Distributed Systems

CS425/ECE428

Instructor: Radhika Mittal

Acknowledgements for some of the materials: Indy Gupta

Logistics

- MP2 due tonight.
- MP3 has been released.
- HW4 due on Wednesday.
- HW5 will be released on Wednesday.

Our agenda for the next 3-4 classes

- Brief overview of key-value stores
- Distributed Hash Tables
  - Peer-to-peer protocol for efficient insertion and retrieval of key-value pairs.
- Key-value stores in the cloud and Cloud job scheduling
  - How to run large-scale distributed computations over key-value stores?
    - Map-Reduce Programming Abstraction
  - How to schedule jobs in the cloud?
  - How to design a large-scale distributed key-value store?
    - Case-study: Facebook's Cassandra

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The Key-value Abstraction

- (Business) Key → Value
  - (twitter.com) tweet id → information about tweet
  - (amazon.com) item number → information about it
  - (kayak.com) Flight number → information about flight, e.g., availability
  - (yourbank.com) Account number → information about it

The Key-value Abstraction (2)

- It's a dictionary data-structure.
  - Insert, lookup, and delete by key
  - E.g., hash table, binary tree

- But *distributed*.

Isn't that just a database?

- *Yes, sort of.*
- Relational Database Management Systems (RDBMSs) have been around for ages
  - e.g. MySQL is the most popular among them
- Data stored in structured tables based on a *Schema*
  - Each row (data item) in a table has a primary key that is unique within that table.
- Queried using SQL (Structured Query Language).
  - Supports joins.

Mismatch with today's workloads

- Data: Large and unstructured
- Lots of random reads and writes
- Sometimes write-heavy
- Foreign keys rarely needed
- Joins infrequent

Key-value/NoSQL Data Model

- NoSQL = "Not Only SQL"
- Necessary API operations: get(key) and put(key, value)

- Tables
  - Like RDBMS tables, but …
  - May be unstructured: May not have schemas
    - Some columns may be missing from some rows
  - Don't always support joins or have foreign keys
  - Can have index tables, just like RDBMSs

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Our focus today

- Brief overview of key-value stores
- Distributed Hash Tables
  - Peer-to-peer protocol for efficient insertion and retrieval of key-value pairs.
- Key-value stores in the cloud
  - How to run large-scale distributed computations over key-value stores?
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Distributed Hash Tables (DHTs)

- Multiple protocols were proposed in early 1990s.
  - Chord, CAN, Pastry, Tapestry
  - Initial usecase: Peer-to-peer file sharing
    - key = hash of the file, value = file
  - Cloud-based distributed key-value stores reuse many techniques from these DHTs.

- Key goals:
  - Balance load uniformly across all nodes (peers).
  - Fault-tolerance
  - Efficient inserts and lookups.

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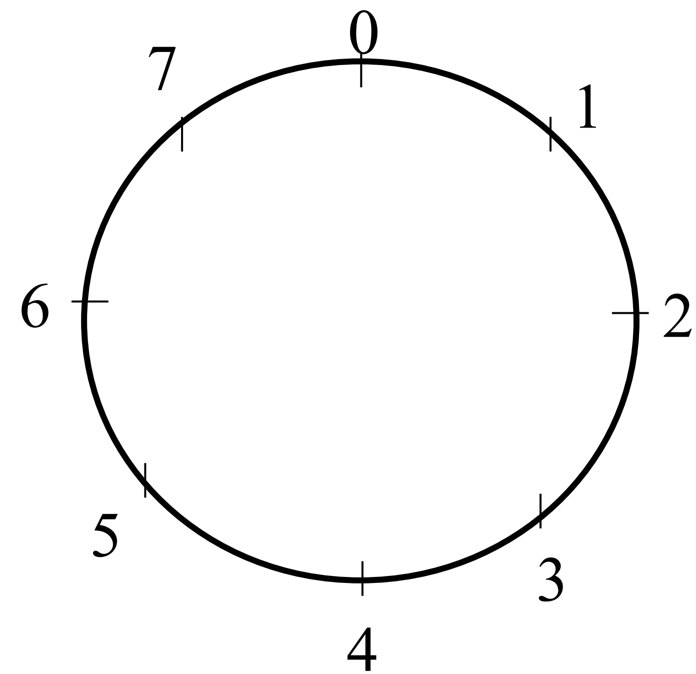
Chord

- Developed at MIT by I. Stoica, D. Karger, F. Kaashoek, H. Balakrishnan, R. Morris
- Key properties:
  - Load balance:
    - spreads keys evenly over nodes.
  - Decentralized:
    - no node is more important than others.
  - Scalable:
    - cost of key lookup is O(logN), N = no. of nodes.
  - High availability:
    - automatically adjusts to new nodes joining and nodes leaving.
  - Flexible naming:
    - no constraints on the structure of keys that it looks up.

Chord: Consistent Hashing

- Uses *Consistent Hashing* on node's (peer's) address
  - SHA-1(ip_address,port) → 160 bit string
  - Truncated to **m** bits (modulo 2^m)
  - Called peer id (number between 0 and 2^m-1)
  - **m** chosen such that negligible chance of id conflicts
  - Can then map peers to one of 2^m logical points on a circle



Circle for m = 3

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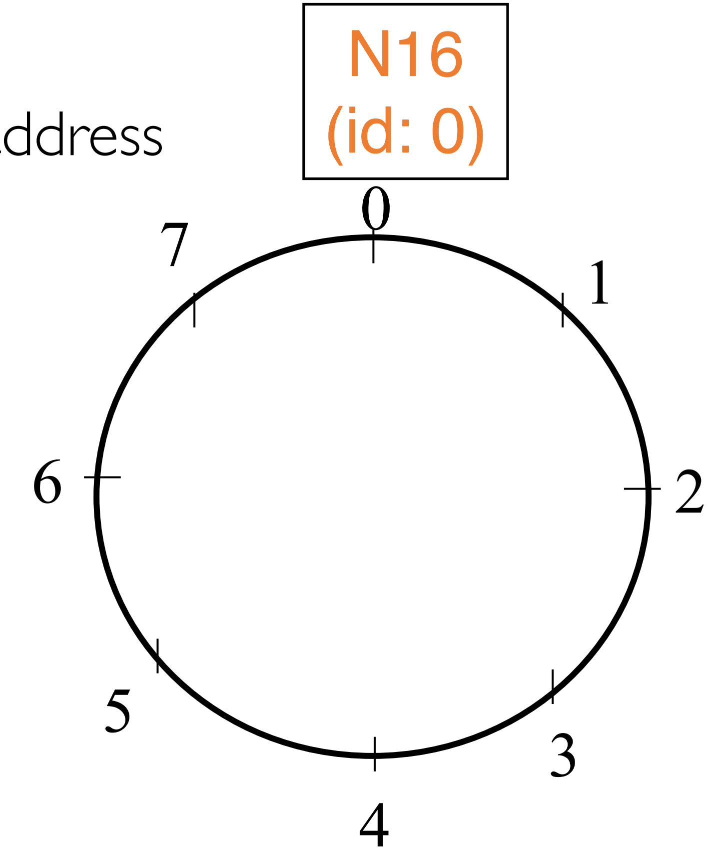

Circle for m = 3

Where will N16 be placed on this circle?

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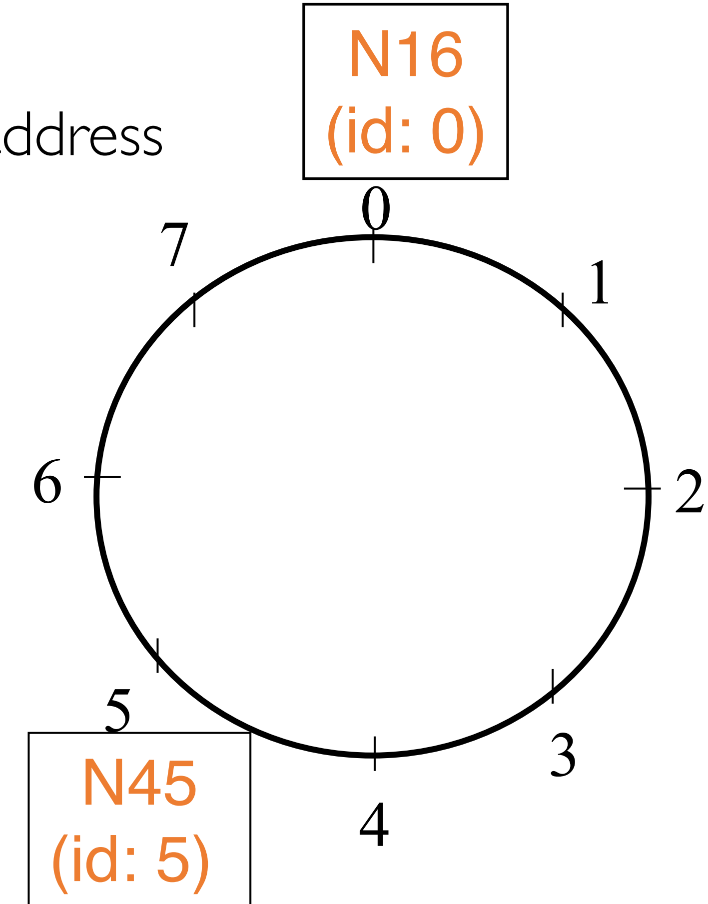
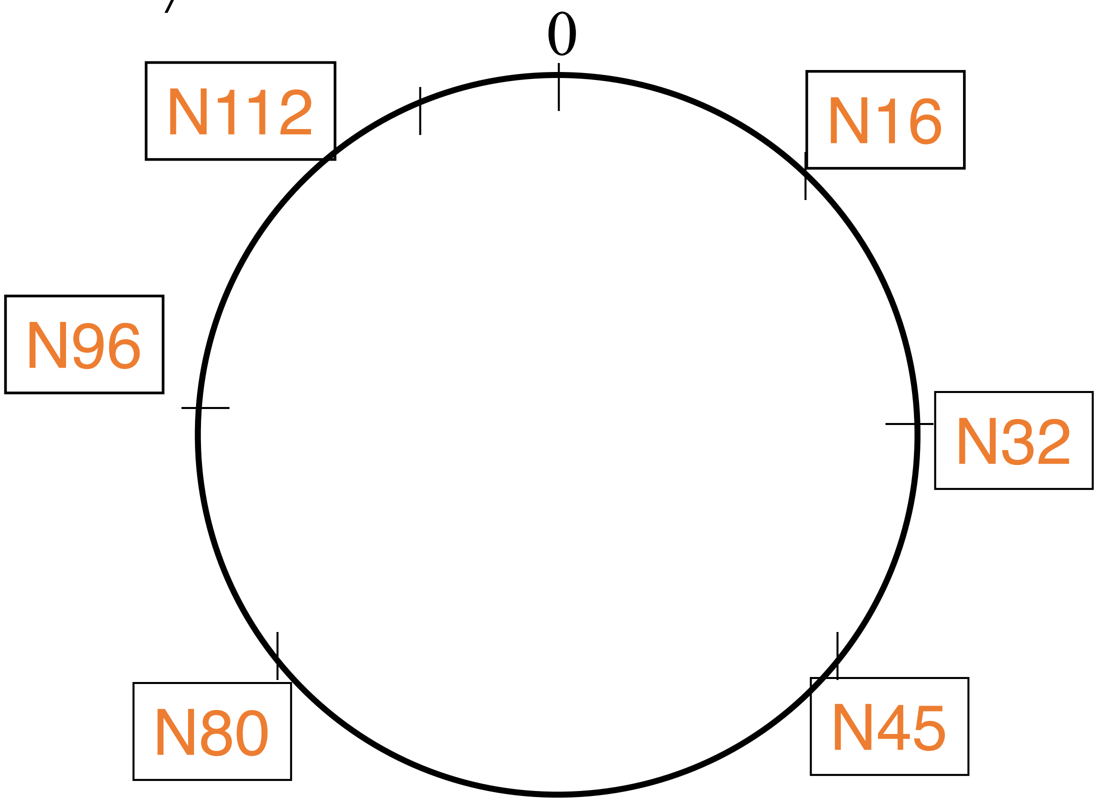


Circle for m = 3

Where will N45 be placed on this circle?

Ring of Peers: Running Example

- Say m=7 (128 possible points on the circle – not shown)
- 6 nodes in the system.

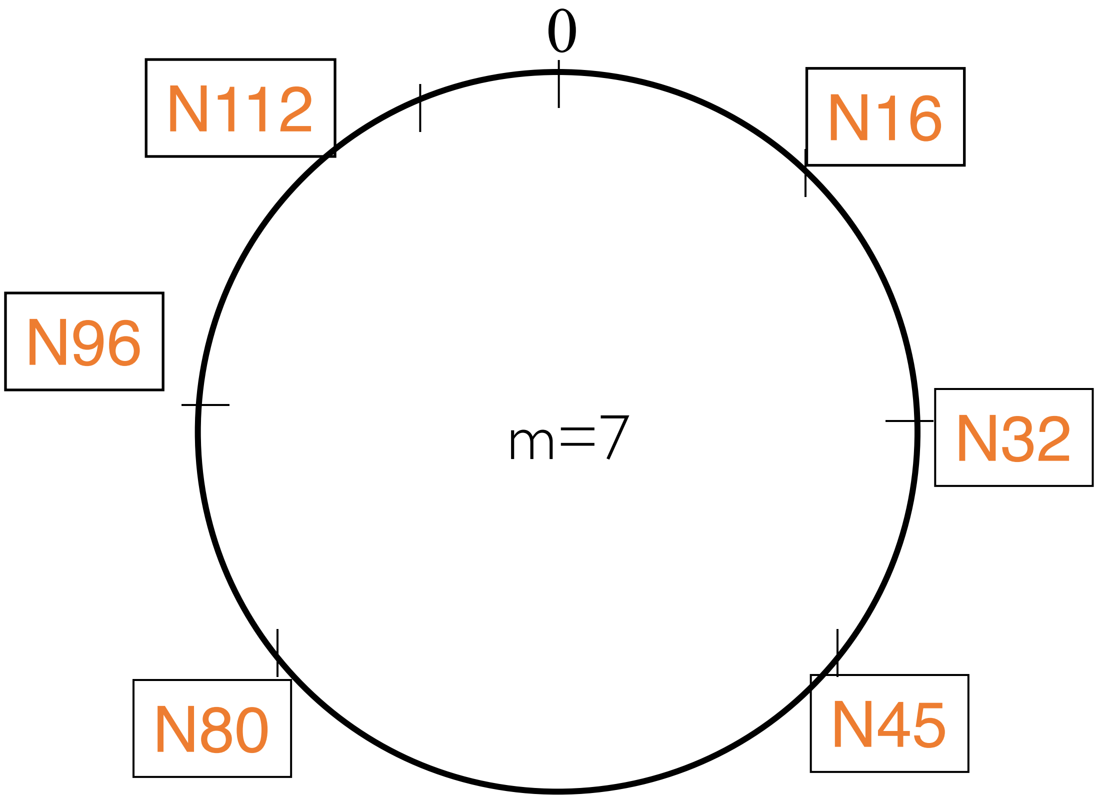


Mapping Keys to Nodes

- Use the same consistent hash function
  - SHA-1(key) → 160 bit string (key identifier)
    - Henceforth, we refer to SHA-1(key) as *key*.
  - The key-value pair stored at the key's *successor* node.
  - *successor(key) = first peer with id greater than or equal to (key mod* 2^m *)*
    - *Cross-over the ring when you reach the end.*
      - *0 < 1 < 2 < 3 …….. < 127 < 0 (for m=7)*

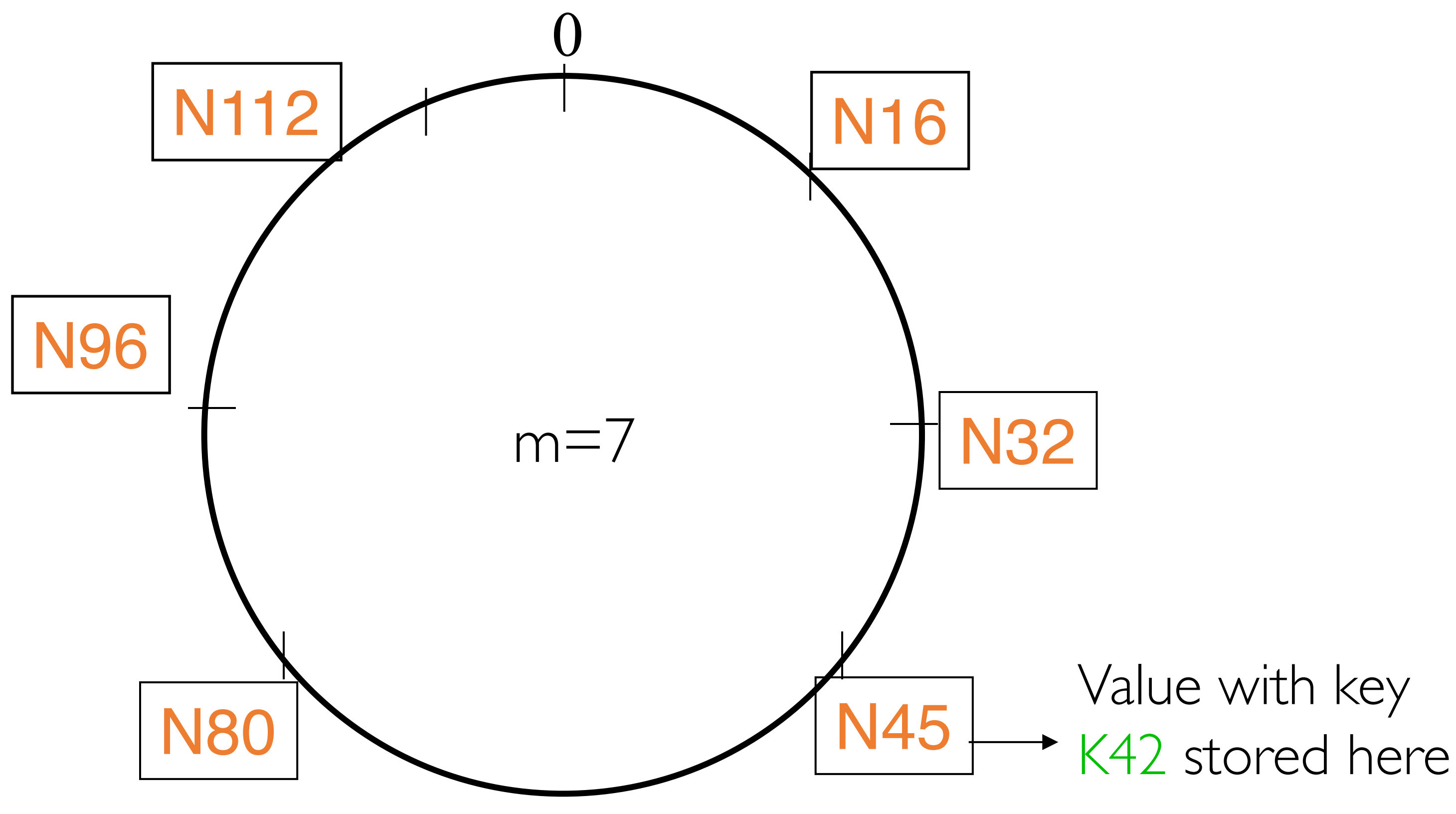
- Consistent Hashing => with K keys and N peers, each peer stores O(K/N) keys. (i.e., < c.K/N, for some constant c)

Ring of Peers: Running Example



Where will the value with key 42 be stored?

Ring of Peers: Running Example



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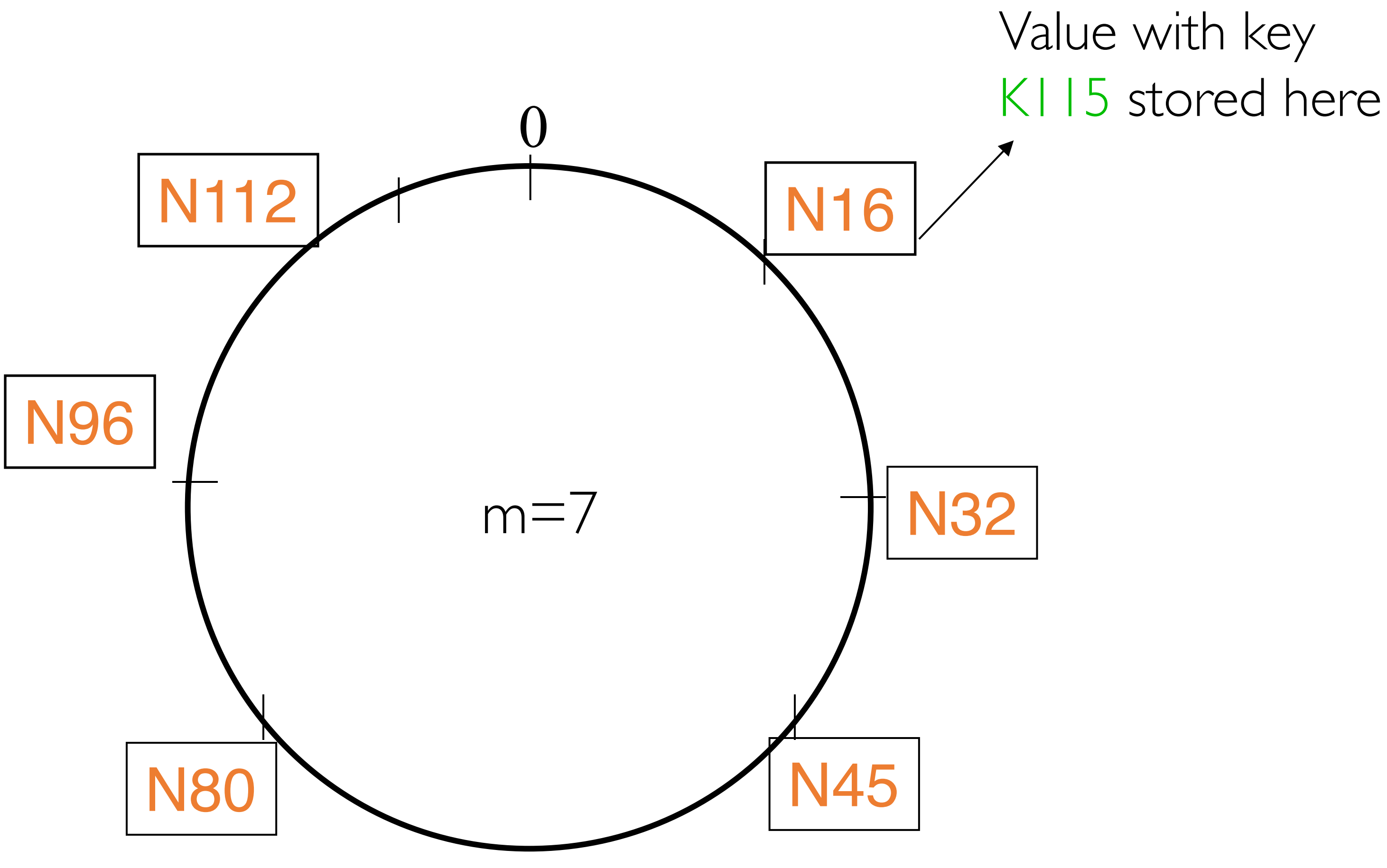
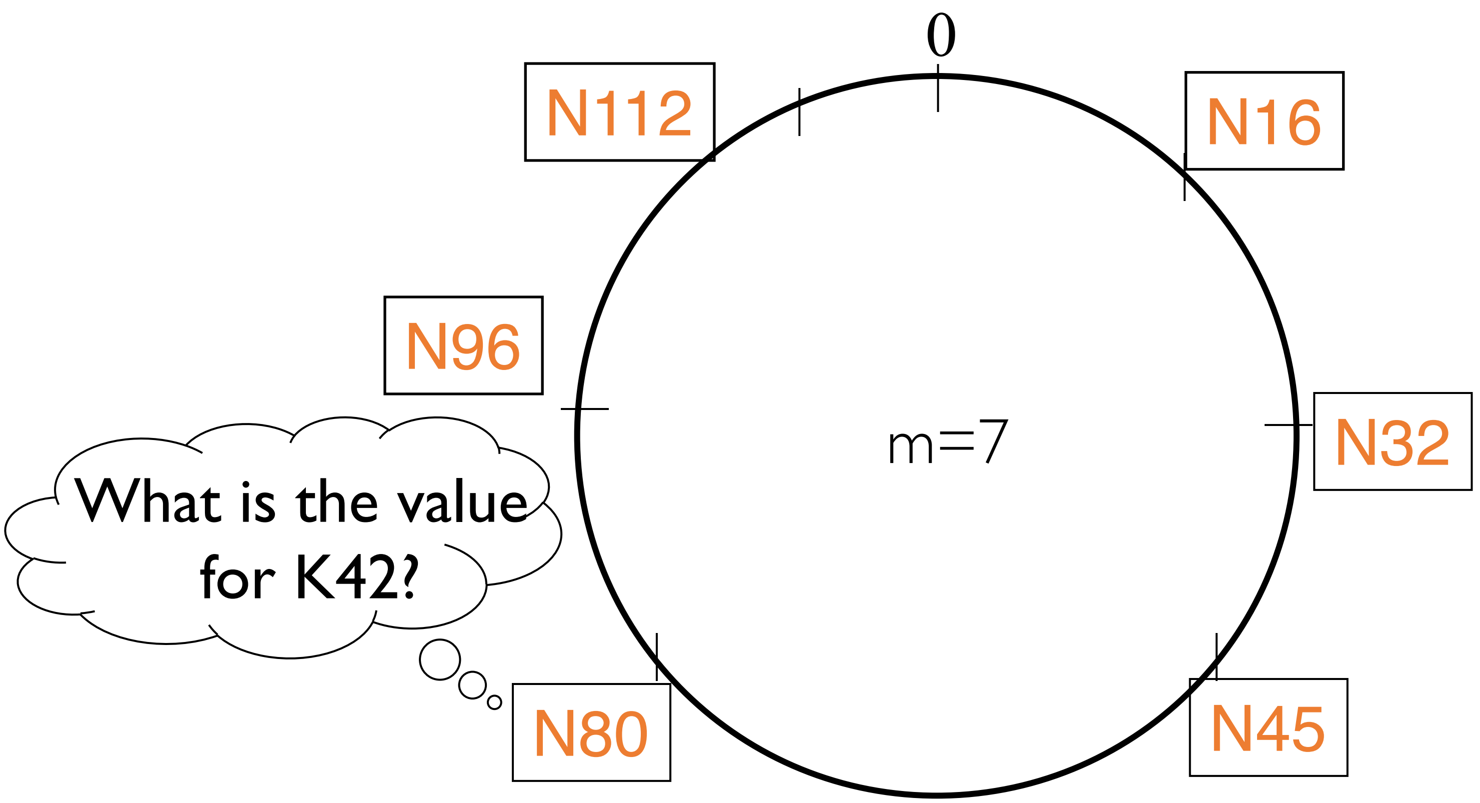
Ring of Peers: Running Example



Where will the value with key 115 be stored?

Performing Lookups

Suppose N80 receives a request to lookup K42.



Need to ask the successor of K42!

Performing Lookups

- Option 1: Each node is aware of (can route to) any other node in the system.
  - Need a very large routing table.
  - Poor scalability with 1000s of nodes.
  - Any node failure and join will require a *necessary* update at all nodes.
- Option 2: Each node is aware of only its ring successor.
  - O(N) lookup. Not very efficient.
- Chord chooses a sweet middle-ground.

Performing Lookups

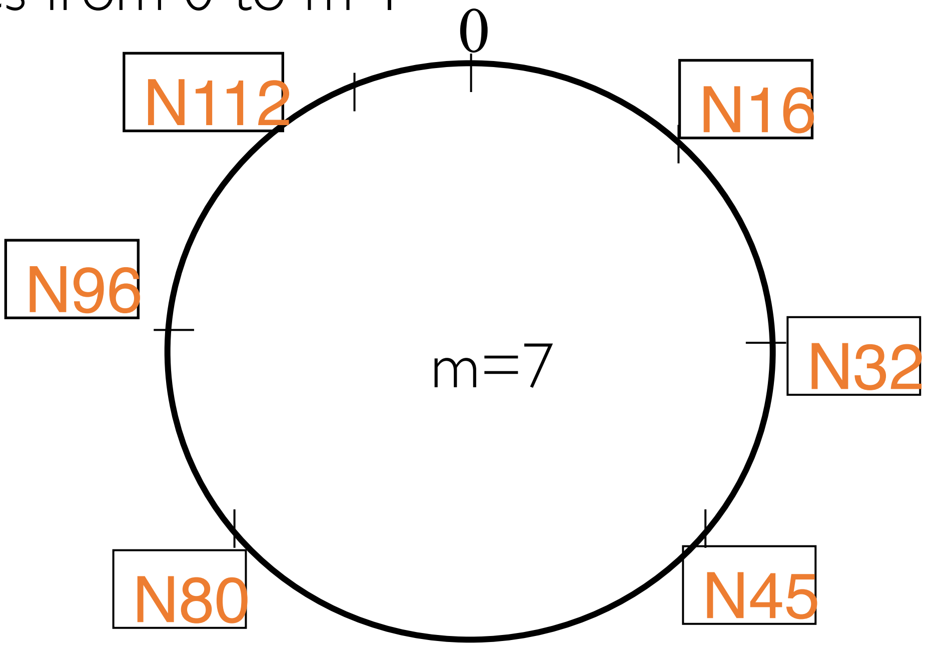
- Chord chooses a sweet middle-ground.
  - Each node is aware of ~**m** other nodes.
  - Maintains a *finger table* with **m** entries.
  - The ith entry of node n's finger table = successor($n + 2^i$)
    - i ranges from 0 to m-1

Finger Tables

Compute the finger table for N80

ith entry of node n's finger table = successor($n + 2^i$),

i ranges from 0 to m-1

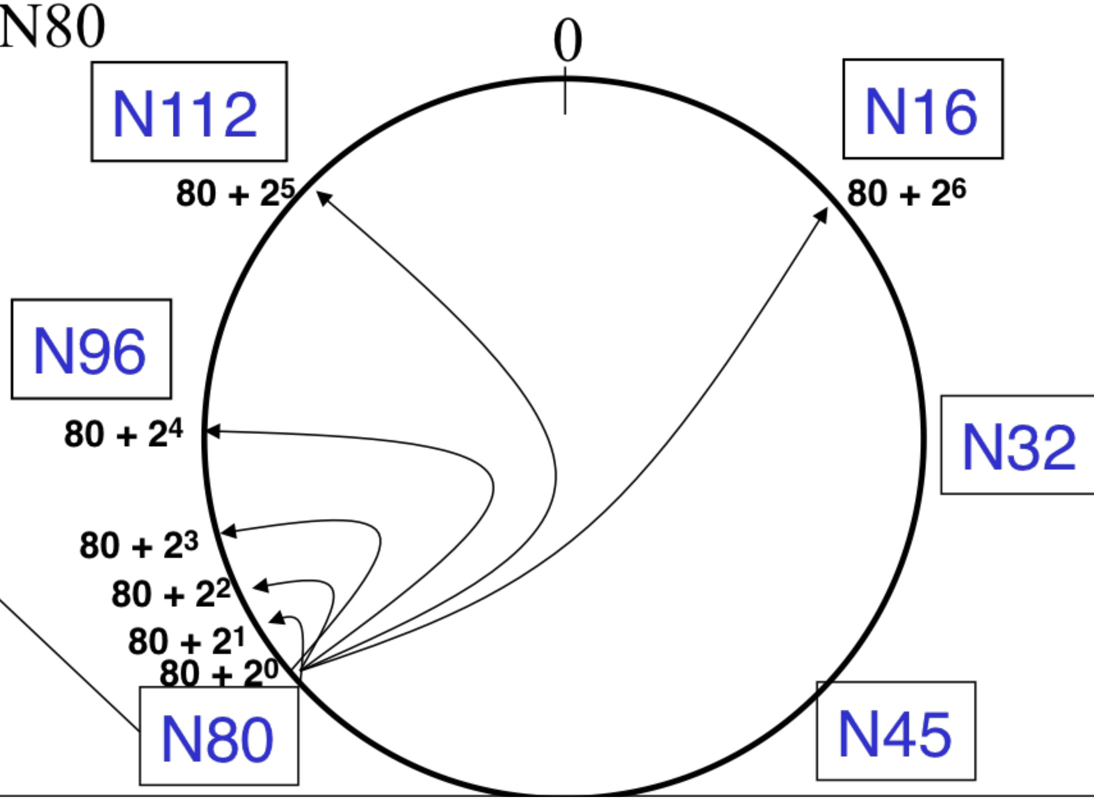


Finger Tables

Say $m=7$

Finger Table at N80

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



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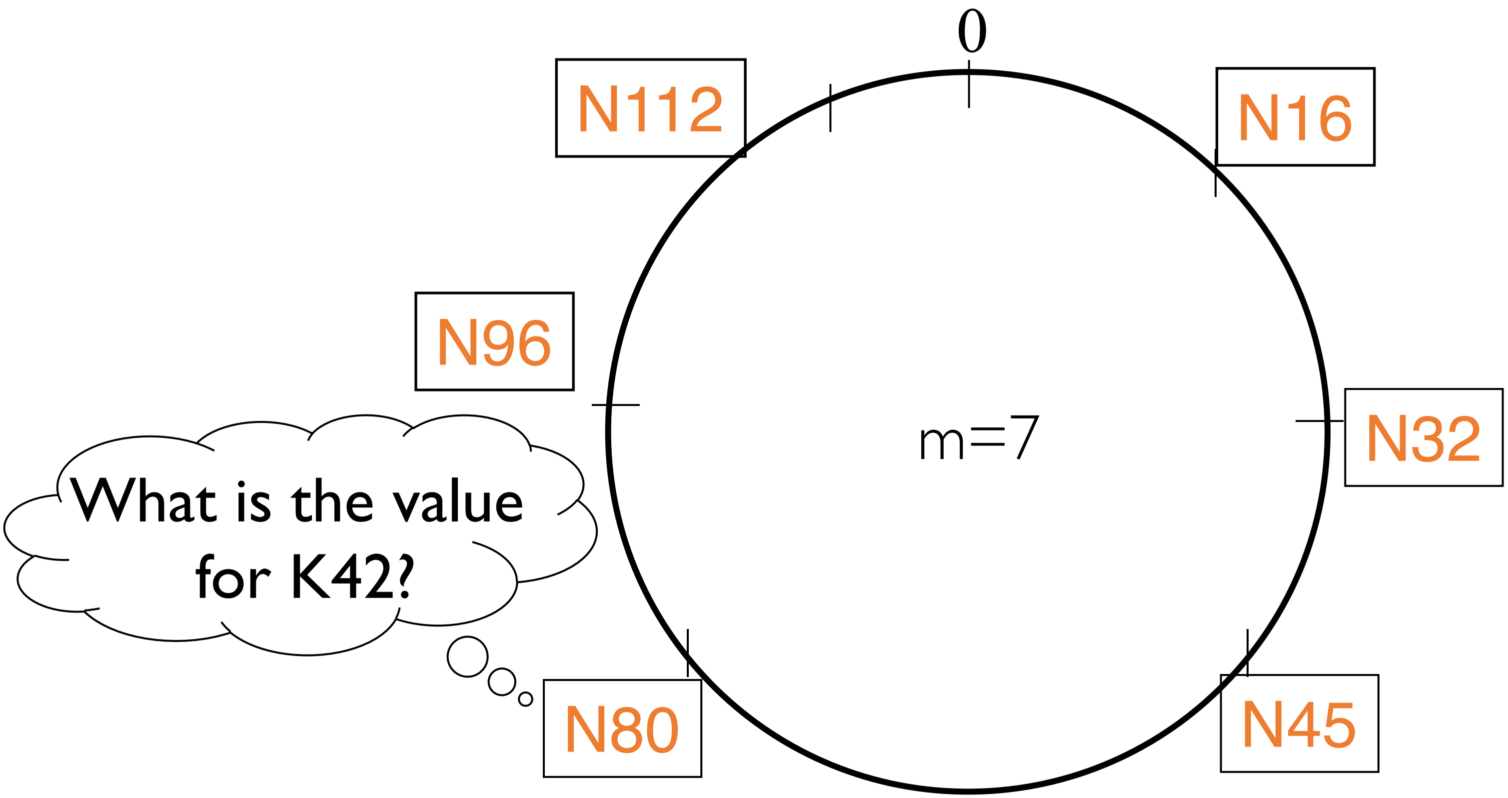

Need to locate successor of K42!

Which nodes is N80 aware of?

Say m=7

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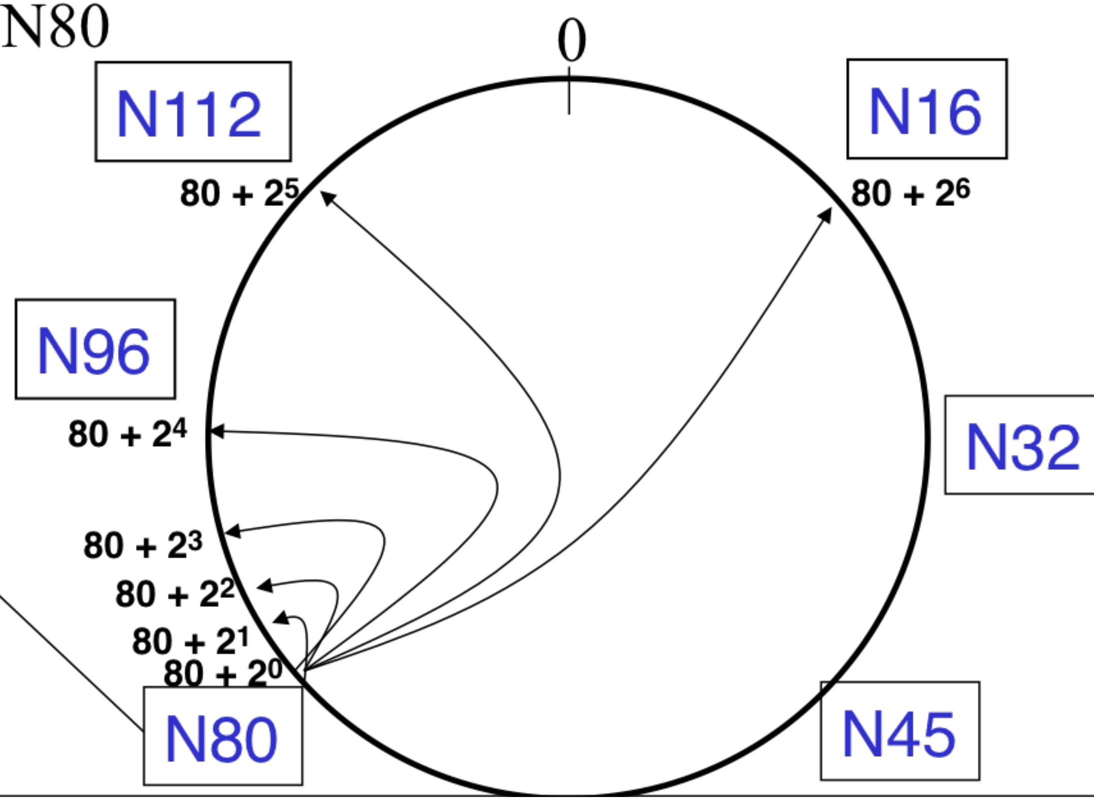

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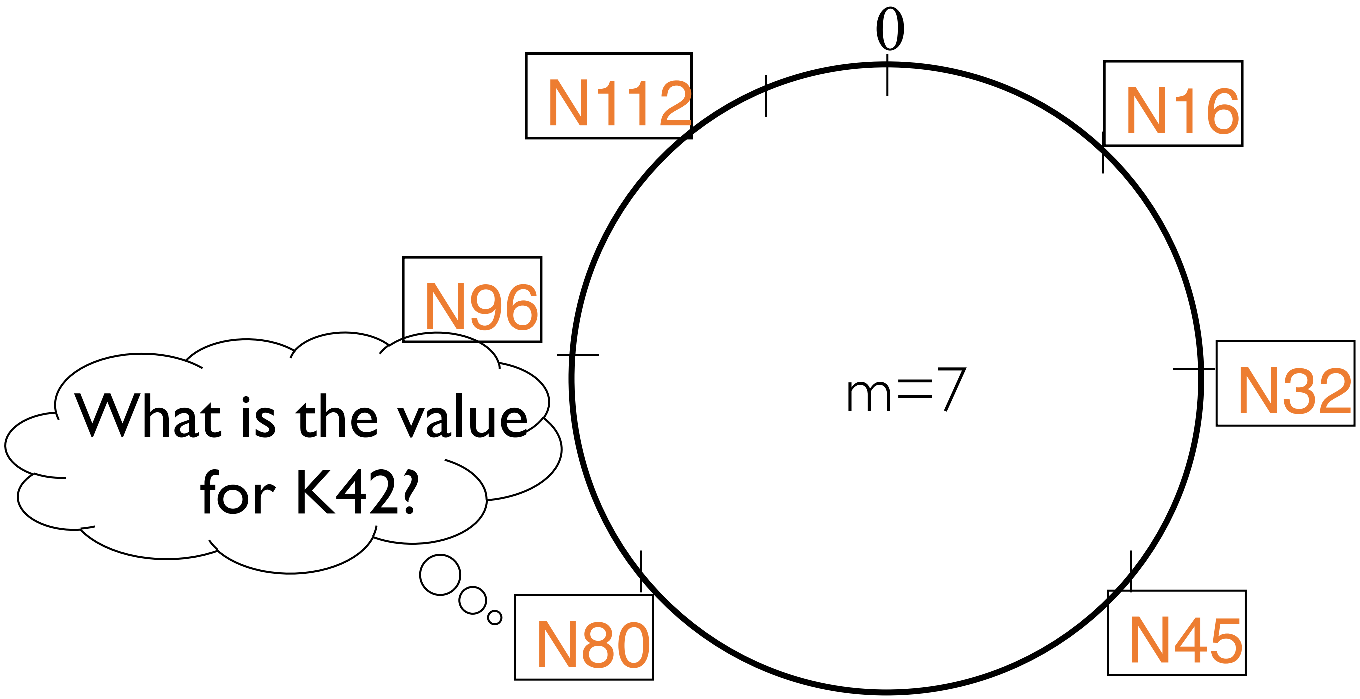


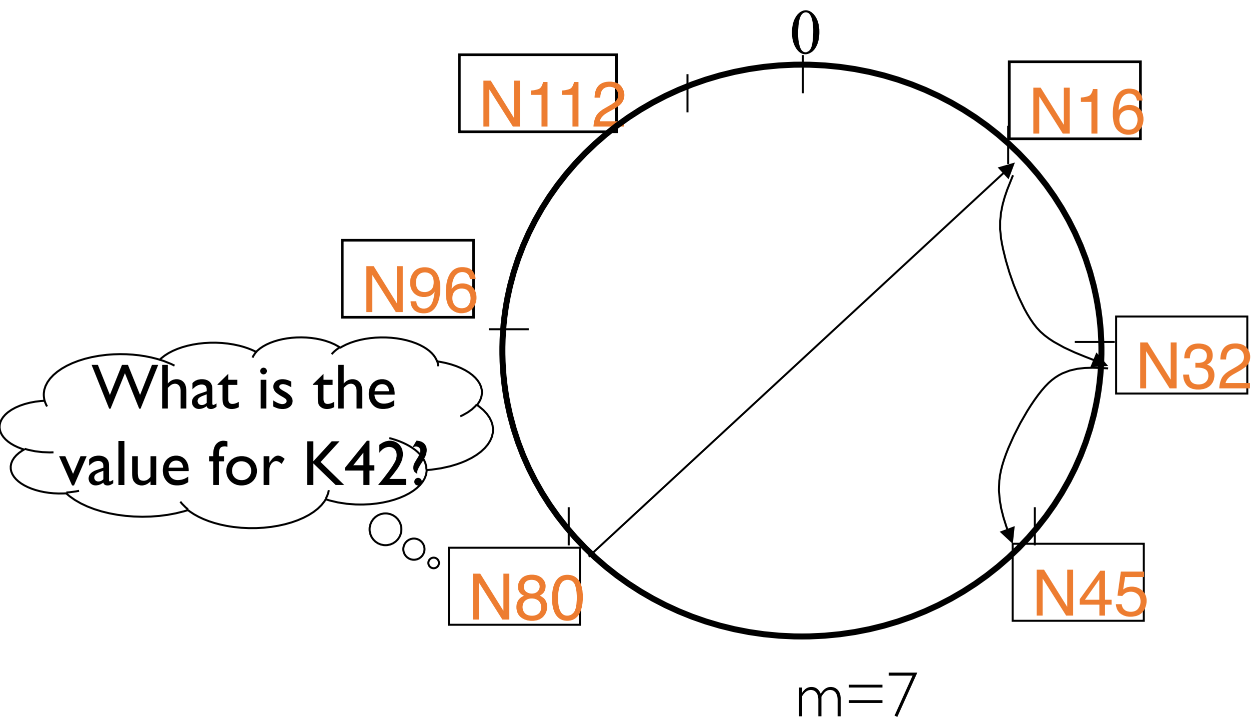
Need to locate successor of K42!

Forward the query to the most promising node you know of.

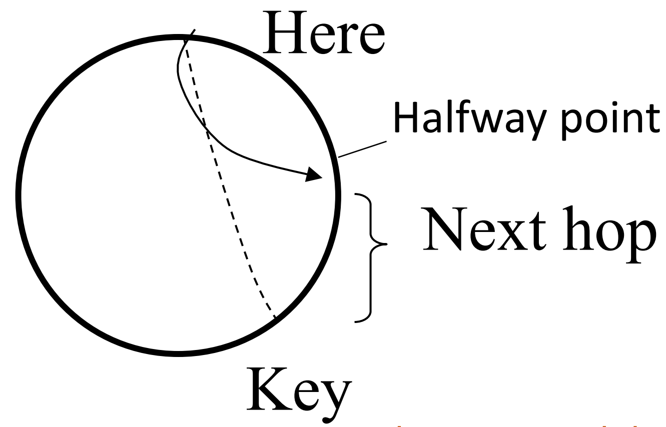
Search for key k at node n

At node n, if k lies in range (n, next(n)], where next(n) is n's *ring successor* then next(n) = successor(key). Send query to next(n)

Else, send query for k to largest finger entry <= k



Analysis



Search takes O(log(N)) time

Proof Intuition:

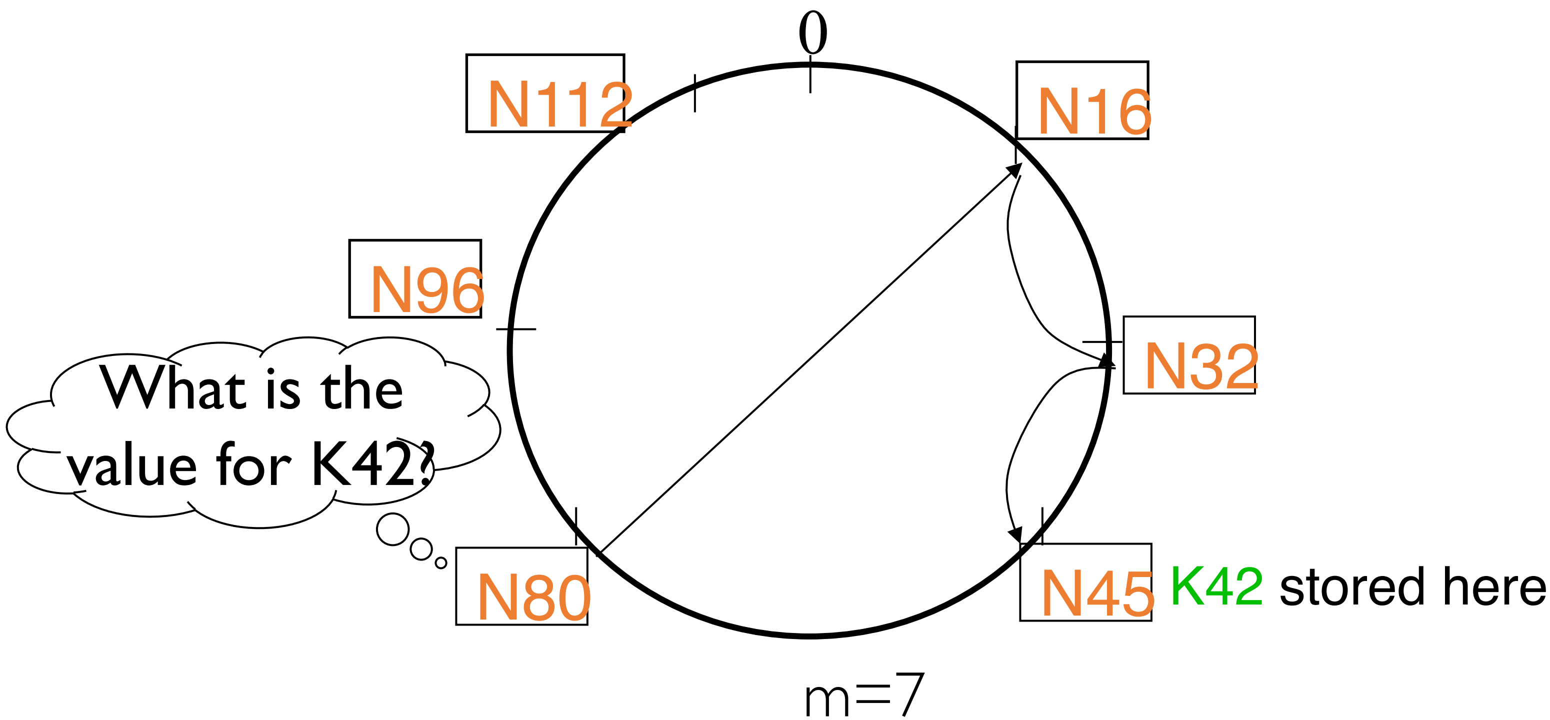
- (intuition): at each step, distance between query and peer-with-file reduces by a factor of at least 2 (why?)
- (intuition): after log(N) forwardings, distance to key is at most $2^m/2^{\log(N)} = 2^m / N$
- Expected number of node identifiers in a range of $2^m / N$:
  - ideally one
  - O(log(N)) with high probability (by properties of consistent hashing)

So using ring successors in that range will use another O(log(N)) hops. Overall lookup time stays O(log(N)).

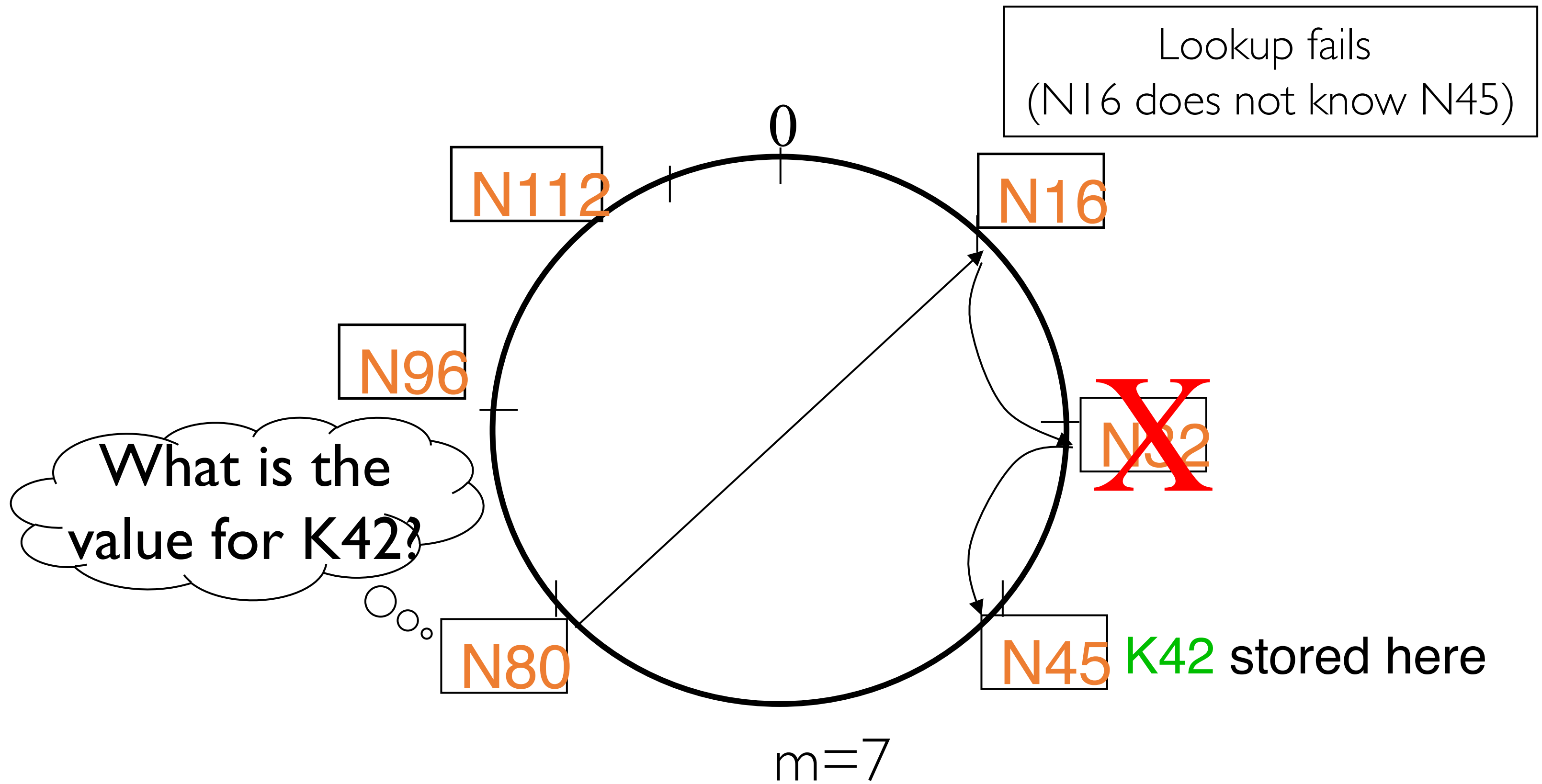
Analysis

- 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
    - Coming up next!

Search for key k at node n



If a node fails



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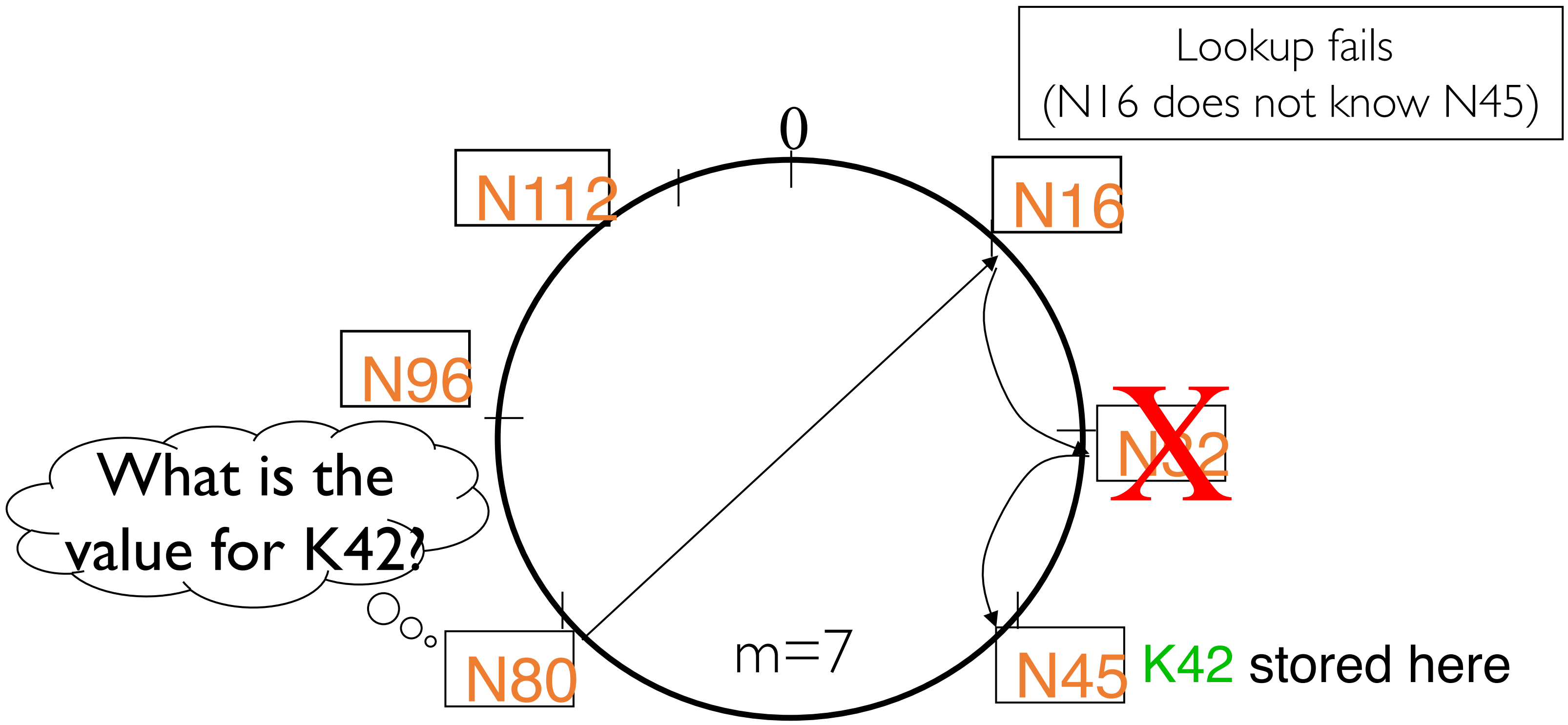
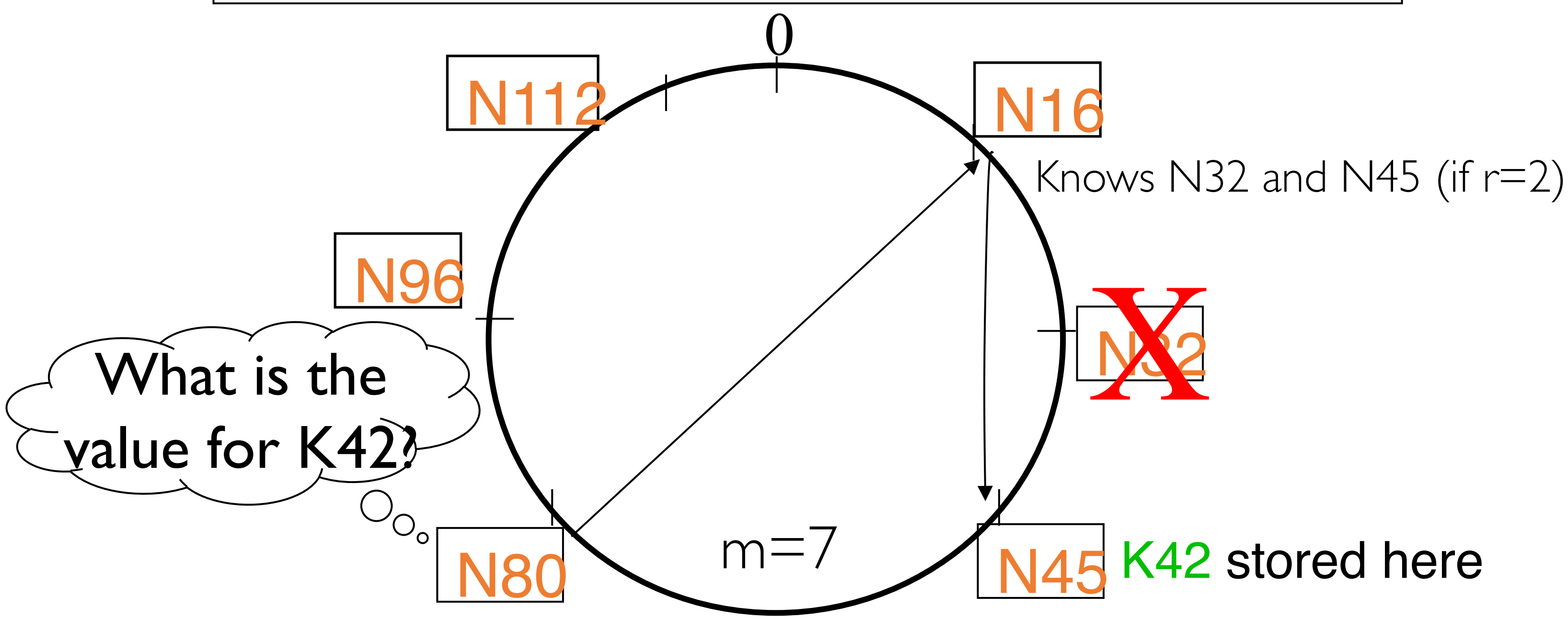


How do we handle this?

If a node fails

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



Search under node failures

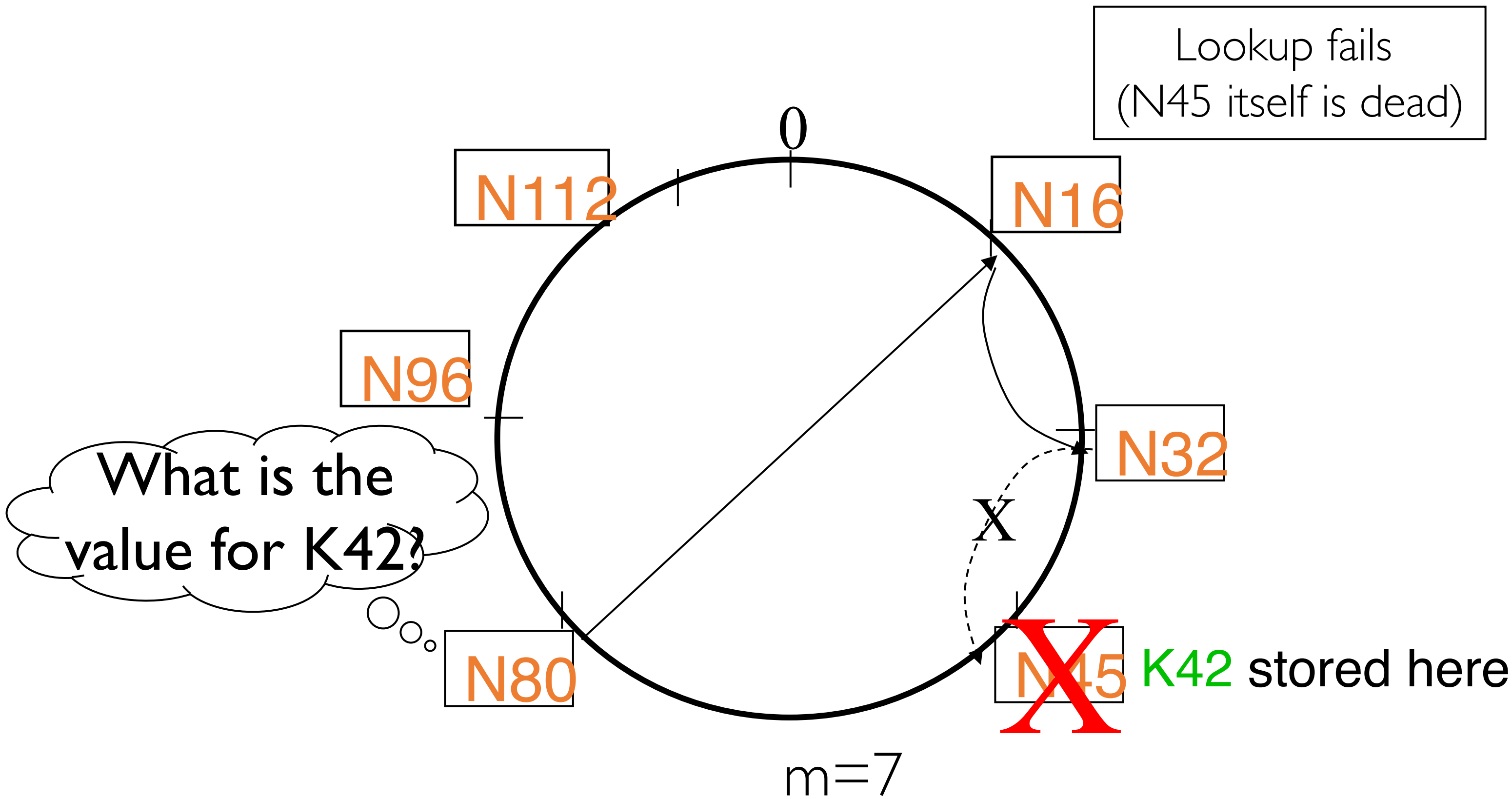
- If every node fails with probability 0.5, choosing r=2log(N) suffices to maintain lookup correctness (i.e. keep the ring connected) with high probability.
  - Intuition:
    - Pr(at given node, at least one predecessor alive)=

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

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

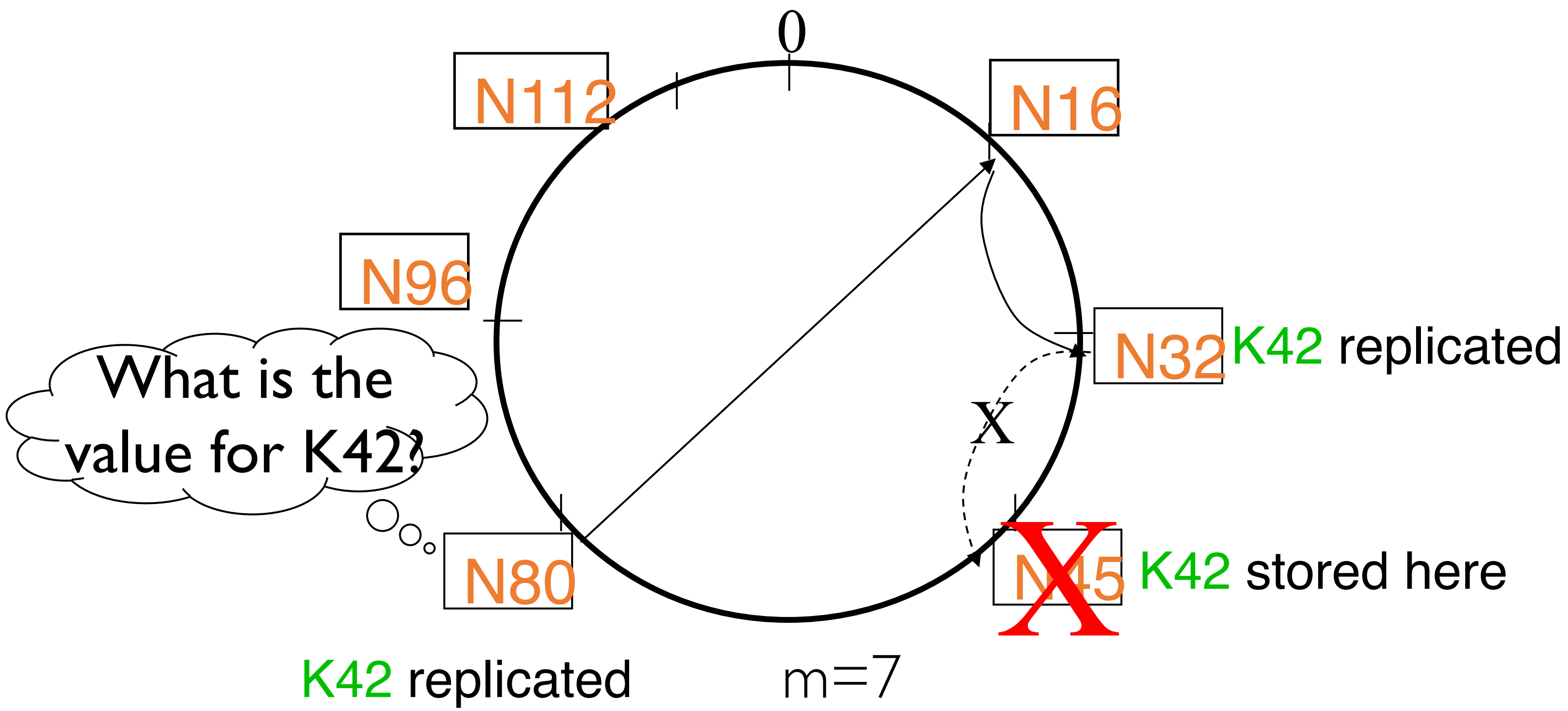
$$\left(1-\frac{1}{N^2}\right)^{N/2}=e^{-\frac{1}{2N}}\approx 1$$

If a node fails



If a node fails

One solution: replicate key-value at r successors and predecessors



Need to deal with dynamic changes

- ✓ Nodes fail
- New nodes join
- Nodes leave

So, all the time, need to:

→ Need to update successors and fingers, and copy keys

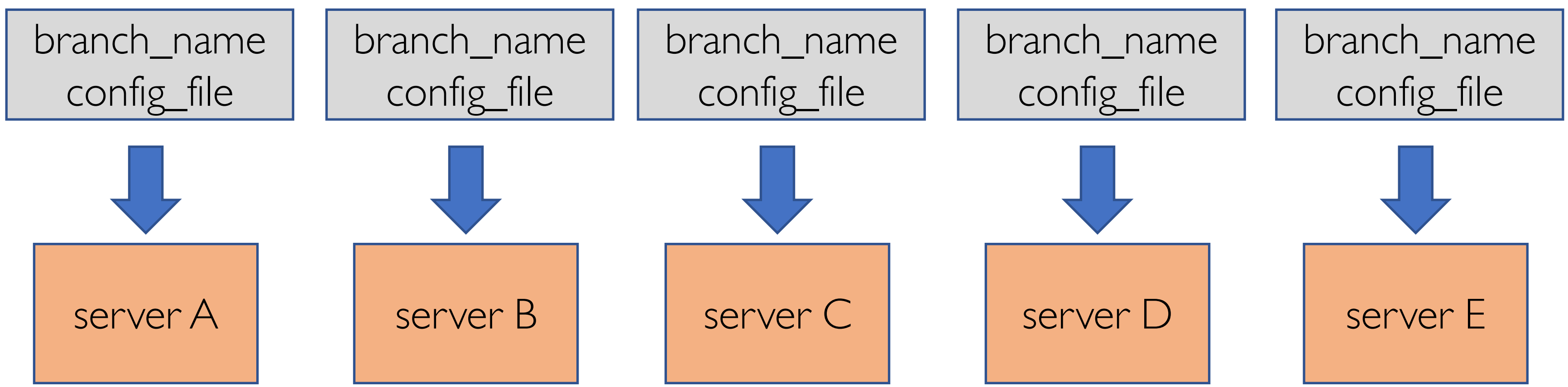
MP3: Distributed Transactions

- https://courses.grainger.illinois.edu/ece428/sp2024/mps/mp3.html
- Lead TA: Sarthak Moorjani

- Task:
  - Build a distributed transaction system that satisfies ACI properties (you do not need to handle Durability).

- Objective:
  - Think through and implement algorithms for achieving atomicity and consistency with distributed transactions (two-phase commit), concurrency control (two-phase locking / timestamped ordering), deadlock detection.

MP3: Distributed Transactions

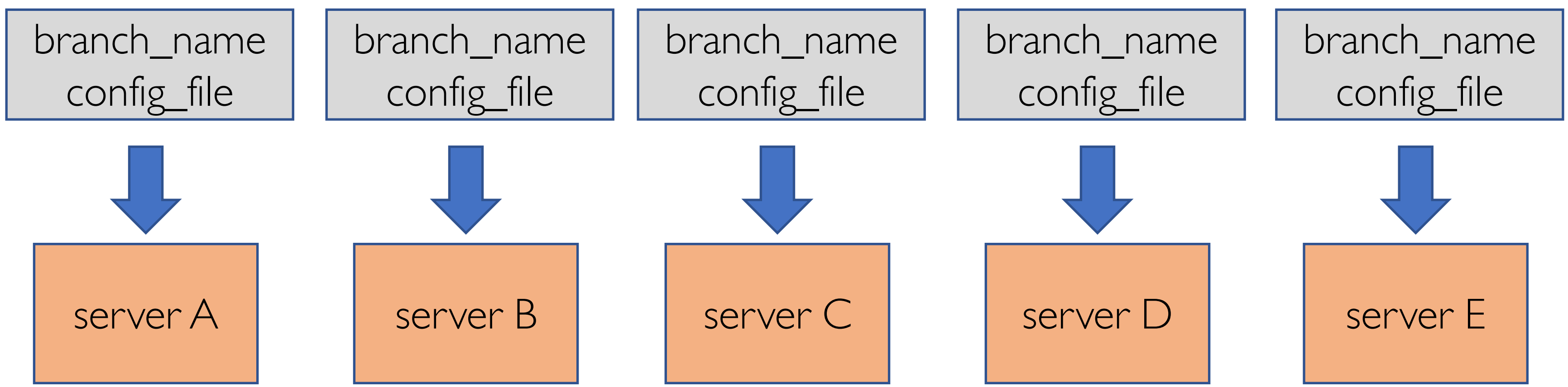


sample config_file

```
A sp23-cs425-0101.cs.illinois.edu 1234
B sp23-cs425-0101.cs.illinois.edu 1234
C sp23-cs425-0101.cs.illinois.edu 1234
D sp23-cs425-0101.cs.illinois.edu 1234
E sp23-cs425-0101.cs.illinois.edu 1234
```

Use this information to establish communication across servers.

MP3: Distributed Transactions



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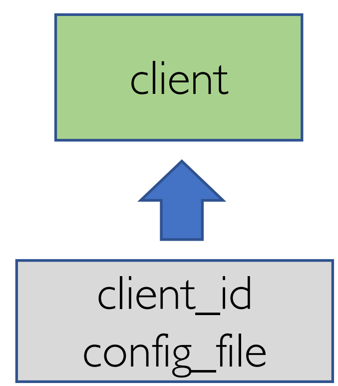

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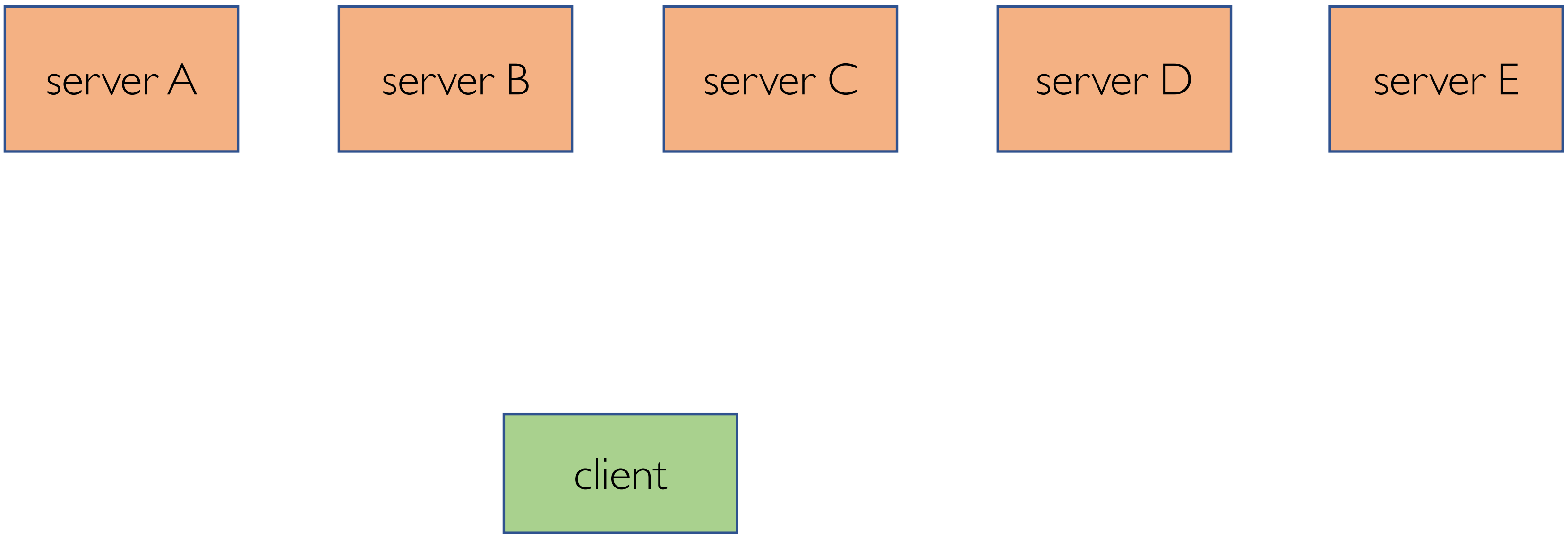
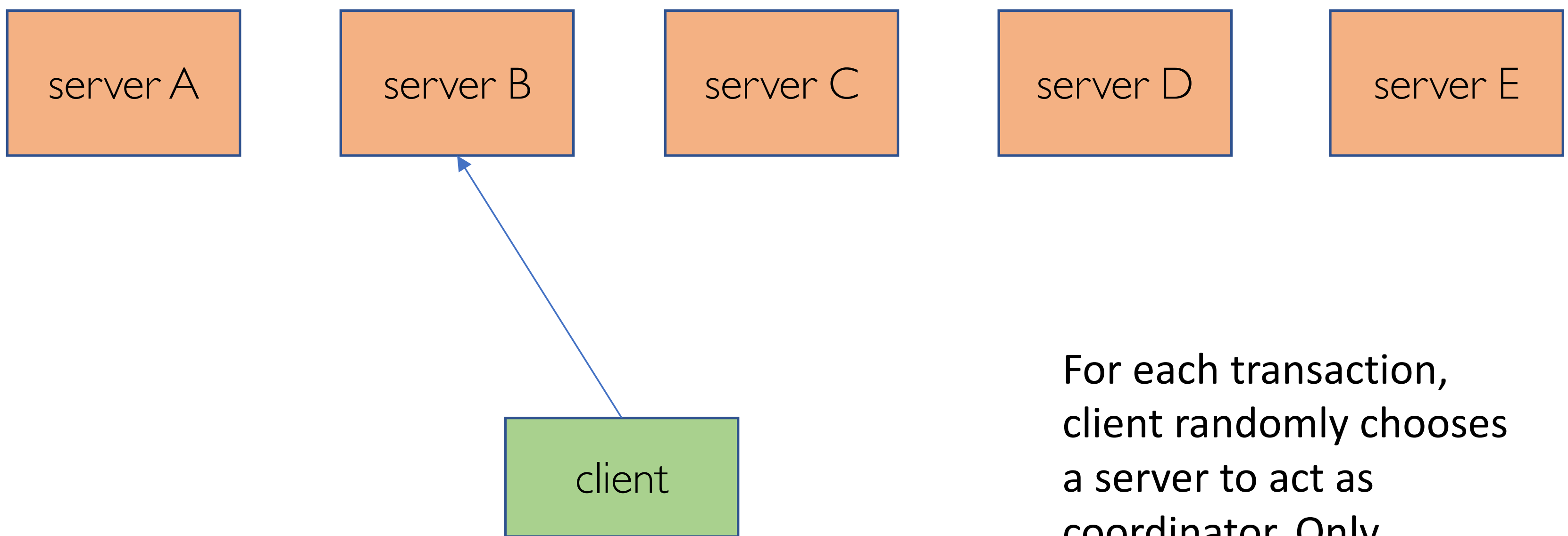


Receives user input (command) from stdin.
Prints output of the command to stdout.

< BEGIN //start a new transaction

MP3: Distributed Transactions

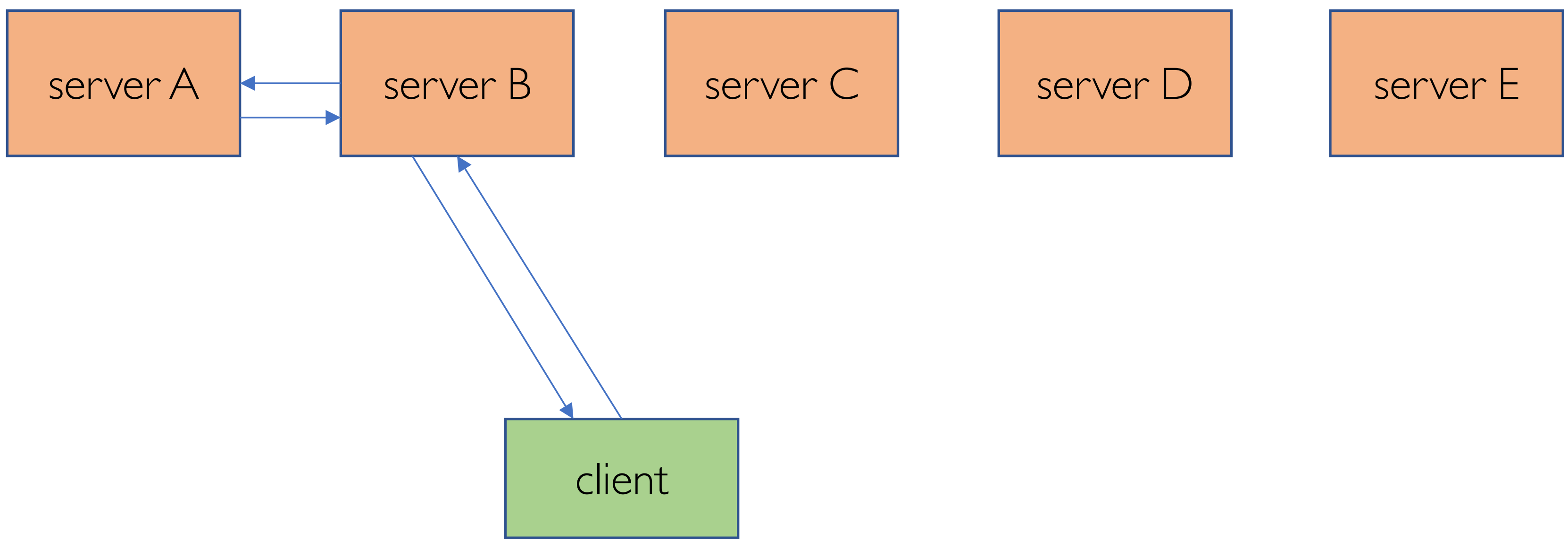


Receives user input (command) from stdin.
Prints output of the command to stdout.

For each transaction, client randomly chooses a server to act as coordinator. Only communicates with the coordinator

< BEGIN //start a new transaction
> OK
< DEPOSIT A.foo 10 //deposit 10 units in account foo at branch A

MP3: Distributed Transactions



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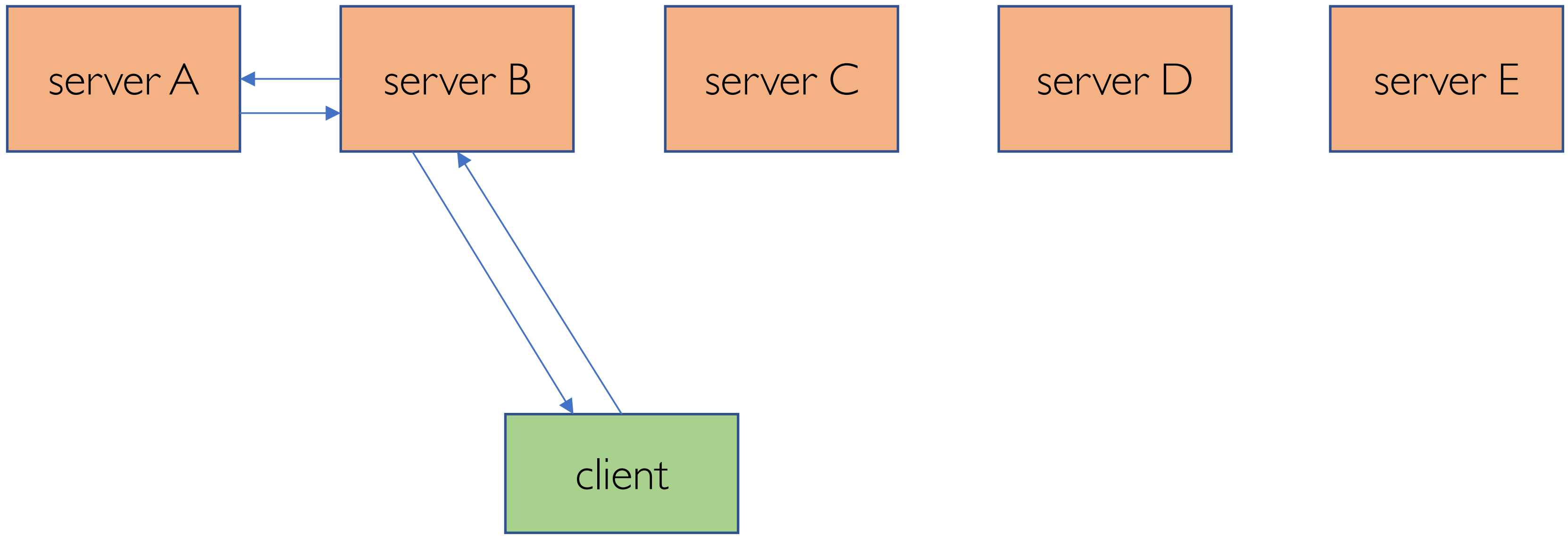

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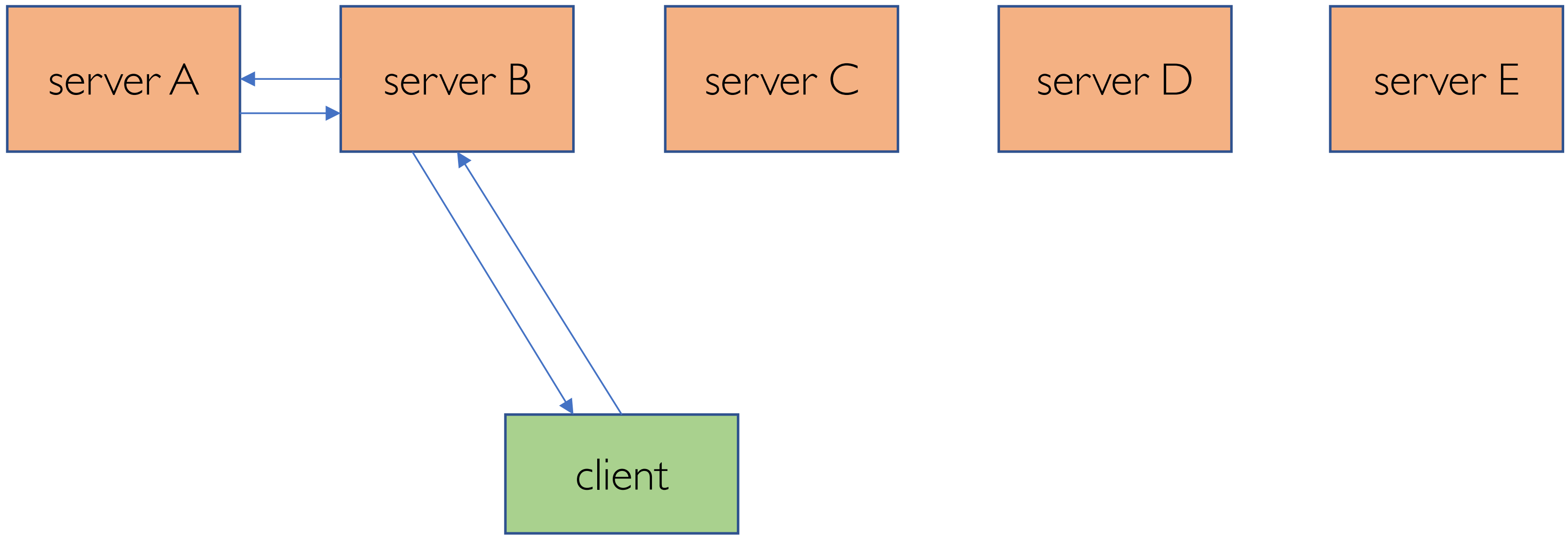
Other possible commands: WITHDRAW and BALANCE (only applicable if the account exists)

MP3: Distributed Transactions



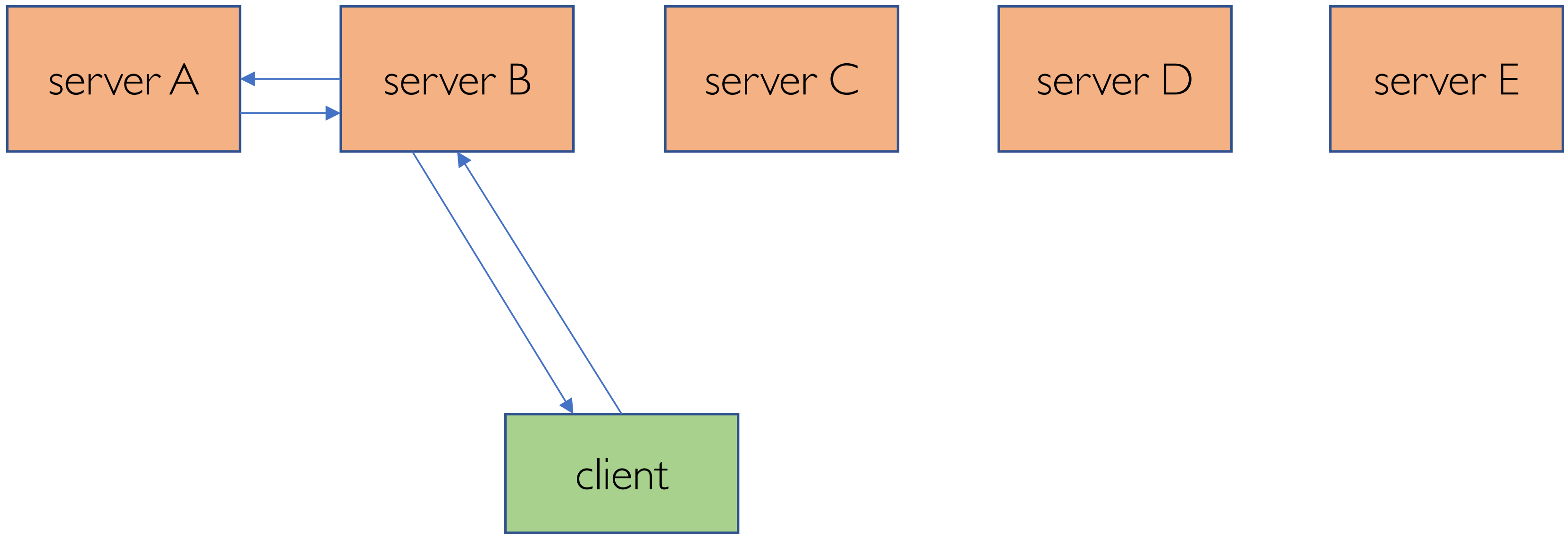
Receives user input (command) from stdin.
Prints output of the command to stdout.

User enters COMMIT or ABORT to end the transaction.

A server may also choose to ABORT a transaction (e.g. if consistency violated, or if needed for concurrency control).

Changes made by one transaction visible to others only after it successful commits.

MP3: Distributed Transactions

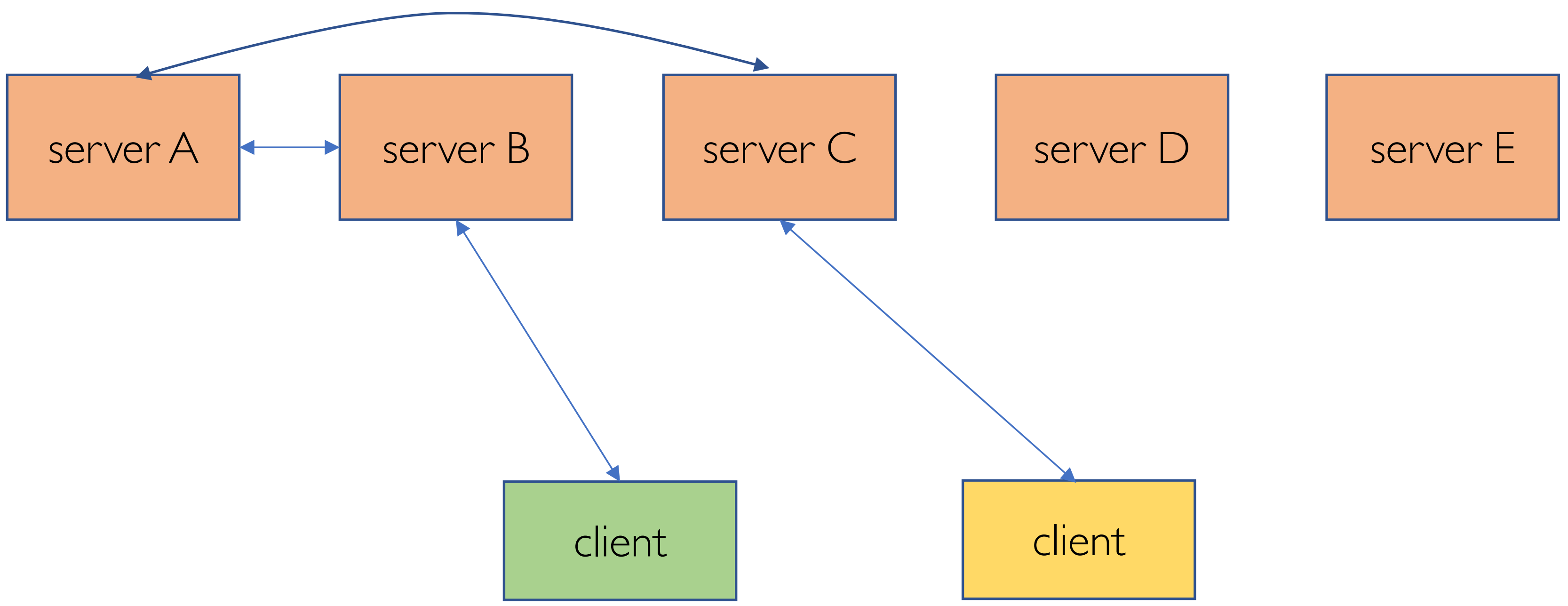


Receives user input (command) from stdin.
Prints output of the command to stdout.

Required properties:

- Atomicity:
  - all servers commit the entire transaction, or all rollback the entire transaction.
- Consistency:
  - cannot withdraw from or read balance of a non-existent account.
  - a transaction cannot result in a negative account balance.

MP3: Distributed Transactions



Receives user input (command) from stdin.
Prints output of the command to stdout.

Required properties:

- Isolation:
  - multiple clients may concurrently issue commands on the object.
  - Must provide serial equivalence.
- Deadlock avoidance.

MP3: Distributed Transactions

- Due on April 29th.
  - Late policy: Can use remainder of your 168hours of grace period accounted per student over the entire semester.
- Read the specification fully and carefully.
  - Required semantics discussed more completely there.
- Start early!