CS 425 / ECE 428
Distributed Systems
Fall 2022

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Lecture 7: Peer-to-peer Systems I

MP2 Released

- You will be implementing
  - Failure detector
  - Membership protocol
- Using concepts you learnt last week!
- Stage 2 (of 4) in building a fully-working distributed system from scratch
  - Stage 3 will be a distributed file system
  - Stage 4 will be a full distributed system

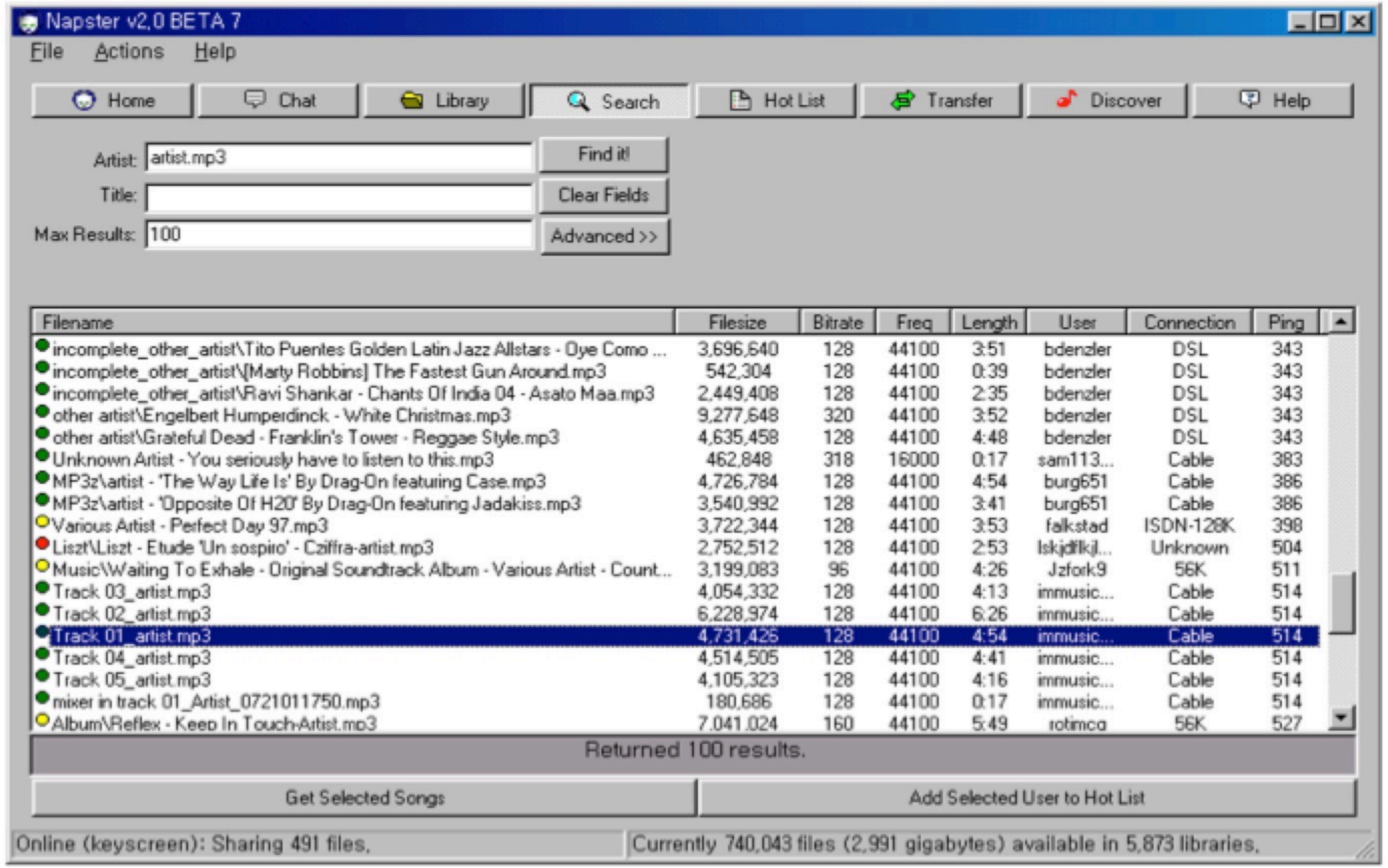
Why Study Peer to Peer Systems?

- First distributed systems that seriously focused on scalability with respect to number of nodes

- P2P techniques abound in cloud computing systems

  - Key-value stores (e.g., Cassandra, Riak, Voldemort) use Chord p2p hashing

Napster UI



Napster v2.0 BETA 7
File Actions Help
Home Chat Library Search Hot List Transfer Discover Help
Artist: artist.mp3
Title:
Max Results: 100
Find it!
Clear Fields
Advanced >>
Filename Filesize Bitrate Freq Length User Connection Ping
incomplete_other_artist\Tito Puentes Golden Latin Jazz Allstars - Oye Como ... 3,696,640 128 44100 3:51 bdenzler DSL 343
incomplete_other_artist\[Marty Robbins] The Fastest Gun Around.mp3 542,304 128 44100 0:39 bdenzler DSL 343
incomplete_other_artist\Ravi Shankar - Chants Of India 04 - Asato Maa.mp3 2,449,408 128 44100 2:35 bdenzler DSL 343
other artist\Engelbert Humperdinck - White Christmas.mp3 9,277,648 320 44100 3:52 bdenzler DSL 343
other artist\Grateful Dead - Franklin's Tower - Reggae Style.mp3 4,635,458 128 44100 4:48 bdenzler DSL 343
Unknown Artist - You seriously have to listen to this.mp3 462,848 318 16000 0:17 sam113... Cable 383
MP3z\artist - 'The Way Life Is' By Drag-On featuring Case.mp3 4,726,784 128 44100 4:54 burg651 Cable 386
MP3z\artist - 'Opposite Of H20' By Drag-On featuring Jadakiss.mp3 3,540,992 128 44100 3:41 burg651 Cable 386
Various Artist - Perfect Day 97.mp3 3,722,344 128 44100 3:53 falkstad ISDN-128K 398
Liszt\Liszt - Etude 'Un sospiro' - Cziffra-artist.mp3 2,752,512 128 44100 2:53 lskjdflkjl... Unknown 504
Music\Waiting To Exhale - Original Soundtrack Album - Various Artist - Count... 3,199,083 96 44100 4:26 Jzfork9 56K 511
Track 03_artist.mp3 4,054,332 128 44100 4:13 immusic... Cable 514
Track 02_artist.mp3 6,228,974 128 44100 6:26 immusic... Cable 514
Track 01_artist.mp3 4,731,426 128 44100 4:54 immusic... Cable 514
Track 04_artist.mp3 4,514,505 128 44100 4:41 immusic... Cable 514
Track 05_artist.mp3 4,105,323 128 44100 4:16 immusic... Cable 514
mixer in track 01_Artist_0721011750.mp3 180,686 128 44100 0:17 immusic... Cable 514
Album\Reflex - Keep In Touch-Artist.mp3 7,041,024 160 44100 5:49 rotimcg 56K 527
Returned 100 results.
Get Selected Songs
Add Selected User to Hot List
Online (keyscreen): Sharing 491 files.
Currently 740,043 files (2,991 gigabytes) available in 5,873 libraries.

A Brief History

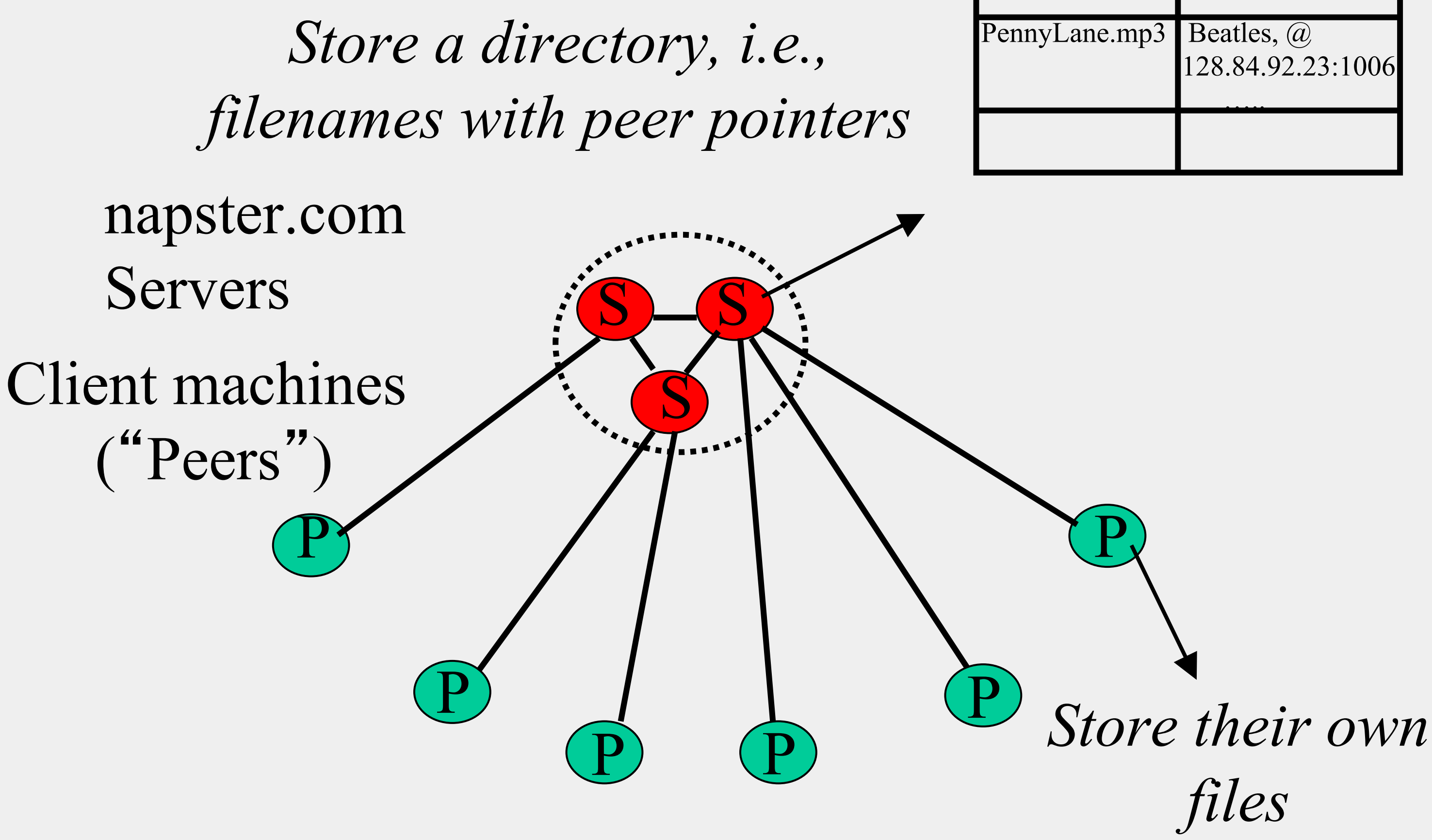
- [6/99] Shawn Fanning (freshman Northeastern U.) releases Napster online music service
- [12/99] RIAA sues Napster, asking $100K per download
- [3/00] 25% UWisc traffic Napster, many universities ban it
- [00] 60M users
- [2/01] US Federal Appeals Court: users violating copyright laws, Napster is abetting this
- [9/01] Napster decides to run paid service, pay % to songwriters and music companies
- [Today] Napster protocol is open, people free to develop opennap clients and servers http://opennap.sourceforge.net
  - Gnutella: http://www.limewire.com (deprecated)
  - Peer to peer working groups: http://p2p.internet2.edu

What We Will Study

- Widely-deployed P2P Systems (This Lecture)
  1. Napster
  2. Gnutella
  3. Fasttrack (Kazaa, Kazaalite, Grokster)
  4. BitTorrent
- P2P Systems with Provable Properties (Next Lecture)
  1. Chord
  2. Pastry
  3. Kelips

Napster Structure

Filename	Info about
PennyLane.mp3	Beatles, @ 128.84.92.23:1006 …..



Napster Operations

Client

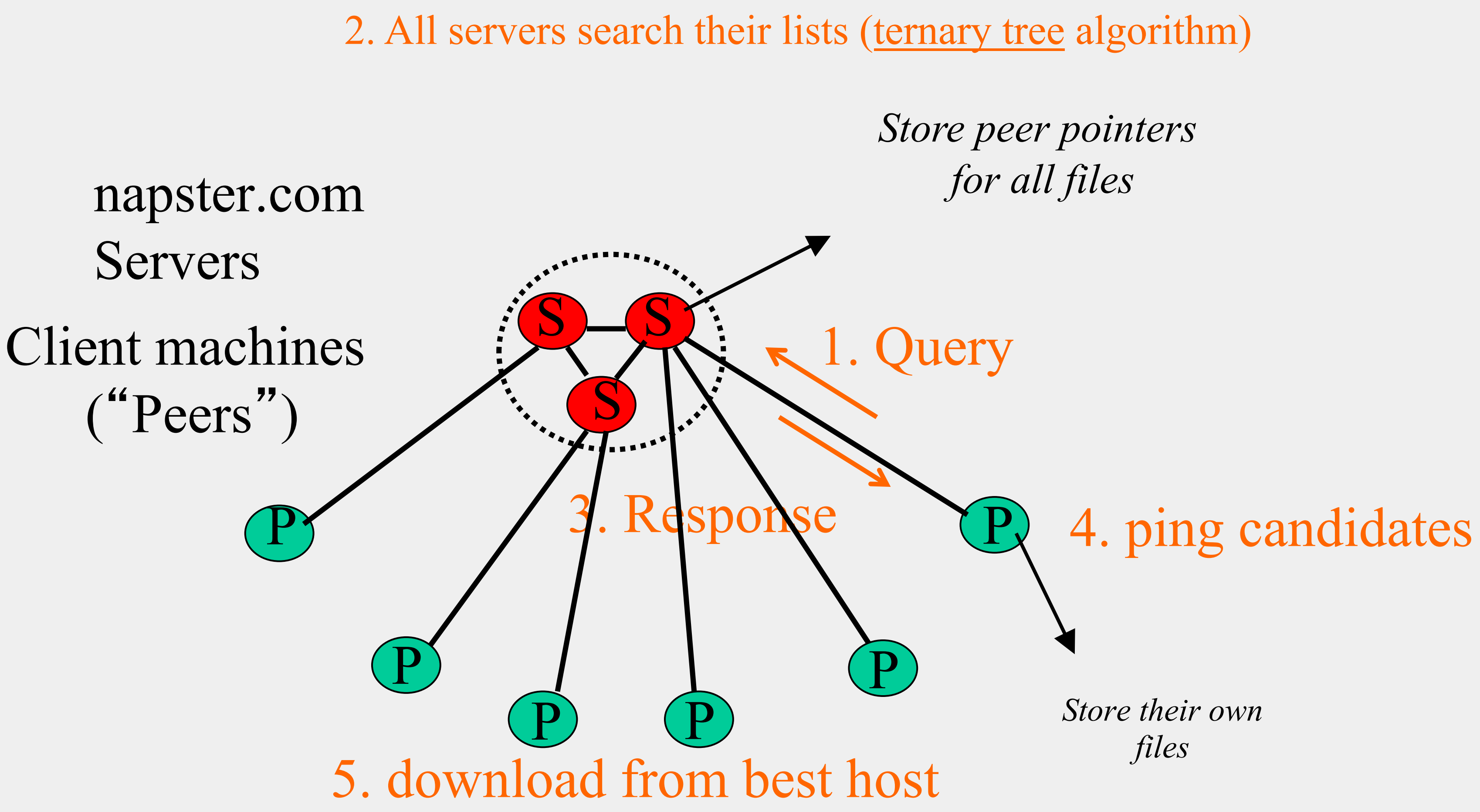
- Connect to a Napster server
  - Upload list of music files that you want to share
  - Server maintains list of <filename, ip_address, portnum> tuples. **Server stores no files.**

Napster Operations

Client (contd.)

- Search
  - Send server keywords to search with
  - (Server searches its list with the keywords)
  - Server returns a list of hosts - <ip_address, portnum> tuples - to client
  - Client pings each host in the list to find transfer rates
  - Client fetches file from best host
- All communication uses TCP (Transmission Control Protocol)
  - Reliable and ordered networking protocol

Napster Search



Joining a P2P system

- Can be used for any p2p system
  - Send an http request to well-known url for that P2P service - `http://www.myp2pservice.com`
  - Message routed (after lookup in DNS=Domain Name system) to introducer, a well known server that keeps track of some recently joined nodes in p2p system
  - Introducer initializes new peers' neighbor table

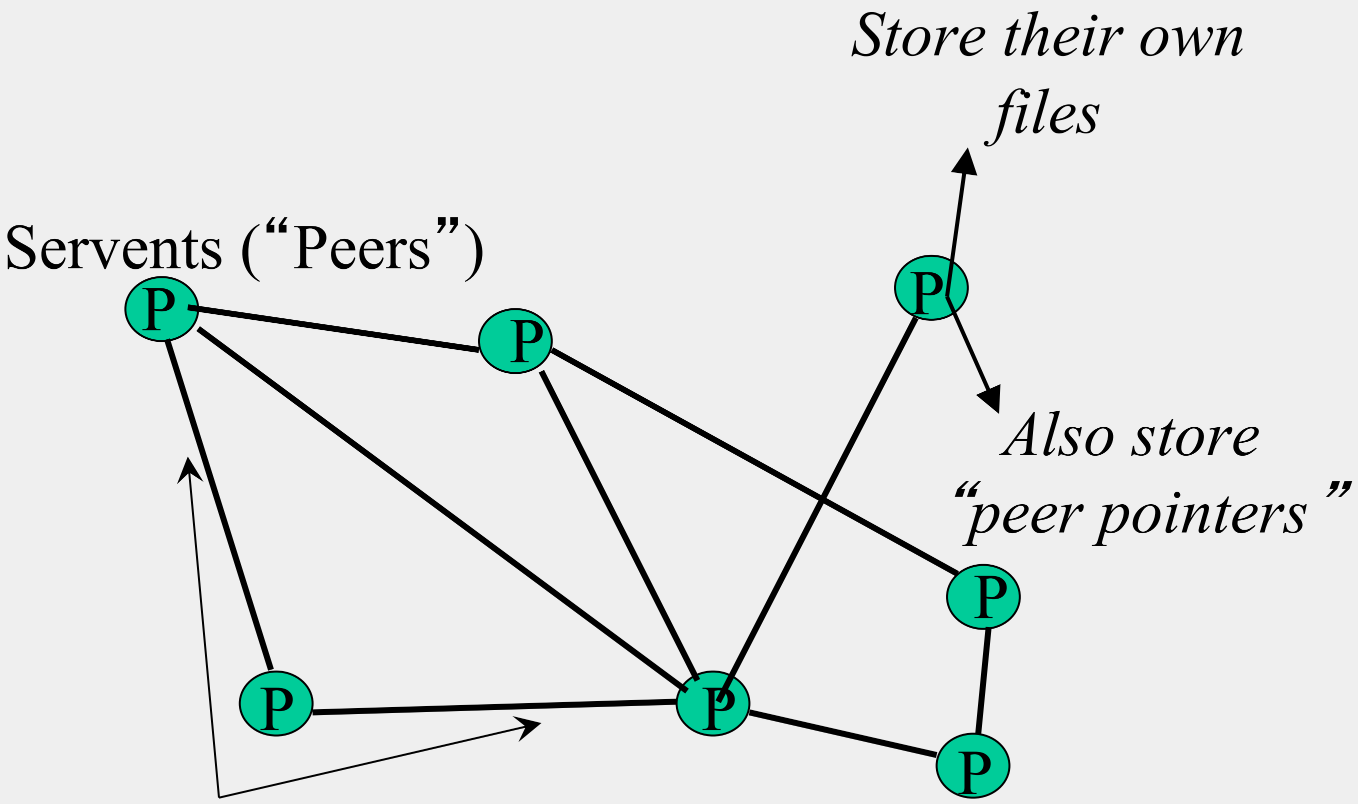
Problems

- Centralized server a source of congestion
- Centralized server single point of failure
- No security: plaintext messages and passwds
- napster.com declared to be responsible for users' copyright violation
  - "Indirect infringement"
  - Next system: Gnutella

Gnutella

- Eliminate the servers
- Client machines search and retrieve amongst themselves
- Clients act as servers too, called **servents**
- [3/00] release by AOL, immediately withdrawn, but 88K users by 3/03
- Original design underwent several modifications

Gnutella



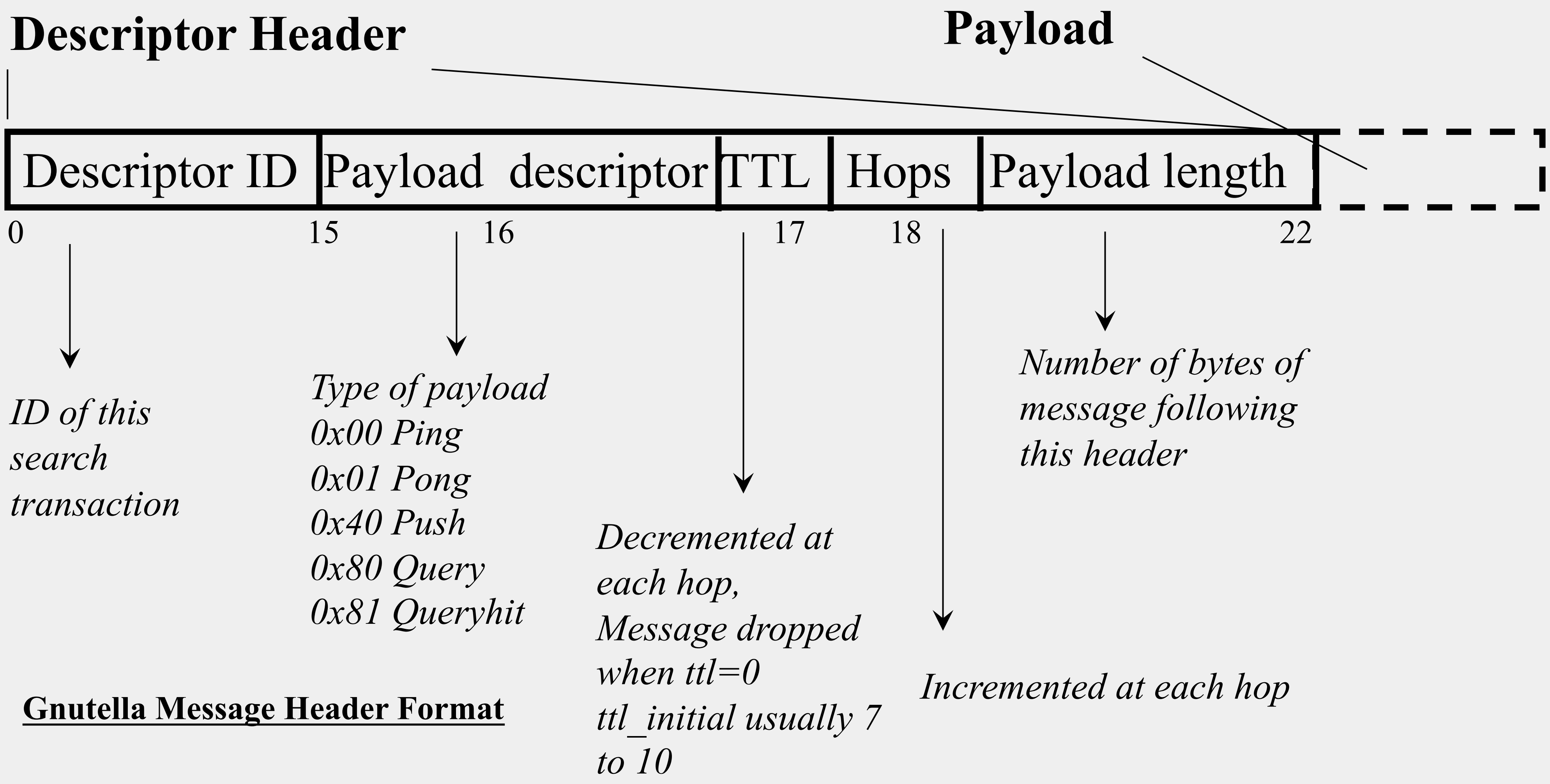
Connected in an **overlay** graph

(== each link is an implicit Internet path)

How do I search for my Beatles file?

- Gnutella *routes* different messages within the overlay graph
- Gnutella protocol has 5 main message types
  - Query (search)
  - QueryHit (response to query)
  - Ping (to probe network for other peers)
  - Pong (reply to ping, contains address of another peer)
  - Push (used to initiate file transfer)
- We' ll go into the message structure and protocol now
  - All fields except IP address are in little-endian format
  - Ox12345678 stored as 0x78 in lowest address byte, then 0x56 in next higher address, and so on.

How do I search for my Beatles file?



Gnutella Message Header Format

How do I search for my Beatles file?

Query (0x80)

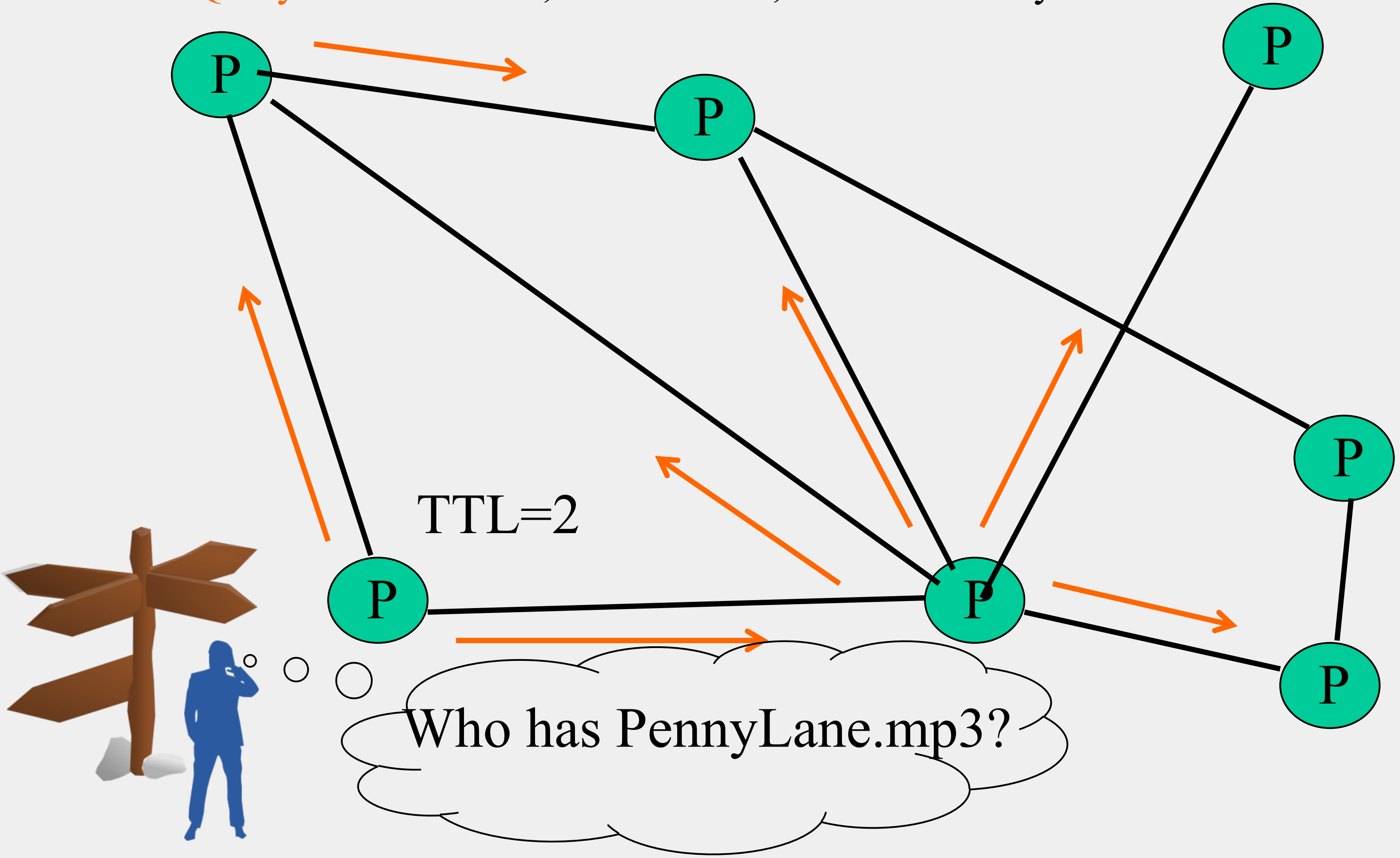
Minimum Speed	Search criteria (keywords)

0 1 …..

Payload Format in Gnutella Query Message

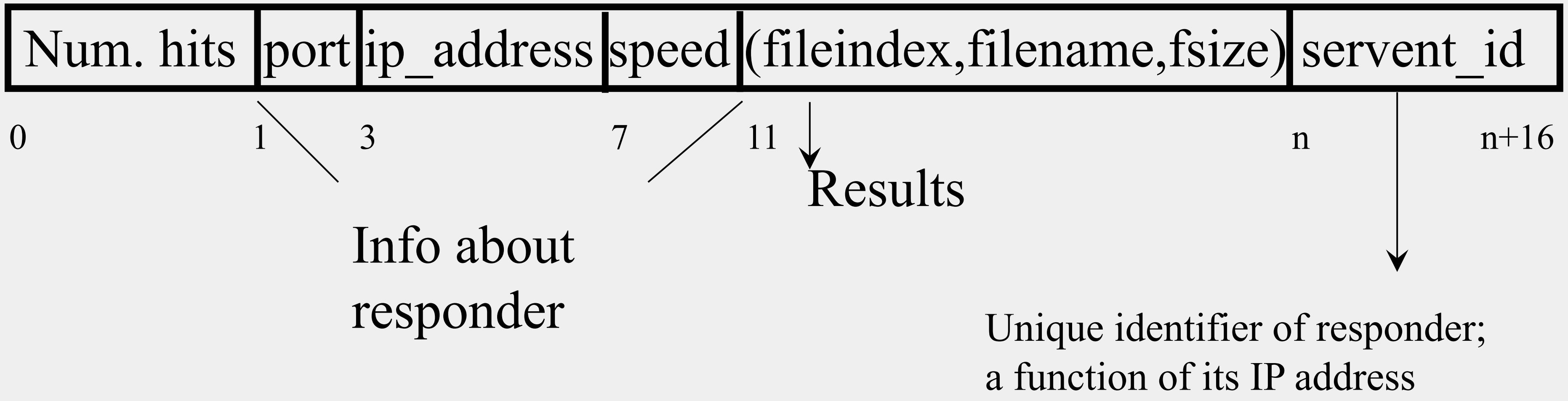
Gnutella Search

Query’s flooded out, ttl-restricted, forwarded only once



Gnutella Search

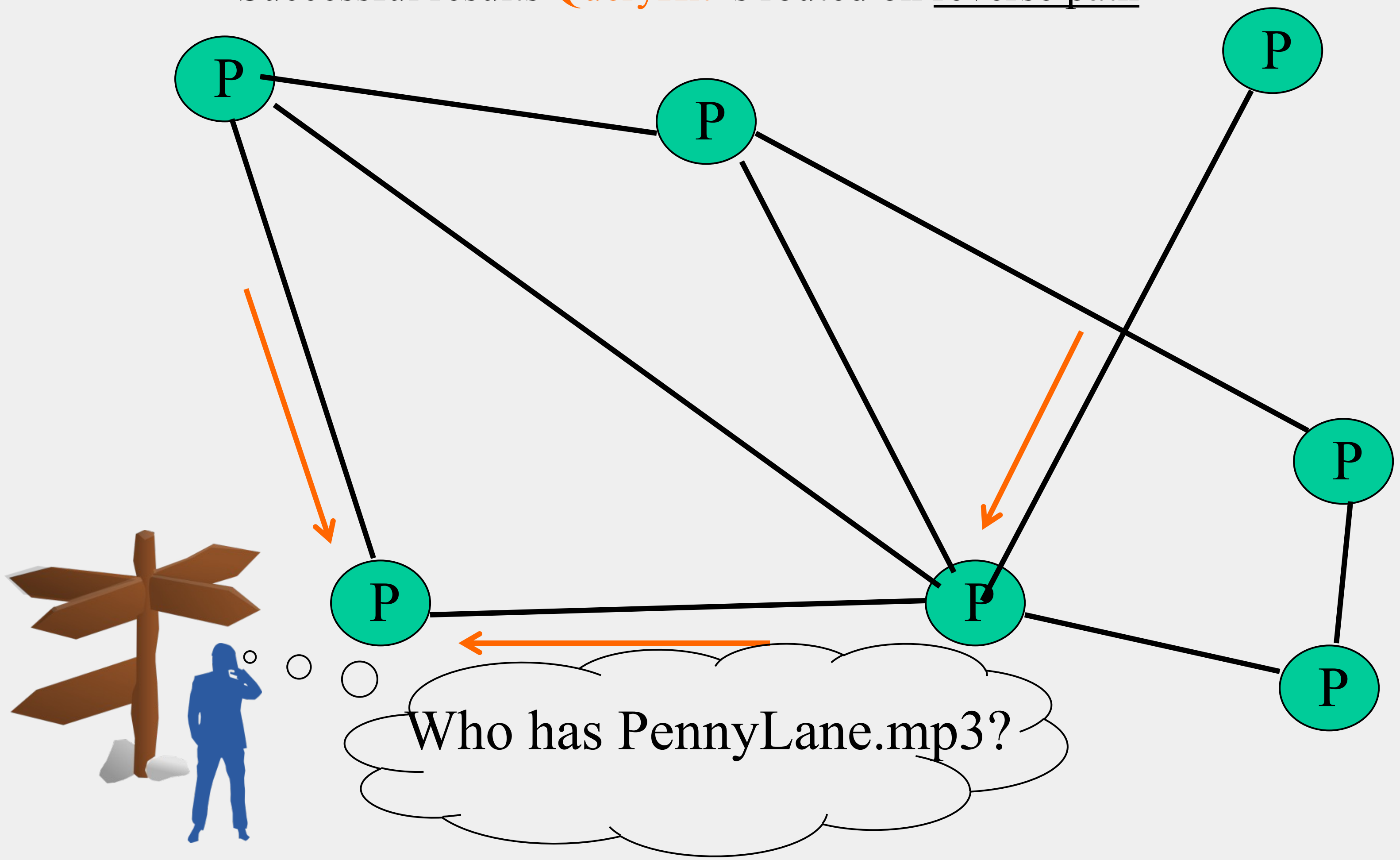
QueryHit (0x81) : successful result to a query



Payload Format in Gnutella QueryHit Message

Gnutella Search

Successful results QueryHit's routed on reverse path



Avoiding excessive traffic

- To avoid duplicate transmissions, each peer maintains a list of recently received messages
- Query forwarded to all neighbors except peer from which received
- Each Query (identified by DescriptorID) forwarded only once
- QueryHit routed back only to peer from which Query received with same DescriptorID
- Duplicates with same DescriptorID and Payload descriptor (msg type, e.g., Query) are dropped
- QueryHit with DescriptorID for which Query not seen is dropped

After receiving QueryHit messages

- Requestor chooses “best” QueryHit responder
  - Initiates HTTP request directly to responder’ s ip+port

GET /get/<File Index>/<File Name>/HTTP/1.0\r\n

Connection: Keep-Alive\r\n

Range: bytes=0-\r\n

User-Agent: Gnutella\r\n

\r\n

- Responder then replies with file packets after this message:

HTTP 200 OK\r\n

Server: Gnutella\r\n

Content-type:application/binary\r\n

Content-length: 1024 \r\n

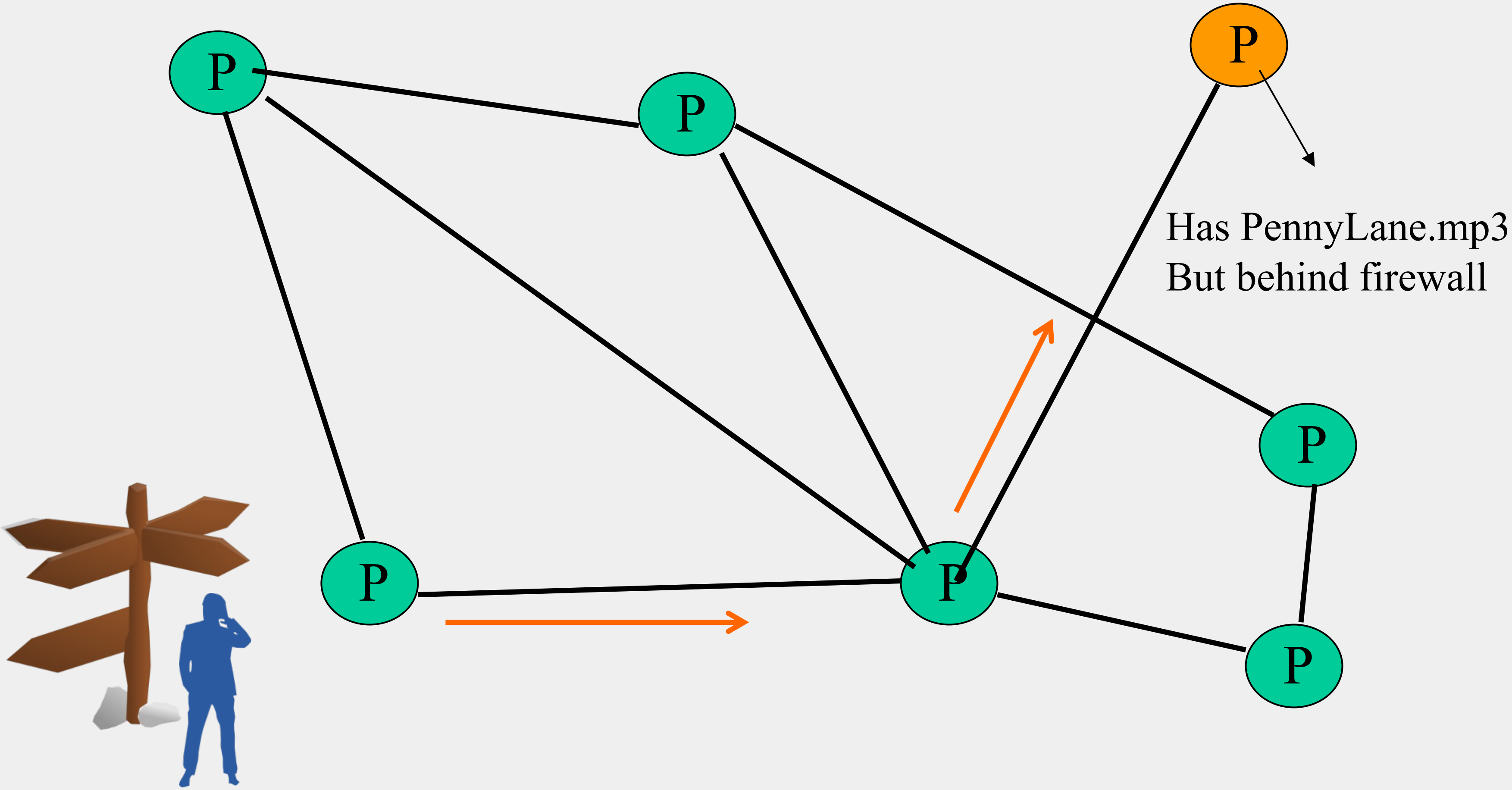
\r\n

After receiving QueryHit messages (2)

- HTTP is the file transfer protocol. Why?
  - Because it’s standard, well-debugged, and widely used.
- Why the “range” field in the GET request?
  - To support partial file transfers.
- What if responder is behind firewall that disallows incoming connections?

Dealing with Firewalls

Requestor sends Push to responder asking for file transfer



Dealing with Firewalls

Push (0x40)

servent_id	fileindex	ip_address	port

same as in received QueryHit

Address at which requestor can accept incoming connections

Dealing with Firewalls

- Responder establishes a TCP connection at ip_address, port specified. Sends

    GIV <File Index>:<Servent Identifier>/<File Name>\n\n

- Requestor then sends GET to responder (as before) and file is transferred as explained earlier

- What if requestor is behind firewall too?
    - Gnutella gives up
    - Can you think of an alternative solution?

Ping-Pong

Ping (0x00)

no payload

Pong (0x01)

Port	ip_address	Num. files shared	Num. KB shared

- Peers initiate Ping's periodically
- Pings flooded out like Querys, Pongs routed along reverse path like QueryHits
- Pong replies used to update set of neighboring peers
  - to keep neighbor lists fresh in spite of peers joining, leaving and failing

Gnutella Summary

- No servers
- Peers/servents maintain "neighbors", this forms an overlay graph
- Peers store their own files
- Queries flooded out, ttl restricted
- QueryHit (replies) reverse path routed
- Supports file transfer through firewalls
- Periodic Ping-pong to continuously refresh neighbor lists
  - List size specified by user at peer : heterogeneity means some peers may have more neighbors
  - Gnutella found to follow **power law** distribution:

$$P(\#links = L) \sim L^{-k} \qquad (k \text{ is a constant})$$

Problems

- Ping/Pong constituted 50% traffic
  - Solution: Multiplex, *cache* and reduce frequency of pings/pongs
- Repeated searches with same keywords
  - Solution: *Cache* Query, QueryHit messages
- Modem-connected hosts do not have enough bandwidth for passing Gnutella traffic
  - Solution: use a central server to act as proxy for such peers
  - Another solution:

    ➔FastTrack System (soon)

Problems (contd.)

- Large number of *freeloaders*
  - 70% of users in 2000 were freeloaders
  - Only download files, never upload own files
- Flooding causes excessive traffic
  - Is there some way of maintaining meta-information about peers that leads to more intelligent routing?

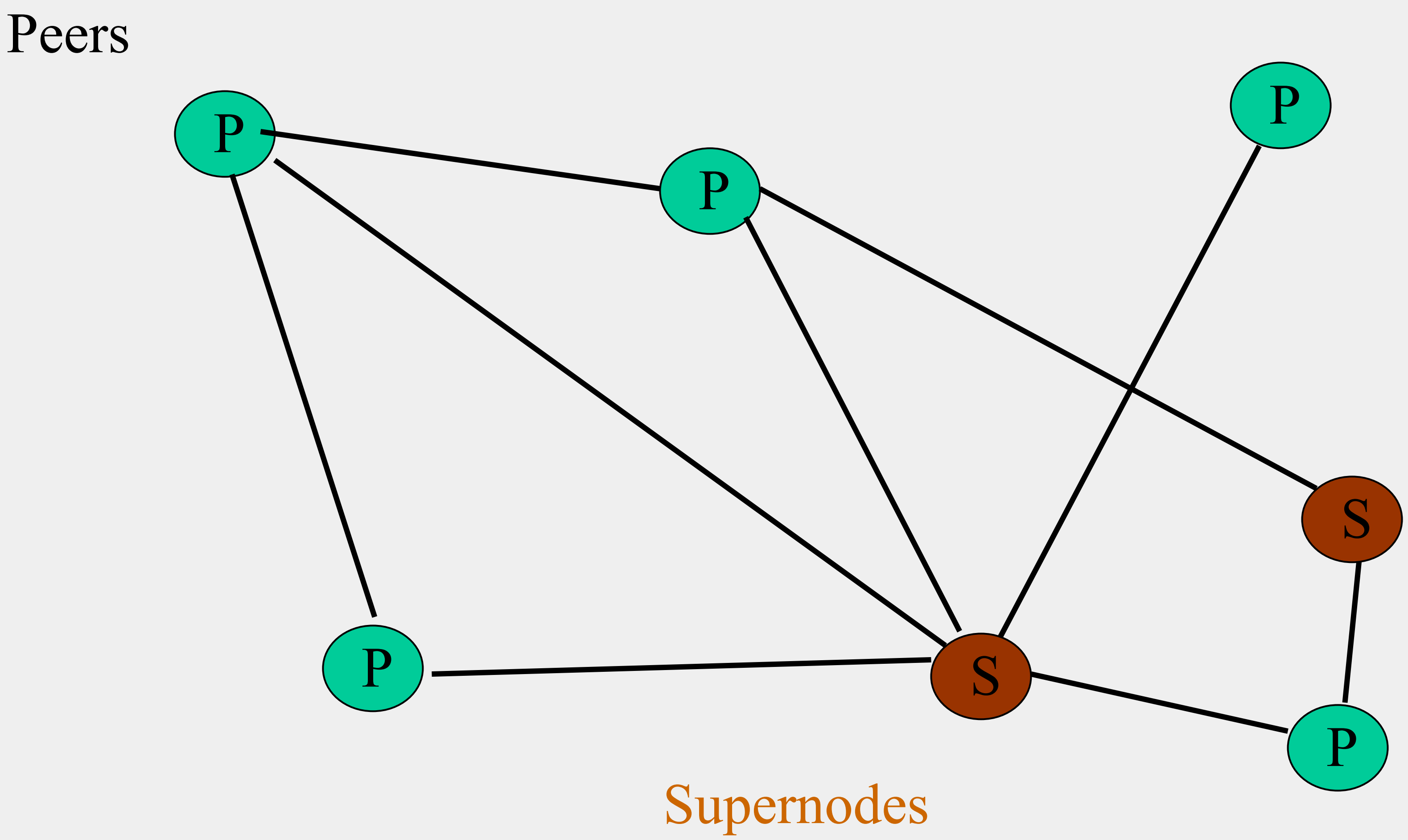
    ➔ Structured Peer-to-peer systems

    e.g., Chord System (coming up next lecture)

FastTrack

- Hybrid between Gnutella and Napster
- Takes advantage of “healthier” participants in the system
- Underlying technology in Kazaa, KazaaLite, Grokster
- Proprietary protocol, but some details available
- Like Gnutella, but with some peers designated as *supernodes*

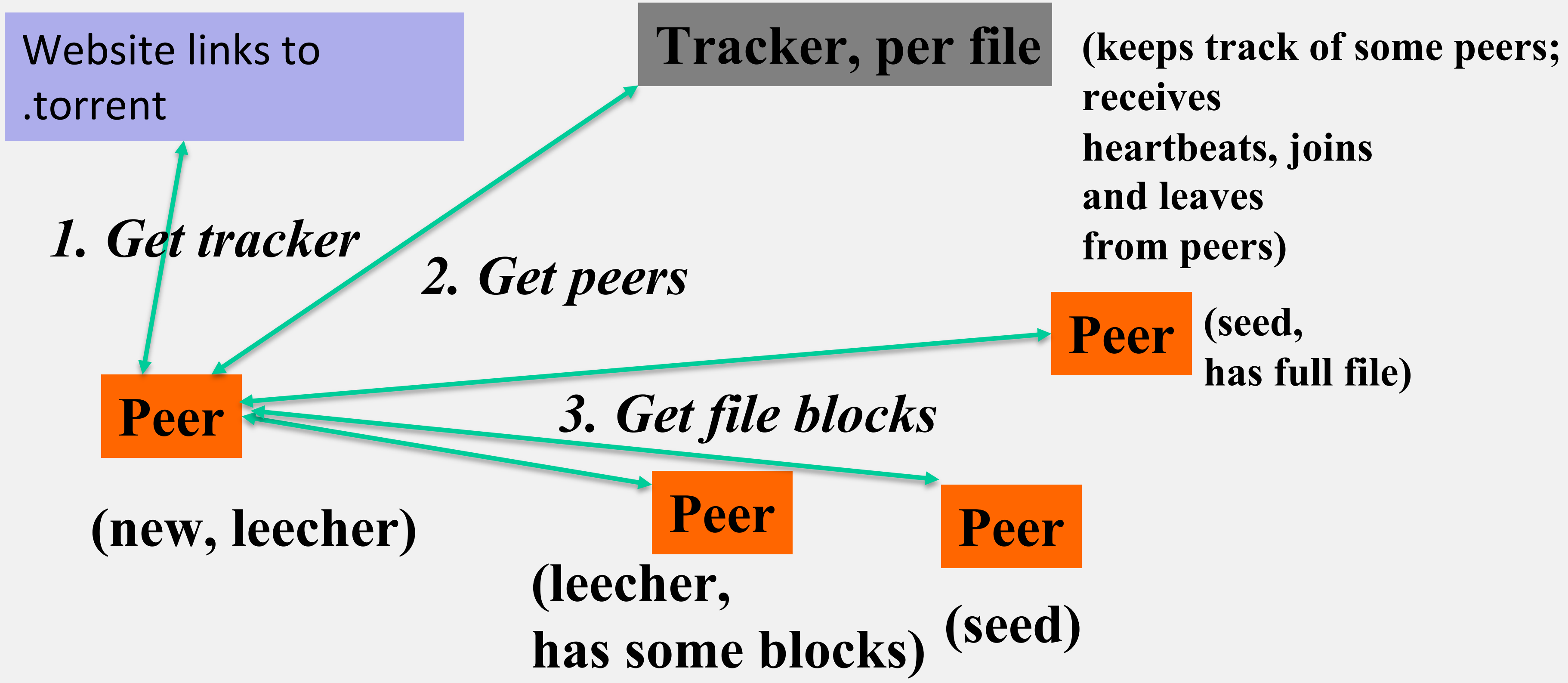
A FastTrack-like System



FastTrack (contd.)

- A supernode stores a directory listing a subset of nearby (<filename,peer pointer>), similar to Napster servers
- Supernode membership changes over time
- Any peer can become (and stay) a supernode, provided it has earned enough *reputation*
    - Kazaalite: participation level (=reputation) of a user between 0 and 1000, initially 10, then affected by length of periods of connectivity and total number of uploads
    - More sophisticated Reputation schemes invented, especially based on economics (See P2PEcon workshop)
- A peer searches by contacting a nearby supernode

BitTorrent


Website links to .torrent
Tracker, per file
(keeps track of some peers; receives heartbeats, joins and leaves from peers)
1. Get tracker
2. Get peers
Peer
(seed, has full file)
3. Get file blocks
Peer
(new, leecher)
Peer
(leecher, has some blocks)
Peer
(seed)

BitTorrent (2)

- File split into blocks (32 KB – 256 KB)
- Download Local Rarest First block policy: prefer early download of blocks that are least replicated among neighbors
  - Exception: New node allowed to pick one random neighbor: helps in bootstrapping
- Tit for tat bandwidth usage: Provide blocks to neighbors that provided it the best download rates
  - Incentive for nodes to provide good upload rates
  - Seeds do the same too
- Choking: Limit number of neighbors to which concurrent uploads <= a number (5), i.e., the “best” neighbors
  - Everyone else choked
  - Periodically re-evaluate this set (e.g., every 10 s)
  - Optimistic unchoke: periodically (e.g., ~30 s), unchoke a random neighbor – helps keep unchoked set fresh

Announcements

- MP1 reports being graded
- MP2 out already, due 9/25 (demos on 9/26)
- HW1 due next Wednesday 2 pm (9/21)
- HW2 will be out then

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Distributed Systems
Fall 2022

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Lecture 8: Peer-to-peer Systems II

What We Are Studying

- Widely-deployed P2P Systems
  1. Napster
  2. Gnutella
  3. Fasttrack (Kazaa, Kazaalite, Grokster)
  4. BitTorrent
- P2P Systems with Provable Properties
  1. Chord
  2. Pastry
  3. Kelips

DHT=Distributed Hash Table

- A hash table allows you to insert, lookup and delete objects with keys
- A *distributed* hash table allows you to do the same in a distributed setting (objects=files)
- Performance Concerns:
  - Load balancing
  - Fault-tolerance
  - Efficiency of lookups and inserts
  - Locality
- Napster, Gnutella, FastTrack are all DHTs (sort of)
- So is Chord, a structured peer to peer system that we study next

Comparative Performance

	Memory	Lookup Latency	#Messages for a lookup	
Napster	$O(1)$ ($O(N)$@server)	$O(1)$	$O(1)$	
Gnutella	$O(N)$	$O(N)$	$O(N)$	

Comparative Performance

	Memory	Lookup Latency	#Messages for a lookup
Napster	*O(1)* (*O(N)*@server)	*O(1)*	*O(1)*
Gnutella	*O(N)*	*O(N)*	*O(N)*
Chord	*O(log(N))*	*O(log(N))*	*O(log(N))*

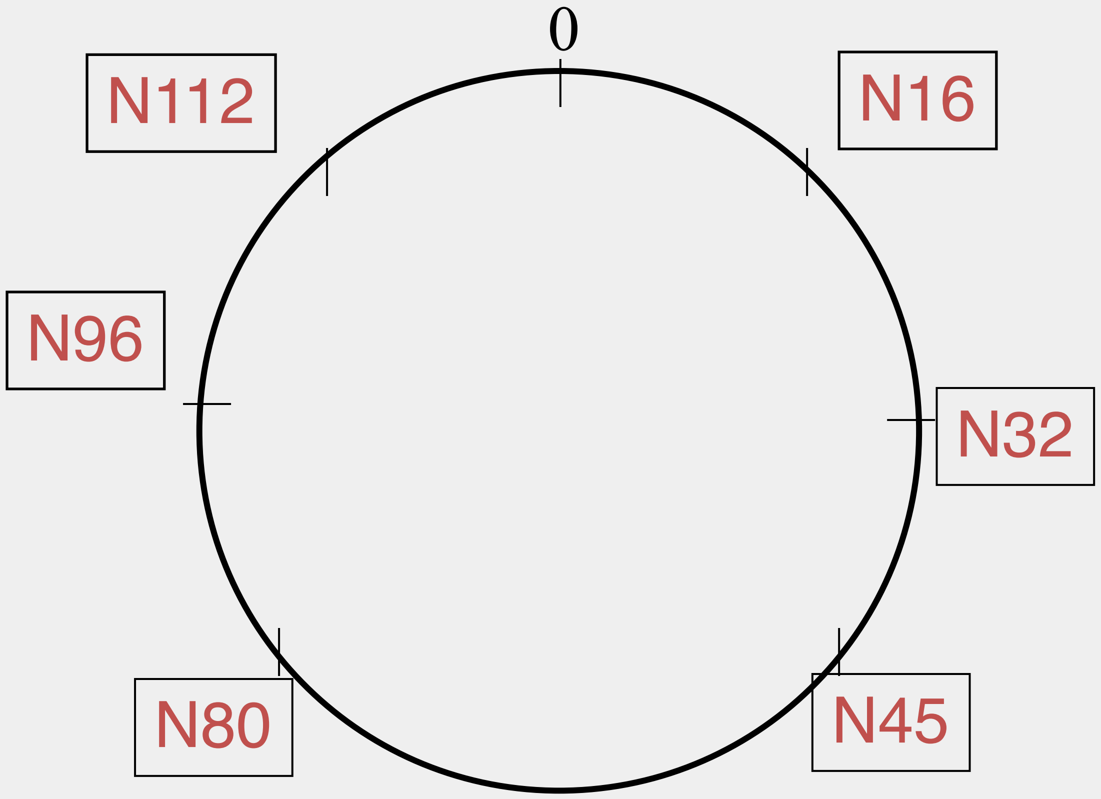
Chord

- Developers: I. Stoica, D. Karger, F. Kaashoek, H. Balakrishnan, R. Morris, Berkeley and MIT
- Intelligent choice of neighbors to reduce latency and message cost of routing (lookups/inserts)
- Uses *Consistent Hashing* on node's (peer's) address
  - SHA-1(ip_address,port) →160 bit string
  - Truncated to *m* bits
  - Called peer *id* (number between 0 and $2^m - 1$)
  - Not unique but id conflicts very unlikely
  - Can then map peers to one of 2^m logical points on a circle

Ring of peers

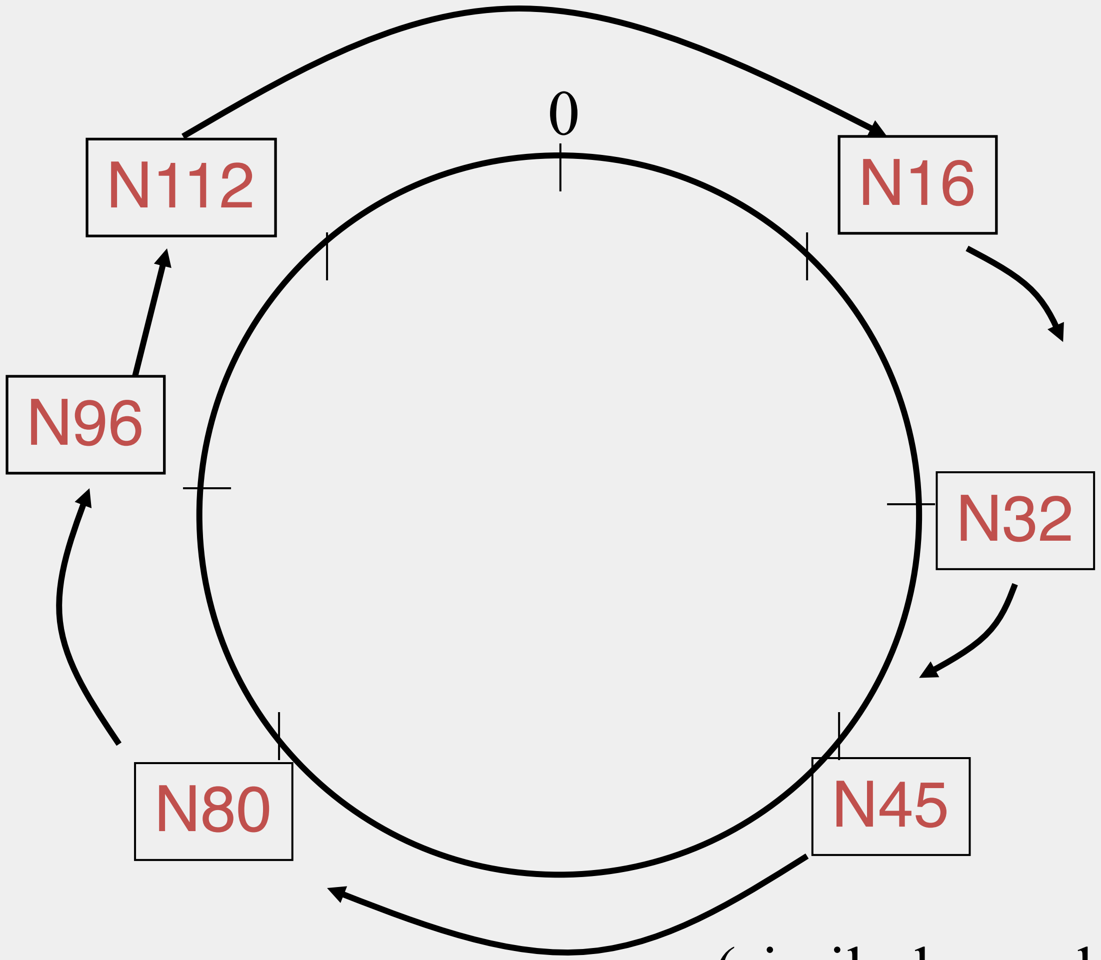
Say m=7

6 nodes



Peer pointers (1): successors

Say m=7



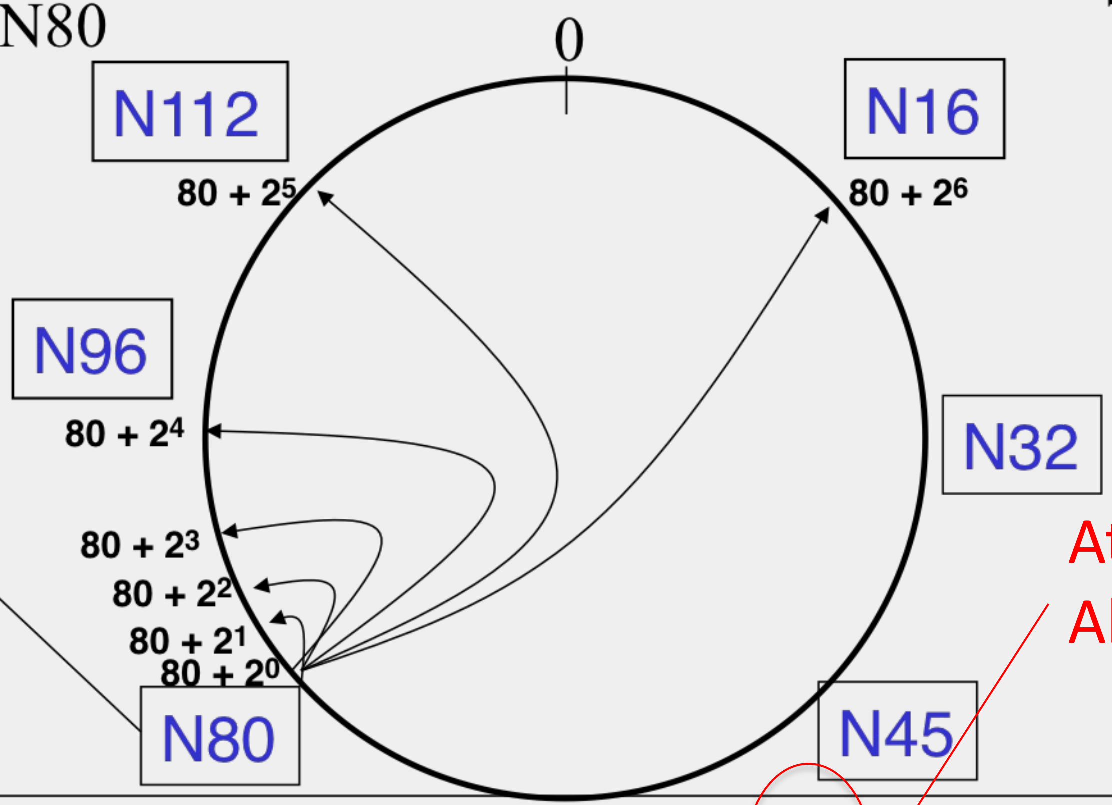
(similarly predecessors)

Peer pointers (2): finger tables

Say m=7

Finger Table at N80

i	$ft[i]$
0	96
1	96
2	96
3	96
4	96
5	112
6	16



At or to the clockwise of

Also, use $(n+2^i) \bmod 2^m$

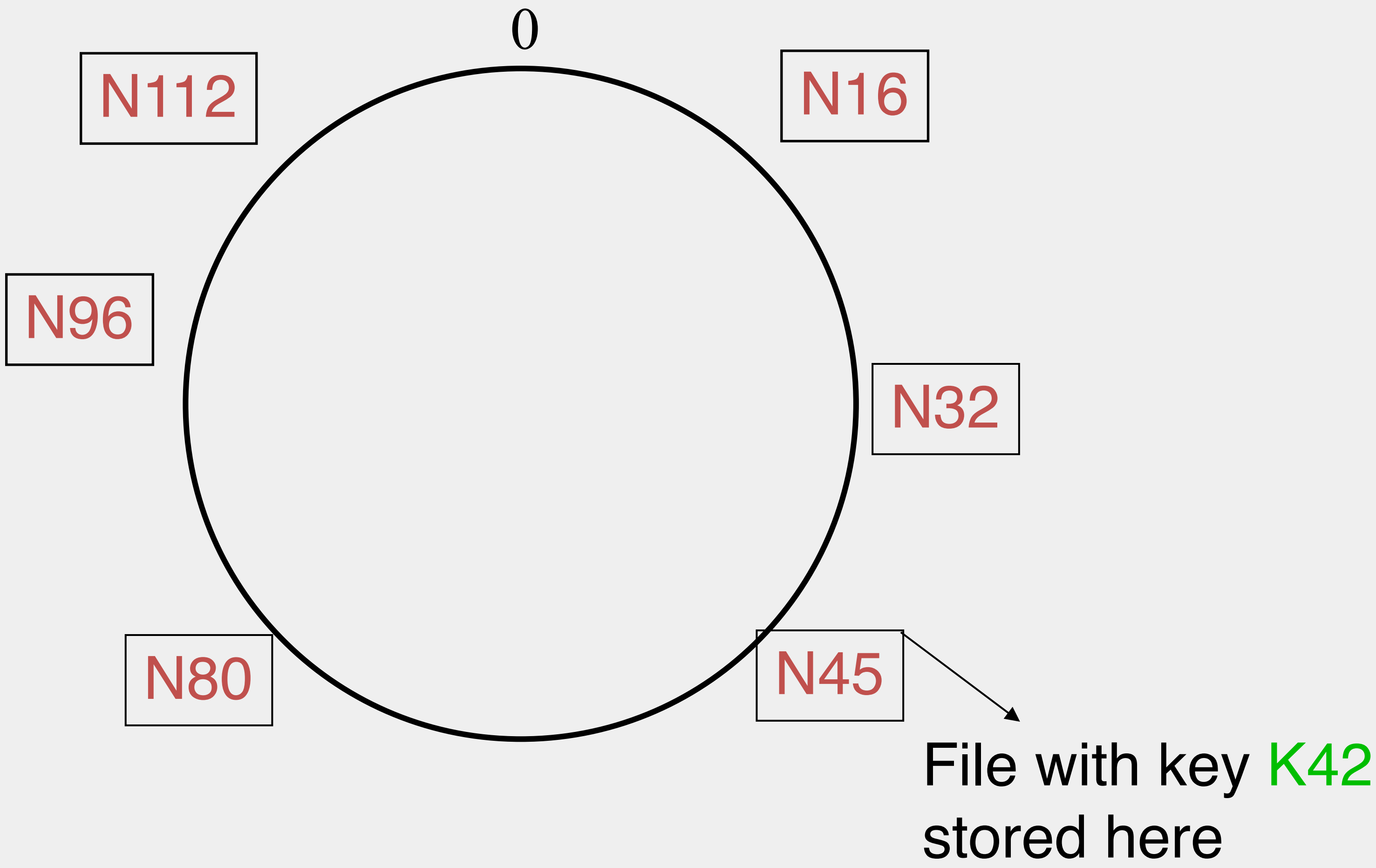
ith entry at peer with id n is first peer with id >= $n + 2^i (\bmod 2^m)$

What about the files?

- Filenames also mapped using same consistent hash function
  - SHA-1(filename) → 160 bit string (*key*)
  - File is stored at first peer with id greater than or equal to its key (mod 2^m)
- File *cnn.com/index.html* that maps to key K42 is stored at first peer with id at or to the clockwise of 42
  - Note that we are considering a different file-sharing application here : *cooperative web caching*
  - The same discussion applies to any other file sharing application, including that of mp3 files.
- Consistent Hashing => with K keys and N peers, each peer stores *O(K/N)* keys. (i.e., < *c.K/N*, for some constant *c*)

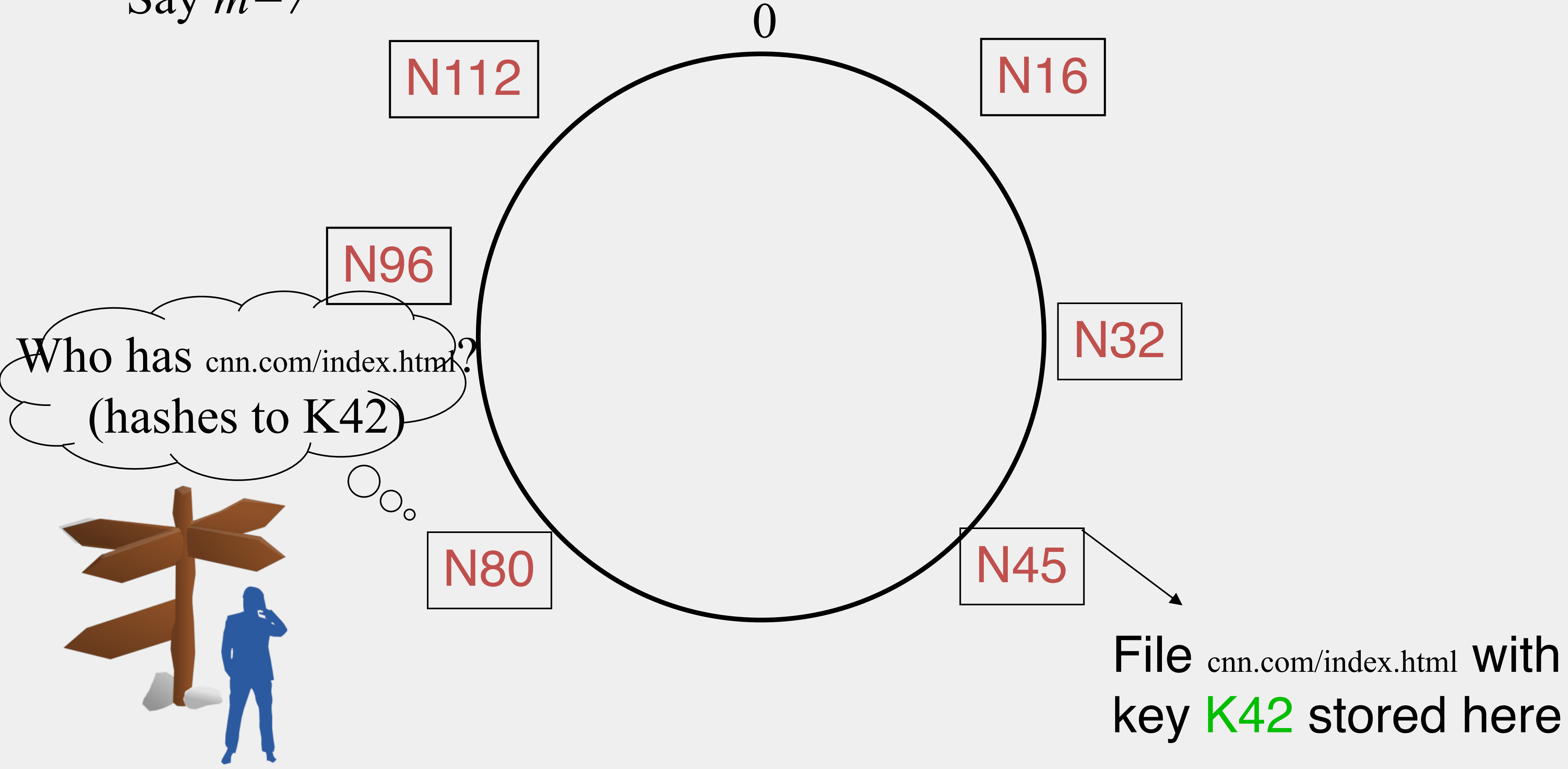
Mapping Files

Say $m=7$



Search

Say $m=7$

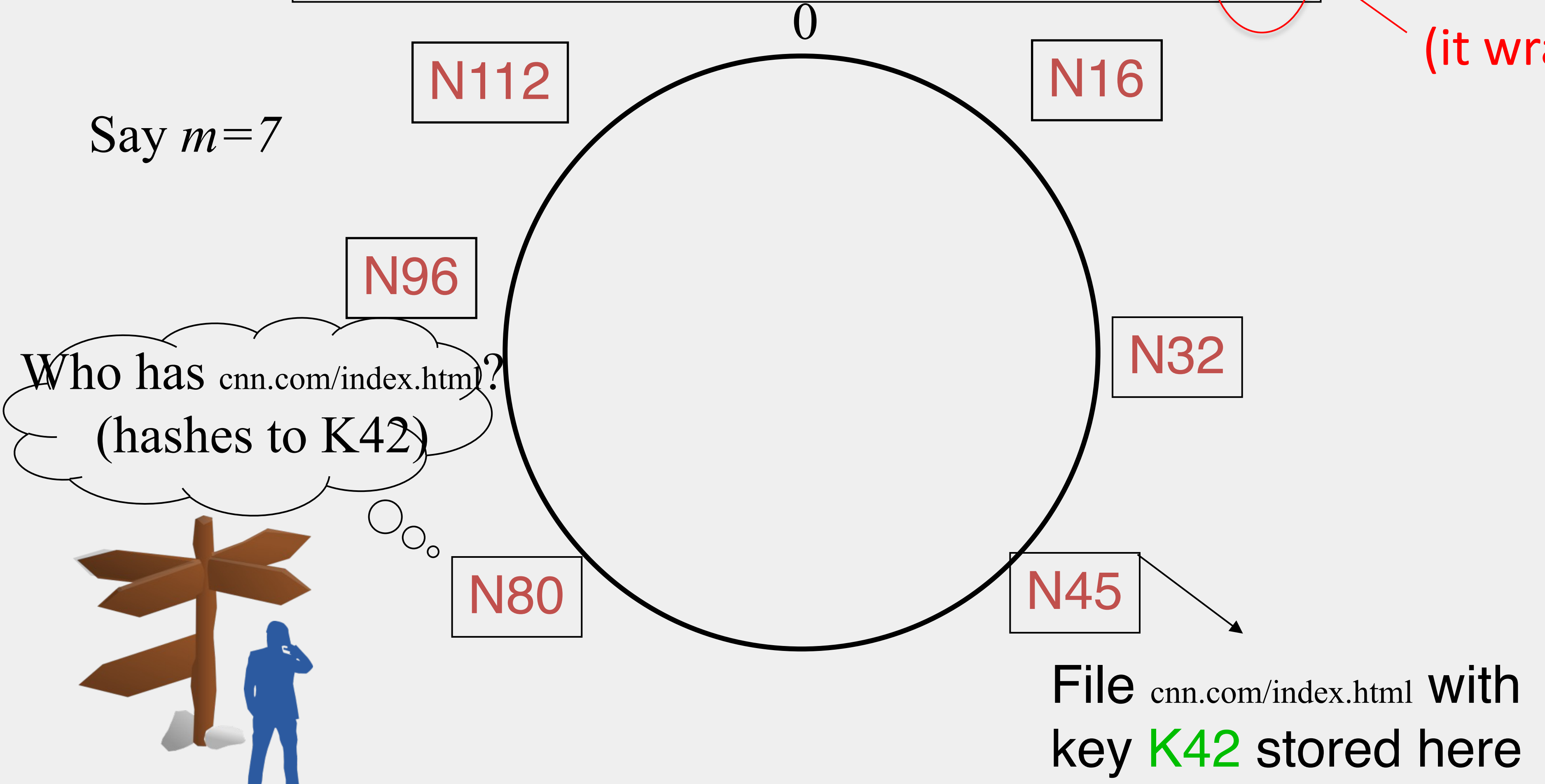


Search

At node n, send query for key k to largest successor/finger entry $<= k$
if none exist, send query to *successor(n)*

At or to the anti-clockwise of *k*
(it wraps around the ring)

Say m=7



Search

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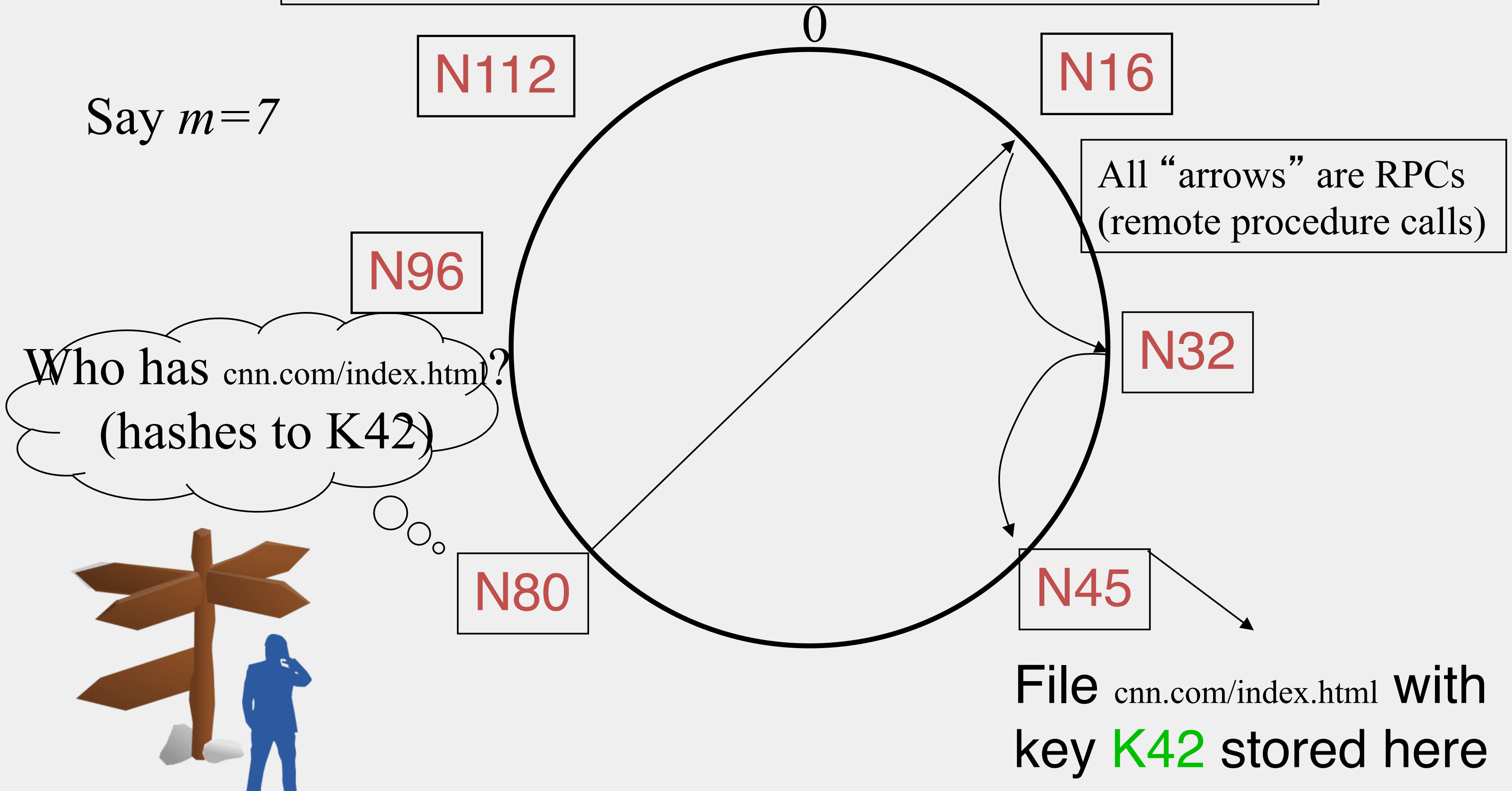
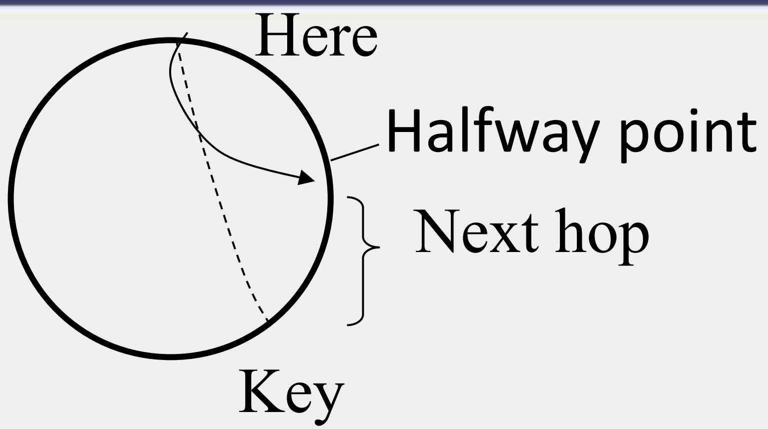
Say m=7



Analysis



Search takes *O(log(N))* time

Proof

- (intuition): *at each step, distance between query and peer-with-file reduces by a factor of at least 2*

- (intuition): after *log(N)* forwardings, distance to key is at most $2^m / 2^{\log(N)} = 2^m / N$
- Number of node identifiers in a range of

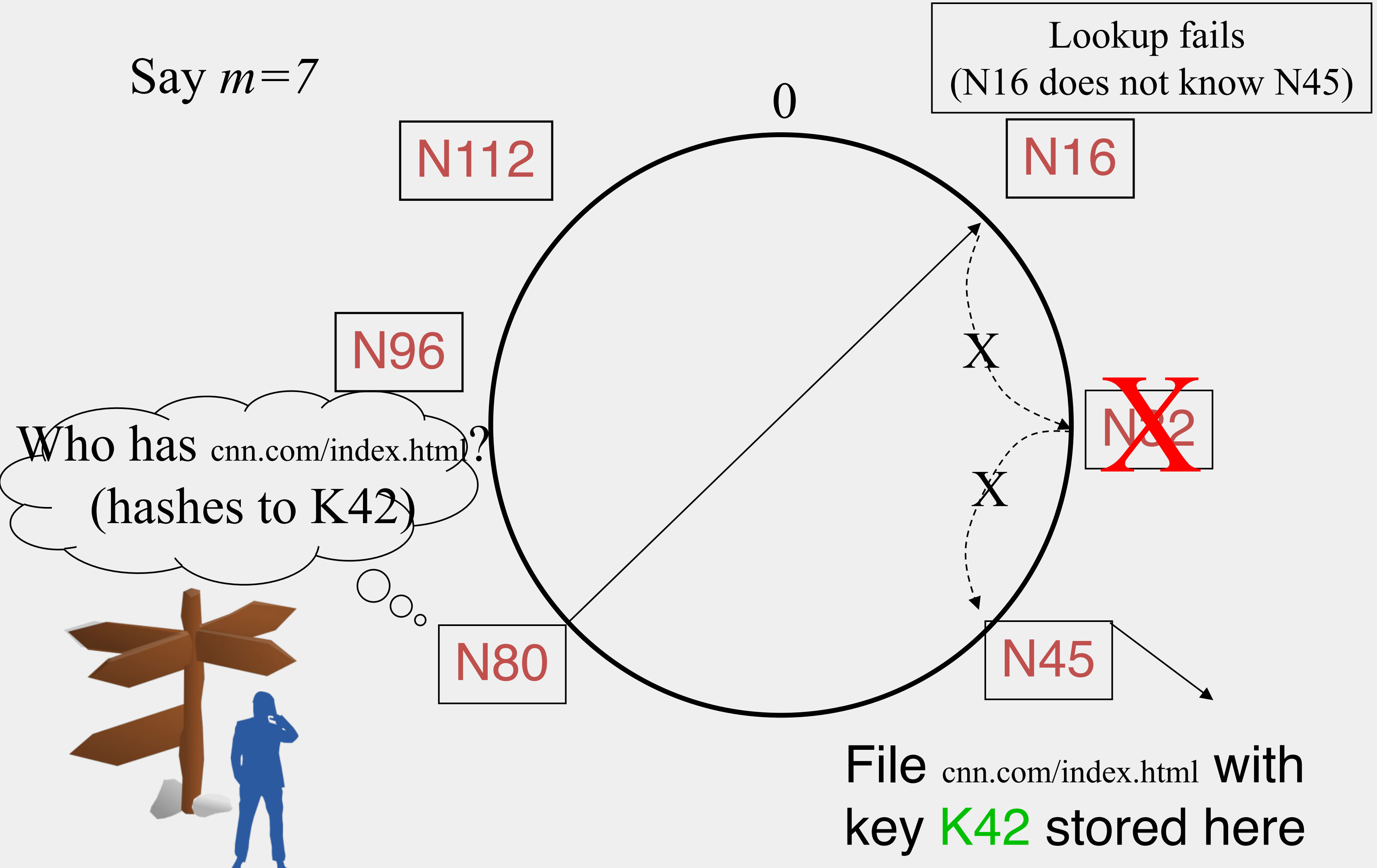
  is *O(log(N))* with high probability (why? SHA-1! and "Balls and Bins")

  So using *successors* in that range will be ok, using another *O(log(N))* hops

Analysis (contd.)

- *O(log(N))* search time holds for file insertions too (in general for *routing to any key*)
  - "Routing" can thus be used as a building block for
    - All operations: insert, lookup, delete
- *O(log(N))* time true only if finger and successor entries correct
- When might these entries be wrong?
  - When you have failures

Search under peer failures

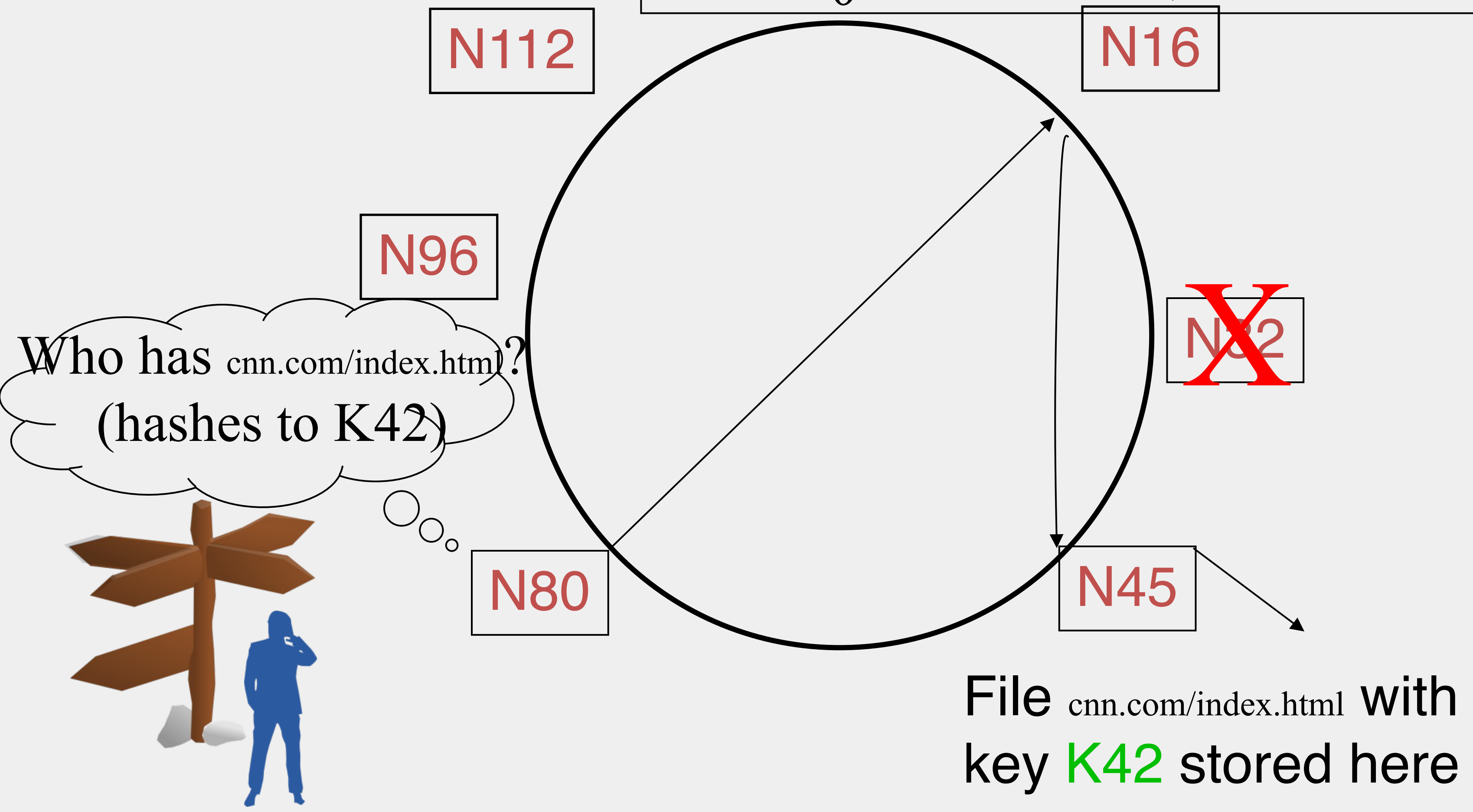


Search under peer failures

Say $m=7$

One solution: maintain r multiple *successor* entries

In case of failure, use successor entries



Search under peer failures

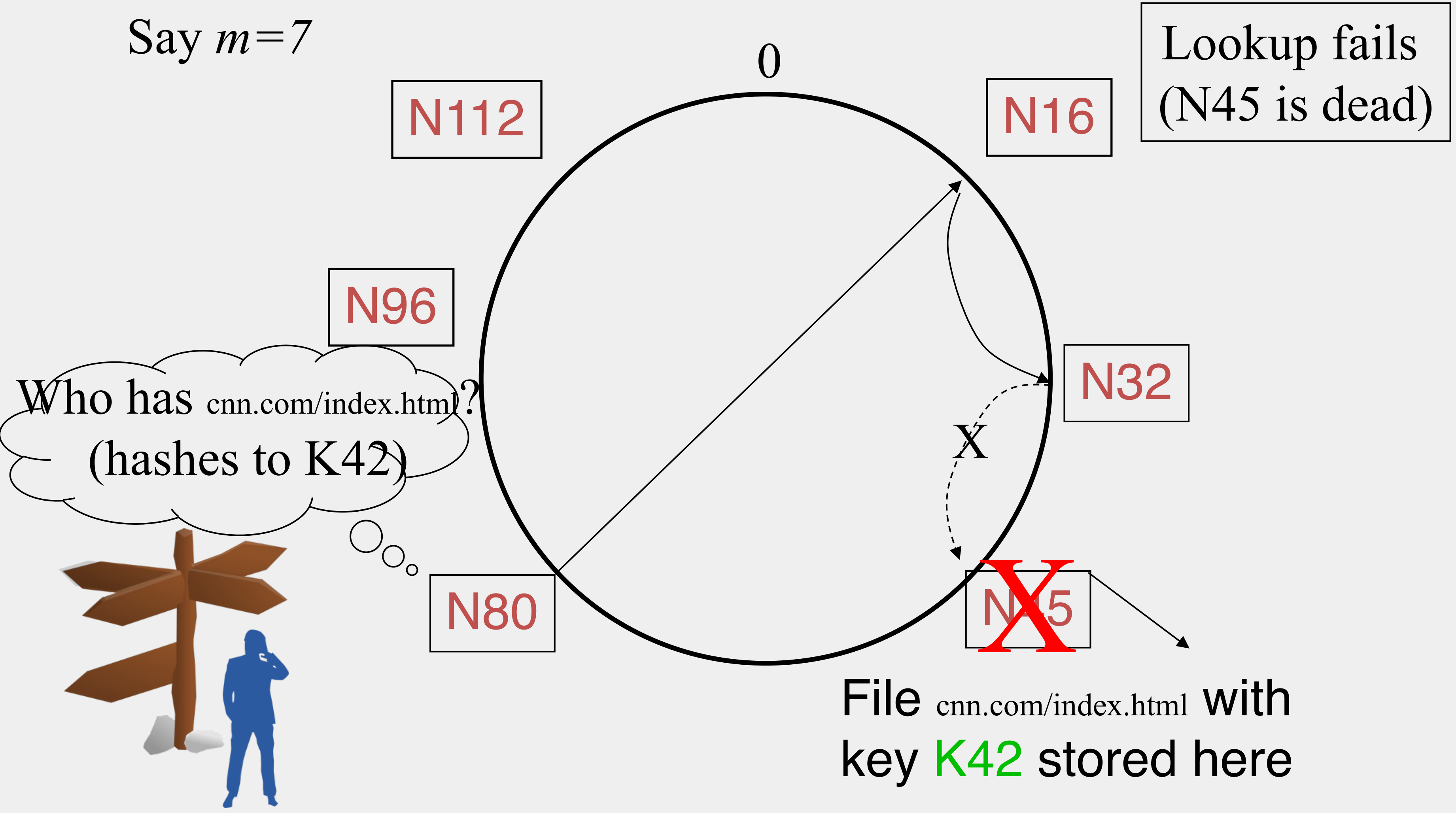
- Choosing *r=2log(N)* suffices to maintain *lookup correctness* w.h.p.(i.e., ring connected)
  - Say 50% of nodes fail
  - Pr(at given node, at least one successor alive)=

$$1-\left(\frac{1}{2}\right)^{2\log N} = 1-\frac{1}{N^2}$$

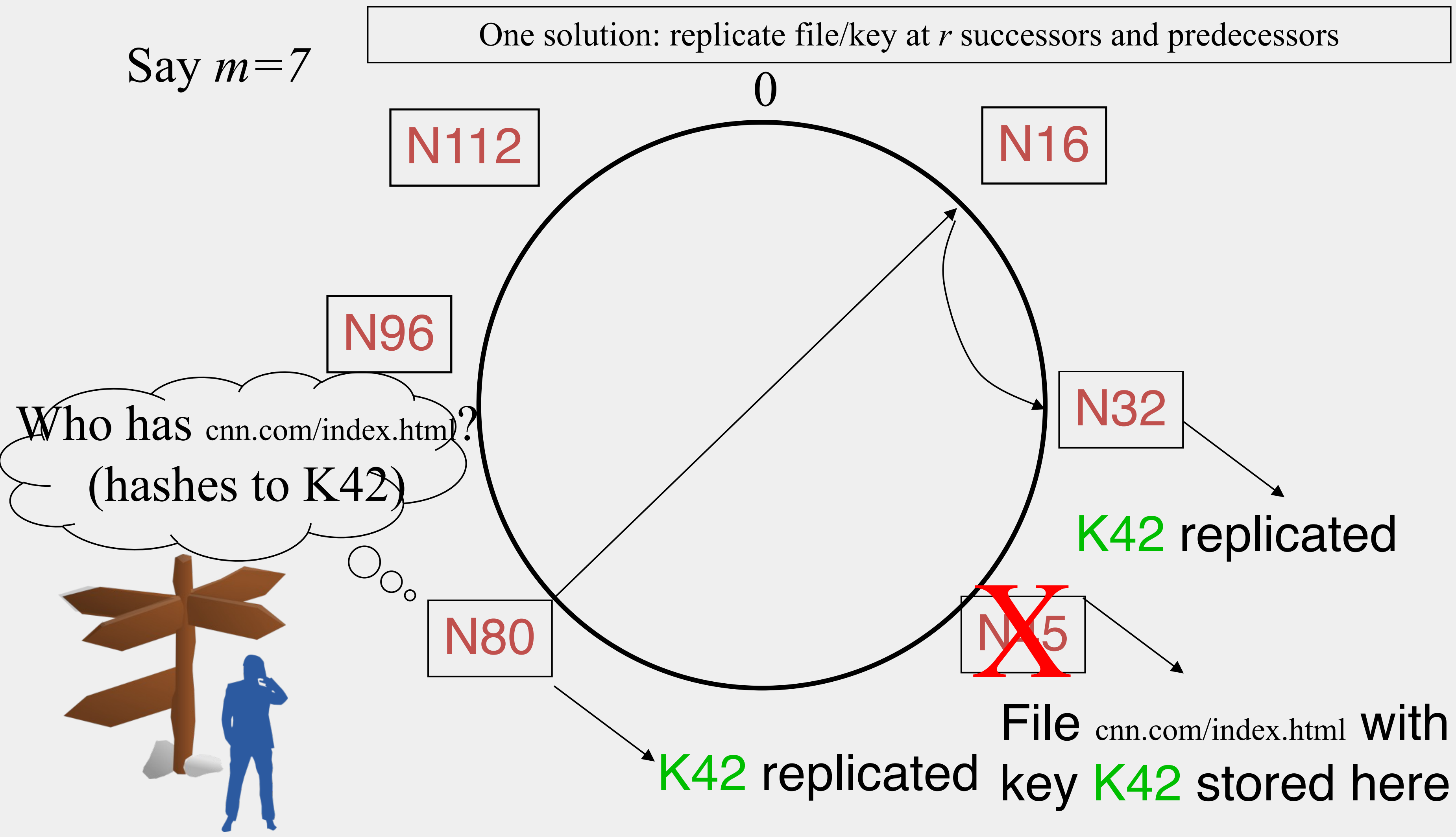
  - Pr(above is true at all alive nodes)=

$$\left(1-\frac{1}{N^2}\right)^{N/2} = e^{-\frac{1}{2N}} \approx 1$$

Search under peer failures (2)



Search under peer failures (2)



Need to deal with dynamic changes

- ✓ Peers fail
- New peers join
- Peers leave
    - P2P systems have a high rate of *churn* (node join, leave and failure)
        - 25% per hour in Overnet (eDonkey)
        - 100% per hour in Gnutella
        - Lower in managed clusters
        - Common feature in all distributed systems, including wide-area (e.g., PlanetLab), clusters (e.g., Emulab), clouds (e.g., AWS), etc.

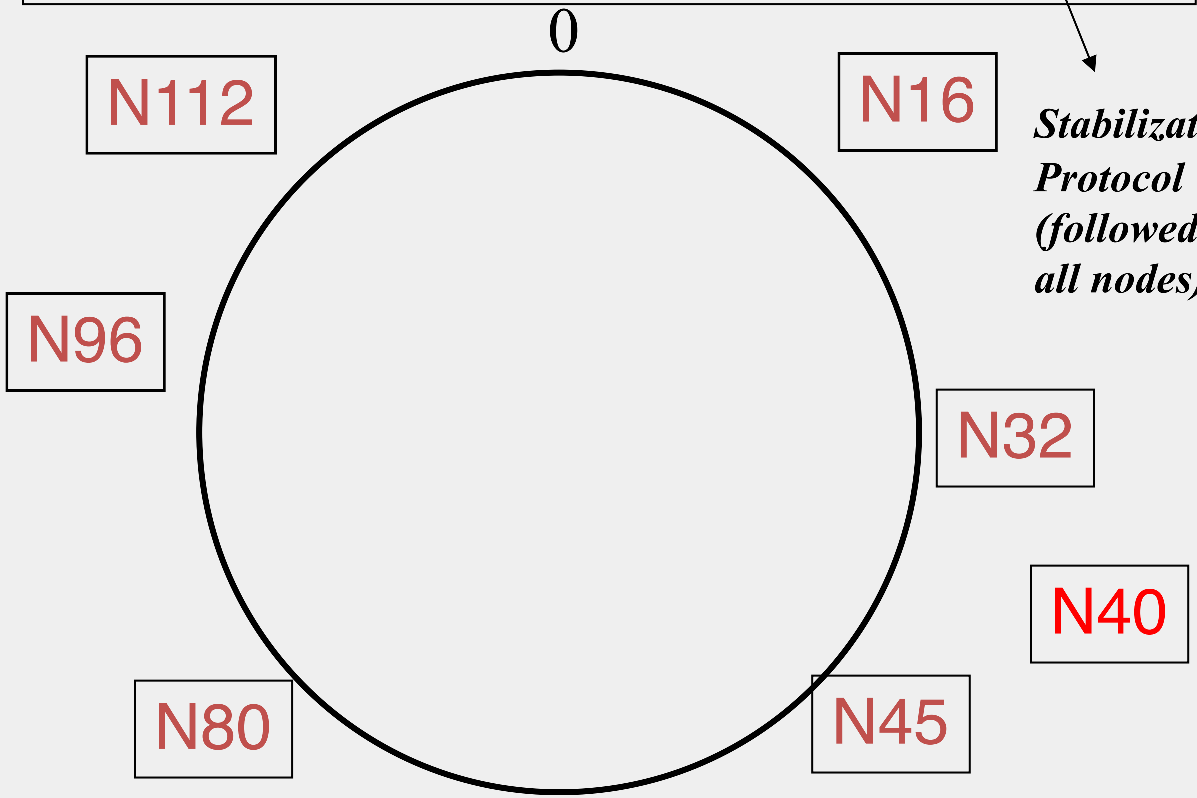
So, all the time, need to:

→ Need to update *successor*s and *finger*s, and copy keys

New peers joining

Introducer directs N40 to N45 (and N32)
N32 updates successor to N40
N40 initializes successor to N45, and inits fingers from it
N40 periodically talks to neighbors to update finger table

Say $m=7$

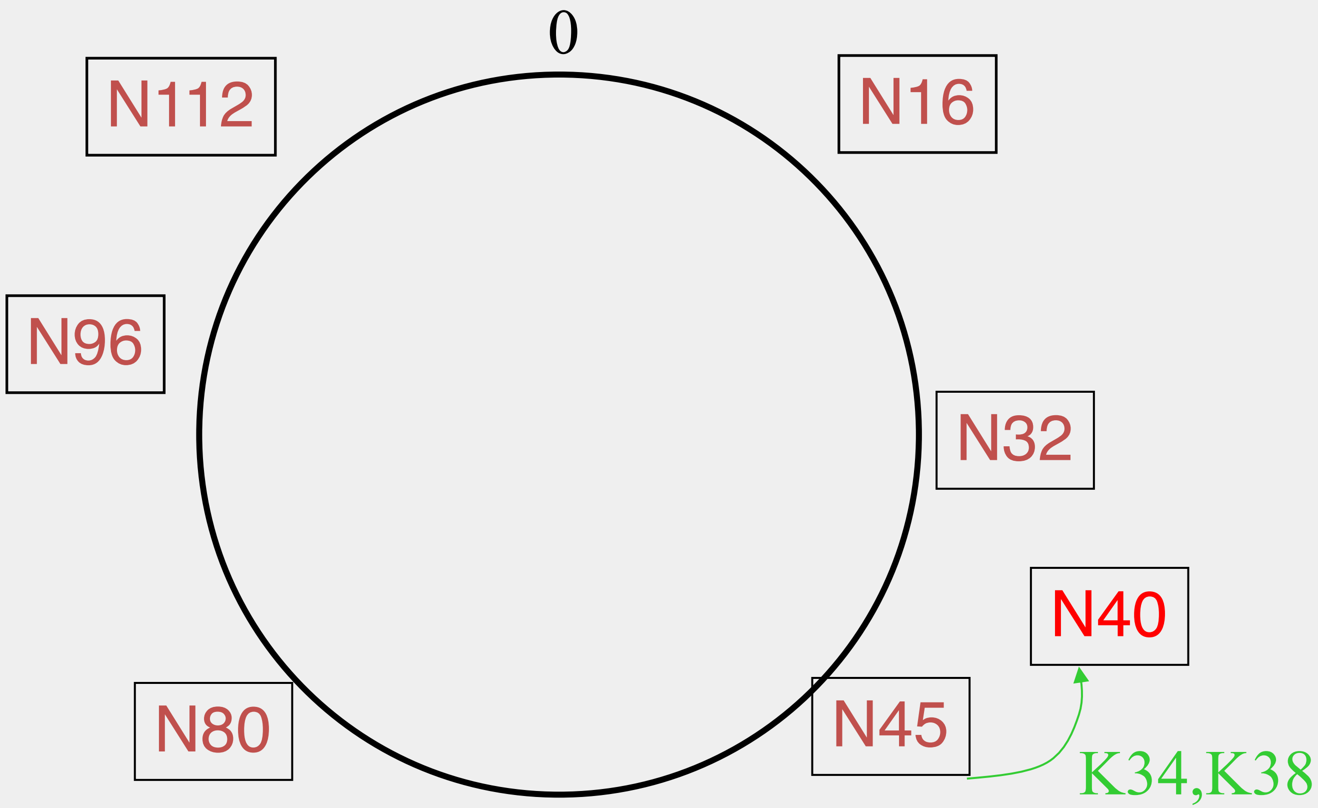


Stabilization Protocol (followed by all nodes)

New peers joining (2)

N40 may need to copy some files/keys from N45
(files with fileid between 32 and 40)

Say $m=7$



New peers joining (3)

- A new peer affects *O(log(N))* other finger entries in the system, on average [Why?]
- Number of messages per peer join= *O(log(N)*log(N))*

- Similar set of operations for dealing with peers leaving
  - For dealing with failures, also need *failure detectors* (you've seen them!)

Stabilization Protocol

- Concurrent peer joins, leaves, failures might cause loopiness of pointers, and failure of lookups
  - Chord peers periodically run a *stabilization* algorithm that checks and updates pointers and keys
  - Ensures *non-loopiness* of fingers, eventual success of lookups and *O(log(N))* lookups w.h.p.
  - Each stabilization round at a peer involves a constant number of messages
  - Strong stability takes $O(N^2)$ stabilization rounds
  - For more see [Extended paper on Chord webpage]

Churn

- When nodes are constantly joining, leaving, failing
  - Significant effect to consider: traces from the Overnet system show *hourly* peer turnover rates (***churn***) could be *25-100%* of total number of nodes in system
  - Leads to excessive (unnecessary) key copying (remember that keys are replicated)
  - Stabilization algorithm may need to consume more bandwidth to keep up
  - Main issue is that files are replicated, while it might be sufficient to replicate only meta information about files
  - Alternatives
    - Introduce a level of indirection, i.e., store only pointers to files (any p2p system)
    - Replicate metadata more, e.g., Kelips (later in this lecture)

Virtual Nodes

- Hash can get non-uniform ➔ Bad load balancing
  - Treat each node as multiple virtual nodes behaving independently
  - Each joins the system
  - Reduces variance of load imbalance

Wrap-up Notes

- Virtual Ring and Consistent Hashing used in Cassandra, Riak, Voldemort, DynamoDB, and other key-value stores

- Current status of Chord project:
  - File systems (CFS,Ivy) built on top of Chord
  - DNS lookup service built on top of Chord
  - Internet Indirection Infrastructure (I3) project at UCB
  - Spawned research on many interesting issues about p2p systems

https://github.com/sit/dht/wiki
(Old: http://www.pdos.lcs.mit.edu/chord/)

Pastry

- Designed by Anthony Rowstron (Microsoft Research) and Peter Druschel (Rice University)
- Assigns ids to nodes, just like Chord (using a virtual ring)
- **Leaf Set** - Each node knows its successor(s) and predecessor(s)

Pastry Neighbors

- **Routing tables** based on **prefix matching**
  - Think of a hypercube
- Routing is thus based on prefix matching, and is thus log(N)
  - And hops are short (in the underlying network)

Pastry Routing

- Consider a peer with id 01110100101. It maintains a neighbor peer with an id matching each of the following prefixes (* = starting bit differing from this peer's corresponding bit):
    - *
    - 0*
    - 01*
    - 011*
    - … 0111010010*
- When it needs to route to a peer, say 01110111001, it starts by forwarding to a neighbor with the largest matching prefix, i.e., 011101*

Pastry Locality

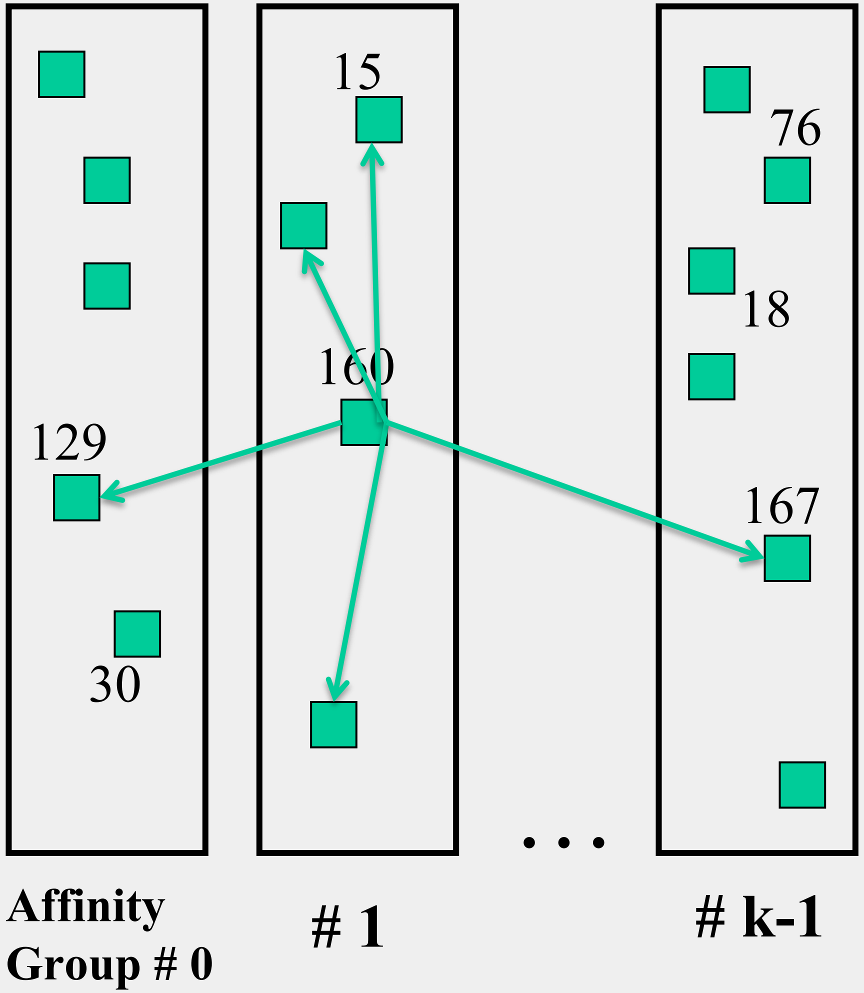
- For each prefix, say 011*, among all potential neighbors with the matching prefix, the neighbor with the shortest round-trip-time is selected
- Since shorter prefixes have many more candidates (spread out throughout the Internet), the neighbors for shorter prefixes are likely to be closer than the neighbors for longer prefixes
- Thus, in the prefix routing, early hops are short and later hops are longer
- Yet overall “stretch”, compared to direct Internet path, stays short

Summary of Chord and Pastry

- Chord and Pastry protocols
  - More structured than Gnutella
  - Black box lookup algorithms
  - Churn handling can get complex
  - *O(log(N))* memory and lookup cost
    - *O(log(N))* lookup hops may be high
    - Can we reduce the number of hops?

Kelips – A 1 hop Lookup DHT

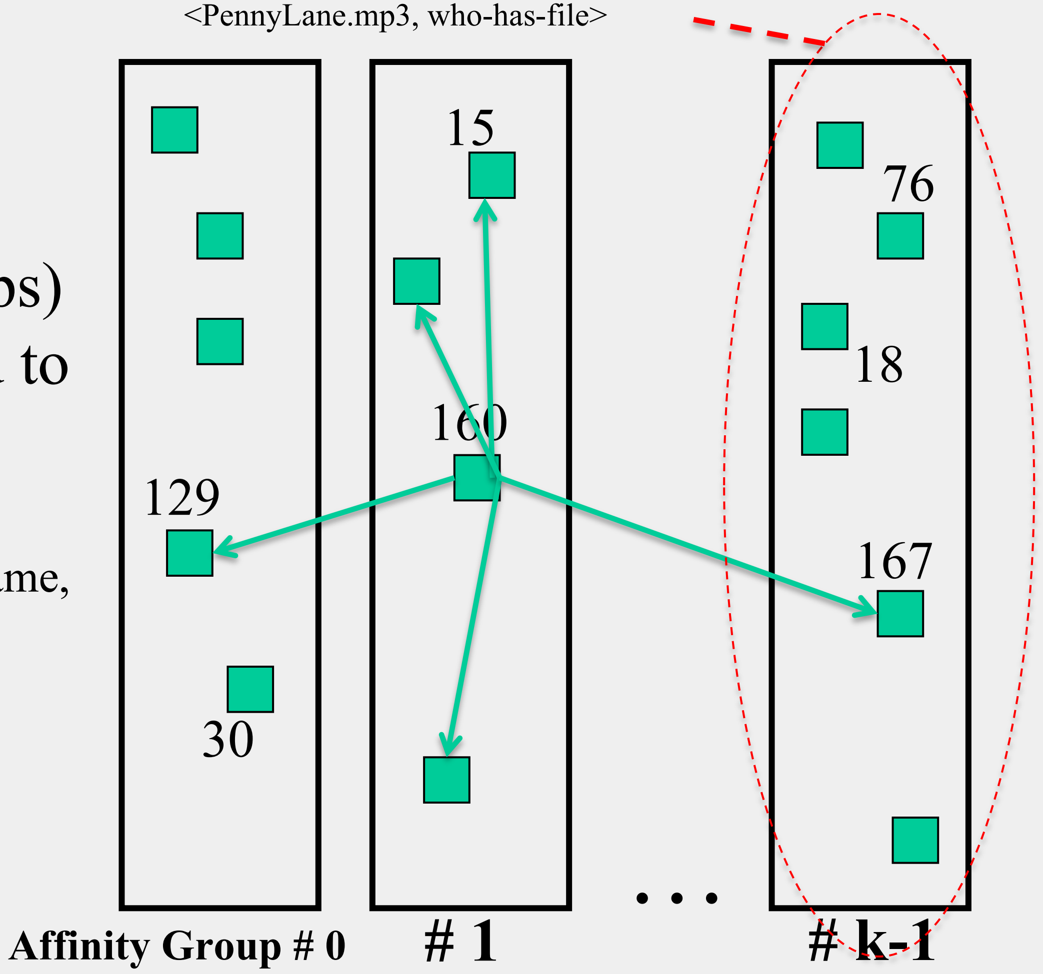
- k "affinity groups"
  - k ~ √ N
- Each node hashed to a group (hash mod k)
- Node's neighbors
  - (Almost) all other nodes in its own affinity group
  - One contact node per foreign affinity group
  - Gossip-style heartbeating



Kelips Files and Metadata

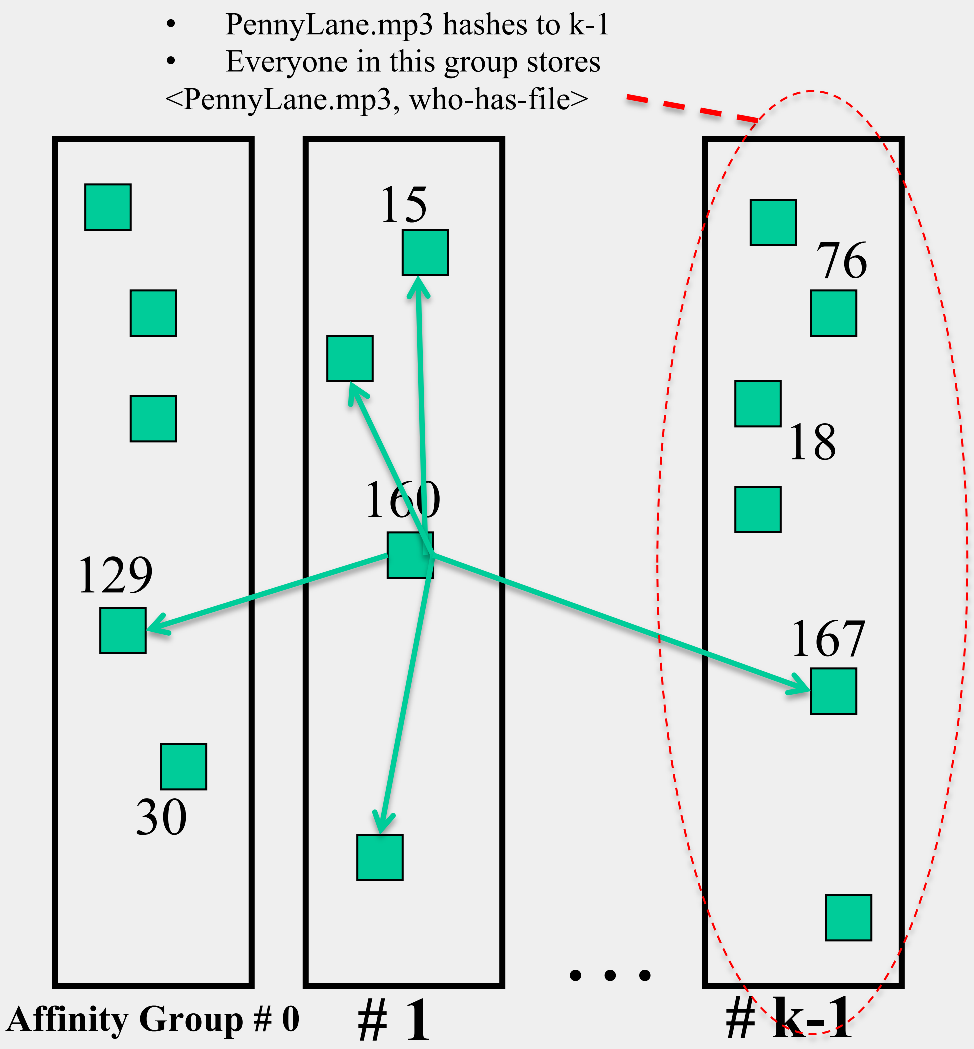
- File can be stored at any (few) node(s)
- Decouple file replication/location (outside Kelips) from file querying (in Kelips)
- Each filename hashed to a group
  - All nodes in the group replicate pointer information, i.e., <filename, file location>
  - Spread using gossip
  - Affinity group <u>does not</u> store files

- PennyLane.mp3 hashes to k-1
- Everyone in this group stores <PennyLane.mp3, who-has-file>



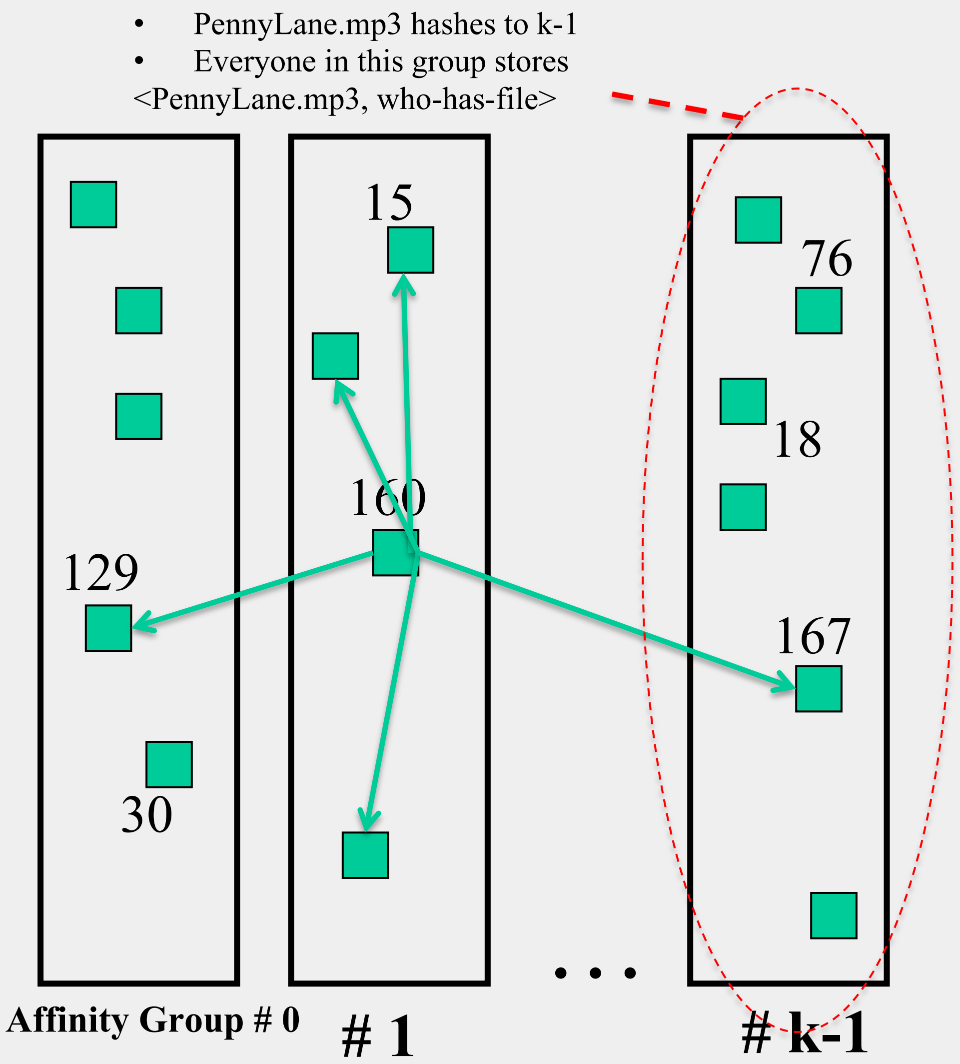
Kelips Lookup

- Lookup
  - Find file affinity group
  - Go to your contact for the file affinity group
  - Failing that try another of your neighbors to find a contact
- Lookup = 1 hop (or a few)
  - Memory cost O(√ N)
  - 1.93 MB for 100K nodes, 10M files
  - Fits in RAM of most workstations/laptops today (COTS machines)



Kelips Soft State

- Membership lists
  - Gossip-based membership
  - Within each affinity group
  - And also across affinity groups
  - *O(log(N))* dissemination time
- File metadata
  - Needs to be periodically refreshed from source node
  - Times out



Chord vs. Pastry vs. Kelips

- Range of tradeoffs available
  - Memory vs. lookup cost vs. background bandwidth (to keep neighbors fresh)

What We Have Studied

- Widely-deployed P2P Systems
  1. Napster
  2. Gnutella
  3. Fasttrack (Kazaa, Kazaalite, Grokster)
  4. BitTorrent
- P2P Systems with Provable Properties
  1. Chord
  2. Pastry
  3. Kelips

Announcements

- MP2 out already, due 9/25 (demos on 9/26)
- HW1 due next Wednesday 2 pm (9/21)
- HW2 will be out then