Network Communication and Remote Procedure Calls

COS 418: *Distributed Systems*
Lecture 2

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Context and today's outline

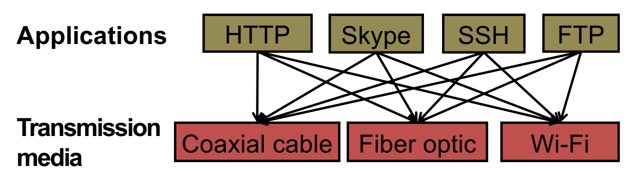
- A ***distributed system*** is many cooperating computers that appear to users as a single service
- **Today—** *How can processes on different cooperating computers* ***exchange information?***

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?*

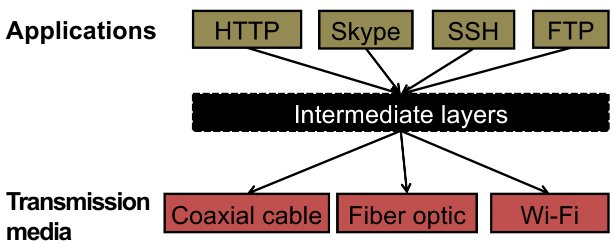
The problem of communication



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

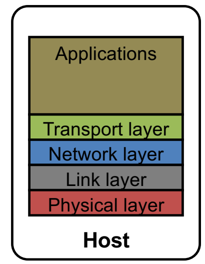
- **No!** But how does the Internet design avoid this?

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

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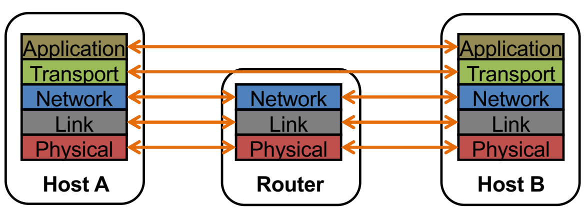
Logical communication between layers

- *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***



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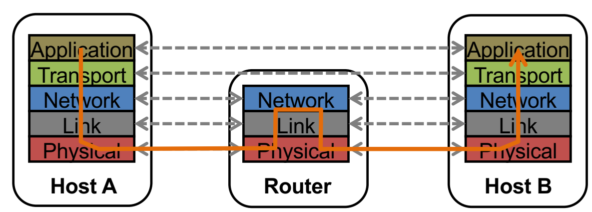
Physical communication

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



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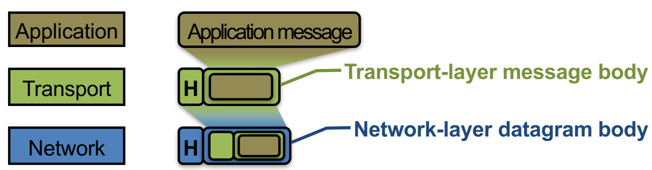
Communication between peers

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

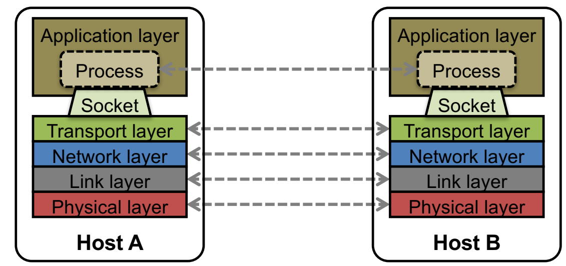
- Layer attaches its own ***header*** (**H**) to communicate with peer
  - Higher layers' headers, data ***encapsulated*** inside message
    - Lower layers don't generally inspect higher layers' headers



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

// Es
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);
```

Sockets don't provide transparency

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
- COS 418 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

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 ($10^3\times$ slower)
     - In the wide area, typically $10^6\times$ 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

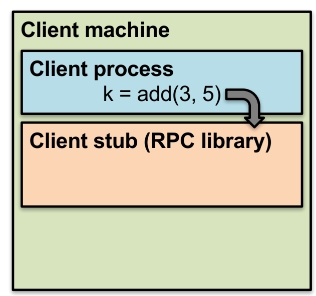
- Then runs an ***IDL compiler*** which generates:
  - Code to ***marshal*** (convert) native data types into machine-independent byte streams
    - And vice-versa, called ***unmarshaling***

  - **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

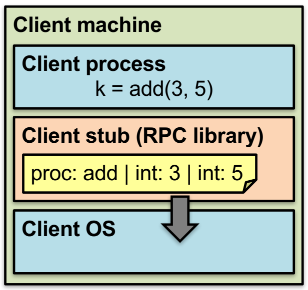
1. **Client calls stub function (pushes params onto stack)**



A day in the life of an RPC

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

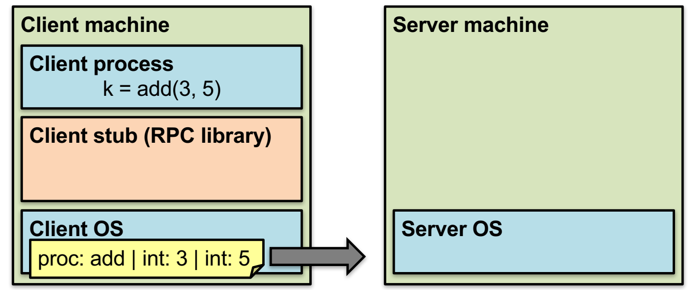
2. **Stub marshals parameters to a network message**



A day in the life of an RPC

2. Stub marshals parameters to a network message

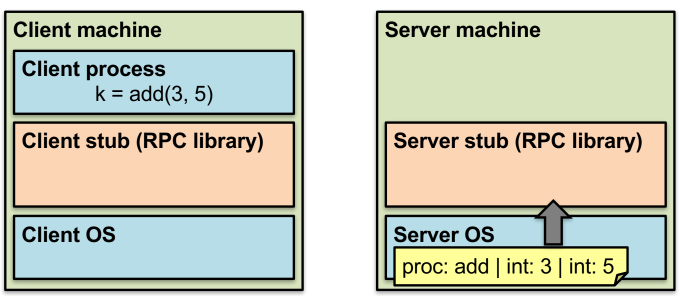
3. **OS sends a network message to the server**



A day in the life of an RPC

3. OS sends a network message to the server

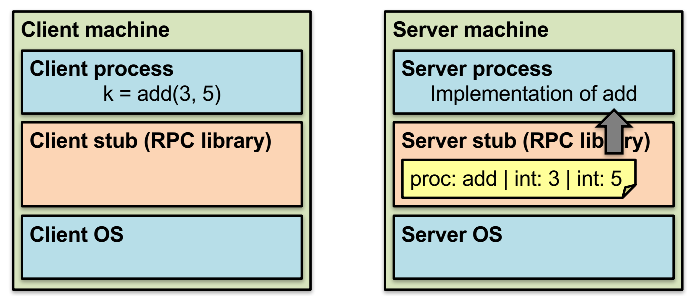
4. **Server OS receives message, sends it up to stub**



A day in the life of an RPC

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

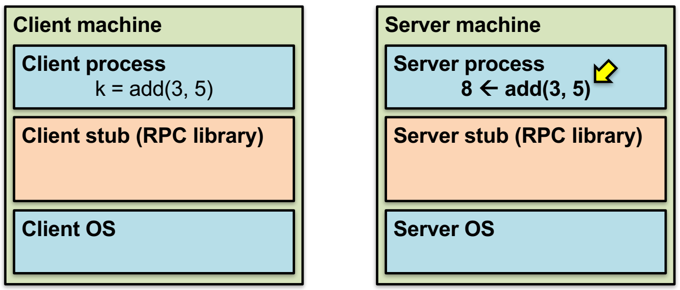
5. **Server stub unmarshals params, calls server function**



A day in the life of an RPC

5. Server stub unmarshals params, calls server function

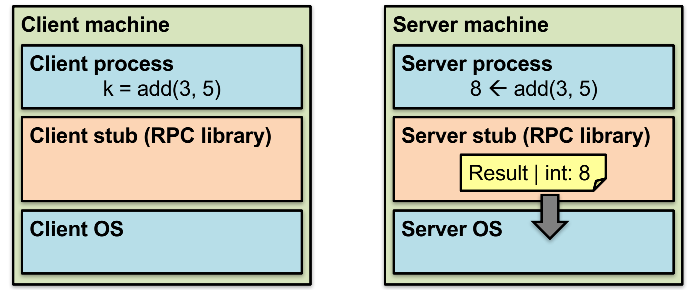
6. **Server function runs, returns a value**



A day in the life of an RPC

6. Server function runs, returns a value

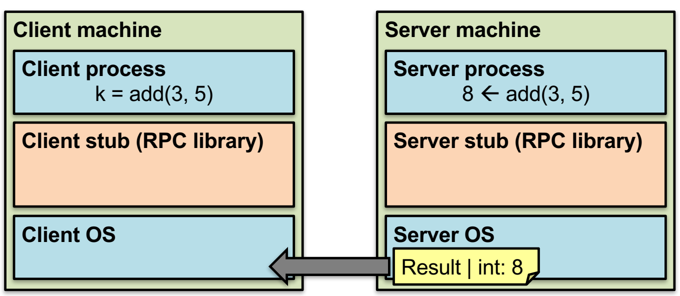
7. **Server stub marshals the return value, sends msg**



A day in the life of an RPC

7. Server stub marshals the return value, sends msg

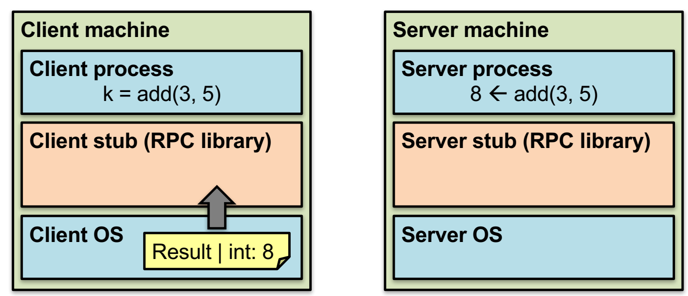
8. **Server OS sends the reply back across the network**



A day in the life of an RPC

8. Server OS sends the reply back across the network

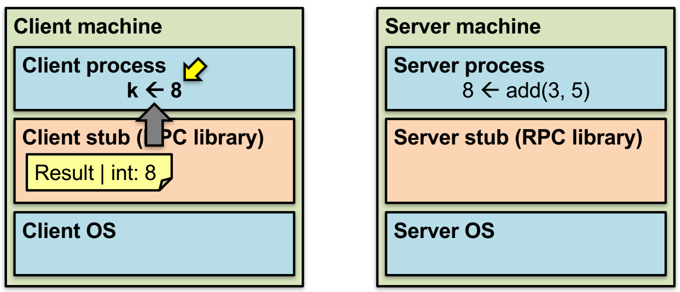
9. **Client OS receives the reply and passes up to stub**



A day in the life of an RPC

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

10. Client stub unmarshals return value, returns to client



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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

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Today's outline

1. Message-Oriented Communication
2. **Remote Procedure Call**
   - Rendezvous and coordination
   - **Failure**
   - Performance
3. Threads

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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…

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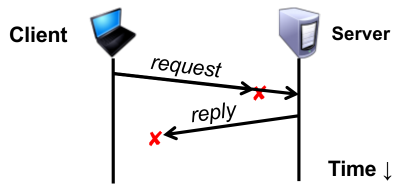
Failures, from client's perspective



The cause of the failure is hidden from the client!

At-Least-Once scheme

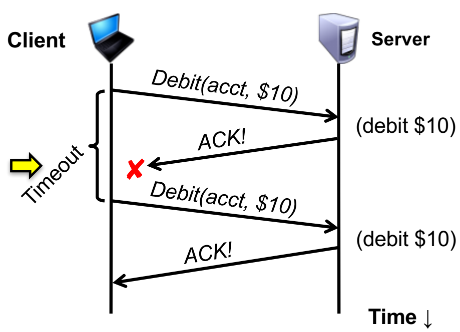
- **Simplest** scheme for handling failures

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

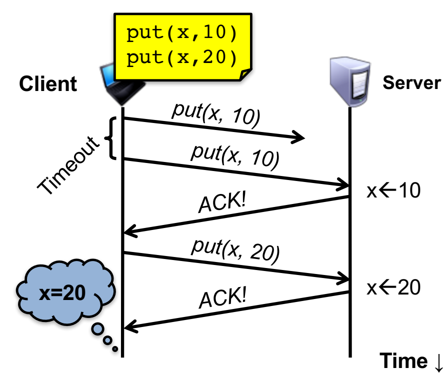
At-Least-Once and side effects

- Client sends a "debit $10 from bank account" RPC



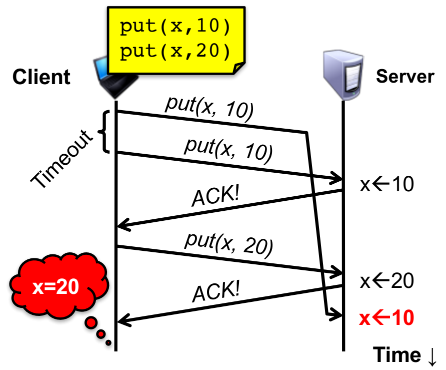
At-Least-Once and writes

- 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

```
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
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 (probabilistic, not certain guarantee)

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

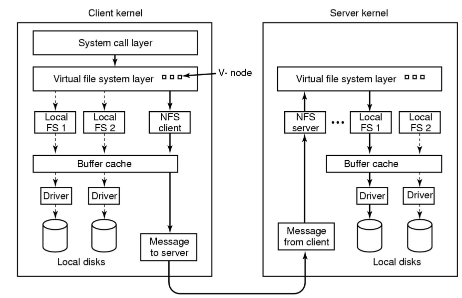
Exactly-once?

- 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 is 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 = **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***

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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!

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Wednesday topic:
Network File Systems

Friday precept:
Concurrency In Go, MapReduce

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APPENDIX

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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"

int 5 at address 0x1000:

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

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

int 5 at address 0x1000:

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