Principles of Software Construction: Objects, Design, and Concurrency

Distributed System Design, Part 1

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• **Homework 5b Thursday**
  - Finish by Friday (14 Nov) 10 a.m. if you want to be considered as a "Best Framework" for Homework 5c

• **Homework grading status**
  - 5a almost done being graded
  - 4c almost done, two graders remaining

• **Homework 3 arena winners in class Thursday?**
Key concepts from last Thursday
Concurrent at the language level

Consider:
```java
int sum = 0;
Iterator i = coll.iterator();
while (i.hasNext()) {
    sum += i.next();
}
```

In python:
```python
sum = 0;
for item in coll:
    sum += item
```
Parallel prefix sums algorithm, winding

- Computes the partial sums in a more useful manner

\[ [13, 9, -4, 19, -6, 2, 6, 3] \]
\[ [13, 22, -4, 15, -6, -4, 6, 9] \]
\[ [13, 22, -4, 37, -6, -4, 6, 5] \]
\[ [13, 22, -4, 37, -6, -4, 6, 42] \]
Parallel prefix sums algorithm, unwinding

- Now unwinds to calculate the other sums

\[
\begin{bmatrix}
13, & 22, & -4, & 37, & -6, & -4, & 6, & 42 \\
13, & 22, & -4, & 37, & -6, & 33, & 6, & 42 \\
13, & 22, & 18, & 37, & 31, & 33, & 39, & 42 \\
\end{bmatrix}
\]

- Recall, we started with:

\[
\begin{bmatrix}
13, & 9, & -4, & 19, & -6, & 2, & 6, & 3 \\
\end{bmatrix}
\]
A framework for asynchronous computation

• The java.util.concurrent.Future<V> interface
  V get();
  V get(long timeout, TimeUnit unit);
  boolean isDone();
  boolean cancel(boolean mayInterruptIfRunning);
  boolean isCancelled();

• The java.util.concurrent.ExecutorService interface
  Future submit(Runnable task);
  Future<V> submit(Callable<V> task);
  List<Future<V>> invokeAll(Collection<Callable<V>> tasks);
  Future<V> invokeAny(Collection<Callable<V>> tasks);
Fork/Join: another common computational pattern

• **In a long computation:**
  - Fork a thread (or more) to do some work
  - Join the thread(s) to obtain the result of the work

• **The java.util.concurrent.ForkJoinPool class**
  - Implements ExecutorService
  - Executes java.util.concurrent.ForkJoinTask<V> or java.util.concurrent.RecursiveTask<V> or java.util.concurrent.RecursiveAction
Today: Distributed system design

- Java networking fundamentals
- Introduction to distributed systems
  - Motivation: reliability and scalability
  - Failure models
  - Techniques for:
    - Reliability (availability)
    - Scalability
    - Consistency
Our destination: Distributed systems

- Multiple system components (computers) communicating via some medium (the network)

- Challenges:
  - Heterogeneity
  - Scale
  - Geography
  - Security
  - Concurrency
  - Failures

(courtesy of http://www.cs.cmu.edu/~dga/15-440/F12/lectures/02-internet1.pdf)
Communication protocols

- Agreement between parties for how communication should take place
  - e.g., buying an airline ticket through a travel agent

(courtesy of http://www.cs.cmu.edu/~dga/15-440/F12/lectures/02-internet1.pdf)
Abstractions of a network connection

HTML | Text | JPG | GIF | PDF | ...

HTTP | FTP | ...

TCP | UDP | ...

IP

data link layer

physical layer
Packet-oriented and stream-oriented connections

- **UDP**: User Datagram Protocol
  - Unreliable, discrete packets of data

- **TCP**: Transmission Control Protocol
  - Reliable data stream
Internet addresses and sockets

- For IP version 4 (IPv4) host address is a 4-byte number
  - e.g. 127.0.0.1
  - Hostnames mapped to host IP addresses via DNS
  - ~4 billion distinct addresses

- Port is a 16-bit number (0-65535)
  - Assigned conventionally
    - e.g., port 80 is the standard port for web servers
Networking in Java

• The java.net.InetAddress:
  static InetAddress getByName(String host);
  static InetAddress getByAddress(byte[] b);
  static InetAddress getLocalHost();

• The java.net.Socket:
  Socket(InetAddress addr, int port);
  boolean isConnected();
  boolean isClosed();
  void close();
  InputStream getInputStream();
  OutputStream getOutputStream();

• The java.net.ServerSocket:
  ServerSocket(int port);
  Socket accept();
  void close();
  ...
Simple sockets demos

- NetworkServer.java

- A basic chat system:
  - TransferThread.java
  - TextSocketClient.java
  - TextSocketServer.java
Higher levels of abstraction

- Application-level communication protocols
- Frameworks for simple distributed computation
  - Remote Procedure Call (RPC)
  - Java Remote Method Invocation (RMI)
- Common patterns of distributed system design
- Complex computational frameworks
  - e.g., distributed map-reduce
Today

• Java networking fundamentals

• Introduction to distributed systems
  - Motivation: reliability and scalability
  - Failure models
  - Techniques for:
    • Reliability (availability)
    • Scalability
    • Consistency
You need to restart your computer. Hold down the Power button for several seconds or press the Restart button.

Veuillez redémarrer votre ordinateur. Maintenez la touche de démarrage enfoncée pendant plusieurs secondes ou bien appuyez sur le bouton de réinitialisation.

Sie müssen Ihren Computer neu starten. Halten Sie dazu die Einschalttaste einige Sekunden gedrückt oder drücken Sie die Neustart-Taste.

コンピュータを再起動する必要があります。パワーボタンを数秒間押し続けるか、リセットボタンを押してください。
Aside: The robustness vs. redundancy curve
Metrics of success

• **Reliability**
  - Often in terms of availability: fraction of time system is working
    • 99.999% available is "5 nines of availability"

• **Scalability**
  - Ability to handle workload growth
A case study: Passive primary-backup replication

- Architecture before replication:

  - Problem: Database server might fail
A case study: Passive primary-backup replication

- **Architecture before replication:**

  - **Problem:** Database server might fail
  - **Solution:** Replicate data onto multiple servers

![Diagram showing client, front-end, and database server with replicated data]

- **Database server:**
  - Primary: \{alice:90, bob:42, ...\}
  - Backup: \{alice:90, bob:42, ...\}

- **Clients:**
  - Access through front-end servers

- **Front-end Access:**
  - \{alice:90, bob:42, ...\}

**Database Operations:**
- Insertions, updates, deletions propagate to both primary and backups.
- Reads and writes primarily directed to primary with fallback to backups.

This setup ensures high availability and reliability in case of primary server failures.
Passive primary-backup replication protocol

1. Front-end issues request with unique ID to primary DB
2. Primary checks request ID
   - If already executed request, re-send response and exit protocol
3. Primary executes request and stores response
4. If request is an update, primary DB sends updated state, ID, and response to all backups
   - Each backup sends an acknowledgement
5. After receiving all acknowledgements, primary DB sends response to front-end
Issues with passive primary-backup replication

- If primary DB crashes, front-ends need to agree upon which unique backup is new primary DB
  - Primary failure vs. network failure?

- If backup DB becomes new primary, surviving replicas must agree on current DB state

- If backup DB crashes, primary must detect failure to remove the backup from the cluster
  - Backup failure vs. network failure?

- If replica fails* and recovers, it must detect that it previously failed

- Many subtle issues with partial failures

- ...
More issues…

• Concurrency problems?
  - Out of order message delivery?
    • Time...

• Performance problems?
  - 2n messages for n replicas
  - Failure of any replica can delay response
  - Routine network problems can delay response

• Scalability problems?
  - All replicas are written for each update
  - Primary DB responds to every request
Types of failure behaviors

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

```plaintext
{alice: 90, bob: 42, ...
```
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
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

Client

Front-end

CMU server:
- {cohen:9, bob:42, ...}

Yale server:
- {alice:90, pete:12, ...}

MIT server:
- {deb:16, reif:40, ...}
Horizontal partitioning

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

<table>
<thead>
<tr>
<th>username</th>
<th>school</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>cohen</td>
<td>CMU</td>
<td>9</td>
</tr>
<tr>
<td>bob</td>
<td>CMU</td>
<td>42</td>
</tr>
<tr>
<td>alice</td>
<td>Yale</td>
<td>90</td>
</tr>
<tr>
<td>pete</td>
<td>Yale</td>
<td>12</td>
</tr>
<tr>
<td>deb</td>
<td>MIT</td>
<td>16</td>
</tr>
<tr>
<td>reif</td>
<td>MIT</td>
<td>40</td>
</tr>
</tbody>
</table>
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

Diagram:

- Client sends request to front-end
- Front-end hashes key and contacts appropriate server
- Server returns data or indicates bucket not found

Example:

Server 0:
{reif: 40}

Server 1:
{} (empty)

Server 3:
{bob: 42}

Server 5:
{pete: 12, alice: 90}

...
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'
Master/tablet-based systems

- Dynamically allocate range-based partitions
  - Master server maintains tablet-to-server assignments
  - Tablet servers store actual data
  - Front-ends cache tablet-to-server assignments

Client

Front-end

Tablet server 1:
- k-z:
  - {pete:12, reif:42}

Tablet server 2:
- a-c: [2]
- d-g: [3,4]
- h-j: [3]
- k-z: [1]

Tablet server 3:
- d-g:
  - {deb:16}
  - h-j:
    - {}

Tablet server 4:
- d-g:
  - {deb:16}
Coming next…

- More distributed systems
  - MapReduce