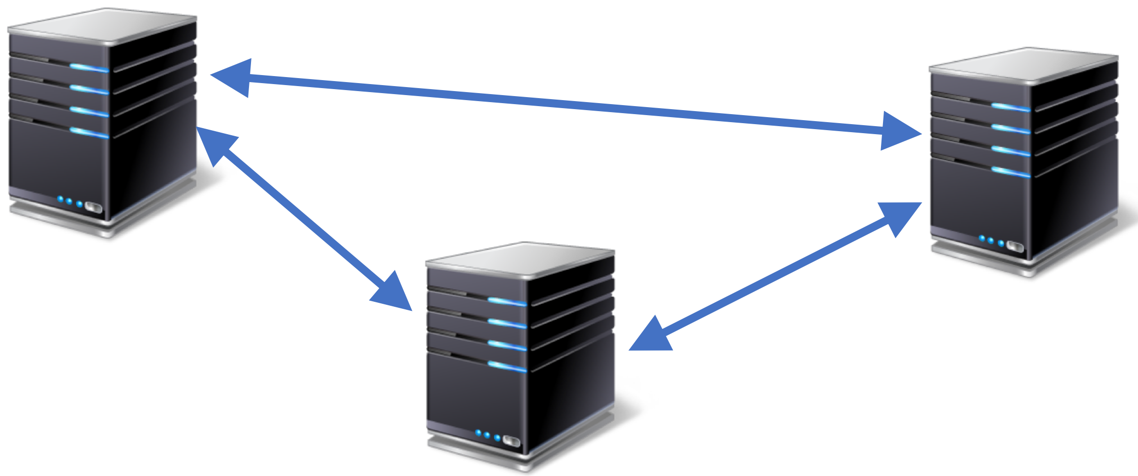
Remote Procedure Call (RPC)

CS 675: Distributed Systems (Spring 2020)
Lecture 2

Yue Cheng

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

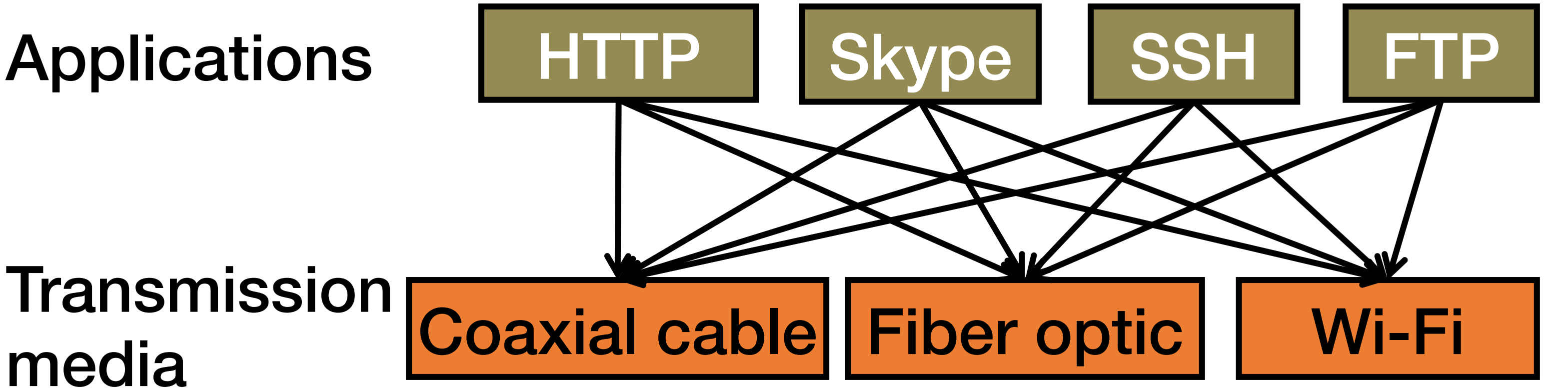
2. Remote procedure call

3. RPCs in Go

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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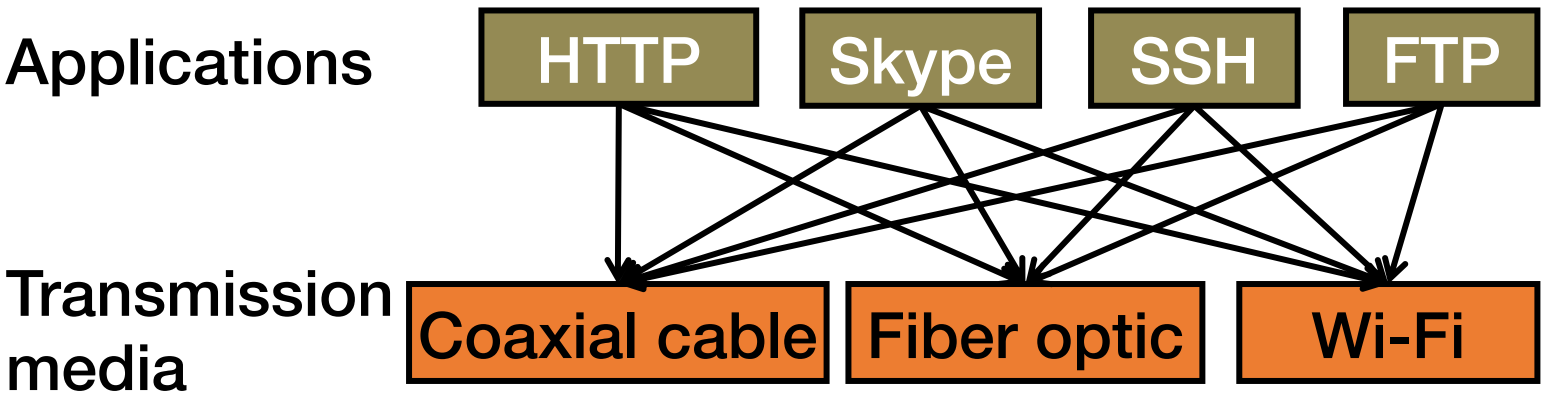

- Re-implement every application for every new underlying transmission medium?
- Change every application on any change to an underlying transmission medium?

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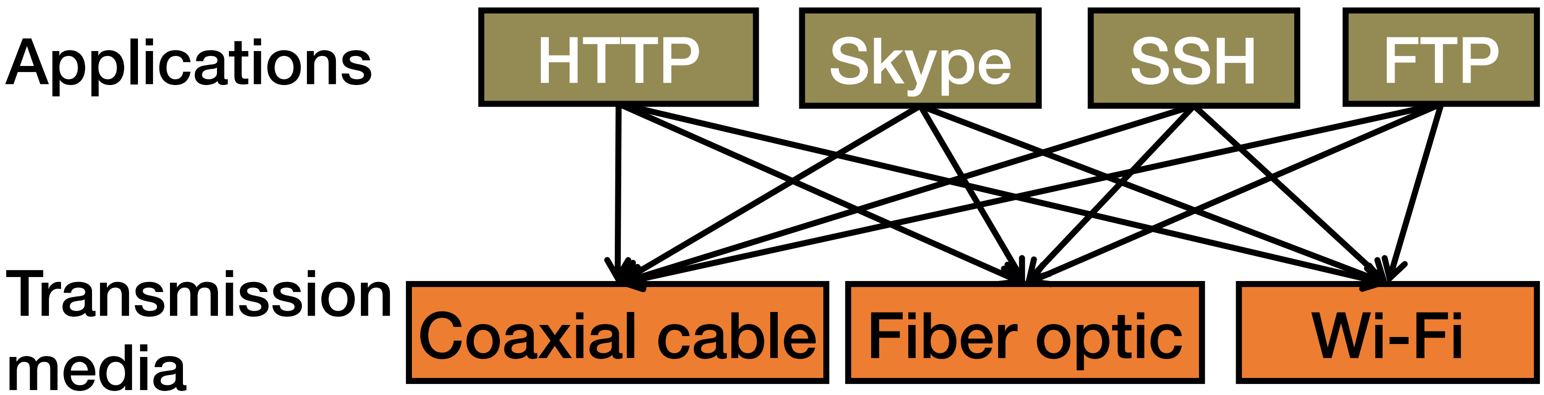
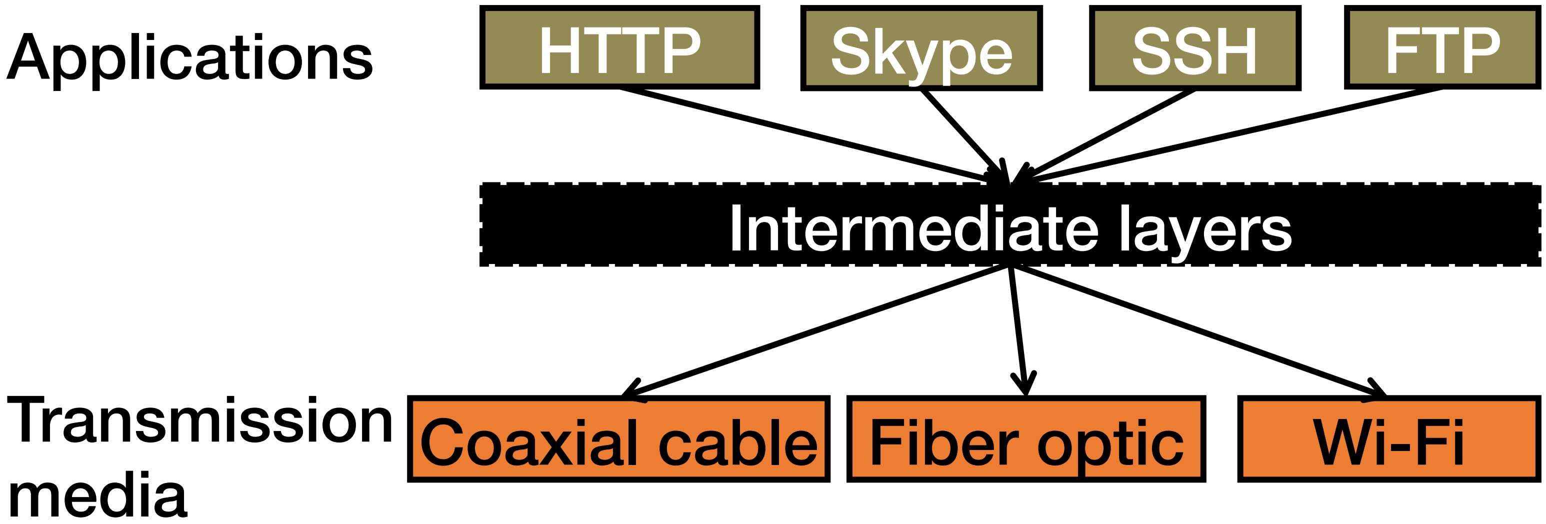


- Re-implement every application for every new underlying transmission medium?
- Change every application on any change to an underlying transmission medium?

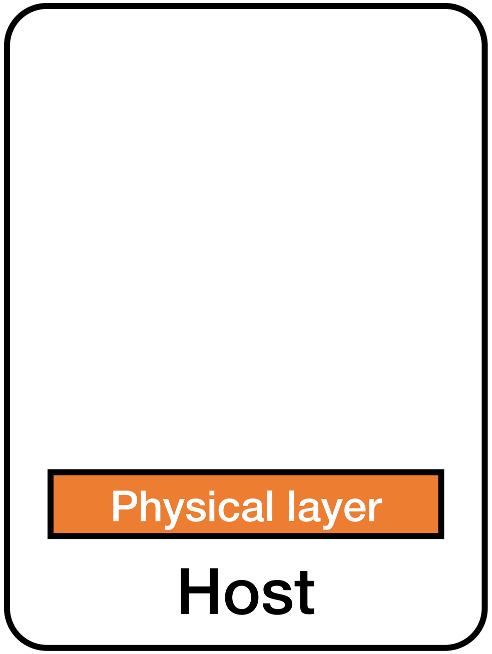
- No! But how does the Internet design avoid this?

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

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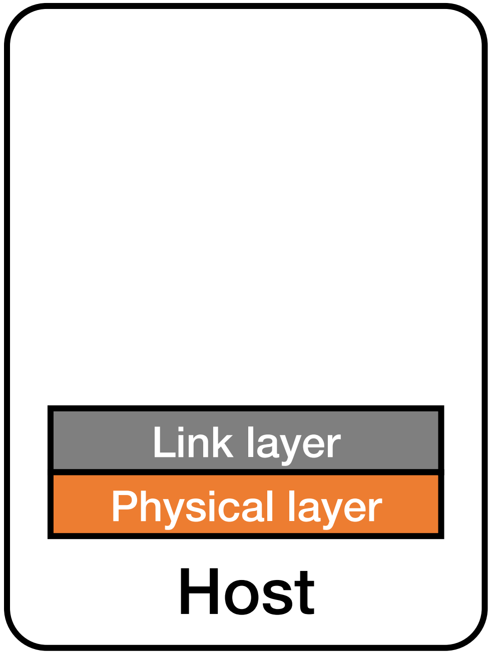

- Link: Enables end hosts to exchange atomic messages with each other
- Physical: Moves bits between two hosts connected by a physical link

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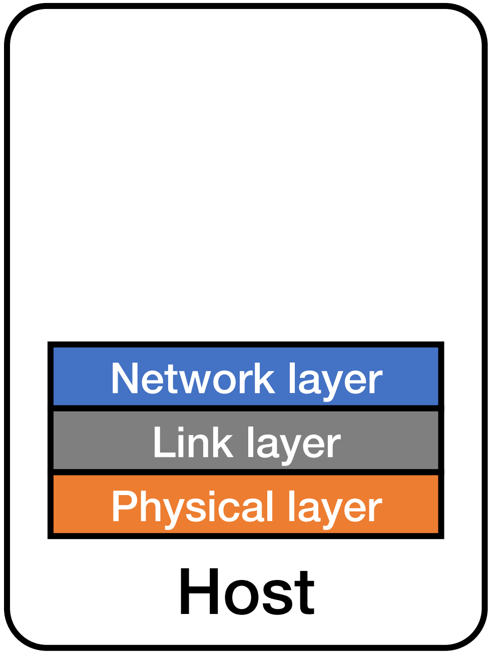

- Network: Deliver packets to destinations on other (heterogeneous) networks
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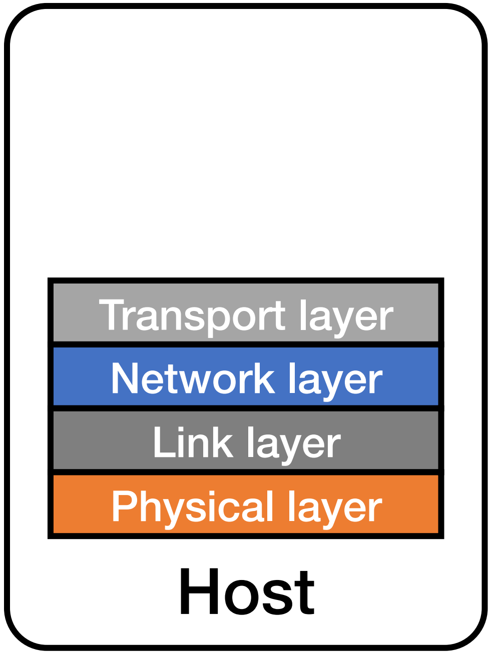

- Transport: Provide end-to-end communication between processes on different hosts
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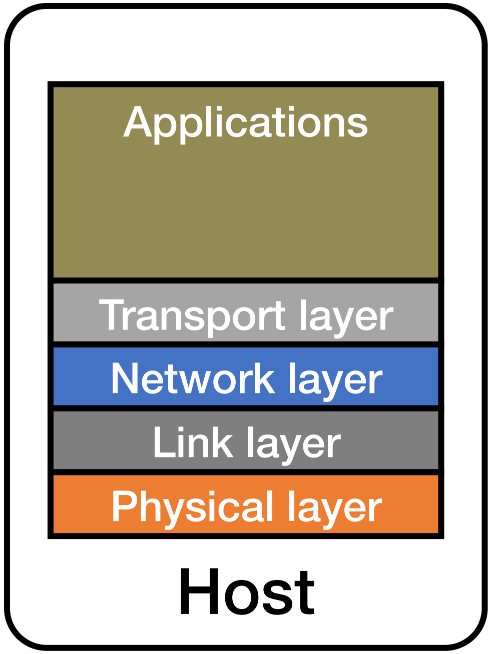

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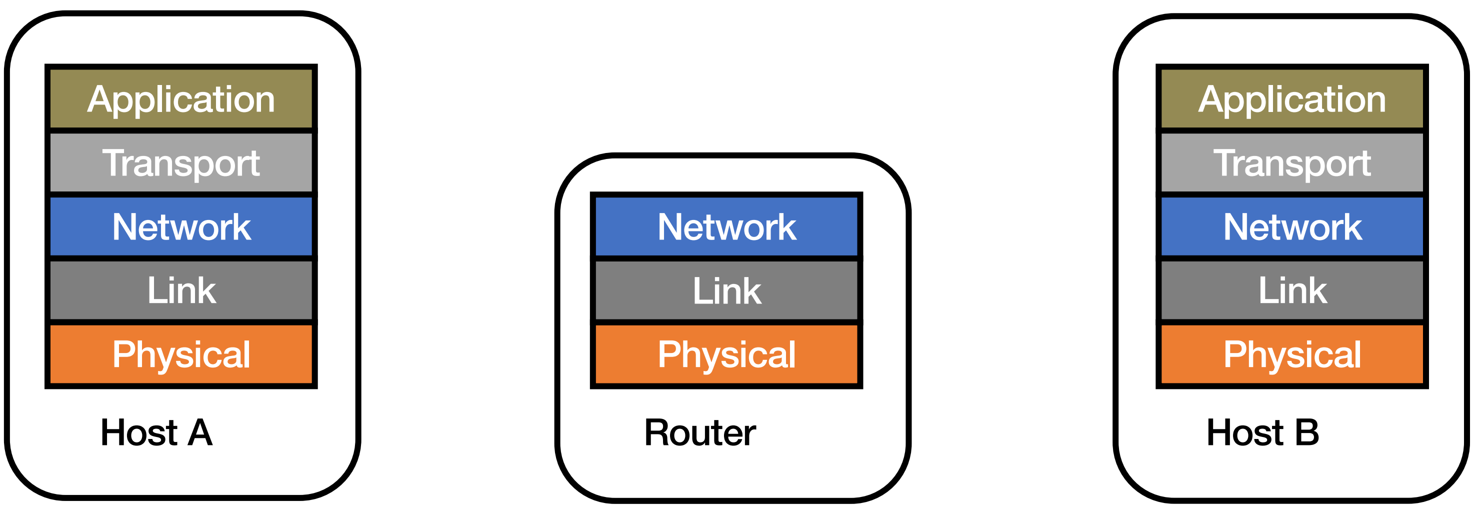
Logical communication between layers

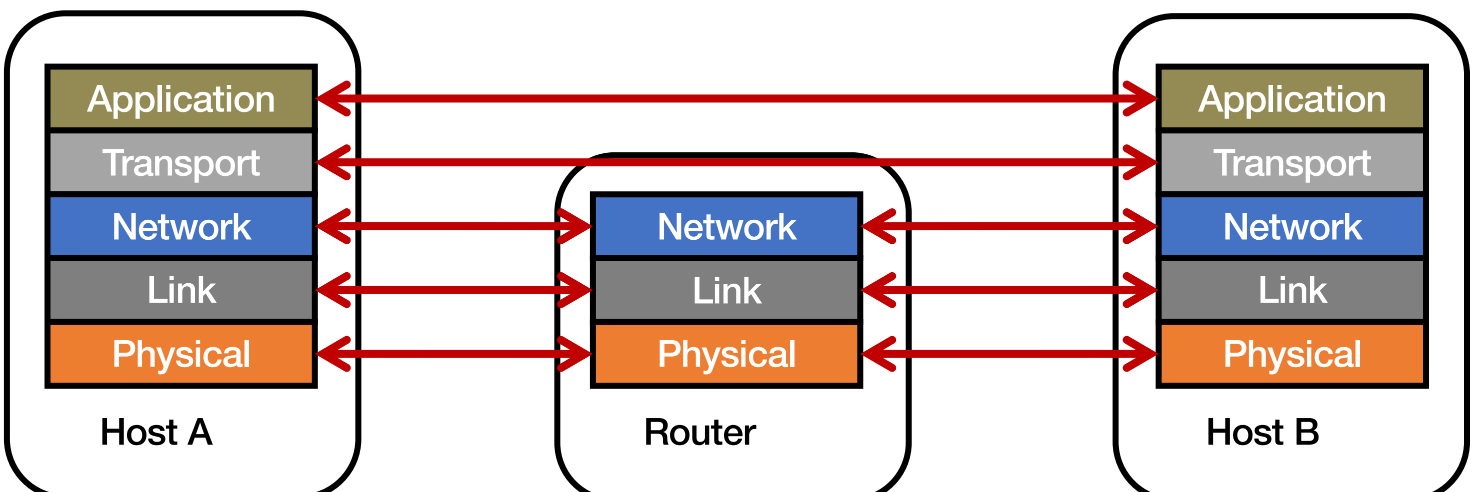
- How to forge agreement on the meaning of the bits exchanged between two hosts?



Logical communication between layers

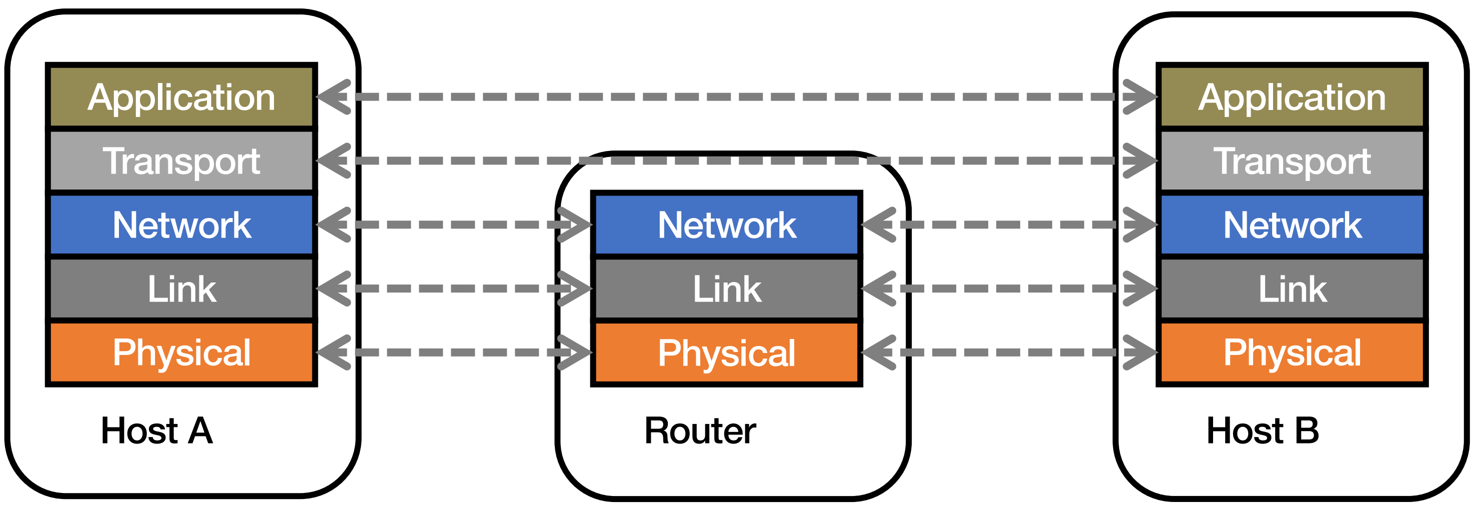
- How to forge agreement on the meaning of the bits exchanged between two hosts?

- 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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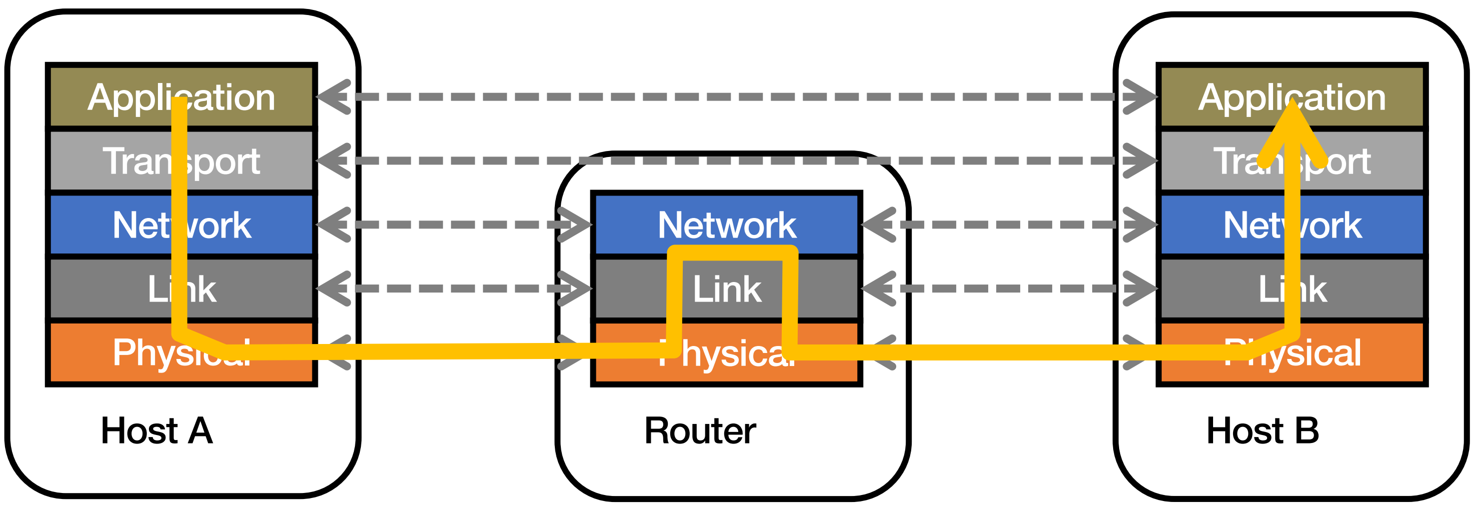
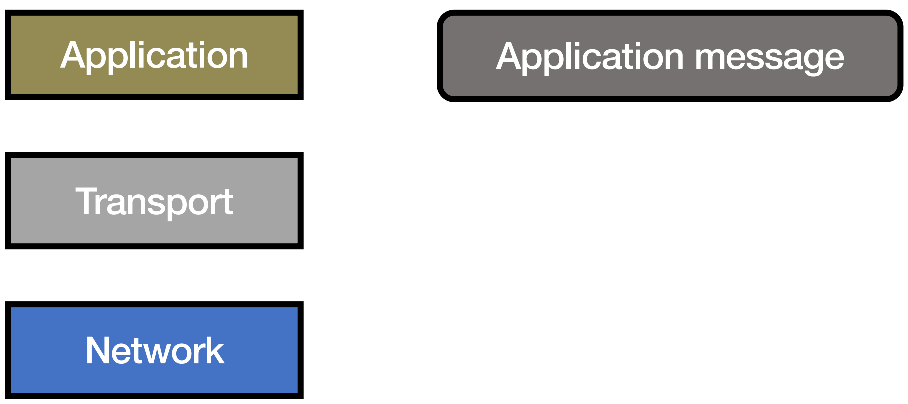


Communication between layers

- 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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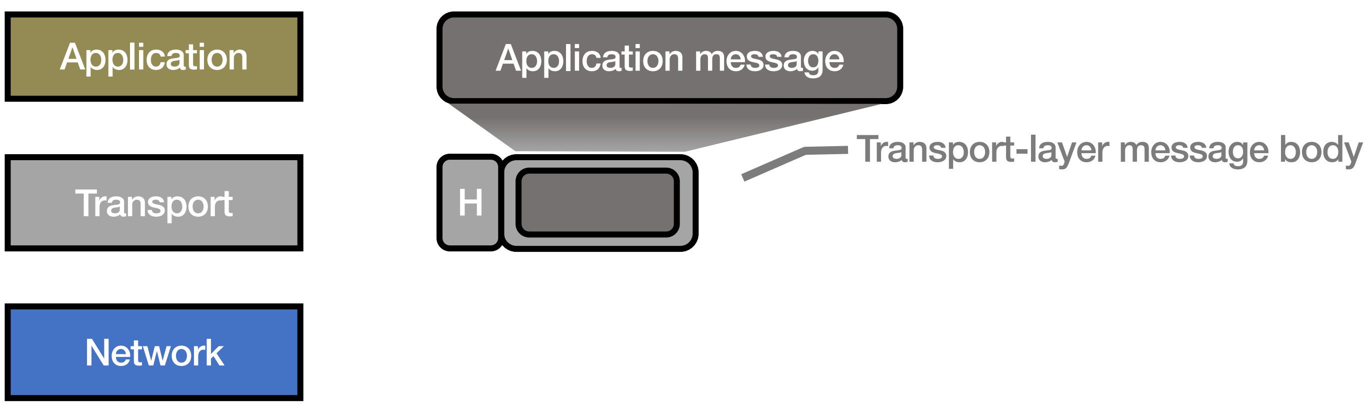

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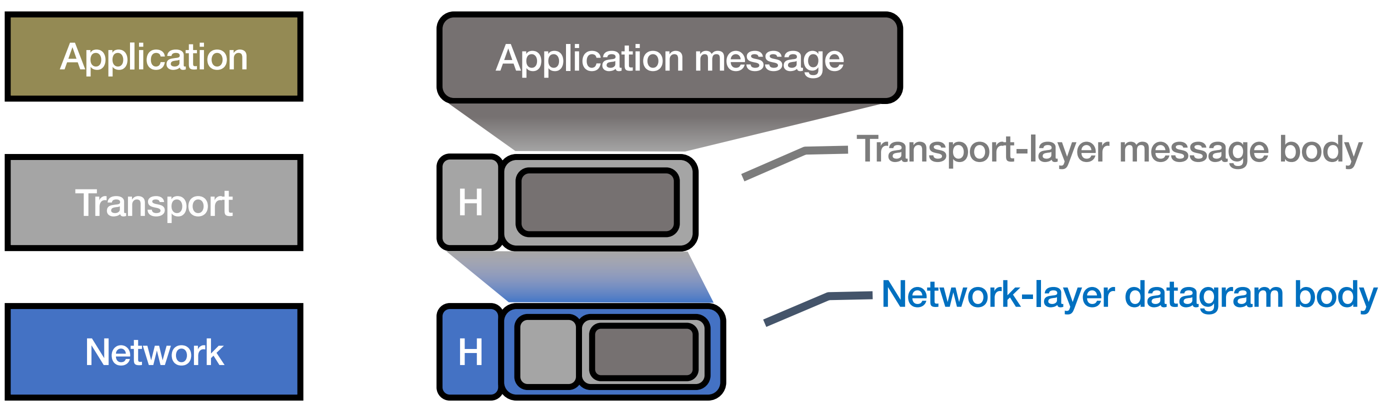
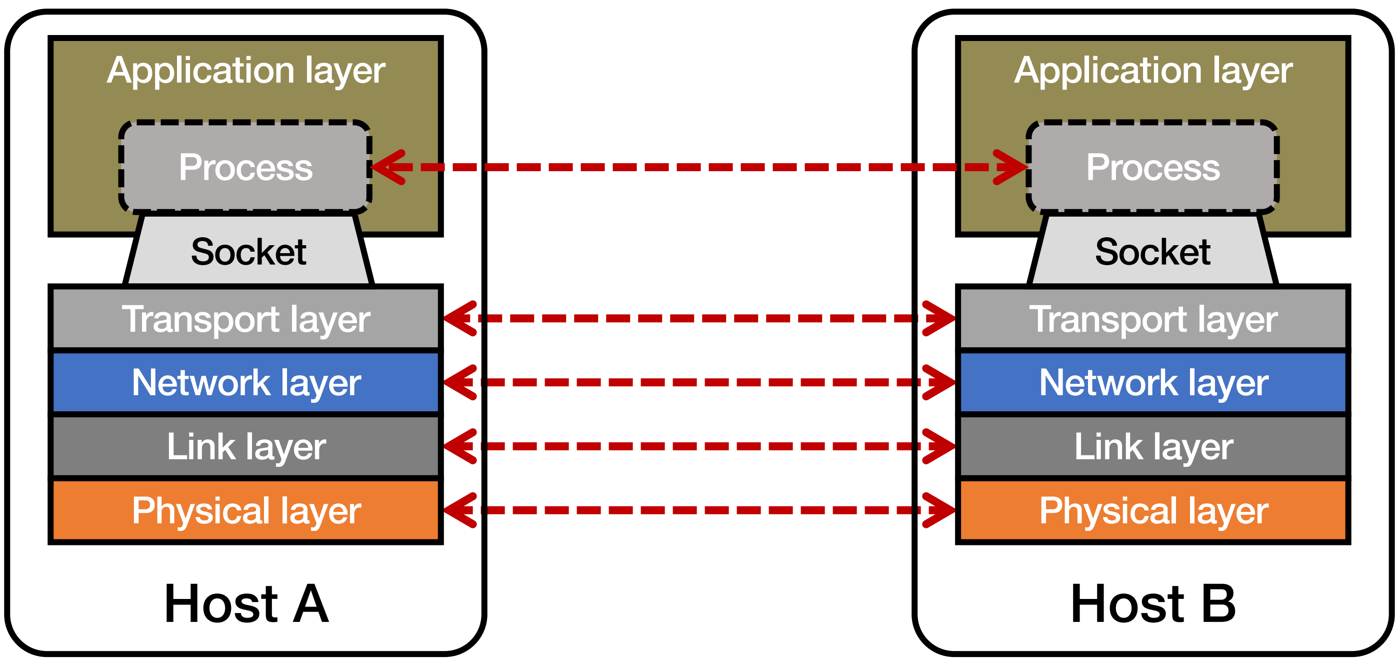


Network socket-based communication

- **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?

```c
// 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);
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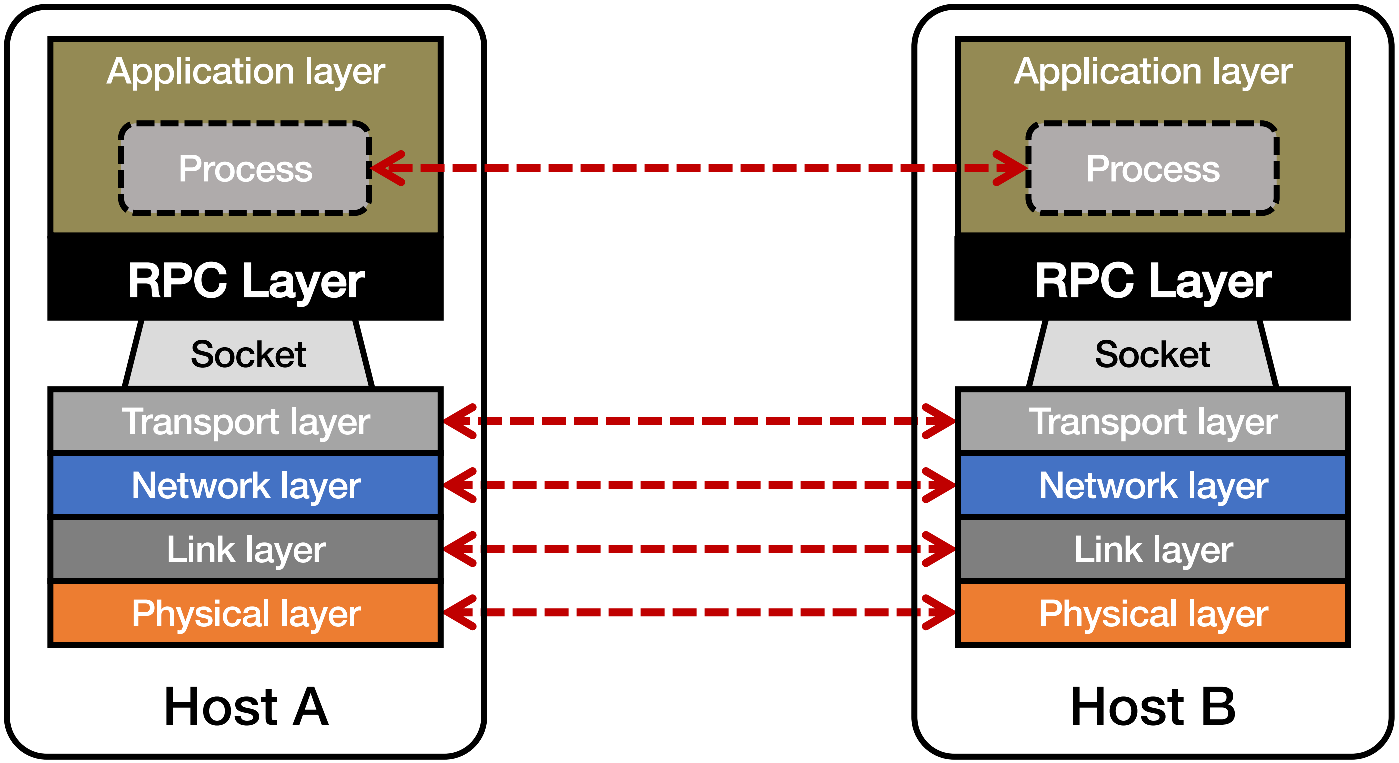
Sockets don't provide transparency

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
3. RPCs in Go

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
- Programming assignments use Go 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

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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
   - Client needs to rendezvous with the server
   - Server must dispatch to the required function
     - What if server is 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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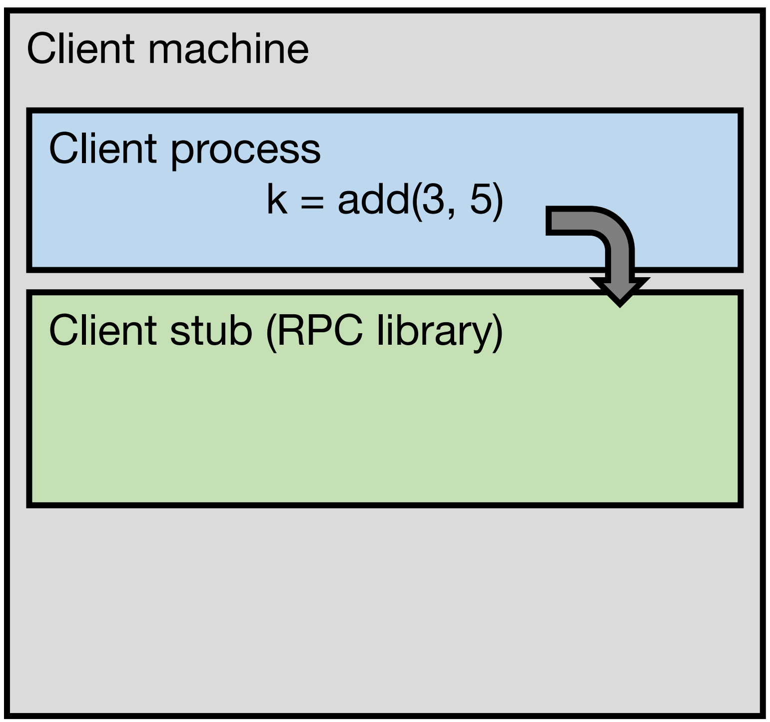
- Programmer may write an interface description in the IDL
  - Defines API for procedure calls: names, parameter/return types

- 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

A day in the life of an RPC

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



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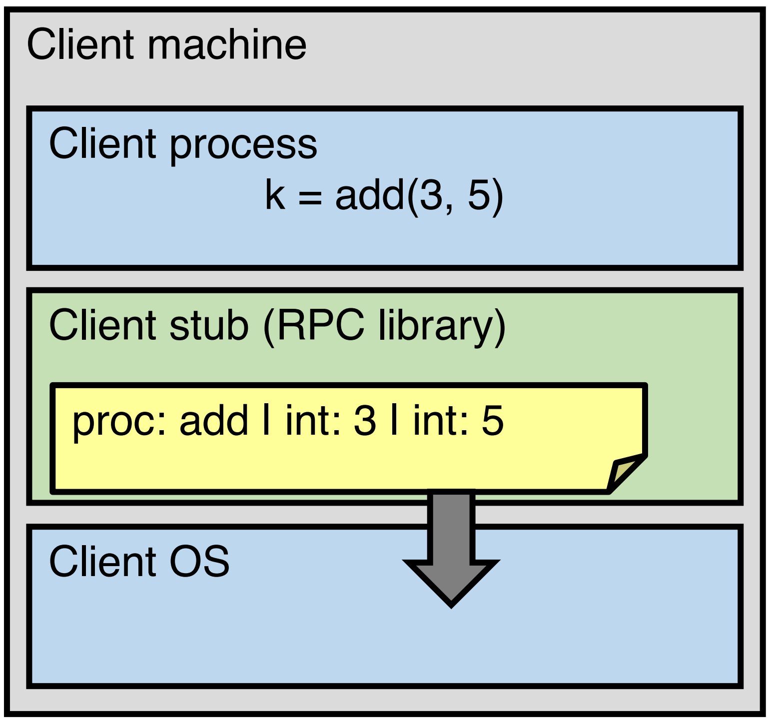

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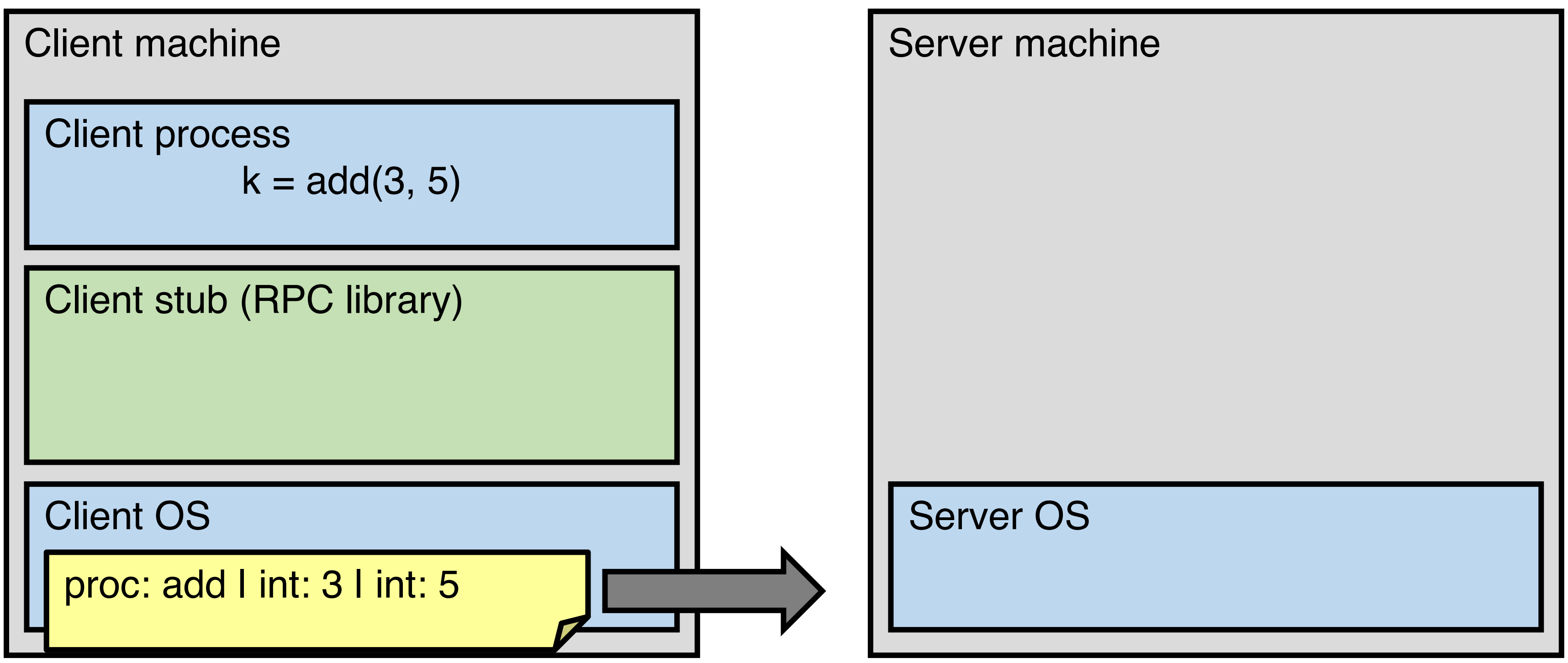
3. OS sends a network message to the server



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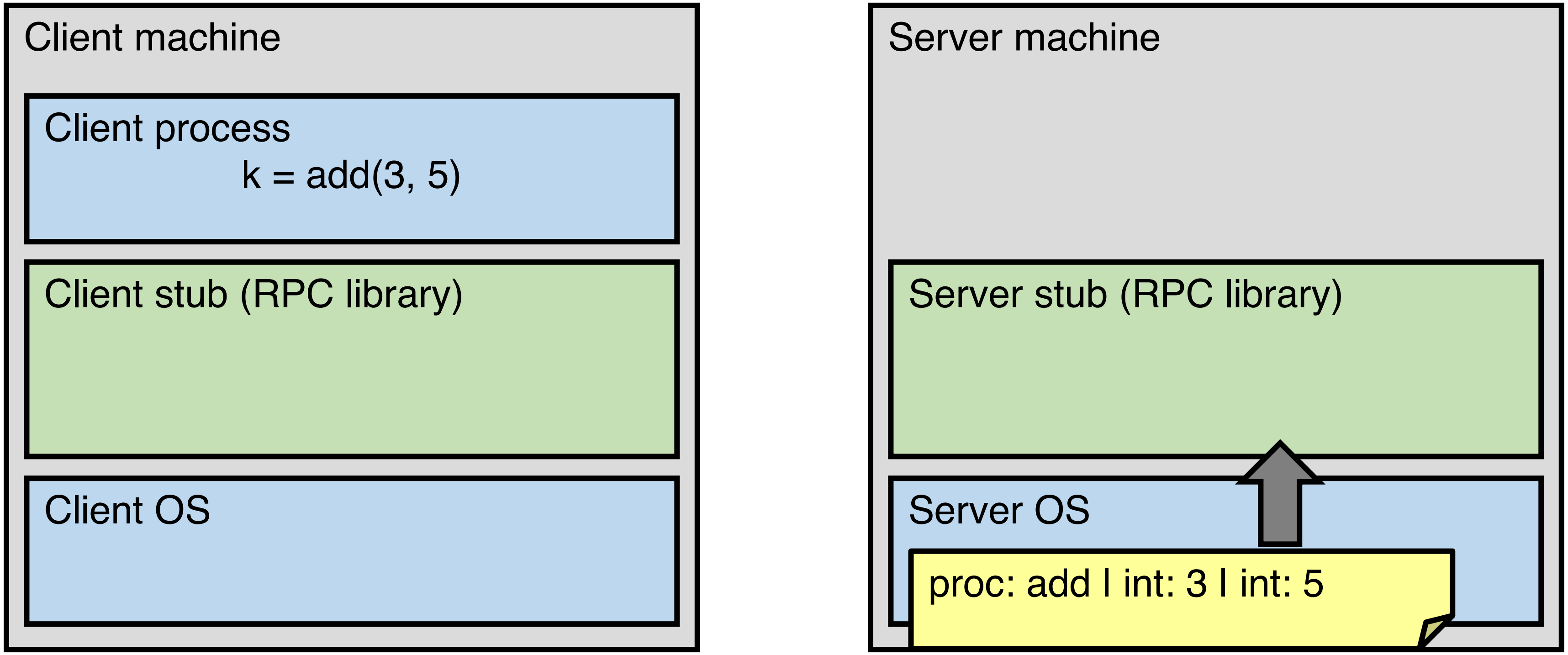
3. OS sends a network message to the server

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



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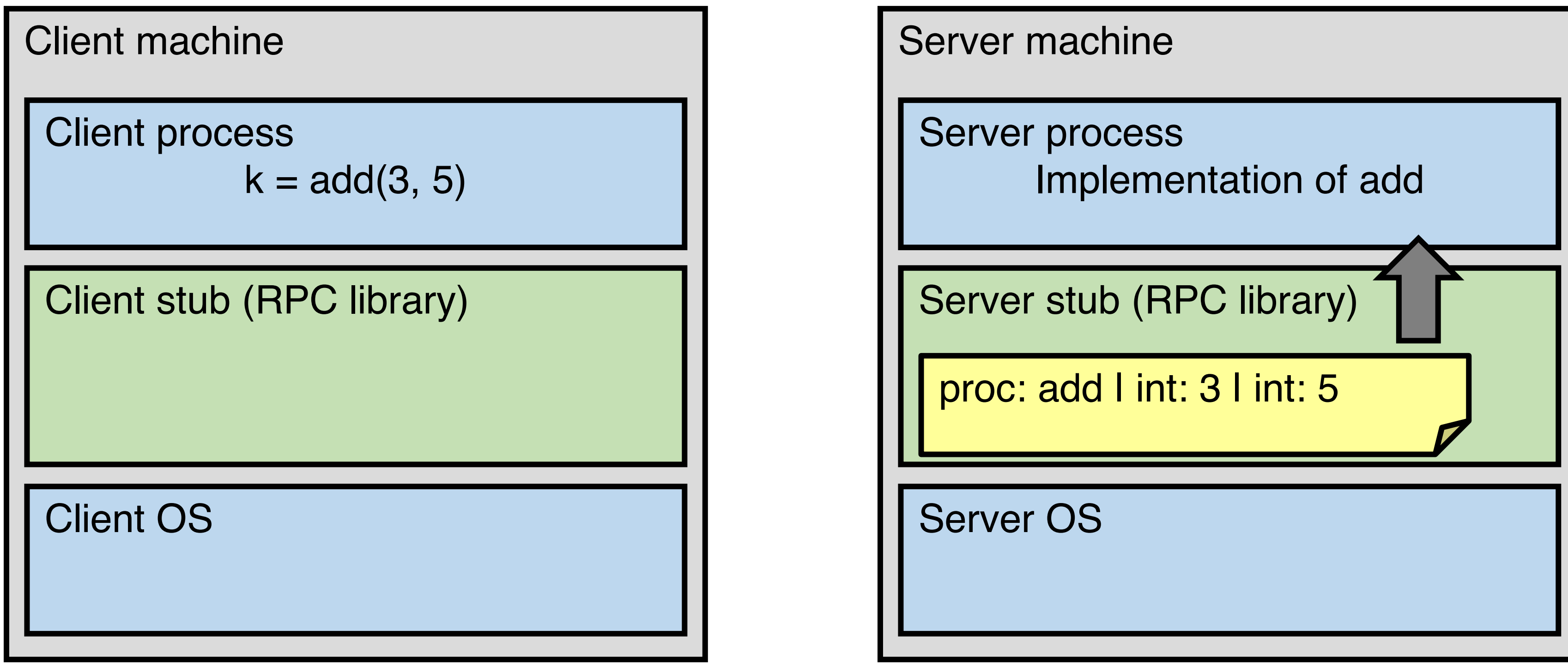
4. Server OS receives message, sends it up to stub

5. Server stub unmarshals params, calls server function



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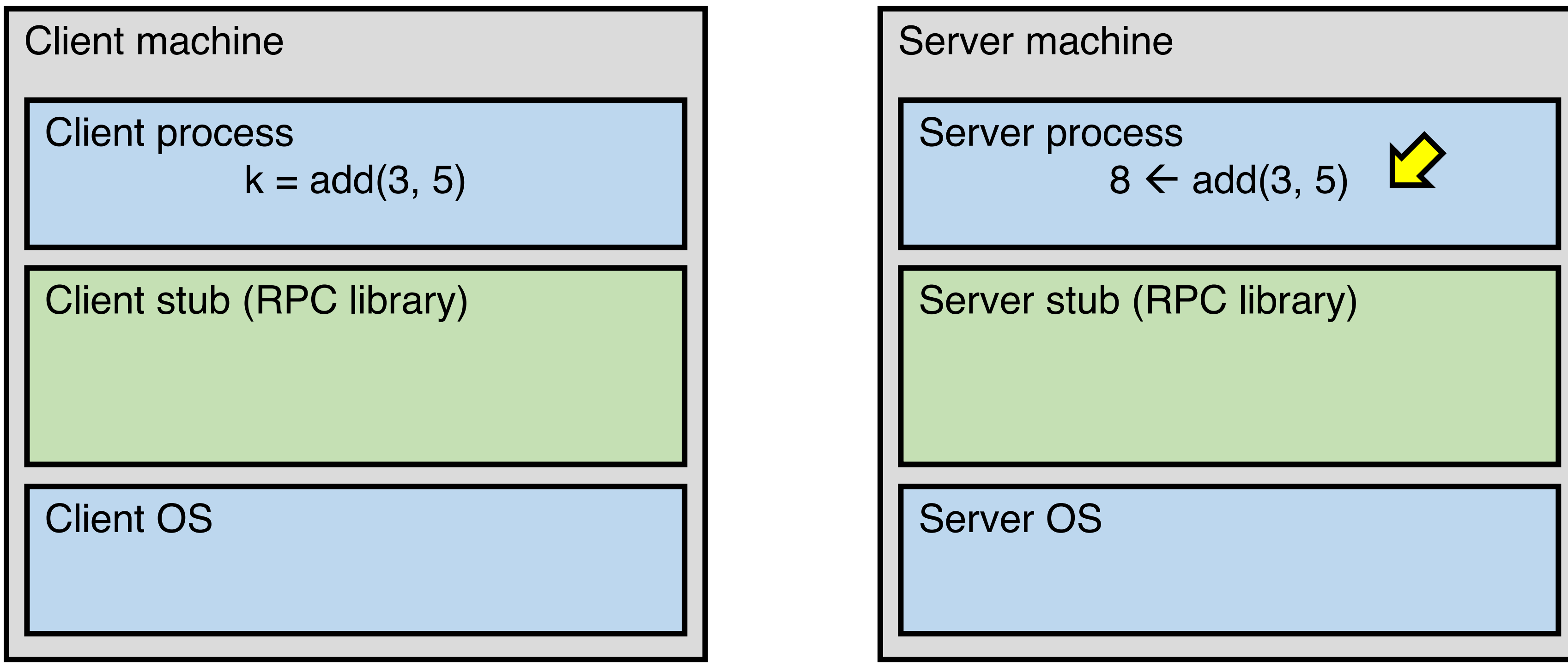
5. Server stub unmarshals params, calls server function

6. Server function runs, returns a value



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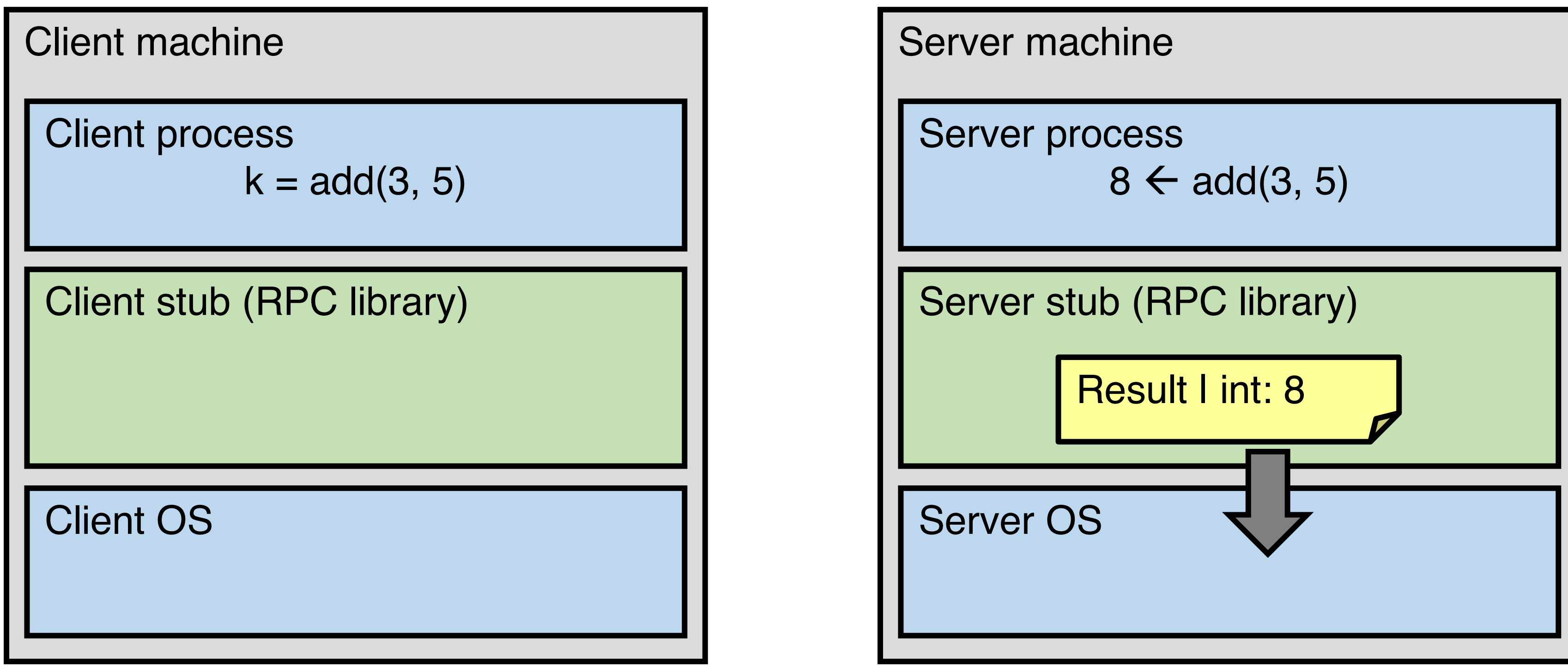
7. Server stub marshals the return value, sends message



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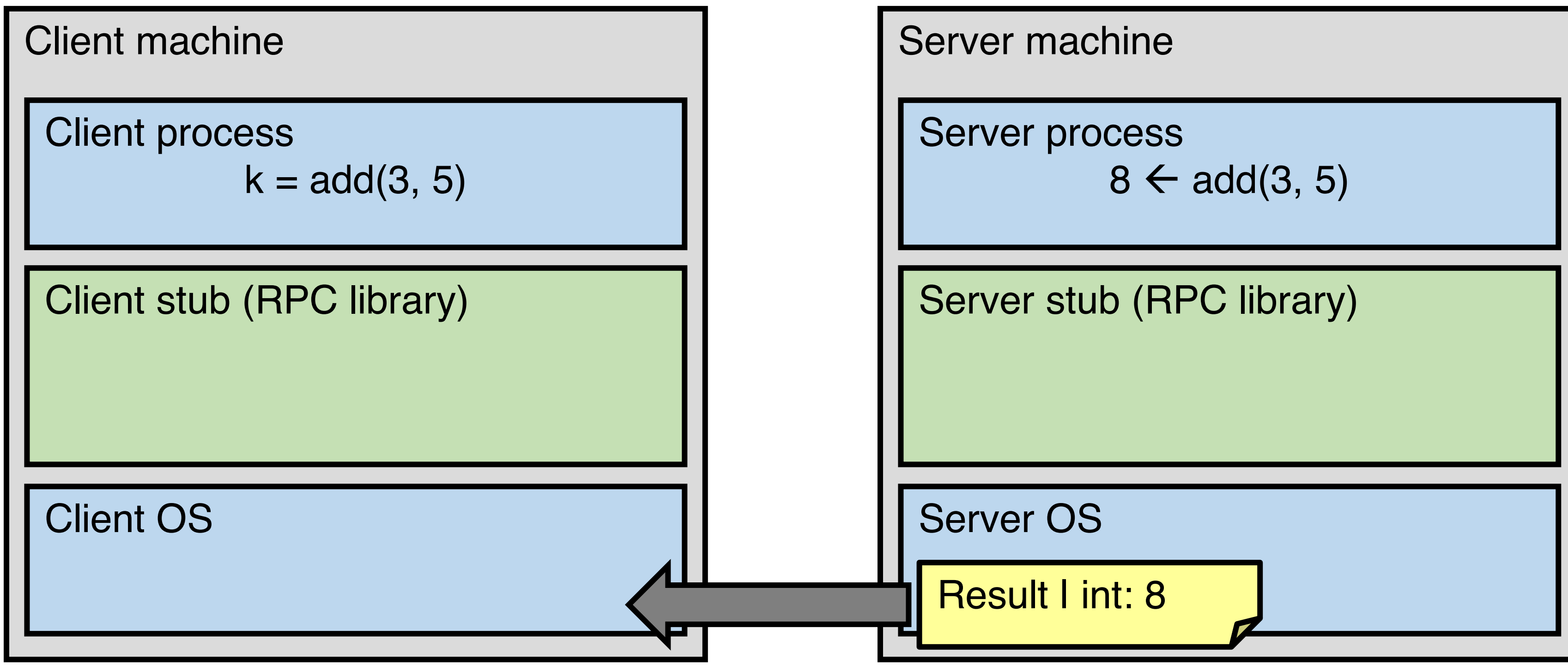
7. Server stub marshals the return value, sends message

8. Server OS sends the reply back across the network



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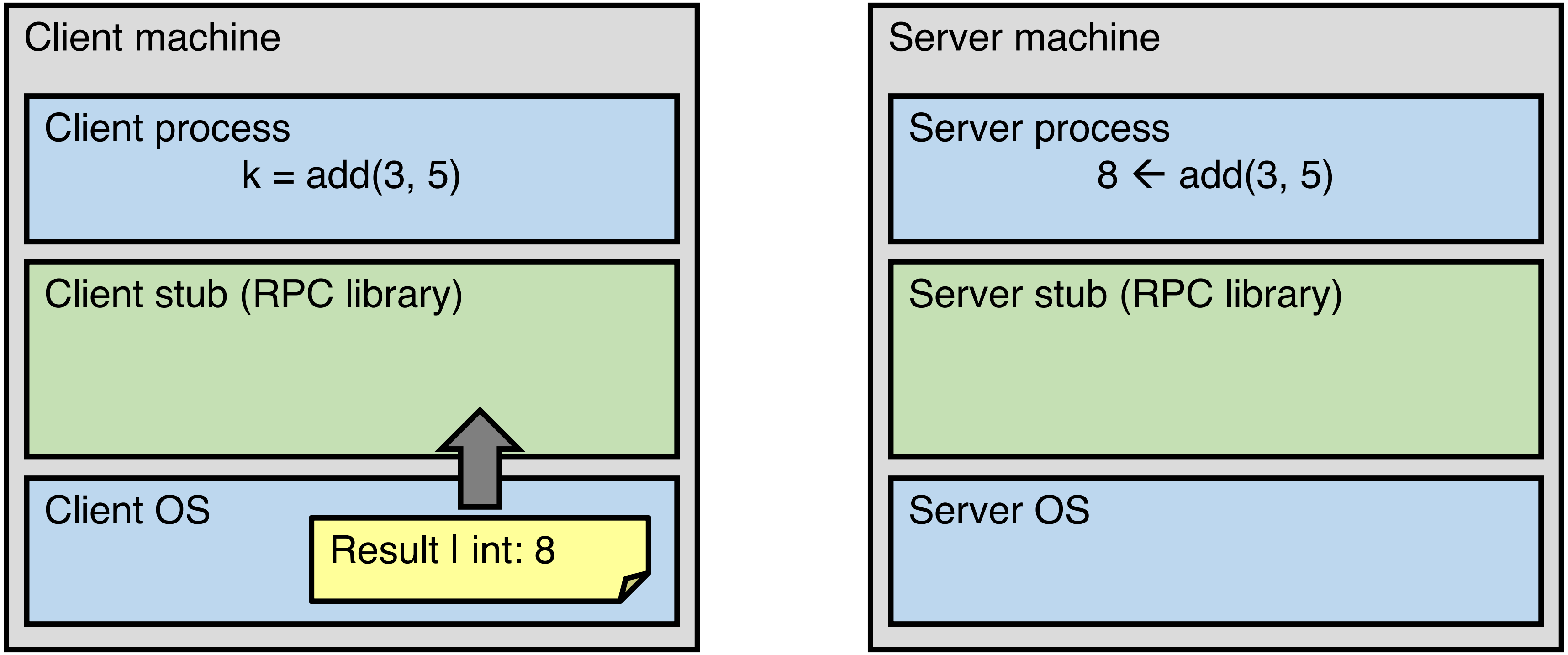
9. Client OS receives the reply and passes up to stub



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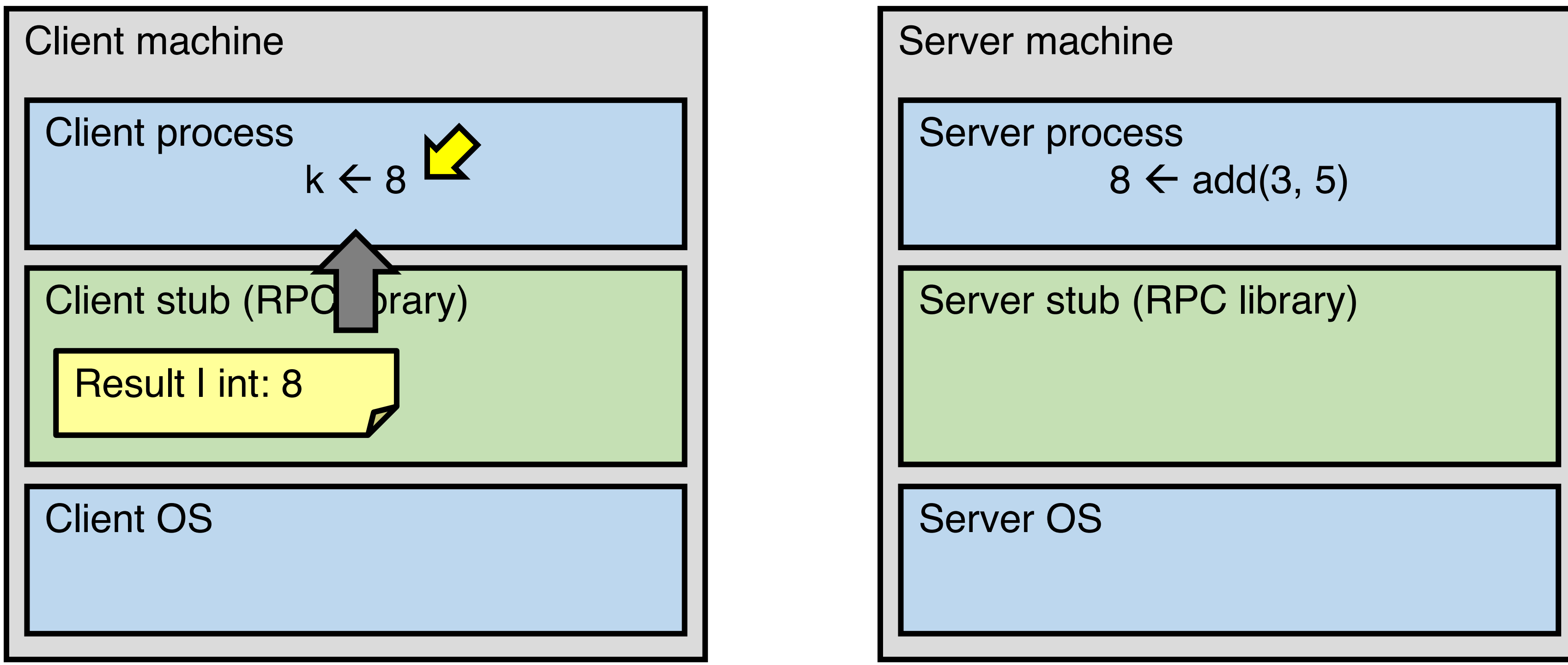
9. Client OS receives the reply and passes up to stub

10. Client stub unmarshals return value, returns to client



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

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

3. RPCs in Go

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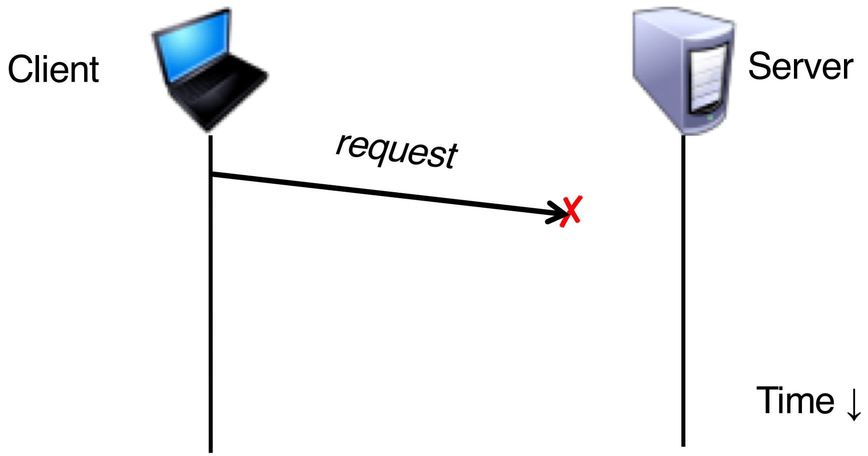
All of these may **look the same** to the client…

Failures, from client's perspective



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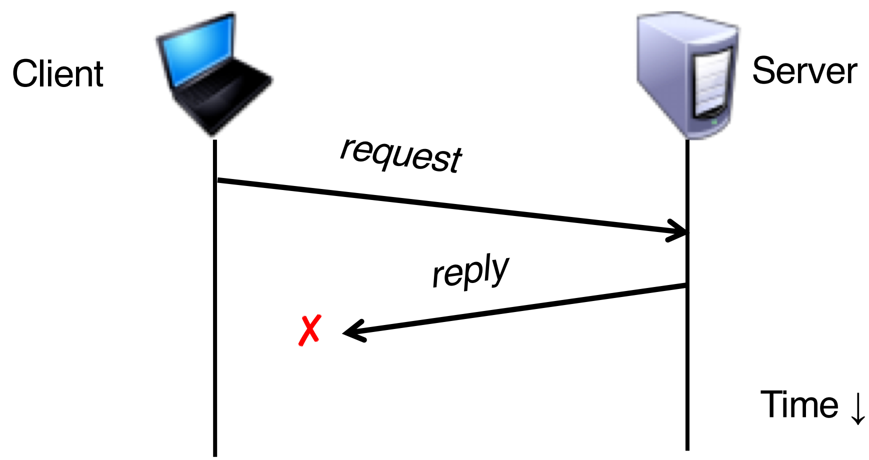

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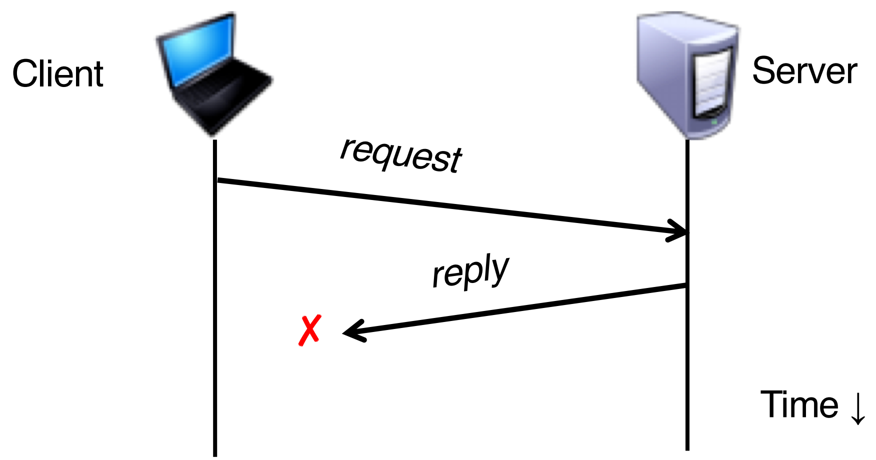

The cause of the failure is hidden from the client!

At-Least-Once scheme

- Simplest scheme for handling failures

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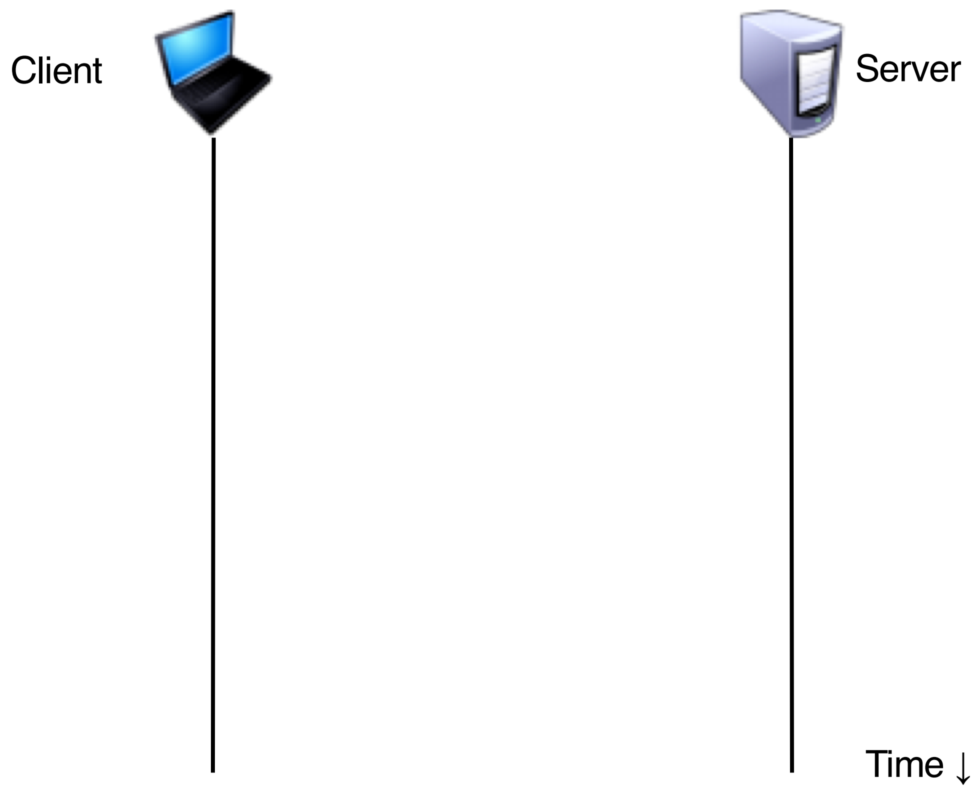
- Repeat the above a few times
    - Still no response? Return an error to the application

At-Least-Once and side effects

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



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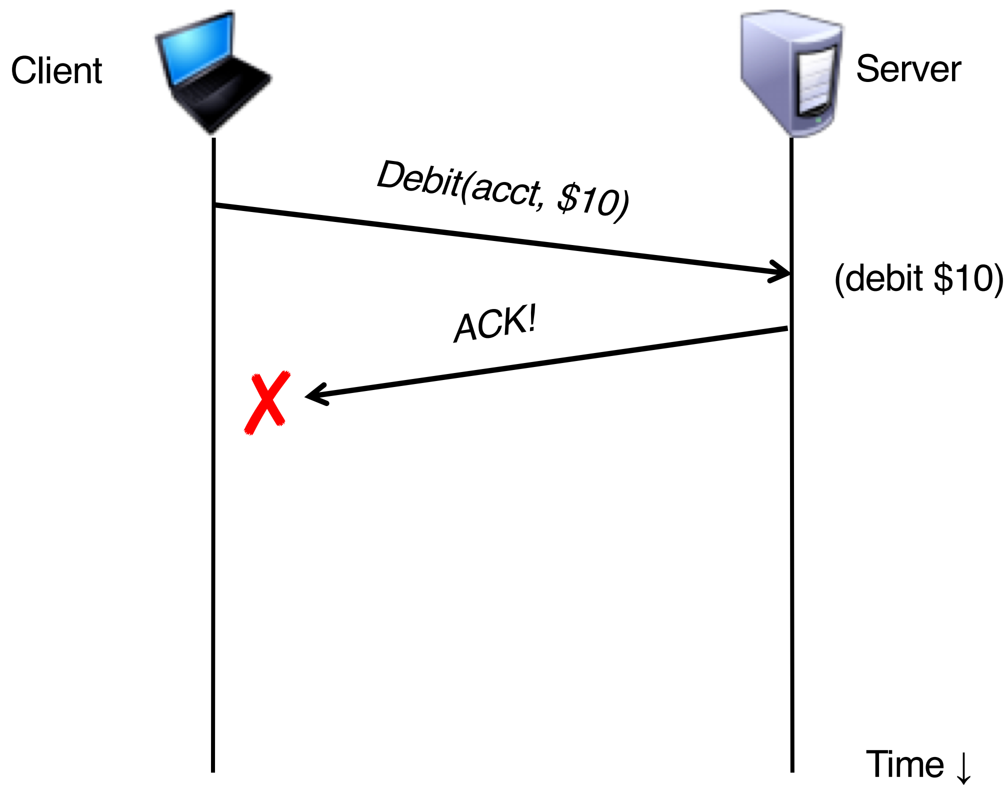

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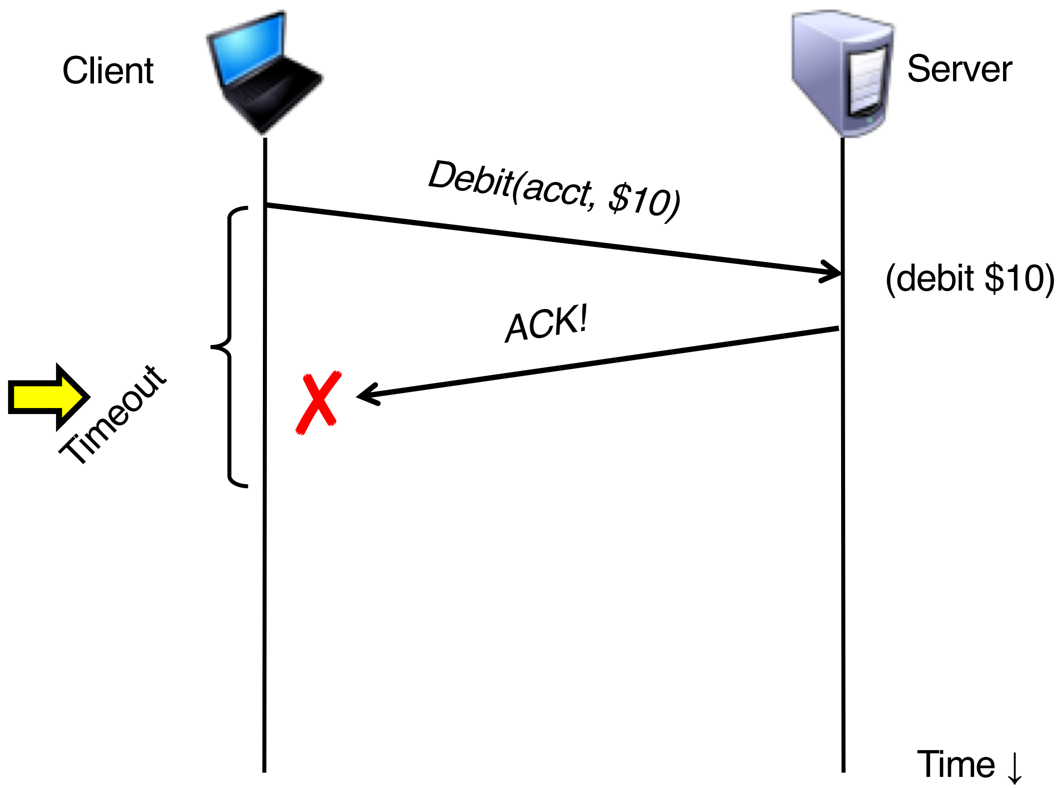

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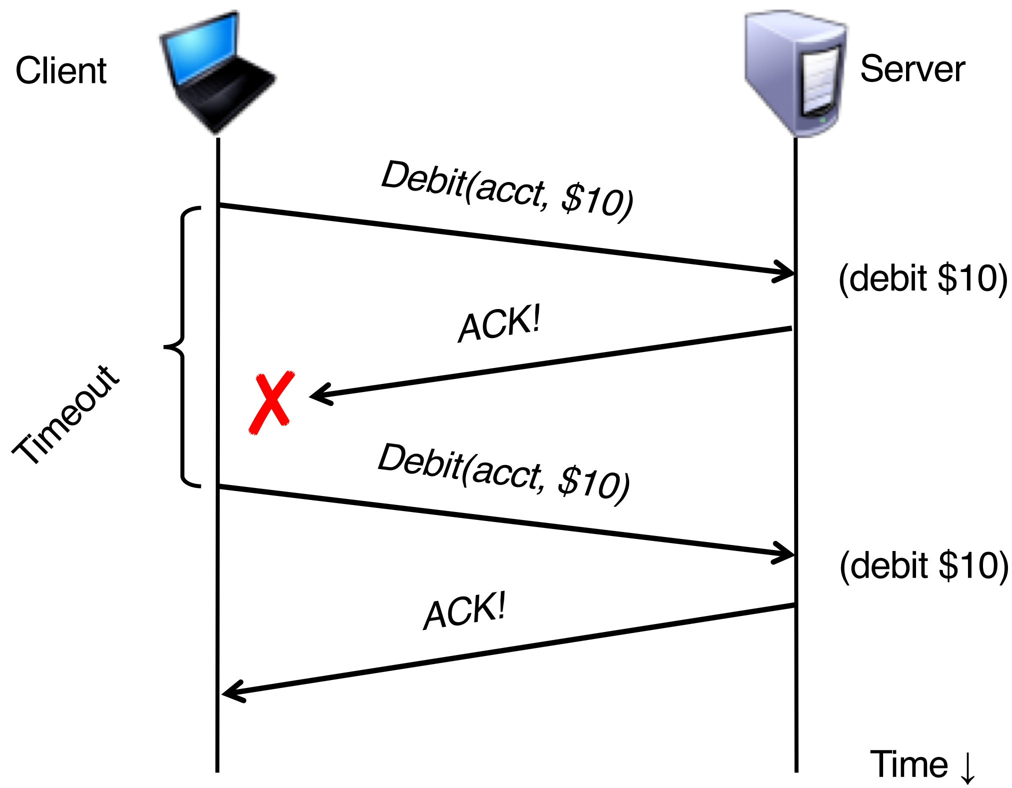

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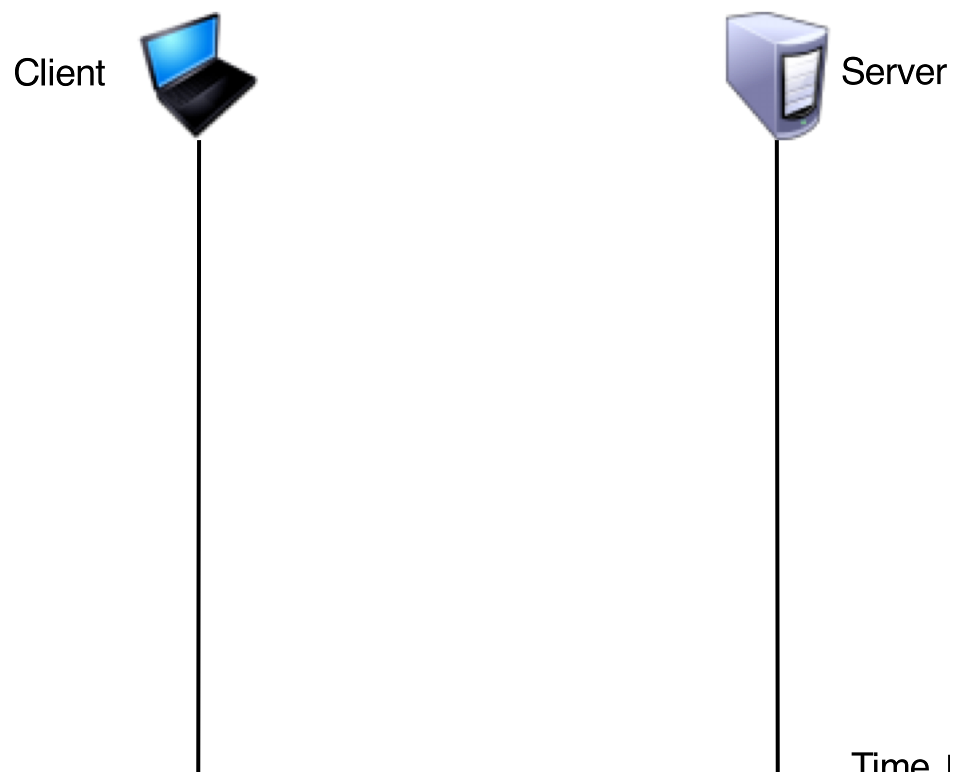

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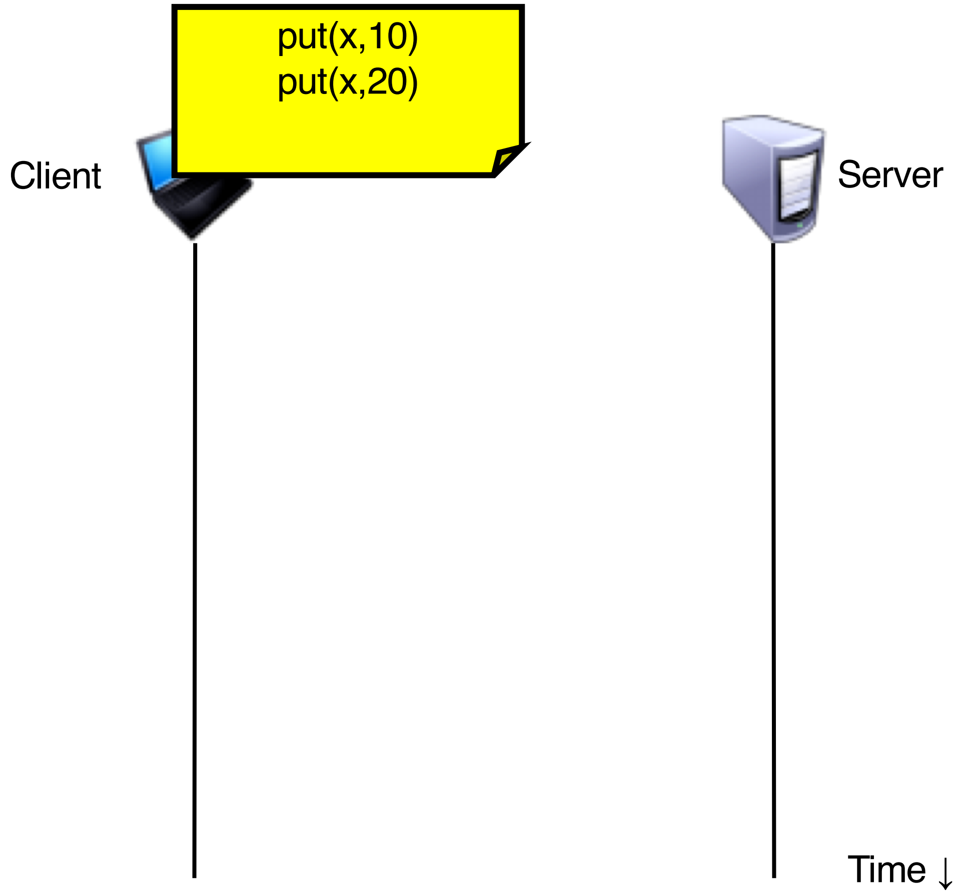

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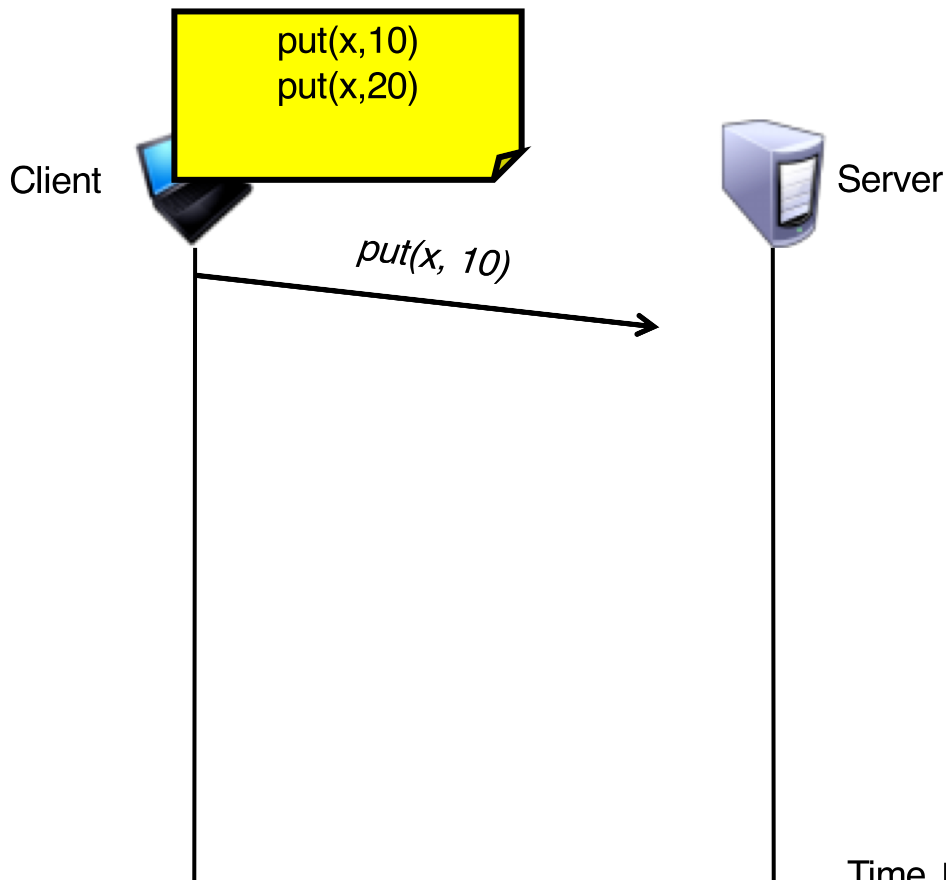

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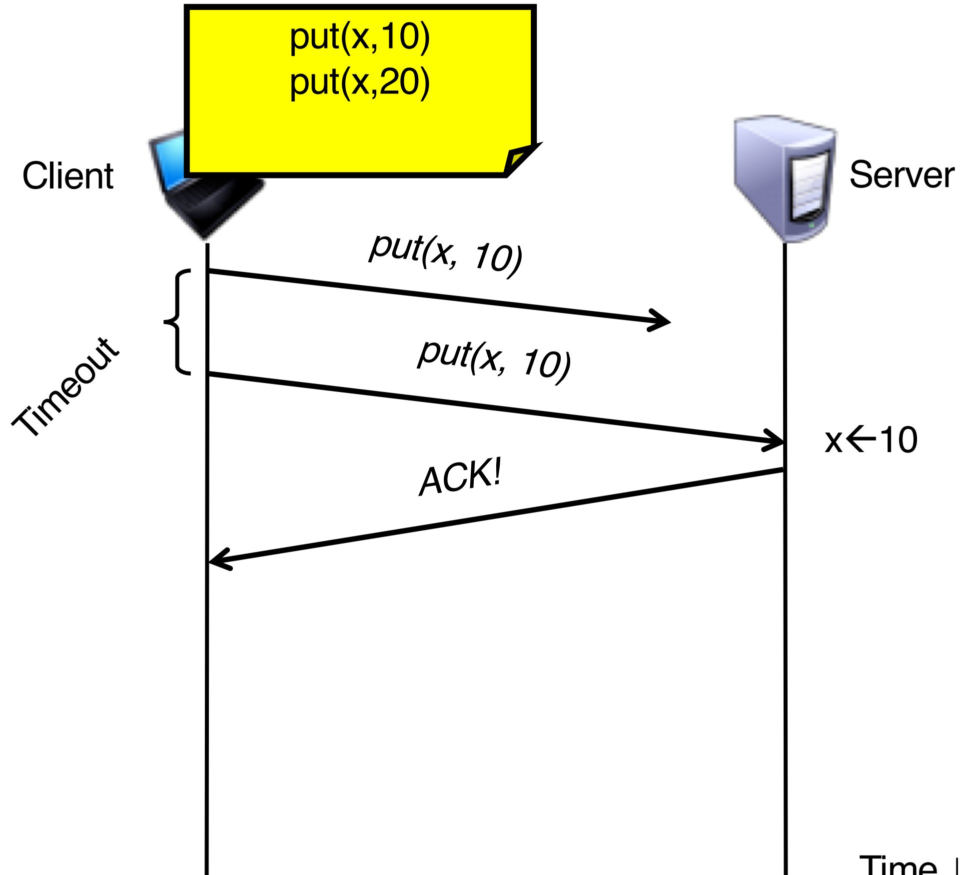

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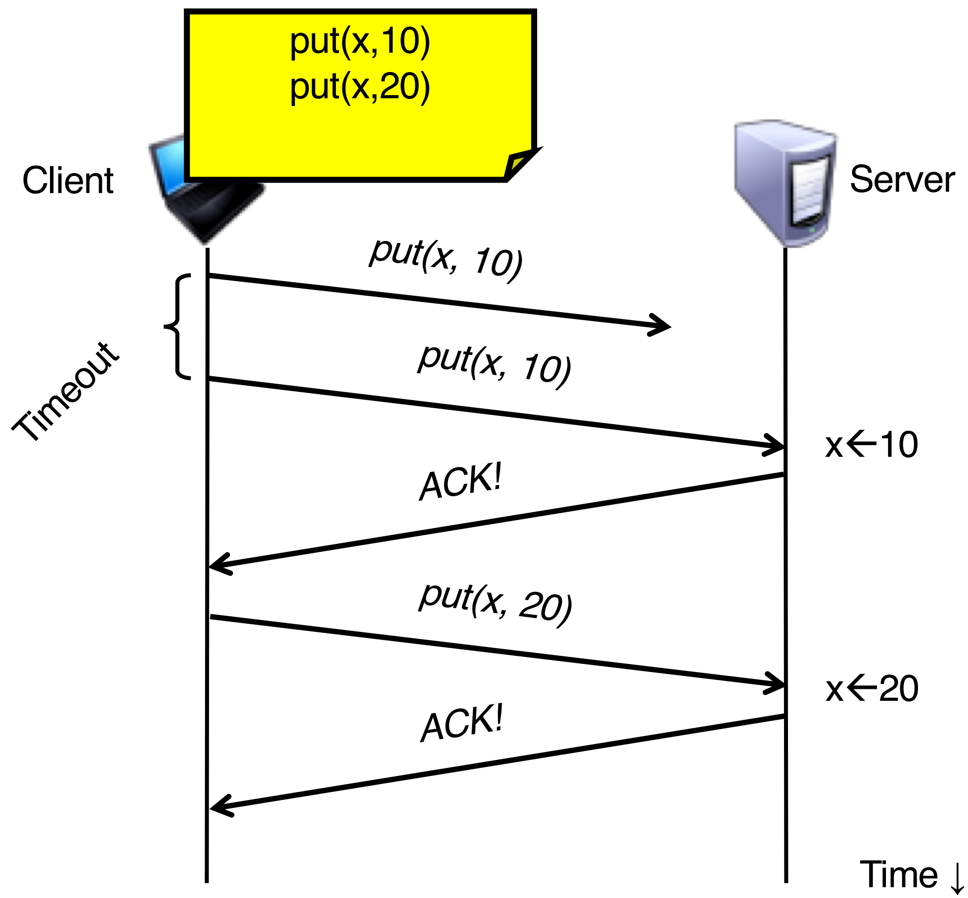

At-Least-Once and writes

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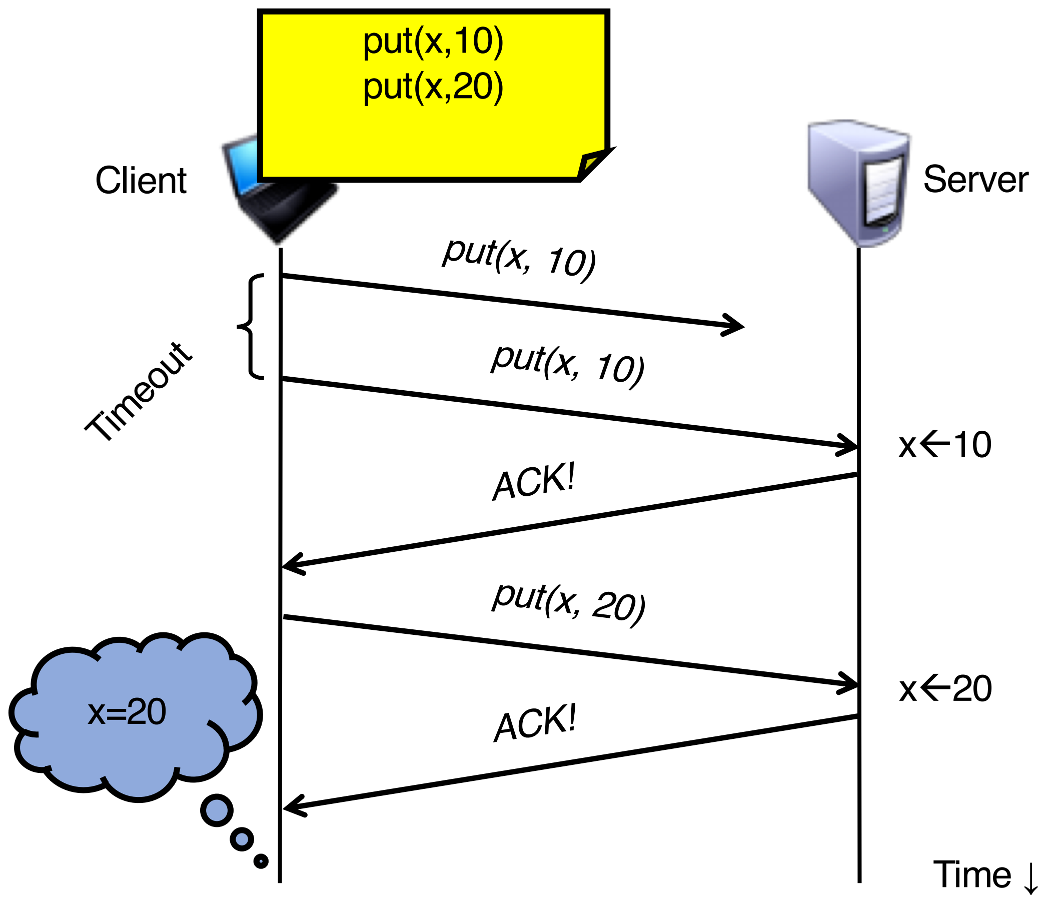
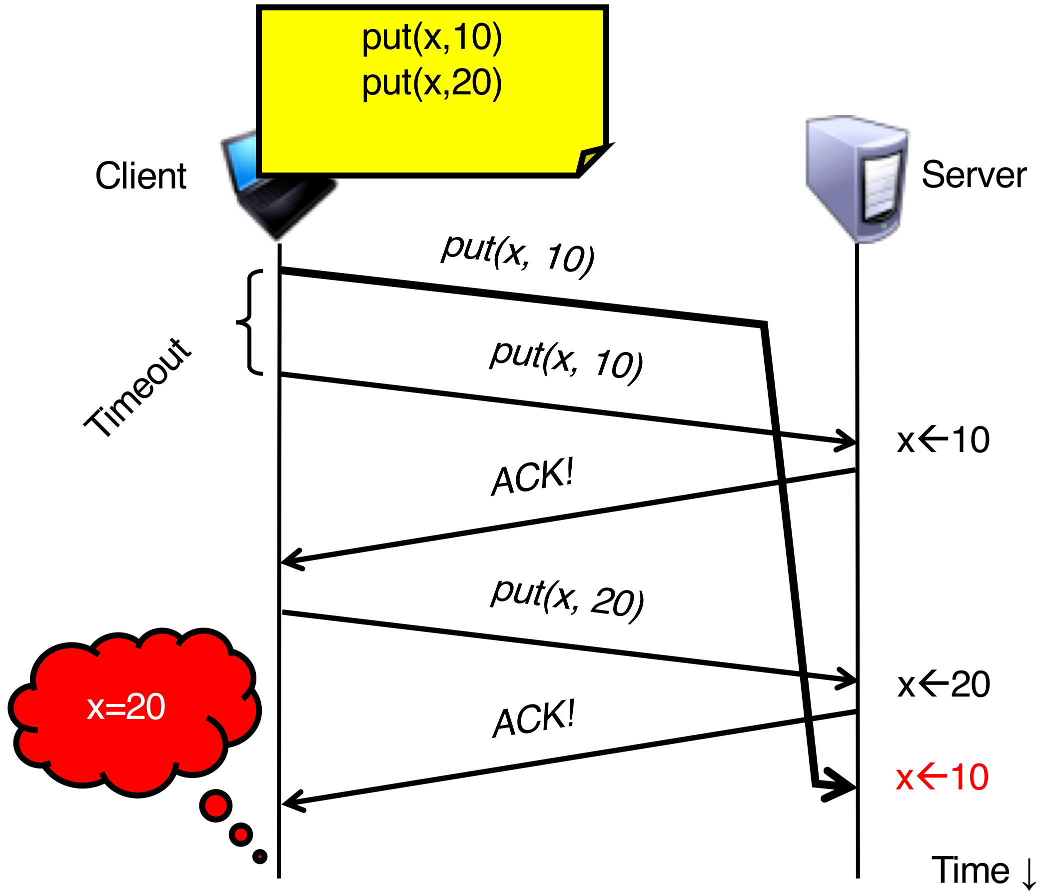


At-Least-Once and writes

- 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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- How to detect a duplicate request?
  - Test: Server sees same function, same arguments twice

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 RPC requests
  - Client uses same xid for retransmitted requests

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

```
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

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

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

At-Most-Once: Providing unique XIDs

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 client crashes and restarts. Can it reuse the same client ID?

3. Big random number (probabilistic, not certain guarantee)

At-Most-Once: Discarding server state

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

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- 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

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Significant overhead if many RPCs are in flight, in parallel

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- 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?

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

Exactly-once?

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- Plus the duplicate filtering of at most once scheme
  - To survive client crashes, client needs to record pending RPCs on disk
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Exactly-once?

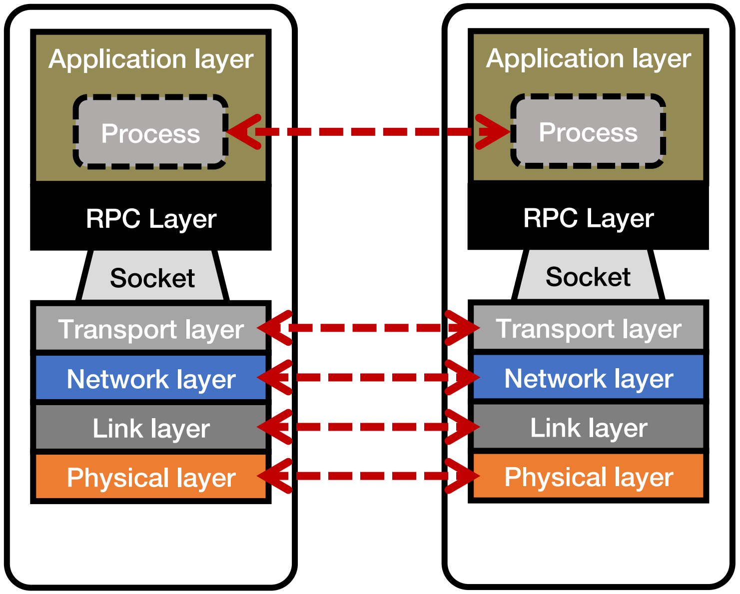
- Need retransmission of at least once scheme
- Plus the duplicate filtering of at most once scheme
  - To survive client crashes, client needs to record pending RPCs on disk
    - So it can replay them with the same unique identifier
- Plus story for making server reliable
  - Even if server fails, it needs to continue with full state
  - To survive server crashes, server should log to disk results of completed RPCs (to suppress duplicates)

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: Network comm. and RPCs

- Layers are our friends!
- RPCs are everywhere
- Necessary issues surrounding machine heterogeneity
- Subtle issues around failures
  - At-least-once w/ retransmission
  - At-most-once w/ duplicate filtering
    - Discard server state w/ cumulative acks
  - Exactly-once with:
    - at-least-once + at-most-once + fault tolerance + no external actions



Today's outline

1. Network sockets

2. Remote procedure call

3. RPCs in Go

Go RPCs

- Implementation in built-in library net/rpc

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- Write stub receiver methods of the form

  - `func (t *T) MethodName(args T1, reply *T2) error`

- Register receiver methods

- Create a listener (i.e., server) that accepts requests

Writing a WordCount RPC server in Go

```go
type WordCountServer struct {
	addr string
}

type WordCountRequest struct {
	Input string
}

type WordCountReply struct {
	Counts map[string]int
}
```

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```

```
func (*WordCountServer) Compute(
            request WordCountRequest,
            reply *WordCountReply) error {
      counts := make(map[string]int)
      input := request.Input
      tokens := strings.Fields(input)
      for _, t := range tokens {
            counts[t] += 1
      }
      reply.Counts = counts
      return nil
}
```

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Writing a WordCount RPC server in Go

```go
func (server *WordCountServer) Listen() {
	rpc.Register(server)
	listener, err := net.Listen("tcp", server.addr)
	checkError(err)
	go func() {
		rpc.Accept(listener)
	}()
}
```

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}
```

WordCount client

```go
func makeRequest(input string, serverAddr string) (map[string]int, error) {
	client, err := rpc.Dial("tcp", serverAddr)
	checkError(err)
	args := WordCountRequest{input}
	reply := WordCountReply{make(map[string]int)}
	err = client.Call("WordCountServer.Compute", args, &reply)
	if err != nil {
		return nil, err
	}
	return reply.Counts, nil
}
```

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func makeRequest(input string, serverAddr string) (map[string]int, error) {
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      err = client.Call("WordCountServer.Compute", args, &reply)
      if err != nil {
            return nil, err
      }
      return reply.Counts, nil
}
```

WordCount client-server

```
func main() {
	serverAddr := "localhost:8888"
	server := WordCountServer{serverAddr}
	server.Listen()
	input1 := "hello I am good hello bye bye bye bye good night hello"
	wordcount, err := makeRequest(input1, serverAddr)
	checkError(err)
	fmt.Printf("Result: %v\n", wordcount)
}
```

WordCount client-server

```go
func main() {
	serverAddr := "localhost:8888"
	server := WordCountServer{serverAddr}
	server.Listen()
	input1 := "hello I am good hello bye bye bye bye good night hello"
	wordcount, err := makeRequest(input1, serverAddr)
	checkError(err)
	fmt.Printf("Result: %v\n", wordcount)
}
```

```
Result: map[hello:3 I:1 am:1 good:2 bye:4 night:1]
```

Is this synchronous or asynchronous?

```
func makeRequest(input string, serverAddr string) (map[string]int, error)
{
      client, err := rpc.Dial("tcp", serverAddr)
      checkError(err)
      args := WordCountRequest{input}
      reply := WordCountReply{make(map[string]int)}
      err = client.Call("WordCountServer.Compute", args, &reply)
      if err != nil {
            return nil, err
      }
      return reply.Counts, nil
}
```

Making client asynchronous

```
func makeRequest(input string, serverAddr string) chan Result {
	client, err := rpc.Dial("tcp", serverAddr)
	checkError(err)
	args := WordCountRequest{input}
	reply := WordCountReply{make(map[string]int)}









	return ch
}
```

Making client asynchronous

```
func makeRequest(input string, serverAddr string) chan Result {
	client, err := rpc.Dial("tcp", serverAddr)
	checkError(err)
	args := WordCountRequest{input}
	reply := WordCountReply{make(map[string]int)}
	ch := make(chan Result)
	go func() {
		err := client.Call("WordCountServer.Compute", args, &reply)
		if err != nil {
			ch <- Result{nil, err} // something went wrong
		} else {
			ch <- Result{reply.Counts, nil} // success
		}
	}()
	return ch
}
```

Making client asynchronous

```
func makeRequest(input string, serverAddr string) *Call {
	client, err := rpc.Dial("tcp", serverAddr)
	checkError(err)
	args := WordCountRequest{input}
	reply := WordCountReply{make(map[string]int)}
	return client.Go("WordCountServer.Compute", args, &reply, nil)
}
```

Making client asynchronous

```
func makeRequest(input string, serverAddr string) *Call {
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      args := WordCountRequest{input}
      reply := WordCountReply{make(map[string]int)}
      return client.Go("WordCountServer.Compute", args, &reply, nil)
}
```

```
call := makeRequest(...)
<-call.Done
checkError(call.Error)
handleReply(call.Reply)
```