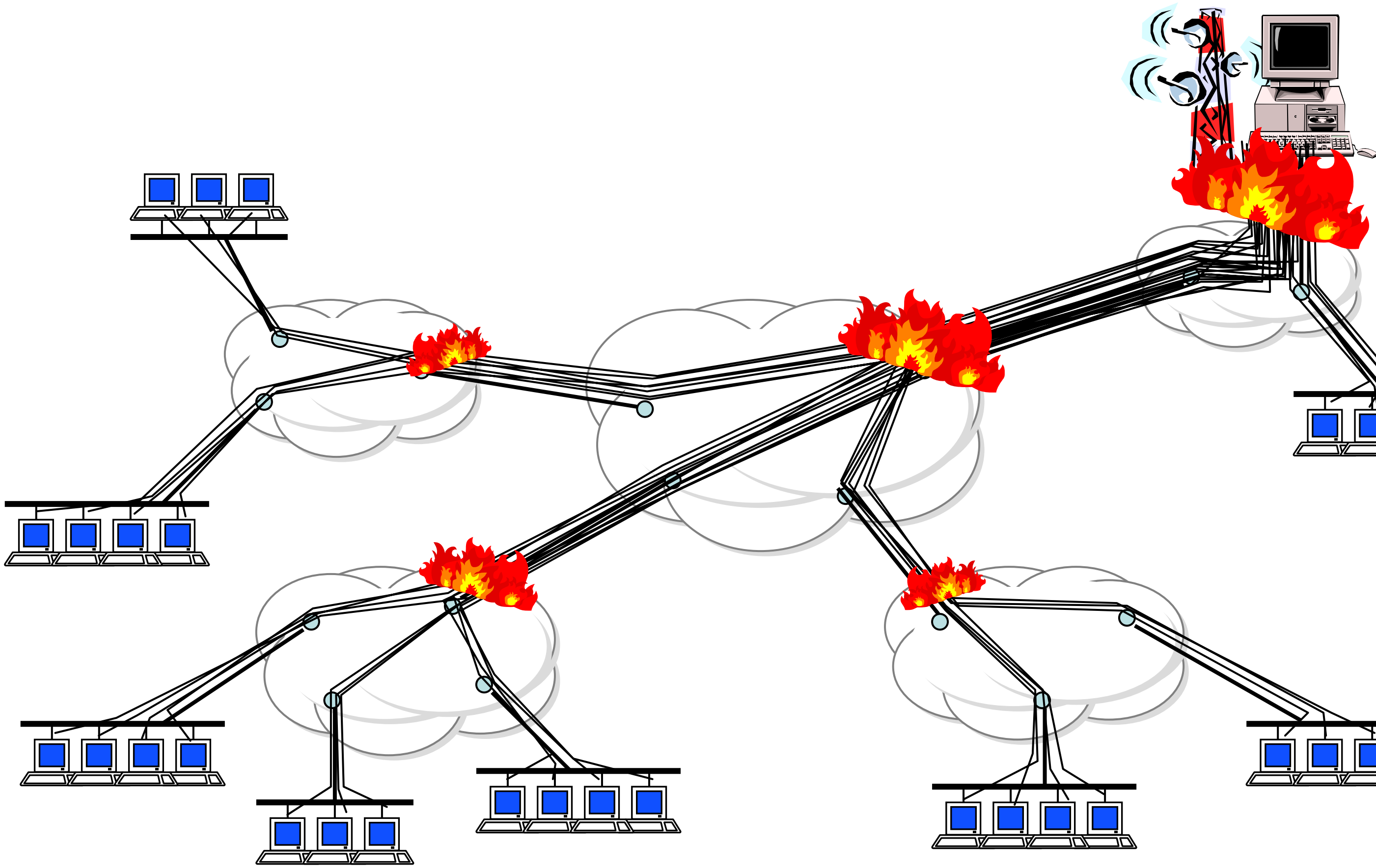
Peer-to-Peer

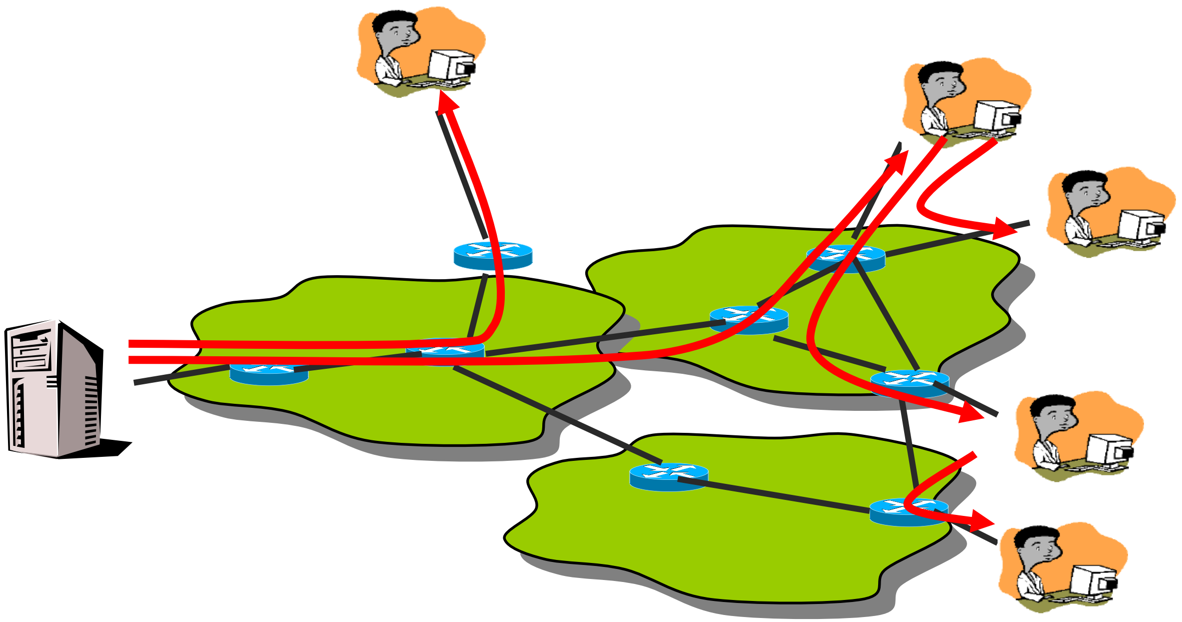
15-441

Scaling Problem

- Millions of clients $\Rightarrow$ server and network meltdown



P2P System



- Leverage the resources of client machines (peers)
  - Computation, storage, bandwidth

Why p2p?

- Harness lots of spare capacity
  - 1 Big Fast Server: 1Gbit/s, $10k/month++
  - 2,000 cable modems: 1Gbit/s, $??
  - 1M end-hosts: Uh, wow.
- Build self-managing systems / Deal with huge scale
  - Same techniques attractive for both companies / servers / p2p
    - E.g., Akamai's 14,000 nodes
    - Google's 100,000+ nodes

Outline

- p2p file sharing techniques
  - Downloading: Whole-file vs. chunks
  - Searching
    - Centralized index (Napster, etc.)
    - Flooding (Gnutella, etc.)
    - Smarter flooding (KaZaA, …)
    - Routing (Freenet, etc.)
- Uses of p2p - what works well, what doesn't?
  - servers vs. arbitrary nodes
  - Hard state (backups!) vs soft-state (caches)
- Challenges
  - Fairness, freeloading, security, …

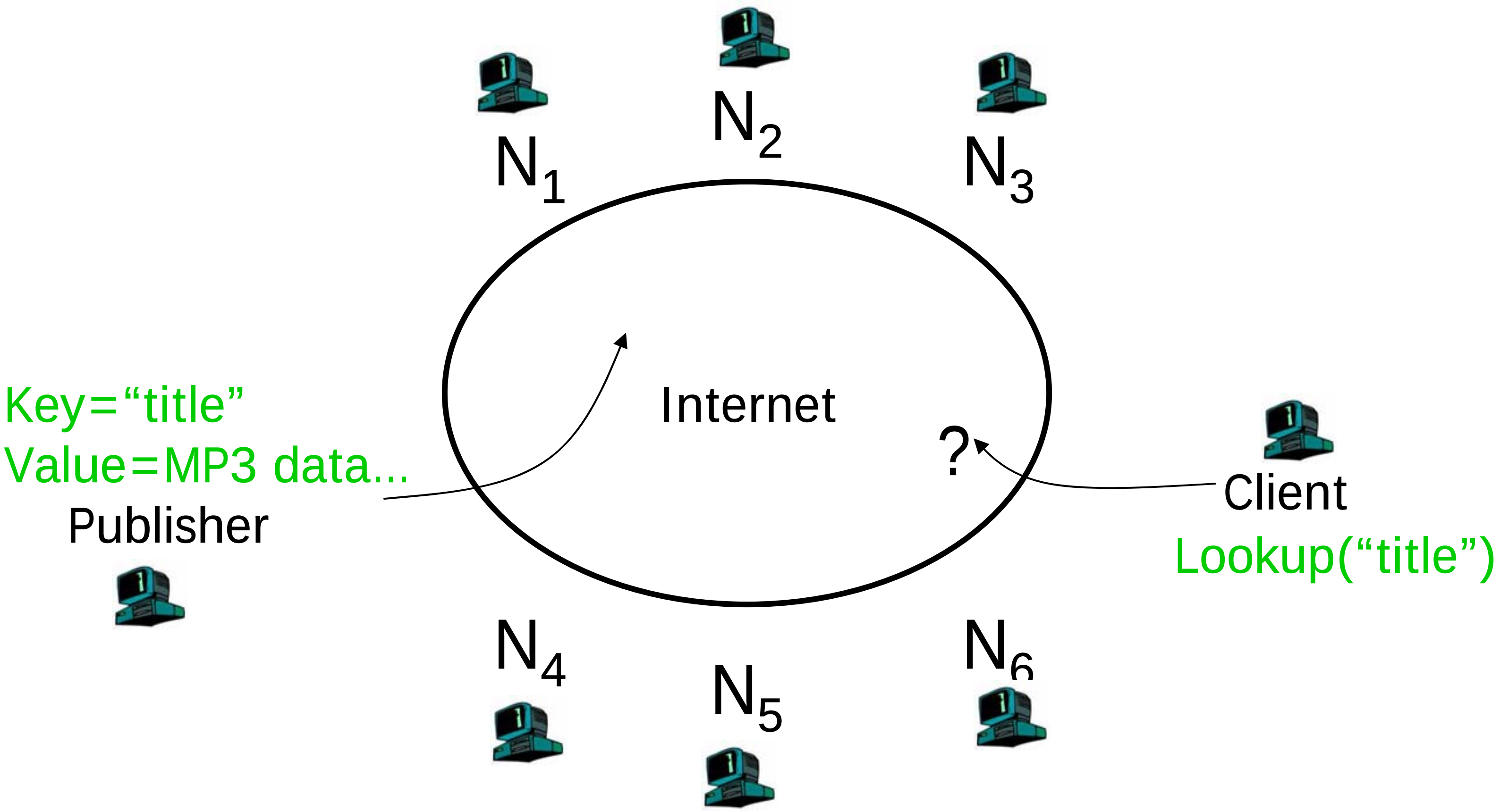
P2p file-sharing

- Quickly grown in popularity
  - Dozens or hundreds of file sharing applications
  - 35 million American adults use P2P networks -- 29% of all Internet users in US!
  - Audio/Video transfer now dominates traffic on the Internet

What's out there?

	Central	Flood	Super-node flood	Route
Whole File	Napster	Gnutella		Freenet
Chunk Based	BitTorrent		KaZaA (bytes, not chunks)	DHTs eDonkey 2000

Searching


N1
N2
N3
Internet
Key="title"
Value=MP3 data...
Publisher
?
Client
Lookup("title")
N4
N5
N6

Searching 2

- Needles vs. Haystacks
  - Searching for top 40, or an obscure punk track from 1981 that nobody’s heard of?
- Search expressiveness
  - Whole word? Regular expressions? File names? Attributes? Whole-text search?
    - (e.g., p2p gnutella or p2p google?)

Framework

- Common Primitives:
  - **Join**: how to I begin participating?
  - **Publish**: how do I advertise my file?
  - **Search**: how to I find a file?
  - **Fetch**: how to I retrieve a file?

Next Topic...

- **Centralized Database**
  - Napster
- **Query Flooding**
  - Gnutella
- **Intelligent Query Flooding**
  - KaZaA
- **Swarming**
  - BitTorrent
- **Unstructured Overlay Routing**
  - Freenet
- **Structured Overlay Routing**
  - Distributed Hash Tables

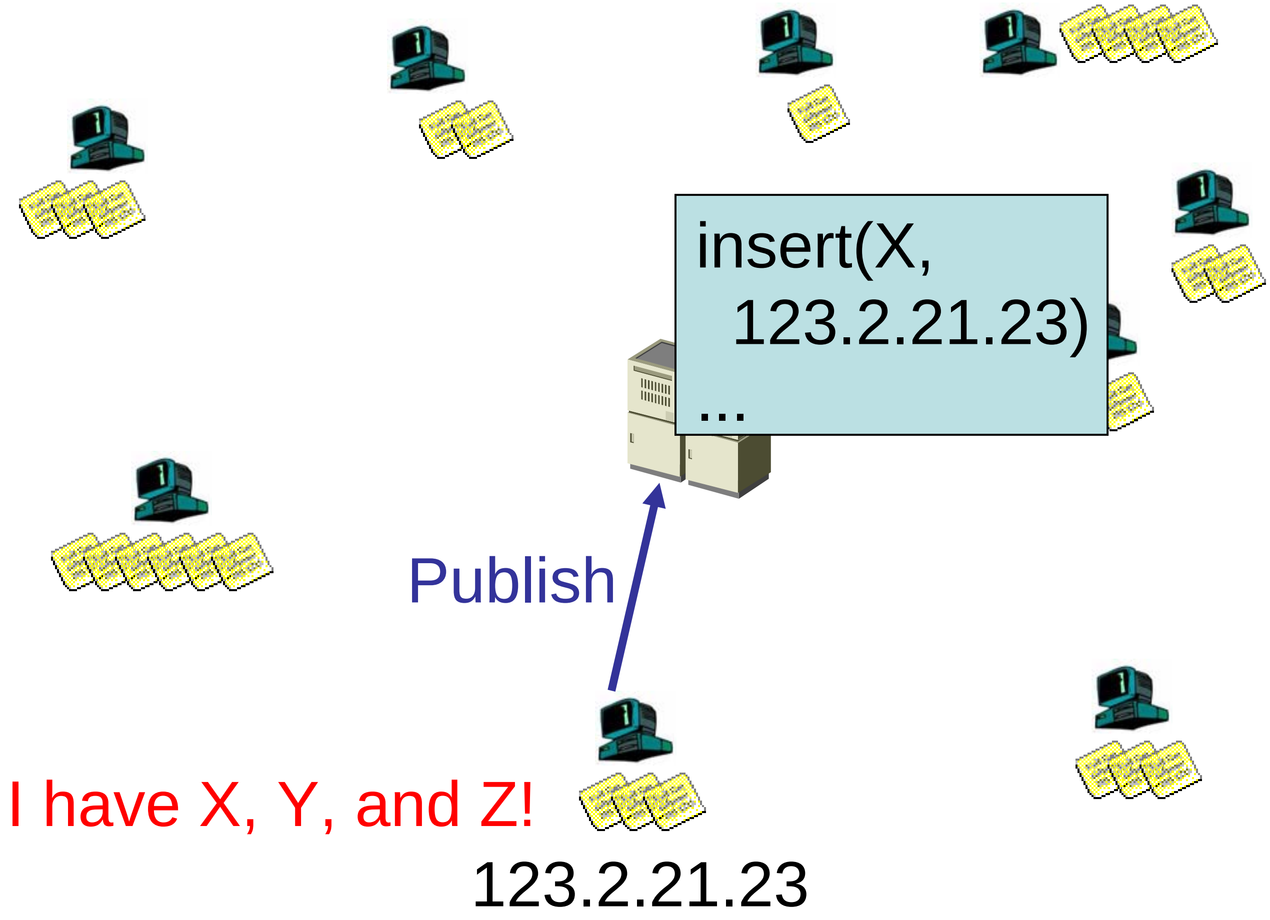
Napster: History

- 1999: Sean Fanning launches Napster
- Peaked at 1.5 million simultaneous users
- Jul 2001: Napster shuts down

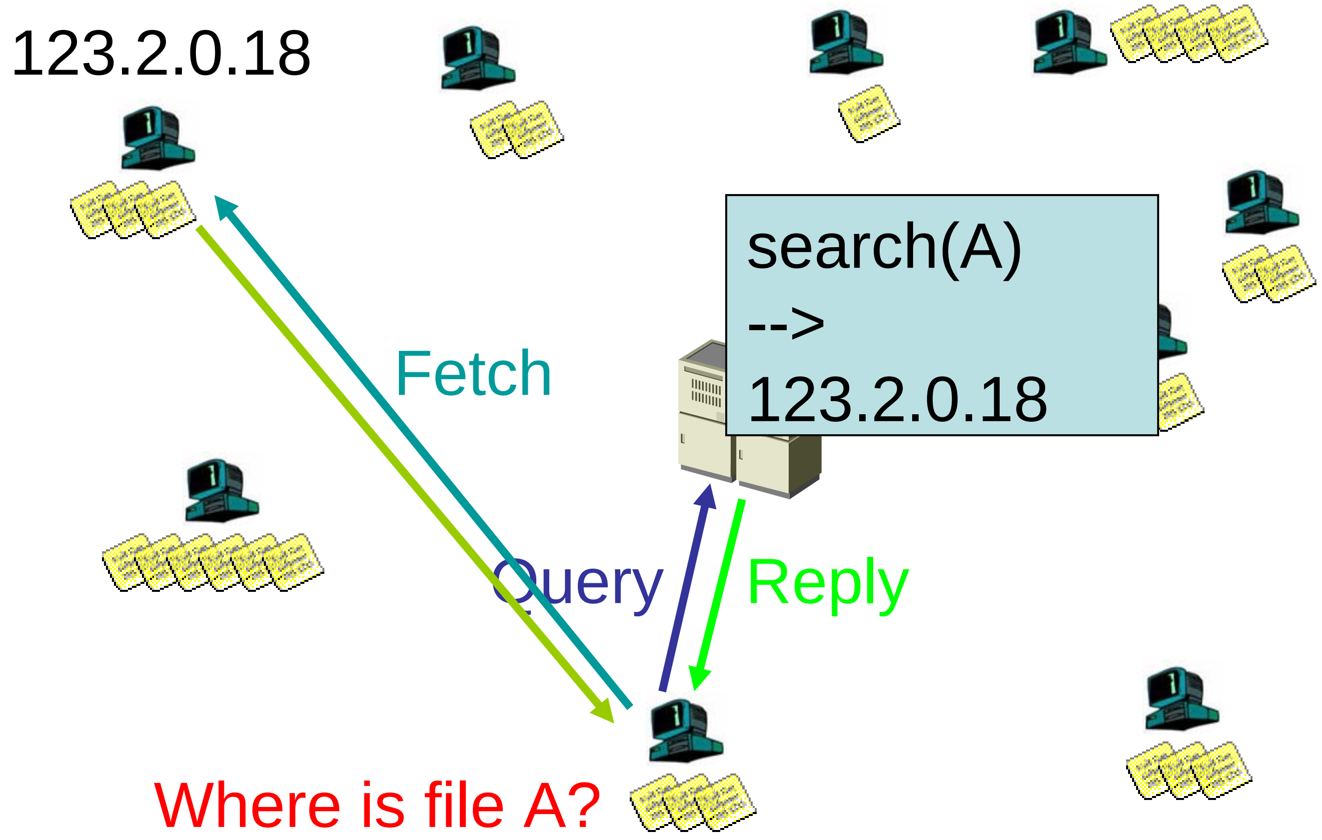
Napster: Overiew

- Centralized Database:
  - **Join**: on startup, client contacts central server
  - **Publish**: reports list of files to central server
  - **Search**: query the server => return someone that stores the requested file
  - **Fetch**: get the file directly from peer

Napster: Publish



Napster: Search



Napster: Discussion

- Pros:
  - Simple
  - Search scope is O(1)
  - Controllable (pro or con?)
- Cons:
  - Server maintains O(N) State
  - Server does all processing
  - Single point of failure

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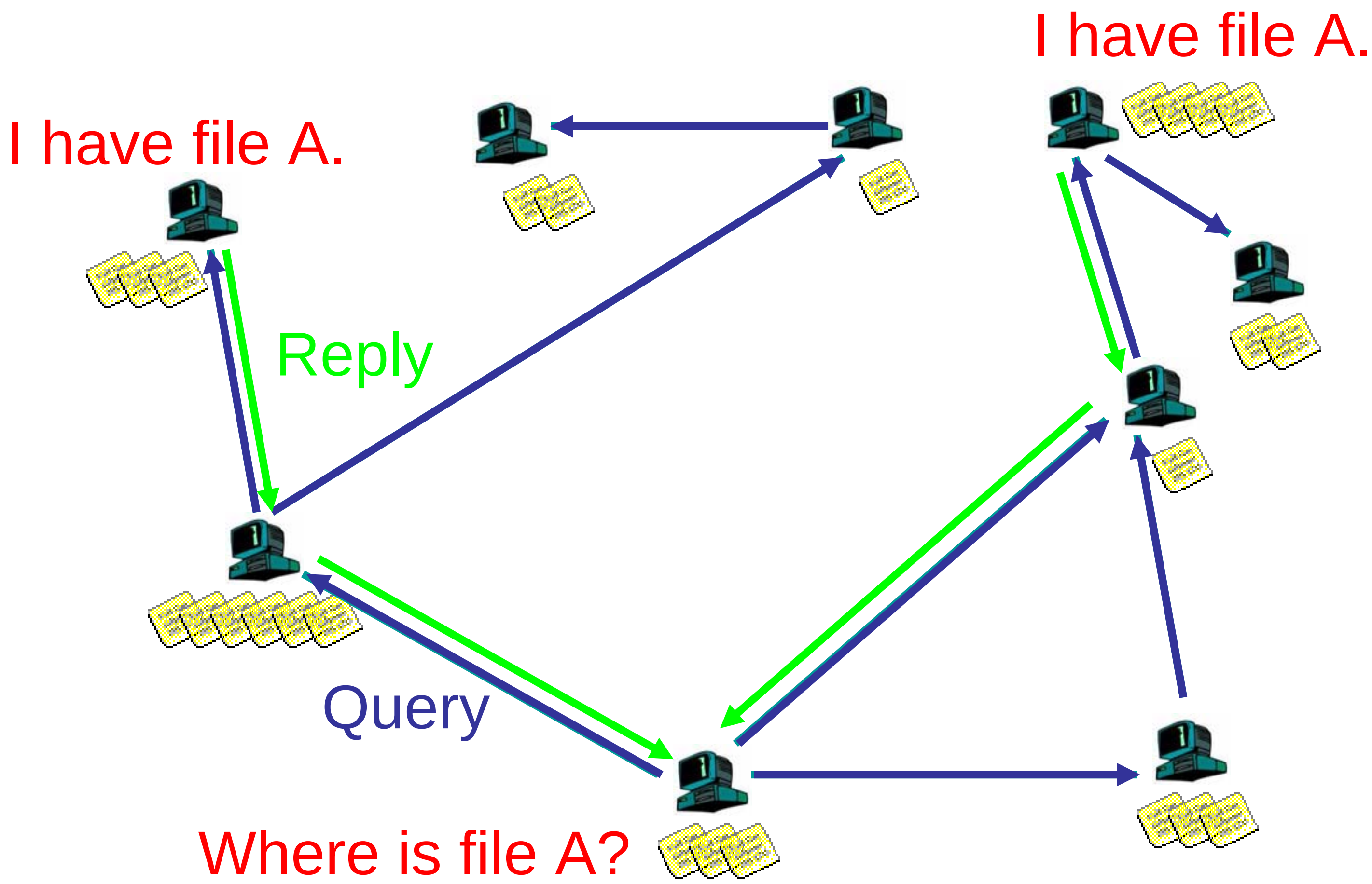
Gnutella: History

- In 2000, J. Frankel and T. Pepper from Nullsoft released Gnutella
- Soon many other clients: Bearshare, Morpheus, LimeWire, etc.
- In 2001, many protocol enhancements including “ultrapeers”

Gnutella: Overview

- Query Flooding:
  - **Join**: on startup, client contacts a few other nodes; these become its "neighbors"
  - **Publish**: no need
  - **Search**: ask neighbors, who ask their neighbors, and so on... when/if found, reply to sender.
    - TTL limits propagation
  - **Fetch**: get the file directly from peer

Gnutella: Search



Gnutella: Discussion

- Pros:
  - Fully de-centralized
  - Search cost distributed
  - Processing @ each node permits powerful search semantics
- Cons:
  - Search scope is O(*N*)
  - Search time is O(???)
  - Nodes leave often, network unstable
- TTL-limited search works well for haystacks.
  - For scalability, does NOT search every node. May have to re-issue query later

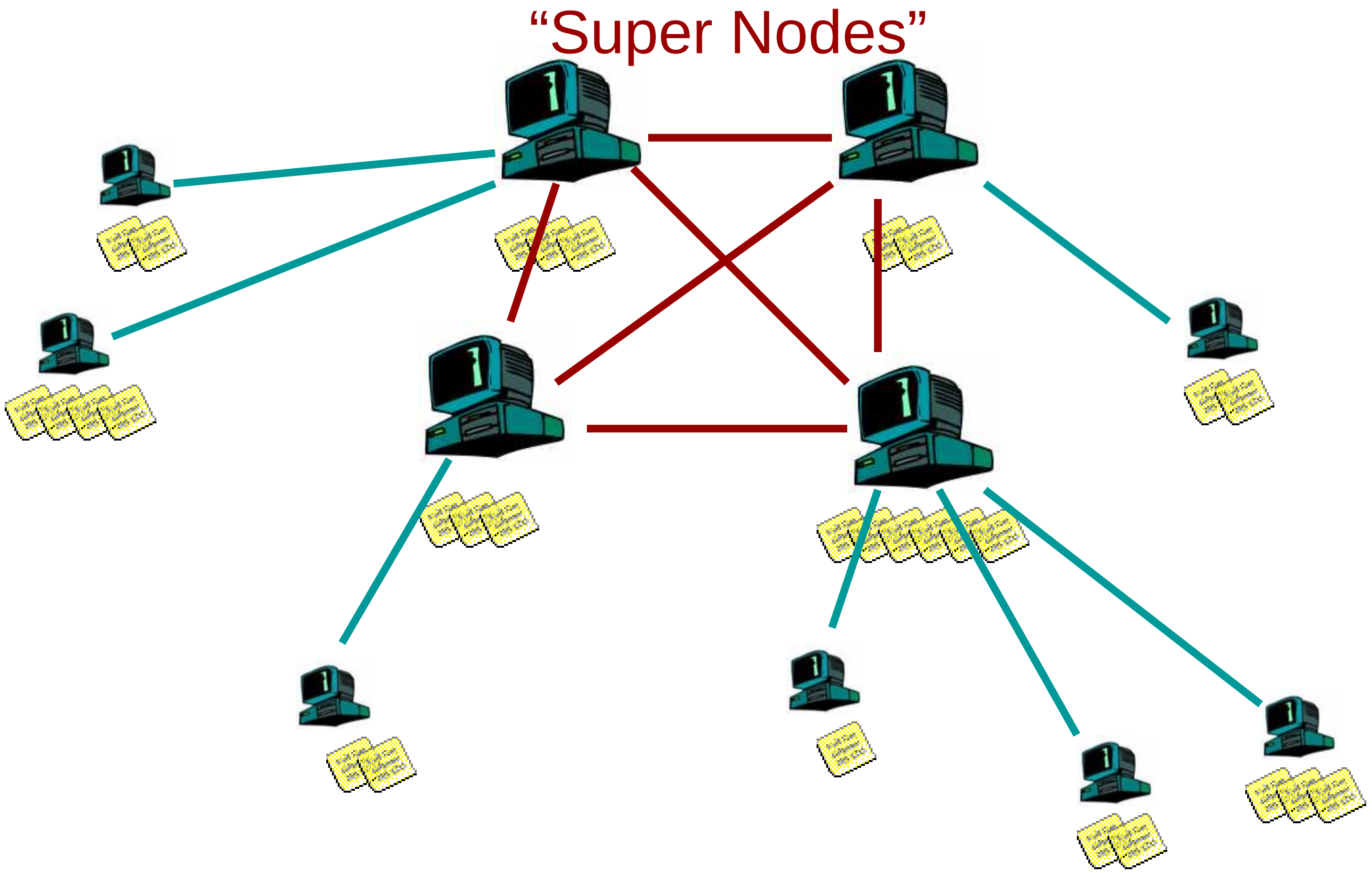
KaZaA: History

- In 2001, KaZaA created by Dutch company Kazaa BV
- Single network called FastTrack used by other clients as well: Morpheus, giFT, etc.
- Eventually protocol changed so other clients could no longer talk to it
- Most popular file sharing network today with >10 million users (number varies)

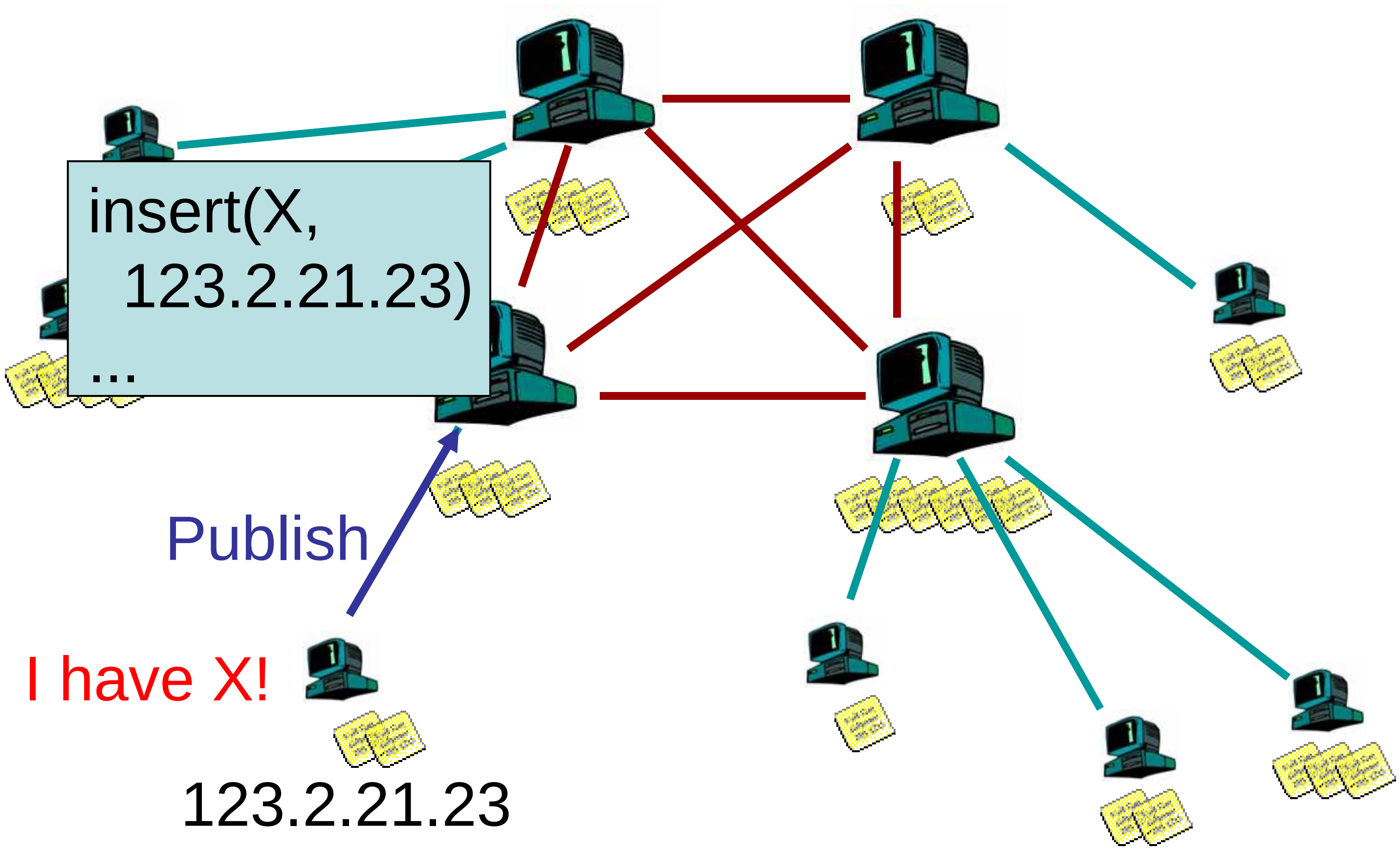
KaZaA: Overview

- “Smart” Query Flooding:
  - **Join**: on startup, client contacts a “supernode” ... may at some point become one itself
  - **Publish**: send list of files to supernode
  - **Search**: send query to supernode, supernodes flood query amongst themselves.
  - **Fetch**: get the file directly from peer(s); can fetch simultaneously from multiple peers

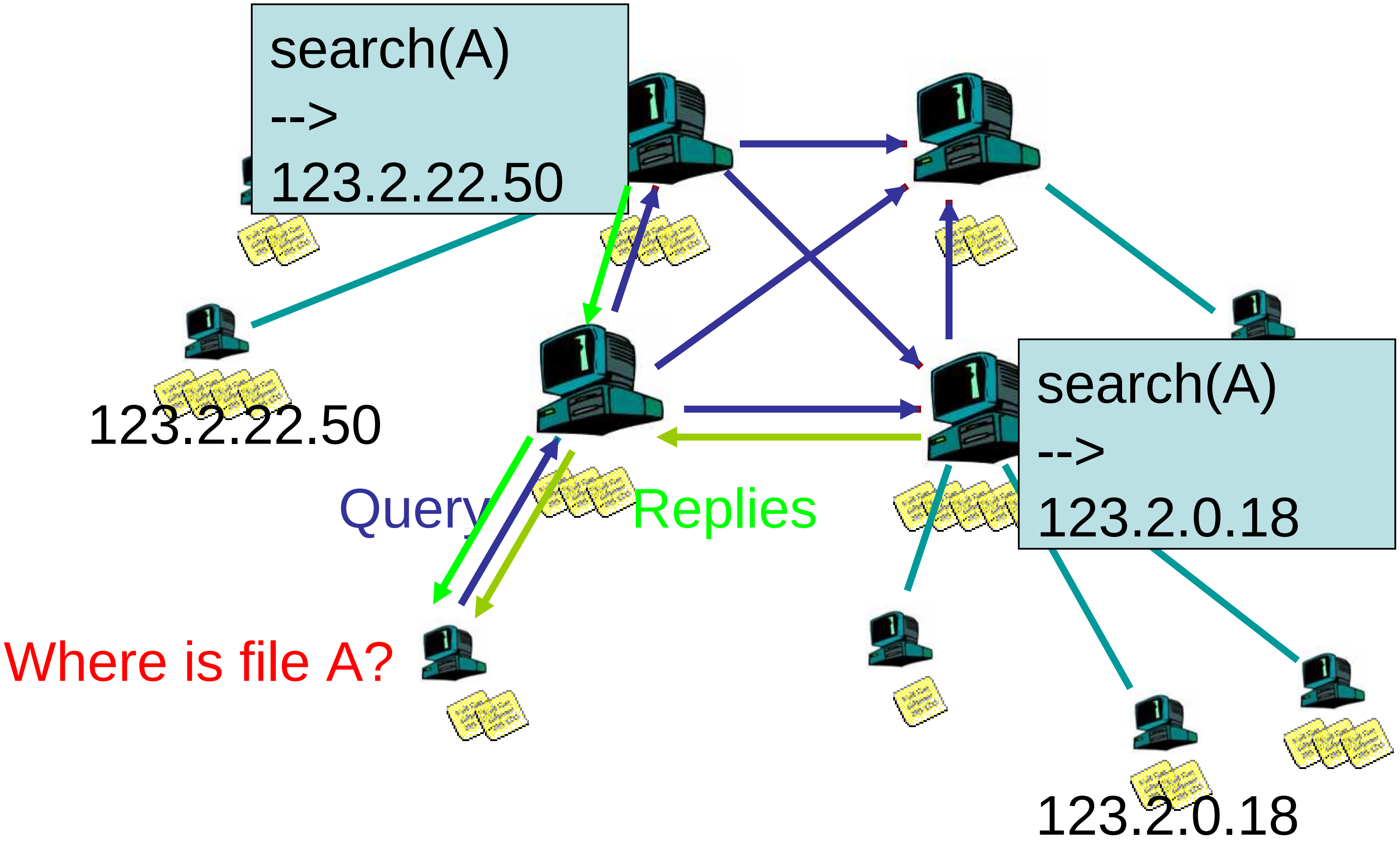
KaZaA: Network Design



KaZaA: File Insert



KaZaA: File Search



KaZaA: Fetching

- More than one node may have requested file...
- How to tell?
  - Must be able to distinguish identical files
  - Not necessarily same filename
  - Same filename not necessarily same file...
- Use Hash of file
  - KaZaA uses UUHash: fast, but not secure
  - Alternatives: MD5, SHA-1
- How to fetch?
  - Get bytes [0..1000] from A, [1001...2000] from B
  - Alternative: Erasure Codes

KaZaA: Discussion

- Pros:
  - Tries to take into account node heterogeneity:
    - Bandwidth
    - Host Computational Resources
    - Host Availability (?)
  - Rumored to take into account network locality
- Cons:
  - Mechanisms easy to circumvent
  - Still no real guarantees on search scope or search time
- Similar behavior to gnutella, but better.

Stability and Superpeers

- Why superpeers?
  - Query consolidation
    - Many connected nodes may have only a few files
    - Propagating a query to a sub-node would take more b/w than answering it yourself
  - Caching effect
    - Requires network stability
- Superpeer selection is time-based
  - How long you've been on is a good predictor of how long you'll be around.

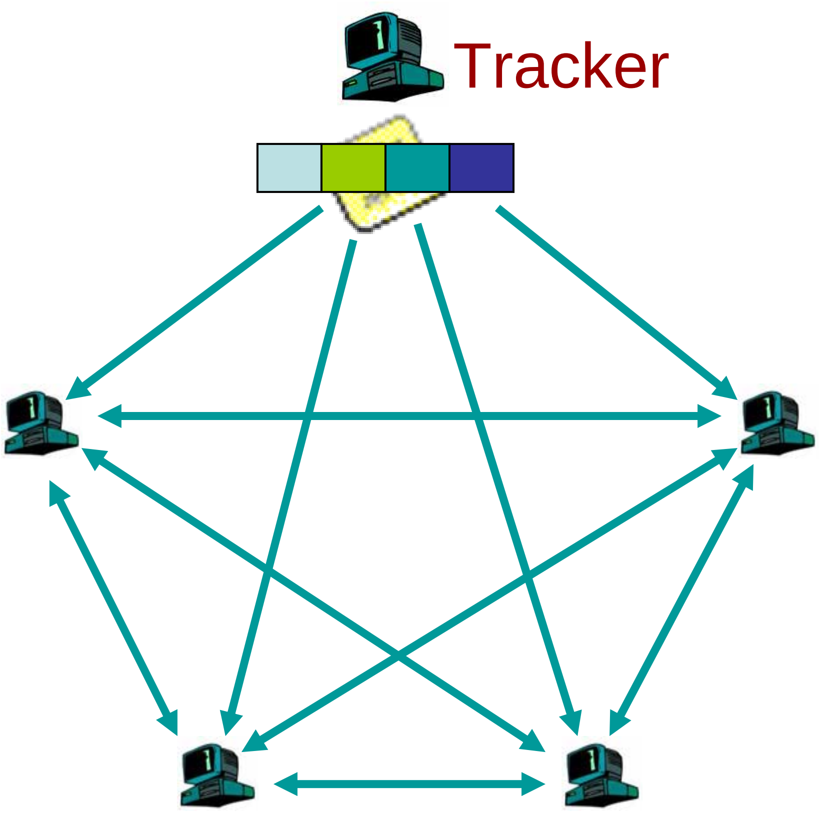
BitTorrent: History

- In 2002, B. Cohen debuted BitTorrent
- Key Motivation:
  - Popularity exhibits temporal locality (Flash Crowds)
  - E.g., Slashdot effect, CNN on 9/11, new movie/game release
- Focused on Efficient *Fetching*, not *Searching*:
  - Distribute the *same* file to all peers
  - Single publisher, multiple downloaders
- Has some "real" publishers:
  - Blizzard Entertainment using it to distribute the beta of their new game

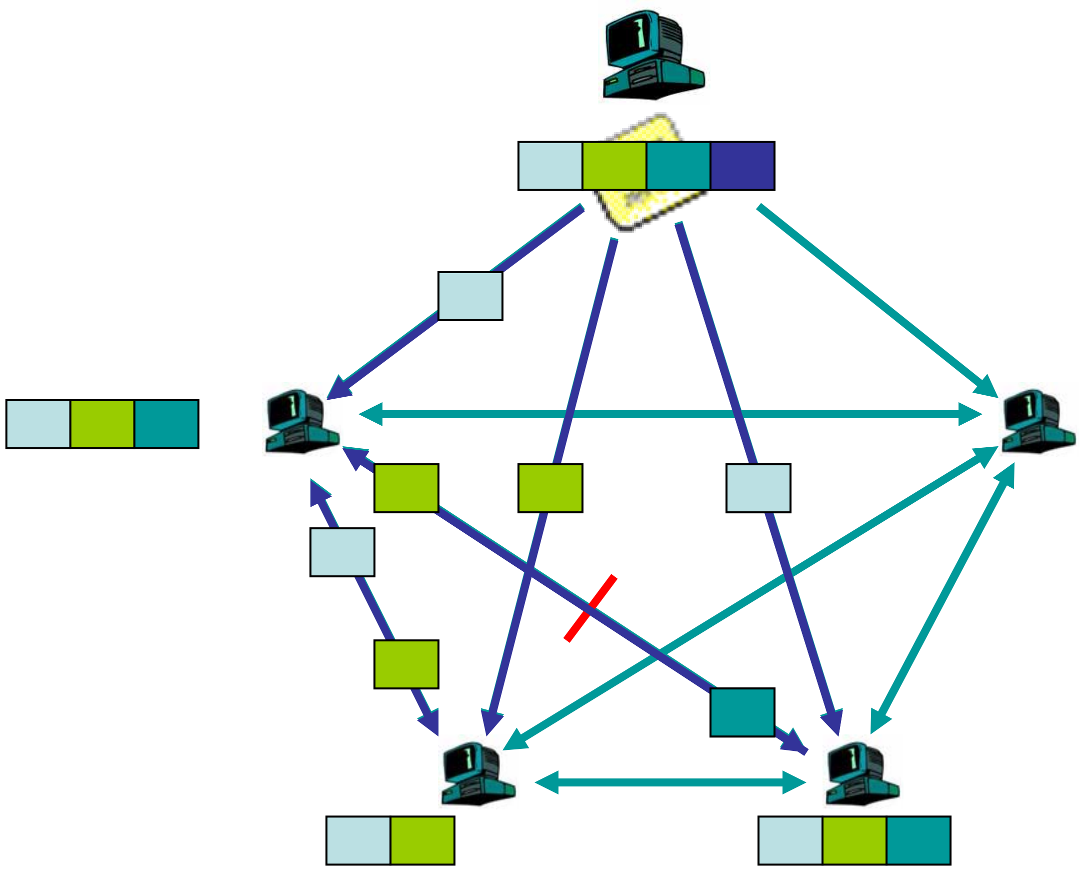
BitTorrent: Overview

- Swarming:
  - **Join**: contact centralized “tracker” server, get a list of peers.
  - **Publish**: Run a tracker server.
  - **Search**: Out-of-band. E.g., use Google to find a tracker for the file you want.
  - **Fetch**: Download chunks of the file from your peers. Upload chunks you have to them.
- Big differences from Napster:
  - Chunk based downloading (sound familiar? :)
  - “few large files” focus
  - Anti-freeloading mechanisms

BitTorrent: Publish/Join



BitTorrent: Fetch



BitTorrent: Sharing Strategy

- Employ “Tit-for-tat” sharing strategy
  - A is downloading from some other people
    - A will let the fastest N of those download from him
  - Be optimistic: occasionally let freeloaders download
    - Otherwise no one would ever start!
    - Also allows you to discover better peers to download from when they reciprocate
  - Let N peop
- Goal: Pareto Efficiency
  - Game Theory: “No change can make anyone better off without making others worse off”
  - Does it work? (don’t know!)

BitTorrent: Summary

- Pros:
  - Works reasonably well in practice
  - Gives peers incentive to share resources; avoids freeloaders
- Cons:
  - Pareto Efficiency relative weak condition
  - Central tracker server needed to bootstrap swarm
  - (Tracker is a design choice, not a requirement, as you know from your projects. Could easily combine with other approaches.)

Next Topic...

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- **Query Flooding**
  - Gnutella
- **Intelligent Query Flooding**
  - KaZaA
- **Swarming**
  - BitTorrent
- **Unstructured Overlay Routing**
  - Freenet
- **Structured Overlay Routing**
  - Distributed Hash Tables (DHT)

Distributed Hash Tables

- Academic answer to p2p
- Goals
  - Guatanteed lookup success
  - Provable bounds on search time
  - Provable scalability
- Makes some things harder
  - Fuzzy queries / full-text search / etc.
- Read-write, not read-only
- Hot Topic in networking since introduction in ~2000/2001

DHT: Overview

- **Abstraction**: a distributed “hash-table” (DHT) data structure:
  - put(id, item);
  - item = get(id);
- **Implementation**: nodes in system form a distributed data structure
  - Can be Ring, Tree, Hypercube, Skip List, Butterfly Network, ...

DHT: Overview (2)

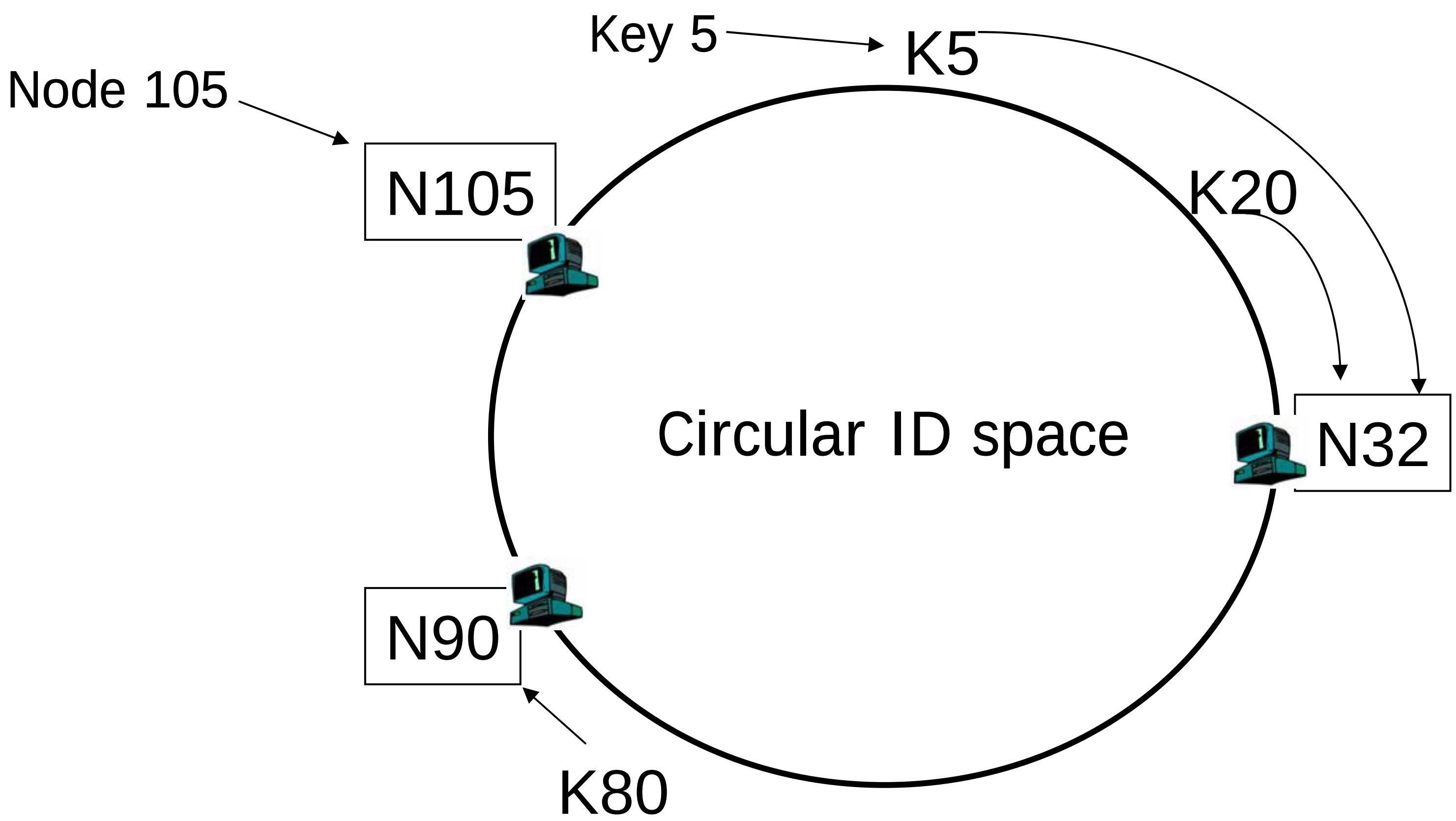
- Structured Overlay Routing:
  - **Join**: On startup, contact a “bootstrap” node and integrate yourself into the distributed data structure; get a *node id*
  - **Publish**: Route publication for *file id* toward a close *node id* along the data structure
  - **Search**: Route a query for file id toward a close node id. Data structure guarantees that query will meet the publication.
  - **Fetch**: Two options:
    - Publication contains actual file => fetch from where query stops
    - Publication says “I have file X” => query tells you 128.2.1.3 has X, use IP routing to get X from 128.2.1.3

DHT: Example - Chord

- Associate to each node and file a unique *id* in an *uni*-dimensional space (a Ring)
  - E.g., pick from the range $[0...2^m]$
  - Usually the hash of the file or IP address
- Properties:
  - Routing table size is O(log *N*) , where *N* is the total number of nodes
  - Guarantees that a file is found in O(log *N*) hops

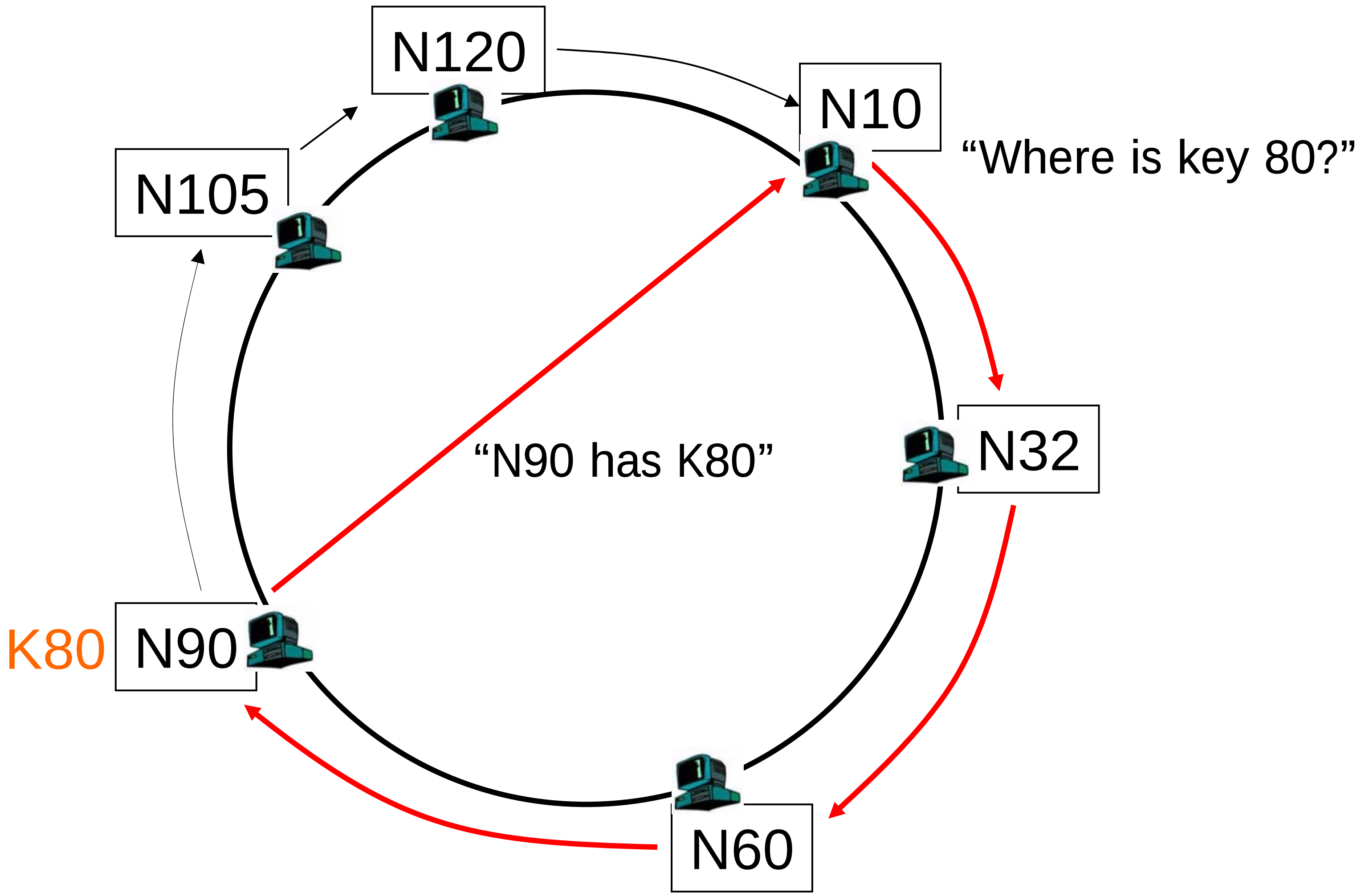
from MIT in 2001

DHT: Consistent Hashing

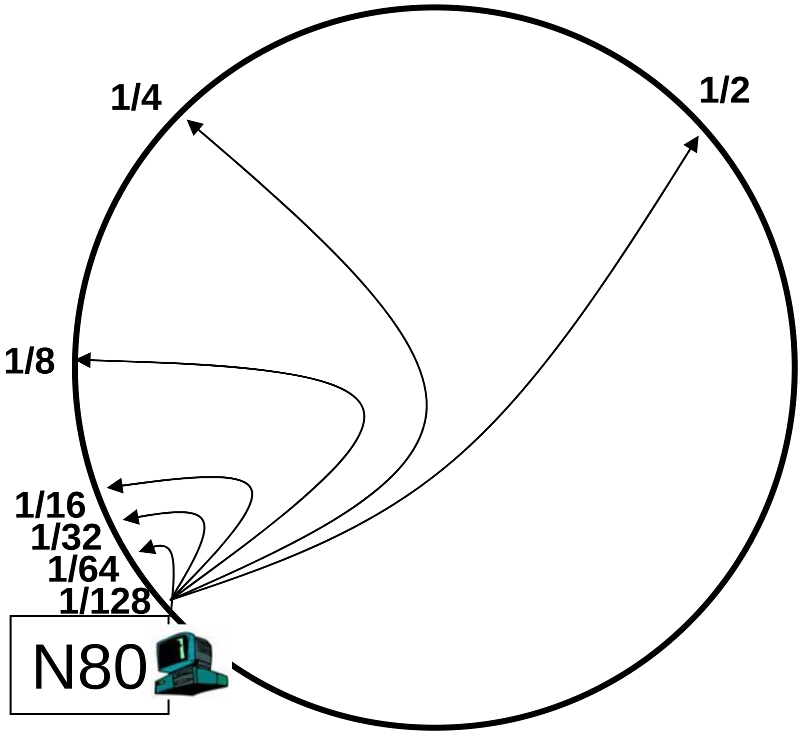


A key is stored at its successor: node with next higher ID

DHT: Chord Basic Lookup



DHT: Chord "Finger Table"

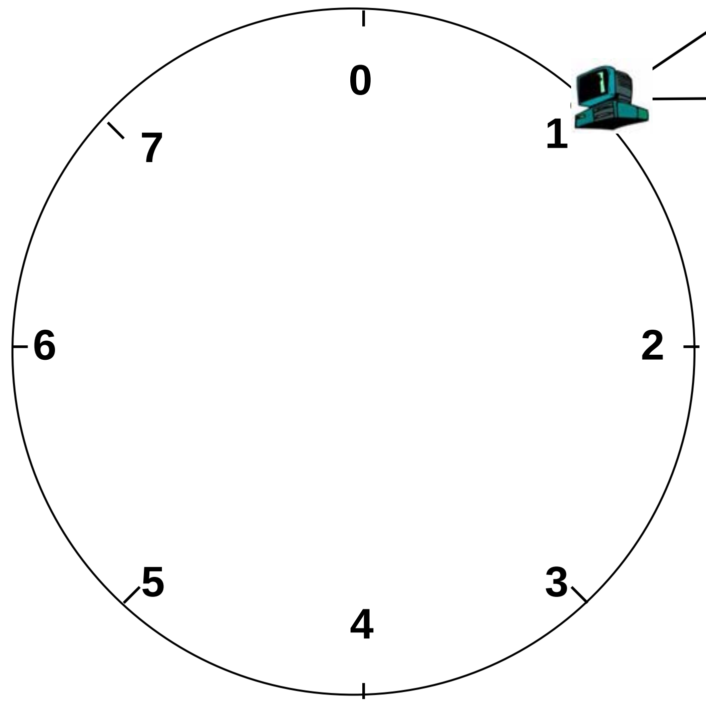


- Entry *i* in the finger table of node *n* is the first node that succeeds or equals $n + 2^i$
- In other words, the ith finger points $1/2^{n-i}$ way around the ring

DHT: Chord Join

- Assume an identifier space [0..8]

- Node n1 joins

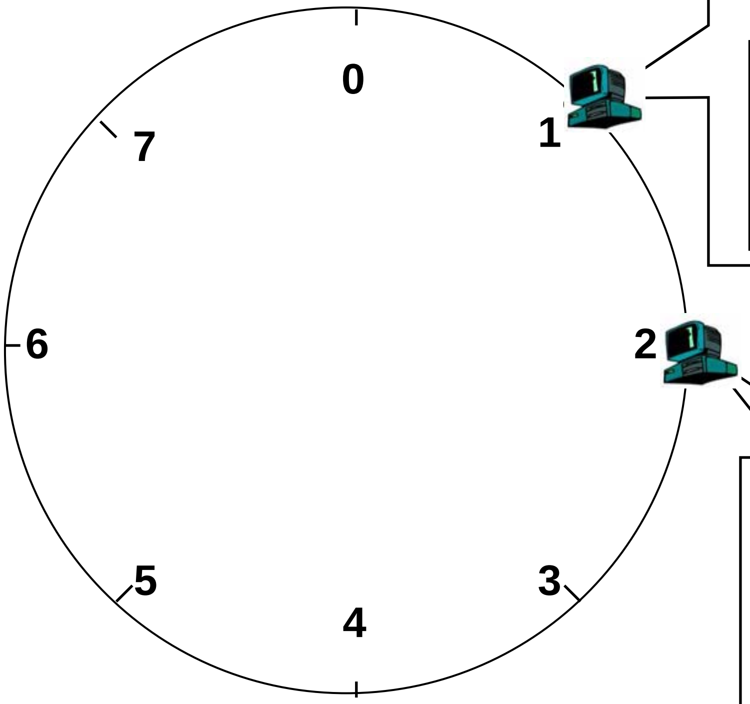


Succ. Table

i	*id*+2^i	succ
0	2	1
1	3	1
2	5	1

DHT: Chord Join

- Node n2 joins



Succ. Table (node 1)

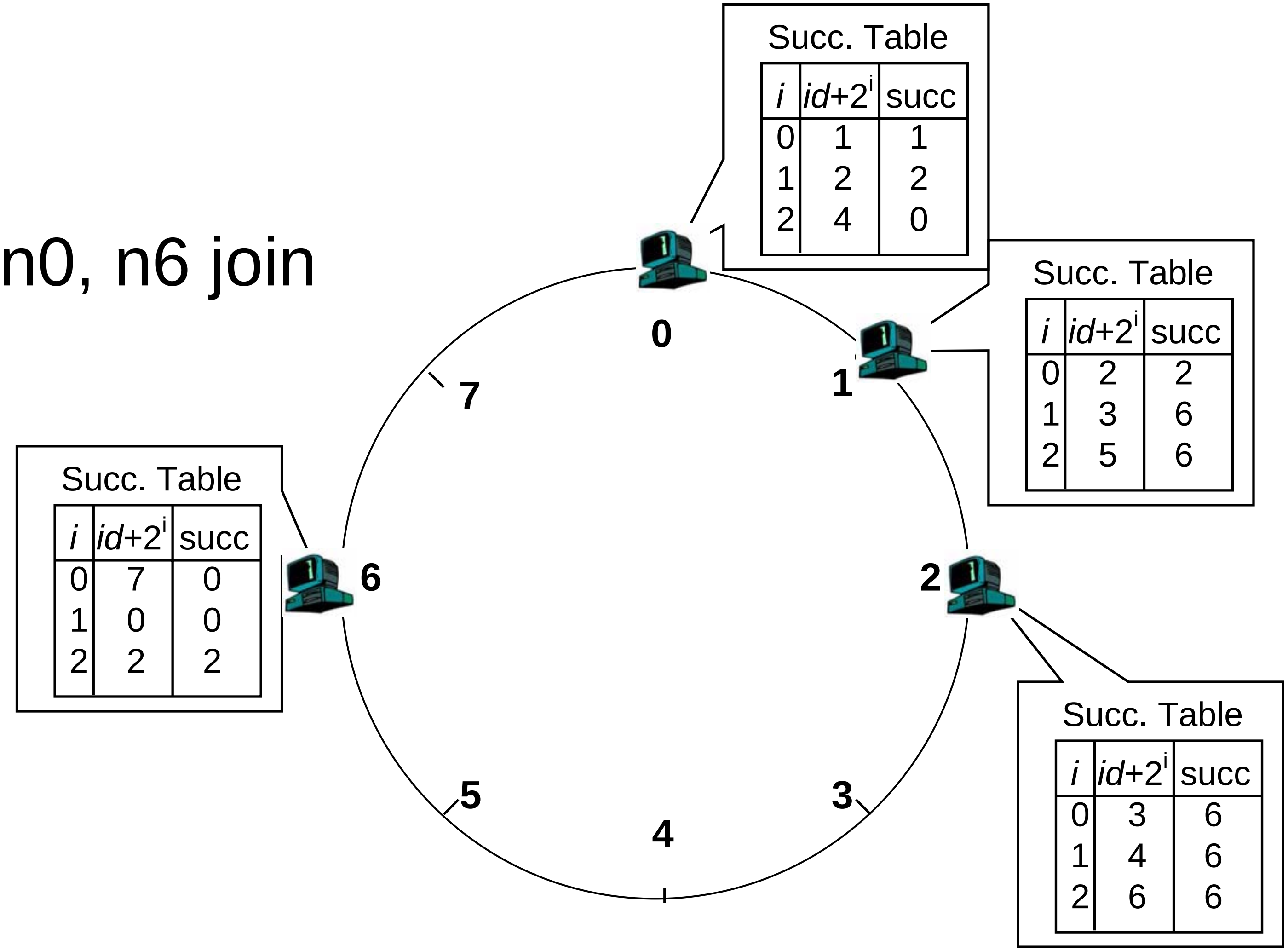
i	*id*+2^i	succ
0	2	2
1	3	1
2	5	1

Succ. Table (node 2)

i	*id*+2^i	succ
0	3	1
1	4	1
2	6	1

DHT: Chord Join

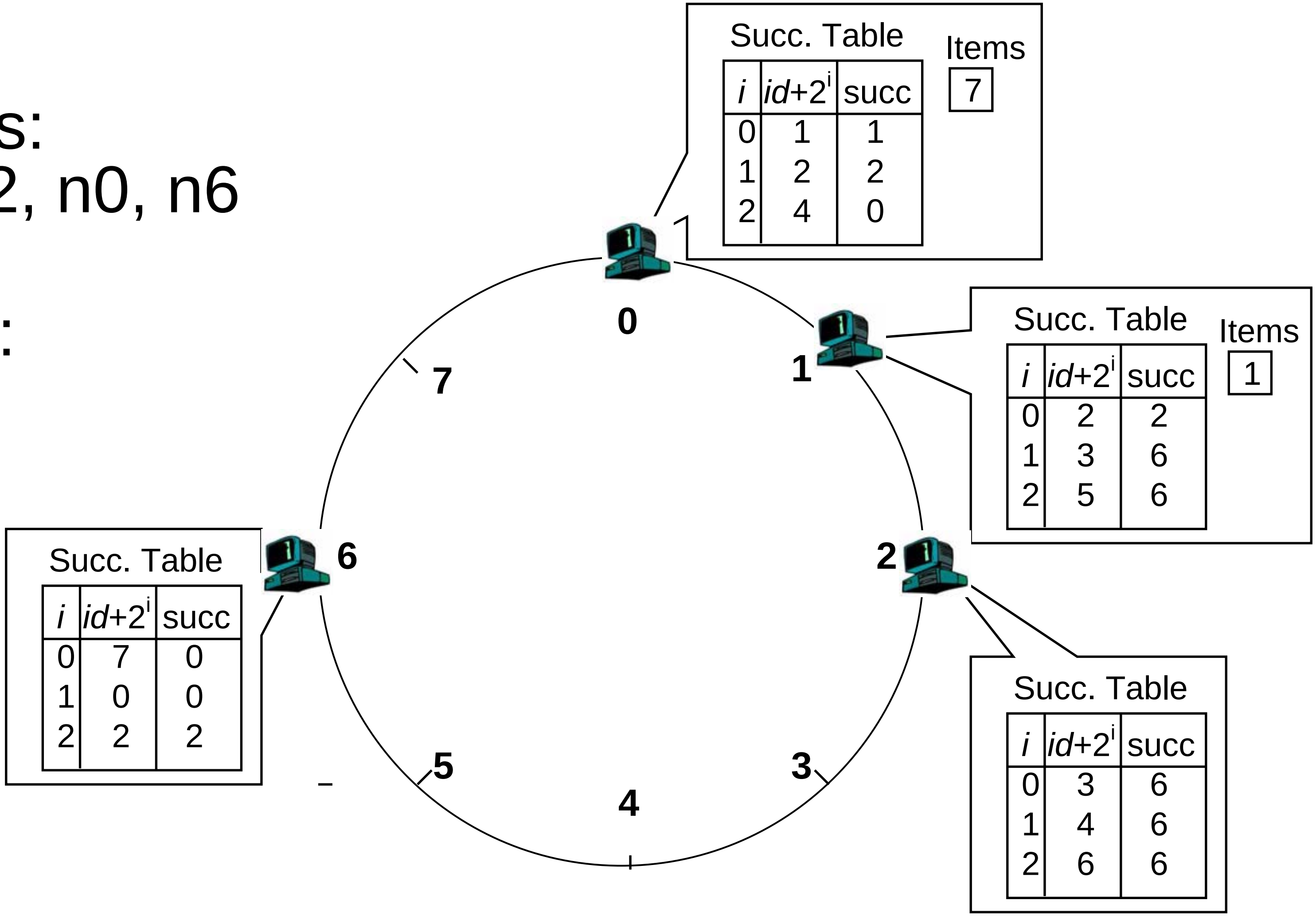
- Nodes n0, n6 join



DHT: Chord Join

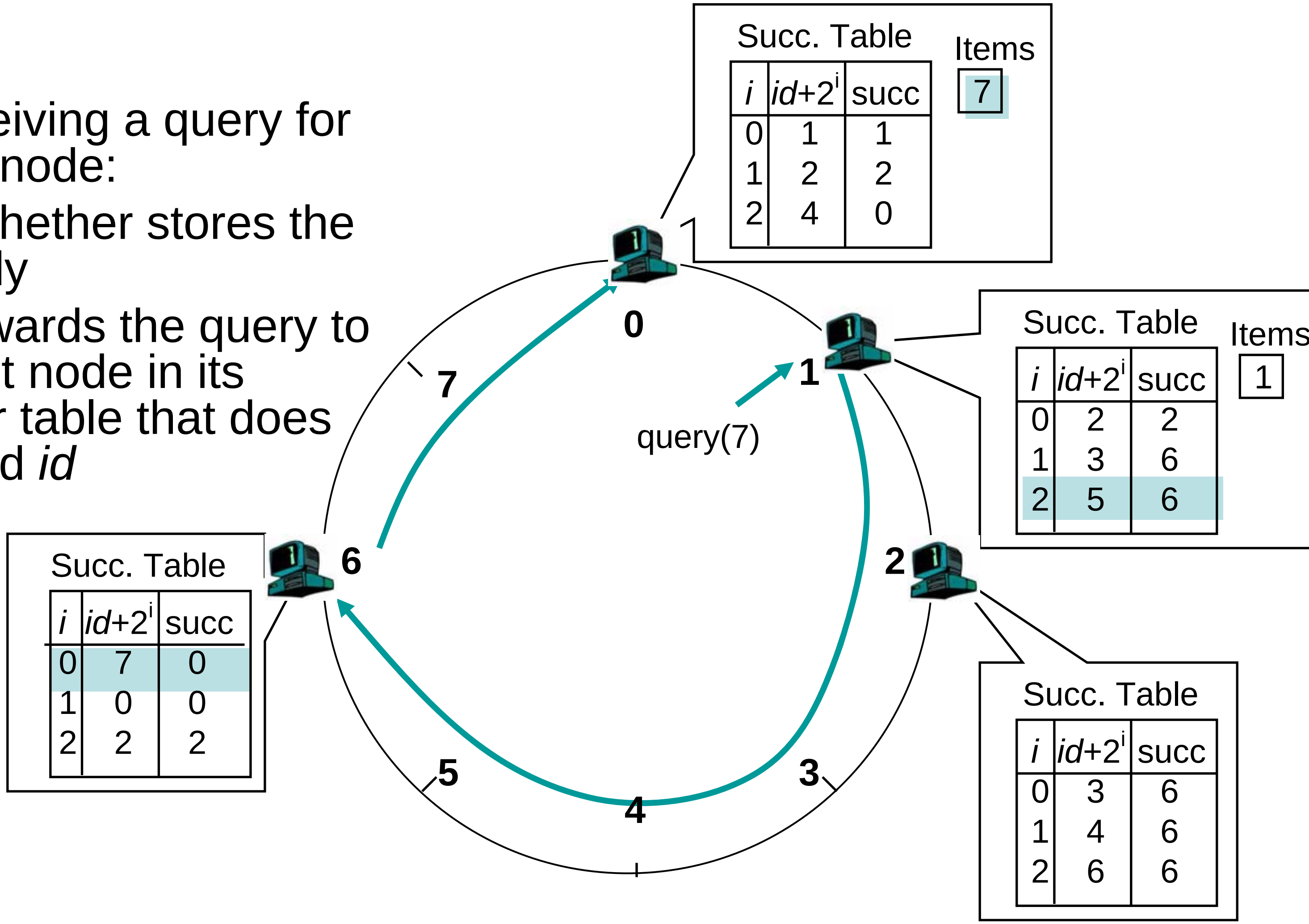
- Nodes:
  n1, n2, n0, n6

- Items:
  f7, f2



DHT: Chord Routing

- Upon receiving a query for item *id*, a node:
- Checks whether stores the item locally
- If not, forwards the query to the largest node in its successor table that does not exceed *id*



Node 0 — Succ. Table

i	*id*+2^i	succ
0	1	1
1	2	2
2	4	0

Items: 7

Node 1 — Succ. Table

i	*id*+2^i	succ
0	2	2
1	3	6
2	5	6

Items: 1

Node 2 — Succ. Table

i	*id*+2^i	succ
0	3	6
1	4	6
2	6	6

Node 6 — Succ. Table

i	*id*+2^i	succ
0	7	0
1	0	0
2	2	2

DHT: Chord Summary

- Routing table size?
  - Log *N* fingers
- Routing time?
  - Each hop expects to 1/2 the distance to the desired id => expect O(log *N*) hops.

DHT: Discussion

- Pros:
  - Guaranteed Lookup
  - O(log *N*) per node state and search scope
- Cons:
  - No one uses them? (only one file sharing app)
  - Supporting non-exact match search is hard

When are p2p / DHTs useful?

- Caching and “soft-state” data
  - Works well! BitTorrent, KaZaA, etc., all use peers as caches for hot data
- Finding read-only data
  - Limited flooding finds hay
  - DHTs find needles
- BUT

A Peer-to-peer Google?

- Complex intersection queries (“the” + “who”)
  - Billions of hits for each term alone
- Sophisticated ranking
  - Must compare many results before returning a subset to user
- Very, very hard for a DHT / p2p system
  - Need high inter-node bandwidth
  - (This is exactly what Google does - massive clusters)

Writable, persistent p2p

- Do you trust your data to 100,000 monkeys?
- Node availability hurts
  - Ex: Store 5 copies of data on different nodes
  - When someone goes away, you must replicate the data they held
  - Hard drives are *huge*, but cable modem upload bandwidth is tiny - perhaps 10 Gbytes/day
  - Takes many days to upload contents of 200GB hard drive. Very expensive leave/replication situation!

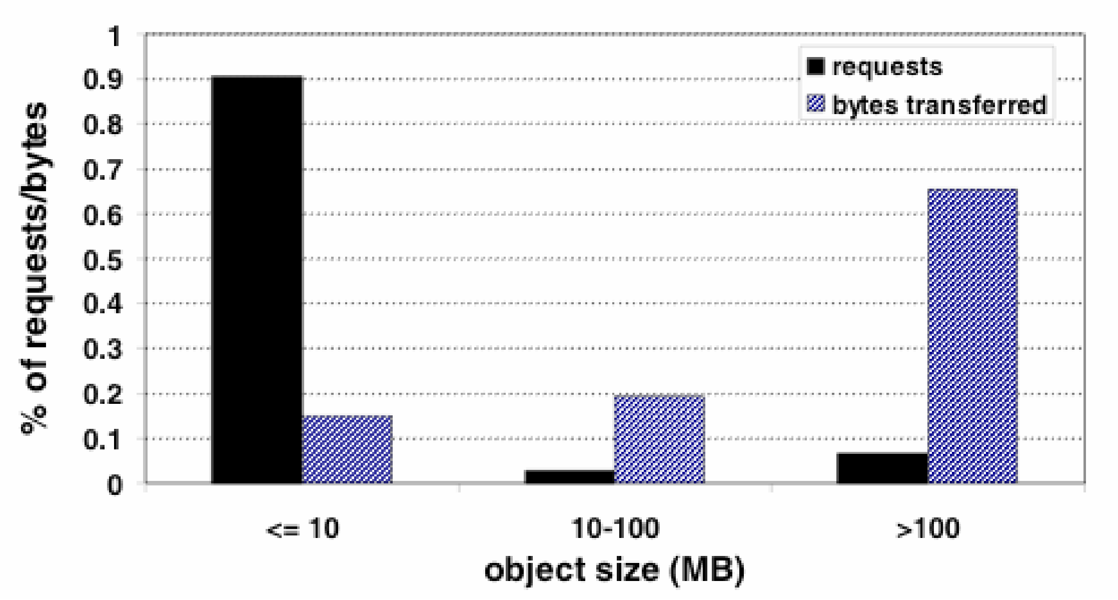
P2P: Summary

- Many different styles; remember pros and cons of each
  - centralized, flooding, swarming, unstructured and structured routing
- Lessons learned:
  - Single points of failure are very bad
  - Flooding messages to everyone is bad
  - Underlying network topology is important
  - Not all nodes are equal
  - Need incentives to discourage freeloading
  - Privacy and security are important
  - Structure can provide theoretical bounds and guarantees

Extra Slides

KaZaA: Usage Patterns

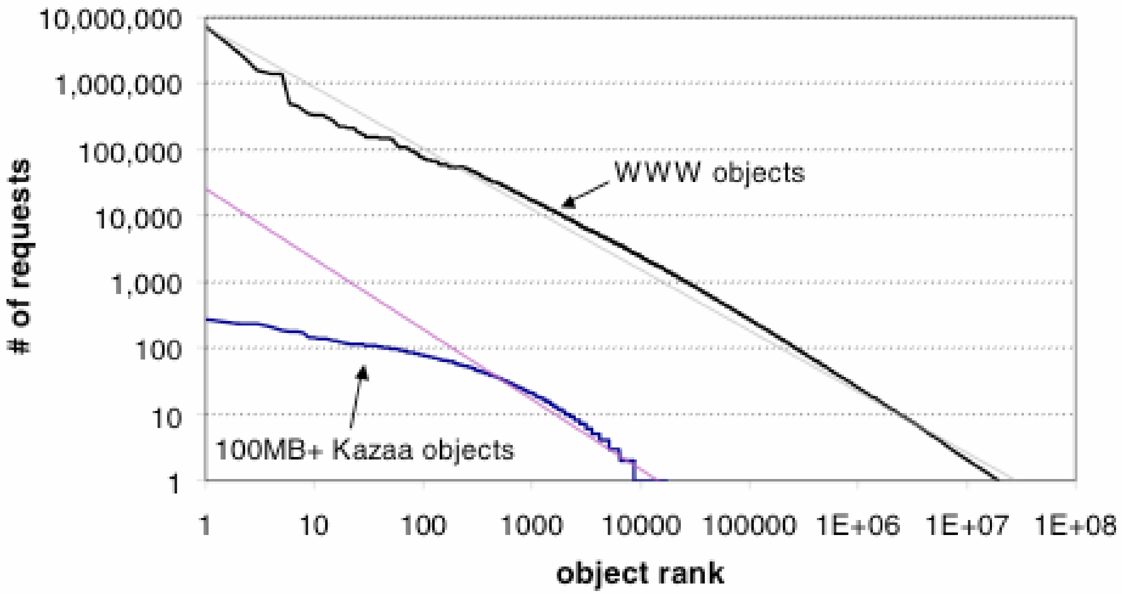
- KaZaA is more than one workload!
  - Many files < 10MB (e.g., Audio Files)
  - Many files > 100MB (e.g., Movies)



from Gummadi *et al.*, *SOSP* 2003

KaZaA: Usage Patterns (2)

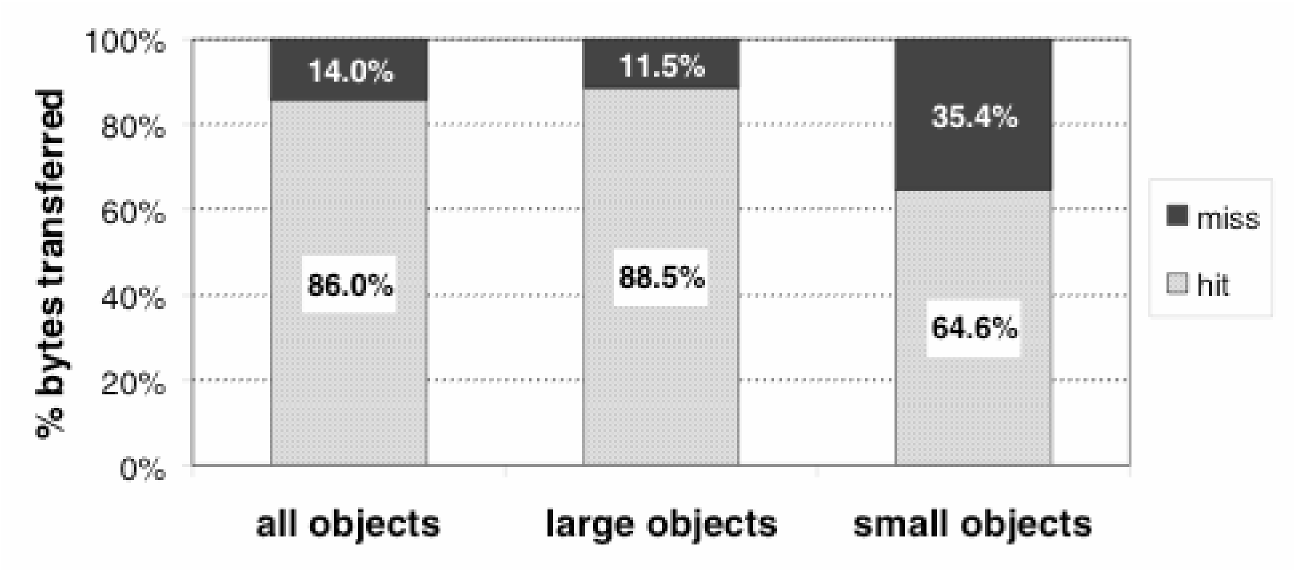
- KaZaA is not Zipf!
  - FileSharing: “Request-once”
  - Web: “Request-repeatedly”



from Gummadi *et al.*, *SOSP* 2003

KaZaA: Usage Patterns (3)

- What we saw:
  - A few big files consume most of the bandwidth
  - Many files are fetched once per client but still very popular
- Solution?
  - Caching!



from Gummadi *et al*., *SOSP* 2003

Freenet: History

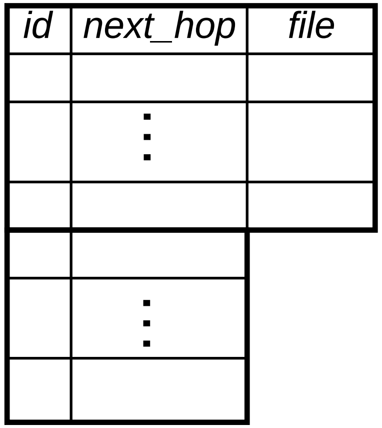
- In 1999, I. Clarke started the Freenet project
- Basic Idea:
  - Employ Internet-like routing on the overlay network to publish and locate files
- Addition goals:
  - Provide anonymity and security
  - Make censorship difficult

Freenet: Overview

- Routed Queries:
  - **Join**: on startup, client contacts a few other nodes it knows about; gets a unique *node id*
  - **Publish**: route file contents toward the *file id*. File is stored at node with *id* closest to *file id*
  - **Search**: route query for *file id* toward the closest *node id*
  - **Fetch**: when query reaches a node containing *file id*, it returns the file to the sender

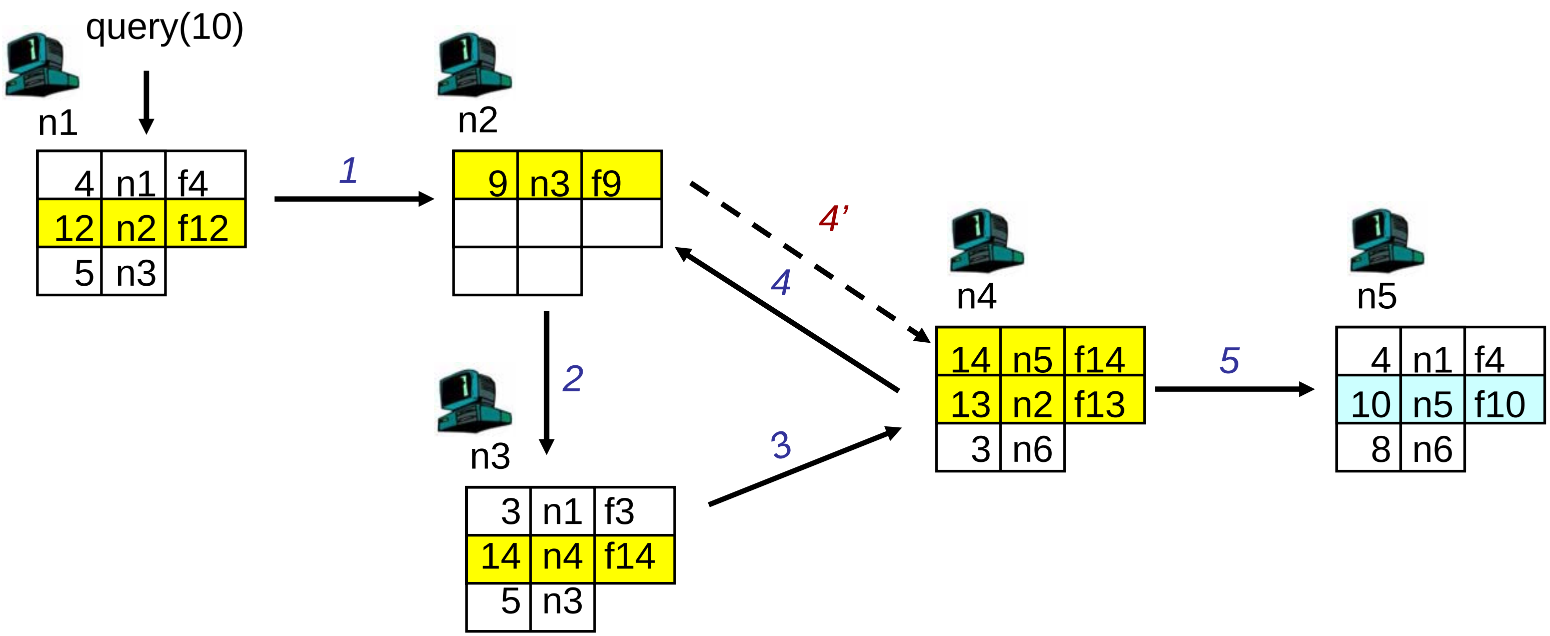
Freenet: Routing Tables

- ***id*** – file identifier (e.g., hash of file)
- ***next_hop*** – another node that stores the file id
- ***file*** – file identified by *id* being stored on the local node



- Forwarding of query for file *id*
  - If file *id* stored locally, then stop
    - Forward data back to upstream requestor
  - If not, search for the "closest" *id* in the table, and forward the message to the corresponding *next_hop*
  - If data is not found, failure is reported back
    - Requestor then tries next closest match in routing table

Freenet: Routing



Freenet: Routing Properties

- “Close” file ids tend to be stored on the same node
  - Why? Publications of similar file ids route toward the same place
- Network tend to be a “small world”
  - Small number of nodes have large number of neighbors (i.e., ~ “six-degrees of separation”)
- Consequence:
  - Most queries only traverse a small number of hops to find the file

Freenet: Anonymity & Security

- Anonymity
  - Randomly modify source of packet as it traverses the network
  - Can use "mix-nets" or onion-routing
- Security & Censorship resistance
  - No constraints on how to choose *ids* for files => easy to have to files collide, creating "denial of service" (censorship)
  - Solution: have a *id* type that requires a private key signature that is verified when updating the file
  - Cache file on the reverse path of queries/publications => attempt to "replace" file with bogus data will just cause the file to be replicated more!

Freenet: Discussion

- Pros:
  - Intelligent routing makes queries relatively short
  - Search scope small (only nodes along search path involved); no flooding
  - Anonymity properties may give you “plausible deniability”
- Cons:
  - Still no provable guarantees!
  - Anonymity features make it hard to measure, debug