Remote Procedure Call (RPC)

CS 4740: Cloud Computing

Fall 2024

Lecture 5

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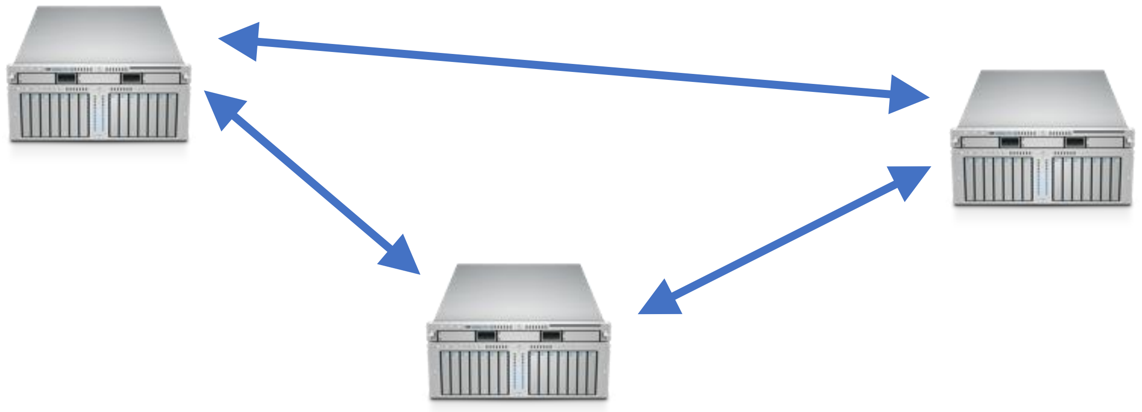
Some material taken/derived from:
- Princeton COS-418 materials created by Michael Freedman and Wyatt Lloyd.
- MIT 6.824 by Robert Morris, Frans Kaashoek, and Nickolai Zeldovich.

Context



- Multiple computers
- Connected by a network
- Doing something together

- A ***distributed system*** is many cooperating computers that appear to users as a single service

Today's outline

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

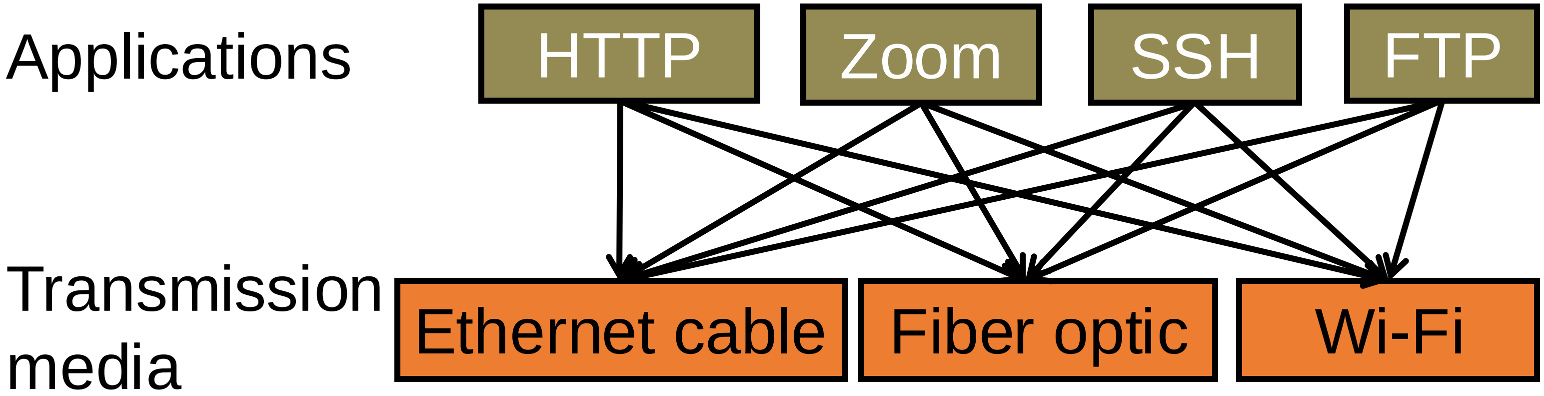
1. Network sockets

2. Remote procedure call

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 bits?
    - How does receiver know which is the last bit?
    - How many bits long is a number?

The problem of communication



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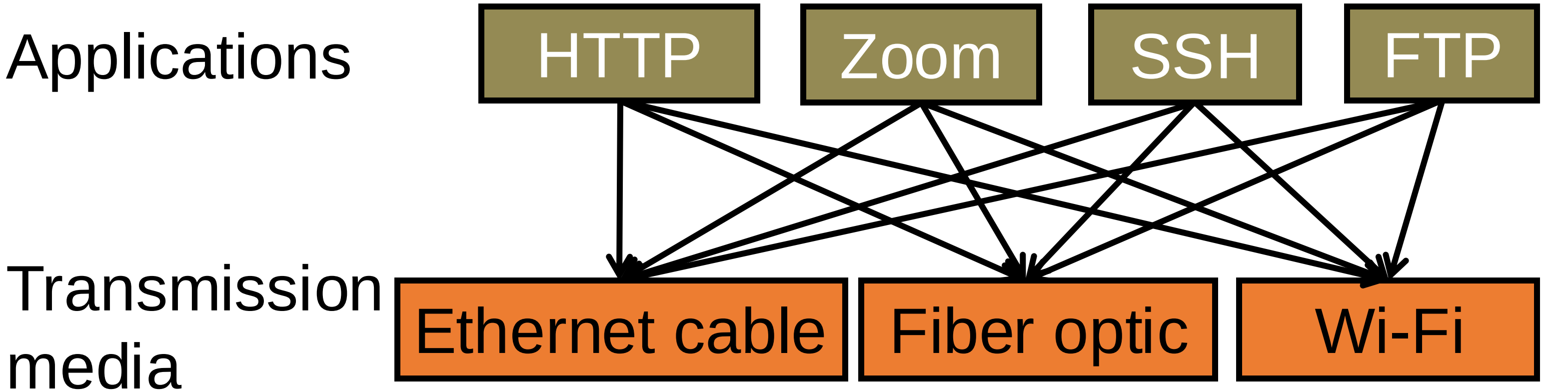

- Re-implement every application for every new underlying transmission medium?
- Change every application on any change to an underlying transmission medium?

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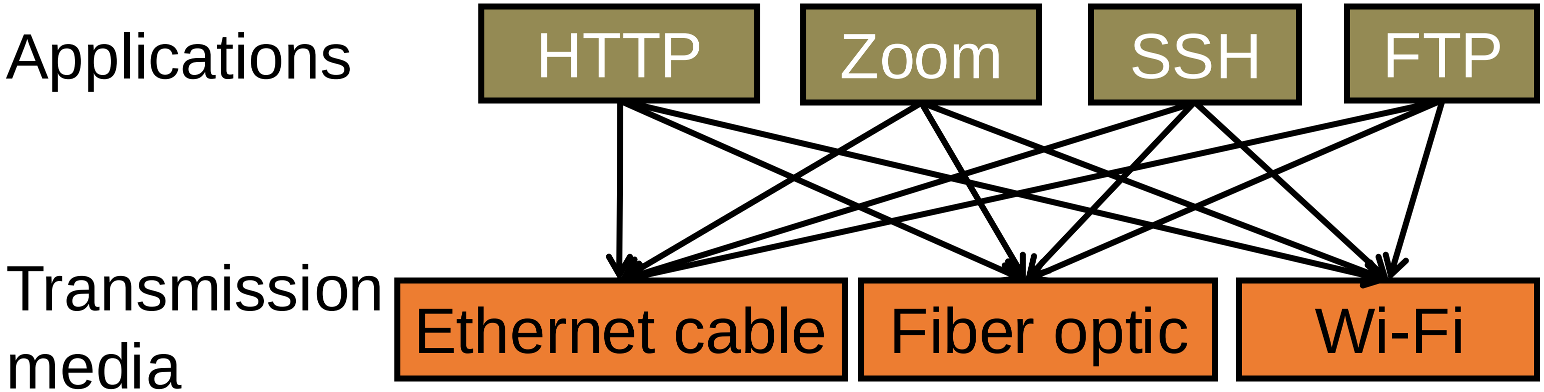
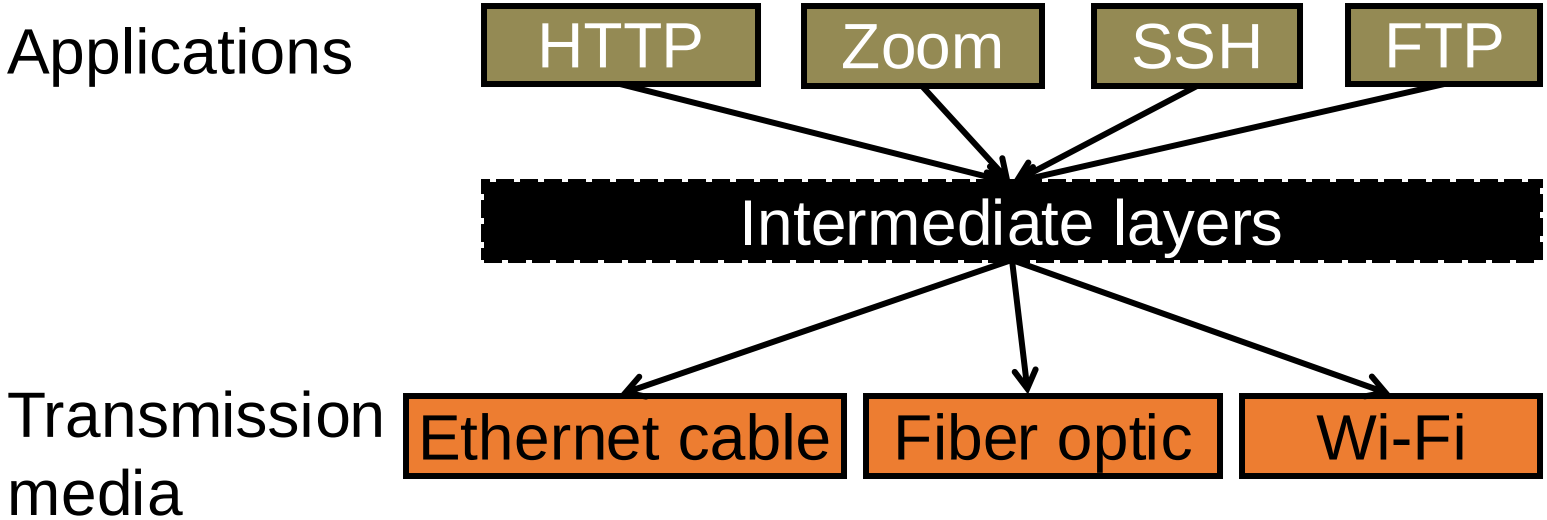


- Re-implement every application for every new underlying transmission medium?
- Change every application on any change to an underlying transmission medium?

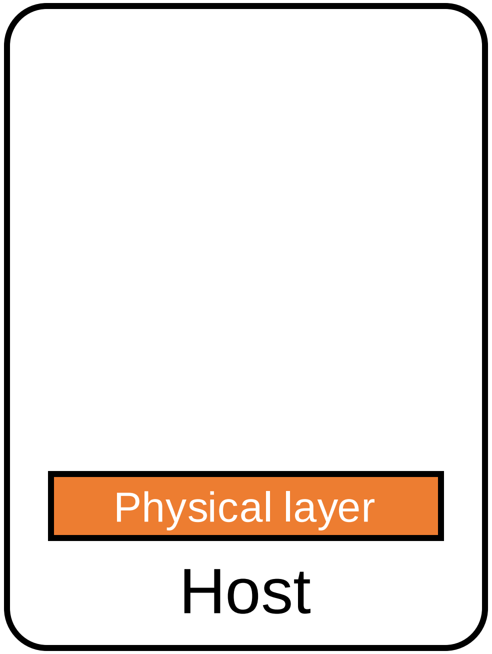
- No! But how does the Internet design avoid this?

Solution: Layering



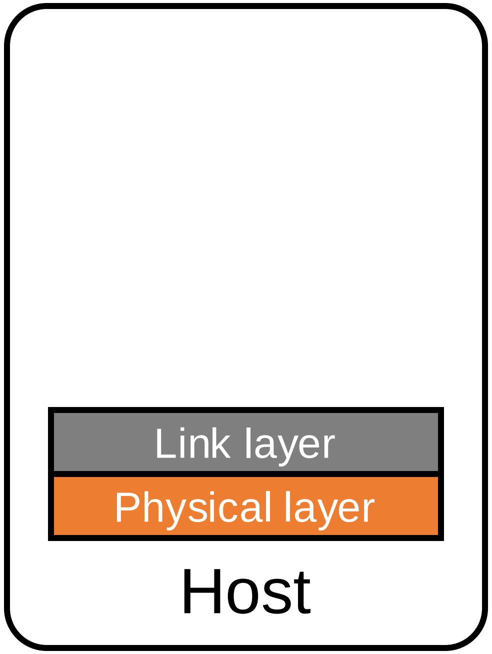
- Intermediate layers provide a set of abstractions for applications and media
- New applications or media need only implement for intermediate layer's interface

Layering in the Internet



- Physical: Moves bits between two hosts connected by a physical link

Layering in the Internet



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

- Physical: Moves bits between two hosts connected by a physical link

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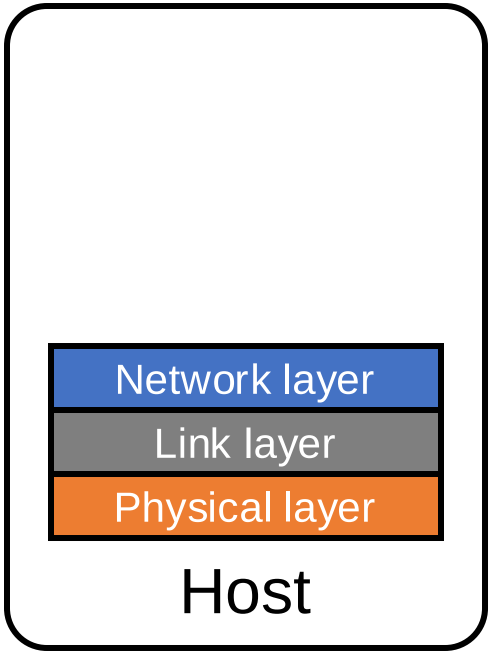

- Network: Deliver packets to destinations on other (heterogeneous) networks
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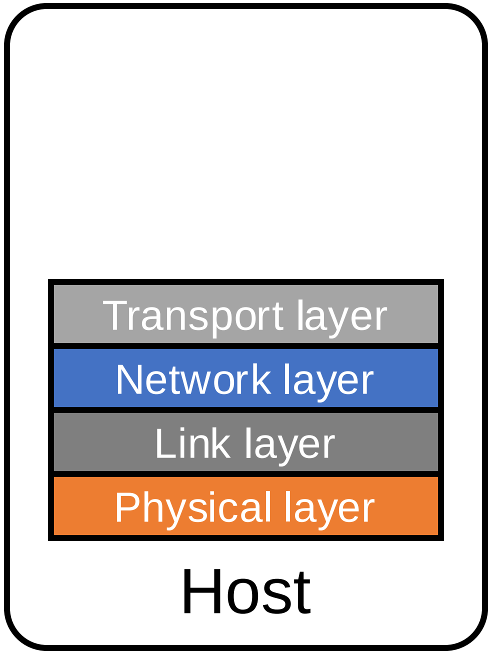

- Transport: Provide end-to-end communication between processes on different hosts
- Network: Deliver packets to destinations on other (heterogeneous) networks
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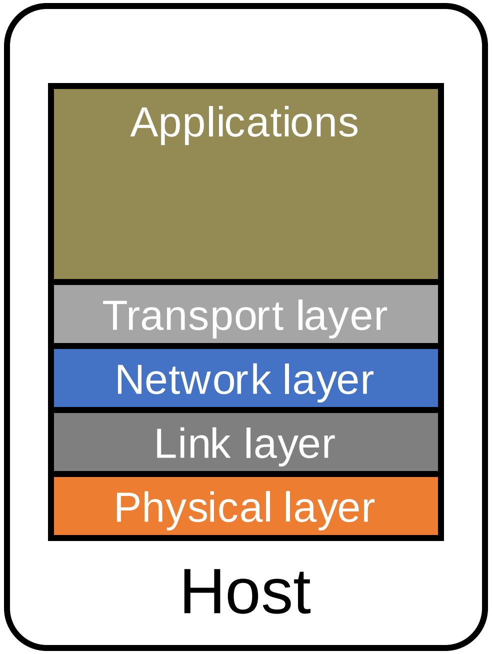

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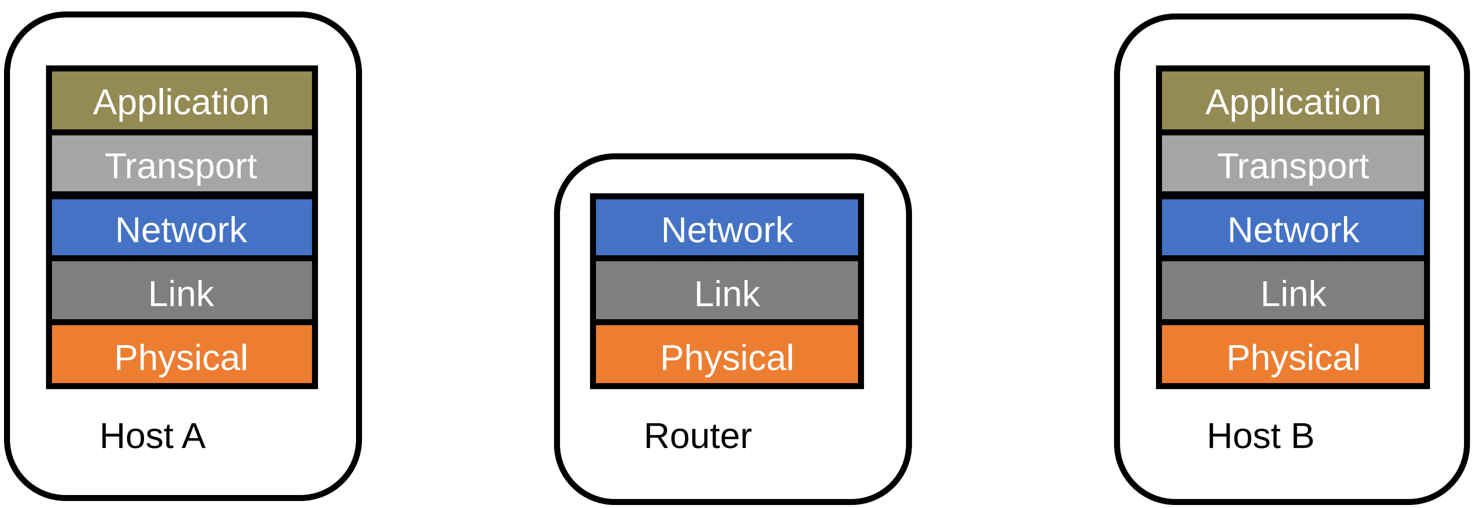
Logical communication between layers

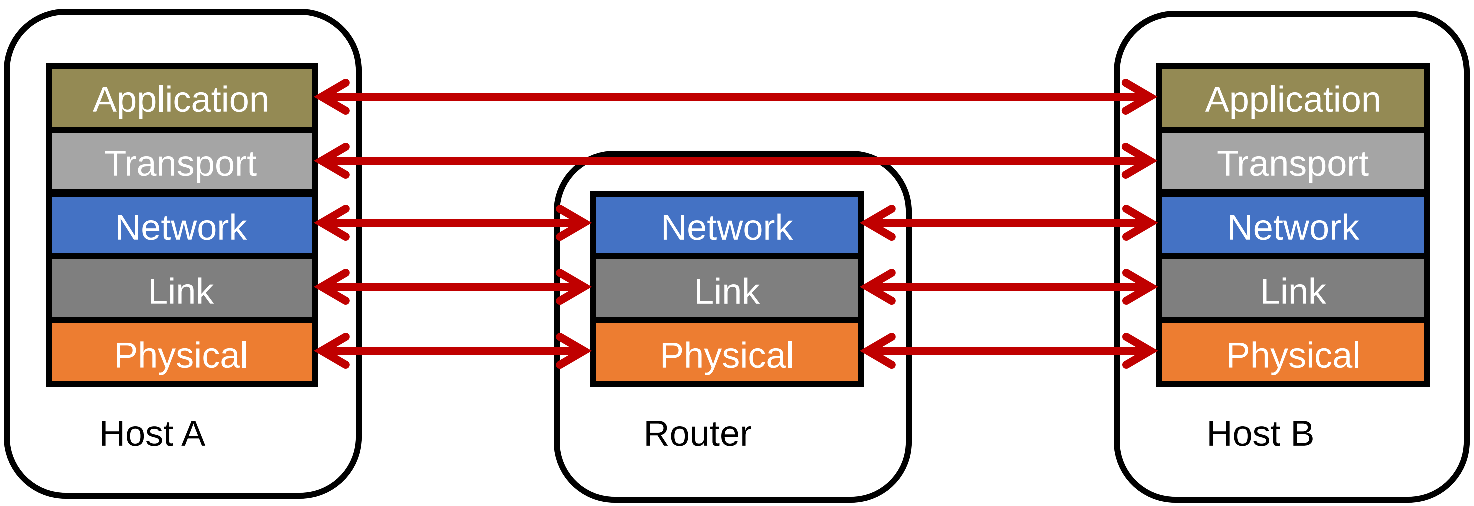
- How to forge agreement on the meaning of the bits exchanged between two hosts?



Logical communication between layers

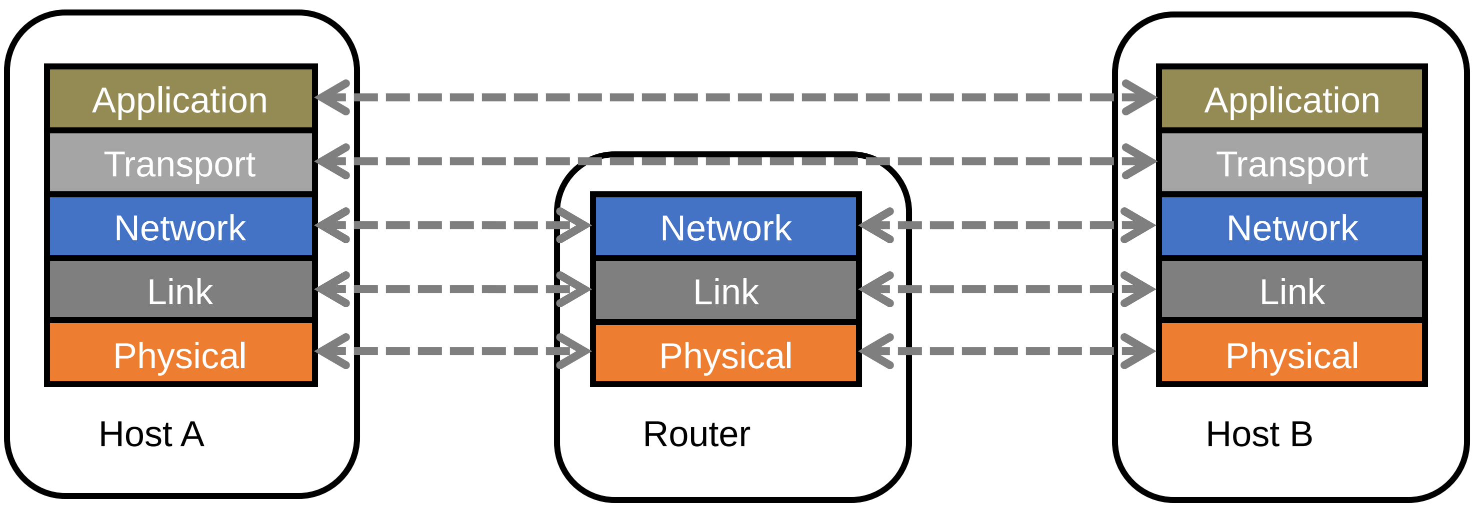
- How to forge agreement on the meaning of the bits exchanged between two hosts?

- **Protocol:** Rules that govern 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



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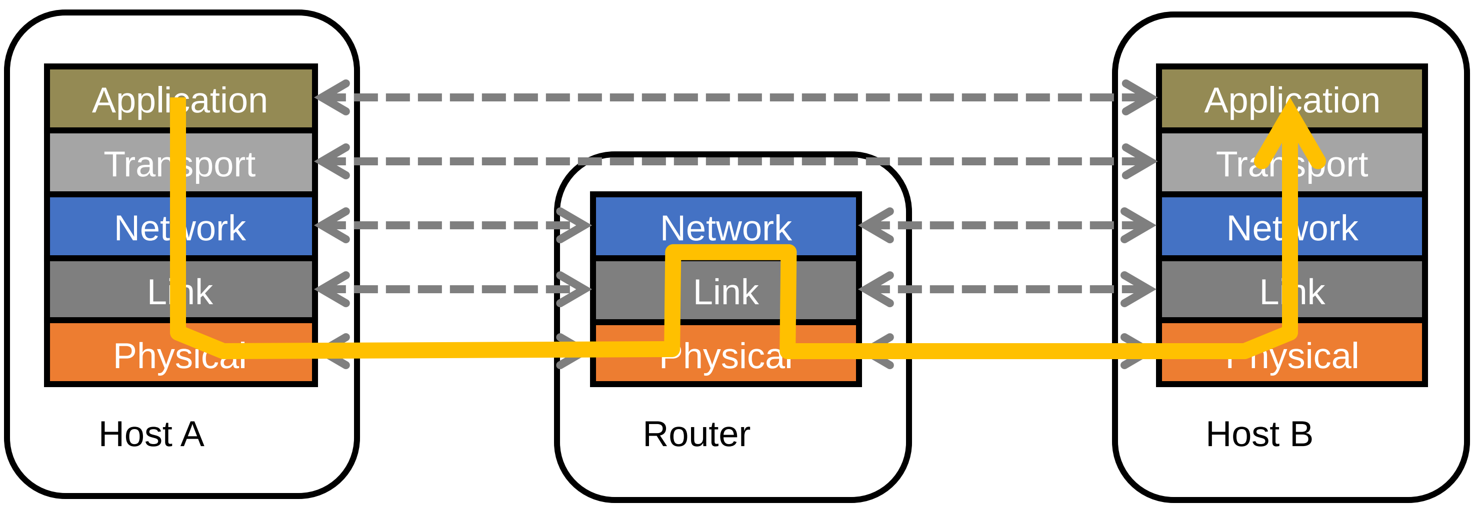
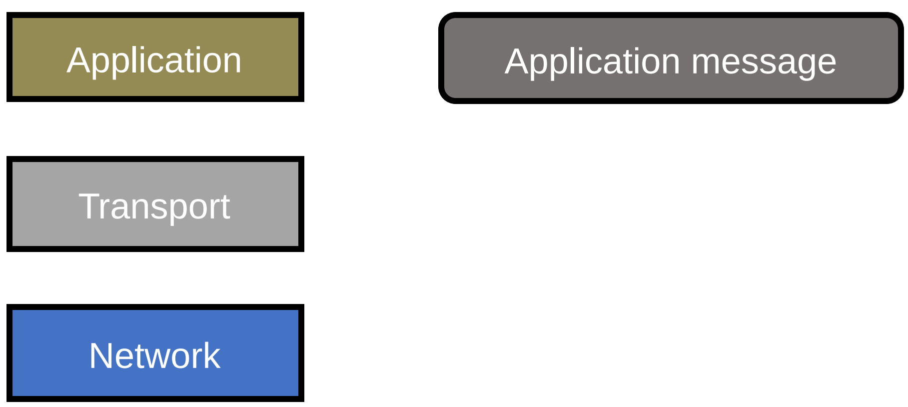


Communication between layers

- 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



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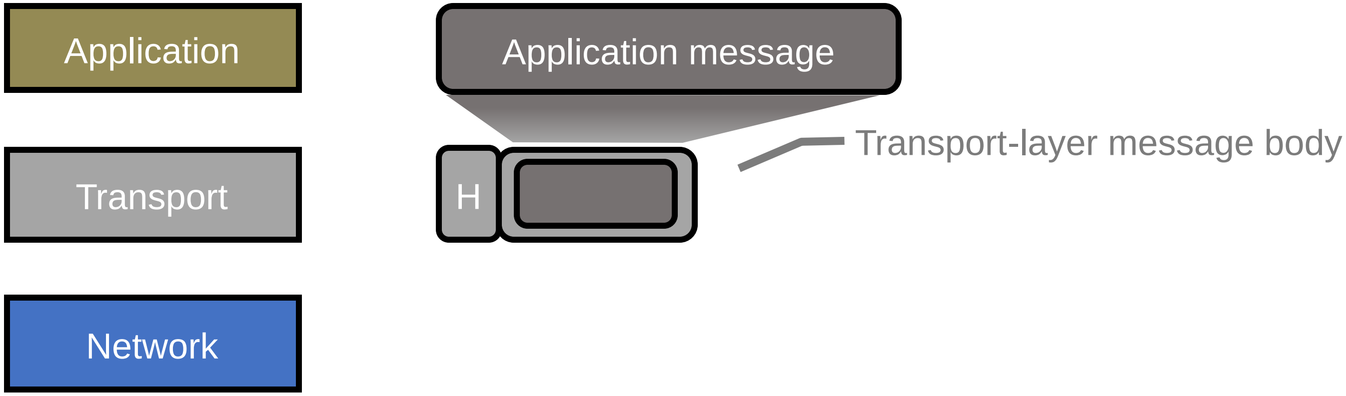

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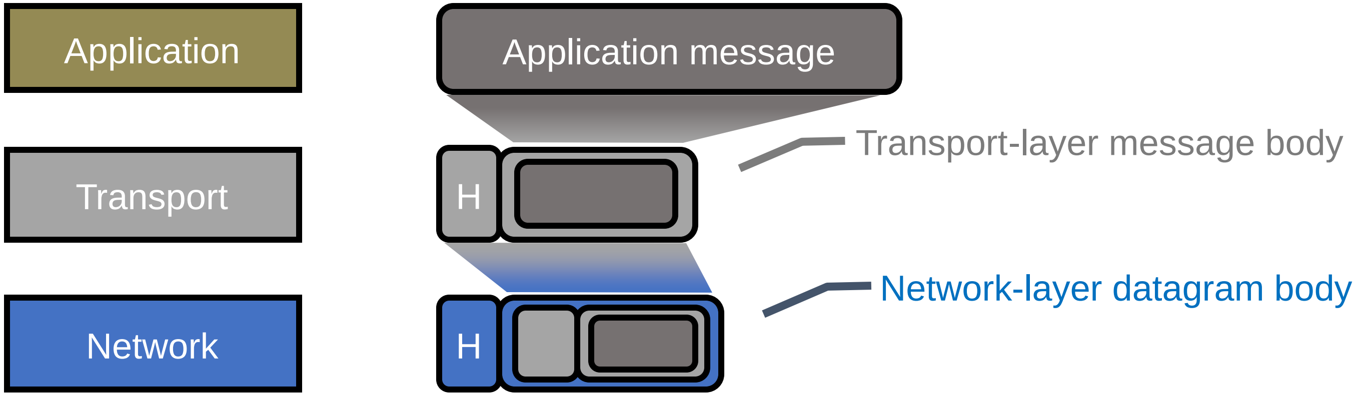
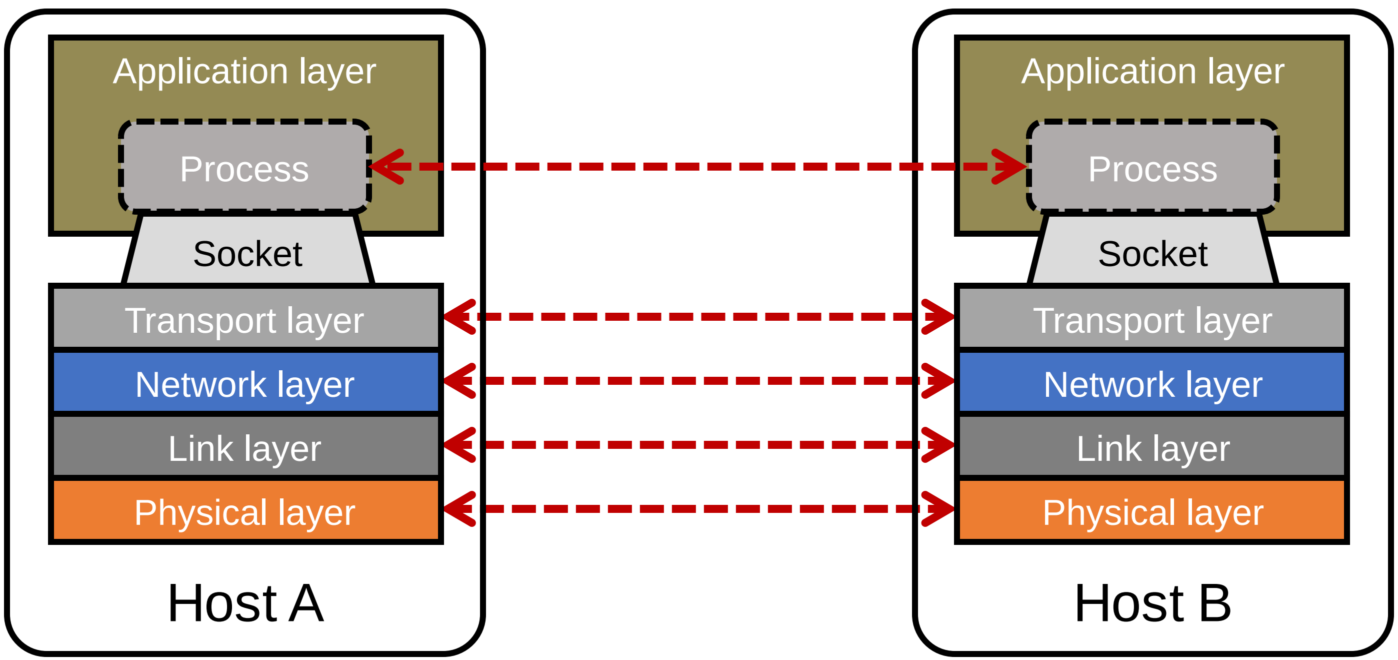


Network socket-based communication

- **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

// 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);
```

```c
// Create a socket for the client
if ((sockfd = socket (AF_INET, SOCK_STREAM, 0)) < 0) {
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```
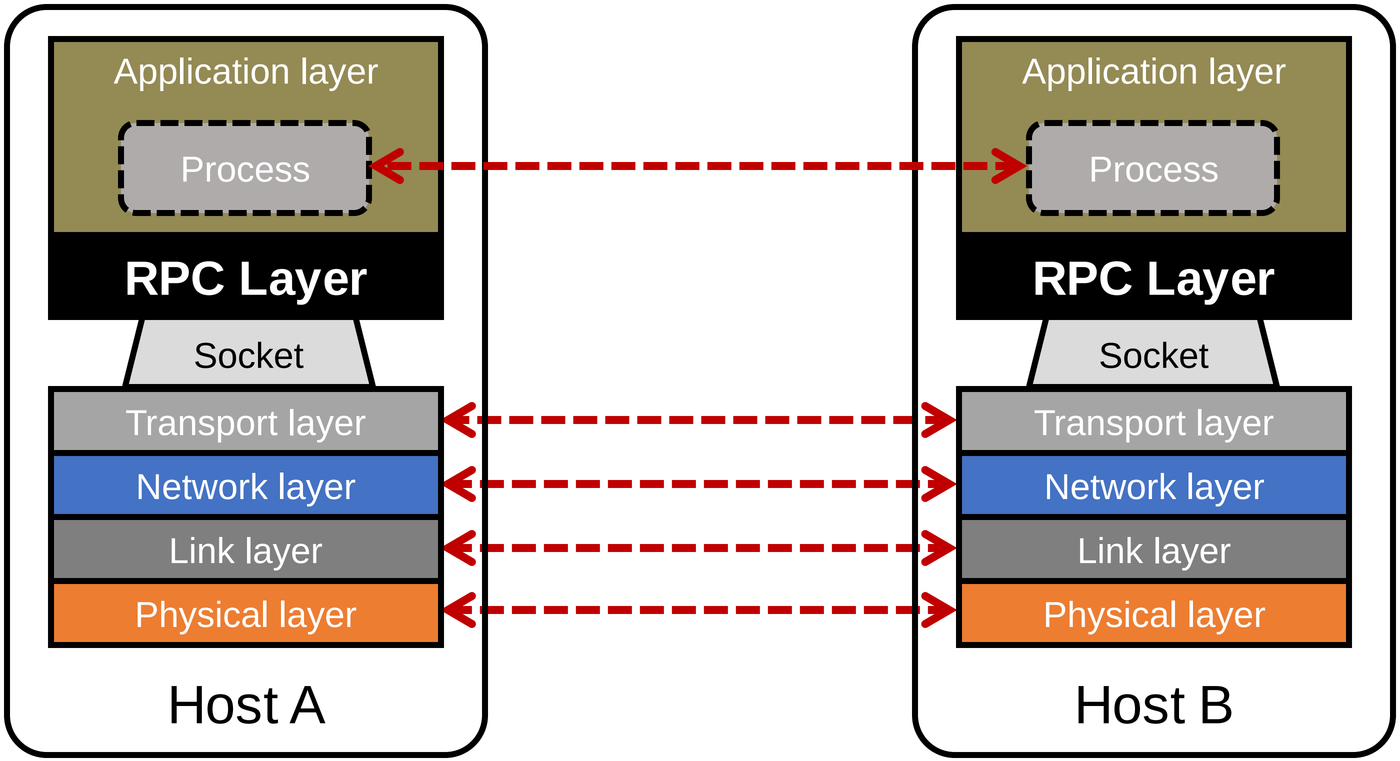

Sockets don’t provide transparency

Takeaway: Socket programming still not ideal (great)

- Lots for the programmer to deal with every time
  - How to separate different requests on the same connection?
  - How to write bytes to the network / read bytes from the network?
    - What if Host A's process is written in Go and Host B's process is in C++?
  - What to do with those bytes?
- Still pretty painful… Have to worry a lot about the network

Solution: Another layer!



Today's outline

1. Network sockets

2. Remote procedure call

Motivation: 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
- Labs use Go RPC (inbuilt lib and simulated ones)

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

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RPC's Goal: make communication appear like a local procedure call: transparency for procedure calls – way less painful than sockets…

RPC issues

1. Heterogeneity
   - Data representations are heterogeneous
   - Programming supports are heterogeneous
   - Server might be different type of machine

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3. Performance
   - Procedure call takes 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 calls

- For a remote procedure call, a remote machine may:
  - Run process written in a different language
  - 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 way of extracting values from complex types
    - C, C++
    - Effectively need sockets glue code underneath
  - Some languages have support that enables RPC
    - Python, Go
    - Exploit type system for some help

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
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- 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

IDL example: Protobuf

- Google's Protocol Buffer
  - A simple language-neutral and platform-neutral IDL for serializing structured data and defining programming interfaces
- gRPC uses Protocol Buffer

```
// The greeter service definition
service Greeter {
    // Sends a greeting
    rpc SayHello (HelloRequest) returns (HelloReply)
{}
}

// The request message containing user name
message HelloRequest {
    string name = 1;
}

// The response message containing the greetings
message HelloReply {
    string message = 1;
}
```

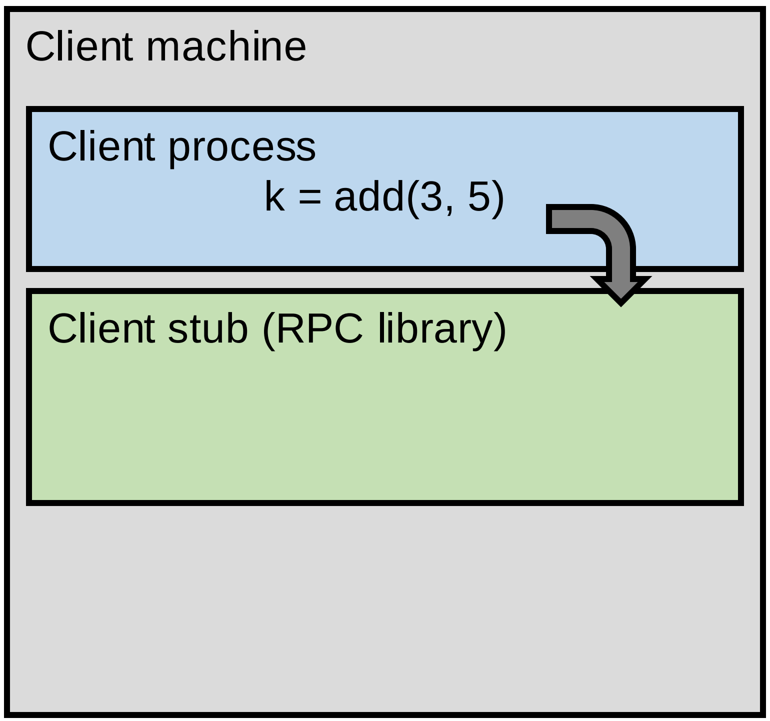
Protobuf: https://cloud.google.com/apis/design/proto3

Protobuf documentation: https://protobuf.dev/

gRPC: https://grpc.io/docs/what-is-grpc/introduction/

A day in the life of an RPC

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



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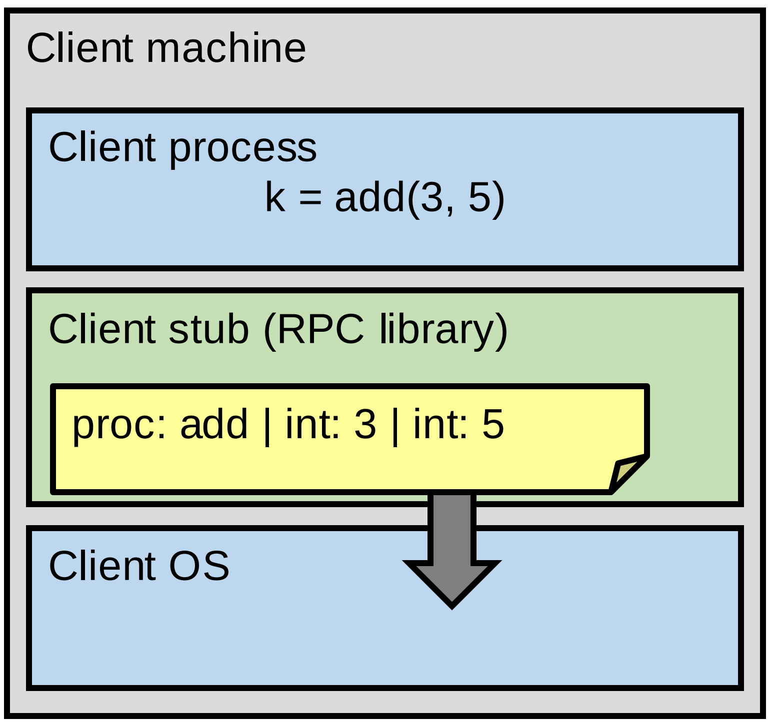
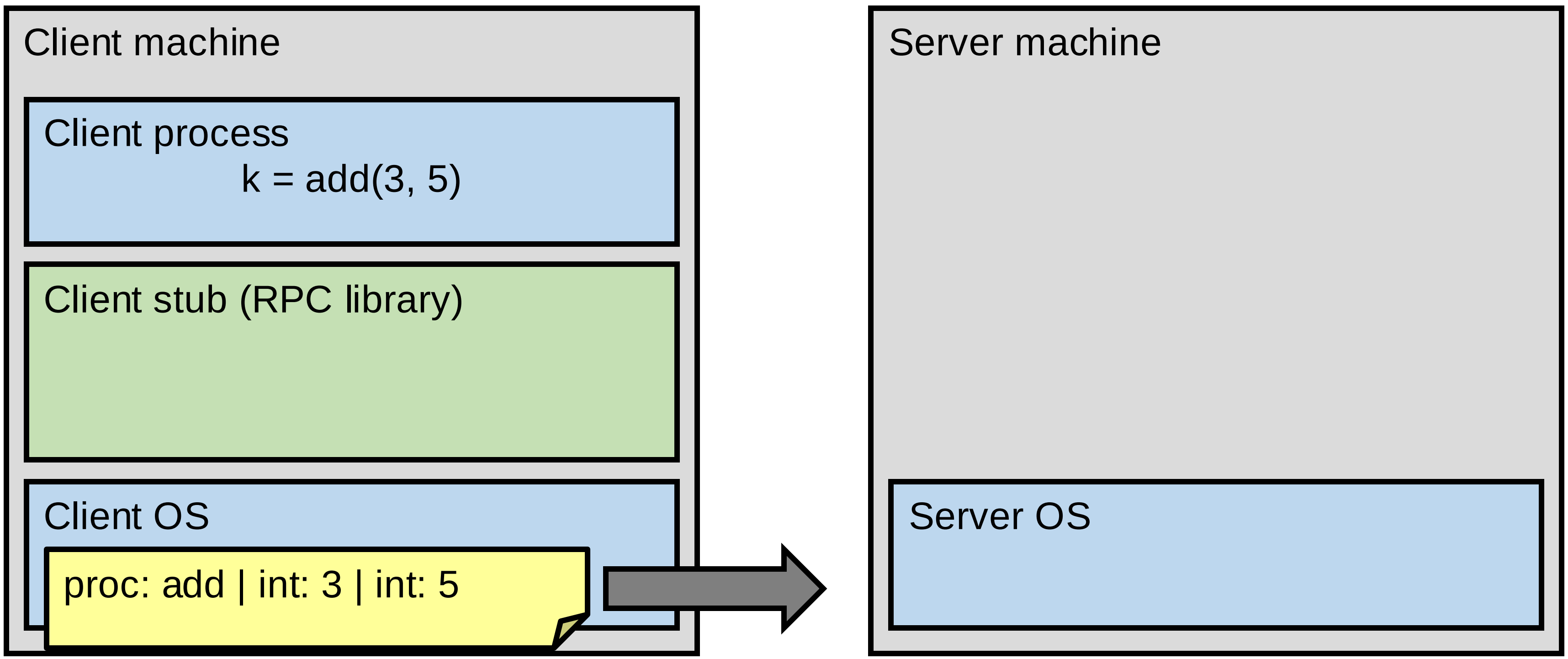


A day in the life of an RPC

2. Stub marshals parameters to a network message

3. OS sends a network message to the server



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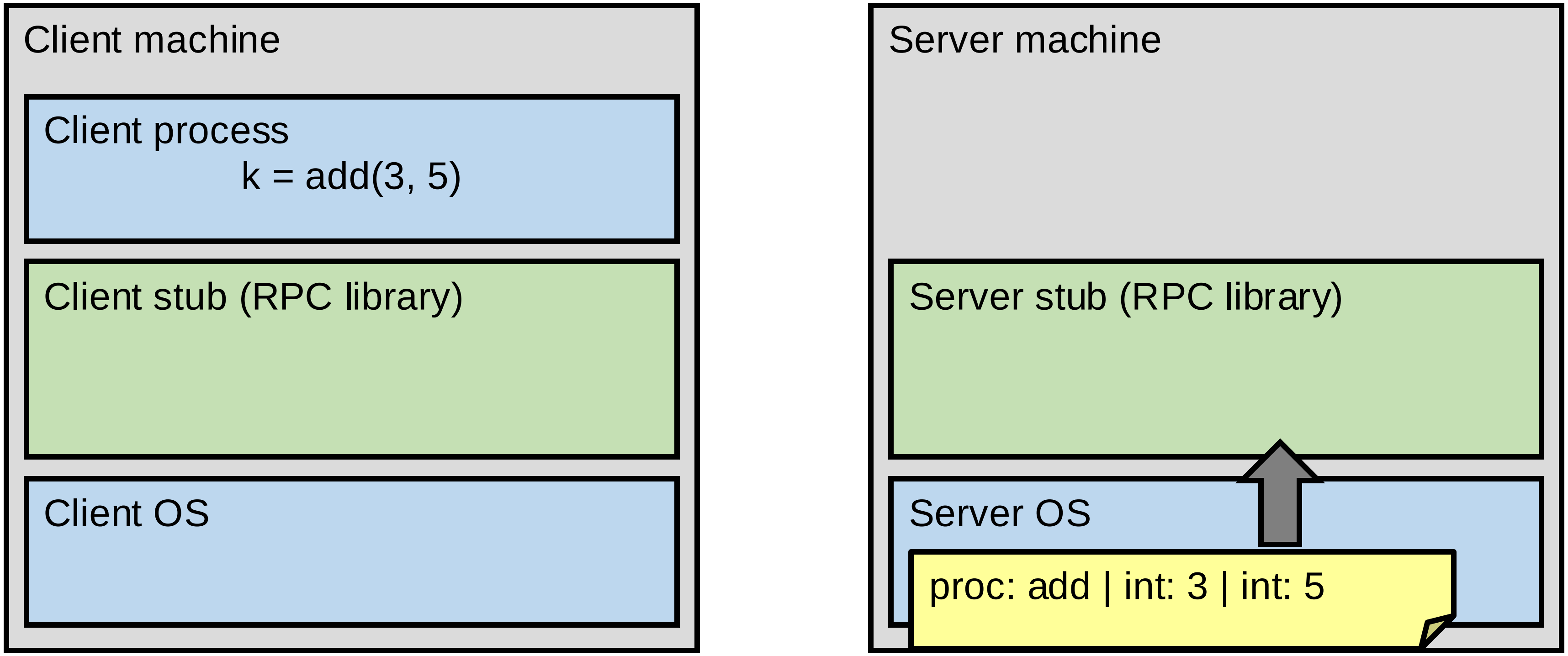
3. OS sends a network message to the server

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



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

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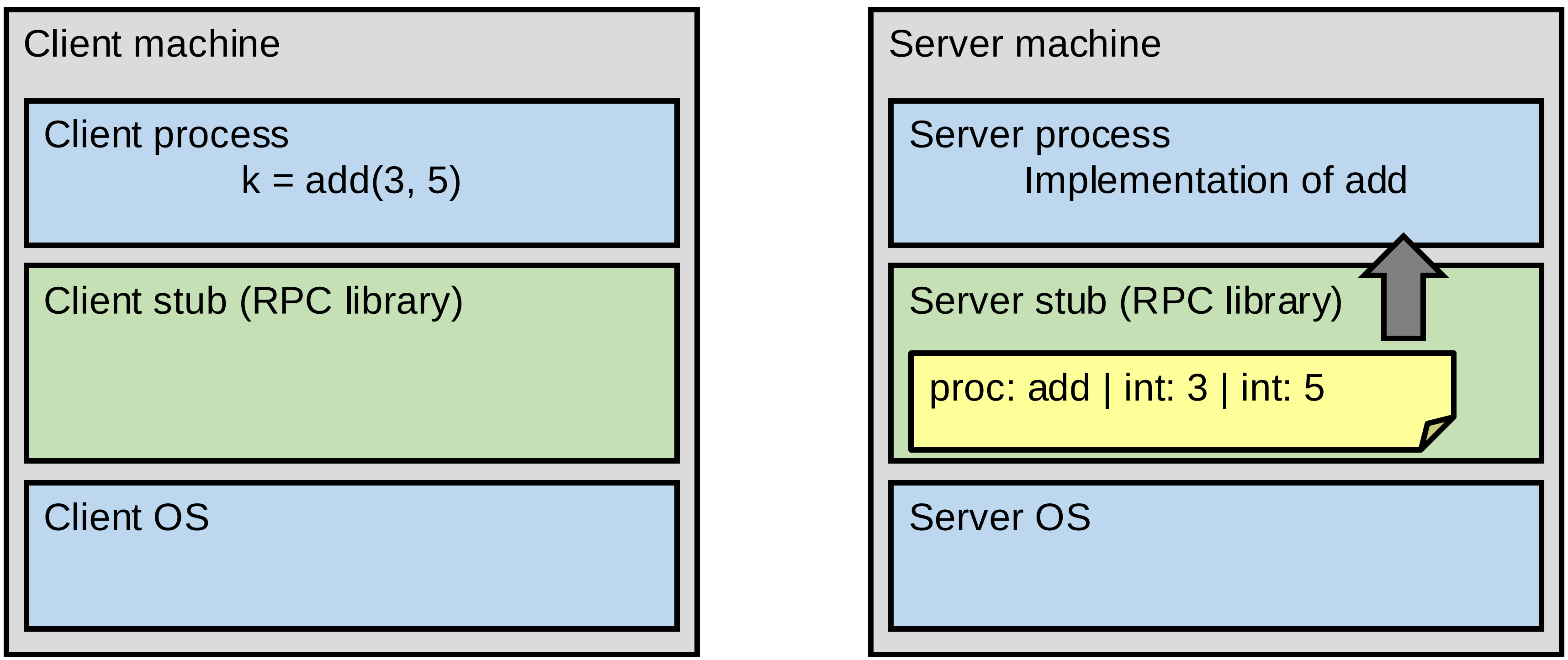

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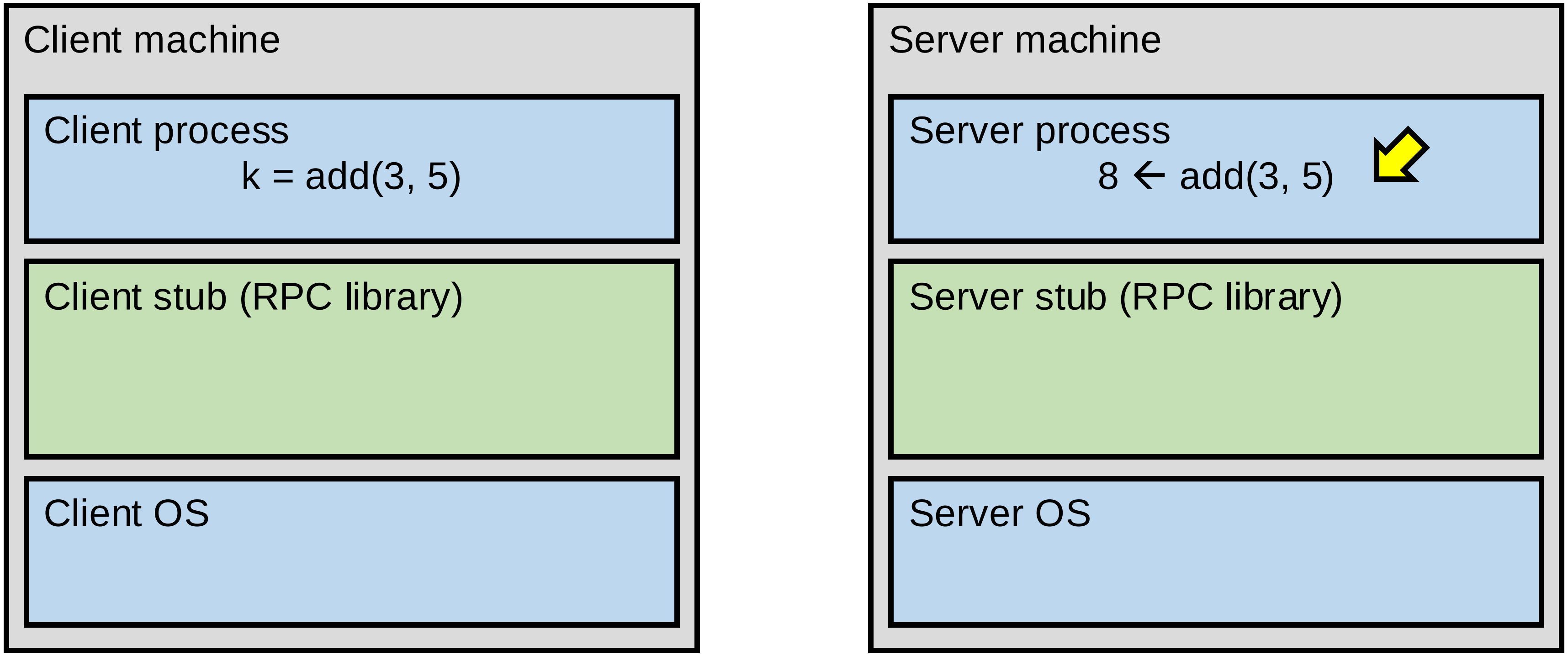
6. Server function runs, returns a value



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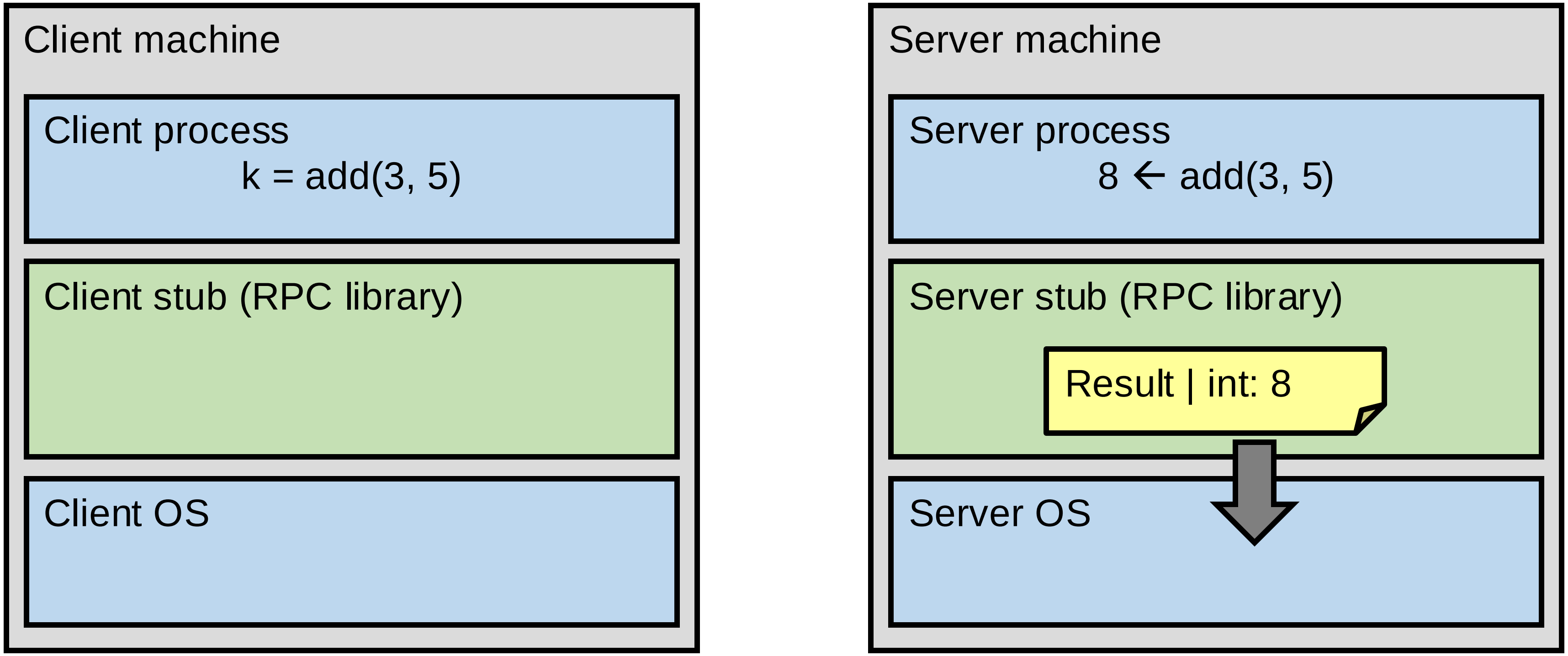

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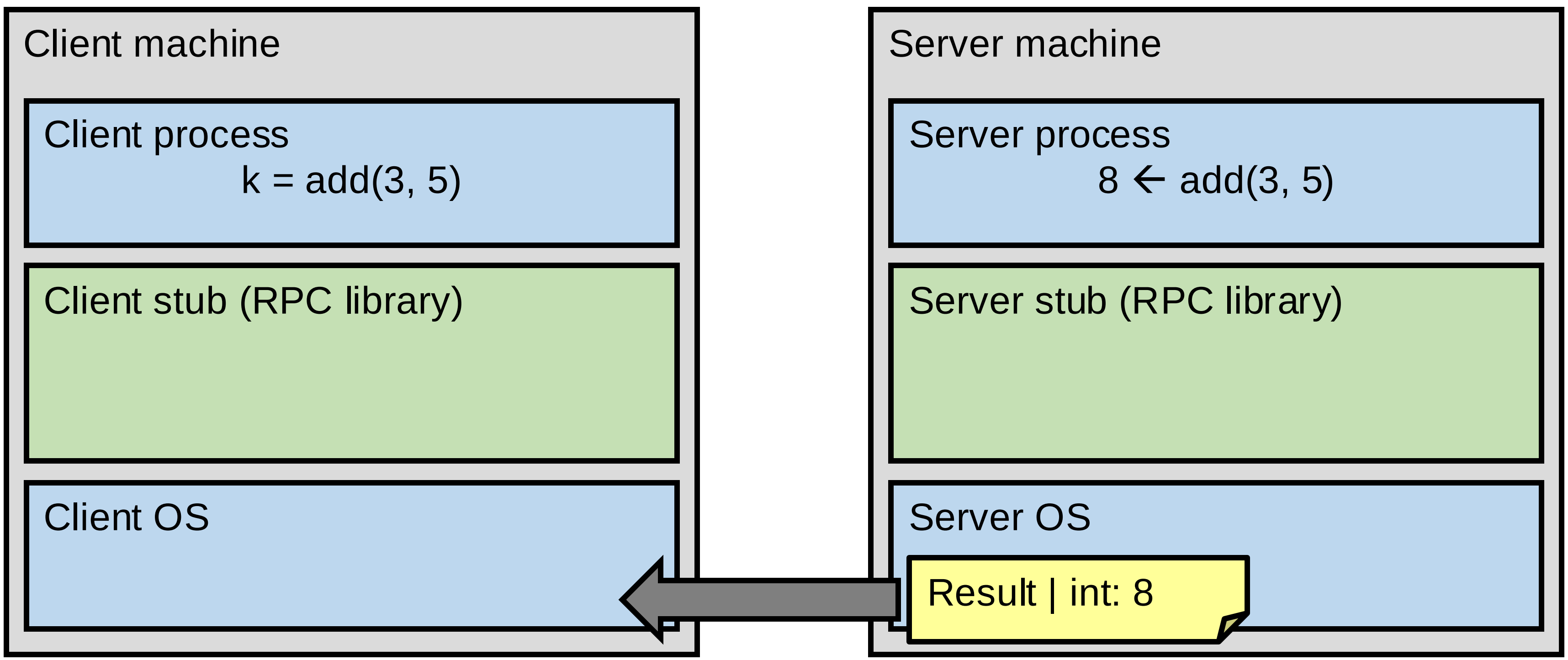
7. Server stub marshals the return value, sends message

8. Server OS sends the reply back across the network



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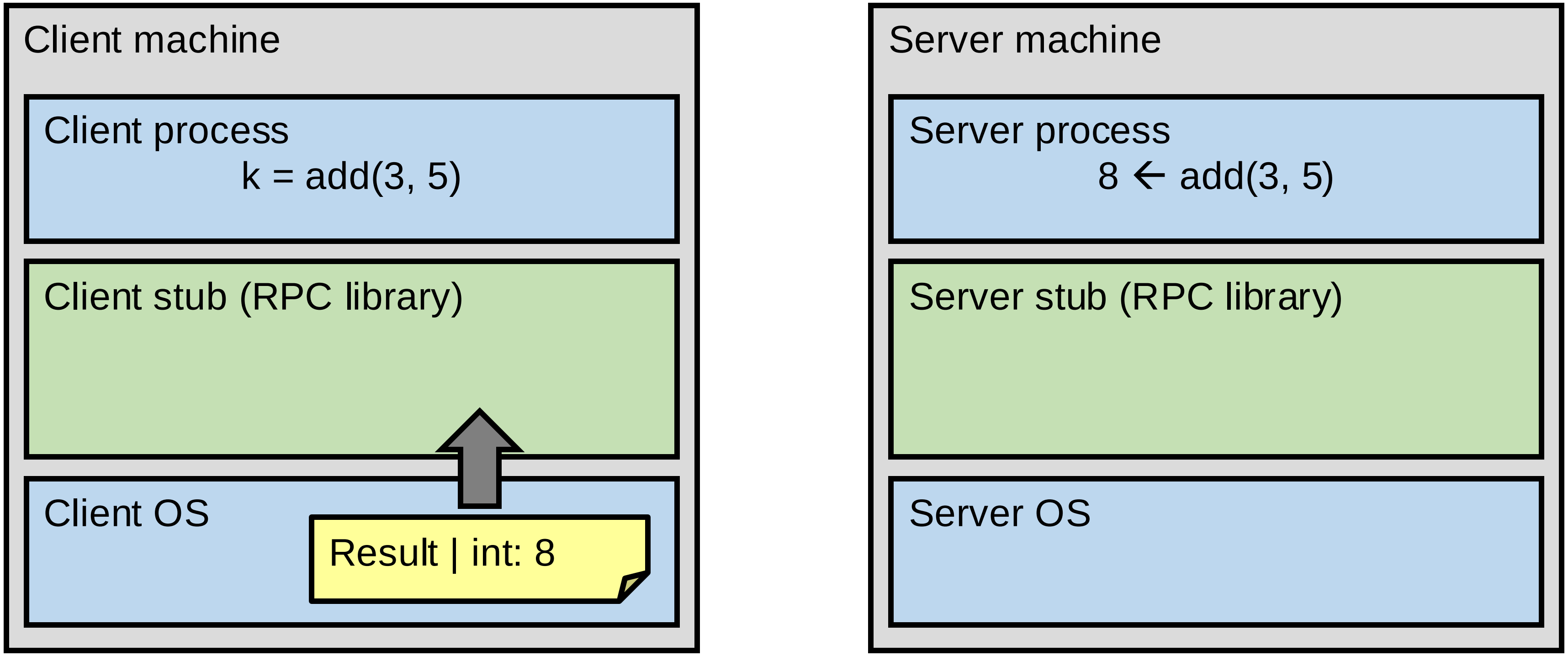
9. Client OS receives the reply and passes up to stub



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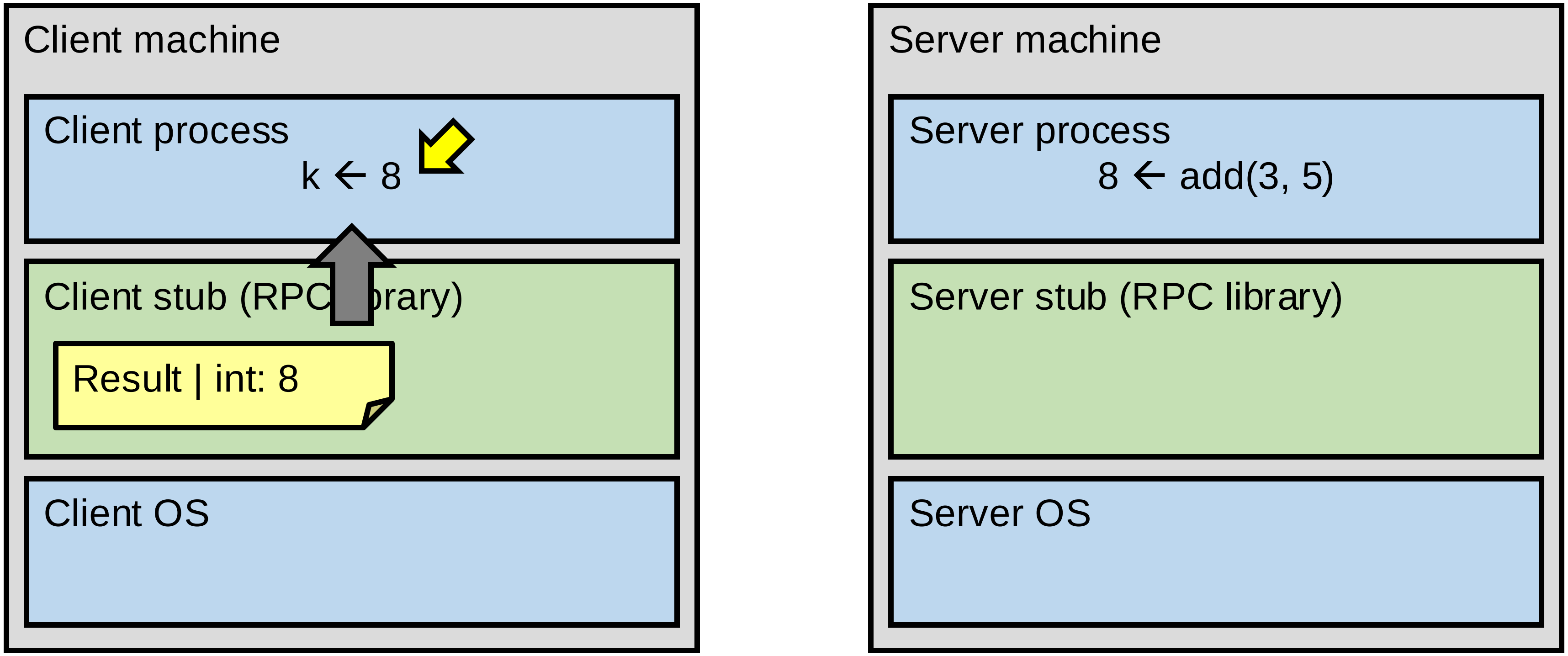
9. Client OS receives the reply and passes up to stub

10. Client stub unmarshals return value, returns to client



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2. Remote procedure call
    - Heterogeneity – use IDL w/ compiler
    - Failure

What could possibly go wrong?

1. Client may crash and reboot

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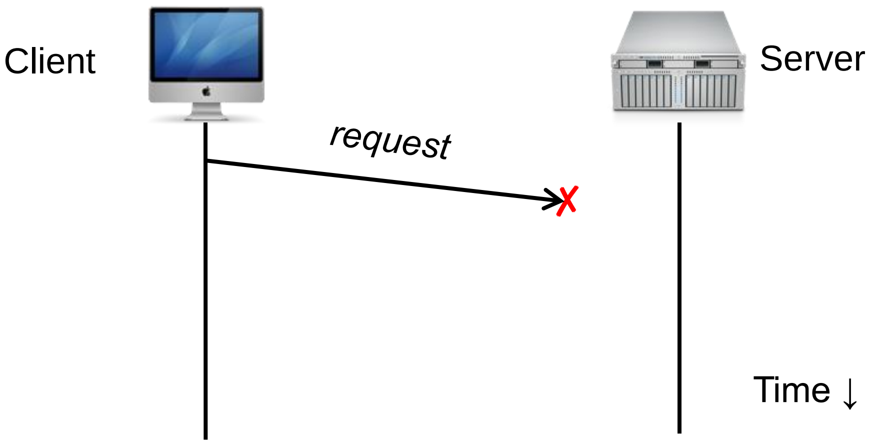
All of these may **look the same** to the client…

Failures, from client's perspective



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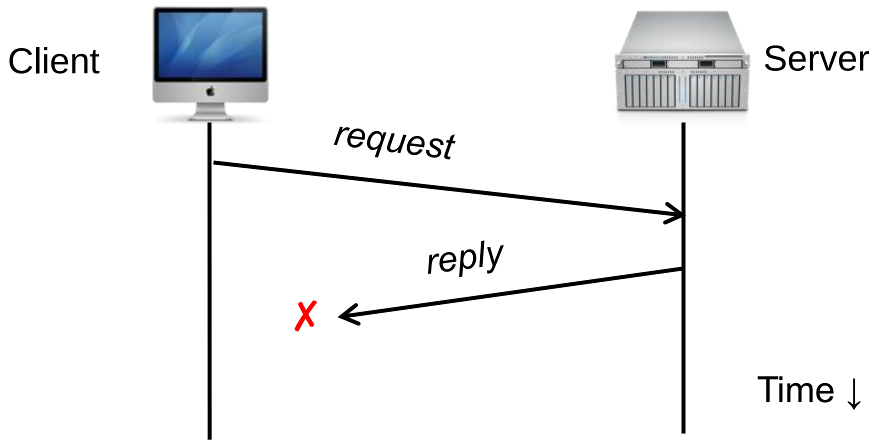

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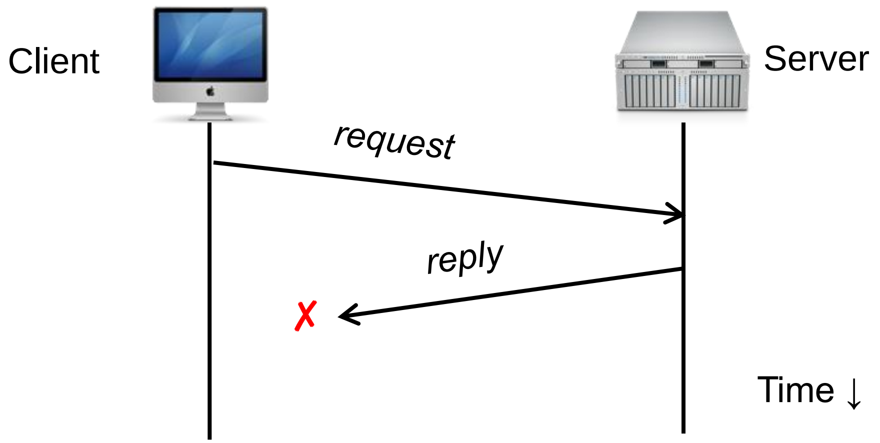

The cause of the failure is hidden from the client!

At-Least-Once scheme

- Simplest scheme for handling failures

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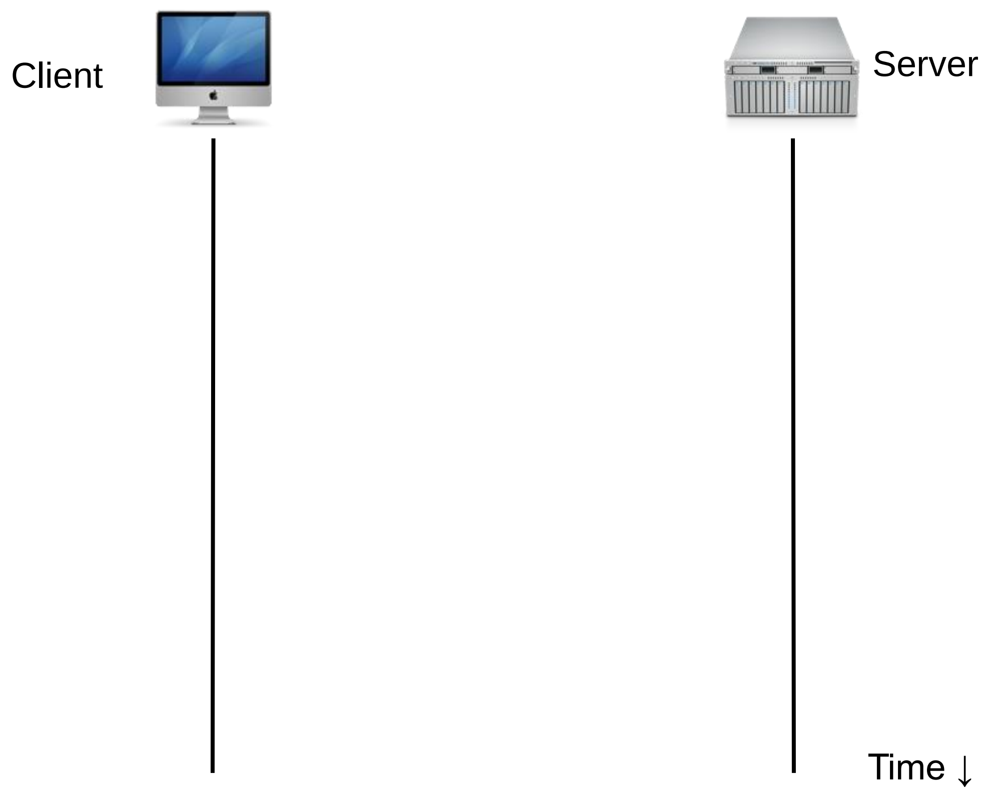
- Repeat the above a few times
  - Still no response? Return an error to the application

At-Least-Once and side effects

- Client sends a “debit $10 from bank account” RPC



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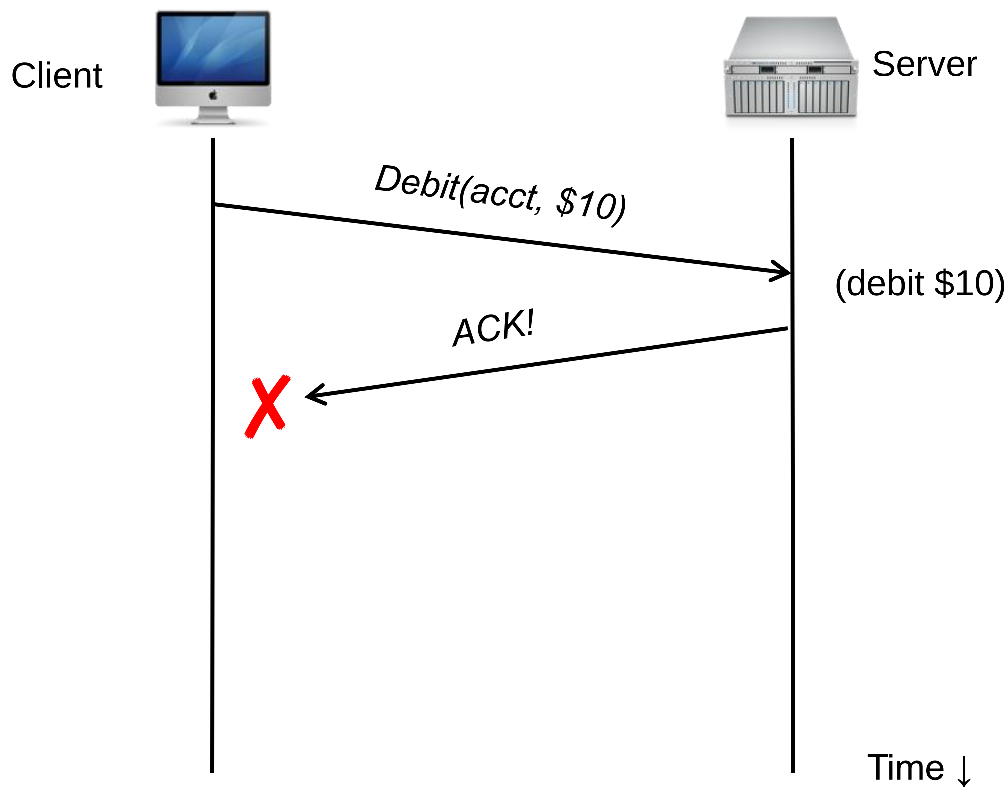

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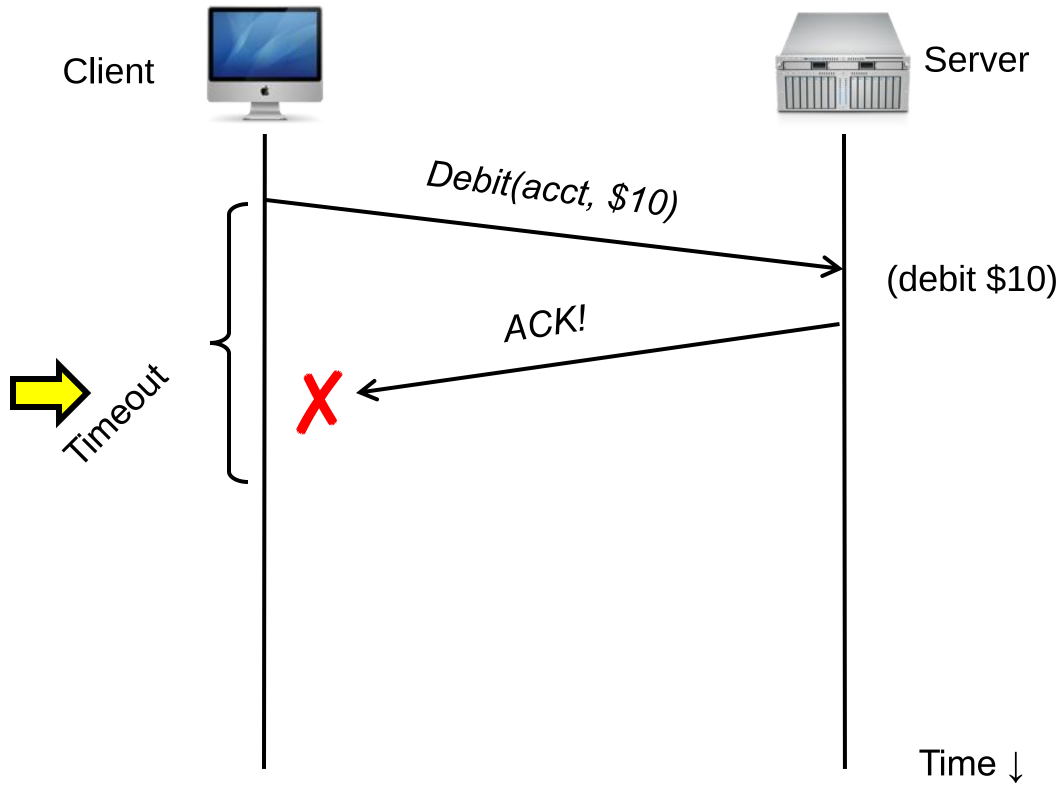

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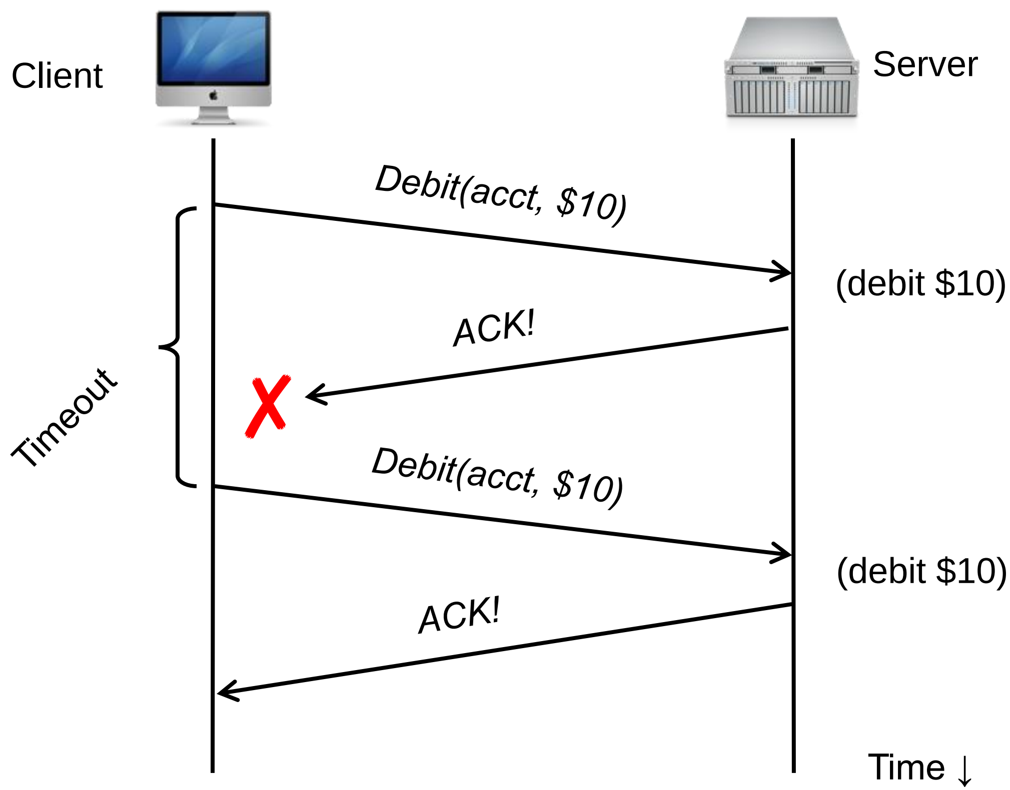
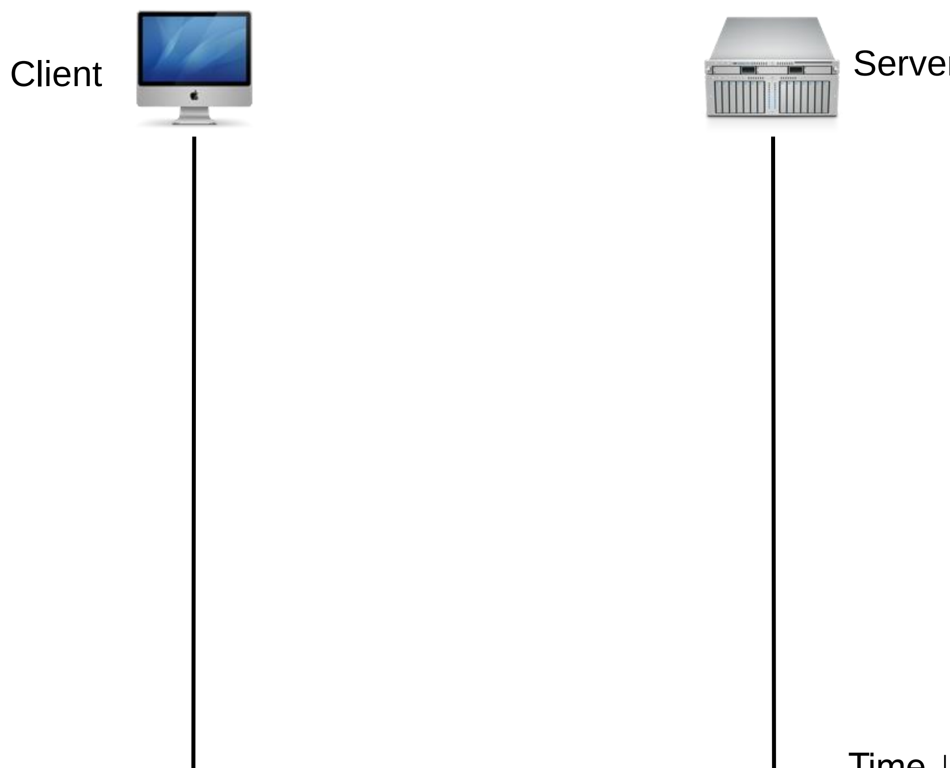


At-Least-Once and writes

- `put(x, value)`, then `get(x)`: expect answer to be *value*



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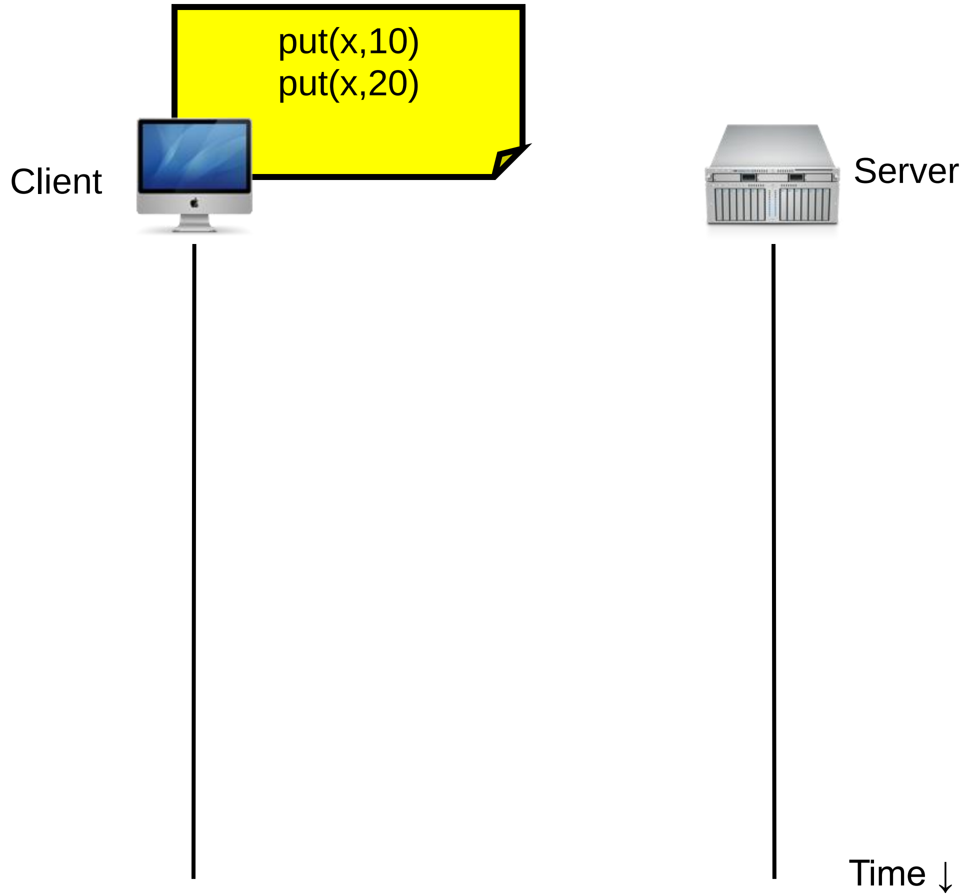

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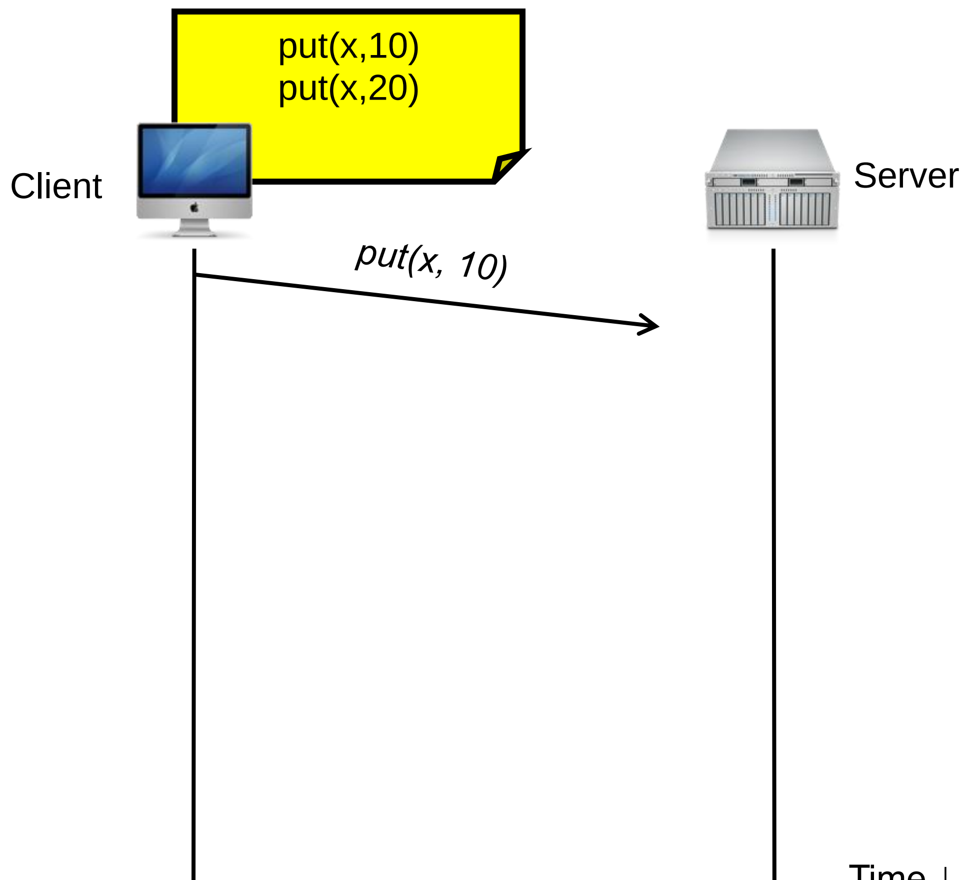

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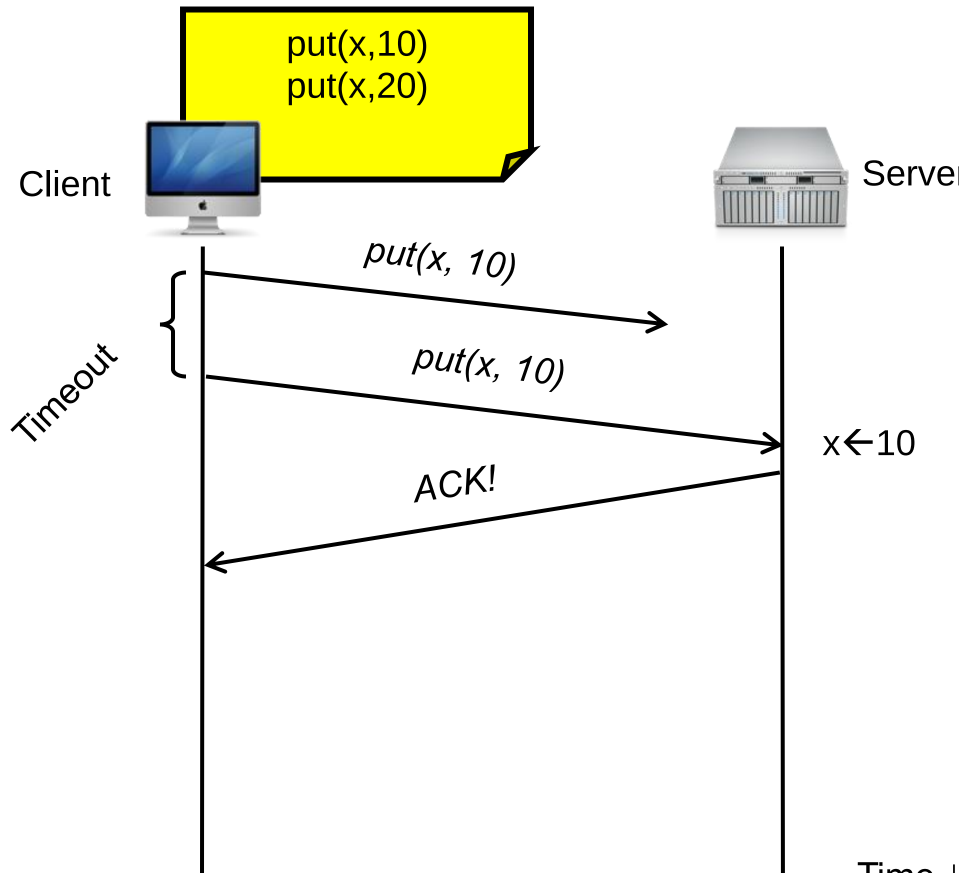

At-Least-Once and writes

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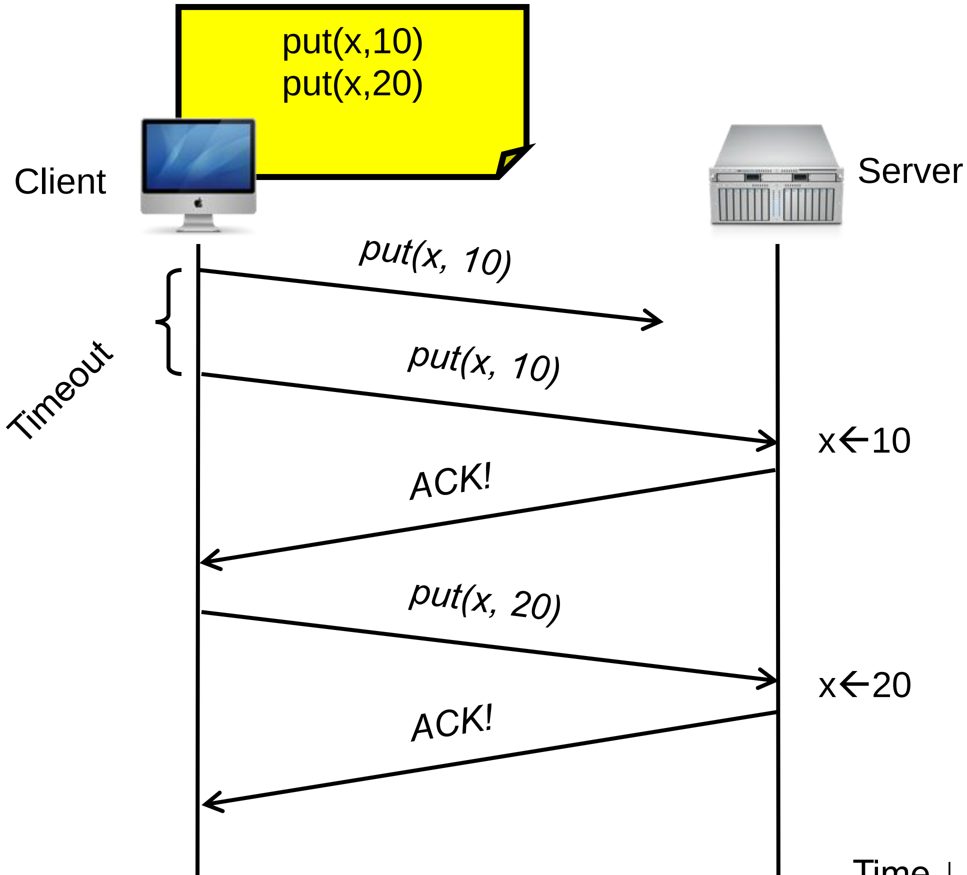

At-Least-Once and writes

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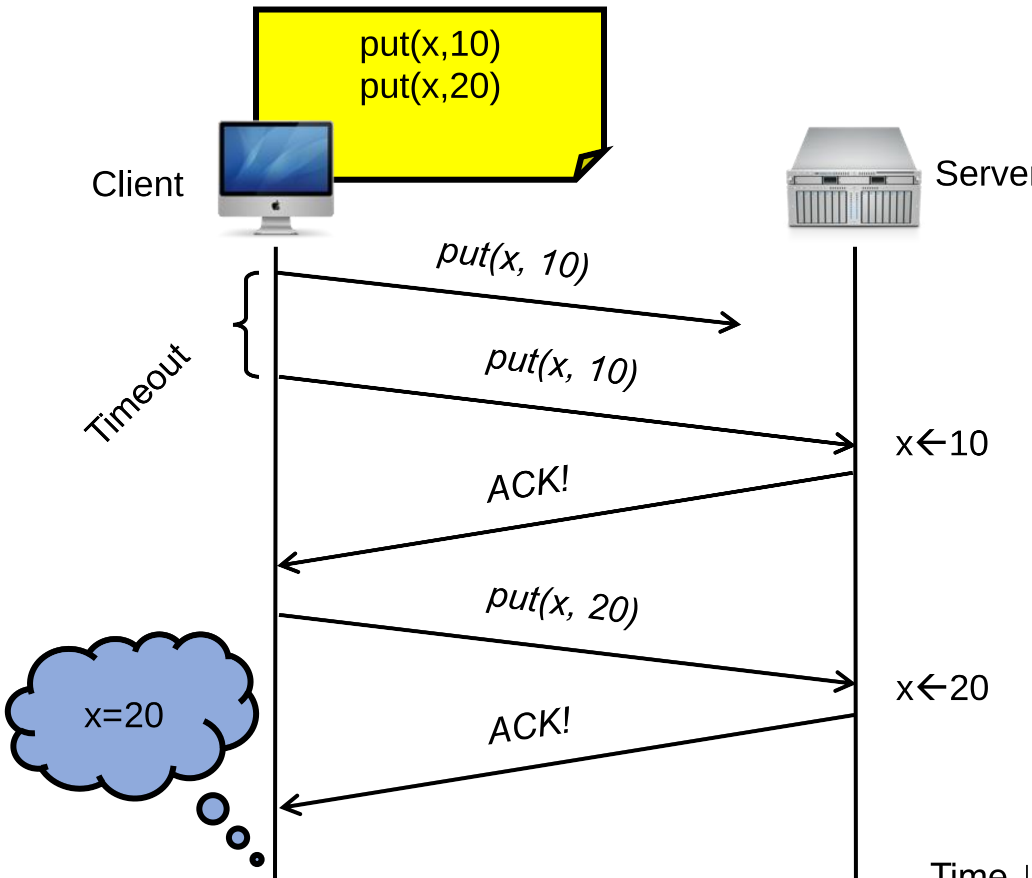
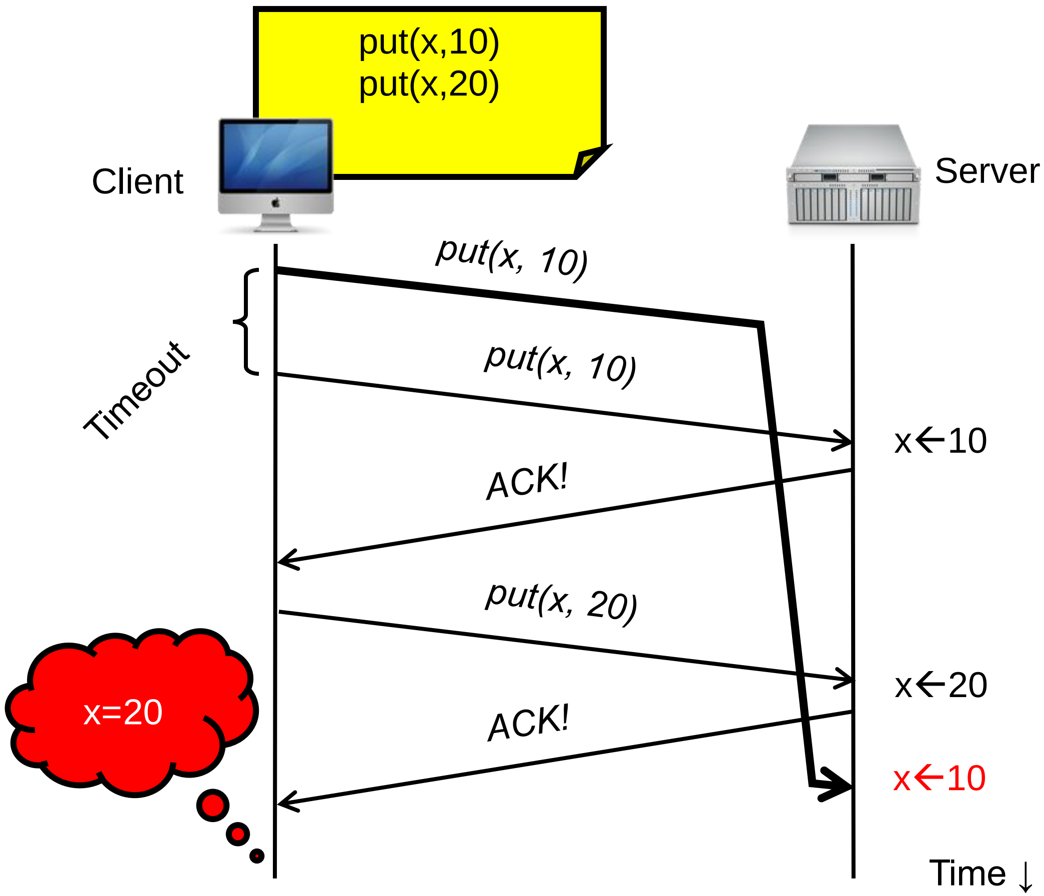


At-Least-Once and writes

- 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

At-Most-Once scheme

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

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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
    - Not a correct solution! 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 RPC requests
  - Client uses same xid for retransmitted requests

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```
At-Most-Once Server
if seen[xid]:
      retval = old[xid]
else:
      retval = handler()
      old[xid] = retval
      seen[xid] = true
return retval
```

At-Most-Once: Providing unique XIDs

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3. Big random number (probabilistic, no guarantee)

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

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  - Have to tell the server about each and every retired xid
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Significant overhead if many RPCs are in flight, in parallel

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- 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?

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)

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 the request
  - Perhaps server processed the request but server/net failed before reply came back

Announcement

- Lab 1 is out and due in two weeks

- Next Monday: Go RPC and Lab 1 tutorial