CS 5450

# Peer-to-Peer Systems

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(slides by Vitaly Shmatikov)

# Overlay Networks

- Overlay network = one network (or a network-like data structure) is superimposed upon an underlying network
- Why?
  - Superimpose some form of routed behavior on a set of nodes
  - The underlying network gives the nodes a way to talk to each other, e.g. over TCP or with IP packets
  - May want a behavior that goes beyond just being able to send packets and reflects some kind of end-user "behavior" that we want to implement

# Examples of Overlay Networks

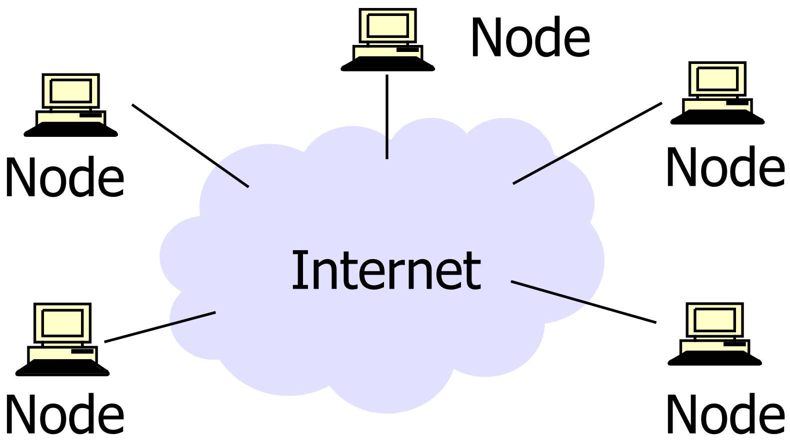
- VPNs
- Tor
- Skype
- Bitcoin
- File sharing services (e.g., BitTorrent)
  - A way to create a list of places that have the file you want
  - A way to connect to one of those places to pull the file from that machine to yours
    - Once you have the file, your system becomes a possible source for other users to download from
    - In practice, some users tend to run servers with better resources and others tend to be mostly downloaders

# Technical Issues

- What's the very best way for a massive collection of computers in the wide-area Internet (the WAN) to implement these two aspects
  - Best way to do search?
  - Best way to implement peer-to-peer downloads?

- Cloud computing solutions often have a search requirement
  - Useful even within a single data center

# Peer-to-Peer (P2P) System




- No centralized control
- Nodes are roughly symmetric in function
- Large number of unreliable nodes

# P2P Environment

- Nodes have symmetric functionalities
  - Anybody can join and leave
    - "Churn": nodes come and go at will, possibly quite frequently (a few minutes)
  - Everybody gives and takes
- Nodes have different capacities
  - Bandwidth, processing, storage
- Nodes may behave badly
  - Promise to do something (store a file) and not do it (free-loaders)
  - Attack the system

# Why P2P?

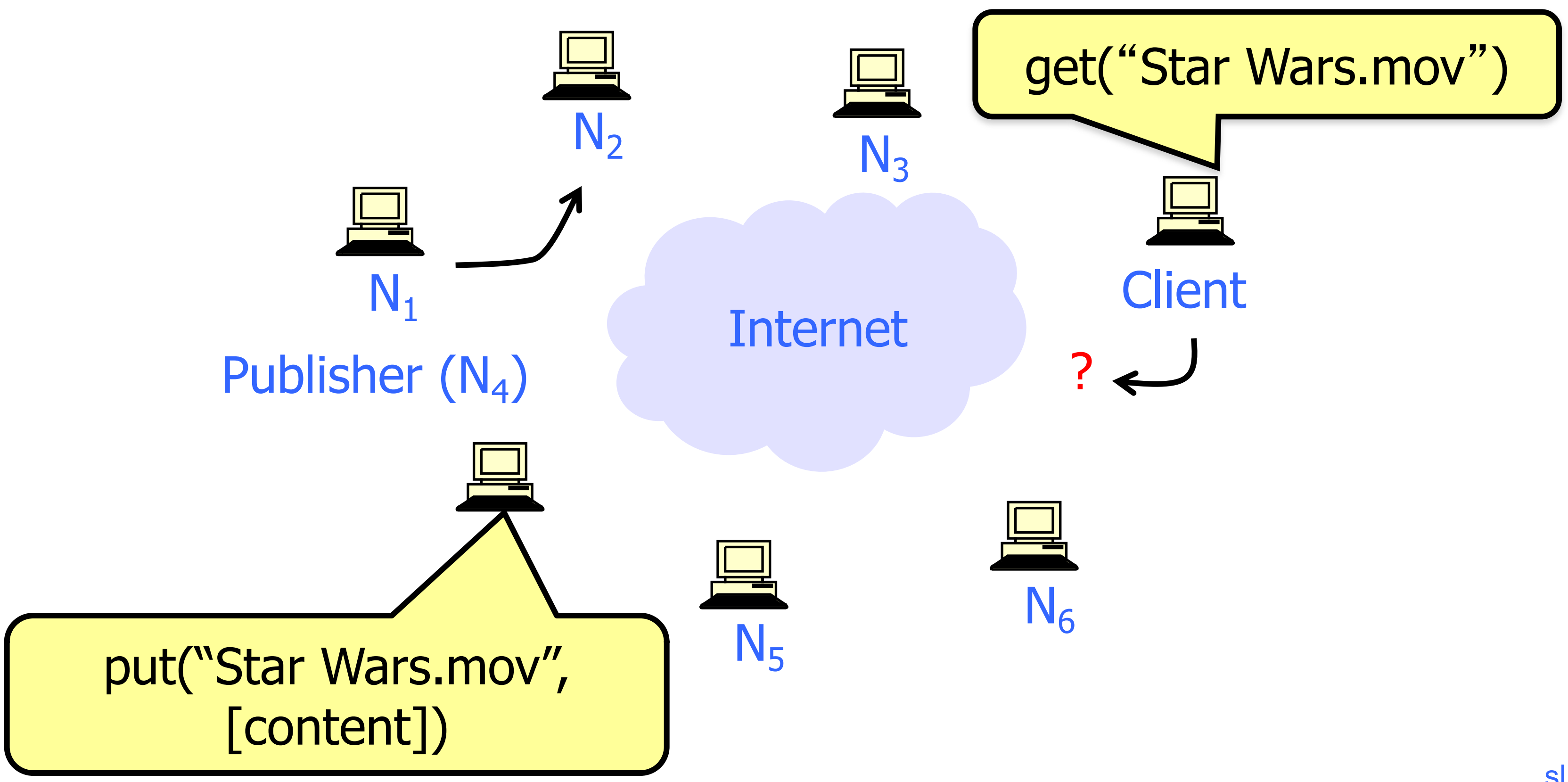
- High capacity through parallelism (potentially)
  - Many disks
  - Many network connections
  - Many CPUs

- Absence of a centralized server or servers
  - Less chance of service overload as load increases
  - Easier deployment
  - A single failure won't wreck the whole system
  - System as a whole is harder to attack

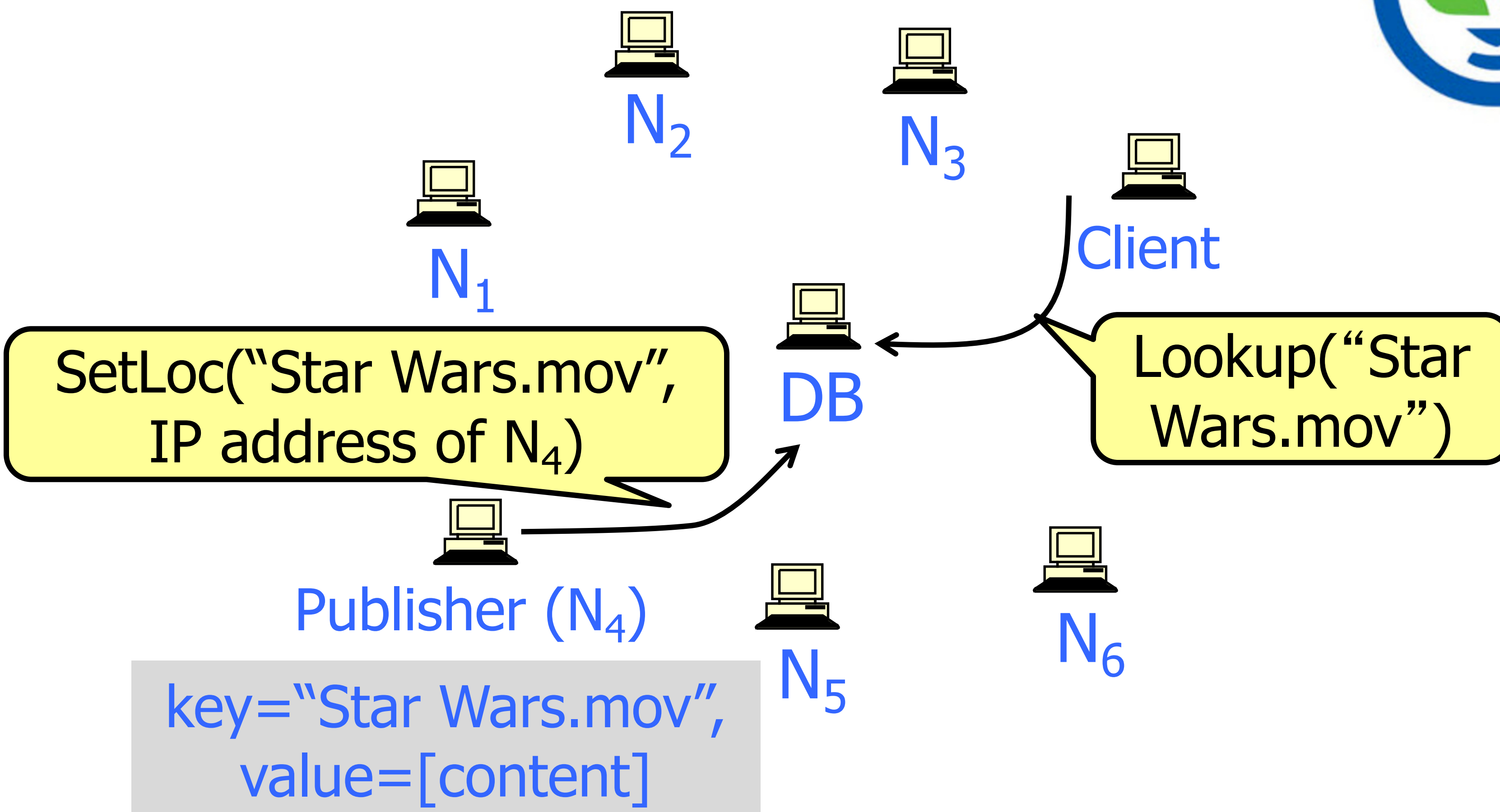
# Basic Problem: Lookup

## How to locate something given its name?

- Examples: file sharing, VoIP, CDNs…



# Centralized Lookup (Napster)



# Centralized Database

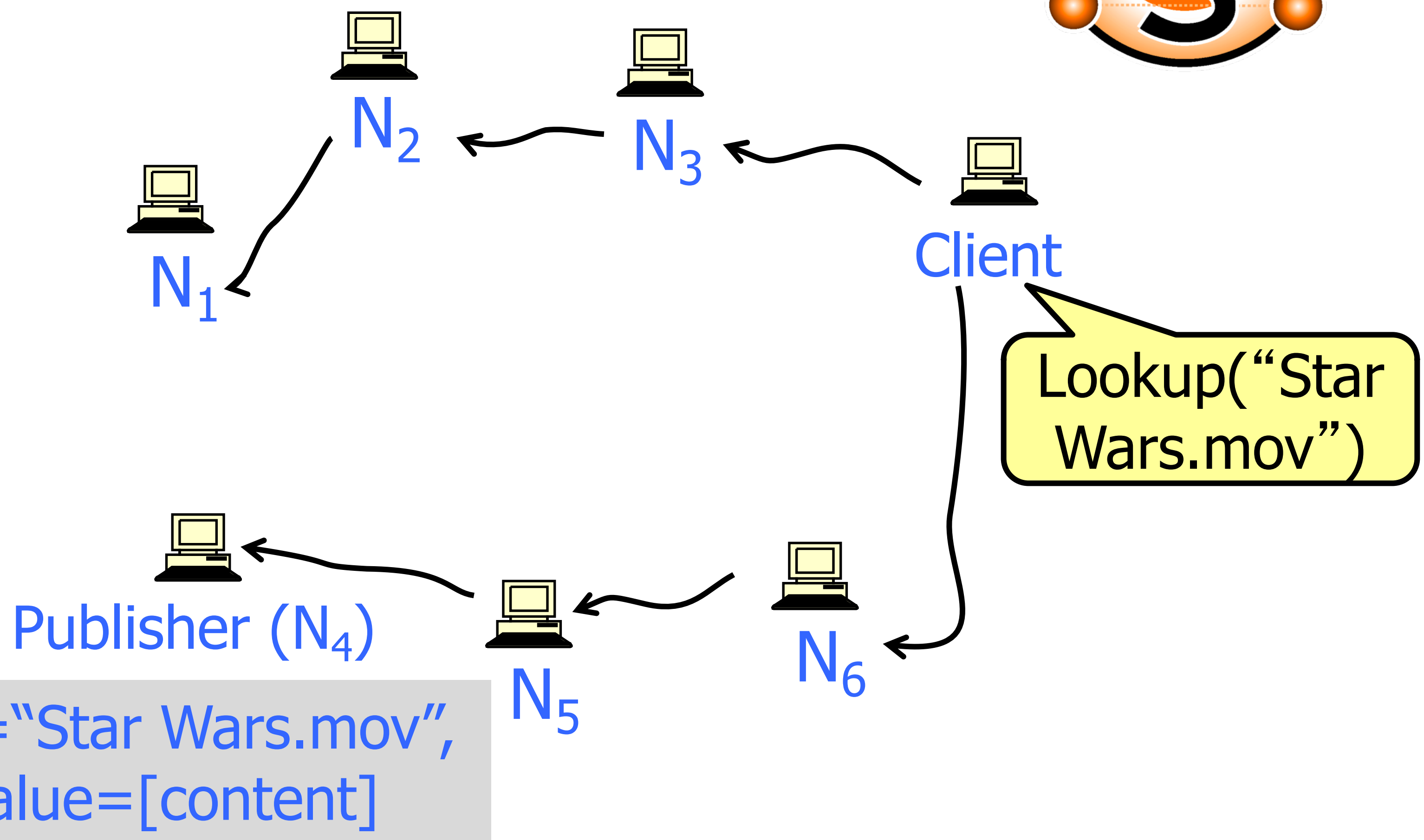
- Join: on startup, client contacts central server
- Publish: reports list of files to central server
- Search: query the server => return someone that stores the requested file
- Fetch: get the file directly from peer

# Centralized DB: Pros and Cons

- 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

# Flooding ("Old" Gnutella)



# Query Flooding

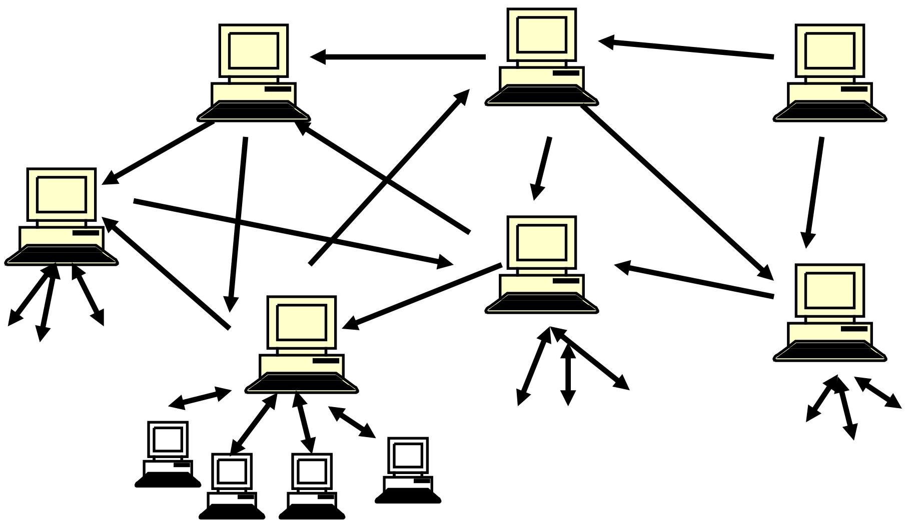
- Join: on startup, client contacts a few other nodes; these become its "neighbors"
- Publish: no need
- Search: ask neighbors, who ask their neighbors, and so on... when/if found, reply to sender.
  - TTL limits propagation
- Fetch: get the file directly from peer

# Query Flooding: Pros and Cons

- Pros
  - Fully de-centralized
  - Search cost distributed
  - Processing at each node permits powerful search semantics

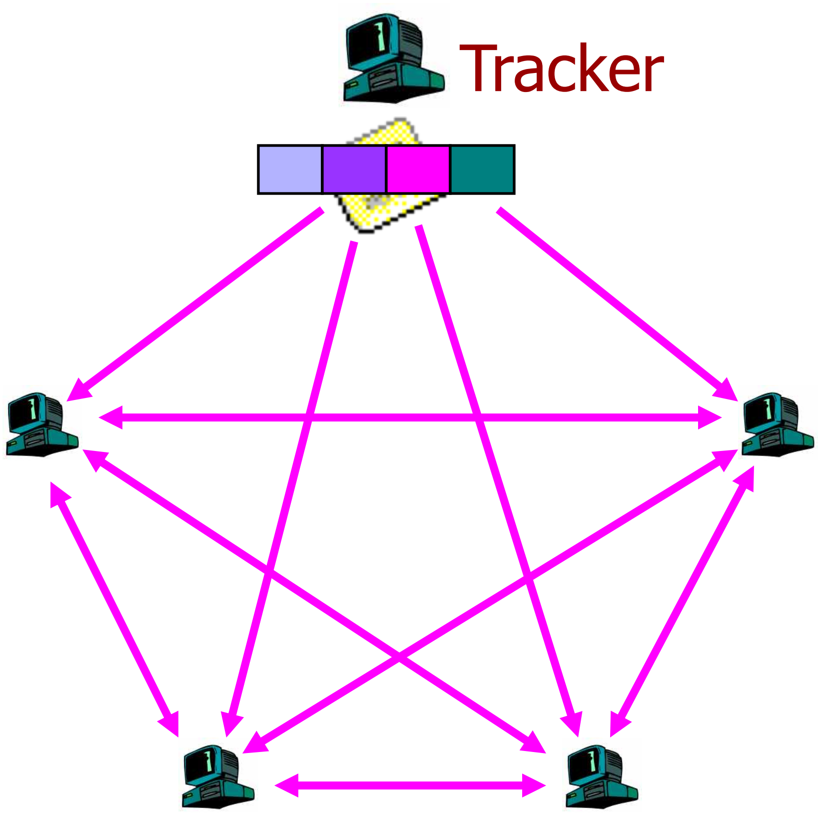
- Cons
  - Search scope is O(N), a lot of traffic
  - Search time is O(???), no guarantee of results
  - Nodes leave often, network unstable

# Improvement: “Super Peers”

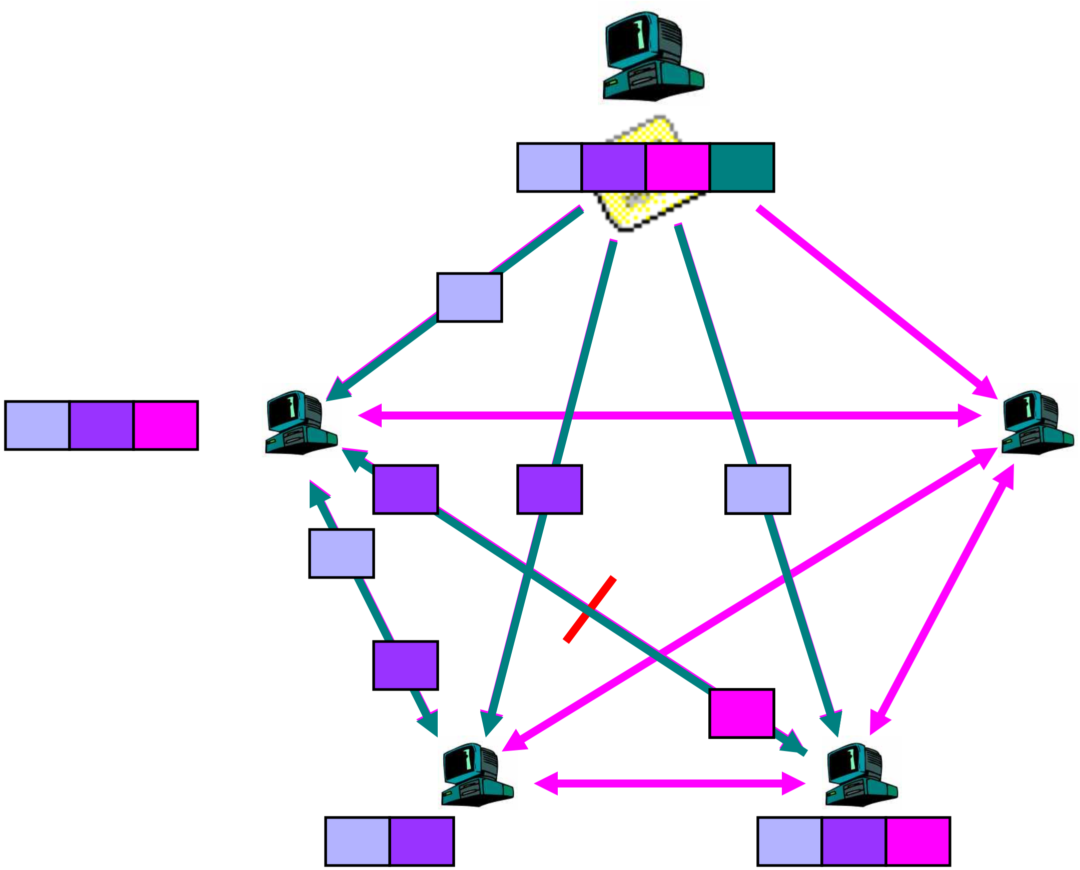


- Examples: Kazaa, Skype
- Lookup only floods super peers
- Still no guarantees for lookup results

# BitTorrent: Publish/Join



# BitTorrent: Fetch



# 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
  - "Few large files" focus
  - Anti-freeloading mechanisms

# 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
- Goal: Pareto Efficiency
  - Game Theory: "No change can make anyone better off without making others worse off"
  - Does it work?  (not perfectly, but perhaps good enough?)

# BitTorrent: Pros and Cons

- 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
    - Alternate tracker designs exist (e.g., DHT-based)

# DHT

- Goal: make sure that an item (file) identified is always found in a reasonable number of steps
- Abstraction: a distributed hash table (DHT) data structure
  - insert(id, item);
  - item = query(id);
  - Item can be anything: a data object, document, file, pointer to a file…
- Implementation: nodes in system form a distributed data structure
  - Can be ring, tree, hypercube, skip list, butterfly network, ...

# Hash Tables

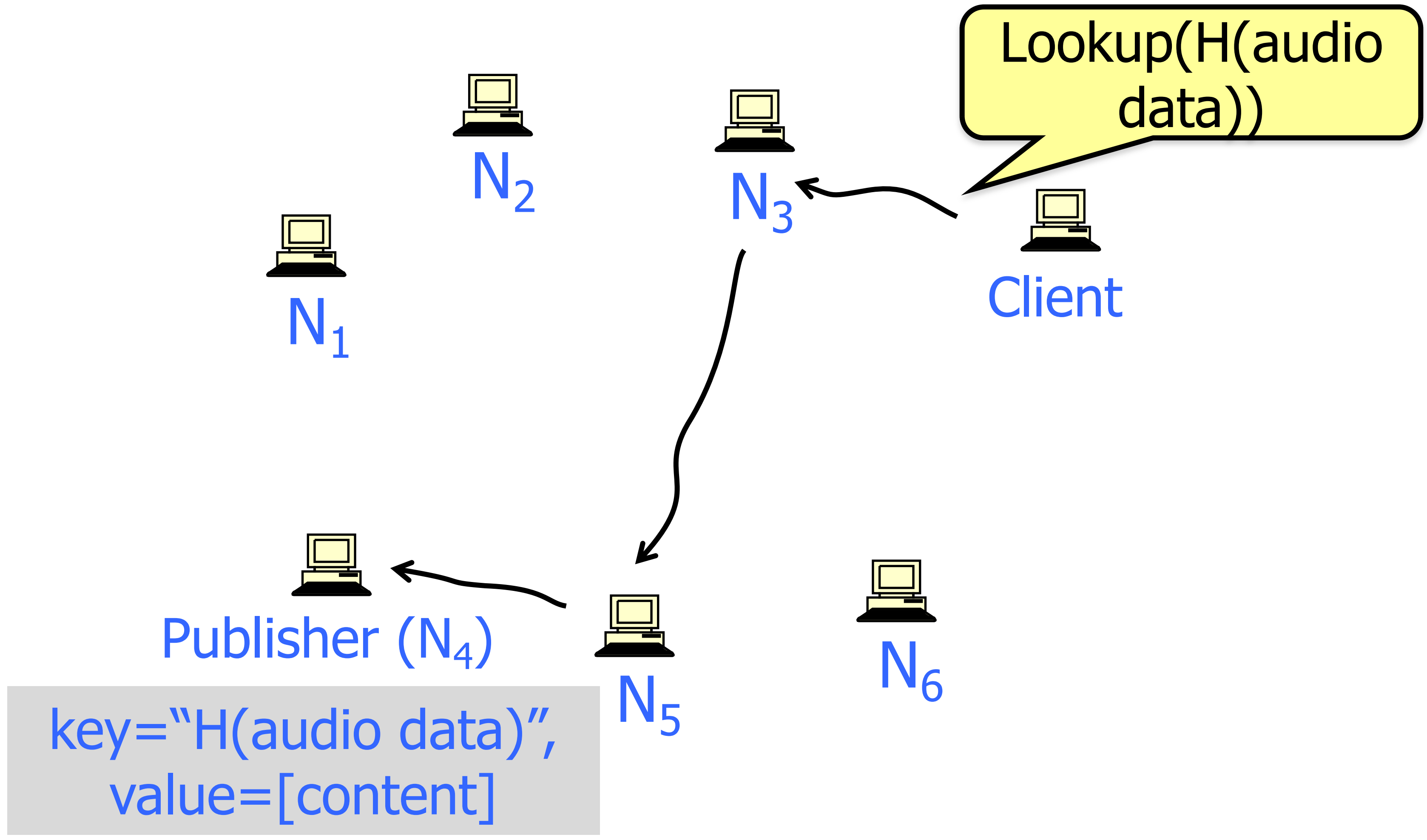
- Local hash table
  - key = Hash(name)
  - put(key, value)
  - get(key) → value
- Constant-time insertion and lookup

- How to do (roughly) this across millions of hosts on the Internet?

# Distributed Hash Tables

- Distributed hash table
  - key = hash(data)
  - lookup(key) → IP addr
  - send-RPC(IP address, put, key, data)
  - send-RPC(IP address, get, key) → data
- Partitioning data in truly large-scale distributed systems
  - Tuples in a global database engine
  - Data blocks in a global file system
  - Files in a P2P file-sharing system

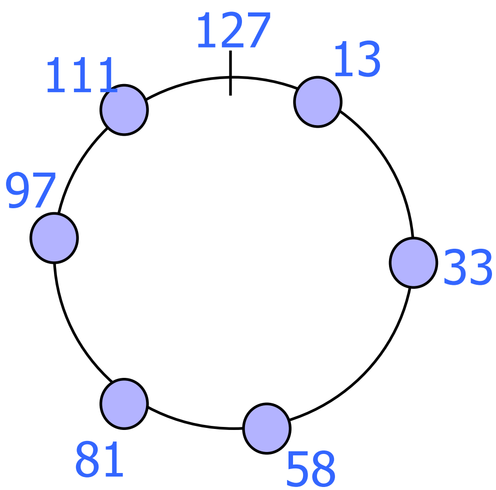
# Routed DHT Queries



# Structured Overlay Routing

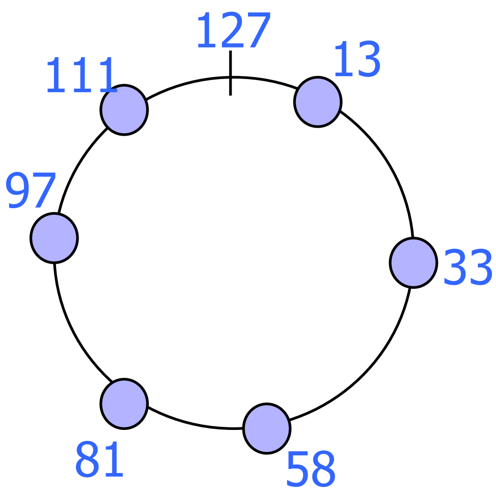
- **Join:** Contact a "bootstrap" node, integrate self into the distributed data structure, get a node id
- **Publish:** Route publication for the file id toward a close node id along the data structure
- **Search:** Route a query for a file id toward a close node id
  - Data structure guarantees query will meet publication
- **Fetch**
  - 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

# Basics of All DHTs




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

# Simple Example (Doesn't Scale)

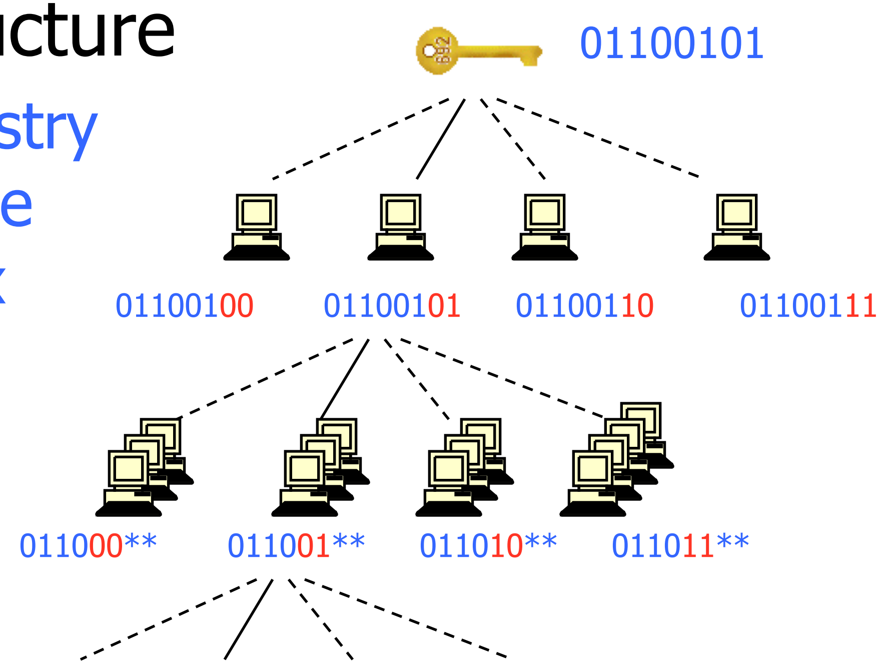



- Circular number space 0 to 127
- Routing rule is to move clockwise until current node ID $\geq$ key, and last hop node ID < key

- Example: key = 42
- Obviously you will route to node 58 from no matter where you start

# Scalable Routing

- Given document XYZ, choose node to use
- Need some notion of "closeness" between nodes
- Example: tree-like structure
  - Pastry, Kademlia, Tapestry
  - Distance = length of the longest matching prefix with the lookup key



# Mapping Hashes to Nodes

Suppose we use modulo as a simple hash function

- Number nodes from 1…n
- Place document XYZ on node (XYZ mod n)
- What happens when a node fails? Or if different people have different measures of n?
  - n → n-1
- Why might this be bad?

# Consistent Hashing

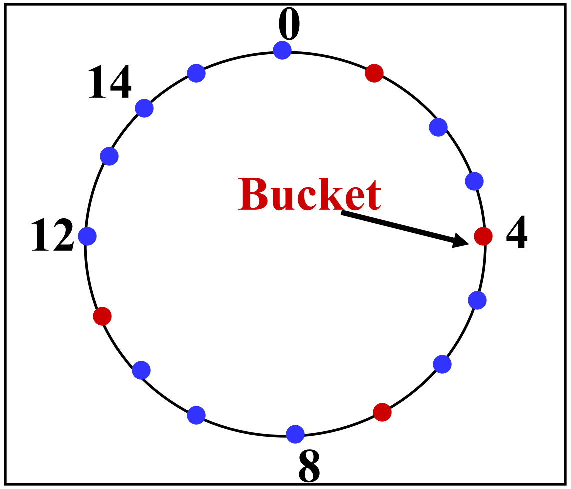
[Karger '97]

"view" = subset of all visible hash buckets (nodes)

- **Smoothness**
  - Little impact on hash bucket contents when buckets are added or removed
- **Spread**
  - Small set of hash buckets that may hold an object regardless of views
- **Load**
  - Across all views the number of objects assigned to hash bucket is small

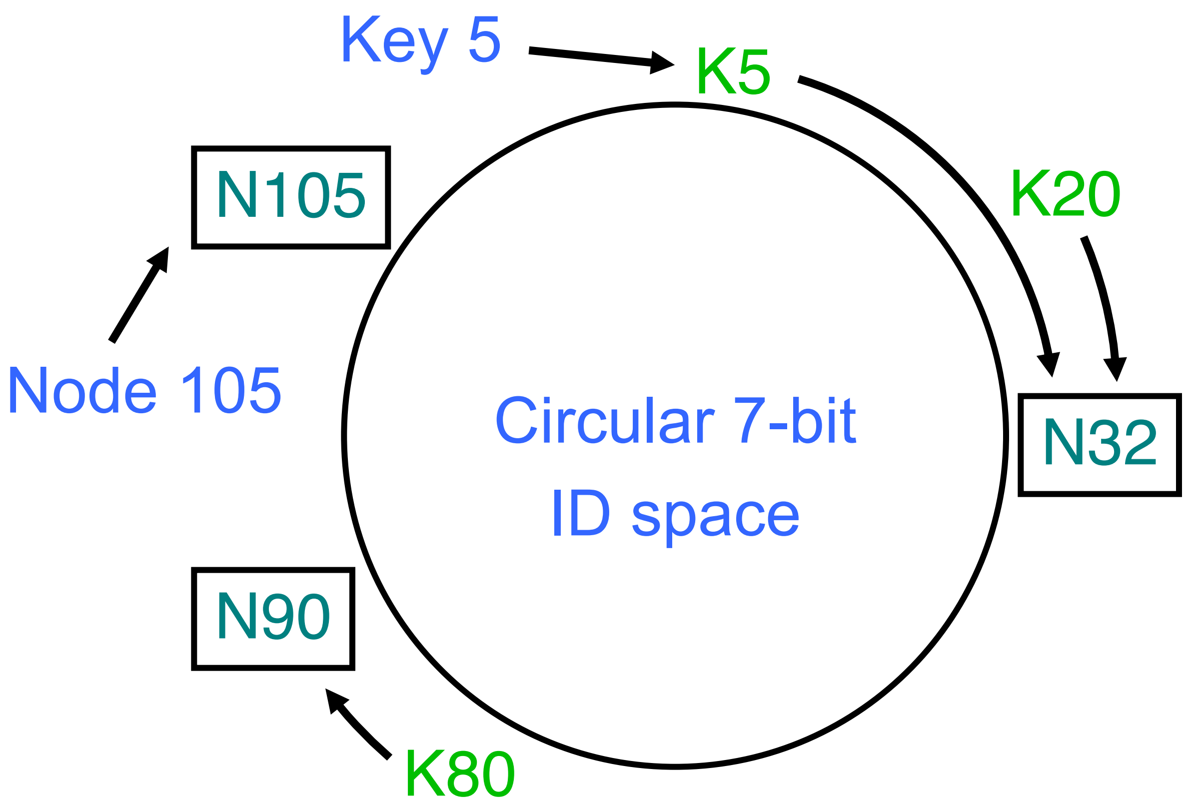
# Consistent Hashing: Example

- Assign each of C hash buckets to random points on mod 2n circle, where hash key size = n
- Map object to random position on unit interval
- Hash of object = closest bucket




- Monotone → addition of bucket does not cause much movement between existing buckets
- Spread load → small set of buckets that lie near object
- Balance → no bucket is responsible for large number of objects

# Consistent Hashing in DHT




Key is stored at the node with next-higher ID

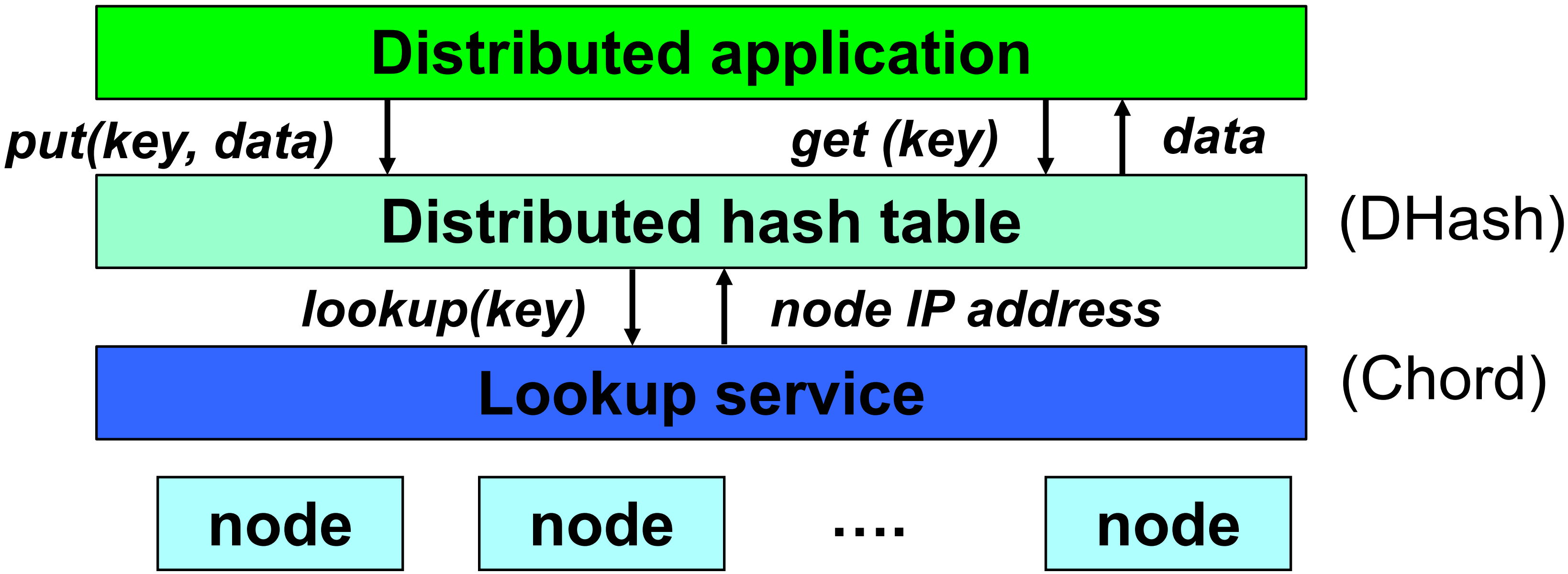
# DHTs: Pros and Cons

- 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

# DHT as Universal Service

- API supports a wide range of applications
  - DHT imposes no structure/meaning on keys
- Key/value pairs are persistent and global
  - Can store keys in other DHT values
  - … and thus build complex data structures

# Cooperative Storage with a DHT




App may be distributed over many nodes

DHT distributes data storage over many nodes

# DHT History

- Original DHTs (CAN, Chord, Kademlia, Pastry, Tapestry) proposed in 2001-02
- Following 5-6 years saw proliferation of DHT-based applications:
  - Filesystems (eCFS, Ivy, OceanStore, Pond, PAST)
  - Naming systems (SFR, Beehive)
  - Application-layer multicast (Scribe, Bayeux, Splitstream)
  - Content distribution systems (Coral)
  - Distributed databases (PIER)

# Why Didn't DHTs Succeed?

- High latency and limited bandwidth between peers
  - Compare: between server cluster in datacenter
- User computers are less reliable than managed servers
- Lack of trust in peers' correct behavior
- Churn
- Securing DHT routing hard, unsolved in practice

# Why DHTs Got Right

- Consistent hashing
  - Elegant way to divide a workload across machines
  - Very useful in clusters: actively used today in Amazon Dynamo and other systems
- Replication for high availability, efficient recovery after node failure
- Incremental scalability: "add nodes, capacity increases"
- Self-management: minimal configuration
- Unique trait: no single server to shut down/monitor