Case Study 3: Scalable Caching with Memcache

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Slides are modified from the original talks by
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Case study on scaling storage

- Facebook's experience with using in-memory caches to scale storage
- The practical problems that were encountered
- How they were solved
- Tradeoffs between performance and consistency

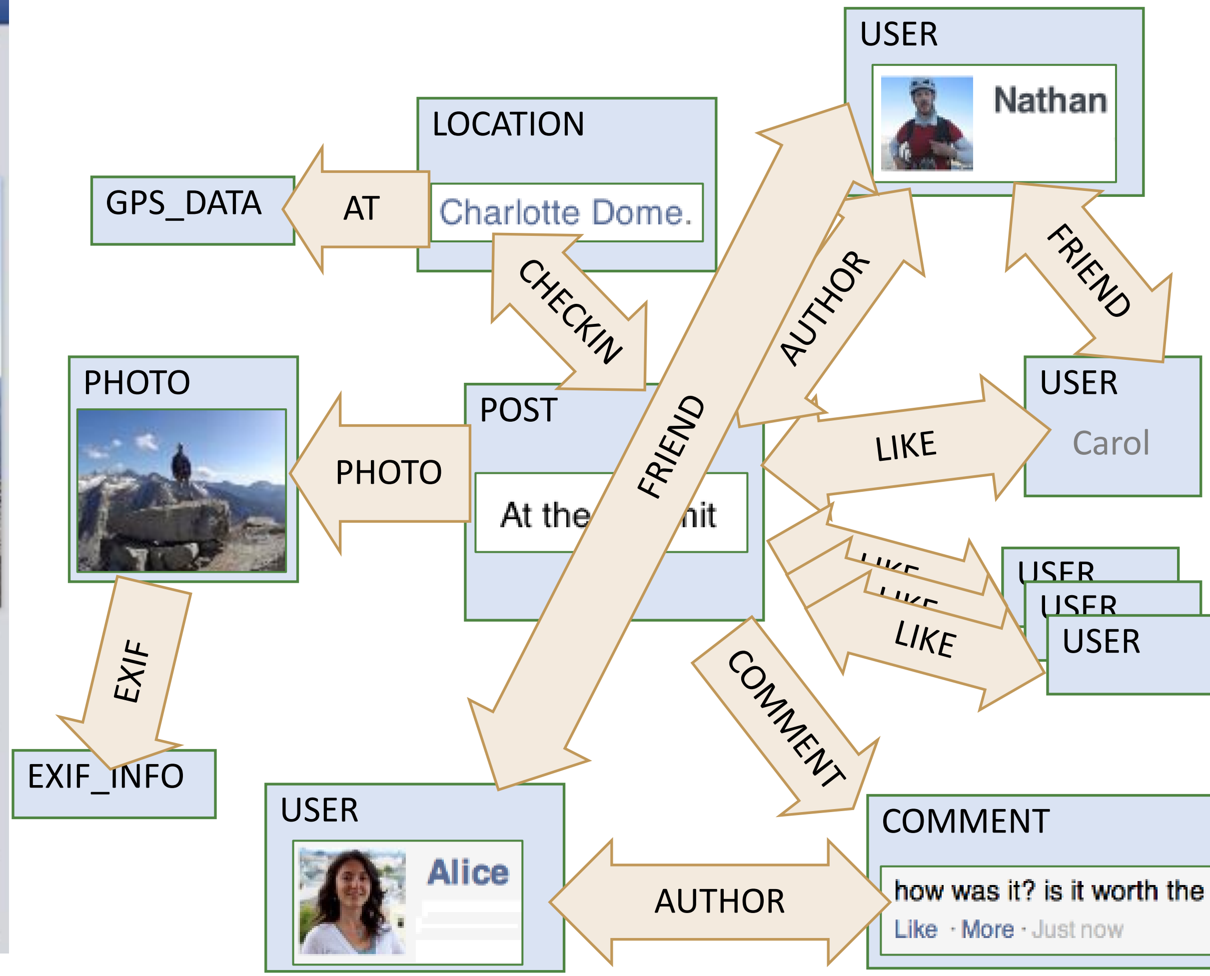
Overview

- Introduction to Facebook storage infrastructure
- One Memcache server
- Memcache servers in a cluster
- Memcache servers in multiple clusters within a region
- Geographically distributed clusters in multiple regions

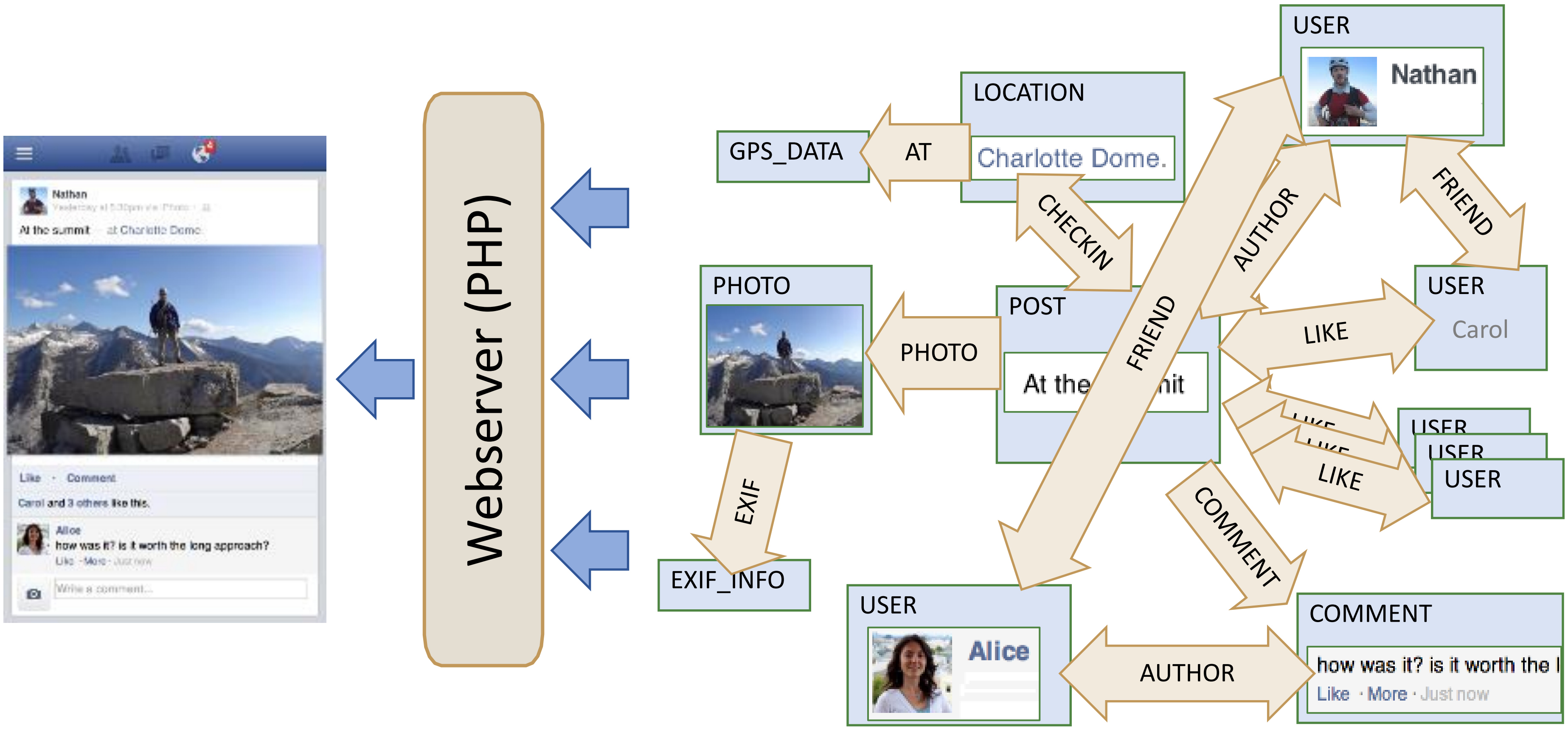
Requirements at Facebook

- Scale to process millions of user requests per second
  - Support heavy read load (over 1 billion reads/sec)
  - Near real-time communication, so tight latency requirements
  - Be able to access and update popular shared content, so hot spots
  - Poor locality for storage accesses
- Scale to petabytes of storage
- Geographically distributed users, multiple data centers

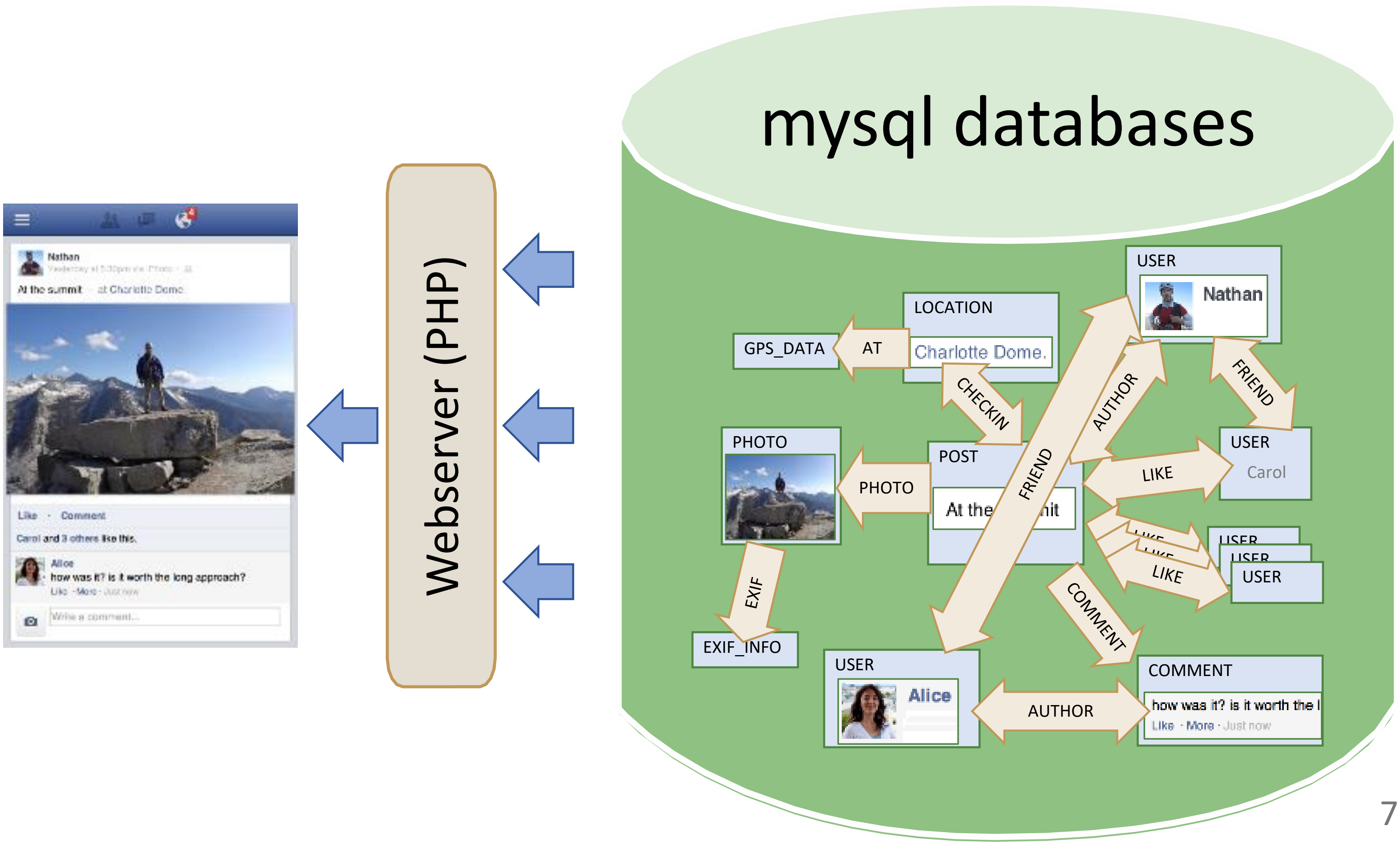
Facebook's social graph



Rendering the social graph

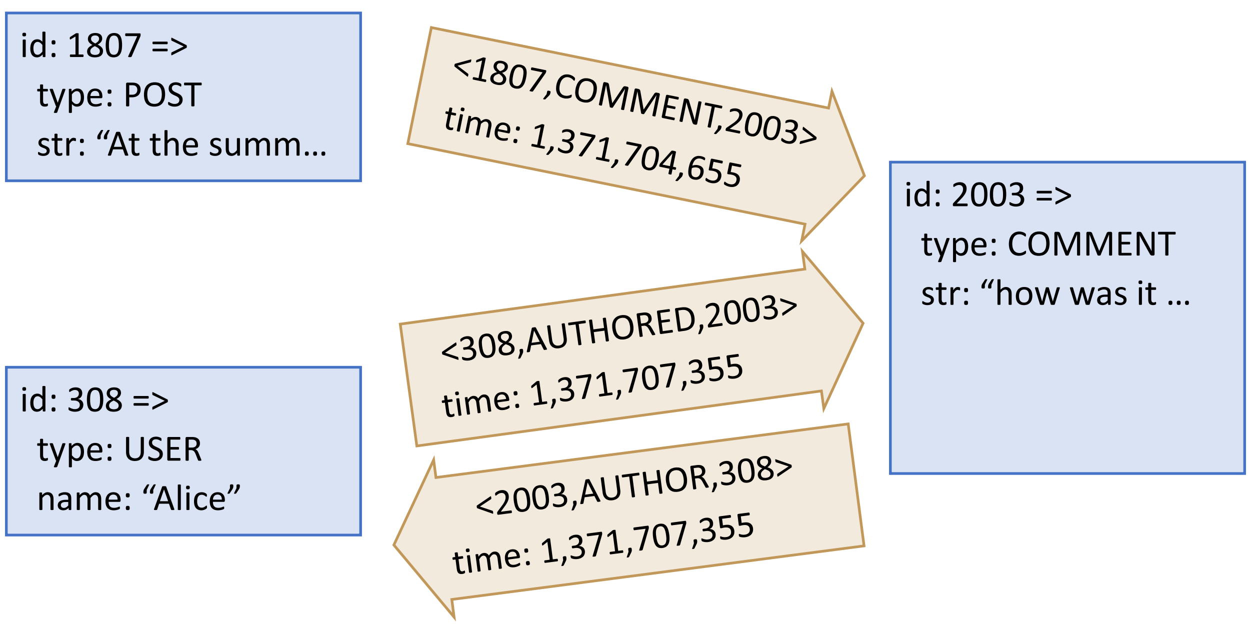


Storing the social graph



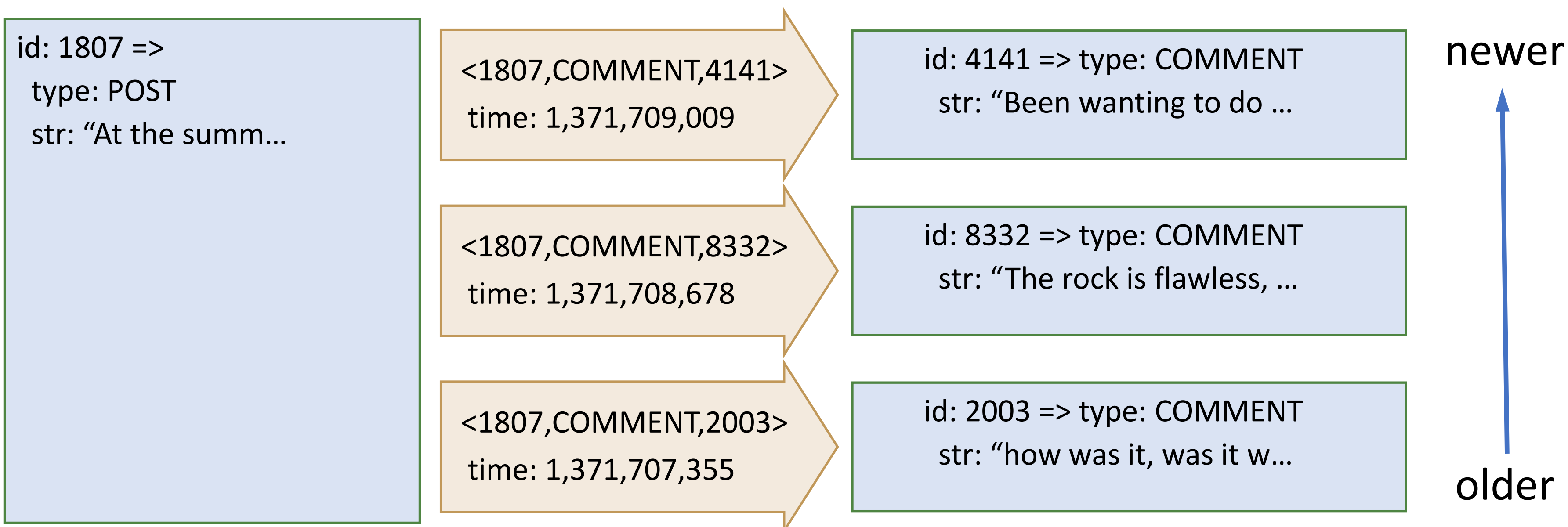
Objects and associations

- Objects, associations stored in separate database tables
  - Objects identified by unique 64-bit IDs
    - Each object has type field and other data fields
  - Associations identified by <id1, type, id2>
    - Associations have a time field and other data fields



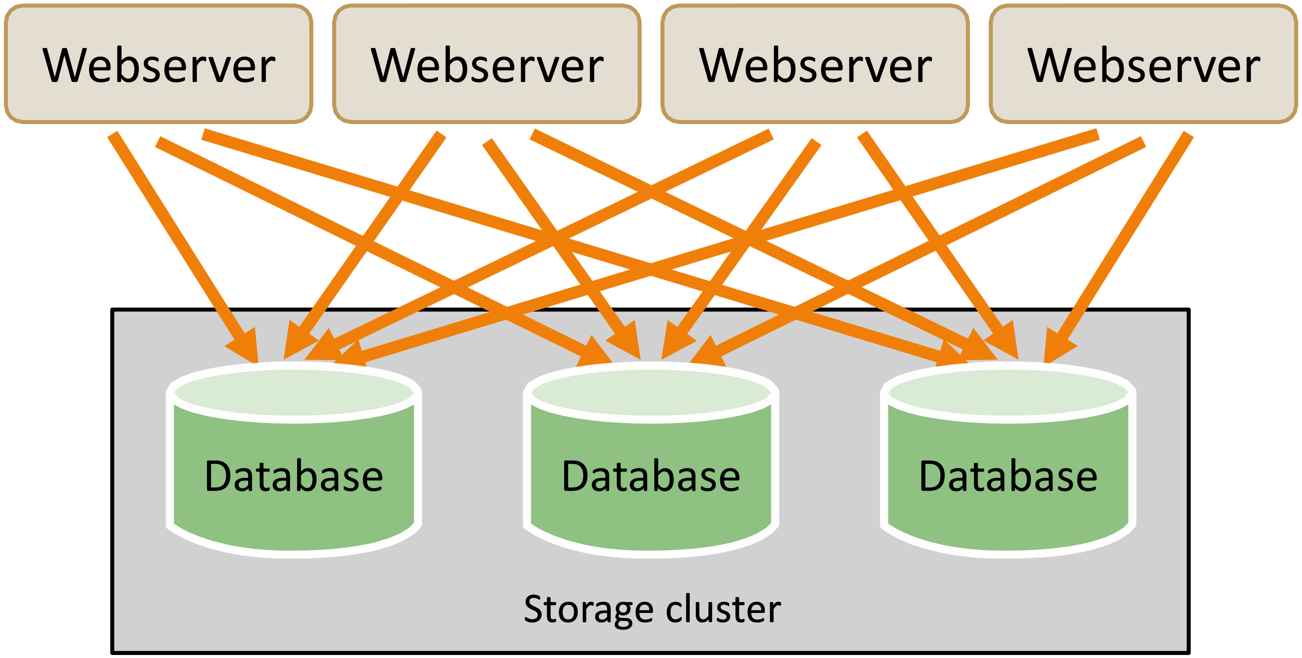
Association lists

- Association queries often require returning a list of associations:
  - assoc_get(1807, COMMENT)
    returns <1807, COMMENT, *>, ordered by time



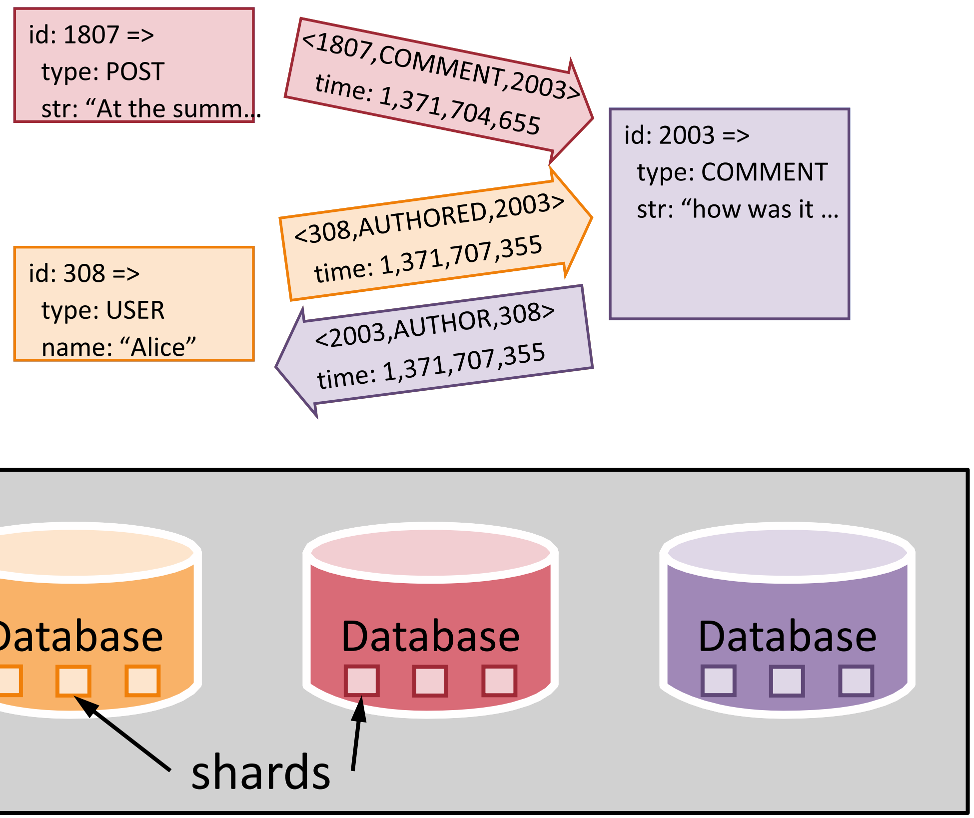
Early days (pre-caching)

- Just a few databases were enough to support the load



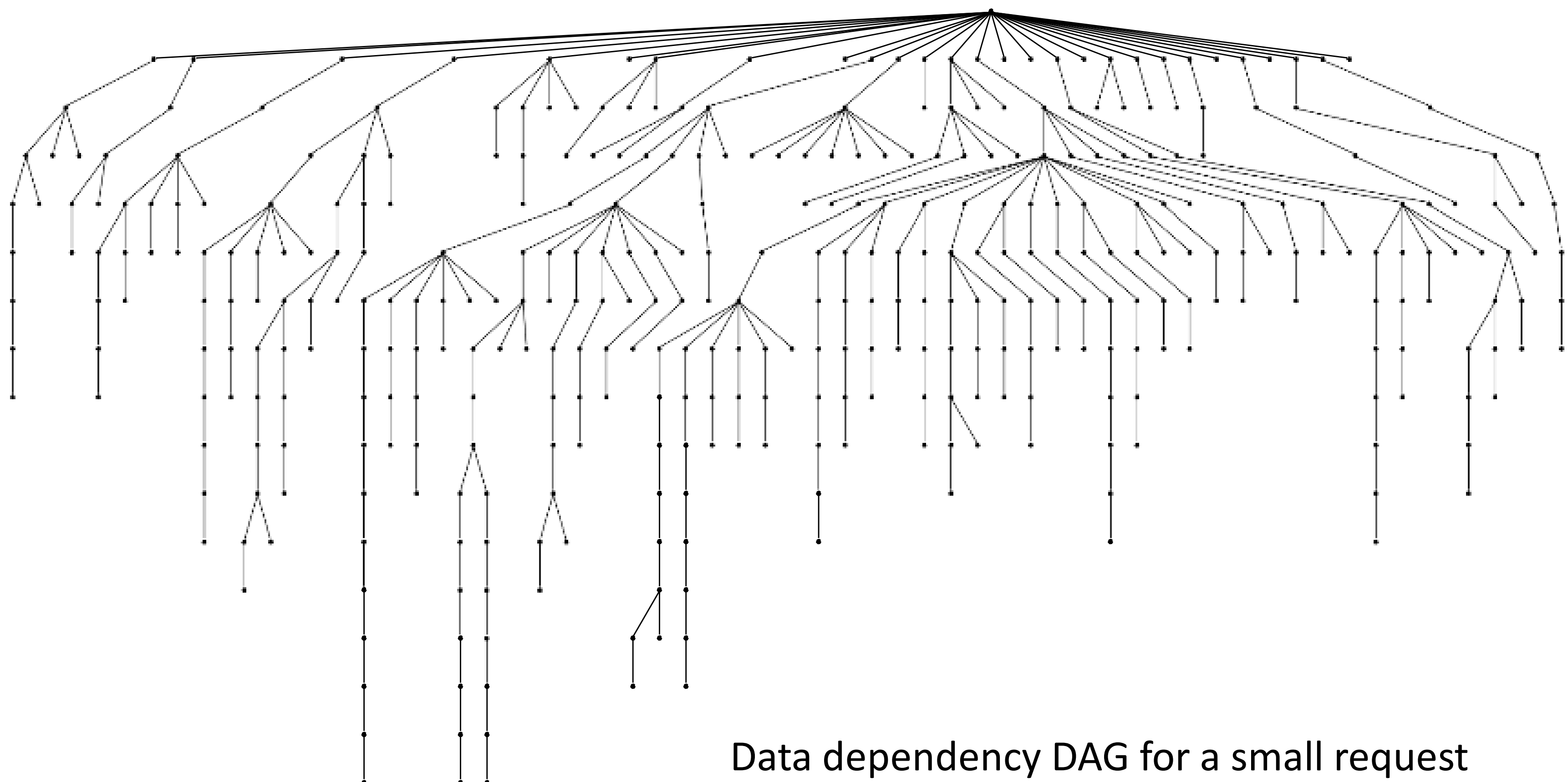
Sharding data across databases

- Data sharded by object id randomly across databases
  - Object and its outgoing associations stored in same shard
  - Association queries for an object served from one shard



Problem

- High fanout and multiple rounds of data fetching
  - Each node issues a database request, poor locality



Data dependency DAG for a small request

Scaling Memcache in 4 "easy" steps

0	No Memcache servers (pre-memcache)
1	One Memcache server
2	Memcache servers in a cluster
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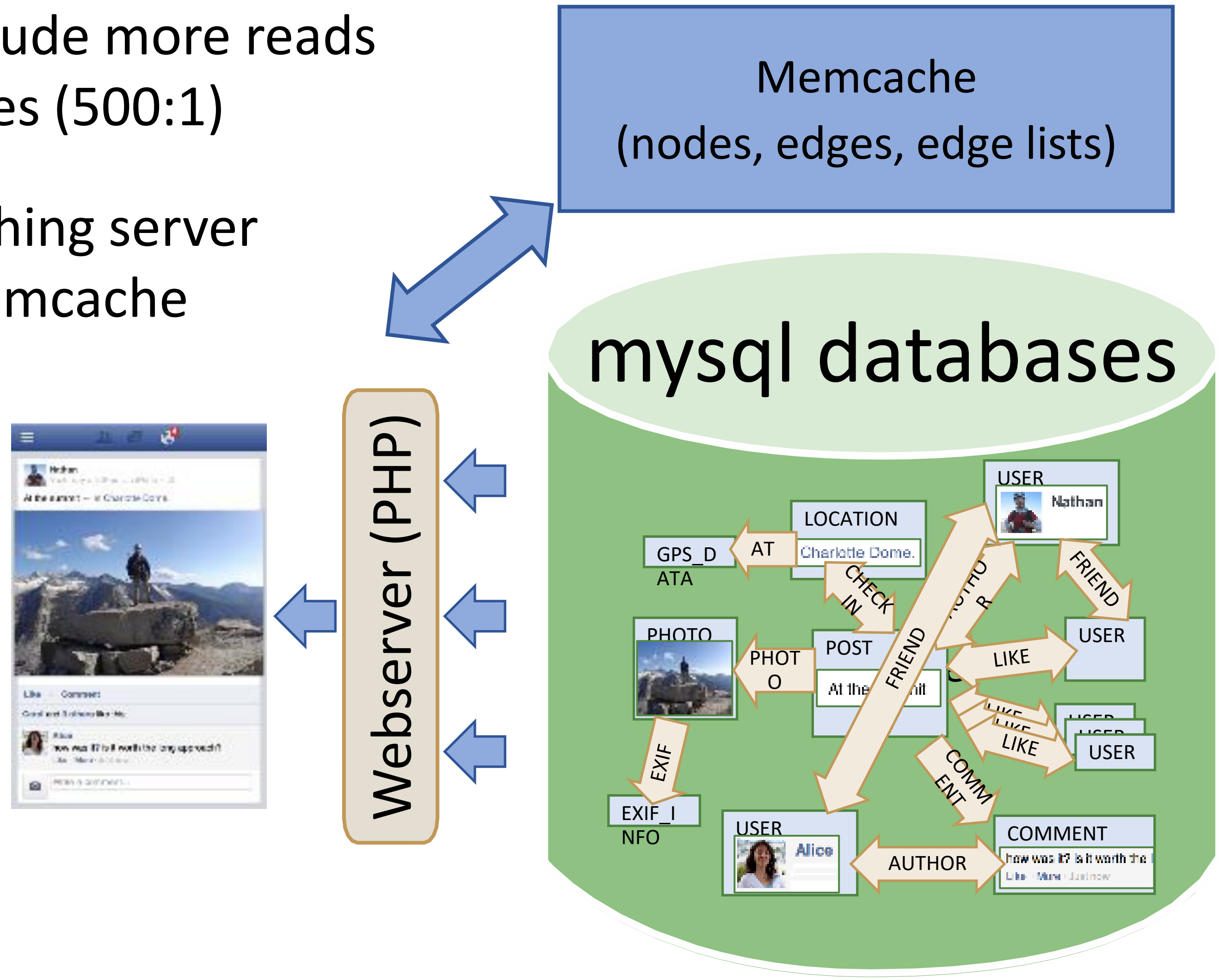
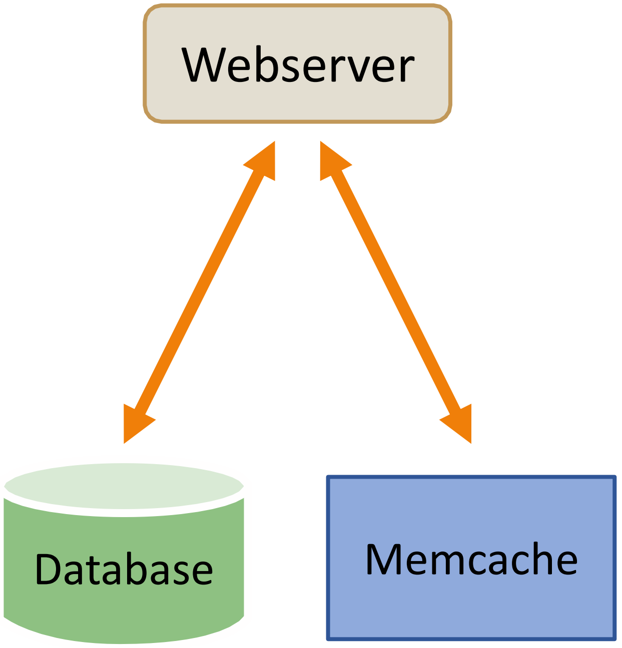
Cache social graph in Memcache

- Facebook has two orders of magnitude more reads than writes (500:1)
- Use a caching server called Memcache



Caching helps read performance

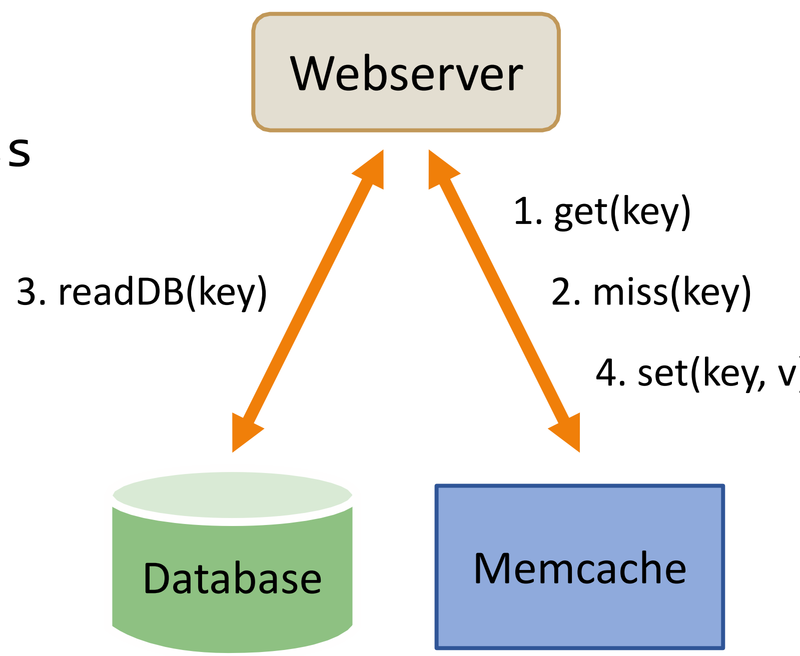
- Memache is a single-node, key-value store that uses a hash table to store key and values
  - Store nodes as keys
  - Stores edge lists as values
- Webserver (client) reads from Memcache
- Reduces load on database



Reading data from Memcache

- Use Memcache as a look-aside cache
  - Avoids any changes to Memcache

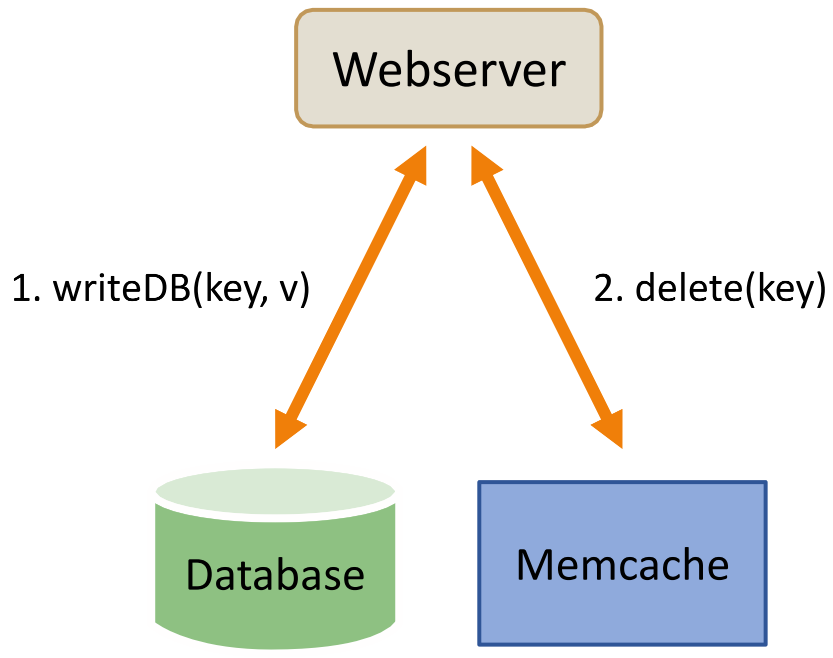
```
read(key)
  v = get(key)
  if (v == NULL) // read miss
    v = readDB(key)
    set(key, v)
```



Handling updates

- On a database update,
  Memcache needs to be synchronized

```
   write(key, v)
1:   writeDB(key, v)
2:   delete(key)
```



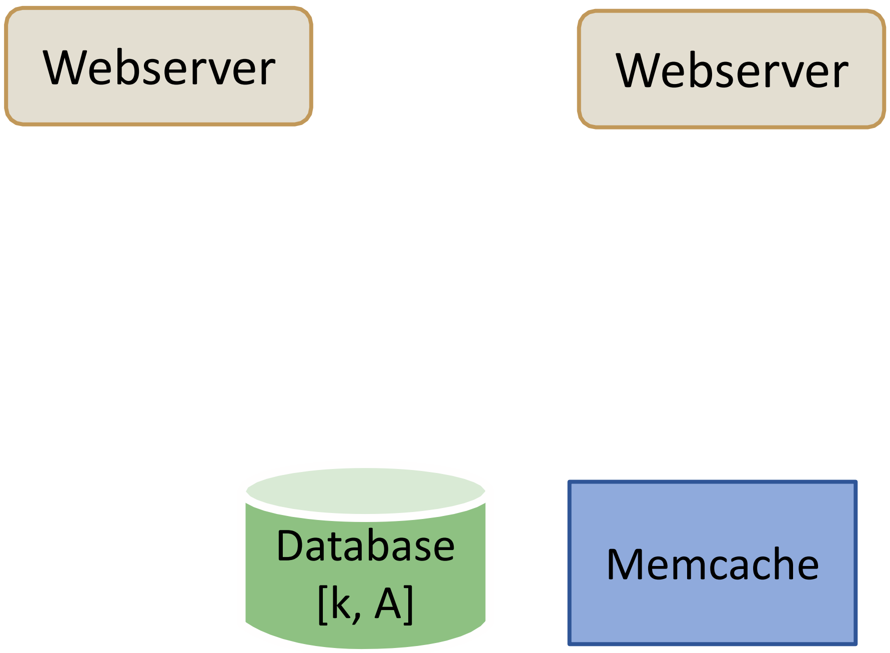
- Webserver uses
  delete (cache invalidation)
  instead of set (cache update)
  - Why is this important?
  - What if another Webserver issues read() between 1 and 2?

Understanding caching strategy

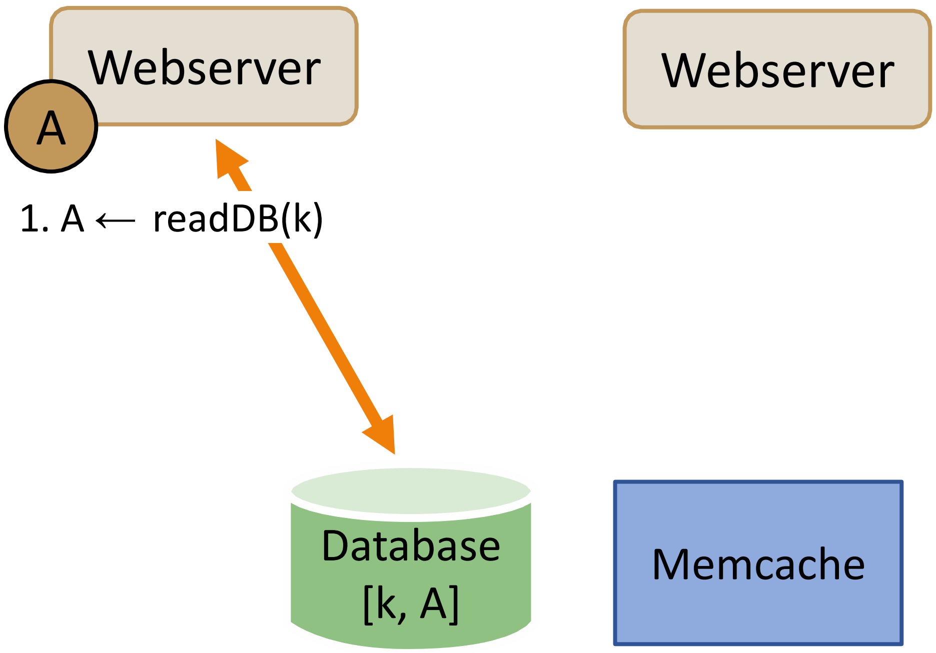
- Will caching increase write performance?
  - No, writes need to be sent to database (and deletes to Memcache)
- Why not use a write-back cache?
  - May cause inconsistency with multiple caches (discussed later)
- Will caching increase read performance?
  - Yes, and reads are dominant in the workload
- Any other benefits?
  - Helps reduce load on the database

Stale set consistency problem

- Concurrent reads and updates to database can cause inconsistency between database and Memcache



Stale set consistency problem



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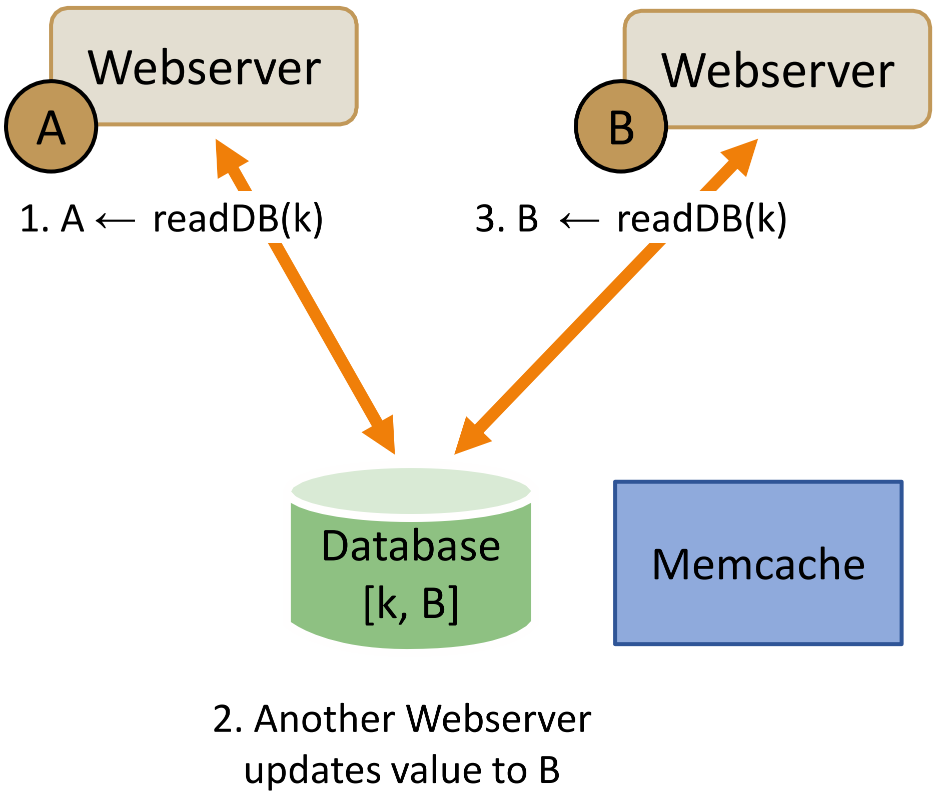

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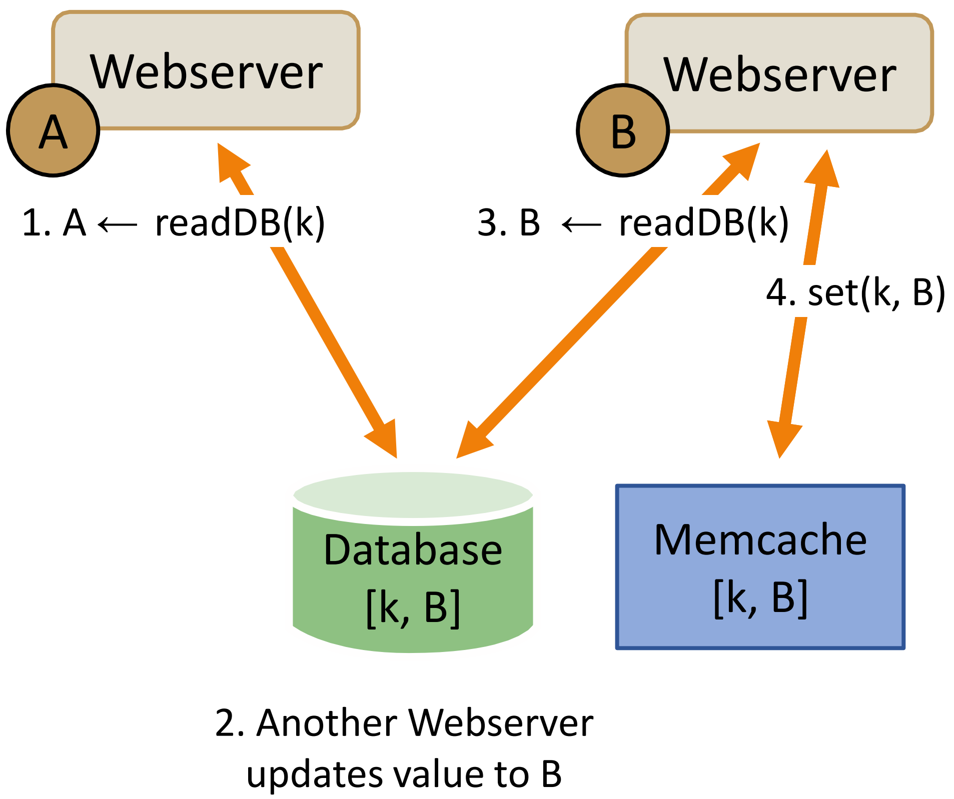

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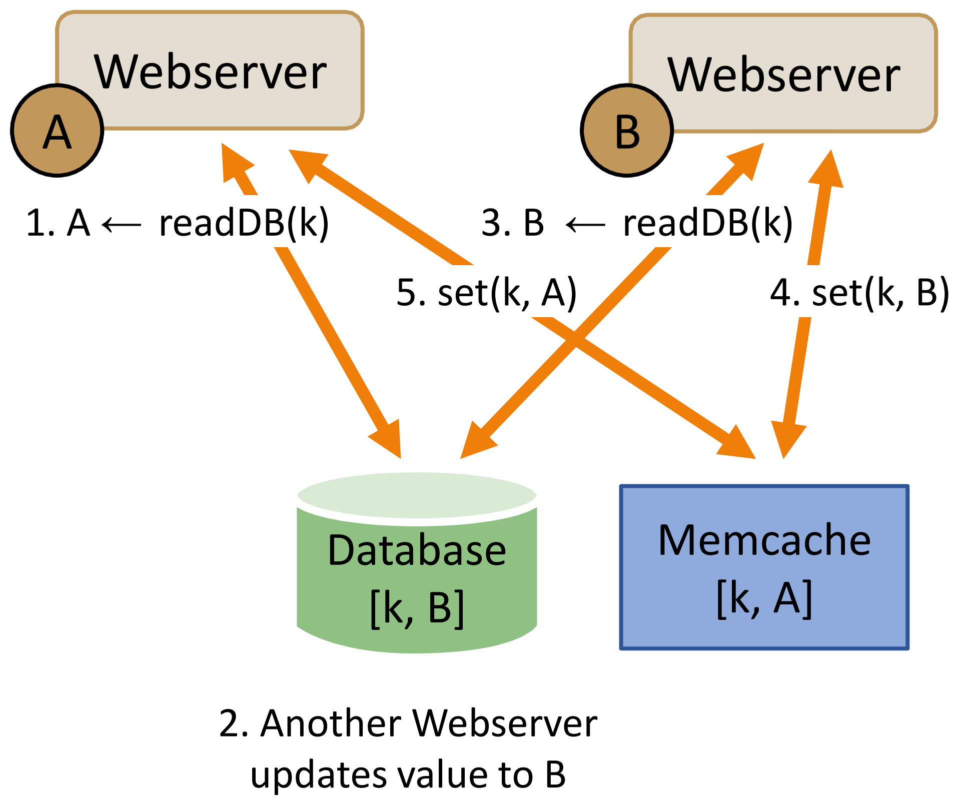
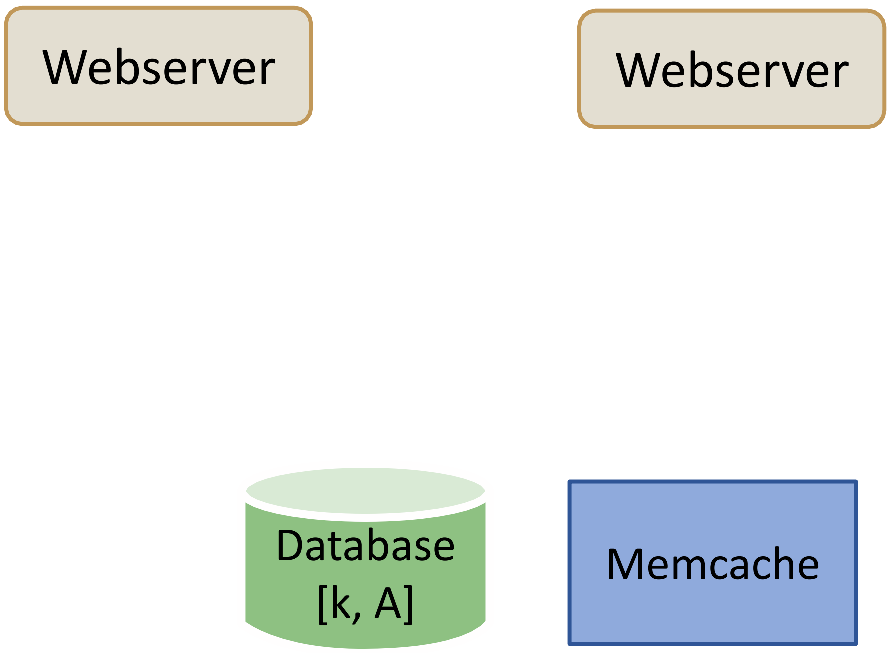


Memcache and database are inconsistent

Why does this problem occur?

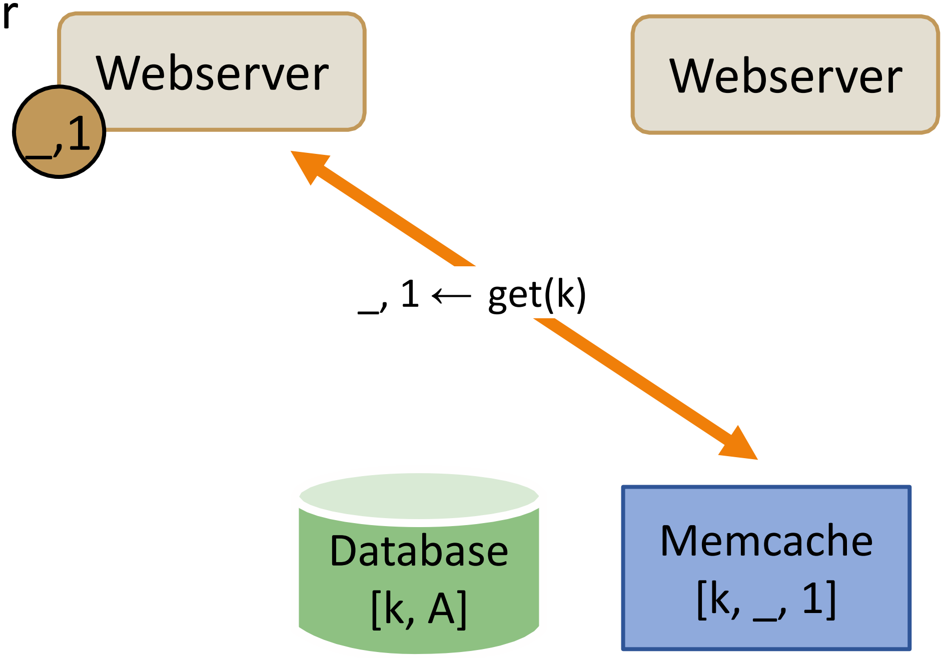
Avoiding stale set problem

- Extend Memcache protocol with “leases”



Avoiding stale set problem

- Extend Memcache protocol with “leases”
  - Step 1: On read-miss, Memcache returns new lease-id to Webserver



Avoiding stale set problem

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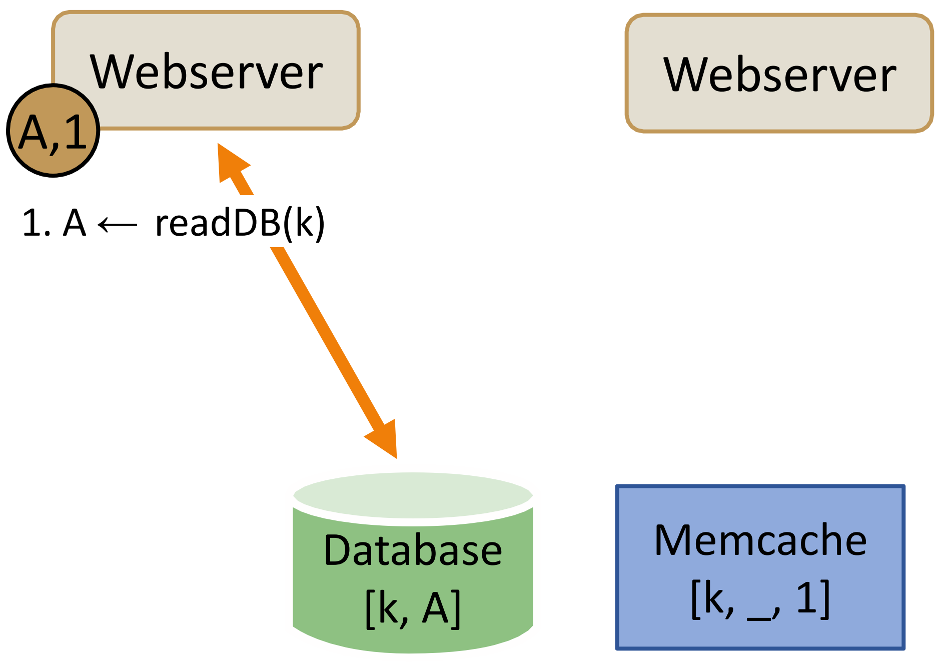

Avoiding stale set problem

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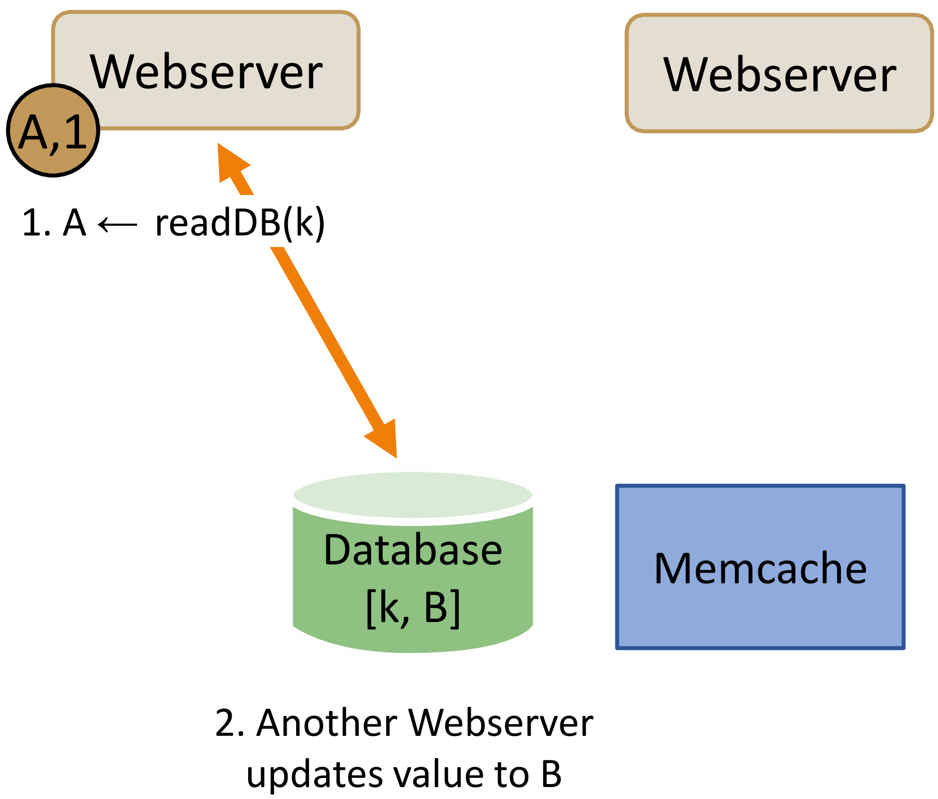
  - Step 2: On update, Memcache invalidates lease-id



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  - Step 1: On read-miss, Memcache returns new lease-id to Webserver, Webserver reads data
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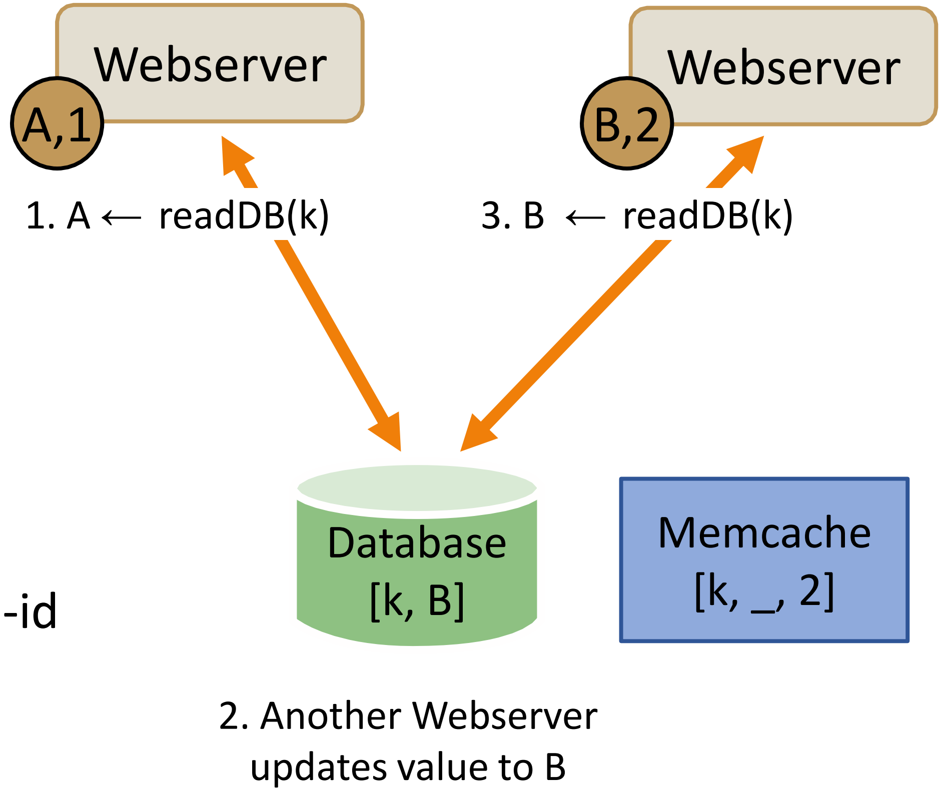
  - Step 3: same as Step 1
  - Steps 4, 5: On set, Memcache checks Webserver provided lease-id



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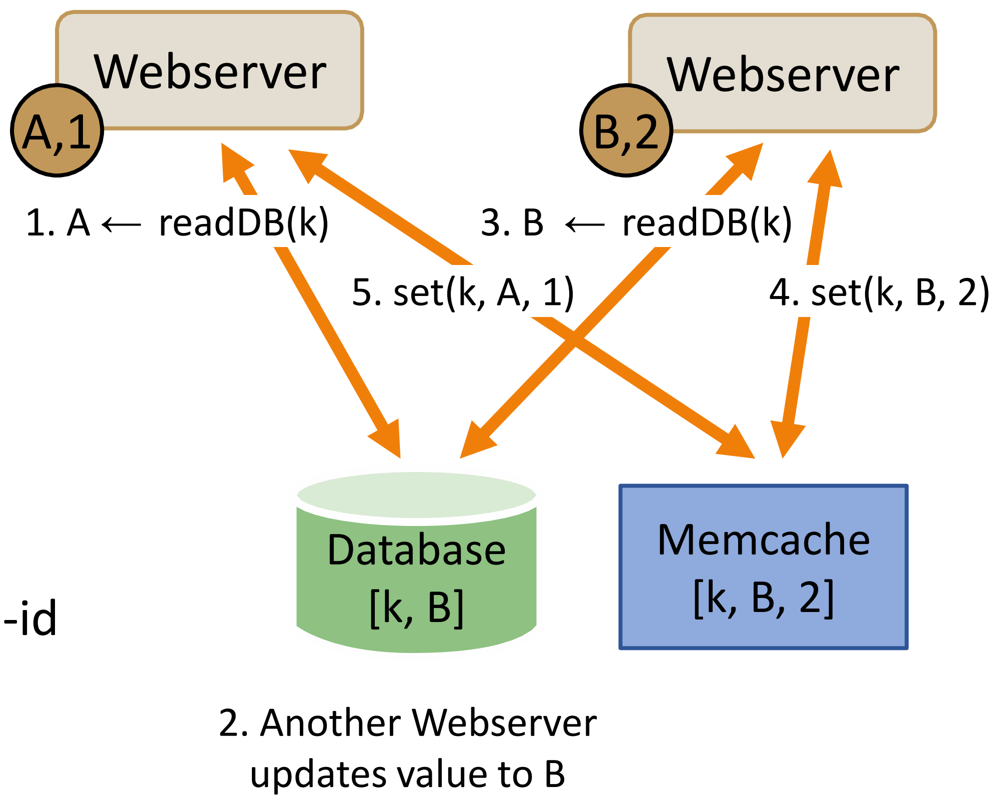
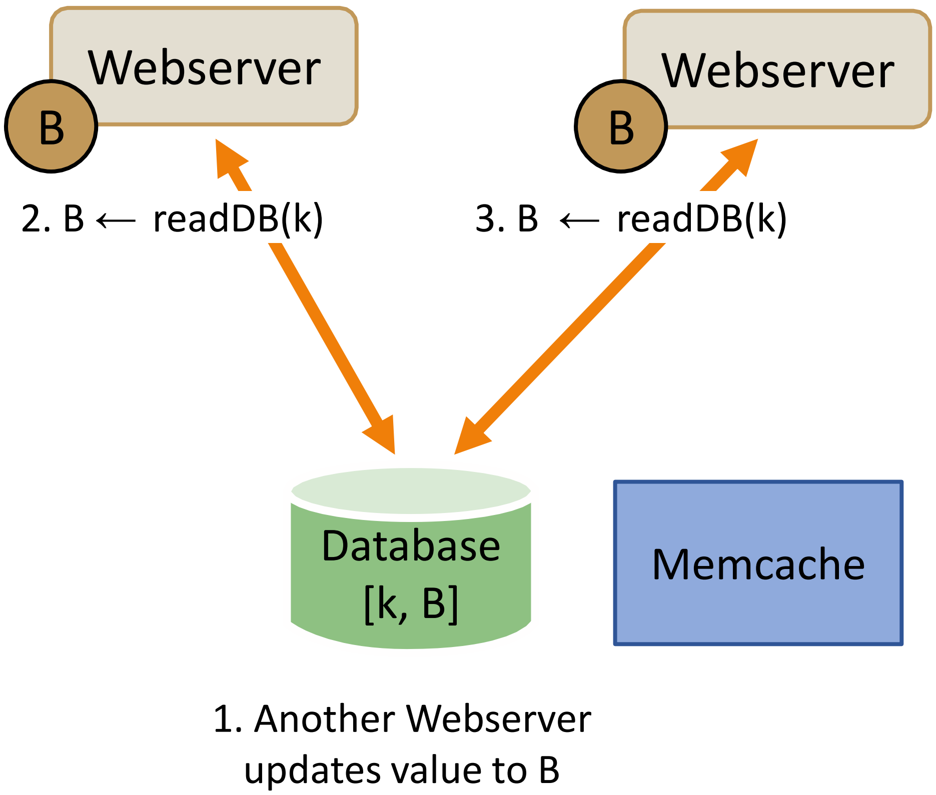
  - Steps 4, 5: On set, Memcache checks Webserver provided lease-id
    - Step 4 allowed
    - Step 5 disallowed



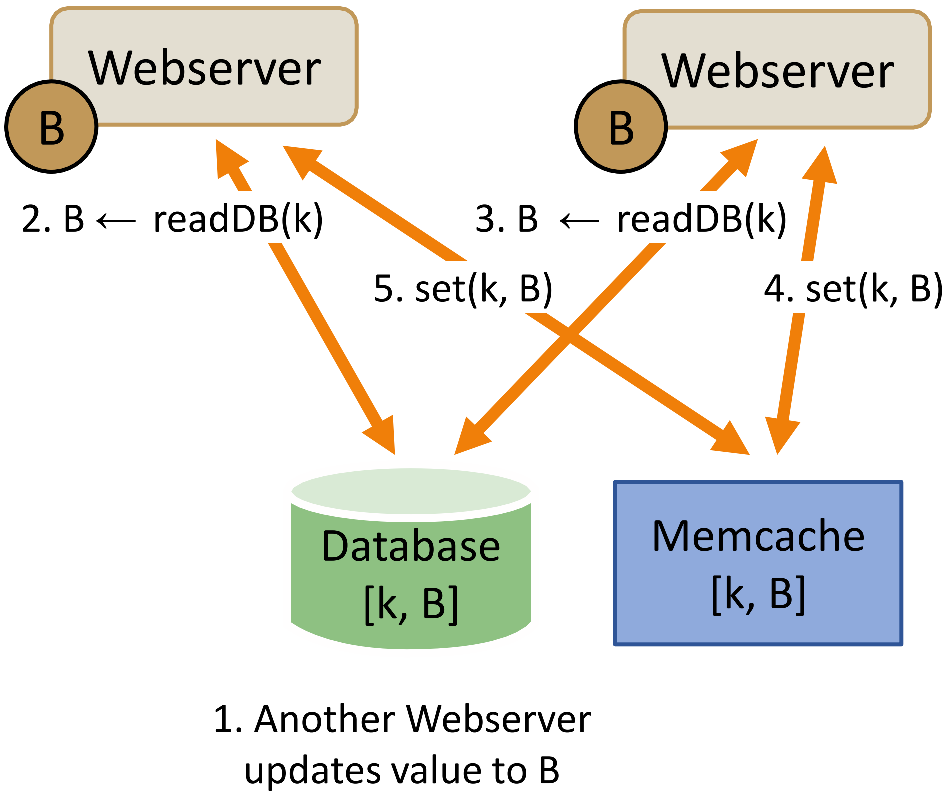
Thundering herd problem

- Say a key is read heavily
- Step 1: key is updated
- Steps 2, 3: all reads will cause read-misses, database accesses



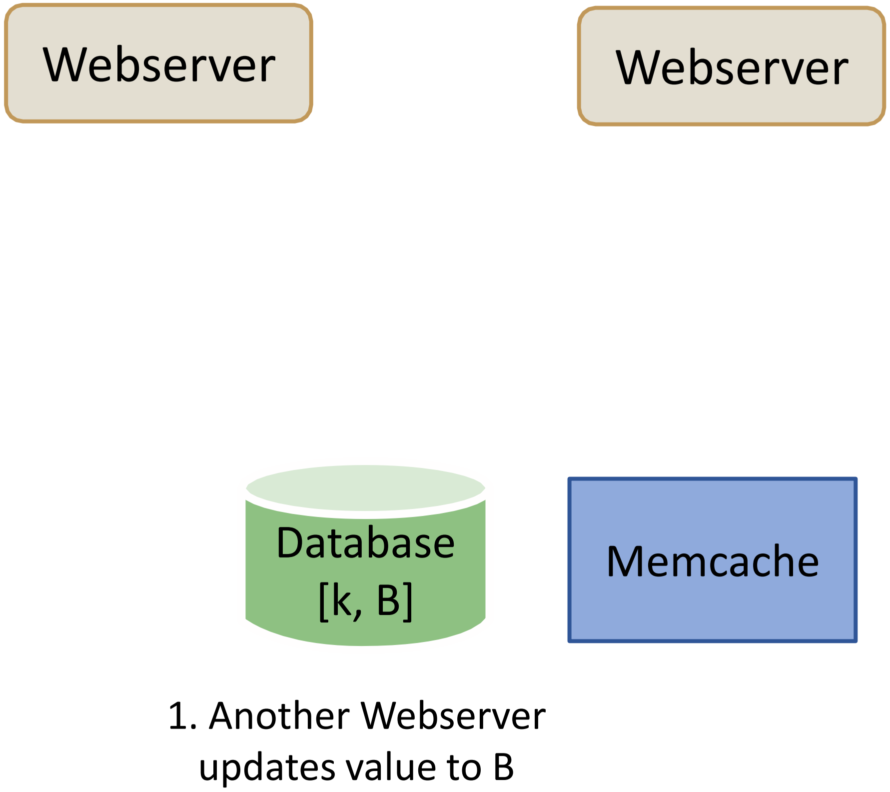
Thundering herd problem

- Say a key is read heavily
- Step 1: key is updated
- Steps 2, 3: all reads will cause read-misses, database accesses
- Steps 4, 5: until key is cached again



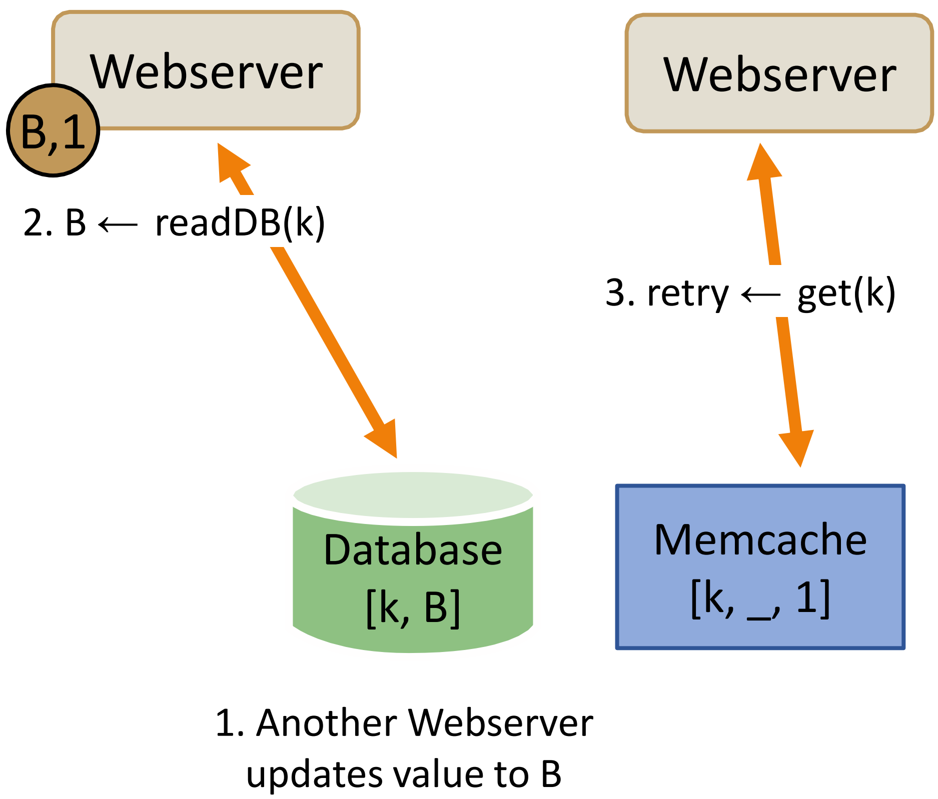
Avoiding thundering herd

- Limit rate at which leases are returned on read miss



Avoiding thundering herd

- Limit rate at which leases are returned on read miss
  - Step 2: On read-miss, Memcache returns new lease-id to Webserver, Webserver reads data
  - Step 3: On next get, within 10 seconds, don't return lease, instead return notification to retry in a few milliseconds



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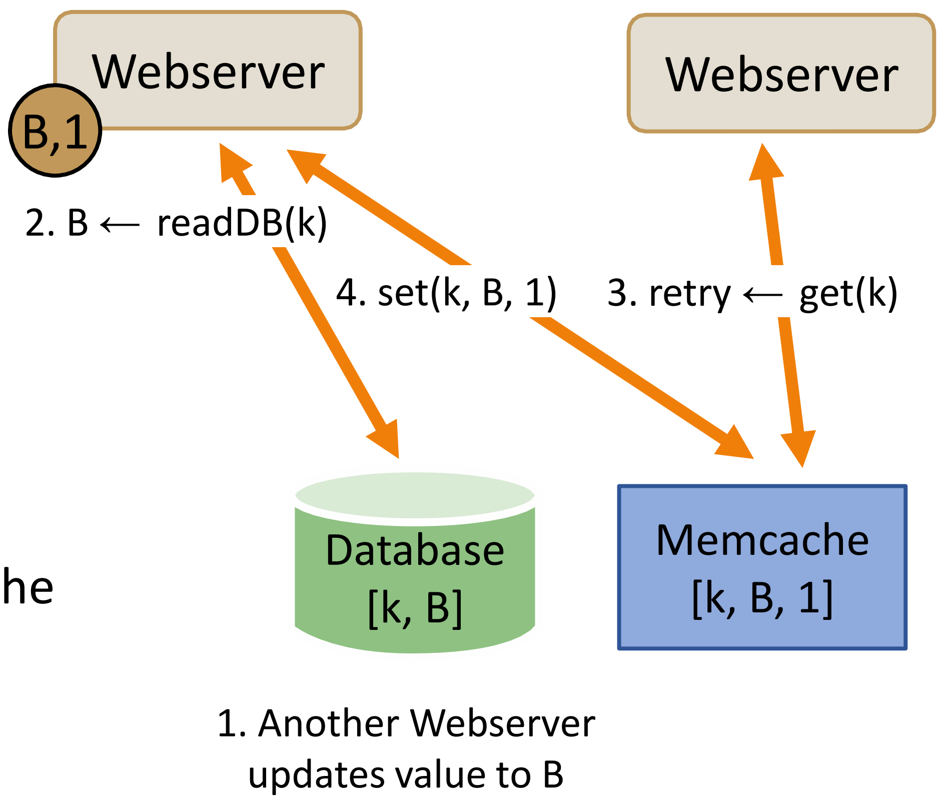

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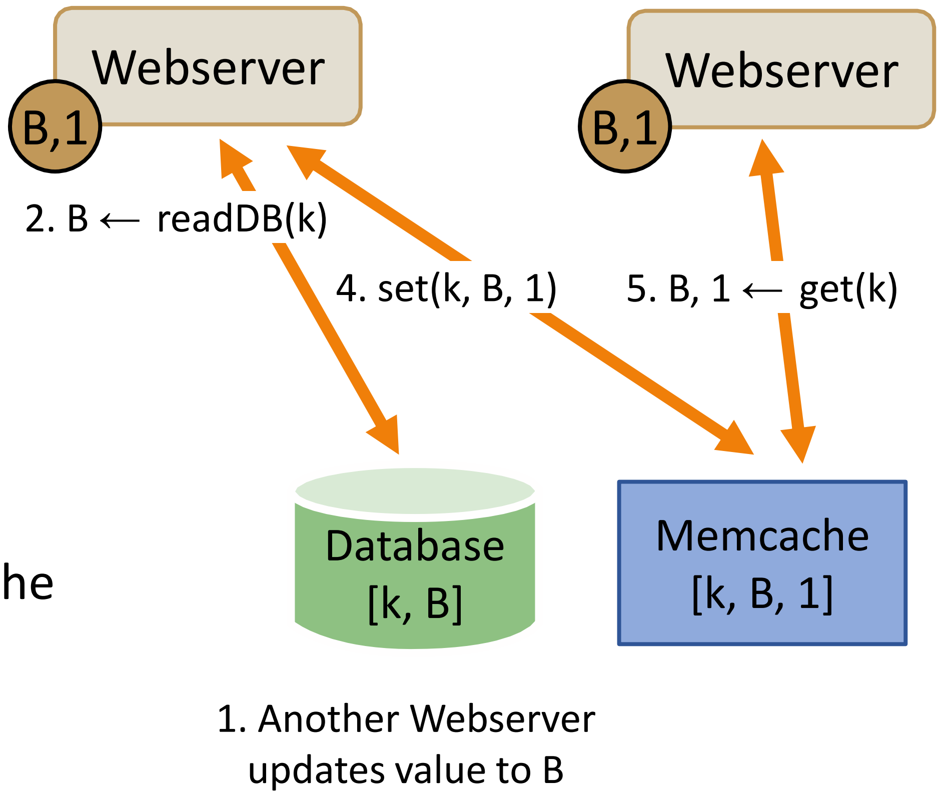
  - Step 4: On set, update cache
  - Step 5: On get again, return cached value

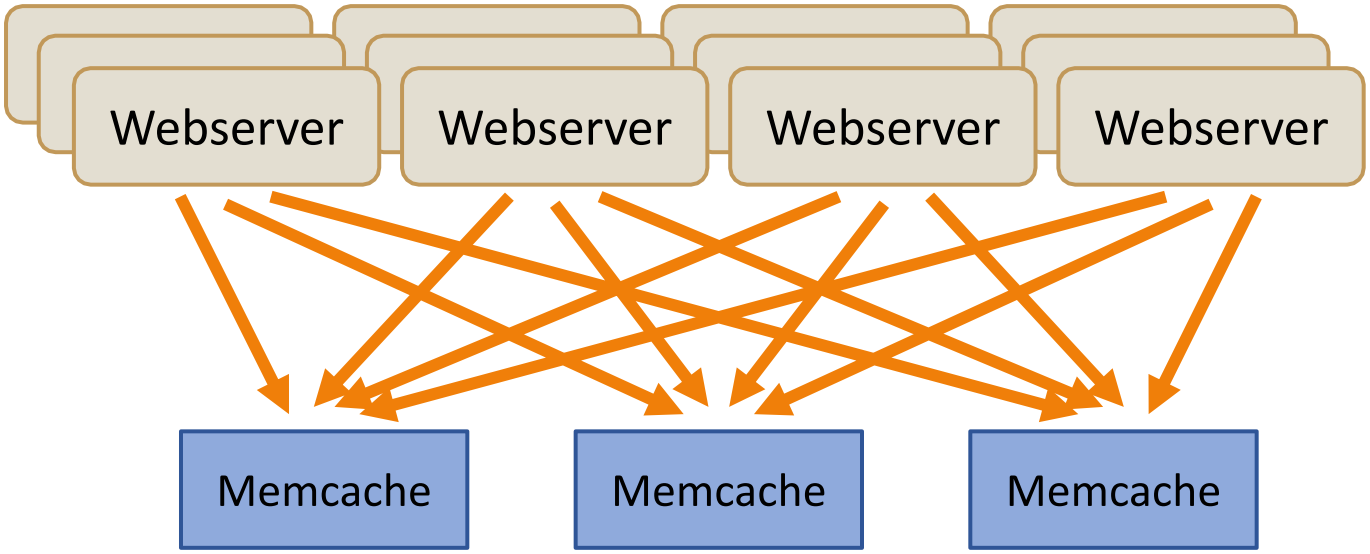


Scaling Memcache in 4 “easy” steps

0	No Memcache servers (pre-memcache)
1	One Memcache server
2	Memcache servers in a cluster
3	Memcache servers in multiple clusters within a region
4	Geographically distributed clusters in multiple regions

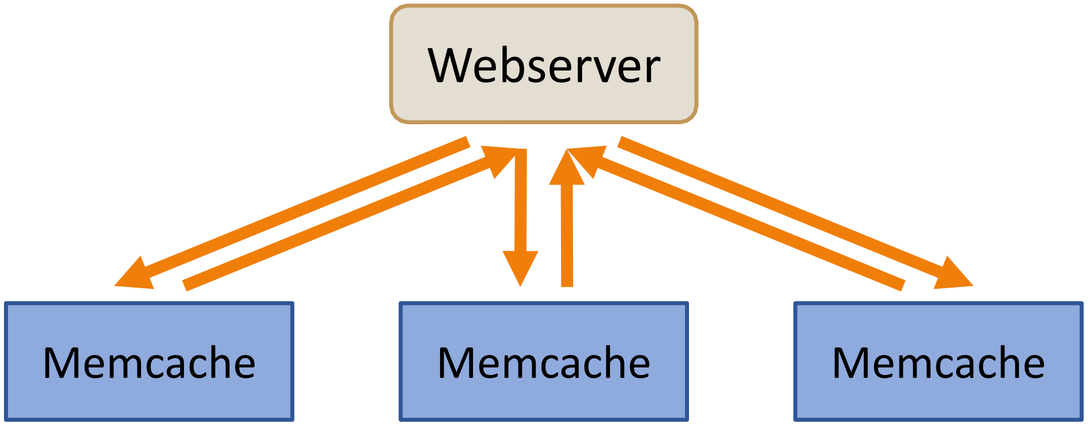
Need even more read capacity

- Use multiple Memcache servers
  - Items are sharded across Memcache servers using consistent hashing on the key, so any Webserver can find a cached key
- All Webservers talk to all Memcache servers



Problem: incast congestion

- For a user request, a Webserver may fetch 500+ keys from 100s of Memcache servers in parallel
  - Many simultaneous responses from Memcache servers may overwhelm networking resources, cause responses to be dropped
- Solution: Limit the number of outstanding requests by Webserver to Memcache with a sliding window (e.g., TCP)
  - Larger windows result in more congestion, smaller windows result in more network round trips



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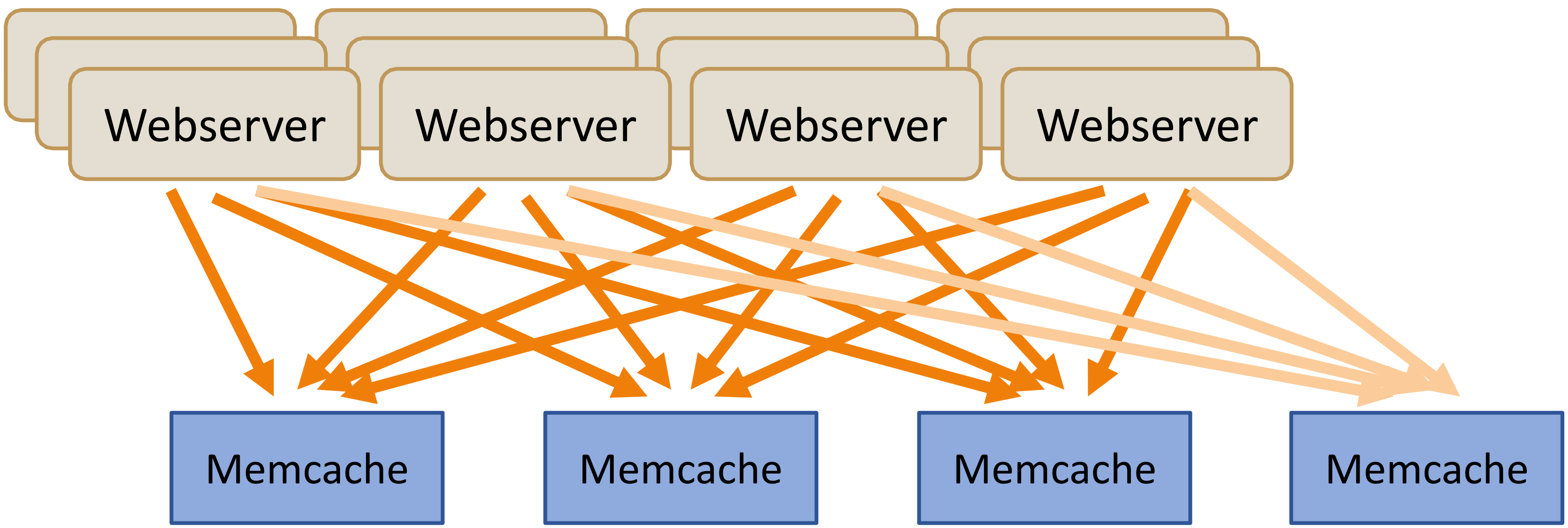
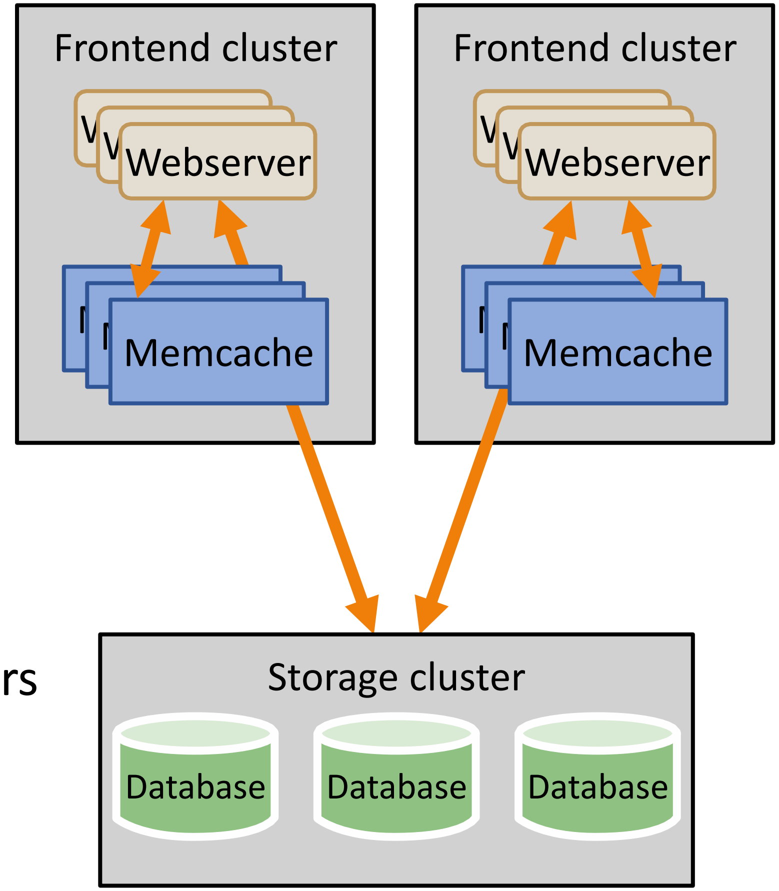
Scaling problem

- All-to-all communication between Webservers and Memcache servers limits horizontal scaling
- Communication ↑ with more Webservers, Memcaches
- Some Memcaches become hotspots, slowing all requests



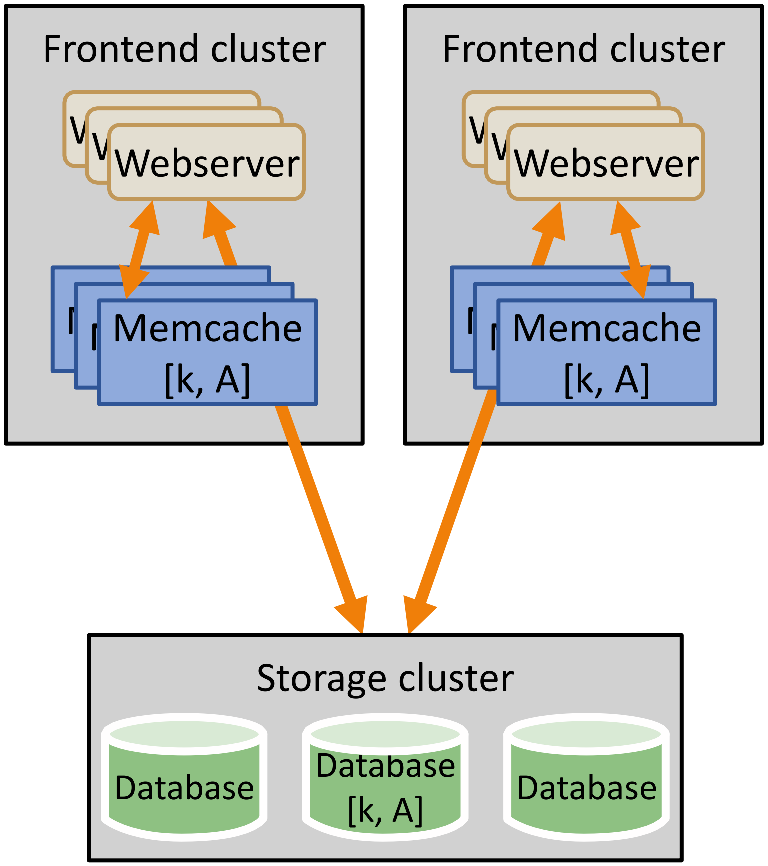
Solution: use multiple clusters

- Each cluster caches data in its own Memcache servers
  - A Webserver only accesses the Memcache servers in its cluster
  - All the clusters are backed by a single storage cluster
- Pros:
  - Helps limit # of servers per cluster
  - Hot keys get cached in multiple clusters
- Cons:
  - Fewer unique keys can be cached across all clusters



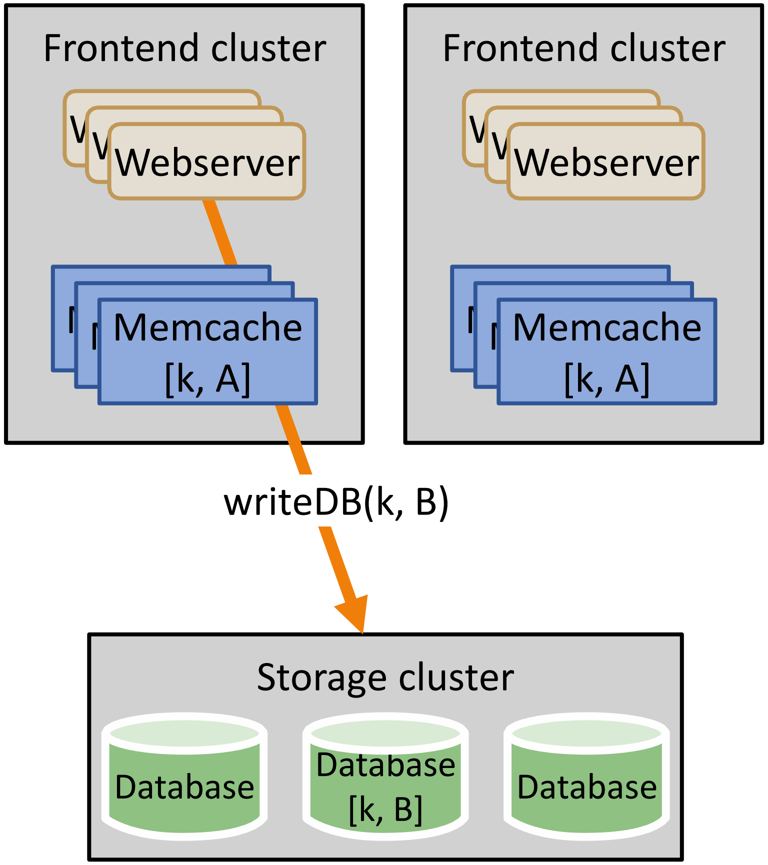
Cache consistency problem

- Same data may be cached in the Memcache servers in different clusters
- Need to keep caches consistent when data is updated



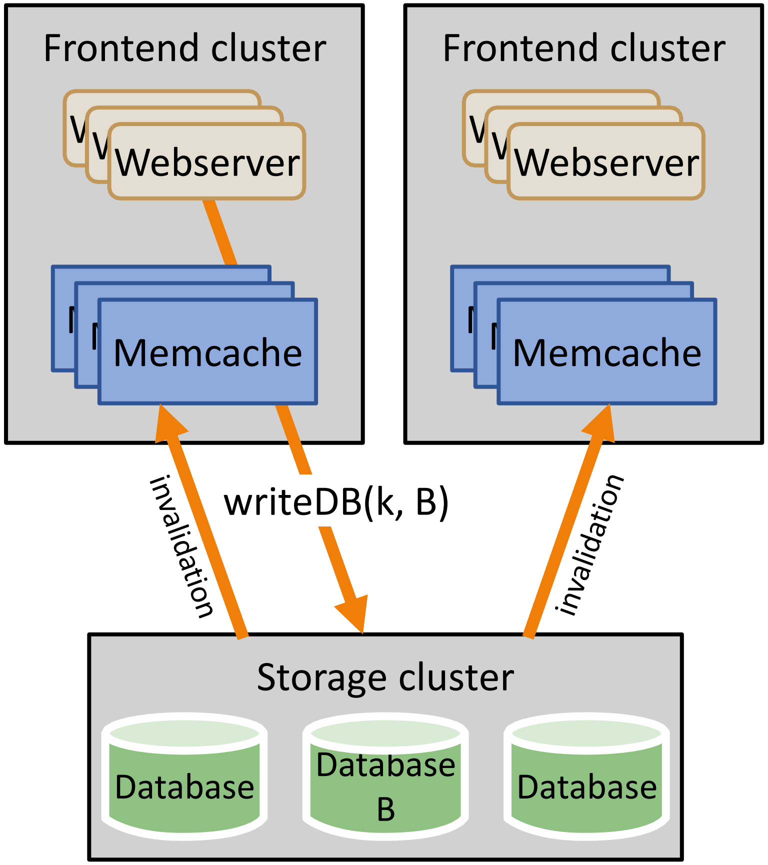
Solution: use invalidations

- When Webserver updates key in database



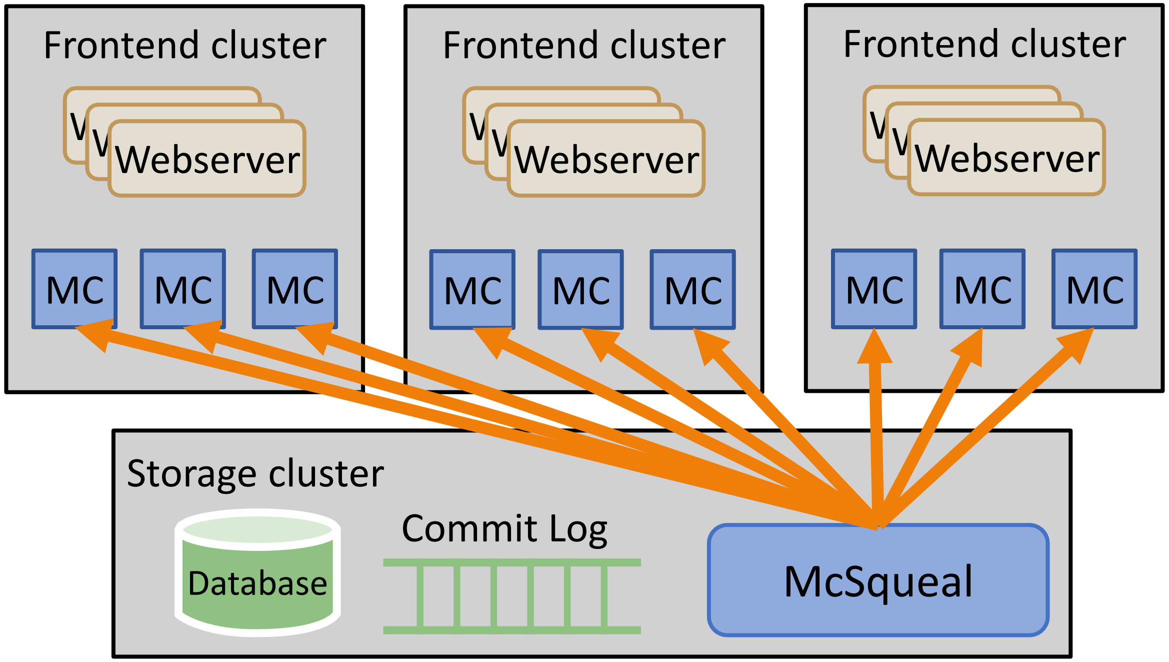
Solution: use invalidations

- When Webserver updates key in database
  - Storage cluster invalidates key in the Memcache servers in all clusters
- What if invalidations are lost?



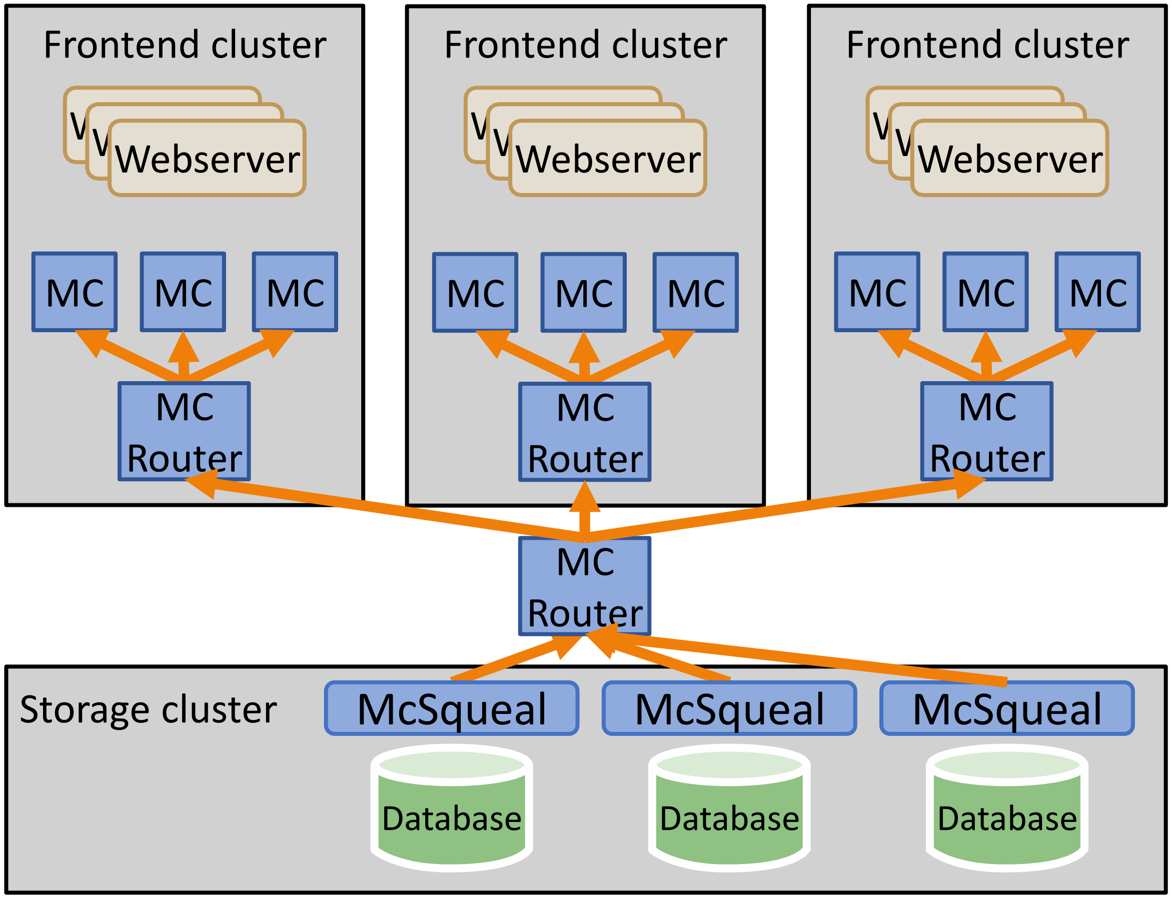
Reliable invalidations

- Storage cluster logs invalidations for updates, before sending them to all Memcache servers
- If frontend cluster fails, invalidation daemons (McSqueal) resend invalidations from log to resynchronize caches



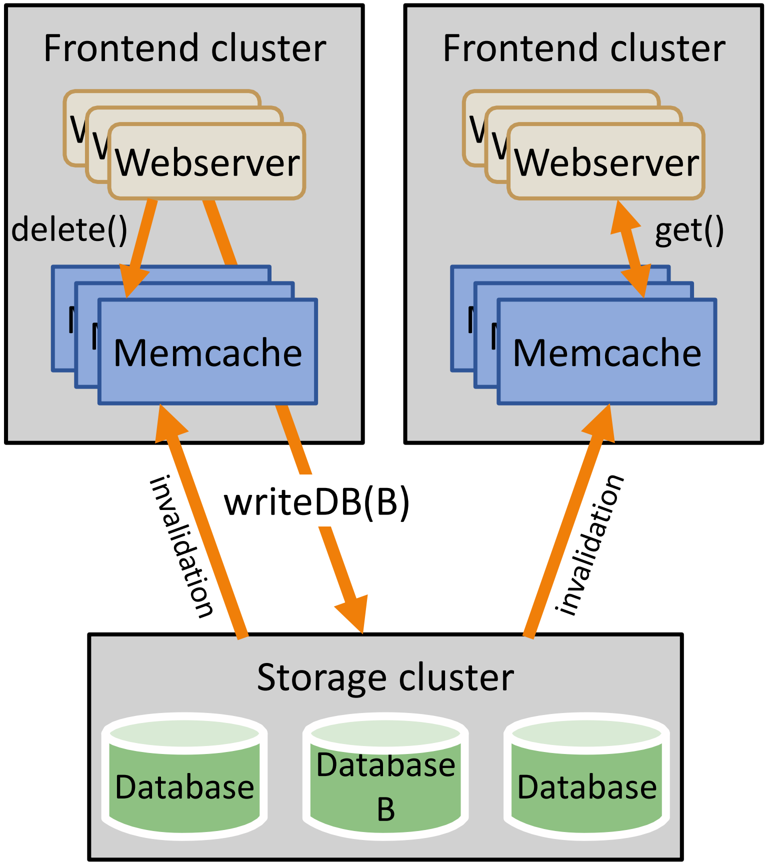
Scalable invalidations

- Invalidations are batched and routed hierarchically to reduce network bandwidth



Cache consistency and performance

- Webserver updates key in database directly
  - Database performs updates in a total order, so no conflicts, then sends invalidations
  - For read-your-write consistency, Webserver deletes key in the Memcache server of the local cluster as well
- For performance, updates do not wait for invalidations to complete
  - So get() at other clusters may return stale cached value for a short time



Why this consistency model?

- Writes are ordered and slow but not lost
  - E.g., “like” count is correct
- Caches are eventually consistent
  - Leases and reliable invalidates ensure that caches do not serve stale data forever
- Reads are fast but may return stale data
  - This is facebook!, data is news feed, likes, etc.
  - Most people will not notice or care about slightly stale data
  - Next refresh will fetch up-to-date data

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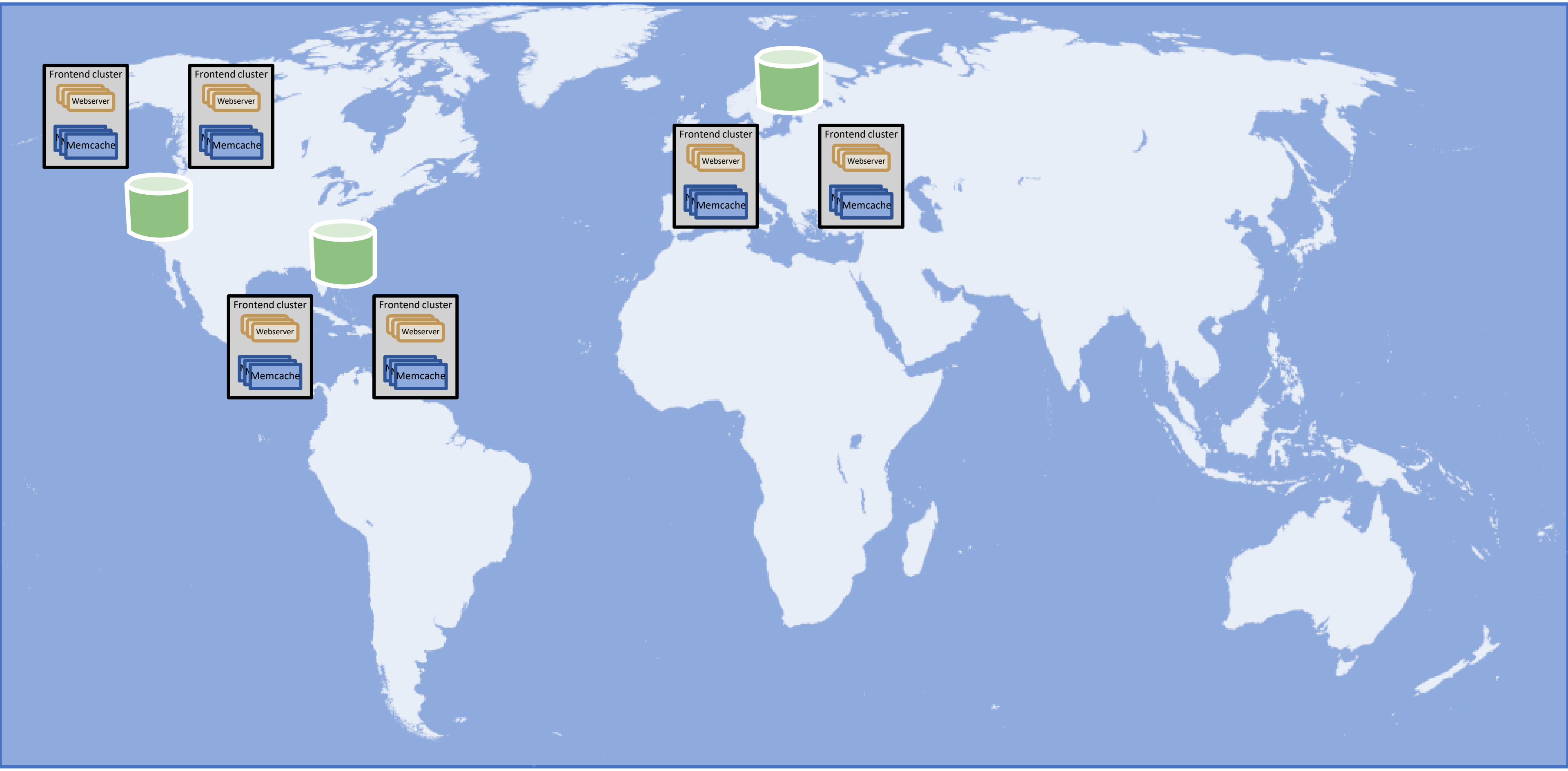
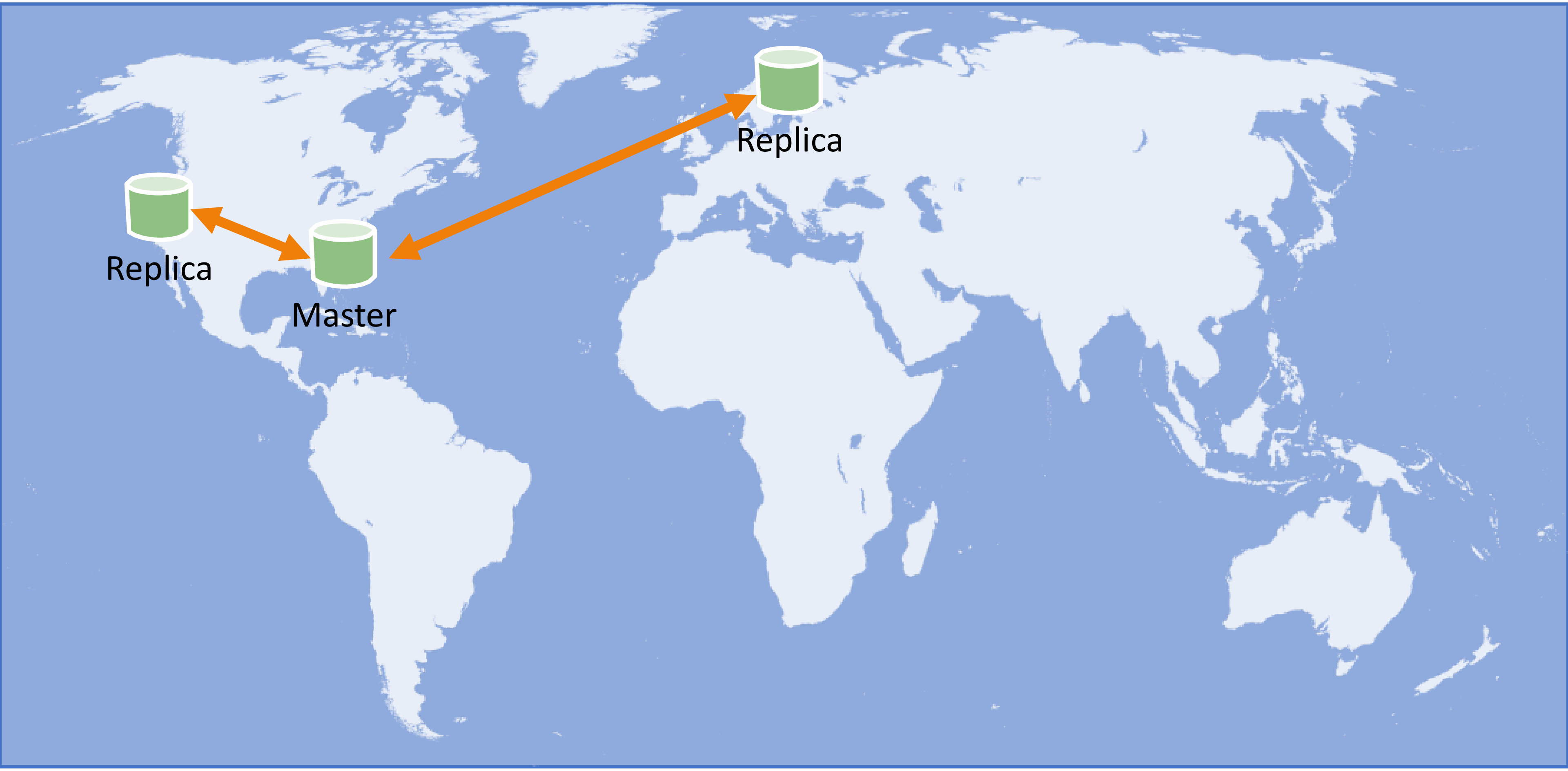
Geographically distributed clusters



Each region has a separate database replica

Why replicate databases, why not partition users?

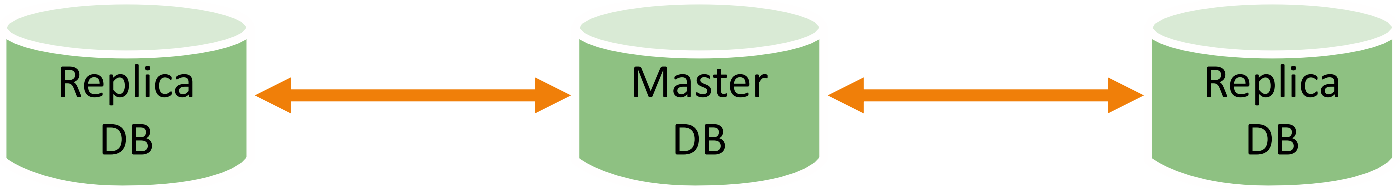
Geographically distributed clusters



One region holds master database,
rest are read-only replicas

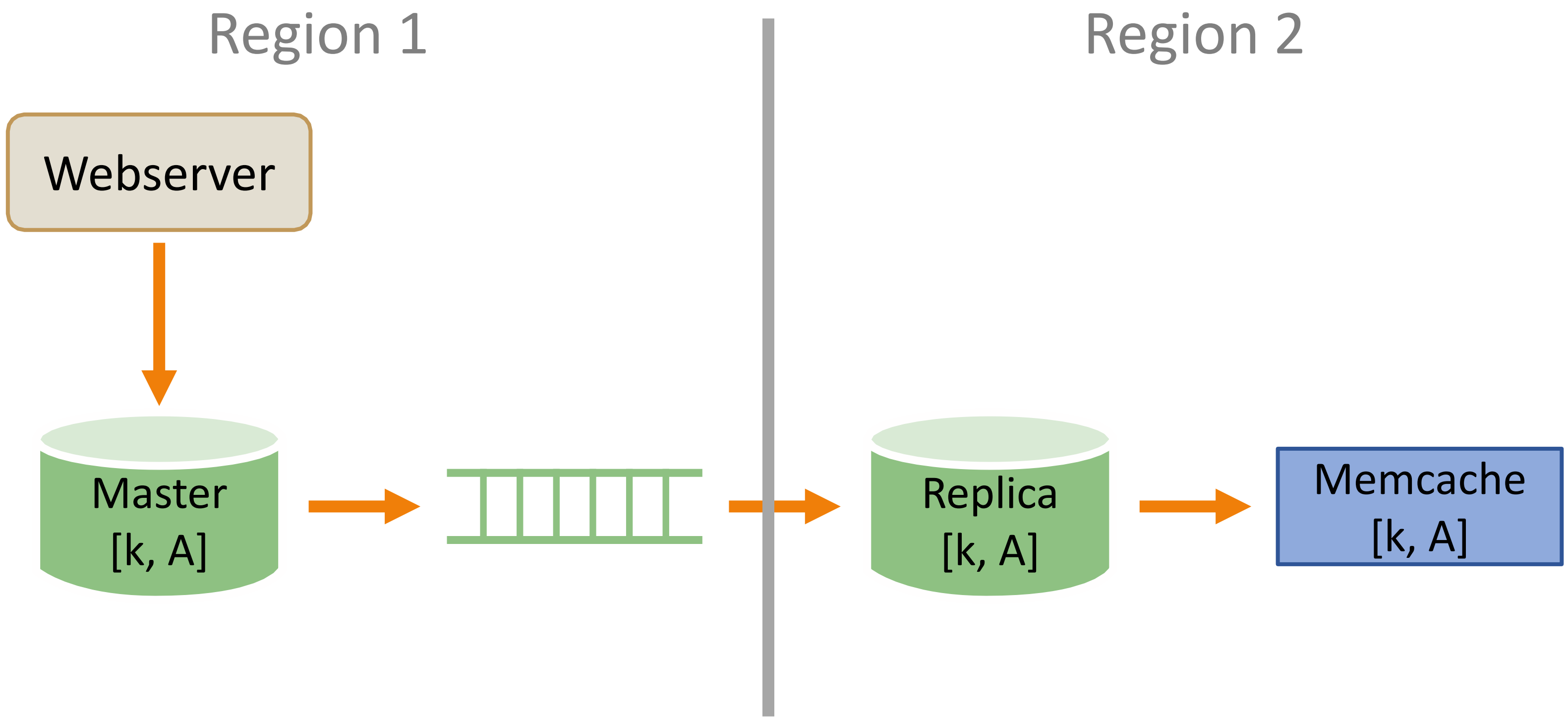
Geographically distributed clusters

- Fast local reads from local Memcache and database replica
- All writes from any region are sent to master
  - Avoids any conflicting writes
  - Why is performance acceptable?
- Master synchronizes replicas asynchronously using database's replication mechanism
  - Replicas lag master, potential for cache inconsistency
  - A replica take over in case master fails



Write at master region

- Ensure consistency of replica and Memcache by reusing invalidation mechanism



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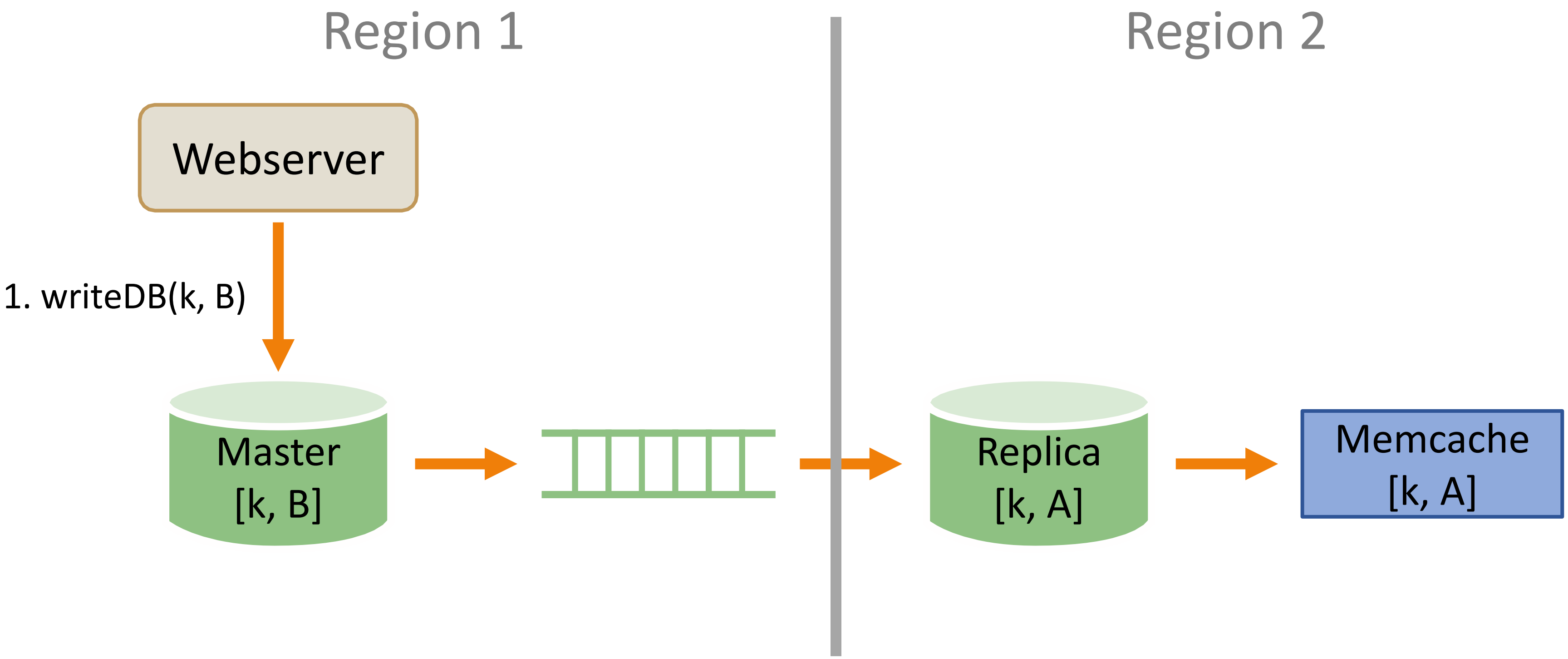
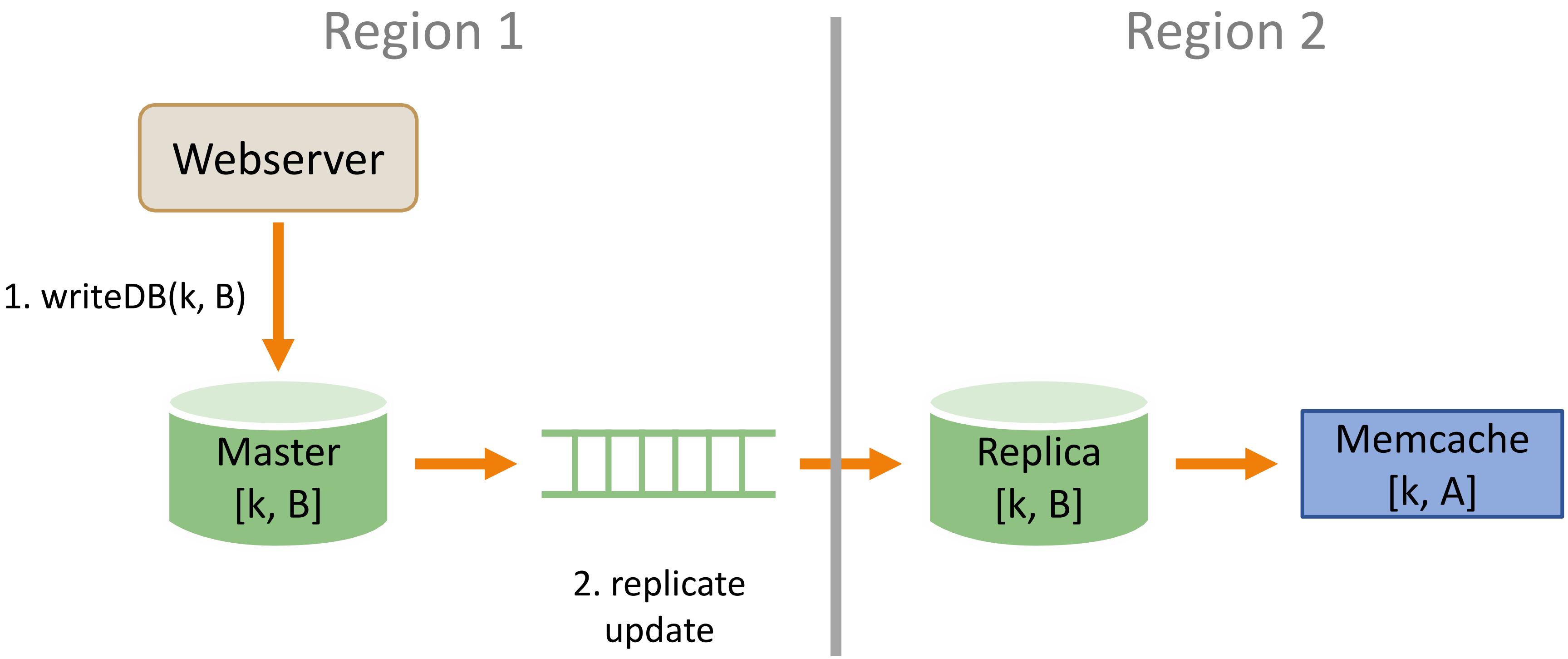


Write at master region

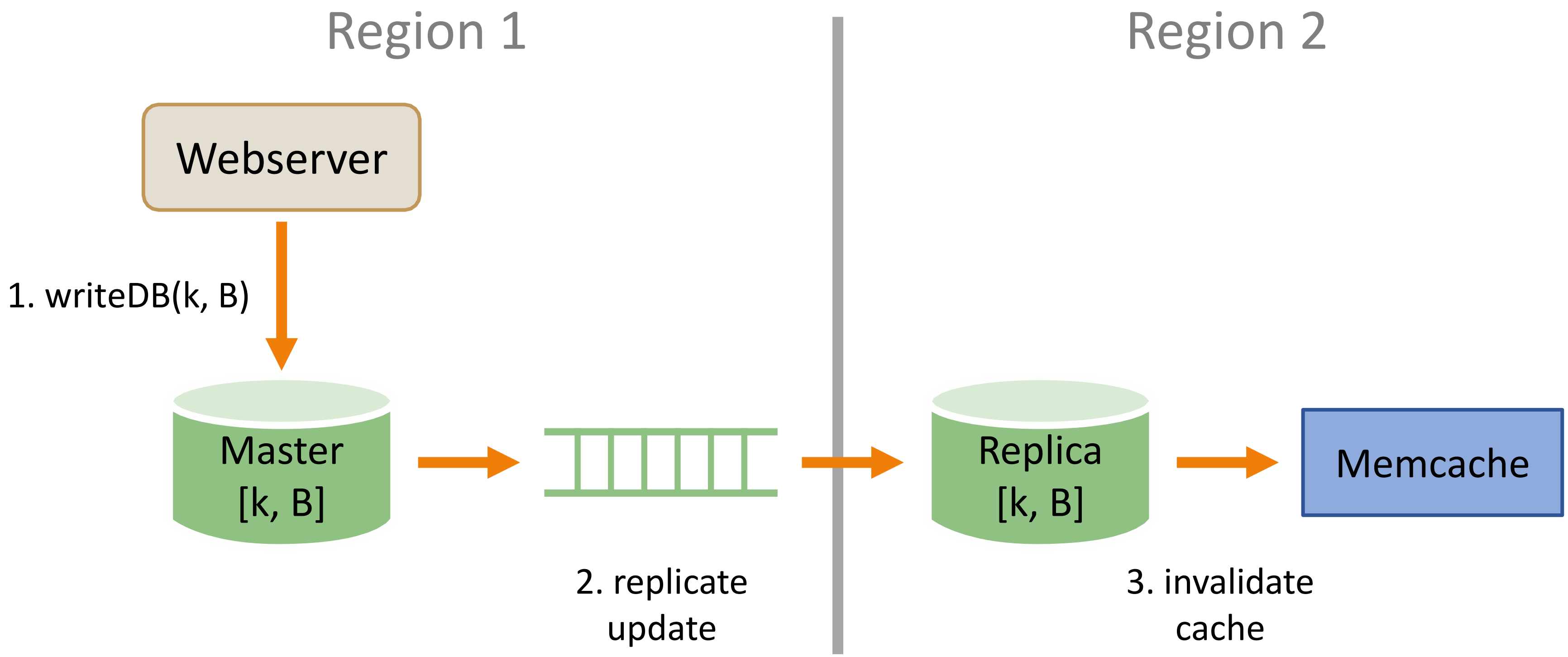
- Ensure consistency of replica and Memcache by reusing invalidation mechanism
  - Replicate update



Write at master region

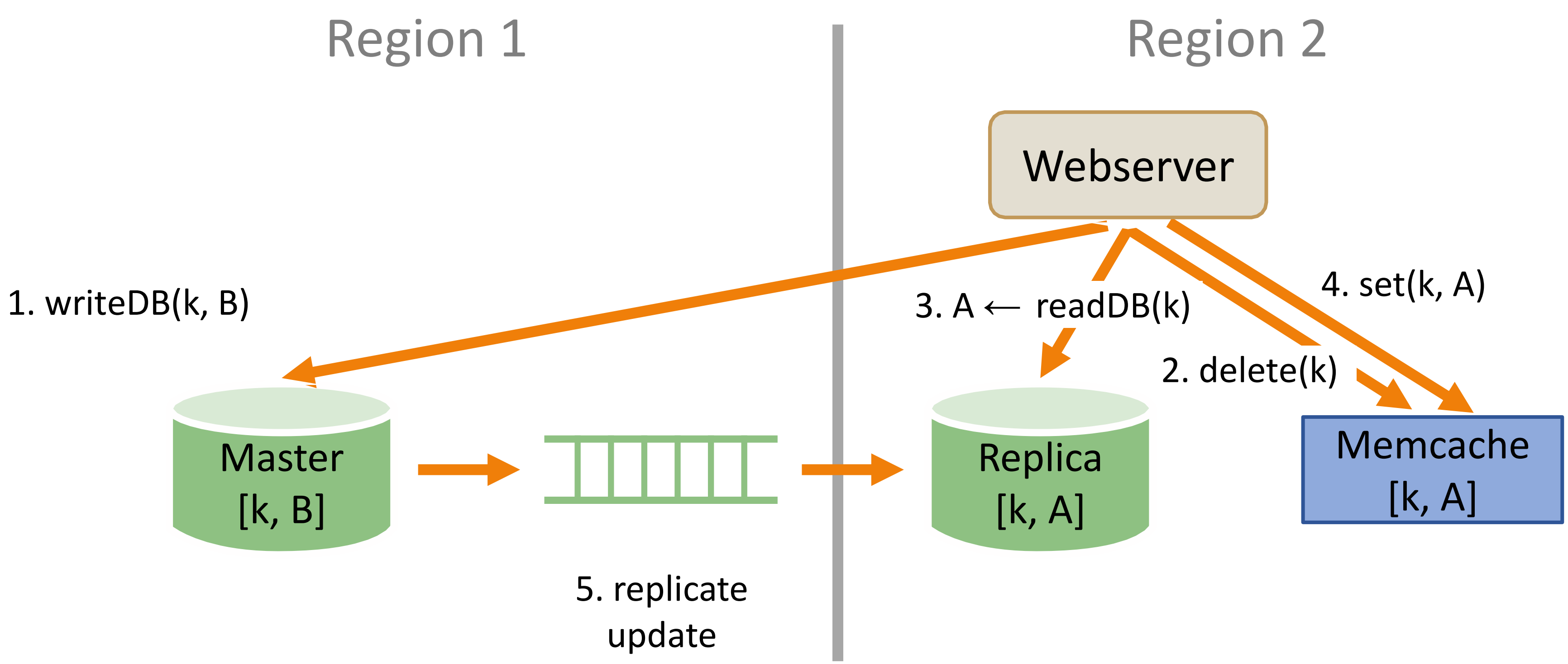
- Ensure consistency of replica and Memcache by reusing invalidation mechanism
  - Replicate update, then
  - Invalidate cache

why replicate and then invalidate?



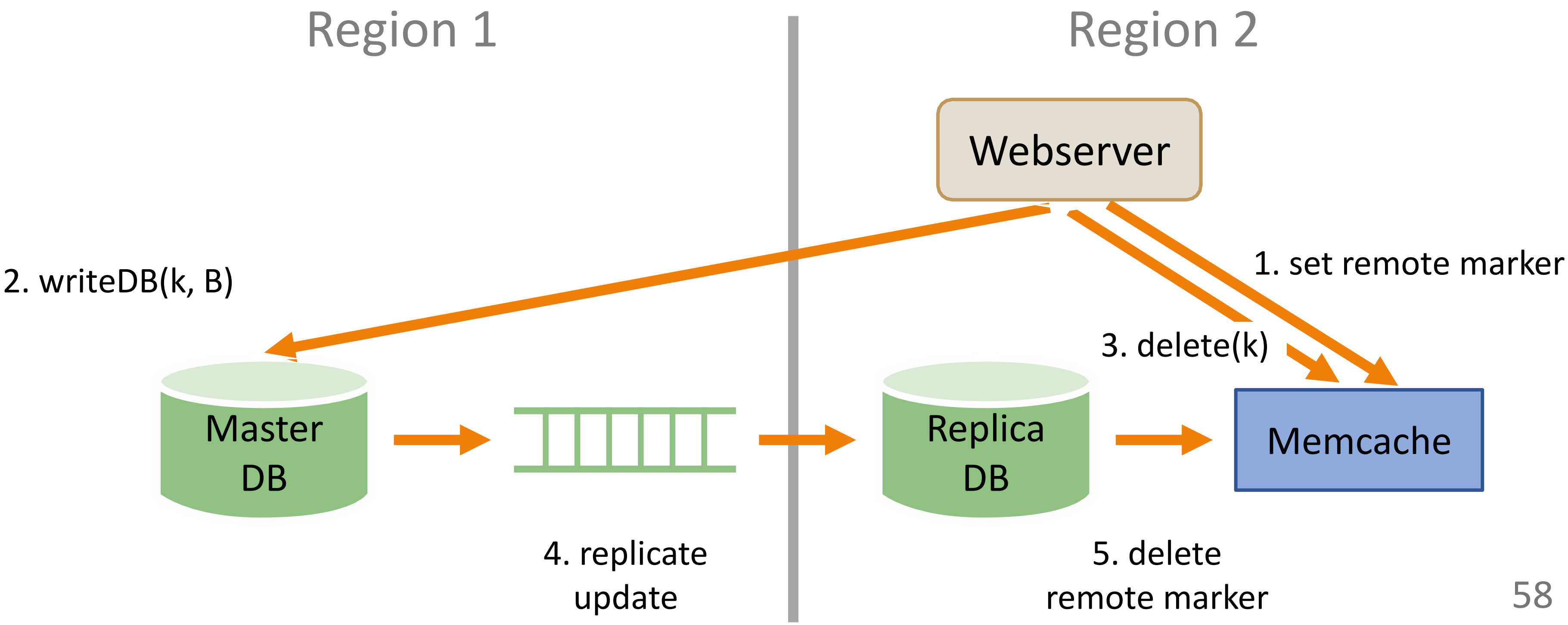
Write at replica region

- After Webserver issues writeDB(k, B) at master (Step 1), it can read and cache stale value from replica (Steps 3, 4) until update is replicated (Step 5)
    - Read-your-write consistency is violated



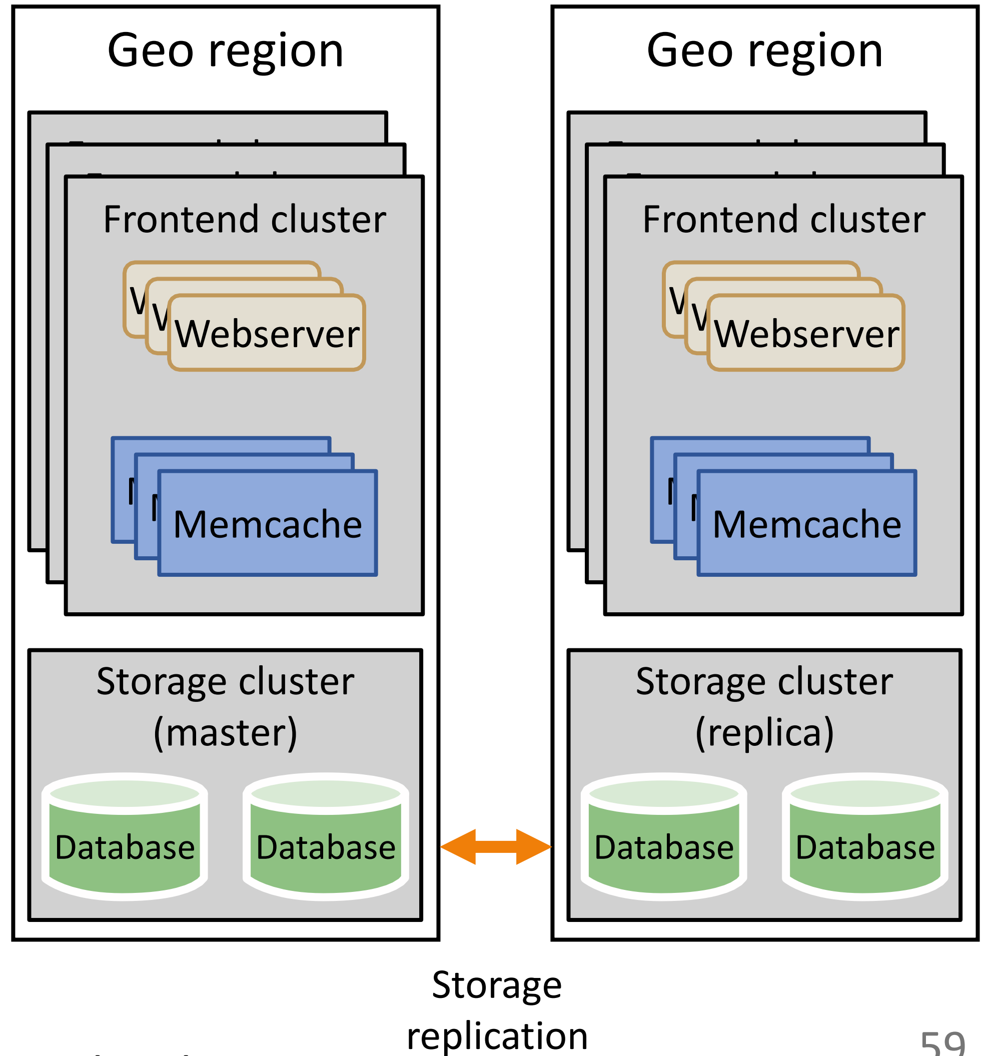
Use remote marker

- Set marker in Memcache indicating replica has stale value
  - If marker is set, read from master, else from replica
  - Ensures read-your-write consistency



Putting it all together

- Start with a single front-end cluster
  - Allows scaling by partitioning data set across caches
- Add multiple front-end clusters in region
  - Allows scaling by replicating caches, reduces communication, hotspots
- Add multiple regions
  - Allows scaling by replicating databases, improves locality



Lessons learned

- Caching reduces latency, vital for surviving high load
- Choose carefully when to shard versus replicate caches
- Provide consistency based on application needs
  - Linearizability will not scale, eventual consistency is okay
- Separate cache and persistent store
  - Allows them to be designed, scaled and operated independently
  - Reusing the standard MySQL database allows reusing standard asynchronous replication mechanisms, replica creation, bulk import, backup, monitoring tools, etc.
- Push complexity into the Webserver, when possible, to simplify design of caching and storage service

Conclusions

- Facebook needed scalable storage for its social graph
- Storage system uses
  - Sharded caches for scaling within a cluster
  - Replicated caches for locality and skew tolerance across clusters
  - Replicated databases for geographic locality across regions
- Design optimized for read-mostly workloads
  - Writes to master database, replicated using primary backup
    - Total order ensures no conflicts, but writes are slower
  - Reads from local database
    - Reads are fast, but may return stale data
    - Idempotent cache invalidations help ensure eventual consistency

Background reading

- *Scaling Memcache at Facebook,* NSDI 2013

Many other practical details

- Regional Memcache pools
- Warming up a new Memcache cluster
- Handling Memcache server failures