Network Communication and Remote Procedure Calls

CS 240: Computing Systems and Concurrency
Lecture 2

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Credits: Michael Freedman and Kyle Jamieson developed much of the original material.
A **distributed system** is many cooperating computers that appear to users as a single service.

**Today**—*How can processes on different cooperating computers exchange information?*

1. Network Sockets
2. Remote Procedure Call
3. Threads
The problem of communication

• Process on Host A wants to talk to process on Host B

  – A and B must agree on the meaning of the bits being sent and received at many different levels, including:

    • How many volts is a 0 bit, a 1 bit?
    • How does receiver know which is the last bit?
    • How many bits long is a number?
The problem of communication

• Re-implement every application for every new underlying transmission medium?
  – Change every application on any change to an underlying transmission medium?

• No! But how does the Internet design avoid this?
Solution: Layering

- Intermediate layers provide a set of abstractions for applications and media
- New applications or media need only implement for intermediate layer’s interface
Layering in the Internet

- **Transport**: Provide end-to-end communication between processes on different hosts

- **Network**: Deliver packets to destinations on other (heterogeneous) networks

- **Link**: Enables end hosts to exchange atomic messages with each other

- **Physical**: Moves bits between two hosts connected by a physical link
Logical communication between layers

• How to **forge agreement** on the **meaning** of the bits exchanged between two hosts?

• **Protocol:** Rules that governs the format, contents, and meaning of messages
  – Each layer on a host interacts with its peer host’s corresponding layer via the **protocol interface**
Physical communication

- Communication goes down to the **physical network**
- Then from **network** peer to peer
- Then up to the **relevant application**
Communication between peers

• *How do peer protocols coordinate with each other?*

• Layer attaches its own *header* \((H)\) to communicate with peer
  – Higher layers’ headers, data *encapsulated* inside message
  • Lower layers don’t generally inspect higher layers’ headers
Network socket-based communication

- **Socket**: The interface the OS provides to the network
  - Provides inter-process *explicit message exchange*

- Can build distributed systems atop sockets: send(), recv()  
  - *e.g.*: `put(key, value) → message`
Network sockets: Summary

- **Principle of transparency:** *Hide* that resource is physically distributed across multiple computers
  - Access resource same way as locally
  - Users can’t tell where resource is physically located

Network sockets provide apps with **point-to-point communication** between processes

- `put(key, value) →` message with sockets?
// Create a socket for the client
if ((sockfd = socket(AF_INET, SOCK_STREAM, 0)) < 0) {
    perror("Socket creation");
    exit(2);
}

// Set server address and port
memset(&servaddr, 0, sizeof(servaddr));
servaddr.sin_family = AF_INET;
servaddr.sin_addr.s_addr = inet_addr(argv[1]);
servaddr.sin_port = htons(SERV_PORT); // to big-endian

// Establish TCP connection
if (connect(sockfd, (struct sockaddr *)&servaddr, sizeof(servaddr)) < 0) {
    perror("Connect to server");
    exit(3);
}

// Transmit the data over the TCP connection
send(sockfd, buf, strlen(buf), 0);
Today’s outline

1. Network Sockets
2. Remote Procedure Call
3. Threads
Why RPC?

- The typical programmer is trained to write single-threaded code that runs in **one place**

- **Goal:** Easy-to-program network communication that makes client-server communication **transparent**
  - Retains the “feel” of writing centralized code
    - Programmer needn’t think about the network

- Course programming assignments use RPC
What’s the goal of RPC?

- Within a single program, running in a single process, recall the well-known notion of a **procedure call**:
  - **Caller** pushes arguments onto stack,
    - jumps to address of **callee** function
  - **Callee** reads arguments from stack,
    - executes, puts return value in register,
    - returns to next instruction in caller

**RPC’s Goal:** To make communication appear like a **local** procedure call: **transparency** for procedure calls
Historical note

• Seems obvious in retrospect, but RPC was only invented in the ’80s
• See Birrell & Nelson, “Implementing Remote Procedure Call” ... or
RPC issues

1. Heterogeneity
   – Client needs to **rendezvous** with the server
   – Server must **dispatch** to the required function
     • What if server is **different** type of machine?

2. Failure
   – What if messages get **dropped**?
   – What if client, server, or network **fails**?

3. Performance
   – Procedure call takes ≈ 10 cycles ≈ 3 ns
   – RPC in a data center takes ≈ 10 μs (10^3 × slower)
     • In the wide area, typically 10^6 × slower
Problem: Differences in data representation

- Not an issue for local procedure call

- For a remote procedure call, a remote machine may:
  - Represent data types using different sizes
  - Use a different byte ordering (endianness)
  - Represent floating point numbers differently
  - Have different data alignment requirements
    - e.g., 4-byte type begins only on 4-byte memory boundary
Problem: Differences in programming support

• Language support varies:
  – Many programming languages have no inbuilt concept of remote procedure calls
    • e.g., C, C++, earlier Java: won’t generate stubs
  – Some languages have support that enables RPC
    • e.g., Python, Haskell, Go
Solution: Interface Description Language

- Mechanism to pass procedure parameters and return values in a machine-independent way

- Programmer may write an *interface description* in the IDL
  - Defines API for procedure calls: names, parameter/return types

- Then runs an *IDL compiler* which generates:
  - Code to *marshal* (convert) native data types into machine-independent byte streams
    - And vice-versa, called *unmarshaling*

- **Client stub**: Forwards local procedure call as a request to server

- **Server stub**: Dispatches RPC to its implementation
A day in the life of an RPC

1. Client calls stub function (pushes params onto stack)

Client machine

Client process
\[ k = \text{add}(3, 5) \]

Client stub (RPC library)
A day in the life of an RPC

1. Client calls stub function (pushes params onto stack)

2. Stub marshals parameters to a network message
A day in the life of an RPC

2. Stub marshals parameters to a network message

3. OS sends a network message to the server

![Diagram showing the life cycle of an RPC, including client and server machines, process, stub, and OS interactions.]

- Client machine
  - Client process
    - $k = \text{add}(3, 5)$
  - Client stub (RPC library)
  - Client OS
    - proc: add | int: 3 | int: 5

- Server machine
  - Server OS
    - proc: add | int: | int: 5
A day in the life of an RPC

3. OS sends a network message to the server

4. Server OS receives message, sends it up to stub

Client machine

Client process
k = add(3, 5)

Client stub (RPC library)

Client OS

Server machine

Server stub (RPC library)

Server OS
proc: add | int: 3 | int: 5
A day in the life of an RPC

4. Server OS receives message, sends it up to stub

5. Server stub unmarshals params, calls server function
A day in the life of an RPC

5. Server stub unmarshals params, calls server function

6. Server function runs, returns a value
A day in the life of an RPC

6. Server function runs, returns a value

7. Server stub marshals the return value, sends msg

Client machine
- Client process
  - $k = \text{add}(3, 5)$
- Client stub (RPC library)
- Client OS

Server machine
- Server process
  - $8 \leftarrow \text{add}(3, 5)$
- Server stub (RPC library)
  - Result | int: 8
- Server OS
A day in the life of an RPC

7. Server stub marshals the return value, sends msg

8. Server OS sends the reply back across the network
A day in the life of an RPC

8. Server OS sends the reply back across the network

9. Client OS receives the reply and passes up to stub

Client machine

Client process
k = add(3, 5)

Client stub (RPC library)

Client OS

Result | int: 8

Server machine

Server process
8 ← add(3, 5)

Server stub (RPC library)

Server OS
9. Client OS receives the reply and passes up to stub

10. Client stub unmarshals return value, returns to client
The server stub is really two parts

- **Dispatcher**
  - Receives a client’s RPC request
    - **Identifies** appropriate server-side method to invoke

- **Skeleton**
  - **Unmarshals** parameters to server-native types
  - **Calls** the local server procedure
  - **Marshals** the response, sends it back to the dispatcher

- **All this is hidden from the programmer**
  - Dispatcher and skeleton may be integrated
    - **Depends on implementation**
Today’s outline

1. Message-Oriented Communication

2. Remote Procedure Call
   - Rendezvous and coordination
   - Failure
   - Performance

3. Threads
What could possibly go wrong?

1. Client may crash and reboot

2. Packets may be dropped
   - Some individual **packet loss** in the Internet
   - **Broken routing** results in many lost packets

3. Server may crash and reboot

4. Network or server might just be very slow

All these may look the same to the client...
Failures, from client’s perspective

The cause of the failure is hidden from the client!
At-Least-Once scheme

- **Simplest** scheme for handling failures

1. Client stub **waits for a response**, for a while
   - Response takes the form of an **acknowledgement message** from the server stub

2. If no response arrives after a fixed **timeout** time period, then client stub **re-sends the request**

- Repeat the above a few times
  - **Still no response?** Return an error to the application
At-Least-Once and side effects

- Client sends a “debit $10 from bank account” RPC
At-Least-Once and writes

- put($x$, $value$), then get($x$): expect answer to be $value$
At-Least-Once and writes

- Consider a client storing key-value pairs in a database – put(x, value), then get(x): expect answer to be value
So is At-Least-Once ever okay?

- **Yes**: If they are read-only operations with no side effects
  - *e.g.*, read a key’s value in a database

- **Yes**: If the application has its own functionality to cope with duplication and reordering
  - You will need this in Assignments 3 onwards
At-Most-Once scheme

- **Idea:** server RPC code detects duplicate requests
  - Returns previous reply *instead of re-running handler*

- **How to detect a duplicate request?**
  - **Test:** Server sees same function, same arguments twice
  - **No!** Sometimes applications *legitimately* submit the same function with same augments, twice in a row
At-Most-Once scheme

• How to detect a duplicate request?
  – Client includes unique transaction ID (xid) with each one of its RPC requests
  – Client uses same xid for retransmitted requests

```python
At-Most-Once Server
if seen[xid]:
  retval = old[xid]
else:
  retval = handler()
old[xid] = retval
seen[xid] = True
return retval
```
At Most Once: Ensuring unique XIDs

• How to ensure that the xid is unique?

1. Combine a unique client ID (e.g., IP address) with the current time of day

2. Combine unique client ID with a sequence number
   – Suppose the client crashes and restarts. Can it reuse the same client ID?

3. Big random number
At-Most-Once: Discarding server state

- **Problem**: seen and old arrays will grow without bound

- **Observation**: By construction, when the client gets a response to a particular xid, it will never re-send it

- Client could **tell** server “I’m done with xid x – delete it”
  - Have to tell the server about each and every retired xid
  - Could **piggyback** on subsequent requests

Significant overhead if many RPCs are in flight, in parallel
At-Most-Once: Discarding server state

- **Problem:** seen and old arrays will **grow without bound**

- Suppose xid = ⟨unique client id, sequence no.⟩
  - e.g. ⟨42, 1000⟩, ⟨42, 1001⟩, ⟨42, 1002⟩

- Client includes “seen all replies ≤ X” with every RPC
  - Much like TCP sequence numbers, acks

- *How does the client **know** that the server received the information about retired RPCs?*
  - Each one of these is cumulative: later seen messages subsume earlier ones
At-Most-Once: Concurrent requests

- **Problem:** How to handle a duplicate request while the original is still executing?
  - Server doesn’t know reply yet. Also, we don’t want to run the procedure twice

- **Idea:** Add a *pending* flag per executing RPC
  - Server waits for the procedure to finish, or ignores
At Most Once: Server crash and restart

- **Problem:** Server may crash and restart

- *Does server need to write its tables to disk?*

- Yes! On **server crash and restart:**
  - If `old[ ]`, `seen[ ]` tables are only in memory:
    - Server will forget, **accept duplicate requests**
Go’s net/rpc is at-most-once

- Opens a TCP connection and writes the request
  - TCP may retransmit but server's TCP receiver will filter out duplicates internally, with sequence numbers
  - No retry in Go RPC code (i.e. will not create a second TCP connection)

- However: Go RPC returns an error if it doesn't get a reply
  - Perhaps after a TCP timeout
  - Perhaps server didn’t see request
  - Perhaps server processed request but server/net failed before reply came back
RPC and Assignments 1 and 2

• Go’s RPC **isn’t enough** for Assignments 1 and 2
  – It only applies to a single RPC call

  – If worker doesn't respond, master **re-sends** to another
  • Go RPC **can't detect** this kind of duplicate

  – **Breaks at-most-once** semantics
  • No problem in Assignments 1 and 2 (handles at application level)

• In Assignment 3 you will explicitly detect duplicates using something like what we’ve talked about
Exactly-once?

- Need retransmission of at least once scheme

- Plus the duplicate filtering of at most once scheme
  - To survive client crashes, client needs to record pending RPCs on disk
    - So it can replay them with the same unique identifier

- Plus story for making server reliable
  - Even if server fails, it needs to continue with full state
  - To survive server crashes, server should log to disk results of completed RPCs (to suppress duplicates)

- Similar to Two-Phase Commit (later)
Exactly-once for external actions?

• Imagine that the remote operation triggers an external physical thing
  – e.g., dispense $100 from an ATM

• The ATM could crash immediately before or after dispensing and lose its state
  – Don’t know which one happened
    • Can, however, make this window very small

• **So can’t achieve exactly-once in general, in the presence of external actions**
Summary: RPC

- **RPC everywhere!**
- **Necessary** issues surrounding machine heterogeneity
- **Subtle** issues around handling **failures**
Today’s outline

1. Network Sockets
2. Remote Procedure Call
3. Threads
Threads

• One goal of this class is to give you experience and wisdom dealing with threads – they are tricky!

• **Go terminology:** threads \( \sim \) goroutines

• Thread = Program counter + set of registers: an execution context
  – Can be multiple threads in the same shared memory address space
Data races

- Challenge: Sharing data
  - Two threads write same memory location
  - One thread writes same memory location, other reads

- Called a *race*

- x = 0 initially. **Thread 1**: x ← x+1; **Thread 2**: x ← x+1
  - Answer has to be 2, but if they run together can get 1
    - Both threads read x before either writes back

- To fix: wrap access to the same variable with a go *mutex*
Waiting

• One thread wants to wait for the other thread to finish

• In Go, use **Channels** for communication between threads

• But beware **deadlock**: can be cycles in the waiting
  – Thread 1 waiting for thread 2 to do something
  – Thread 2 waiting for thread 1 to do something
  – Sounds silly but comes up if you are not careful!
Next lecture topic:
Virtualization and Cloud computing
APPENDIX
Review: Byte order

• x86-64 is a **little endian** architecture
  – Least significant byte of multi-byte entity at **lowest** memory address
    • “Little end goes first”

• Some other systems use **big endian**
  – Most significant byte of multi-byte entity at **lowest** memory address
    • “Big end goes first”

```
0x1000:  0000 0101
0x1001:  0000 0000
0x1002:  0000 0000
0x1003:  0000 0000
```

```
0x1000:  0000 0000
0x1001:  0000 0000
0x1002:  0000 0000
0x1003:  0000 0101
```