Distributed Systems

16. Distributed Lookup

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Fall 2018

Distributed Lookup

- Look up (*key, value*)
- Cooperating set of nodes
- Ideally:
  - No central coordinator
  - Some nodes can be down

Approaches

1. Central coordinator
   – Napster

2. Flooding
   – Gnutella

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

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 (master)
  - 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

- Well-known nodes act as anchors
  - Nodes with files inform an anchor about their existence
  - Nodes select other nodes as peers

2. Query Flooding

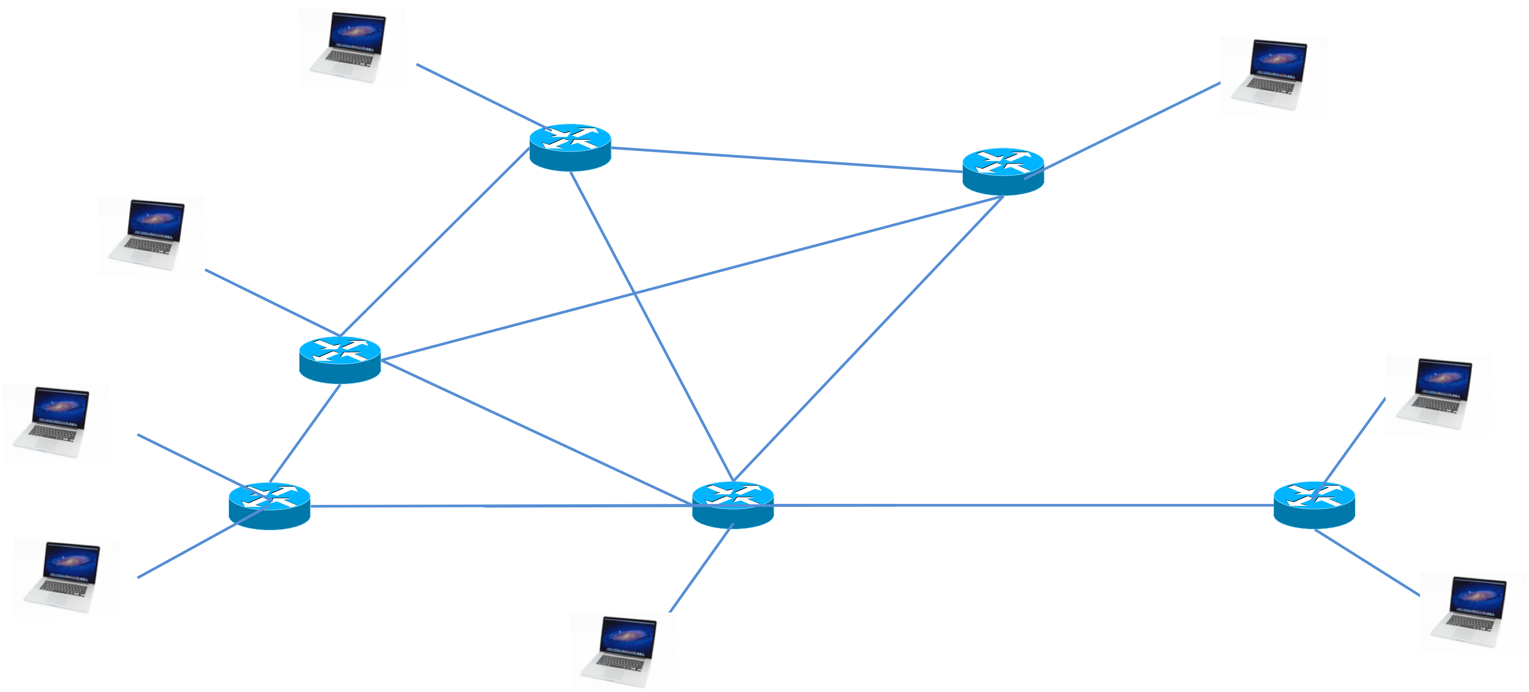
- Send a query to peers if a file is not present locally
  - Each request contains:
    - Query key
    - Unique request ID
    - Time to Live (TTL, maximum hop count)

- Peer either responds or routes the query to its neighbors
  - Repeat until TTL = 0 or if the request ID has been processed
  - If found, send response (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

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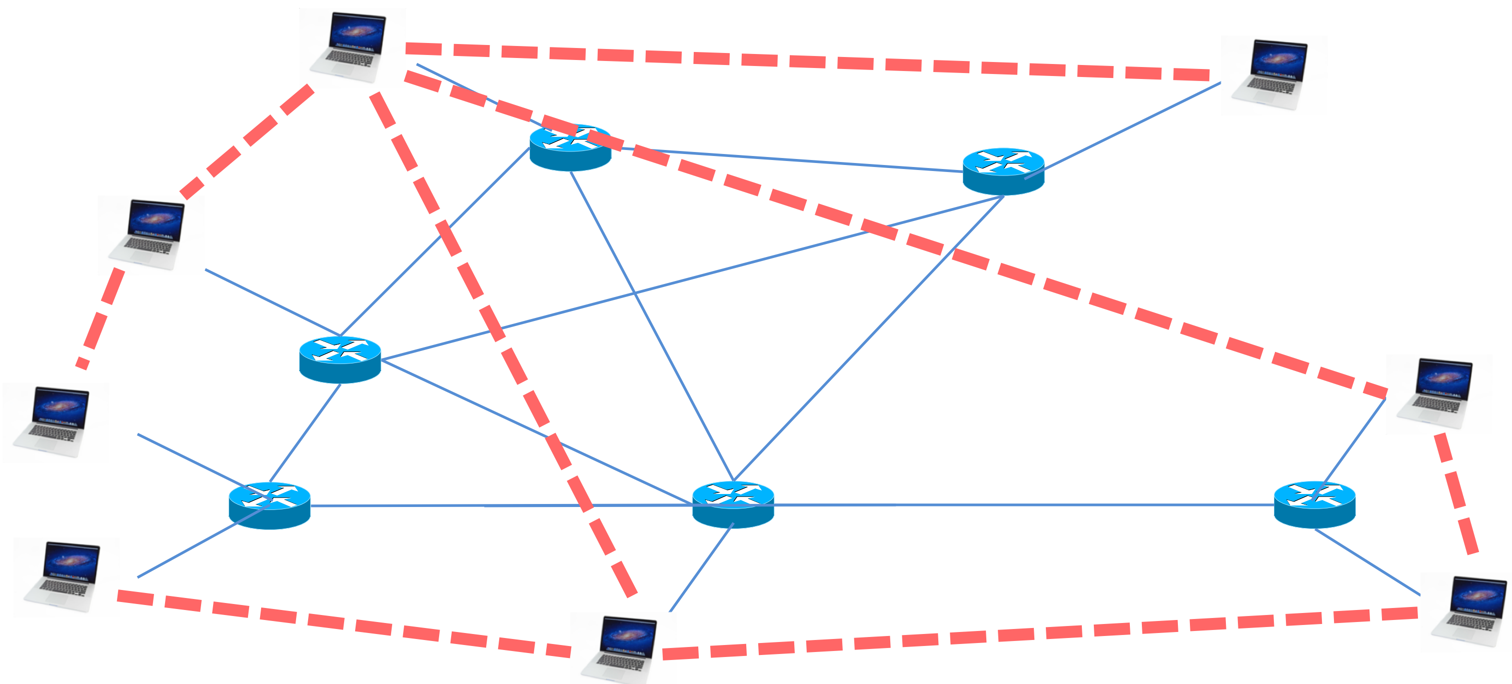
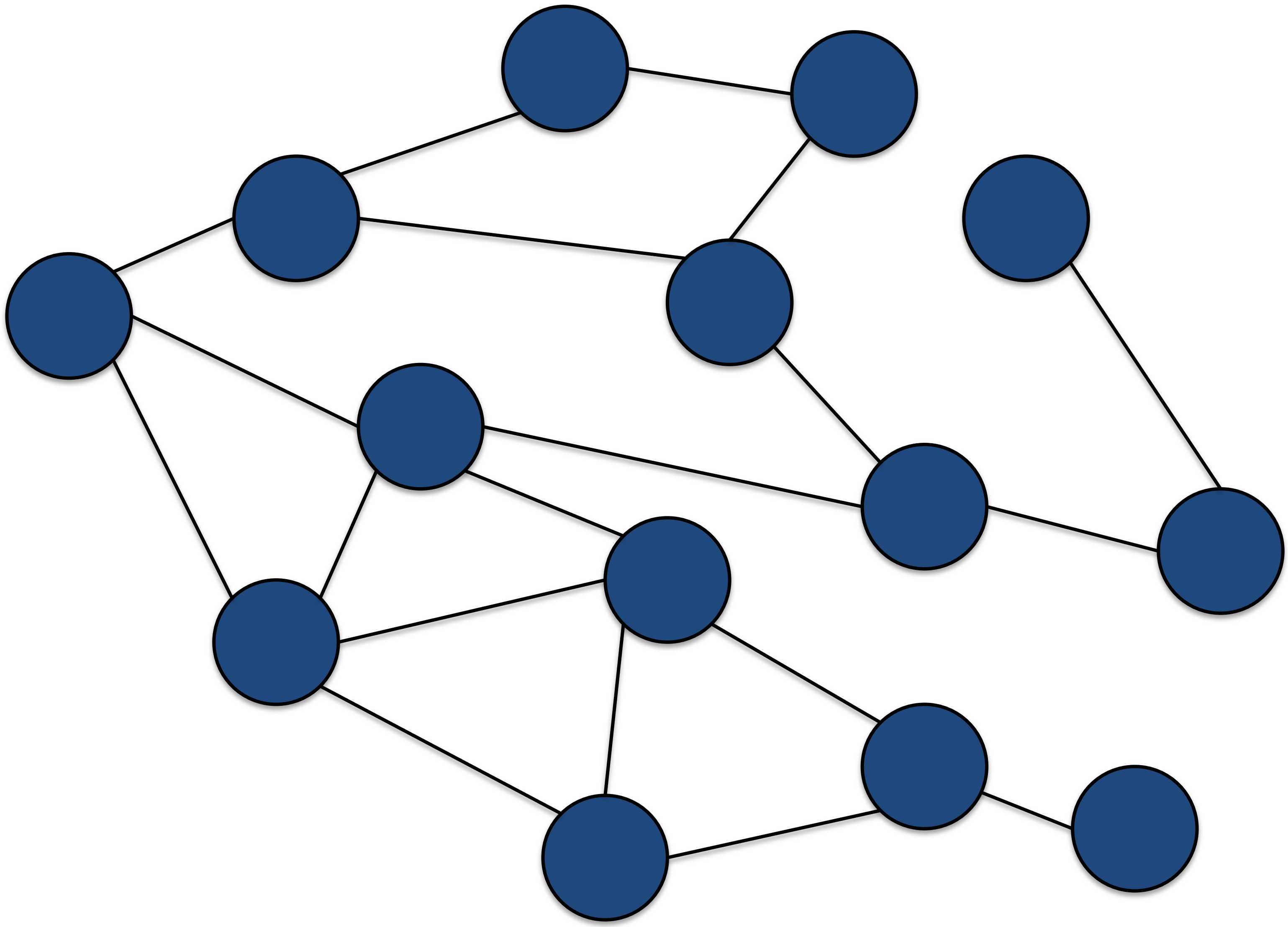
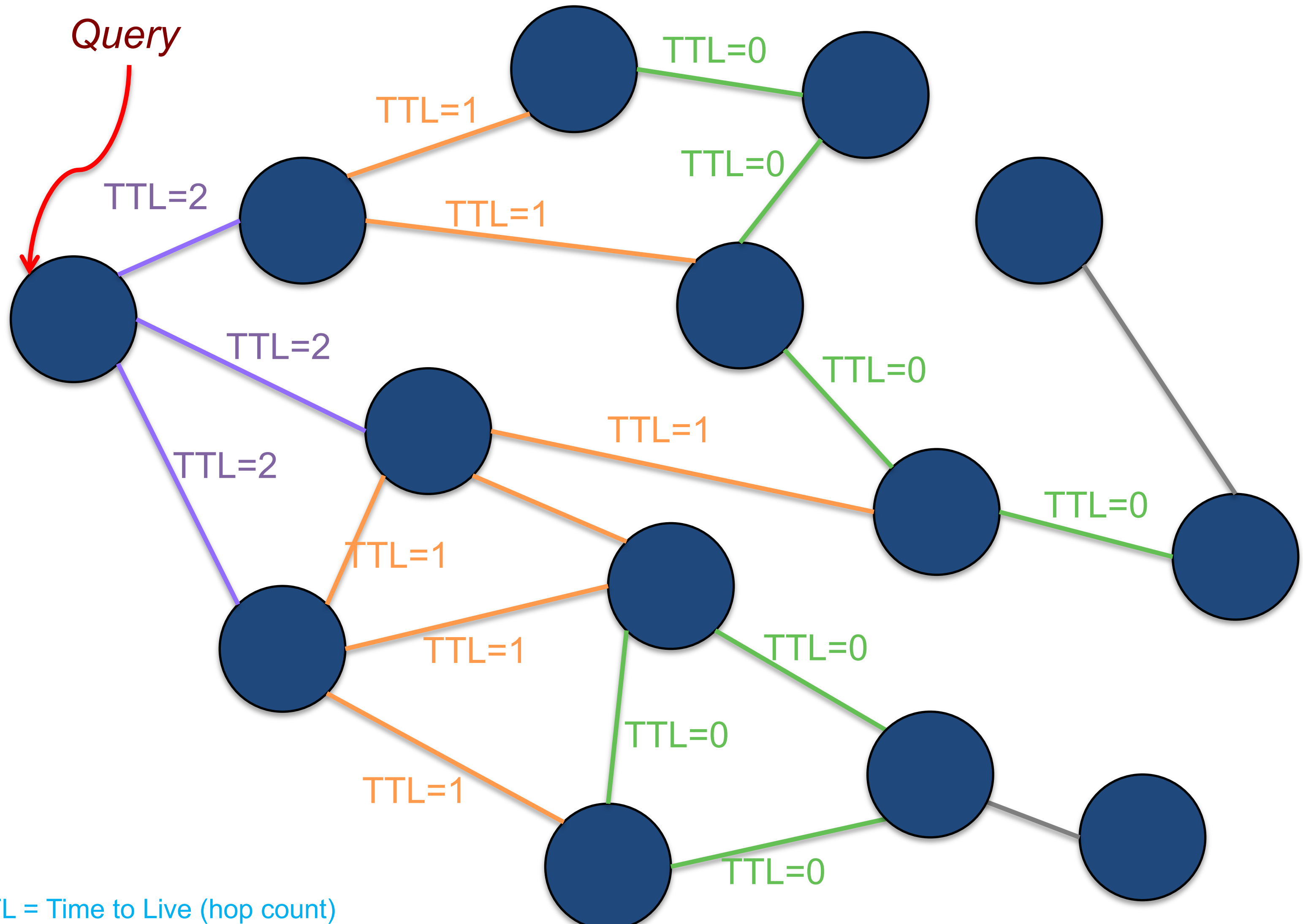


Overlay Network

Flooding Example: Overlay Network

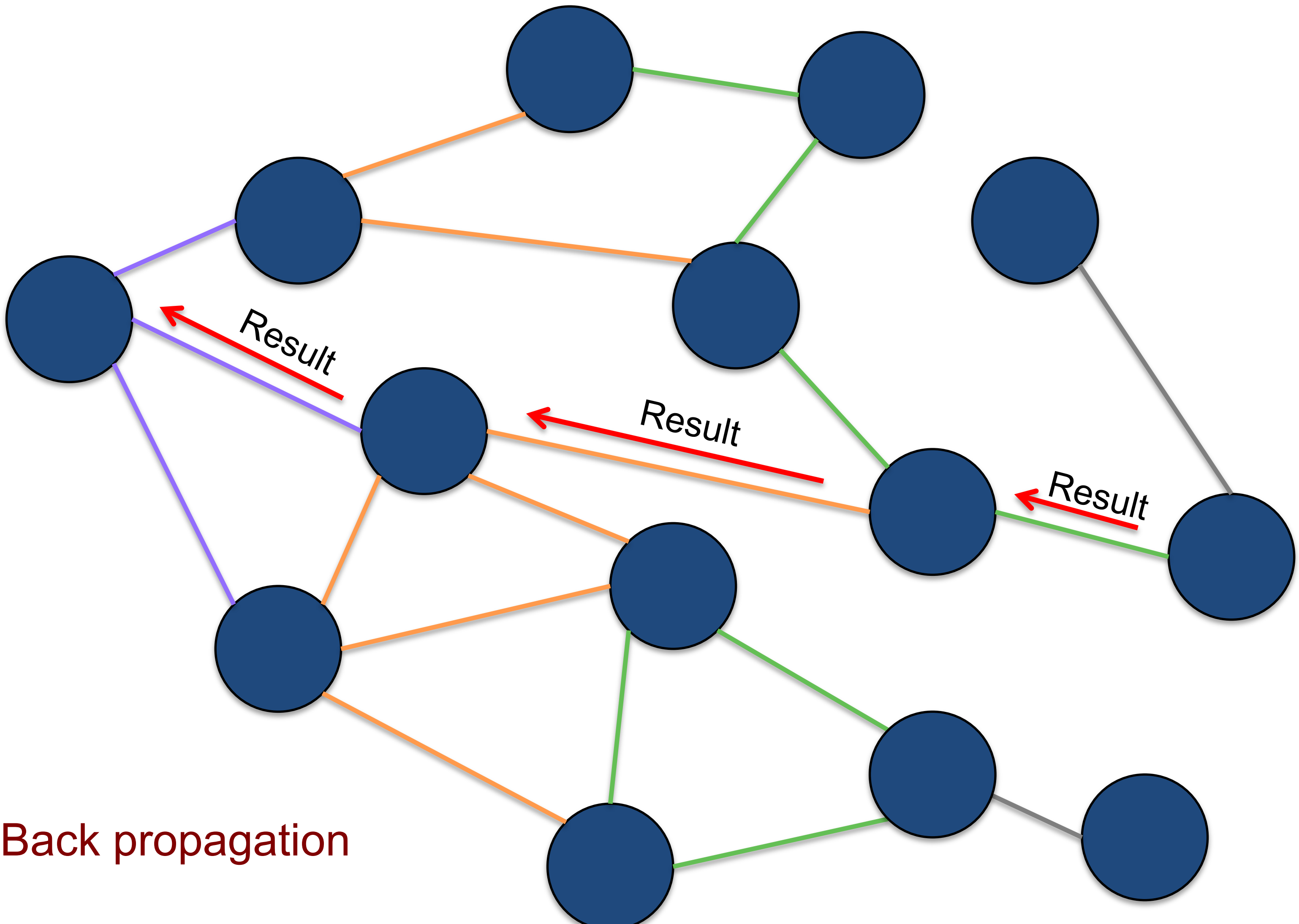


Flooding Example: Query Flood



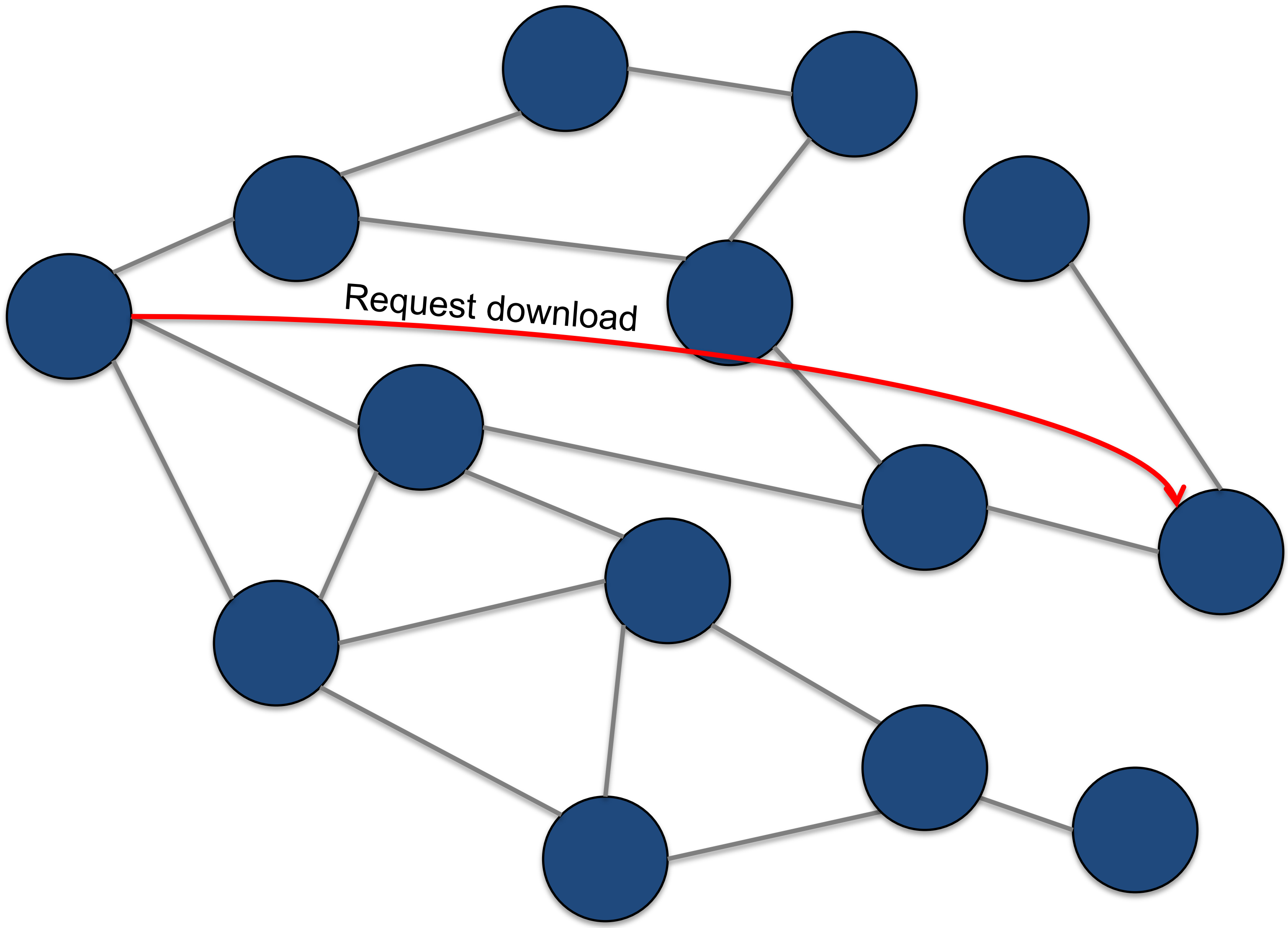
TTL = Time to Live (hop count)

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
  – Gnutella & Kazaa dealt with this by classifying some nodes as special ("ultrapeers" in Gnutella, "supernodes" in Kazaa,)
- Poor use of network resources
- Potentially high latency
  – Requests get forwarded from one machine to another
  – Back propagation (e.g., in Gnutella's design), where the replies go through the same chain of machines used in the query, increases latency even more

3. Distributed Hash Tables

Hash tables

- Remember hash functions & hash tables?
  - Linear search: O(*N*)
  - Tree: O(log*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) and generates a (usually smaller) fixed length result (e.g., 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*
      table of *N* elements
      `i = hash(key)`
      `table[i]` contains the item
  - 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)

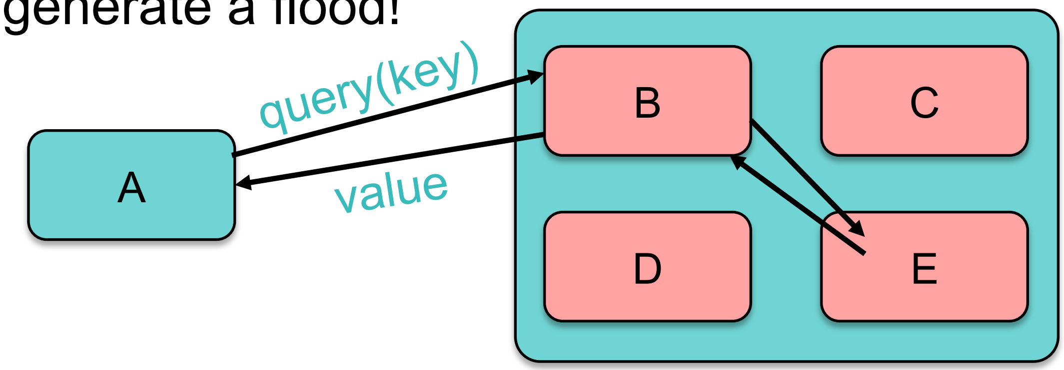
Create a peer-to-peer version of a (*key, value*) data store

How we want it to work

1. A peer (*A*) queries the data store with a key
2. The data store finds the peer (*B*) that has the value
3. That peer (*B*) returns the (key, value) pair to the querying peer (*A*)

Make it efficient!

– A query should not generate a flood!

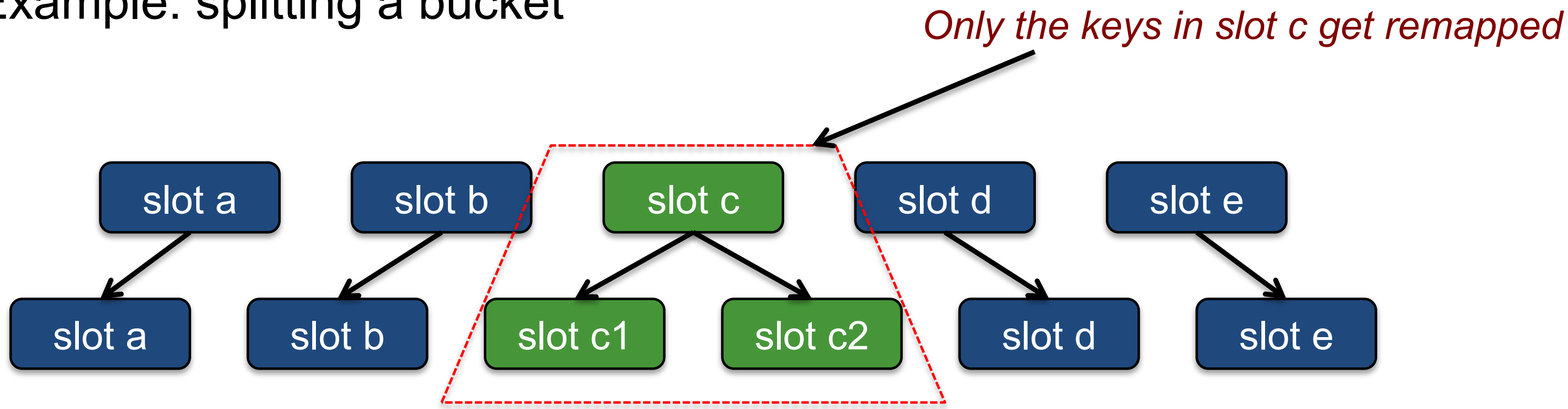


Consistent hashing

- Conventional hashing
  - Practically all keys have to 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



3. Distributed hashing

- Spread the hash table across multiple nodes
- Each node stores a portion of the key space

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
Case Study

CAN: Content Addressable Network

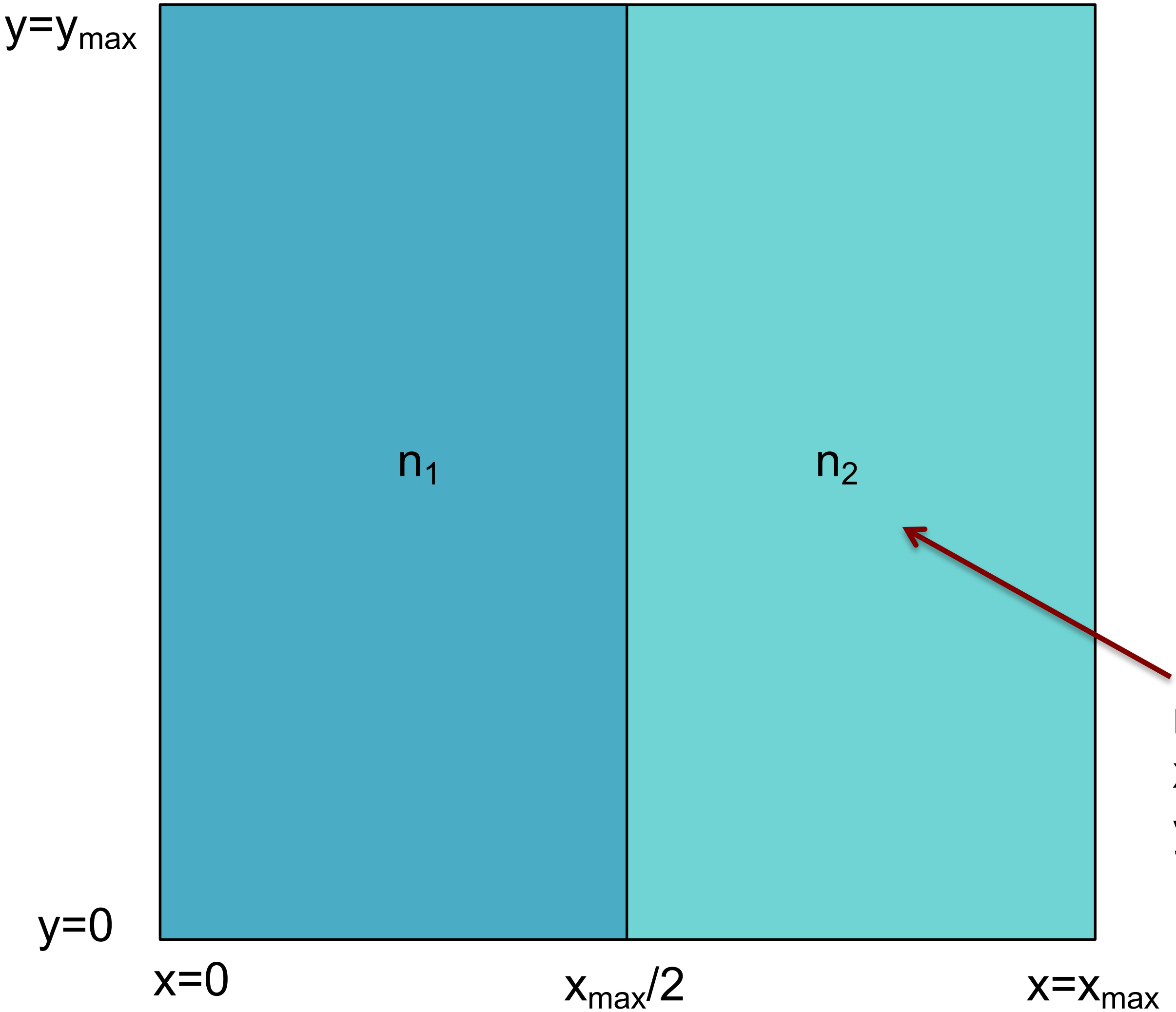
CAN design

- 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



$x = hash_x(key)$

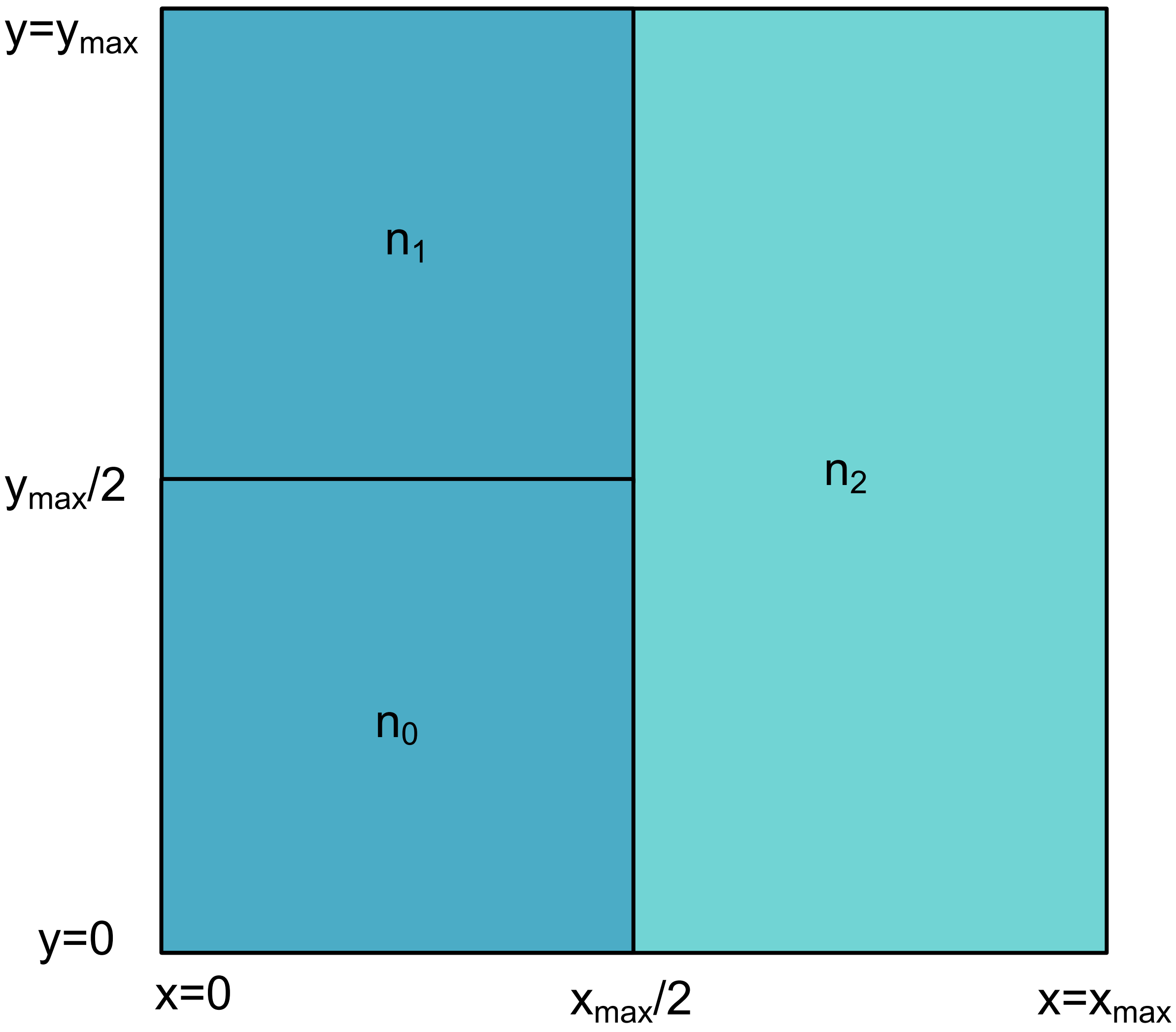
$y = hash_y(key)$

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

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

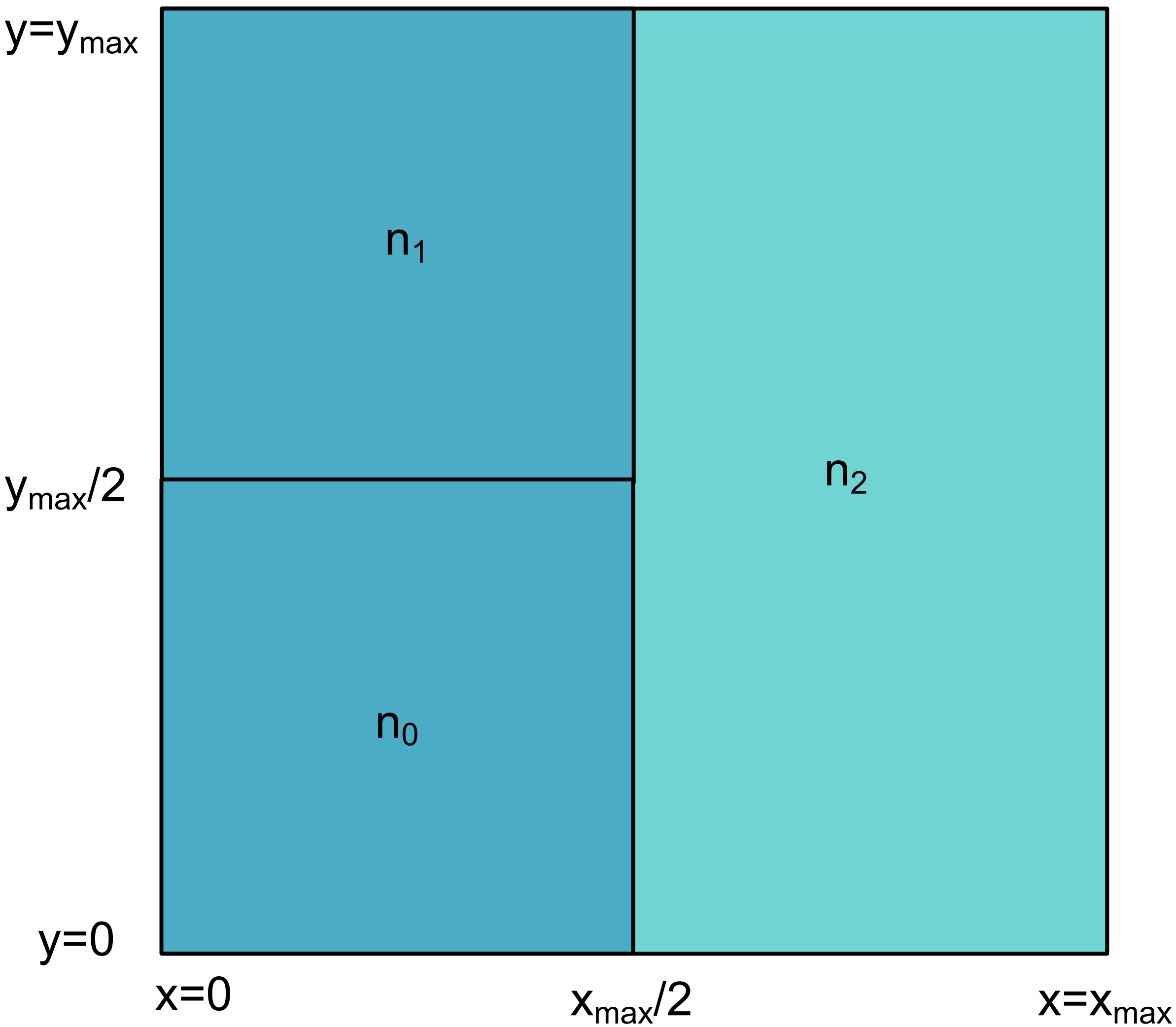
n_2 is responsible for a zone
$x=(x_{max}/2 .. x_{max})$,
$y=(0 .. y_{max})$

CAN partitioning



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

CAN key→node mapping



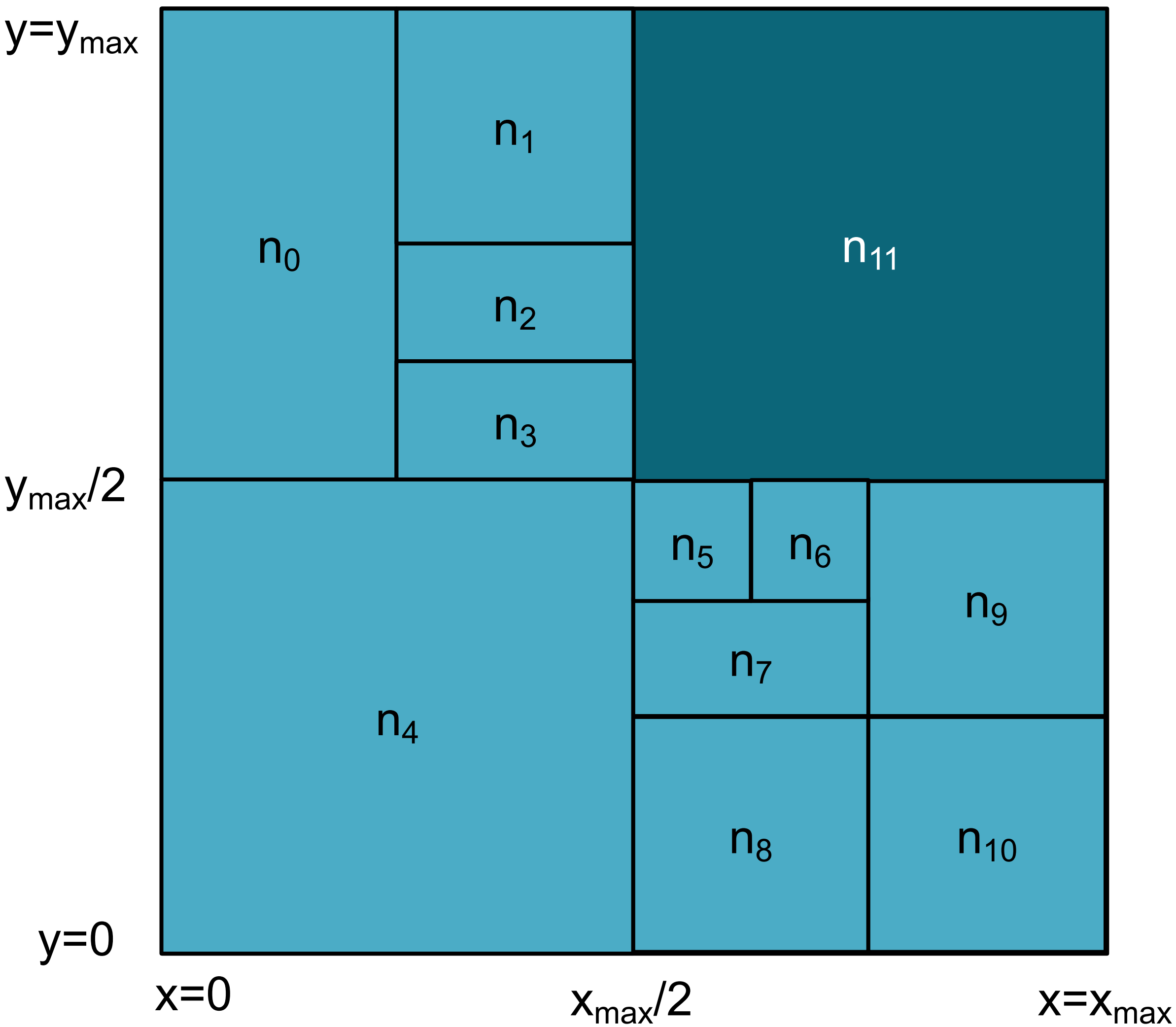
$x = hash_x(key)$

$y = hash_y(key)$

```
if x < (x_max/2) {
   if y < (y_max/2)
       n_0 has (key, value)
   else
       n_1 has (key, value)
}

if x ≥ (x_max/2)
       n_2 has (key, value)
```

CAN partitioning



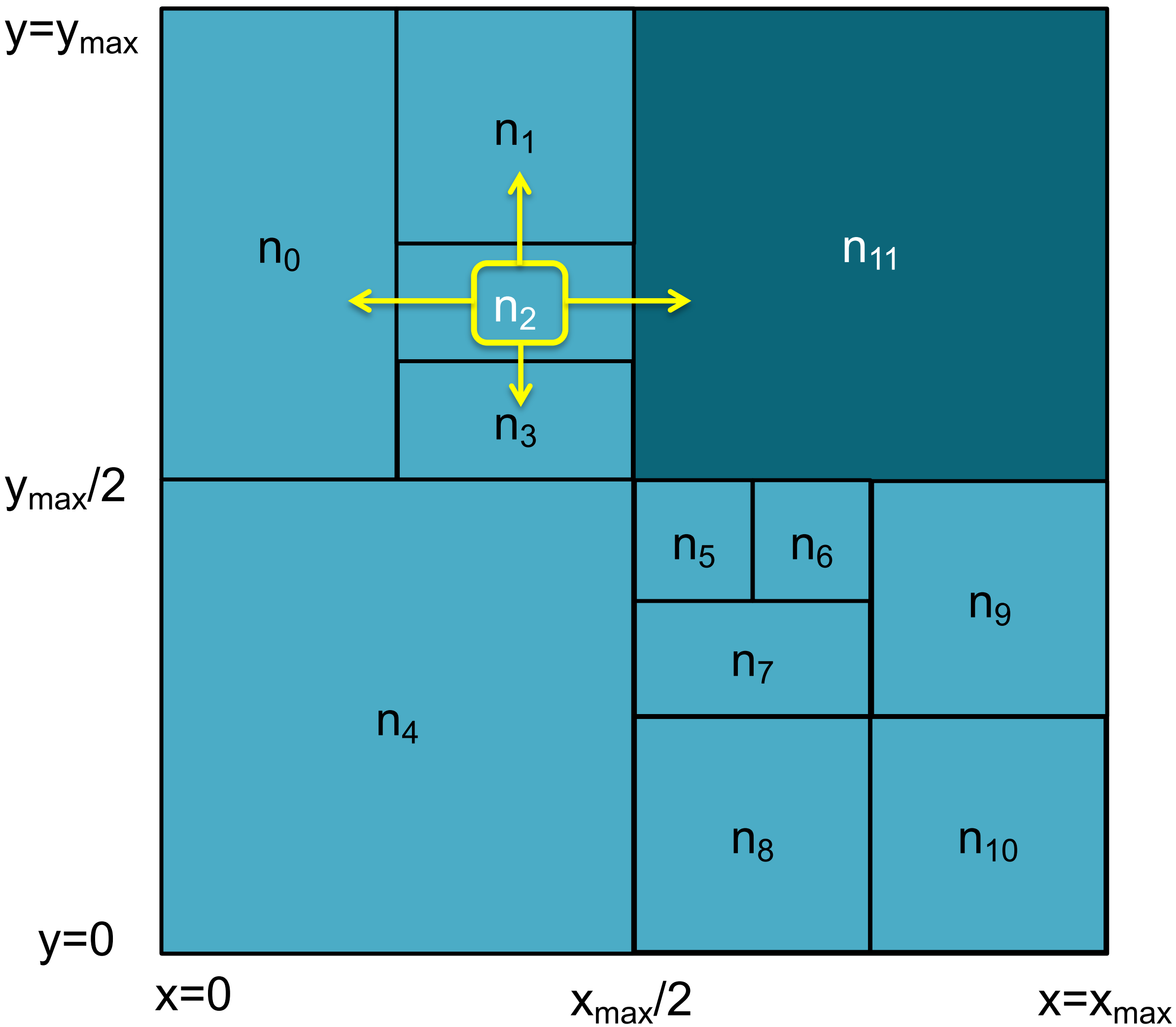
Any node can be split in two – either horizontally or vertically

Associated data has to be moved to the new node based on *hash*(*key*)

Neighbors need to be made aware of the new node

A node knows only of its neighbors

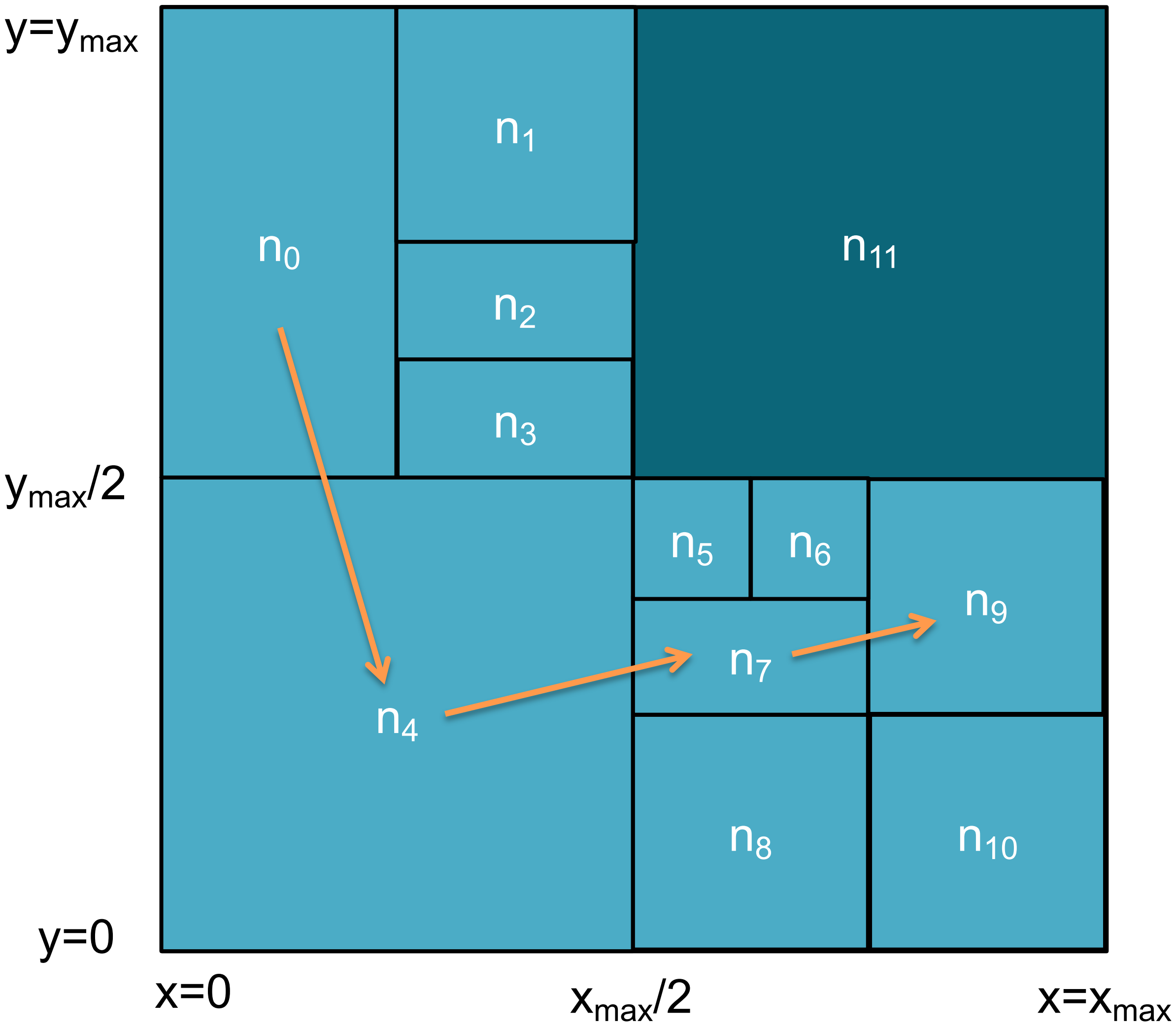
CAN neighbors



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) on a node that does not own the value

Compute *$hash_x$(key)*, *$hash_y$(key)* and route request to a neighboring node

Ideally: route to minimize distance to destination

CAN

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

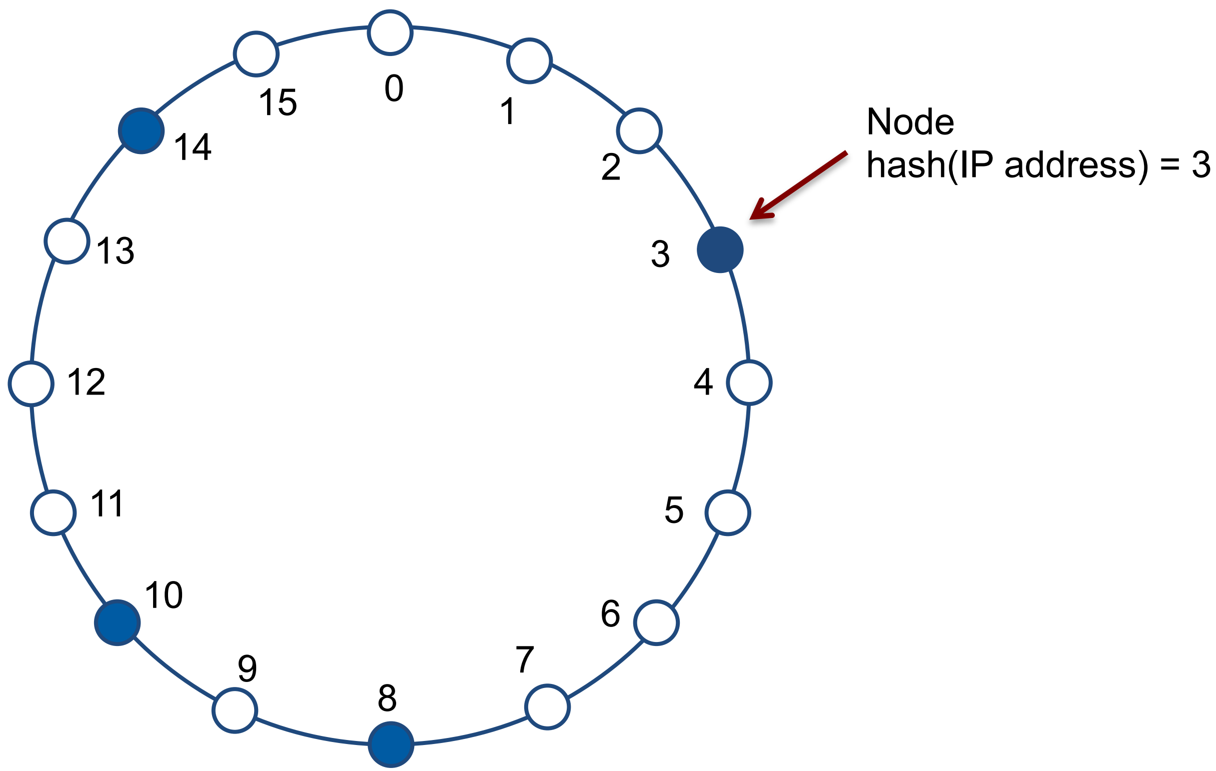
- To handle failures
  - Share knowledge of neighbor's neighbors
  - One of the node's neighbors takes over the failed zone

Distributed Hashing Case Study

Chord

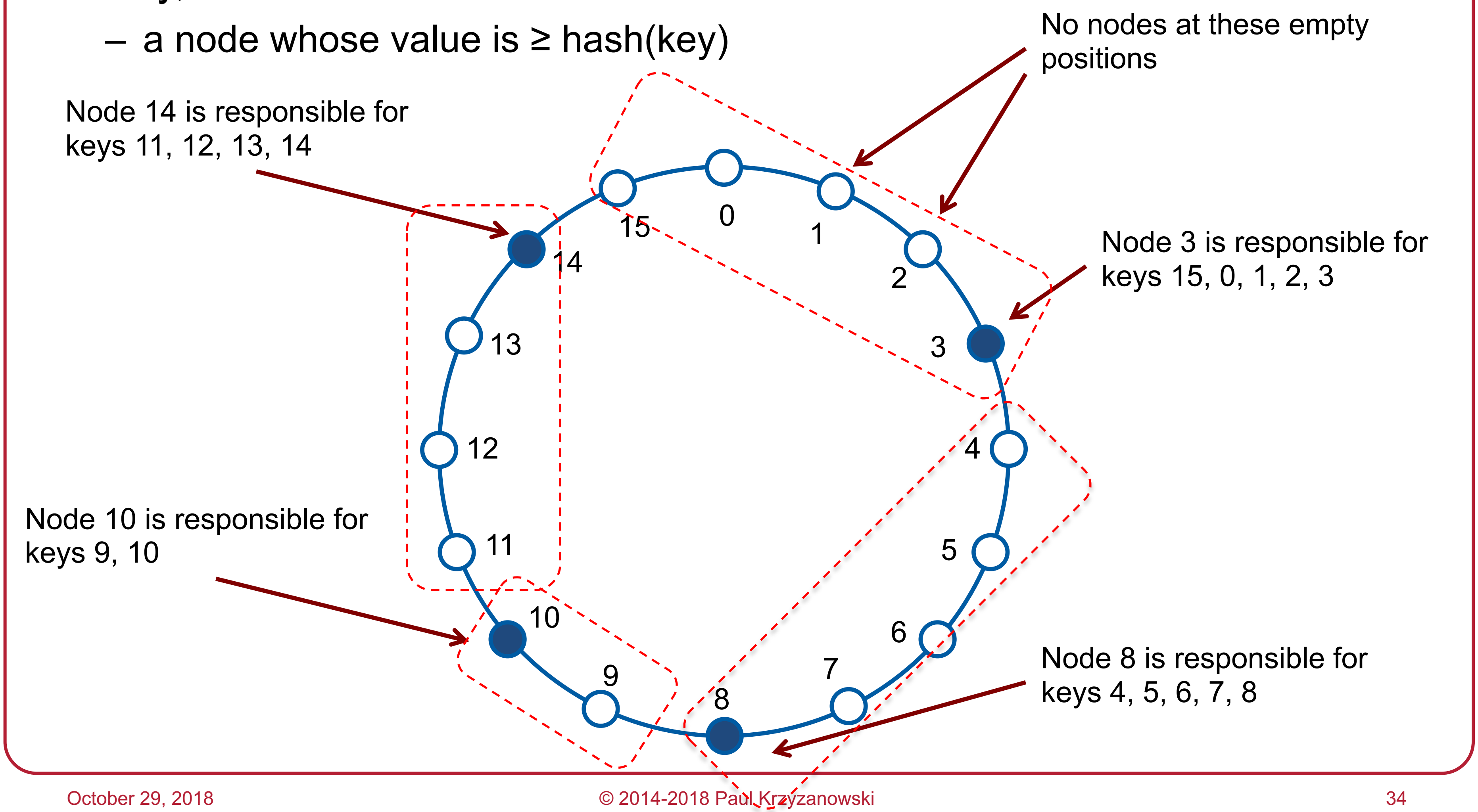
Chord & consistent hashing

- 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)*



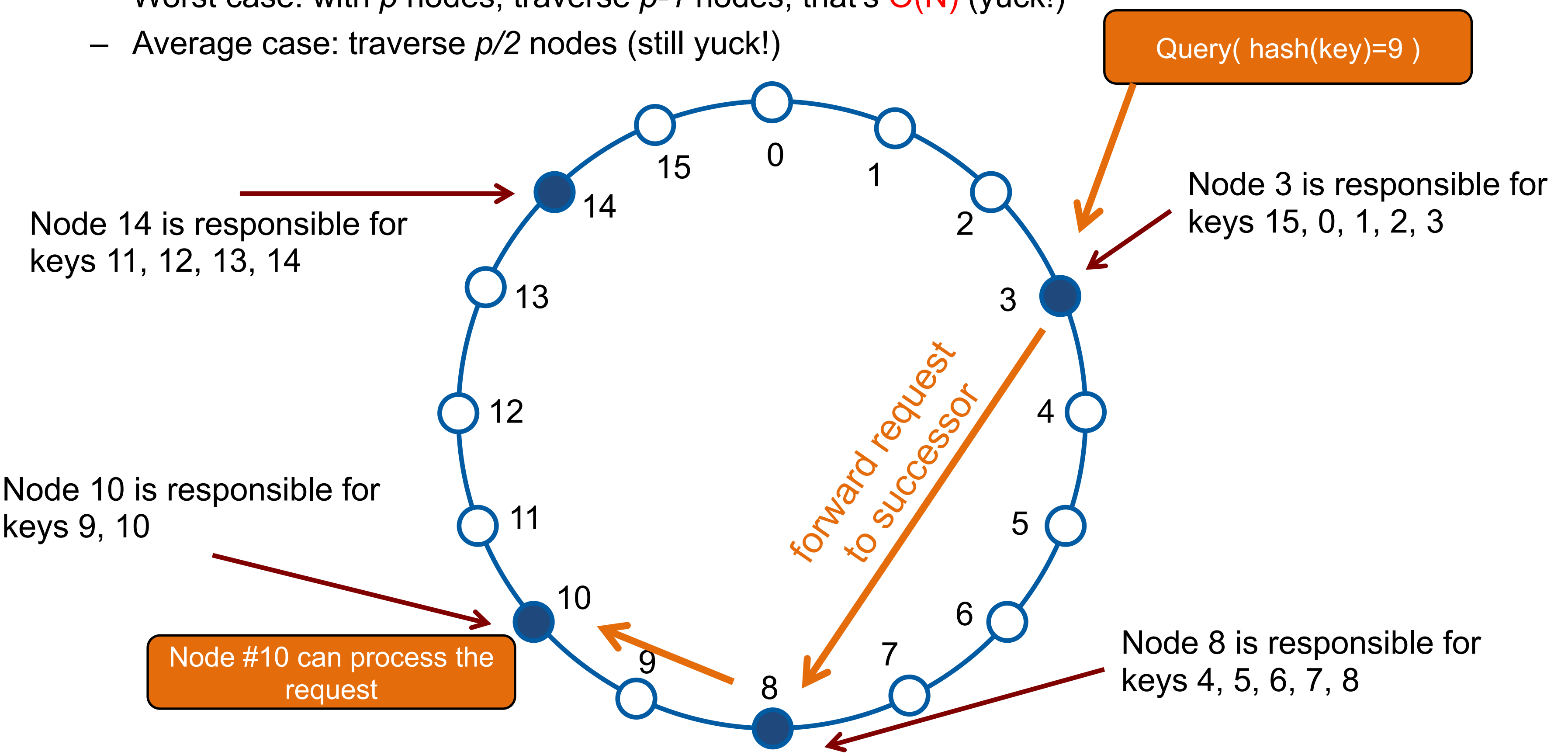
Key assignment

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



Handling 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 a successor.
- The process continues until the responsible node is found
  - Worst case: with *p* nodes, traverse *p-1* nodes; that's O(N) (yuck!)
  - Average case: traverse *p/2* nodes (still yuck!)

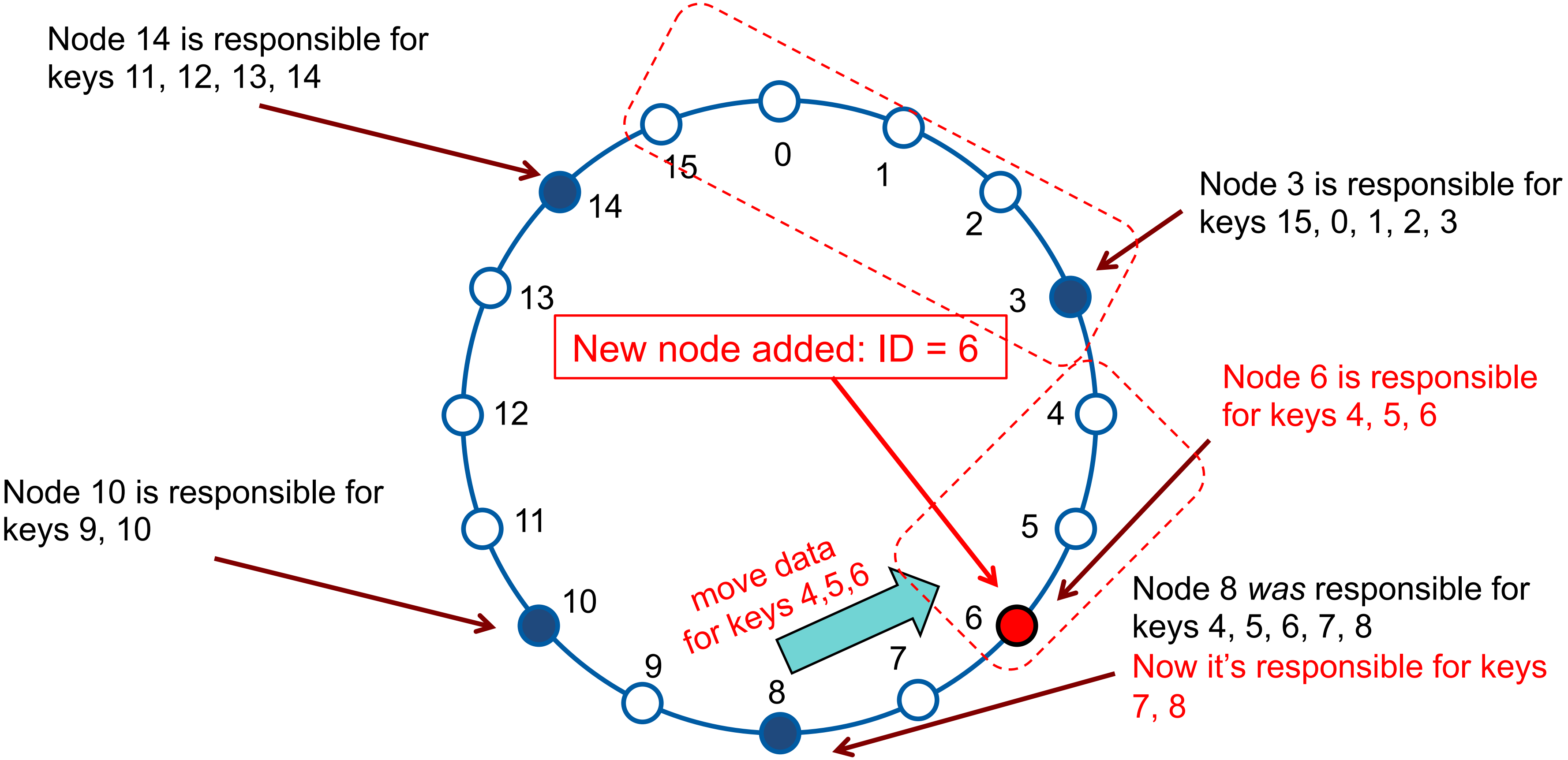


Let's figure out three more things

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

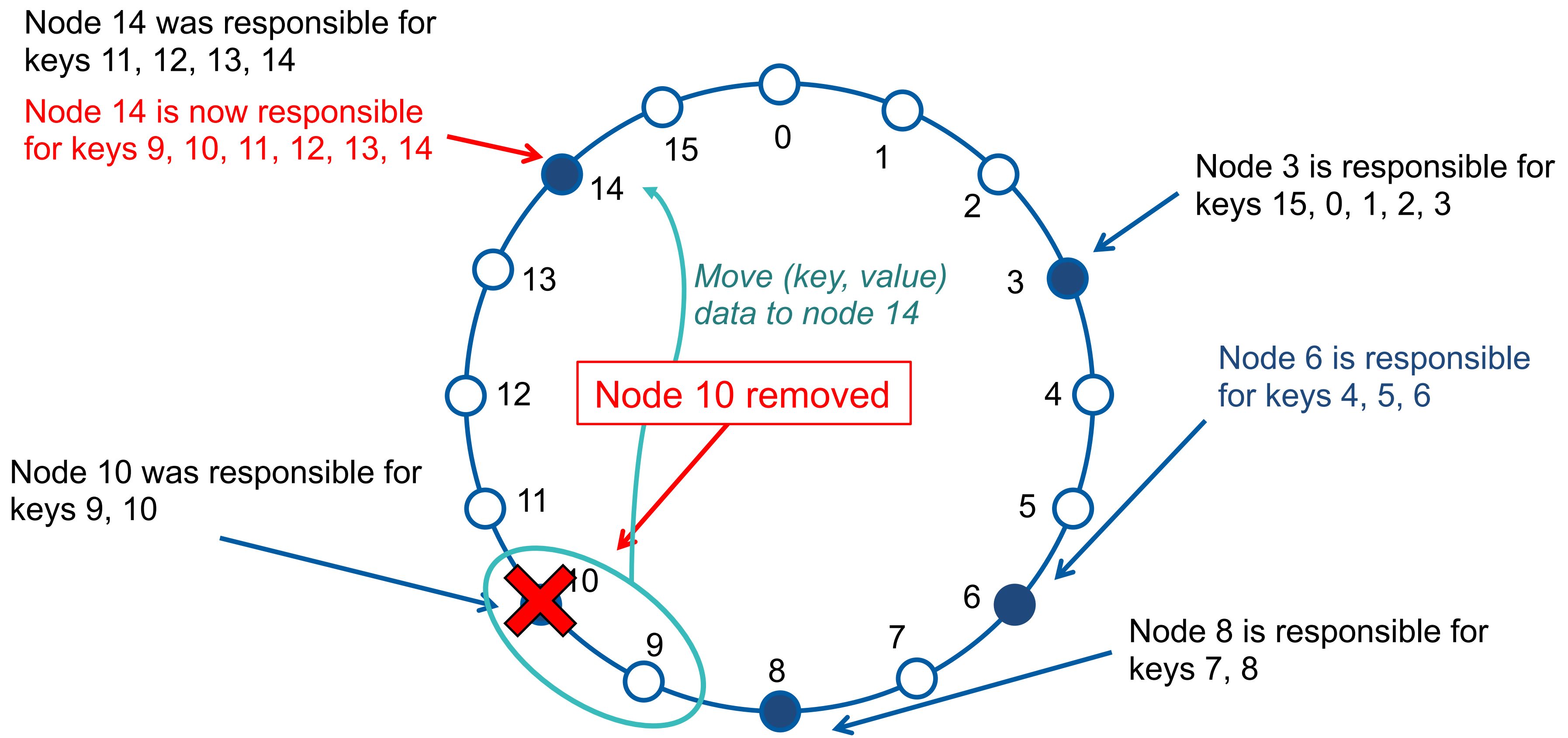
Adding a node

- 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
  - Any changes need to be propagated to all replicas

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 node, 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 millions of peers (huge 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
  - …
- *O(log N)* nodes need to be contacted to find the node that owns a key
  … not as cool 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 **all** other nodes

Distributed Hashing
Case Study

Amazon Dynamo

Amazon Dynamo

- Not exposed as a web service
  - Used to power parts of Amazon Web Services and internal services
  - Highly available, key-value storage system

- In an infrastructure with millions of components, something is always failing!
  - Failure is the normal case

- A lot of services within Amazon only need primary-key access to data
  - Best seller lists, shopping carts, preferences, session management, sales rank, product catalog
  - No need for complex querying or management offered by an RDBMS
    - Full relational database is overkill: limits scale and availability
    - Still not efficient to scale or load balance RDBMS on a large scale

Core Assumptions & Design Decisions

- Two operations: **get(key)** and **put(key, data)**
  - Binary objects (data) identified by a unique key
  - Objects tend to be small (< 1MB)
- ACID gives poor availability
  - Use weaker consistency (C) for higher availability.
- Apps should be able to configure Dynamo for desired latency & throughput
  - Balance performance, cost, availability, durability guarantees.
- At least 99.9% of read/write operations must be performed within a few hundred milliseconds:
  - Avoid routing requests through multiple nodes
- Dynamo can be thought of as a **zero-hop DHT**

Core Assumptions & Design Decisions

- Incremental scalability
  - System should be able to grow by adding a storage host (node) at a time
- Symmetry
  - Every node has the same set of responsibilities
- Decentralization
  - Favor decentralized techniques over central coordinators
- Heterogeneity (mix of slow and fast systems)
  - Workload partitioning should be proportional to capabilities of servers

Consistency & Availability

- Strong consistency & high availability cannot be achieved simultaneously

- Optimistic replication techniques – eventually consistent model
  - propagate changes to replicas in the background
  - can lead to conflicting changes that have to be detected & resolved

- When do you resolve conflicts?
  - **During writes**: traditional approach – reject write if cannot reach all (or majority) of replicas – ***but don't deal with conflicts***
  - **Resolve conflicts during reads**: Dynamo approach
    - Design for an "always writable" data store - highly available
    - read/write operations can continue even during network partitions
    - Rejecting customer updates won't be a good experience
      - A customer should always be able to add or remove items in a shopping cart

Consistency & Availability

- Who resolves conflicts?
  - Choices: the *data store system* or the *application*?
- Data store
  - Application-unaware, so choices limited
  - Simple policy, such as "last write wins”
- Application
  - App is aware of the meaning of the data
  - Can do application-aware conflict resolution
  - E.g., merge shopping cart versions to get a unified shopping cart.

- Fall back on "*last write wins*" if app doesn't want to bother

Reads & Writes

Two operations:

- get(key) returns
  1. object or list of objects with conflicting versions
  2. context (resultant version per object)
- put(key, context, value)
  - stores replicas
  - *context*: ignored by the application but includes version of object
  - key is hashed with MD5 to create a 128-bit identifier that is used to determine the storage nodes that serve the key

hash(key) identifies node

Partitioning the data

- Break up database into chunks distributed over all nodes
  – Key to scalability

- Relies on consistent hashing
  – K/n keys need to be remapped, K = # keys, n = # slots

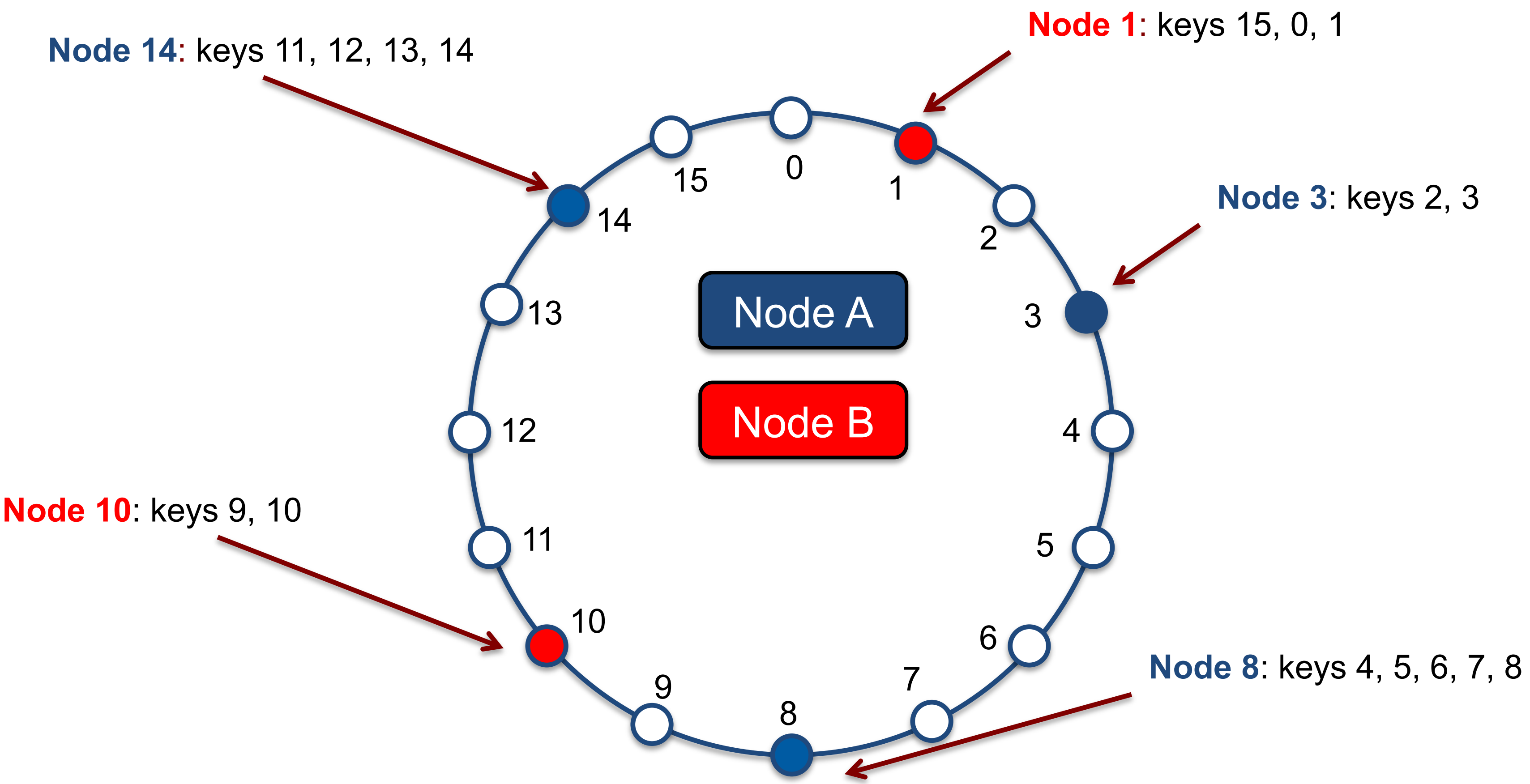
- Logical ring of nodes: just like Chord
  – Each node assigned a random value in the hash space: position in ring
  – Responsible for all hash values between its value and predecessor's value
  – Hash(key); then walk ring clockwise to find first node with position>hash
  – Adding/removing nodes affects only immediate neighbors

Partitioning: virtual nodes

- A node is assigned to multiple points in the ring
- Each point is a "virtual node"

Dynamo virtual nodes

- A physical node holds contents of multiple virtual nodes
- In this example: 2 physical nodes, 5 virtual nodes



Partitioning: virtual nodes

Advantage: balanced load distribution

- If a node becomes unavailable, load is evenly dispersed among available nodes
- If a node is added, it accepts an equivalent amount of load from other available nodes
- # of virtual nodes per system can be based on the capacity of that node
  - Makes it easy to support changing technology and addition of new, faster systems

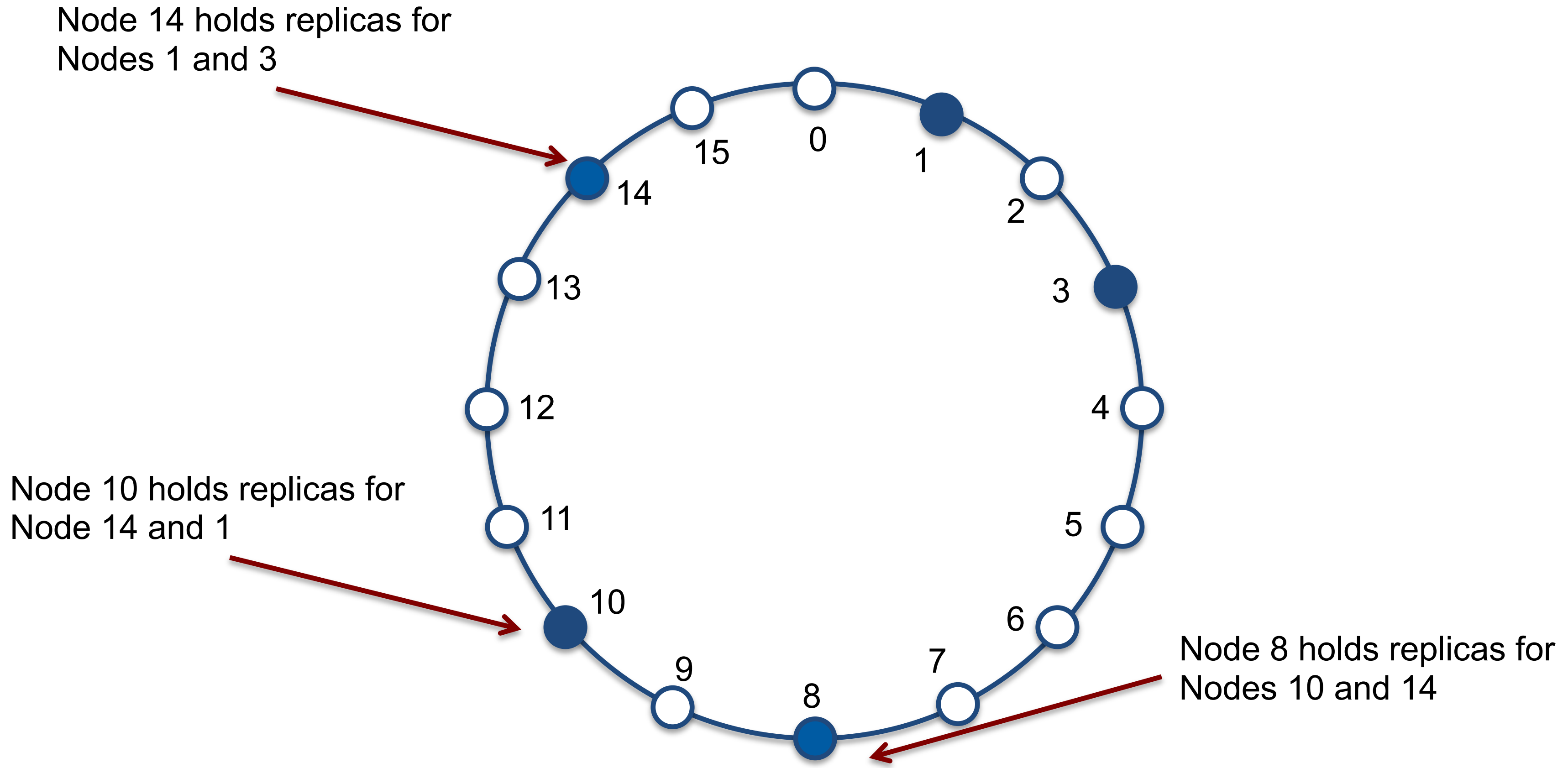
Replication

- Data replicated on *N* hosts (*N* is configurable)
  - Key is assigned a coordinator node (via hashing) = main node
  - Coordinator is in charge of replication
- Coordinator replicates keys at the *N-1* clockwise successor nodes in the ring

Dynamo Replication

Coordinator replicates keys at the *N-1* clockwise successor nodes in the ring

Example: N=3



Versioning

- Not all updates may arrive at all replicas
  – Clients may modify or read stale data

- Application-based reconciliation
  – Each modification of data is treated as a new version

- Vector clocks are used for versioning
  – Capture causality between different versions of the same object
  – Vector clock is a set of (node, counter) pairs
  – Returned as a context from a get() operation

Availability

- Configurable values
  - *R*: minimum # of nodes that must participate in a successful read operation
  - *W*: minimum # of nodes that must participate in a successful write operation
- Metadata hints to remember original destination
  - If a node was unreachable, the replica is sent to another node in the ring
  - Metadata sent with the data states the original desired destination
  - Periodically, a node checks if the originally targeted node is alive
    - if so, it will transfer the object and may delete it locally to keep # of replicas in the system consistent
- Data center failure
  - System must handle the failure of a data center
  - Each object is replicated across multiple data centers

Storage Nodes

Each node has three components

1. *Request* coordination
   - Coordinator executes read/write requests on behalf of requesting clients
   - State machine contains all logic for identifying nodes responsible for a key, sending requests, waiting for responses, retries, processing retries, packaging response
   - Each state machine instance handles one request
2. Membership and failure detection
3. Local persistent storage
   - Different storage engines may be used depending on application needs
     - Berkeley Database (BDB) Transactional Data Store (most popular)
     - BDB Java Edition
     - MySQL (for large objects)
     - In-memory buffer with persistent backing store

Amazon S3 (Simple Storage Service)

Commercial service that implements many of Dynamo's features

- Storage via web services interfaces (REST, SOAP, BitTorrent)
  - Stores more than 449 billion objects
  - 99.9% uptime guarantee (43 minutes downtime per month)
  - Proprietary design
  - Stores arbitrary objects up to 5 TB in size
- Objects organized into buckets and within a bucket identified by a unique user-assigned key
- Buckets & objects can be created, listed, and retrieved via REST or SOAP
  - http://s3.amazonaws/bucket/key
- objects can be downloaded via HTTP GET or BitTorrent protocol
  - S3 acts as a seed host and any BitTorrent client can retrieve the file
  - reduces bandwidth costs
- S3 can also host static websites

The end

