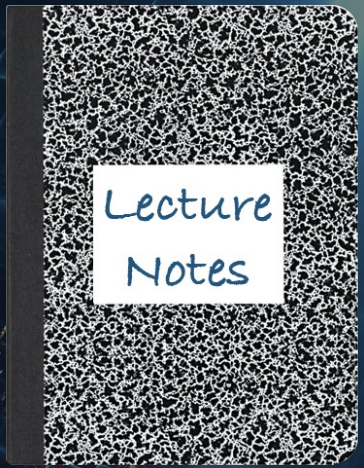
CS 417 – DISTRIBUTED SYSTEMS



Week 7: Distributed Lookup:

Part 1: Distributed Hash Tables

Paul Krzyzanowski

Distributed Lookup

Interface:

```
store(key, value)
value = lookup(key)
```

Obect storage	File storage
Flat namespace	Hierarchical namespace
Read/write entire content	Partial read/writes
Atomic access	Concurrent access (usually)

Distributed lookup: cooperating set of nodes store & retrieve data

Ideally:

– **Peer-to-peer**: no central coordinator – all nodes have the same capabilities
– **Efficient**: route requests to the node that holds the data
– **Fault-tolerant**: some nodes can be down
– **Scalable**: Easy to add or remove nodes as capacity changes

Approaches

1. **Central coordinator**
   – Napster

2. **Flooding**
   – Gnutella

3. **Distributed hash tables**
   – CAN, Chord, Amazon Dynamo, Tapestry, Kademlia, …

1. Central Coordinator

Example: Napster

- Central directory
- Identifies content (names) and the servers that host it
- *lookup(name)* → {list of servers}
- Download from any of available servers
  - Pick the best one by pinging and comparing response times

Another example: GFS

- Controlled environment compared to Napster
- Content for a given key is broken into chunks
- Master handles all queries … but not the data

1. Central Coordinator - Napster

- Pros
  - Super simple
  - Search is handled by a single server
  - The directory server is a single point of control
    - Provides definitive answers to a query

- Cons
  - Master has to maintain state of all peers
  - Server gets all the queries
  - The directory server is a single point of control
    - No directory, no service!

2. Query Flooding

Example: Gnutella distributed file sharing

- Each node joins a group – but only knows about some group members
  - Well-known nodes act as anchors
  - New nodes with files inform an anchor about their existence
  - Nodes use other nodes they know about as peers

2. Query Flooding

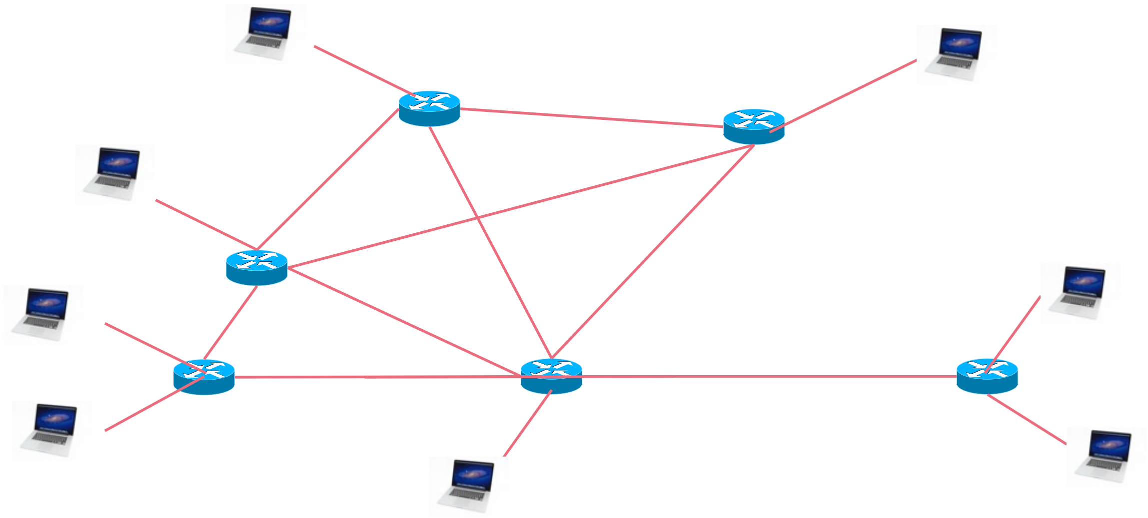
- Send a query to peers if a file is not present locally
  - Each request contains:
    - Query key
    - Unique request ID
    - Time to Live (TTL, maximum hop count)

- Peer either responds or routes the query to its neighbors
  - Repeat until TTL = 0 or if the request ID has been processed
  - If found, return a response containing the node address to the requestor
  - **Back propagation**: response hops back to reach originator

Overlay network

An **overlay network** is a virtual network formed by **peer connections**

- Any node might know about a small set of machines
- “Neighbors” may not be physically close to you

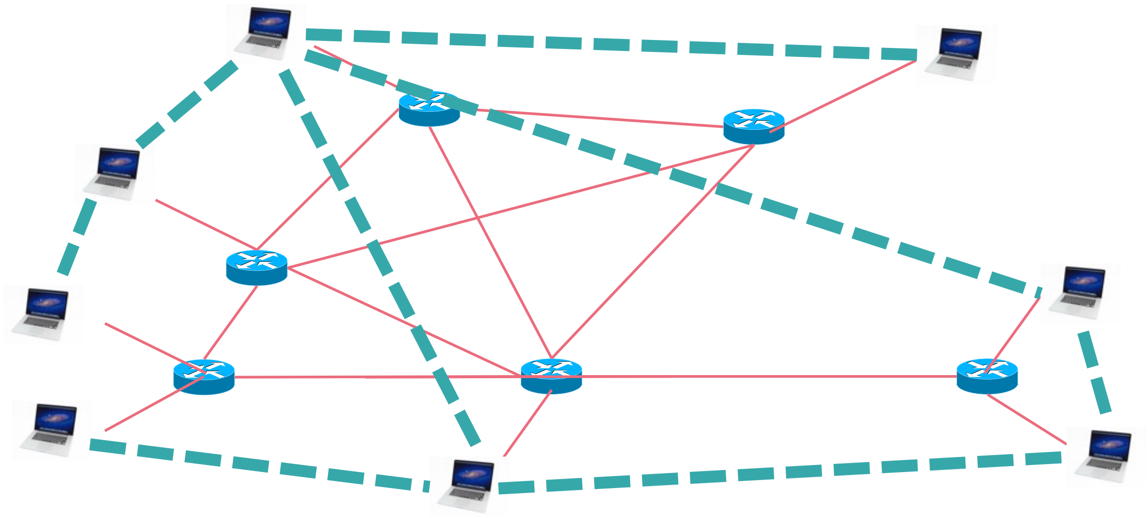


Underlying IP Network

Overlay network

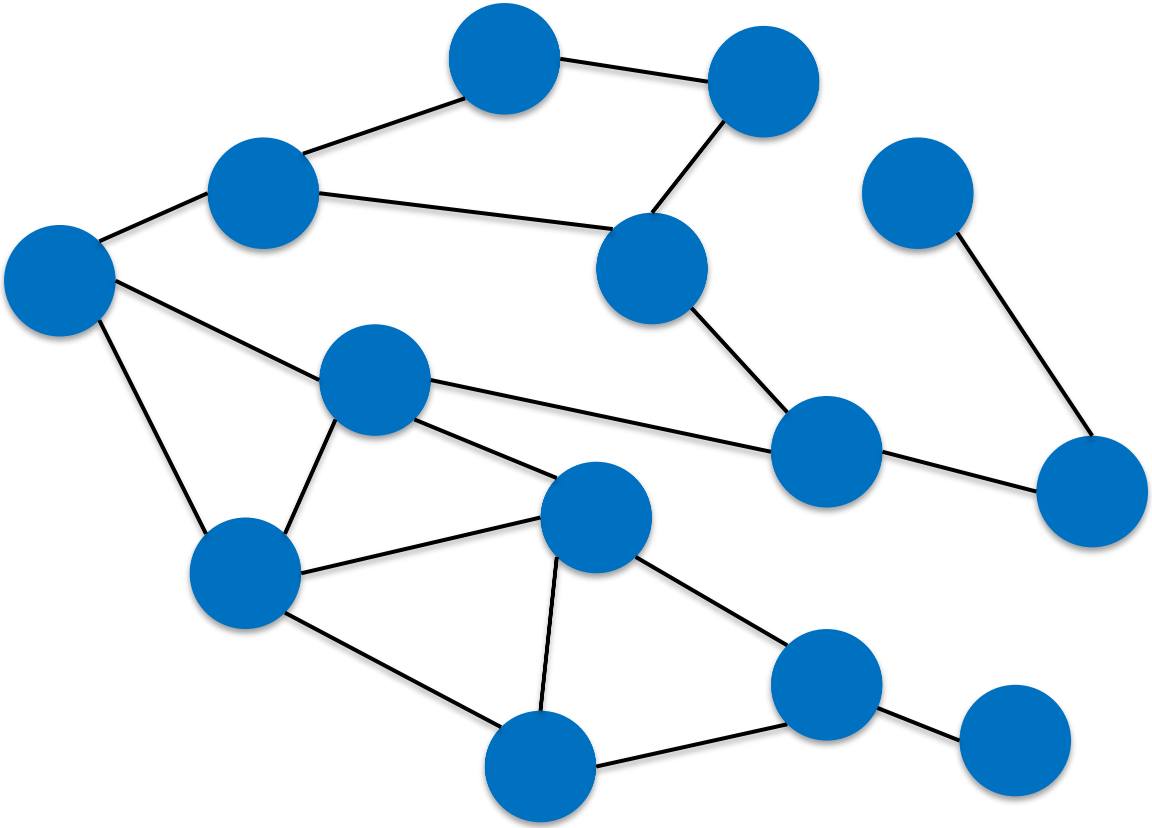
An **overlay network** is a virtual network formed by **peer connections**

- Any node might know about a small set of machines
- "Neighbors" may not be physically close to you

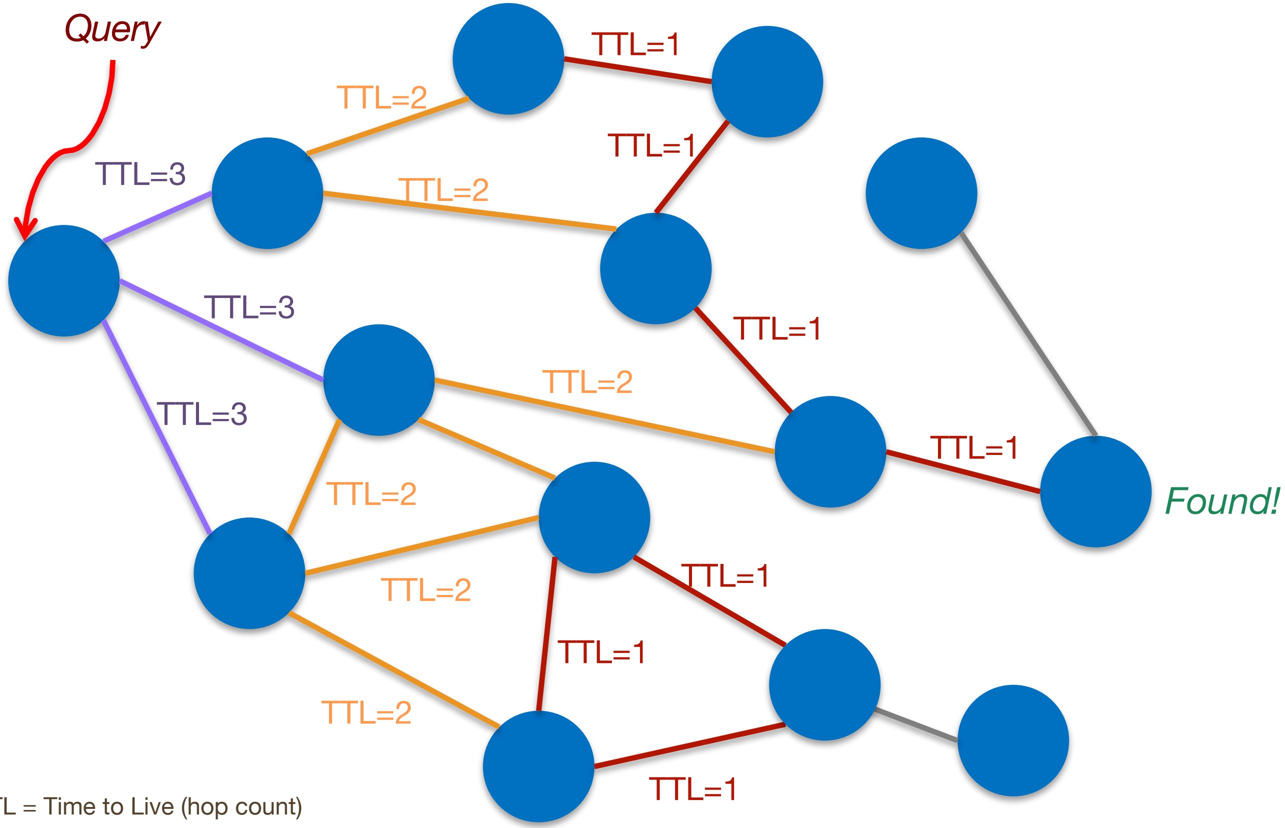


Overlay Network

Flooding Example: Overlay Network

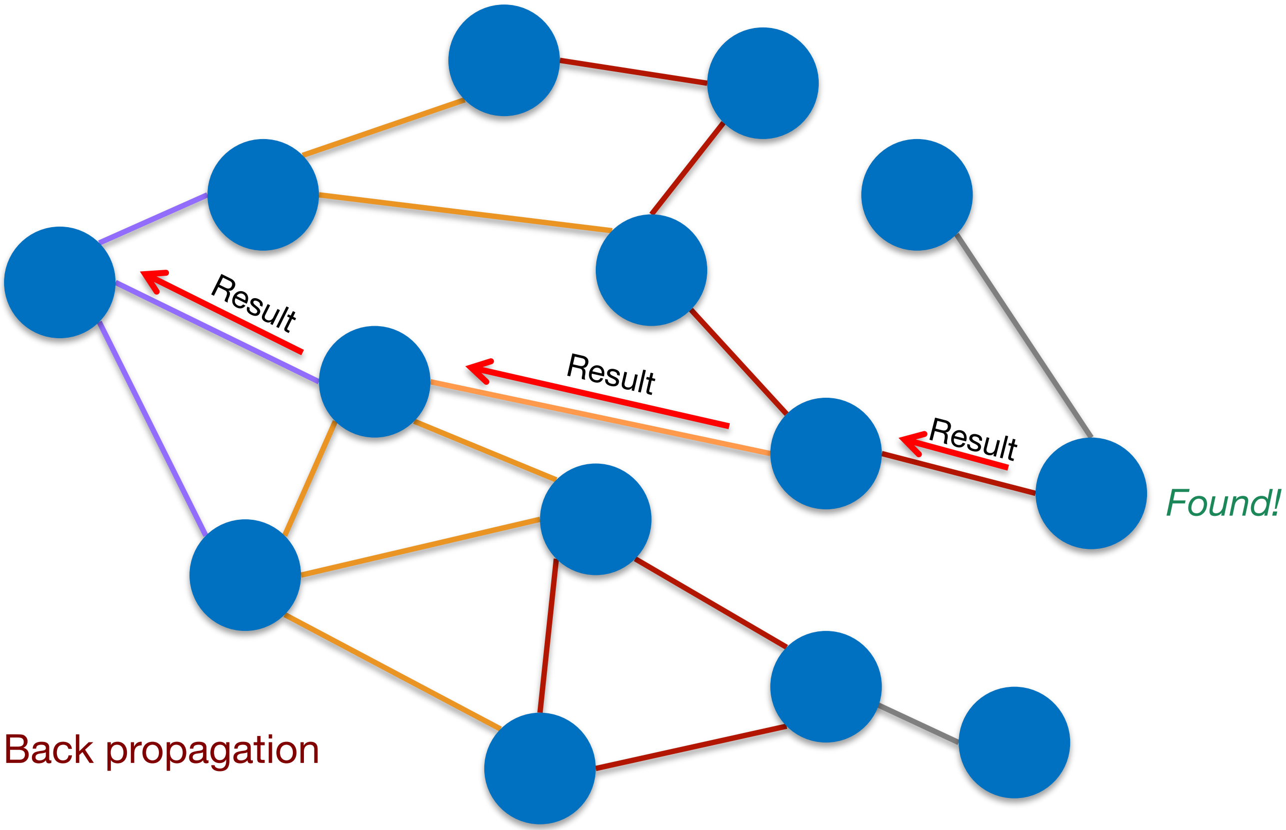


Flooding Example: Query Flood



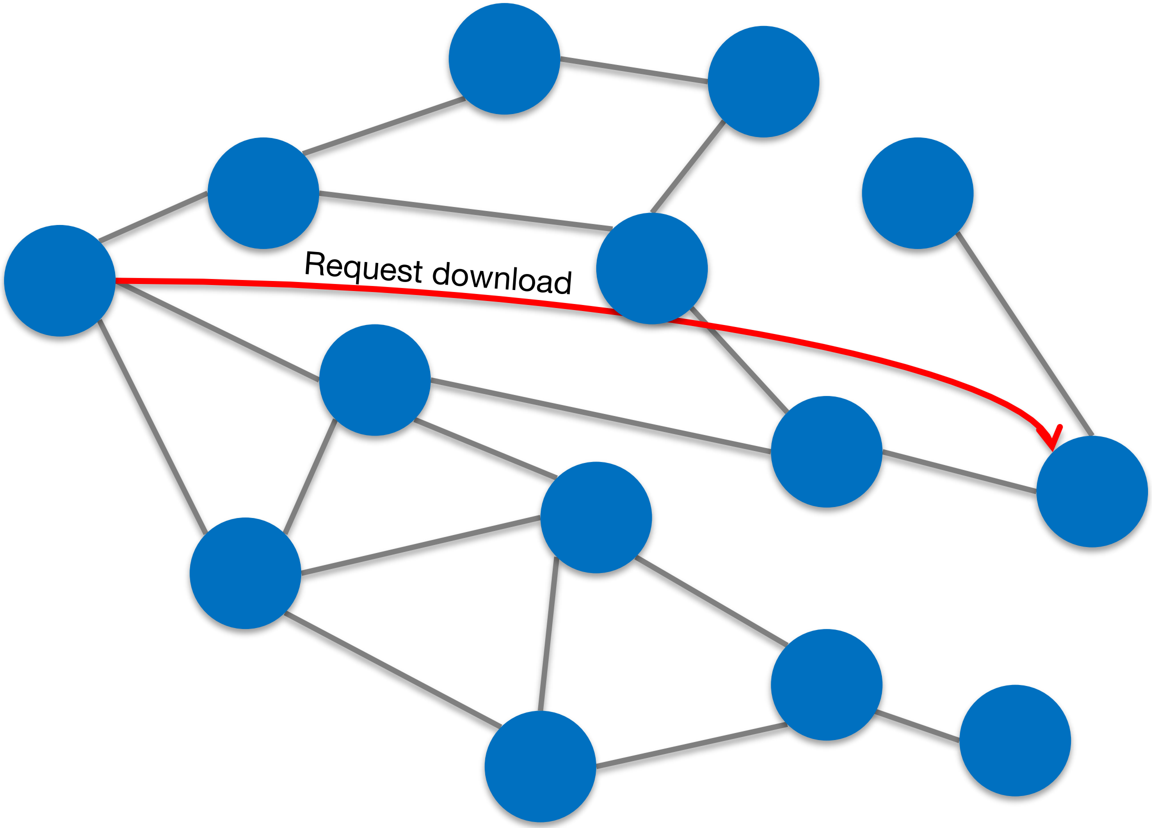
TTL = Time to Live (hop count)

Flooding Example: Query response



Back propagation

Flooding Example: Download



What's wrong with flooding?

- Some nodes are not always up, and some are slower than others
  - Kazaa was created to deal with this: **super nodes** = more powerful with better uptime
  - Gnutella later did the same, classifying some nodes as special ("**ultrapeers**")
  - Regular nodes send all content info to ultrapeers
- Poor use of network resources
  - Lots of messages throughout the entire network (until TTL=0 kicks in)
- Potentially high latency
  - Requests get forwarded from one machine to another
  - If back propagation is used:
    replies go through the same sequence of systems used in the query, increasing latency even more – useful in preserving anonymity

3. Distributed Hash Tables

Hash tables

Remember hash functions & hash tables?

- Linear search: $O(N)$
- Tree or binary search: $O(\log_2 N)$
- Hash table: $O(1)$

What's a hash function? (refresher)

Hash function

- A function that takes a variable length input (e.g., a string or any object) and generates a (usually smaller) fixed length result (i.e., an integer)
- Example: hash strings to a range 0-7:

```
hash("Newark") → 1
hash("Jersey City") → 6
hash("Paterson") → 2
```

Hash table

- Table of *(key, value)* tuples
- Look up a key:

  Hash function maps *keys* to a range *0 … N-1*

  Index into a table of *N* elements

```
i = hash(key)
item = table[i]
```

- No need to search through the table!

Considerations with hash tables (refresher)

- Picking a good hash function
  - We want uniform distribution of all values of *key* over the space *0 … N-1*
- Collisions
  - Multiple keys may hash to the same value

    `hash("Paterson")` → 2

    `hash("Edison")` → 2
  - `table[i]` is a bucket (slot) for all such *(key, value)* sets
  - Within `table[i]`, use a linked list or another layer of hashing
- Think about a hash table that grows or shrinks
  - If we add or remove buckets → need to rehash keys and move items

Distributed Hash Tables (DHT): Goal

Create a peer-to-peer version of a (*key, value*) data store

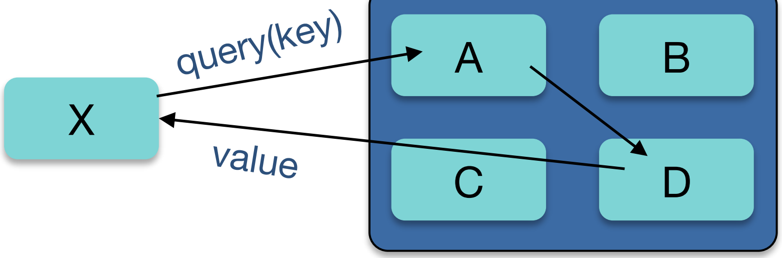
How we want it to work

1. A client (*X*) queries any peer (A) in the data store with a key
2. The data store finds the peer (*D*) that has the value
3. That peer (*D*) returns the *value* for the key to the client

Make it efficient!

A query should not generate a flood
or go be forwarded through too many nodes

Distributed Hash Table
Object Storage

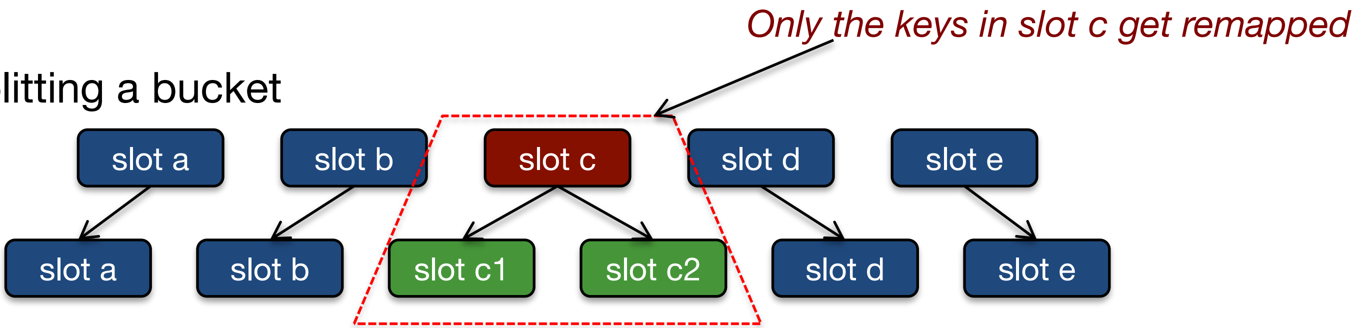


Consistent hashing

- Conventional hashing
  - Practically all keys must be remapped if the table size changes
- **Consistent hashing**
  - Most keys will hash to the same value as before
  - On average, *K*/*n* keys will need to be remapped

    K = # keys, *n* = # of buckets

Example: splitting a bucket



Designing a distributed hash table

- Spread the hash table across multiple nodes (peers)
- Each node stores a portion of the key space – it's a bucket

lookup(key) → *node ID* that holds (*key*, *value*)

lookup(node_ID, key) → *value*

Questions

How do we partition the data & do the lookup?

& keep the system decentralized?

& make the system scalable (lots of nodes with dynamic changes)?

& fault tolerant (replicated data)?

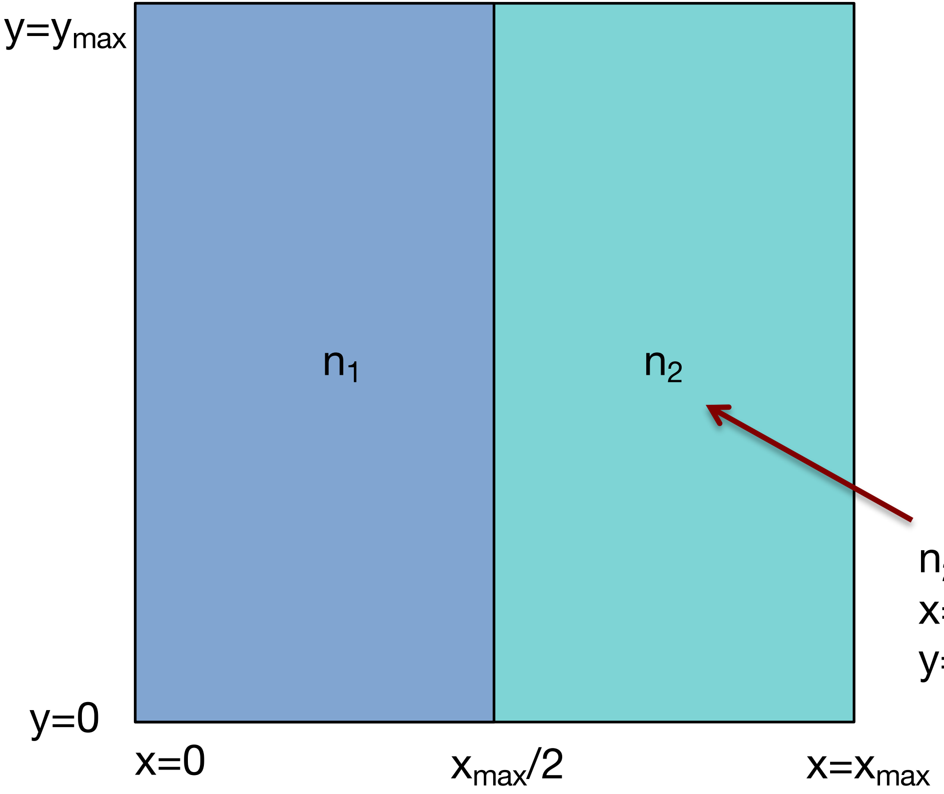
Distributed Hashing

CAN: Content Addressable Network

CAN design

- Create a logical grid
  - x-y in 2-D (but not limited to two dimensions)
- Separate hash function per dimension
  - $h_x(key)$, $h_y(key)$
- A node
  - Is responsible for a range of values in each dimension
  - Knows its neighboring nodes

CAN *key→node* mapping: 2 nodes



$x = hash_x(key)$

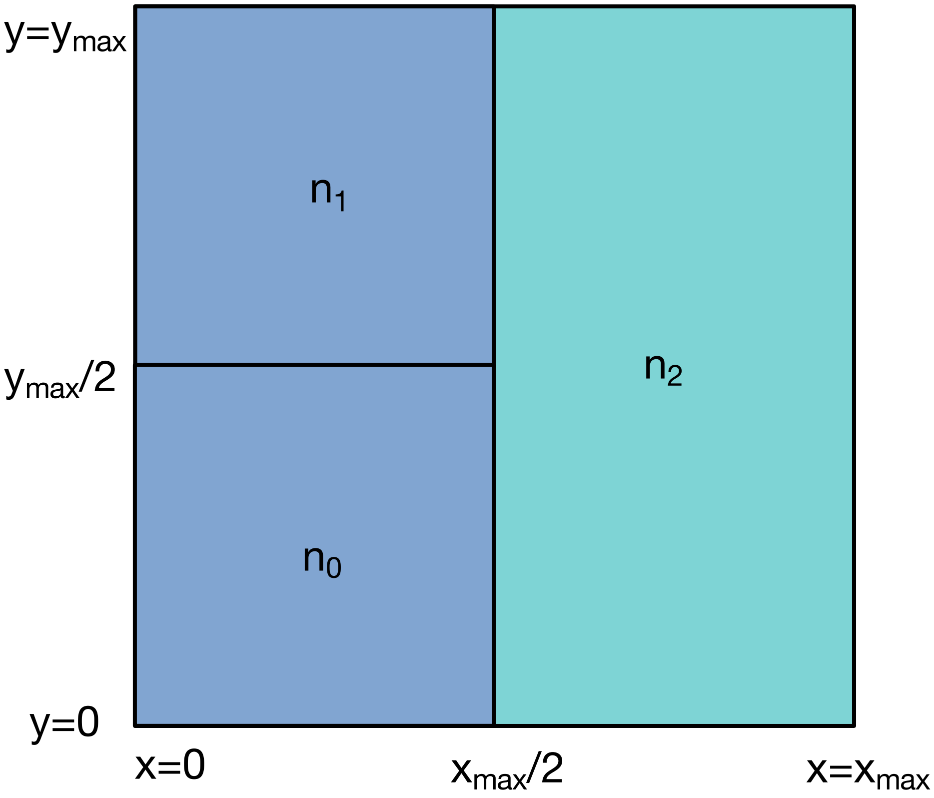
$y = hash_y(key)$

if $x < (x_{max}/2)$
n_1 has (*key, value*)

if $x \geq (x_{max}/2)$
n_2 has (*key, value*)

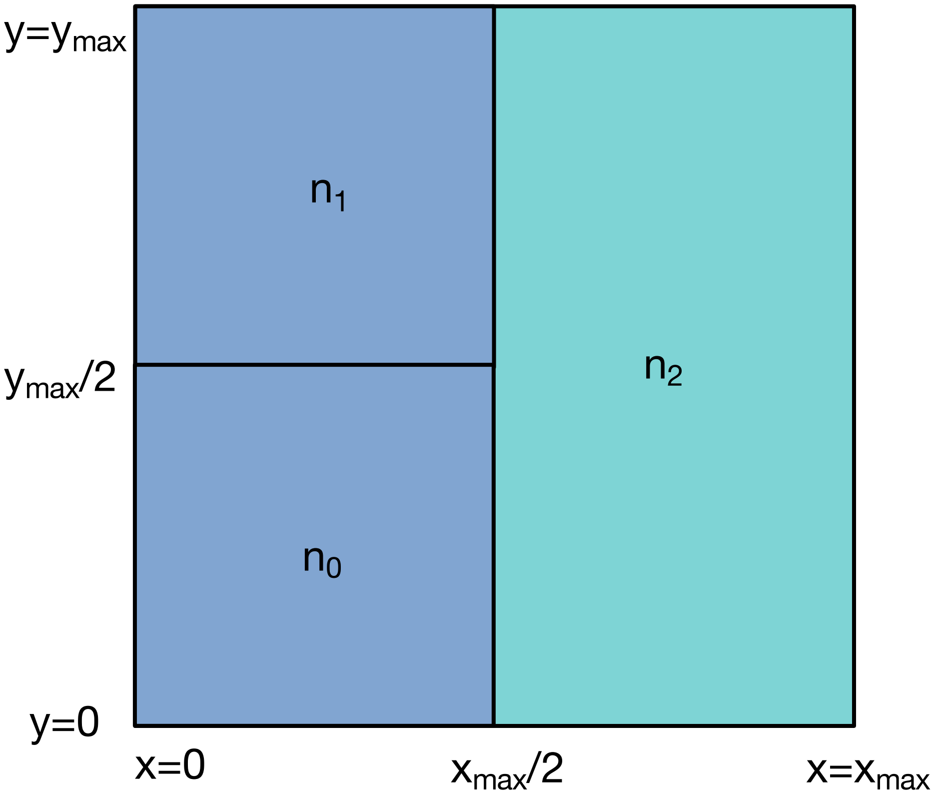
n_2 is responsible for a zone
$x=(x_{max}/2 .. x_{max})$,
$y=(0 .. y_{max})$

CAN partitioning



Any node can be split in two – either horizontally or vertically

CAN key→node mapping



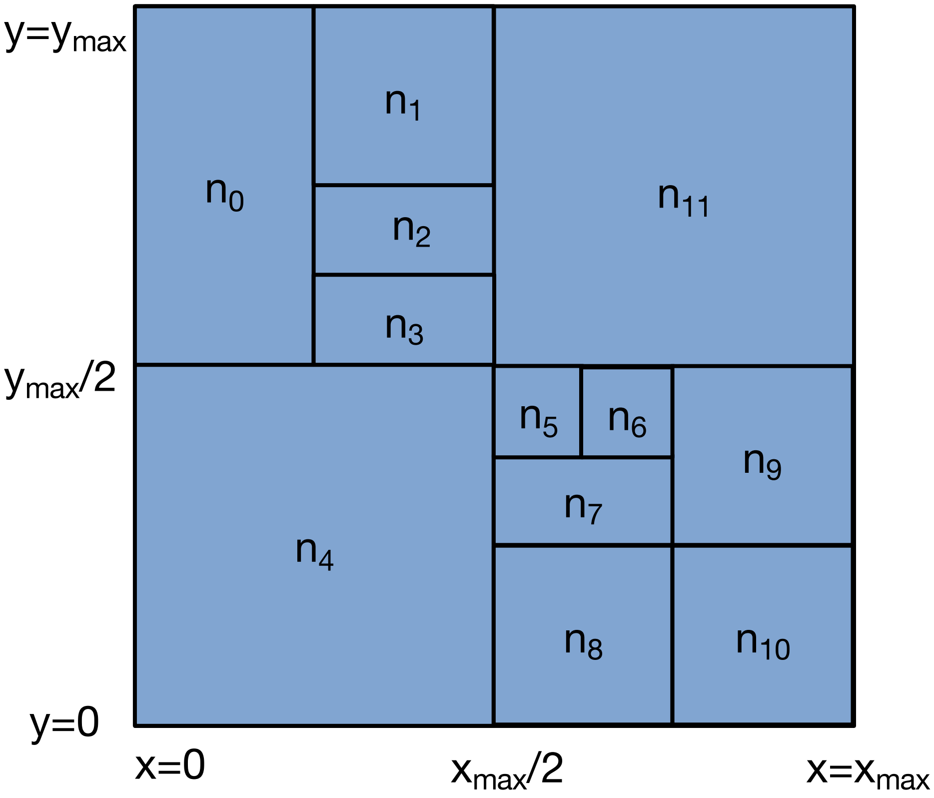
$x = hash_x(key)$

$y = hash_y(key)$

if $x < (x_{max}/2)$ {
    if $y < (y_{max}/2)$
        n_0 has (*key, value*)
    else
        n_1 has (*key, value*)
}

if $x \geq (x_{max}/2)$
        n_2 has (*key, value*)

CAN partitioning



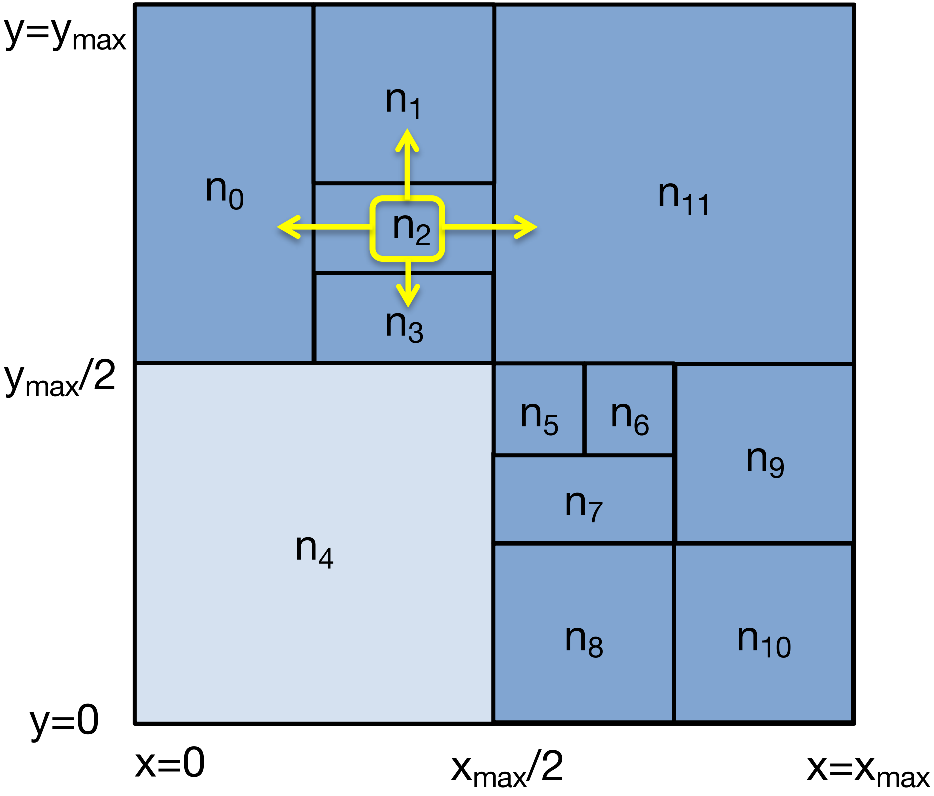
Any node can be split in two: either horizontally or vertically

Some data must be moved to the new node based on *hash*(*key*)

Neighbors need to be made aware of the new node

A node needs to know only one neighbor in each direction

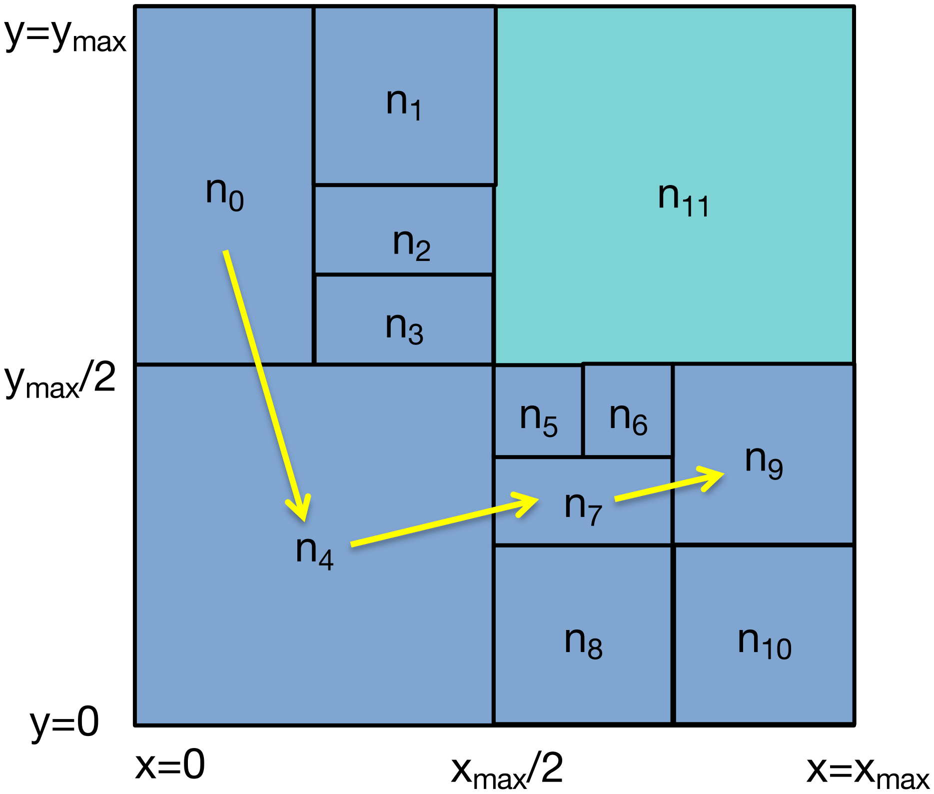
CAN neighbors



Neighbors refer to nodes that share adjacent zones in the overlay network

n_4 only needs to keep track of n_5, n_7, *or* n_8 as its right neighbor.

CAN routing



lookup(key):

Compute
hash_x(key), hash_y(key)

If the node is responsible for the (x, y) value then look up the key locally

Otherwise route the query to a neighboring node

CAN

- Performance
  - For *n* nodes in *d* dimensions
  - # neighbors = *2d*
  - Average route for 2 dimensions = $O(\sqrt{n})$ hops

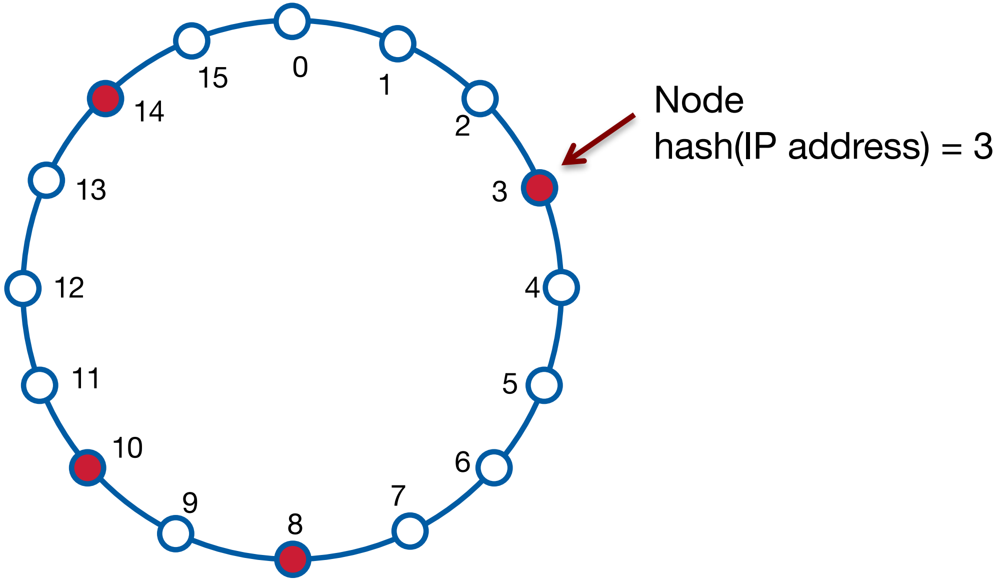
- To handle failures
  - Share knowledge of neighbor's neighbors
  - One of the node's neighbors takes over the failed zone

Distributed Hashing Case Study

Chord

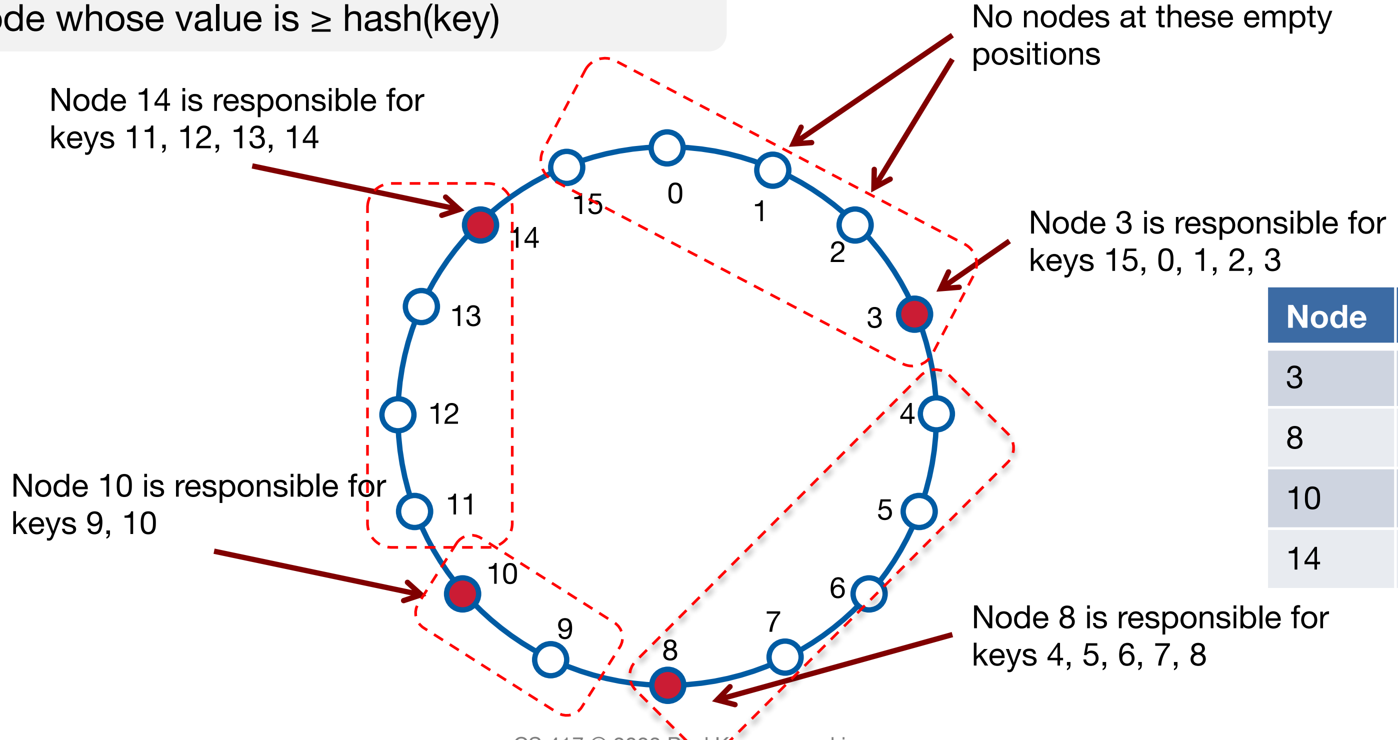
Chord & consistent hashing

- A key is hashed to an *m*-bit value: 0 … (2^m-1)
- A logical ring is constructed for the values 0 ... (2^m-1)
- Nodes are placed on the ring at *hash(IP address)*



Key assignment

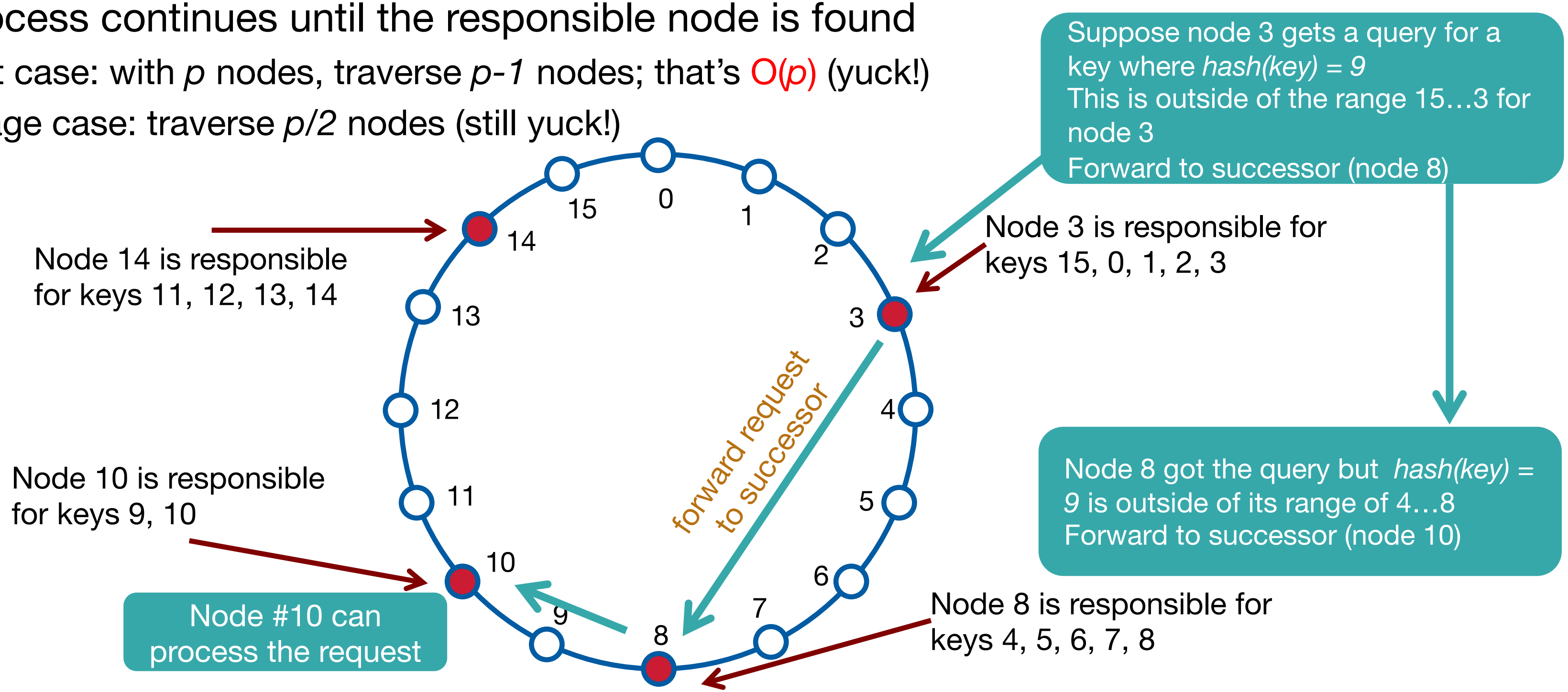
- Example: *n=16;* system with 4 nodes (so far)
- *(key, value)* data is stored at a **successor**
  - a node whose value is ≥ hash(key)



Node	Hash range
3	0-3, 15
8	4-8
10	9-10
14	11-14

Handling *insert* or *query* requests

- Any peer can get a request (*insert* or *query*).
- If the *hash(key)* is not for its ranges of keys, it forwards the request to the successor.
- The process continues until the responsible node is found
  - Worst case: with *p* nodes, traverse *p-1* nodes; that's O(*p*) (yuck!)
  - Average case: traverse *p/2* nodes (still yuck!)

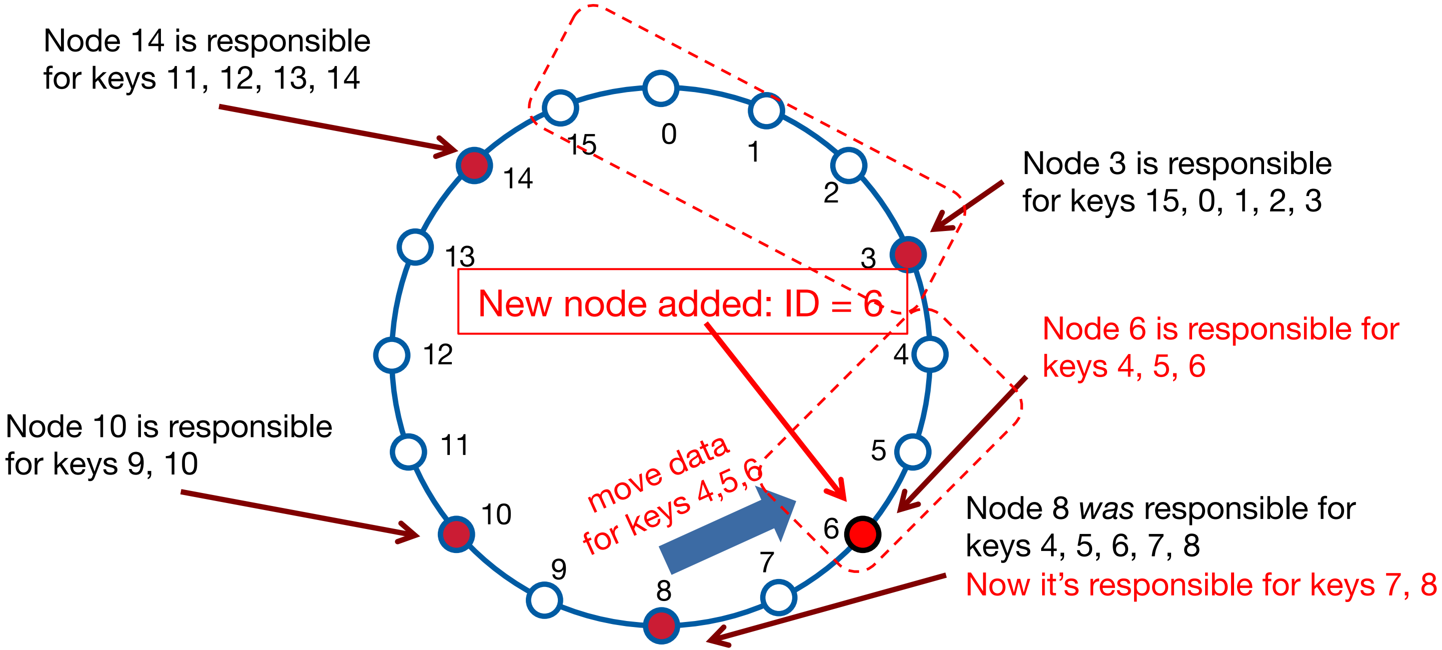


Let’s figure out three more things

1. Adding/removing nodes
2. Improving lookup time
3. Providing fault tolerance

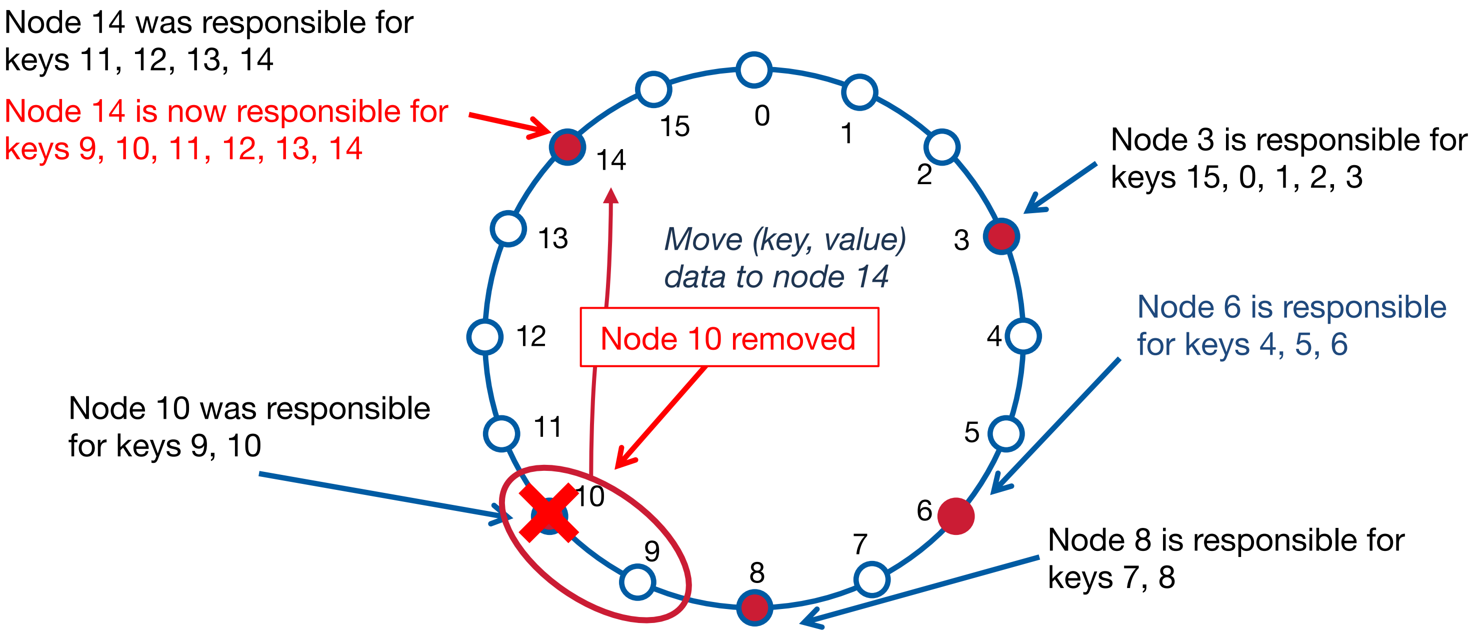
Adding a node

- Some keys that were assigned to a node's successor now get assigned to the new node
- Data for those *(key, value)* pairs must be moved to the new node



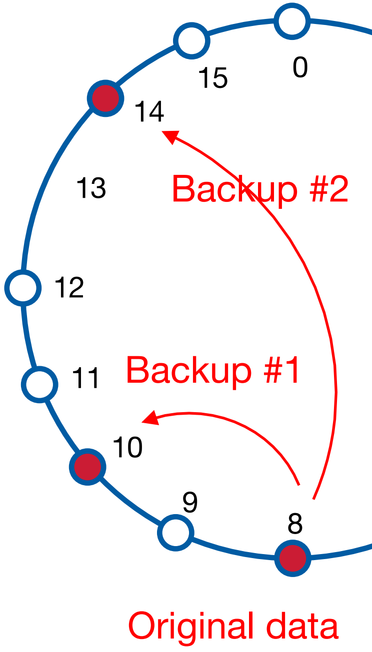
Removing a node

- Keys are reassigned to the node's successor
- Data for those *(key, value)* pairs must be moved to the successor



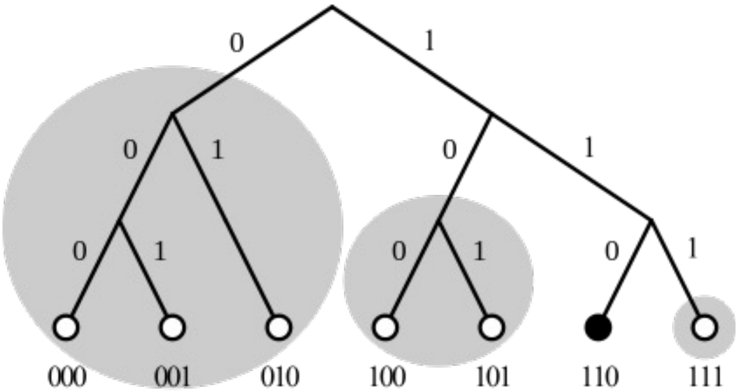
Fault tolerance

- Nodes might die
  - *(key, value)* data should be replicated
  - Create *R* replicas, storing each one at *R-1* successor nodes in the ring
- Need to know multiple successors
  - A node needs to know how to find its successor's successor (or more)
    - Easy if it knows all nodes!
  - When a node is back up, it needs to:
    - Check with successors for updates of data it owns
    - Check with predecessors for updates of data it stores as backups



Kademlia DHT

- Similar in concept to Chord
- Uses a logical tree structure instead of a ring
- Distance = peer_1 ⊕ peer_2



Performance

- We're not thrilled about *O(N)* lookup

- Simple approach for great performance
  - Have all nodes know about each other
  - When a peer gets a query, it searches its table of nodes for the node that owns those values
  - Gives us *O(1)* performance
  - Add/remove node operations must inform everyone
  - Maybe not a good solution if we have lots of peers (large tables)

Finger tables

- Compromise to avoid large tables at each node
  - Use finger tables to place an upper bound on the table size

- Finger table = partial list of nodes, progressively more distant

- At each node, i^{th} entry in finger table identifies node that succeeds it by at least 2^{i-1} in the circle
  - `finger_table[0]`: immediate (1^{st}) successor
  - `finger_table[1]`: successor after that (2^{nd})
  - `finger_table[2]`: 4^{th} successor
  - `finger_table[3]`: 8^{th} successor
  - …

In the kademlia DHT
finger table ≡ **skip list**

- *O(log N)* nodes need to be contacted to find the node that owns a key

  … not as good as *O(1)* but way better than *O(N)*

Improving performance even more

- Let's revisit O(1) lookup
- Each node keeps track of all current nodes in the group
  - Is that really so bad?
  - We might have thousands of nodes … so what?
- Any node will now know which node holds a *(key, value)*
- Add or remove a node: send updates to **<u>all</u>** other nodes

Some uses of DHTs

- General purpose distributed object store: names, passwords, user profiles, …
- Coral content delivery network, Tox instant messaging, Freenet anonymous content sharing, Scribe event notification
- **Amazon** – shopping carts, best seller lists, customer preferences, sales rank, session info, product catalog
- **BitTorrent** – distributed tracker
  - key = infohash   infohash =hash(file_contents)
  - value = IP addresses of peers willing to serve the file
- **InterPlanetary File System (IPFS)** – 3 DHTs
  1. Find peers that have the desired file data (look up by hash of the file)
  2. Find the pathname given the file's content (hash)
  3. Get a set of addresses for a peer given its ID

The End