Distributed systems

Lecture 9: Introduction to distributed systems, client-server computing, and RPC

Michaelmas 2019

Dr Martin Kleppmann

(With thanks to Dr Robert N. M. Watson and Dr Steven Hand)

Recommended reading

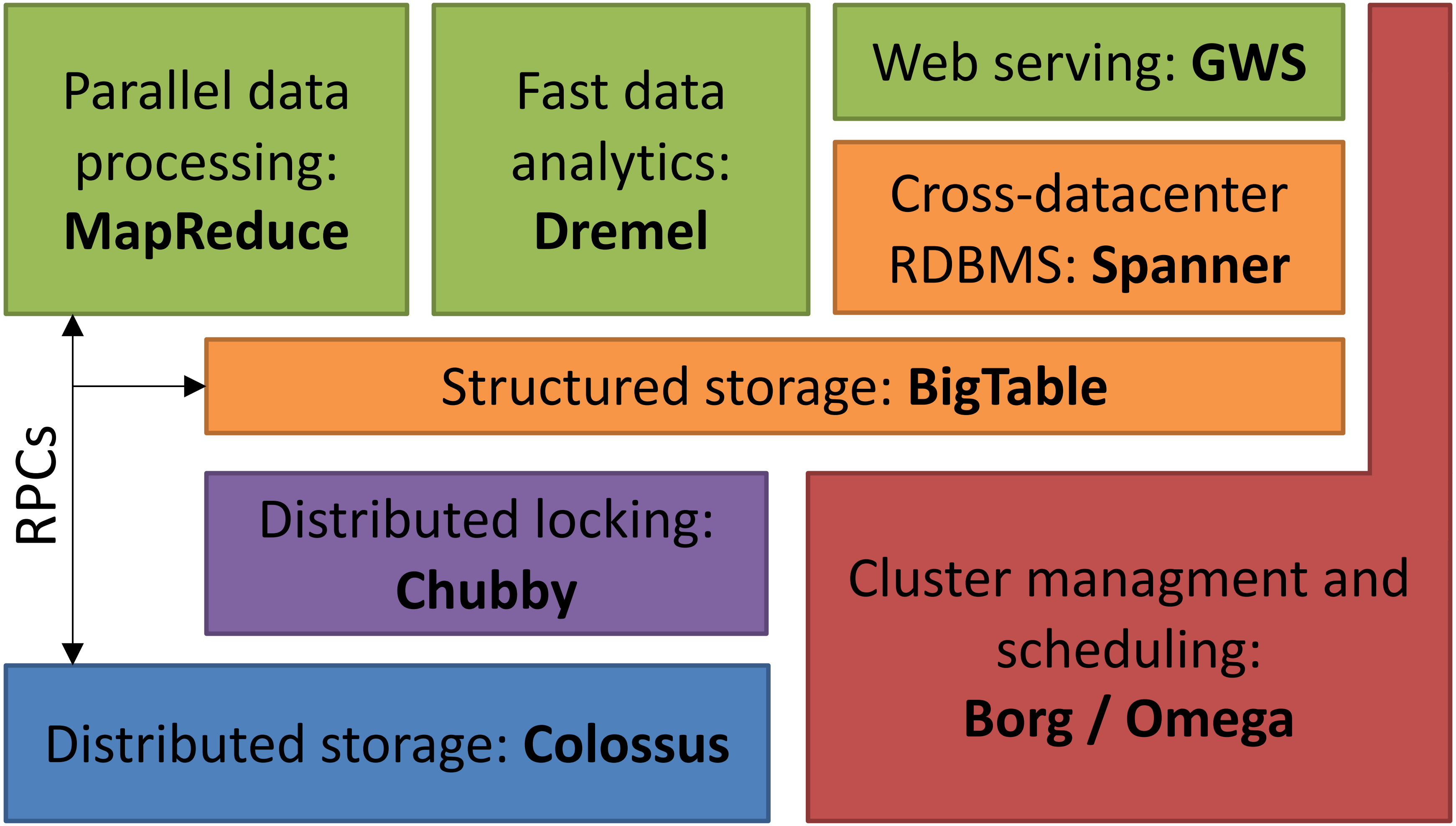
- "***Distributed Systems: Concepts and Design***", (5th Ed) Coulouris et al, Addison-Wesley 2012
- "***Distributed Systems: Principles and Paradigms***" (2nd Ed), Tannenbaum et al, Prentice Hall, 2006
- ***"Designing Data-Intensive Applications"***, Kleppmann, O'Reilly Media, 2017
- "***Operating Systems, Concurrent and Distributed S/W Design***", Bacon & Harris, Addison-Wesley 2003
  - or "***Concurrent Systems***", (2nd Ed), Jean Bacon, Addison-Wesley 1997

What are distributed systems?

- A set of discrete computers (“nodes”) that cooperate to perform a computation
  - Operates “as if” it were a single computing system
- Examples include:
  - Compute clusters (e.g. CERN, HPCF)
  - BOINC (aka SETI@Home and friends)
  - Distributed storage systems (e.g. NFS, Dropbox, …)
  - The Web (client/server; CDNs; and back-end too!)
  - Peer-to-peer systems such as Tor
  - Vehicles, factories, buildings (?)

Preview: Lecture 15 - Google architecture

(Or: *How to treat 100,000 computers as 1 computer*)



Concurrent systems reminder

- Foundations of concurrency: processor(s), threads
- Mutual exclusion: locks, semaphores, monitors, etc.
- Producer-consumer, active objects, message passing
- Races, deadlock, livelock, starvation, priority inversion
- Transactions, ACID, isolation, serialisability, schedules
- 2-phase locking, rollback, time-stamp ordering (TSO), optimistic concurrency control (OCC)
- Durability, write-ahead logging, recovery
- Lock-free algorithms, transactional memory
- Operating-system case study

These problems were **not hard enough** – distributed systems add:
loss of global visibility; **loss of global ordering**; **new failure modes**

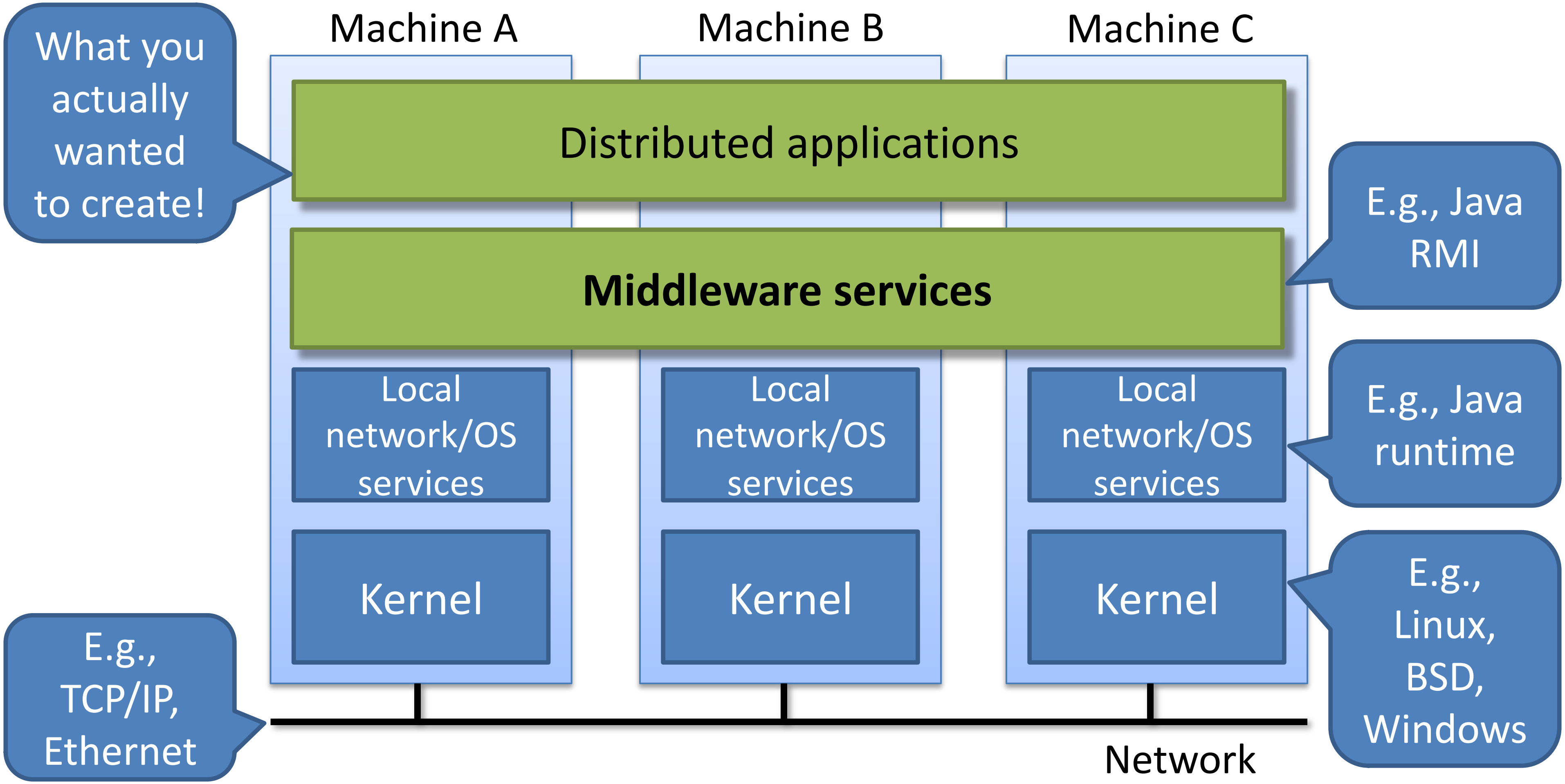
Distributed systems: advantages

- **Scale and performance**
  - Cheaper to buy 100 PCs than a supercomputer…
  - … and easier to incrementally scale up too!
- **Sharing and Communication**
  - Allow access to shared resources (e.g. a printer) and information (e.g. distributed FS or DBMS)
  - Enable explicit communication between machines (e.g. EDI, CDNs) or people (e.g. email, twitter)
- **Reliability**
  - Can hopefully continue to operate even if some parts of the system are inaccessible, or simply crash

Distributed systems: challenges

- **Distributed Systems are *Concurrent Systems***
  - Need to coordinate independent execution at each node (c/f first part of course)
- **Faults arise in any component** (nodes, network)
  - At any time, for any reason
  - Often we want to **tolerate** faults
- **Network delays**
  - Can't distinguish congestion from crash/partition
- **No global visibility**
  - Can't even agree what time it is, let alone anything more profound

Middleware



- **Middleware** helps application authors write software intended to run on more than one machine at a time.

Transparency & middleware

- Recall a distributed system should appear "as if" it were executing on a single computer
- We often call this **transparency**:
  - User is unaware of multiple machines
  - Programmer is unaware of multiple machines
- How "unaware" can vary quite a bit
  - e.g. web user probably aware that there's network communication ... but not the number or location of the various machines involved
  - e.g. programmer may explicitly code communication, or may have layers of abstraction: **middleware**

Types of transparency

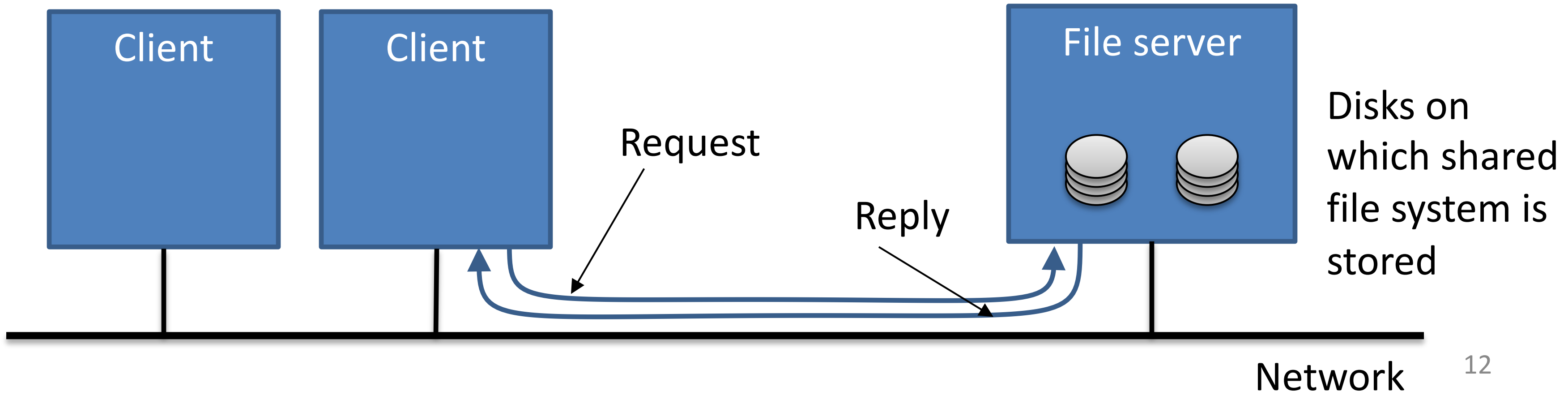
Transparency	Description
Access	Hide differences in data representation and how a resource is accessed
Location	Hide where a resource is located
Migration	Hide that a resource may move to another location
Relocation	Hide that a resource may be moved to another location .. while in use
Replication	Hide that a resource may be provided by multiple cooperating systems
Concurrency	Hide that a resource may be simultaneously shared by several competitive users
Failure	Hide the failure and recovery of a resource
Persistence	Hide whether a (software) resource is in memory or on disk
Performance	Hide the level of demand for a service as demand changes

In Distributed Systems…

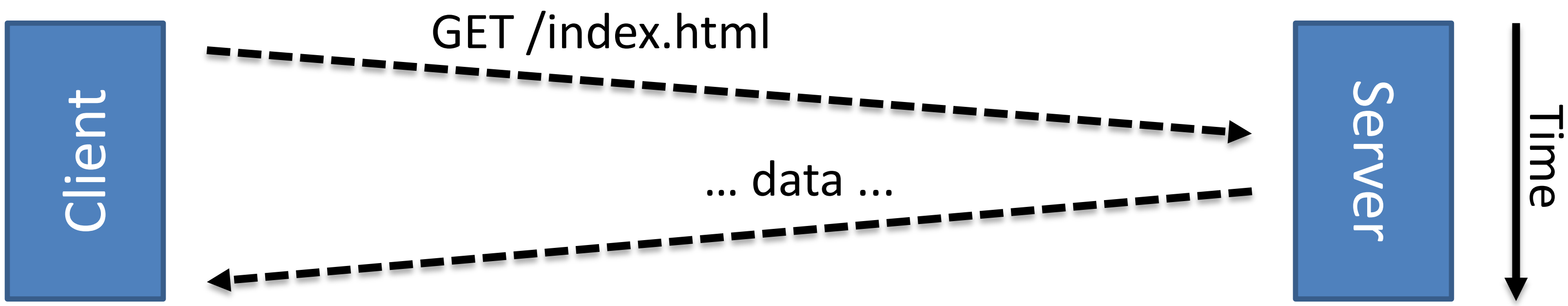
- We will look at techniques, protocols & algorithms used in distributed systems
  - in many cases, these will be provided for you by a middleware software suite
  - but knowing how things work will still be useful!
- Assume OS & networking support
  - processes, threads, synchronization
  - basic communication via messages
  - (will see later how assumptions about messages will influence the systems we [can] build)
- Let’s start with a simple **client-server systems**

Client-server model

- 1970s: development of **Local Area Networks (LANs)**
- 1980s: standard deployment involves small number of **servers**, plus many **workstations**
  - Servers: always-on, powerful machines
  - Workstations: personal computers
- Workstations request 'service' from servers over the network, e.g. access to a shared file-system:



Request-reply protocols



- Basic scheme:
  - Client issues a request message
  - Server performs operation, and sends reply
- Example: HTTP 1.0
  - Client (browser) sends “GET /index.html”
  - Web server loads file and returns it
  - Browser displays HTML web page

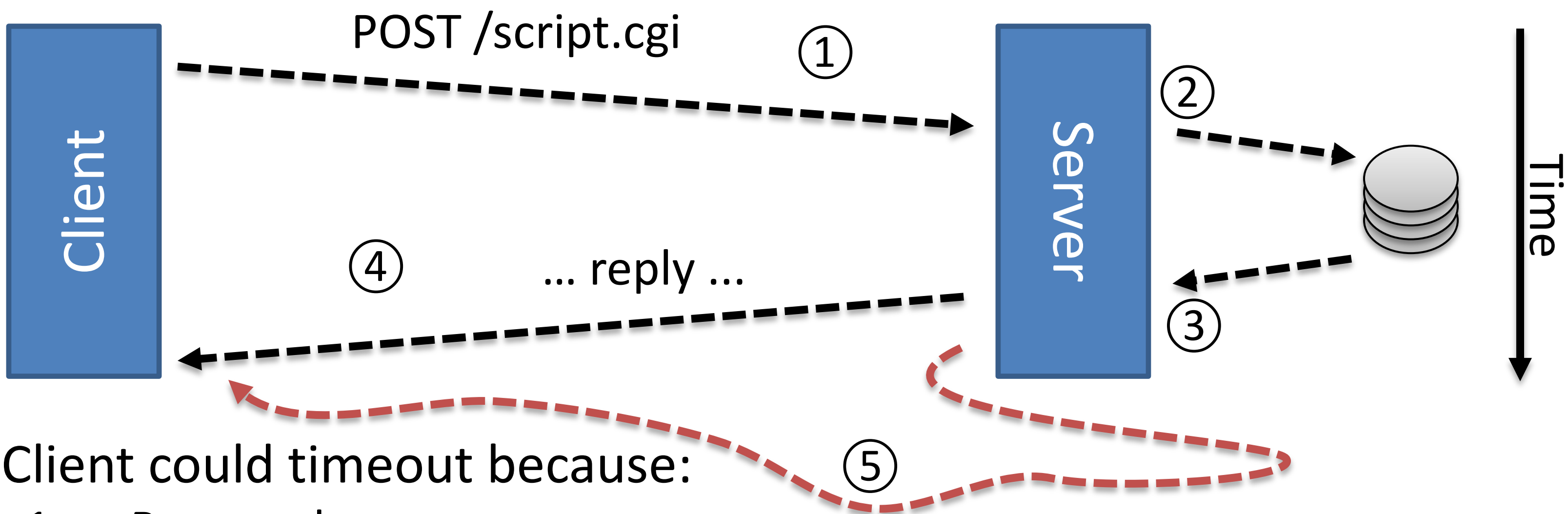
Synchrony and asynchrony

- **Synchrony** and **asynchrony** have to do with waiting
- For software, this relates to a program's event model:
  - **Synchronous clients** block awaiting a reply
  - **Asynchronous clients** can continue work while awaiting a reply
  - E.g., a command-line fetch tool vs. an interactive web browser
- For protocols, this relates to the ability to express multiple concurrent operations within a logical connection:
  - **Synchronous protocols** require that replies be issued in the same order that requests are sent
  - **Asynchronous protocols** allow **out-of-order replies** – e.g., by tagging replies with the ID number of the request
  - E.g., SMTP (one operation at a time) vs. IMAP (tagged requests)
- We often find complex combinations of synchrony and asynchrony within a single software/protocol stack

Errors, faults, and failures

- **Errors** are **application-level** things => easy ;-)
  - E.g. client requests non-existent web page
  - Need special reply (e.g. "404 Not Found")
- **Faults** are things that go wrong in the system
  - lost message, client/server crash, network down, …
- **Fault-tolerant** systems try to prevent faults from escalating into **failures**
  - **Failure**: system fails to provide required service to the user
  - To detect/handle faults: timeout, retry, replicate, …
  - How do you choose timeout period **T**?

Retry semantics



- Client could timeout because:
  1. Request lost
  2. Request sent, but server crashed before op. performed
  3. Request sent & received, op. performed, server crashed before reply
  4. Request sent & received, operation performed, reply sent … but lost
  5. As #4, but reply has just been delayed for longer than T
- For **read-only stateless requests** (e.g., HTTP GET), can retry in all cases, but what if request was an order with Amazon?
  - For #1, we (probably) want to re-order… in #5 we want to wait ….?
- **Worse: We don't know which case it actually was!**

Ideal semantics

- What we want is **exactly-once** semantics:
  - Our request occurs once no matter how many times we retry (or if the network duplicates our messages)
- E.g. add a **unique ID** to every request
  - Server remembers IDs, and associated responses
  - If sees a duplicate, just returns old response
  - Client ignores duplicate responses
- Pretty tricky to ensure exactly-once in practice
  - E.g. if server explodes ;-)

Practical semantics

- In practice, protocols guarantee one of:
- **All-or-nothing** (atomic) semantics
  - Use scheme on previous page; persistent log
  - (similar idea to transaction processing)
- **At-most-once** semantics
  - Request carried out once, or not at all
  - If no reply, we don't know which outcome it was
  - e.g. send one request; give up on timeout
- **At-least-once** semantics
  - Retry on timeout; risk operation occurring again
  - Ok if the operation is read-only, or **idempotent**
- Note: Assumption of no network duplication

Server state required to suppress retries

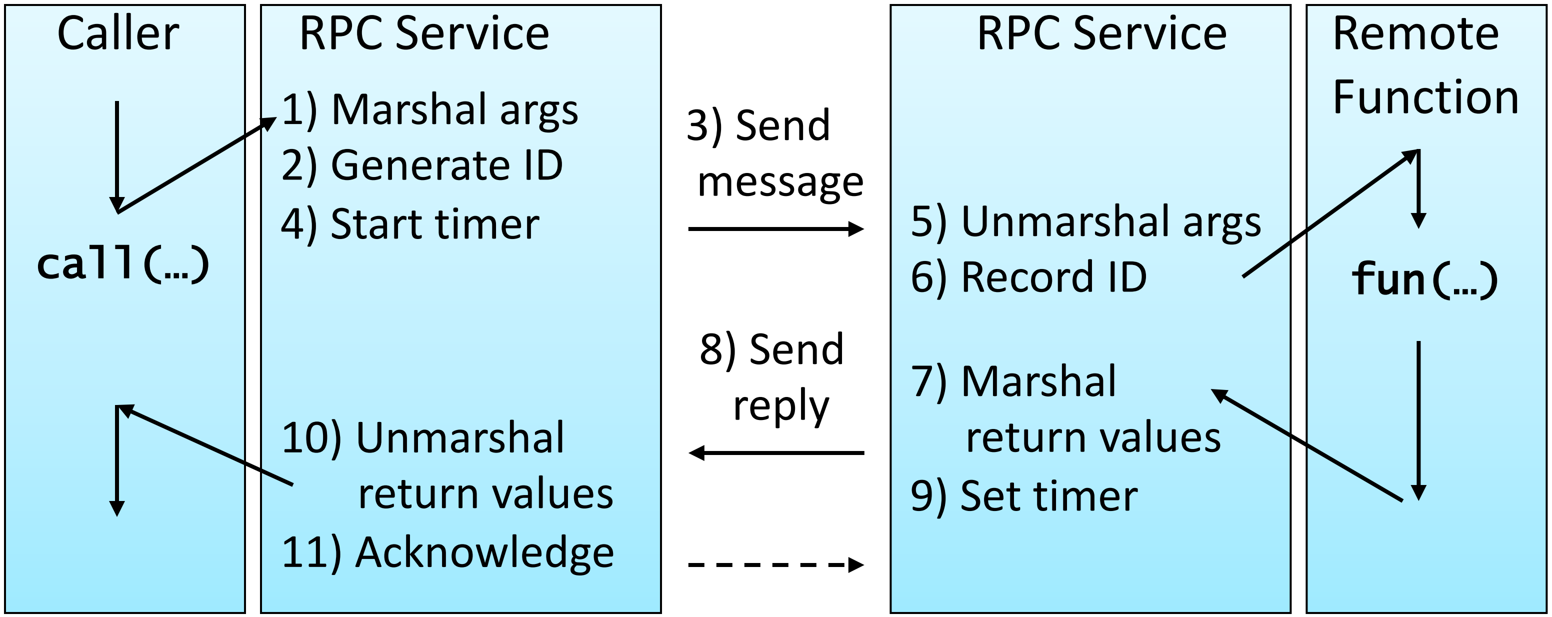
Server state not required

Remote Procedure Call (RPC)

- Request/response protocols are useful – and widely used – but rather clunky to use
  - e.g. need to define the set of requests, including how they are represented in network messages
- A nicer abstraction is **Remote Procedure Call (RPC)**
  - Programmer simply invokes a procedure…
  - …but it executes on a remote machine (the server)
  - RPC subsystem handles message formats, sending & receiving, handling timeouts, etc
- Aim is to make distribution (mostly) transparent
  - Certain failure cases wouldn't happen locally
  - Distributed and local function call performance different

Marshalling arguments

- RPC is integrated with the programming language
  - Some additional magic to specify things are remote
- RPC layer **marshals** parameters to the call, as well as any return value(s), e.g.



IDLs and stubs

- To marshal, the RPC layer (on both sides!) must know:
  - how many arguments the procedure has,
  - how many results are expected, and
  - the types of all of the above
- The programmer must specify this by describing things in an **interface definition language (IDL)**
  - In higher-level languages, this may already be included as standard (e.g. C#, Java)
  - In others (e.g. C), IDL is part of the middleware
- The RPC layer can then automatically generate **stubs**
  - Small pieces of code at client and server (see previous)
  - May also provide authentication, encryption
  - Provides integrity, confidentiality

Example: SunRPC

- Developed mid 80's for Sun Unix systems
- Simple request/response protocol:
  - Server registers one or more "programs" (services)
  - Client issues requests to invoke specific procedures within a specific service
- Messages can be sent over any transport protocol (most commonly UDP/IP and later TCP/IP)
  - Requests have a unique **transaction id** which can be used to detect & handle retransmissions
  - **At-least-once** semantics
  - Various types of **access transparency** including byte-order

eXternal Data Representation (XDR)

- SunRPC used **XDR** for describing interfaces:

```
// file: test.x
program test {
  version testver {
    int get(getargs) = 1;  // procedure number
    int put(putargs) = 2;  // procedure number
  } = 1;                   // version number
} = 0x12345678;            // program number
```

- **rpcgen** generates [un]marshaling code, stubs
  - Single arguments… but recursively convert values
  - Some support for following pointers too
- Data on the wire always in big-endian format (oops!)

Using SunRPC

1. Write XDR, and use rpcgen to generate skeleton code
2. Fill in blanks (i.e. write client/server), compile code
3. Run server & register with **portmapper** (now: **rpcbind**)
   - Mappings from { prog#, ver#, proto } -> port
   - (on Linux/UNIX, try "**/usr/sbin/rpcinfo –p**")
   - **Portmapper** is an RPC service on a **well-known port**
4. Server process will then listen(), awaiting clients
5. When a client starts, client stub calls clnt_create()
   - Sends { prog#, ver#, proto } to portmapper on server, receives port number to use for actual RPC connection
   - Client invokes remote procedures as needed
6. Lately: GSS authentication/encryption (e.g., Kerberos)

Summary + next time

- About this course
- Advantages and challenges of distributed systems
- Types of transparency (+scalability)
- Middleware, the client-server model
- Errors and retry semantics
- RPC, marshalling, SunRPC, and XDR

- Case study: the Network File System (NFS)