Principles of Software Construction: Objects, Design, and Concurrency

Distributed System Design, Part 3

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Administrivia

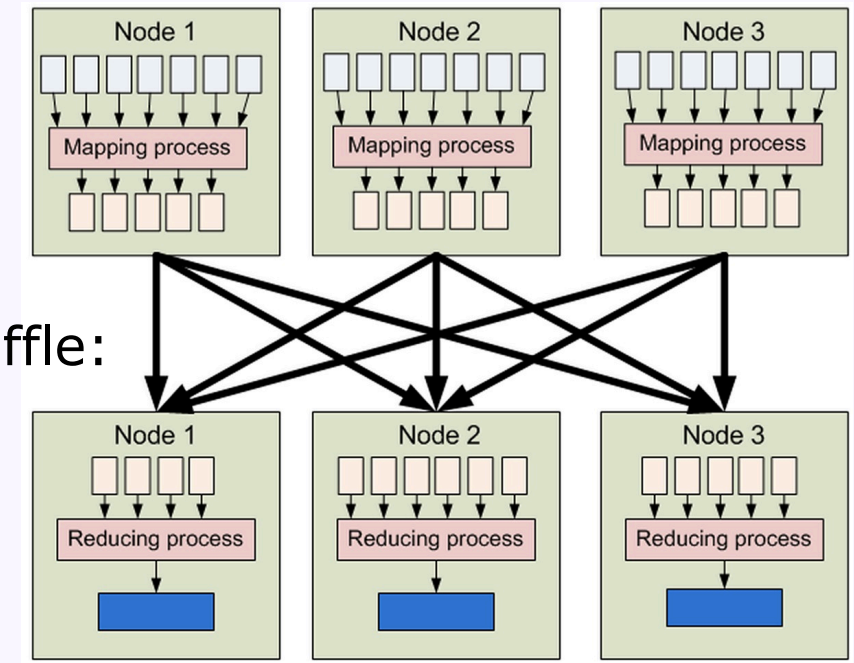
- Homework 6…
- 15-313

Last time…

MapReduce with key/value pairs (Google style)

- Master
  - Assign tasks to workers
  - Ping workers to test for failures
- Map workers
  - Map for each key/value pair
  - Emit intermediate key/value pairs
- Reduce workers
  - Sort data by intermediate key and aggregate by key
  - Reduce for each key

the shuffle:



MapReduce to count all words in a corpus

- E.g., for each word on the Web, count the number of times that word occurs
  - For Map: `key1` is a document name, `value` is the contents of that document
  - For Reduce: `key2` is a word, `values` is a list of the number of counts of that word

```
f1(String key1, String value):
  for each word w in value:
    EmitIntermediate(w, 1);
```

```
f2(String key2, Iterator values):
  int result = 0;
  for each v in values:
    result += v;
  Emit(key2, result);
```

Map: (key1, v1) → (key2, v2)* Reduce: (key2, v2*) → (key3, v3)*

MapReduce: (key1, v1)* → (key3, v3)*

MapReduce: (docName, docText)* → (word, wordCount)*

MapReduce to count mutual friends

- E.g., for pair in a social network graph, output the number of mutual friends they have
  - For Map: `key1` is a person, `value` is the list of her friends
  - For Reduce: `key2` is a pair of people, `values` is a list of 1s, for each mutual friend that pair has

```
f1(String key1, String value):
  for each pair of friends
       in value:
    EmitIntermediate(pair, 1);
```

```
f2(String key2, Iterator values):
  int result = 0;
  for each v in values:
    result += v;
  Emit(key2, result);
```

MapReduce: (person, friends)* → (pair of people, count of mutual friends)*

Today: Distributed system design, part 3

- MapReduce, continued
- General distributed systems design
  - Failure models, assumptions
  - General principles
  - Replication and partitioning
  - Consistent hashing

MapReduce to count incoming links

- E.g., for each page on the Web, count the number of pages that link to it
  - For Map: `key1` is a document name, `value` is the contents of that document
  - For Reduce: `key2` is ???, `values` is a list of ???

```
f1(String key1, String value):
```

```
f2(String key2, Iterator values):
```

MapReduce: (docName, docText)* → (docName, number of incoming links)*

MapReduce to count incoming links

- E.g., for each page on the Web, count the number of pages that link to it
  - For Map: `key1` is a document name, `value` is the contents of that document
  - For Reduce: `key2` is ???, `values` is a list of ???

```
f1(String key1, String value):
  for each link in value:
    EmitIntermediate(link, 1)
```

```
f2(String key2, Iterator values):
  int result = 0;
  for each v in values:
    result += v;
  Emit(key2, result);
```

MapReduce: (docName, docText)* → (docName, number of incoming links)*

MapReduce to create an inverted index

- E.g., for each page on the Web, create a list of the pages that link to it
  - For Map: `key1` is a document name, `value` is the contents of that document
  - For Reduce: `key2` is ???, `values` is a list of ???

```
f1(String key1, String value):
  for each link in value:
    EmitIntermediate(link, key1)
```

```
f2(String key2, Iterator values):
  Emit(key2, values)
```

MapReduce: (docName, docText)* → (docName, list of incoming links)*

List the mutual friends

- E.g., for each pair in a social network graph, list the mutual friends they have
  - For Map: `key1` is a person, `value` is the list of her friends
  - For Reduce: `key2` is ???, `values` is a list of ???

```
f1(String key1, String value):
```

```
f2(String key2, Iterator values):
```

MapReduce: (person, friends)* → (pair of people, list of mutual friends)*

List the mutual friends

- E.g., for each pair in a social network graph, list the mutual friends they have
  - For Map: `key1` is a person, `value` is the list of her friends
  - For Reduce: `key2` is ???, `values` is a list of ???

```
f1(String key1, String value):

  for each pair of friends
       in value:

    EmitIntermediate(pair, key1);
```

```
f2(String key2, Iterator values):

  Emit(key2, values)
```

MapReduce: (person, friends)* → (pair of people, list of mutual friends)*

Count friends + friends of friends

- E.g., for each person in a social network graph, count their friends and friends of friends
  - For Map: `key1` is a person, `value` is the list of her friends
  - For Reduce: `key2` is ???, `values` is a list of ???

```
f1(String key1, String value):
```

```
f2(String key2, Iterator values):
```

MapReduce: (person, friends)* → (person, count of f + fof)*

Count friends + friends of friends

- E.g., for each person in a social network graph, count their friends and friends of friends
  - For Map: `key1` is a person, `value` is the list of her friends
  - For Reduce: `key2` is ???, `values` is a list of ???

```
f1(String key1, String value):
  for each friend1 in value:
    EmitIntermediate(friend1, key1)
    for each friend2 in value:
      EmitIntermediate(friend1,
                       friend2);
```

```
f2(String key2, Iterator values):
  distinct_values = {}
  for each v in values:
    if not v in distinct_values:
      distinct_values.insert(v)
  Emit(key2, len(distinct_values))
```

MapReduce: (person, friends)* → (person, count of f + fof)*

Friends + friends of friends + friends of friends of friends

- E.g., for each person in a social network graph, count their friends and friends of friends and friends of friends of friends
  - For Map: `key1` is a person, `value` is the list of her friends
  - For Reduce: `key2` is ???, `values` is a list of ???

```
f1(String key1, String value):
```

```
f2(String key2, Iterator values):
```

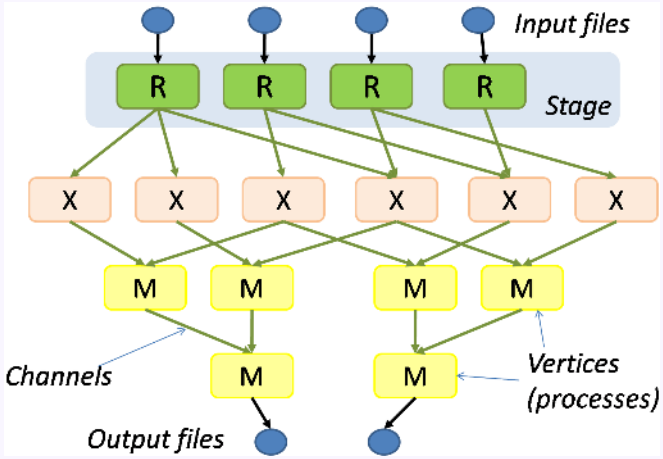
MapReduce: (person, friends)* → (person, count of f + fof + fofof)*

Problem: How to reach distance 3 nodes?

- Solution: Iterative MapReduce
  - Use MapReduce to get distance 1 and distance 2 nodes
  - Feed results as input to a second MapReduce process
- Also consider:
  - Breadth-first search
  - PageRank
  - …

Dataflow processing

- High-level languages and systems for complex MapReduce-like processing
  - Yahoo Pig, Hive
  - Microsoft Dryad, Naiad
- MapReduce generalizations…

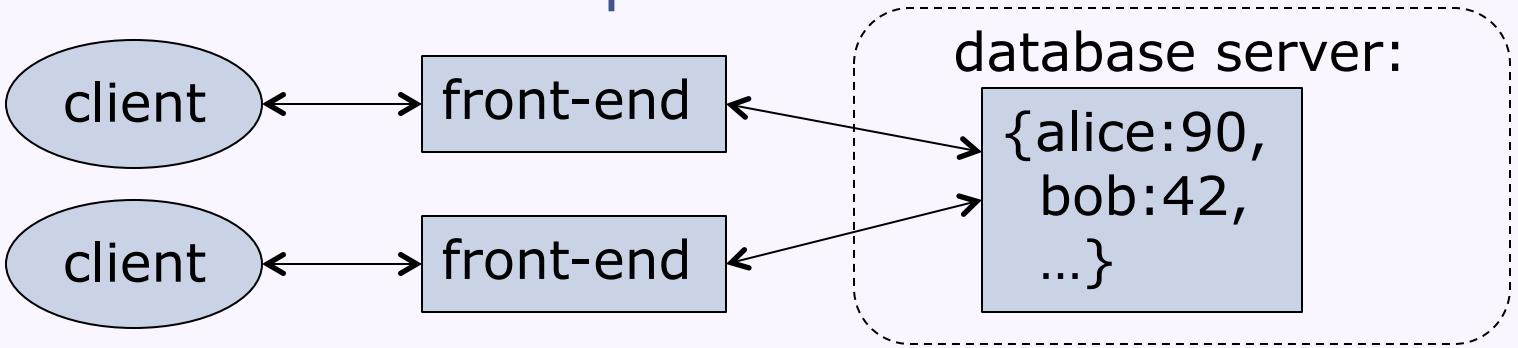


Today: Distributed system design, part 3

- MapReduce, continued
- General distributed systems design
  - Failure models, assumptions
  - General principles
  - Replication and partitioning
  - Consistent hashing

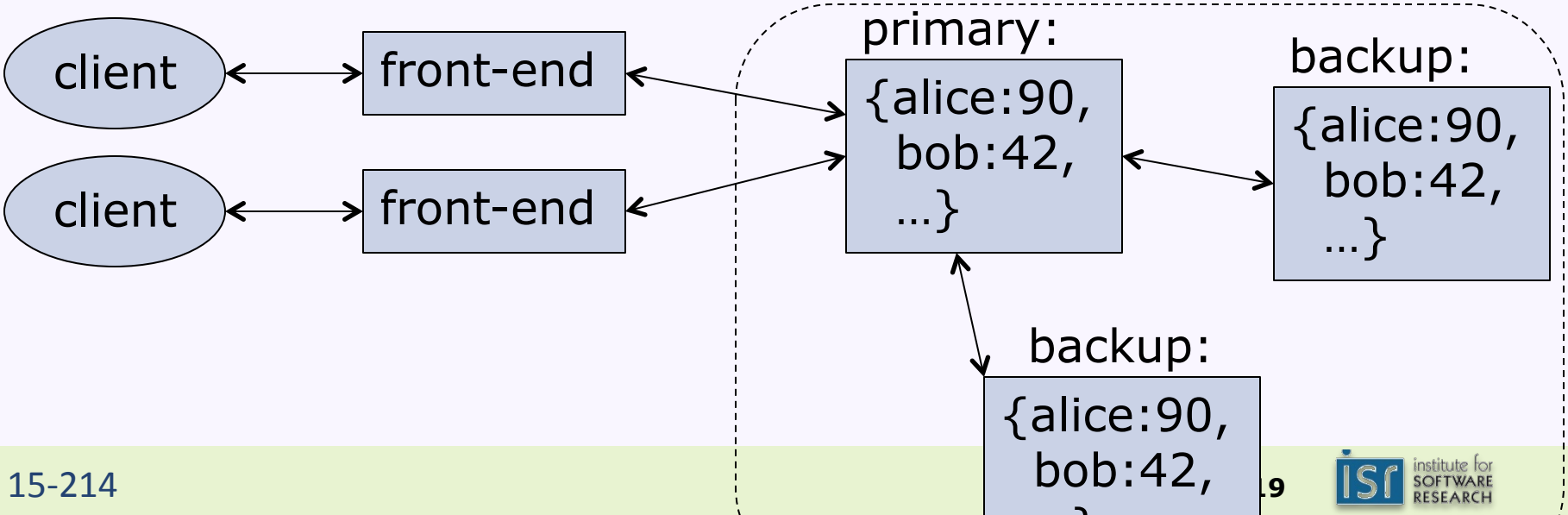
Recall passive primary-backup replication

- Architecture before replication:



  - Problem: Database server might fail

- Solution: Replicate data onto multiple servers



Types of failure behaviors

- Fail-stop
- Other halting failures
- Communication failures
  - Send/receive omissions
  - Network partitions
  - Message corruption
- Performance failures
  - High packet loss rate
  - Low throughput
  - High latency
- Data corruption
- Byzantine failures

Common assumptions about failures

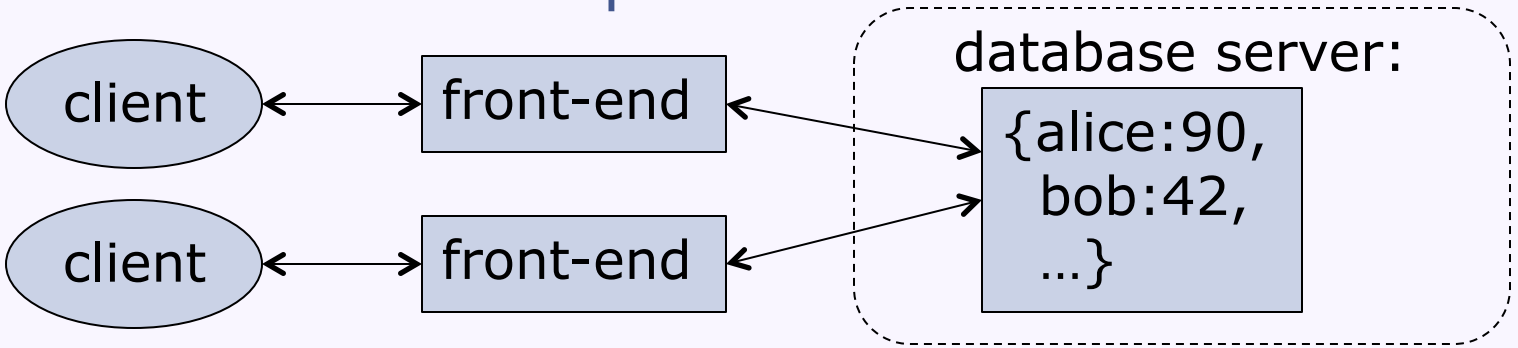
- Behavior of others is fail-stop (ugh)
- Network is reliable (ugh)
- Network is semi-reliable but asynchronous
- Network is lossy but messages are not corrupt
- Network failures are transitive
- Failures are independent
- Local data is not corrupt
- Failures are reliably detectable
- Failures are unreliably detectable

Some distributed system design goals

- The end-to-end principle
  - When possible, implement functionality at the end nodes (rather than the middle nodes) of a distributed system
- The robustness principle
  - Be strict in what you send, but be liberal in what you accept from others
    - Protocols
    - Failure behaviors
- Benefit from incremental changes
- Be redundant
  - Data replication
  - Checks for correctness

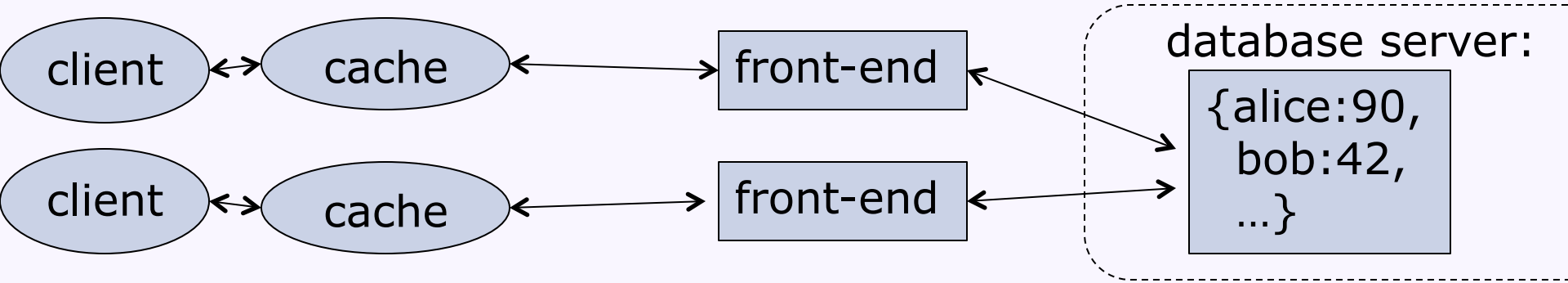
Replication for scalability: Client-side caching

- Architecture before replication:



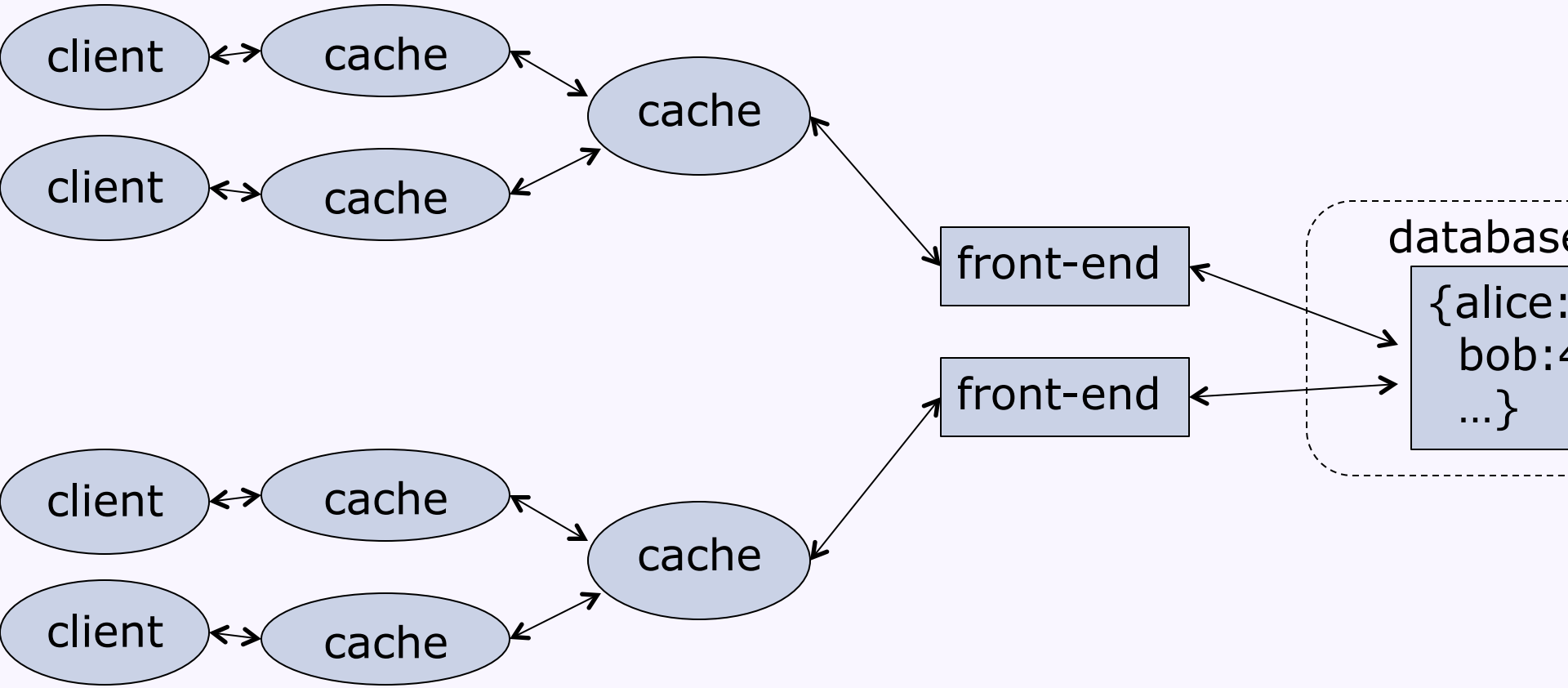
  - Problem: Server throughput is too low

- Solution: Cache responses at (or near) the client
  - Cache can respond to repeated read requests



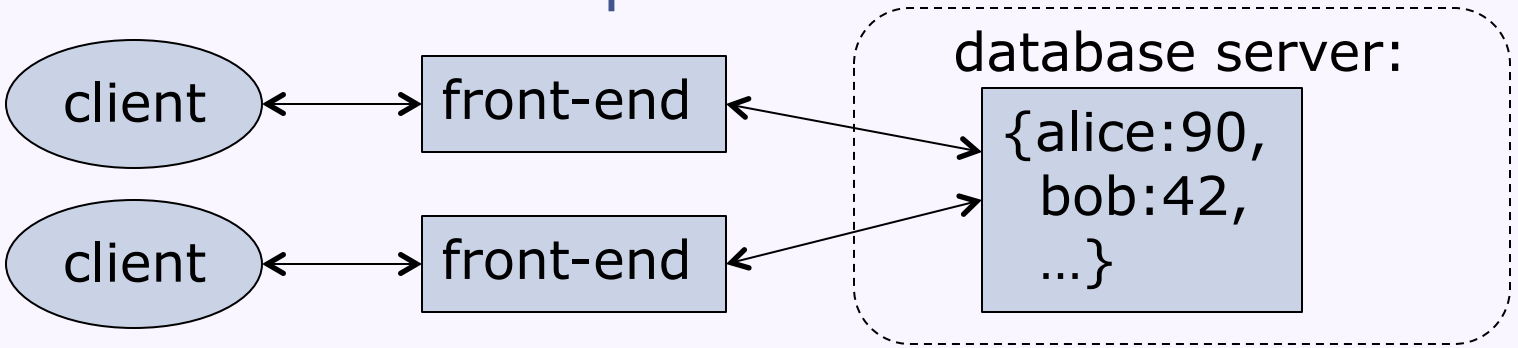
Replication for scalability: Client-side caching

- Hierarchical client-side caches:



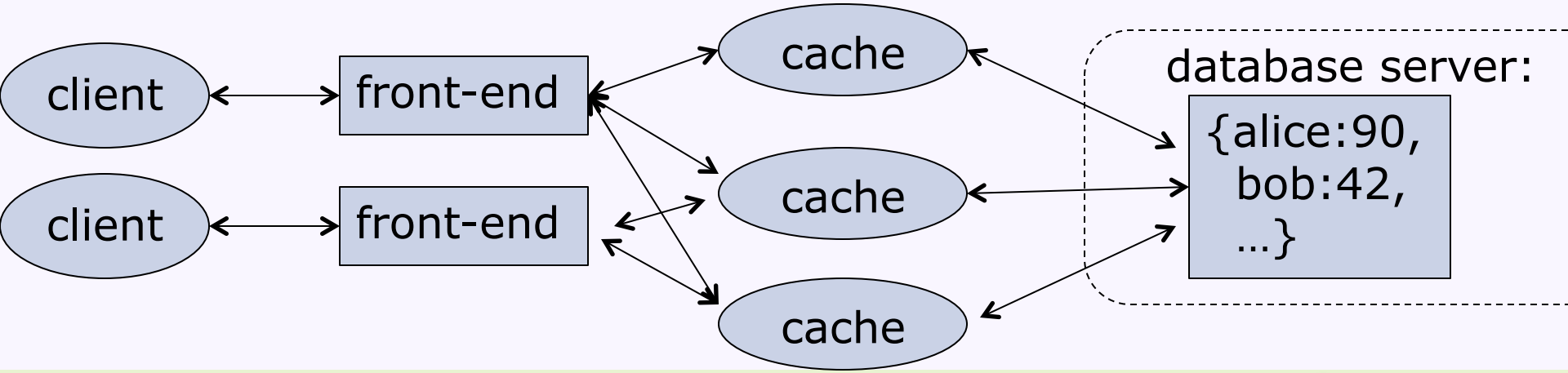
Replication for scalability: Server-side caching

- Architecture before replication:



  - Problem: Database server throughput is too low

- Solution: Cache responses on multiple servers
  - Cache can respond to repeated read requests



Cache invalidation

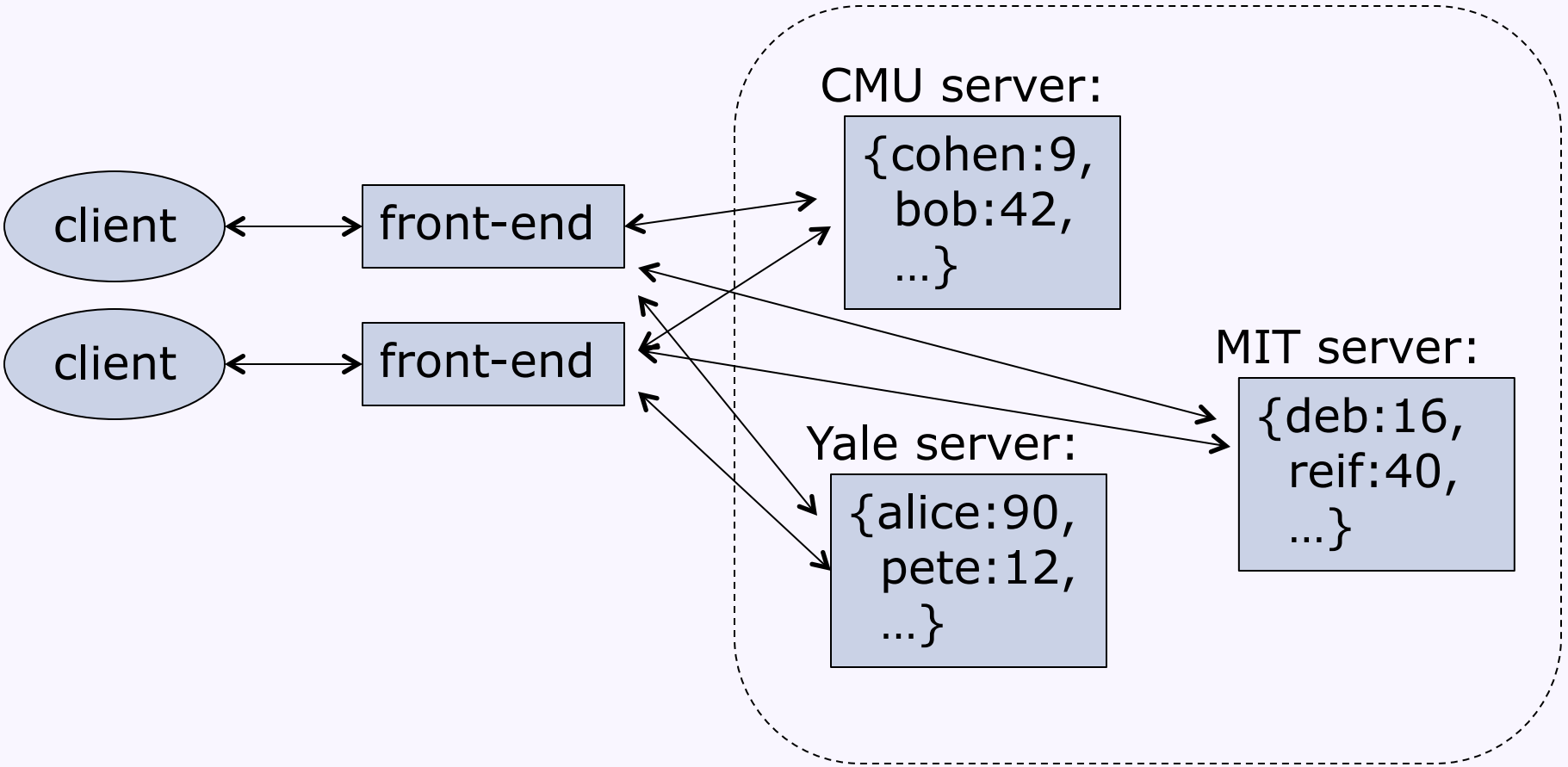
- Time-based invalidation (a.k.a. expiration)
  - Read-any, write-one
  - Old cache entries automatically discarded
  - No expiration date needed for read-only data
- Update-based invalidation
  - Read-any, write-all
  - DB server broadcasts invalidation message to all caches when the DB is updated
- What are the advantages and disadvantages of each approach?

Cache replacement policies

- Problem: caches have finite size
- Common* replacement policies
  - Optimal (Belady's) policy
    - Discard item not needed for longest time in future
  - Least Recently Used (LRU)
    - Track time of previous access, discard item accessed least recently
  - Least Frequently Used (LFU)
    - Count # times item is accessed, discard item accessed least frequently
  - Random
    - Discard a random item from the cache

Partitioning for scalability

- Partition data based on some property, put each partition on a different server



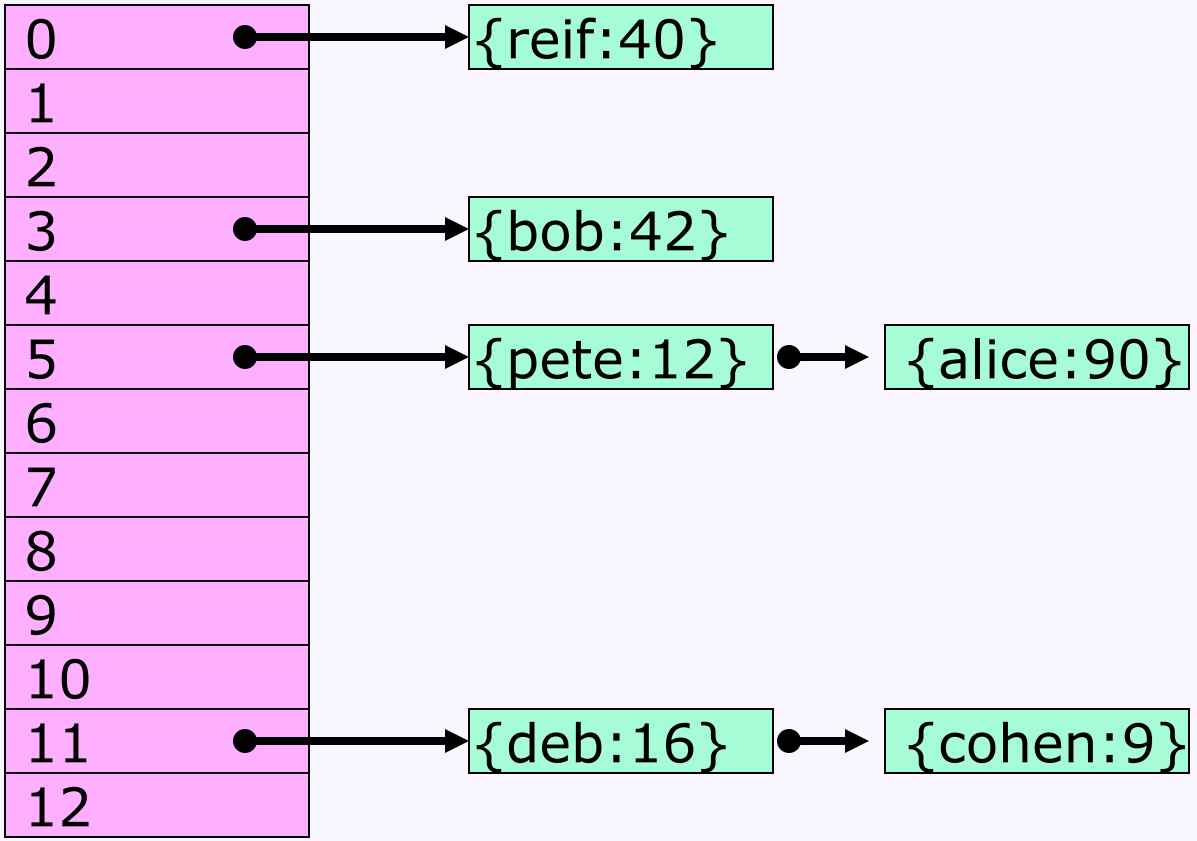
Horizontal partitioning

- a.k.a. "sharding"
- A table of data:

username	school	value
cohen	CMU	9
bob	CMU	42
alice	Yale	90
pete	Yale	12
deb	MIT	16
reif	MIT	40

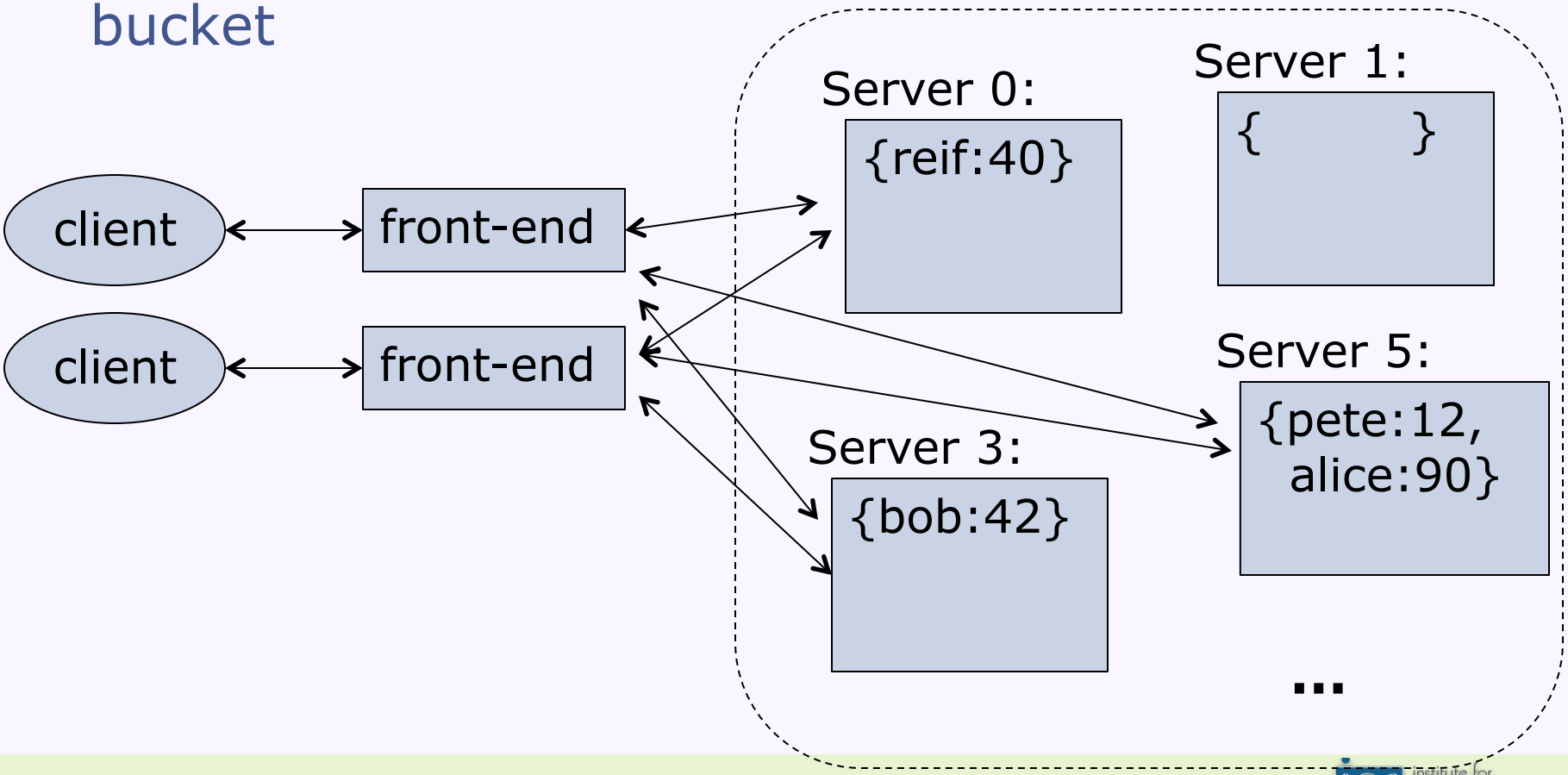
Recall: Basic hash tables

- For `n`-size hash table, put each item `x` in the bucket: `x.hashCode() % n`



Partitioning with a distributed hash table

- Each server stores data for one bucket
- To store or retrieve an item, front-end server hashes the key, contacts the server storing that bucket



Consistent hashing

- Goal: Benefit from incremental changes
  - Resizing the hash table (i.e., adding or removing a server) should not require moving many objects
- E.g., Interpret the range of hash codes as a ring
  - Each bucket stores data for a range of the ring
    - Assign each bucket an ID in the range of hash codes
    - To store item `x` don't compute `x.hashCode() % n`. Instead, place `x` in bucket with the same ID as or next higher ID than `x.hashCode()`

Problems with hash-based partitioning

- Front-ends need to determine server for each bucket
  - Each front-end stores look-up table?
  - Master server storing look-up table?
  - Routing-based approaches?
- Places related content on different servers
  - Consider *range* queries:

```
SELECT * FROM users WHERE lastname STARTSWITH 'G'
```

Next week

- More distributed systems…
- Serializability