CS162
Operating Systems and Systems Programming
Lecture 23

RPC, Key-Value Stores, Chord

November 15th, 2017

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Goals of Today's Lecture

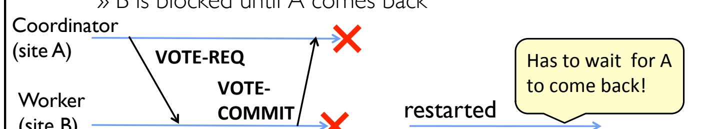
- Ending previous lecture (PAXOS)
- RPC
- Key-value storage

Recap: Distributed Decision Making Discussion (1/2)

- Why is distributed decision making desirable?
  - Fault Tolerance!
  - A group of machines can come to a decision even if one or more of them fail during the process
    - » Simple failure mode called "failstop" (different modes later)
  - After decision made, result recorded in multiple places

Distributed Decision Making Discussion (2/2)

- Undesirable feature of Two-Phase Commit: Blocking
  - One machine can be stalled until another site recovers:
    - » Site B writes `"prepared to commit"` record to its log, sends `"yes"` vote to coordinator (site A) and crashes
    - » Site A crashes
    - » Site B wakes up, check its log, and realizes that it has voted `"yes"` on the update. It sends a message to site A asking what happened. At this point, B cannot decide to abort, because update may have committed
    - » B is blocked until A comes back

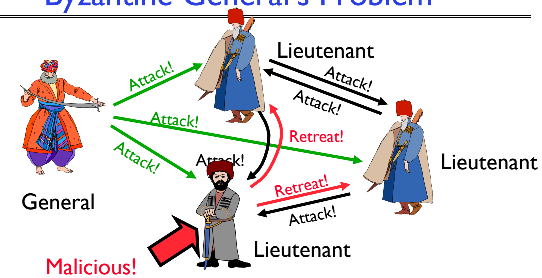


  - B blocked while holding resources (locks on updated items, pages pinned in memory, etc) until hears from A

PAXOS

- PAXOS: An alternative used by Google and others that does not have this blocking problem and work when nodes are malicious
  - Develop by Leslie Lamport (Turing Award Winner)
- What happens if one or more of the nodes is malicious?
  - Malicious: attempting to compromise the decision making

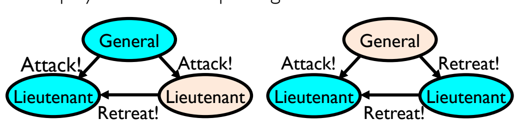
Byzantine General's Problem



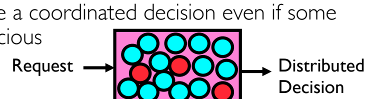
- Byazantine General's Problem (n players):
  - One General and n-1 Lieutenants
  - Some number of these (*f*) can be insane or malicious
- The commanding general must send an order to his n-1 lieutenants such that the following Integrity Constraints apply:
  - IC1: All loyal lieutenants obey the same order
  - IC2: If the commanding general is loyal, then all loyal lieutenants obey the order he sends

Byzantine General's Problem (con't)

- Impossibility Results:
  - Cannot solve Byzantine General's Problem with $n=3$ because one malicious player can mess up things



  - With f faults, need $n > 3f$ to solve problem
- Various algorithms exist to solve problem
  - Original algorithm has #messages exponential in n
  - Newer algorithms have message complexity $O(n^2)$
    - » One from MIT, for instance (Castro and Liskov, 1999)
- Use of BFT (Byzantine Fault Tolerance) algorithm
  - Allow multiple machines to make a coordinated decision even if some subset of them ($< n/3$) are malicious



Goals of Today's Lecture

- Ending previous lecture (PAXOS)
- RPC
- Key-value storage

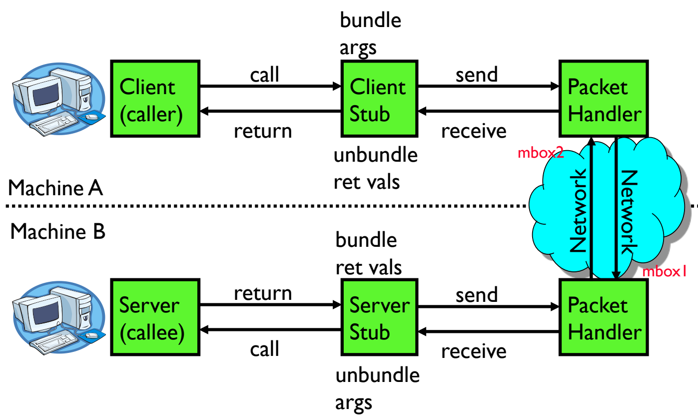
Remote Procedure Call (RPC)

- Raw messaging is a bit too low-level for programming
  - Must wrap up information into message at source
  - Must decide what to do with message at destination
  - May need to sit and wait for multiple messages to arrive
- Another option: Remote Procedure Call (RPC)
  - Calls a procedure on a remote machine
  - Client calls:
    `remoteFileSystem→Read("rutabaga");`
  - Translated automatically into call on server:
    `fileSys→Read("rutabaga");`

RPC Implementation

- Request-response message passing (under covers!)
- "Stub" provides glue on client/server
  - Client stub is responsible for "marshalling" arguments and "unmarshalling" the return values
  - Server-side stub is responsible for "unmarshalling" arguments and "marshalling" the return values.
- Marshalling involves (depending on system)
  - Converting values to a canonical form, serializing objects, copying arguments passed by reference, etc.

RPC Information Flow



RPC Details (1/3)

- Equivalence with regular procedure call
  - Call & parameters ⇔ Request Message
    - » Result ⇔ Reply message
  - Name of Procedure: Passed in request message
  - Return Address: mbox2 (client return mail box)
- Stub generator: Compiler that generates stubs
  - Input: interface definitions in an "interface definition language (IDL)"
    - » Contains, among other things, types of arguments/return
  - Output: stub code in the appropriate source language
    - » Code for client to pack message, send it off, wait for result, unpack result and return to caller
    - » Code for server to unpack message, call procedure, pack results, send them off

RPC Details (2/3)

- Cross-platform issues:
  - What if client/server machines are different architectures/ languages?
    - » Convert everything to/from some canonical form
    - » Tag every item with an indication of how it is encoded (avoids unnecessary conversions)
- How does client know which mbox to send to?
  - Need to translate name of remote service into network endpoint (Remote machine, port, possibly other info)
  - Binding: the process of converting a user-visible name into a network endpoint
    - » This is another word for "naming" at network level
    - » Static: fixed at compile time
    - » Dynamic: performed at runtime

RPC Details (3/3)

- Dynamic Binding
  - Most RPC systems use dynamic binding via name service
    - » Name service provides dynamic translation of service → mbox
  - Why dynamic binding?
    - » Access control: check who is permitted to access service
    - » Fail-over: If server fails, use a different one
- What if there are multiple servers?
  - Could give flexibility at binding time
    - » Choose unloaded server for each new client
  - Could provide same mbox (router level redirect)
    - » Choose unloaded server for each new request
    - » Only works if no state carried from one call to next
- What if multiple clients?
  - Pass pointer to client-specific return mbox in request

Problems with RPC: Non-Atomic Failures

- Different failure modes in dist. system than on a single machine
- Consider many different types of failures
  - User-level bug causes address space to crash
  - Machine failure, kernel bug causes all processes on same machine to fail
  - Some machine is compromised by malicious party
- Before RPC: whole system would crash/die
- After RPC: One machine crashes/compromised while others keep working
- Can easily result in inconsistent view of the world
  - Did my cached data get written back or not?
  - Did server do what I requested or not?
- Answer? Distributed transactions/Byzantine Commit

Problems with RPC: Performance

- Cost of Procedure call « same-machine RPC « network RPC
- Means programmers must be aware that RPC is not free
  - Caching can help, but may make failure handling complex

Administrivia

- Midterm 3 coming up on **Wen 11/29 6:30-8PM**
  - All topics up to and including Lecture 24
    - » Focus will be on Lectures 17 – 24 and associated readings, and Projects 3
    - » But expect 20-30% questions from materials from Lectures 1-16
  - Closed book
  - 2 sides hand-written notes both sides

BREAK

Goals of Today's Lecture

- Ending previous lecture (PAXOS)
- RPC
- Key-value storage

Key Value Storage

- Handle huge volumes of data, e.g., PetaBytes!
  - Store (key, value) tuples
- Simple interface
  - `put(key, value);` // insert/write "value" associated with "key"
  - `value = get(key);` // get/read data associated with "key"
- Used sometimes as a simpler but more scalable "database"

Key Values: Examples

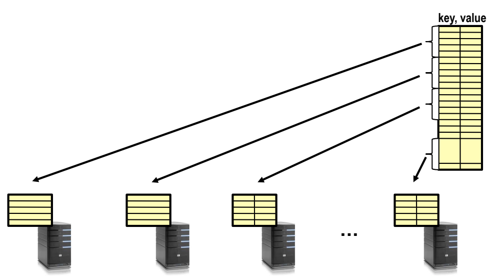
- Amazon:
  - Key: customerID
  - Value: customer profile (e.g., buying history, credit card, ..)
- Facebook, Twitter:
  - Key: UserID
  - Value: user profile (e.g., posting history, photos, friends, …)
- iCloud/iTunes:
  - Key: Movie/song name
  - Value: Movie, Song

Key-Value Storage Systems in Real Life

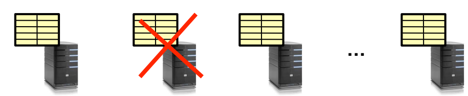
- Amazon
  - DynamoDB: internal key value store used for Amazon.com (cart)
  - Simple Storage System (S3)
- **BigTable/HBase:** distributed, scalable data store
- **Cassandra:** "distributed data management system" (developed by Facebook)
- **Memcached:** in-memory key-value store for small chunks of arbitrary data (strings, objects)
- …

Key Value Store

- Also called Distributed Hash Tables (DHT)
- Main idea: partition set of key-values across many machines



Challenges



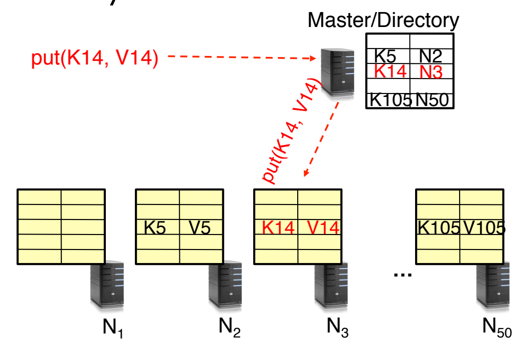
- **Fault Tolerance:** handle machine failures without losing data and without degradation in performance
- **Scalability:**
  - Need to scale to thousands of machines
  - Need to allow easy addition of new machines
- **Consistency:** maintain data consistency in face of node failures and message losses
- **Heterogeneity** (if deployed as peer-to-peer system):
  - Latency: 1ms to 1000ms
  - Bandwidth: 32Kb/s to 100Mb/s

Key Questions

- `put(key, value)`: where to store a new (key, value) tuple?
- `get(key)`: where is the value associated with a given "key" stored?
- And, do the above while providing
  - Fault Tolerance
  - Scalability
  - Consistency

Directory-Based Architecture

- Have a node maintain the mapping between **keys** and the **machines (nodes)** that store the **values** associated with the **keys**



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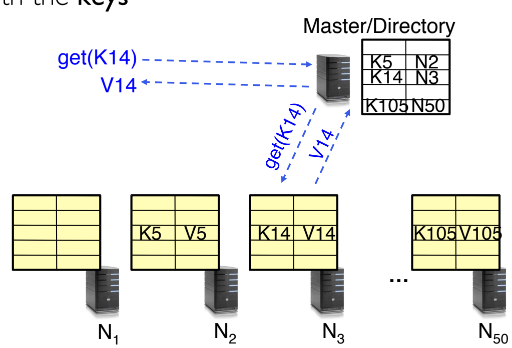
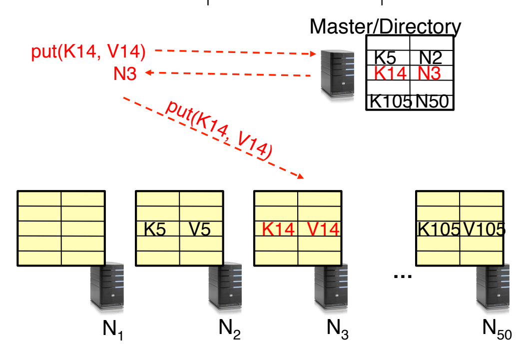


Directory-Based Architecture

- Having the master relay the requests → **recursive query**
- Another method: **iterative query** (this slide)
  - Return node to requester and let requester contact node



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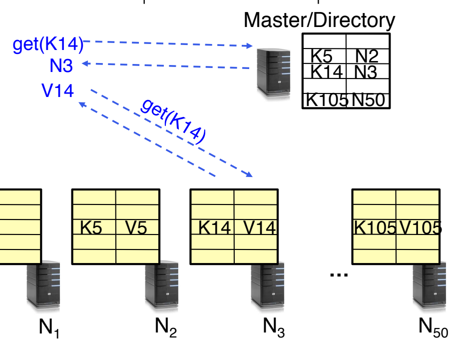
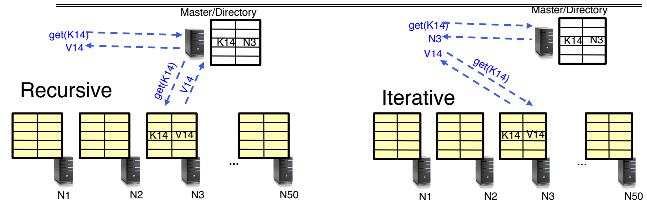


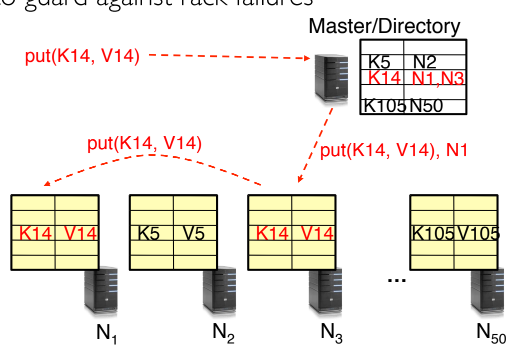
Discussion: Iterative vs. Recursive Query



- Recursive Query:
  - Advantages:
    - » Faster, as typically master/directory closer to nodes
    - » Easier to maintain consistency, as master/directory can serialize puts()/gets()
  - Disadvantages: scalability bottleneck, especially for large "values", as all "values" go through master/directory
- Iterative Query
  - Advantages: more scalable
  - Disadvantages: slower, harder to enforce data consistency

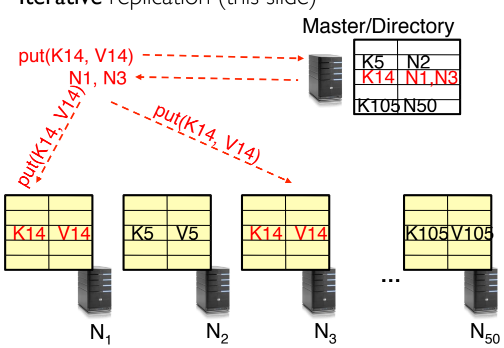
Fault Tolerance

- Replicate value on several nodes
- Usually, place replicas on different racks in a datacenter to guard against rack failures



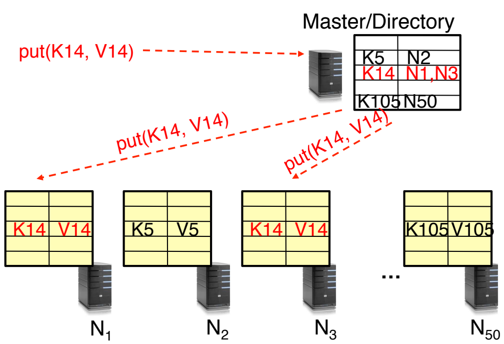
Fault Tolerance

- Again, we can have
  - **Recursive** replication (previous slide)
  - **Iterative** replication (this slide)



Fault Tolerance

- Or we can use **recursive** query and **iterative** replication…



Scalability

- More storage: use more nodes
- More tread requests:
  - Can serve requests from all nodes on which a value is stored in parallel
  - Master can replicate a popular value on more nodes
- Master/directory scalability:
  - Replicate it
  - Partition it, so different keys are served by different masters/directories
    - » How do you partition?

Scalability: Load Balancing

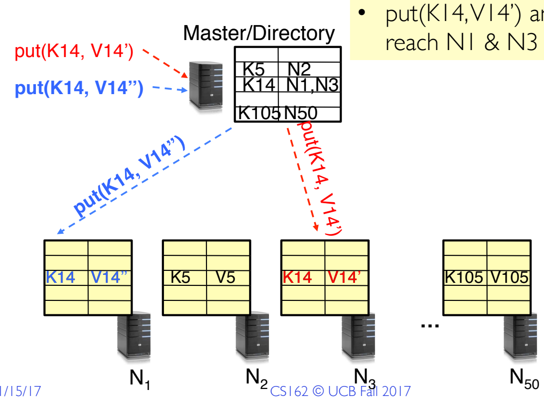
- Directory keeps track of the storage availability at each node
  - Preferentially insert new values on nodes with more storage available
- What happens when a new node is added?
  - Cannot insert only new values on new node. Why?
  - Move values from the heavy loaded nodes to the new node
- What happens when a node fails?
  - Need to replicate values from fail node to other nodes

Consistency

- Need to make sure that a value is replicated correctly
- How do you know a value has been replicated on every node?
  - Wait for acknowledgements from every node
- What happens if a node fails during replication?
  - Pick another node and try again
- What happens if a node is slow?
  - Slow down the entire put()? Pick another node?
- In general, with multiple replicas
  - Slow puts and fast gets

Consistency (cont'd)

- If concurrent updates (i.e., puts to same key) may need to make sure that updates happen in the same order
  - put(K14,V14') and put(K14,V14'') reach N1 & N3 in reverse order



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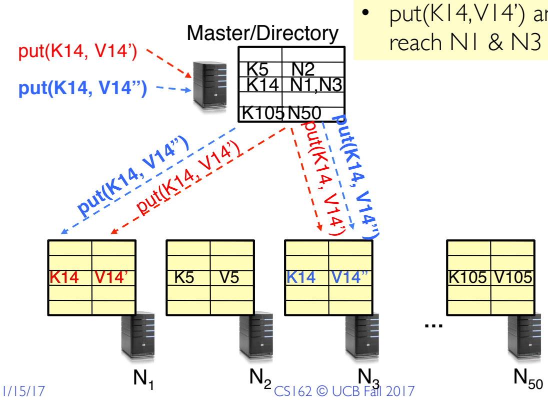
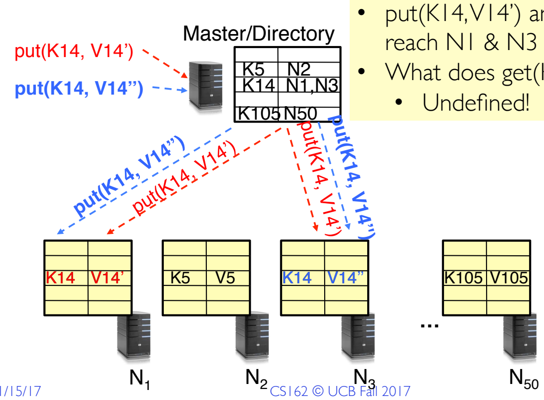


Consistency (cont'd)

- If concurrent updates (i.e., puts to same key) may need to make sure that updates happen in the same order
  - put(K14,V14') and put(K14,V14'') reach N1 & N3 in reverse order
  - What does get(K14) return?
    - Undefined!



Large Variety of Consistency Models

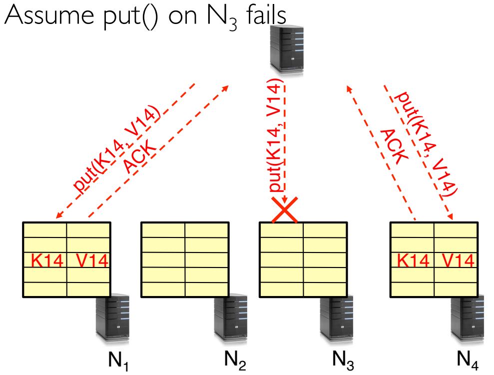
- Atomic consistency (linearizability): reads/writes (gets/puts) to replicas appear as if there was a single underlying replica (single system image)
  - Think "one updated at a time"
  - Transactions
- Eventual consistency: given enough time all updates will propagate through the system
  - One of the weakest form of consistency; used by many systems in practice
  - Must eventually converge on single value/key (coherence)
- *And many others: causal consistency, sequential consistency, strong consistency, …*

Quorum Consensus

- Improve put() and get() operation performance
- Define a replica set of size N
  - put() waits for acknowledgements from at least W replicas
  - get() waits for responses from at least R replicas
  - W+R > N
- Why does it work?
  - There is at least one node that contains the update
- Why might you use W+R > N+1?

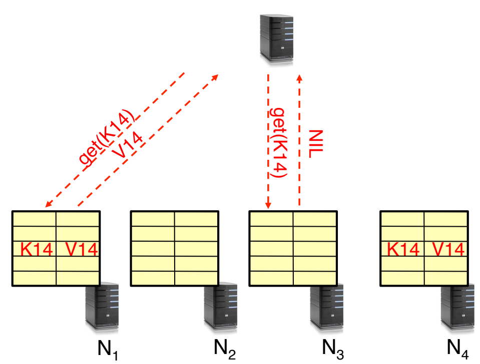
Quorum Consensus Example

- N=3, W=2, R=2
- Replica set for K14: {N_1, N_3, N_4}
- Assume put() on N_3 fails



Quorum Consensus Example

- Now, issuing get() to any two nodes out of three will return the answer

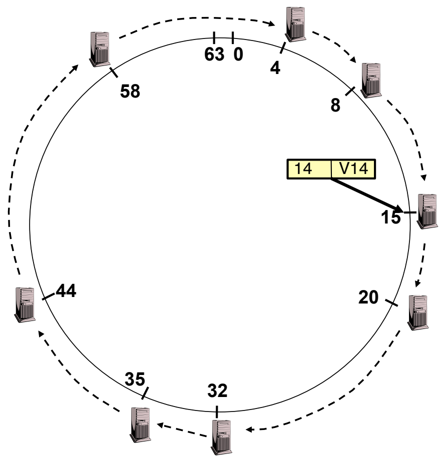


Scaling Up Directory

- Challenge:
  - Directory contains a number of entries equal to number of (key, value) tuples in the system
  - Can be tens or hundreds of billions of entries in the system!
- Solution: consistent hashing
- Associate to each node a unique *id* in an *uni*-dimensional space $0..2^m-1$
  - Partition this space across *m* machines
  - Assume keys are in same uni-dimensional space
  - Each (Key, Value) is stored at the node with the smallest ID larger than Key

Key to Node Mapping Example

- m = 8 → ID space: 0..63
- Node 8 maps keys [5,8]
- Node 15 maps keys [9,15]
- Node 20 maps keys [16, 20]
- …
- Node 4 maps keys [59, 4]



Scaling Up Directory

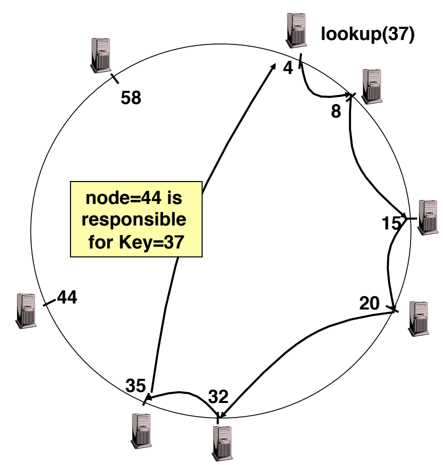
- With consistent hashing, directory contains only a number of entries equal to number of nodes
  - Much smaller than number of tuples
- Next challenge: every query still needs to contact the directory
- Solution: distributed directory (a.k.a. lookup) service:
  - Given a **key**, find the **node** storing value associated to the key
- Key idea: route request from node to node until reaching the node storing the request's key
- Key advantage: totally distributed
  - No point of failure; no hot spot

Chord: Distributed Lookup (Directory) Service

- Key design decision
  - Decouple correctness from efficiency
- Properties
  - Each node needs to know about O(log(*M*)), where *M* is the total number of nodes
  - Guarantees that a tuple is found in O(log(*M*)) steps
- Many other lookup services: CAN, Tapestry, Pastry, Kademlia, …

Lookup

- Each node maintains pointer to its successor
- Route packet (Key, Value) to the node responsible for ID using successor pointers
- E.g., node=4 lookups for node responsible for Key=37



Stabilization Procedure

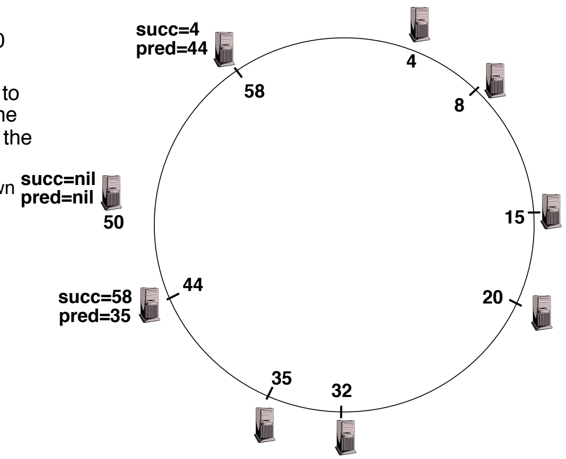
- Periodic operation performed by each node n to maintain its successor when new nodes join the system

```
n.stabilize()
  x = succ.pred;
  if (x ∈ (n, succ))
     succ = x;     // if x better successor, update
  succ.notify(n); // n tells successor about itself

n.notify(n')
  if (pred = nil or n' ∈ (pred, n))
     pred = n';      // if n' is better predecessor, update
```

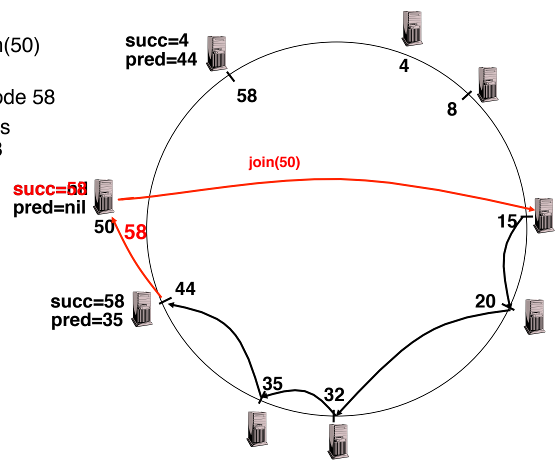

Joining Operation

- Node with id=50 joins the ring
- Node 50 needs to know at least one node already in the system
  - Assume known node is 15



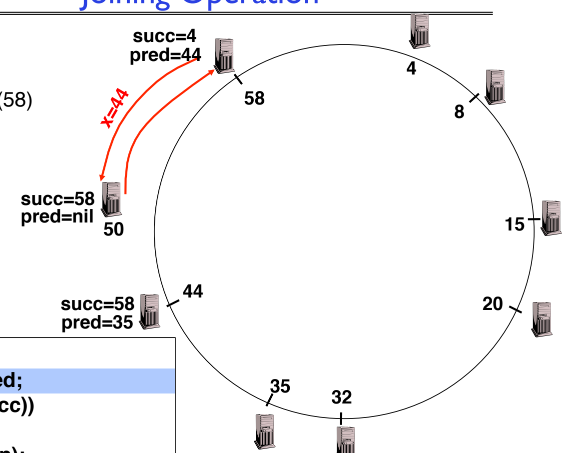
Joining Operation

- n=50 sends join(50) to node 15
- n=44 returns node 58
- n=50 updates its successor to 58



Joining Operation

- n=50 executes stabilize()
- n's successor (58) returns x = 44

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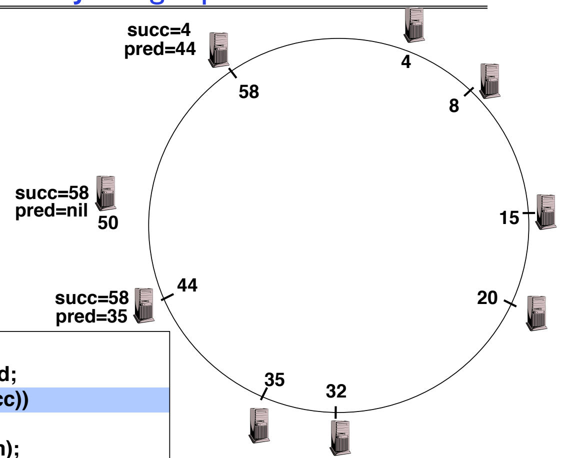


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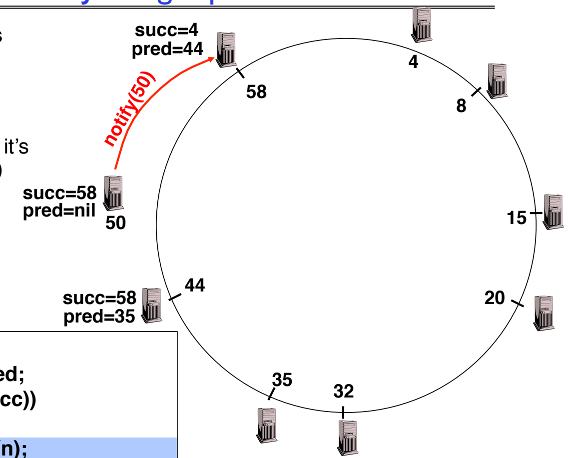
Joining Operation

- n=50 executes stabilize()
  - x = 44
  - succ = 58
- n=50 sends to it's successor (58) notify(50)

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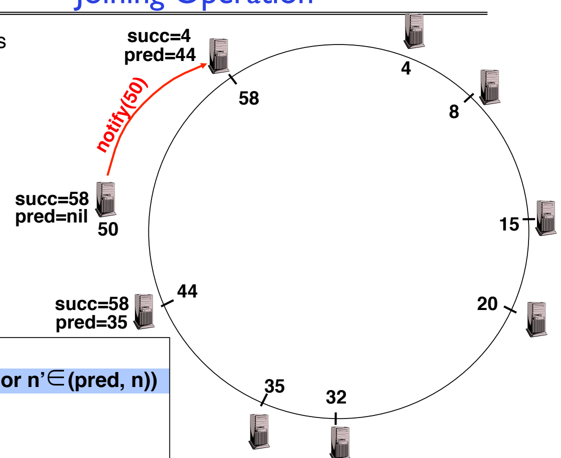
Joining Operation

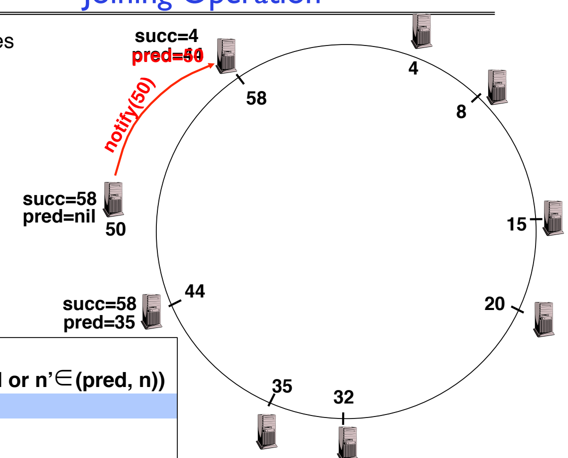
- n=58 processes notify(50)
  - pred = 44
  - n' = 50




```
n.notify(n')
  if (pred = nil or n'∈(pred, n))
    pred = n'
```


Joining Operation

- n=58 processes notify(50)
  - pred = 44
  - n' = 50
- set pred = 50

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Joining Operation

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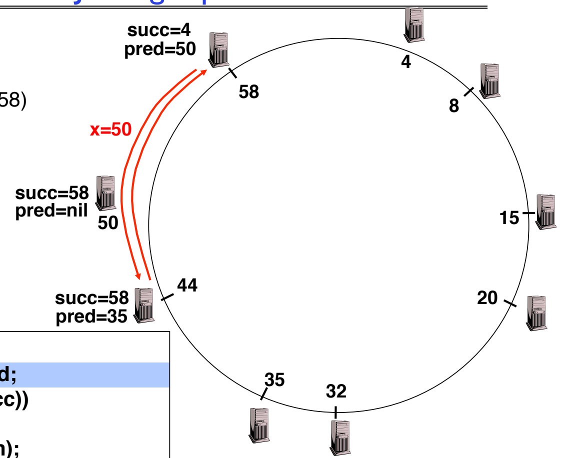


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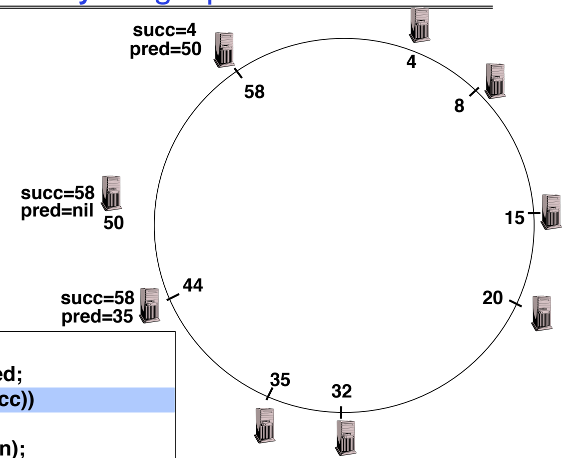


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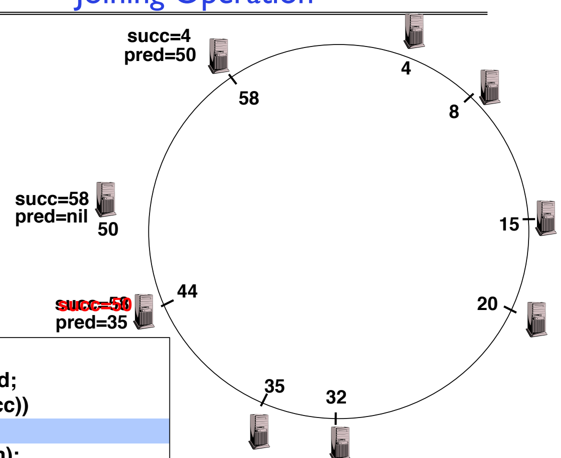
  x = succ.pred;
  if (x∈(n, succ))
     succ = x;
  succ.notify(n);
```


Joining Operation

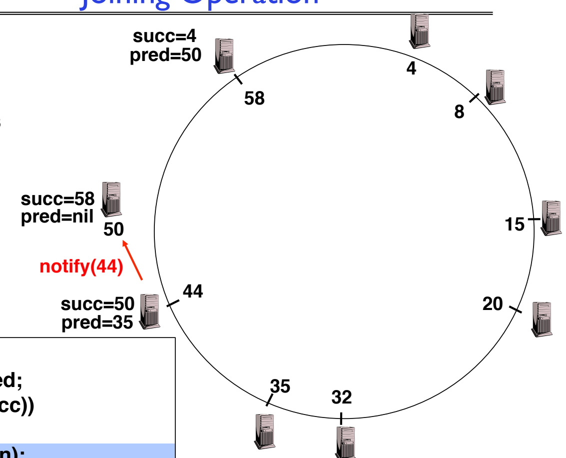
- n=44 runs stabilize()
  - x = 50
  - succ = 58
- n=44 sets succ=50




```
n.stabilize()
  x = succ.pred;
  if (x∈(n, succ))
     succ = x;
  succ.notify(n);
```


Joining Operation

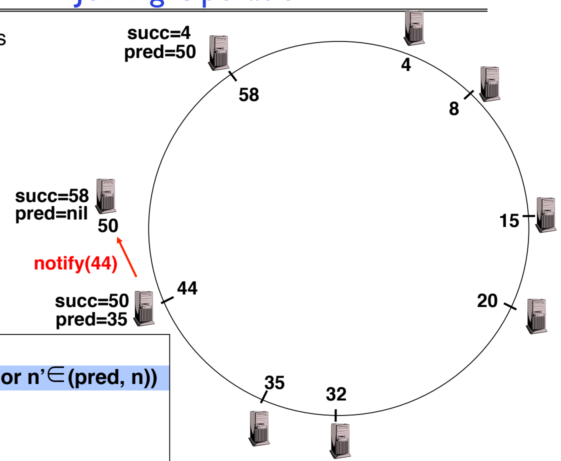
- n=44 runs stabilize()
- n=44 sends notify(44) to its successor




```
n.stabilize()
  x = succ.pred;
  if (x∈(n, succ))
     succ = x;
  succ.notify(n);
```

Joining Operation

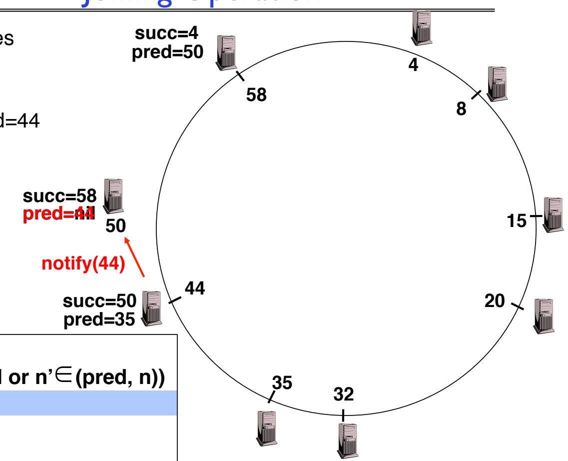
- n=50 processes notify(44)
  - pred = nil




```
n.notify(n')
  if (pred = nil or n'∈(pred, n))
    pred = n'
```


Joining Operation

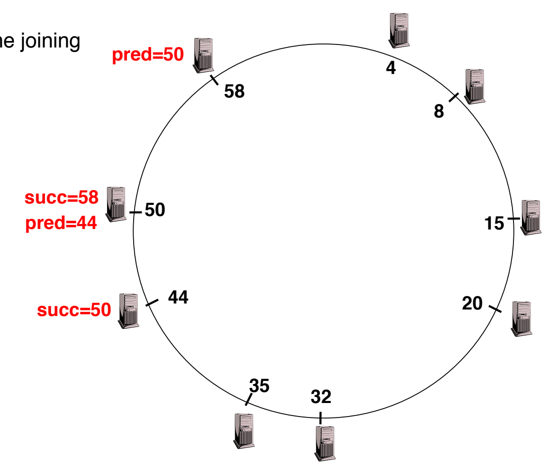
- n=50 processes notify(44)
  - pred = nil
- n=50 sets pred=44




```
n.notify(n')
  if (pred = nil or n'∈(pred, n))
    pred = n'
```


Joining Operation (cont'd)

- This completes the joining operation!

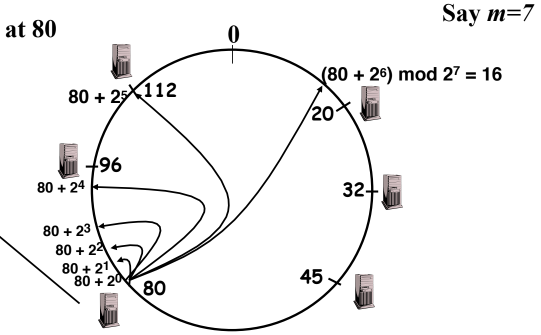


Achieving Efficiency: *finger tables*

Say *m=7*

Finger Table at 80

i	*ft[i]*
0	96
1	96
2	96
3	96
4	96
5	112
6	20



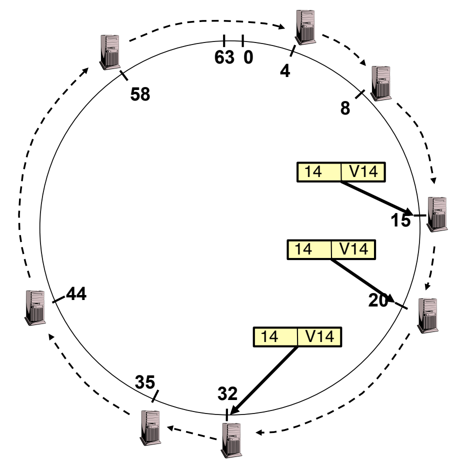
*i*th entry at peer with id *n* is first peer with id >= $n + 2^i \pmod{2^m}$

Achieving Fault Tolerance for Lookup Service

- To improve robustness each node maintains the k (> 1) immediate successors instead of only one successor
- In the pred() reply message, node A can send its k-1 successors to its predecessor B
- Upon receiving pred() message, B can update its successor list by concatenating the successor list received from A with its own list
- If k = log(M), lookup operation works with high probability even if half of nodes fail, where M is number of nodes in the system

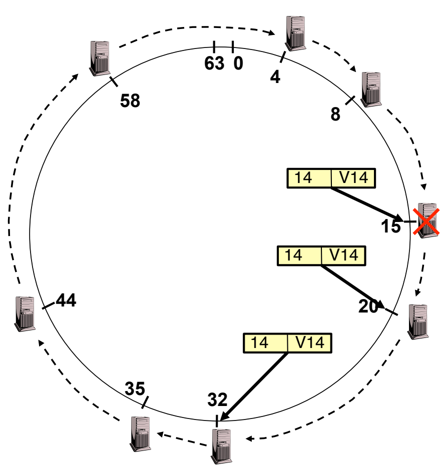
Storage Fault Tolerance

- Replicate tuples on successor nodes
- Example: replicate (K14, V14) on nodes 20 and 32



Storage Fault Tolerance

- If node 15 fails, no reconfiguration needed
  - Still have two replicas
  - All lookups will be correctly routed
- Will need to add a new replica on node 35



Summary (1/2)

- Remote Procedure Call (RPC): Call proc on remote machine
  - Provides same interface as procedure
  - Automatic packing and unpacking of arguments (in stub)
- Key-Value Store:
  - Two operations
    - » put(key, value)
    - » value = get(key)
  - Challenges
    - » Fault Tolerance → replication
    - » Scalability → serve get()'s in parallel; replicate/cache hot tuples
    - » Consistency → quorum consensus to improve put() performance

Summary (2/2)

- Chord:
  - Highly scalable distributed lookup protocol
  - Each node needs to know about O(log(*M*)), where *m* is the total number of nodes
  - Guarantees that a tuple is found in O(log(*M*)) steps
  - Highly resilient: works with high probability even if half of nodes fail