Scaling Out Key-Value Storage and Dynamo

COS 418: Distributed Systems
Lecture 10

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Availability: vital for web applications

- Web applications are expected to be "always on"
  - Down time → pisses off customers, costs $
- System design considerations relevant to availability
  - **Scalability**: always on under growing demand
  - **Reliability**: always on despite failures
  - *Performance*: 10 sec latency considered available?
    - "an availability event can be modeled as a long-lasting performance variation" (Amazon Aurora SIGMOD '17)

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Scalability: up or out?

- Scale-up (vertical scaling)
  - Upgrade hardware
  - E.g., Macbook Air → Macbook Pro
  - Down time during upgrade; stops working quickly
- **Scale-out** (horizontal scaling)
  - Add machines, divide the work
  - E.g., a supermarket adds more checkout lines
  - No disruption; works great with careful design

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Reliability: available under failures

- More machines, more likely to fail
  - p = probability one machine fails; n = # of machines
  - Failures happen with a probability of **$1-(1-p)^n$**
- For 50K machines, each with **99.99966%** available
  - **16%** of the time, data center experiences failures
- For 100K machines, failures happen **30%** of the time!

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Two questions (challenges)

- How is data partitioned across machines so the system scales?
- How are failures handled so the system is always on?

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Today: Amazon Dynamo

1. Background and system model
2. Data partitioning
3. Failure handling

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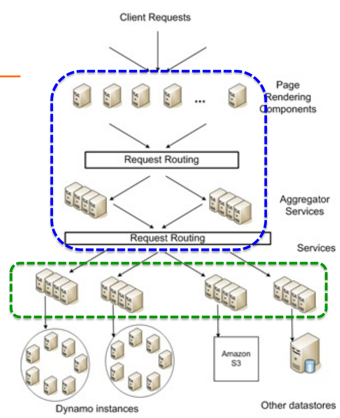
Amazon in 2007

- 10^4s of servers in multiple datacenters
  - 10^6s of servers, 80+ DCs (as of now)
- 10^7s of customers at peak times
  - 20M+ purchases in US. (Prime Day 2020)
- Tiered architecture (similar today)
  - Stateless web servers & aggregators
  - Stateful storage servers



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Basics in Dynamo

- A key-value store (vs. relational DB)
  - get(key) and put(key, value)
  - Nodes are symmetric
  - Remember DHT?
- Service-Level Agreement (SLA)
  - E.g., “provide a response within 300ms for 99.9% of its requests for peak client load of 500 requests/sec”

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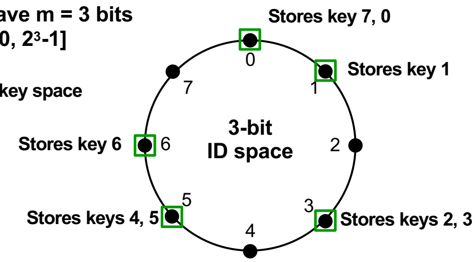
Today: Amazon Dynamo

1. Background and system model
2. **Data partitioning**
   - **Incremental scalability**
   - **Load balancing**
3. Failure handling

Consistent hashing recap

Identifiers have m = 3 bits
Key space: [0, 2^3-1]

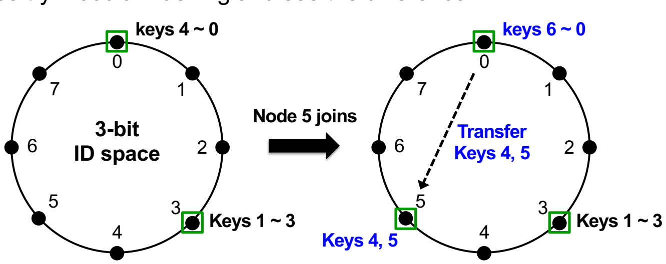
● **Identifiers/key space**
□ **Node**



Key is stored at its **successor:** node with next-higher ID

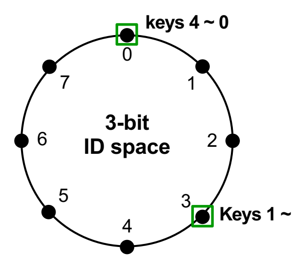
Incremental scalability (why consistent hashing)

- Minimum data is moved around when nodes join and leave
- Please try modular hashing and see the difference



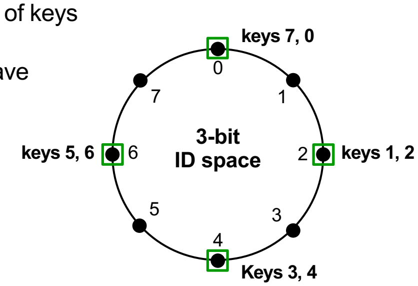
Challenge: unbalanced load

- Nodes are assigned different # of keys



Challenge: unbalanced load

- Nodes are assigned different # of keys
- Unbalanced with nodes join/leave



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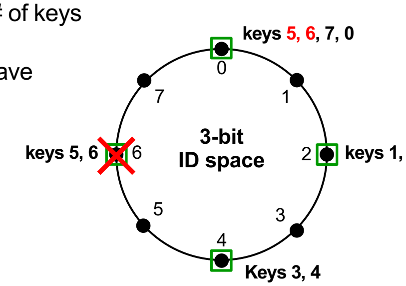

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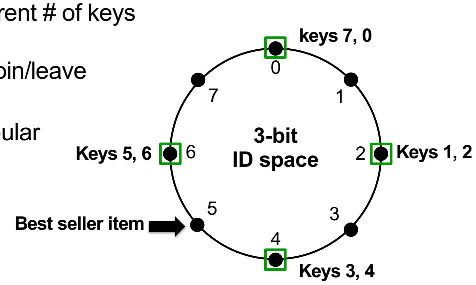
Challenge: unbalanced load

- Nodes are assigned different # of keys
- Unbalanced with nodes join/leave
- Some keys are more popular



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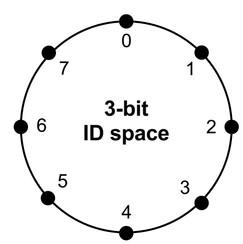
Solution: virtual nodes

- An extra level of mapping
  - From node id in the ring to physical node
  - Node ids are now virtual nodes (tokens)
  - Multiple node ids → same physical node



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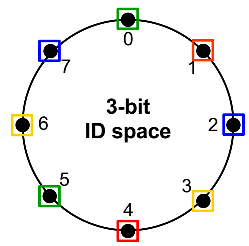
● Identifiers/key space

☐ Virtual node:
same color → same physical node

4 phyiscal nodes (servers)
2 vnodes / server



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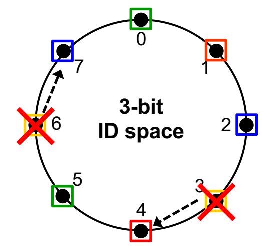
Gold server leaves
Keys moved to blue and red



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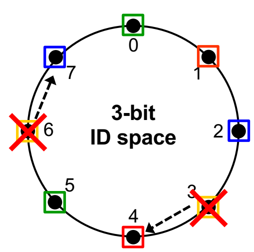
Solution: virtual nodes (vnodes)

- An extra level of mapping
  - From node id in the ring to physical node
  - Node ids are now virtual nodes (tokens)
  - Multiple node ids → same physical node
- More virtual nodes, more balanced
- Faster data transfer for join/leave
- Controllable # of vnodes / server
  - Server capacity, e.g., CPU, memory, network.

● Identifiers/key space

☐ Virtual node:
same color → same physical node



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Today: Amazon Dynamo

1. Background and system model
2. Data partitioning
3. **Failure handling**
   - **Data replication**

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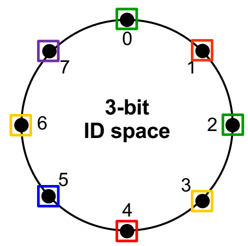
Preference list (data replication)

- Key replicated on M vnodes
  - Remember “r-successor” in DHT?
- All M vnodes on distinct servers across different datacenters

● Identifiers/key space

☐ Virtual node:
5 colors → 5 physical nodes



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Preference list (data replication)

- Key replicated on M vnodes
  - Remember “r-successor” in DHT?
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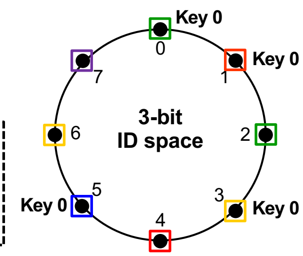
● Identifiers/key space

☐ Virtual node:
5 colors → 5 physical nodes

M = 4
Key 0’s Preference list could be vnodes: {0, 1, 3, 5} mapping to servers: {green, red, gold, blue}
Green is the **coordinator** server of key 0



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Read and write requests

- Received by the coordinator
  - Either the client (web server) knows the mapping or re-routed. (This is not Chord)
- Sent to the first N “healthy” servers in the preference list (coordinator included)
  - Durable writes: my updates recorded on multiple servers
  - Fast reads: possible to avoid straggler
- A write creates a new immutable version of the key instead of overwriting it
  - Multi-versioned data store
- Quorum-based protocol: W + R > N
  - A write succeeds if W out of N servers reply (write quorum)
  - A read succeeds if R out of N servers reply (read quorum)

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Quorum implications (W, R, and N)

- N determines the durability of data (Dynamo N = 3)
- W and R plays around with the **availability-consistency tradeoff**
  - W = 1 (R = 3): fast write, weak durability, slow read (read availability)
  - R = 1 (W = 3): slow write (write availability), good durability, fast read
  - Dynamo: W = R = 2
- Why W + R > N ?
  - Read and write quorums overlap **when there are no failures**!
  - Reads see all updates without failures
    - What if there are failures?

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Failure handing: sloppy quorum + hinted handoff

- Sloppy: not always the same servers used in N
  - First N servers in the preference list without failures
  - Later servers in the list take over if some in the first N fail
- Consequences
  - Good performance: no need to wait for failed servers in N to recover
  - Eventual (weak) consistency: conflicts are possible, versions diverge
  - Another decision on **availability-consistency tradeoff**!

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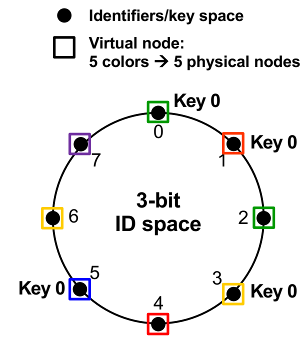
Failure handing: sloppy quorum + hinted handoff

- Key 0's preference list {green, red, gold, blue}
- N = 3: {green, red, gold} without failures
- If red fails, requests go to {green, gold, blue}
- Hinted handoff
  - Blue temporarily serves requests
  - Hinted that red is the intended recipient
  - Send replica back to red when red is on



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An example of conflicting writes (versions)

Preference list (M = 5, N = 3)

Shopping cart:	**A**	**B**	**C**	**D**	**E**
CL1: Add Item x	**x**	**x**			
A and B fail					

Time

27

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An example of conflicting writes (versions)

Preference list (M = 5, N = 3)

Shopping cart:	~~**A**~~	~~**B**~~	**C**	**D**	**E**
CL1: Add Item x	**x**	**x**			
A and B fail					
CL2: Add Item y			**y**	**y**	

Time

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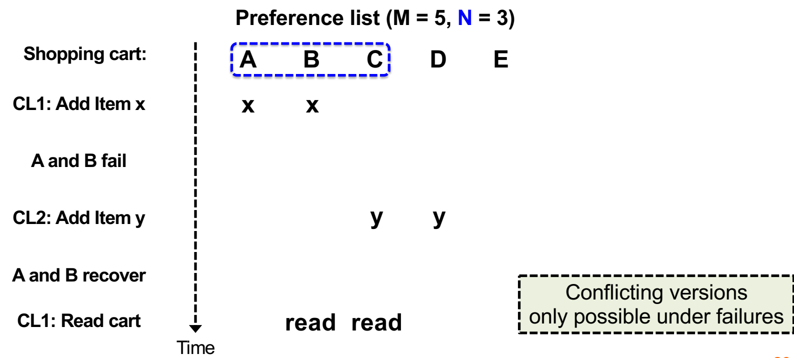
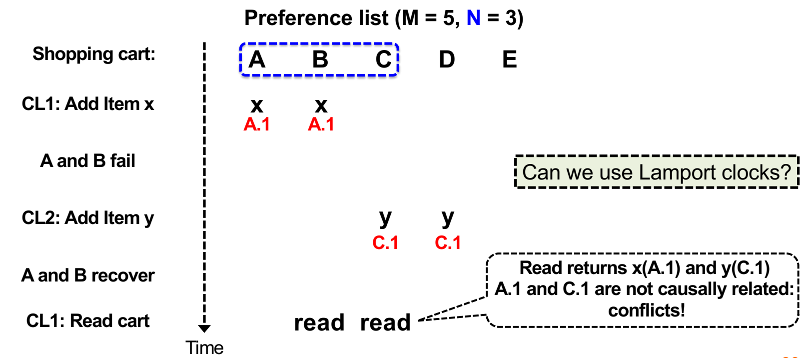
An example of conflicting writes (versions)



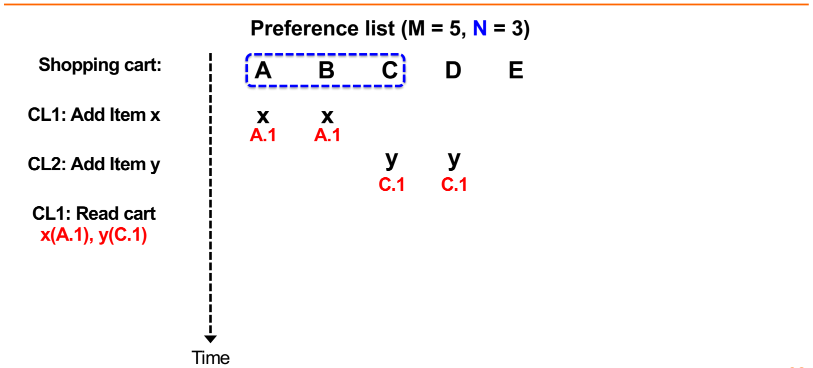
Vector clocks: handling conflicting versions



Conflict resolution (reconciliation)

- If vector clocks show causally related (not really conflicting)
  - System overwrites with the later version
- For conflicting versions
  - *System handles it automatically, e.g., last-writer-wins, limited use case*
  - **Application specific resolution (most common)**
    - Clients resolve the conflict via reads, e.g., merge shopping cart

Vector clocks: handling conflicting versions



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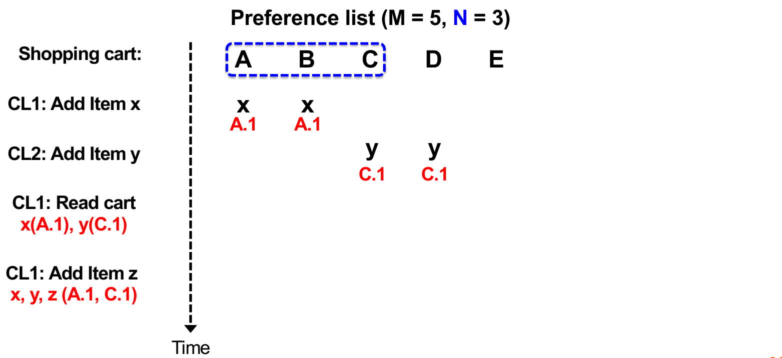

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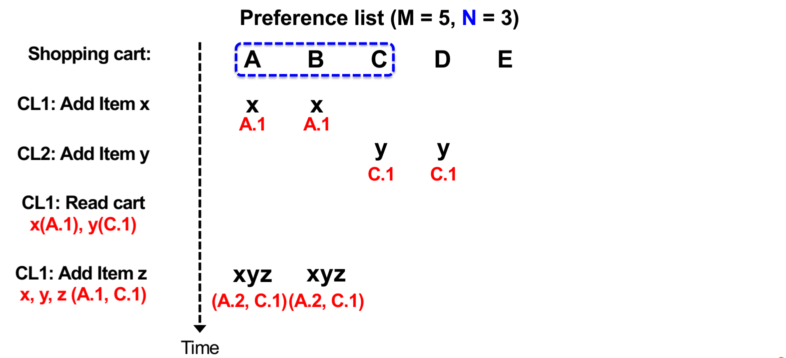
Vector clocks: handling conflicting versions



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Anti-entropy (replica synchronization)

- Each server keeps one Merkle tree per virtual node (a range of keys)
  - A leaf is the hash of a key's value: # of leaves = # keys on the virtual node
  - An internal node is the hash of its children
- Replicas exchange trees from top down, depth by depth
  - If root nodes match, then identical replicas, stop
  - Else, go to next level, compare nodes pair-wise

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Failure detection and ring membership

- Server A considers B has failed if B does not reply to A's message
  - Even if B replies to C
  - A then tries alternative nodes
  - With servers join and permanently leave
- Servers periodically send gossip messages to their neighbors to sync who are in the ring
  - Some servers are chosen as seeds, i.e., common neighbors to all nodes

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Conclusion

- Availability is important
  - Systems need to be scalable and reliable
- Dynamo is eventually consistent
  - Many design decisions trade consistency for availability
- Core techniques
  - Consistent hashing: data partitioning
  - Preference list, sloppy quorum, hinted handoff: handling transient failures
  - Vector clocks: conflict resolution
  - Anti-entropy: synchronize replicas
  - Gossip: synchronize ring membership