CS 525

Advanced Distributed Systems
Spring 2015

Indranil Gupta (Indy)
Lecture 4, 5
Peer to Peer Systems
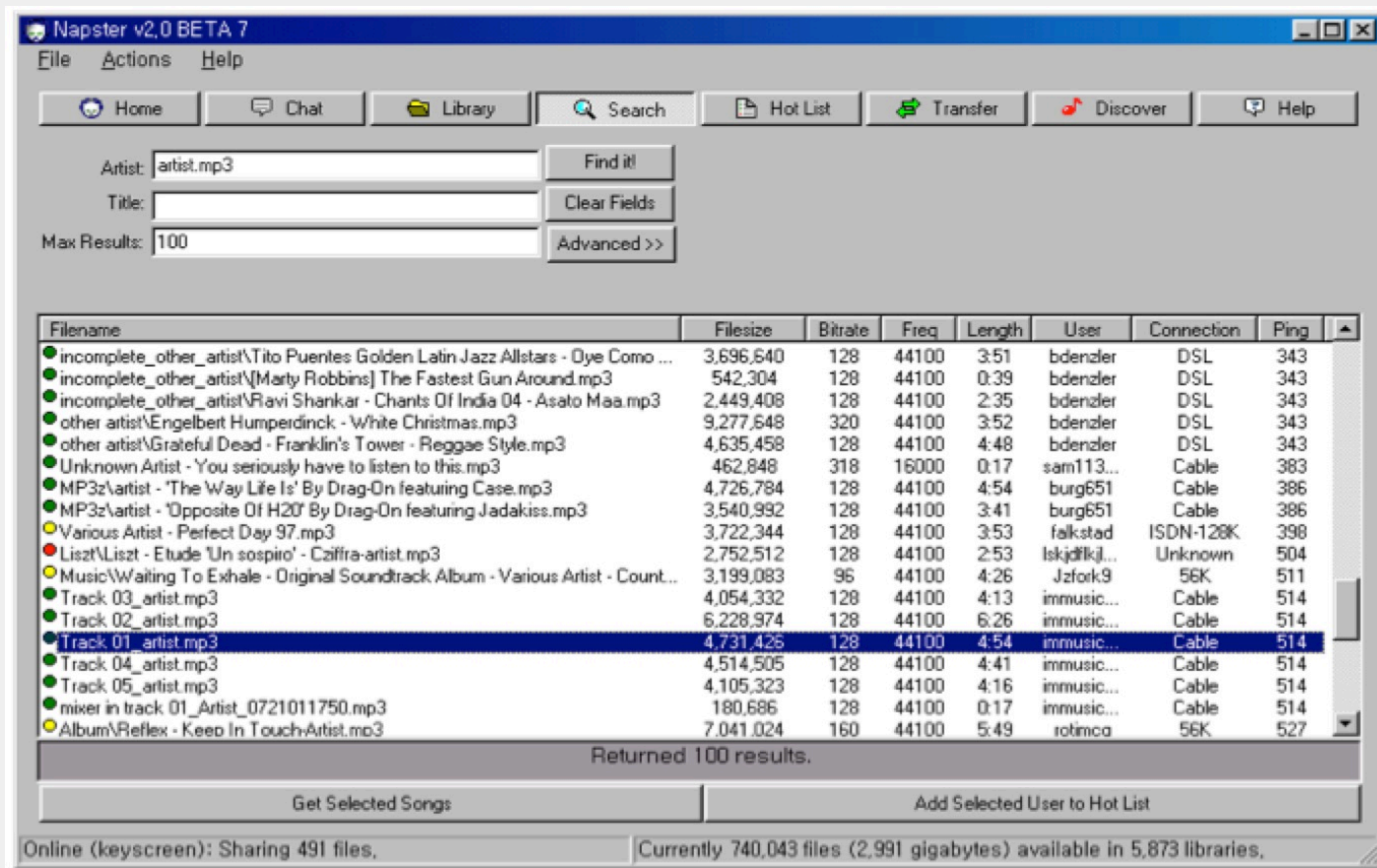January 29, 2015

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

Why Study Peer to Peer Systems?

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

NAPSTER STRUCTURE

Store a directory, i.e., filenames with peer pointers

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

napster.com
Servers

Client machines
("Peers")
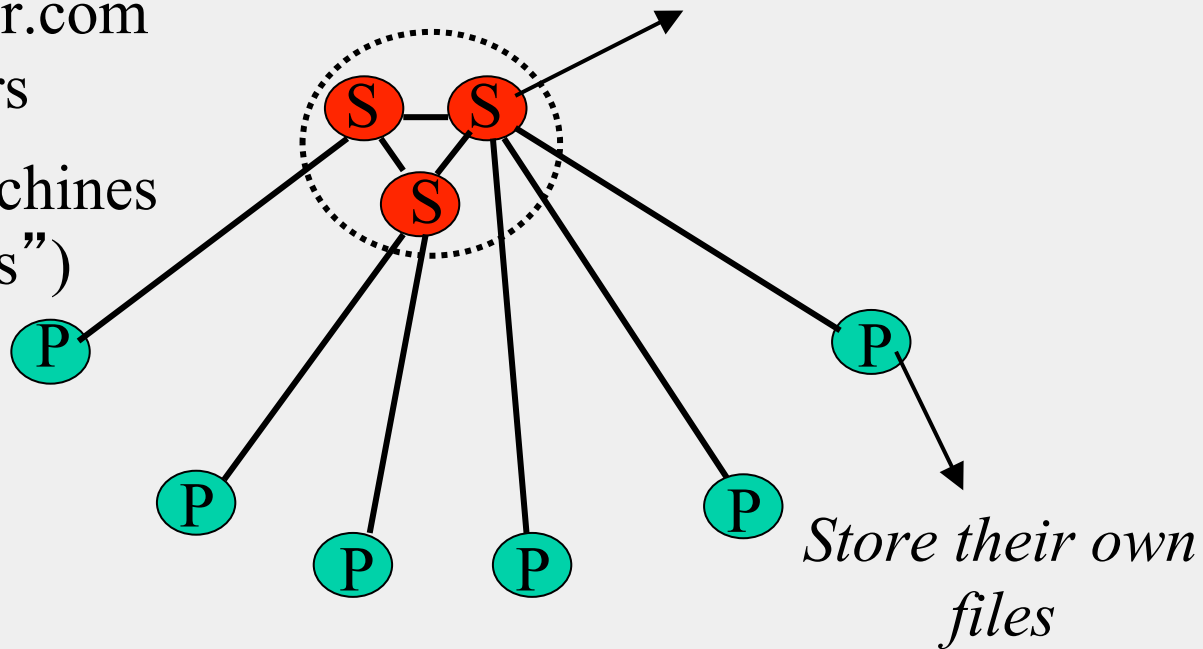
Store their own files

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

2. All servers search their lists (ternary tree algorithm)

Store peer pointers for all files

napster.com
Servers

Client machines
("Peers")

S   S

S

1. Query

3. Response

P

P

4. ping candidates

P   P

P

Store their own files

5. download from best host
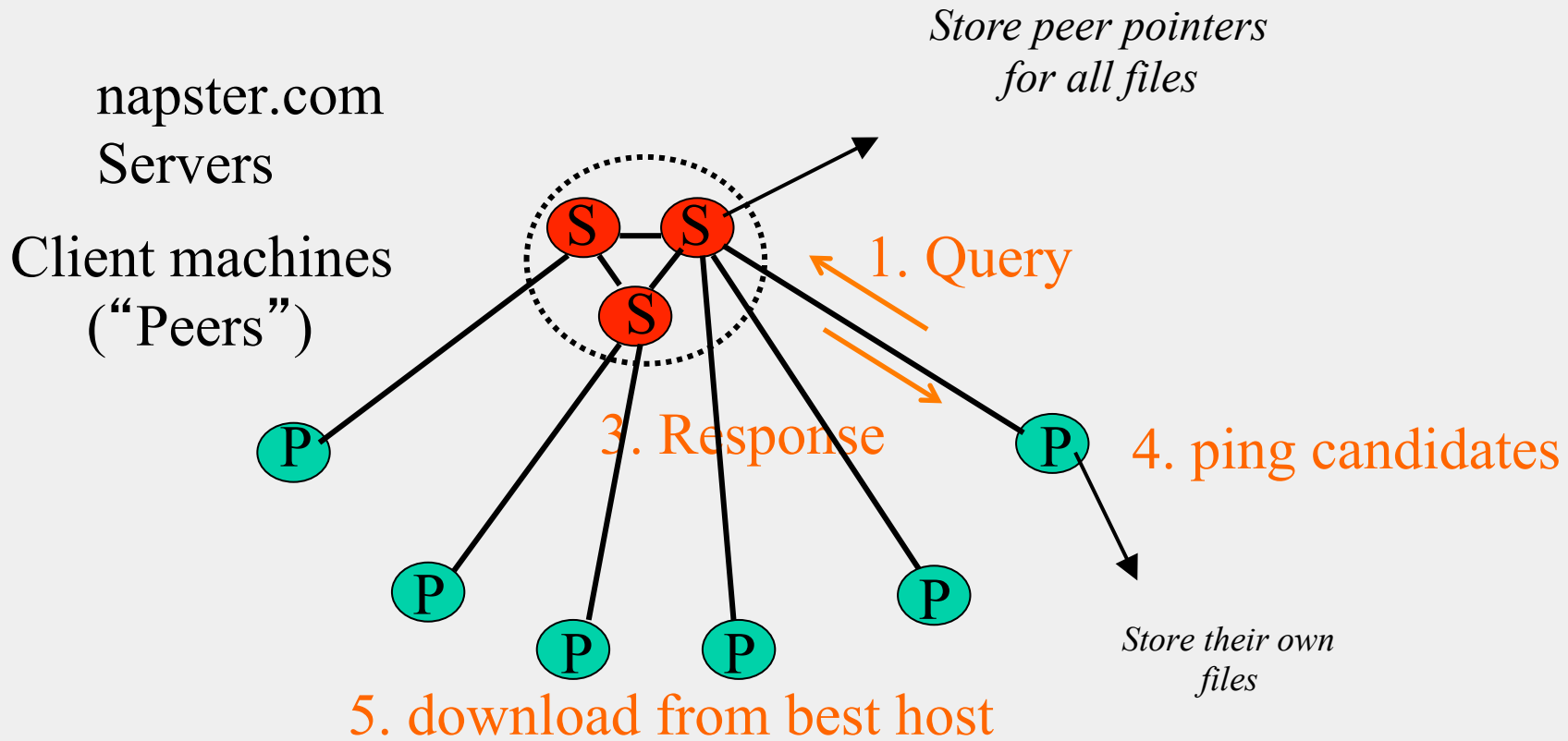
Joining a P2P system

- 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

Store their own
files

Servents ("Peers")

Also store
"peer pointers"
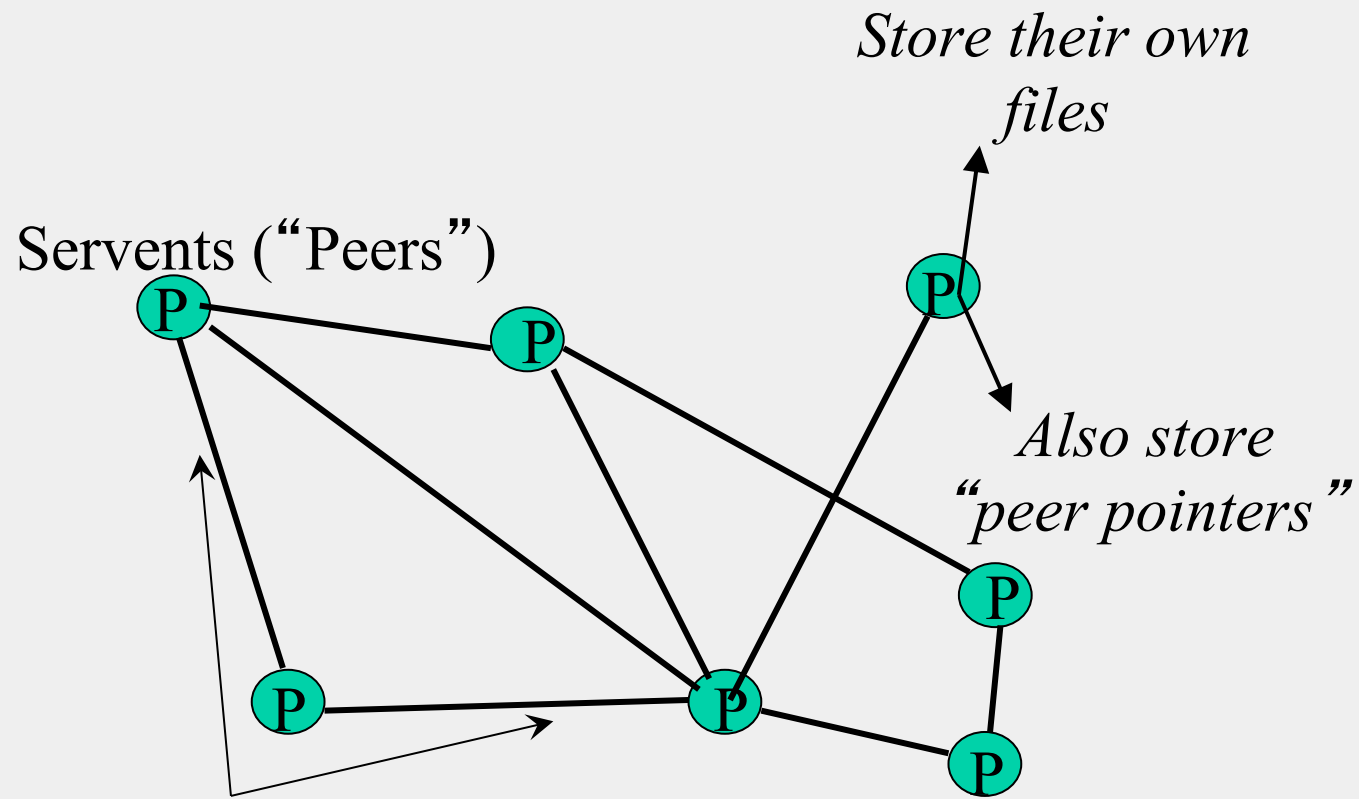
Connected in an **overlay** graph
(== each link is an implicit Internet path)

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
  - 0x12345678 stored as 0x78 in lowest address byte, then 0x56 in next higher address, and so on.

How do I search for my Beatles file?

Descriptor Header

Payload

Descriptor ID	Payload descriptor	TTL	Hops	Payload length	
0 15	16	17	18	22	

ID of this search transaction

Type of payload
0x00 Ping
0x01 Pong
0x40 Push
0x80 Query
0x81 Queryhit

Decremented at each hop, Message dropped when ttl=0 ttl_initial usually 7 to 10

Incremented at each hop

Number of bytes of message following this header

Gnutella Message Header Format
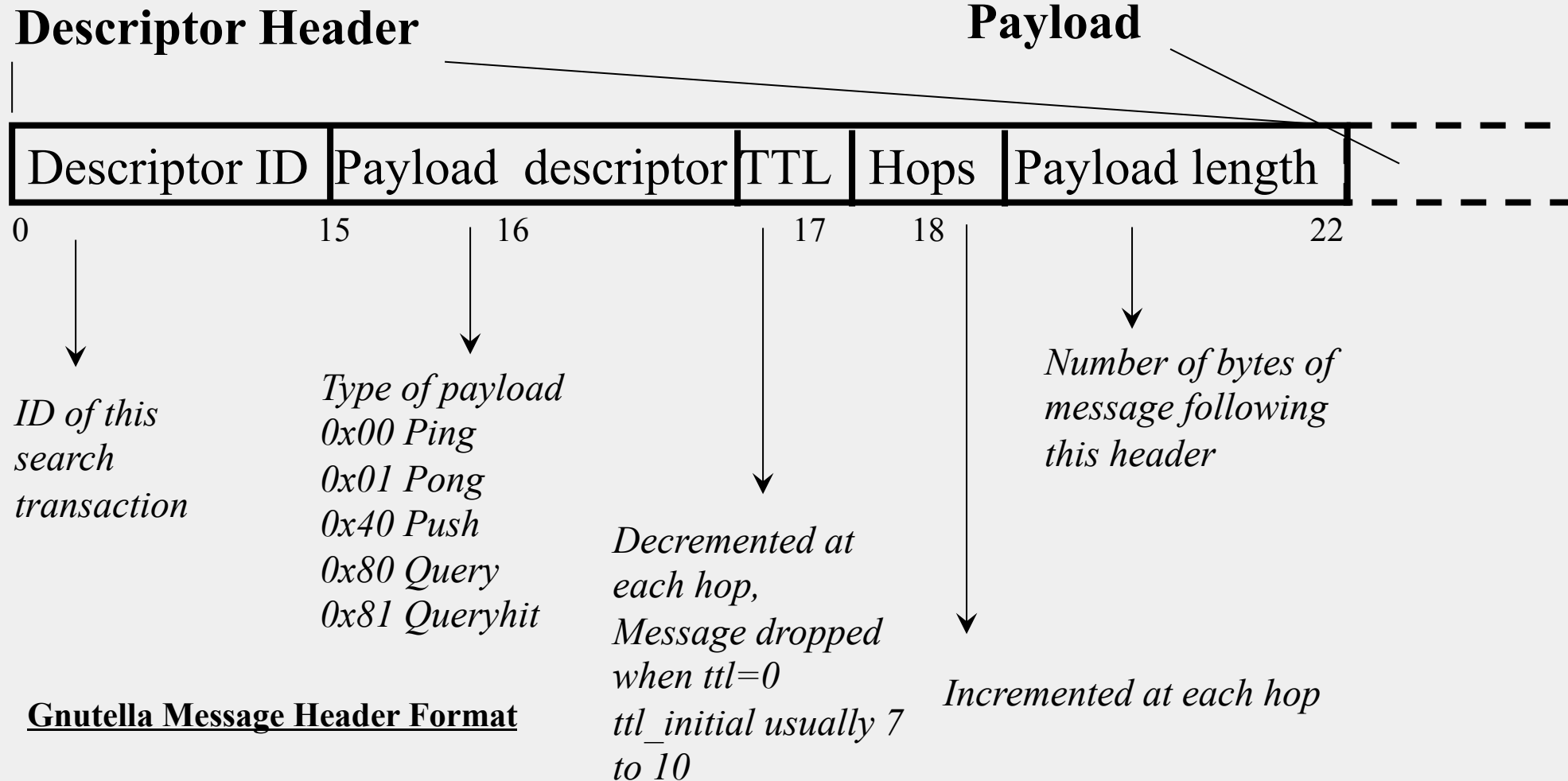
How do I search for my Beatles file?

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

TTL=2

Who has PennyLane.mp3?
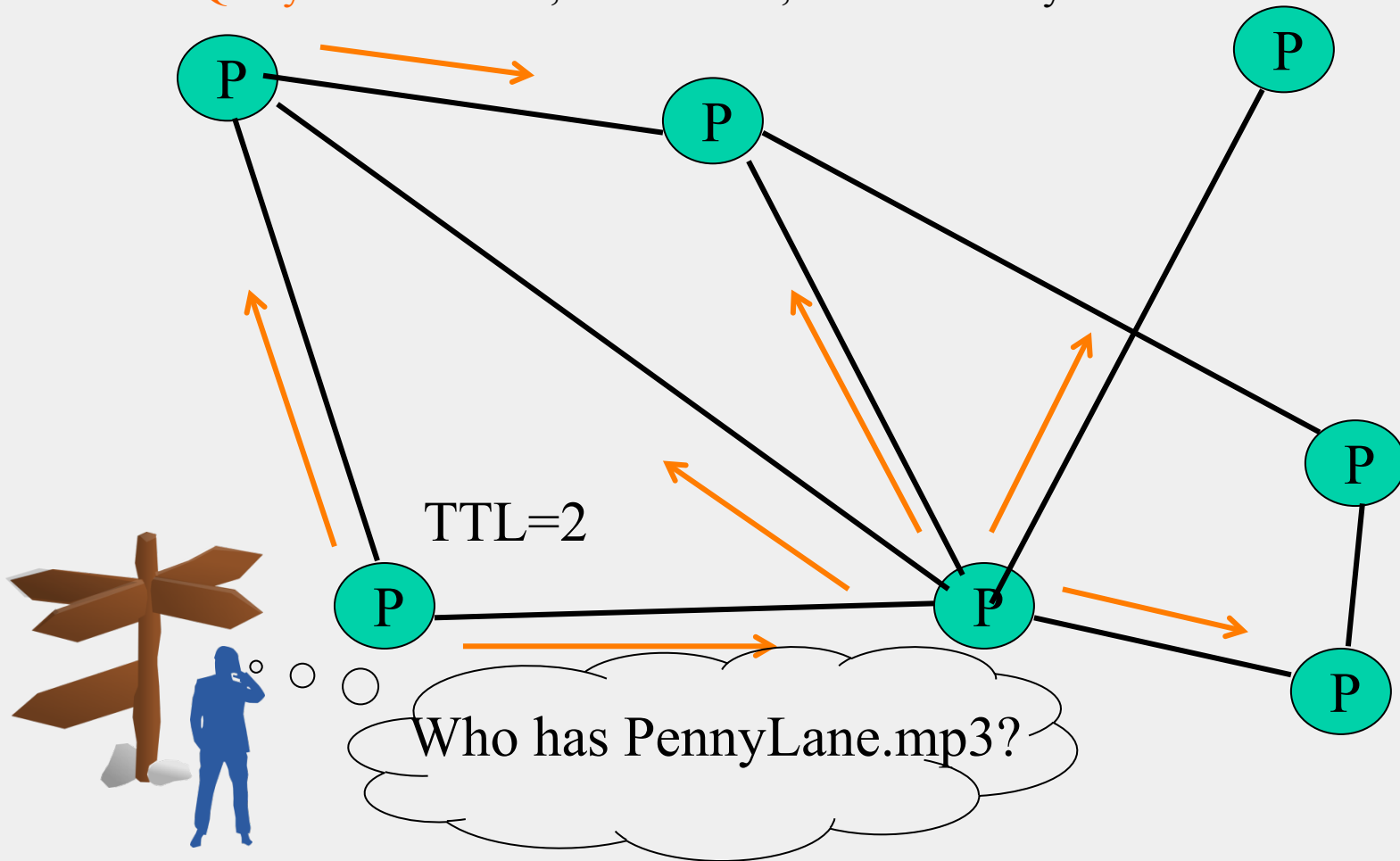
Gnutella Search

QueryHit (0x81) : successful result to a query

Num. hits	port	ip_address	speed	(fileindex,filename,fsize)	servent_id

0   1   3   7   11   n   n+16

Results

Info about responder

Unique identifier of responder;
a function of its IP address
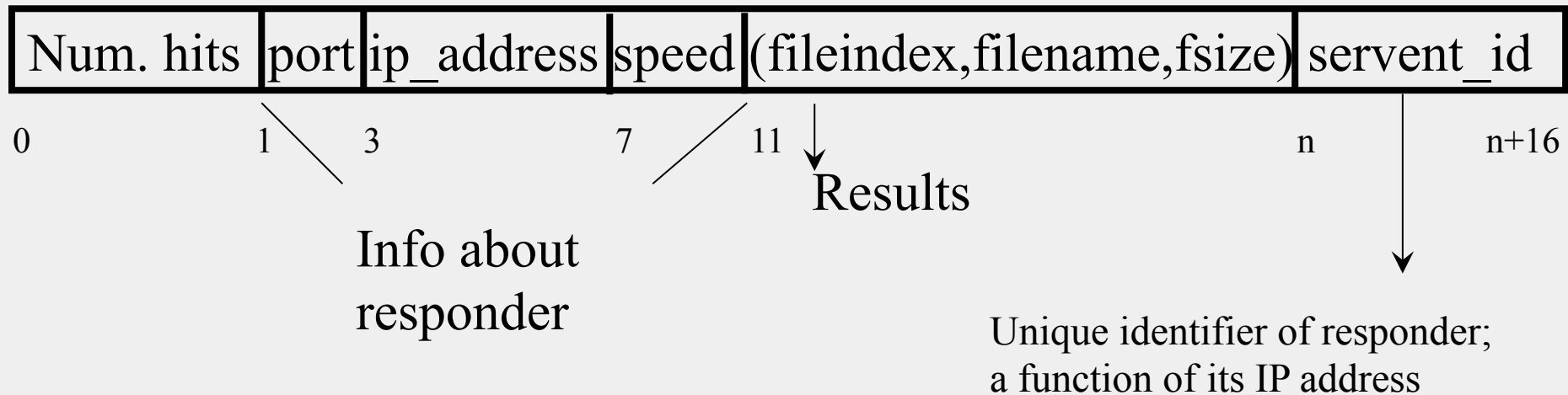
Payload Format in Gnutella QueryHit Message

Gnutella Search

Successful results QueryHit's routed on reverse path
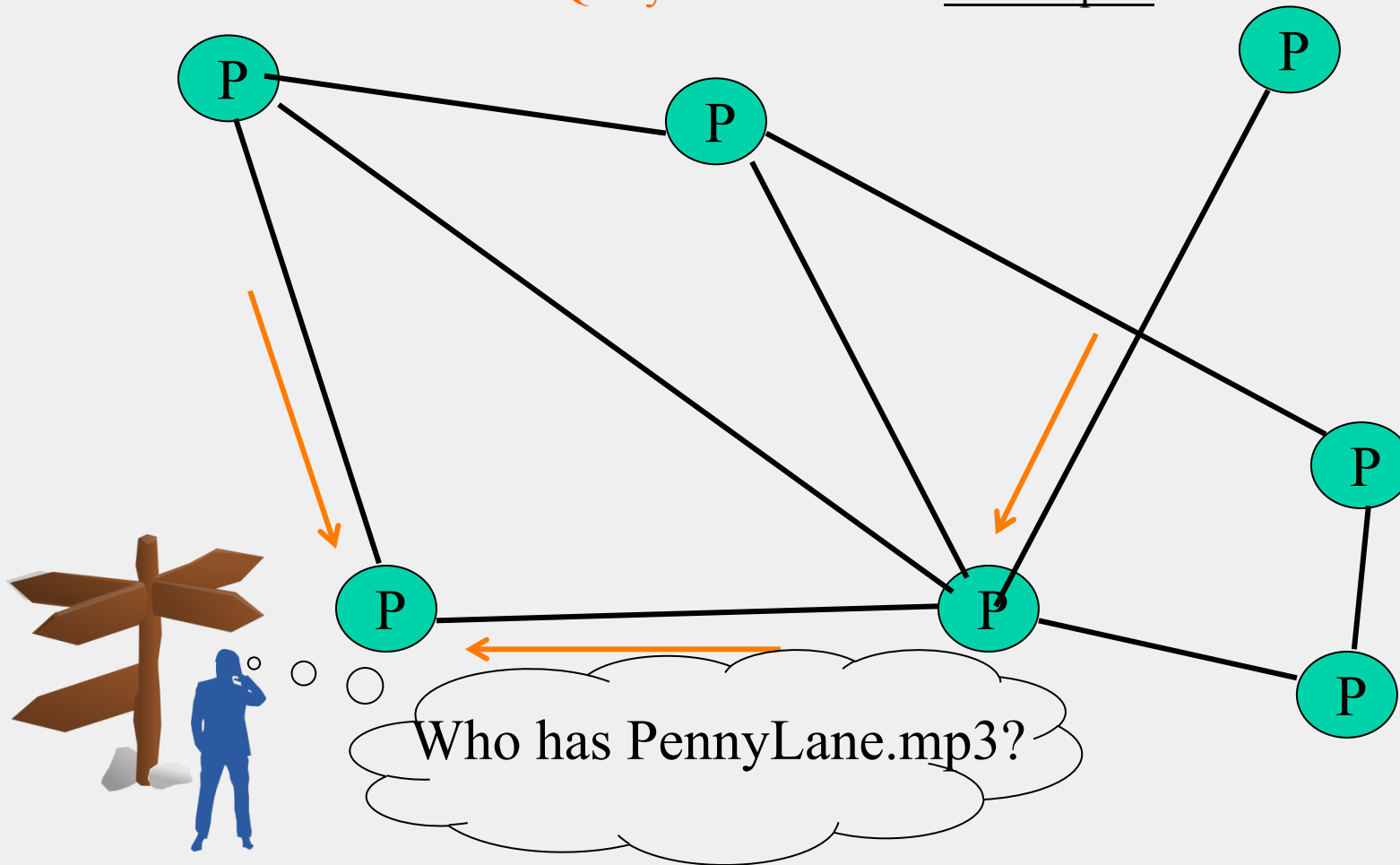
AVOIDING EXCESSIVE TRAFFIC

- 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

Has PennyLane.mp3
But behind firewall
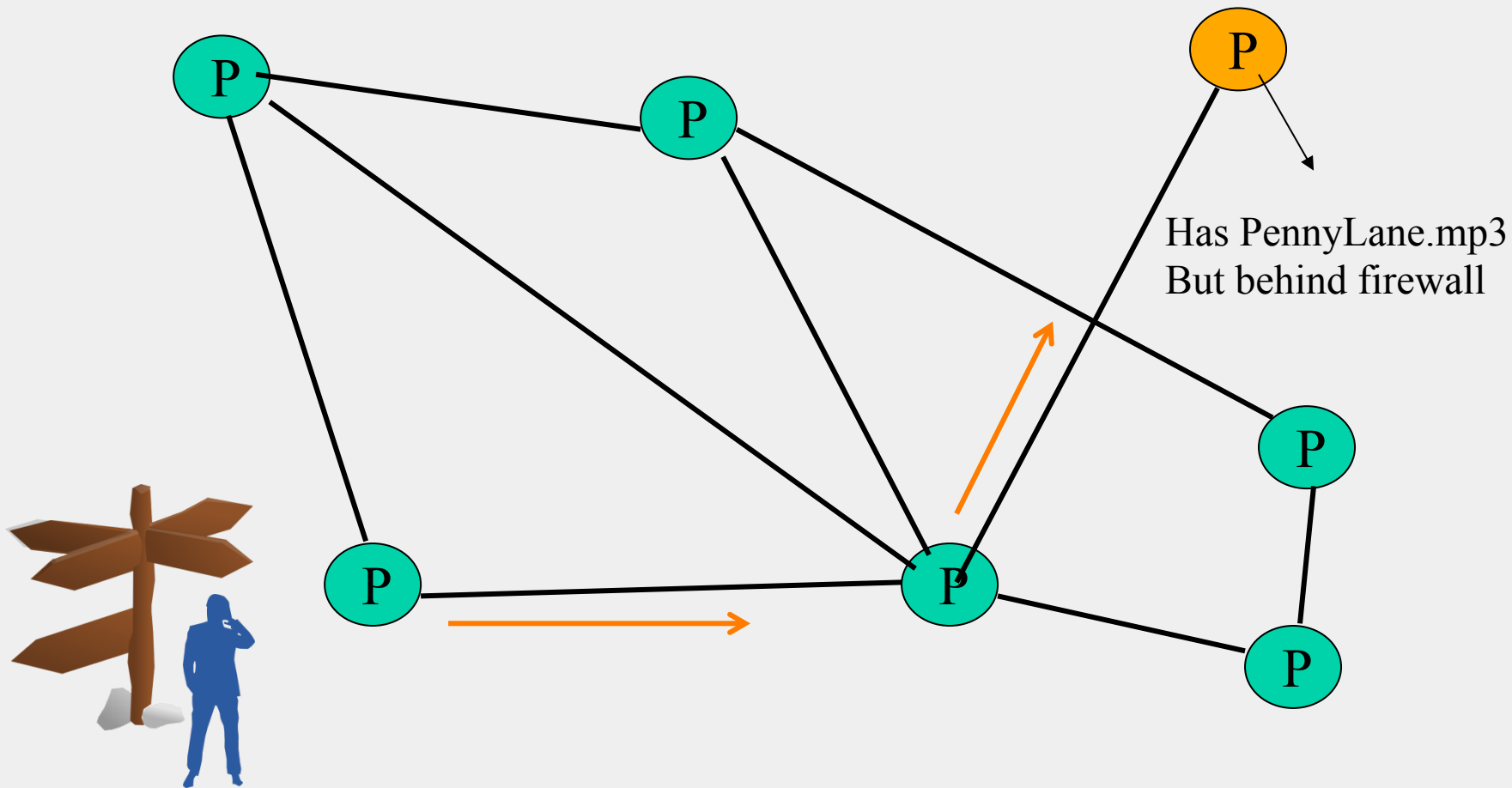
Dealing with Firewalls

Push (0x40)

servent_id	fileindex	ip_address	port

same as in
received QueryHit

Address at which
<u>requestor</u> 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:

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

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

Peers
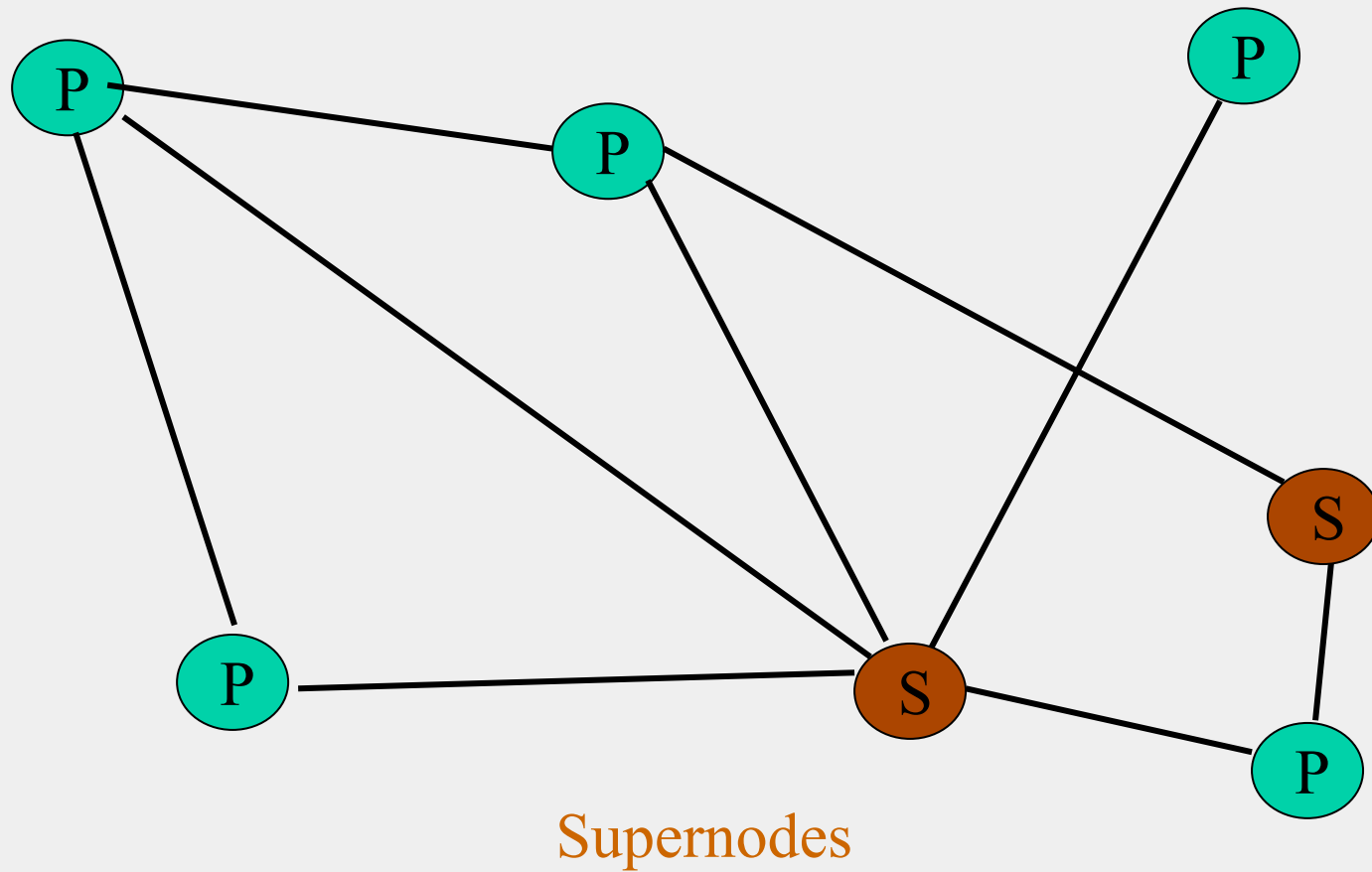
Supernodes

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)

Peer

3. Get file blocks

(new, leecher)

Peer

(leecher, has some blocks)

Peer

(seed)
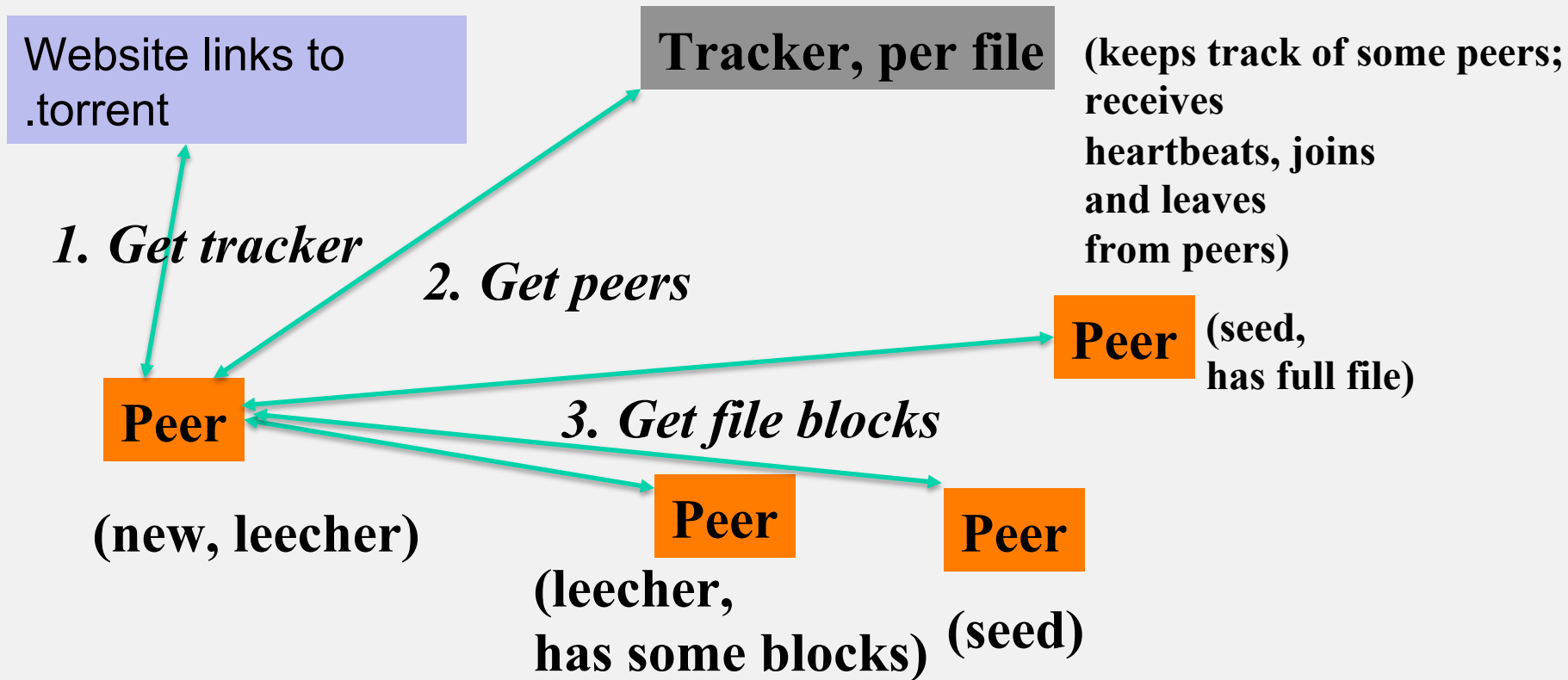
BITTORRENT (2)

- 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 download rates

  - Seeds do the same too

BitTorrent (3)

- 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 neigbhor – helps keep unchoked set fresh

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
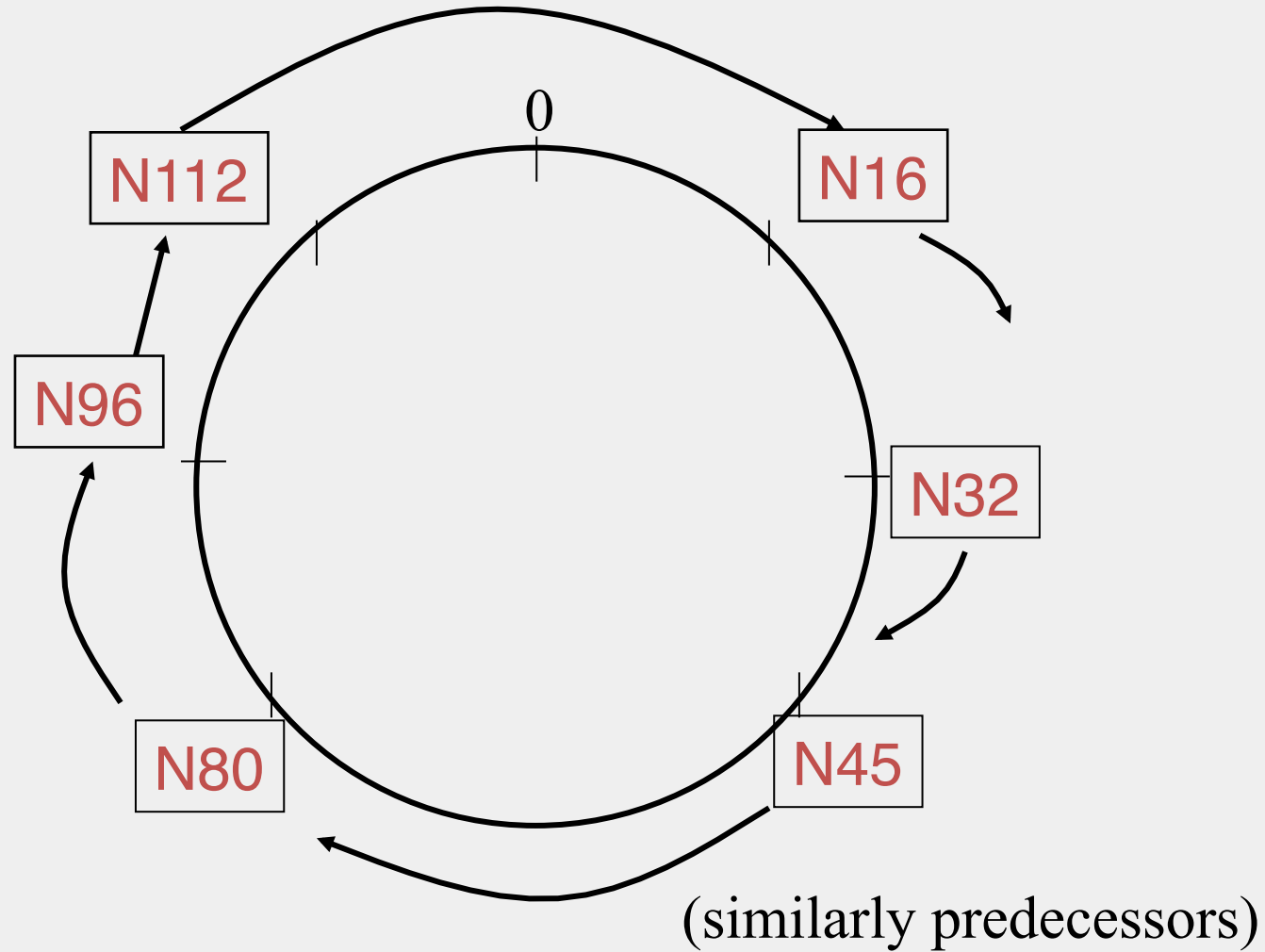 - Can then map peers to one of 2^m logical points on a circle

Ring of peers

Say *m=7*

6 nodes

0

N112

N16

N96

N32

N80

N45
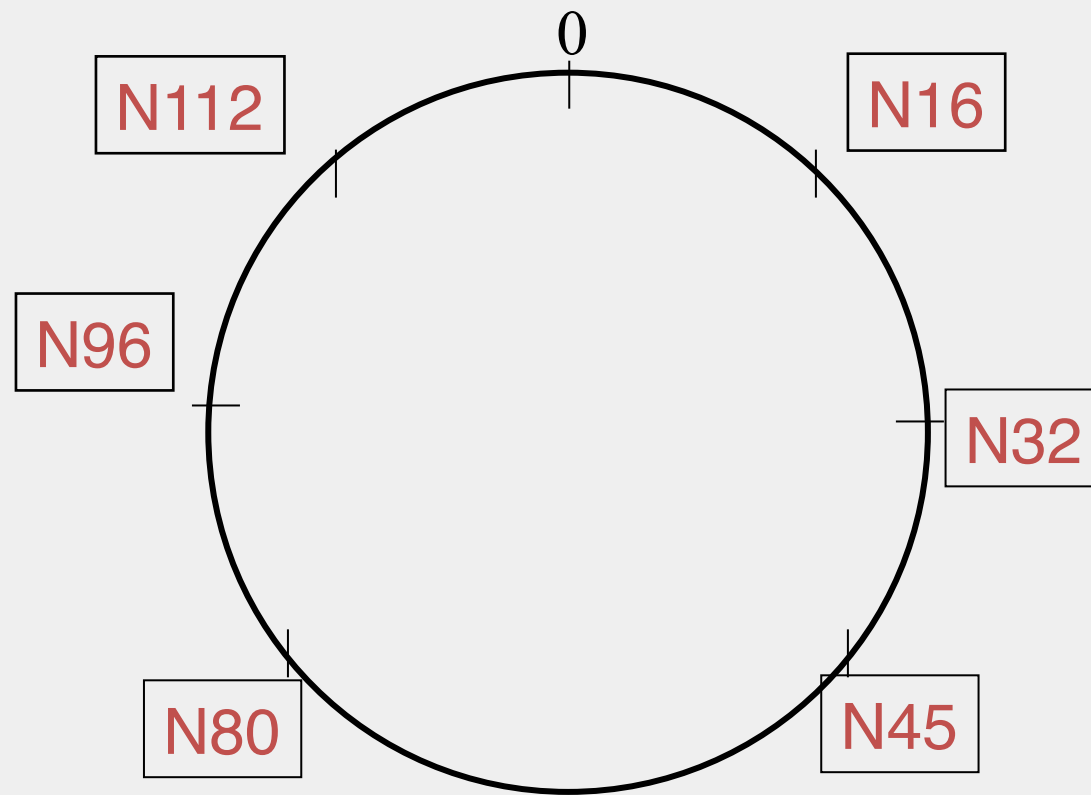
Peer pointers (1): successors

Say *m=7*

(similarly predecessors)

Say $m=7$

Finger Table at N80

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

N112

N16

N96

N32

0

$80 + 2^5$

$80 + 2^6$

$80 + 2^4$

$80 + 2^3$

$80 + 2^2$

$80 + 2^1$

$80 + 2^0$

N80

N45
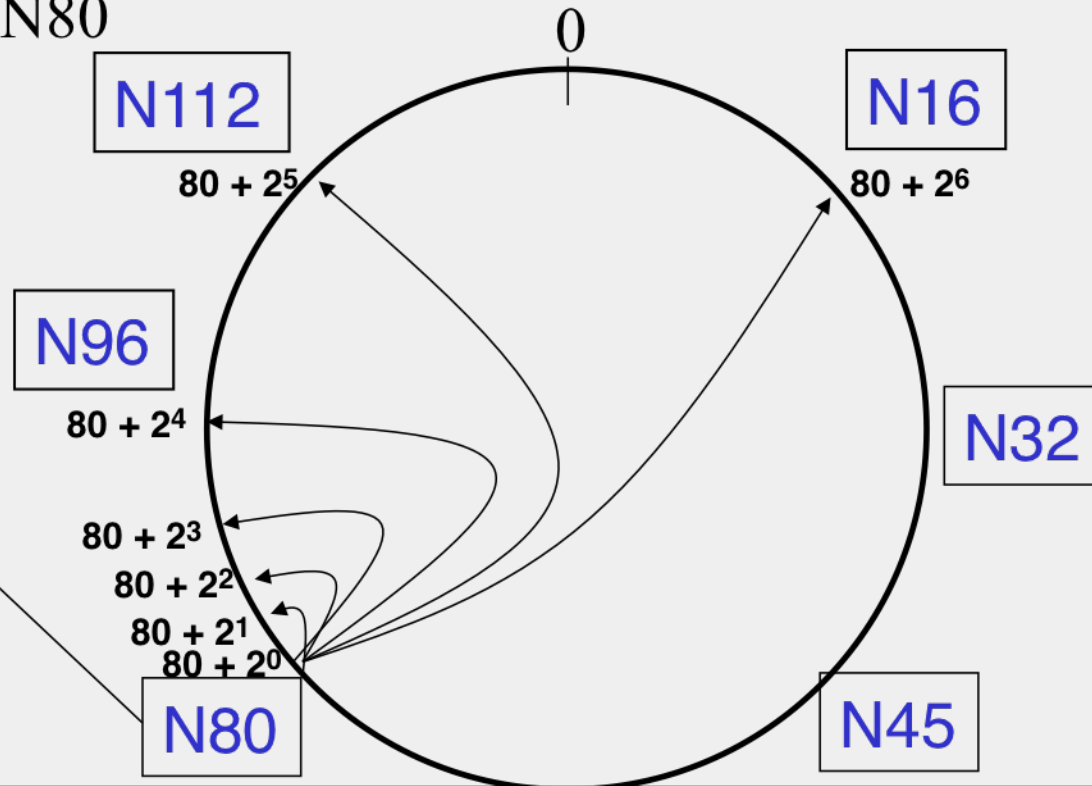
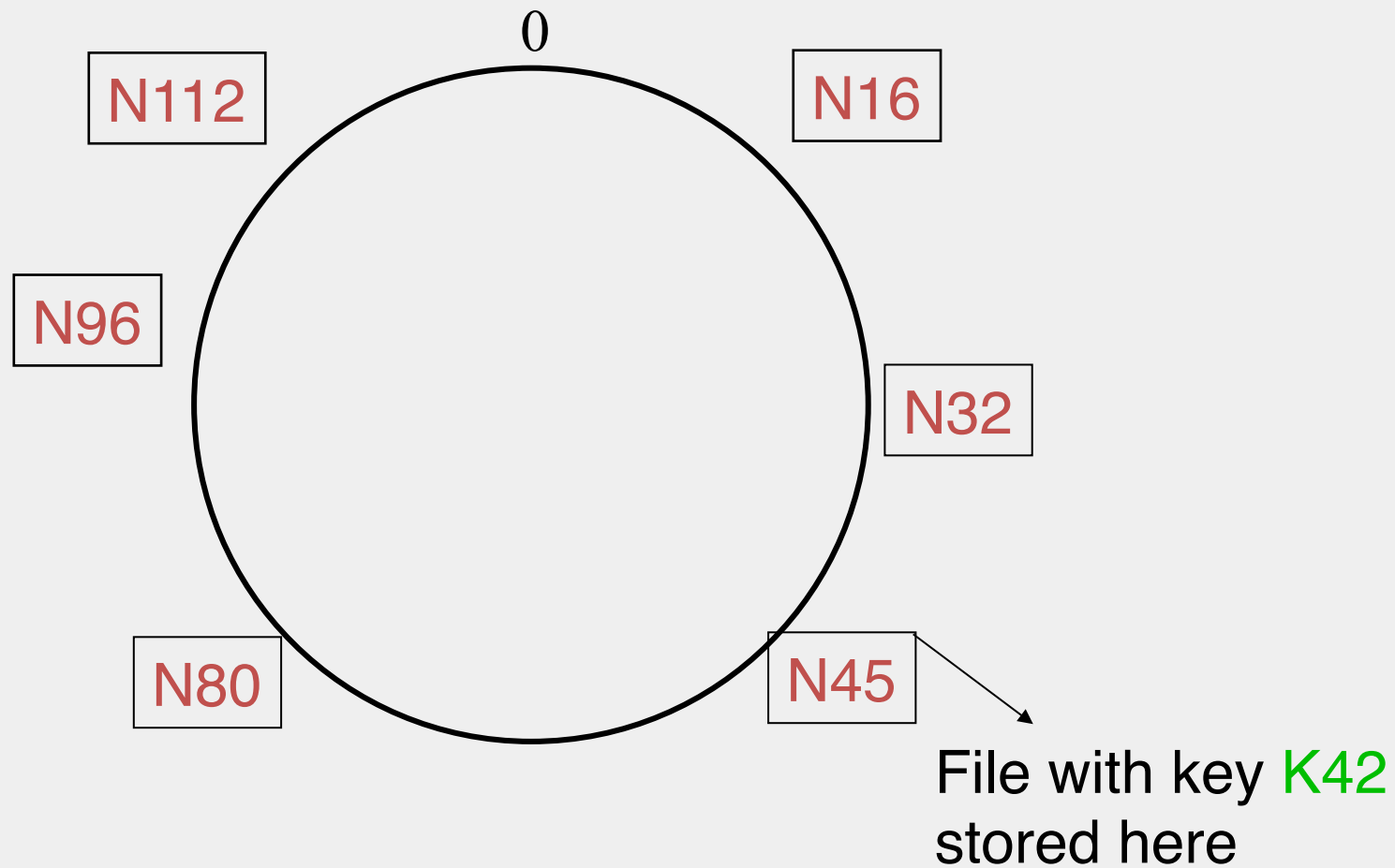ith entry at peer with id n is first peer with id $>= \ n + 2^i (\bmod 2^m)$

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 greater than 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*

N112

N96

N80

0

N16

N32

N45

File with key K42 stored here

Search

Say *m=7*

0

N112

N16

N96

N32

Who has cnn.com/index.html?
(hashes to K42)

N80

N45

File cnn.com/index.html with
key K42 stored here
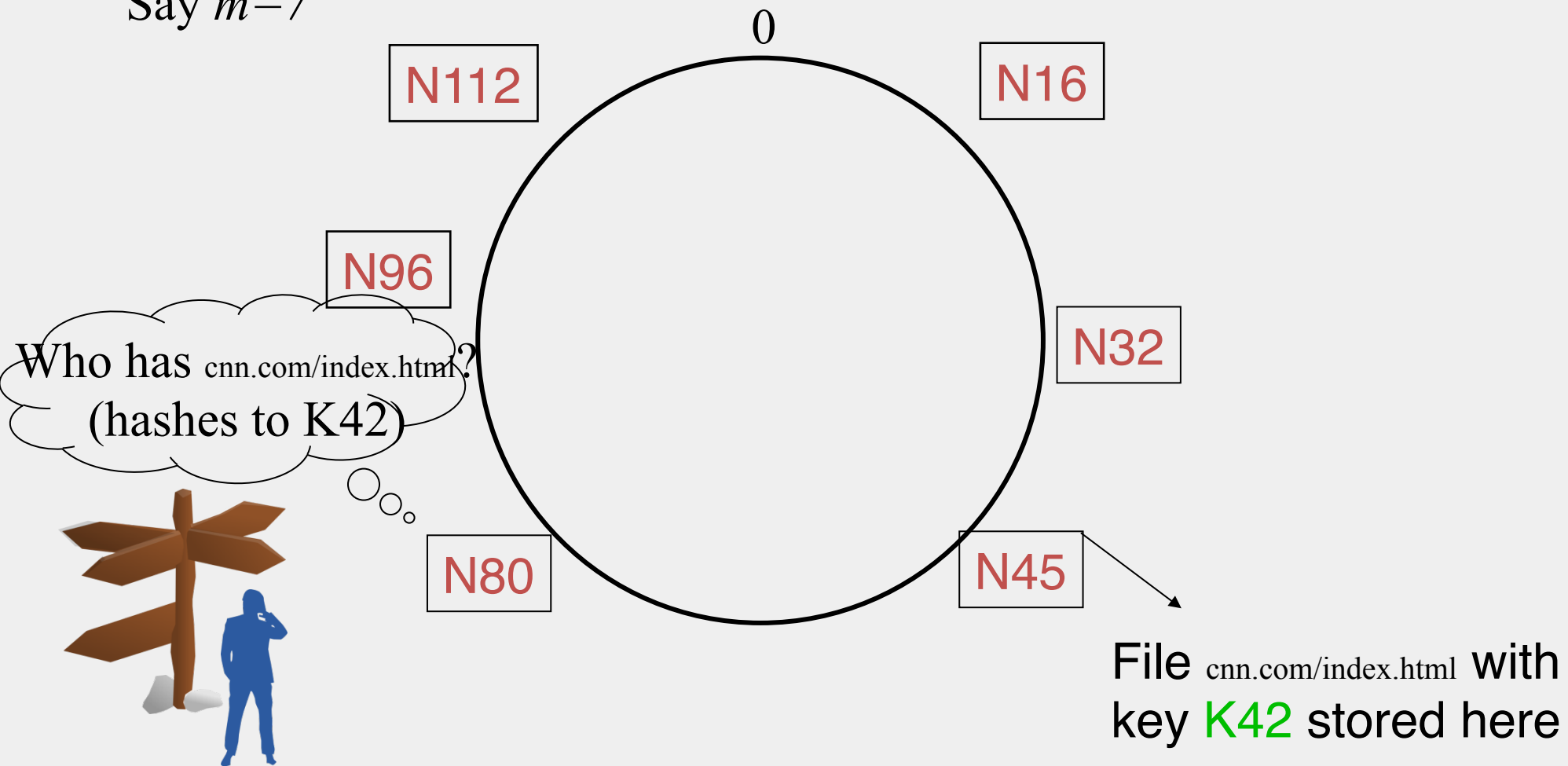
SEARCH

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)

0

N112

N16

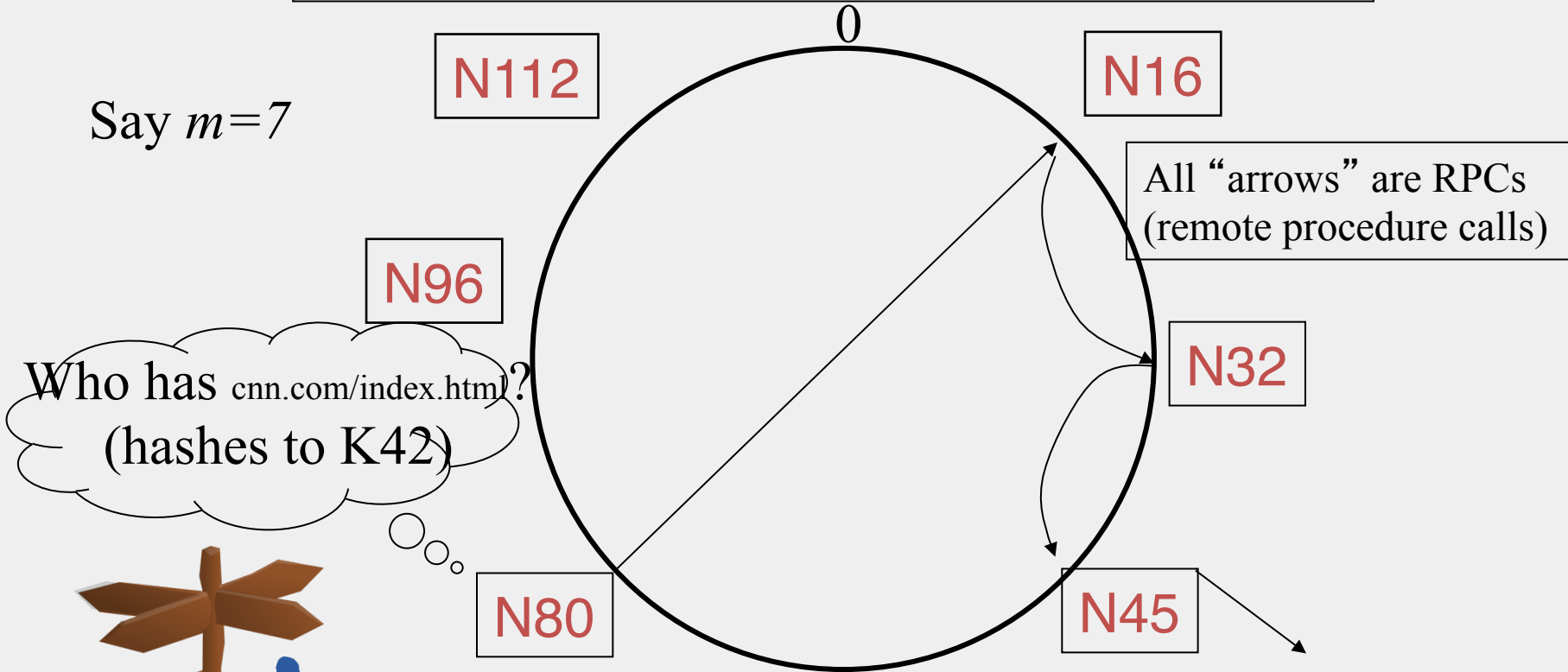Say $m=7$

N96

N32

Who has cnn.com/index.html?
(hashes to K42)

N80

N45

File cnn.com/index.html with
key K42 stored here

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

0

N112

N16

Say *m=7*

All "arrows" are RPCs
(remote procedure calls)

N96

N32

Who has cnn.com/index.html?
(hashes to K42)

N80

N45

File cnn.com/index.html with
key K42 stored here

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*

Here

Next hop

Key

- (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")

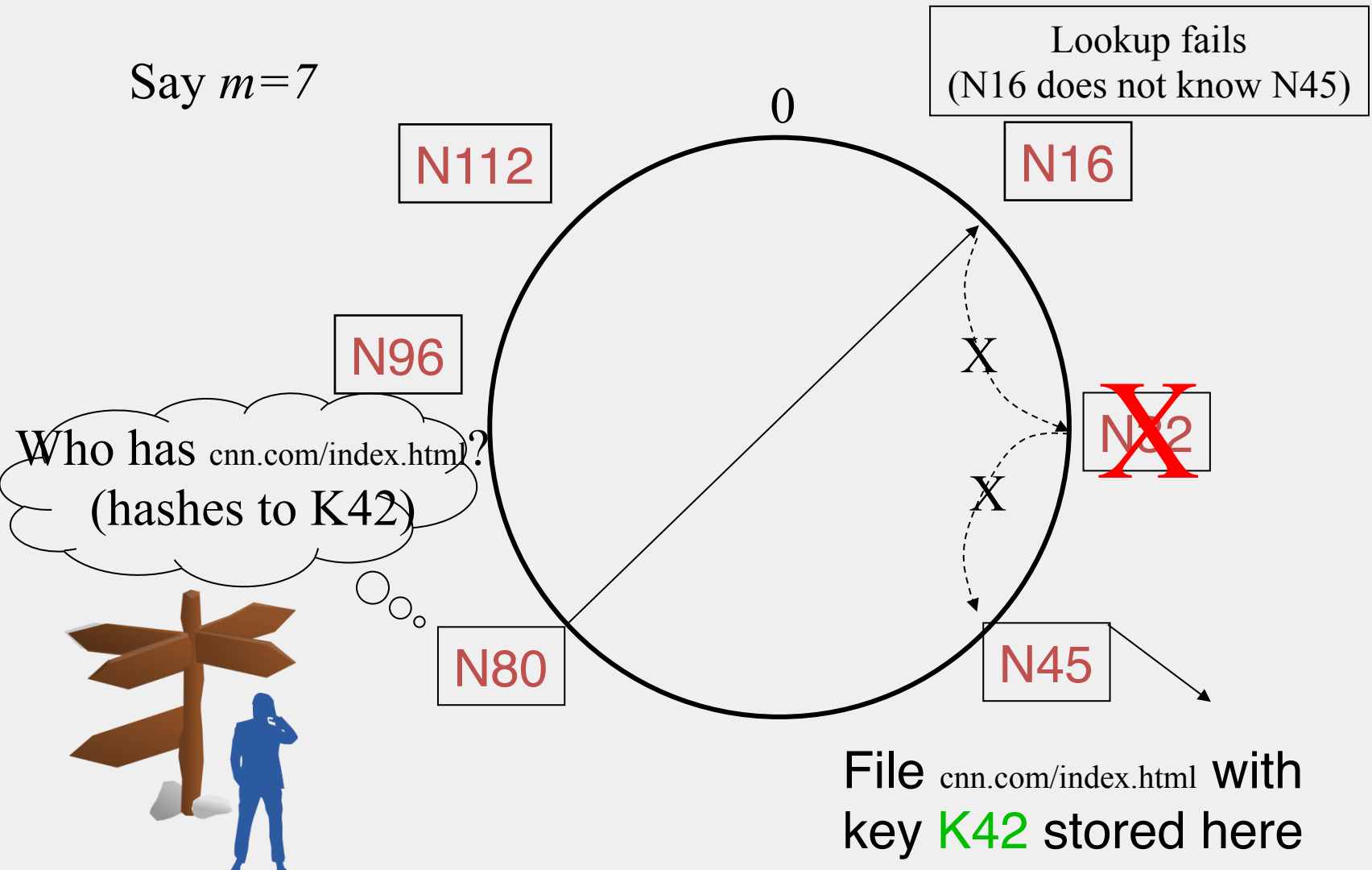 So using *successor*s in that range will be ok, using another *O(log(N))* hops
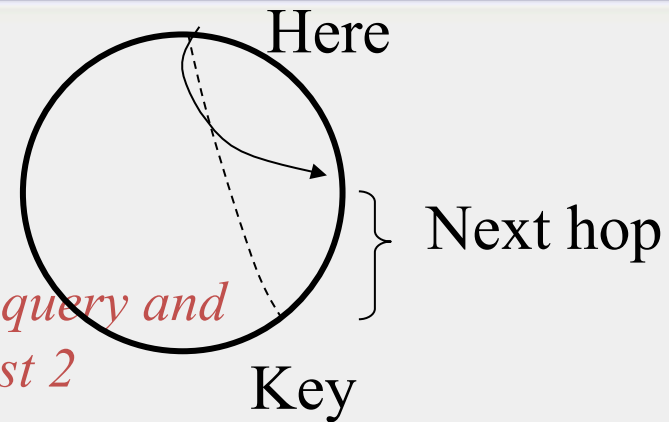
ANALYSIS (CONTD.)

- *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

Say *m=7*

Lookup fails
(N16 does not know N45)

0

N112

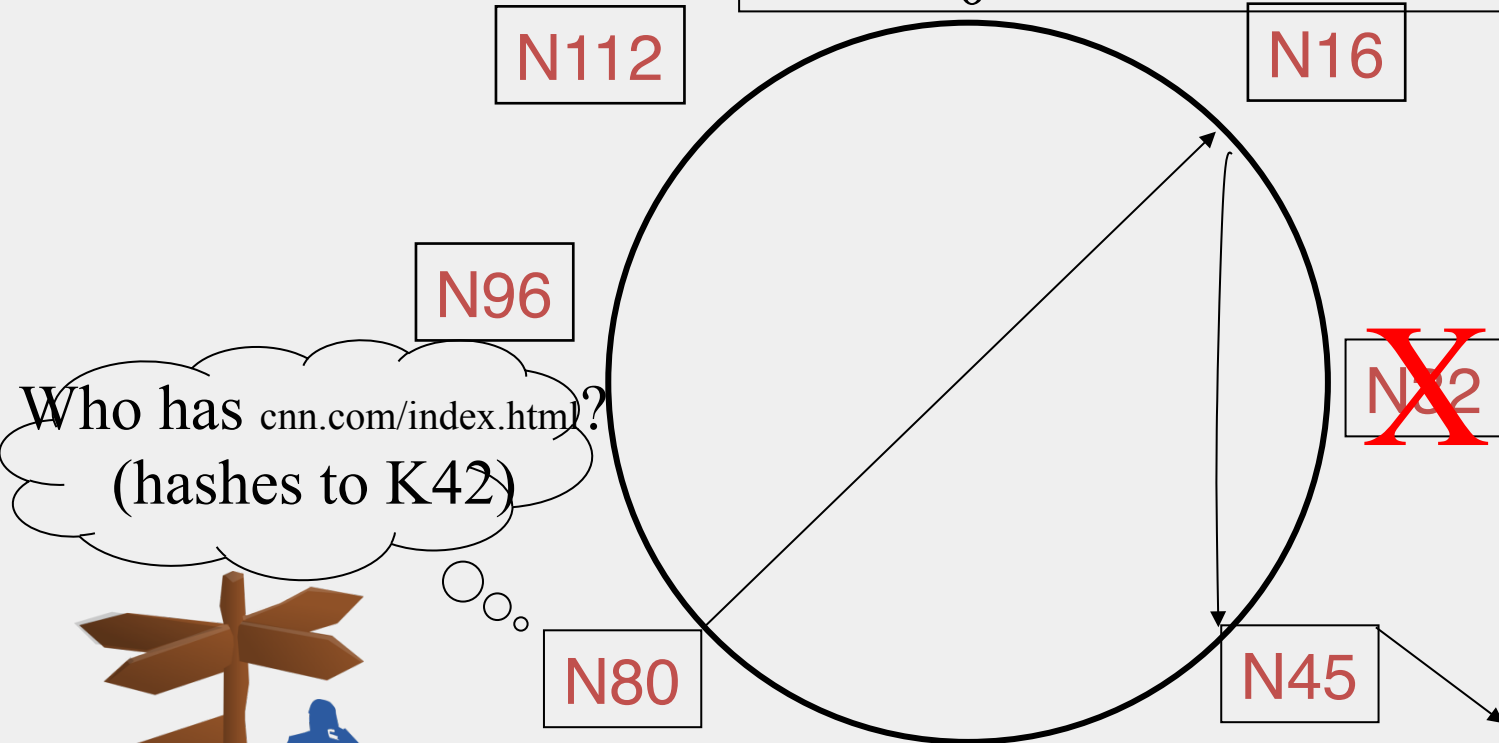N16

N96

X

Who has cnn.com/index.html?
(hashes to K42)

X

N32

X

N80

N45

File cnn.com/index.html with
key K42 stored here

SEARCH UNDER PEER FAILURES

Say *m=7*

One solution: maintain *r* multiple *successor* entries
In case of failure, use successor entries

N112

0

N16

N96

N80

X N32

N45

Who has cnn.com/index.html?
(hashes to K42)

File cnn.com/index.html with
key K42 stored here

- 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)=

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

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

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

Say *m=7*

N112

N96

0

N16

Lookup fails
(N45 is dead)

N32

X

Who has cnn.com/index.html?
(hashes to K42)

N80

N45

File cnn.com/index.html with
key K42 stored here

Say *m=7*

One solution: replicate file/key at *r* successors and predecessors

0

N112

N16

N96

Who has cnn.com/index.html?
(hashes to K42)

N32

K42 replicated

N80

N45

K42 replicated

File cnn.com/index.html with key K42 stored here
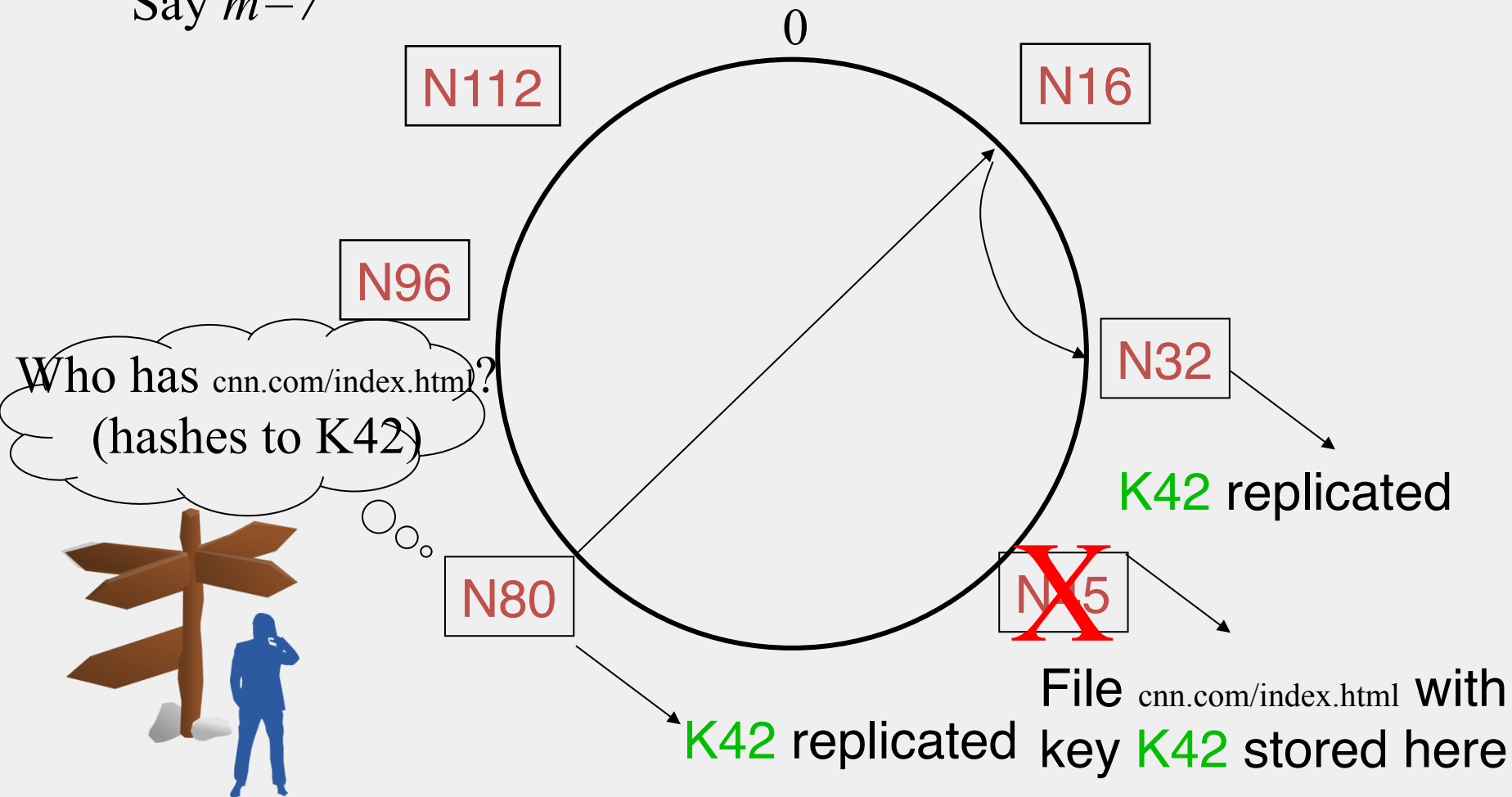
NEED TO DEAL WITH DYNAMIC CHANGES

✓ 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

Say *m=7*

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

0

N112

N16

Stabilization Protocol (followed by all nodes)

N96

N32

N40

N80

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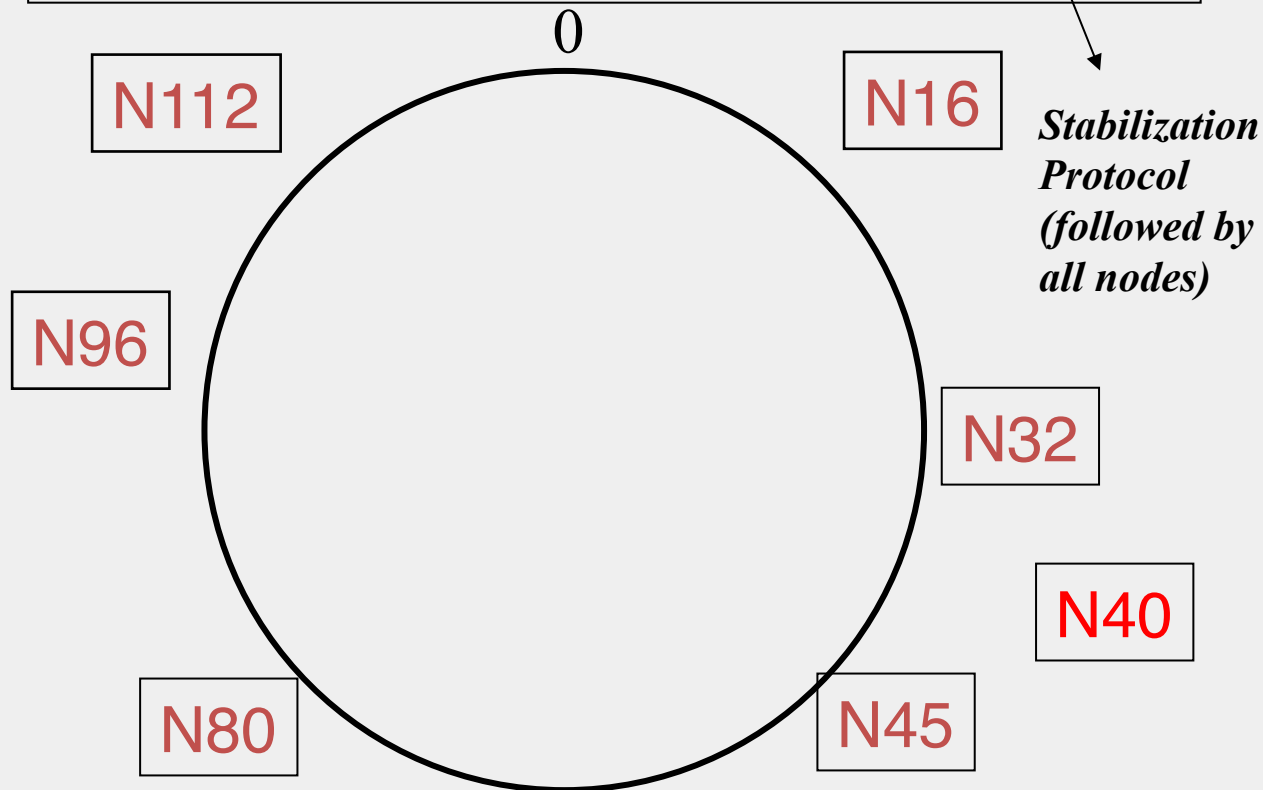
N40 may need to copy some files/keys from N45
(files with fileid between 32 and 40)

Say *m=7*

0

N112

N16

N96

N32

N40

N80

N45

K34,K38

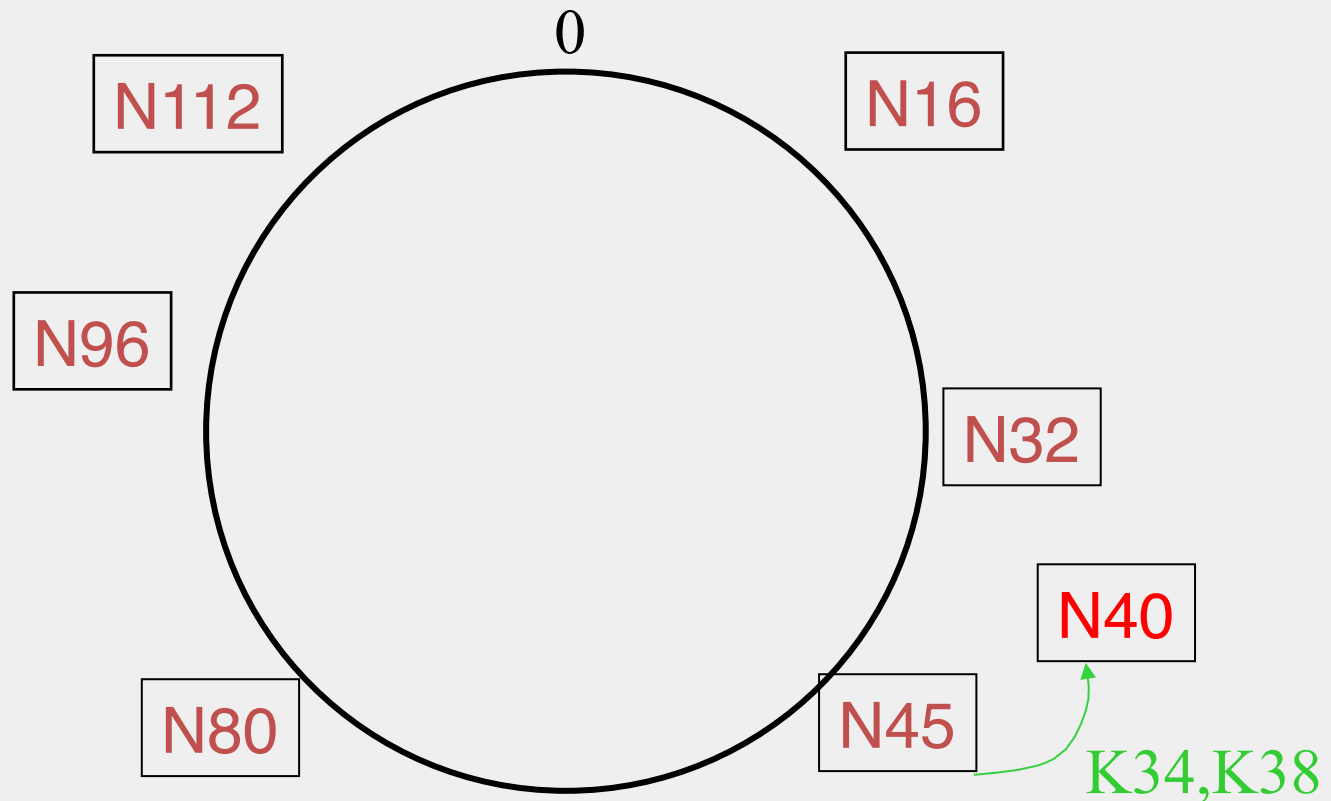# New peers joining (3)

- 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* (we'll see these later in the course!)

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 [TechReport 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 (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

Chord 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

    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 **<u>prefix matching</u>**
  - 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 (* = bit different 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

Affinity Group # 0   # 1   # k-1
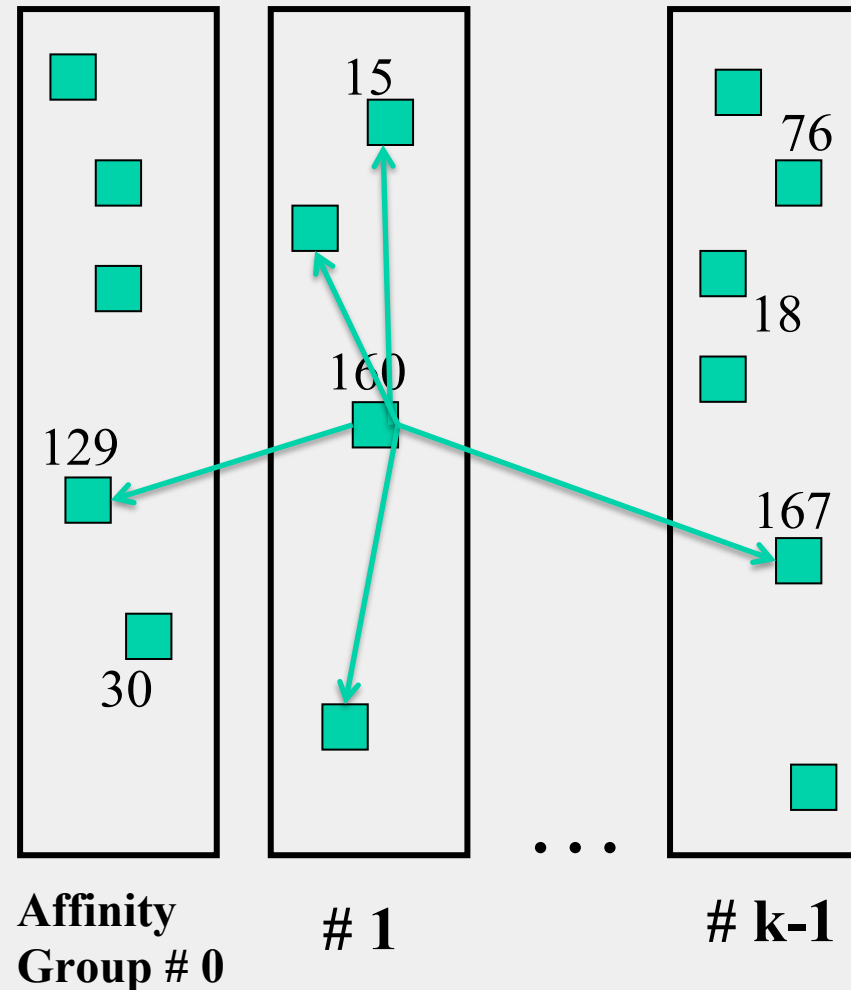
Kelips Files and Metadata

- 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>

15

76

160

18

129

167

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Affinity Group # 0   **# 1**   . . .   **# k-1**
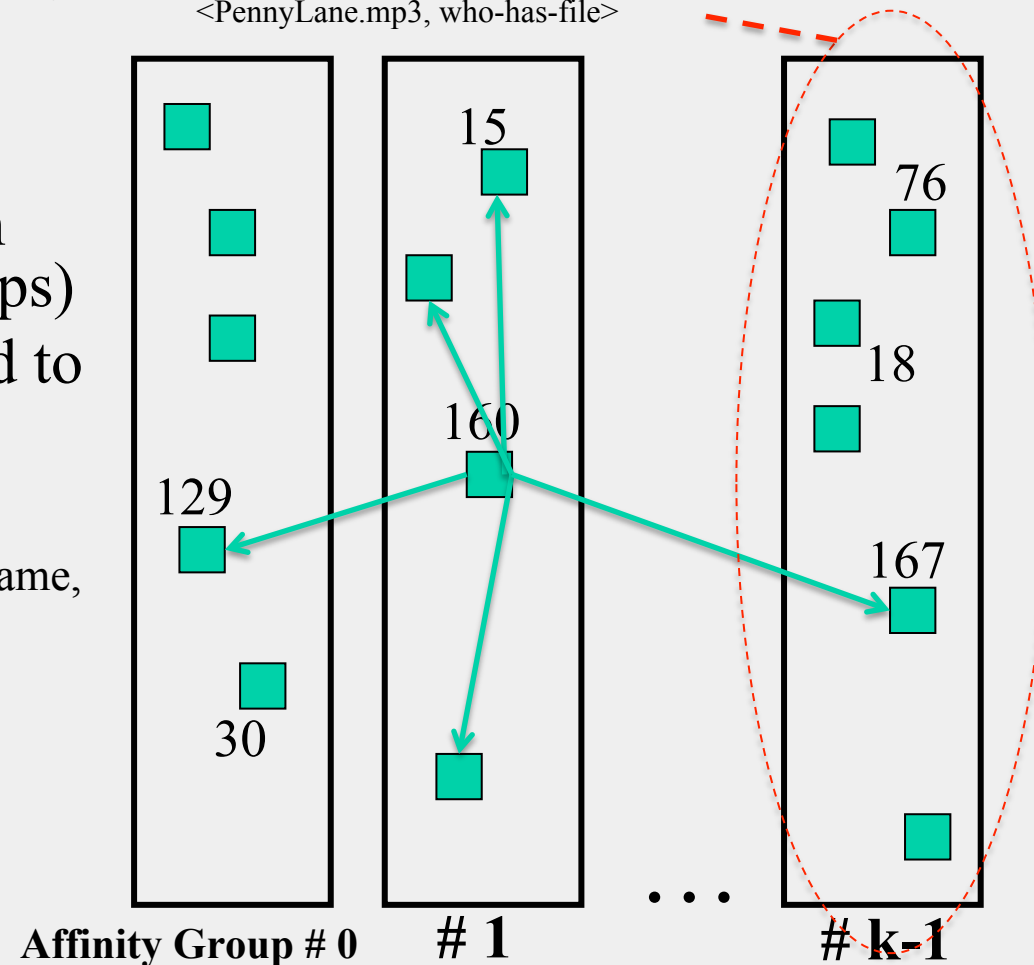
Kelips Lookup

- 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 $O(\sqrt{N})$
- 1.93 MB for 100K nodes, 10M files
- Fits in RAM of most workstations/laptops today (COTS machines)

- PennyLane.mp3 hashes to k-1
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Affinity Group # 0   **# 1**   · · ·   **# k-1**
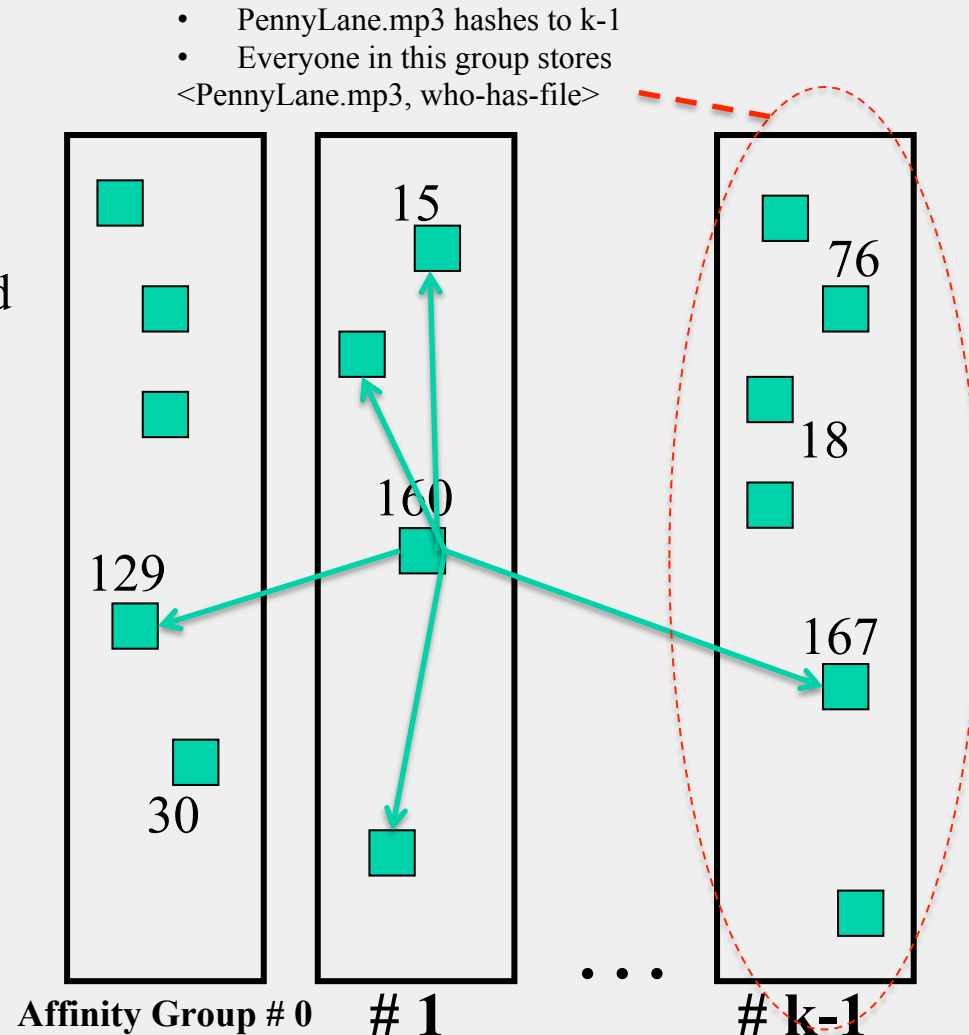
Kelips Soft State

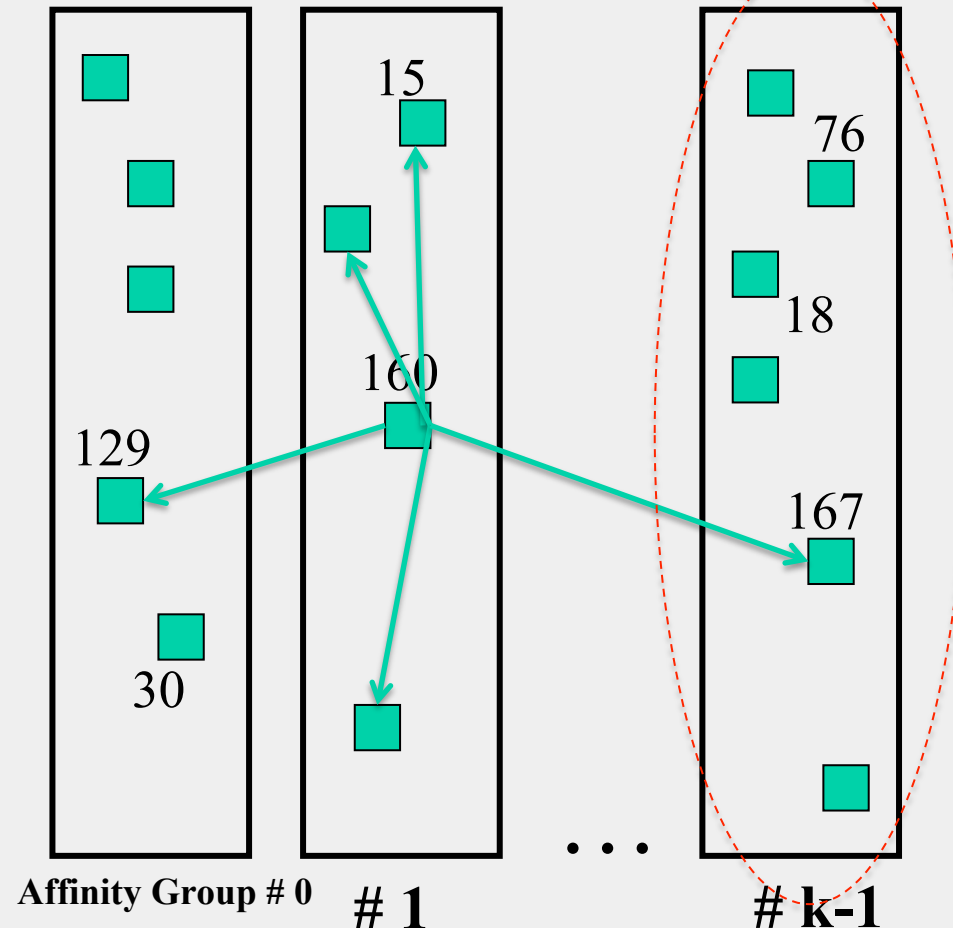- Membership lists
  - Gossip-based membership
  - Within each affinity group
  - And also across affinity groups
  - *O(log(N))* dissemination time

- File metadata
  - Needs to be periodically refreshed from source node
  - Times out

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- Everyone in this group stores <PennyLane.mp3, who-has-file>

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Affinity Group # 0   # 1   . . .   # k-1

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