Distributed Systems
8L for Part IB

Lecture 7

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Last time

- Looked at general issue of **consensus**:
  - How to get processes to agree on something
  - (FLP says "impossible" in asynchronous networks with at least 1 failure … but in practice we're ok ;-)
  - General idea useful for distributed mutual exclusion, leader election: relies being able to detect failures
- Also looked at **distributed transactions**:
  - Need to commit a set of "sub-transactions" across multiple servers – want all-or-nothing semantics
  - Use **atomic commit** protocol like 2PC
- Started on **replication**: using multiple copies to gain **performance**, **load-balancing** & **fault tolerance**

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Replication in Distributed Systems

- 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 one)
- Can easily extend to allow updates by **P**
  - When updating object O, send invalidate(O) to all S_i
  - (Or add just tag all objects with 'valid-until' field)
- In essence, this is how web caching / CDNs work today

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Replication and Consistency

- Gets 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:
  - i.e. in above, C2 should get the value 5
  - requires coordination between all servers
- With **weak consistency**, C2 may get 3 or 5 (or …?)
  - Less satisfactory, but much easier to implement

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Achieving Strong Consistency

- Need to ensure any update propagates to all replicas before allow any subsequent reads
- One solution:
  - When S_i receives request to update x, first locks x at all other replicas
  - Once successful, S_i makes update, and propagates to all other replicas, who acknowledge
  - Finally, S_i instructs all replicas to unlock
- Need to handle failure (of replica, or network)
  - Add step to tentatively apply update, and only actually apply ("commit") update if all replicas agree
- We've reinvented distributed transactions & 2PC ;-)

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Quorum Systems

- Transactional consistency works, but:
  - High overhead, and
  - Poor availability during update (worse if crash!)
- An alternative is a **quorum system**:
  - Imagine there are N replicas, a **write quorum Q_w**, and a **read quorum Q_r**, where $Q_w > N/2$ and $(Q_w + Q_r) > N$
- To perform a write, must update Q_w replicas
  - Ensures a majority of replicas have new value
- To perform a read, must read Q_r replicas
  - Ensures that we read *at least one* updated value

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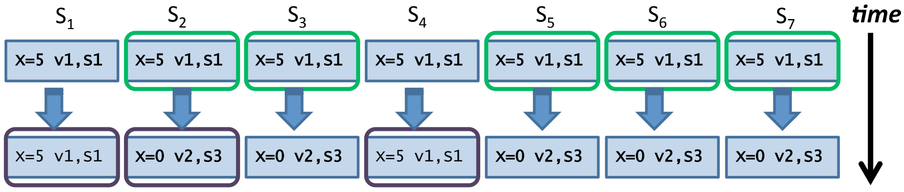
Example



- Seven replicas (N=7), $Q_w = 5$, $Q_r = 3$
- All objects have associated version (T, S)
  - T is logical timestamp, initialized to zero
  - S is a server ID (used to break ties)
- Any write will update at least Q_w replicas
- Performing a read is easy:
  - Choose replicas to read from until get Q_r responses
  - Correct value is the one with highest version

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Quorum Systems: Writes

- Performing a write is trickier:
  - Must ensure get entire quorum, or cannot update
  - Hence need a commit protocol (as before)
- In fact, transactional consistency is a quorum protocol with $Q_w = N$ and $Q_r = 1$!
  - But when $Q_w < N$, additional complexity since must bring replicas up-to-date before updating
- Quorum systems are good when expect failures
  - Additional work on update, additional work on reads...
  - ... but increased **availability** during failure

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Weak Consistency

- Maintaining strong consistency has costs:
  - Need to coordinate updates to all (or Q_w) replicas
  - Slow… and will block other accesses for the duration
- **Weak consistency** provides fewer guarantees:
  - e.g. C1 updates (replica of) object x at S3
  - S3 lazily propagates changes to other replicas
  - Other clients can potentially read old ("stale") value
- Considerably **more efficient**:
  - Write is simpler, and doesn't need to wait for communication with lots of other replicas…
  - … hence is also **more available** (i.e. fault tolerant)

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FIFO Consistency

- As with group communication primitives, various ordering guarantees possible
- **FIFO consistency**: all updates at S_i occur in the same order at all other replicas
  - As with FIFO multicast, can buffer for as long as we like!
  - But says nothing about how S_i's updates are interleaved with S_j's at another replica (may put S_j first, or S_i, or mix)
- Still useful in some circumstances
  - e.g. single user accessing different replicas at disjoint times
  - Essentially primary replication with primary=last accessed

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Eventual Consistency

- FIFO consistency doesn't provide very nice semantics:
  - e.g. we write first version of file f to S_1
  - later we read f from S_2, and write version 2
  - later again we read f from S_3 – changes lost!
- What happened?
  - Update from S_1 arrived to S_3 after those from S_2, who thus overwrote them (stoooopid S_3)
- A desirable property in weakly consistent systems is that they converge to a more correct state
  - i.e. in the absence of further updates, every replica will eventually end up with the same latest version
- This is called **eventual consistency**

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Implementing Eventual Consistency

- Servers S_i keep a **version vector** $V_i(O)$ for each object
  - For each update of O on S_i, increment $V_i(O)[i]$
  - (essentially a vector clock reused as a version number)
- Servers synchronize pair-wise from time to time
  - For each object O, compare $V_i(O)$ to $V_j(O)$
  - If $V_i(O) < V_j(O)$, S_i gets an up-to-date copy from S_j; if $V_j(O) < V_i(O)$, S_j gets an up-to-date copy from S_i.
- If Vi(O) ~ Vj(O) we have a **write-conflict**:
  - Concurrent updates have occurred at 2 or more servers
  - Must apply some kind of reconciliation method
  - (similar to revision control systems, and equally painful)

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Example: Amazon's Dynamo

- Storage service used within Amazon's WS
  - By Amazon itself, and by 3rd party service providers
- Designed to emphasize availability above consistency:
  - SLA to ensure bounded response time 99.99% of the time
  - if customer wants to add something to shopping basket and there's a failure… still want addition to 'work'
  - Even if get (temporarily) inconsistent view… fix later!
- Built around notion of a so-called **sloppy quorum**:
  - Have N, Q_w, Q_r as before … but don't actually require that $Q_w > N/2$, or that $(Q_w + Q_r) > N$
  - Instead make tunable: **lower Q values = higher availability**
  - Also let system continue during failure; add a new replica

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Session Guarantees

- Eventual consistency seems great, but how can you program to it?
  - Need to know something about what guarantees are provided to the client
- These are called **session guarantees**:
  - Not system wide, just for one (identified) client
  - Client must be a more active participant, e.g. client maintains version vectors of objects it has read & written
- Example: **Read Your Writes (RYW)**:
  - if C_i writes a new value to x, a subsequent read of x should see this update … even if C_i is now reading from a different replica
  - Need C_i to remember highest id of any update it made
  - Only read from a server if it has seen that update

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Session Guarantees & Availability

- There are a variety of session guarantees
  - All deal with allowable state on replica given history of accesses by a specific client
  - (further examples included in additional, non-examinable material downloadable from course web page)
- Session guarantees are weaker than strong consistency, but stronger than 'pure' weak consistency:
  - But this means that they **sacrifice availability**
  - i.e. choosing not to allow a read or write if it would break a session guarantee means not allowing that operation!
  - 'pure' weak consistency would allow the operation
- Can we get the best of both worlds?

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Consistency, Availability & Partitions

- Short answer: No ;-)
- The CAP Theorem (Brewer 2000, Gilbert & Lynch 2002) says you can only guarantee two of:
  - **Consistent data, Availability, Partition-tolerance**
- … in a single system.
- In local-area systems, can sometimes drop partition-tolerance by using redundant networks
- In the wide-area, this is not an option:
  - **Must choose between consistency & availability**
  - Most Internet-scale systems ditch consistency
- **NB**: this doesn't mean that things are always inconsistent, just that they're not always guaranteed to be consistent

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Replication and Fault-Tolerance

- Can also use replication for a **service**:
- Easiest is for **stateless services**:
  - Simply duplicate functionality in K machines
  - Clients use any (e.g. closest), fail over to another
- Very few totally stateless services, but e.g. much of the web only has per-session soft-state:
  - State generated per-client, lost when client leaves
- Commonly used to scale multi-tier web farms:
  - First and second tiers (web servers and app servers) only have per-session soft-state => trivial to replicate
  - (clients are independent, so no coordination needed)
  - Third tier (storage/db tier) either partitioned (disjoint clients on different servers), or implements consistent replication

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Primary/Backup (Passive) Replication

- A solution for stateful services is **primary/backup**:
  - Backup server takes over in case of failure
- Based around persistent logs and 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 – just needs to load primary state
  - **Hot-standby**: backup server mirrors primary work, but output is discarded; on failure, enable output

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Active Replication

- 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 each perform operation and respond to front-end
  - Front-end gathers responses, and replies to client
- Typically require replicas to be "**state machines**":
  - i.e. act deterministically based on input
  - Idea is that all replicas operate 'in lock step'
- Active replication is expensive (in terms of resources)…
  - … and not really worth it in the common case.
  - However valuable if consider **Byzantine failures**

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