CS514: Intermediate Course in Computer Systems

Lecture 30: April 4, 2003

"All about DHTs"

What is a Distributed Hash Table (DHT)?

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- Exactly that ☺
- A service, distributed over multiple machines, with hash table semantics
  - *Put*(key, value), Value = *Get*(key)
- Designed to work in a peer-to-peer (P2P) environment
  - No central control
  - Nodes under different administrative control
- But of course can operate in an "infrastructure" sense

More specifically

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- Hash table semantics:
  - *Put*(key, value),
  - Value = *Get*(key)
  - Key is a single flat string
  - Limited semantics compared to keyword search
- *Put*() causes value to be stored at one (or more) peer(s)
- *Get*() retrieves value from a peer
- *Put*() and *Get*() accomplished with unicast routed messages
  - In other words, it scales
- Other API calls to support application, like notification when neighbors come and go

P2P “environment”

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- Nodes come and go at will (possibly quite frequently---a few minutes)
- Nodes have heterogeneous capacities
  - Bandwidth, processing, and storage
- Nodes may behave badly
  - Promise to do something (store a file) and not do it (free-loaders)
  - Attack the system

Several flavors, each with variants

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- Tapestry (Berkeley)
  - Based on Plaxton trees---similar to hypercube routing
  - The first* DHT
  - Complex and hard to maintain (hard to understand too!)
- CAN (ACIRI), Chord (MIT), and Pastry (Rice/MSR Cambridge)
  - Second wave of DHTs (contemporary with and independent of each other)

* Landmark Routing, 1988, used a form of DHT called Assured Destination Binding (ADB)

Basics of all DHTs

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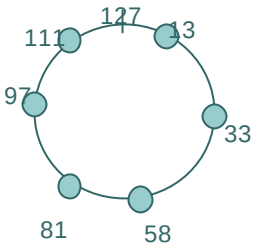

- Goal is to build some “structured” overlay network with the following characteristics:
  - Node IDs can be mapped to the hash key space
  - Given a hash key as a “destination address”, you can route through the network to a given node
  - Always route to the same node no matter where you start from

Simple example (doesn't scale)

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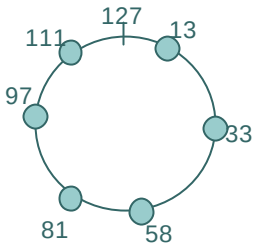

- Circular number space 0 to 127
- Routing rule is to move counter-clockwise until current node ID ≥ key, and last hop node ID < key
- Example: key = 42
- Obviously you will route to node 58 from no matter where you start

Building any DHT

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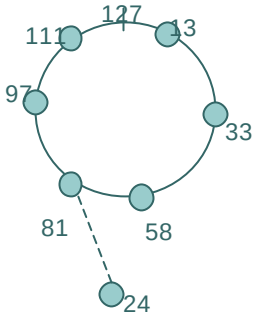
- Newcomer always starts with at least one known member



Building any DHT

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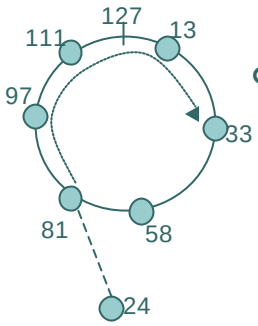

- Newcomer always starts with at least one known member
- Newcomer searches for “self” in the network
  - hash key = newcomer’s node ID
  - Search results in a node in the vicinity where newcomer needs to be

Building any DHT

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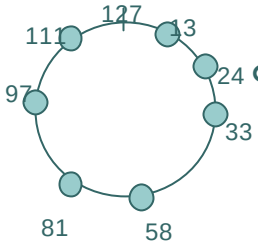

- Newcomer always starts with at least one known member
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- Links are added/removed to satisfy properties of network

Building any DHT

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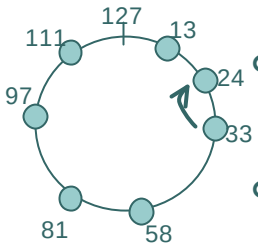

- Newcomer always starts with at least one known member
- Newcomer searches for "self" in the network
  - hash key = newcomer's node ID
- Search results in a node in the vicinity where newcomer needs to be
- Links are added/removed to satisfy properties of network
- Objects that now hash to new node are transferred to new node

Insertion/lookup for any DHT

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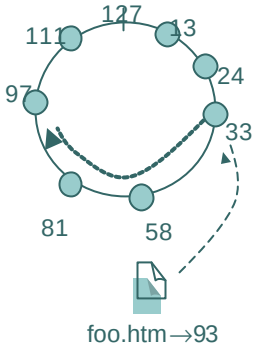

- Hash name of object to produce key
  - Well-known way to do this
- Use key as destination address to route through network
  - Routes to the target node
- Insert object, or retrieve object, at the target node

Properties of all DHTs

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- Memory requirements grow (something like) logarithmically with N
- Routing path length grows (something like) logarithmically with N
- Cost of adding or removing a node grows (something like) logarithmically with N
- Has caching, replication, etc…

DHT Issues

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- Resilience to failures
- Load Balance
  - Heterogeneity
  - Number of objects at each node
  - Routing hot spots
  - Lookup hot spots
- Locality (performance issue)
- Churn (performance and correctness issue)
- Security

We're going to look at four DHTs

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- At varying levels of detail…
  - CAN (Content Addressable Network)
    - ACIRI (now ICIR)
  - Chord
    - MIT
  - Kelips
    - Cornell
  - Pastry
    - Rice/Microsoft Cambridge

Things we're going to look at

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- What is the structure?
- How does routing work in the structure?
- How does it deal with node departures?
- How does it scale?
- How does it deal with locality?
- What are the security issues?

CAN structure is a cartesian coordinate space in a D dimensional torus

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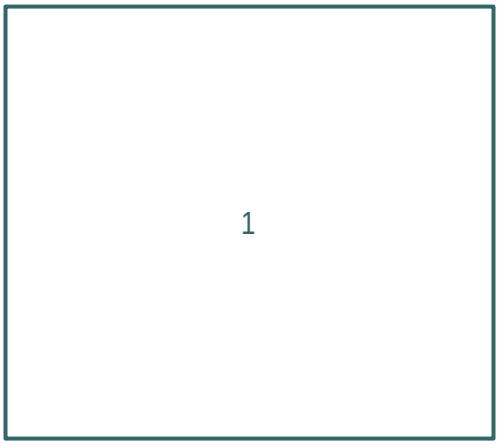

CAN graphics care of Santashil PalChaudhuri, Rice Univ

Simple example in two dimensions

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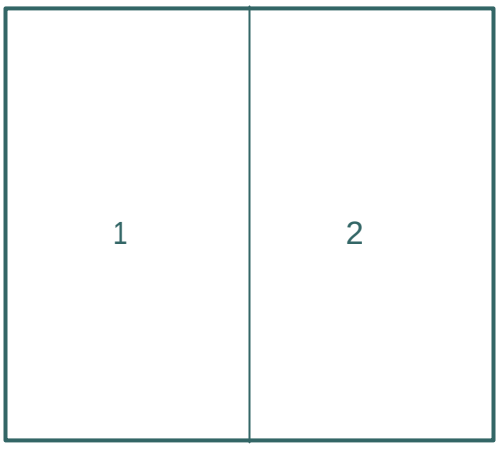

Note: torus wraps on “top” and “sides”

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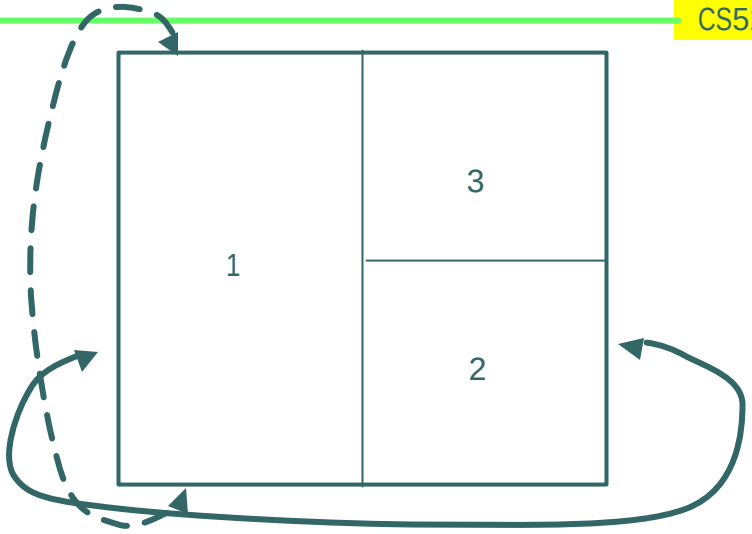

Each node in CAN network occupies a “square” in the space

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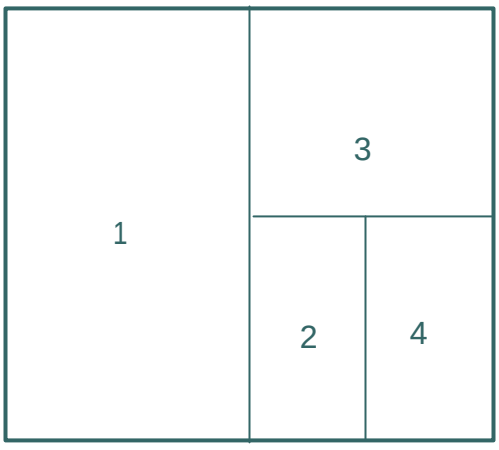

With relatively uniform square sizes

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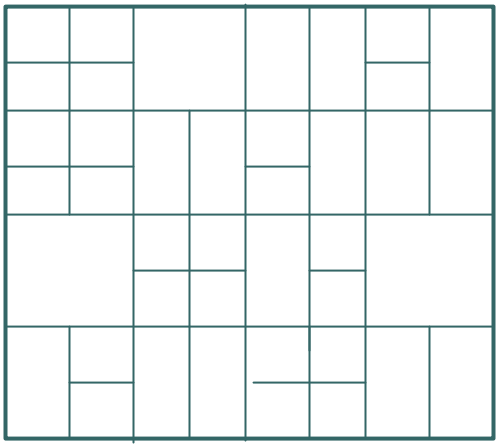

Neighbors in CAN network

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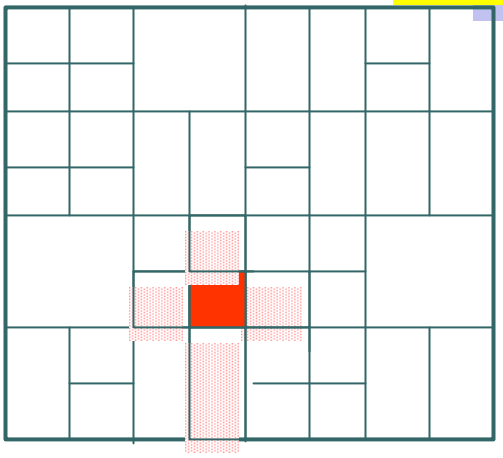
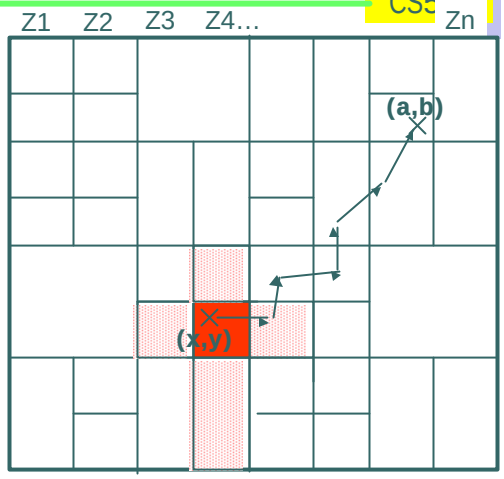
- Neighbor is a node that:
- Overlaps d-1 dimensions
- Abuts along one dimension

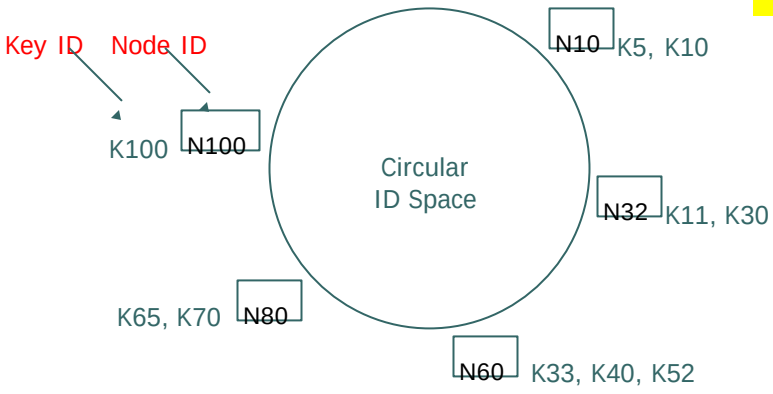


Route to neighbors that are closer to target

- d-dimensional space
- n zones
  - Zone is space occupied by a “square” in one dimension
- Avg. route path length
  - $(d/4)(n^{1/d})$
- Number neighbors = O(d)
- Tunable (vary d or n)
- Can factor proximity into route decision



Chord uses a circular ID space



- Successor: node with next highest ID

Chord slides care of Robert Morris, MIT

Basic Lookup

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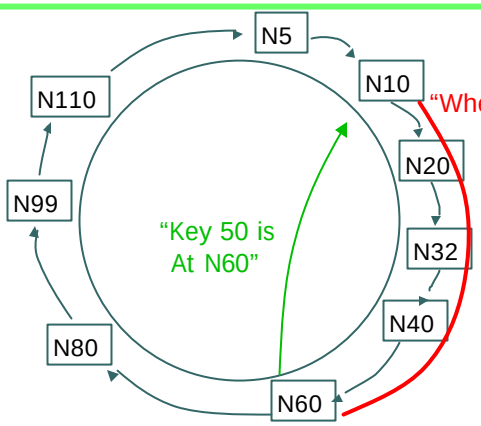

- Lookups find the ID's predecessor
- Correct if successors are correct

Successor Lists Ensure Robust Lookup

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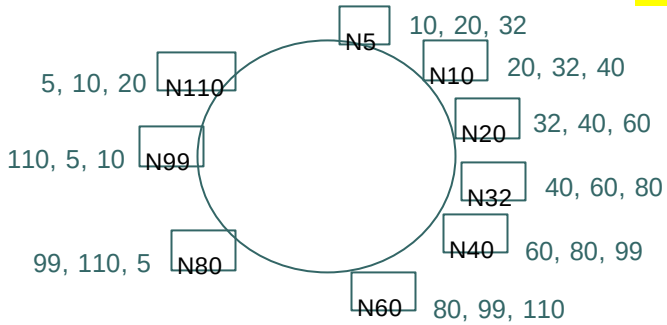

- Each node remembers r successors
- Lookup can skip over dead nodes to find blocks
- Periodic check of successor and predecessor links

Chord "Finger Table" Accelerates Lookups

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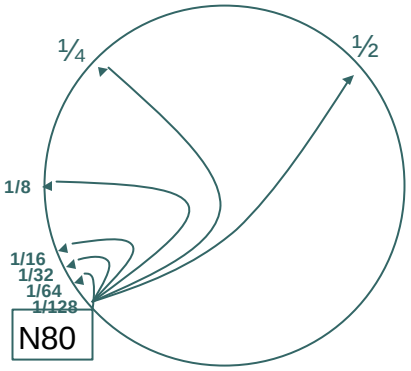

To build finger tables, new node searches for the key values for each finger

To do it efficiently, new nodes obtain successor's finger table, and use as a hint to optimize the search

Chord lookups take O(log N) hops

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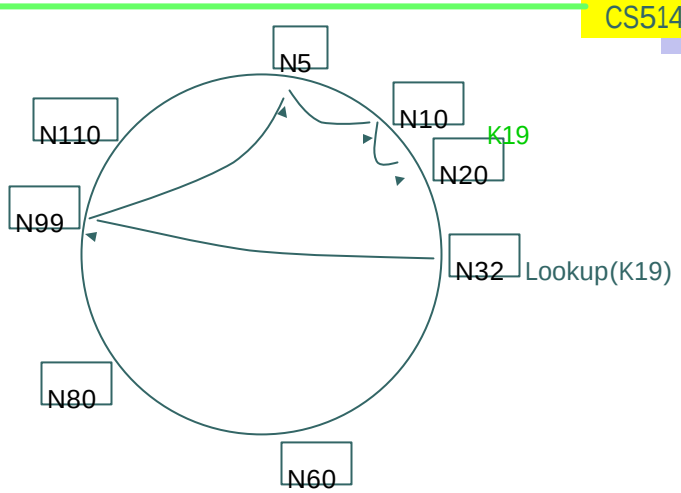

Drill down on Chord reliability

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- Interested in maintaining a correct routing table (successors, predecessors, and fingers)
- Primary invariant: correctness of successor pointers
  - Fingers, while important for performance, do not have to be exactly correct for routing to work
  - Algorithm is to “get closer” to the target
  - Successor nodes always do this

Maintaining successor pointers

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- Periodically run “stabilize” algorithm
  - Finds successor’s predecessor
  - Repair if this isn’t self
- This algorithm is also run at join
- Eventually routing will repair itself
- Fix_finger also periodically run
  - For randomly selected finger

Initial: 25 wants to join correct ring (between 20 and 30)

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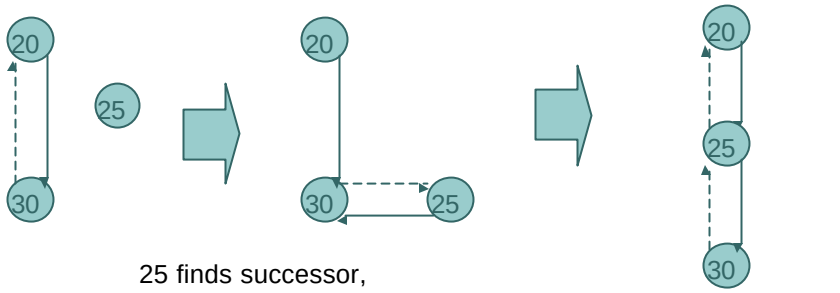

25 finds successor, and tells successor (30) of itself

20 runs “stabilize”:
20 asks 30 for 30’s predecessor
30 returns 25
20 tells 25 of itself

This time, 28 joins before 20 runs “stabilize”

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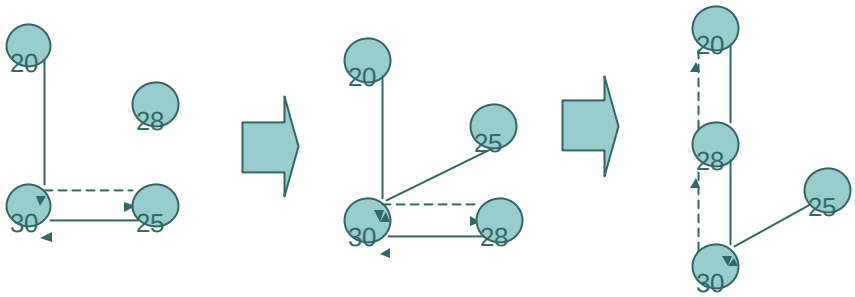
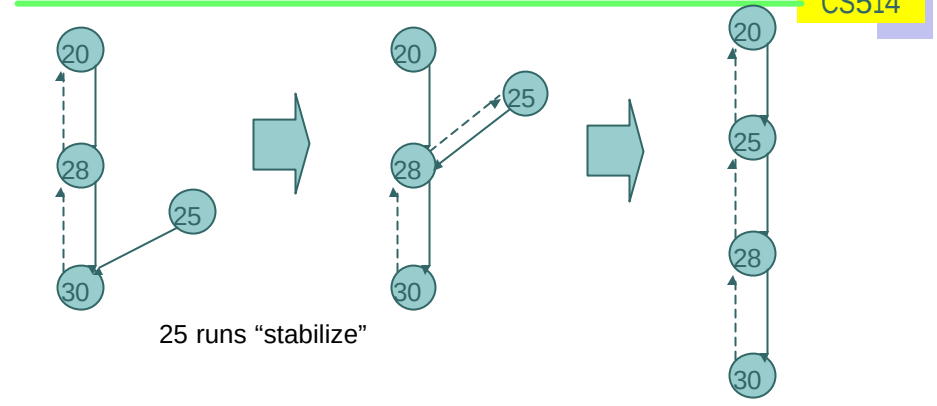
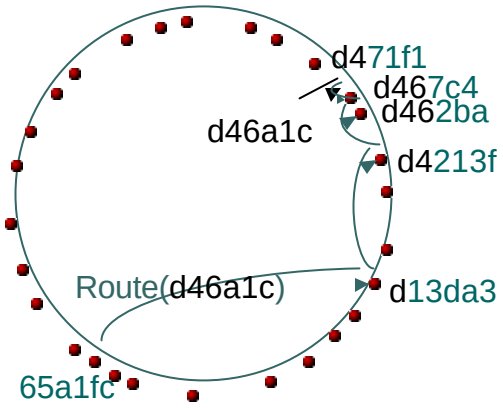


28 finds successor, and tells successor (30) of itself

20 runs “stabilize”:
20 asks 30 for 30’s predecessor
30 returns 28
20 tells 28 of itself

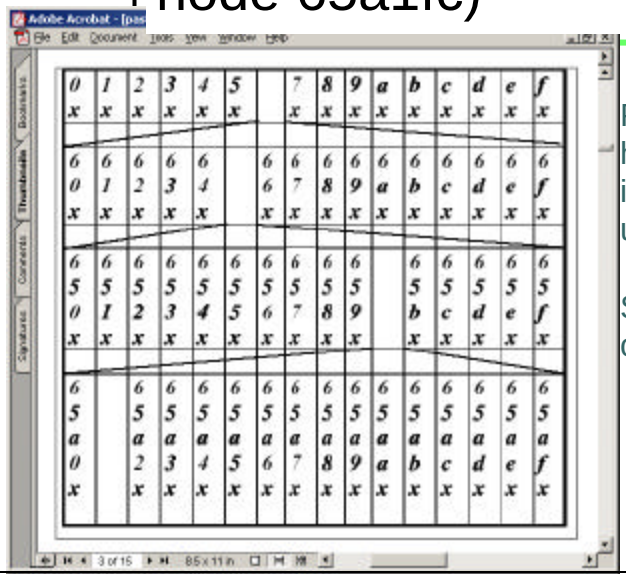


Pastry also uses a circular number space



- Difference is in how the “fingers” are created
- Pastry uses prefix match overlap rather than binary splitting
- More flexibility in neighbor selection

Pastry routing table (for node 65a1fc)



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Pastry nodes also have a “leaf set” of immediate neighbors up and down the ring

Similar to Chord’s list of successors

Pastry join

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- X = new node, A = bootstrap, Z = nearest node
- A finds Z for X
- In process, A, Z, and all nodes in path send state tables to X
- X settles on own table
  - Possibly after contacting other nodes
- X tells everyone who needs to know about itself
- Pastry paper doesn’t give enough information to understand how concurrent joins work
  - 18th IFIP/ACM, Nov 2001

Pastry leave

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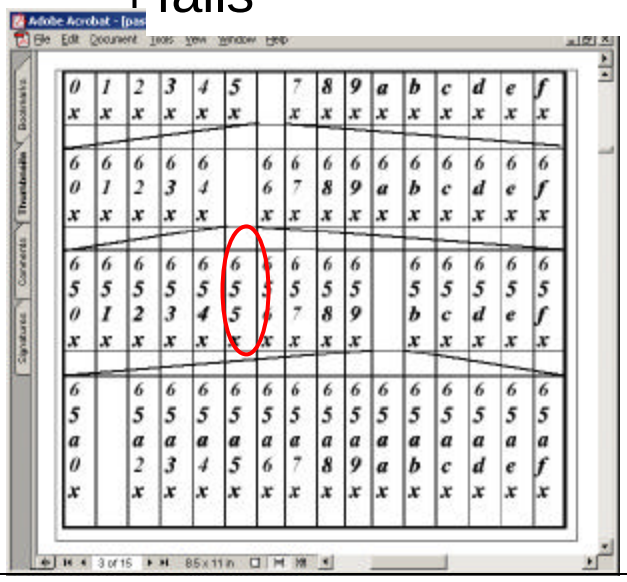
- Noticed by leaf set neighbors when leaving node doesn't respond
  - Neighbors ask highest and lowest nodes in leaf set for new leaf set
- Noticed by routing neighbors when message forward fails
  - Immediately can route to another neighbor
  - Fix entry by asking another neighbor in the same "row" for its neighbor
  - If this fails, ask somebody a level up

For instance, this neighbor fails



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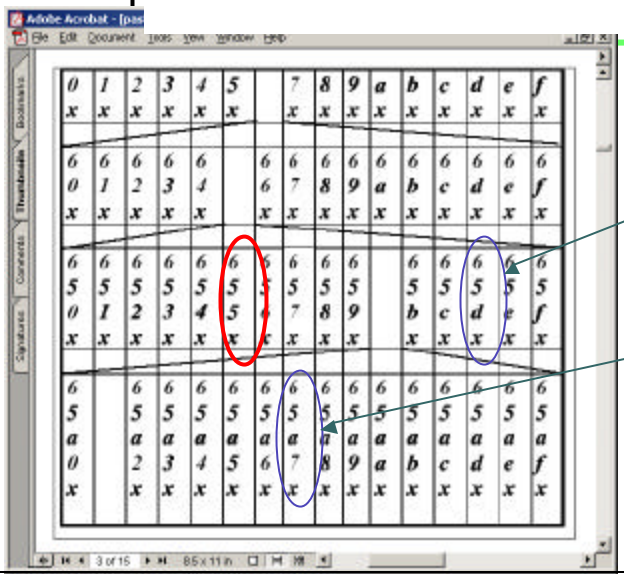
Ask other neighbors



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Try asking some neighbor in the same row for its 655x entry

If it doesn't have one, try asking some neighbor in the row below, etc.

CAN, Chord, Pastry differences

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- CAN, Chord, and Pastry have deep similarities
- Some (important???) differences exist
  - CAN nodes tend to know of multiple nodes that allow equal progress
    - Can therefore use additional criteria (RTT) to pick next hop
  - Pastry allows greater choice of neighbor
    - Can thus use additional criteria (RTT) to pick neighbor
  - In contrast, Chord has more determinism
    - Harder for an attacker to manipulate system?

Security issues

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- In many P2P systems, members may be malicious
- If peers untrusted, all content must be signed to detect forged content
  - Requires certificate authority
  - Like we discussed in secure web services talk
  - This is not hard, so can assume at least this level of security

Security issues: Sybil attack

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- Attacker pretends to be multiple system
  - If surrounds a node on the circle, can potentially arrange to capture all traffic
  - Or if not this, at least cause a lot of trouble by being many nodes
- Chord requires node ID to be an SHA-1 hash of its IP address
  - But to deal with load balance issues, Chord variant allows nodes to replicate themselves
- *A central authority must hand out node IDs and certificates to go with them*
  - Not P2P in the Gnutella sense

General security rules

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- Check things that can be checked
  - Invariants, such as successor list in Chord
- Minimize invariants, maximize randomness
  - Hard for an attacker to exploit randomness
- Avoid any single dependencies
  - Allow multiple paths through the network
  - Allow content to be placed at multiple nodes
- But all this is expensive…

Load balancing

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- Query hotspots: given object is popular
  - Cache at neighbors of hotspot, neighbors of neighbors, etc.
  - Classic caching issues
- Routing hotspot: node is on many paths
  - Of the three, Pastry seems most likely to have this problem, because neighbor selection more flexible (and based on proximity)
  - This doesn't seem adequately studied

Load balancing

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- Heterogeneity (variance in bandwidth or node capacity
- Poor distribution in entries due to hash function inaccuracies
- One class of solution is to allow each node to be multiple virtual nodes
  - Higher capacity nodes virtualize more often
  - But security makes this harder to do

Chord node virtualization

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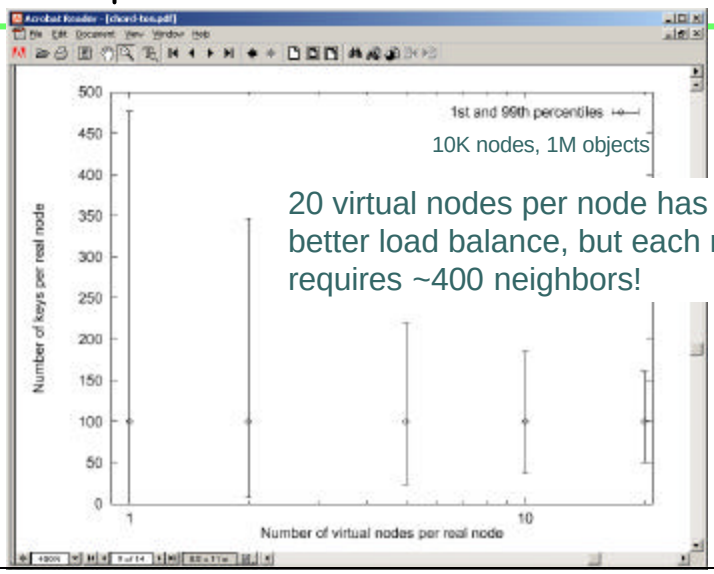

Primary concern: churn

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- Churn: nodes joining and leaving frequently
- Join or leave requires a change in some number of links
- Those changes depend on correct routing tables in other nodes
  - Cost of a change is higher if routing tables not correct
  - In chord, ~6% of lookups fail if three failures per stabilization
- But as more changes occur, probability of incorrect routing tables increases

Control traffic load generated by churn

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- Chord and Pastry appear to deal with churn differently
- Chord join involves some immediate work, but repair is done periodically
  - Extra load only due to join messages
- Pastry join and leave involves immediate repair of all effected nodes' tables
  - Routing tables repaired more quickly, but cost of each join/leave goes up with frequency of joins/leaves
  - Scales quadratically with number of changes???
  - Can result in network meltdown???

Kelips takes a different approach

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- Network partitioned into $\sqrt{N}$ "affinity groups"
- Hash of node ID determines which affinity group a node is in
- Each node knows:
  - One or more nodes in each group
  - All objects and nodes in own group
- *But this knowledge is soft-state, spread through peer-to-peer "gossip" (epidemic multicast)!*

Kelips

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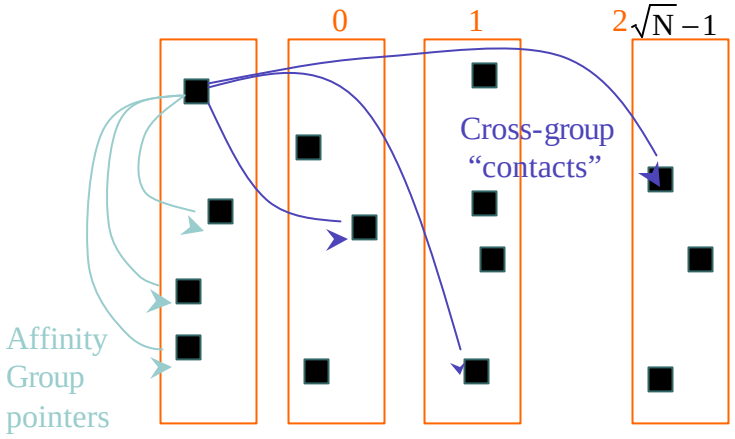

Graphics courtesy Indranil Gupta, Cornell

Kelips

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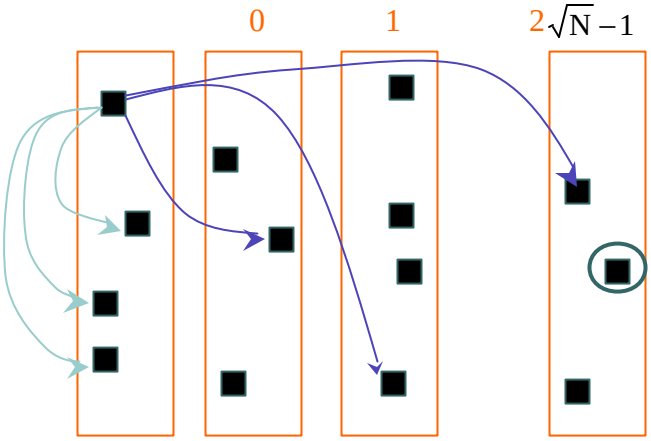

File inserted here (Affinity group chosen based on hash of file name)

Kelips

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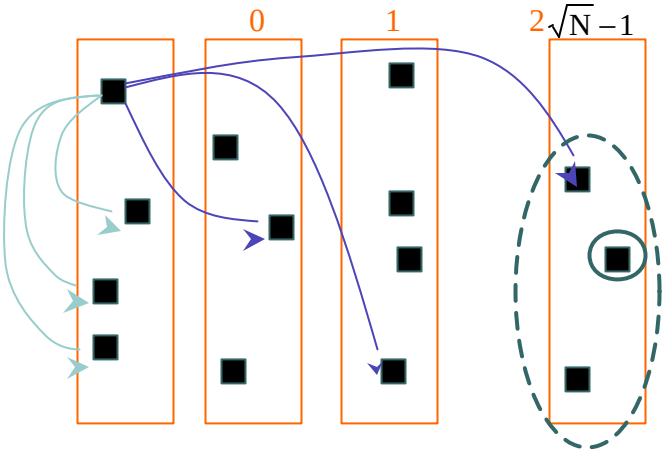

Pointer to file gossiped through affinity group

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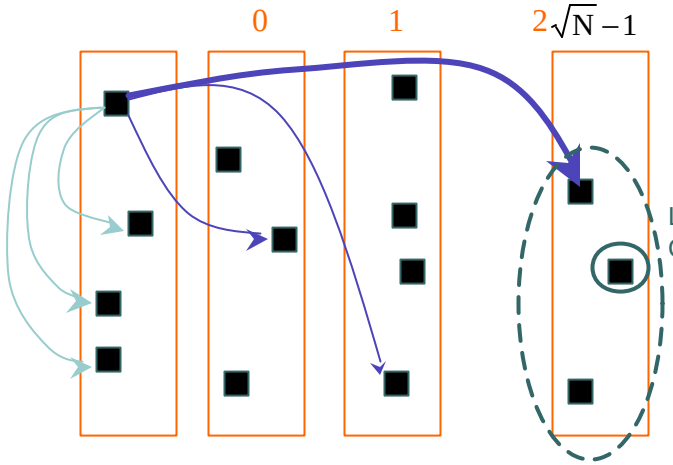

Lookup occurs in O(1) hop

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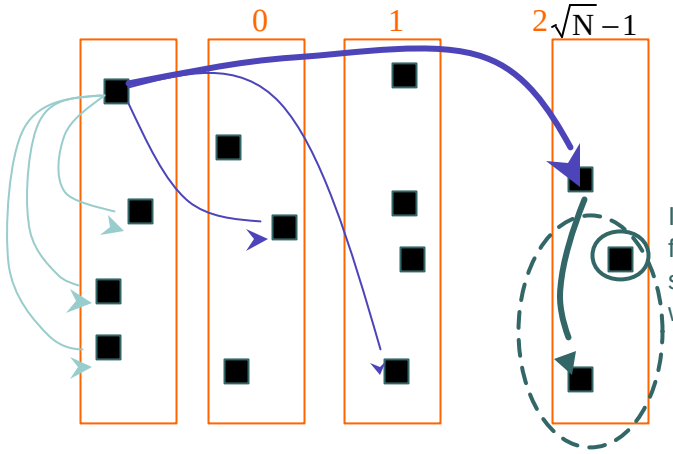

If file pointer not fully gossiped, short random walk will find file quickly

Kelips gossip

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- Operates at constant “background” rate
  - Independent of frequency of changes in the system
  - Average overhead may be higher than other DHTs, but not bursty
- If churn too high, system performs poorly (failed lookups), *but does not collapse…*

Control traffic load generated by churn

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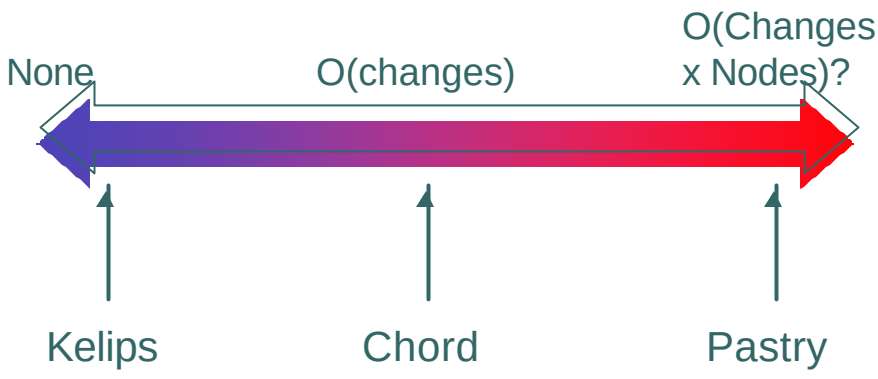

DHT applications

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- Ken will talk about file system and archival storage applications for DHT
- DNS as a DHT application
  - No structure required in name!
  - Fewer administration errors
  - No DoS target
- DNS over Chord
  - Median lookup time increased from 43ms (DNS) to 350ms

To finish up

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- Various applications have been designed over DHTs
  - File system, DNS-like service, pub/sub system
- DHTs are elegant and promising tools
- Concerns about churn and security