Peer-to-peer systems and Distributed Hash Tables (DHTs)

COS 461: Computer Networks
Spring 2009 (MW 1:30-2:50 in COS 105)

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http://www.cs.princeton.edu/courses/archive/spring09/cos461/

Overlay Networks

- P2P applications need to:
  - Track identities & (IP) addresses of peers
    - May be many and may have significant churn
    - Best not to have n^2 ID references
      - Thus, nodes' "views" << view in consistent hashing
  - Route messages among peers
    - If you don't keep track of all peers, this is "multi-hop"
- *Overlay network*
  - Peers doing both naming and routing
  - IP becomes "just" the low-level transport
    - All the IP routing is opaque
    - Assumption that network is fully-connected (← true?)

(Many slides borrowed from Joe Hellerstein's VLDB keynote)

Many New Challenges

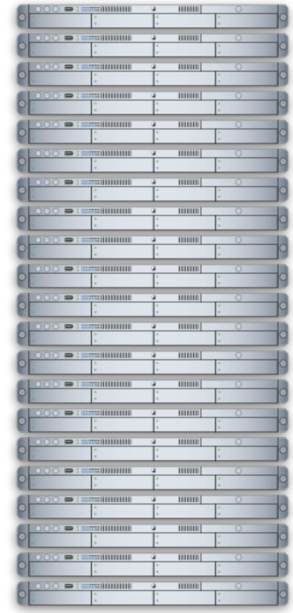
- Relative to other parallel/distributed systems
  - Partial failure
  - Churn
  - Few guarantees on transport, storage, etc.
  - Huge optimization space
  - Network bottlenecks & other resource constraints
  - No administrative organizations
  - Trust issues: security, privacy, incentives

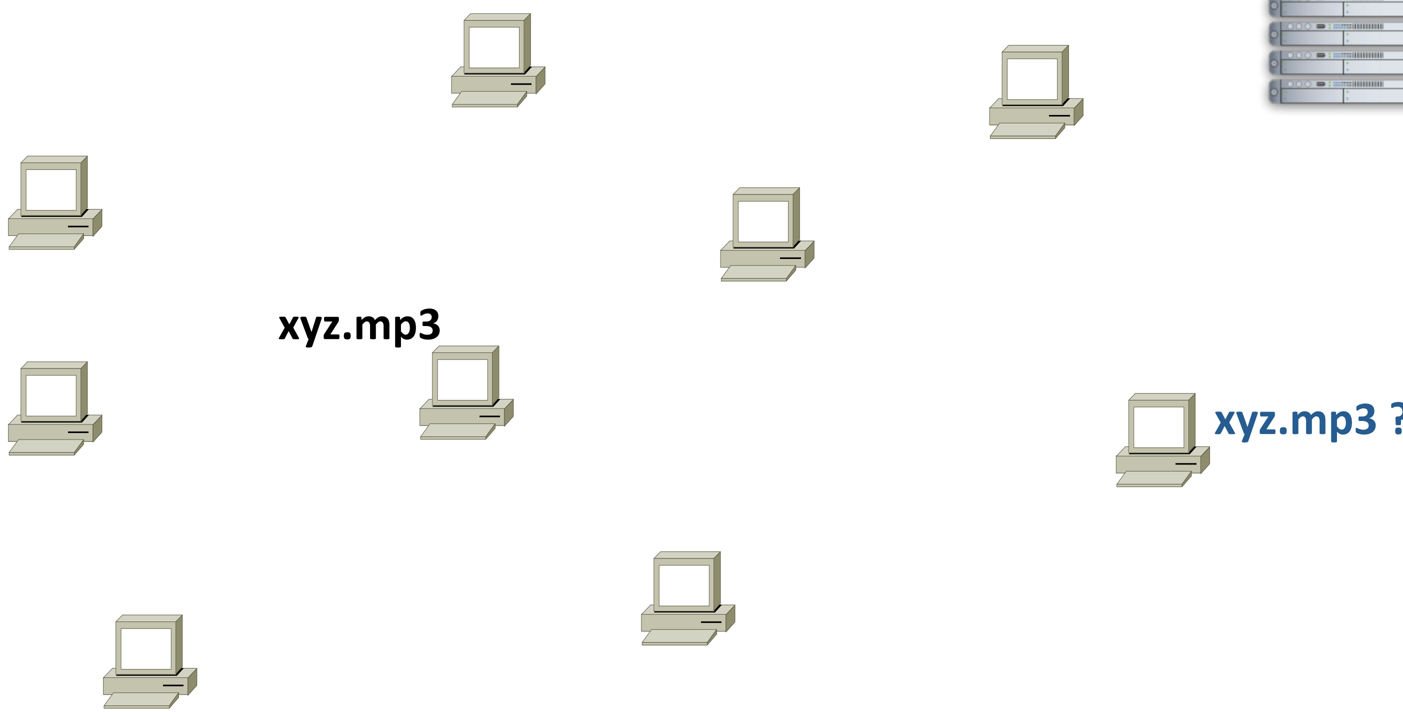
- Relative to IP networking
  - Much higher function, more flexible
  - Much less controllable/predictable

Early P2P

Early P2P I: Client-Server

- Napster





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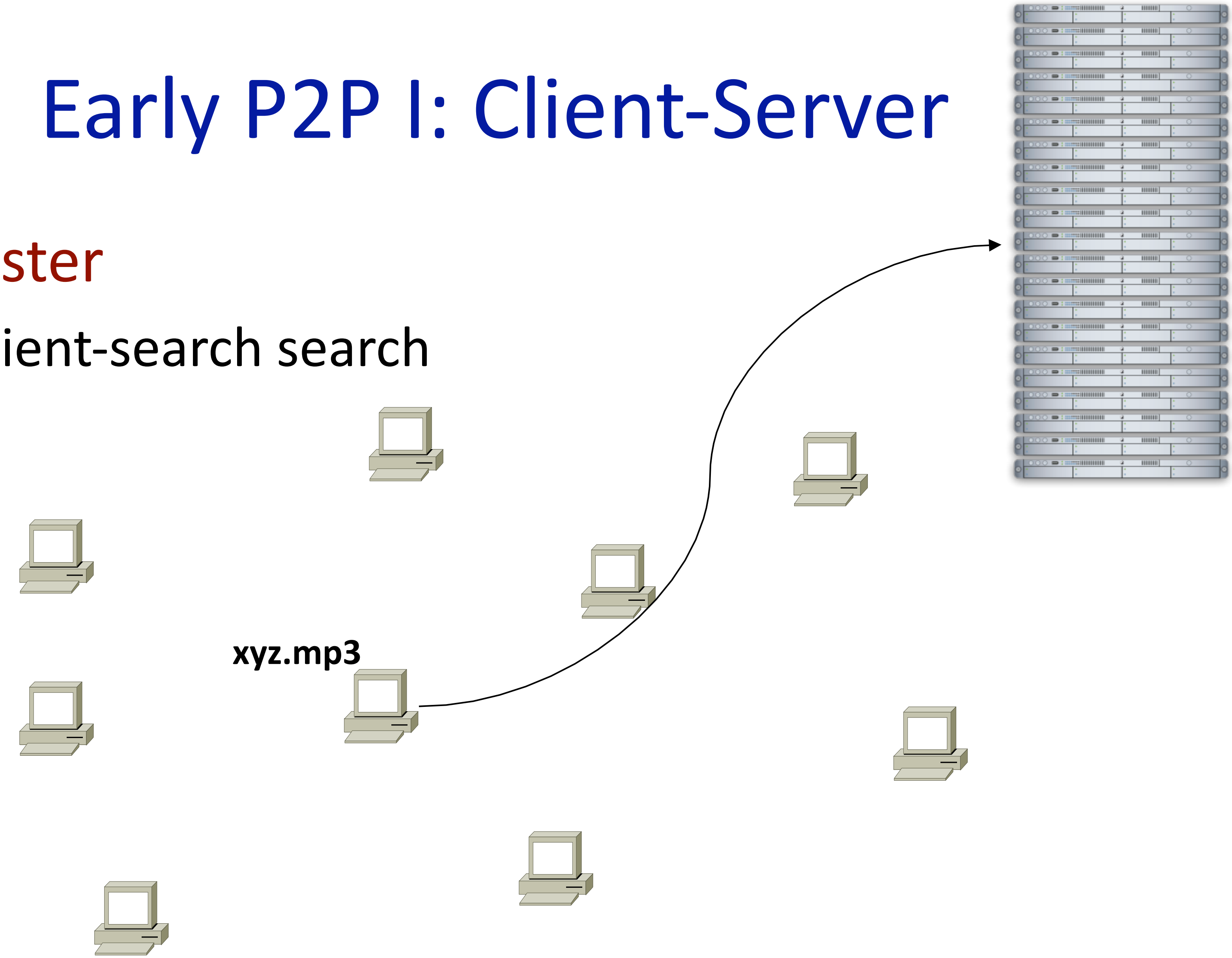
  - Client-search search



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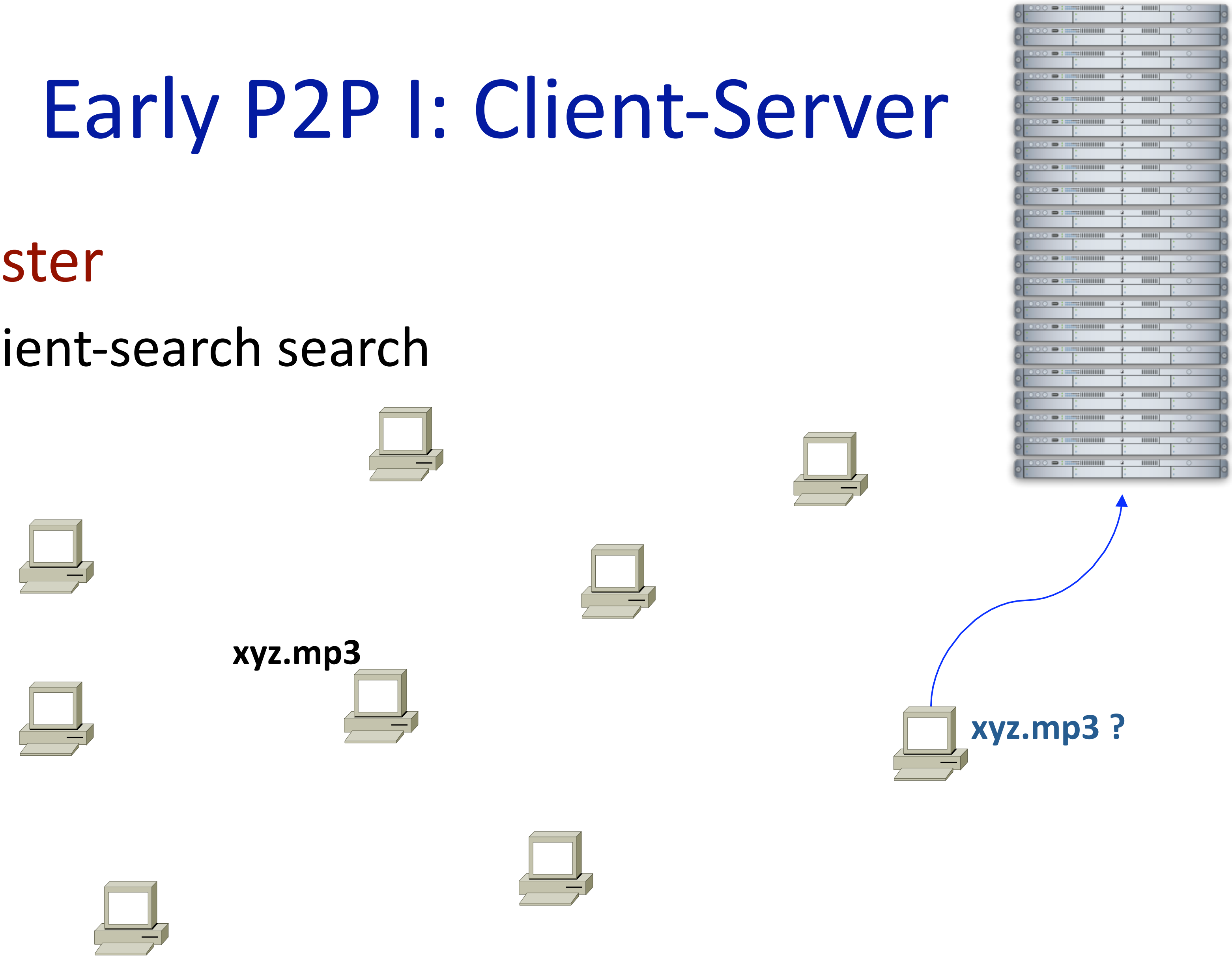

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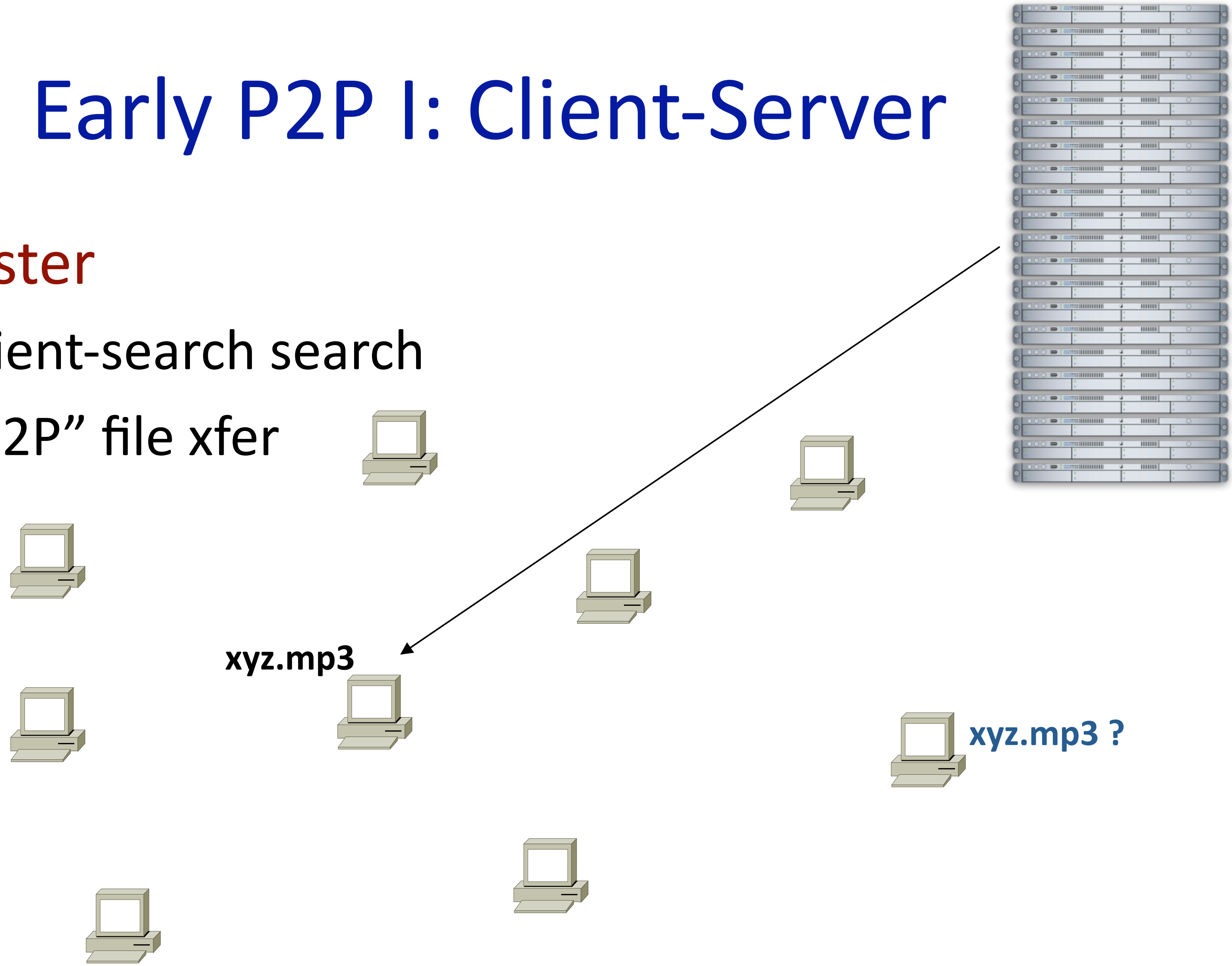
  - “P2P” file xfer



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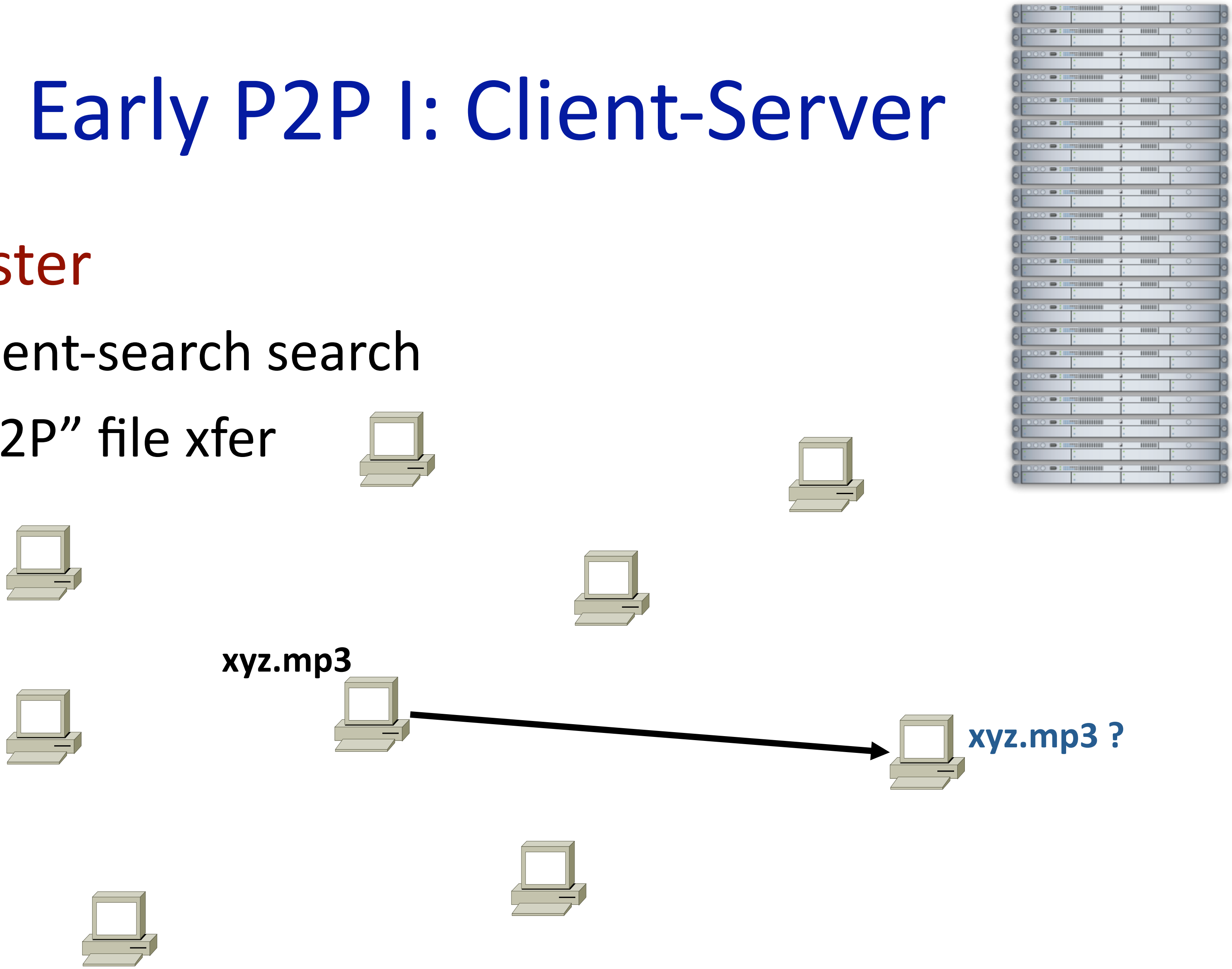
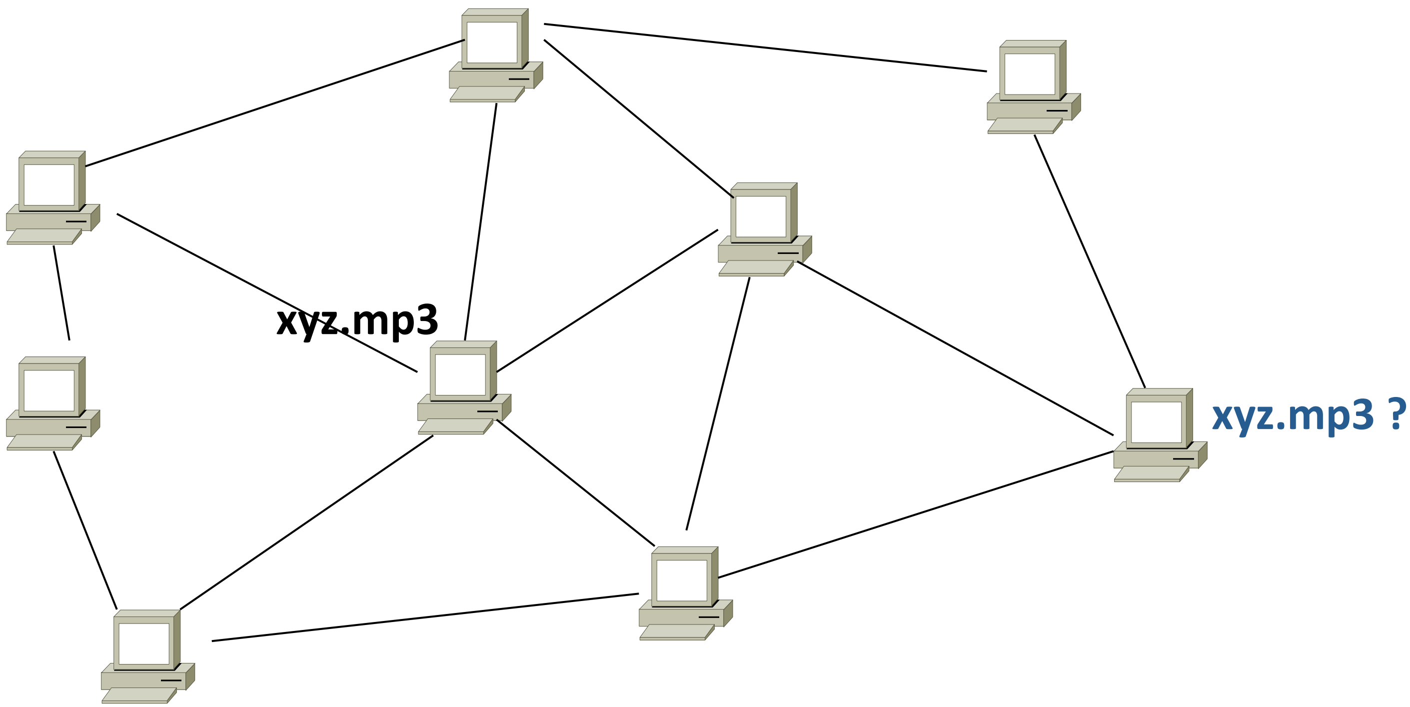


Early P2P II: Flooding on Overlays



An "unstructured" *overlay network*

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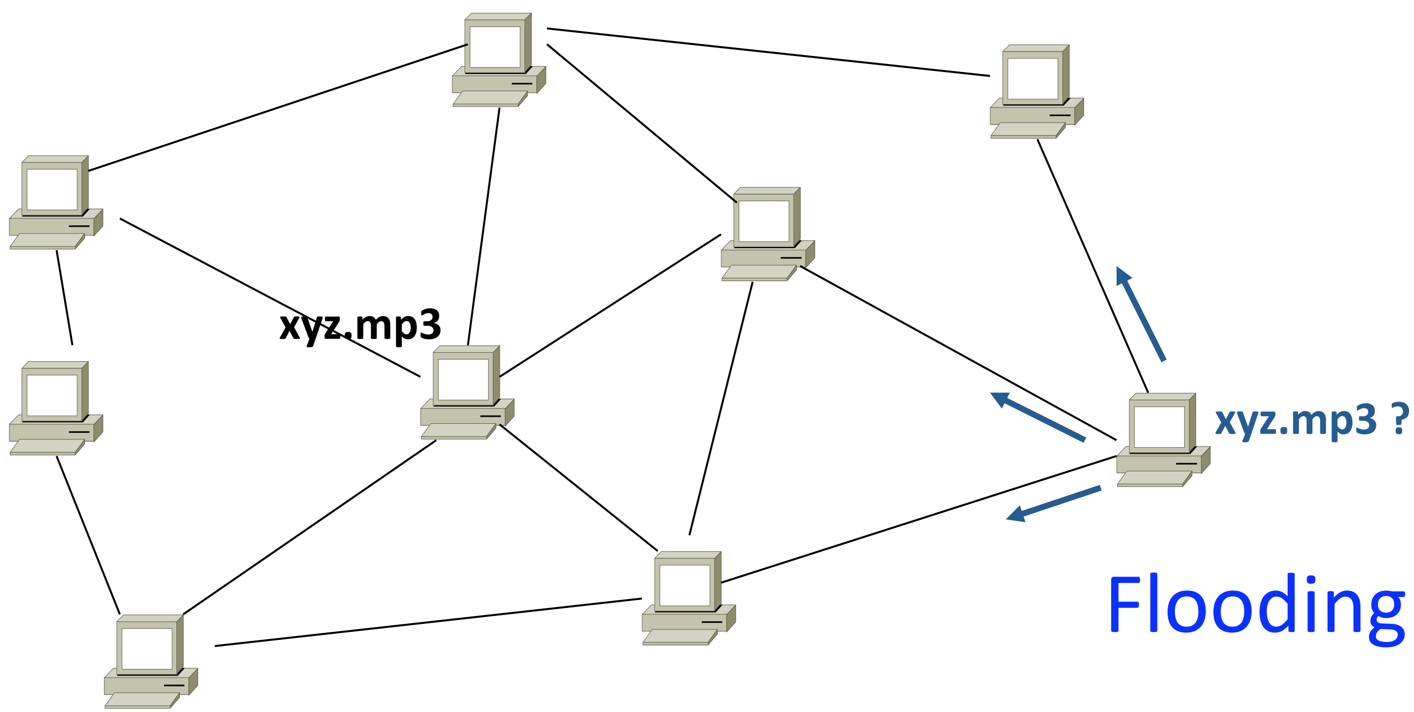

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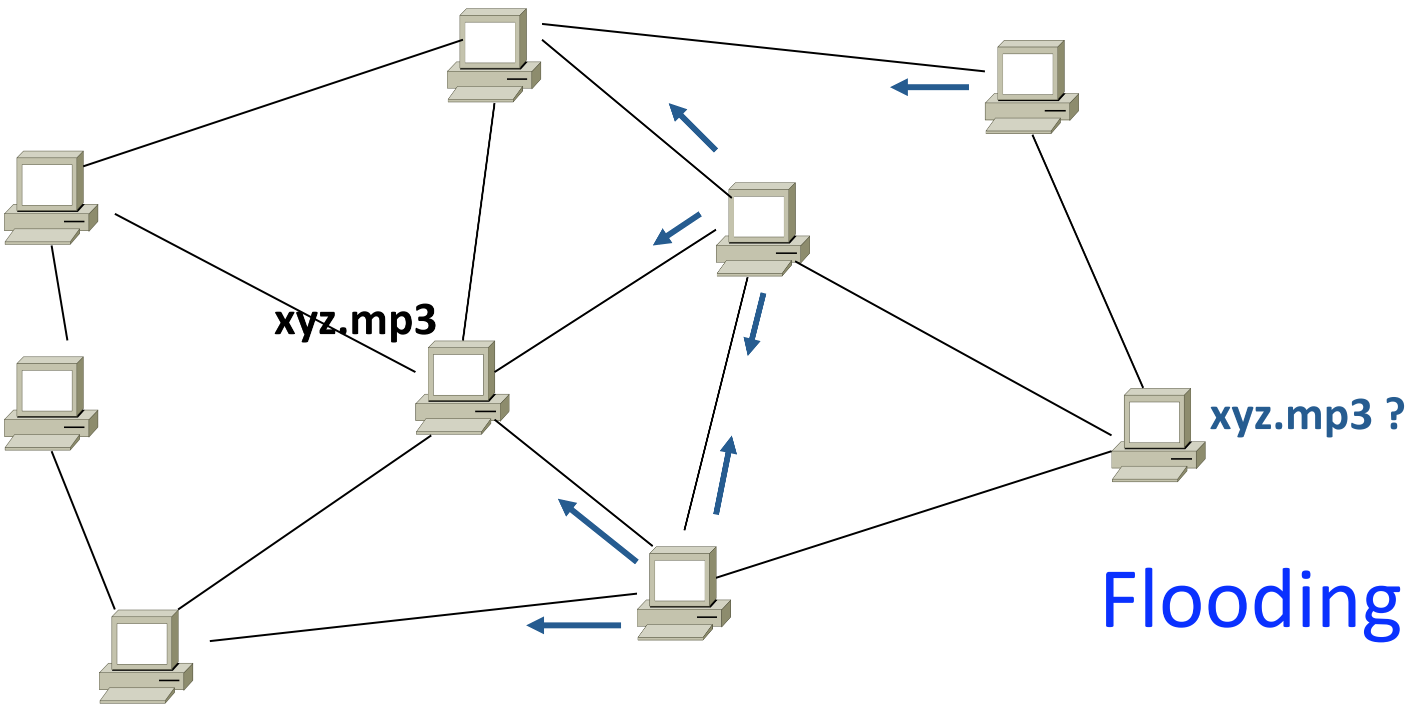
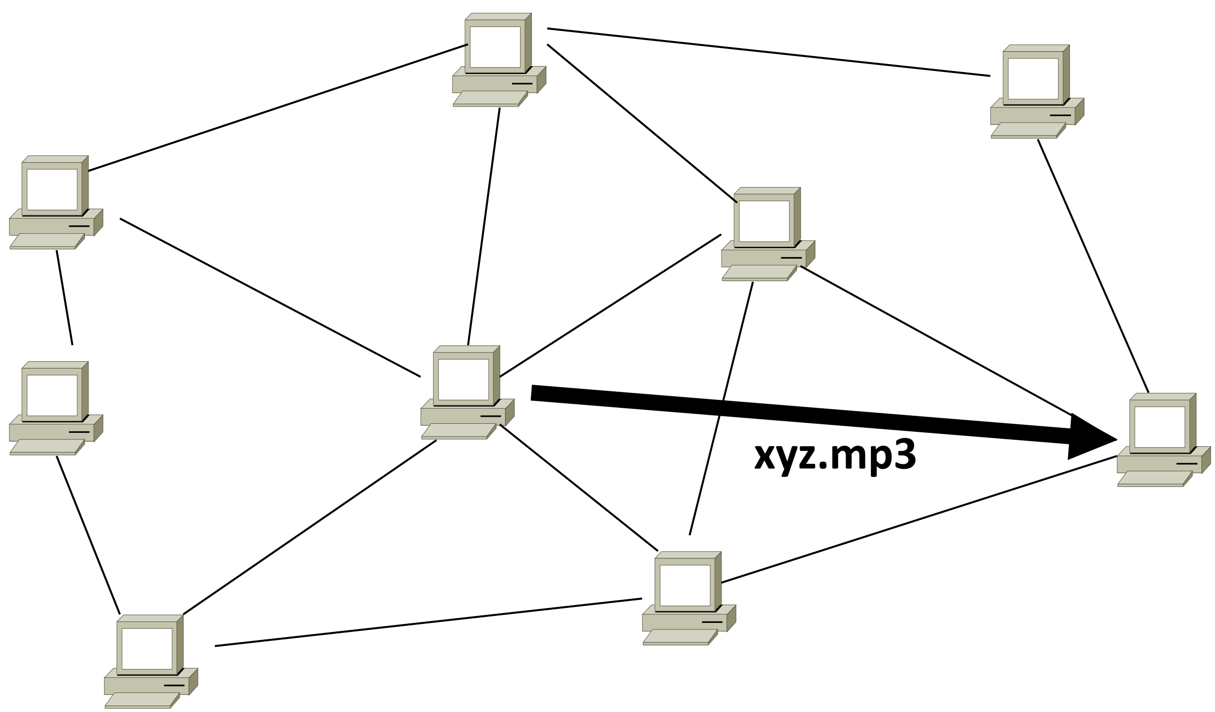


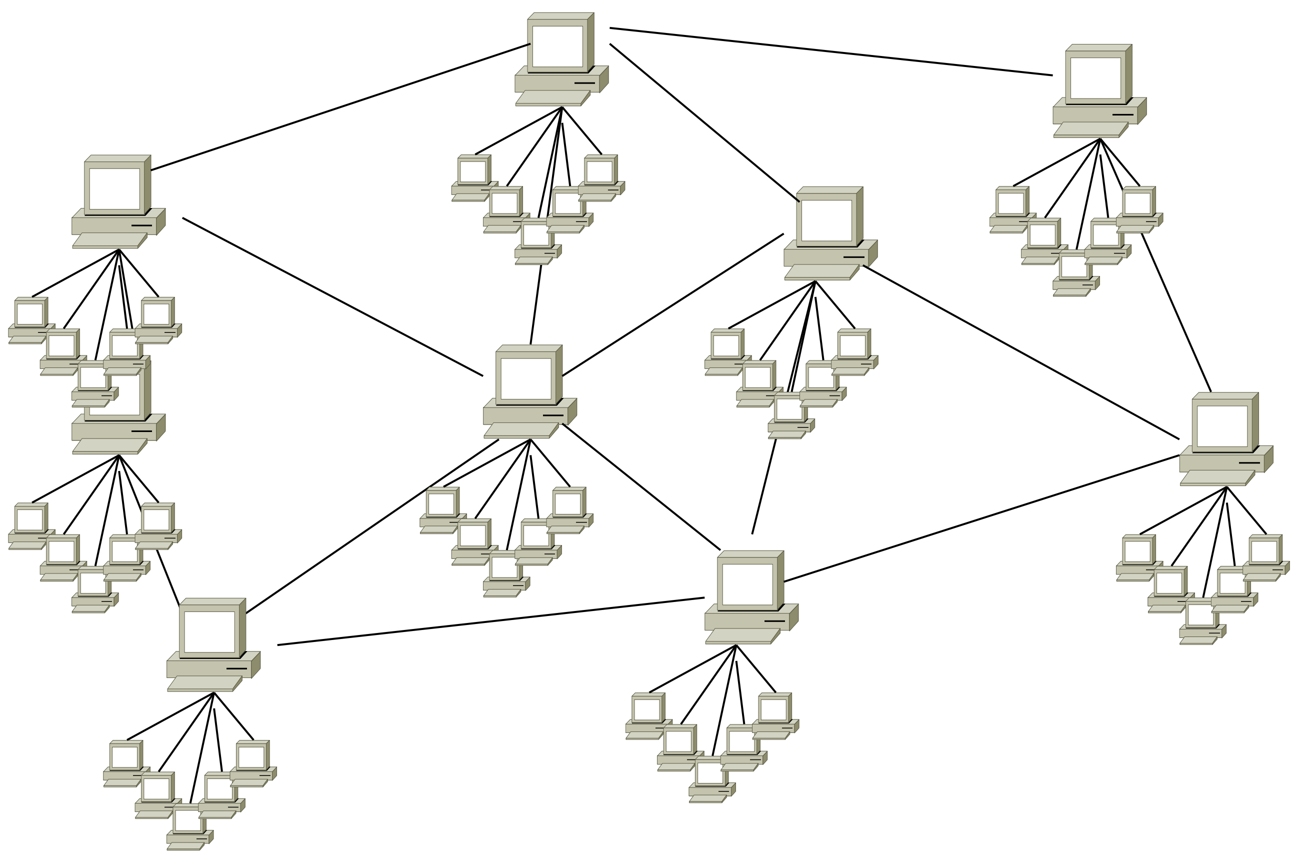
Flooding

Early P2P II: Flooding on Overlays



Early P2P II.v: “Ultra/super peers”

- Ultra-peers can be installed (KaZaA) or self-promoted (Gnutella)
  - Also useful for NAT circumvention, e.g., in Skype



Hierarchical Networks (& Queries)

- IP
  - Hierarchical name space (www.vldb.org, 141.12.12.51)
  - Hierarchical routing: AS's corr. with name space (not perfectly)
- DNS
  - Hierarchical name space ("clients" + hierarchy of servers)
  - Hierarchical routing w/aggressive caching
- Traditional pros/cons of hierarchical mgmt
  - Works well for things aligned with the hierarchy
    - E.g., physical or administrative locality
  - Inflexible
    - No data independence!

Lessons and Limitations

- Client-Server performs well
  - But not always feasible: Performance not often 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
  - Fancy *distributed* queries
  - Vulnerabilities: data poisoning, tracking, etc.
  - Guarantees about anything (answer quality, privacy, etc.)

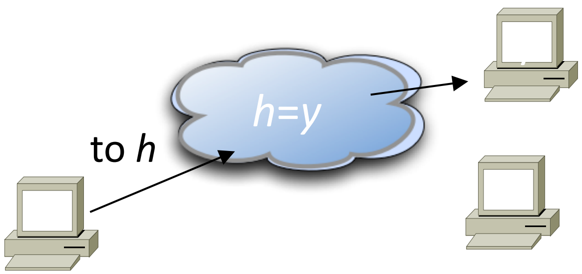
Structured Overlays:
Distributed Hash Tables

DHT Outline

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

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



High-Level Idea: Indirection

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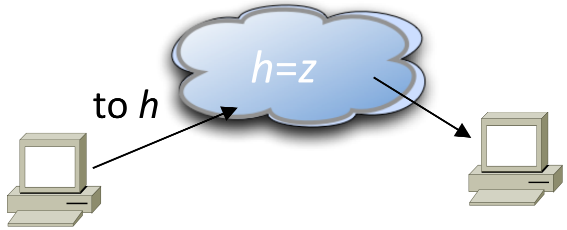
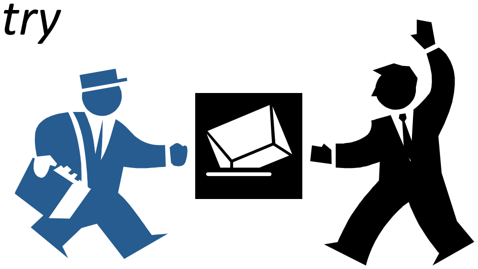


- Indirection in time
  - Temporally decouple send and receive
  - Persistence required. Hence, typical sol'n: soft state
    - Combo of persistence via *storage* and via *retry*
      - "Publisher" requests TTL on storage
      - Republishes as needed



- Metaphor: Distributed Hash Table

What is a DHT?

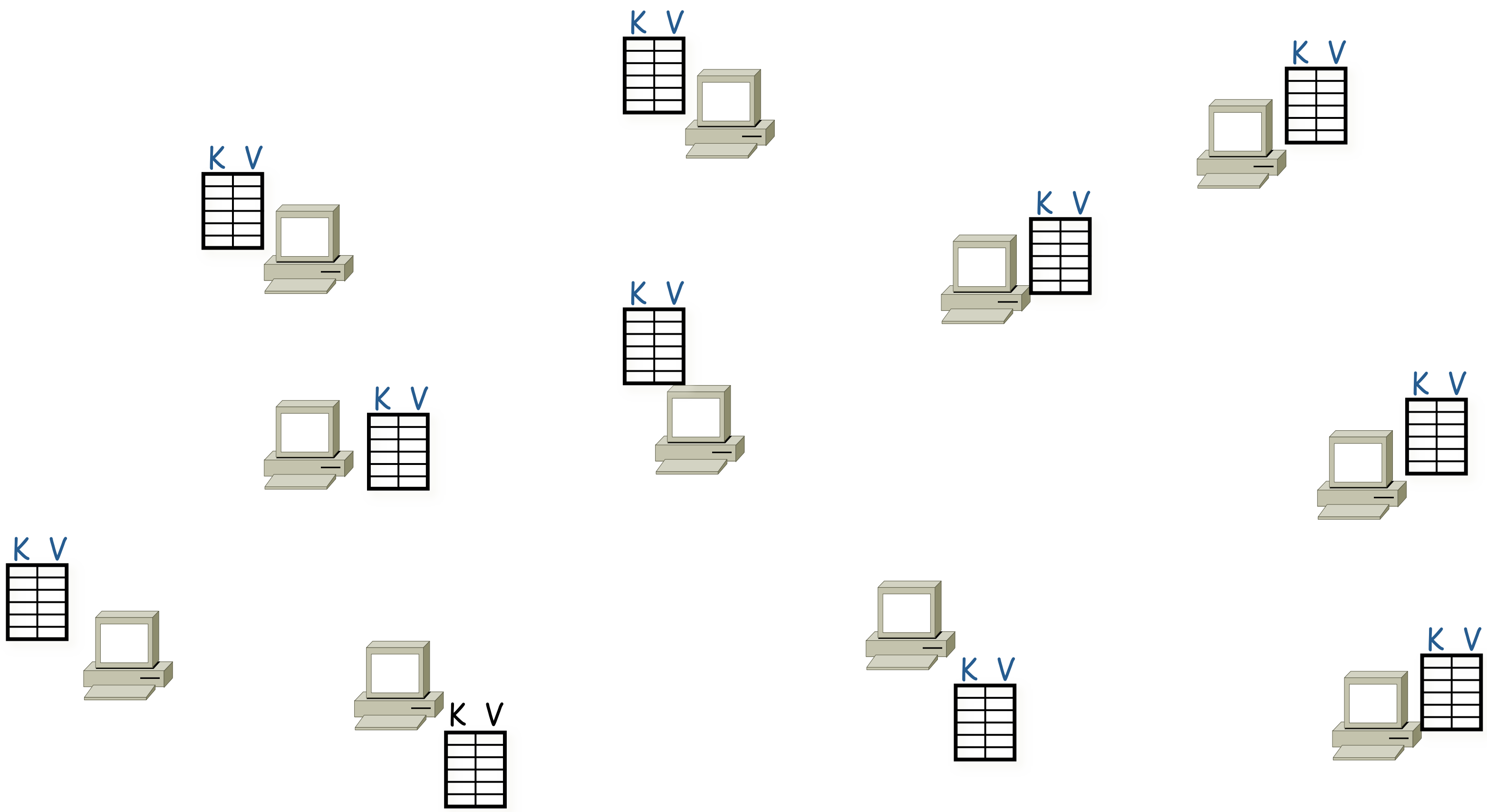
- Hash Table
  - Data structure that maps “keys” to “values”
  - Essential building block in software systems
- Distributed Hash Table (DHT)
  - Similar, but spread across the Internet
- Interface
  - insert (key, value) or put (key, value)
  - lookup (key) or get (key)

How?

Every DHT node supports a single operation:

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

DHT in action



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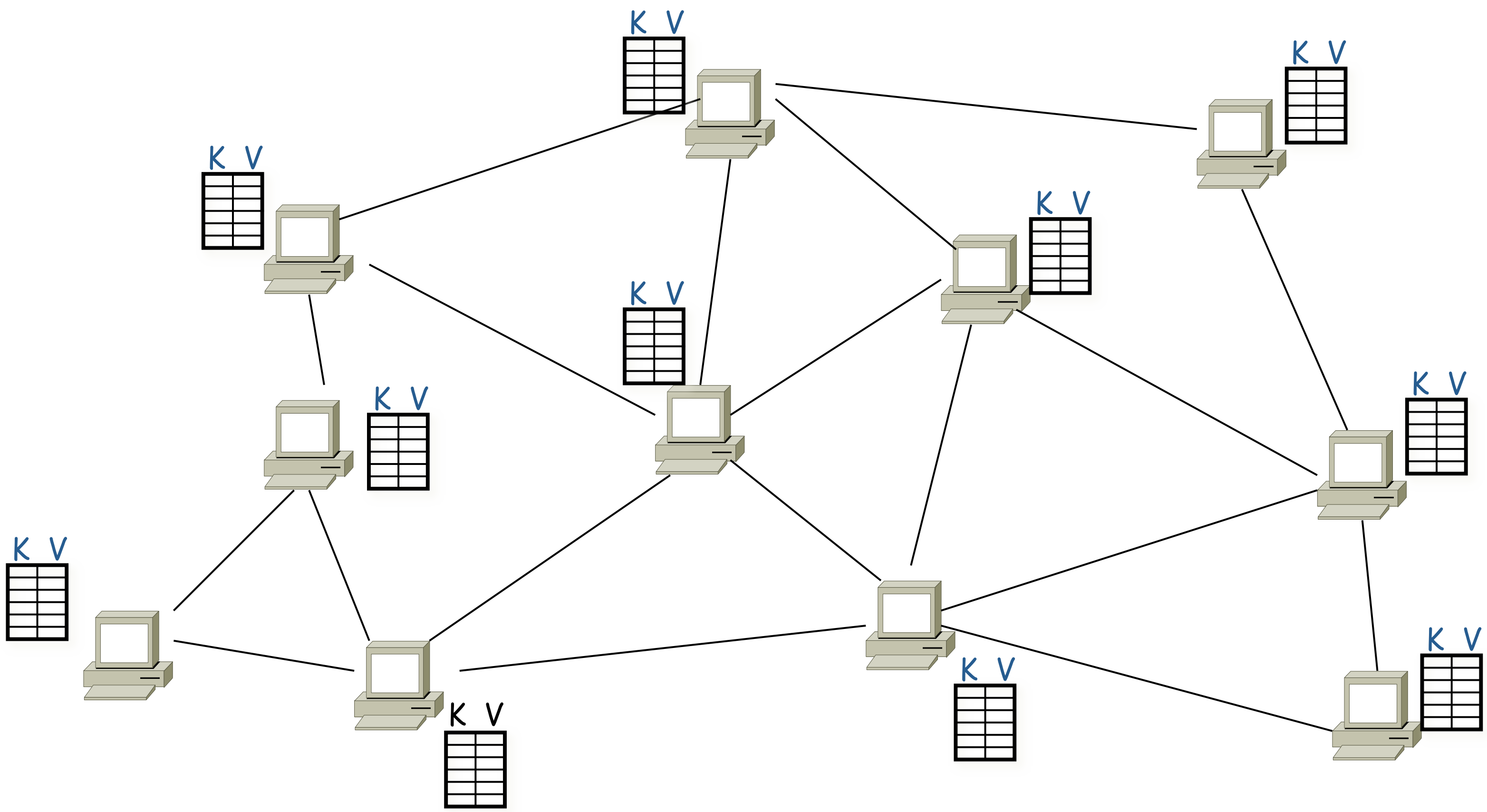

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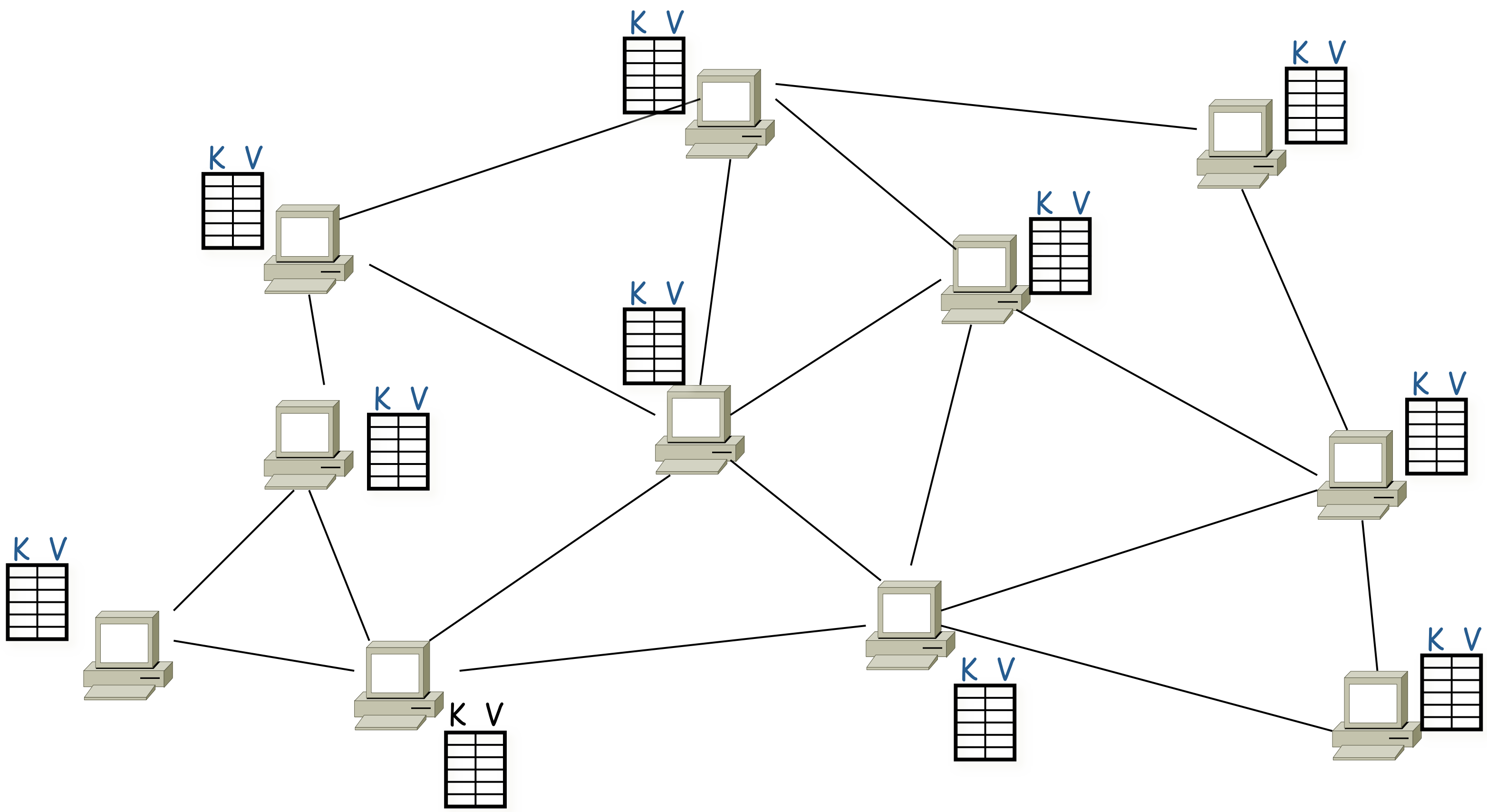
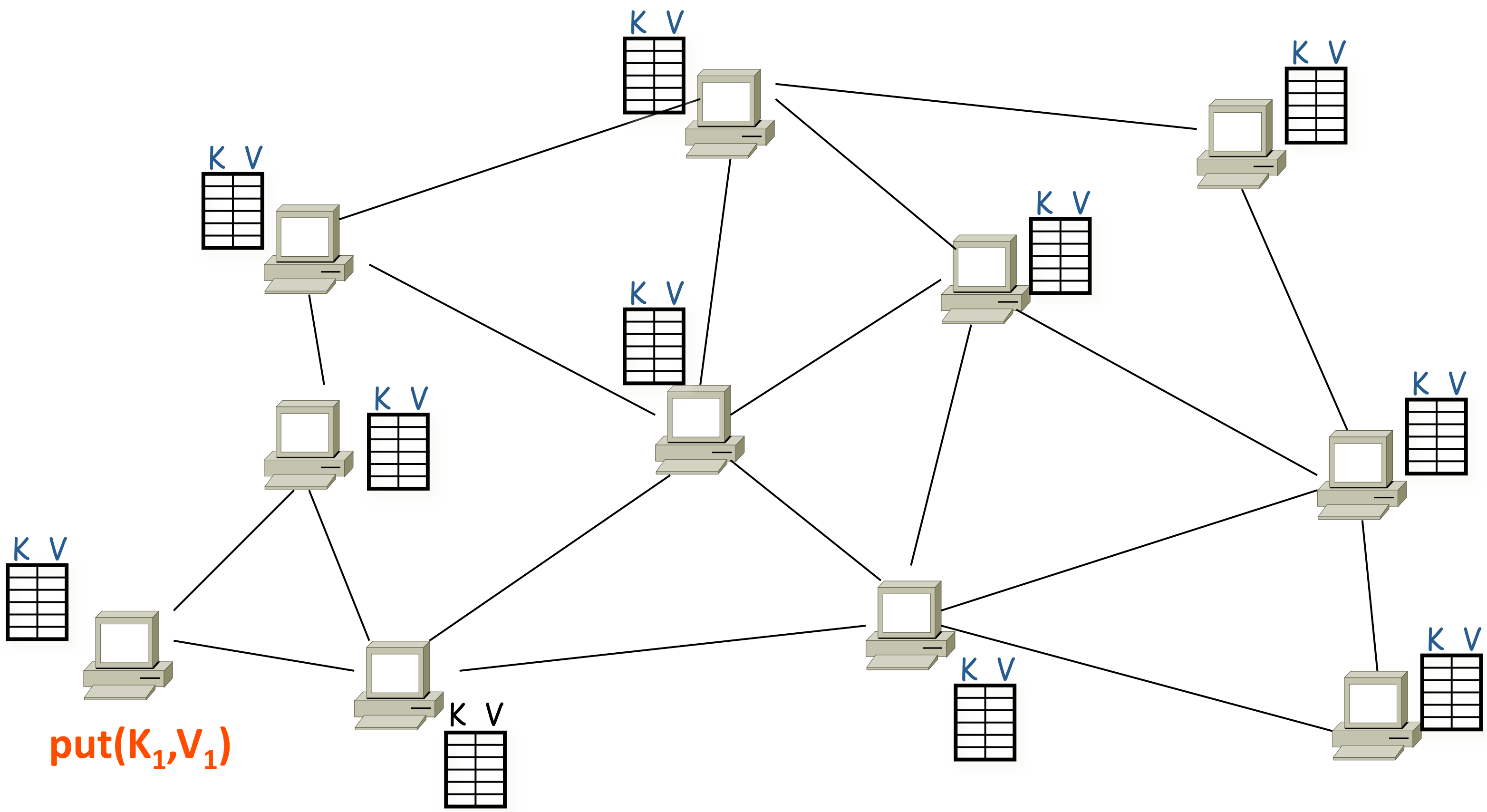


Operation: take *key* as input; route msgs to node holding *key*

DHT in action: put()



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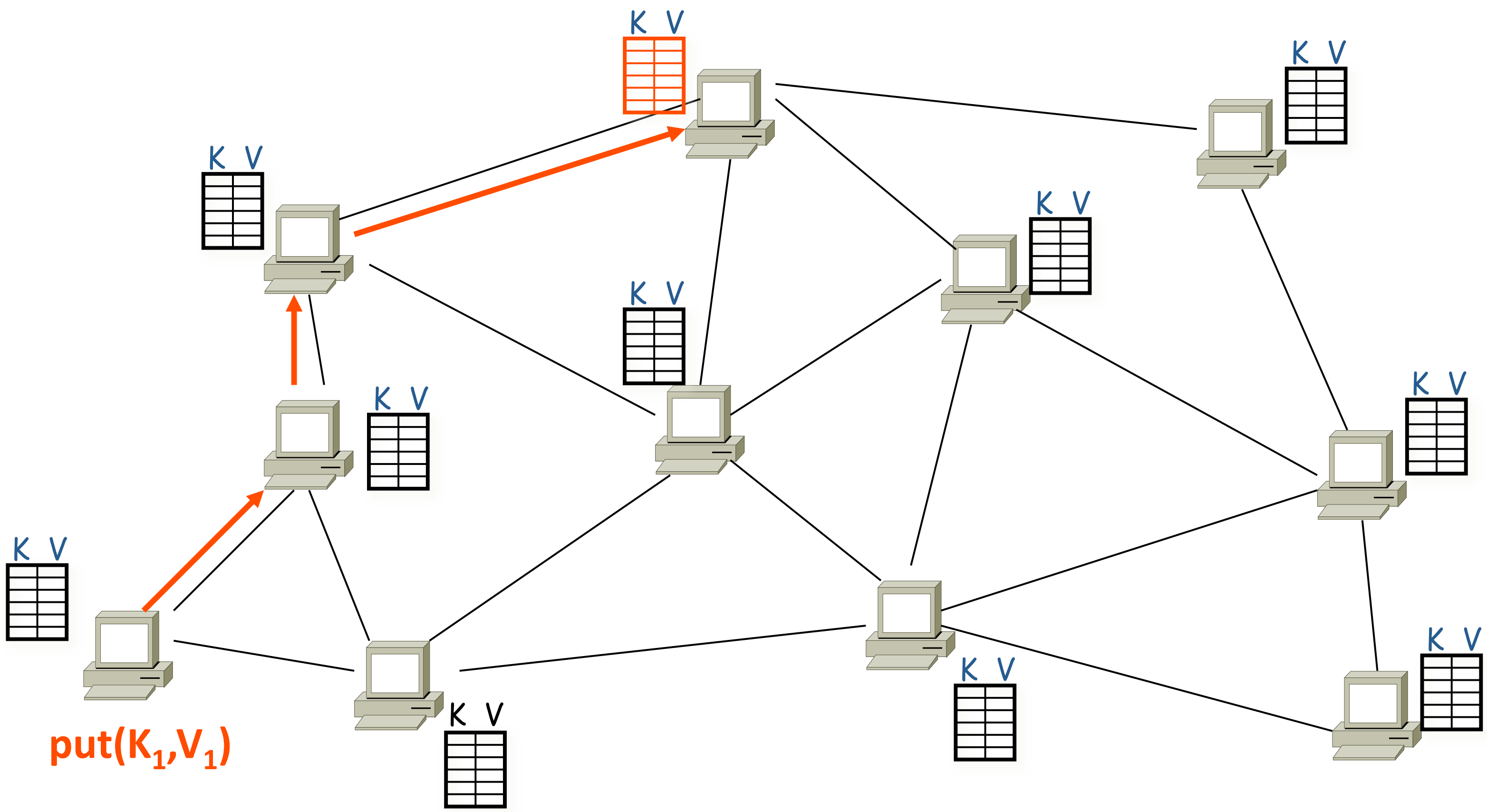

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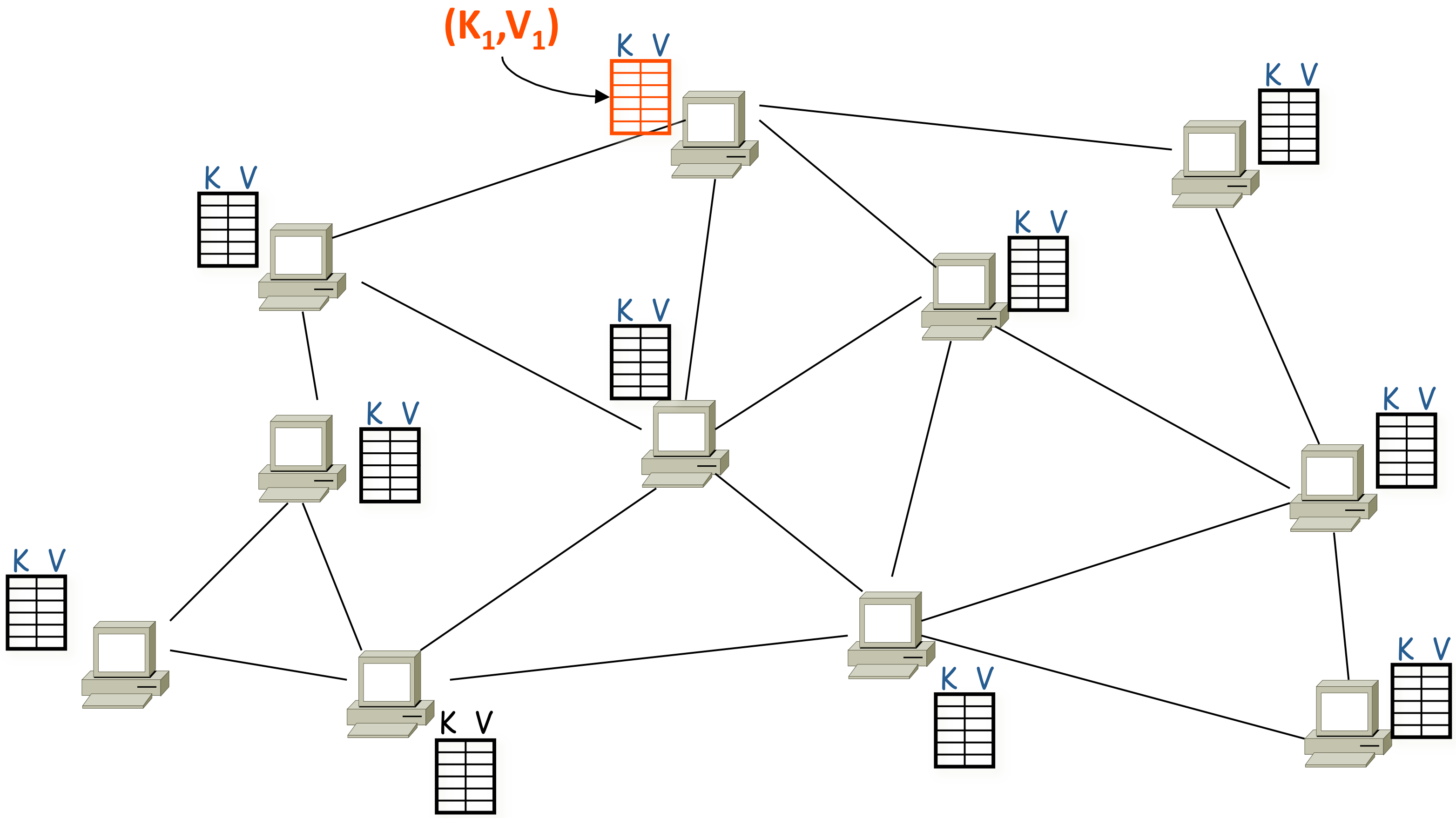
DHT in action: put()



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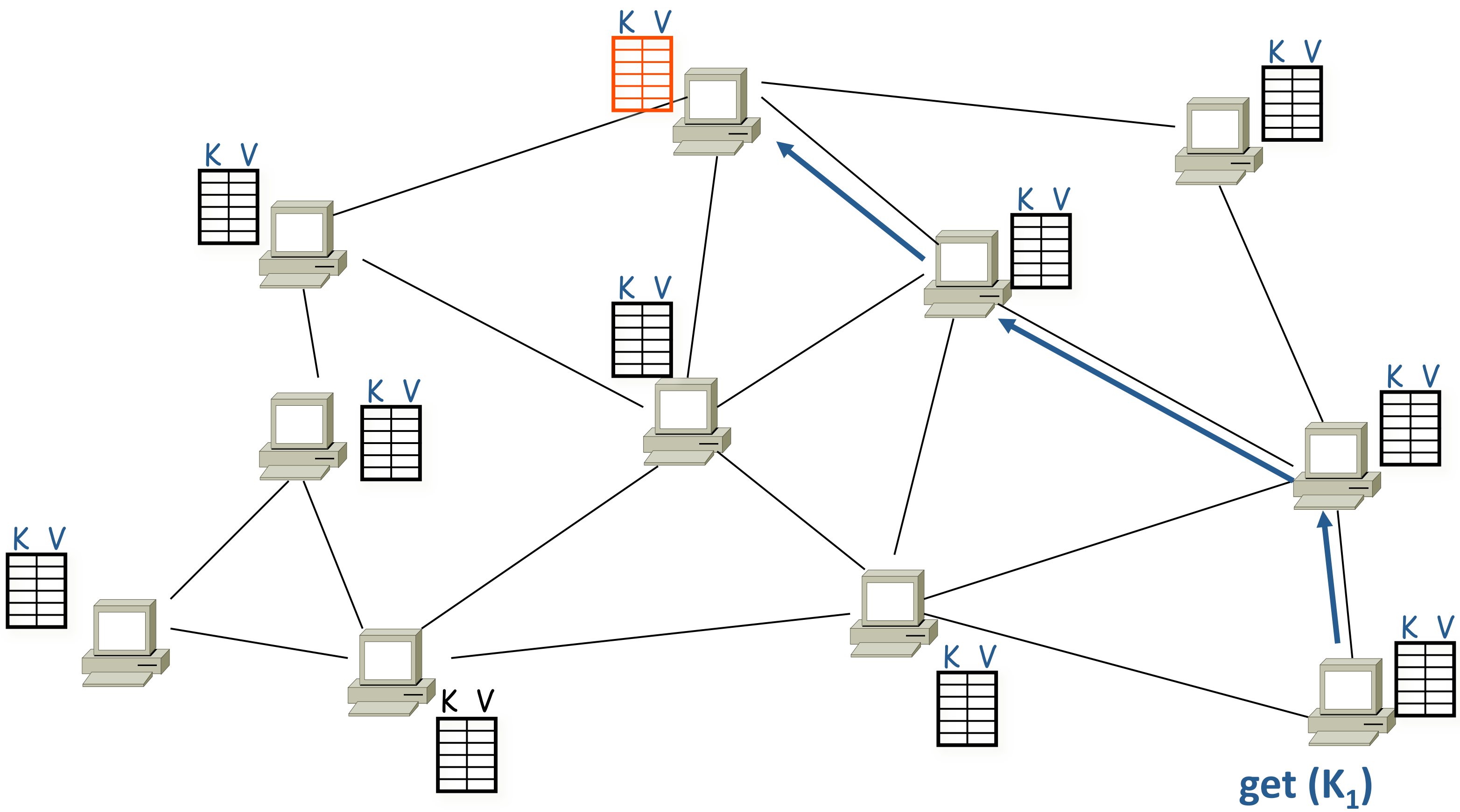
DHT in action: get()



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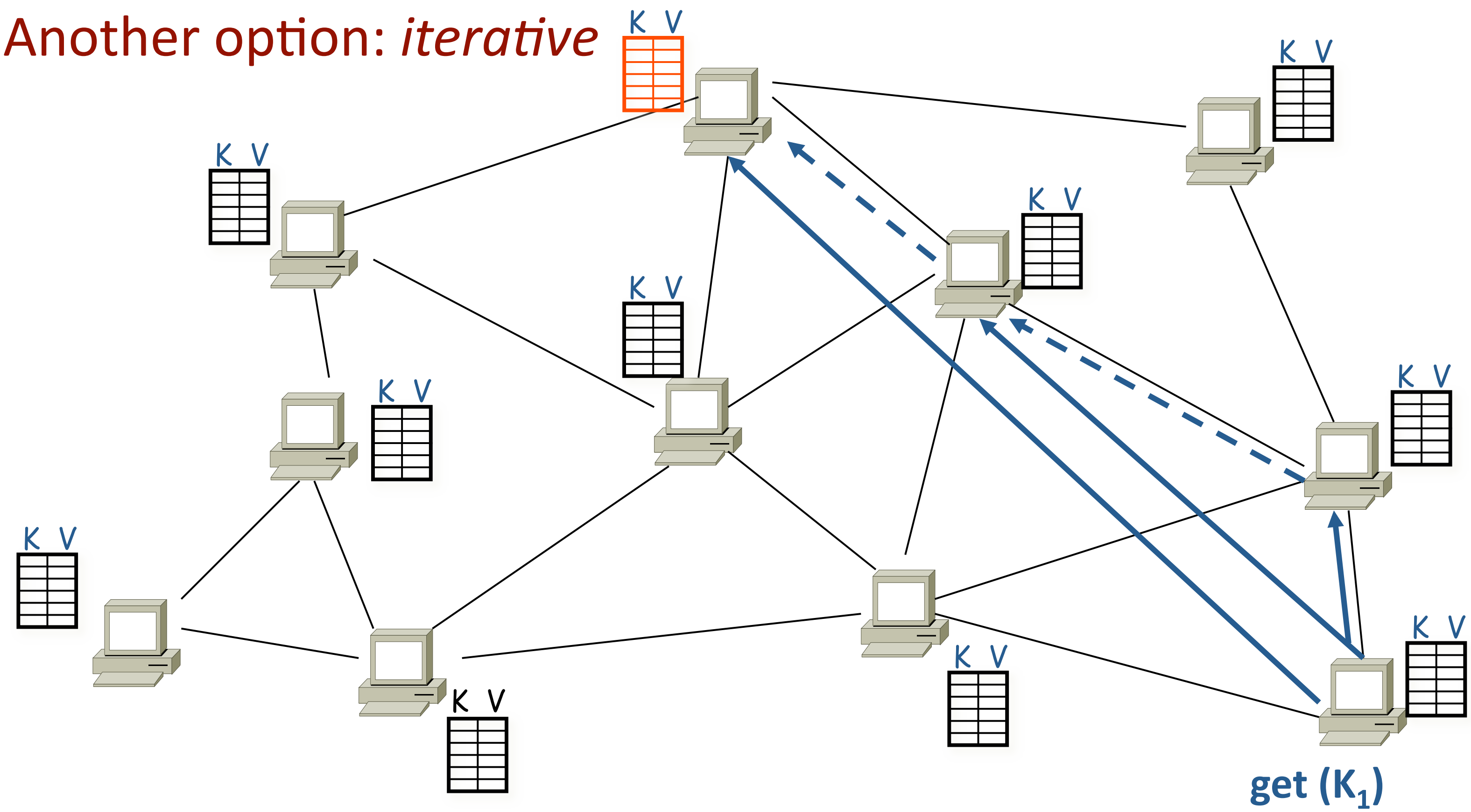
Iterative vs. Recursive Routing

Previously showed *recursive.*

Another option: *iterative*



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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")
- Different "storage" mechanisms considered:
  - Persistence w/ additional mechanisms for fault recovery
  - Best effort caching and maintenance via soft state

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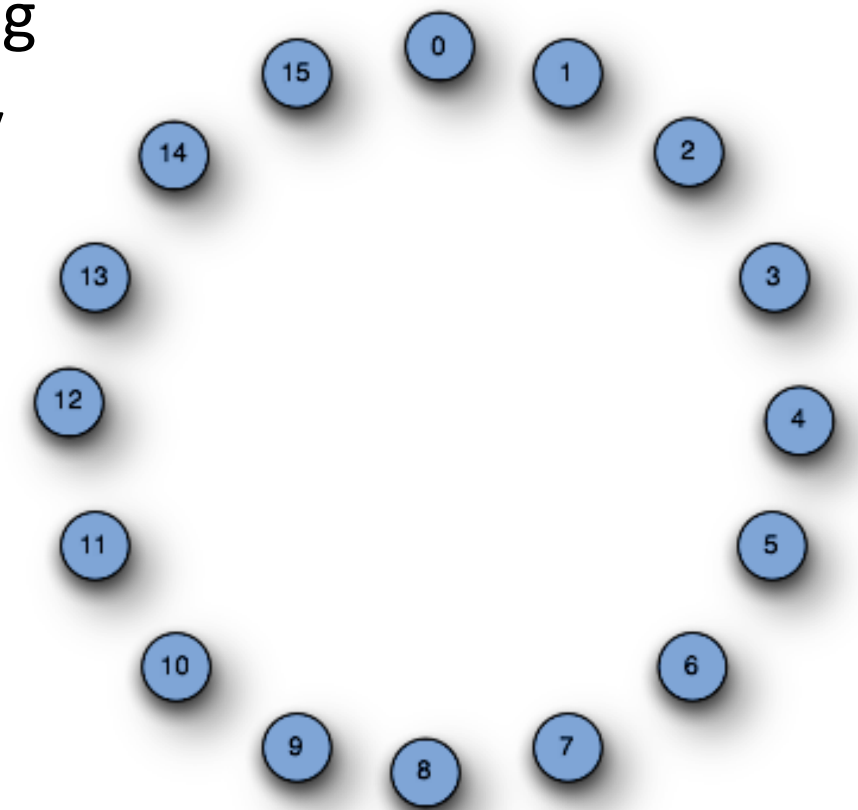
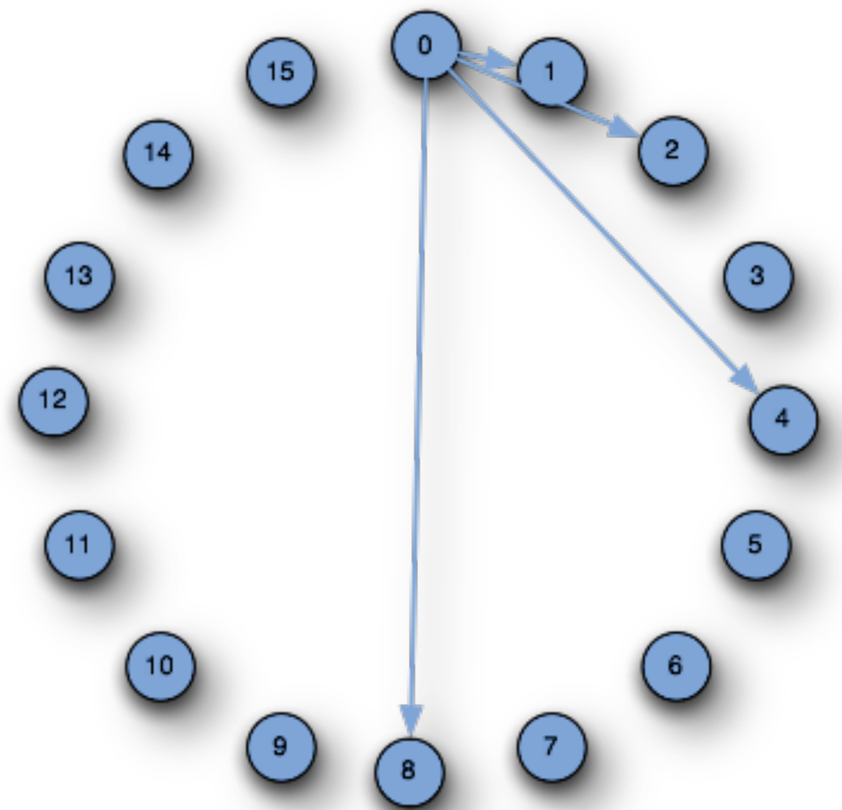
An Example DHT: Chord

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



An Example DHT: Chord

- Each node has particular view of network
  - Set of known neighbors



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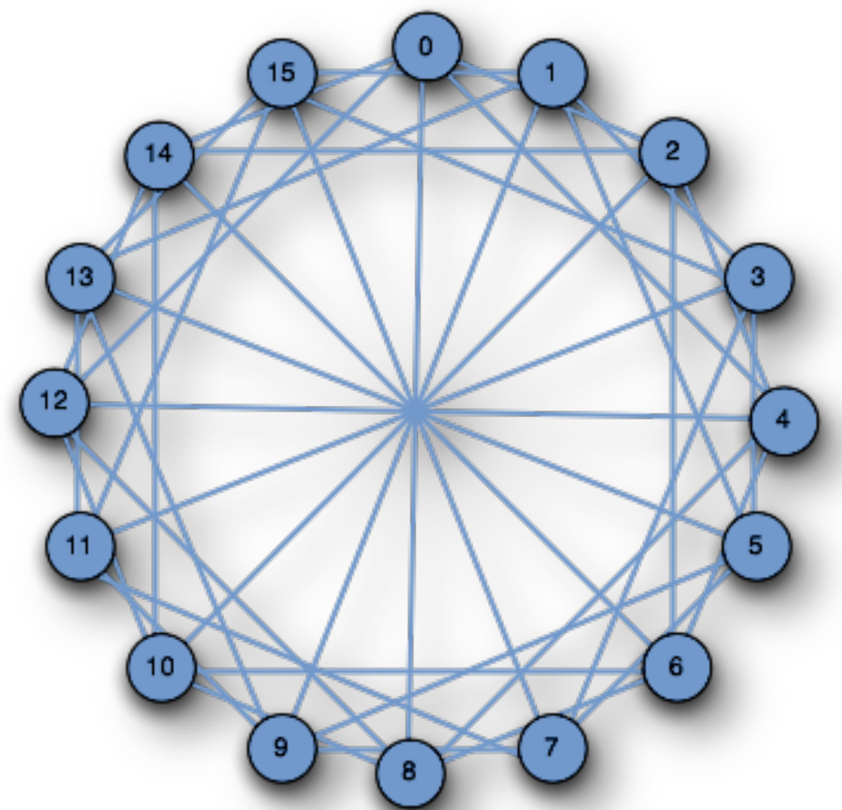

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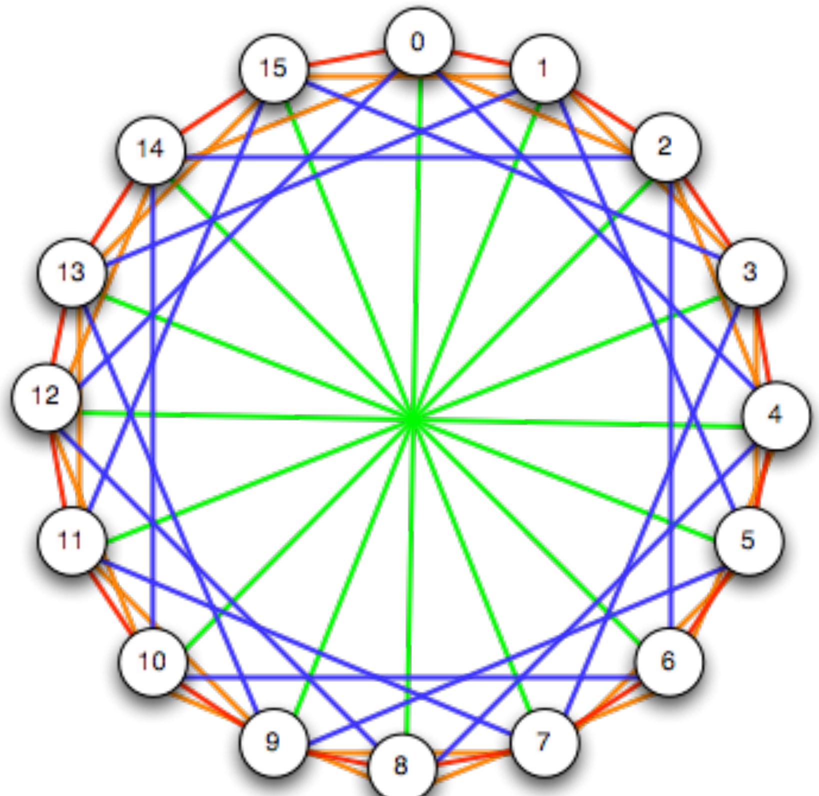
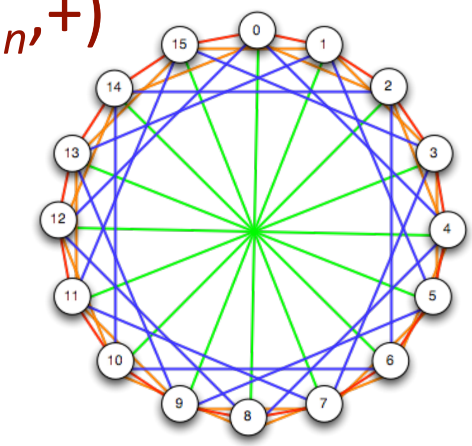


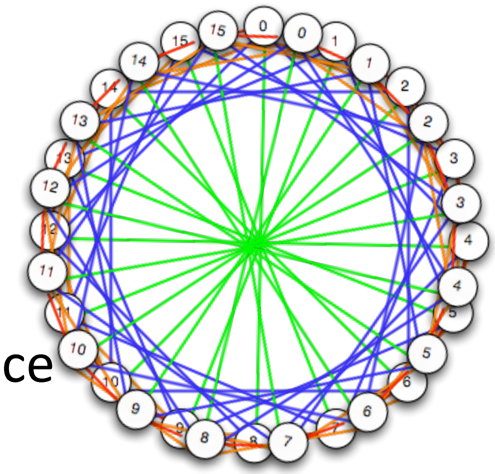
Cayley Graphs

- 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 polygons are all about!



- Fact: Most (complete) DHTs are Cayley graphs
  - And they didn't even know it!
  - Follows from parallel InterConnect Networks (ICNs)

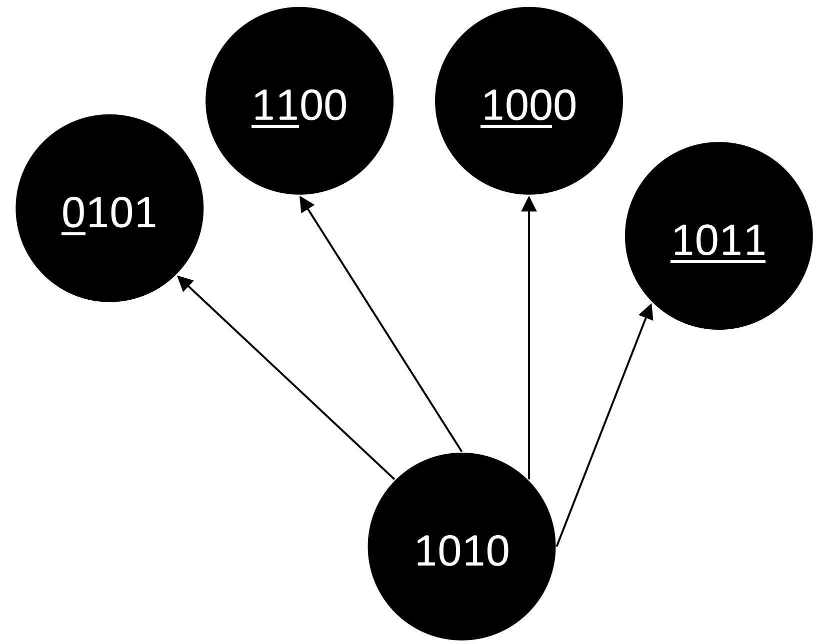
How Hairy met Cayley



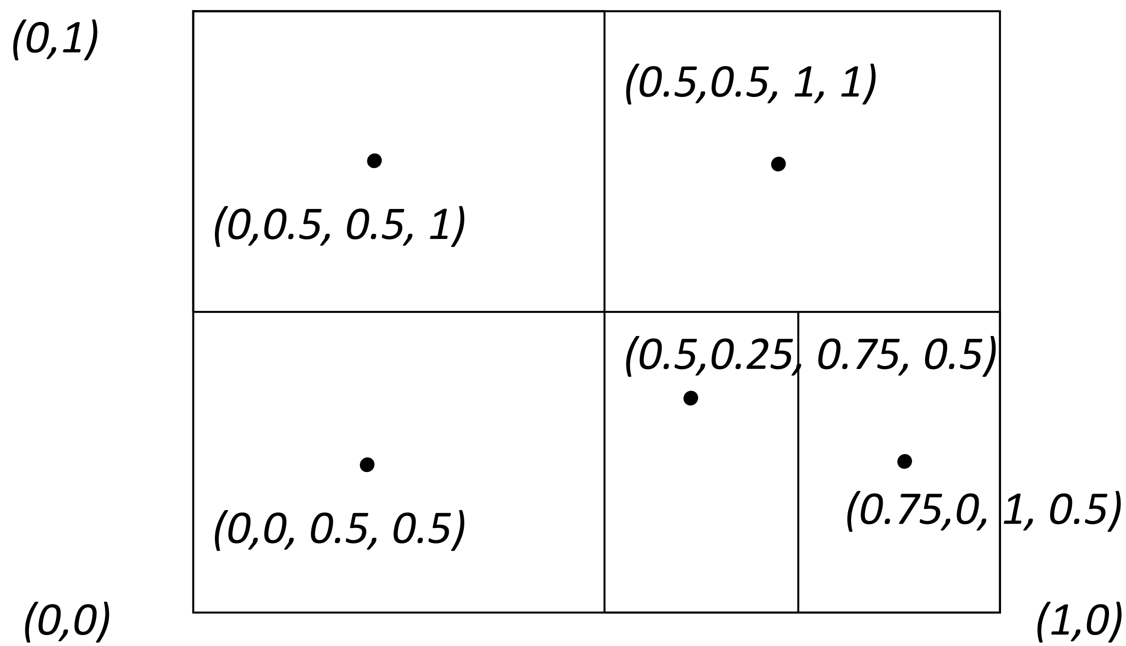
- What do you want in a structured network?
  – Uniformity of routing logic
  – Efficiency/load-balance of routing and maintenance
  – Generality at different scales
- Theorem: All Cayley graphs are *vertex symmetric.*
  – I.e. isomorphic under swaps of nodes
  – So routing from *y* to *x* looks just like routing from (*y*-*x*) to 0
    - The routing code at each node is the same
    - 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

Pastry/Bamboo

- Based on Plaxton Mesh
- Names are fixed bit strings
- Topology: Prefix Hypercube
  - For each bit from left to right, pick 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

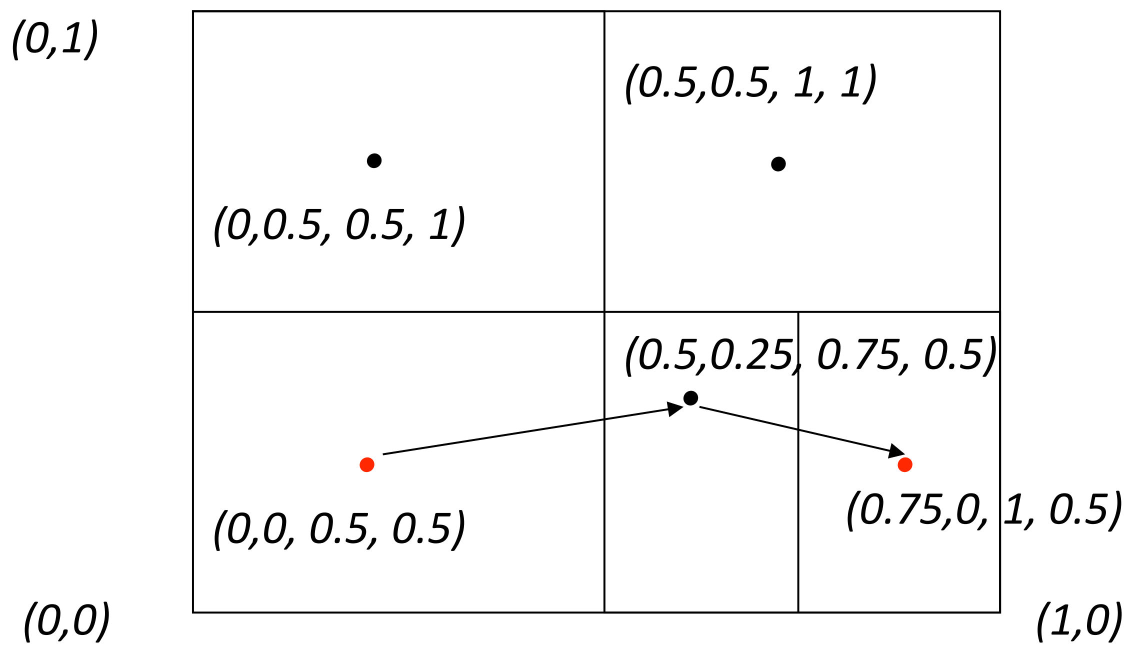


CAN: Content Addressable Network



- Exploit multiple dimensions
- Each node is assigned a zone
- Nodes ID'd by zone boundaries
- Join: chose random point, split its zones

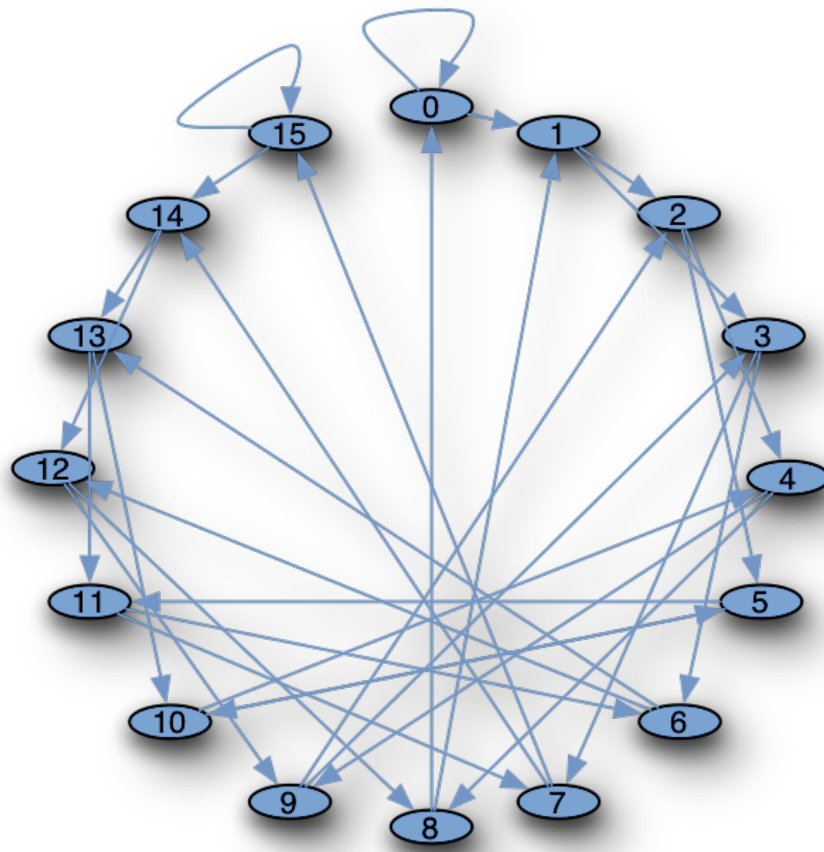
Routing in 2-dimensions



- 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

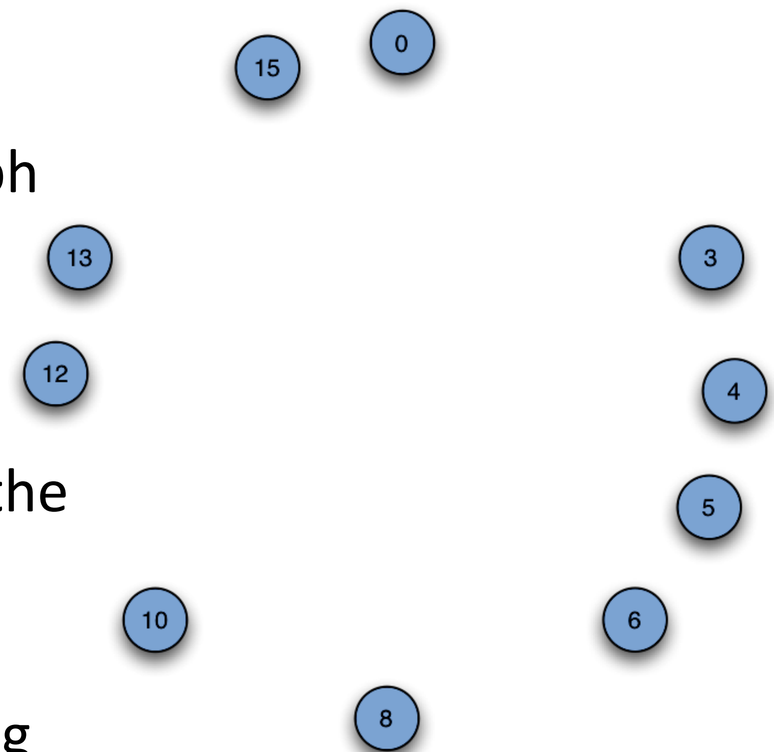


Topologies of Other Oft-cited DHTs

- Tapestry
  - Very similar to Pastry/Bamboo topology
  - No ring
- Kademlia
  - Also similar to Pastry/Bamboo
  - But the "ring" is ordered by the XOR metric: "bidirectional"
  - Used by the eMule / BitTorrent / Azureus (Vuze) systems
- Viceroy
  - An emulated Butterfly network
- Symphony
  - A randomized "small-world" network

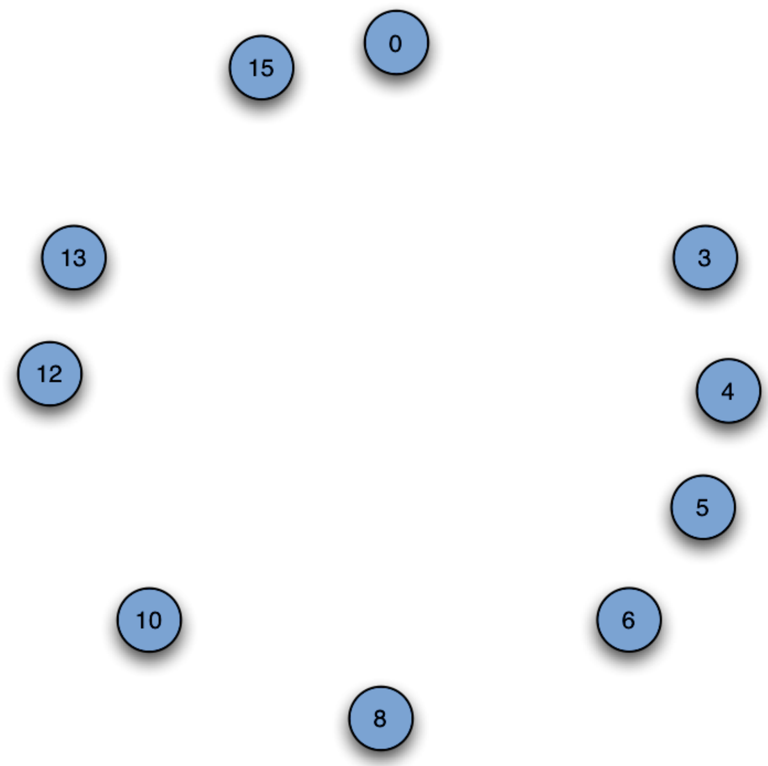
Incomplete Graphs: Emulation

- For Chord, we assumed exactly 2^m nodes. What if not?
  - Need to "emulate" a complete graph even when incomplete.
- 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



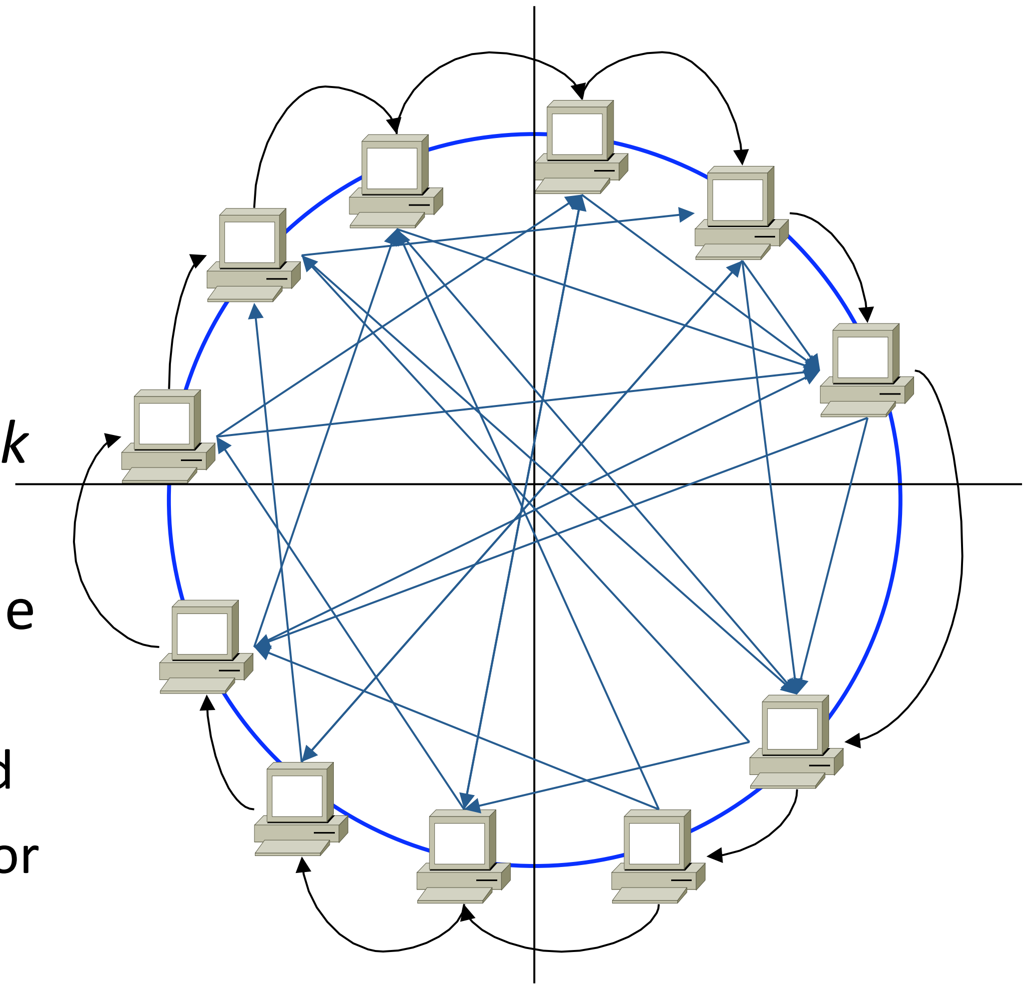
Handle node heterogeneity

- Sources of unbalanced load
  - Unequal portion of keyspace
  - Unequal load per key
- Balancing keyspace
  - Consistent hashing: Region owned by single node is O(1/n (1 + *log* n))
  - What about node hetergeneity?
    - Nodes create "virtual nodes" of # proportional to capacity
- Load per key
  - Assumes many keys per region



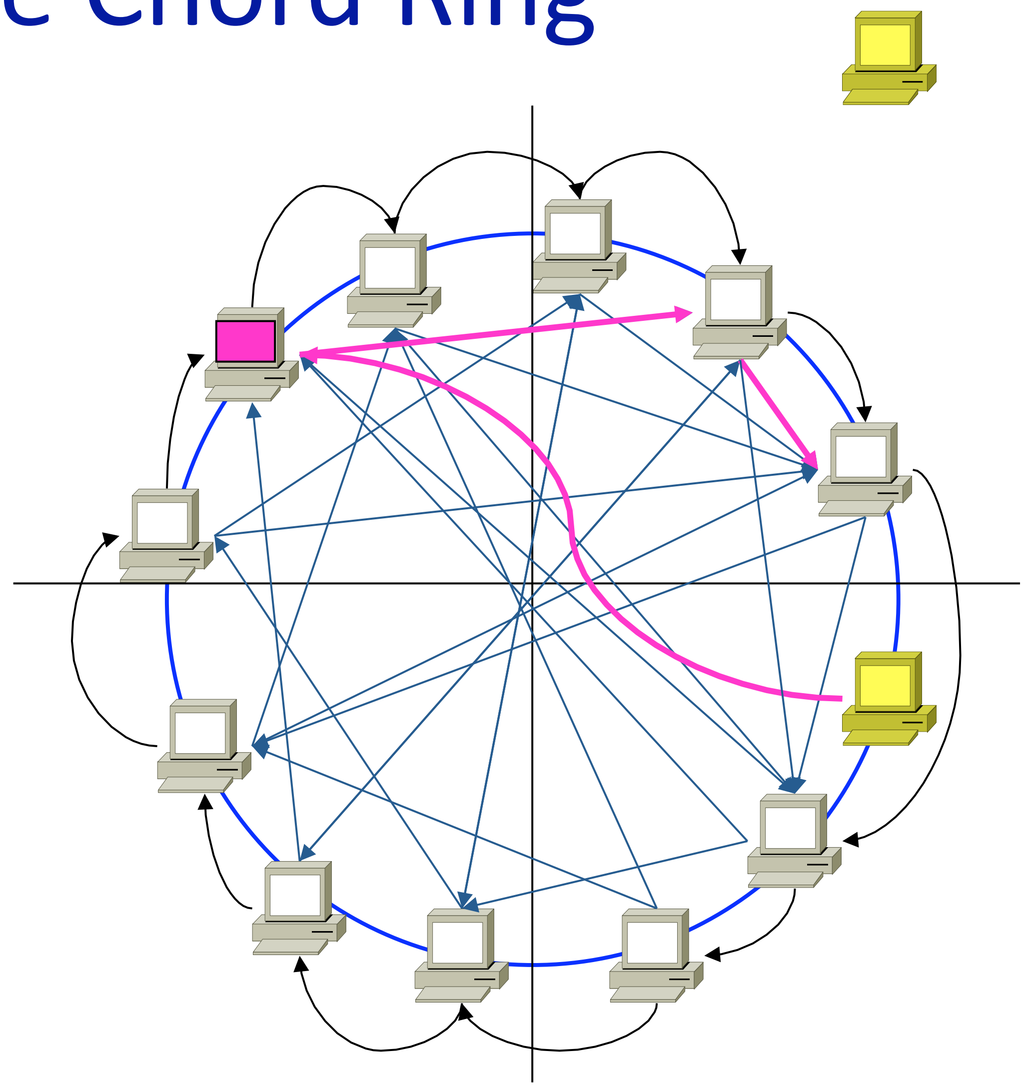
Chord in Flux

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



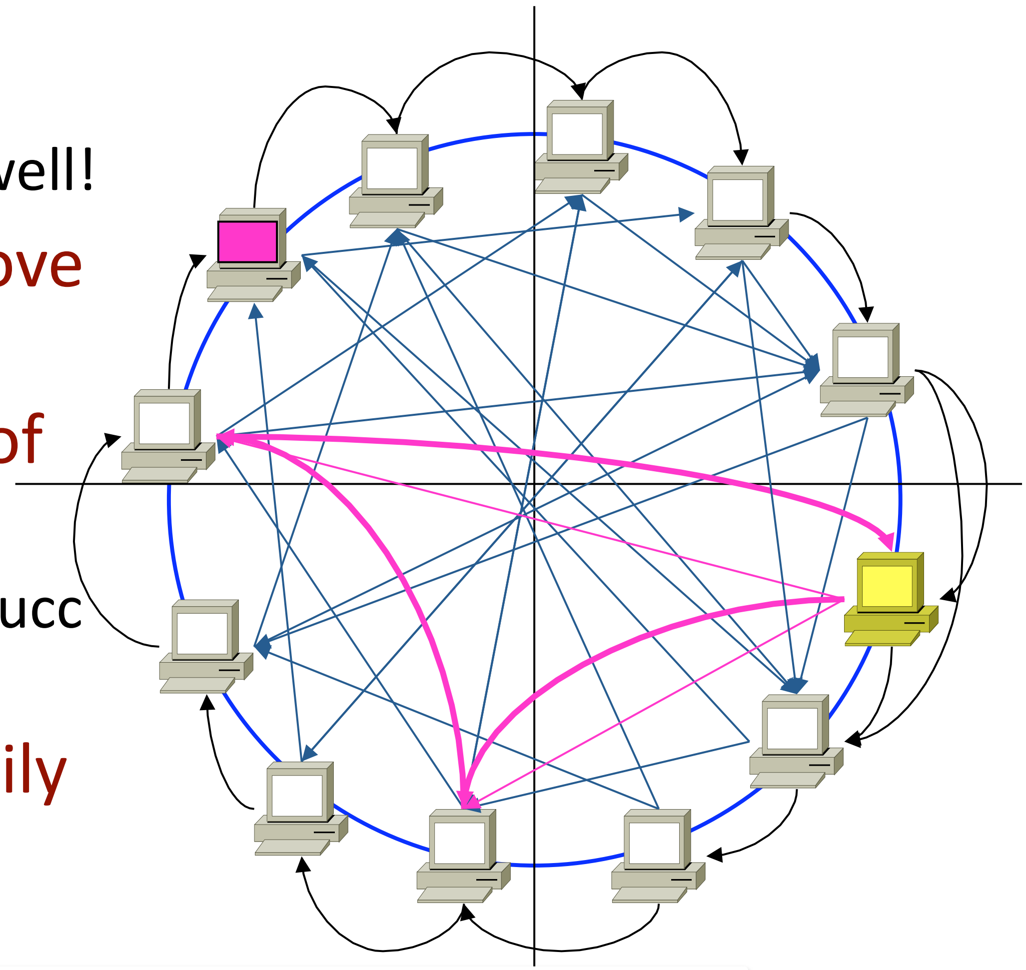
Joining the Chord Ring

- 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 in Chord routing



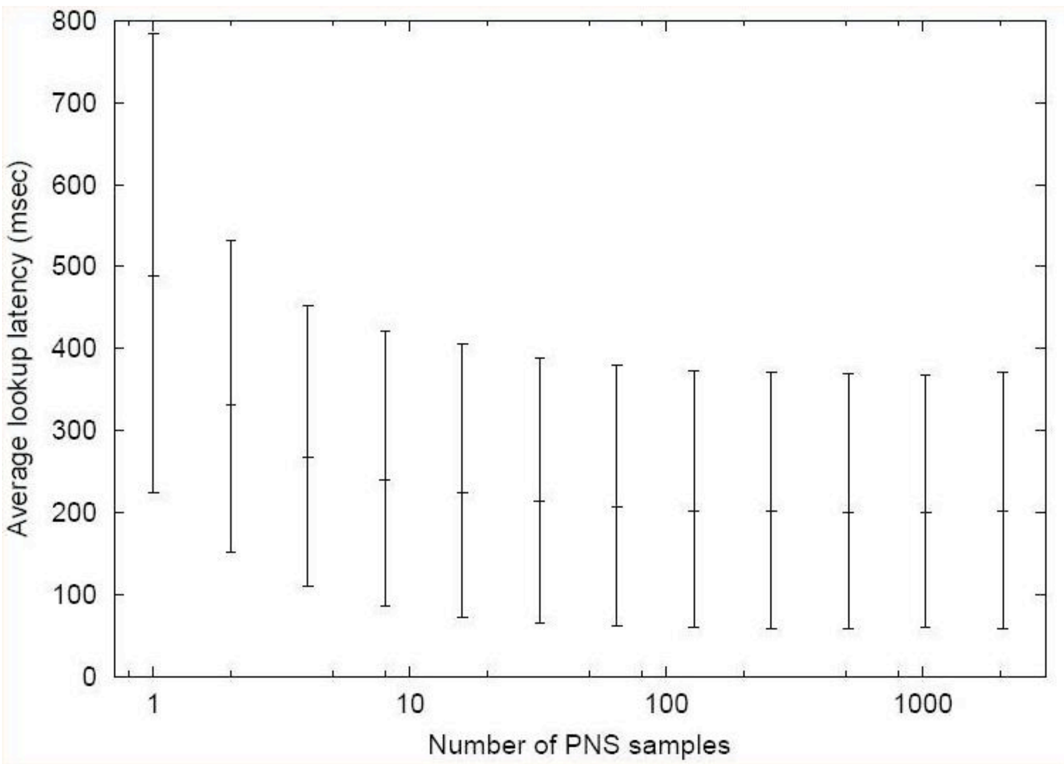
Joining the Chord Ring

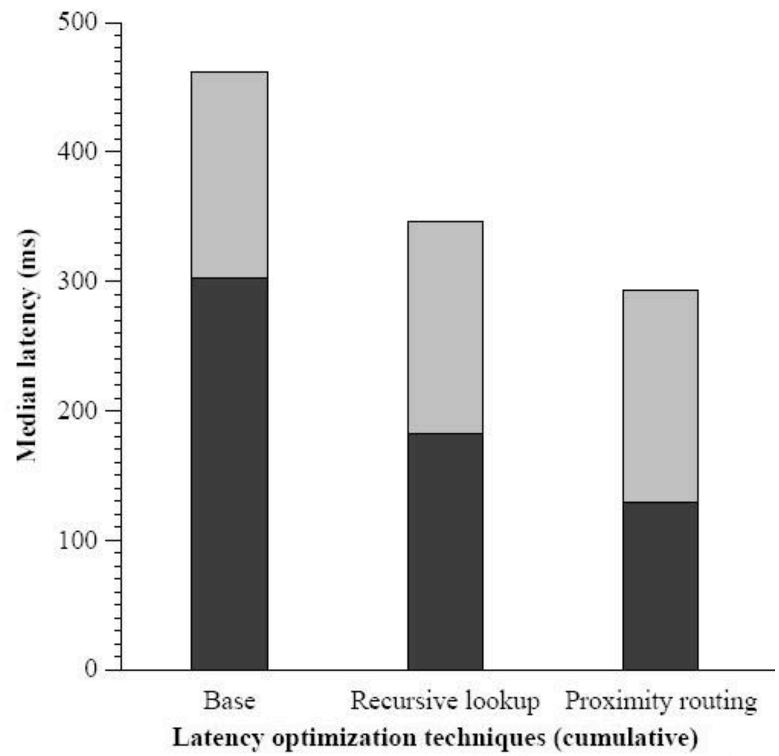
- Update pred/succ links
  - Once ring is in place, all well!
- Inform application to move data appropriately
- Search to find "fingers" of varying powers of 2
  - Or just copy from pred /succ and check!
- Inbound fingers fixed lazily



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

Fingers must be constrained?





- No: Proximity Neighbor Selection (PNS)

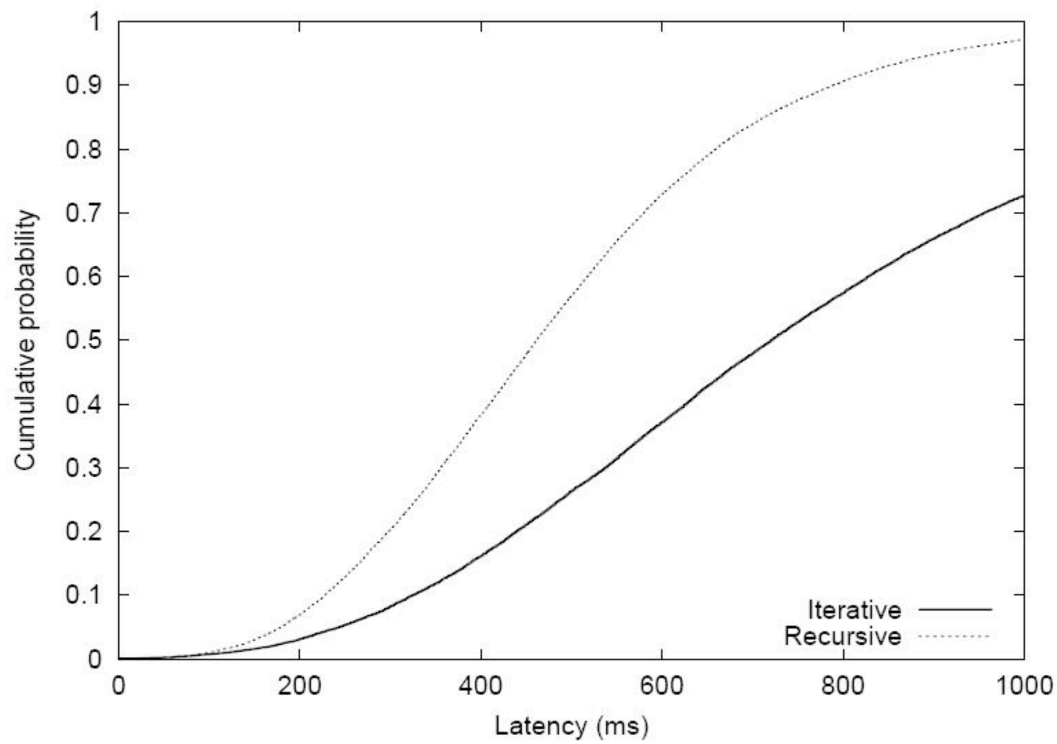
Handling Churn

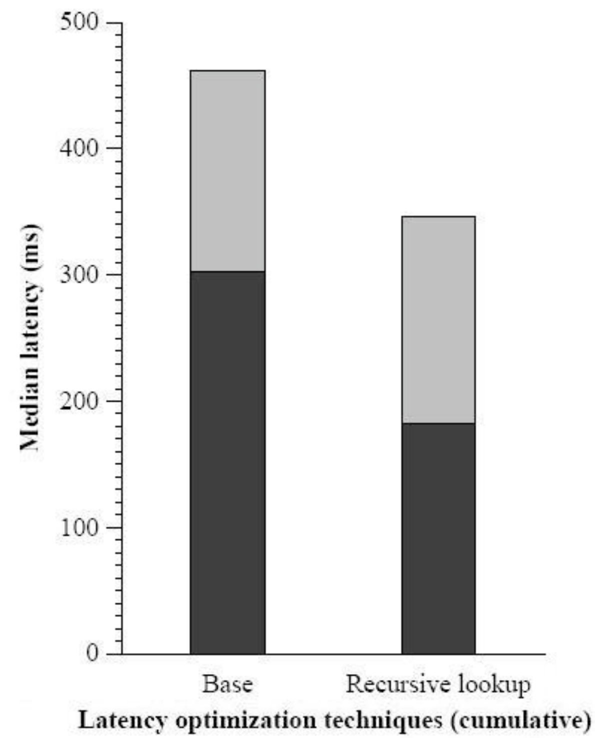
- Churn
  - Session time? Life time?
    - For system resilience, session time is what matters
- Three main issues
  - Determining timeouts
    - Significant component of lookup latency under churn
  - Recovering from a lost neighbor in “leaf set”
    - Periodic, not reactive!
    - Reactive causes feedback 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
  - 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 [Vivaldi, etc.]
  - 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

Recursive vs. Iterative





Left: Simulation of 20,000 lkps for random keys
Recursive lookup takes 0.6 times as long as iterative

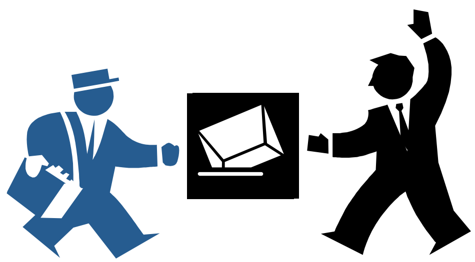
Right Figure: 1,000 lookups in test-bed; confirms simulation

Recursive vs. Iterative

- Recursive
  - Faster under many conditions
    - Fewer round-trip-times
    - Better proximity neighbor selection
    - Can timeout individual RPCs more tightly
  - Better tolerance to network failure
    - Path between neighbors already known
- Iterative
  - Tighter control over entire lookup
    - Easily support windowed RPCs for parallelism
    - Easier to timeout entire lookup as failed
  - Faster to return data directly than use recursive path

Storage Models for DHTs

- Up to now we focused on routing
  - DHTs as “content-addressable network”
- Implicit in “DHT” name 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



Storage models

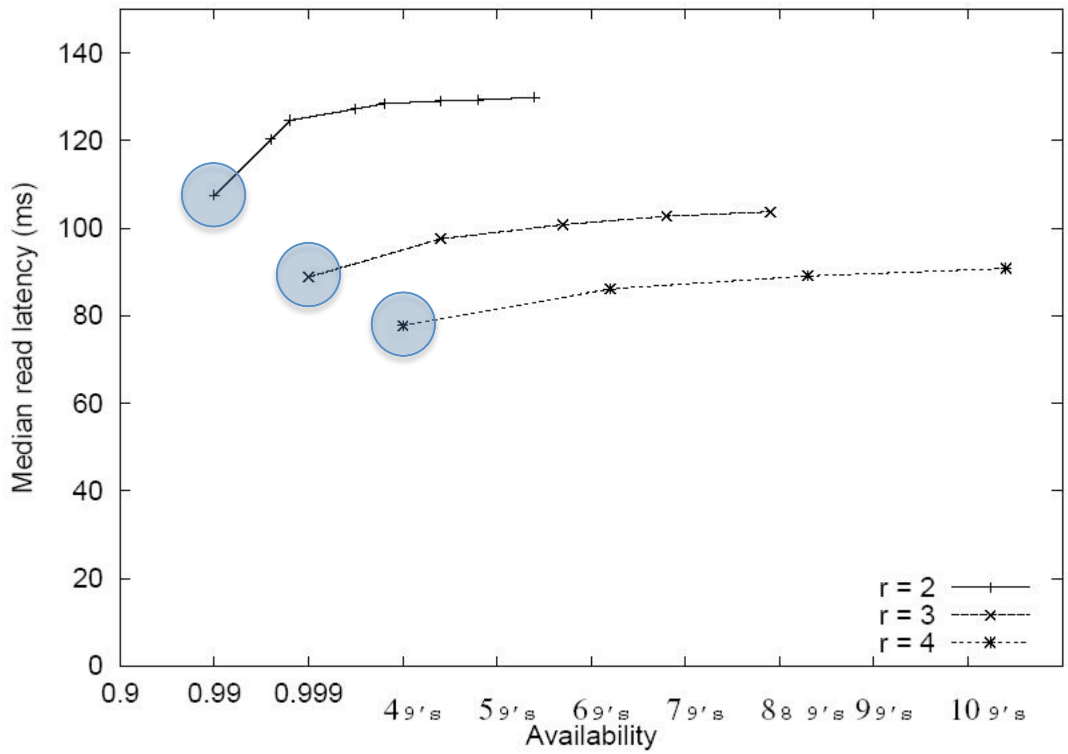
- Store *only* on key's immediate successor
  - Churn, routing issues, packet loss make lookup failure more likely
- Store on *k* successors
  - When nodes detect succ/pred fail, re-replicate
- Cache along reverse lookup path
  - Provided data is immutable
  - …and performing recursive responses

Storage on successors?

- Erasure-coding
  - Data block split into l fragments
  - m diff. fragments necessary to reconstruct the block
  - Redundant storage of data
- Replication
  - Node stores entire block
  - Special case: m = 1 and l is number of replicas
  - Redundant information spread over fewer nodes
- Comparison of both methods
  - $r = l / m$ amount of redundancy
- Prob. block available:

$$p_{avail} = \sum_{i=m}^{l} \binom{l}{i} p_0^i (i - p_0)^{l-i}$$

Latency: Erasure-coding vs. replication



- Replication: slightly lower latency
- Erasure-coding: higher availability
  - DHash++ uses erasure-coding with m = 7 and l = 14

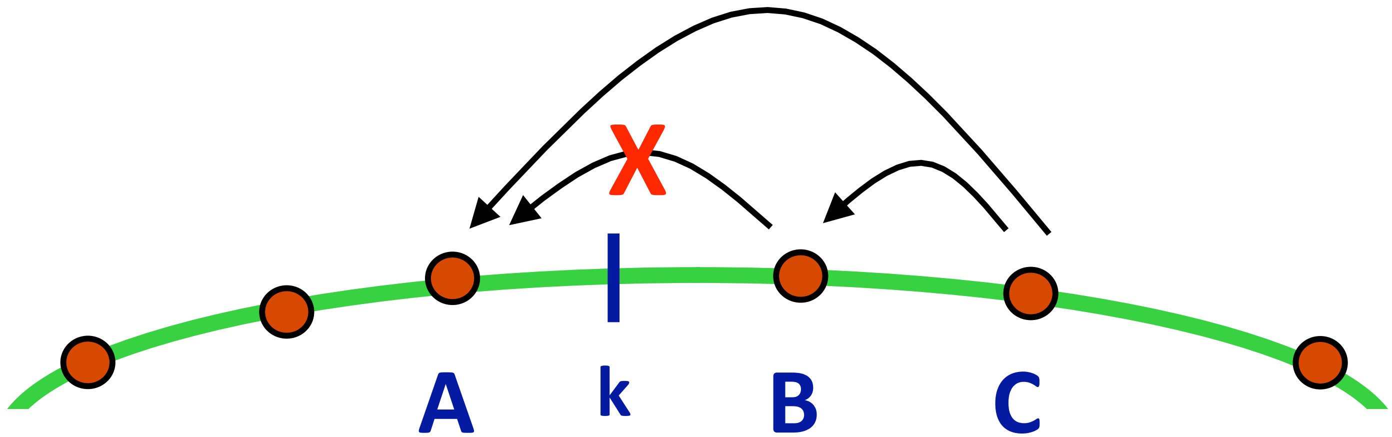
What about mutable data?

- Ugh!

- Different views
  - Ivy: Create version trees [Muthitacharoen, OSDI '02]
    - Think "distributed version control" system

- Global agreement?
  - Reach consensus among all nodes belonging to a successor groups: "distributed agreement"
    - Difficult, especially at scale

An oft overlooked assumption: The underlay isn't perfect!



- All have implicit assumption: full connectivity
- *Non-transitive connectivity (NTC)* not uncommon

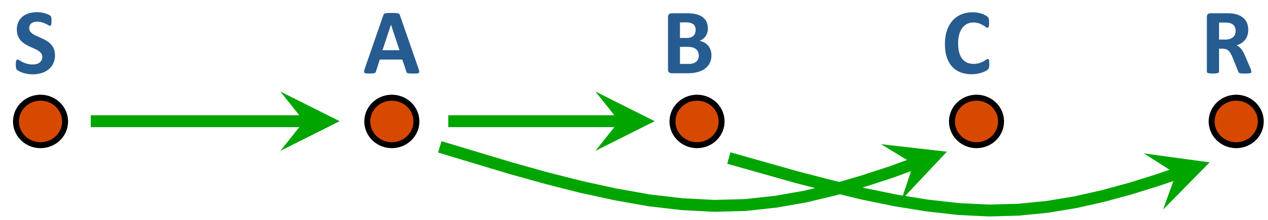
$$B \leftrightarrow C \ , \ C \leftrightarrow A \ , \ A \not\leftrightarrow B$$

- A thinks C is its successor!

Does non-transitivity exist?

- Gerding/Stribling PlanetLab study
  - 9% of all node triples exhibit NTC
  - Attributed high extent to Internet-2
- Yet NTC is also transient
  - One 3 hour PlanetLab all-pair-pings trace
  - 2.9% have persistent NTC
  - 2.3% have intermittent NTC
  - 1.3% fail only for a single 15-minute snapshot
- Level3 ↮ *Cogent, but Level3 ↔ X ↔ Cogent*
- NTC motivates RON and other overlay routing!

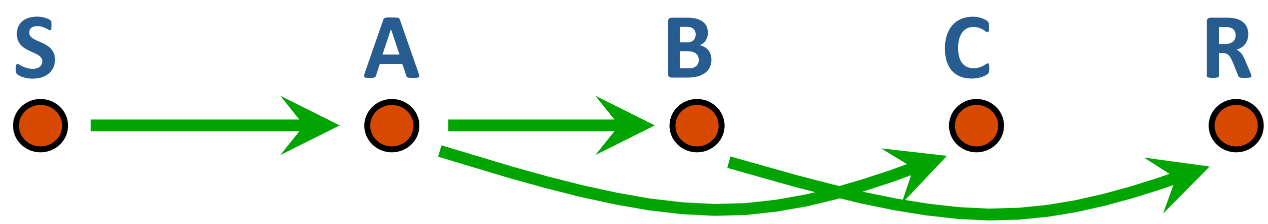
NTC problem fundamental?



Traditional routing

S → R	A
A → R	B
B → R	R

NTC problem fundamental?



Traditional routing

S → R	A
A → R	B
B → R	R

Greedy routing

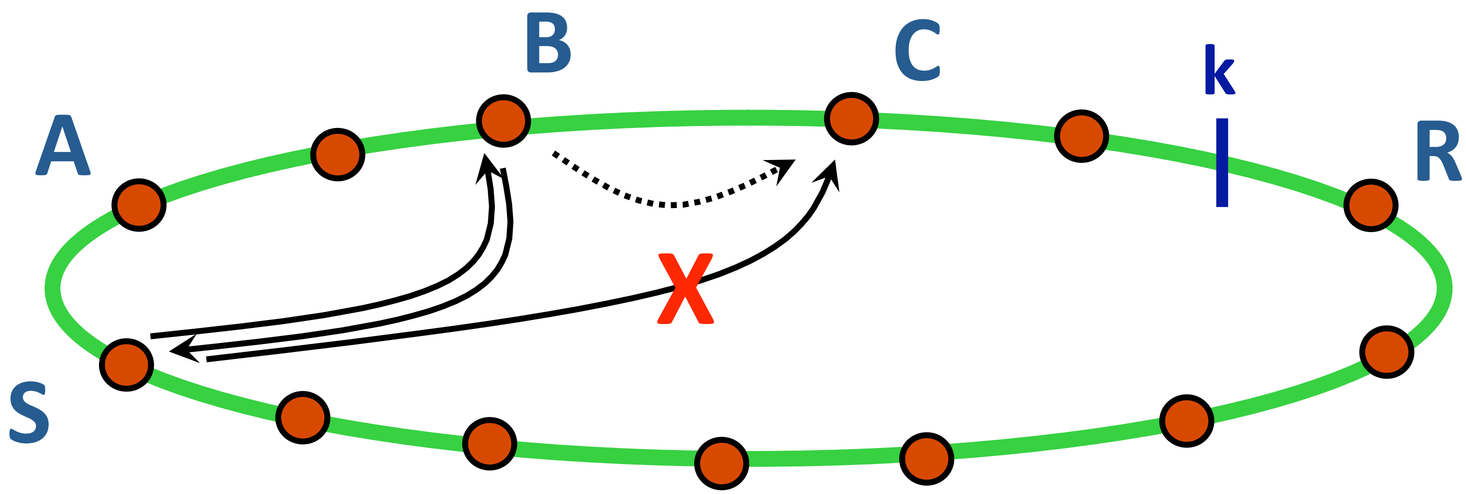
S → R	A
A → R	C
C → R	X

- DHTs implement greedy routing for scalability
- Sender might not use path, even though exists: finds local minima when id-distance routing

Potential problems?

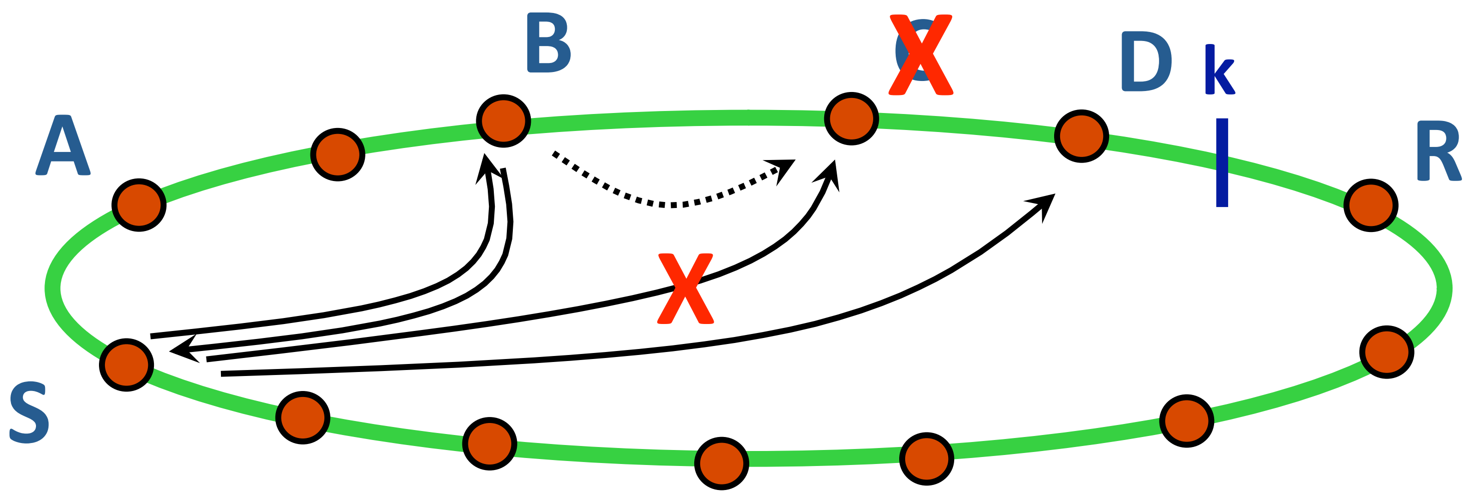
- Invisible nodes
- Routing loops
- Broken return paths
- Inconsistent roots

Iterative routing: Invisible nodes



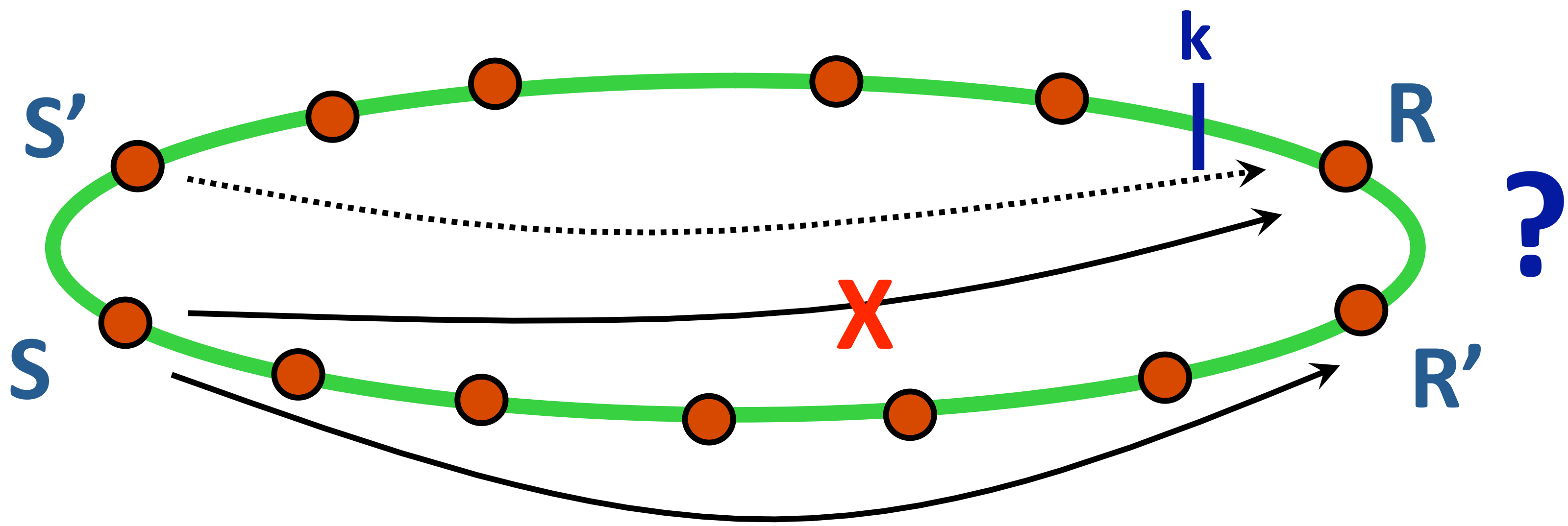
- Invisible nodes cause lookup to halt

Iterative routing: Invisible nodes



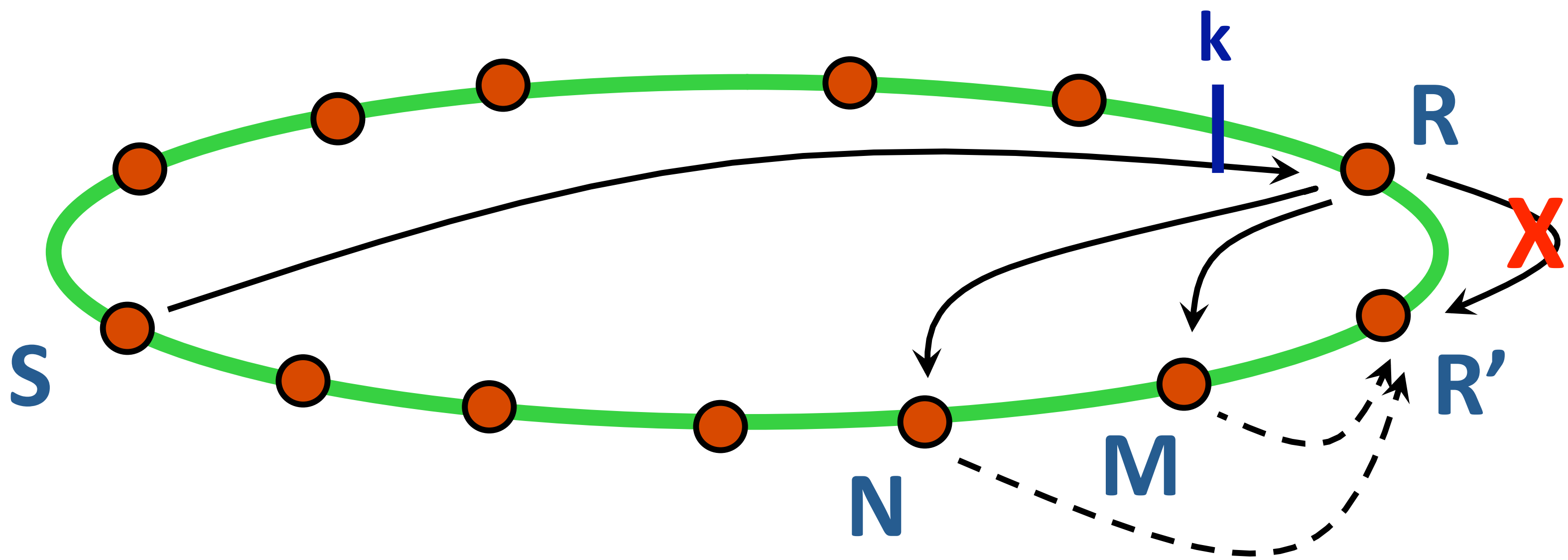
- Invisible nodes cause lookup to halt
- Enable lookup to continue
    - Tighter timeouts via network coordinates
    - Lookup RPCs in parallel
    - Unreachable node cache

Inconsistent roots



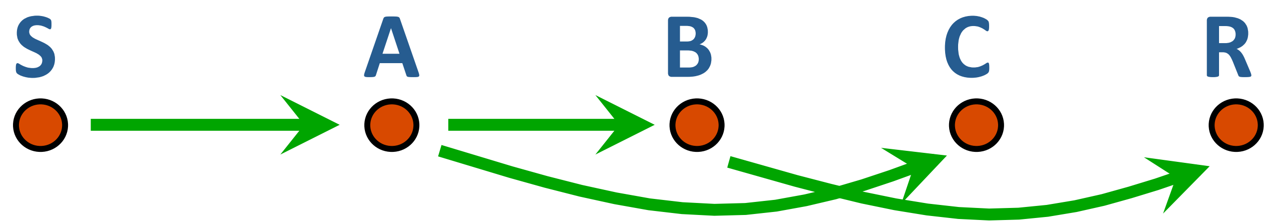
- Nodes do not agree where key is assigned: inconsistent views of root
  - Can be caused by membership changes
  - Also due to non-transitive connectivity: may persist!

Inconsistent roots



- Root replicates (key,value) among leaf set
  - Leafs periodically synchronize
  - Get gathers results from multiple leafs
- Not applicable when require fast update

Longer term solution?



Traditional routing

S → R	A
A → R	B
B → R	R

Greedy routing

S → R	A
A → R	C
C → R	X

- Route around local minima when possible
- Have nodes maintain link-state of neighbors
  - Perform one-hop forwarding if necessary (think RON!)

Summary

- Peer-to-peer systems
  - Unstructured systems
    - Finding hay, performing keyword search
  - Structured systems (DHTs)
    - Finding needles, exact match
- Distributed hash tables
  - Based around consistent hashing with views of O(log n)
  - Chord, Pastry, CAN, Koorde, Kademlia, Tapestry, Viceroy, …
- Lots of systems issues
  - Heterogeneity, storage models, locality, churn management, underlay issues, …
  - DHTs (Kademlia) deployed in wild: Vuze is 1M+ active users