Cloud-Based Data Processing

Distributed System Models

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Quick recap of last week

- What are the benefits of data partitioning?
- Which types of partitioning exist?
- When we have partitioned data, how can a client know which node to ask for the data it needs?
- Often partitions need to be rebalanced (due to data skew, load skew, or cluster changes).
  How does one go about it?
- How would you partition the data for ...
  - Scalability?
  - Better performance?
  - High availability?

Agenda

- **LO1: Understand what one needs to be careful of when working with distributed systems.**
  - Identify the type of **faults** present in a data-center
  - Design around the requirements and quality targets of the selected/chosen workloads.

- **LO2: Explain how to build a reliable system from unreliable components.**
  - Know what the key components are
  - Understand what can go wrong and how to capture that in the model (of the world)
  - Reason about effects of the component's behavior and how to use it when designing distributed algorithms.

- **LO3: Differentiate between the types and**

Reliable cloud application

- **Identify workloads and their usage requirements**
  - e.g., availability, scalability, data consistency, disaster recovery
- **Identify critical components and paths**
- **Establish availability metrics**
  - mean time to recovery (MTTR) and mean time between failures (MTBF)
  - Use these to determine when to add redundancy and to determine the SLAs to customers
- **Define the availability targets**

Availability targets

- **Availability = uptime = fraction of time that a service is functioning correctly**
  - “two nines” = 99% up = down 3.7 days/year
  - “three nines” = 99.9% up = down 8.8 hours/year
  - “four nines” = 99.99% up = down 53 minutes/year
  - “five nines” = 99.999% up = down 5.3 minutes/year

- **Service-Level Objective (SLO):**
  percentage of requests that need to return a correct response time within a specified timeout, as measured by the client over a certain period of time.

  e.g., “99.9% of requests in a day get a response in 200 ms”

- **Service-Level Agreement (SLA):**
  contract specifying some SLO, penalties for violation

Reliable cloud application cont.

- **Do a failure mode analysis (FMA)**
  identify the types of failures your application may experience and possible recovery strategies

- Create a **redundancy plan** based on the application needs

- **Design for scalability** and use **load-balancing to distribute requests**

- Implement **resiliency strategy –** e.g., resilience design patters, or resilient distributed algorithms.

- **Manage the data**: store, back-up and replicate data
  - Choose the replication method
  - Document the failover and failback process
  - Plan for data recovery

- Efficient **monitoring** and fault-**recovery**

Fault-tolerance

Terminology

- **Failure:** system as a whole is not working

- **Fault:** some part of the system is not working
  - **Node fault –** crash (crash-stop/crash-recovery), deviating from algorithm (Byzantine)
  - **Network fault –** dropping or significantly delaying messages

- **Fault tolerance:**
  System as a whole continues working, despite faults.
  (some maximum number of faults assumed)

- **Single point of failure (SPOF):**
  node/network link whose fault leads to a failure

Failure detectors

- **Failure detector:**
  Algorithm that detects whether another node is faulty

- **Perfect failure detector**:
  labels a node as faulty *if and only if* it has crashed

- **Typical implementation for crash-stop/crash-recovery**:
  send message, await response, label node as crashed if no reply within some timeout

- **Q: What problem can you identify with this?**
- A: One cannot tell the different between
  - a crashed node,
  - temporarily unresponsive node,
  - lost message and
  - delayed message

Detecting faults

- **Q: Why do we need to automatically detect faulty nodes?**

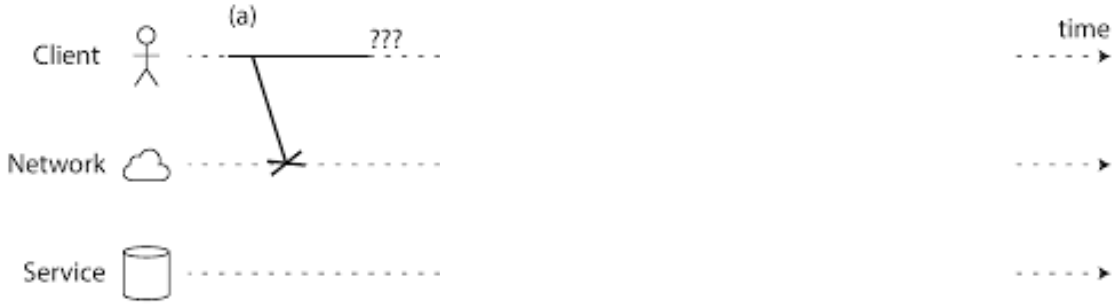
  - For example:
    - A load balancer needs to stop sending requests to a node that is dead
    - A distributed database with a single-leader replication, if the leader fails, one of the followers needs to be promoted to be a leader

Task: Build a reliable system from unreliable components

- **No shared memory**
  - Instead message passing over an **unreliable network** with variable delays
- System may suffer from **partial failures**
- Each process may experience **unreliable processing pauses**
- Machines have **unreliable clocks**
- The **truth** is defined by the **majority** → requires reaching a **quorum.**

Unreliable components (network)

- **DC networks are asynchronous**:



  (a) Your request may be lost
  Your request may be waiting in a queue and will be delivered later
  (b) The remote node may have failed
  The remote node may have temporarily stopped responding, but will start responding again later
  (c) The remote node may have processed your request, but the response has been lost
  The remote node may have processed your request, but the response has been delayed

- Typical we handle these problems by **sending a response message**, but even that may be lost
  - **Supported with a timeout**: when to give up on waiting and assume the response is not going to arrive.

- **Q: How long should a timeout be? What challenges can we anticipate with unbounded delays?**
  - A short timeout detects faults faster, but can declare a node dead prematurely and case a domino.

Models of distributed systems

System models

When designing a distributed algorithm, we use a **system model** to specify our assumptions about what faults may occur.

- **Capture assumptions in a system model consisting of:**
  - **Network** behavior (e.g., message loss)
  - **Node** behavior (e.g., crashes)
  - **Timing** behavior (e.g., latency).
- **There is a specific choice of models for each of these parts.**

System model: network behavior

- **No network is perfectly reliable**
  - e.g., accidentally unplug the wrong cable, sharks and cows can cause damage and interruption to long-distance networks, or a network may be temporarily overloaded (e.g., by a DoS attack).

- Assume a bi-directional **point-to-point** communication between two nodes, with one of:
  - **Reliable** (perfect) links
    a message is received if and only if it is sent. Messages may be reordered.
  - **Fair-loss** links:
    a message may be lost, duplicated or reordered. By retrying, a message eventually gets through.
  - **Arbitrary** links (active adversary):
    a malicious adversary may interfere with messages (spy, modify, drop, spoof, replay).

- **Network partition** some links dropping / delaying all messages for an extended period of time.

System model: node behavior

Each node executes a specified algorithm, assuming one of the following:

- **Crash-stop** (fail-stop):
  a node is faulty if it crashes (at any moment). After crashing, it stops executing forever.

- **Crash-recovery** (fail-recovery):
  a node may crash at any moment, losing its in-memory state. It may resume executing, sometime later.

- **Byzantine** (fail-arbitrary):
  a node is faulty if it deviates from the algorithm. Faulty nodes may do anything, including crashing or malicious behavior.

A node that is not faulty, is called **correct.**

System model: synchrony (timing) assumptions

Assume one of the following for the network and nodes:

- **Synchronous:**
  message latency no greater than a known upper bound.
  Nodes execute algorithm at a known speed.

- **Partially synchronous:**
  The system is asynchronous for some finite (but unknown) periods of time, synchronous otherwise.

- **Asynchronous:**
  Messages may be delayed arbitrarily. Nodes can pause execution arbitrarily. No timing guarantees at all.

Violations of synchrony in practice

- **Networks usually have quite predictable latency, which can occasionally increase:**
  - Message loss requiring retry
  - Congestion/contention causing queuing
  - Network/route reconfiguration

- **Nodes usually execute code at a predictable speed, with occasional pauses:**
  - OS scheduling issues (e.g., priority inversion)
  - Stop-the-world garbage collection pauses
  - Page faults, swap, thrashing

- **Real time operating systems (RTOS) provide scheduling guarantees, but most distributed systems do not use RTOS.**

System models summary

For each of the three parts, pick one:

- **Network:**
  reliable, fair-loss, or arbitrary
- **Nodes:**
  crash-stop, crash-recovery, or Byzantine
- **Timing:**
  synchronous, partially-synchronous, or asynchronous

This is the basis for any distributed algorithm. If your assumptions are wrong, all bets are off!

Unreliability of clocks

Clocks and time in distributed systems

- **Q: Why do we need to measure time in a distributed system?**

- **Distributed systems often need to measure time, e.g.:**
  - Schedulers, timeouts, failure detectors, retry timers,
  - Performance measurements, statistics, profiling
  - Log files and databases: record when an event occurred
  - Data with time-limited validity (e.g., cache entries)
  - Determine order of events across several nodes

- **Q: When does it make sense to measure physical time vs. logical time?**

- **We distinguish two types of clocks:**
  - **Physical clocks:** count number of seconds elapsed
  - **Logical clocks:** count events, e.g., messages sent

Physical clocks

- **Quartz clocks** (wristwatch, computer and phones, etc.) are cheap but not totally accurate.

- Quartz clock error: **drift**
  - One clock runs slightly faster, another slower
  - Drift is measured in parts per million (ppm).
    1 ppm = 1 microsecond/second = 86 ms/day = 32s/year
  - Most computer clocks correct within 50 ppm

- For greater accuracy, use **atomic clocks**.
- **Leap seconds** – to keep the UTC and TAI in sync (linked to the rotation of earth)

- **Computers and time**
  - Unix time: number of seconds since 1 January 1970 (epoch) – not counting leap seconds
  - ISO 8601: year, month, day, hour, minute, second and timezone offset relative to UTC

- **To be correct, software that works with timestamps needs to know about leap seconds.**

Clock synchronization

- Computers track physical time/UTC with a quartz clock
- Due to **clock drift**, clock error gradually increases.
- **Clock skew:** difference between two clocks at a point in time
- **Q: How can we handle clock skew?**
- **Solution:** periodically get the current time from a server that has a more accurate time source (atomic clock or GPS receiver)
- **Protocols: Network Time Protocol (NTP), Precision Time Protocol (PTP)**
  - Make multiple requests to the same server,
    use statistics to reduce error due to variations in network latency
  - Reduces clock skew to a few milliseconds in good network conditions.

Time-of-day and monotonic clocks

```
// BAD
long startTime = System.currentTimeMillis();
doSomething();
long endTime = System.currentTimeMillis();
long elapsedMillis = endTime - startTime;
// elapsedMillis may be negative!
```

← NTP client steps the clock during this

```
// GOOD
long startTime = System.nanoTime();
doSomething();
long endTime = System.nanoTime();
long elapsedNanos = endTime - startTime;
// elapsedNanos is always >= 0
```

Time-of-day and monotonic clocks

- **Time-of-day clock:**
  - Time since a fixed date (e.g., 1 January 1970 epoch)
  - **May suddenly move forwards or backwards** (NTP stepping), **subject to leap second adjustments**
  - **Timestamps can be compared across nodes (if synced)**
  - Java: System.curretTimeMillis()
  - Linux: clock_gettime(CLOCK_REALTIME)

- **Monotonic clock:**
  - Time since arbitrary point (e.g., when the machine booted up)
  - **Always moves forward at near constant speed**
  - **Good for measuring elapsed time on a single node**
  - Java: System.nanoTime():
  - Linux: clock_gettime(CLOCK_MONOTONIC)

Clock readings should have a confidence interval

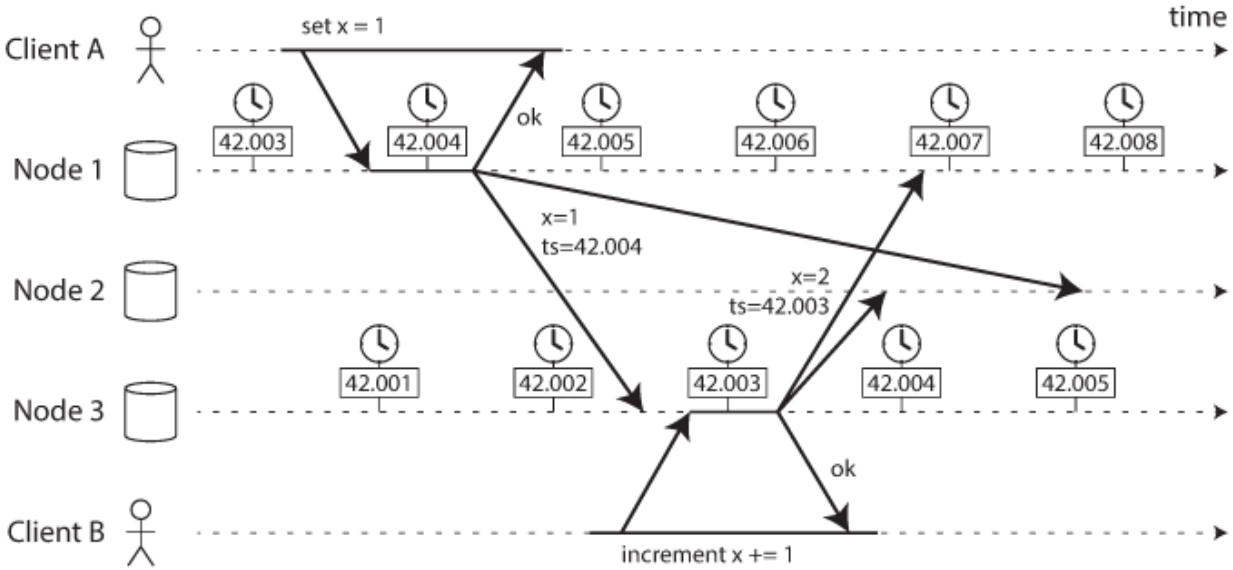
- **When getting the time from a server, the uncertainty is based on:**
  - the expected quartz drift since your last sync,
  - the reference server's uncertainty,
  - and the network round-trip time to the reference server.

  e.g., A system may be 90% confident that the time now is between 10.3 and 10.5 seconds past the minute.

- **Most systems do not expose this uncertainty**

  Notable exception: Google's TrueTime API, which explicitly reports the confidence interval on the local clock.
  - When you ask it for the current time, you get back two values [earliest, latest], which are the earliest possible and the latest possible timestamp.
  - Used in Spanner (to be covered in a few weeks).

Ordering of messages



Logical vs. physical clocks

- **Physical** clock: count number of **seconds elapsed**
- **Logical** clock: count number of **events occurred**

Physical timestamps: useful for many things, but may be **inconsistent with causality.**

Logical clocks: designed to **capture causal dependencies**

$(e_1 \rightarrow e_2) \xrightarrow{\text{yields}} (T(e_1) < T(e_2))$

Distributed systems/algorithms typically cover two types of logical clocks:

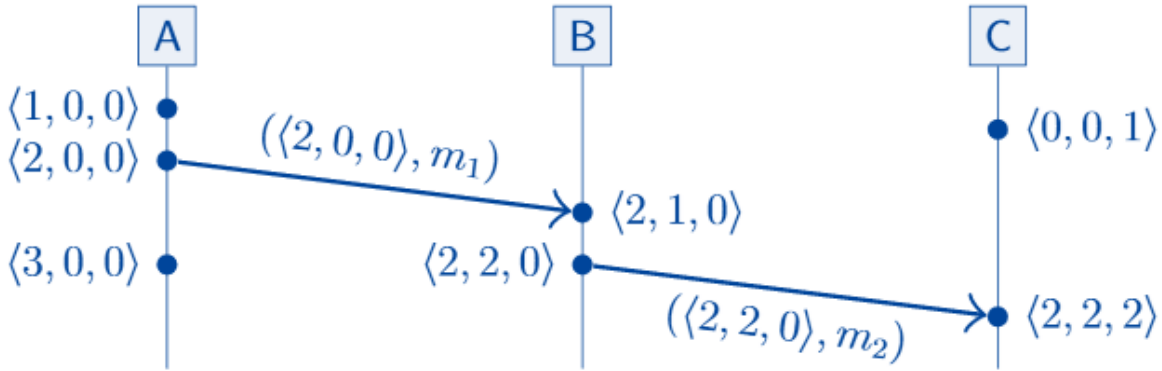
- **Lamport** clocks
- **Vector** clocks

Vector clocks

- **When we want to detect concurrent events, we use vector clocks:**
  - Assume n nodes in the system, $N = < N_1, N_2, \dots, N_n >$
  - Vector timestamp of event a is $V(a) =< t_1, t_2, \dots, t_n >$
  - t_i, is number of events observed by node N_i
  - Each node has a current vector timestamp T
  - On event at node N_i, increment vector element $T[i]$
  - Attach current vector timestamp to each message
  - Recipient merges message vector into its logical vector

Vector clocks example

- Assuming the vector of nodes is



- The vector timestamp of an event e represents a set of events:
  e and its causal dependencies: $\{e\} \cup \{a \mid a \rightarrow e\}$

- For example, $\langle 2,2,0 \rangle$ represents
  the first two events from A, the first two events from B,and no events from C

Majority decides the **truth**

- In a distributed system, the **truth** is defined by the majority
  - A single node cannot trust its own judgement of a situation
  - Many distributed algorithms rely on a **quorum,** i.e., voting among the nodes.
    - Including when to declare a node as dead
  - Quorums are especially important for our upcoming discussion on consensus (next week).

References

The material covered in this class is mainly based on:

- The book *“Designing Data-Intensive Applications – The Big Ideas Behind Reliable, Scalable, and Maintainable Systems”* by Martin Kleppmann (Chapters 8 and part of 9) (link)
- Slides from “*Distributed Systems”* course from University of Cambridge (link)

Some information about application-level design were based on material from:

- Microsoft’s Azure Application Architecture Guide
  - Design Reliable Applications (link)
  - Design for self-healing (link)