Introduction to Distributed Systems

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Today's Lecture

- Introduction
- Course details
- RPCs
- Primary-backup systems (start discussion)

Distributed Systems are everywhere!

- Some of the most powerful services are powered using distributed systems
  - systems that span the world,
  - serve millions of users,
  - and are always up!
- … but also pose some of the hardest CS problems
- Incredibly relevant today

What is a distributed system?

- multiple interconnected computers that cooperate to provide some service

- what are some examples of distributed systems?

Why distributed systems?

- Higher capacity and performance
- Geographical distribution
- Build reliable, always-on systems

- What are the challenges in building distributed systems?

(Partial) List of Challenges

- Fault tolerance
  - different failure models, different types of failures
- Consistency/correctness of distributed state
- System design and architecture
- Performance
- Scaling
- Security
- Testing

- We want to build distributed systems to be more scalable, and more reliable

- But it’s easy to make a distributed system that’s less scalable and less reliable than a centralized one!

Challenge: failure

- Want to keep the system doing useful work in the presence of partial failures

Consider a datacenter

- E.g., Facebook, Prineville OR
- 10x size of this building, $1B cost, 30 MW power
  - 200K+ servers
  - 500K+ disks
  - 10K network switches
  - 300K+ network cables
- What is the likelihood that all of them are functioning correctly at any given moment?

Typical first year for a cluster

[Jeff Dean, Google, 2008]

- ~0.5 overheating (power down most machines in <5 mins, ~1-2 days to recover)
- ~1 PDU failure (~500-1000 machines suddenly disappear, ~6 hours to come back)
- ~1 rack-move (plenty of warning, ~500-1000 machines powered down, ~6 hours)
- ~1 network rewiring (rolling ~5% of machines down over 2-day span)
- ~20 rack failures (40-80 machines instantly disappear, 1-6 hours to get back)
- ~5 racks go wonky (40-80 machines see 50% packetloss)
- ~8 network maintenances (4 might cause ~30-minute random connectivity losses)
- ~12 router reloads (takes out DNS and external vips for a couple minutes)
- ~3 router failures (have to immediately pull traffic for an hour)
- ~dozens of minor 30-second blips for dns
- ~1000 individual machine failures
- ~thousands of hard drive failures
- slow disks, bad memory, misconfigured machines, flaky machines, etc

- At any given point in time, there are many failed components!
- Leslie Lamport (c. 1990): “A distributed system is one where the failure of a computer you didn’t know existed renders your own computer useless”

Challenge: Managing State

- Question: what are the issues in managing state?

State Management

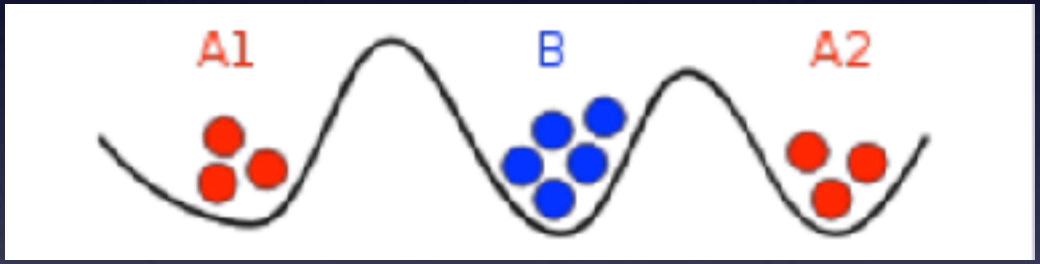
- Keep data available despite failures:
  - make multiple copies in different places
- Make popular data fast for everyone:
  - make multiple copies in different places
- Store a huge amount of data:
  - split it into multiple partitions on different machines
- How do we make sure that all these copies of data are consistent with each other?
- How do we do all of this efficiently?

Lot of subtleties

- Simple idea: make two copies of data so you can tolerate one failure
- We will spend a non-trivial amount of time this quarter learning how to do this correctly!
    - What if one replica fails?
    - What if one replica just thinks the other has failed?
    - What if each replica thinks the other has failed?

The Two Generals Problem

- Two armies are encamped on two hills surrounding a city in a valley



- The generals must agree on the same time to attack the city.
- Their only way to communicate is by sending a messenger through the valley, but that messenger could be captured (and the message lost)

The Two-Generals Problem

- No solution is possible!
- If a solution were possible:
  - it must have involved sending some messages
  - but the last message could have been lost, so we must not have really needed it
  - so we can remove that message entirely
- We can apply this logic to any protocol, and remove all the messages — contradiction

- What does this have to do with distributed systems?

Distributed Systems are Hard

- Distributed systems are hard because many things we want to do are provably impossible
  - consensus: get a group of nodes to agree on a value (say, which request to execute next)
  - be certain about which machines are alive and which ones are just slow
  - build a storage system that is always consistent and always available (the “CAP theorem”)

- We need to make the right assumptions and also resort to “best effort” guarantees

This Course

- Introduction to the major challenges in building distributed systems
- Will cover key ideas, algorithms, and abstractions in building distributed system
- Will also cover some well-known systems that embody such as ideas

Topics

- Implementing distributed systems: system and protocol design
- Understanding the global state of a distributed system
- Building reliable systems from unreliable components
- Building scalable systems
- Managing concurrent accesses to data with transactions
- Abstractions for big data analytics
- Building secure systems from untrusted components
- Latest research in distributed systems

Course Components

- Readings and discussions of research papers (20%)
  - no textbook
  - online response to discussion questions — one or two paras
  - we will pick the best 7 out of 8 scores

- Programming assignments (80%)
  - building a scalable, consistent key-value store
  - three parts (if done as individuals) or four parts (if done as groups of two)
  - total of 5 slack days with no penalty

Course Staff

- Instructor: Arvind
- TAs:
  - Kaiyuan Zhang
  - Paul Yau
- Contact information on the class page

Canvas

- Link on class webpage
- Post responses to weekly readings
- Please use Canvas “discussions” to discuss/clarify the assignment details
- Upload assignment submissions

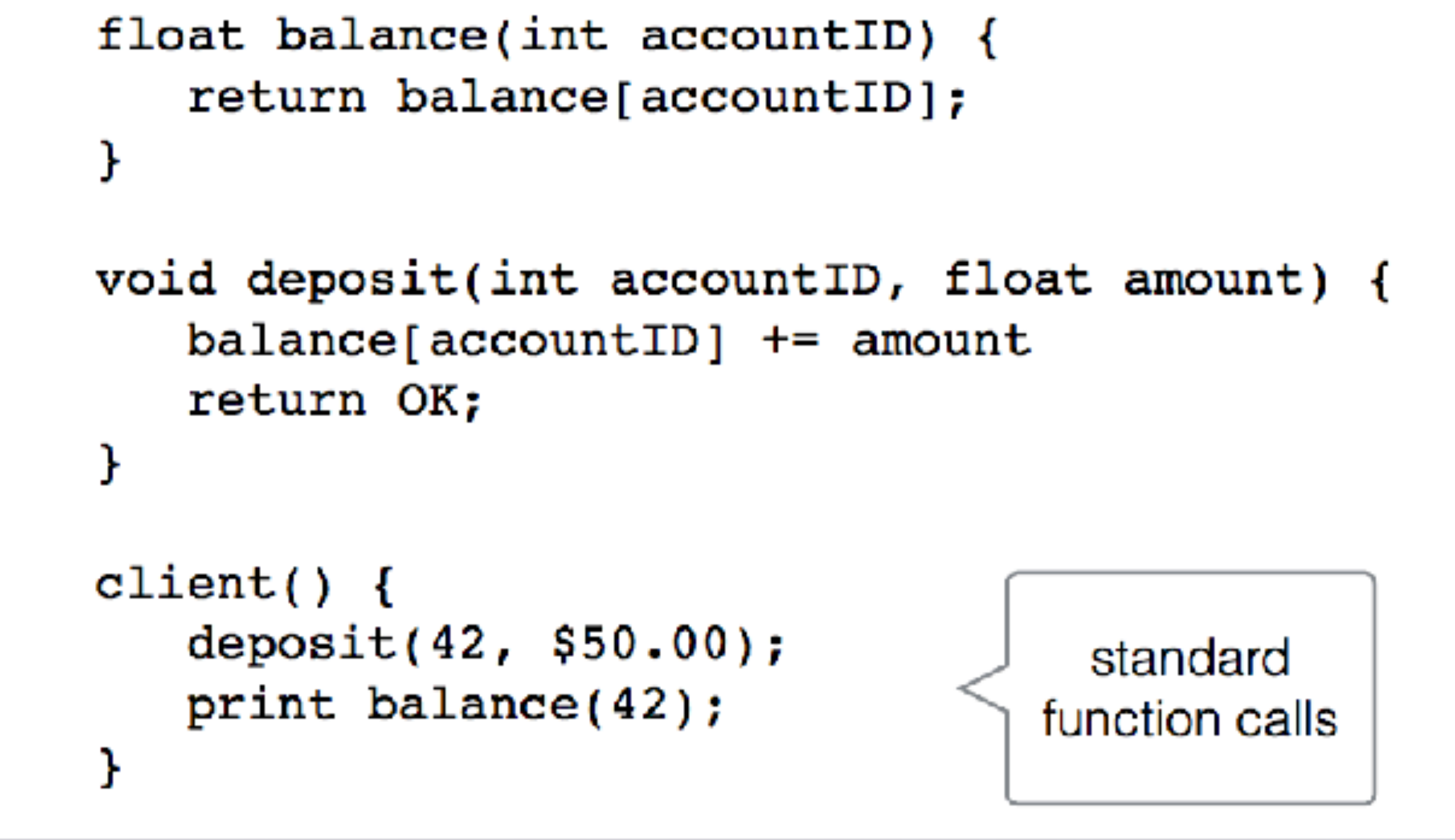
Remote Procedure Call

- How should we communicate between nodes in a distributed system?
- Could communicate with explicit message patterns
  - But that could be too low-level
- RPC is a communication abstraction to make programming distributed systems easier

Common Pattern: Client/server

- Client requires an operation to be performed on a server and desires the result
- RPC fits this design pattern:
  - hides most details of client/server communication
  - client call is much like ordinary procedure call
  - server handlers are much like ordinary procedures

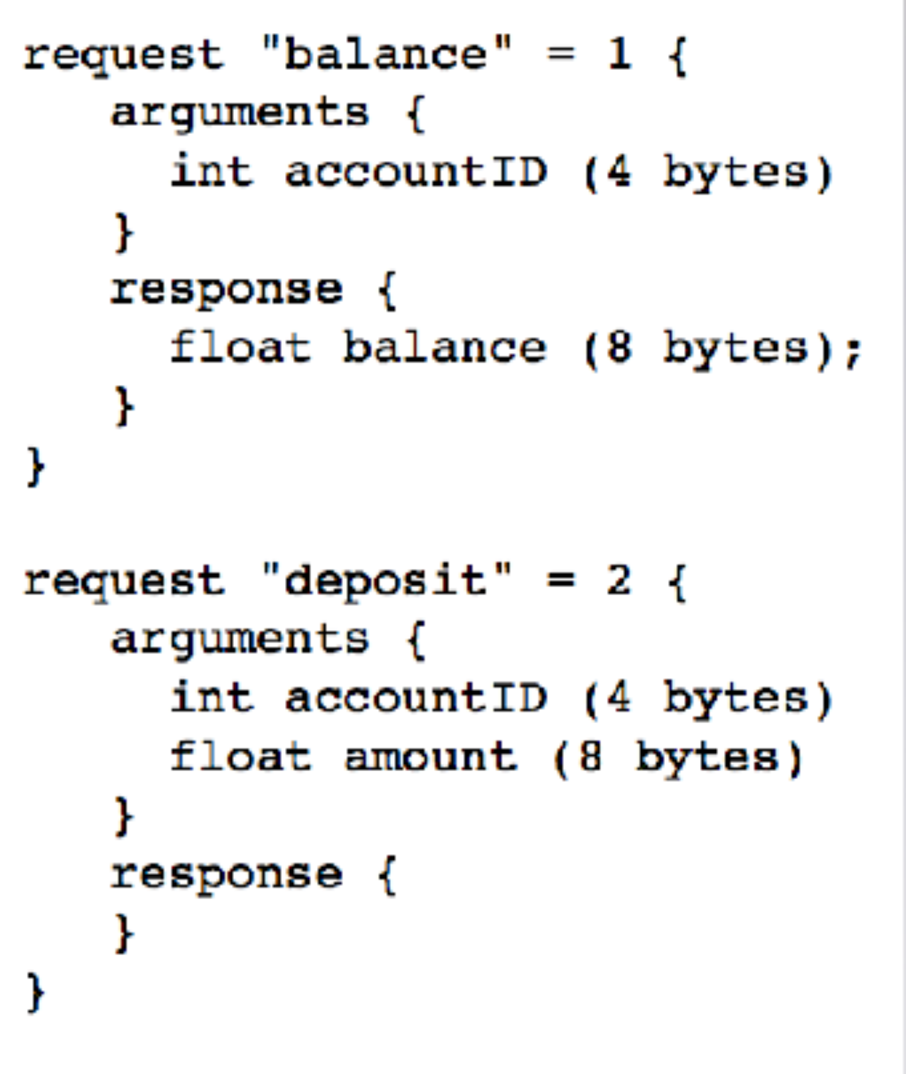
Local Execution



```
float balance(int accountID) {
   return balance[accountID];
}

void deposit(int accountID, float amount) {
   balance[accountID] += amount
   return OK;
}

client() {
   deposit(42, $50.00);
   print balance(42);
}
```

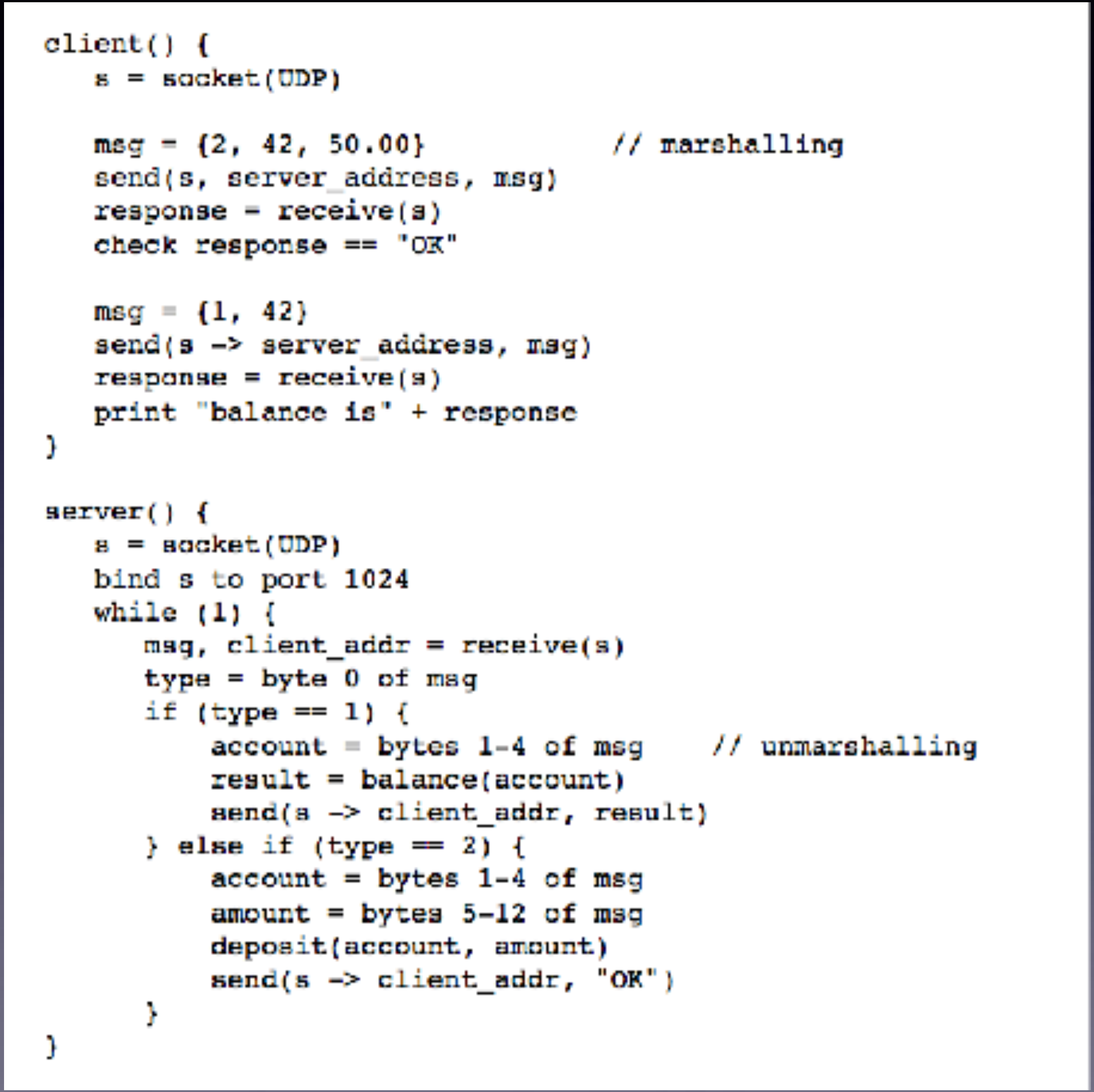
standard
function calls

Hard-coded Distributed Protocol



```
request "balance" = 1 {
   arguments {
     int accountID (4 bytes)
   }
   response {
     float balance (8 bytes);
   }
}

request "deposit" = 2 {
   arguments {
     int accountID (4 bytes)
     float amount (8 bytes)
   }
   response {
   }
}
```

Hard-coding Client/Server



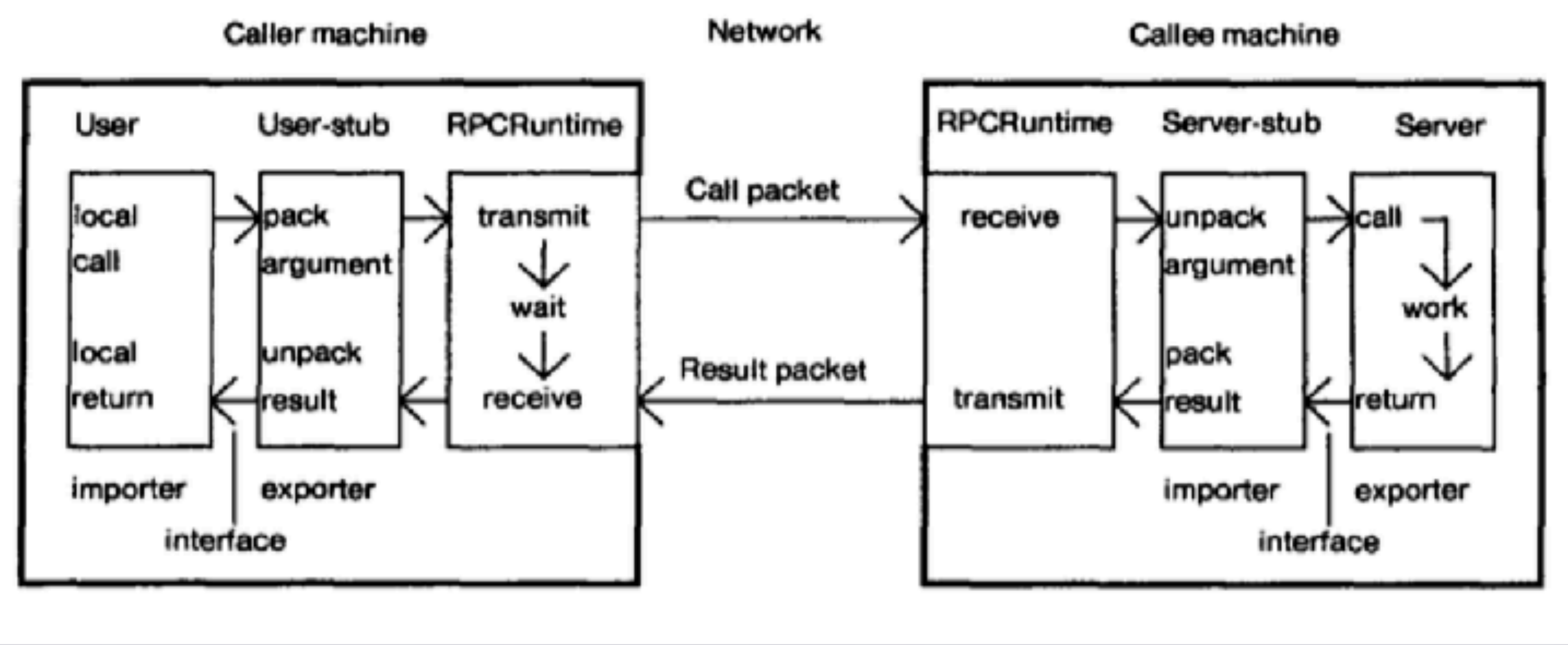
```
client() {
   s = socket(UDP)

   msg = {2, 42, 50.00}           // marshalling
   send(s, server_address, msg)
   response = receive(s)
   check response == "OK"

   msg = {1, 42}
   send(s -> server_address, msg)
   response = receive(s)
   print "balance is" + response
}

server() {
   s = socket(UDP)
   bind s to port 1024
   while (1) {
      msg, client_addr = receive(s)
      type = byte 0 of msg
      if (type == 1) {
          account = bytes 1-4 of msg    // unmarshalling
          result = balance(account)
          send(s -> client_addr, result)
      } else if (type == 2) {
          account = bytes 1-4 of msg
          amount = bytes 5-12 of msg
          deposit(account, amount)
          send(s -> client_addr, "OK")
      }
}
```

Question:
Why is this a bad approach to developing systems?

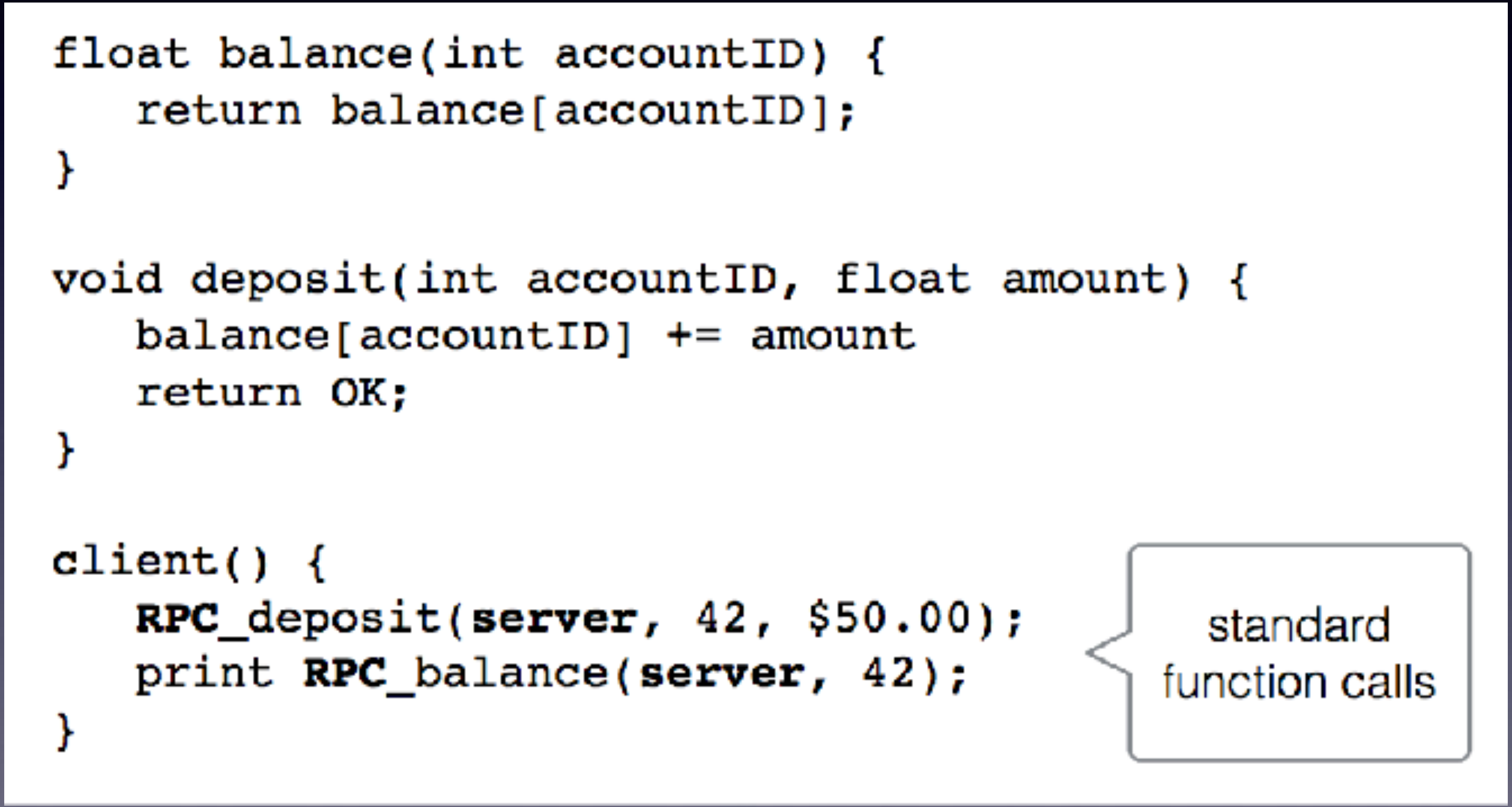
RPC Approach

- Compile high level protocol specs into stubs that do marshalling/unmarshalling
- Make a remote call look like a normal function call

RPC Approach



RPC hides complexity



```
float balance(int accountID) {
   return balance[accountID];
}

void deposit(int accountID, float amount) {
   balance[accountID] += amount
   return OK;
}

client() {
   RPC_deposit(server, 42, $50.00);
   print RPC_balance(server, 42);
}
```

standard
function calls

- Question: is the complexity all gone?
  - what are the issues that we still would have to deal with?

Dealing with Failures

- Client failures
- Server failures
- Communication failures

- Client might not know when failure happened
  - E.g., client never sees a response from the server — server could have failed before or after handling the message

At-least-once RPC

- Client retries request until it gets a response
- Implications:
  - requests might be executed twice
  - might be okay if requests are idempotent

Alternative: at-most-once

- Include a unique ID in every request
- Server keeps a history of requests it has already answered, their IDs, and the results
- If duplicate, server resends result

- Question: how do you guarantee uniqueness of IDs?
- Question: how can we garbage collect the history?

First Assignment

- Implement RPCs for a key-value store
- Simple assignment — goal is to get you familiar with the framework
- Due on 1/16 at 5pm

Primary-Backup Replication

- Widely used
- Reasonably simple to implement
- Hard to get desired consistency and performance
- Will revisit this and consider other approaches later in the class

Fault Tolerance

- we'd like a service that continues despite failures!
- available: still useable despite *some class of* failures
- strong consistency: act just like a single server to clients
- very useful!
- very hard!

Core Idea: replication

- Two servers (or more)
- Each replica keeps state needed for the service
- If one replica fails, others can continue

Key Questions

- What state to replicate?
- How does replica get state?
- When to cut over to backup?
- Are anomalies visible at cut-over?
- How to repair/re-integrate?

Two Main Approaches

- State transfer
  - "Primary" replica executes the service
  - Primary sends [new] state to backups
- Replicated state machine
  - All replicas execute all operations
  - If same start state, same operations, same order, deterministic → then same end state

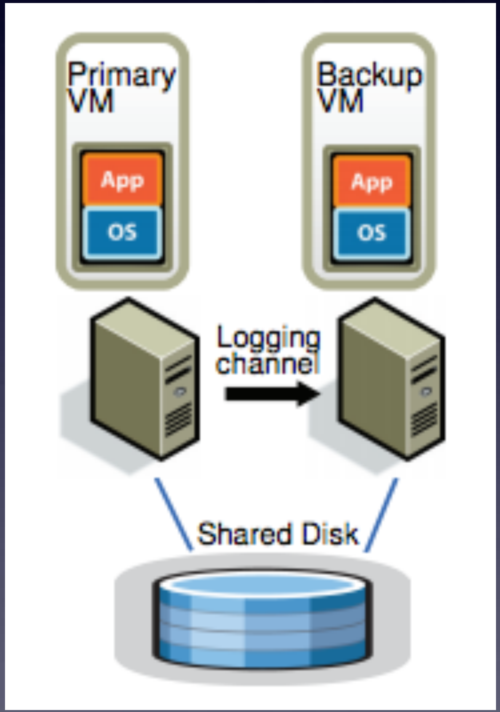
- There are tradeoffs: complexity, costs, consistency

VMware’s FT Virtual Machines

- Whole-system replication
- Completely transparent to applications and clients
- High availability for any existing software
- Failure model:
  - independent hardware faults
  - site-wide power failure
- Limited to uniprocessor VMs

Overview

- two machines, primary and backup
- shared-disk for persistent storage
- back-up in "lock step" with primary
  - primary sends all inputs to backup
  - outputs of backup are dropped
- heart beats between primary and backup
  - if primary fails, start backup executing!



Challenges

- Making it look like a single reliable server
- How to avoid two primaries? (“split-brain syndrome")
- How to make backup an exact replica of primary
- What inputs must send to backup?
- How to deal with non-determinism?

Technique 1: Deterministic Replay

- Goal: make x86 platform deterministic
  - idea: use hypervisor to make virtual x86 platform deterministic
- Log all hardware events into a log
  - clock interrupts, network interrupts, i/o interrupts, etc.
  - for non-deterministic instructions, record additional info
    - e.g., log the value of the time stamp register
    - on replay: return the value from the log instead of the actual register

Deterministic Replay

- Replay: deliver inputs in the same order, at the same instructions
  - if during recording delivered clock interrupt at nth instr.
  - during replay also deliver the interrupt at the nth instr.
- Given an event log, deterministic replay recreates VM
  - hypervisor delivers first event
  - lets the machine execute to the next event
  - using special hardware registers to stop the processor at the right instruction
  - OS runs identical, applications runs identical
- Limitation: cannot handle multicore processors and interleaving

Applying Deterministic Replay to VM-FT

- Hypervisor at primary records
  - Sends log entries to backup over logging channel
- Hypervisor at backup replays log entries
  - We need to stop virtual x86 at instruction of next event
  - We need to know what is the next event
  - backup lags behind one event

Example

- Primary receives network interrupt
  - hypervisor forwards interrupt plus data to backup
  - hypervisor delivers network interrupt to OS kernel
  - OS kernel runs, kernel delivers packet to server
  - server/kernel write response to network card
  - hypervisor gets control and puts response on the wire
- Backup receives log entries
  - backup delivers network interrupt
  - …
  - hypervisor does *not* put response on the wire
  - hypervisor ignores local clock interrupts

Technique 2: FT Protocol

- Primary delays any output until the backup acks
  - Log entry for each output operation
  - Primary sends output after backup acked receiving output operation
- Performance optimization:
  - primary keeps executing past output operations
  - buffers output until backup acknowledges

Questions

- Why send output events to backup and delay output until backup has acked?
- What happens when primary fails after receiving network input but before sending a corresponding log entry to backup?
- Can the same output be produced twice?

Design Space

- Active or passive replicas
- Symmetric replicas or primary-backup
- Replicate commands or low-level inputs

Lab Framework

- Designed with the following requirements in mind:
  - single machine, centralized orchestration
  - simulate arbitrary network behavior
  - allow for model checking, visualization
- First lab:
  - introduce the framework, understand “client” and “timeout”
- Second and subsequent labs:
  - all interactions through messages
  - you have complete control over everything