Distributed systems

Lecture 14: Elections, distributed transactions, and replication

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(With thanks to Dr Robert N. M. Watson
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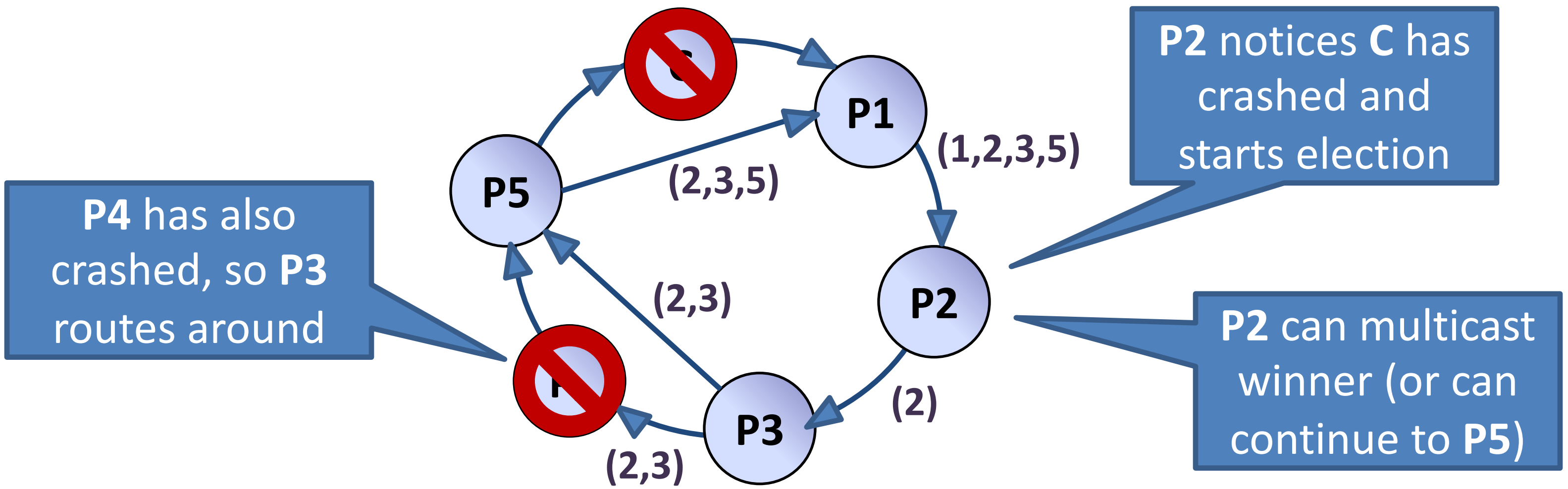
Last time

- **Vector clocks** and **consistent global state**
- Saw how we can build **ordered multicast**
  - Messages between processes in a group
  - Need to distinguish **receipt** and **delivery**
  - Several ordering options: **FIFO**, **causal** or **total**
- Considered **distributed mutual exclusion**:
  - Want to limit one process to a **critical section** at a time
  - Central server OK; but bottleneck & **Single Point of Failure (SPoF)**
  - Token passing OK: but traffic, repair, token loss
  - Totally-Ordered Multicast: OK, but high number of messages and problems with failures

Leader election

- Many schemes are built on the notion of having a well-defined '**leader**' (master, coordinator)
  - Examples seen so far include the **Berkeley time synchronization protocol**, and the **central lock server**
- An **election algorithm** is a dynamic scheme to choose a unique process to play a certain role
  - Assume process $\mathbf{P_i}$ contains state variable $\mathbf{elected_i}$
  - When $\mathbf{P_i}$ first joins the group, $\mathbf{elected_i}$ = UNDEFINED
- By the end of the election, for every $\mathbf{P_i}$
  - $\mathbf{elected_i}$ = $\mathbf{P_x}$ where $\mathbf{P_x}$ is the winner of the election, or
  - $\mathbf{elected_i}$ = UNDEFINED, or
  - $\mathbf{P_i}$ has crashed or otherwise left the system
- Common theme: **live node with the highest ID wins**
  - But many interesting ways this can be accomplished

Ring-based election

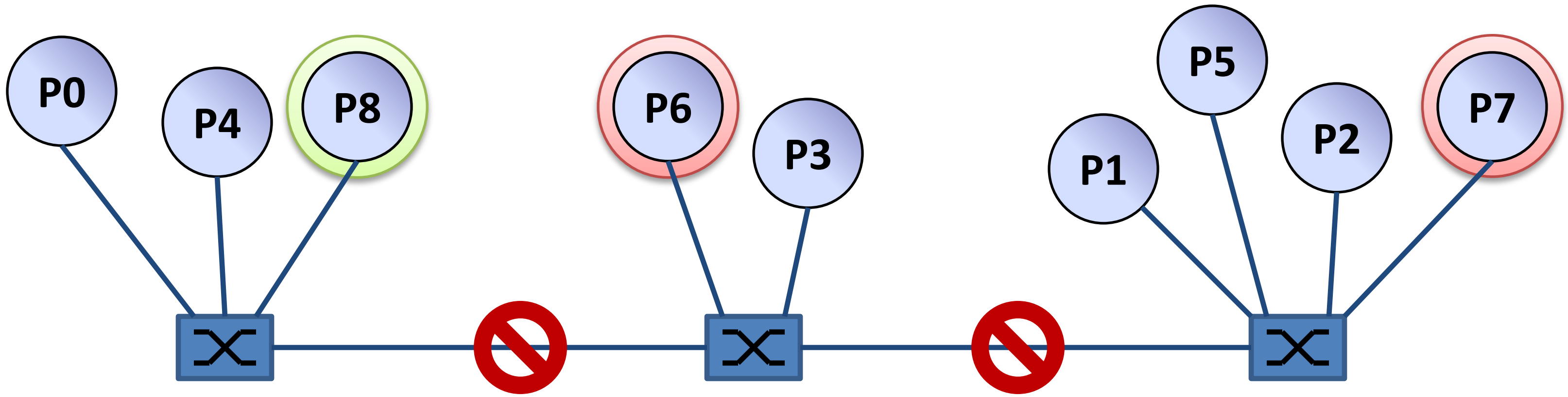


- System has coordinator who crashes
- Some process notices, and starts an election
  - Find node with **highest ID** who will be new leader
  - Puts its ID into a message, and sends to its successor
  - On receipt, a process acks to sender (not shown), and then appends its ID and forwards the election message
  - Finished when a process receives message containing its ID

The Bully Algorithm

- Algorithm proceeds by attempting to **elect the process still alive with the highest ID**
  - Assume that we know the IDs of all processes
  - Assumes we can reliably detect failures by timeouts
- If process $\mathbf{P_i}$ sees current leader has crashed, sends **election** message to all processes with higher IDs, and starts a timer
  - Concurrent initiation by multiple processes is fine
  - On receiving an election message reply **OK** to sender, start their own election (if not in progress)
  - If a process hears nothing back before timeout, it declares itself the winner, and multicasts result
- A recovering dead process (or new process joining) starts an election – the [new] highest ID will be elected

Problems with elections



- Algorithms rely on timeouts to reliably detect failure
- However, networks also fail: a **network partition**
  - Some processes can speak to others, but not all
- Can lead to **split-brain syndrome**:
  - Each partition independently elects a leader → too many bosses!
- To fix, need some secondary (& tertiary?) communication scheme
  - e.g. secondary network, shared disk, serial cables, …
- This is important because we want to implement distributed algorithms dependent on **the invariant that the leader is unique**

Aside on consensus

- Elections are a specific example of a more general problem: **consensus**
  - Given a set of **N** processes in a distributed system, how can we get them all to agree on something?
- Classical treatment has every process $\mathbf{P_i}$ propose something (a value $\mathbf{V_i}$)
  - Want to arrive at some deterministic function of $\mathbf{V_i}$'s (e.g. 'majority' or 'maximum' will work for election)
- A correct solution to consensus must satisfy:
  - **Agreement**: all nodes arrive at the same answer
  - **Validity**: answer is one that was proposed by someone
  - **Termination**: all nodes eventually decide

“Consensus is impossible”

- Famous result due to Fischer, Lynch & Patterson (1985)
  - Focuses on an **asynchronous network** (unbounded delays) with at least one process failure
  - Shows that it is possible to get an infinite sequence of states, and hence **never terminate**
  - Given the Internet is an asynchronous network, then this seems to have major consequences!
- Not really:
  - Result actually says we can’t **always guarantee** consensus, **not** that we can **never achieve** consensus
  - And in practice, we can use tricks to mask failures (such as reboot, or replication), and to ignore asynchrony
  - Have seen solutions already, and will see more later

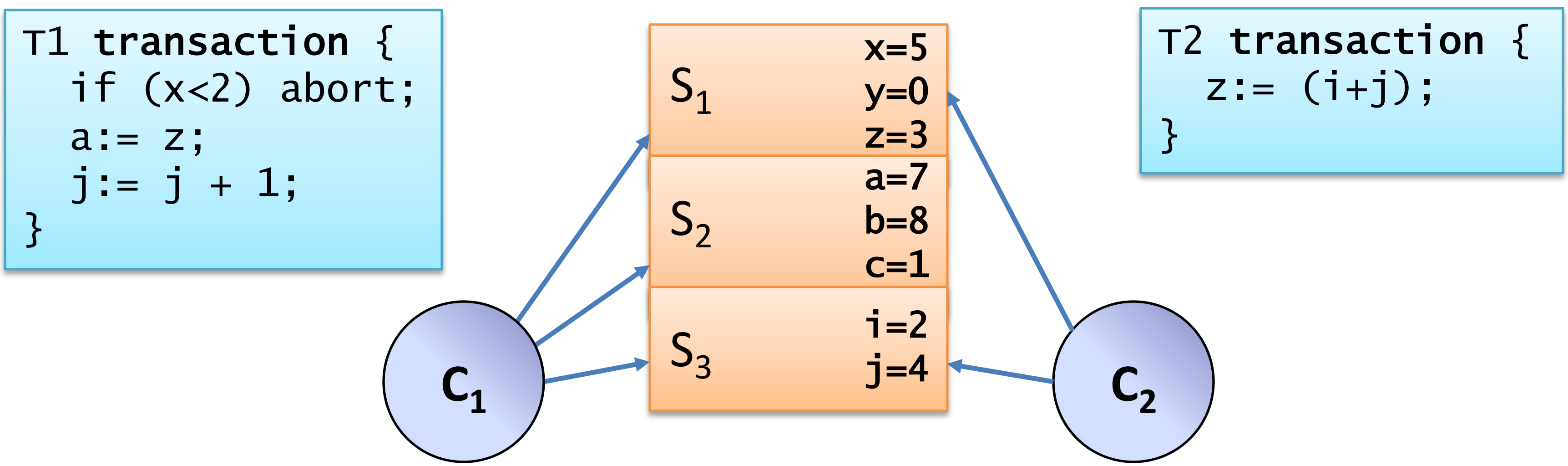
Transaction processing systems

- Earlier looked at **transactions**:
  - **ACID** properties
  - Support for **composite operations** (i.e. a collection of reads and updates to a set of objects)
- A transaction is **atomic** ("all-or-nothing")
  - If it **commits**, all operations are applied
  - If it **aborts**, it's as if nothing ever happened
- A committed transaction moves system from one **consistent** state to another
- Transaction processing systems also provide:
  - **isolation** (between concurrent transactions)
  - **durability** (committed transactions survive a crash)
- **Q: Can we bring the {scalability, fault tolerance, …} benefits of distributed systems to transaction processing?**

Distributed transactions

- Scheme described earlier was client/server:
  - E.g., a program (client) accessing a database (server)
- However **distributed transactions** are those which span **multiple** transaction processing servers
- E.g. booking a complex trip from London to Vail, CO
  - Could fly LHR -> LAX -> EGE + hire a car…
  - … or fly LHR -> ORD -> DEN + take a public bus
- Want a complete trip (i.e. atomicity)
  - Not get stuck in an airport with no onward transport!
- Must coordinate actions across multiple parties

A model of distributed transactions



- Multiple servers (**S_1**, **S_2**, **S_3**, …), each holding some objects which can be **read** and **written** within client transactions
- Multiple concurrent clients (**C_1**, **C_2**, …) who perform transactions that interact with one or more servers
  - E.g. **T1** reads **x**, **z** from **S_1**, writes **a** on **S_2**, reads+writes **j** on **S_3**
  - E.g. **T2** reads **i**, **j** from **S_3**, then writes **z** on **S_1**
- A successful **commit** implies agreement at all servers

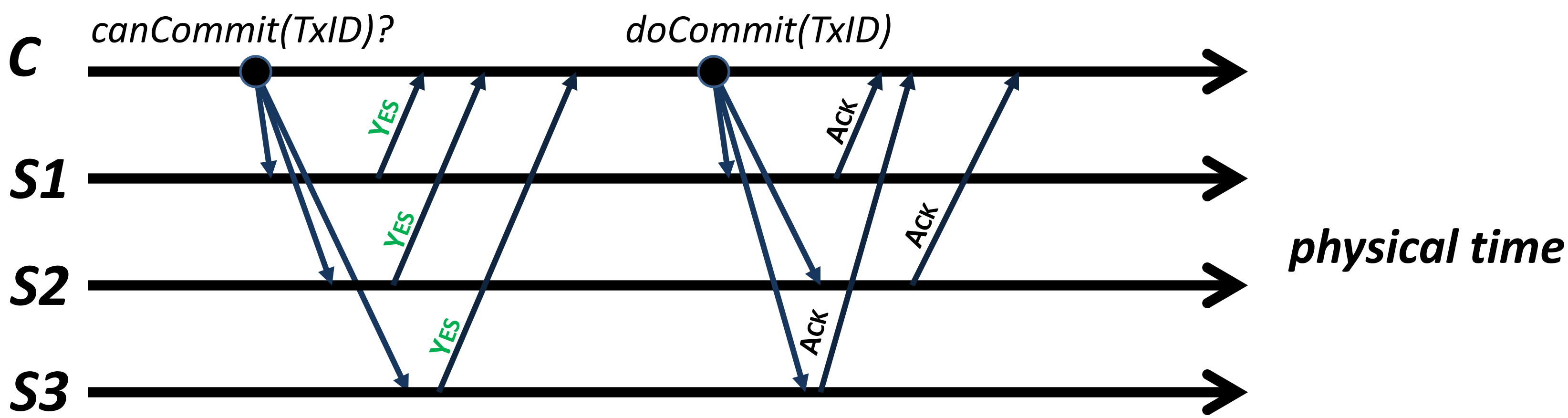
Implementing distributed transactions

- Can build on top of solution for single server:
  - e.g. use **locking** or **shadowing** to provide **isolation**
  - e.g. use **write-ahead log** for durability
- Need to coordinate to either **commit** or **abort**
  - Assume clients create **unique transaction ID**: **TxID**
  - Uses **TxID** in every read or write request to a server $\mathbf{S_i}$
  - First time $\mathbf{S_i}$ sees a given **TxID**, it starts a tentative transaction associated with that transaction ID
  - When client wants to commit, must perform **atomic commit** of all tentative transactions across all servers

Atomic commit protocols

- A naïve solution would have client simply invoke **commit**(**TxID**) on each server in turn
  - Will work only if no concurrent conflicting clients, every server commits (or aborts), and no server crashes
- To handle **concurrent clients**, introduce a **coordinator**:
  - A designated machine (can be one of the servers)
  - Clients ask coordinator to commit on their behalf… and hence coordinator can **serialize** concurrent commits
- To handle **inconsistency/crashes**, the coordinator:
  - Asks all involved servers if they *could* commit **TxID**
  - Servers $\mathbf{S_i}$ reply with a vote $\mathbf{V_i}$ = { **COMMIT**, **ABORT** }
  - If all $\mathbf{V_i}$ = COMMIT, coordinator multicasts **doCommit**(**TxID**)
  - Otherwise, coordinator multicasts **doAbort**(**TxID**)

Two-phase commit (2PC)



- This scheme is called **two-phase commit (2PC)**:
  - First phase is **voting**: collect votes from all parties
  - Second phase is **completion**: either abort or commit
- Doesn't require ordered multicast, but needs reliability
  - If server fails to respond by timeout, implicit vote to **abort**
- Once all ACKs received, inform client of commit success

2PC: additional details

- Client (or any server) can abort during execution: simply multicasts **doAbort**(**TxID**) to all servers
  - E.g., if client transaction explicitly aborts or server fails
- If a server votes **NO**, can **abort** at once locally
- If a server votes **YES**, it **must** be able to commit if subsequently asked by coordinator:
  - Before voting to commit, server will **prepare** by writing entries into log and flushing to disk
  - Records all requests from/responses to coordinator
  - Hence even if crashes **after** voting to commit, will be able to recover on reboot

2PC: coordinator crashes

- Coordinator must also **persistently log** events:
  - Including initial message from client, requesting votes, receiving replies, and final decision made
  - Lets it reply if (restarted) client or server asks for outcome
  - Also lets coordinator recover from reboot, e.g. re-send any vote requests without responses, or reply to client
- One additional problem occurs if coordinator crashes **after phase 1**, but **before initiating phase 2**:
  - Servers will be uncertain of outcome…
  - If voted to commit, will have to continue to hold locks, etc
- Other schemes (3PC, Paxos, …) can deal with this

Replication

- Many distributed systems involve **replication**
  - Multiple copies of some object stored at different servers
  - Multiple servers capable of providing some operation(s)
- Three key advantages:
  - **Load-Balancing**: if have many replicas, then can spread out work from clients between them
  - **Lower Latency**: if replicate an object/server close to a client, will get better performance
  - **Fault-Tolerance**: can tolerate the failure of some replicas and still provide service
- Examples include DNS, web & file caching (& content-distribution networks), replicated databases, …

Replication in a single system

- A good single-system example is **RAID**:
  - RAID = Redundant Array of Inexpensive Disks
  - Disks are cheap, so use several instead of just one
  - If replicate data across disks, can tolerate disk crash
  - If don't replicate data, appearance of a single larger disk
- A variety of different configurations (levels)
  - RAID 0: **stripe** data across disks, i.e. block 0 to disk 0, block 1 to disk 1, block 2 to disk 0, and so on
  - RAID 1: **mirror** (replicate) data across disks, i.e. block 0 written on disk 0 and disk 1
  - RAID 5: **parity** – write block 0 to disk 0, block 1 to disk 1, and (block 0 XOR block 1) to disk 2
- Improved performance as can access disks in parallel
- With RAID 1, 5 also get fault-tolerance
- NB: More disks **increase risk of single-disk failure** while **reducing probability of fatal multi-disk failure**

Distributed data replication

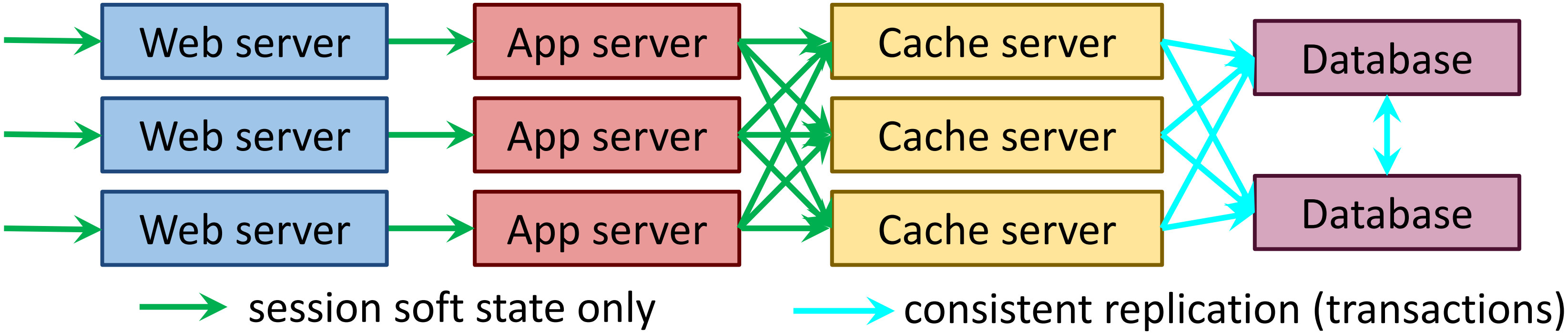
- Have some number of servers (**S_1, S_2, S_3**, …)
  - Each holds a copy of all objects
- Each client **C_i** can access any replica (any **S_i**)
  - E.g. clients can choose closest, or least loaded
- If objects are **read-only**, then trivial:
  - Start with one primary server **P** having all data
  - If client asks **S_i** for an object, **S_i** returns a copy
  - (**S_i** fetches a copy from **P** if it doesn't already have a fresh one)
- Can easily extend to allow updates by **P**
  - When updating object **O**, send **invalidate(O)** to all **S_i**
- In essence, this is how web caching / CDNs work today
- **But what if clients can perform updates?**

Replication and consistency

- More challenging if clients can perform updates
- For example, imagine **x** has value **3** (in all replicas)
  - **C1** requests **write(x, 5)** from **S4**
  - **C2** requests **read(x)** from **S3**
  - What should occur?
- With **strong consistency**, the distributed system behaves as if there is **no replication present**:
  - That is, **C2** should get the value **5**, above
  - Requires coordination between all servers
- With **weak consistency**, **C2** may get 3 or 5 (or …?)
  - Less satisfactory, but much easier to implement
  - Recall **close-to-open consistency** in NFS

Replication for fault tolerance

- Replication for **services**, not just data objects
- Easiest is for a **stateless service**:
  - Simply duplicate functionality over ***k*** machines
  - Clients use any (e.g. closest), fail over to another
- Very few totally stateless services
  - But e.g. many web apps have per-session soft state
  - State generated per-client, lost when client leaves
- For example: multi-tier web farms (Facebook, …):



Passive replication

- Stateful servces can use **primary/backup**:
  - Backup server takes over in case of failure
- Based on **persistent logs**, **system checkpoints**:
  - Periodically (or continuously) checkpoint primary
  - If detect failure, start backup from checkpoint
- A few variants trade-off fail-over time:
  - **Cold-standby**: backup server must start service (software), load checkpoint & parse logs
  - **Warm-standby**: backup server has software running in anticipation, must load primary state
  - **Hot-standby**: backup server mirrors primary work, but output is discarded; on failure, enable output

Active replication

- **Alternative**: have ***k*** replicas running at **all** times
- Front-end server acts as an **ordering node**:
  - Receives requests from client and forwards them to all replicas using **totally ordered multicast**
  - Replicas perform operation and respond to front-end
  - Front-end gathers responses, and replies to client
- Typically require replicas to be "**state machines**":
  - That is, they must act deterministically based on input
  - Idea is that all replicas operate 'in lock step'
- **Active replication** can be resource-intensive…
  - … and not really worth it in the common case
  - However valuable if consider **Byzantine failures**

Summary + next time

- Leader elections + distributed consensus
- Distributed transactions + atomic commit protocols
- Replication + consistency

- (More) replication and consistency
  - Strong consistency
  - Quorum-based systems
  - Weaker consistency
- Consistency, availability and partitions
- Further replication models
- Amazon/Google case studies