Beyond Theory: DHTs in Practice

CS 194 - Distributed Systems

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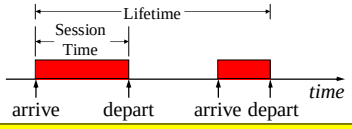
Talk Outline

- Bamboo: a churn-resilient DHT
  - Churn resilience at the lookup layer [USENIX'04]
  - Churn resilience at the storage layer [Cates'03], [Unpublished]
- OpenDHT: the DHT as a service
  - Finding the right interface [IPTPS'04]
  - Protecting against overuse [Under Submission]
- Future work

Making DHTs Robust: The Problem of Membership Churn

- In a system with 1,000s of machines, some machines failing / recovering at all times
- This process is called *churn*
- Without repair, quality of overlay network degrades over time
- A significant problem deployed peer-to-peer systems

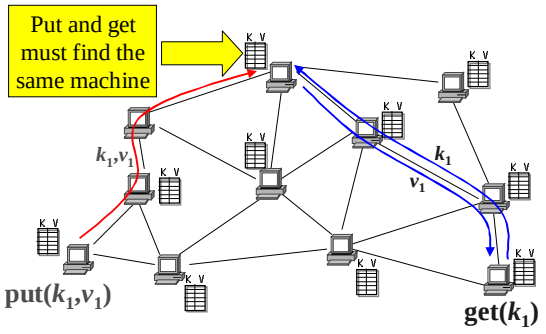
How Bad is Churn in Real Systems?



An hour is an incredibly short MTTF!

Authors	*Systems Observed*	*Session Time*
SGG02	Gnutella, Napster	50% < 60 minutes
CLL02	Gnutella, Napster	31% < 10 minutes
SW02	FastTrack	50% < 1 minute
BSV03	Overnet	50% < 60 minutes
GDS03	Kazaa	50% < 2.4 minutes

Refresher: DHT Lookup/Routing

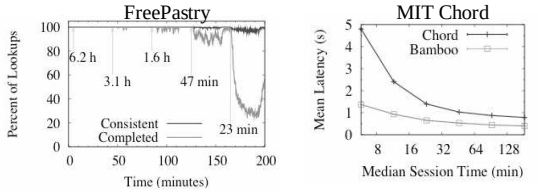


Can DHTs Handle Churn? A Simple Test

- Start 1,000 DHT processes on a 80-CPU cluster
  - Real DHT code, emulated wide-area network
  - Models cross traffic and packet loss
- Churn nodes at some rate
- Every 10 seconds, each machine asks:
  "Which machine is responsible for key *k*?"
  - Use several machines per key to check consistency
  - Log results, process them after test

Test Results

- In Tapestry (the OceanStore DHT), overlay partitions
  - Leads to very high level of inconsistencies
  - Worked great in simulations, but not on more realistic network
- And the problem isn't limited to Tapestry:



The Bamboo DHT

- Forget about comparing Chord-Pastry-Tapestry
  - Too many differing factors
  - Hard to isolate effects of any one feature
- Instead, implement a new DHT called Bamboo
  - Same overlay structure as Pastry
  - Implements many of the features of other DHTs
  - Allows testing of individual features independently

How Bamboo Handles Churn (Overview)

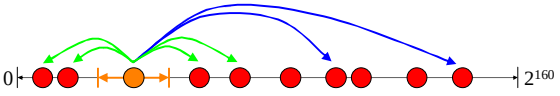
1. Routes around suspected failures quickly
   - Abnormal latencies indicate failure or congestion
   - Route around them before we can tell difference
2. Recovers failed neighbors periodically
   - Keeps network load independent of churn rate
   - Prevents overlay-induced positive feedback cycles
3. Chooses neighbors for network proximity
   - Minimizes routing latency in non-failure case
   - Allows for shorter timeouts

Bamboo Basics: Partition Key Space

- Each node in DHT will store some *k*,*v* pairs
- Given a key space *K*, *e.g.* [0, 2^{160}):
  - Choose an identifier for each node, $id_i \in K$, uniformly at random
  - A pair *k*,*v* is stored at the node whose identifier is closest to *k*

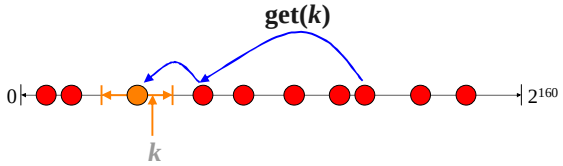
Bamboo Basics: Build Overlay Network

- Each node has two sets of neighbors
- **Immediate neighbors in the key space**
  - Important for correctness
- **Long-hop neighbors**
  - Allow puts/gets in O(log *n*) hops



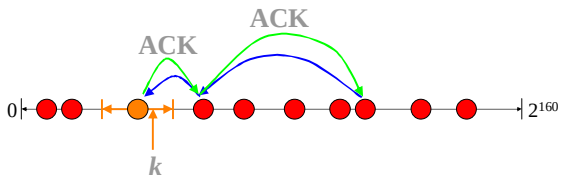
Bamboo Basics: Route Puts/Gets Thru Overlay

- Route greedily, always making progress



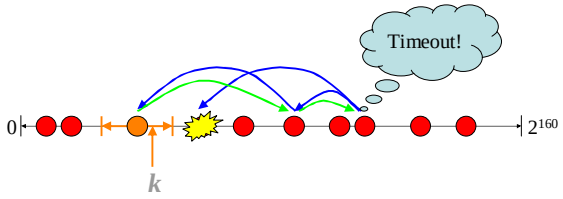
Routing Around Failures

- Under churn, neighbors may have failed
- To detect failures, acknowledge each hop



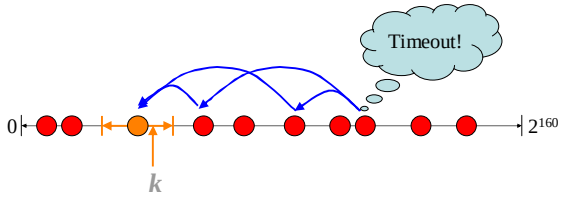
Routing Around Failures

- If we don't receive an ACK, resend through different neighbor



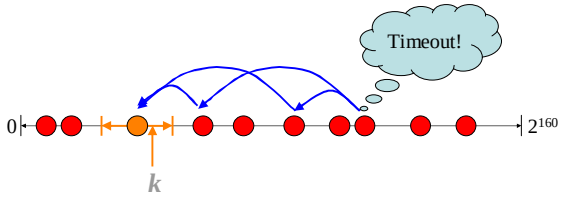
Computing Good Timeouts

- Must compute timeouts carefully
  - If too long, increase put/get latency
  - If too short, get message explosion



Computing Good Timeouts

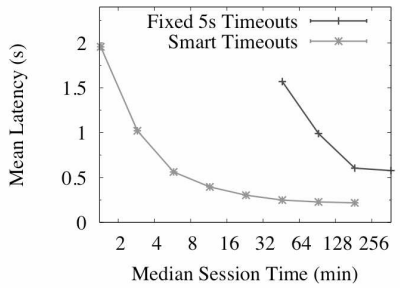
- Chord errs on the side of caution
  - Very stable, but gives long lookup latencies



Computing Good Timeouts

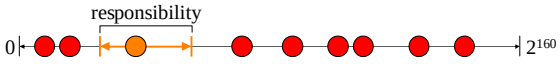
- Keep past history of latencies
  - Exponentially weighted mean, variance
- Use to compute timeouts for new requests
  - timeout = mean + 4 × variance
- When a timeout occurs
  - Mark node "possibly down": don't use for now
  - Re-route through alternate neighbor

Timeout Estimation Performance



Recovering From Failures

- Can't route around failures forever
  - Will eventually run out of neighbors
- Must also find new nodes as they join
  - Especially important if they're our immediate predecessors or successors:



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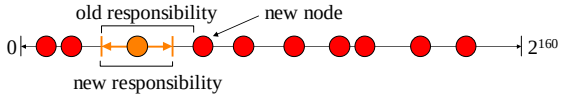
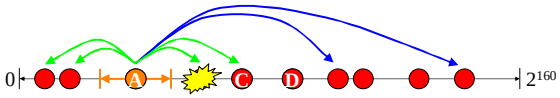


Recovering From Failures

- Obvious algorithm: *reactive* recovery
  - When a node stops sending acknowledgements, notify other neighbors of potential replacements
  - Similar techniques for arrival of new nodes



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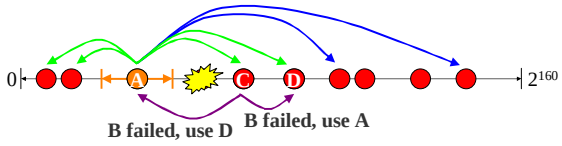
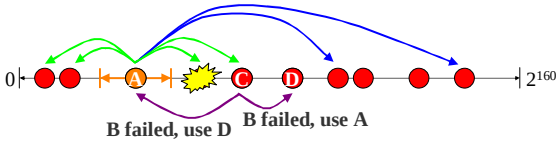


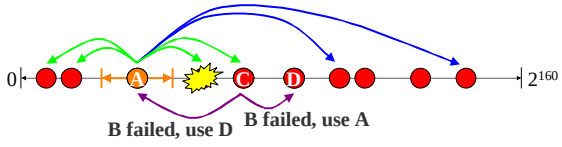
The Problem with Reactive Recovery

- What if B is alive, but network is congested?
  - C still perceives a failure due to dropped ACKs
  - C starts recovery, further congesting network
  - More ACKs likely to be dropped
  - Creates a positive feedback cycle



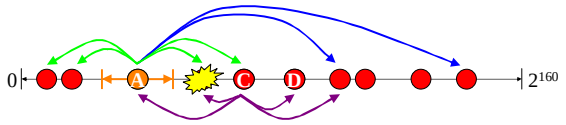
The Problem with Reactive Recovery

- What if B is alive, but network is congested?
- This was the problem with Pastry
  - Combined with poor congestion control, causes network to partition under heavy churn



Periodic Recovery

- Every period, each node sends its neighbor list to each of its neighbors



my neighbors are A, B, D, and E

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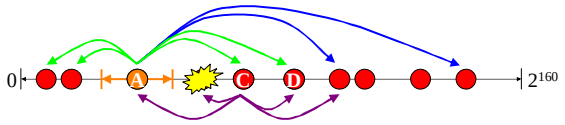

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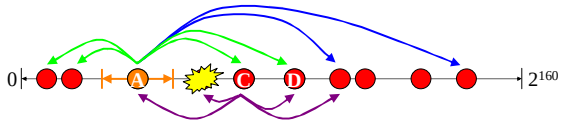
Sean C. Rhea OpenDHT: A Public DHT Service April 14, 2005

Periodic Recovery

- Every period, each node sends its neighbor list to each of its neighbors
  - Breaks feedback loop



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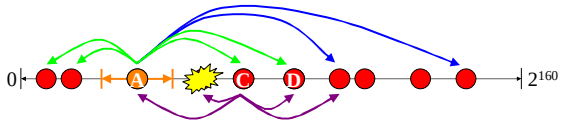
Periodic Recovery

- Every period, each node sends its neighbor list to each of its neighbors
  - Breaks feedback loop
  - Converges in logarithmic number of periods



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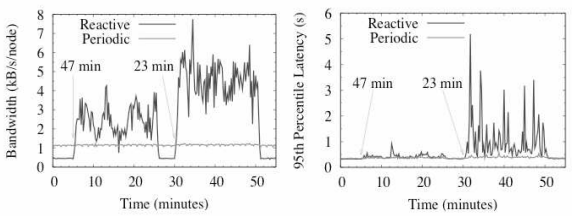
Periodic Recovery Performance

- Reactive recovery expensive under churn
- Excess bandwidth use leads to long latencies



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Proximity Neighbor Selection (PNS)

- For each neighbor, may be many candidates
  - Choosing closest with right prefix called PNS

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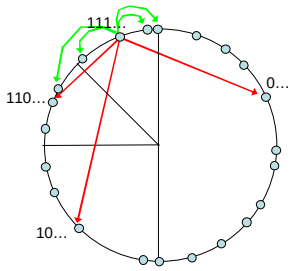


Proximity Neighbor Selection (PNS)

- For each neighbor, may be many candidates
  - Choosing closest with right prefix called PNS
- Tapestry has sophisticated algorithms for PNS
  - Provable nearest neighbor under some assumptions
  - Nearest neighbors give constant stretch routing
  - But reasonably complicated implementation
- Can we do better?

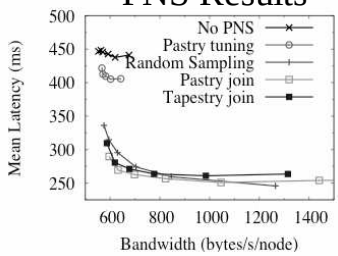
How Important is PNS?

- Only need leaf set for correctness
  - Must know predecessor and successor to determine what keys a node is responsible for
- Any filled routing table gives efficient lookups
  - Need one neighbor that shares no prefix, one that shares one bit, etc., but that's all
- Insight: treat PNS as an optimization only
  - Find initial neighbor set using lookup

PNS by Random Sampling

- Already looking for new neighbors periodically
  - Because doing periodic recovery
- Can use results for random sampling
  - Every period, find potential replacement with lookup
  - Compare latency with existing neighbor
  - If better, swap

PNS Results



- Random sampling almost as good as everything else
  - 24% latency improvement free
  - 42% improvement for 40% more b.w.
  - Compare to 68%-84% improvement by using good timeouts

Talk Outline

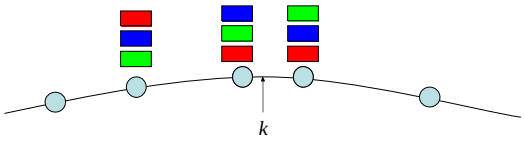
- Bamboo: a churn-resilient DHT
  - Churn resilience at the lookup layer
  - Churn resilience at the storage layer
- OpenDHT: the DHT as a service
  - Finding the right interface
  - Protecting against overuse
- Future work

A Reliable Storage Layer

- Don't just want to do lookup, also want to do
  - DHASH's put/get: store (key, value) pairs
  - Tapestry's publish/route: store (key, pointer) pairs
- Problem statement:
  Keep data/pointers available despite churn

Why Storage Is Tricky

- The claim: DHT replicates within leaf set
  - A pair (*k*,*v*) is stored by the node closest to *k* and replicated on its successor and predecessor
- Why is this hard?

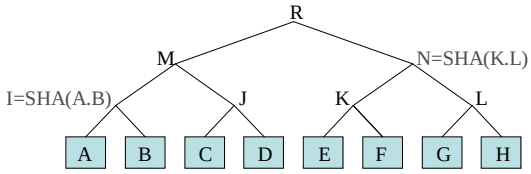


DHTs Meet Epidemics

- Candidate Algorithm
  - For each (*k*,*v*) stored locally, compute SHA(*k*.*v*)
  - Every period, pick a random leaf set neighbor
  - Ask neighbor for all its hashes
  - For each unrecognized hash, ask for key and value
- This is an epidemic algorithm
  - All *m* members will have all (*k*,*v*) in log *m* periods
  - But as is, the cost is O(*C*), where *C* = disk size (although the constant is pretty small)

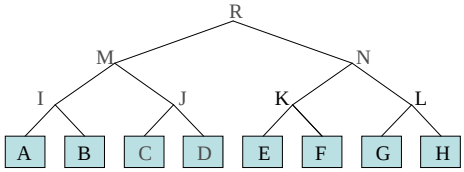
Merkle Trees

- Merkle trees are an efficient summary technique
  - Interior nodes are the secure hashes of their children
  - E.g., I = SHA(A.B), N = SHA(K.L), etc.



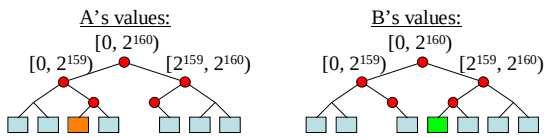
Merkle Trees

- Merkle trees are an efficient summary technique
  - If the top node is signed and distributed, this signature can later be used to verify any individual block, using only O(log *n*) nodes, where *n* = # of leaves
  - E.g., to verify block C, need only R, M, N, I, J, C, & D



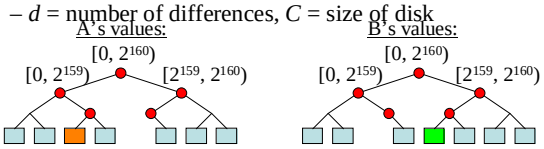
Using Merkle Trees as Summaries

- Improvement: use Merkle tree to summarize keys
  - B gets tree root from A, if same as local root, done
  - Otherwise, recurse down tree to find difference



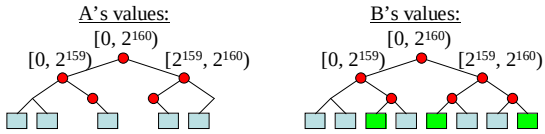
Using Merkle Trees as Summaries

- Improvement: use Merkle tree to summarize keys
  - B gets tree root from A, if same as local root, done
  - Otherwise, recurse down tree to find difference
- New cost is O(d log C)
  - d = number of differences, C = size of disk



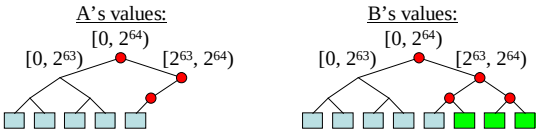
Using Merkle Trees as Summaries

- Still too costly:
  - If A is down for an hour, then comes back, changes will be randomly scattered throughout tree



Using Merkle Trees as Summaries

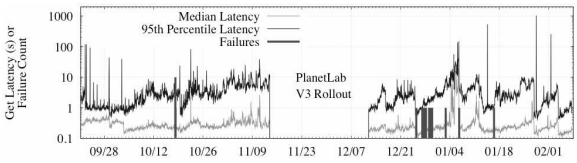
- Still too costly:
  - If A is down for an hour, then comes back, changes will be randomly scattered throughout tree
- Solution: order values by time instead of hash
  - Localizes values to one side of tree



PlanetLab Deployment

- Been running Bamboo / OpenDHT on PlanetLab since April 2004
- Constantly run a put/get test
  - Every second, put a value (with a TTL)
  - DHT stores 8 replicas of each value
  - Every second, get some previously put value (that hasn't expired)
- Tests both routing correctness and replication algorithms (latter not discussed here)

Excellent Availability



- Only 28 of 7 million values lost in 3 months
  - Where "lost" means unavailable for a full hour
- On Feb. 7, 2005, lost 60/190 nodes in 15 minutes to PL kernel bug, only lost one value

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  - Churn resilience at the storage layer
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A Small Sample of
DHT Applications

- Distributed Storage Systems
  - CFS, HiveCache, PAST, Pastiche, OceanStore, Pond
- Content Distribution Networks / Web Caches
  - Bslash, Coral, Squirrel
- Indexing / Naming Systems
  - Chord-DNS, CoDoNS, DOA, SFR
- Internet Query Processors
  - Catalogs, PIER
- Communication Systems
  - Bayeux, i3, MCAN, SplitStream

Questions:

- How many DHTs will there be?
- Can all applications share one DHT?

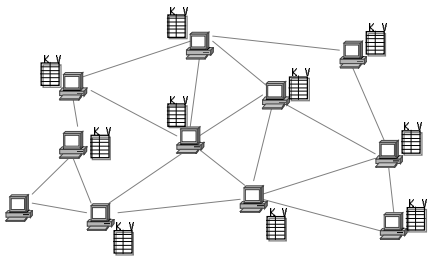
Benefits of Sharing a DHT

- Amortizes costs across applications
  - Maintenance bandwidth, connection state, etc.
- Facilitates "bootstrapping" of new applications
  - Working infrastructure already in place
- Allows for statistical multiplexing of resources
  - Takes advantage of spare storage and bandwidth
- Facilitates upgrading existing applications
  - "Share" DHT between application versions

Challenges in Sharing a DHT

- Robustness
  - Must be available 24/7
- Shared Interface Design
  - Should be general, yet easy to use
- Resource Allocation
  - Must protect against malicious/over-eager users
- Economics
  - What incentives are there to provide resources?

The DHT as a Service



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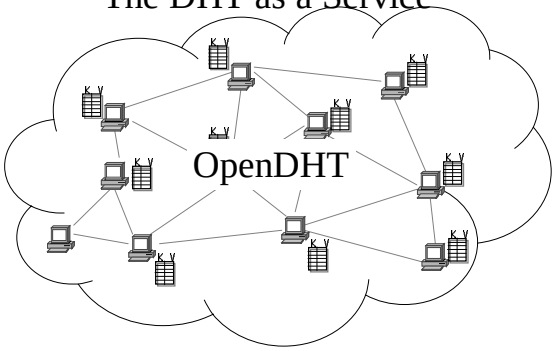

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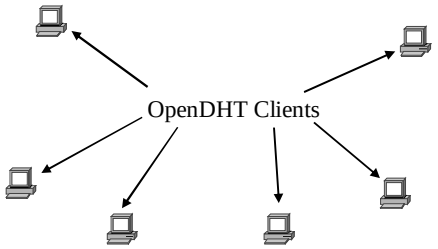

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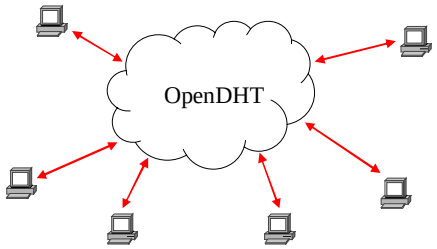

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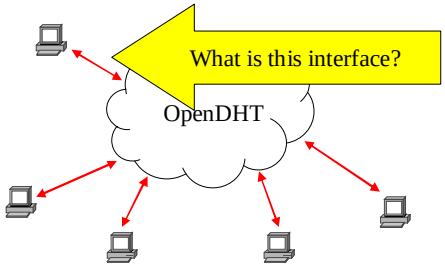
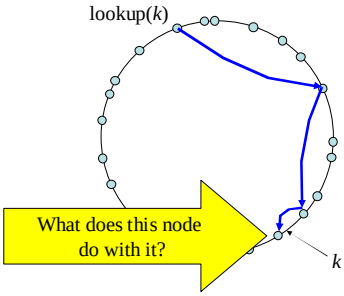


It's not lookup()



Challenges:
1. Distribution
2. Security

How are DHTs Used?

1. Storage
   - CFS, UsenetDHT, PKI, etc.
2. Rendezvous
   - Simple: Chat, Instant Messenger
   - Load balanced: *i*3
   - Multicast: RSS Aggregation, White Board
   - Anycast: Tapestry, Coral

What about put/get?

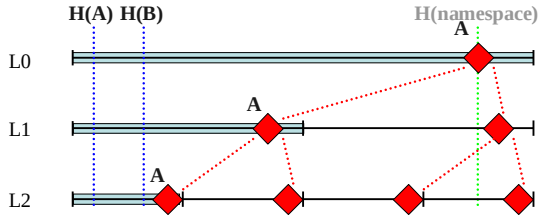
- Works easily for storage applications
- Easy to share
  - No upcalls, so no code distribution or security complications
- But does it work for rendezvous?
  - Chat? Sure: put(my-name, my-IP)
  - What about the others?

Recursive Distributed Rendezvous

- Idea: prove an equivalence between lookup and put/get
  - We know we can implement put/get on lookup
  - Can we implement lookup on put/get?
- It turns out we can
  - Algorithm is called Recursive Distributed Rendezvous (ReDiR)

ReDiR

- Goal: Implement two functions using put/get:
  - join(*namespace*, *node*)
  - *node* = lookup(*namespace*, *identifier*)



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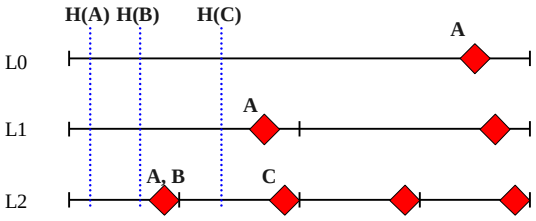

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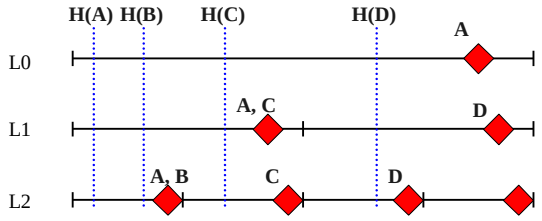

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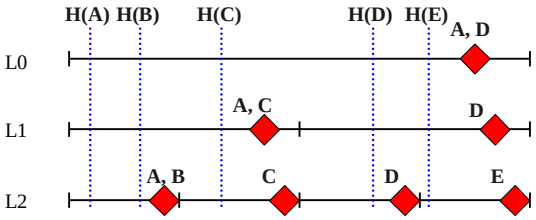

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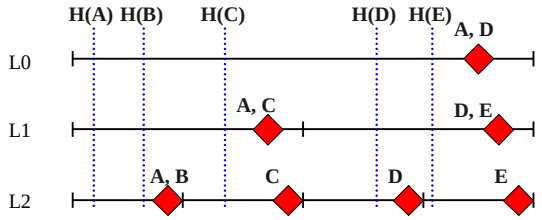
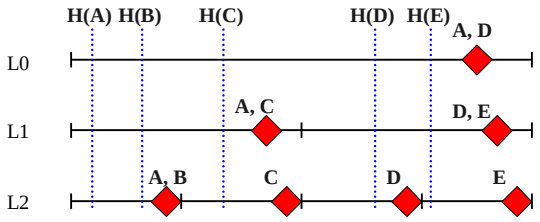


ReDiR

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



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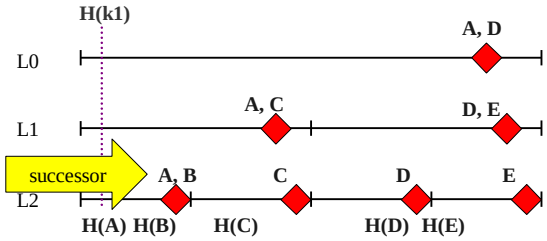

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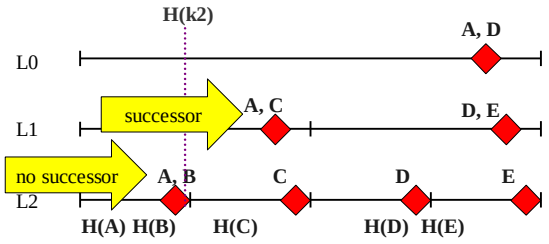

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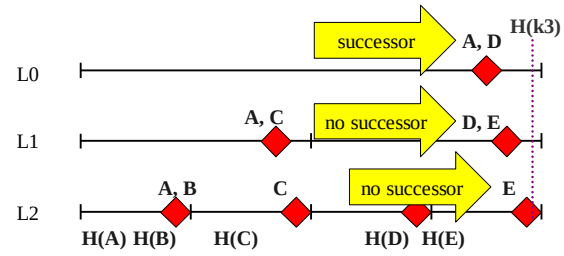
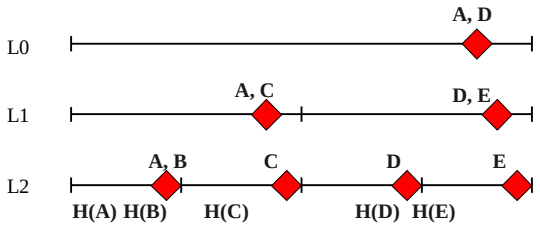


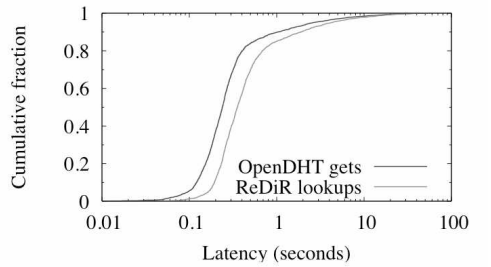
ReDiR

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



ReDiR Performance

(On PlanetLab)



OpenDHT Service Model

- Storage Applications:
  - Just use put/get
- Rendezvous Applications:
  - You provide the nodes
  - We provide cheap, scalable rendezvous

Talk Outline

- Bamboo: a churn-resilient DHT
  - Churn resilience at the lookup layer
  - Churn resilience at the storage layer
- OpenDHT: the DHT as a service
  - Finding the right interface
  - Protecting against overuse
- Future work

Protecting Against Overuse

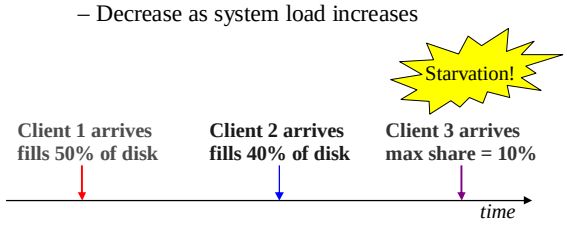
- Must protect system resources against overuse
  - Resources include network, CPU, and disk
  - Network and CPU straightforward
  - Disk harder: usage persists long after requests
- Hard to distinguish malice from eager usage
  - Don't want to hurt eager users if utilization low
- Number of active users changes over time
  - Quotas are inappropriate

Fair Storage Allocation

- Our solution: give each client a fair share
  - Will define "fairness" in a few slides
- Limits strength of malicious clients
  - Only as powerful as they are numerous
- Protect storage on each DHT node separately
  - Must protect each subrange of the key space
  - Rewards clients that balance their key choices

The Problem of Starvation

- Fair shares change over time
  - Decrease as system load increases

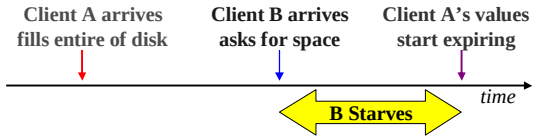


Preventing Starvation

- Simple fix: add time-to-live (TTL) to puts
  - put (key, value) → put (key, value, ttl)
  - (A different approach is used by Palimpsest.)
- Prevents long-term starvation
  - Eventually all puts will expire

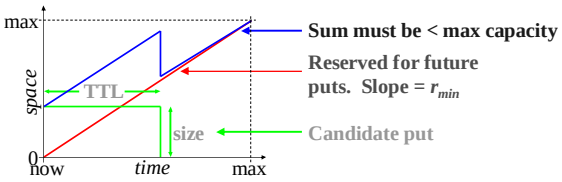
Preventing Starvation

- Simple fix: add time-to-live (TTL) to puts
  - put (key, value) → put (key, value, ttl)
  - (A different approach is used by Palimpsest.)
- Prevents long-term starvation
  - Eventually all puts will expire
- Can still get short term starvation



Preventing Starvation

- Stronger condition:
  Be able to accept r_{min} bytes/sec new data at all times
- This is non-trivial to arrange!



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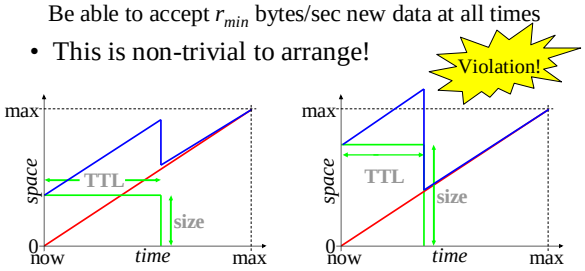
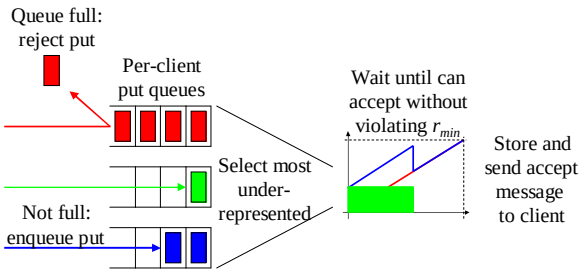


Preventing Starvation

- Formalize graphical intuition:
  $f(\tau) = B(t_{now}) - D(t_{now}, t_{now}+\tau) + r_{min} \times \tau$
- To accept put of size x and TTL l:
  $f(\tau) + x < C$ for all $0 \le \tau < l$
- Can track the value of f efficiently with a tree
  - Leaves represent inflection points of f
  - Add put, shift time are O(log n), n = # of puts

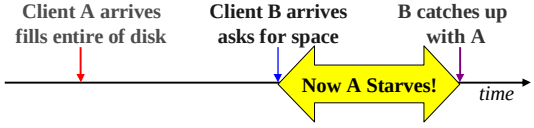
Fair Storage Allocation



The Big Decision: Definition of "most under-represented"

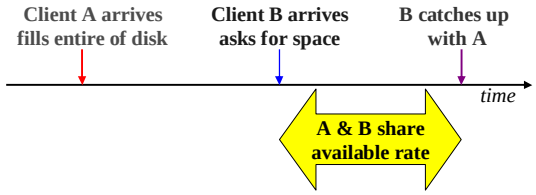
Defining "Most Under-Represented"

- Not just sharing disk, but disk over time
  - 1 byte put for 100s same as 100 byte put for 1s
  - So units are bytes × seconds, call them *commitments*
- Equalize total commitments granted?
  - No: leads to starvation
  - A fills disk, B starts putting, A starves up to max TTL



Defining "Most Under-Represented"

- Instead, equalize *rate* of commitments granted
  - Service granted to one client depends only on others putting "at same time"



Defining "Most Under-Represented"

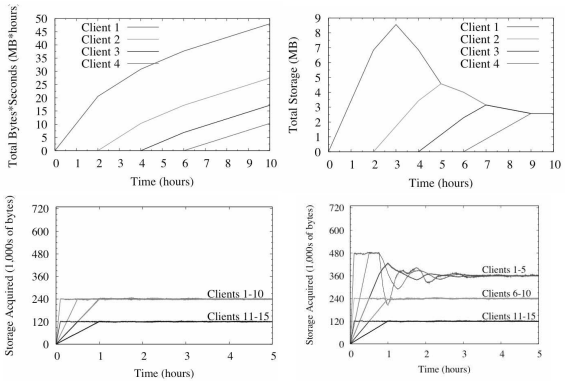
- Instead, equalize *rate* of commitments granted
  - Service granted to one client depends only on others putting "at same time"
- Mechanism inspired by Start-time Fair Queuing
  - Have virtual time, v(t)
  - Each put gets a start time $S(p_c^i)$ and finish time $F(p_c^i)$

$$F(p_c^i) = S(p_c^i) + size(p_c^i) \times ttl(p_c^i)$$

$$S(p_c^i) = \max(v(A(p_c^i)) - \varepsilon, F(p_c^{i-1}))$$

$v(t)$ = maximum start time of all accepted puts

FST Performance



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Future Work: Throughput

- High DHT throughput remains a challenge
  - Each put/get can be to a different destination node
- Only one existing solution (STP)
  - Assumes client's access link is bottleneck

Future Work: Throughput

- High DHT throughput remains a challenge
  - Each put/get can be to a different destination node
- Only one existing solution (STP)
  - Assumes client's access link is bottleneck
- Have complete control of DHT routers
  - Can do fancy congestion control: maybe ECN?
- Have many available paths
  - Take advantage for higher throughput: mTCP?

Future Work: Upcalls

- OpenDHT makes a great common substrate for:
  - Soft-state storage
  - Naming and rendezvous
- Many P2P applications also need to:
  - Traverse NATs
  - Redirect packets within the infrastructure (as in *i3*)
  - Refresh puts while intermittently connected
- All of these can be implemented with upcalls
  - Who provides the machines that run the upcalls?

Future Work: Upcalls

- We don't want to add upcalls to the core DHT
  - Keep the main service simple, fast, and robust
- Can we build a separate upcall service?
  - Some other set of machines organized with ReDiR
  - Security: can only accept *incoming* connections, can't write to local storage, etc.
- This should be enough to implement
  - NAT traversal, reput service
  - Some (most?) packet redirection
- What about more expressive security policies?

For more information, see
http://bamboo-dht.org/
http://opendht.org/