CS162
Operating Systems and Systems Programming

Key Value Storage Systems

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Who am I?

- Ion Stoica
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- Research focus
  - Cloud computing (Mesos, Spark, Tachyon)
    - » Co-director of AMPLab
  - Past work
    - » Network architectures (i3, Declarative Networks, …)
    - » P2P (Chord, OpenDHT)

Key Value Storage

- Handle huge volumes of data, e.g., PBs
  - 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

Examples

- **Amazon**
  - DynamoDB: internal key value store used to power Amazon.com (shopping cart)
  - Simple Storage System (S3)

- **BigTable/HBase/Hypertable:** distributed, scalable data storage

- **Cassandra**: "distributed data management system" (developed by Facebook)

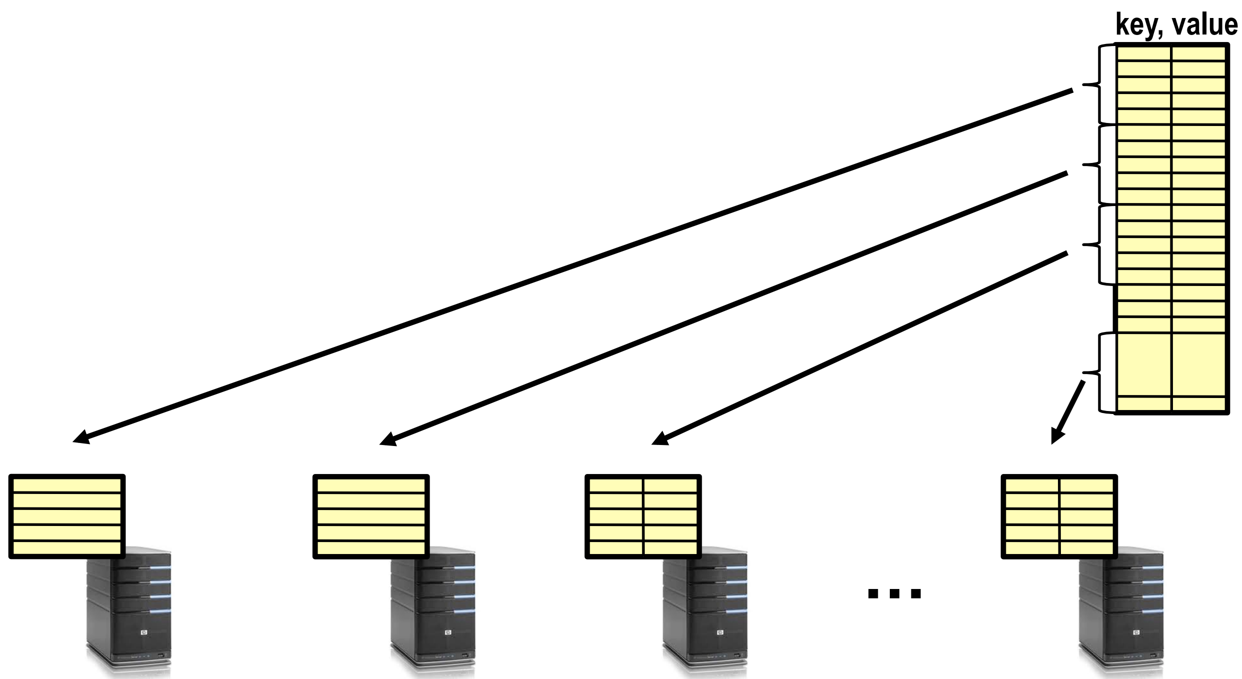
- **Memcached:** in-memory key-value store for small chunks of arbitrary data (strings, objects)

- **eDonkey/eMule:** peer-to-peer sharing system

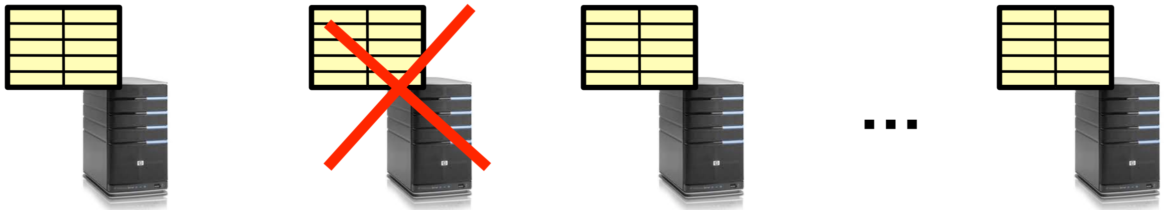
- …

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 systems):
  – Latency: 1ms to 1000ms
  – Bandwidth: 32Kb/s to 100Mb/s

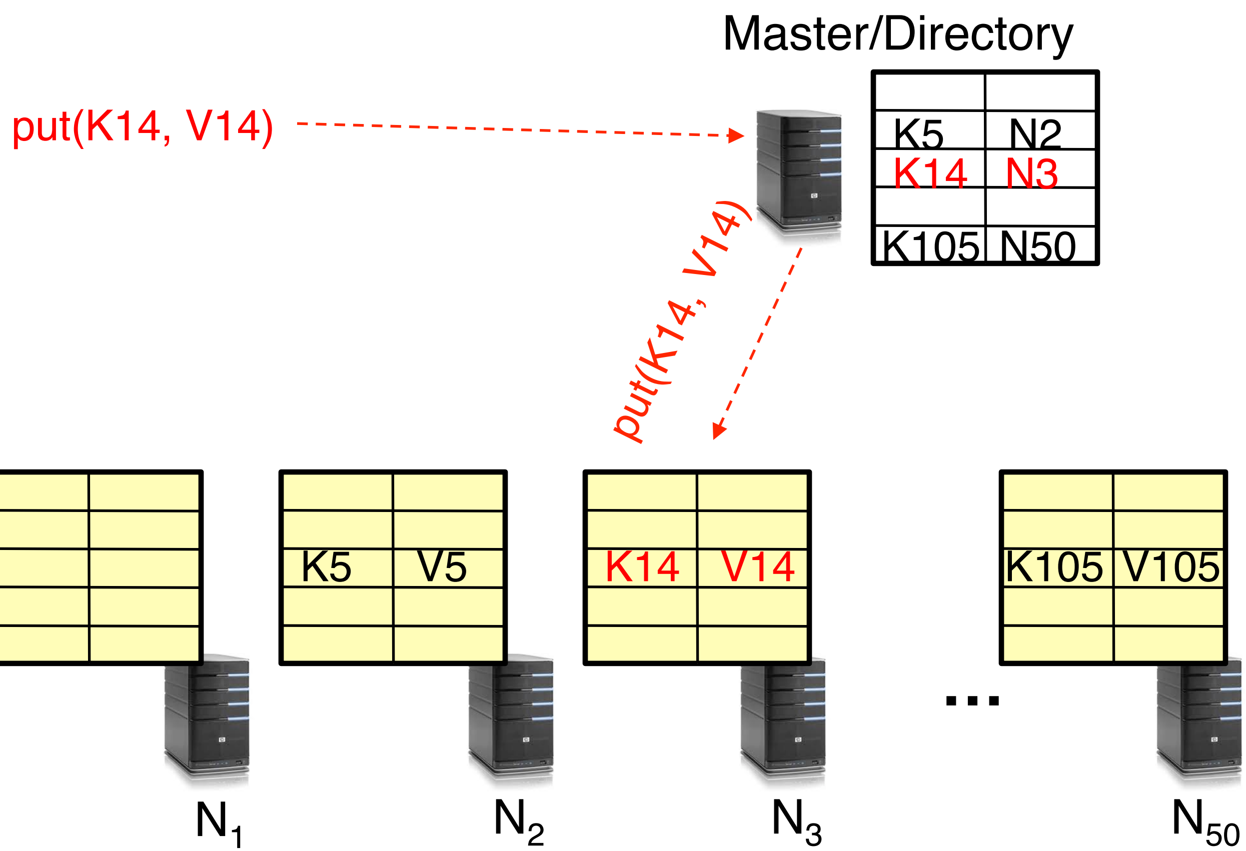
Key Questions

- **put(key, value)**: where do you 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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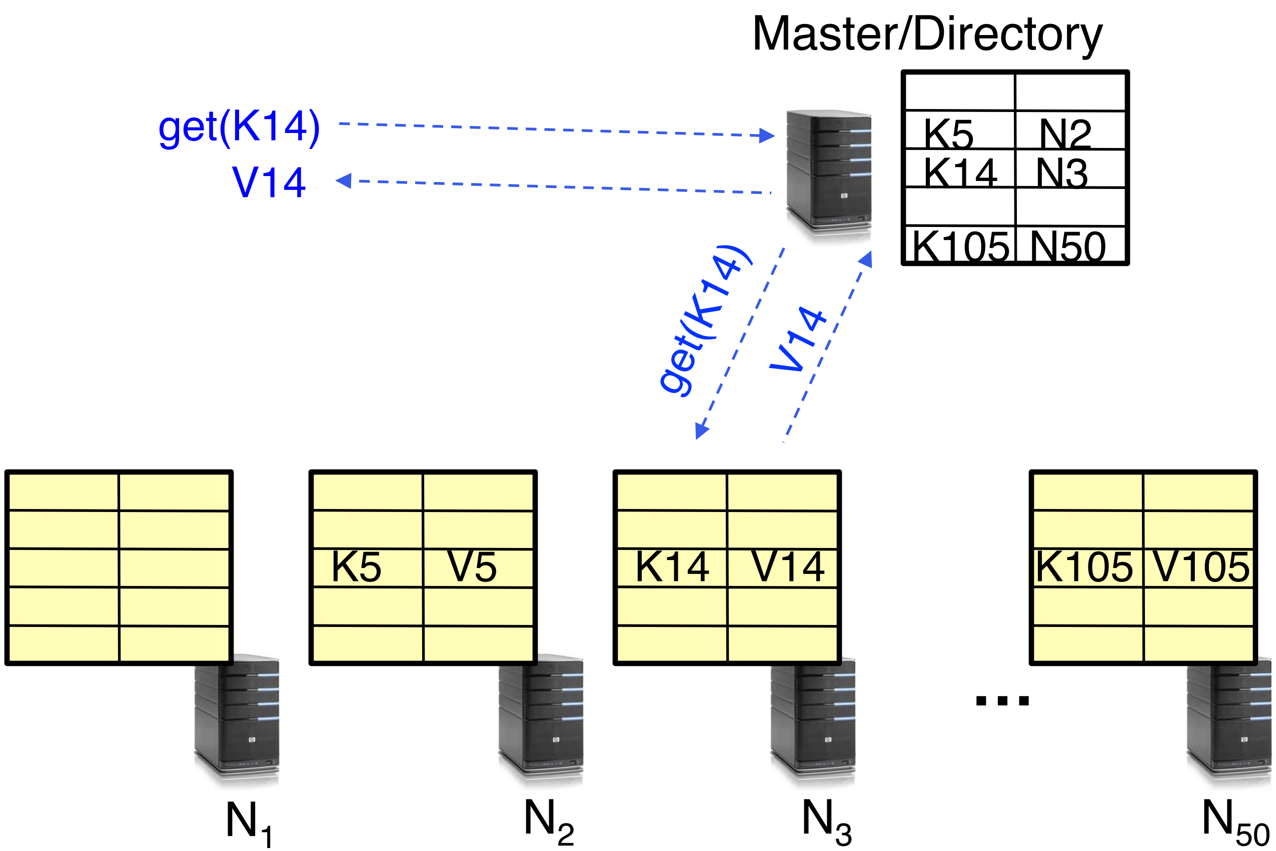
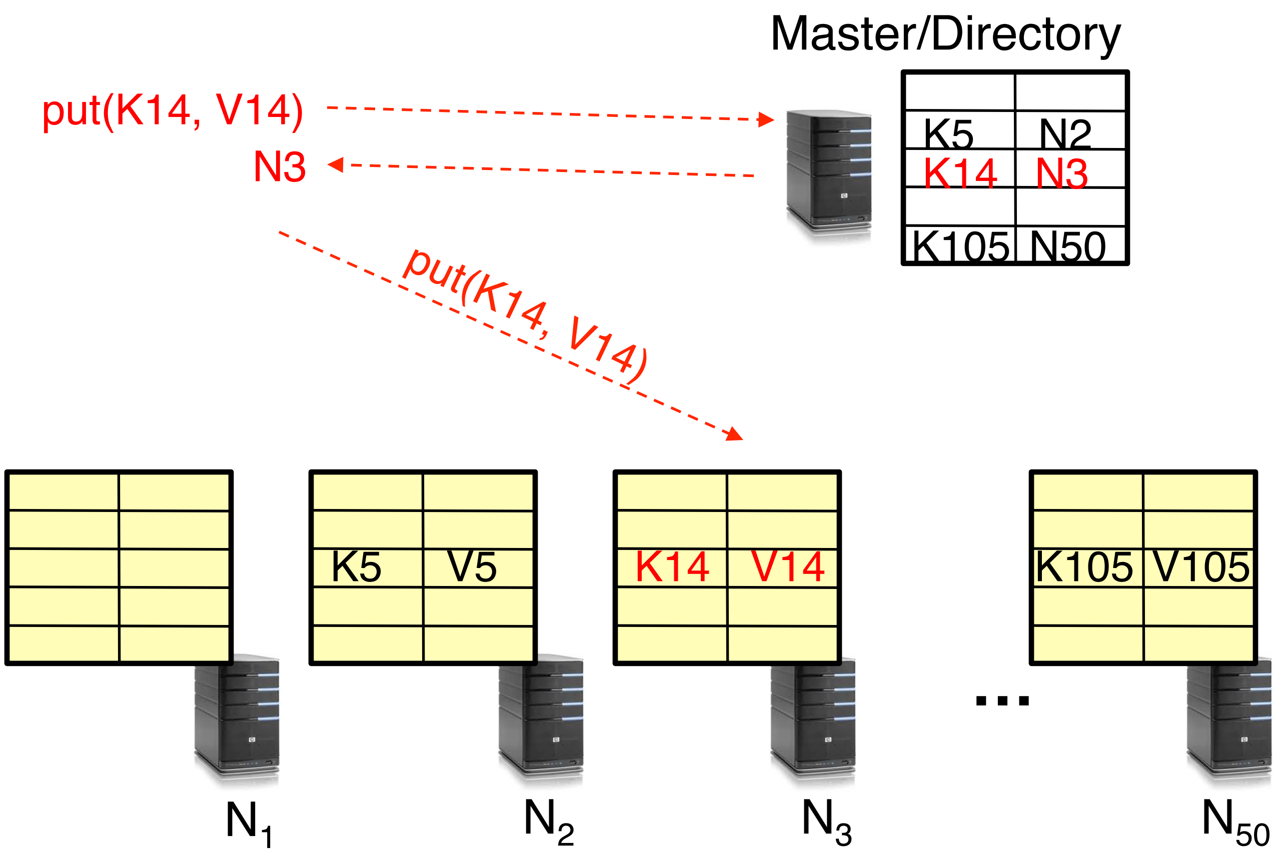


Directory-Based Architecture

- 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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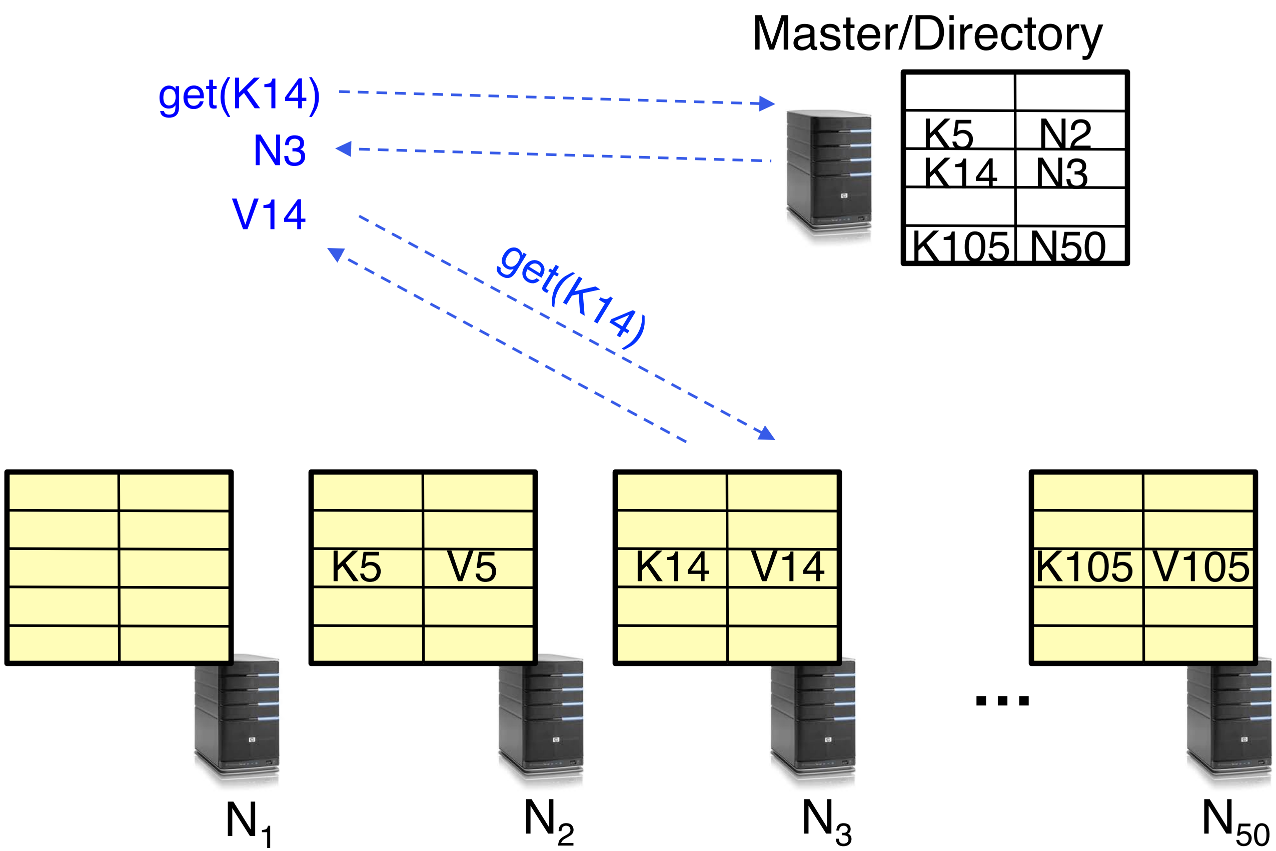
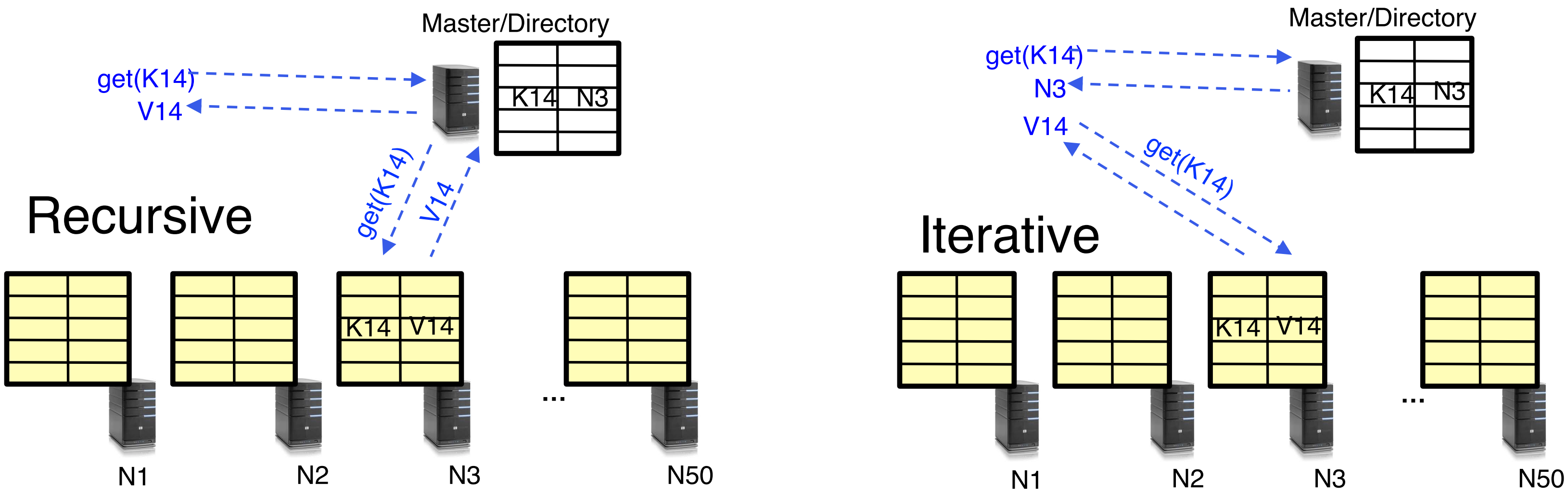


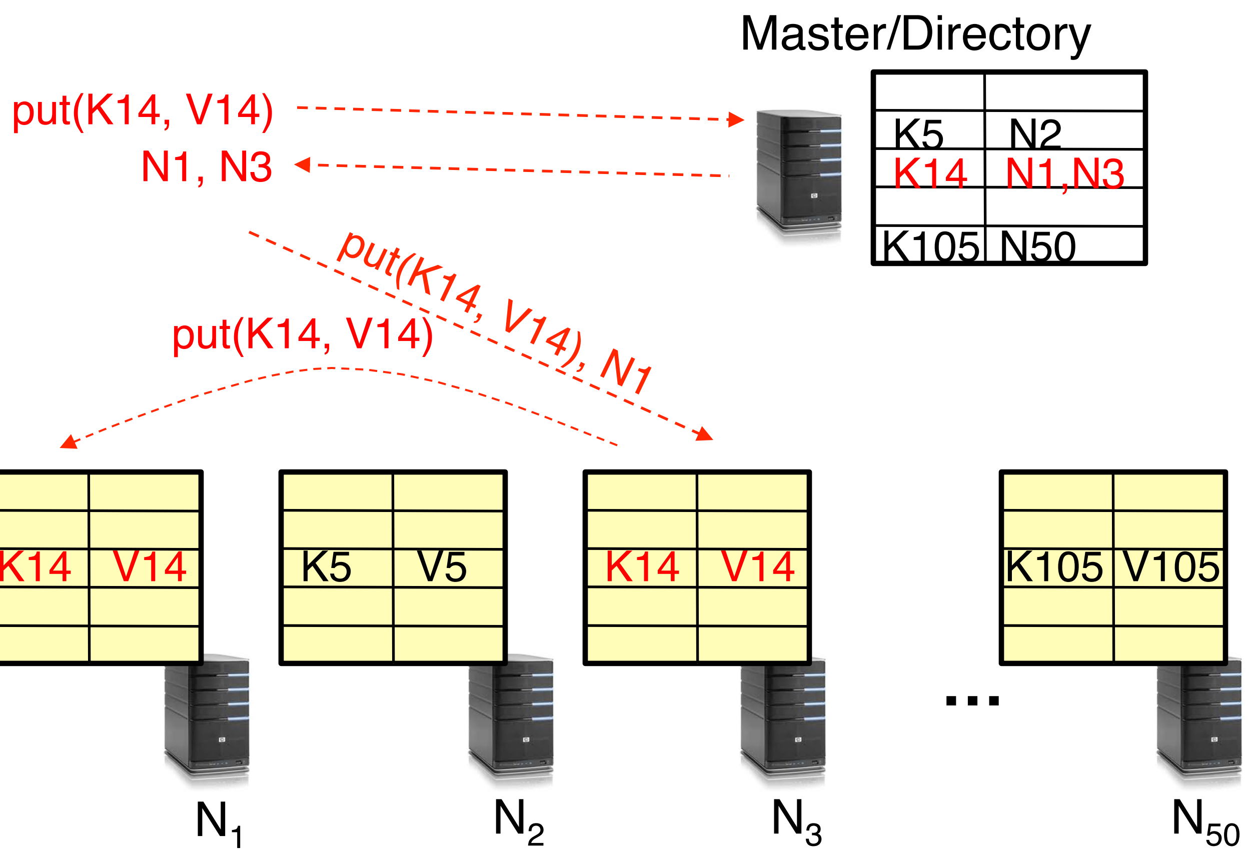
Discussion: Iterative vs. Recursive Query



- 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, as all "Values" go through master/directory
- Iterative Query
  - Advantages: more scalable
  - Disadvantages: slower, harder to enforce data consistency

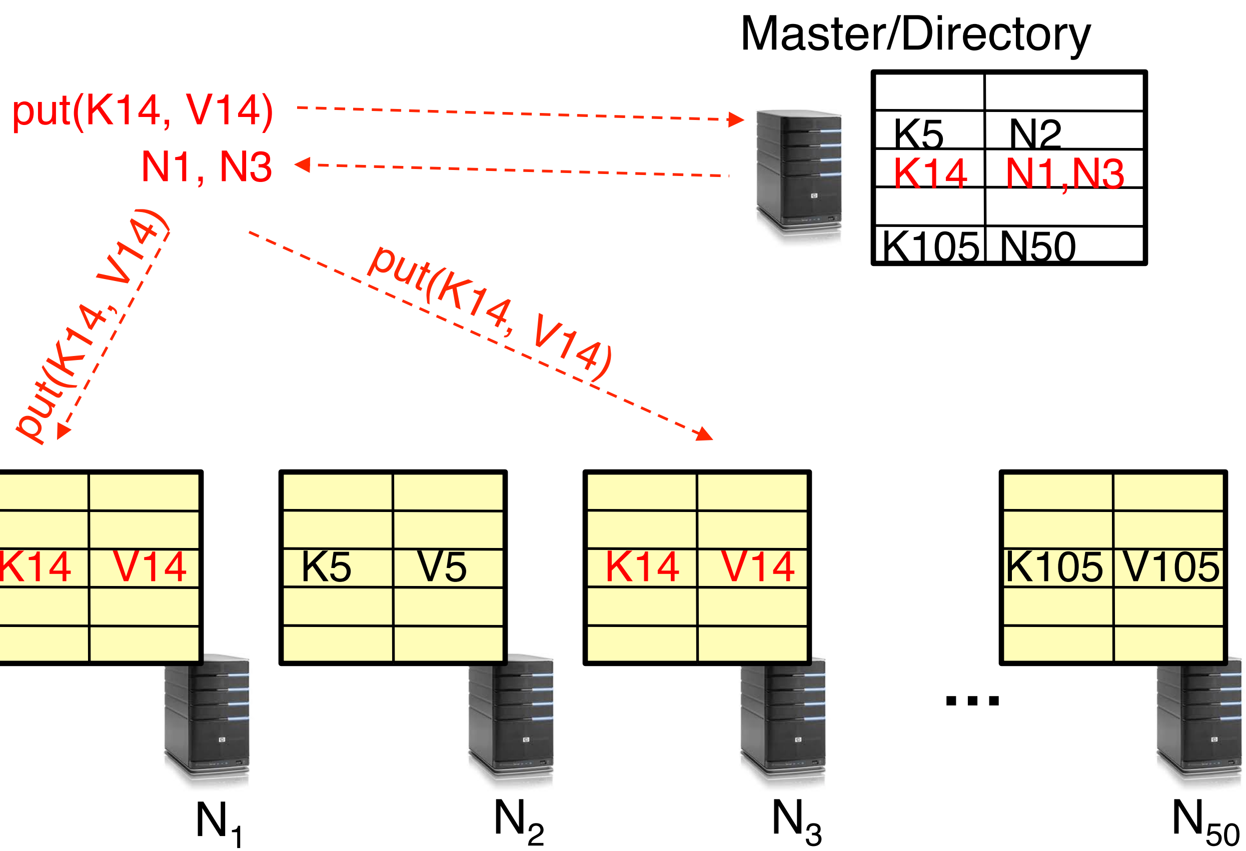
Fault Tolerance

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



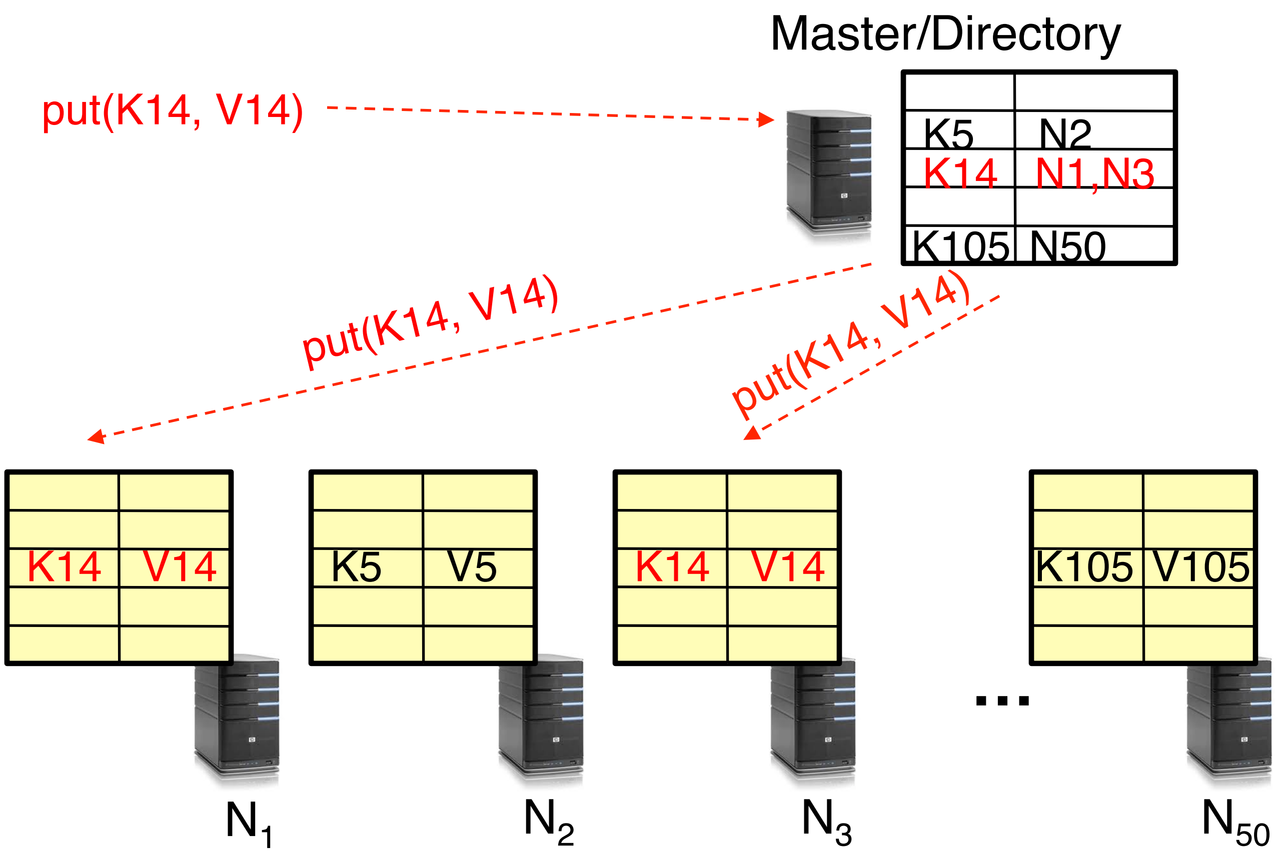
Fault Tolerance

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



Fault Tolerance

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



Scalability

- Storage: use more nodes
- Number of 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

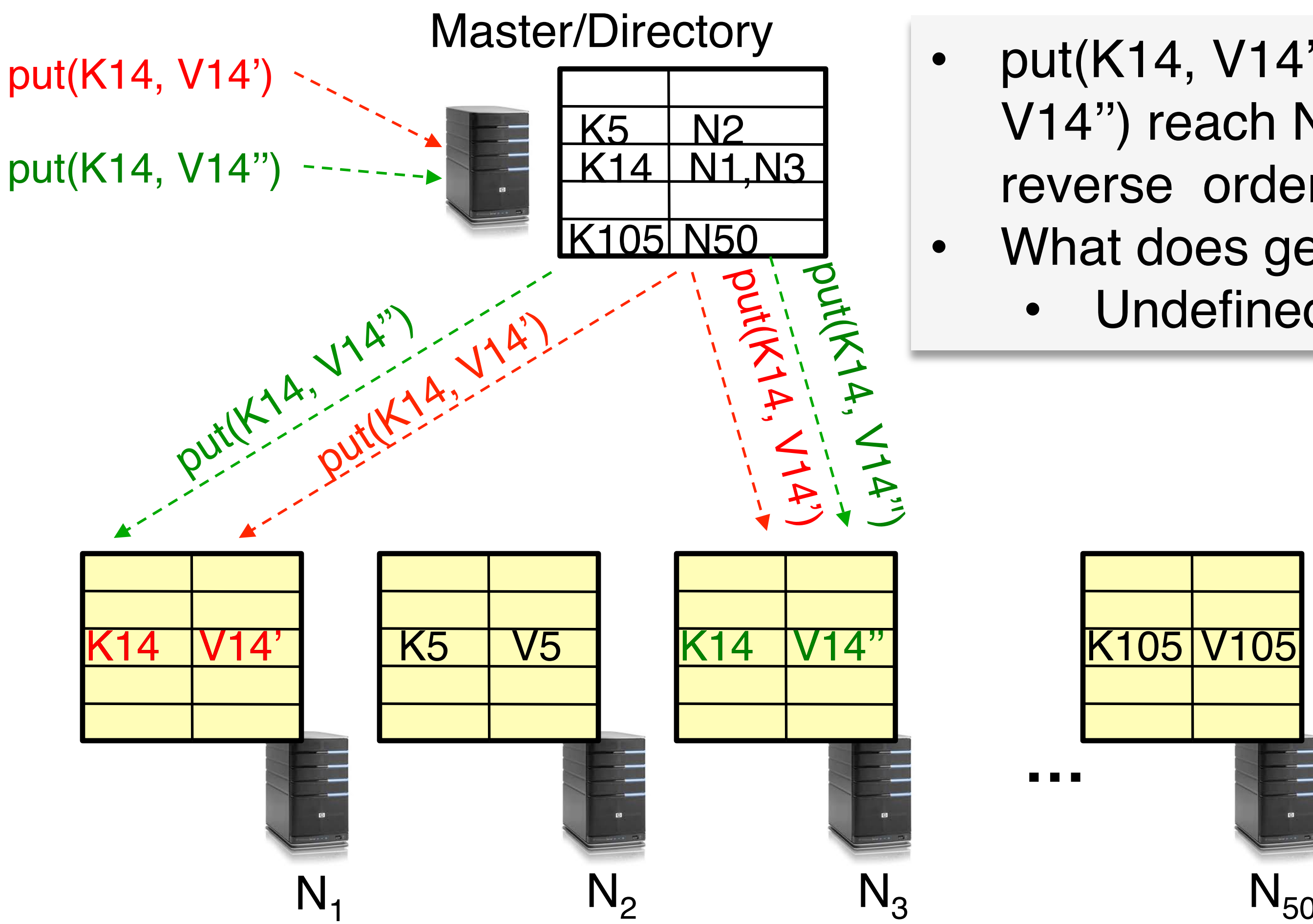
- Directory keeps track of the storage availability at each node
  - Preferentially insert new values on nodes with more storage available
- What happens when a new node is added?
  - Cannot insert only new values on new node. Why?
  - Move values from the heavy loaded nodes to the new node
- What happens 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 and N3 in reverse order
- What does get(K14) return?
  - Undefined!

Consistency (cont'd)

- 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
  - And many others: causal consistency, sequential consistency, strong consistency, …

Quorum Consensus

- Improve put() and get() operation performance

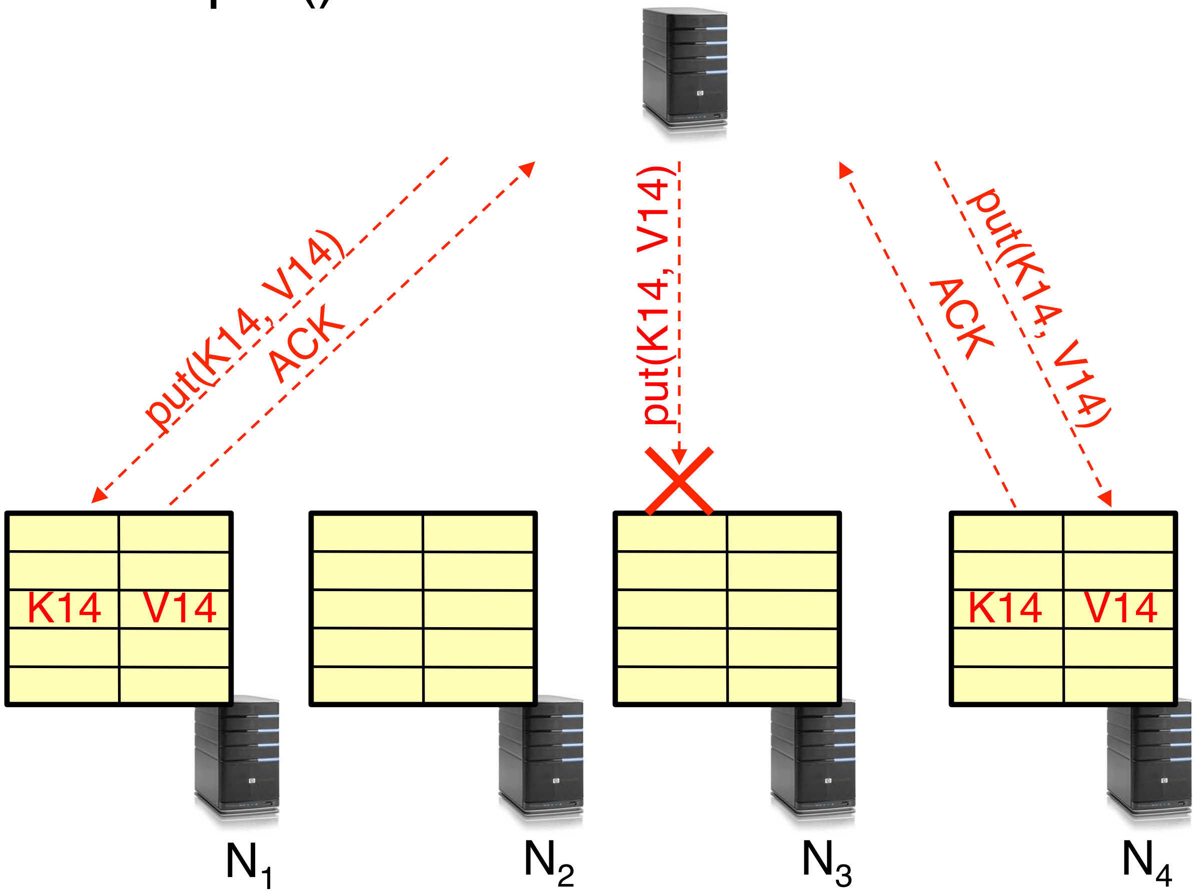
- Define a replica set of size N
- put() waits for acknowledgements from at least W replicas
- get() waits for responses from at least R replicas
- W+R > N

- Why does it work?
  - There is at least one node that contains the update

- Why you may use W+R > N+1?

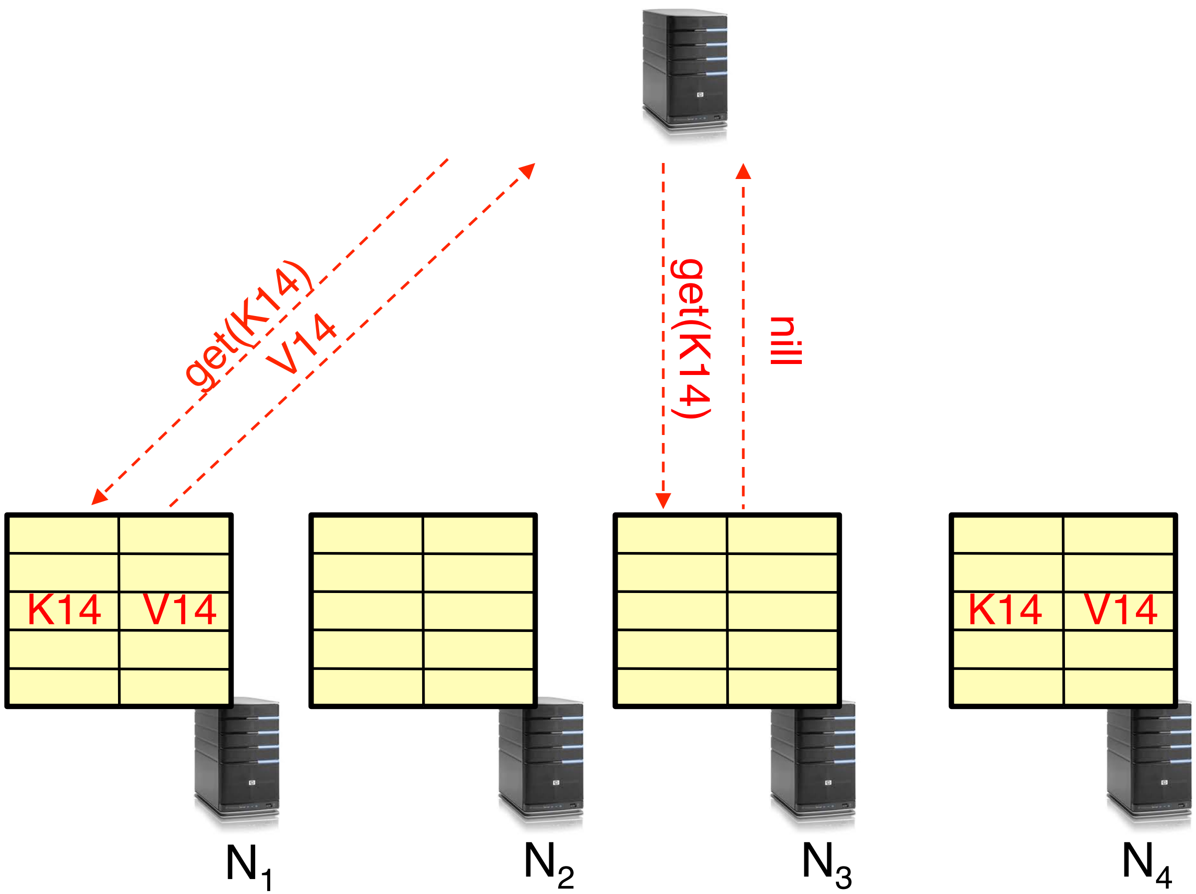
Quorum Consensus Example

- N=3, W=2, R=2
- Replica set for K14: {N1, N2, N4}
- Assume put() on N3 fails



Quorum Consensus Example

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



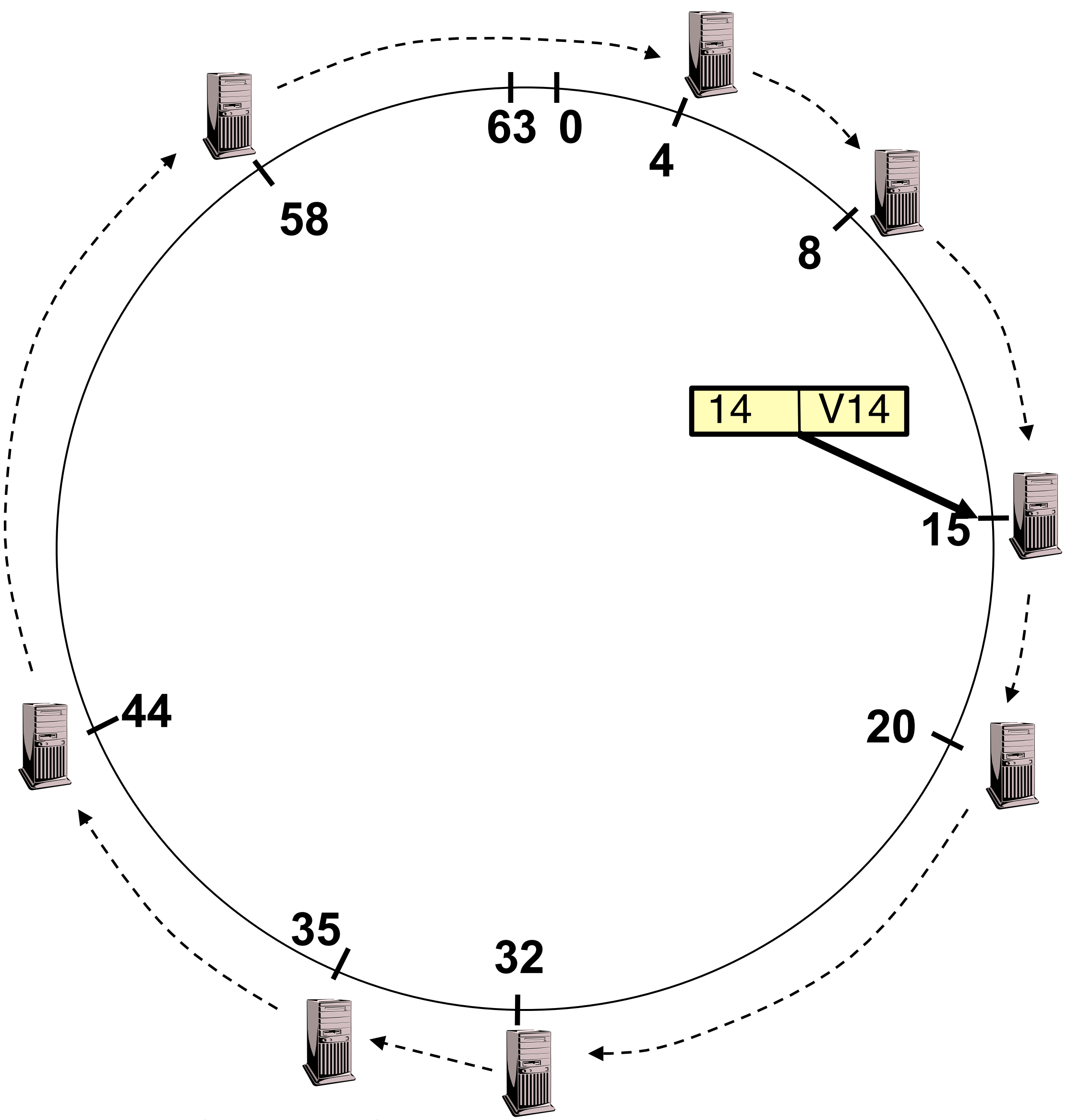
Scaling Up Directory

- 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]



Conclusions: Key Value Store

- Very large scale storage systems
- 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