lots of connotations
  - Simple filestealing systems
  - Very end-user-centric
- Our focus here is on:
  - Many participating machines, symmetric in function
  - Very Large Scale (MegaNodes, not PetaBytes)
  - Minimal (or non-existent) management
  - Note: user model is flexible
    - Could be embedded (e.g. in OS, HW, firewall, etc.)
    - Large-scale hosted services a la Akamai or Google
      - A key to achieving "autonomic computing"?

Overlay Networks

- P2P applications need to:
  - Track identities & (IP) addresses of peers
    - May be many!
    - May have significant Churn
    - Best not to have n^2 ID references
  - Route messages among peers
    - If you don't keep track of all peers, this is "multi-hop"
- This is an *overlay network*
  - Peers are doing both naming and routing
  - IP becomes "just" the low-level transport
    - All the IP routing is opaque
- Control over naming and routing is powerful
  - And as we'll see, brings networks into the database era

Many New Challenges

- Relative to other parallel/distributed systems
  - Partial failure
  - Churn
  - Few guarantees on transport, storage, etc.
  - Huge optimization space
  - Network bottlenecks & other resource constraints
  - No administrative organizations
  - Trust issues: security, privacy, incentives
- Relative to IP networking
  - Much higher function, more flexible
  - Much less controllable/predictable

Why Bother? Not the Gold Standard

- Given an infinite budget, would you go p2p?
- Highest performance? No.
  - Hard to beat hosted/managed services
  - p2p Google appears to be infeasible
    [Li, et al. IPTPS 03]
- Most Resilient? Hmmmm.
  - In principle more resistant to DoS attacks, etc.
  - Today, still hard to beat hosted/managed services
    - Geographically replicated, hugely provisioned
    - People who "do it for dollars" today don't do it p2p

Why Bother II: Positive Lessons from Filestealing

- P2P enables *organic scaling*
  - Vs. the top few killer services -- no VCs required!
  - Can afford to "place more bets", try wacky ideas
- Centralized services engender scrutiny
  - Tracking users is trivial
  - Provider is liable (for misuse, for downtime, for local laws, etc.)
- Centralized means business
  - Need to pay off startup & maintenance expenses
  - Need to protect against liability
  - Business requirements drive to particular short-term goals
    - *Tragedy of the commons*

Why Bother III? Intellectual motivation

- Heady mix of theory and systems
  - Great community of researchers have gathered
  - Algorithms, Networking, Distributed Systems, Databases
  - Healthy set of publication venues
    - IPTPS workshop as a catalyst
  - Surprising degree of collaboration across areas
    - In part supported by NSF Large ITR (project IRIS)
      - UC Berkeley, ICSI, MIT, NYU, and Rice

Infecting the Network, Peer-to-Peer

- The Internet is hard to change.
- But Overlay Nets are easy!
  - P2P is a wonderful "host" for infecting network designs
  - The "next" Internet is likely to be very different
    - "Naming" is a key design issue today
    - Querying and data independence key tomorrow?
- Don't forget:
  - The Internet was originally an overlay on the telephone network
  - There is no money to be made in the bit-shipping business
- A modest goal for DB research:
  - Don't query the Internet.

Infecting the Network, Peer-to-Peer

Be the Internet.

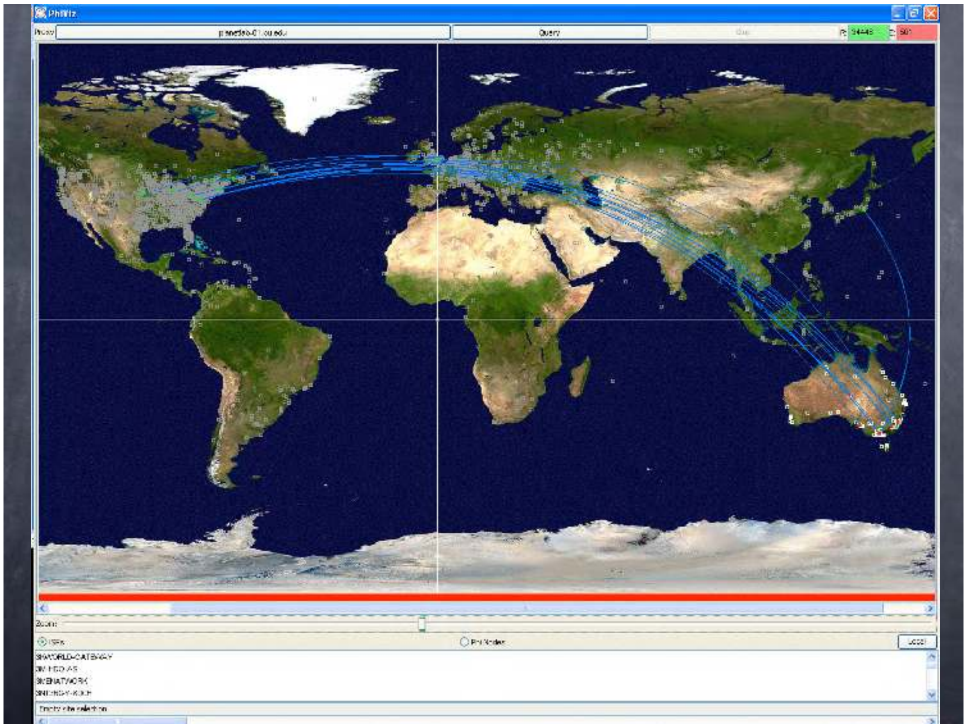
- A modest goal for DB research:
  - Don't query the Internet.

Some Guiding Applications

- *φ*
  - Intel Research & UC Berkeley
- LOCKSS
  - Stanford, HP Labs, Sun, Harvard, Intel Research
- LiberationWare

φ: Public Health for the Internet

- Security tools focused on “medicine”
  - Vaccines for Viruses
  - Improving the world one patient at a time
- Weakness/opportunity in the “Public Health” arena
  - Public Health: population-focused, community-oriented
  - Epidemiology: incidence, distribution, and control in a *population*
- *φ:* A New Approach
  - Perform *population-wide measurement*
  - Enable massive sharing of data and query results
    - The “Internet Screensaver”
  - Engage end users: education and prevention
  - Understand risky behaviors, at-risk populations.
- Prototype running over *PIER*



φ Vision: Network Oracle

- Suppose there existed a Network Oracle
  - Answering questions about current Internet state
    - Routing tables, link loads, latencies, firewall events, etc.
  - How would this change things
    - Social change (Public Health, safe computing)
    - Medium term change in distributed application design
      - Currently distributed apps do some of this on their own
    - Long term change in network protocols
      - App-specific custom routing
      - Fault diagnosis
      - Etc.

LOCKSS: Lots Of Copies Keep Stuff Safe

- Digital Preservation of Academic Materials
- Librarians are scared with good reason
  - Access depends on the fate of the publisher
  - Time is unkind to bits after decades
  - Plenty of enemies (ideologies, governments, corporations)
- Goal: *Archival* storage and access

LOCKSS Approach

- Challenges:
  - Very low-cost hardware, operation and administration
  - No central control
  - Respect for access controls
  - A long-term horizon
- Must anticipate and degrade gracefully with
  - Undetected bit rot
  - Sustained attacks
    - Esp. Stealth modification
- Solution:
  - P2P auditing and repair system for replicated docs

LiberationWare

- Take your favorite Internet application
  - Web hosting, search, IM, filesharing, VoIP, email, etc.
  - Consider using centralized versions in a country with a repressive government
    - Trackability and liability will prevent this being used for free speech
  - Now consider p2p
    - Enhanced with appropriate security/privacy protections
    - Could be the medium of the next Tom Paines
- Examples: FreeNet, Publius, FreeHaven
  - p2p storage to avoid censorship & guarantee privacy
  - PKI-encrypted storage
  - Mix-net privacy-preserving routing

"Upleveling": Network Data Independence

SIGMOD Record, Sep. 2003

Recall Codd's Data Independence

- Decouple app-level API from data organization
  - Can make changes to data layout without modifying applications
  - Simple version: location-independent names
  - Fancier: declarative queries

"As clear a paradigm shift as we can hope to find in computer science"
- C. Papadimitriou

The Pillars of Data Independence

- Indexes
  - Value-based lookups have to compete with direct access
  - Must adapt to shifting data distributions
  - Must guarantee performance
- Query Optimization
  - Support declarative queries beyond lookup/search
  - Must adapt to shifting data distributions
  - Must adapt to changes in environment

DBMS
B-Tree
Join Ordering, AM Selection, etc.

Generalizing Data Independence

- A classic "level of indirection" scheme
  - Indexes are exactly that
  - Complex queries are a richer indirection
- The key for data independence:
  - It's all about *rates of change*
- Hellerstein's Data Independence Inequality:
  - Data independence matters when

d(environment)/dt >> d(app)/dt

Data Independence in Networks

d(environment)/dt >> d(app)/dt

- In databases, the RHS is unusually small
  - This drove the relational database revolution
- In extreme networked systems, LHS is unusually high
  - And the applications increasingly complex and data-driven
  - Simple indirections (e.g. local lookaside tables) insufficient

The Pillars of Data Independence

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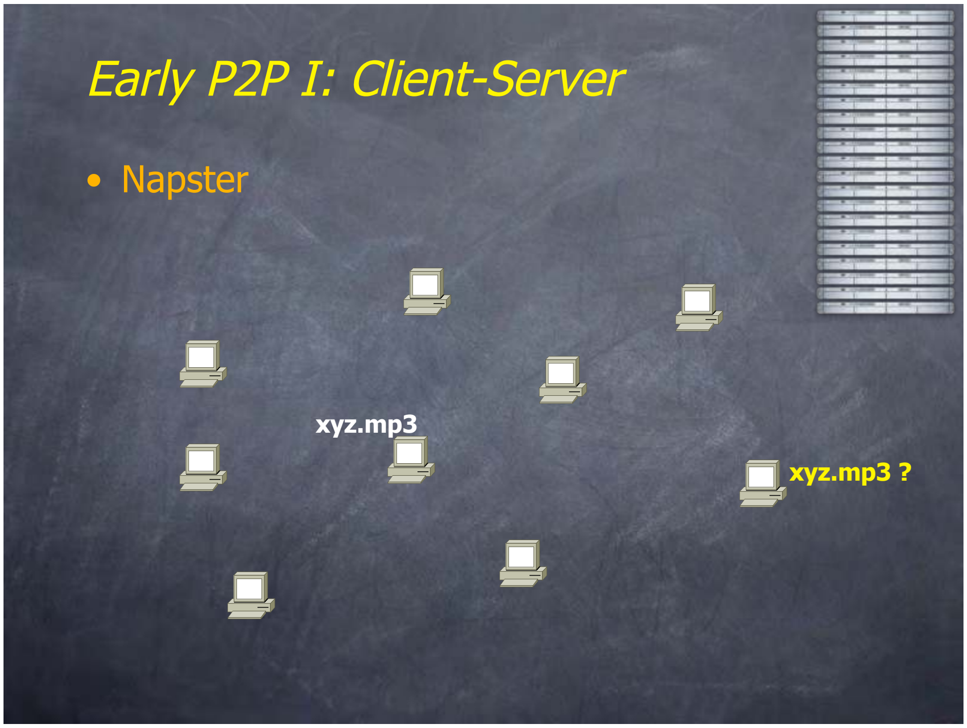
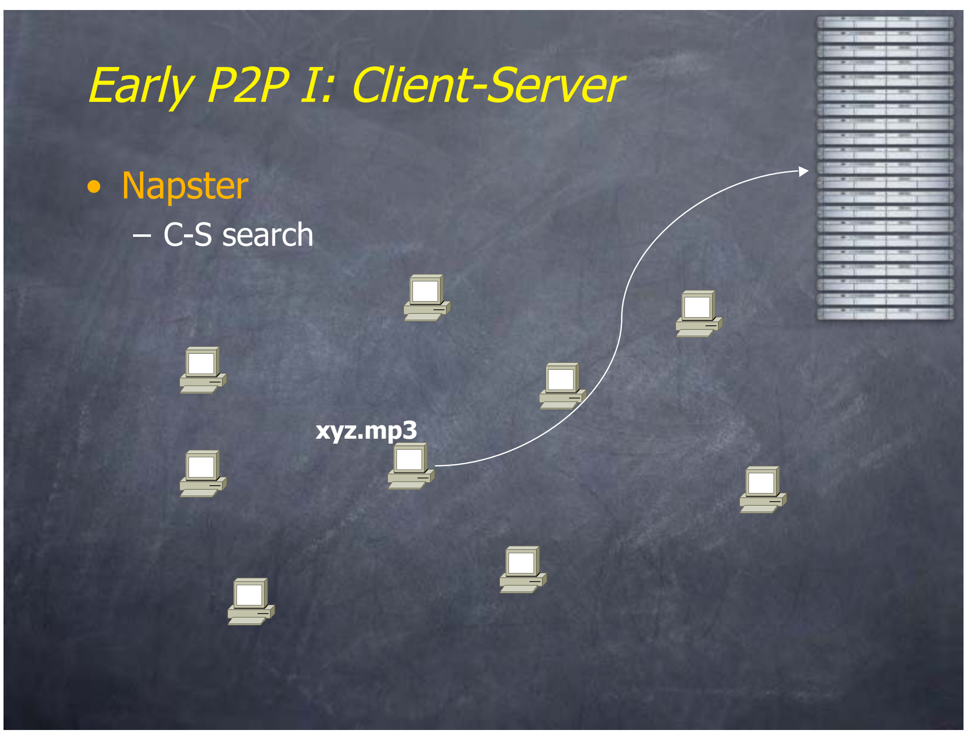
DBMS	P2P
B-Tree	Content-Addressable Overlay Networks (DHTs)
Join Ordering, AM Selection, etc.	Multiquery dataflow sharing?

Early P2P


Early P2P I: Client-Server
• Napster
xyz.mp3
xyz.mp3 ?


Early P2P I: Client-Server
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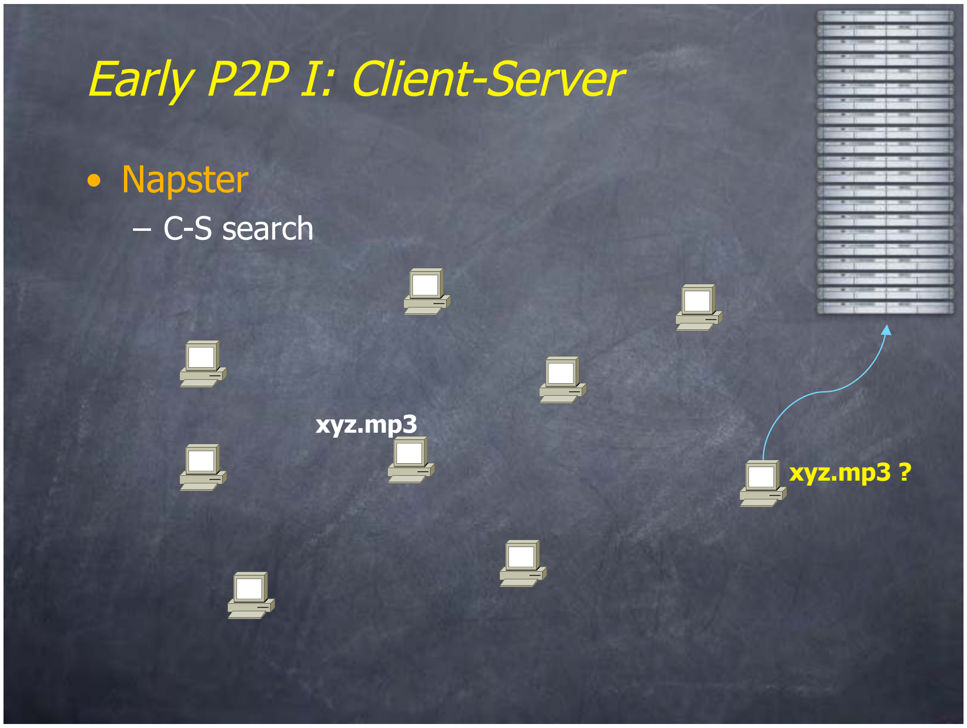
– C-S search
xyz.mp3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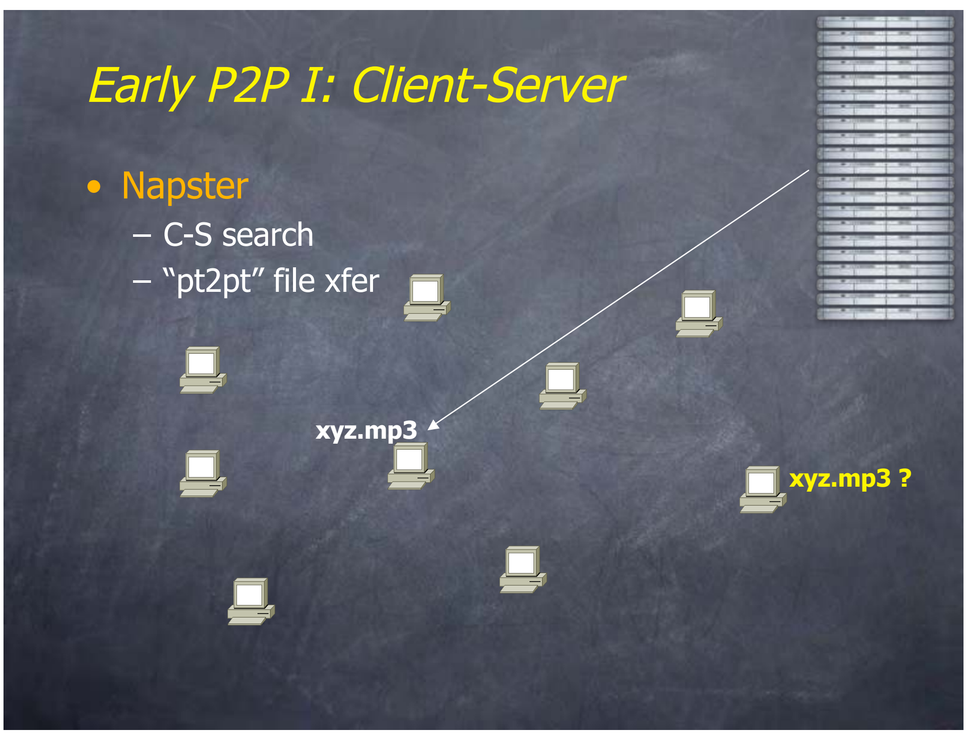
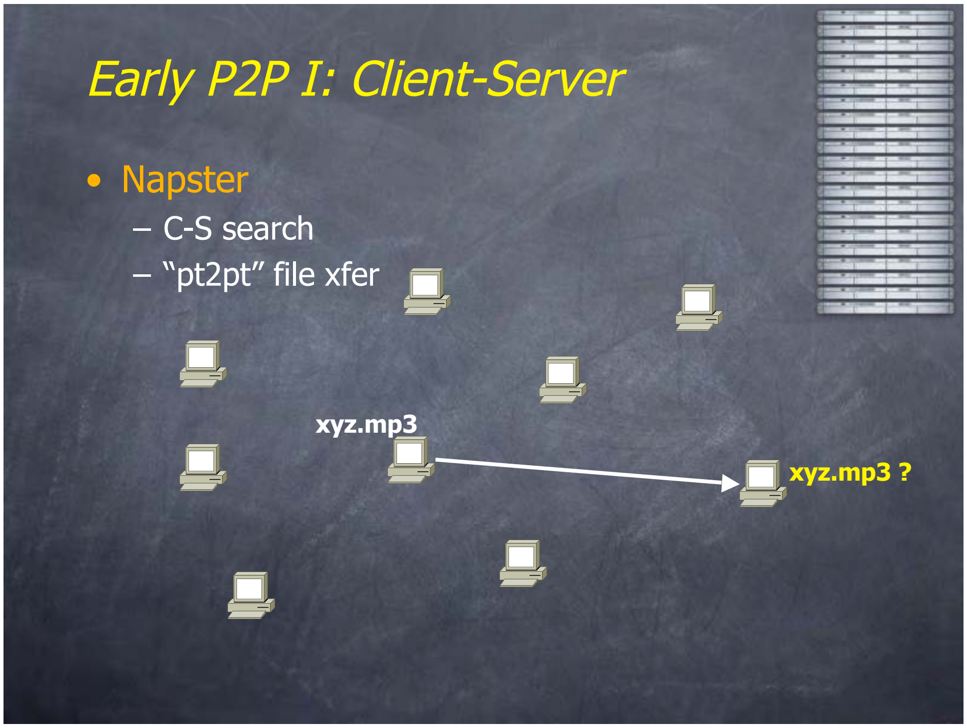

Early P2P I: Client-Server
• Napster
– C-S search
– "pt2pt" file xfer
xyz.mp3
xyz.mp3 ?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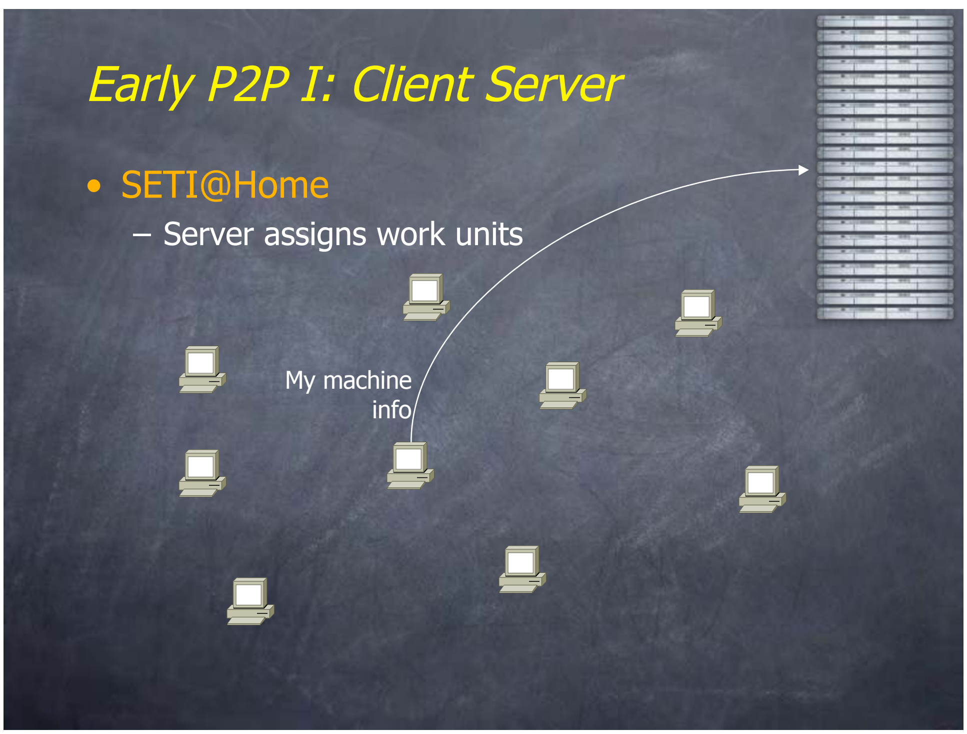
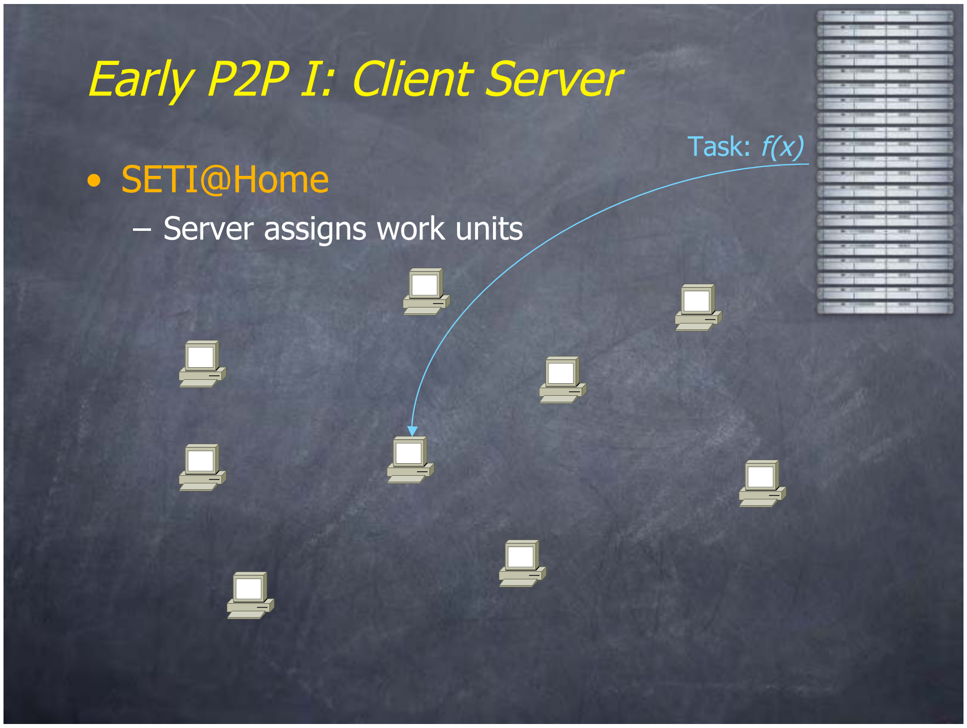

Early P2P I: Client Server
• SETI@Home
– Server assigns work units
My machine
info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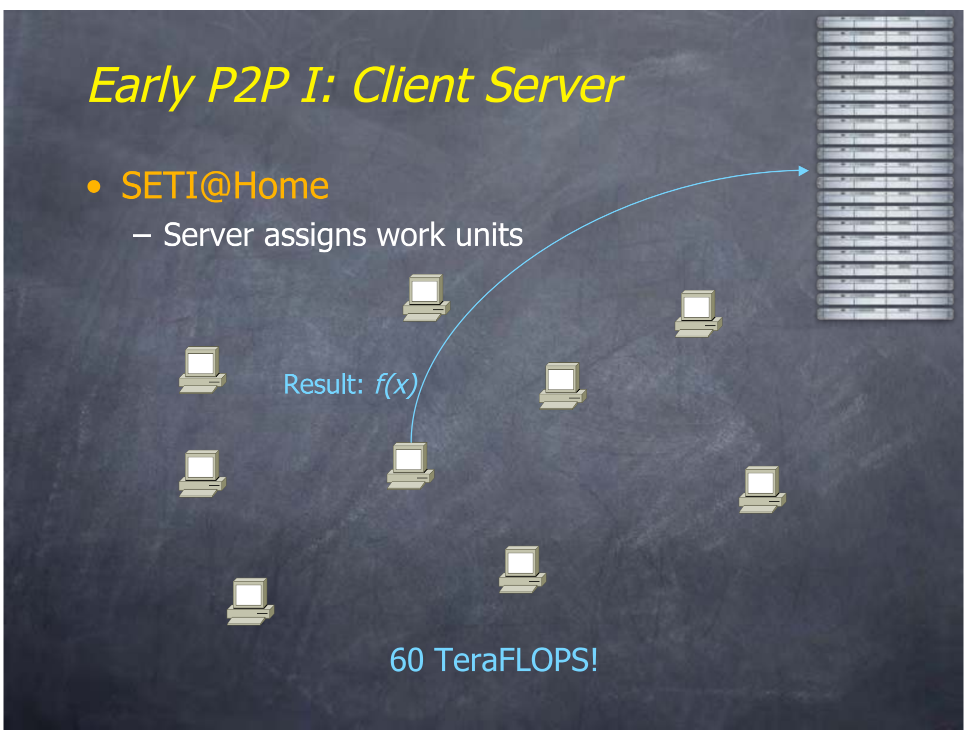
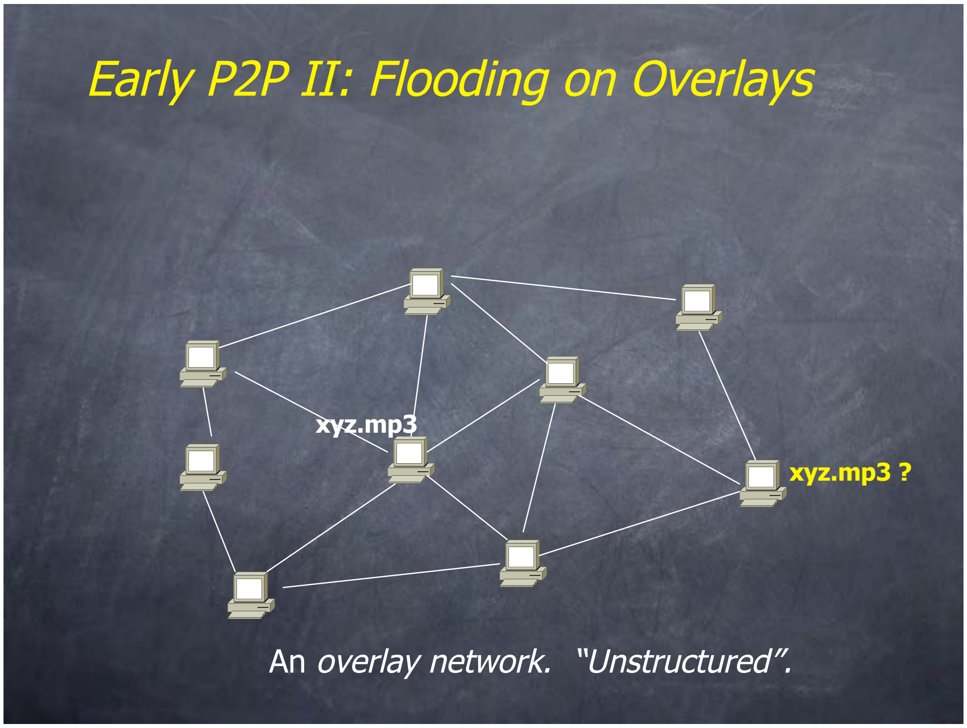
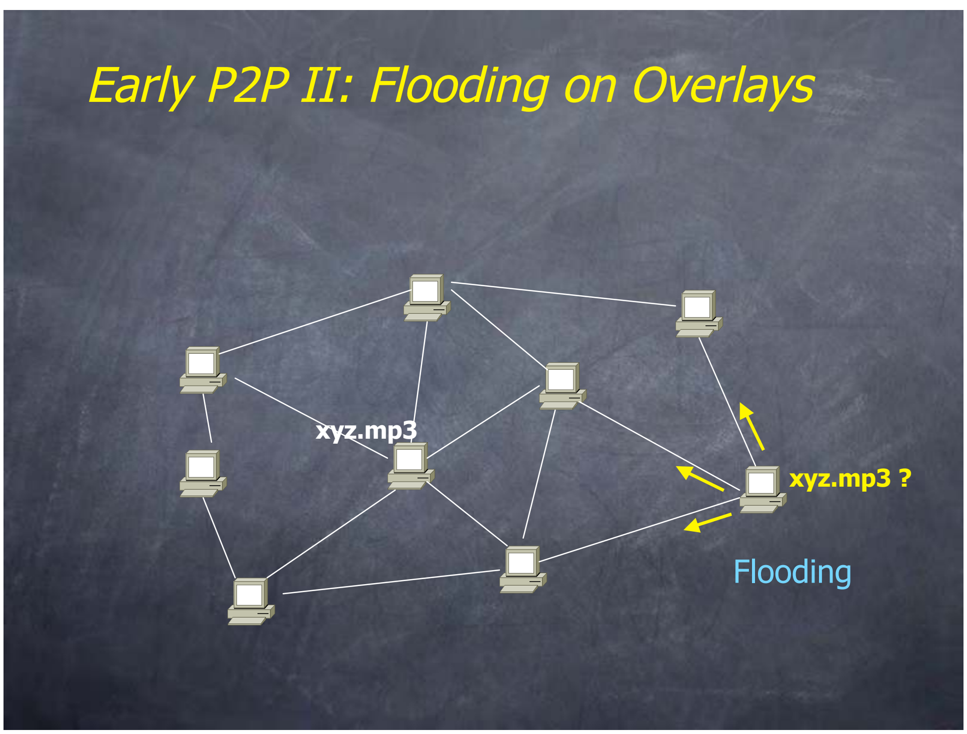
Task: f(x)


Early P2P I: Client Server
• SETI@Home
– Server assigns work units
Result: f(x)
60 TeraFLOPS!


Early P2P II: Flooding on Overlays
xyz.mp3
xyz.mp3 ?
An overlay network. "Unstructured".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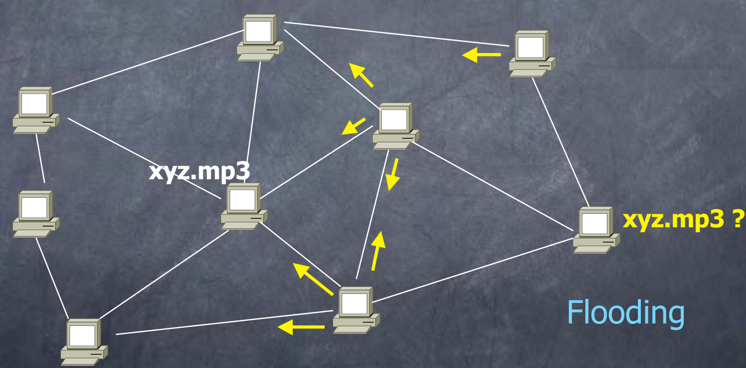
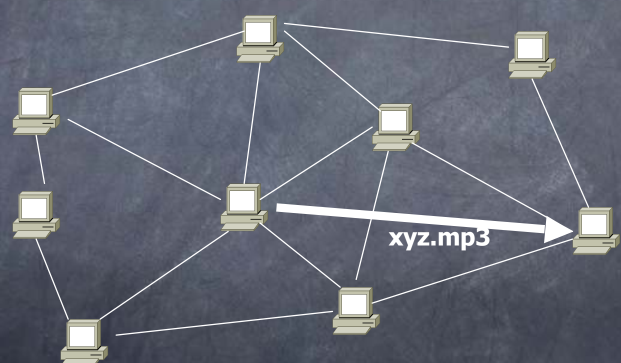
xyz.mp3 ?
Flooding

Early P2P II: Flooding on Overlays

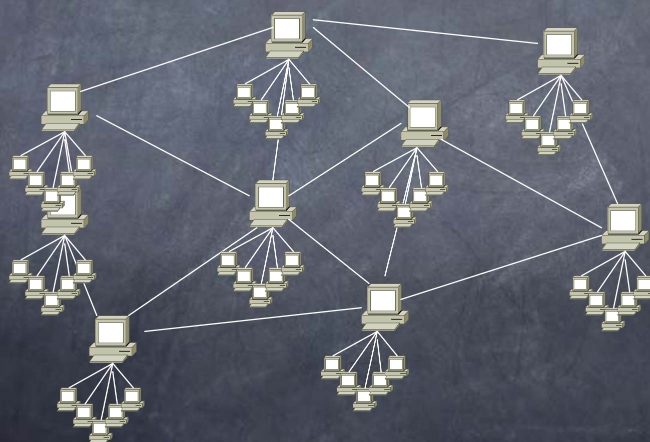


Early P2P II: Flooding on Overlays



Early P2P II.v: "Ultrapeers"

- Ultrapeers can be installed (KaZaA) or self-promoted (Gnutella)



Hierarchical Networks (& Queries)

- IP
  - Hierarchical name space (www.vldb.org, 141.12.12.51)
  - Hierarchical routing
    - Autonomous Systems correlate with name space (though not perfectly)
  - Astrolabe [Birman, et al. TOCS 03]
    - OLAP-style aggregate queries down the IP hierarchy
- DNS
  - Hierarchical name space ("clients" + hierarchy of servers)
  - Hierarchical routing w/aggressive caching
    - 13 managed "root servers"
  - IrisNet [Deshpande, et al. SIGMOD 03]
    - Xpath queries over (selected) DNS (sub)-trees.
- Traditional pros/cons of Hierarchical data mgmt
  - Works well for things aligned with the hierarchy
    - Esp. physical locality a la Astrolabe
  - Inflexible
    - No data independence!

Commercial Offerings

- JXTA
  - Java/XML Framework for p2p applications
  - Name resolution and routing is done with floods & superpeers
    - Can always add your own if you like
- MS WinXP p2p networking
  - An unstructured overlay, flooded publication and caching
  - "does not yet support distributed searches"
- Both have some security support
  - Authentication via signatures (assumes a trusted authority)
  - Encryption of traffic
- Groove
  - Platform for p2p "experience". IM and asynch collab tools.
  - Client-serverish name resolution, backup services, etc.

Lessons and Limitations

- Client-Server performs well
  - But not always feasible
    - Ideal performance is often not the key issue!
- Things that flood-based systems do well
  - Organic scaling
  - Decentralization of visibility and liability
  - Finding popular stuff
  - Fancy *local* queries
- Things that flood-based systems do poorly
  - Finding unpopular stuff [Loo, et al VLDB 04]
  - Fancy *distributed* queries
  - Vulnerabilities: data poisoning, tracking, etc.
  - Guarantees about anything (answer quality, privacy, etc.)

A Little Gossip

Gossip Protocols (Epidemic Algorithms)

- Originally targeted at database replication [Demers, et al. PODC '87]
  - Especially nice for unstructured networks
  - *Rumor-mongering:* propagate newly-received update to *k* random neighbors
- Extended to routing
  - Point-to-point routing [Vahdat/Becker TR, '00]
  - Rumor-mongering of queries instead of flooding [Haas, et al Infocom '02]
- Extended to aggregate computation [Kempe, et al, FOCS 03]
- Mostly theoretical analyses
  - Usually of two forms:
    - What is the "tipping point" where an epidemic infects the whole population? (Percolation theory)
    - What is the expected # of messages for infection?
- A Cornell specialty
  - Demers, Kleinberg, Gehrke, Halpern, …

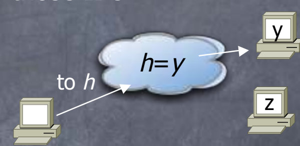
Structured Overlays: Distributed Hash Tables (DHTs)

DHT Outline

- High-level overview
- Fundamentals of structured network topologies
  - And examples
- One concrete DHT
  - Chord
- Some systems issues
  - Storage models & soft state
  - Locality
  - Churn management

High-Level Idea: Indirection

- Indirection in space
  - Logical (content-based) IDs, routing to those IDs
    - "Content-addressable" network
  - Tolerant of *churn*
    - nodes joining and leaving the network



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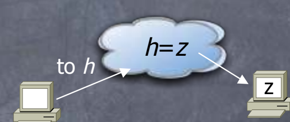


- Indirection in time
  - Want some scheme to temporally decouple send and receive
  - Persistence required. Typical Internet solution: soft state
    - Combo of persistence via *storage* and via *retry*
      - "Publisher" requests TTL on storage
      - Republishes as needed

- Metaphor: Distributed Hash Table

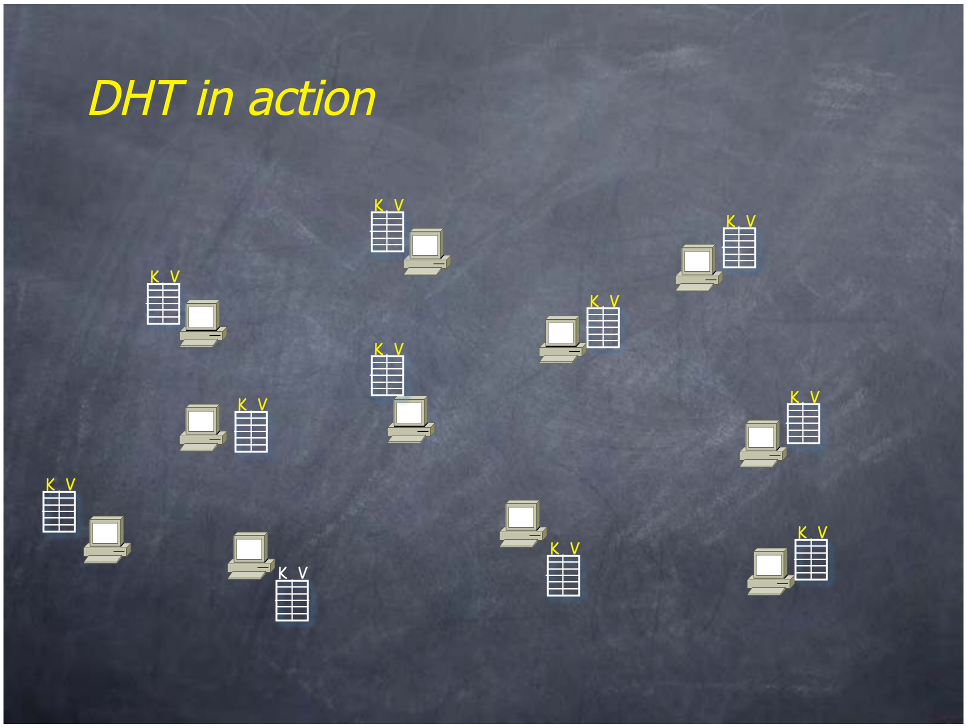
What is a DHT?

- Hash Table
  - data structure that maps “keys” to “values”
  - essential building block in software systems
- Distributed Hash Table (DHT)
  - similar, but spread across the Internet
- Interface
  - insert(key, value)
  - lookup(key)

How?

Every DHT node supports a single operation:

- Given *key* as input; route messages toward node holding *key*


DHT in action
K V
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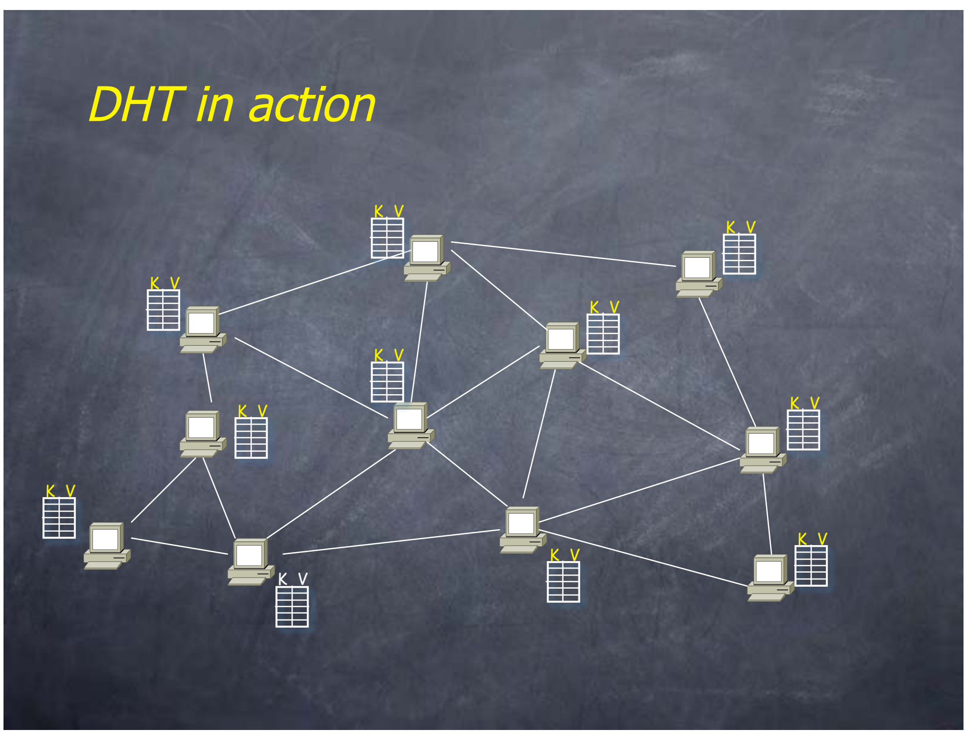
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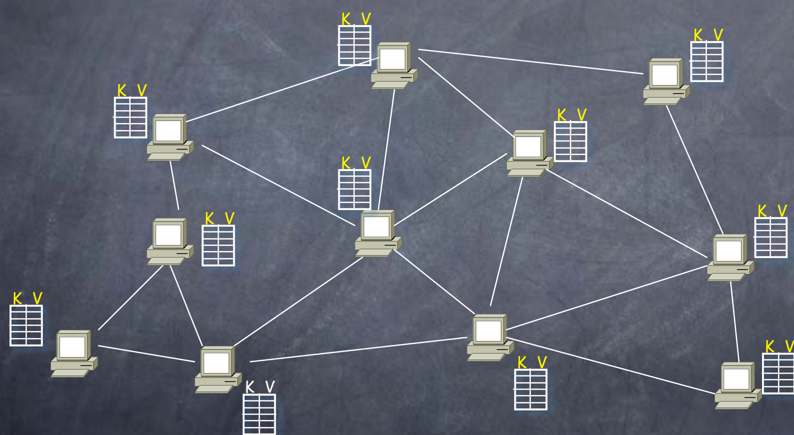
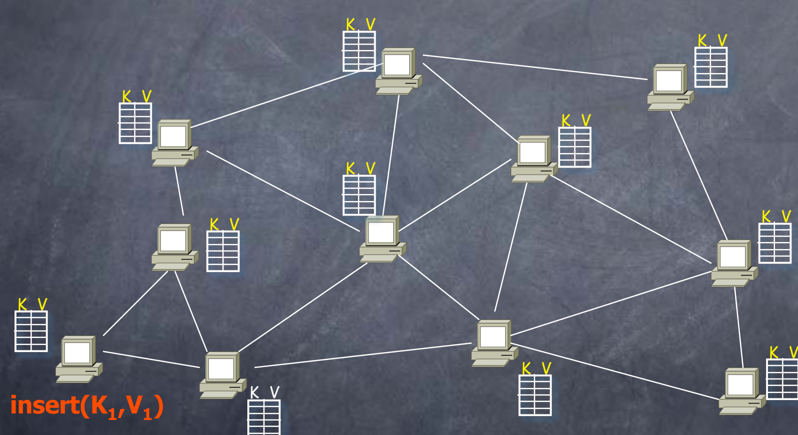


Operation: take *key* as input; route messages to node holding *key*

DHT in action: put()



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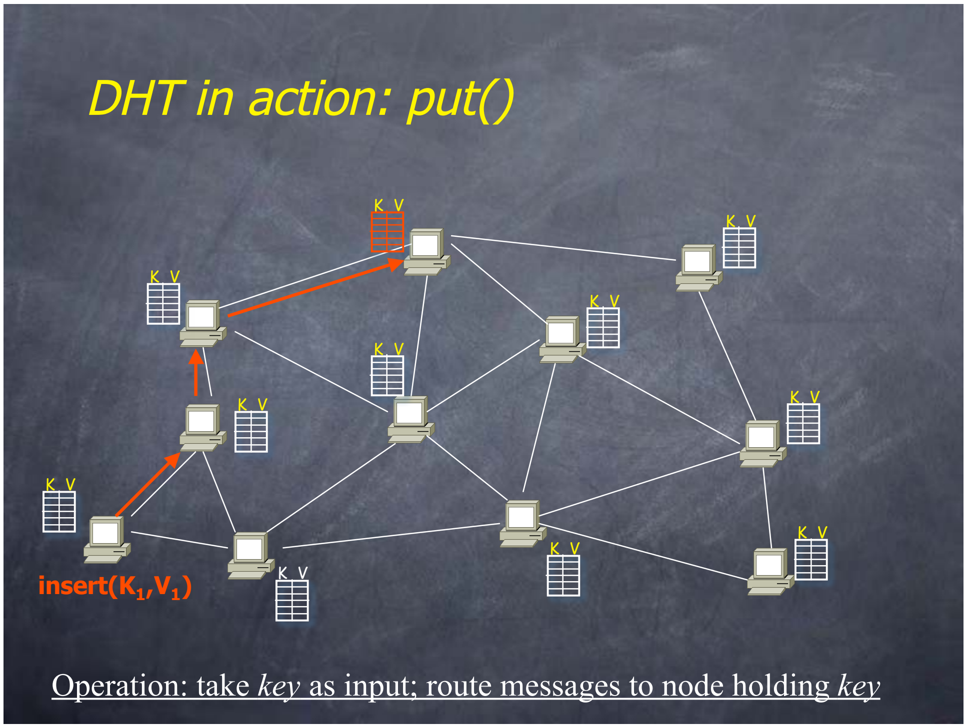
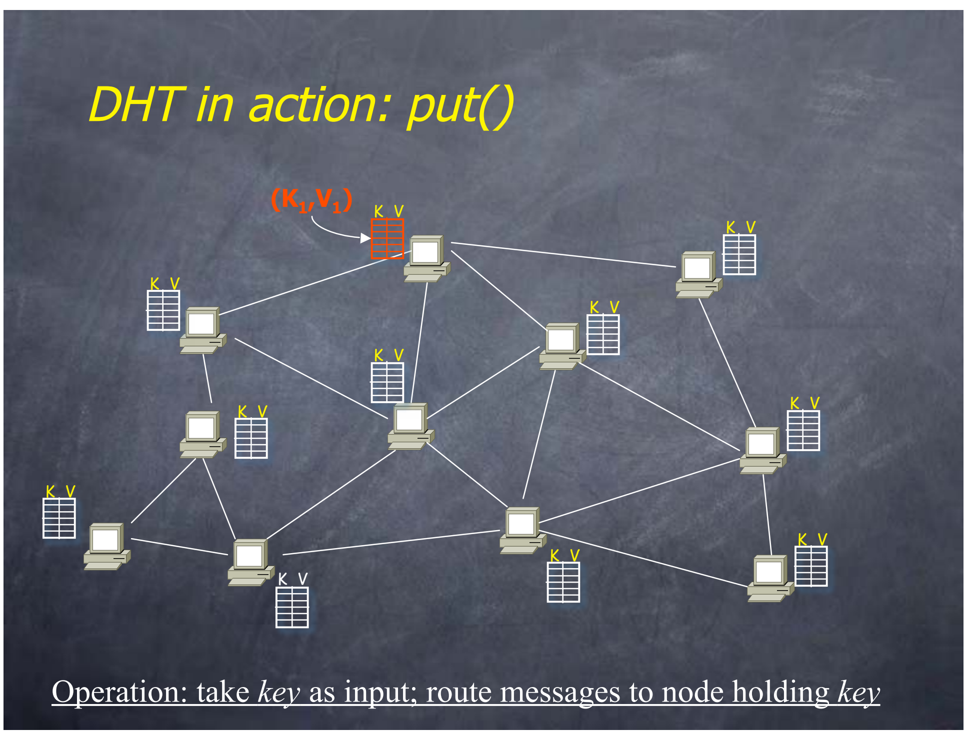

DHT in action: put()
K V
insert(K1,V1)
Operation: take key as input; route messages to node holding key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K V
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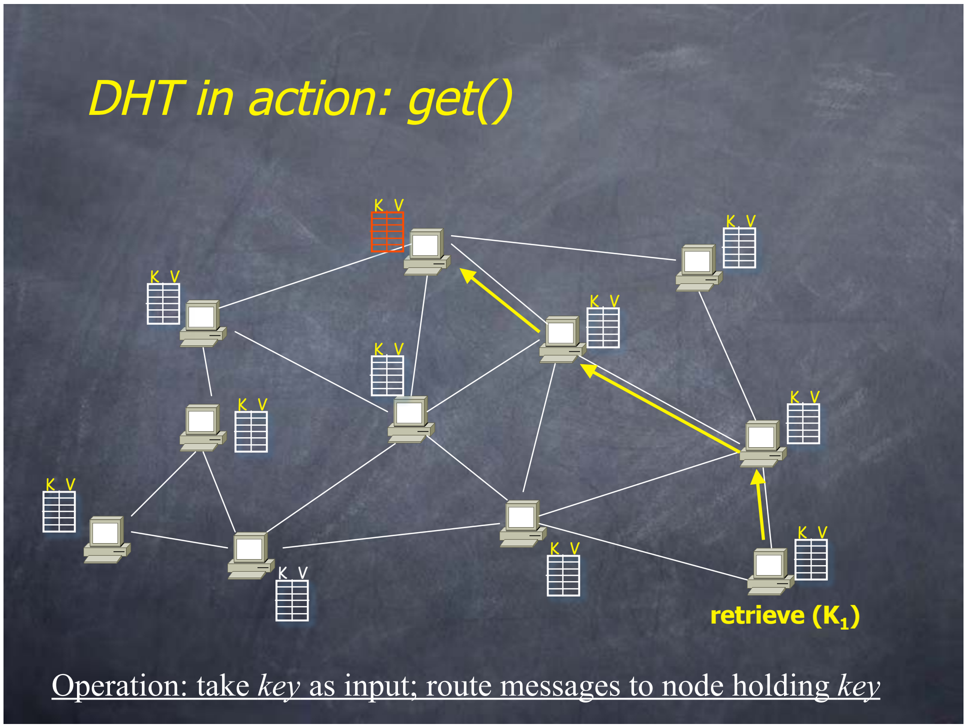
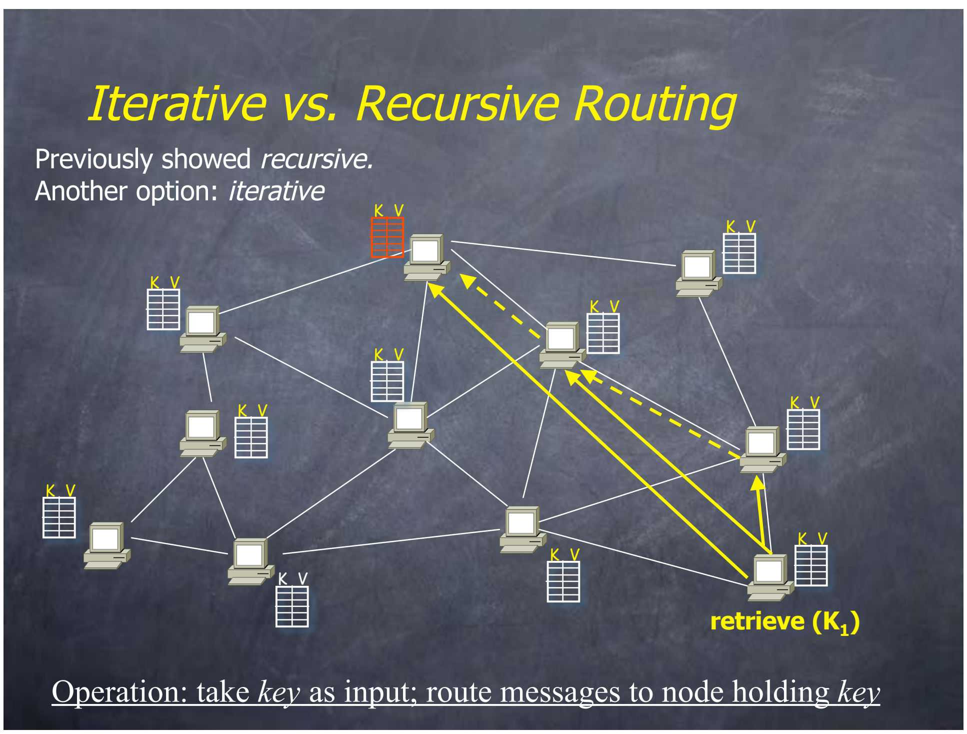

DHT in action: get()
K V
retrieve (K1)
Operation: take key as input; route messages to node holding key


Iterative vs. Recursive Routing
Previously showed recursive.
Another option: iterative
K V
retrieve (K1)
Operation: take key as input; route messages to node holding key

DHT Design Goals

- An "overlay" network with:
  - Flexible mapping of keys to physical nodes
  - Small network diameter
  - Small degree (fanout)
  - Local routing decisions
  - Robustness to churn
  - Routing flexibility
  - Decent locality (low "stretch")
- A "storage" or "memory" mechanism with
  - No guarantees on persistence
  - Maintenance via soft state

Peers vs Infrastructure

- Peer:
  - Application users provide nodes for DHT
  - Examples: filesharing, etc
- Infrastructure:
  - Set of managed nodes provide DHT service
  - Perhaps serve many applications
  - A p2p "incubator"?
    - We'll discuss this at the end of the tutorial

Library or Service

- Library: DHT code bundled into application
  - Runs on each node running application
  - Each application requires own routing infrastructure
- Service: single DHT shared by applications
  - Requires common infrastructure
  - But eliminates duplicate routing systems

DHT Outline

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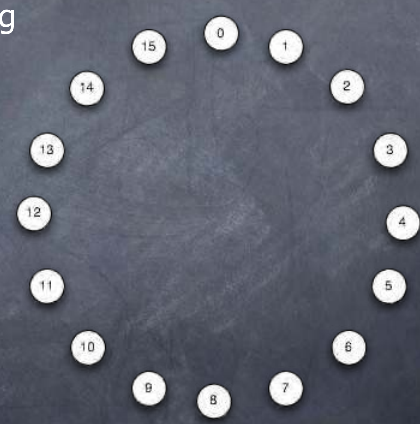
  - And examples
- One concrete DHT
  - Chord
- Some systems issues
  - Storage models & soft state
  - Locality
  - Churn management

An Example DHT: Chord

- Assume $n = 2^m$ nodes for a moment
  - A "complete" Chord ring
  - We'll generalize shortly



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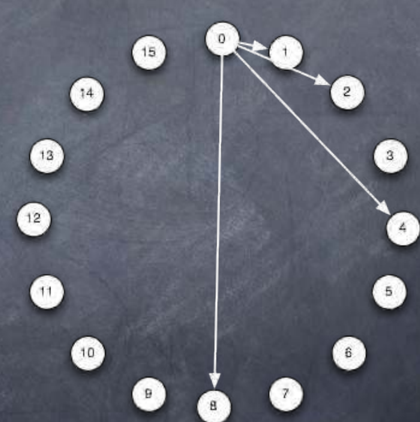

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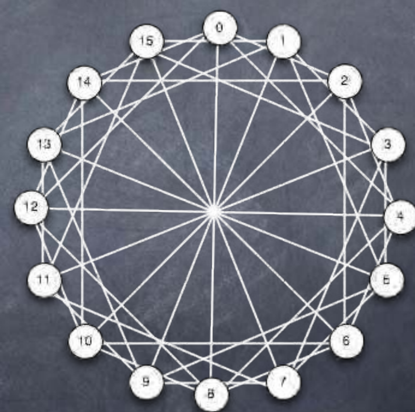
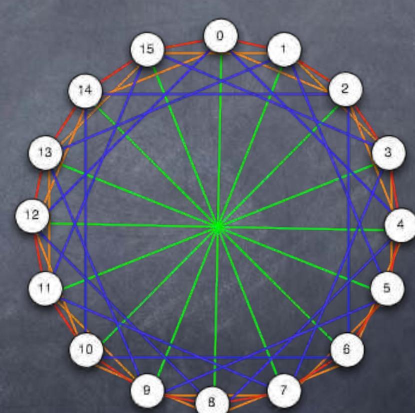


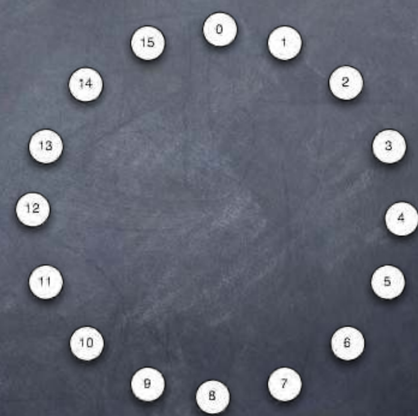
An Example DHT: Chord

- Overlayed 2^k-Gons



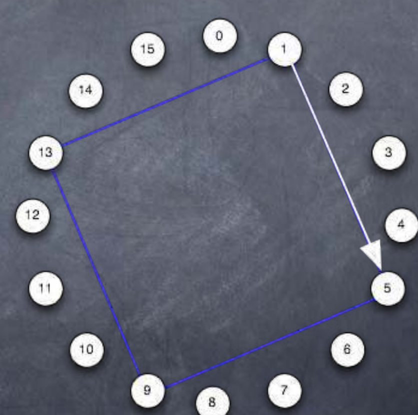
Routing in Chord

- At most one of each Gon
- E.g. 1-to-0



Routing in Chord

- At most one of each Gon
- E.g. 1-to-0



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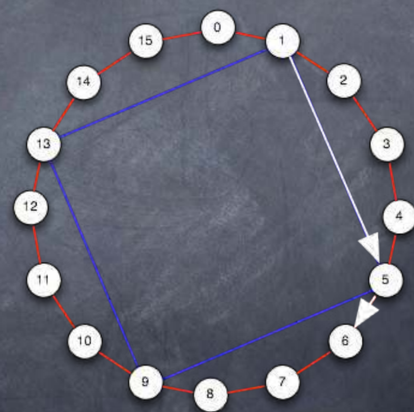

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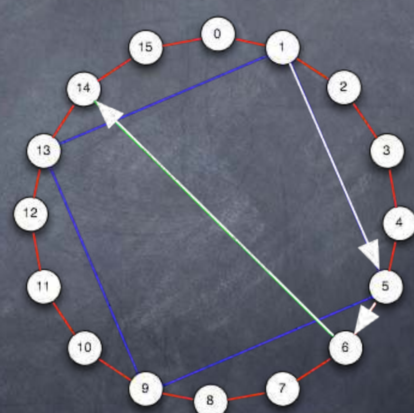

Routing in Chord

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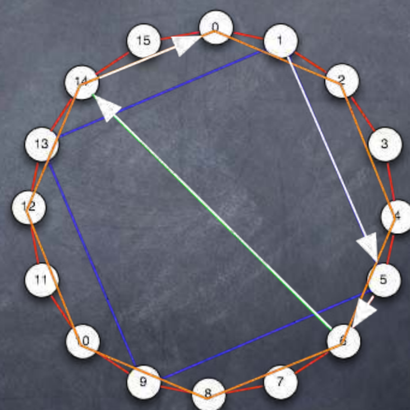
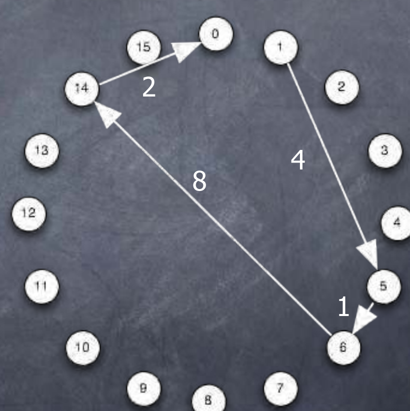


Routing in Chord

- At most one of each Gon
- E.g. 1-to-0
- What happened?
  - We constructed the binary number 15!
  - Routing from *x* to *y* is like computing *y* - *x* mod *n* by summing powers of 2



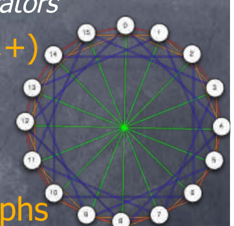
Diameter: log *n* (1 hop per gon type)
Degree: log *n* (one outlink per gon type)

What is happening here? Algebra!

- Underlying group-theoretic structure
  - Recall a *group* is a set *S* and an operator ● such that:
    - *S* is closed under ●
    - Associativity: $(AB)C = A(BC)$
    - There is an *identity* element $I \in S$ s.t. $IX = XI = X$ for all $X \in S$
    - There is an inverse $X^{-1} \in S$ for each element $X \in S$ s.t. $XX^{-1} = X^{-1}X = I$
- The *generators* of a group
  - Elements $\{g_1, \ldots, g_n\}$ s.t. application of the operator on the generators produces all the members of the group.
- Canonical example: $(Z_n, +)$
  - Identity is 0
  - A set of generators: {1}
  - A different set of generators: {2, 3}

Cayley Graphs

- The *Cayley Graph (S, E)* of a group:
  - Vertices corresponding to the underlying set *S*
  - Edges corresponding to the *actions of the generators*
- (Complete) Chord is a Cayley graph for $(Z_n,+)$
  - $S = Z \bmod n$ $(n = 2^k)$.
  - Generators $\{1, 2, 4, \ldots, 2^{k-1}\}$
  - That's what the gons are all about!
- Fact: Most (complete) DHTs are Cayley graphs
  - And they didn't even know it!
  - Follows from parallel InterConnect Networks (ICNs)
    - Shown to be group-theoretic [Akers/Krishnamurthy '89]

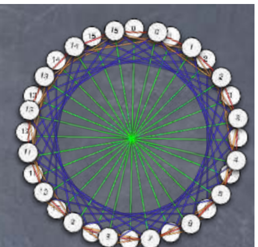


Note: the ones that aren't Cayley Graphs are *coset graphs*, a related group-theoretic structure

So…?

- Two questions:
  - How did this happen?
  - Why should you care?

How Hairy met Cayley



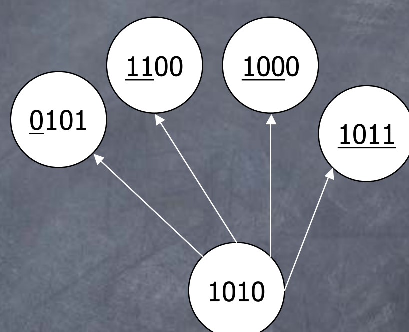
- What do you want in a structured network?
  - Uniformity of routing logic
  - Efficiency/load-balance of routing and maintenance
  - Generality at different scales
- Theorem: All Cayley graphs are *vertex symmetric.*
  - I.e. isomorphic under swaps of nodes
  - So routing from y to x looks just like routing from (y-x) to 0
    - The routing code at each node is the same! Simple software.
    - Moreover, under a random workload the routing responsibilities (congestion) at each node are the same!
- Cayley graphs tend to have good degree/diameter tradeoffs
  - Efficient routing with few neighbors to maintain
- Many Cayley graphs are *hierarchical*
  - Made of smaller Cayley graphs connected by a new generator
    - E.g. a Chord graph on 2^{m+1} nodes looks like 2 interleaved (half-notch rotated) Chord graphs of 2^m nodes with half-notch edges
    - Again, code is nice and simple

Upshot

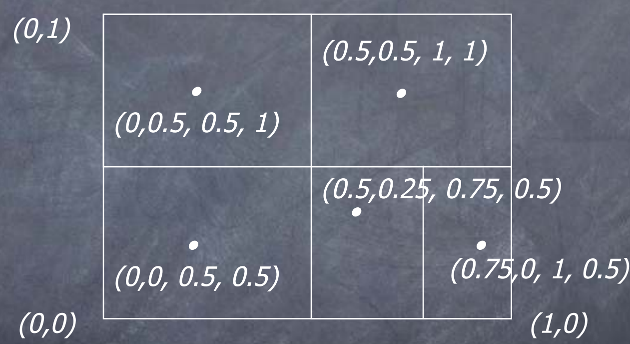
- Good DHT topologies will be Cayley/Coset graphs
  - A replay of ICN Design
  - But DHTs can use funky "wiring" that was infeasible in ICNs
  - All the group-theoretic analysis becomes suggestive
- Clean math describing the topology helps crisply analyze efficiency
  - E.g. degree/diameter tradeoffs
  - E.g. shapes of trees we'll see later for aggregation or join
- Really no excuse to be "sloppy"
  - ISAM vs. B-trees

Pastry/Bamboo

- Based on Plaxton Mesh
  [Plaxton, et al SPAA 97]
- Names are fixed bit strings
- Topology: Prefix Hypercube
  - For each bit from left to right, pick a neighbor ID with common flipped bit and common prefix
  - log *n* degree & diameter
- Plus a ring
  - For reliability (with k pred/succ)
- Suffix Routing from A to B
  - "Fix" bits from left to right
  - E.g. 1010 to 0001:
    1010 → 0101 → 0010 → 0000 → 0001

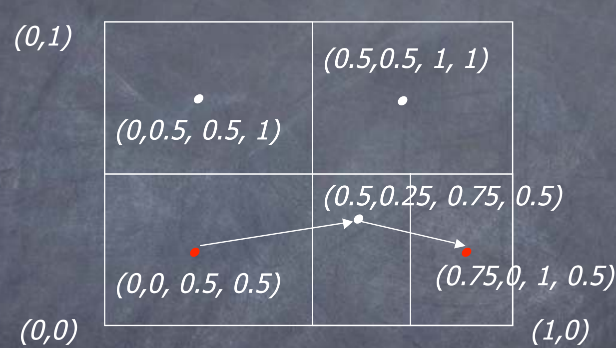


CAN: Content Addressable Network



- Exploit multiple dimensions
- Each node is assigned a zone
- Nodes are identified by zone boundaries
- Join: chose random point, split its zone

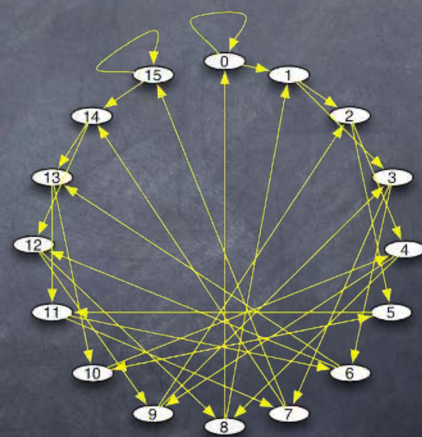
Routing in 2-dimensions



- Routing is navigating a *d*-dimensional ID space
  - Route to closest neighbor in direction of destination
  - Routing table contains O(d) neighbors
- Number of hops is $O(dN^{1/d})$

Koorde

- DeBruijn graphs
  - Link from node *x* to nodes 2*x* and 2*x*+1
  - Degree 2, diameter log *n*
    - Optimal!
- Koorde is Chord-based
  - Basically Chord, but with DeBruijn fingers



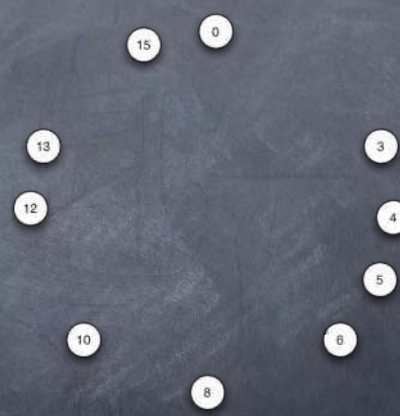
Note: Not vertex-symmetric!
Not a Cayley graph. But a coset graph of the "butterfly" topology.

Topologies of Other Oft-cited DHTs

- Tapestry
  - Very similar to Pastry/Bamboo topology
  - No ring
- Kademlia
  - Also similar to Pastry/Bamboo
  - But the "ring" is ordered by the XOR metric
  - Used by the Overnet/eDonkey filesharing system
- Viceroy
  - An emulated Butterfly network
- Symphony
  - A randomized "small-world" network

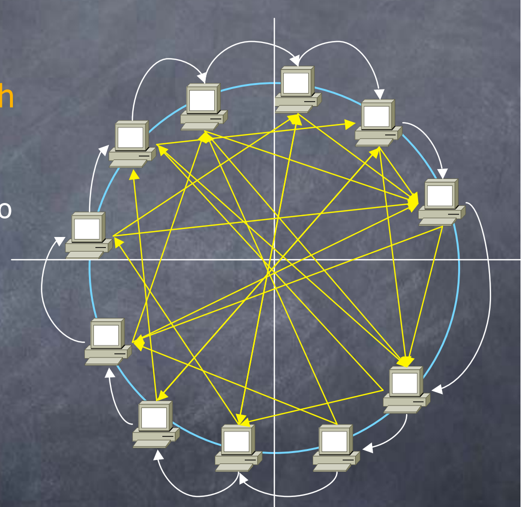
Incomplete Graphs: Emulation

- For Chord, we assumed 2^m nodes. What if not?
  - Need to "emulate" a complete graph even when incomplete.
  - Note: you've seen this problem before!
    - Litwin's Linear Hashing emulates hashtables of length 2^m!
- DHT-specific schemes used
  - In Chord, node *x* is responsible for the range [*x*, succ(*x*))
  - The "holes" on the ring should be randomly distributed due to hashing
  - *Consistent Hashing* [Karger, et al. STOC 97]



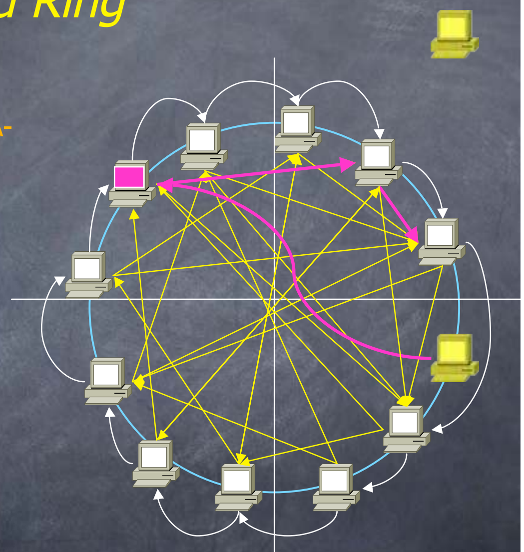
Chord in Flux

- Essentially never a "complete" chord graph
  - Maintain a "ring" of successor nodes
  - For redundancy, point to *k* successors
  - Point to nodes responsible for *IDs* at powers of 2
    - Sometimes called "fingers"
    - 1st finger is the successor



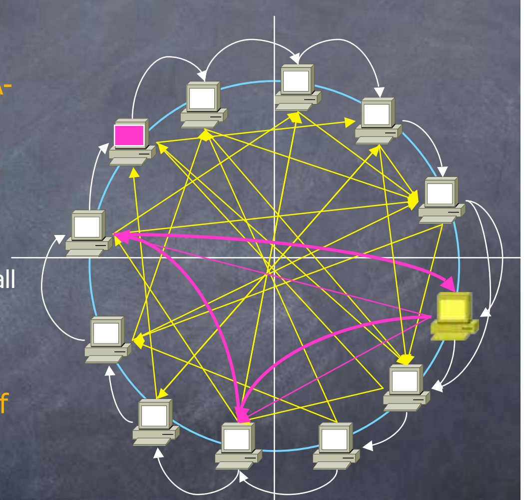
Joining the Chord Ring

- Need IP of some node
- Pick a random ID (e.g. SHA-1(IP))
- Send msg to current owner of that ID
  - That's your predecessor



Joining the Chord Ring

- Need IP of some node
- Pick a random ID (e.g. SHA-1(IP))
- Send msg to current owner of that ID
  - That's your predecessor
- Update pred/succ links
  - Once the ring is in place, all is well!
- Inform app to move data appropriately
- Search to install "fingers" of varying powers of 2
  - Or just copy from pred/succ and check!
- Inbound fingers fixed lazily



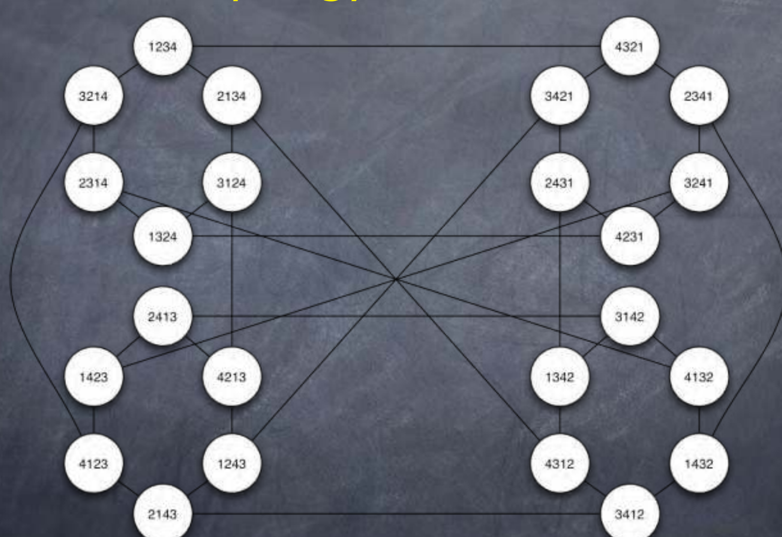
Theorem: If consistency is reached before network *doubles*, lookups remain log *n*

ICN Emulation

- At least 3 "generic" emulation schemes have been proposed
  - [Naor/Wieder SPAA '03]
  - [Abraham, et al. IPDPS '03]
  - [Manku PODC '03]
- As an exercise, funky ICN + emulation scheme = new DHT
  - IHOP: Internet Hashing on Pancake graphs [Ratajczak/Hellerstein '04]
    - Pancake graph† ICN + Abraham, et al. emulation.

†Based on Bill Gates' only paper.
Trivia question: who was his advisor/co-author?

Pancake Topology



A "Generalized DHT"

- Pick your favorite InterConnection Network
  - Hypercube, Butterfly, DeBruijn, Chord, Pancake, etc.
- Pick an "emulation" scheme
  - To handle the "incomplete" case
- Pick a way to let new nodes choose IDs
  - And maintain load balance

PhD Thesis, Gurmeet Singh Manku, 2004

Storage Models for DHTs

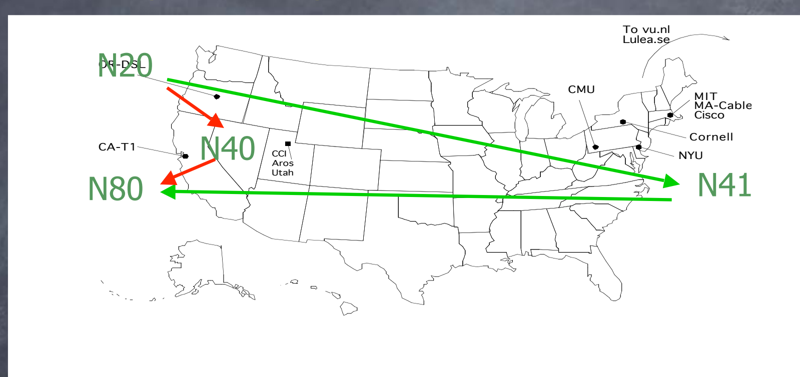
- Up to now we focused on routing
  - DHTs as "content-addressable network"
- Implicit in the name "DHT" is some kind of storage
  - Or perhaps a better word is "memory"
  - Enables indirection in time
  - But also can be viewed as a place to store things

- Soft state is the name of the game in Internet systems

A Note on Soft State

- A hybrid persistence scheme
  - Persistence via *storage & retry*
- Joint responsibility of publisher and storage node
  - Item published with a Time-To-Live (TTL)
  - Storage node attempts to preserve it for that time
    - Best effort
  - Publisher wants it to last longer?
    - Must republish it (or renew it)
- Must balance reliability and republishing overhead
  - Longer TTL = longer potential outage but less republishing
- On failure of a storage node
  - Publisher eventually republishes elsehere
- On failure of a publisher
  - Storage node eventually "garbage collects"

Optimizing routing to reduce latency



- Nodes close on ring, but far away in Internet
- Goal: put nodes in routing table that result in few hops and low latency

Locality-Centric Neighbor Selection

- Much recent work [Gummadi, et al. SIGCOMM '03, Abraham, et al. SODA '04, Dabek, et al. NSDI 04, Rhea, et al. USENIX '04, etc.]
  - We saw flexibility in neighbor selection in Pastry/Bamboo
  - Can also introduce some randomization into Chord, CAN, etc.
- How to pick
  - Analogous to ad-hoc networks
    1. Ping random nodes
    2. Swap neighbor sets with neighbors
       - Combine with random pings to explore
    3. Provably-good algorithm to find nearby neighbors based on sampling [Karger and Ruhl 02]

Geometry and its effects

[Gummadi, et al. SIGCOMM '03]

- Some topologies allow more choices
  - Choice of neighbors in the neighbor tables (e.g. Pastry)
  - Choice of routes to send a packet (e.g. Chord)
  - Cast in terms of "geometry"
    - But really a group-theoretic type of analysis
- Having a ring is very helpful for resilience
  - Especially with a decent-sized "leaf set" (successors/predecessors)
    - Say ~ log *n*

Handling Churn

- Bamboo [Rhea, et al, USENIX 04]
  - Pastry that doesn't go bad (?)
- Churn
  - Session time? Life time?
    - For system resilience, session time is what matters.
- Three main issues
  - Determining timeouts
    - Significant component of lookup latency under churn
  - Recovering from a lost neighbor in "leaf set"
    - Periodic, not reactive!
    - Reactive causes feedback cycles
      - Esp. when a neighbor is stressed and timing in and out
  - Neighbor selection again

Timeouts

- Recall Iterative vs. Recursive Routing
  - Iterative: Originator requests IP address of each hop
    - Message transport is actually done via direct IP
  - Recursive: Message transferred hop-by-hop
- Effect on timeout mechanism
  - Need to track latency of communication channels
  - Iterative results in direct $n \times n$ communication
    - Can't keep timeout stats at that scale
    - Solution: virtual coordinate schemes [Dabek et al. NSDI '04]
  - With recursive can do TCP-like tracking of latency
    - Exponentially weighted mean and variance
- Upshot: Both work OK up to a point
  - TCP-style does somewhat better than virtual coords at modest churn rates (23 min. or more mean session time)
  - Virtual coords begins to fail at higher churn rates

Complex Query Processing

DHTs Gave Us Equality Lookups

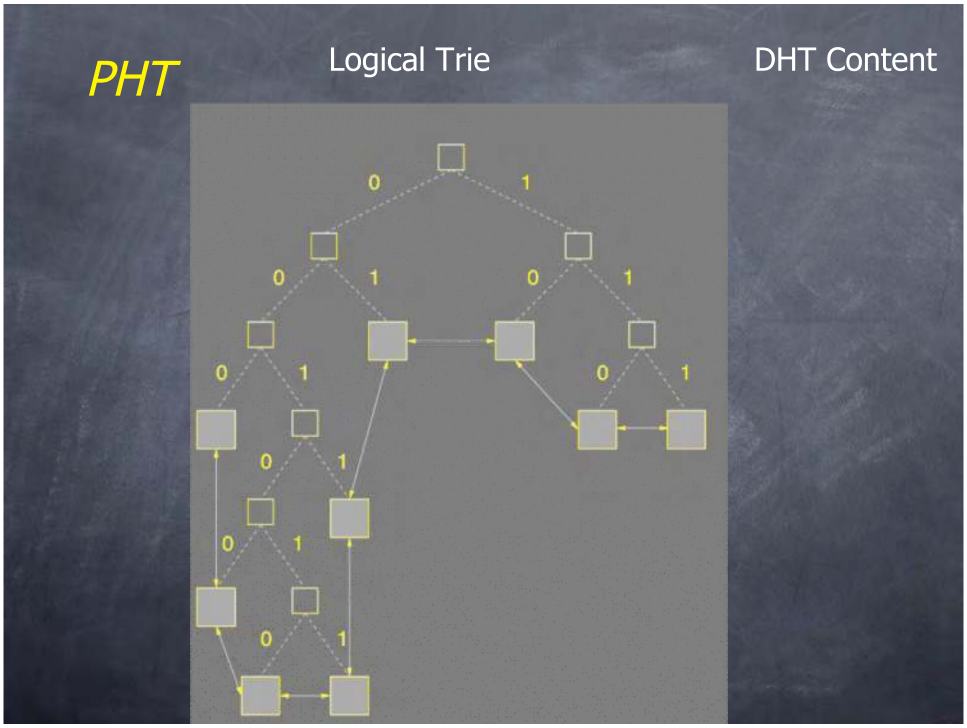
- What else might we want?
  - Range Search
  - Aggregation
  - Group By
  - Join
  - Intelligent Query Dissemination
- Theme
  - All can be built elegantly on DHTs!
    - This is the approach we take in PIER
  - But in some instances other schemes are also reasonable
    - I will try to be sure to call this out
    - The flooding/gossip strawman is always available

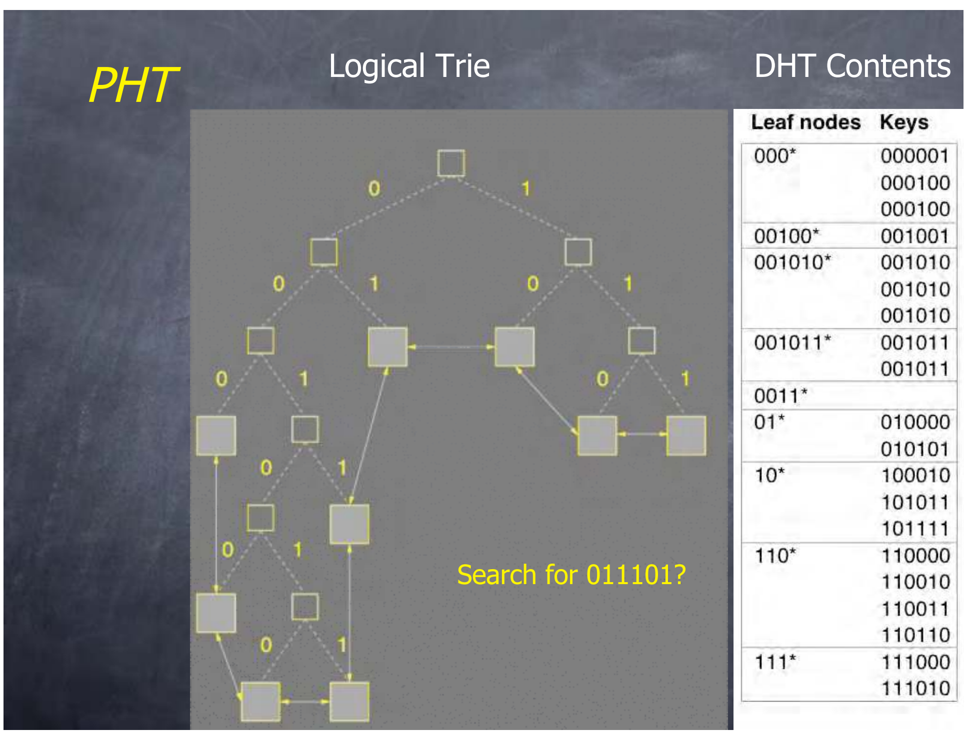
Range Search

- Numerous proposals in recent years
  - Chord w/o hashing, + load-balancing [Karger/Ruhl SPAA '04, Ganesan/Bawa VLDB '04]
  - Mercury [Bharambe, et al. SIGCOMM '04]. Specialized "small-world" DHT.
  - P-tree [Crainiceanu et al. WebDB '04]. A "wrapped" B-tree variant.
  - P-Grid [Aberer, CoopIS '01]. A distributed trie with random links.
  - (Apologies if I missed your favorite!)
- We'll do a very simple, elegant scheme here
  - Prefix Hash Tree (PHT). [Ratnasamy, et al '04]
  - Works over *any* DHT
  - Simple robustness to failure
  - Hints at generic idea: *direct-addressed distributed data structures*

Prefix Hash Tree (PHT)

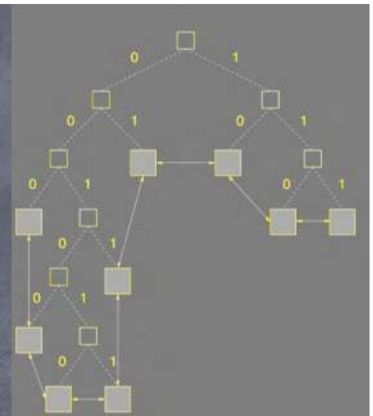
- Recall the *trie* (assume binary trie for now)
  - Binary tree structure with edges labeled 0 and 1
  - Path from root to leaf is a *prefix* bit-string
  - A key is stored at the minimum-distinguishing prefix (depth)
- PHT is a bucket-based trie addressed via a DHT
  - Modify trie to allow *b* items per leaf "bucket" before a split
  - Store contents of leaf bucket at DHT address corresponding to prefix
    - So far, not unlike Litwin's "Trie Hashing" scheme, but hashed on a DHT.
    - Punchline in a moment...





Leaf nodes	Keys
000*	000001 000100 000100
00100*	001001
001010*	001010 001010 001010
001011*	001011 001011
0011*	
01*	010000 010101
10*	100010 101011 101111
110*	110000 110010 110011 110110
111*	111000 111010

PHT Search



- Observe: The DHT allows *direct addressing* of PHT nodes
  - Can *jump* into the PHT at any node
    - Internal, leaf, or *below a leaf!*
  - So, can find leaf by binary search
    - *loglog |D|* search cost!
    - If you knew (roughly) the data distribution, even better
  - Moreover, consider a failed machine in the system
    - Equals a failed node of the trie
    - Can "hop over" failed nodes directly!
  - And… consider concurrency control
    - A link-free data structure: simple!

Reusable Lessons from PHTs

- Direct-addressing a lovely way to emulate robust, efficient "linked" data structures in the network
- Direct-addressing requires regularity in the data space partitioning
  - *E.g.* works for regular space-partitioning indexes (tries, quad trees)
  - Not so simple for data-partitioning (B-trees, R-trees) or irregular space partitioning (kd-trees)

Aggregation

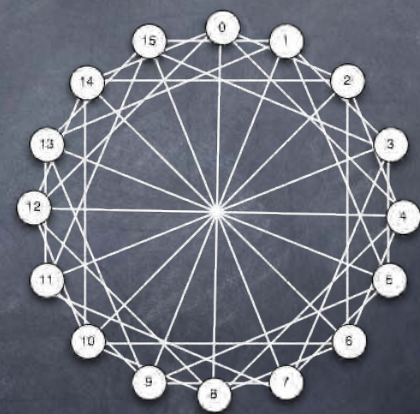
- Two key observations for DHTs
  - DHTs are multi-hop, so hierarchical aggregation can reduce BW
    - E.g., the TAG work for sensornets [Madden, OSDI 2002]
  - DHTs provide tree construction in a very natural way
- But what if I don't use DHTs?
  - Hold that thought!

An API for Aggregation in DHTs

- Uses a basic hook in DHT routing
  - When routing a multi-hop msg, intermediate nodes can intercept
- Idea
  - To aggregate in a DHT, pick an aggregating ID at random
  - All nodes send their tuples toward that ID
  - Nodes along the way intercept and aggregate before forwarding
- Questions
  - What does the resulting agg tree look like?
  - What shape of tree would be good?
- Note: tree-construction will be key to other tasks!

Consider Aggregation in Chord

- Everybody sends their message to node 0
- Assume greedy jumps (increasing Gon-order)
- Intercept messages and aggregate along the way



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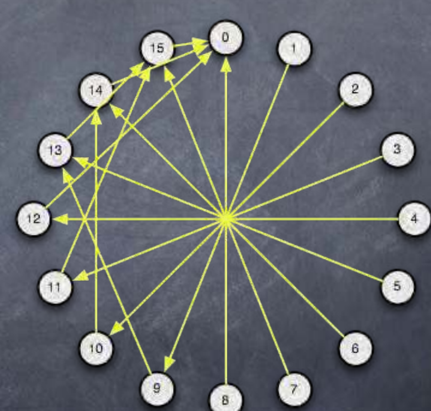

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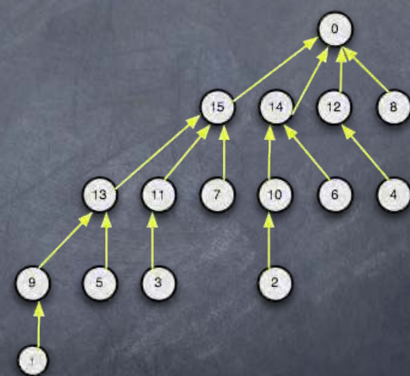
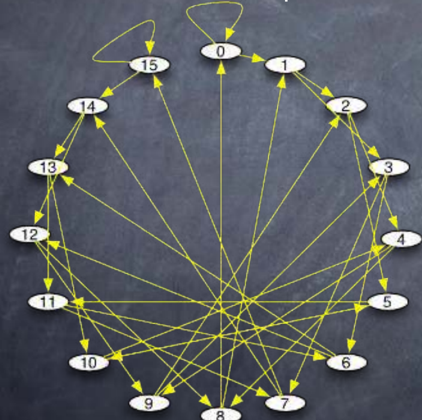
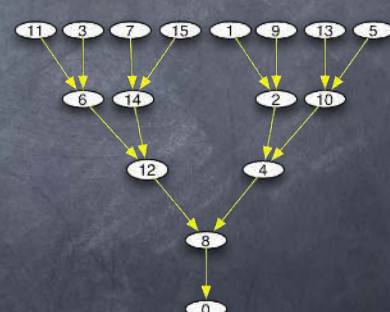


Binomial Tree!!

Aggregation in Koorde

- Recall the DeBruijn graph:
  - Each node x points to $2x \bmod n$ and $(2x + 1) \bmod n$





(But note: not node-symmetric)

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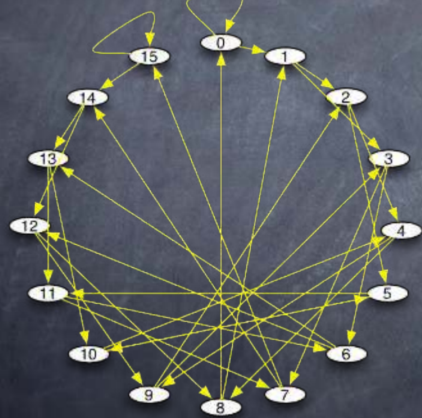
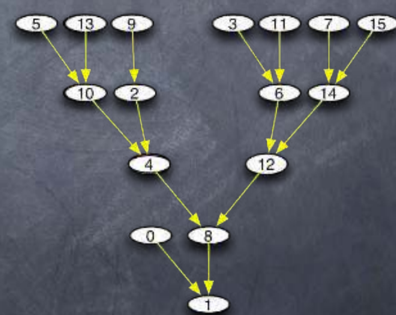
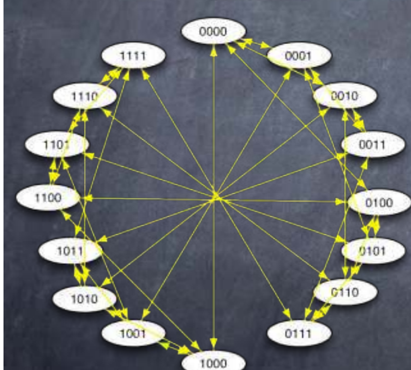


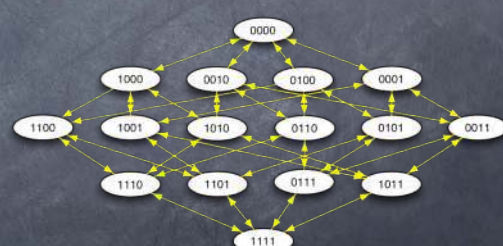


(But note: not node-symmetric)

Aggregation in Pastry/Bamboo

- Depends on choice of neighbors
  - But if you flip exactly one bit each hop:





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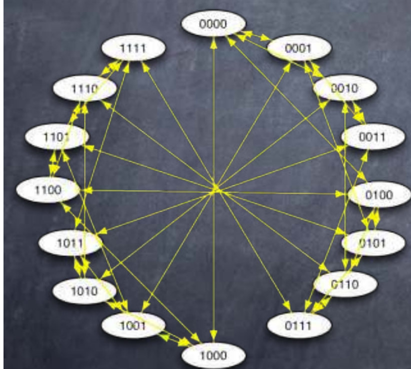
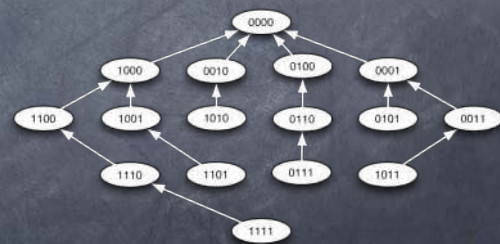




Metrics for Aggregation Trees

- What makes a good/bad agg tree?
  - Number of edges? No!
    - Always n-1. With distributive/algebraic aggs, msg size is fixed.
  - Degree of fan-in
    - Affects congestion
  - Height
    - Determines latency
  - Predictability of subtree shape
    - Determines ability to control timing tightly
  - Stability in the face of churn
    - Changing tree shape while accumulating can result in errors
  - Subtree size distribution
    - Affects "jeopardy" of lost messages

So what if I don't have a DHT?

- Need another tree-construction mechanism
  - There are many in the NW literature (e.g. for multicast)
  - Require maintenance messages akin to DHTs
    - Do you maintain for the life of your query engine? Or setup/teardown as needed?
- Can pick a tree shape of your own
  - Not at the mercy of the DHT topologies
  - E.g. could do high fan-in trees to minimize latency
- As we noted before, we will reuse tree-construction for multiple purposes
  - It's handy that they're trivial in DHTs
  - But could reuse another scheme for multiple purposes as well
- Or, can do aggregation via gossip [Kempe, et al FOCS '03]

Group By

- A piece of cake in a DHT
  - Every node sends tuples toward the hash ID of the grouping columns
  - An agg tree is naturally constructed per group
- Note nice dual-purpose use of DHT
  - Hash-based partitioning for parallel group by
    - Just like parallel DBMS (Gamma, the *Exchange* op in Volcano)
  - Agg tree construction in multi-hop overlay network

Hash Join

- We just did hash-based group by.
- Hash-based join is roughly the same deal, twice:
  - Given R.a Join S.b
  - Each node:
    - sends each R tuple toward H(R.a)
    - sends each S tuple toward H(S.b)
- Again, DHT gives
  - Hash-based partitioning for parallel hash join
  - Tree construction (no reduction along the way here, though)
- Note the resulting communication pattern
  - A tree is constructed *per hash destination!*
    - That's a lot of trees!
    - No big deal for the DHT -- it already had that topology there.

Fetch Matches Join

- Essentially a distributed index join
  - Name comes from R* (Mackert & Lohman)
- Given R.a Join S.b
  - Assume <S.b, tuple> was already "published" (indexed)
- For each tuple of R, query DHT for S tuples matching R.a
  - Each S.b value will get some subset of the nodes visiting it
    - So a lot of "partial" trees
  - Note: if S.b is *not* already indexed in the DHT via S.b, that has to happen on the fly
    - Half a hash join :-)

Symmetric Semi-Join and Bloom Join

- Query rewriting tricks from distributed DBs
- Semi-Joins a la SDD-1
  - But do it to both sides of the join
  - Rewrite R.a Join S.b as
    - (<S.ID,S.b> semi-join <R.id,R.a>) join R.a join S.b
    - Latter 2 joins can be Fetch Matches
- Bloom Joins a la R*
  - Requires a bit more finesse here
  - Aggregate R.a Bloom filters to a fixed hash ID. Same for S.b.
  - All the R.a Bloom filters are OR'ed, eventually multicasted to all nodes storing S tuples
  - Symmetric for S.b Bloom filter
  - Can in principle stream refining Bloom filters

Query Dissemination

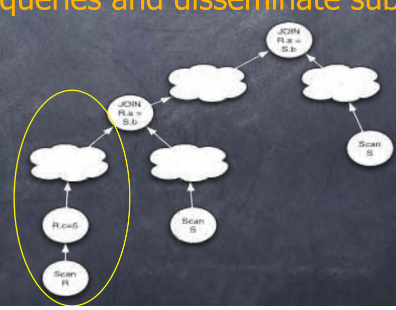
- How do nodes find out about a query?
  - Up to now we conveniently ignored this!
- Case 1: Broadcast
  - As far as we know, all nodes need to participate
  - Need to have a broadcast tree out of the query node
  - This is the opposite of an aggregation tree!
    - But how to instantiate it?
- Naïve solution: Flood
  - Each nodes sends query to all its neighbors
  - Problem: nodes will receive query multiple times
    - wasted bandwidth

SCRIBE

- Redundancy-free broadcast
- Upon joining the network, route a message to some canonical hash ID
  - Parent intercepts msg, makes a note of new child, discards message
  - At the end, each node knows its children, so you have a broadcast tree
    - Tree needs to deal with joins and leaves on its own; the DHT won't help.
  - MSR/Rice, NGC '01

Query Dissemination II

- Suppose you have a simple equality query
  - Select * From R Where R.c = 5
  - If R.c is already indexed in the DHT, can route query via DHT
- Query Dissemination is an "access method"
  - Basically the same as an index
- Can take more complex queries and disseminate sub-parts
  - Select * From R, S, T
    Where R.a = S.b
    And S.c = T.d
    And R.c = 5



PIER

- Peer-to-Peer Information Exchange & Retrieval
  - Puts together many of the techniques described above
  - Aggressively uses DHTs
    - But agnostic to choice
    - Uses Bamboo, has worked on CAN and Chord
  - [Huebsch, et al. VLDB '03]
- Deployed
  - Running φ queries on ~400 nodes around the world (PlanetLab)
  - Simulated on up to 10K nodes
- Current Applications
  - Improved Filesharing
  - Internet Monitoring (φ)
  - Customizable Routing via Recursive Queries

http://pier.cs.berkeley.edu

DHTs in PIER

- PIER uses DHTs for:
  - Query Broadcast (TC)
  - Indexing (CBR + S)
  - Range Indexing Substrate (CBR+S)
  - Hash-partitioned parallelism (CBR)
  - Hash tables for group-by, join (CBR + S)
  - Hierarchical Aggregation (TC + S)

DBMS Analogy

Hash Index

B+-Tree

Exchange

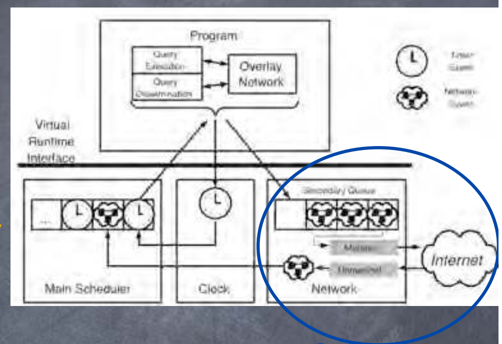
HashJoin

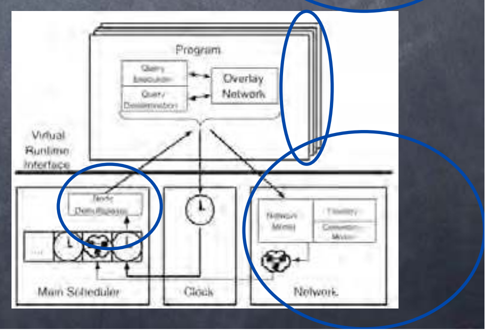
Key:

TC = Tree Construction
CBR = Content-Base Routing
S = Storage

Native Simulation

- Entire system is event-driven
- Enables discrete-event simulation to be "slid in"
  - Replaces lowest-level networking & scheduler
  - Runs all the rest of PIER natively
- *Very* helpful for debugging a massively distributed system!





Initial Tidbits from PIER Efforts

- "Multiresolution" simulation critical
  - Native simulator was hugely helpful
  - Emulab allows control over link-level performance
  - PlanetLab is a nice approximation of reality
- Debugging still very hard
  - Need to have a traced execution mode.
    - Radiological dye? Intensive logging?
- DB workloads on NW technology: mismatches
  - E.g. Bamboo aggressively changes neighbors for single-message resilience/performance
    - Can wreak havoc with stateful aggregation trees
  - E.g. returning results: SELECT * from Firewalls
    - 1 MegaNode of machines want to send you a tuple!
- A relational query processor w/o storage
  - Where's the metadata?

Storage Models & Systems

Traditional FileSystems on p2p?

- Lots of projects
  - OceanStore, FarSite, CFS, Ivy, PAST, etc.
- Lots of challenges
  - Motivation & Viability
    - Short & long term
  - Resource mgmt
    - Load balancing w/heterogeneity, etc.
    - Economics come strongly into play
      - Billing and capacity planning?
  - Reliability & Availability
    - Replication, server selection
    - Wide-area replication (+ consistency of updates)
  - Security
    - Encryption & key mgmt, rather than access control

Non-traditional Storage Models

- Very long term archival storage
  - LOCKSS
- Ephemeral storage
  - Palimpsest, OpenDHT

LOCKSS

[Maniatis, et al. SOSP '04]

- Digital Preservation of Academic Materials
  - Academic publishing is moving from paper to digital *leasing*
- Librarians are scared with good reason
  - Access depends on the fate of the publisher
  - Time is unkind to bits after decades
  - Plenty of enemies (ideologies, governments, corporations)
- Goal: Preserve access for local patrons, for a very long time

Protocol Threats

- Assume conventional platform/social attacks
- Mitigate further damage through protocol
- Top adversary goal: Stealth Modification
  - Modify replicas to contain adversary's version
  - Hard to reinstate original content after large proportion of replicas are modified
- Other goals
  - Denial of service
  - System slowdown
  - Content theft

The LOCKSS Solution

- Peer-to-peer auditing and repair system for replicated documents / no file sharing
- A peer periodically audits its own replica, by calling an opinion poll
- When a peer suspects an attack, it raises an alarm for a human operator
  - Correlated failures
  - IP address spoofing
  - System slowdown
- 2nd iteration of a deployed system

Sampled Opinion Poll

- Each peer holds
  - reference list of peers it has discovered
  - friends list of peers it knows externally
- Periodically (faster than rate of bit rot)
  - Take a sample of the reference list
  - Invite them to send a hash of their replica
- Compare votes with local copy
  - Overwhelming agreement (>70%) ☞ Sleep blissfully
  - Overwhelming disagreement (<30%) ☞ Repair
  - Too close to call ☞ Raise an alarm
- To repair, the peer gets the copy of somebody who disagreed and then reevaluates the same votes

Reference List Update

- Take out voters in the poll
  - So that the next poll is based on different group
- Replenish with some "strangers" and some "friends"
  - Strangers: Accepted nominees proposed by voters
  - Friends: From the friends list
  - The measure of favoring friends is called churn factor

LOCKSS Defenses

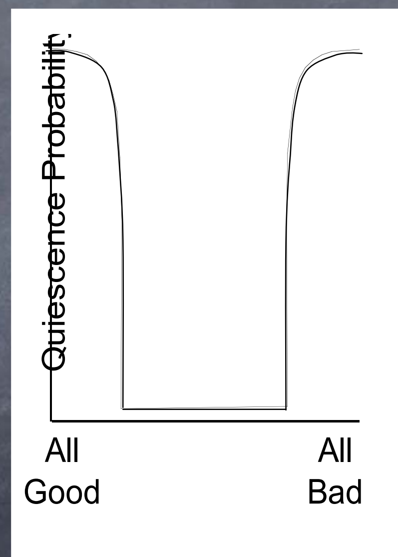
- Limit the rate of operation
- Bimodal system behavior
- Churn friends into reference list

Limit the rate of operation

- Peers determine their rate of operation autonomously
  - Adversary must wait for the next poll to attack through the protocol
- No operational path is faster than others
  - Artificially inflate "cost" of cheap operations
  - No attack can occur faster than normal ops

Bimodal System Behavior

- When most replicas are the same, no alarms
- In between, many alarms
- To get from mostly correct to mostly wrong replicas, system must pass through "moat" of alarming states



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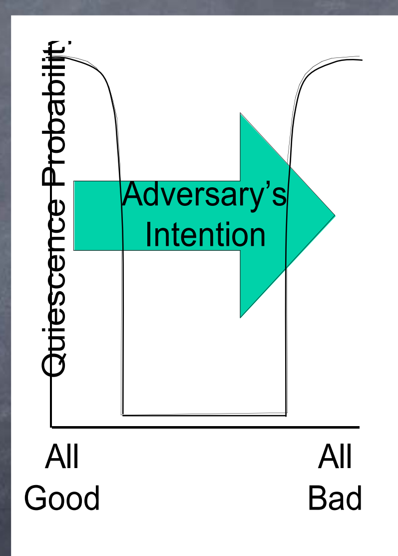

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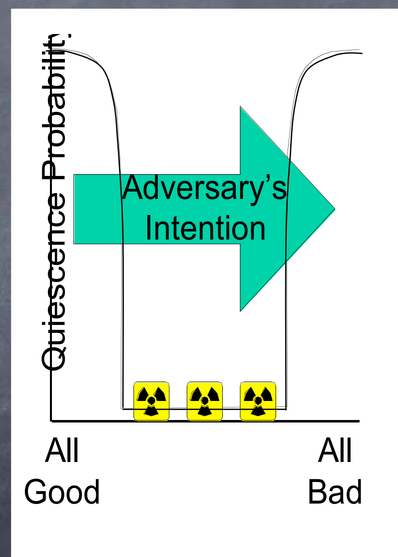


Churn Friends into Reference List

- Churn adjusts the bias in the reference list
- High churn favors friends
  - Reduces the effects of Sybil attacks
  - But offers easy targets for focused attack
- Low churn favors strangers
  - It offers Sybil attacks free reign
    - Bad peers nominate bad; good peers nominate some bad
  - Makes focused attack harder, since adversary can predict less of the poll sample
- Goal: strike a balance

Palimpsest *[Roscoe & Hand, HotOS 03]*

- Robust, available, secure *ephemeral* storage
- Small and very simple
- Soft-capacity – for service providers
- Congestion-based pricing
- Automatic space reclamation
- Flexible client and server policies

- *We'll ignore the economics*

Service Model for Ephemeral Storage

- For clients:
  - Data highly available for limited period of time
  - Secure from unauthorized readers
  - Resistant to DoS attacks
  - Tradeoff cost/reliability/performance
- For service providers:
  - Charging that makes economic sense
  - Capacity planning
  - Simplicity of operation and billing

How does it do this?

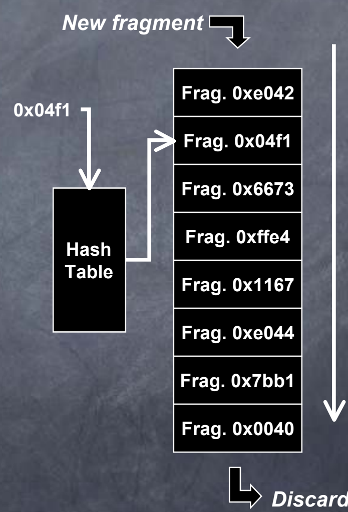
- To write a file:
  - Erasure code it
  - Route it through a network of simple block stores
  - Pay to store it
- Each block store is a fixed-length FIFO
  - Block stores may be owned by multiple providers
  - Block stores don't care who the users are
  - No one store needs to be trusted
  - Blocks are eventually lost off the end of the queue

Storing a file

- Each file has a *name* and a *key.*
- File Dispersal
  - Use a rateless code to spread blocks into fragments
    - Rabin's IDA over GF(2^{16}), 1024-byte blocks
- Fragment Encryption
  - Security, authenticity, identification
    - AES in Offset Codebook Mode
- Fragment Placement
  - Encrypt: (SHA256(name) $\oplus$ frag.id) $\Rightarrow$ 256-bit ID
  - Send (fragment, ID) to a block store using DHT
    - Any DHT will do

What happens at the block store?

- Fixed-size (virtual) block stores
  - Use > 1 per node for scaling
- FIFO queue of fragments
- Indexed by fragment id
- Re-writing a fragment id moves to tail of queue
  Note: fragment ID is *not* related to content (c.f. CFS)
- Block stores *ignore* user identity
  - No authentication needed



Retrieving a file

- Generate enough fragment IDs
- Request fragments from block stores
- Wait until *n* come back to you
- Decrypt and verify
- Invert the IDA
- *Voila!*

Unfortunately…

Files disappear

- This is a storage system which, in use, is *guaranteed* to forget *everything*
  - c.f. Elephant, Postgres, etc.
- Not a problem for us provided we know how long files stay around for
  - Can refresh files
  - Can abandon them
  - Note: there is no delete operation
- How do we do this?

Sampling the time constant

- Each block store has a *time constant* τ
  - How long fragment takes to reach end of queue
- Clients query block stores for τ
  - Operation piggy-backed on reads/writes
- Maintain exponentially-weighted estimate of *system* τ, τ_s
  - Fragment lifetimes Normally distributed around τ_s
- Use this to predict file lifetimes
  - Allows extensive application-specific tradeoffs

Security and Trust

Trustworthy P2P

- Many challenges here. Examples:
  - Authenticating peers
  - Authenticating/validating data
    - Stored (poisoning) and in flight
  - Ensuring communication
  - Validating distributed computations
  - Avoiding Denial of Service
    - Ensuring fair resource/work allocation
  - Ensuring privacy of messages
    - Content, quantity, source, destination
  - Abusing the power of the network
- We'll just do a sampler today

Free Riders

- Filesharing studies
  - Lots of people download
  - Few people serve files
- Is this bad?
  - If there's no incentive to serve, why do people do so?
  - What if there are strong disincentives to being a major server?

Simple Solution: Threshholds

- Many programs allow a threshhold to be set
  - Don't upload a file to a peer unless it shares > k files
- Problems:
  - What's k?
  - How to ensure the shared files are interesting?

BitTorrent

- Server-based search
  - suprnova.org, chat rooms, etc. serve ".torrent" files
    - metadata including "tracker" machine for a file
- Bartered "Tit for Tat" download bandwidth
  - Download one (random) chunk from a storage peer, slowly
  - Subsequent chunks *bartered* with concurrent downloaders
    - As tracked by the tracker for the file
  - The more chunks you can upload, the more you can download
    - Download speed starts slow, then goes fast
  - Great for large files
    - Mostly videos, warez

One Slide on Game Theory

- Typical game theory setup
  - Assume self-interested (selfish) parties, acting autonomously
  - Define some benefit & cost functions
  - Parties make "moves" in the game
    - With resulting costs and benefits for themselves and others
  - A *Nash equilibrium:*
    - A state where no party increases its benefit by moving
    - Note:
      - Equilibria need not be unique nor equal
      - Time to equilibrium is an interesting computational twist
- *Mechanism Design*
  - Design the states/moves/costs/benefits of a game
  - To achieve particular globally-acceptable equilibria
    - I.e. selfish play leads to global good

DAMD P2P!

- Distributed Algorithmic Mechanism Design (DAMD)
  - A natural approach for P2P
- An Example: Fair-share storage [Ngan, et al., Fudico04]
  - Every node *n* maintains a *usage record:*
    - Advertised capacity
    - *Hosted list* of objects n is hosting (nodeID, objID)
    - *Published list* of objects people host for *n* (nodeID, objID)
  - Can publish if capacity - $p \cdot \sum(\text{published list}) > 0$
    - Recipient of publish request should check *n*'s usage record
  - Need schemes to authenticate/validate usage records
    - Selfish Audits: *n* periodically checks that the elements of its hosted list appear in published lists of publishers
    - Random Audits: *n* periodically picks a peer and checks all its hosted list items

Secure Routing in DHTs

- The "Sybil" attack [Douceur, IPTPS 02]
  - Register many times with multiple identities
  - Control enough of the space to capture particular traffic

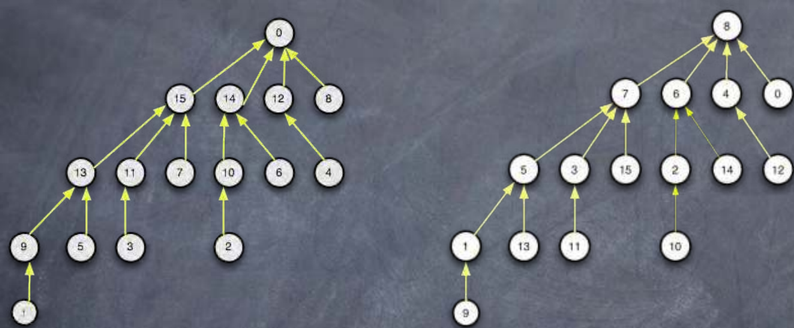
Squelching Sybil

- Certificate authority
  - Centralize one thing: the signing of ID certificates
    - Central server is otherwise out of the loop
  - Or have an "inner ring" of trusted nodes do this
    - Using practical Byzantine agreement protocols [Castro/Liskov OSDI '01]
- Weak secure IDs
  - ID = SHA-1(IP address)
  - Assume attacker controls a modest number of nodes
  - Before routing through a node, challenge it to produce the right IP address
    - Requires iterative routing

Redundant Computation

- Correctness via redundancy
  - An old idea (e.g. process pairs)
  - Applied in an adversarial environment
  - Using topological properties of DHTs
- Two Themes
  - Change "support" contents per peer across copies
  - Equalize "influence" of each peer

Example: Redundant Agg in Chord



- |support(0)| = 16
- |support(1-8)| = 1
- |support(9-12)| = 2
- |support(13-14)| = 4
- |support(15)| = 8

- |support(8)| = 16
- |support(9-0)| = 1
- |support(1-4)| = 2
- |support(5-6)| = 4
- |support(7)| = 8

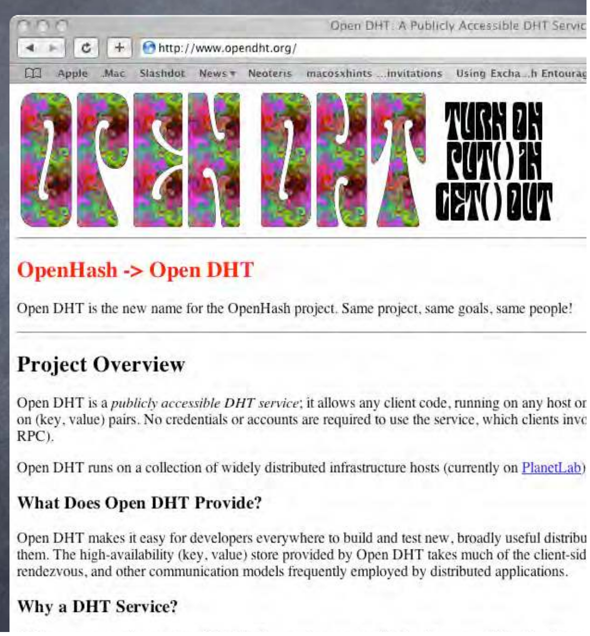
log(n) roles w/binomial size distribution (avg = 3)

Joining the Fun

- Consortium of academia and industry
  - Catalyzed by Intel Research in 2002
  - Now hosted at Princeton U
  - 25% of SOSP '03 papers used PlanetLab
- DB folks should get more involved!

OpenDHT

- A shared DHT *service*
  - The Bamboo DHT
  - Hosted on PlanetLab
  - Simple RPC API
  - You don't need to deploy or host to play with a *real* DHT!
- A playground for killer apps?
  - Needn't be as big as PIER!
  - Example: FreeDB replacement
- Research in sharing DHT svc!
  - ReDiR [Karp, et al. IPTPS '04]
    - Recursive Distributed Rendezvous
    - Enables multiple apps on subsets of nodes
  - New resource mgmt scheme to do fair-share storage



Closing Thoughts

Much Fun to Be Had Here

- Potentially high-impact area
  - New classes of applications enabled
    - A useful question: "What apps need/deserve this scale"
    - Intensity of the scale keeps the research scope focused
      - Zero-administration, sub-peak performance, semantic homogeneity, etc.
  - A chance to reshape the Internet
    - More than just a packet delivery service
    - φ is an effort in this direction

Much Fun to Be Had Here

- Rich cross-disciplinary rallying point
  - Networks, algorithms, distributed systems, databases, economics, security…
  - Top-notch people at the table
  - Many publication venues to choose from
    - Including new ones like NSDI, IPTPS, WORLDS

Much Fun to Be Had Here

- DHT and similar overlays are a real breakthough
  - Building block for data independence
  - Multiple metaphors
    - Hashtable storage/index
    - Content-addressable routing
    - Topologically interesting tree construction
  - Each stimulates ideas for distributed computation
- Relatively solid DHT implementations available
  - Bamboo, OpenDHT (Intel & UC Berkeley)
  - Chord (MIT)

The DB Community Has Much to Offer

- Complex (multi-operator) queries & optimization
  - NW folks have tended to build single-operator "systems"
    - E.g. aggregation only, or multi-d range-search only
  - Adaptivity required
    - But may not look like adaptive QP in databases…
- Declarative language semantics
  - Deal with streaming, clock jitter and soft state!
- Data reduction techniques
  - For visualization, approximate query processing
- Bulk-computation workloads
  - Quite different from the ones the NW and systems folks envision
- Recursive query processing
  - The network *is* a graph!

Metareferences

- Your favorite search engine should find the inline refs
- Project IRIS has a lot of participants' papers online
  - http://www.project-iris.org
- IEEE Distributed Systems Online
  - http://dsonline.computer.org/os/related/p2p/
- O'Reilly OpenP2P
  - http://www.openp2p.com
- Karl Aberer's ICDE 2002 tutorial
  - http://lsirpeople.epfl.ch/aberer/Talks/ICDE2002-Tutorial.pdf
- Ross/Rubenstein InfoCom 2003 tutorial
  - http://cis.poly.edu/~ross/tutorials/P2PtutorialInfocom.pdf
- PlanetLab
  - http://www.planet-lab.org
- OpenDHT
  - http://www.opendht.org

Some of the p2p DB groups

- PIER
  - http://pier.cs.berkeley.edu
- Stanford Peers
  - http://www-db.stanford.edu/peers/
- P-Grid
  - http://www.p-grid.org/ (EPFL)
- Pepper
  - http://www.cs.cornell.edu/database/pepper/pepper.htm
- BestPeer (PeerDB)
  - http://xena1.ddns.comp.nus.edu.sg/p2p/
- Hyperion
  - http://www.cs.toronto.edu/db/hyperion/
- Piazza
  - http://data.cs.washington.edu/p2p/piazza/