Distributed Systems

The second half of *Concurrent and Distributed Systems*

https://www.cl.cam.ac.uk/teaching/current/ConcDisSys

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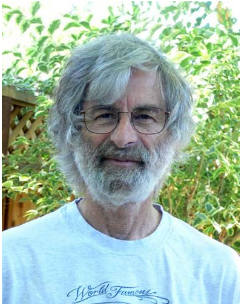
University of Cambridge

Computer Science Tripos, Part IB

A distributed system is...

- *"...a system in which the failure of a computer you didn't even know existed can render your own computer unusable."* — Leslie Lamport



A distributed system is...

- *"... a system in which the failure of a computer you didn't even know existed can render your own computer unusable."* — Leslie Lamport
- ... multiple computers communicating via a network...
- ... trying to achieve some task together
- Consists of "nodes" (computer, phone, car, robot, ...)

Recommended reading

- van Steen & Tanenbaum.
  "**Distributed Systems**"
  (any ed), free ebook available
- Cachin, Guerraoui & Rodrigues.
  "**Introduction to Reliable and Secure Distributed Programming**" (2nd ed), Springer 2011
- Kleppmann.
  "**Designing Data-Intensive Applications**",
  O'Reilly 2017
- Bacon & Harris.
  "**Operating Systems: Concurrent and Distributed Software Design**", Addison-Wesley 2003

Relationships with other courses

- **Concurrent Systems** – Part IB
  (every distributed system is also concurrent)
- **Operating Systems** – Part IA
  (inter-process communication, scheduling)
- **Databases** – Part IA
  (many modern databases are distributed)
- **Computer Networking** – Part IB Lent term
  (distributed systems involve network communication)
- **Further Java** – Part IB Michaelmas
  (distributed programming practical exercises)
- **Security** – Part IB Easter term
  (network protocols with encryption & authentication)
- **Cloud Computing** – Part II
  (distributed systems for processing large amounts of data)

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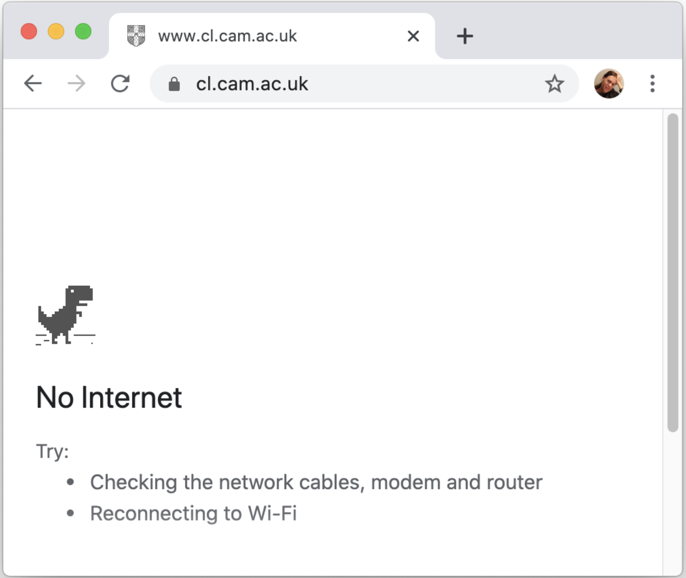
  even if one node fails, the system as a whole keeps functioning
- **For better performance:**
  get data from a nearby node rather than one halfway round the world
- **To solve bigger problems:**
  e.g. huge amounts of data, can't fit on one machine


www.cl.cam.ac.uk
cl.cam.ac.uk
No Internet
Try:
Checking the network cables, modem and router
Reconnecting to Wi-Fi

Why NOT make a system distributed?

The trouble with distributed systems:

- Communication may fail (and we might not even know it has failed).
- Processes may crash (and we might not know).
- All of this may happen nondeterministically.

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- Processes may crash (and we might not know).
- All of this may happen nondeterministically.

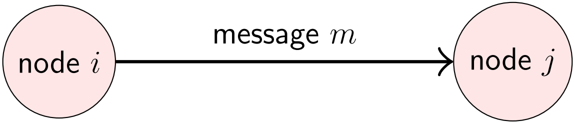
Fault tolerance: we want the system as a whole to continue working, even when some parts are faulty.

This is hard.

Writing a program to run on a single computer is comparatively easy?!

Distributed Systems and Computer Networking

We use a simple abstraction of communication:



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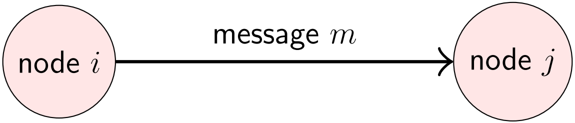

Reality is much more complex:

- **Various network operators:**
  eduroam, home DSL, cellular data, coffee shop wifi, submarine cable, satellite...
- **Physical communication:**
  electric current, radio waves, laser, hard drives in a van...

Hard drives in a van?!

https://docs.aws.amazon.com/snowball/latest/ug/using-device.html

High latency, high bandwidth!

Latency and bandwidth

Latency: time until message arrives

- In the same building/datacenter: ≈ 1 ms
- One continent to another: ≈ 100 ms
- Hard drives in a van: ≈ 1 day

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Bandwidth: data volume per unit time

- 3G cellular data: ≈ 1 Mbit/s
- Home broadband: ≈ 10 Mbit/s
- Hard drives in a van: 50 TB/box ≈ 1 Gbit/s

(Very rough numbers, vary hugely in practice!)

Concurrent and Distributed Sys ×

Not Secure | cst.cam.ac.uk/teaching/2021/ConcDisSys

Department of Computer Science and Technology

Concurrent and Distributed Systems

Principal lecturer: Dr David Greaves
Martin Kleppmann

Students: Part IB CST 50%, Part IB CST 75%

Course code: ConcDisSys

Prerequisite course: Object-Oriented Programming
Operating Systems

This course is a prerequisite for: Cloud Computing
Distributed Ledger Technologies: Foundations and Applications
Mobile and Sensor Systems

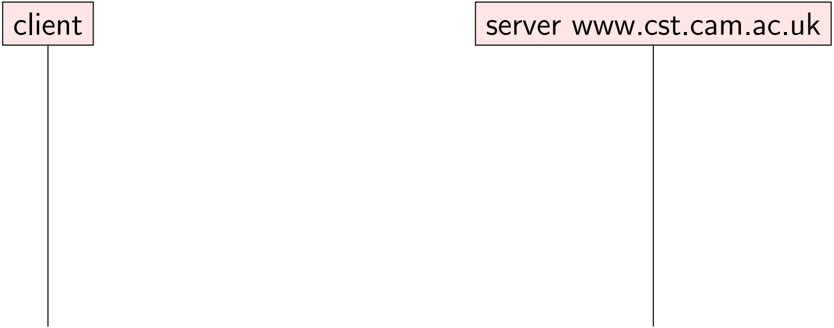
Related links

Course materials

Information for supervisors

Client-server example: the web

Time flows from top to bottom.



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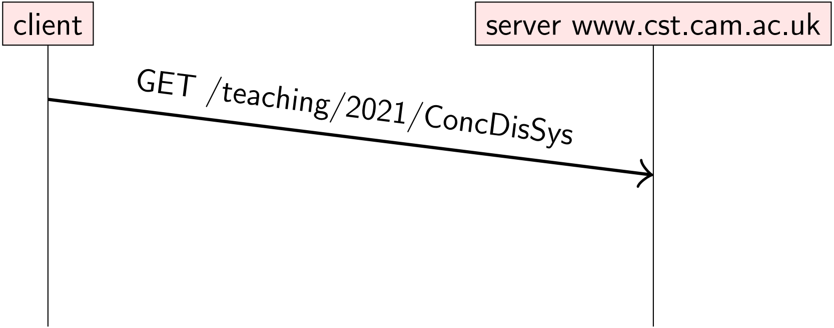

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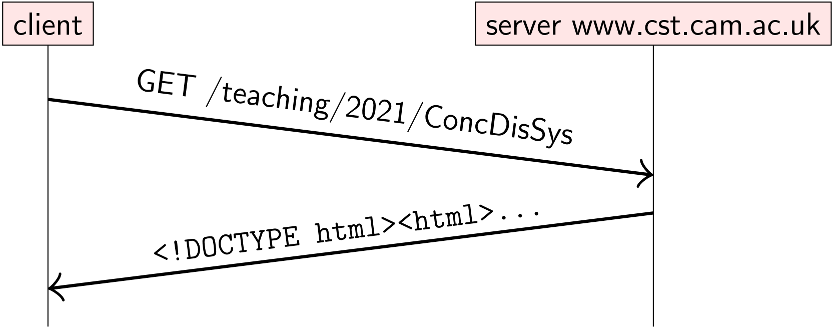
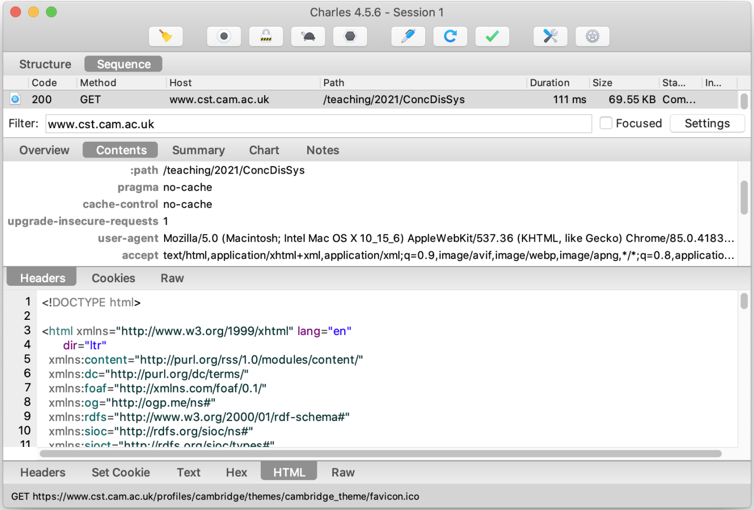
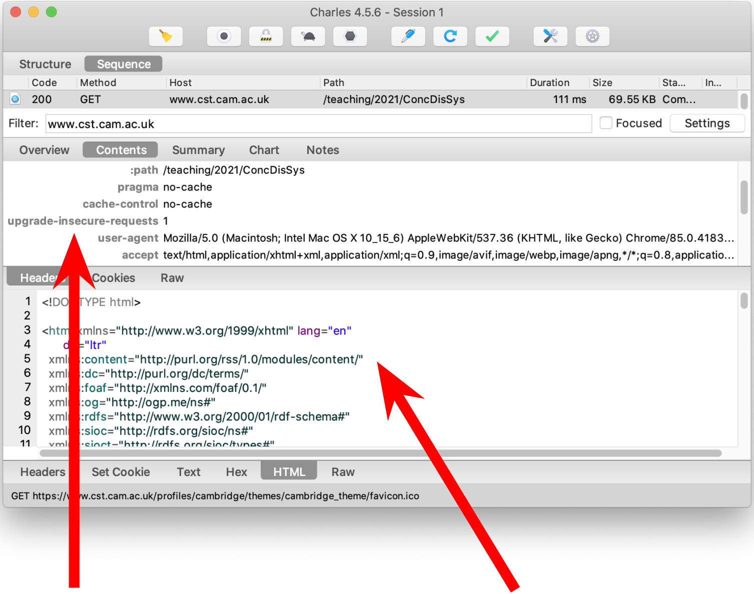
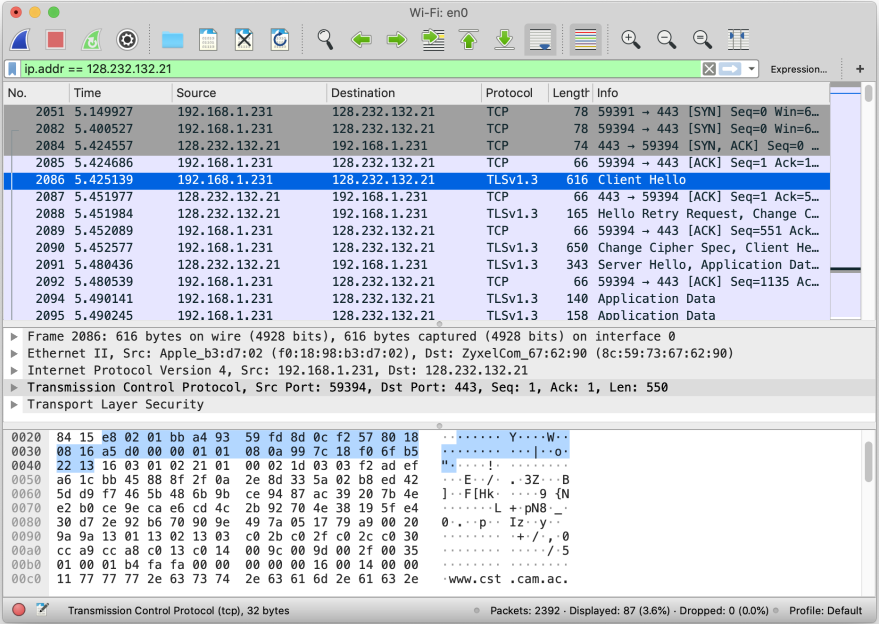



Charles 4.5.6 - Session 1
Structure
Sequence
Code
Method
Host
Path
Duration
Size
Sta...
In...
200
GET
www.cst.cam.ac.uk
/teaching/2021/ConcDisSys
111 ms
69.55 KB
Com...
Filter:
www.cst.cam.ac.uk
Focused
Settings
Overview
Contents
Summary
Chart
Notes
:path /teaching/2021/ConcDisSys
pragma no-cache
cache-control no-cache
upgrade-insecure-requests 1
user-agent Mozilla/5.0 (Macintosh; Intel Mac OS X 10_15_6) AppleWebKit/537.36 (KHTML, like Gecko) Chrome/85.0.4183...
accept text/html,application/xhtml+xml,application/xml;q=0.9,image/avif,image/webp,image/apng,*/*;q=0.8,applicatio...
Headers
Cookies
Raw
1 <!DOCTYPE html>
2
3 <html xmlns="http://www.w3.org/1999/xhtml" lang="en"
4 dir="ltr"
5 xmlns:content="http://purl.org/rss/1.0/modules/content/"
6 xmlns:dc="http://purl.org/dc/terms/"
7 xmlns:foaf="http://xmlns.com/foaf/0.1/"
8 xmlns:og="http://ogp.me/ns#"
9 xmlns:rdfs="http://www.w3.org/2000/01/rdf-schema#"
10 xmlns:sioc="http://rdfs.org/sioc/ns#"
Headers
Set Cookie
Text
Hex
HTML
Raw
GET https://www.cst.cam.ac.uk/profiles/cambridge/themes/cambridge_theme/favicon.ico



request message

response message


Wi-Fi: en0
ip.addr == 128.232.132.21
Expression...
No. Time Source Destination Protocol Length Info
2051 5.149927 192.168.1.231 128.232.132.21 TCP 78 59391 → 443 [SYN] Seq=0 Win=6…
2082 5.400527 192.168.1.231 128.232.132.21 TCP 78 59394 → 443 [SYN] Seq=0 Win=6…
2084 5.424557 128.232.132.21 192.168.1.231 TCP 74 443 → 59394 [SYN, ACK] Seq=0 …
2085 5.424686 192.168.1.231 128.232.132.21 TCP 66 59394 → 443 [ACK] Seq=1 Ack=1…
2086 5.425139 192.168.1.231 128.232.132.21 TLSv1.3 616 Client Hello
2087 5.451977 128.232.132.21 192.168.1.231 TCP 66 443 → 59394 [ACK] Seq=1 Ack=5…
2088 5.451984 128.232.132.21 192.168.1.231 TLSv1.3 165 Hello Retry Request, Change C…
2089 5.452089 192.168.1.231 128.232.132.21 TCP 66 59394 → 443 [ACK] Seq=551 Ack…
2090 5.452577 192.168.1.231 128.232.132.21 TLSv1.3 650 Change Cipher Spec, Client He…
2091 5.480436 128.232.132.21 192.168.1.231 TLSv1.3 343 Server Hello, Application Dat…
2092 5.480539 192.168.1.231 128.232.132.21 TCP 66 59394 → 443 [ACK] Seq=1135 Ac…
2094 5.490141 192.168.1.231 128.232.132.21 TLSv1.3 140 Application Data
2095 5.490245 192.168.1.231 128.232.132.21 TLSv1.3 158 Application Data
Frame 2086: 616 bytes on wire (4928 bits), 616 bytes captured (4928 bits) on interface 0
Ethernet II, Src: Apple_b3:d7:02 (f0:18:98:b3:d7:02), Dst: ZyxelCom_67:62:90 (8c:59:73:67:62:90)
Internet Protocol Version 4, Src: 192.168.1.231, Dst: 128.232.132.21
Transmission Control Protocol, Src Port: 59394, Dst Port: 443, Seq: 1, Ack: 1, Len: 550
Transport Layer Security
0020 84 15 e8 02 01 bb a4 93 59 fd 8d 0c f2 57 80 18
0030 08 16 a5 d0 00 00 01 01 08 0a 99 7c 18 f0 6f b5
0040 22 13 16 03 01 02 21 01 00 02 1d 03 03 f2 ad ef
0050 a6 1c bb 45 88 8f 2f 0a 2e 8d 33 5a 02 b8 ed 42
0060 5d d9 f7 46 5b 48 6b 9b ce 94 87 ac 39 20 7b 4e
0070 e2 b0 ce 9e ca e6 cd 4c 2b 92 70 4e 38 19 5f e4
0080 30 d7 2e 92 b6 70 90 9e 49 7a 05 17 79 a9 00 20
0090 9a 9a 13 01 13 02 13 03 c0 2b c0 2f c0 2c c0 30
00a0 cc a9 cc a8 c0 13 c0 14 00 9c 00 9d 00 2f 00 35
00b0 01 00 01 b4 fa fa 00 00 00 00 00 16 00 14 00 00
00c0 11 77 77 77 2e 63 73 74 2e 63 61 6d 2e 61 63 2e
·www.cst .cam.ac.
Transmission Control Protocol (tcp), 32 bytes
Packets: 2392 · Displayed: 87 (3.6%) · Dropped: 0 (0.0%)
Profile: Default

Client-server example: online payments

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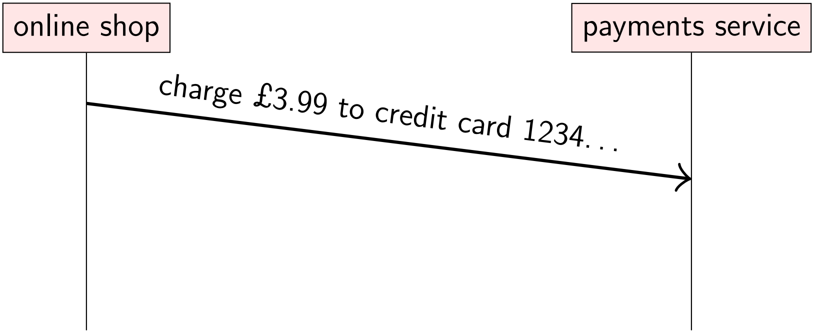

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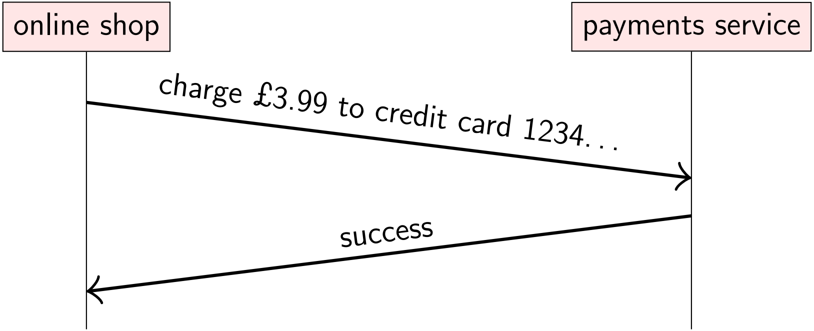

Remote Procedure Call (RPC) example

```java
// Online shop handling customer's card details
Card card = new Card();
card.setCardNumber("1234 5678 8765 4321");
card.setExpiryDate("10/2024");
card.setCVC("123");

Result result = paymentsService.processPayment(card,
    3.99, Currency.GBP);

if (result.isSuccess()) {
    fulfilOrder();
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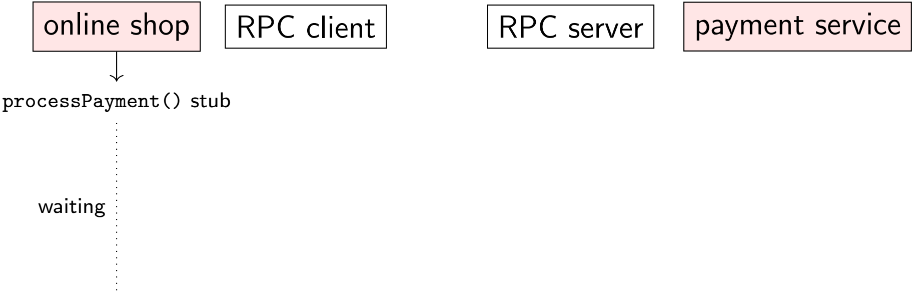
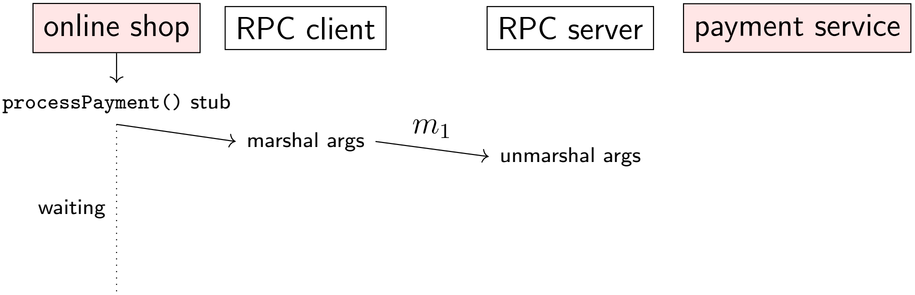
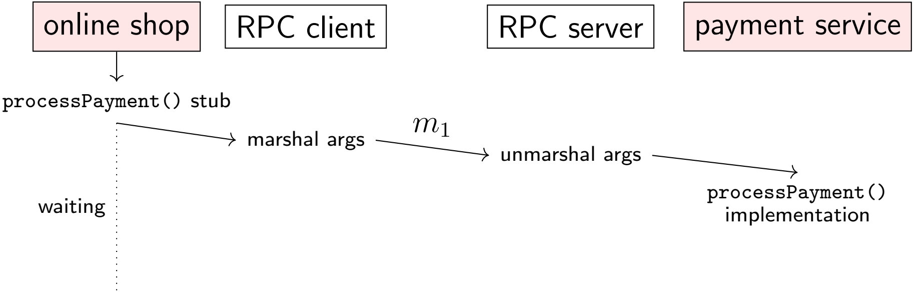
Implementation of this function is on another node!


online shop
RPC client
RPC server
payment service
processPayment() stub
waiting



$m_1 =$

```json
{
  "request": "processPayment",
  "card": {
    "number": "1234567887654321",
    "expiryDate": "10/2024",
    "CVC": "123"
  },
  "amount": 3.99,
  "currency": "GBP"
}
```



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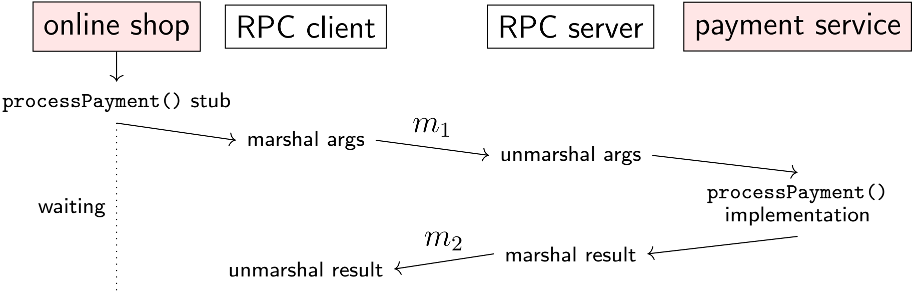

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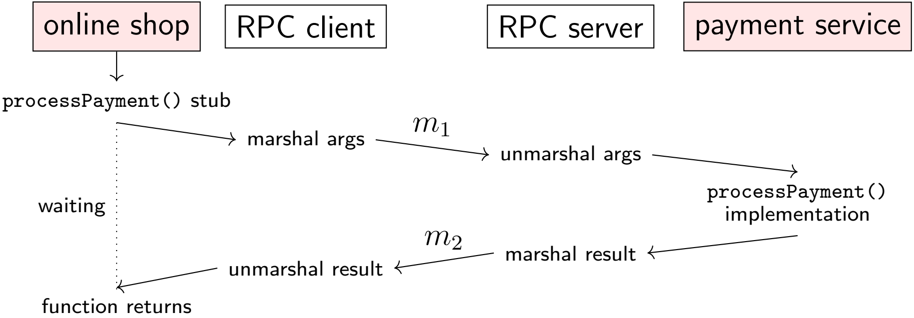
}
```


$m_2 =$


```json
{
  "result": "success",
  "id": "XP61hHw2Rvo"
}
```



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    "CVC": "123"
  },
  "amount": 3.99,
  "currency": "GBP"
}
```


$m_2 =$


```
{
  "result": "success",
  "id": "XP61hHw2Rvo"
}
```

Remote Procedure Call (RPC)

Ideally, RPC makes a call to a remote function look the same as a local function call.

“Location transparency”:
system hides where a resource is located.

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In practice. . .

- what if the service crashes during the function call?
- what if a message is lost?
- what if a message is delayed?
- if something goes wrong, is it safe to retry?

RPC history

- SunRPC/ONC RPC (1980s, basis for NFS)
- CORBA: object-oriented middleware, hot in the 1990s
- Microsoft's DCOM and Java RMI (similar to CORBA)
- SOAP/XML-RPC: RPC using XML and HTTP (1998)
- Thrift (Facebook, 2007)
- gRPC (Google, 2015)
- REST (often with JSON)
- Ajax in web browsers

RPC/REST in JavaScript

```
let args = {amount: 3.99, currency: 'GBP', /*...*/};
let request = {
  method:  'POST',
  body:    JSON.stringify(args),
  headers: {'Content-Type': 'application/json'}
};

fetch('https://example.com/payments', request)
  .then((response) => {
    if (response.ok) success(response.json());
    else failure(response.status); // server error
  })
  .catch((error) => {
    failure(error); // network error
  });
```

RPC in enterprise systems

“Service-oriented architecture” (SOA) / “microservices”:

splitting a large software application into multiple services (on multiple nodes) that communicate via RPC.

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Different services implemented in different languages:

- interoperability: datatype conversions
- **Interface Definition Language** (IDL): language-independent API specification

gRPC IDL example

```
message PaymentRequest {
  message Card {
    required string cardNumber  = 1;
    optional int32  expiryMonth = 2;
    optional int32  expiryYear  = 3;
    optional int32  CVC         = 4;
  }
  enum Currency { GBP = 1; USD = 2; }

  required Card     card     = 1;
  required int64    amount   = 2;
  required Currency currency = 3;
}

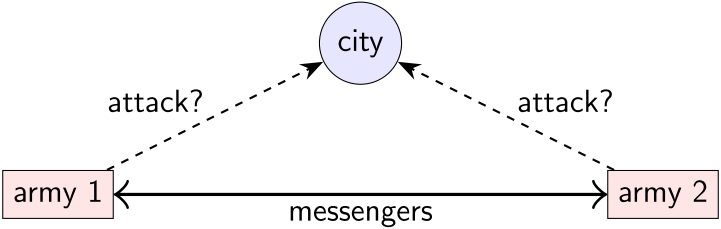
message PaymentStatus {
  required bool   success      = 1;
  optional string errorMessage = 2;
}

service PaymentService {
  rpc ProcessPayment(PaymentRequest) returns (PaymentStatus) {}
}
```

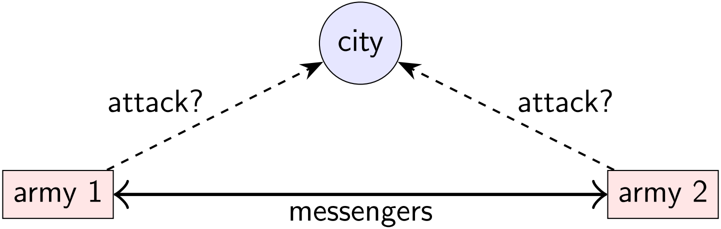
Lecture 2

Models of distributed systems

The two generals problem



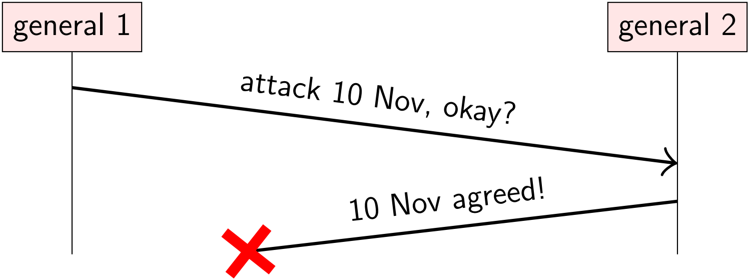
The two generals problem



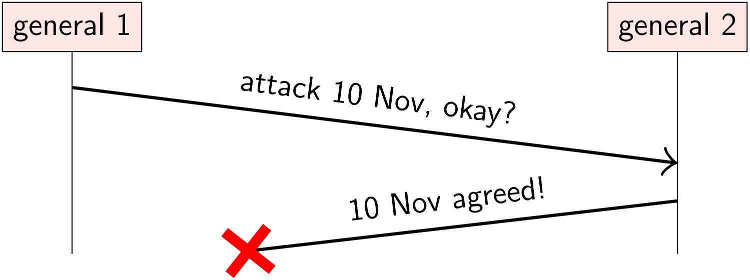
army 1	army 2	outcome
does not attack	does not attack	nothing happens
attacks	does not attack	army 1 defeated
does not attack	attacks	army 2 defeated
attacks	attacks	city captured

Desired: army 1 attacks *if and only if* army 2 attacks

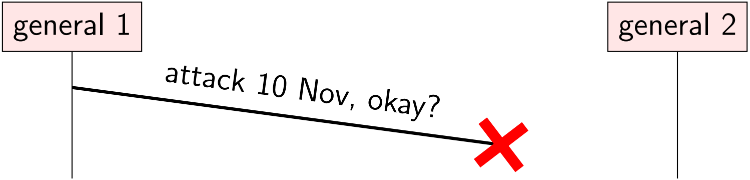
The two generals problem



The two generals problem



From general 1's point of view, this is indistinguishable from:



How should the generals decide?

1. General 1 always attacks, even if no response is received?
    - Send lots of messengers to increase probability that one will get through
    - If all are captured, general 2 does not know about the attack, so general 1 loses

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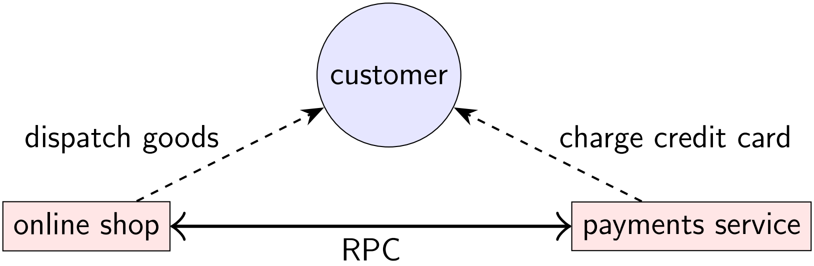
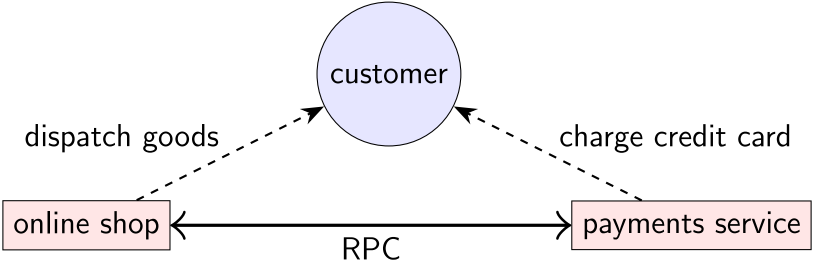
No common knowledge: the only way of knowing something is to communicate it

The two generals problem applied



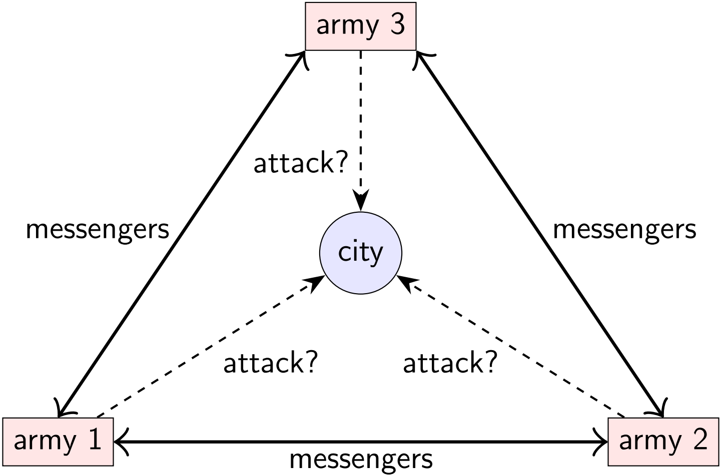
The two generals problem applied



online shop	payments service	outcome
does not dispatch	does not charge	nothing happens
dispatches	does not charge	shop loses money
does not dispatch	charges	customer complaint
dispatches	charges	everyone happy

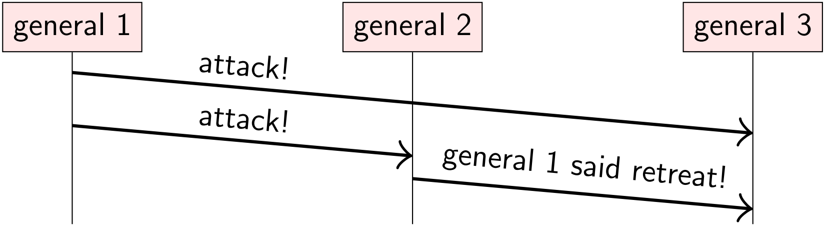
Desired: online shop dispatches *if and only if* payment made

The Byzantine generals problem



Problem: some of the generals might be traitors

Generals that might lie



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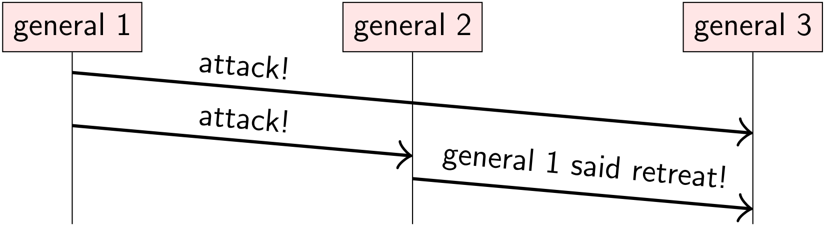
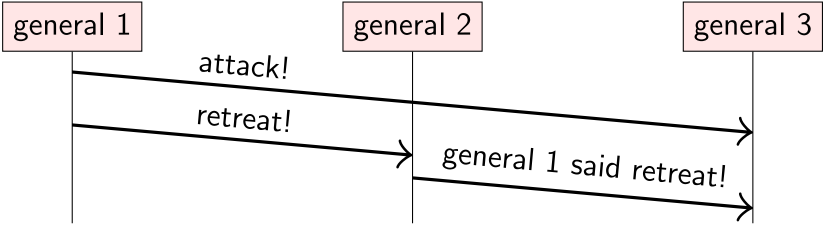


From general 3's point of view, this is indistinguishable from:



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- Up to f generals might behave maliciously
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- The malicious generals may collude
- Nevertheless, honest generals must agree on plan

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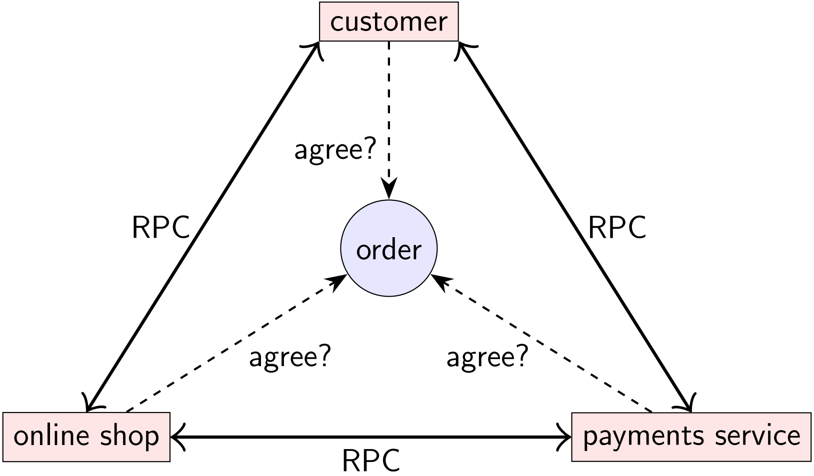
- Nevertheless, honest generals must agree on plan

- Theorem: need $3f + 1$ generals in total to tolerate f malicious generals (i.e. $< \frac{1}{3}$ may be malicious)
- Cryptography (digital signatures) helps – but problem remains hard

Trust relationships and malicious behaviour



Who can trust whom?

The Byzantine empire (650 CE)

Byzantium/Constantinople/Istanbul

Source: https://commons.wikimedia.org/wiki/File:Byzantiumby650AD.svg

"Byzantine" has long been used for "excessively complicated, bureaucratic, devious" (e.g. *"the Byzantine tax law"*)

System models

We have seen two thought experiments:

- Two generals problem: a model of networks
- Byzantine generals problem: a model of node behaviour

In real systems, both nodes and networks may be faulty!

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Capture assumptions in a **system model** consisting of:

- Network behaviour (e.g. message loss)
- Node behaviour (e.g. crashes)
- Timing behaviour (e.g. latency)

Choice of models for each of these parts.

Networks are unreliable

In the sea, sharks bite fibre optic cables

https://slate.com/technology/2014/08/shark-attacks-threaten-google-s-undersea-internet-cables-video.html

On land, cows step on the cables

https://twitter.com/uhoelzle/status/1263333283107991558

System model: network behaviour

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  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 behaviour.

A node that is not faulty is called **“correct”**

System model: synchrony (timing) assumptions

Assume one of the following for network and nodes:

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

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  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 can be delayed arbitrarily.
  Nodes can pause execution arbitrarily.
  No timing guarantees at all.

Note: other parts of computer science use the terms "synchronous" and "asynchronous" differently.

Violations of synchrony in practice

Networks usually have quite predictable latency, which can occasionally increase:

- Message loss requiring retry
- Congestion/contention causing queueing
- Network/route reconfiguration

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Nodes usually execute code at a predictable speed, with occasional pauses:

- Operating system 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!

Availability

Online shop wants to sell stuff 24/7!
Service unavailability = downtime = losing money

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
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Service-Level Objective (SLO):
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

Achieving high availability: fault tolerance

Failure: system as a whole isn't working

Fault: some part of the system isn't 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 failure

Failure detectors

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algorithm that detects whether another node is faulty

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send message, await response, label node as crashed if no reply within some timeout

Problem:
cannot tell the difference between crashed node, temporarily unresponsive node, lost message, and delayed message

Failure detection in partially synchronous systems

Perfect timeout-based failure detector exists only in a synchronous crash-stop system with reliable links.

Eventually perfect failure detector:

- May *temporarily* label a node as crashed, even though it is correct
- May *temporarily* label a node as correct, even though it has crashed
- But *eventually*, labels a node as crashed if and only if it has crashed

Reflects fact that detection is not instantaneous, and we may have spurious timeouts

Lecture 3

Time, clocks, and ordering of events

A detective story

In the night from 30 June to 1 July 2012 (UK time), many online services and systems around the world crashed simultaneously.

Servers locked up and stopped responding.

Some airlines could not process any reservations or check-ins for several hours.

What happened?

Clocks and time in distributed systems

Distributed systems often need to measure time, e.g.:

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- **physical clocks**: count number of seconds elapsed
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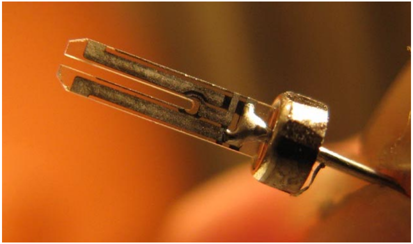
NB. Clock in digital electronics (oscillator)
$\neq$ clock in distributed systems (source of **timestamps**)

Quartz clocks

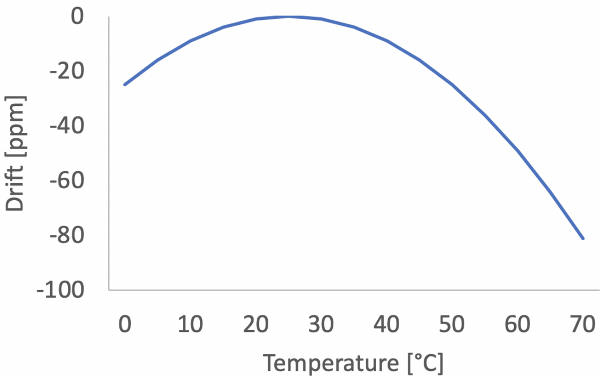
- Quartz crystal laser-trimmed to mechanically resonate at a specific frequency
- Piezoelectric effect: mechanical force $\Leftrightarrow$ electric field
- Oscillator circuit produces signal at resonant frequency
- Count number of cycles to measure elapsed time



Quartz clock error: drift

- One clock runs slightly fast, another slightly slow
- Drift measured in **parts per million** (ppm)
- 1 ppm = 1 microsecond/second = 86 ms/day = 32 s/year
- Most computer clocks correct within ≈ 50 ppm

Temperature significantly affects drift



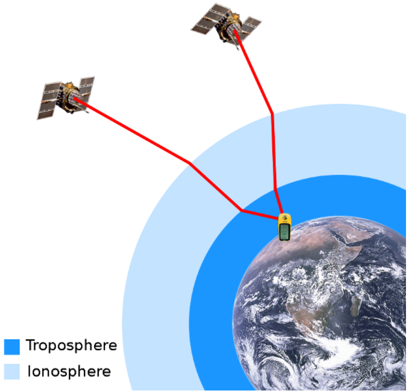
Atomic clocks

- Caesium-133 has a resonance ("hyperfine transition") at ≈ 9 GHz
- Tune an electronic oscillator to that resonant frequency
- 1 second = 9,192,631,770 periods of that signal
- Accuracy ≈ 1 in 10^{-14} (1 second in 3 million years)
- Price $\approx$ £20,000 (?) (can get cheaper rubidium clocks for $\approx$ £1,000)

https://www.microsemi.com/product-directory/cesium-frequency-references/4115-5071a-cesium-primary-frequency-standard

GPS as time source

- 31 satellites, each carrying an atomic clock
- satellite broadcasts current time and location
- calculate position from speed-of-light delay between satellite and receiver
- corrections for atmospheric effects, relativity, etc.
- in datacenters, need antenna on the roof



https://commons.wikimedia.org/wiki/File:Gps-atmospheric-efects.png

Coordinated Universal Time (UTC)

Greenwich Mean Time (GMT, solar time): it's noon when the sun is in the south, as seen from the Greenwich meridian

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Time zones and **daylight savings time** are offsets to UTC

Leap seconds

Every year, on 30 June and 31 December at 23:59:59 UTC, one of three things happens:

- The clock immediately jumps forward to 00:00:00, skipping one second (**negative leap second**)
- The clock moves to 00:00:00 after one second, as usual
- The clock moves to 23:59:60 after one second, and then moves to 00:00:00 after one further second (**positive leap second**)

This is announced several months beforehand.

http://leapsecond.com/notes/leap-watch.htm

How computers represent timestamps

Two most common representations:

- **Unix time**: number of seconds since 1 January 1970 00:00:00 UTC (the "epoch"), *not counting leap seconds*
- **ISO 8601**: year, month, day, hour, minute, second, and timezone offset relative to UTC
  example: `2020-11-09T09:50:17+00:00`

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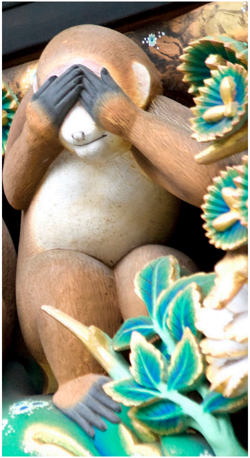
Conversion between the two requires:

- Gregorian calendar: 365 days in a year, except leap years
  ```
  (year % 4 == 0 && (year % 100 != 0 ||
                     year % 400 == 0))
  ```
- Knowledge of past and future leap seconds. . . ?!

How most software deals with leap seconds

By ignoring them!



https://www.flickr.com/photos/ru_boff/37915499055/

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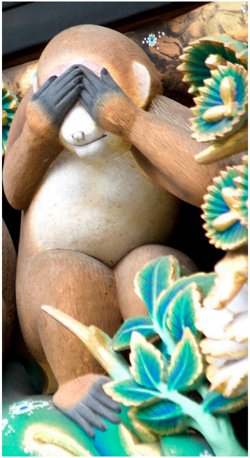
However, OS and DistSys often need timings with sub-second accuracy.



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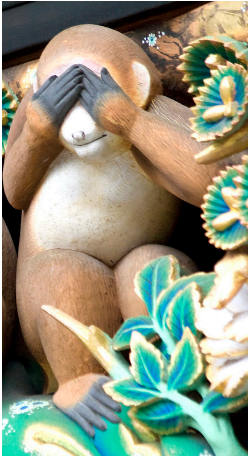

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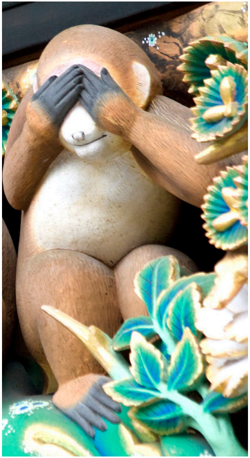
Pragmatic solution: "**smear**" (spread out) the leap second over the course of a day



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Clock synchronisation

Computers track physical time/UTC with a quartz clock
(with battery, continues running when power is off)

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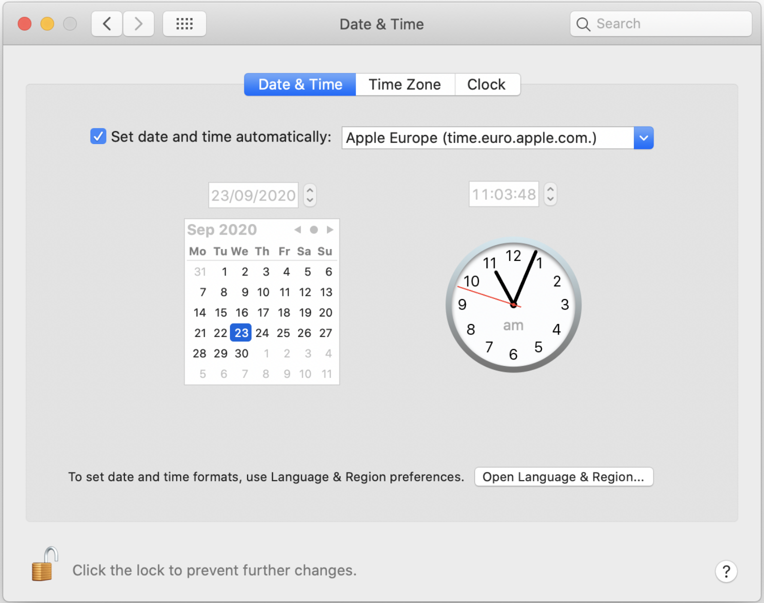
Due to **clock drift**, clock error gradually increases

Clock skew: difference between two clocks at a point in time

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**)


Date & Time
Search
Date & Time
Time Zone
Clock
Set date and time automatically:
Apple Europe (time.euro.apple.com.)
23/09/2020
11:03:48
Sep 2020
Mo Tu We Th Fr Sa Su
am
To set date and time formats, use Language & Region preferences.
Open Language & Region...
Click the lock to prevent further changes.
?

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May contact multiple servers, discard outliers, average rest

Makes multiple requests to the same server, use statistics to reduce random error due to variations in network latency

Reduces clock skew to a few milliseconds in good network conditions, but can be much worse!

Estimating time over a network

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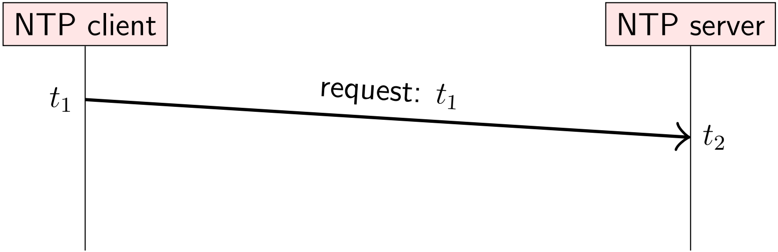

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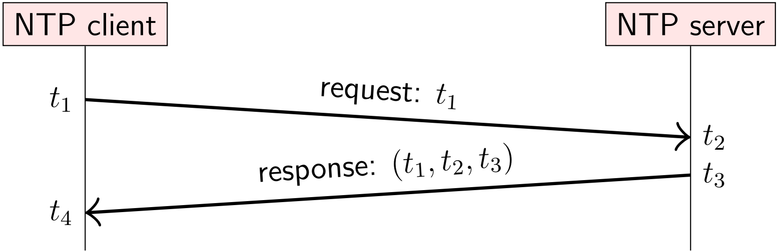

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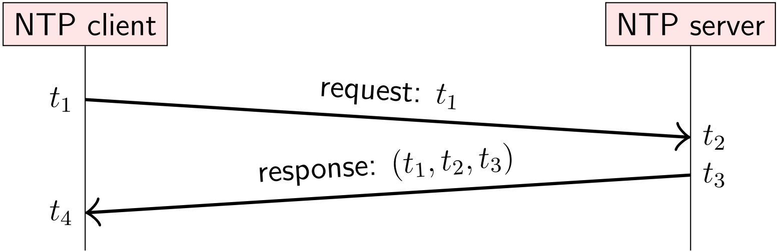

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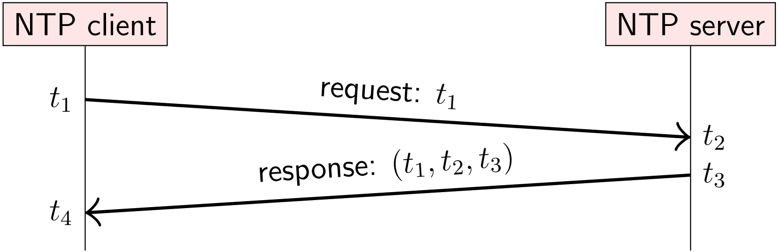

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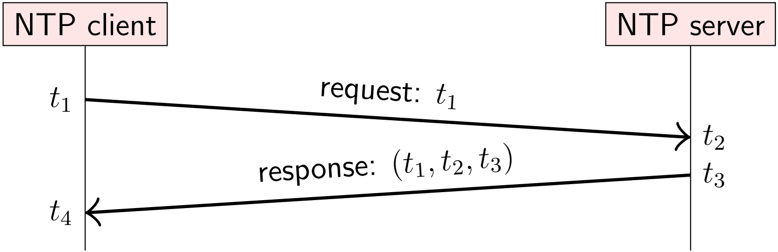

Round-trip network delay: $\delta = (t_4 - t_1) - (t_3 - t_2)$

Estimated server time when client receives response: $t_3 + \dfrac{\delta}{2}$

Estimated clock skew: $\theta = t_3 + \dfrac{\delta}{2} - t_4 = \dfrac{t_2 - t_1 + t_3 - t_4}{2}$

Correcting clock skew

Once the client has estimated the clock skew θ, it needs to apply that correction to its clock.

- If $|\theta| < 125$ ms, **slew** the clock:
  slightly speed it up or slow it down by up to 500 ppm
  (brings clocks in sync within $\approx$ 5 minutes)

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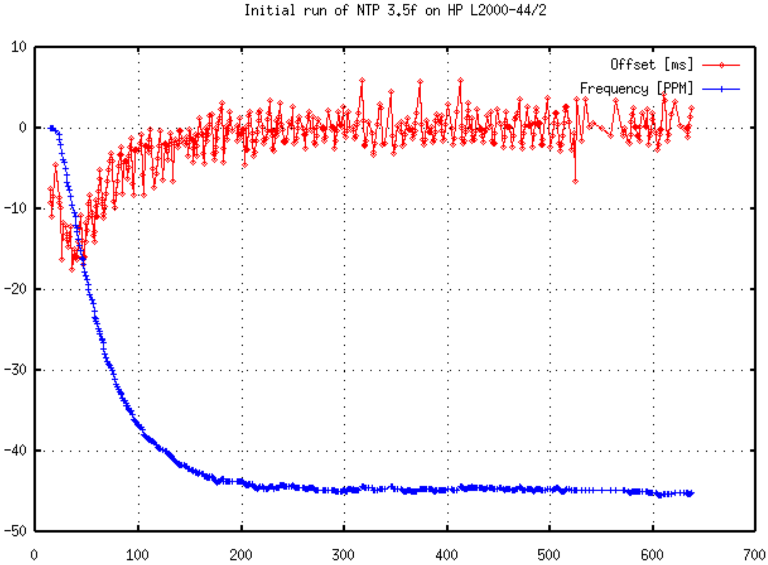
  suddenly reset client clock to estimated server timestamp
- If $|\theta| \geq$ 1,000 s, **panic** and do nothing
  (leave the problem for a human operator to resolve)

Systems that rely on clock sync need to monitor clock skew!



http://www.ntp.org/ntpfaq/NTP-s-algo.htm

Monotonic and time-of-day clocks

```java
// BAD:
long startTime = System.currentTimeMillis();
doSomething();
long endTime = System.currentTimeMillis();
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// elapsedMillis may be negative!
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```
// GOOD:
long startTime = System.nanoTime();
doSomething();
long endTime = System.nanoTime();
long elapsedNanos = endTime - startTime;
// elapsedNanos is always >= 0
```

Monotonic and time-of-day clocks

Time-of-day clock:

- Time since a fixed date (e.g. 1 January 1970 epoch)

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- Time since arbitrary point (e.g. when machine booted up)

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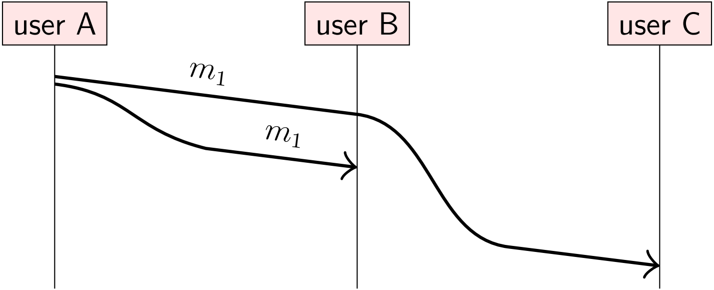
Ordering of messages



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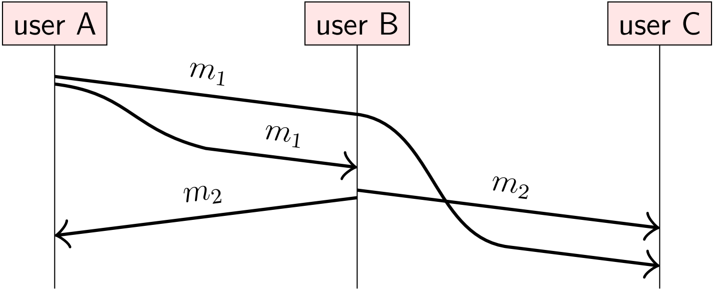

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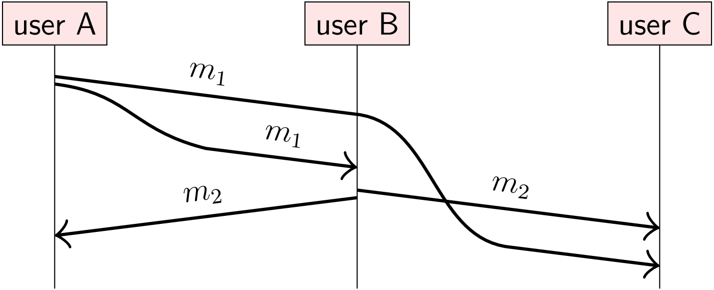

$m_1 =$ "A says: The moon is made of cheese!"
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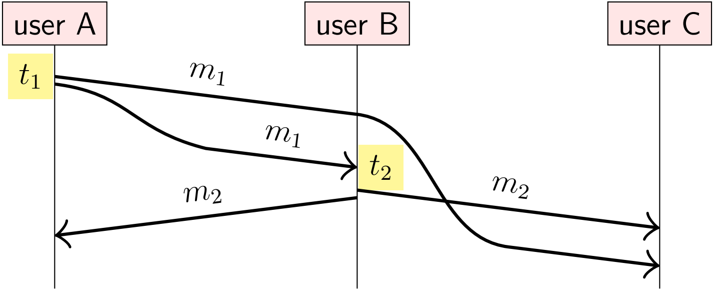
C sees m_2 first, m_1 second,
even though logically m_1 **happened before** m_2.

Ordering of messages using timestamps?



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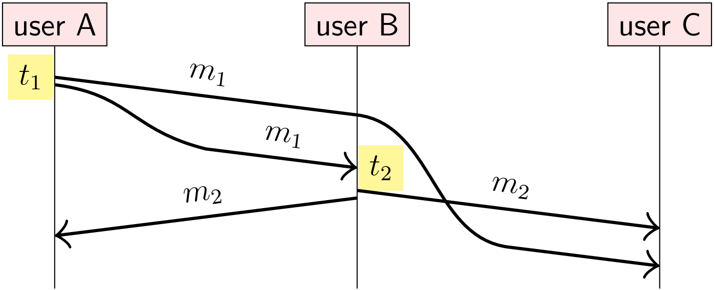

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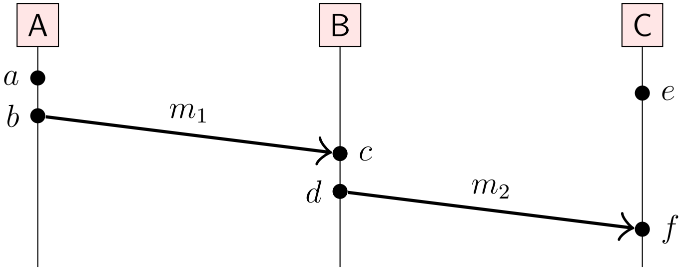
The happens-before relation is a partial order: it is possible that neither $a \to b$ nor $b \to a$. In that case, a and b are **concurrent** (written $a \parallel b$).

Happens-before relation example



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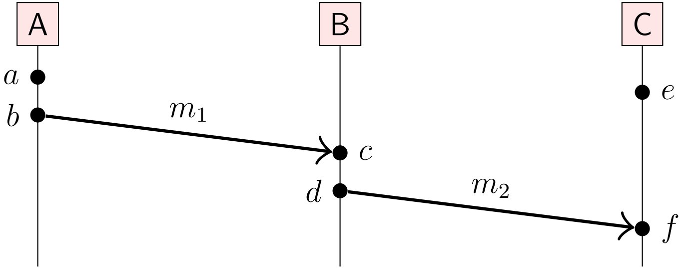

- $a \to b$, $c \to d$, and $e \to f$ due to node execution order

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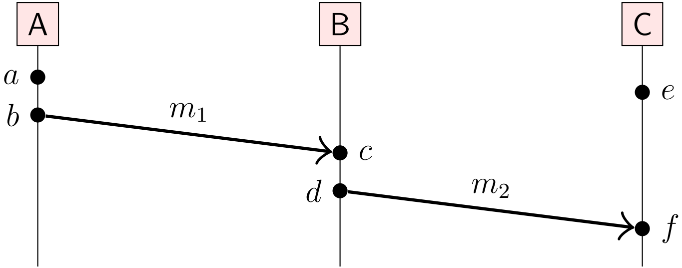

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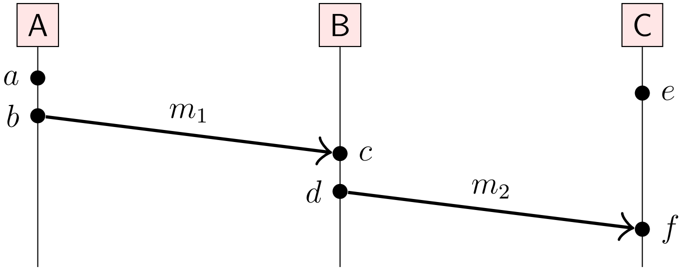

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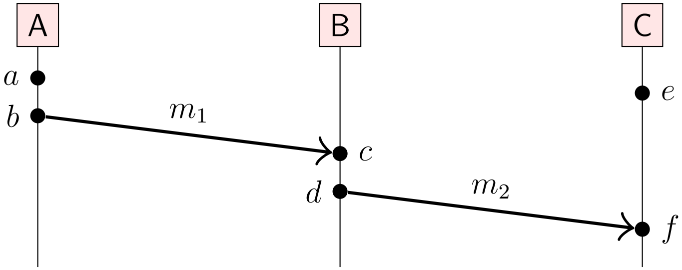

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- $a \parallel e$, $b \parallel e$, $c \parallel e$, and $d \parallel e$

Causality

Taken from physics (relativity).

- When $a \rightarrow b$, then a **might have caused** b.
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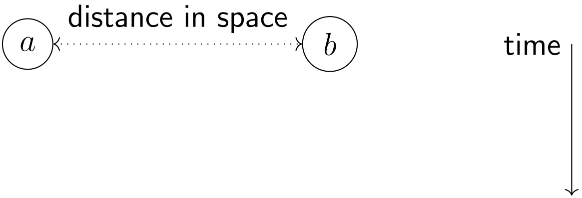

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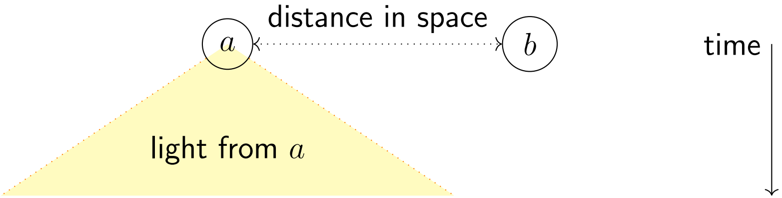

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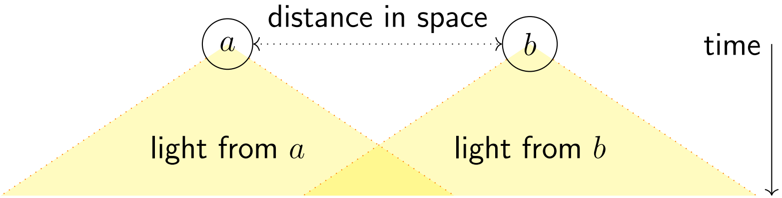

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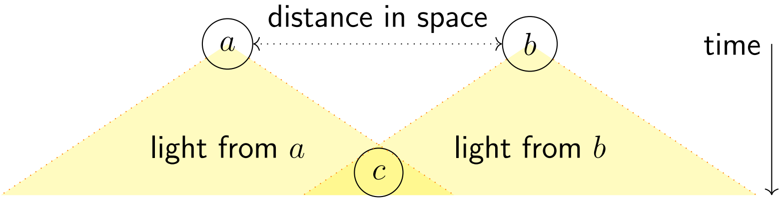

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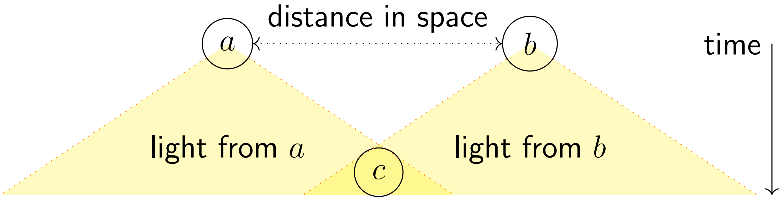
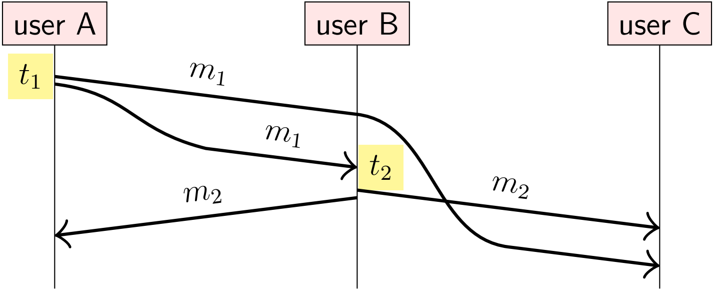


Let $\prec$ be a strict total order on events.
If $(a \to b) \implies (a \prec b)$ then $\prec$ is a **causal order**
(or: $\prec$ is "consistent with causality").
NB. "causal" $\neq$ "casual"!

Lecture 4

Broadcast protocols and logical time

Physical timestamps inconsistent with causality



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Logical vs. physical clocks

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$$(e_1 \rightarrow e_2) \implies (T(e_1) < T(e_2))$$

We will look at two types of logical clocks:

- Lamport clocks
- Vector clocks

Lamport clocks algorithm

on initialisation **do**
  $t := 0$ ▷ each node has its own local variable t
end on

on any event occurring at the local node **do**
  $t := t + 1$
end on

on request to send message m **do**
  $t := t + 1$; send (t, m) via the underlying network link
end on

on receiving (t', m) via the underlying network link **do**
  $t := \max(t, t') + 1$
  deliver m to the application
end on

Lamport clocks in words

- Each node maintains a counter t,
  incremented on every local event e
- Let $L(e)$ be the value of t after that increment
- Attach current t to messages sent over network
- Recipient moves its clock forward to timestamp in the message (if greater than local counter), then increments

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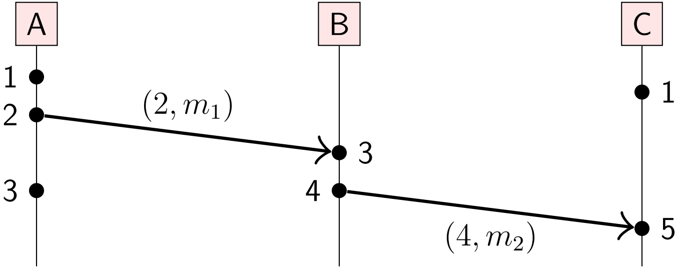
Lamport clocks example



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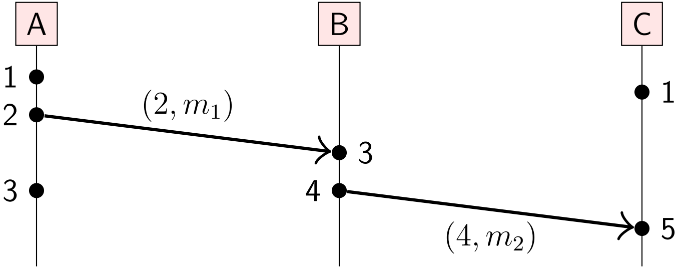

Let $N(e)$ be the node at which event e occurred.
Then the pair $(L(e), N(e))$ **uniquely identifies** event e.

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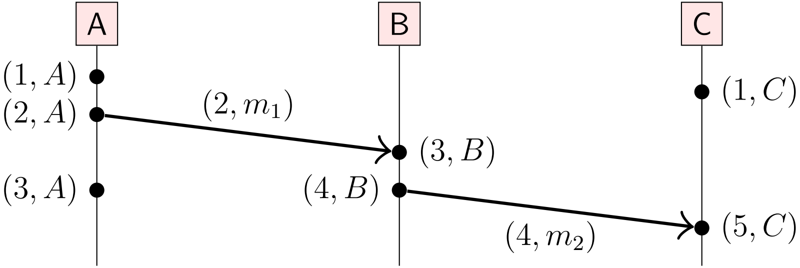

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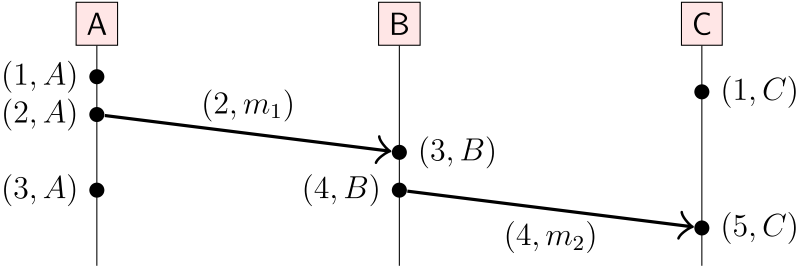

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Define a **total order** $\prec$ using Lamport timestamps:

$$(a \prec b) \iff (L(a) < L(b) \lor (L(a) = L(b) \land N(a) < N(b)))$$

This order is **causal**: $(a \to b) \implies (a \prec b)$

Vector clocks

Given Lamport timestamps $L(a)$ and $L(b)$ with $L(a) < L(b)$ we can't tell whether $a \to b$ or $a \parallel b$.

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- Vector timestamp of event a is $V(a) = \langle t_1, t_2, \dots, t_n \rangle$
- t_i is number of events observed by node N_i

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- 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 local vector

Vector clocks algorithm

on initialisation at node N_i **do**
  $T := \langle 0, 0, \ldots, 0 \rangle$ $\triangleright$ local variable at node N_i
end on

on any event occurring at node N_i **do**
  $T[i] := T[i] + 1$
end on

on request to send message m at node N_i **do**
  $T[i] := T[i] + 1$; send (T, m) via network
end on

on receiving (T', m) at node N_i via the network **do**
  $T[j] := \max(T[j], T'[j])$ for every $j \in \{1, \ldots, n\}$
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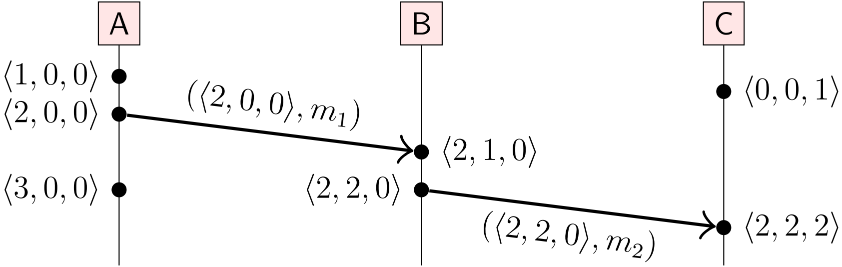
end on

Vector clocks example

Assuming the vector of nodes is $N = \langle A, B, C \rangle$:



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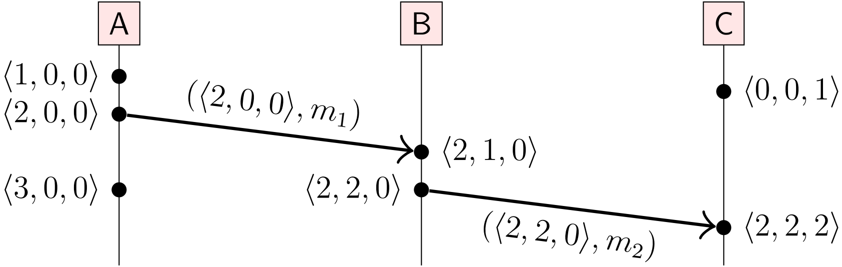

The vector timestamp of an event e represents a set of events, e and its causal dependencies: $\{e\} \cup \{a \mid a \rightarrow e\}$

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.

Vector clocks ordering

Define the following order on vector timestamps (in a system with n nodes):

- $T = T'$ iff $T[i] = T'[i]$ for all $i \in \{1, \ldots, n\}$
- $T \leq T'$ iff $T[i] \leq T'[i]$ for all $i \in \{1, \ldots, n\}$
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Properties of this order:

- $(V(a) < V(b)) \iff (a \rightarrow b)$
- $(V(a) = V(b)) \iff (a = b)$
- $(V(a) \parallel V(b)) \iff (a \parallel b)$

Broadcast protocols

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- Can be **best-effort** (may drop messages) or **reliable** (non-faulty nodes deliver every message, by retransmitting dropped messages)

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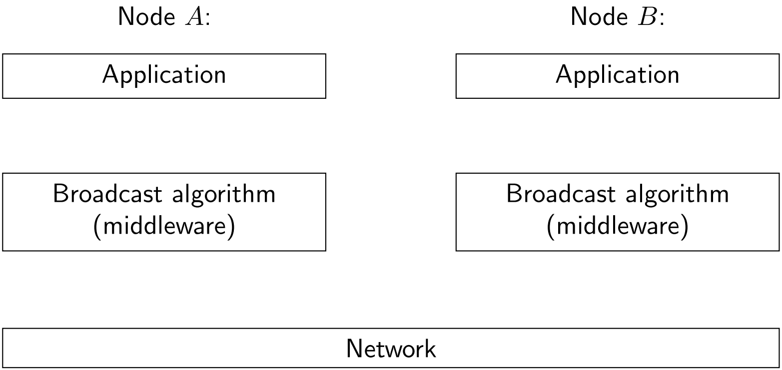
Build upon system models from lecture 2:

- Can be **best-effort** (may drop messages) or
  reliable (non-faulty nodes deliver every message,
  by retransmitting dropped messages)
- Asynchronous/partially synchronous timing model
  $\Longrightarrow$ **no upper bound** on message latency

Receiving versus delivering



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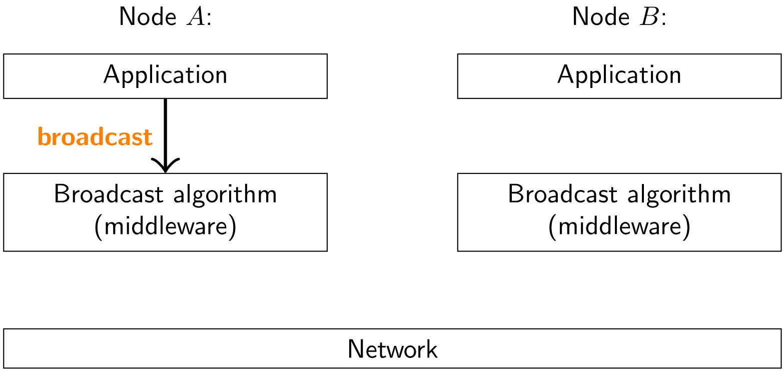

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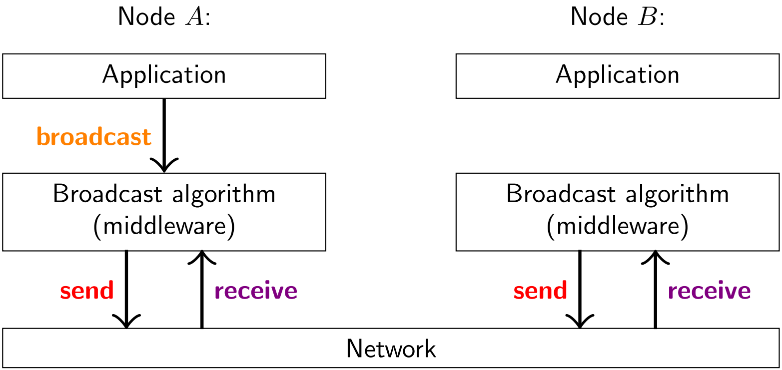
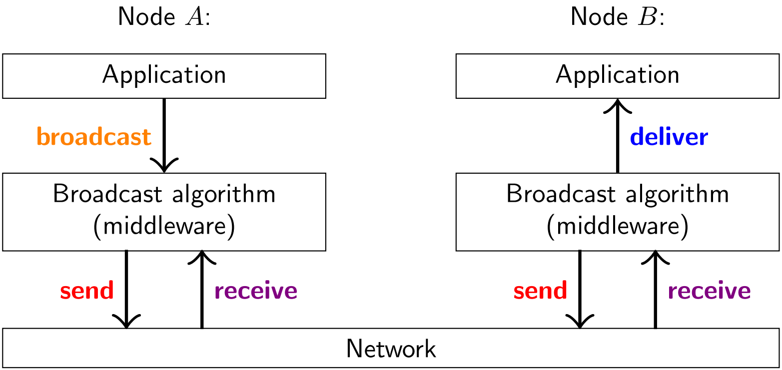


Assume network provides point-to-point **send**/**receive**

Receiving versus delivering



Assume network provides point-to-point **send**/**receive**

After broadcast algorithm **receives** message from network, it may buffer/queue it before **delivering** to the application

Forms of reliable broadcast

FIFO broadcast:
If m_1 and m_2 are broadcast by the same node, and broadcast$(m_1) \rightarrow$ broadcast(m_2), then m_1 must be delivered before m_2

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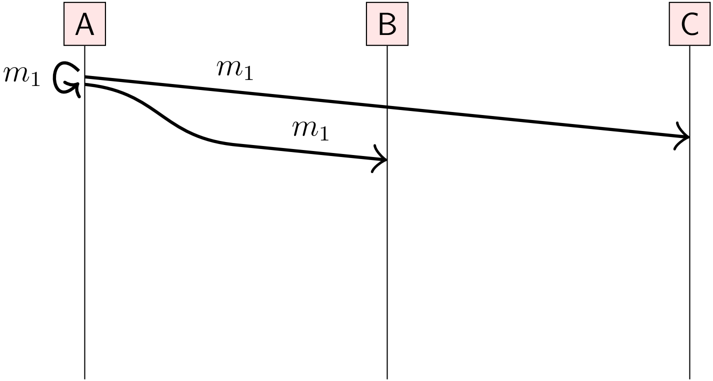
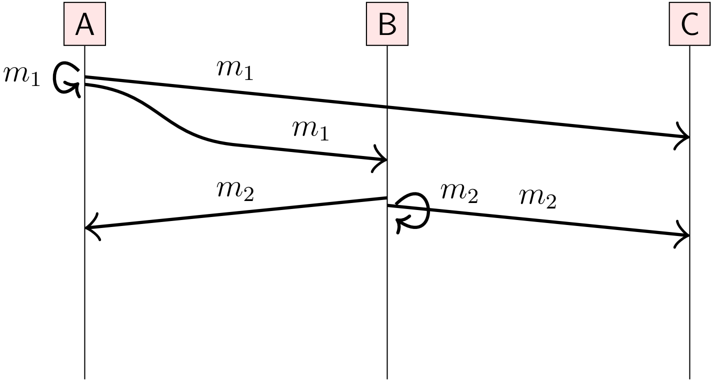
FIFO-total order broadcast:
Combination of FIFO broadcast and total order broadcast

FIFO broadcast



FIFO broadcast



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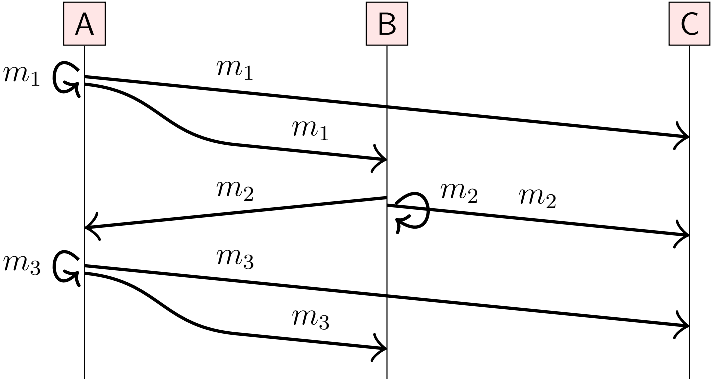
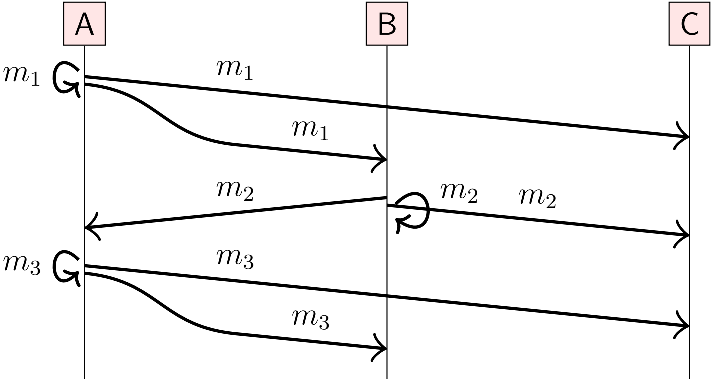


FIFO broadcast



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Messages sent by different nodes can be delivered in any order.

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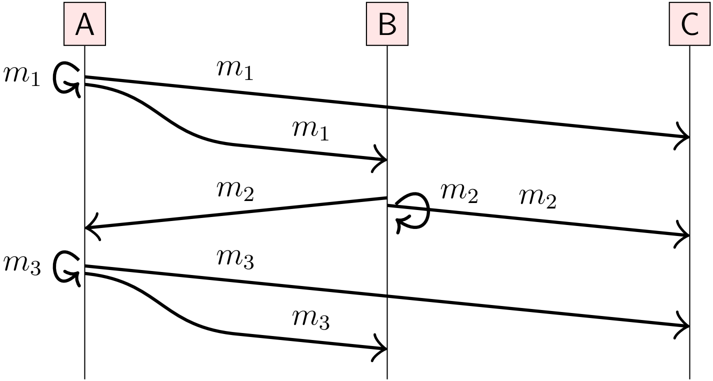

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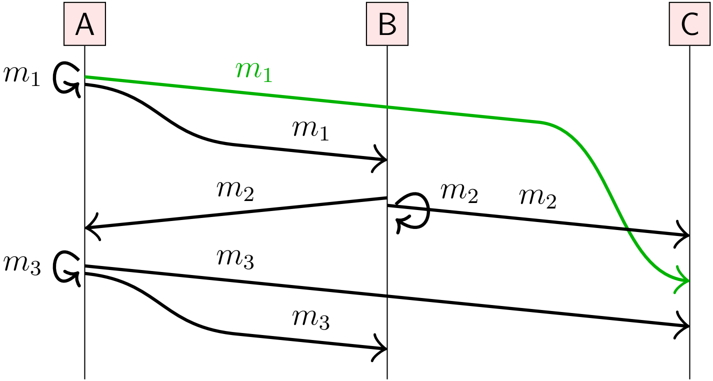
Messages sent by different nodes can be delivered in any order.
Valid orders: (m_2, m_1, m_3) or (m_1, m_2, m_3) or (m_1, m_3, m_2)

FIFO broadcast



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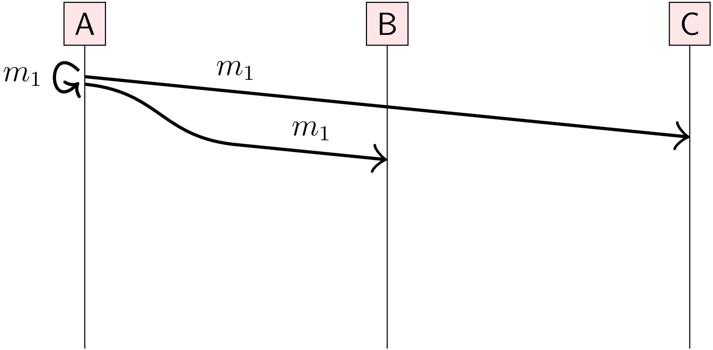

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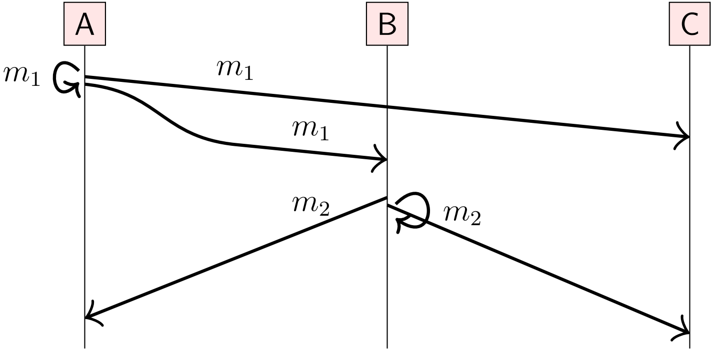

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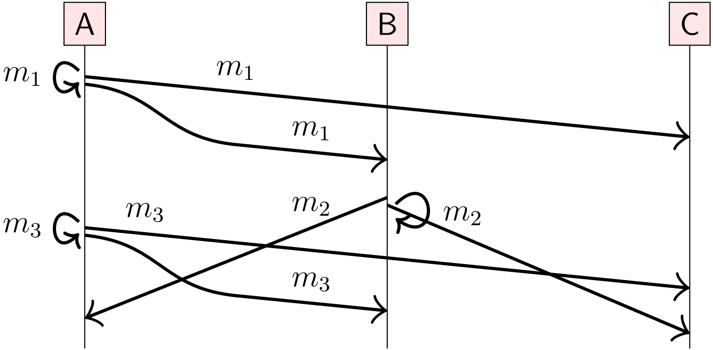

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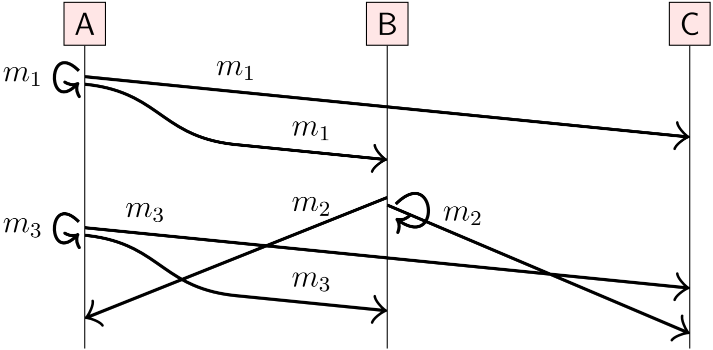
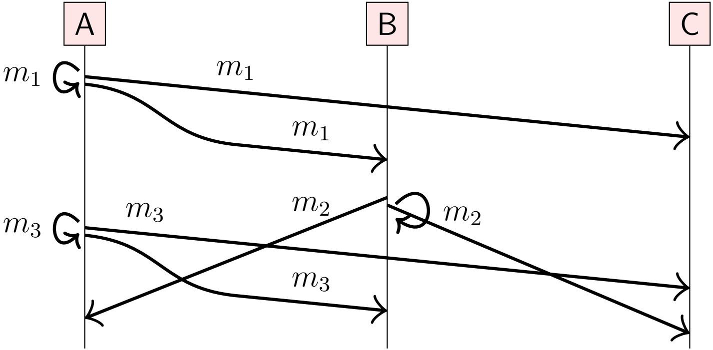


Causally related messages must be delivered in causal order.
Concurrent messages can be delivered in any order.

Causal broadcast



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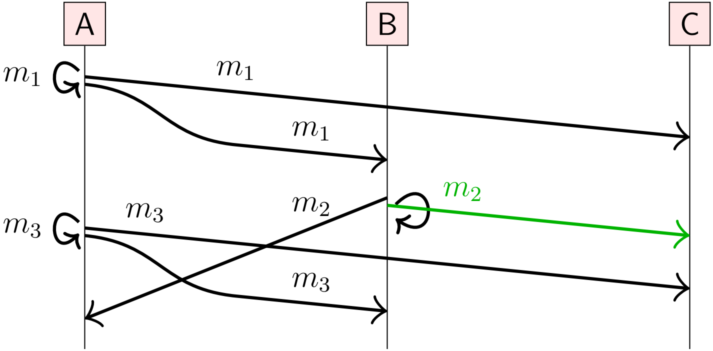

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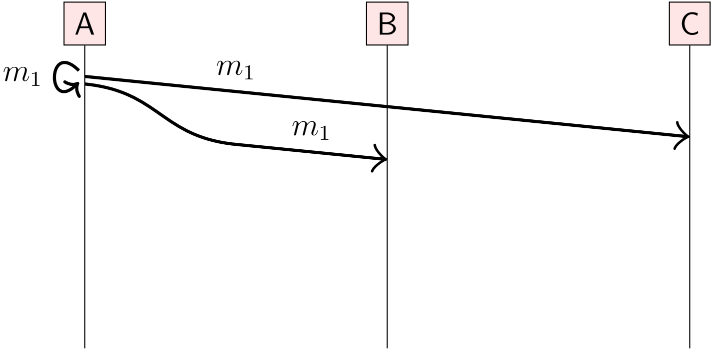

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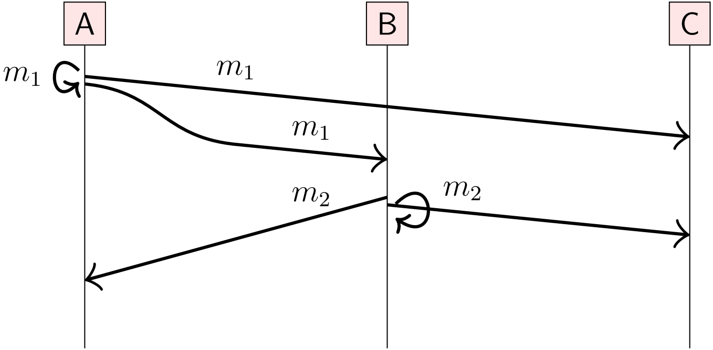

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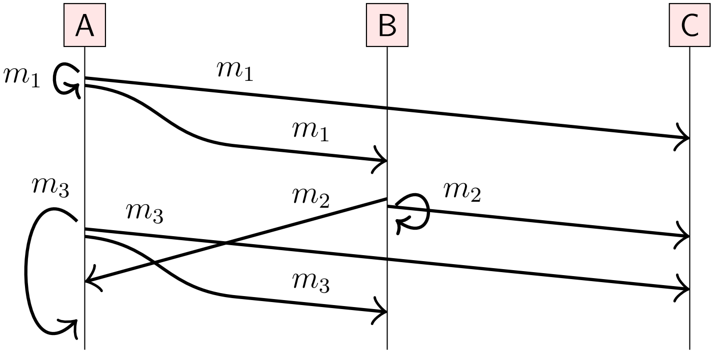

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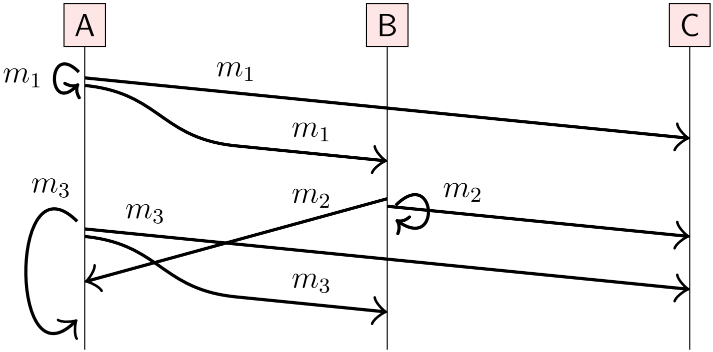

All nodes must deliver messages in **the same** order
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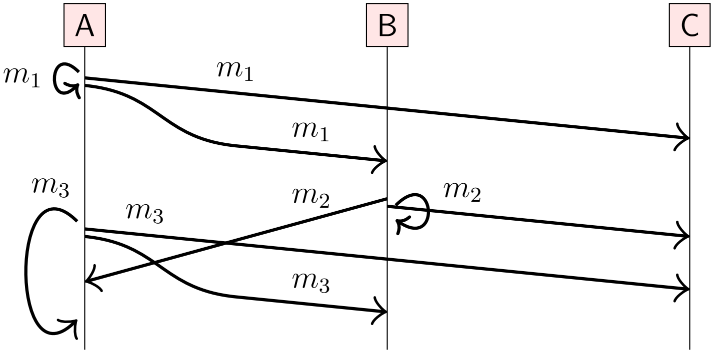

All nodes must deliver messages in **the same** order
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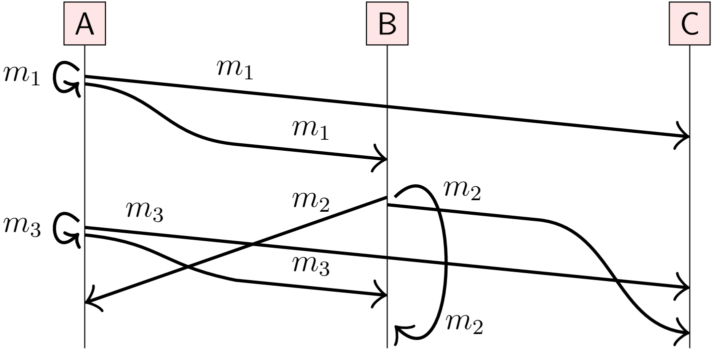
This includes a node's deliveries to itself!

Total order broadcast (2)



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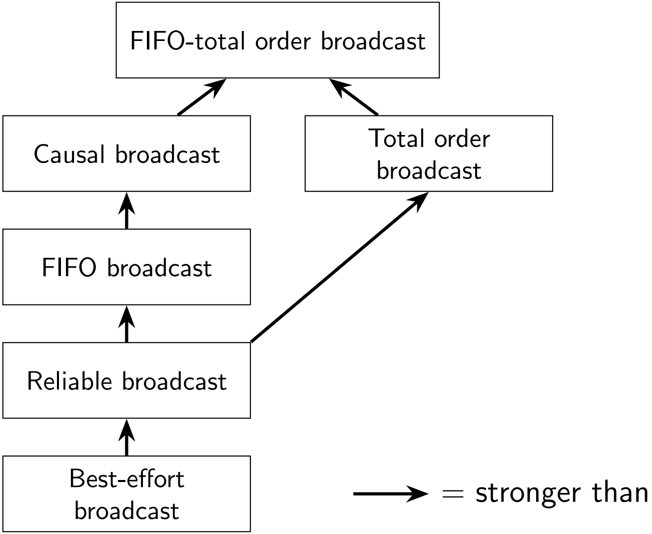
Relationships between broadcast models



Broadcast algorithms

Break down into two layers:

1. Make best-effort broadcast reliable by retransmitting dropped messages
2. Enforce delivery order on top of reliable broadcast

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First attempt: **broadcasting node sends message directly** to every other node

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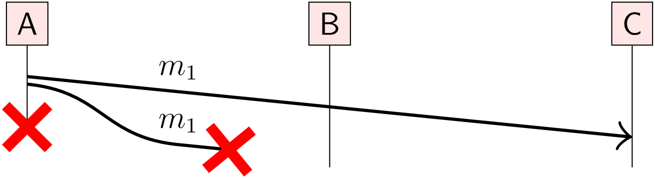
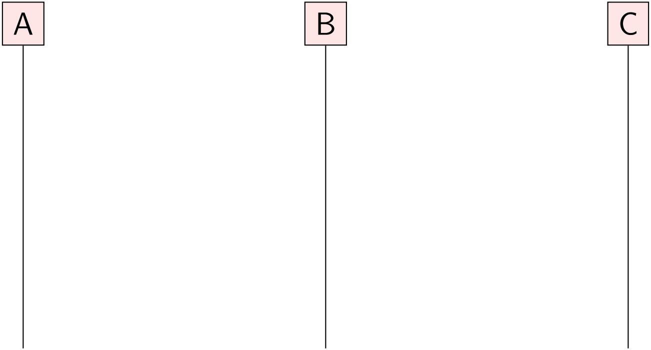
- Use reliable links (retry + deduplicate)
- Problem: node may crash before all messages delivered



Eager reliable broadcast

Idea: the **first time** a node receives a particular message, it **re-broadcasts** to each other node (via reliable links).



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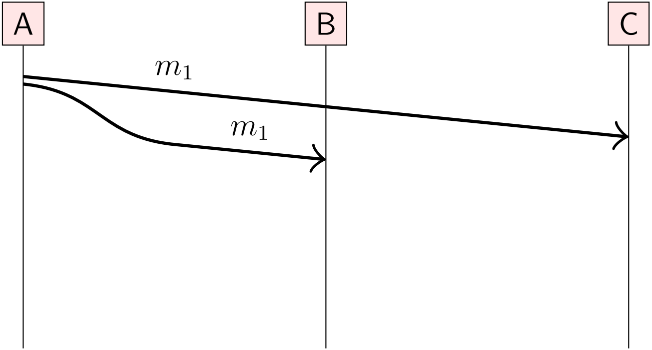

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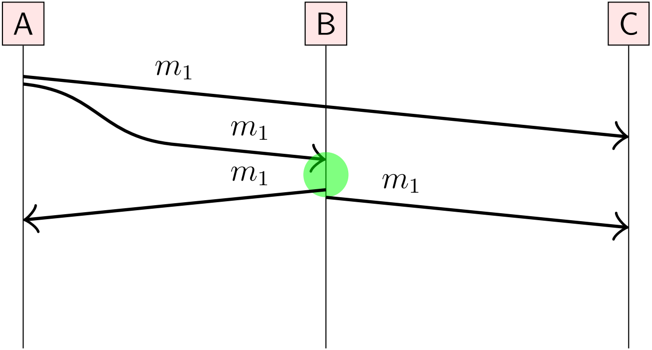

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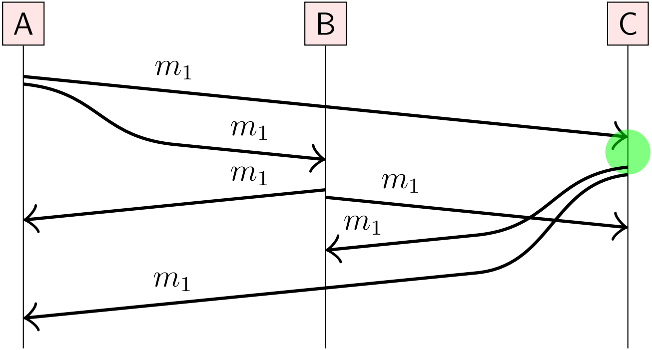

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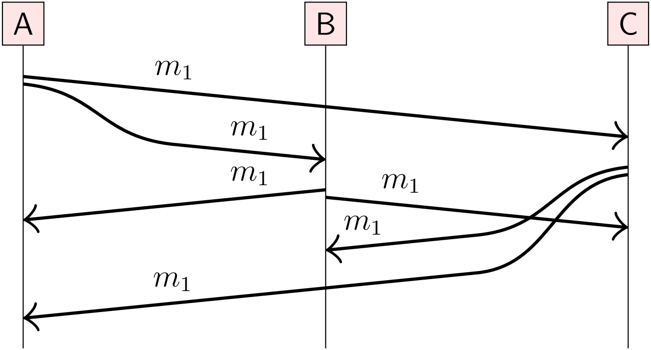
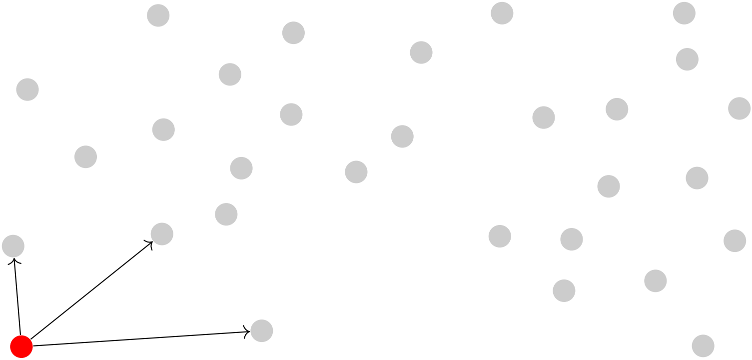


Reliable, but... up to $O(n^2)$ messages for n nodes!

Gossip protocols

Useful when broadcasting to a large number of nodes.
Idea: when a node receives a message for the first time, **forward it to 3 other nodes**, chosen randomly.



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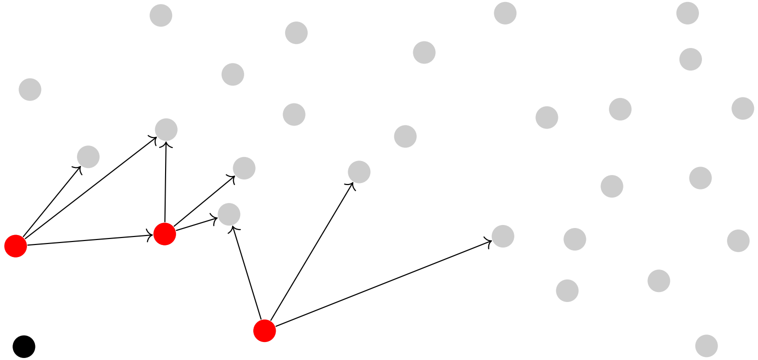

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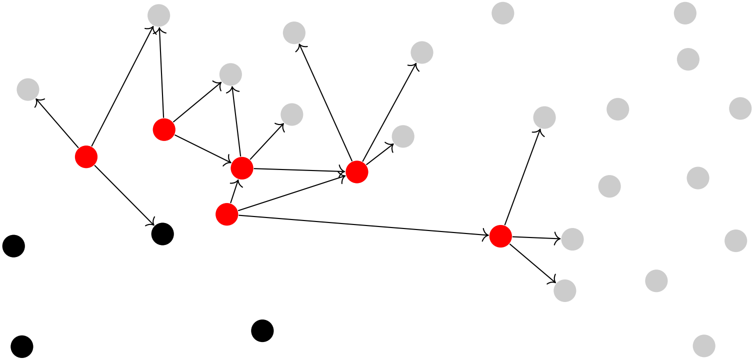

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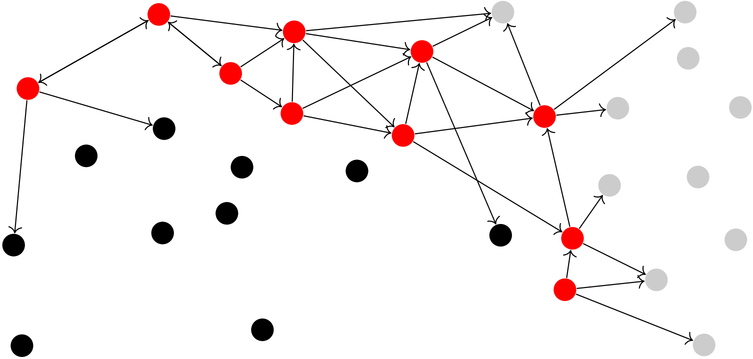

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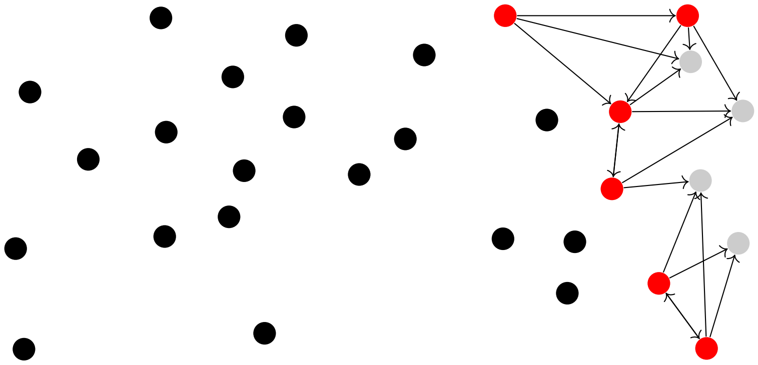

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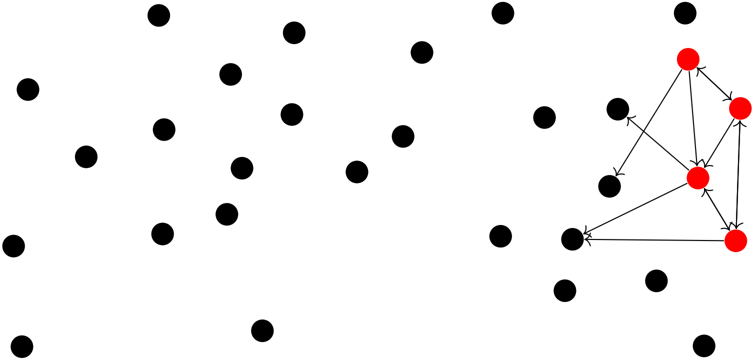

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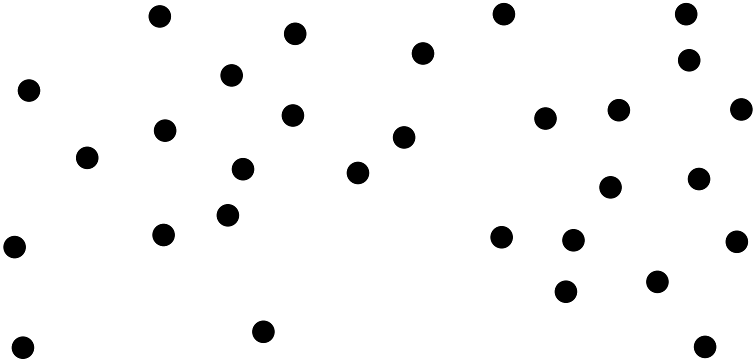

Eventually reaches all nodes (with high probability).

FIFO broadcast algorithm

on initialisation **do**
  $sendSeq := 0;\ delivered := \langle 0, 0, \dots, 0 \rangle;\ buffer := \{\}$
end on

on request to broadcast m at node N_i **do**
  send $(i, sendSeq, m)$ via reliable broadcast
  $sendSeq := sendSeq + 1$
end on

on receiving msg from reliable broadcast at node N_i **do**
  $buffer := buffer \cup \{msg\}$
  while $\exists sender, m.\ (sender, delivered[sender], m) \in buffer$ **do**
    deliver m to the application
    $delivered[sender] := delivered[sender] + 1$
  end while
end on

Causal broadcast algorithm

on initialisation **do**
  $sendSeq := 0;\ delivered := \langle 0, 0, \ldots, 0 \rangle;\ buffer := \{\}$
end on

on request to broadcast m at node N_i **do**
  $deps := delivered; deps[i] := sendSeq$
  send $(i, deps, m)$ via reliable broadcast
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end on

on receiving msg from reliable broadcast at node N_i **do**
  $buffer := buffer \cup \{msg\}$
  while $\exists(sender, deps, m) \in buffer.\ deps \leq delivered$ **do**
    deliver m to the application
    $buffer := buffer \setminus \{(sender, deps, m)\}$
    $delivered[sender] := delivered[sender] + 1$
  end while
end on

Vector clocks ordering

Define the following order on vector timestamps (in a system with n nodes):

- $T = T'$ iff $T[i] = T'[i]$ for all $i \in \{1, \dots, n\}$
- $T \leq T'$ iff $T[i] \leq T'[i]$ for all $i \in \{1, \dots, n\}$
- $T < T'$ iff $T \leq T'$ and $T \neq T'$
- $T \parallel T'$ iff $T \not\leq T'$ and $T' \not\leq T$

Total order broadcast algorithms

Single leader approach:

- One node is designated as leader (sequencer)
- To broadcast message, send it to the leader; leader broadcasts it via FIFO broadcast.

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Lamport clocks approach:

- Attach Lamport timestamp to every message
- Deliver messages in total order of timestamps

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Lamport clocks approach:

- Attach Lamport timestamp to every message
- Deliver messages in total order of timestamps
- Problem: how do you know if you have seen all messages with timestamp $< T$? Need to use FIFO links and wait for message with timestamp $\geq T$ from *every* node

Lecture 5

Replication

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- Keeping a copy of the same data on multiple nodes
- Databases, filesystems, caches, ...
- A node that has a copy of the data is called a **replica**

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Compare to **RAID** (Redundant Array of Independent Disks): replication within a single computer

- RAID has single controller; in distributed system, each node acts independently
- Replicas can be distributed around the world, near users

Retrying state updates

User A: The moon is not actually made of cheese!

Like 12,300 people like this.

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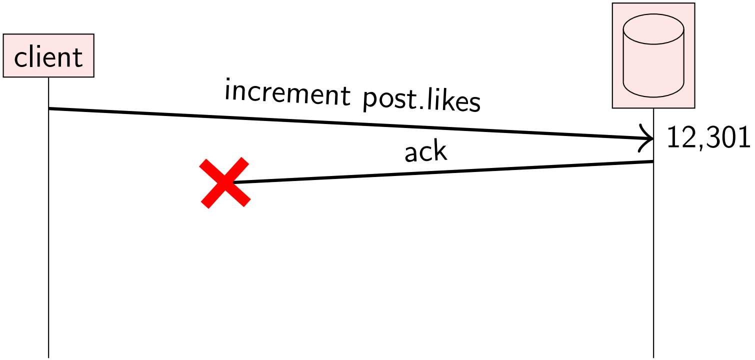

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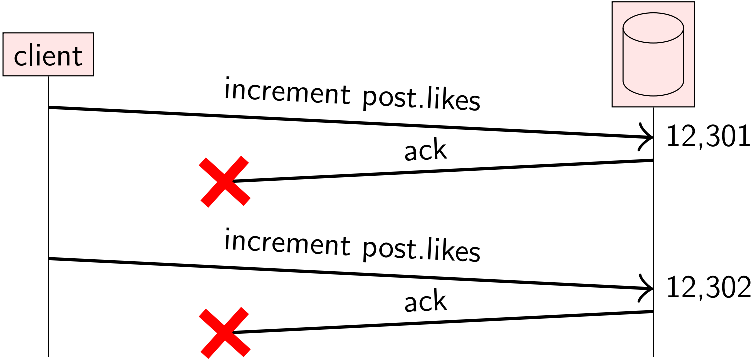

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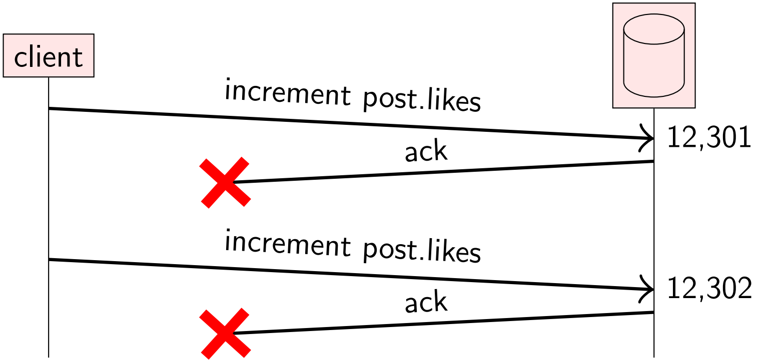
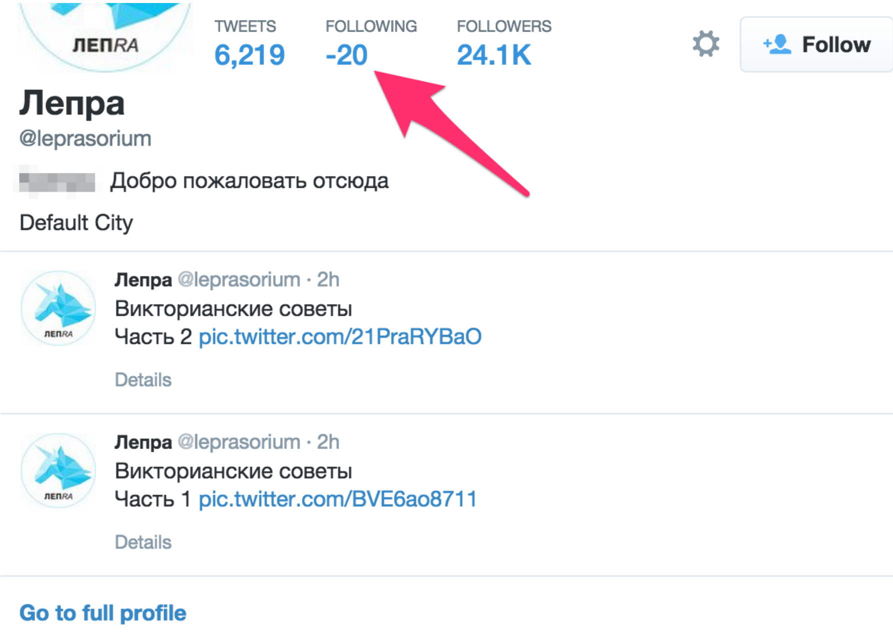


Deduplicating requests requires that the database tracks which requests it has already seen (in stable storage)



ЛЕПRA
TWEETS
6,219
FOLLOWING
-20
FOLLOWERS
24.1K
Follow
Лепра
@leprasorium
Добро пожаловать отсюда
Default City
Лепра @leprasorium · 2h
Викторианские советы
Часть 2 pic.twitter.com/21PraRYBaO
Details
Лепра @leprasorium · 2h
Викторианские советы
Часть 1 pic.twitter.com/BVE6ao8711
Details
Go to full profile

Idempotence

A function f is idempotent if $f(x) = f(f(x))$.

- **Not idempotent:** $f(likeCount) = likeCount + 1$
- **Idempotent:** $f(likeSet) = likeSet \cup \{userID\}$

Idempotent requests can be retried without deduplication.

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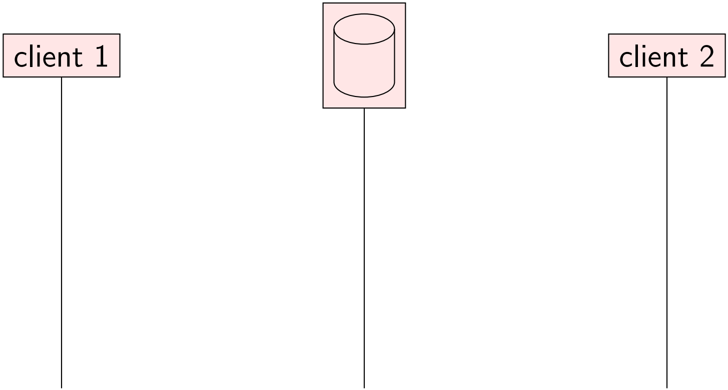
Idempotent requests can be retried without deduplication.

Choice of retry behaviour:

- **At-most-once** semantics:
  send request, don't retry, update may not happen
- **At-least-once** semantics:
  retry request until acknowledged, may repeat update
- **Exactly-once** semantics:
  retry $+$ idempotence or deduplication

Adding and then removing again



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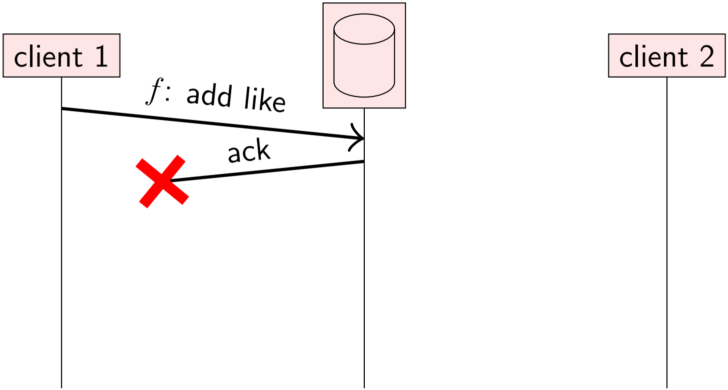

$$f(likes) = likes \cup \{userID\}$$

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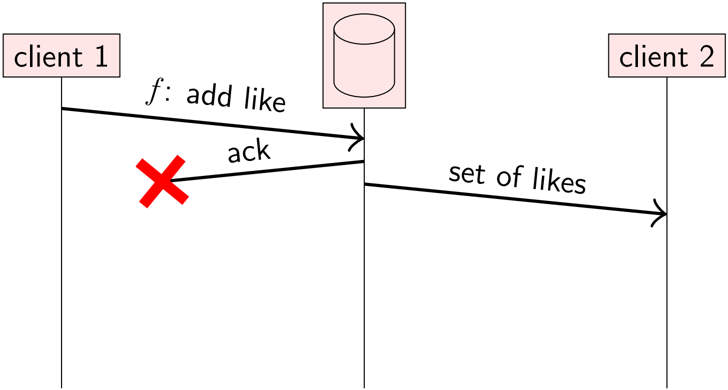

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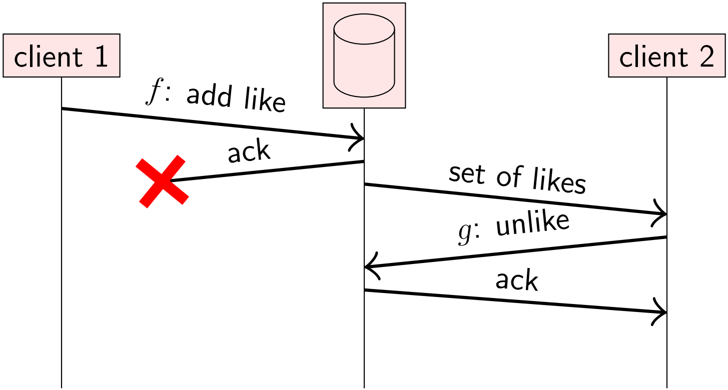

$$f(likes) = likes \cup \{userID\}$$
$$g(likes) = likes \setminus \{userID\}$$

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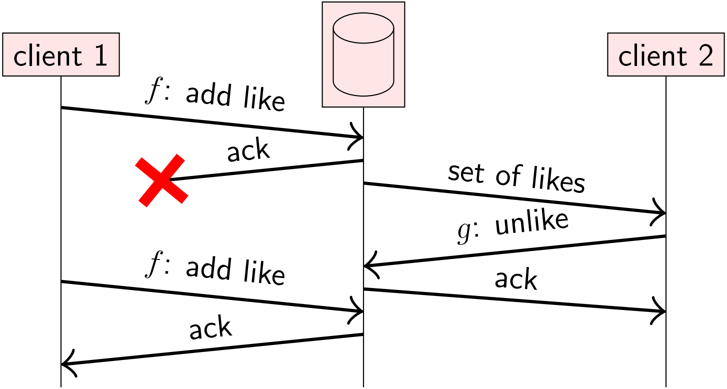

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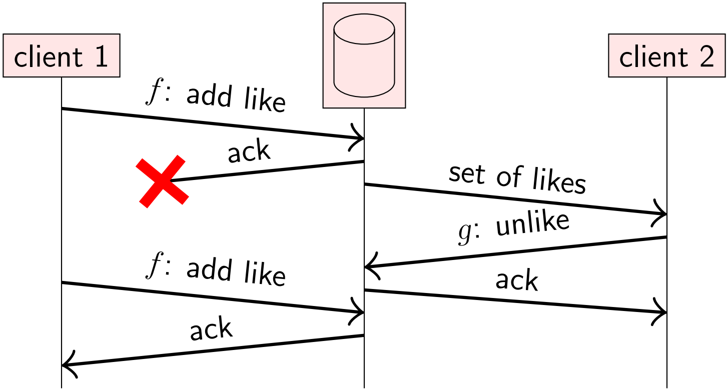

$f(likes) = likes \cup \{userID\}$
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Idempotent? $f(f(x)) = f(x)$ but $f(g(f(x))) \neq g(f(x))$

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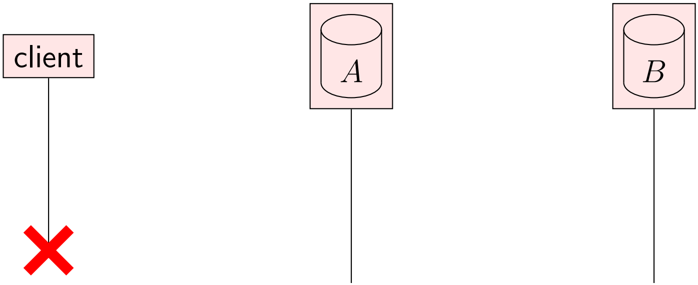

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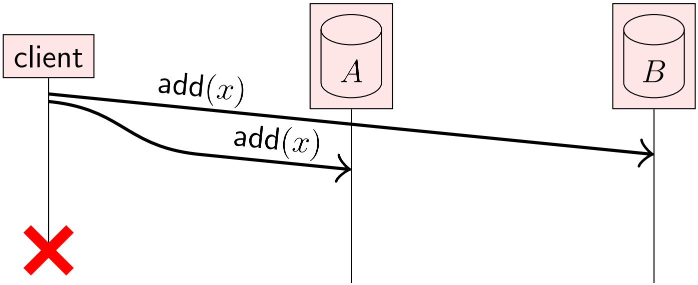

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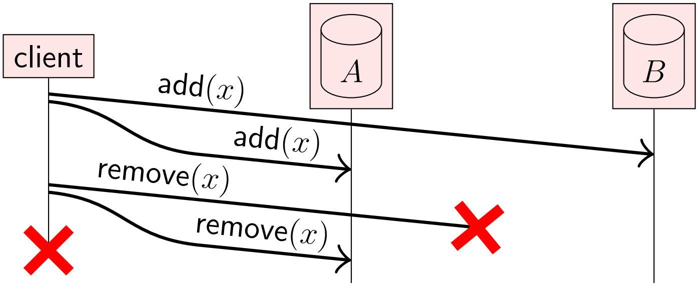

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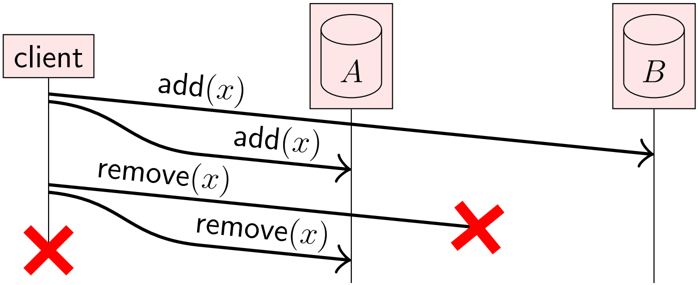

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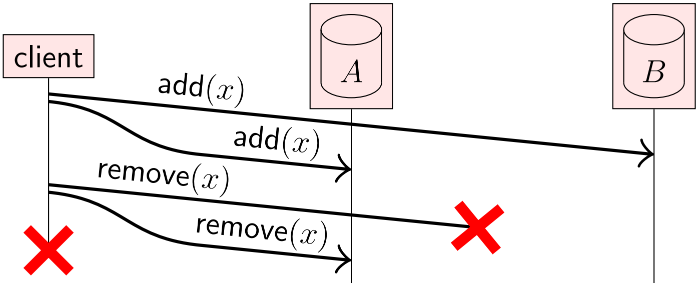

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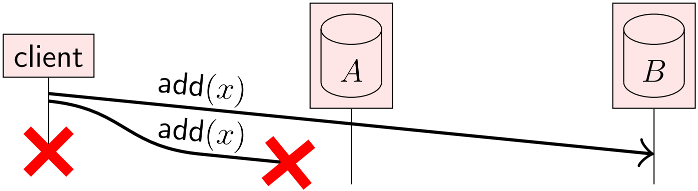

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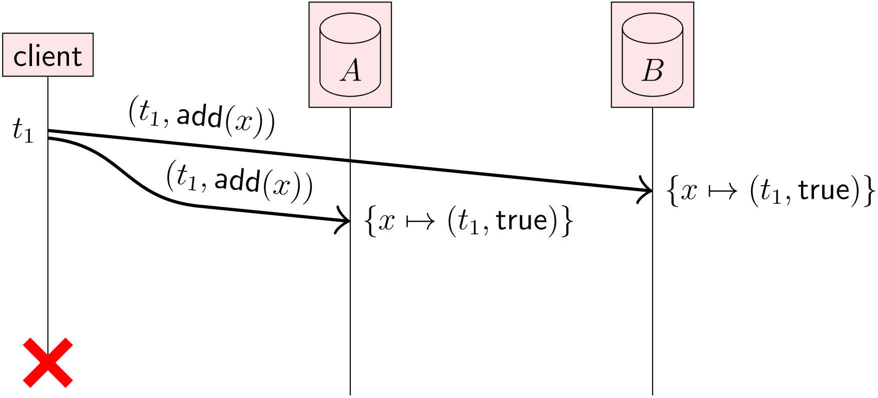

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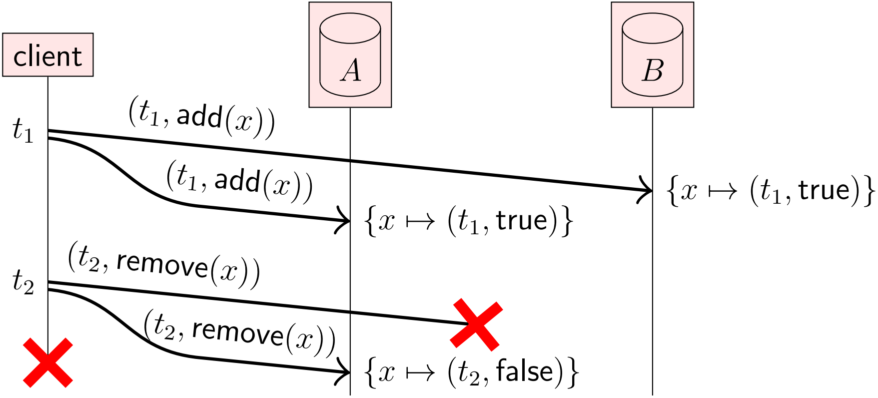

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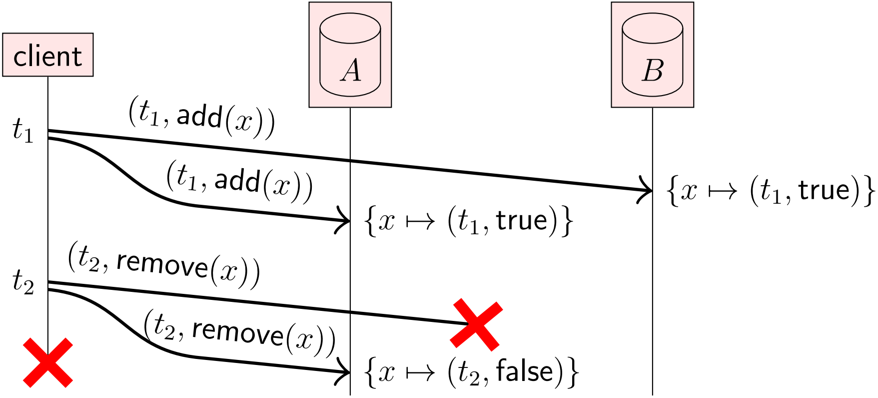

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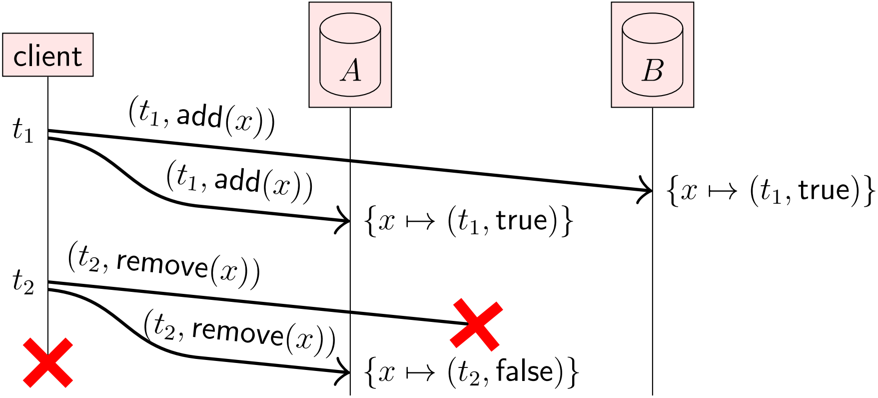

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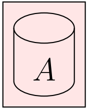
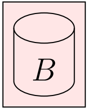
Every record has **logical timestamp** of last write

Reconciling replicas

Replicas periodically communicate among themselves
to check for any inconsistencies.





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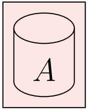

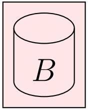

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$$\downarrow \qquad\qquad\qquad\qquad \downarrow$$

$$\{x \mapsto (t_2, \text{false})\} \qquad t_1 < t_2 \qquad \{x \mapsto (t_2, \text{false})\}$$

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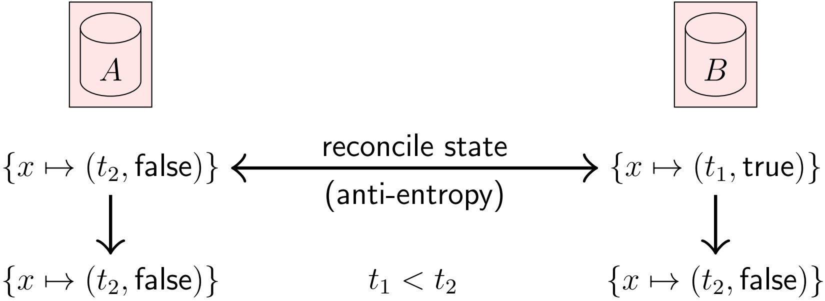
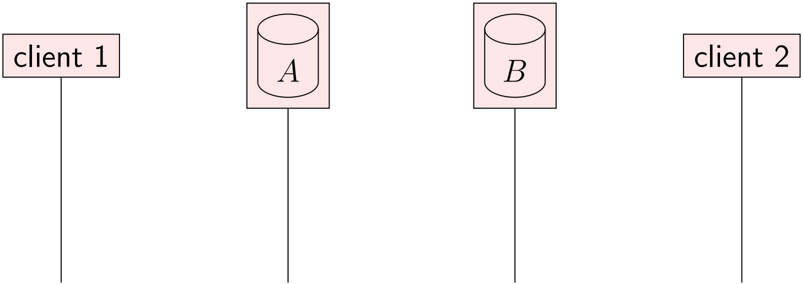


Propagate the record with the latest timestamp, discard the records with earlier timestamps (for a given key).

Concurrent writes by different clients



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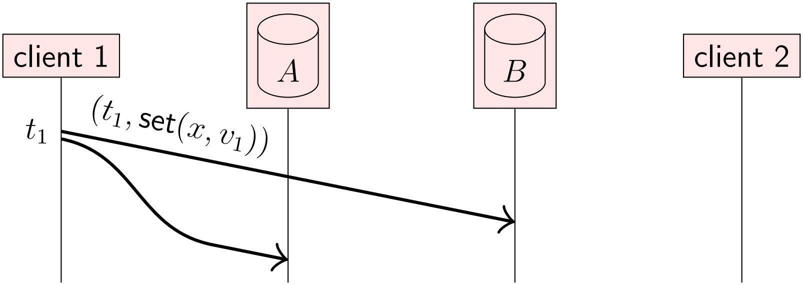

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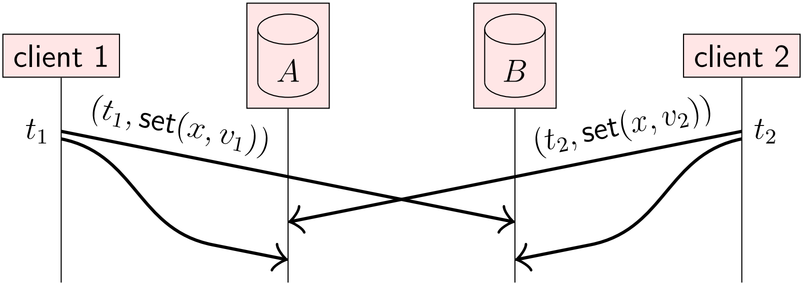

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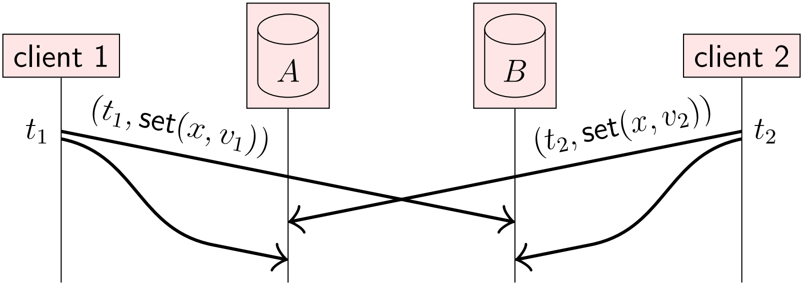

Two common approaches:

- **Last writer wins** (LWW):
  Use timestamps with total order (e.g. Lamport clock)
  Keep v_2 and discard v_1 if $t_2 > t_1$. Note: **data loss**!

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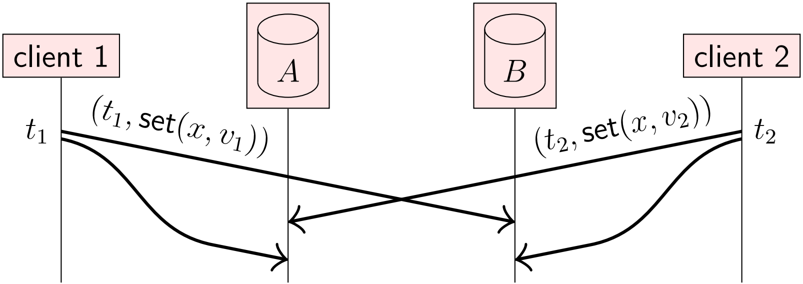

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- **Multi-value register**:
  Use timestamps with partial order (e.g. vector clock)
  v_2 replaces v_1 if $t_2 > t_1$; preserve both $\{v_1, v_2\}$ if $t_1 \parallel t_2$

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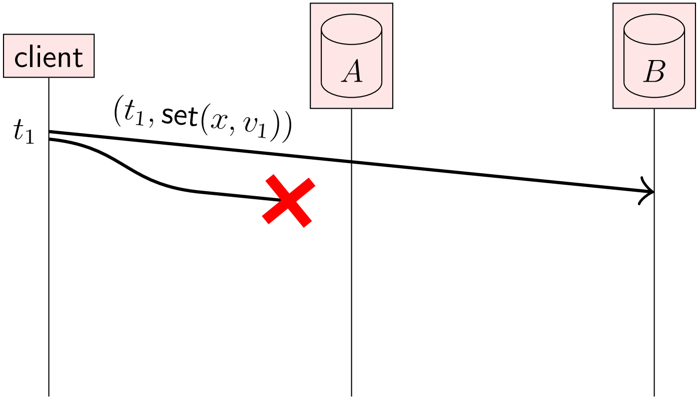
Example with $p = 0.01$:

replicas n	$P(\geq 1$ faulty)	$P(\geq \frac{n+1}{2}$ faulty)	$P($all n faulty)
1	0.01	0.01	0.01
3	0.03	$3 \cdot 10^{-4}$	10^{-6}
5	0.049	$1 \cdot 10^{-5}$	10^{-10}
100	0.63	$6 \cdot 10^{-74}$	10^{-200}

Read-after-write consistency



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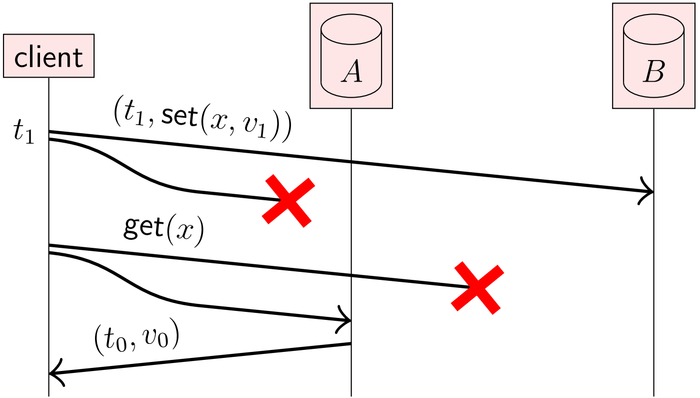

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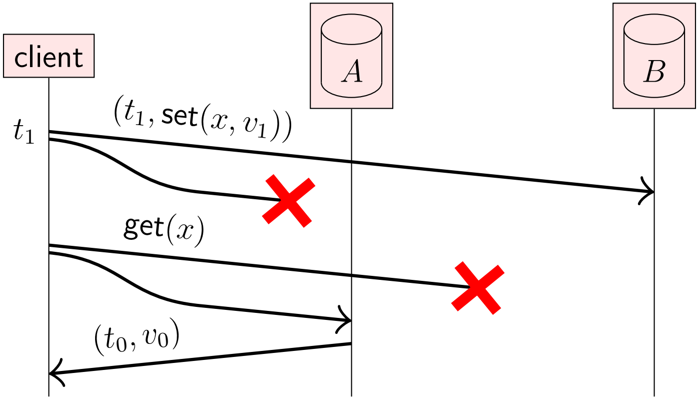

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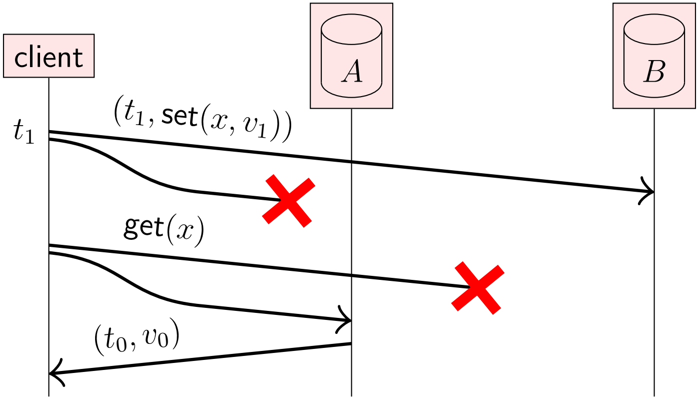
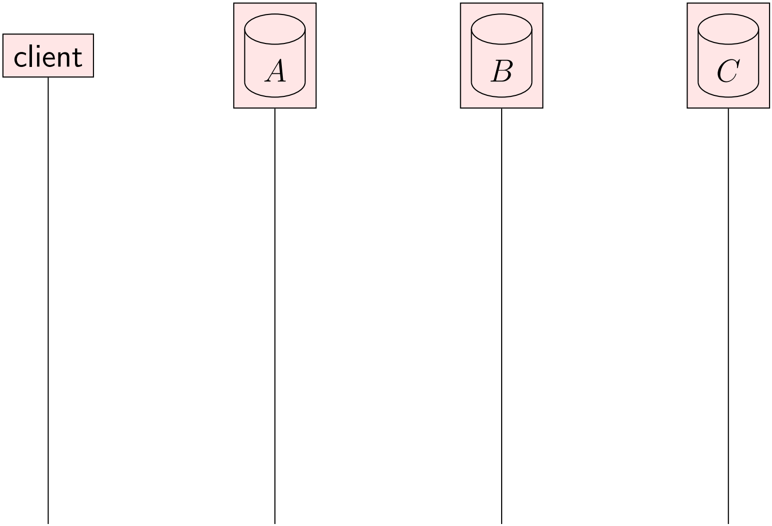


Writing to one replica, reading from another: client does not read back the value it has written

Require writing to/reading from both replicas $\implies$ cannot write/read if one replica is unavailable

Quorum (2 out of 3)



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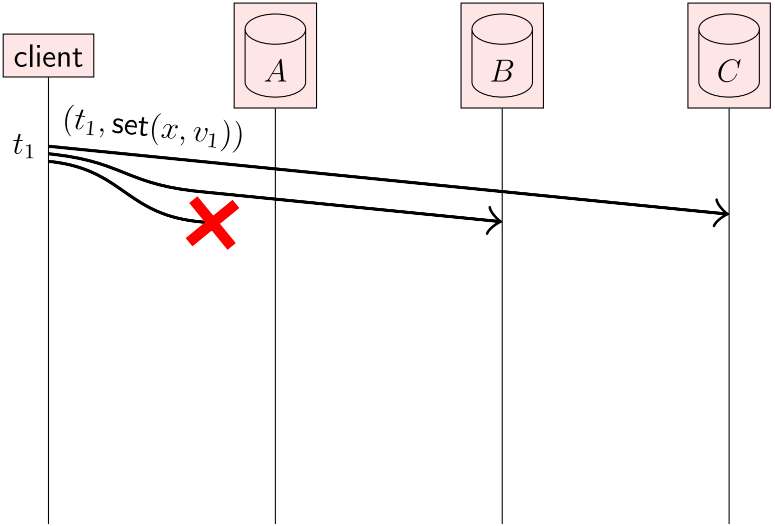

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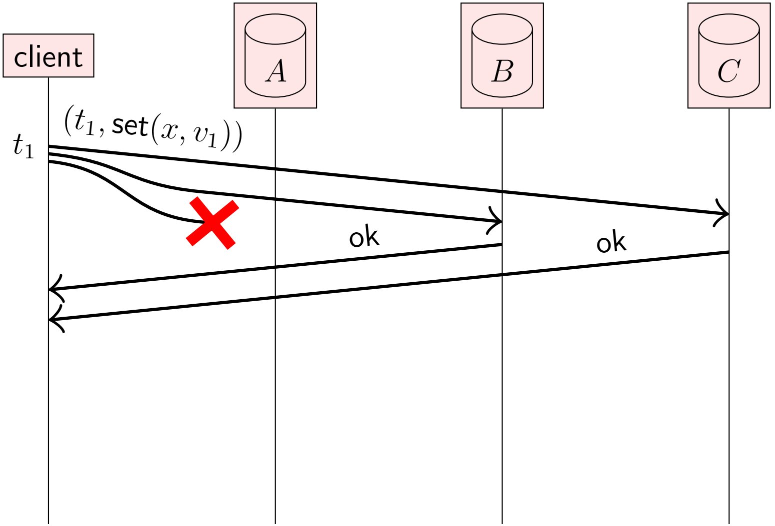

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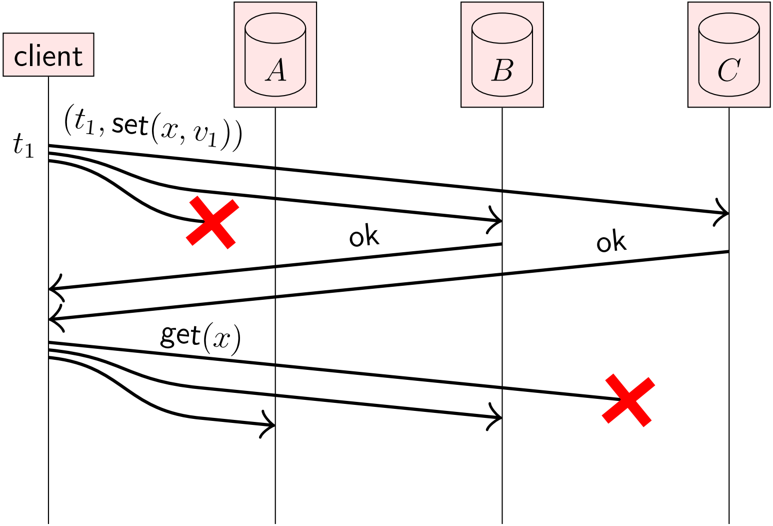

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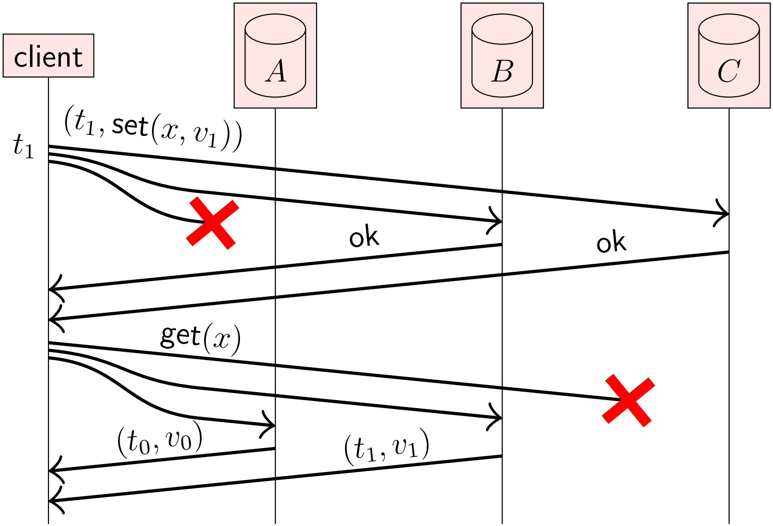

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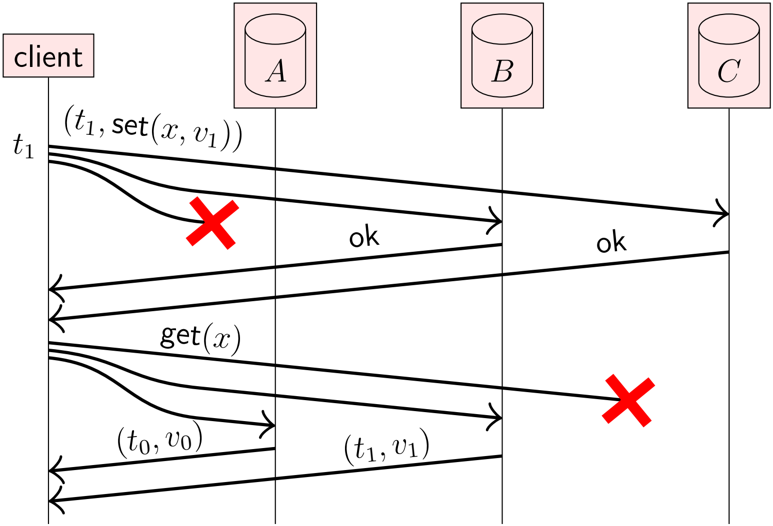

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Choose between (t_0, v_0) and (t_1, v_1) based on timestamp

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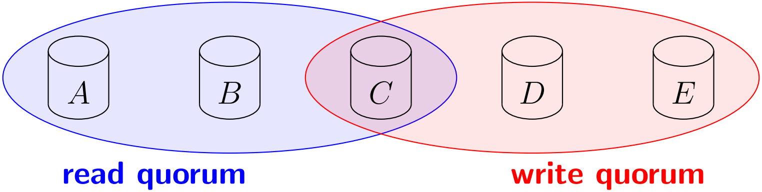

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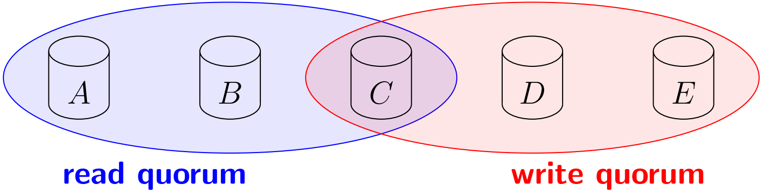
- Read quorum and write quorum share ≥ 1 replica
- Typical: $r = w = \frac{n+1}{2}$ for $n = 3, 5, 7, \ldots$ (majority)
- Reads can tolerate $n - r$ unavailable replicas, writes $n - w$



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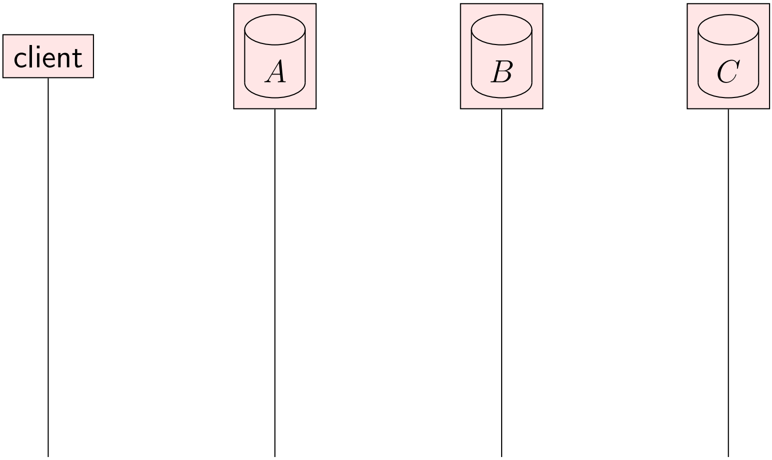

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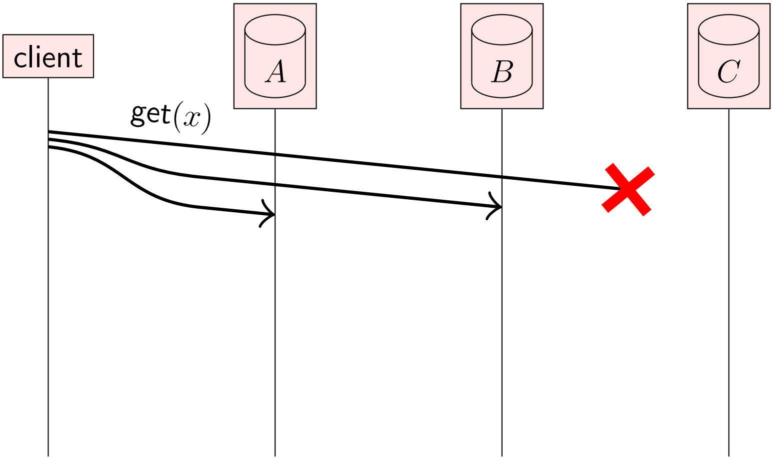

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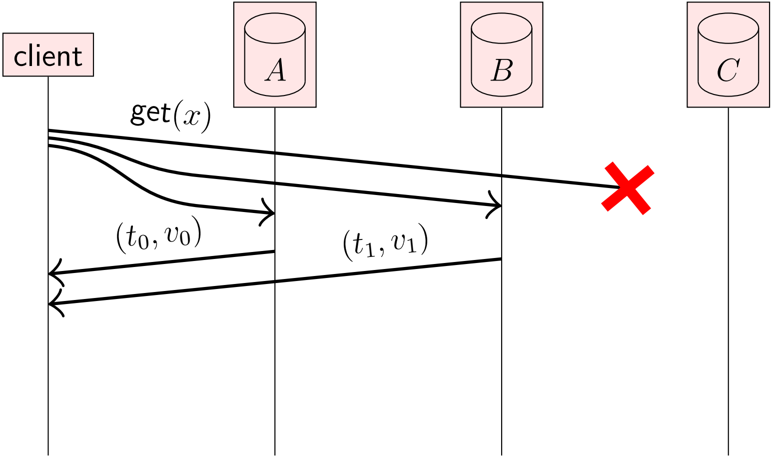

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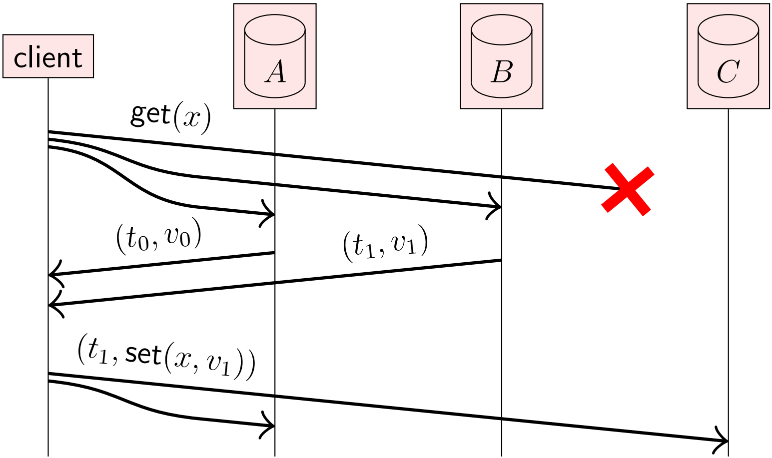

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Client helps **propagate** (t_1, v_1) to other replicas.

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- Applying an update is deterministic
- Replica is a **state machine**: starts in fixed initial state, goes through same sequence of state transitions in the same order $\implies$ all replicas end up in the same state

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on request to perform update u **do**
    send u via FIFO-total order broadcast
end on

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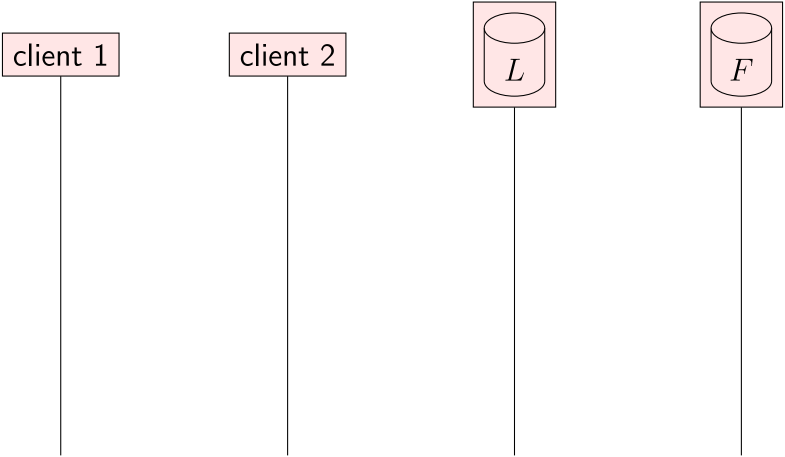
- Need fault-tolerant total order broadcast: see lecture 6

Database leader replica

Leader database replica L ensures total order broadcast



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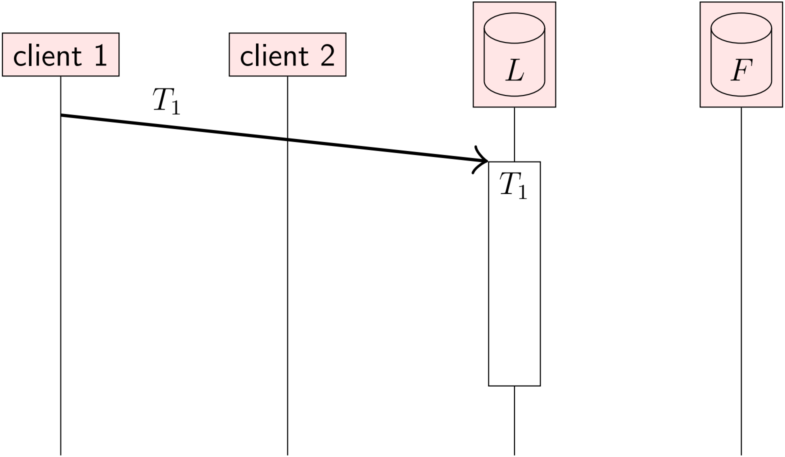

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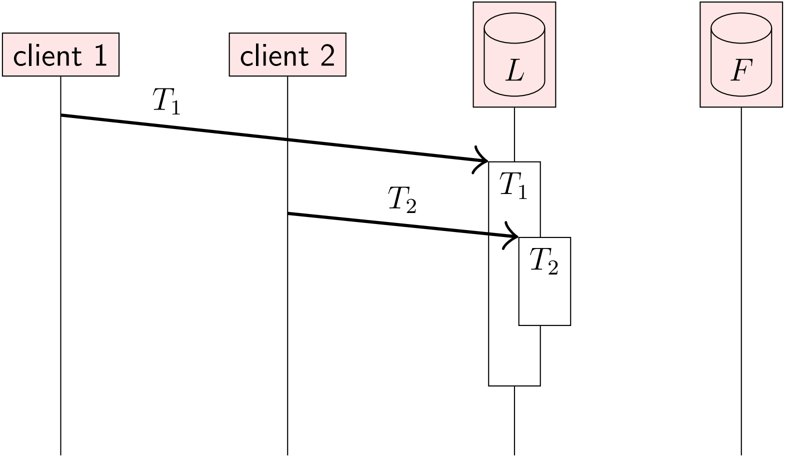

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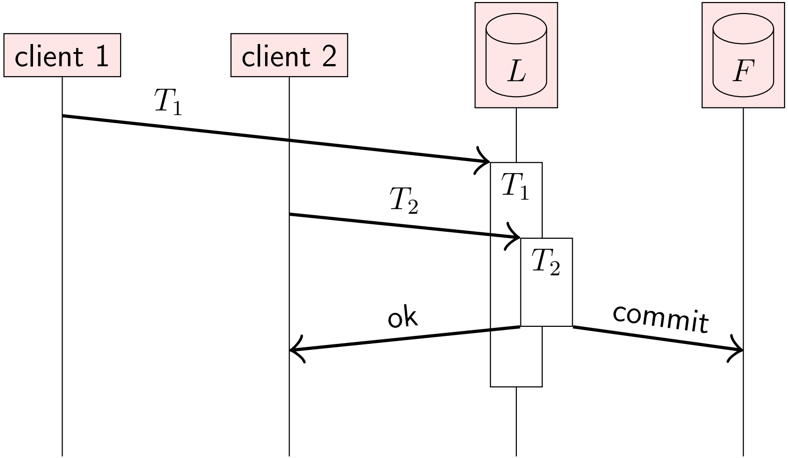

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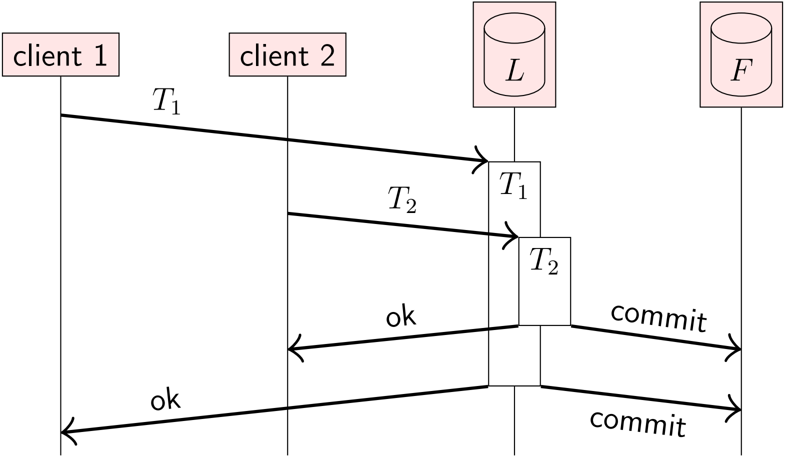

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broadcast	**assumptions about state update function**
total order	deterministic (SMR)
causal	deterministic, concurrent updates commute
reliable	deterministic, all updates commute
best-effort	deterministic, commutative, idempotent, tolerates message loss

Lecture 6

Consensus

Fault-tolerant total order broadcast

Total order broadcast is very useful for state machine replication.

Can implement total order broadcast by sending all messages via a single **leader**.

Problem: what if leader crashes/becomes unavailable?

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- Can we **automatically choose a new leader**?

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Common consensus algorithms:

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Common consensus algorithms:

- **Paxos**: single-value consensus
  Multi-Paxos: generalisation to total order broadcast
- **Raft**, **Viewstamped Replication**, **Zab**:
  FIFO-total order broadcast by default

Consensus system models

Paxos, Raft, etc. assume a **partially synchronous, crash-recovery** system model.

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There are also consensus algorithms for a partially synchronous **Byzantine** system model (used in blockchains)

Leader election

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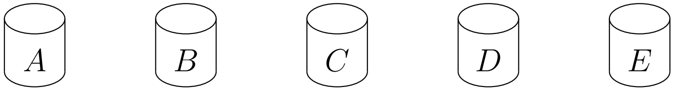

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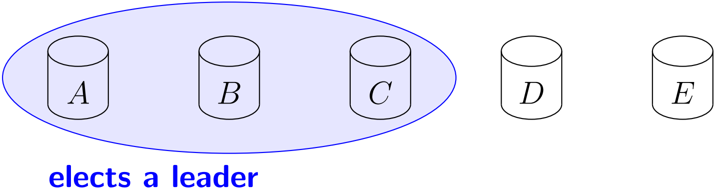

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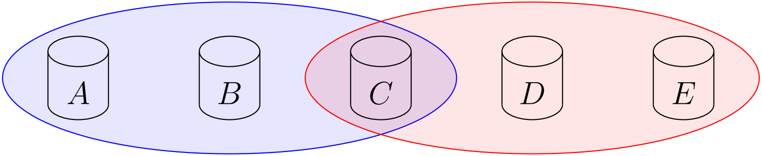

elects a leader

cannot elect a different leader
because C already voted

Can we guarantee there is only one leader?

Can guarantee unique leader **per term**.

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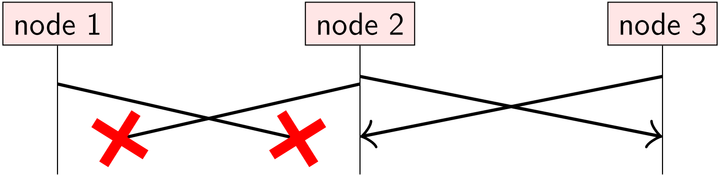

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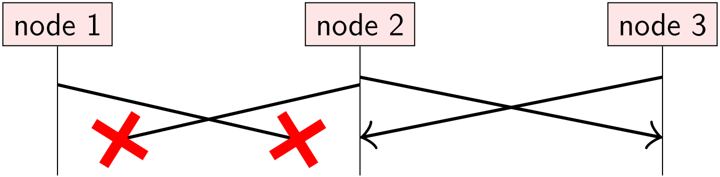
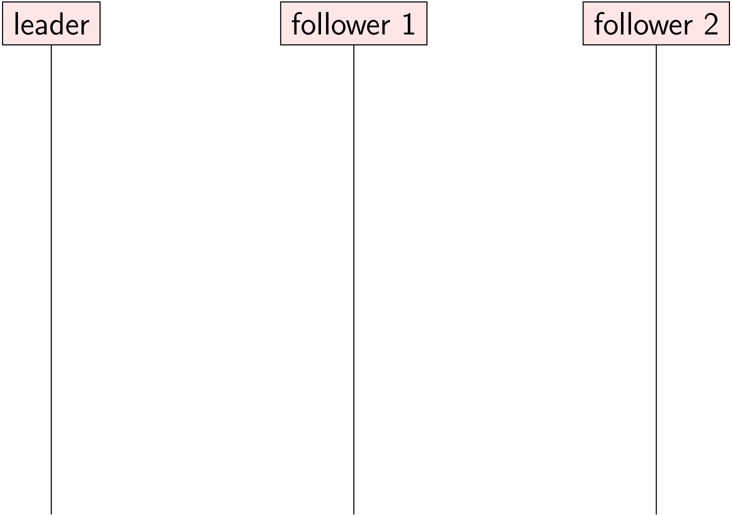


Nodes 2 and 3 may elect a new leader in term $t + 1$.

Node 1 may not even know that a new leader has been elected!

Checking if a leader has been voted out

For every decision (message to deliver), the leader must first get acknowledgements from a quorum.



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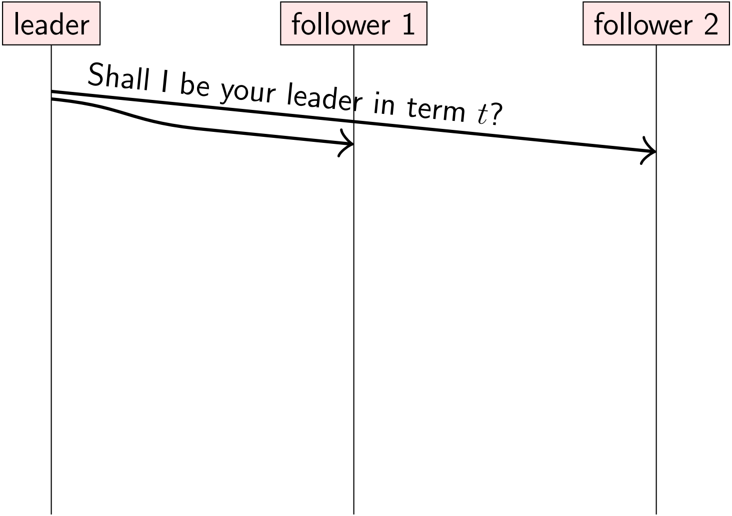

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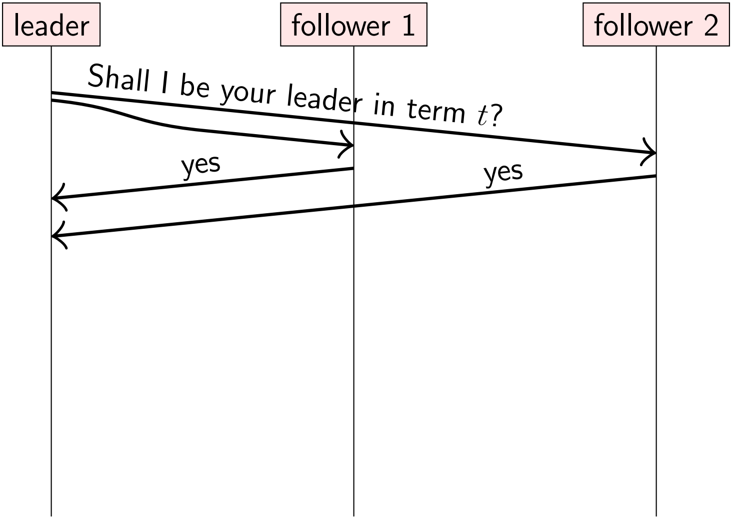

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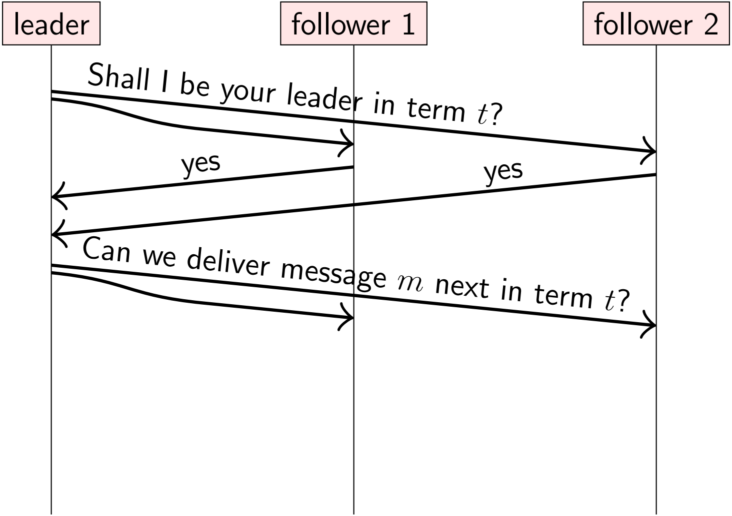

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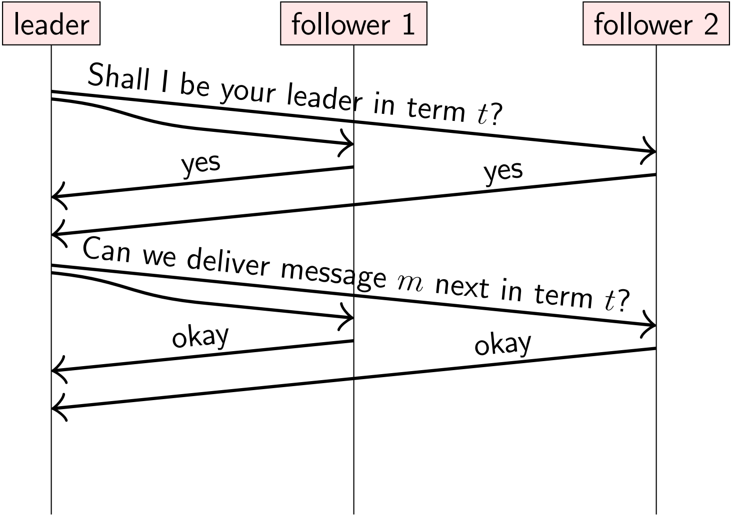

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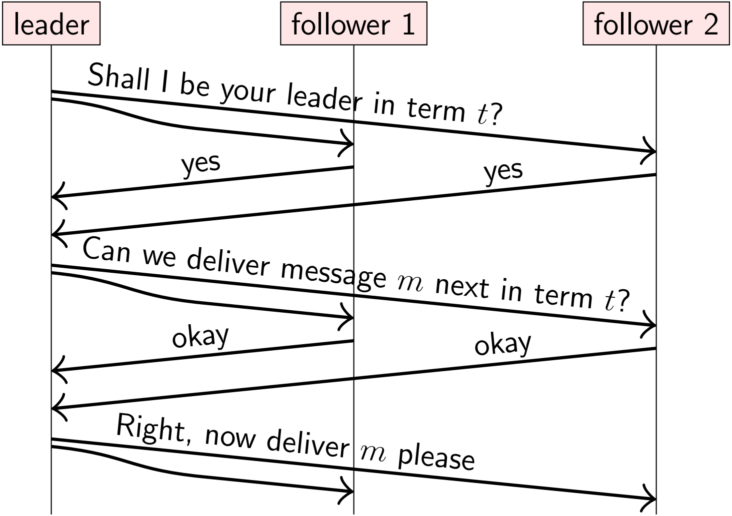
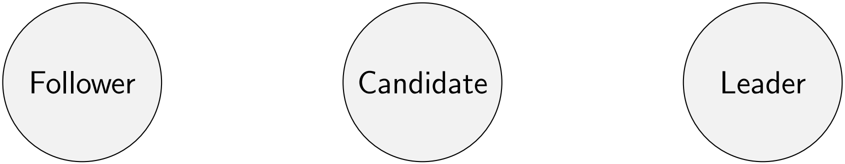


Node state transitions in Raft



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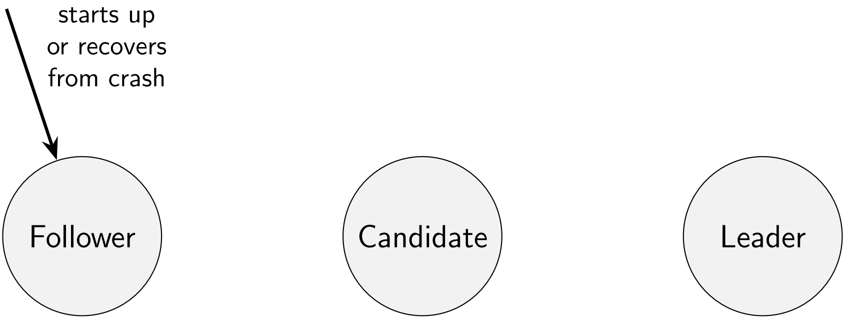

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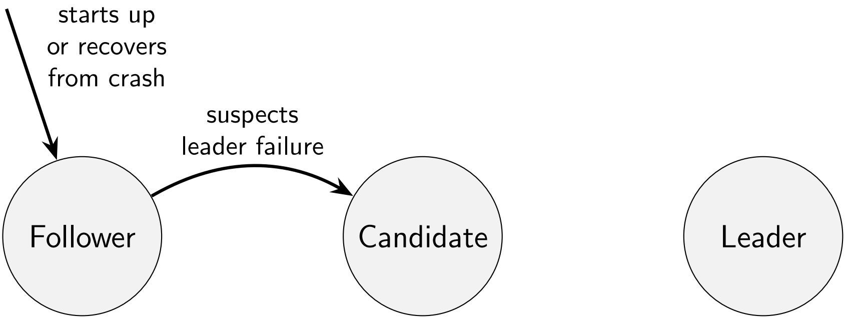

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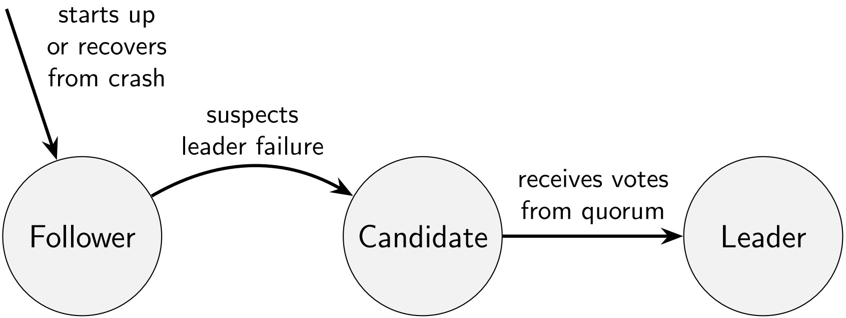

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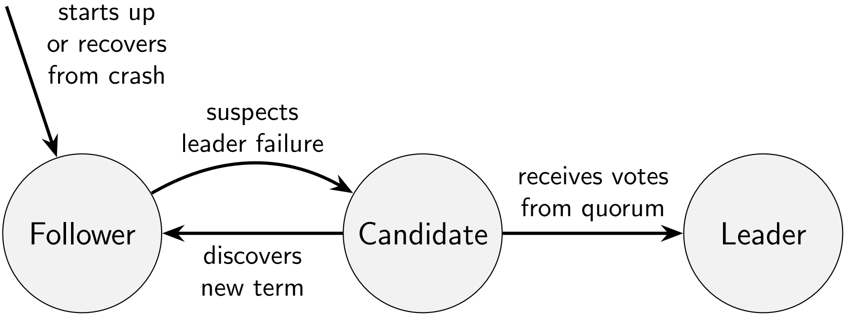

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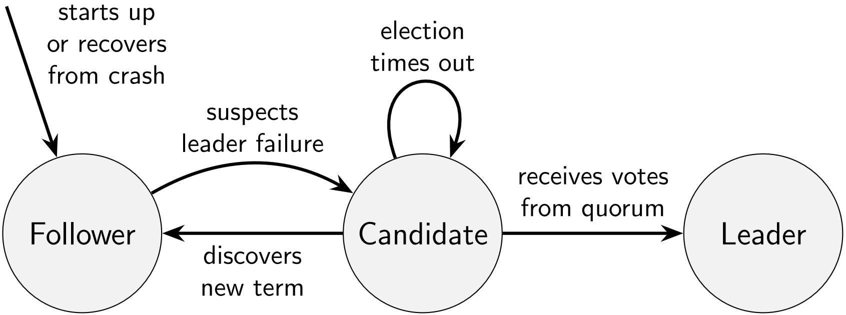

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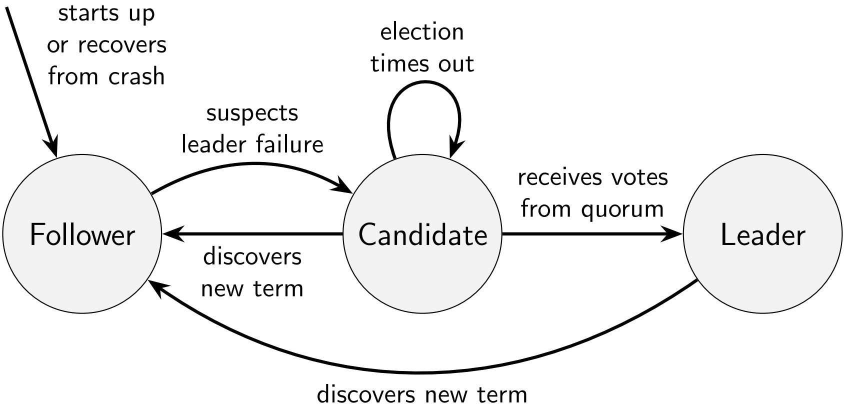

Raft (1/9): initialisation

on initialisation **do**
  $currentTerm := 0;\ votedFor :=$ null
  $log := \langle\rangle;\ commitLength := 0$
  $currentRole :=$ follower; $currentLeader :=$ null
  $votesReceived := \{\};\ sentLength := \langle\rangle;\ ackedLength := \langle\rangle$
end on

on recovery from crash **do**
  $currentRole :=$ follower; $currentLeader :=$ null
  $votesReceived := \{\};\ sentLength := \langle\rangle;\ ackedLength := \langle\rangle$
end on

on node $nodeId$ suspects leader has failed, or on election timeout **do**
  $currentTerm := currentTerm + 1;\ currentRole :=$ candidate
  $votedFor := nodeId;\ votesReceived := \{nodeId\};\ lastTerm := 0$
  if log.length > 0 **then** $lastTerm := log[log.\text{length} - 1]$.term; **end if**
  $msg :=$ (VoteRequest, $nodeId, currentTerm, log$.length, $lastTerm$)
  for each $node \in nodes$: **send** msg to $node$
  start election timer
end on

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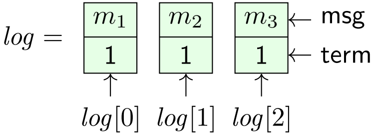

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  for each $node \in nodes$: **send** msg to $node$
  start election timer
end on

Raft (2/9): voting on a new leader

on receiving $(\text{VoteRequest}, cId, cTerm, cLogLength, cLogTerm)$
at node $nodeId$ **do**

$myLogTerm := log[log.\text{length} - 1].\text{term}$

$logOk := (cLogTerm > myLogTerm) \lor$
$(cLogTerm = myLogTerm \land cLogLength \geq log.\text{length})$

$termOk := (cTerm > currentTerm) \lor$
$(cTerm = currentTerm \land votedFor \in \{cId, \text{null}\})$

if $logOk \land termOk$ **then**

$currentTerm := cTerm$

$currentRole := \text{follower}$

$votedFor := cId$

send $(\text{VoteResponse}, nodeId, currentTerm, \text{true})$ to node cId

else

send $(\text{VoteResponse}, nodeId, currentTerm, \text{false})$ to node cId

end if

end on

Raft (2/9): voting on a new leader

c for candidate

on receiving (VoteRequest, cId, $cTerm$, $cLogLength$, $cLogTerm$)
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$termOk := (cTerm > currentTerm) \vee$
$(cTerm = currentTerm \wedge votedFor \in \{cId, \text{null}\})$

if $logOk \wedge termOk$ **then**

$currentTerm := cTerm$

$currentRole :=$ follower

$votedFor := cId$

send (VoteResponse, $nodeId$, $currentTerm$, true) to node cId

else

send (VoteResponse, $nodeId$, $currentTerm$, false) to node cId

end if

end on

Raft (3/9): collecting votes

on receiving $(\text{VoteResponse}, voterId, term, granted)$ at $nodeId$ **do**
  if $currentRole = \text{candidate} \wedge term = currentTerm \wedge granted$ **then**
    $votesReceived := votesReceived \cup \{voterId\}$
    if $|votesReceived| \geq \lceil (|nodes| + 1)/2 \rceil$ **then**
      $currentRole := \text{leader};\ currentLeader := nodeId$
      cancel election timer
      for each $follower \in nodes \setminus \{nodeId\}$ **do**
        $sentLength[follower] := log.\text{length}$
        $ackedLength[follower] := 0$
        $\textsc{ReplicateLog}(nodeId, follower)$
      end for
    end if
  else if $term > currentTerm$ **then**
    $currentTerm := term$
    $currentRole := \text{follower}$
    $votedFor := \text{null}$
    cancel election timer
  end if
end on

Raft (4/9): broadcasting messages

on request to broadcast msg at node $nodeId$ **do**
  if $currentRole =$ leader **then**
    append the record $(\text{msg} : msg,\ \text{term} : currentTerm)$ to log
    $ackedLength[nodeId] := log.\text{length}$
    for each $follower \in nodes \setminus \{nodeId\}$ **do**
      $\textsc{ReplicateLog}(nodeId, follower)$
    end for
  else
    forward the request to $currentLeader$ via a FIFO link
  end if
end on

periodically at node $nodeId$ **do**
  if $currentRole =$ leader **then**
    for each $follower \in nodes \setminus \{nodeId\}$ **do**
      $\textsc{ReplicateLog}(nodeId, follower)$
    end for
  end if
end do

Raft (5/9): replicating from leader to followers

Called on the leader whenever there is a new message in the log, and also periodically. If there are no new messages, $\mathit{entries}$ is the empty list. LogRequest messages with $\mathit{entries} = \langle\rangle$ serve as heartbeats, letting followers know that the leader is still alive.

function $\textsc{ReplicateLog}(\mathit{leaderId}, \mathit{followerId})$
  $i := \mathit{sentLength}[\mathit{followerId}]$
  $\mathit{entries} := \langle \mathit{log}[i],\ \mathit{log}[i+1],\ \ldots,\ \mathit{log}[\mathit{log}.\text{length} - 1]\rangle$
  $\mathit{prevLogTerm} := 0$
  if $i > 0$ **then**
    $\mathit{prevLogTerm} := \mathit{log}[i-1].\text{term}$
  end if
  send $(\text{LogRequest}, \mathit{leaderId}, \mathit{currentTerm}, i, \mathit{prevLogTerm},$
    $\mathit{commitLength}, \mathit{entries})$ to $\mathit{followerId}$
end function

Raft (6/9): followers receiving messages

on receiving (LogRequest, $leaderId$, $term$, $logLength$, $logTerm$,
$leaderCommit$, $entries$) at node $nodeId$ **do**
if $term > currentTerm$ **then**
$currentTerm := term$; $votedFor :=$ null
end if
$logOk := (log.\text{length} \geq logLength)$
if $logOk \wedge (logLength > 0)$ **then**
$logOk := (logTerm = log[logLength - 1].\text{term})$
end if

if $term = currentTerm \wedge logOk$ **then**
$currentRole :=$ follower; $currentLeader := leaderId$
$\textsc{AppendEntries}(logLength, leaderCommit, entries)$
$ack := logLength + entries.\text{length}$
send (LogResponse, $nodeId$, $currentTerm$, ack, true) to $leaderId$
else
send (LogResponse, $nodeId$, $currentTerm$, 0, false) to $leaderId$
end if
end on

Raft (7/9): updating followers' logs

function $\textsc{AppendEntries}(logLength, leaderCommit, entries)$
    if $entries$.length $> 0 \ \wedge \ log$.length $> logLength$ **then**
        if $log[logLength]$.term $\neq entries[0]$.term **then**
            $log := \langle log[0], \, log[1], \, \ldots, \, log[logLength - 1] \rangle$
        end if
    end if
    if $logLength + entries$.length $> log$.length **then**
        for $i := log$.length $- \, logLength$ **to** $entries$.length $- 1$ **do**
            append $entries[i]$ to log
        end for
    end if
    if $leaderCommit > commitLength$ **then**
        for $i := commitLength$ **to** $leaderCommit - 1$ **do**
            deliver $log[i]$.msg to the application
        end for
        $commitLength := leaderCommit$
    end if
end function

Raft (8/9): leader receiving log acknowledgements

on receiving (LogResponse, $follower, term, ack, success$) at $nodeId$ **do**
  if $term = currentTerm \ \wedge \ currentRole =$ leader **then**
    if $success =$ true $\wedge \ ack \geq ackedLength[follower]$ **then**
      $sentLength[follower] := ack$
      $ackedLength[follower] := ack$
      $\textsc{CommitLogEntries}()$
    else if $sentLength[follower] > 0$ **then**
      $sentLength[follower] := sentLength[follower] - 1$
      $\textsc{ReplicateLog}(nodeId, follower)$
    end if
  else if $term > currentTerm$ **then**
    $currentTerm := term$
    $currentRole :=$ follower
    $votedFor :=$ null
  end if
end on

Raft (9/9): leader committing log entries

Any log entries that have been acknowledged by a quorum of nodes are ready to be committed by the leader. When a log entry is committed, its message is delivered to the application.

define $\mathrm{acks}(\mathit{length}) = |\{n \in \mathit{nodes} \mid \mathit{ackedLength}[n] \geq \mathit{length}\}|$

function CommitLogEntries
  $\mathit{minAcks} := \lceil (|\mathit{nodes}| + 1)/2 \rceil$
  $\mathit{ready} := \{\mathit{len} \in \{1, \ldots, \mathit{log}.\text{length}\} \mid \mathrm{acks}(\mathit{len}) \geq \mathit{minAcks}\}$
  if $\mathit{ready} \neq \{\} \;\wedge\; \max(\mathit{ready}) > \mathit{commitLength} \;\wedge$
    $\mathit{log}[\max(\mathit{ready}) - 1].\text{term} = \mathit{currentTerm}$ **then**
    for $i := \mathit{commitLength}$ **to** $\max(\mathit{ready}) - 1$ **do**
      deliver $\mathit{log}[i]$.msg to the application
    end for
    $\mathit{commitLength} := \max(\mathit{ready})$
  end if
end function

Lecture 7

Replica consistency

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  e.g. "every course with students enrolled must have at least one lecturer"

- **Read-after-write consistency** (lecture 5)

- **Replication**: replica should be "consistent" with other replicas

  "consistent" = in the same state? (when exactly?)

  "consistent" = read operations return same result?

- **Consistency model**: many to choose from

Distributed transactions

Recall **atomicity** in the context of ACID transactions:

- A transaction either **commits** or **aborts**

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- A transaction either **commits** or **aborts**
- If it commits, its updates are durable
- If it aborts, it has no visible side-effects
- ACID consistency (preserving invariants) relies on atomicity

Distributed transactions

Recall **atomicity** in the context of ACID transactions:

- A transaction either **commits** or **aborts**
- If it commits, its updates are durable
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If the transaction updates data on multiple nodes, this implies:

- Either all nodes must commit, or all must abort
- If any node crashes, all must abort

Ensuring this is the **atomic commitment** problem.
Looks a bit similar to consensus?

Atomic commit versus consensus

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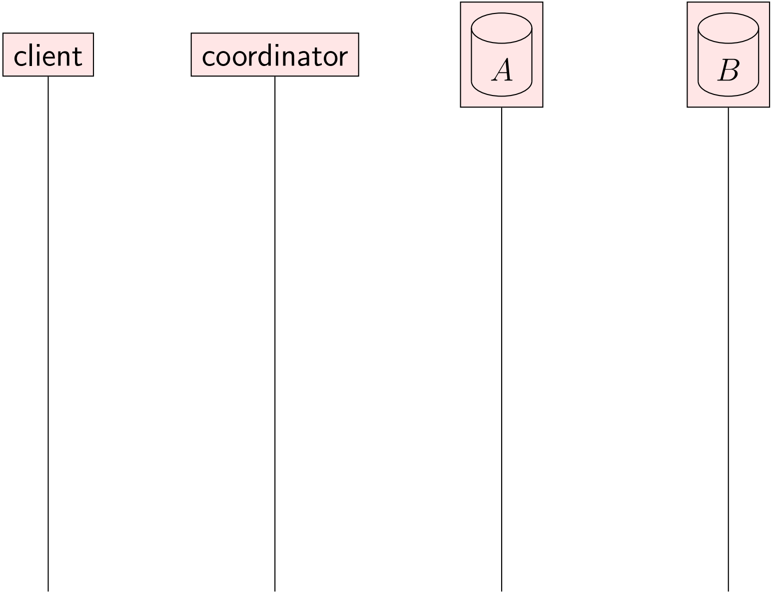
Crashed nodes can be tolerated, as long as a quorum is working	Must abort if a participating node crashes

Two-phase commit (2PC)



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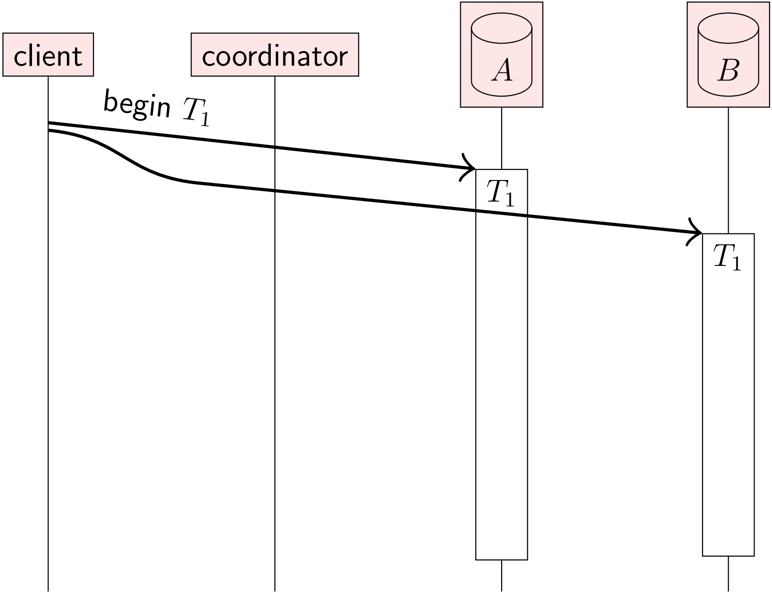

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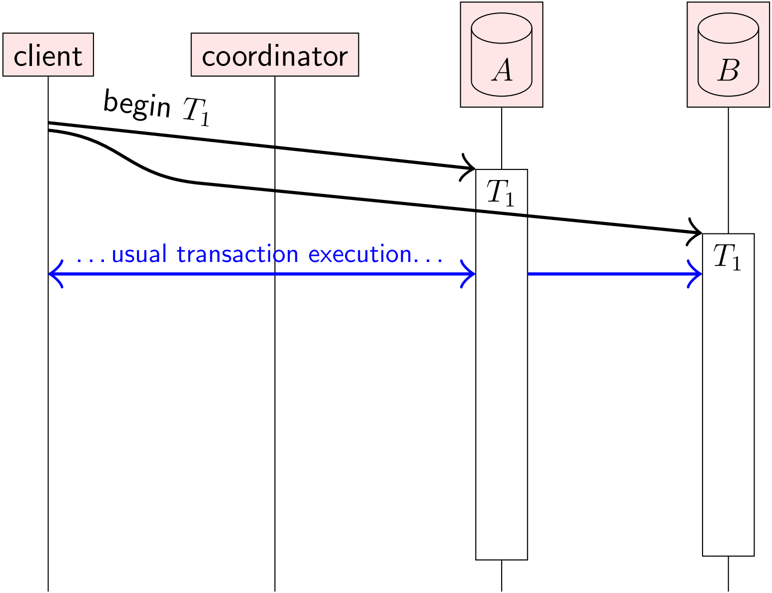

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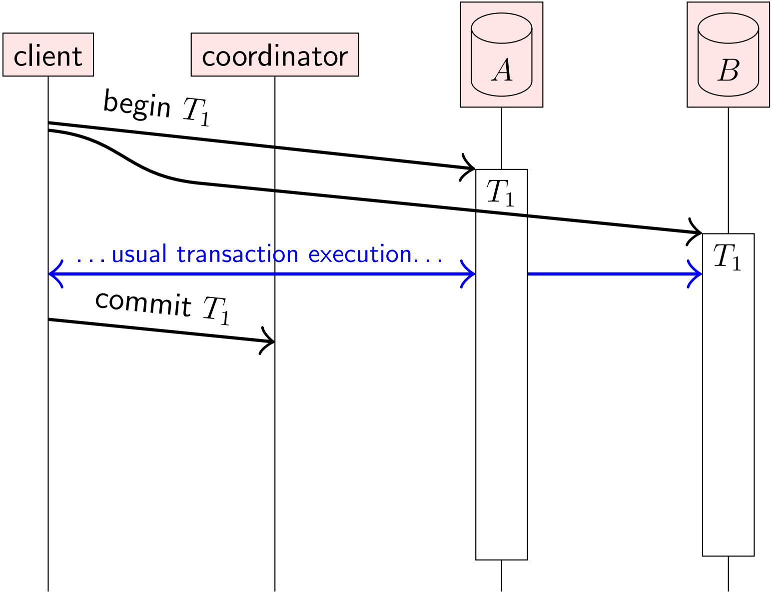

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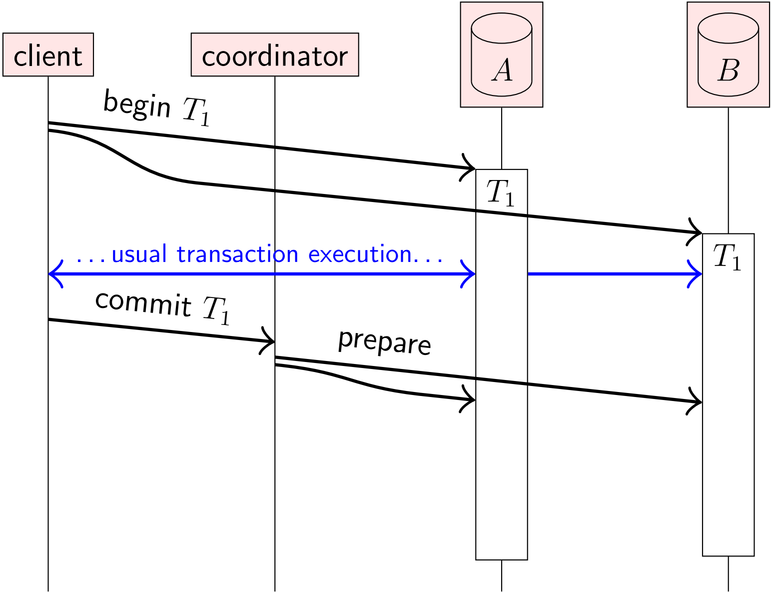

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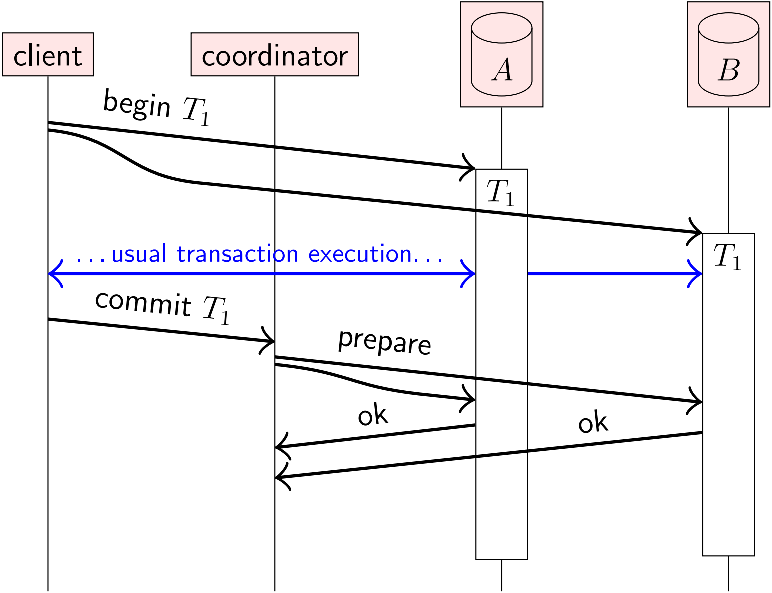

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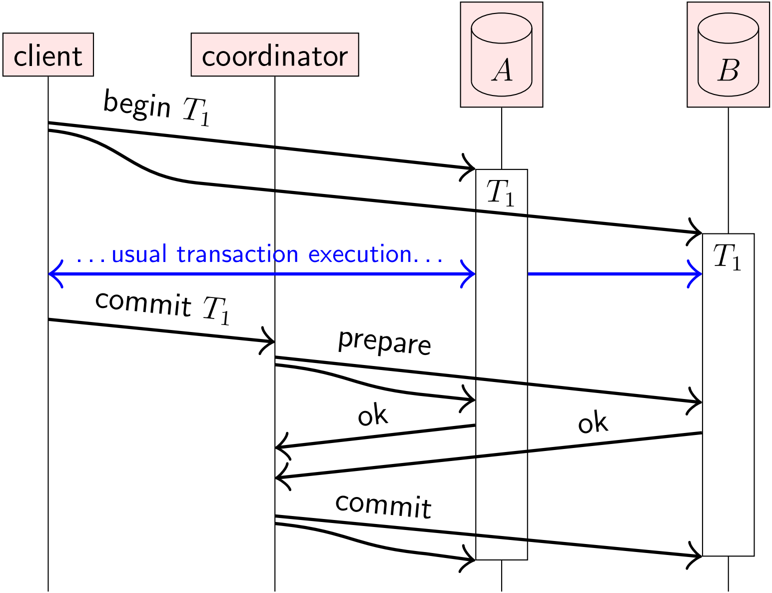

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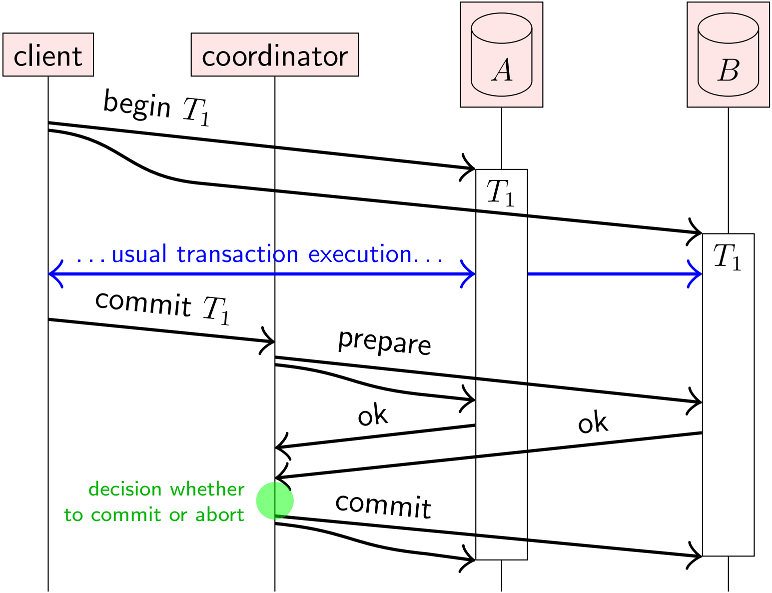

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- Replicas participating in transaction cannot commit or abort after responding "ok" to the *prepare* request (otherwise we risk violating atomicity)
- Algorithm is blocked until coordinator recovers

Fault-tolerant two-phase commit (1/2)

on initialisation for transaction T **do**
$commitVotes[T] := \{\}$; $replicas[T] := \{\}$; $decided[T] :=$ false
end on

on request to commit transaction T with participating nodes R **do**
for each $r \in R$ **do** send $(\text{Prepare}, T, R)$ to r
end on

on receiving $(\text{Prepare}, T, R)$ at node $replicaId$ **do**
$replicas[T] := R$
$ok =$ "is transaction T able to commit on this replica?"
total order broadcast $(\text{Vote}, T, replicaId, ok)$ to $replicas[T]$
end on

on a node suspects node $replicaId$ to have crashed **do**
for each transaction T in which $replicaId$ participated **do**
total order broadcast $(\text{Vote}, T, replicaId, \text{false})$ to $replicas[T]$
end for
end on

Fault-tolerant two-phase commit (2/2)

on delivering $(\text{Vote}, T, \mathit{replicaId}, \mathit{ok})$ by total order broadcast **do**
    if $\mathit{replicaId} \notin \mathit{commitVotes}[T] \;\wedge\; \mathit{replicaId} \in \mathit{replicas}[T] \;\wedge$
            $\neg \mathit{decided}[T]$ **then**
        if $\mathit{ok} = \text{true}$ **then**
            $\mathit{commitVotes}[T] := \mathit{commitVotes}[T] \cup \{\mathit{replicaId}\}$
            if $\mathit{commitVotes}[T] = \mathit{replicas}[T]$ **then**
                $\mathit{decided}[T] := \text{true}$
                commit transaction T at this node
            end if
        else
            $\mathit{decided}[T] := \text{true}$
            abort transaction T at this node
        end if
    end if
end on

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Note: linearizability $\neq$ serializability!

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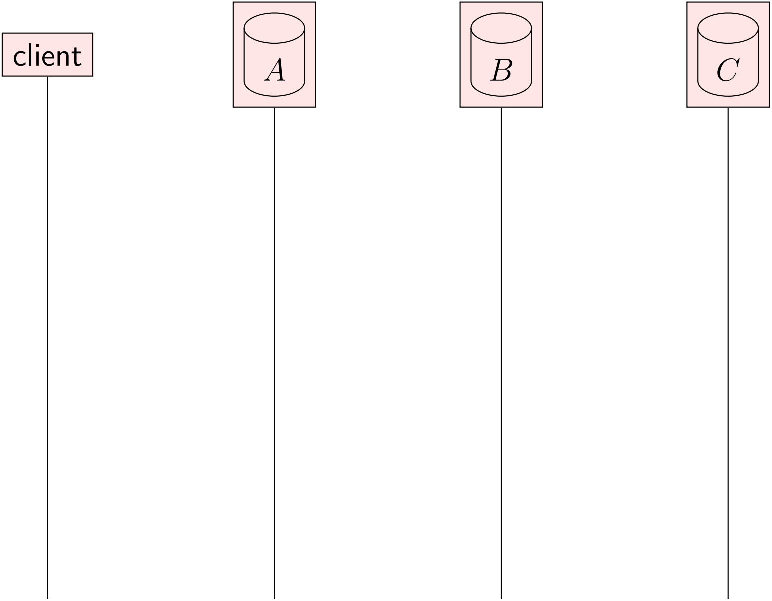

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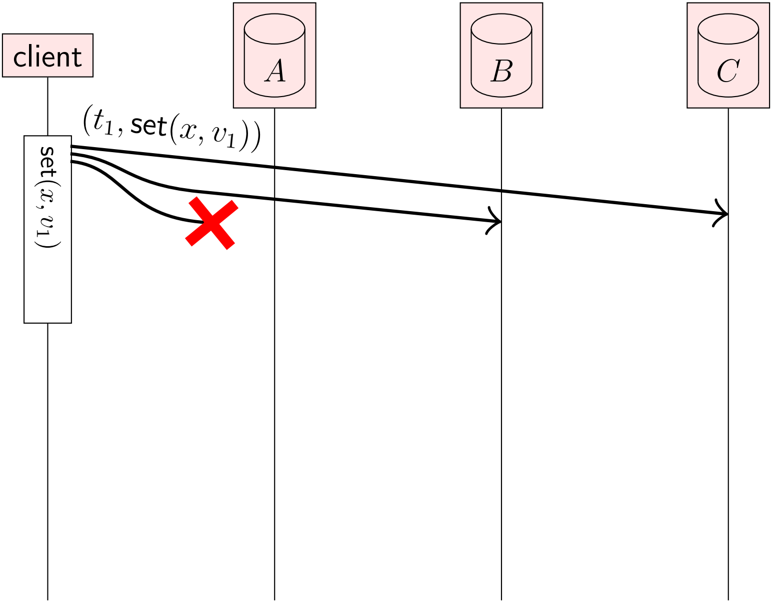

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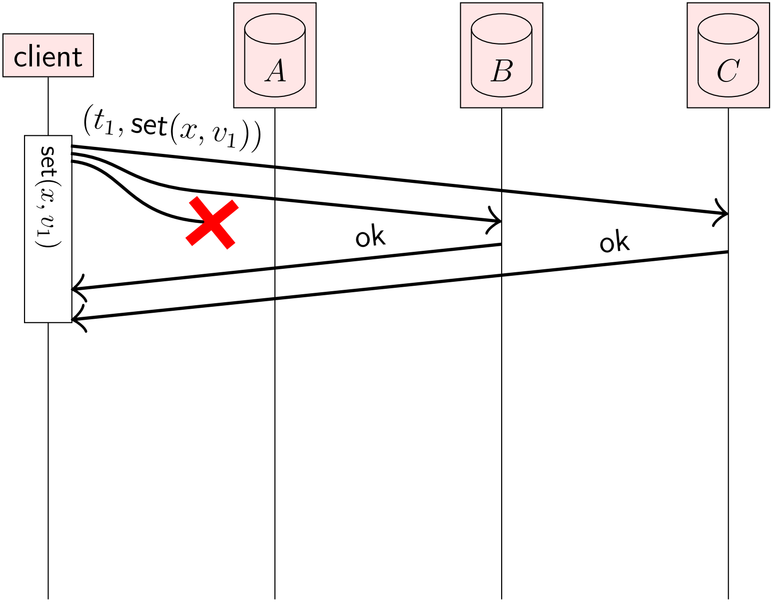

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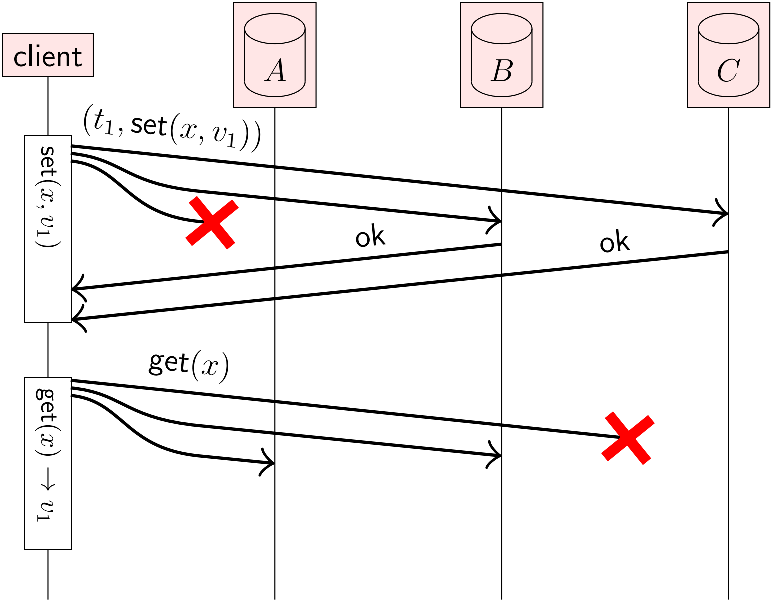

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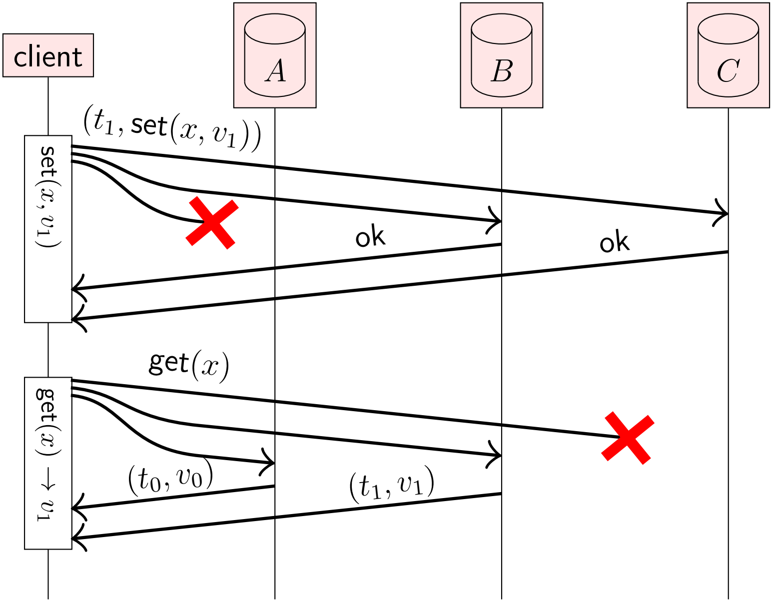

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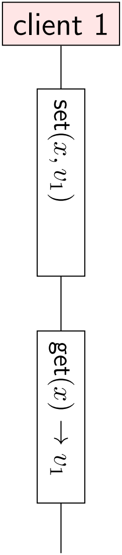

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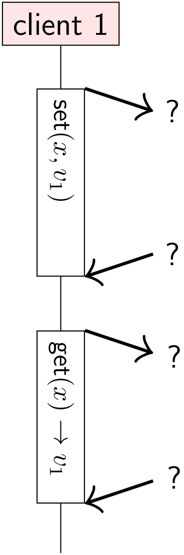

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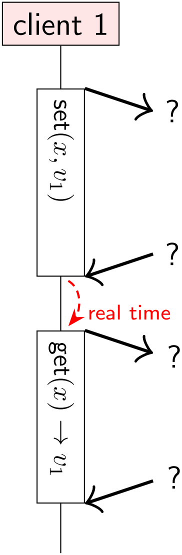

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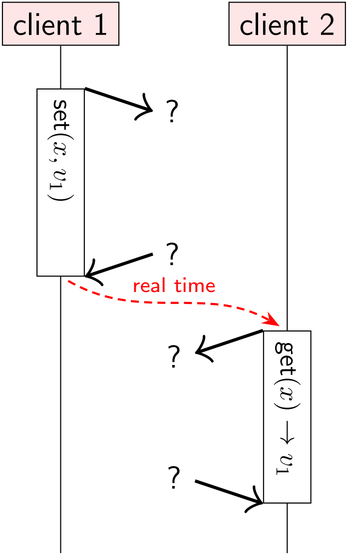

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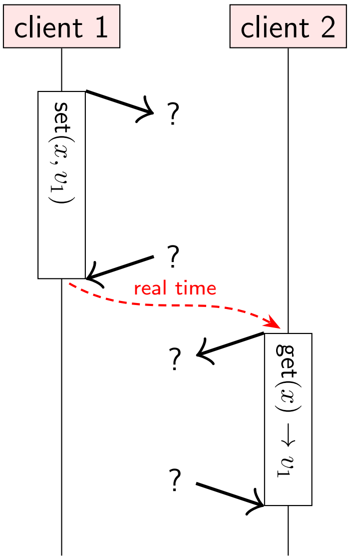

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- Did operation A finish before operation B started?
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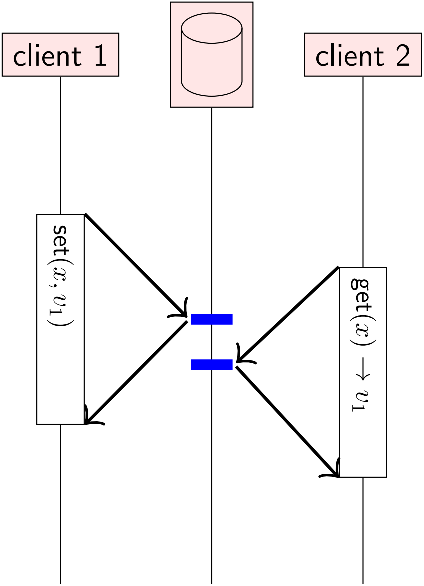
- **This is not happens-before**: we want client 2 to read value written by client 1, even if the clients have not communicated!

Operations overlapping in time



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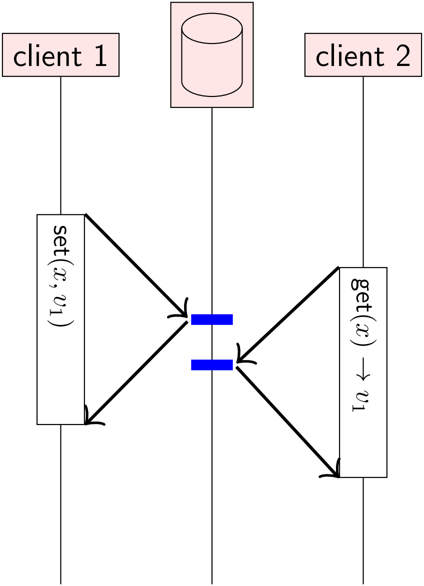

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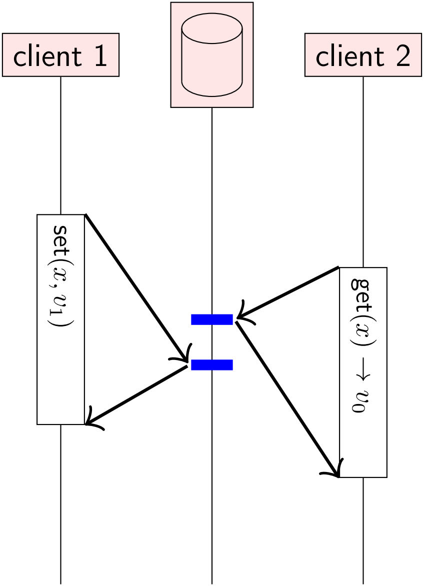

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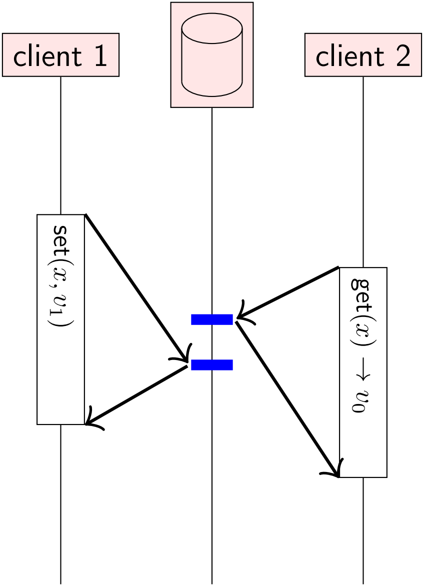

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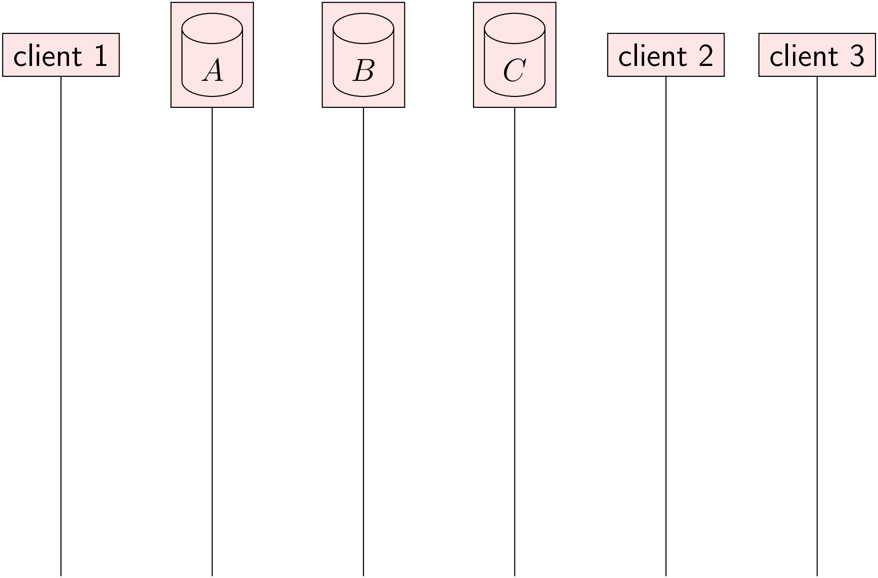
Not linearizable, despite quorum reads/writes



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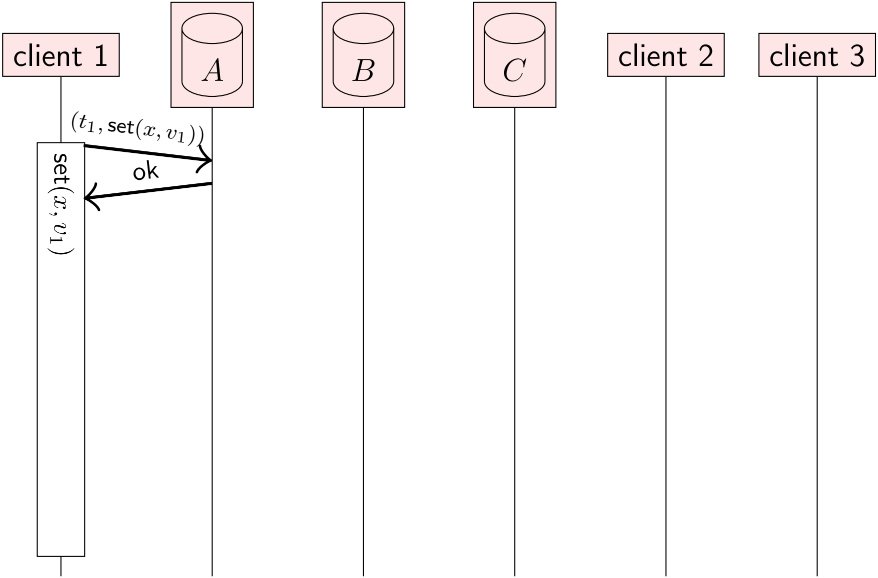

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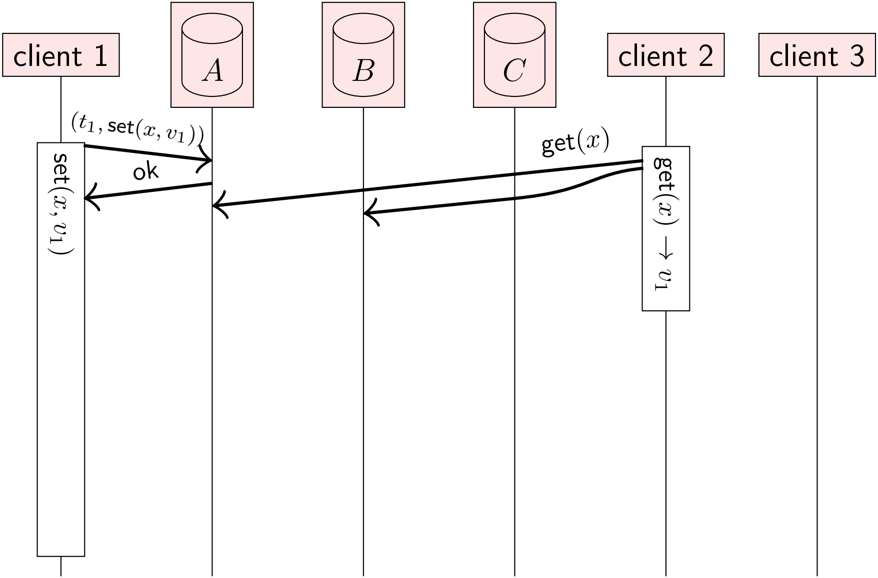

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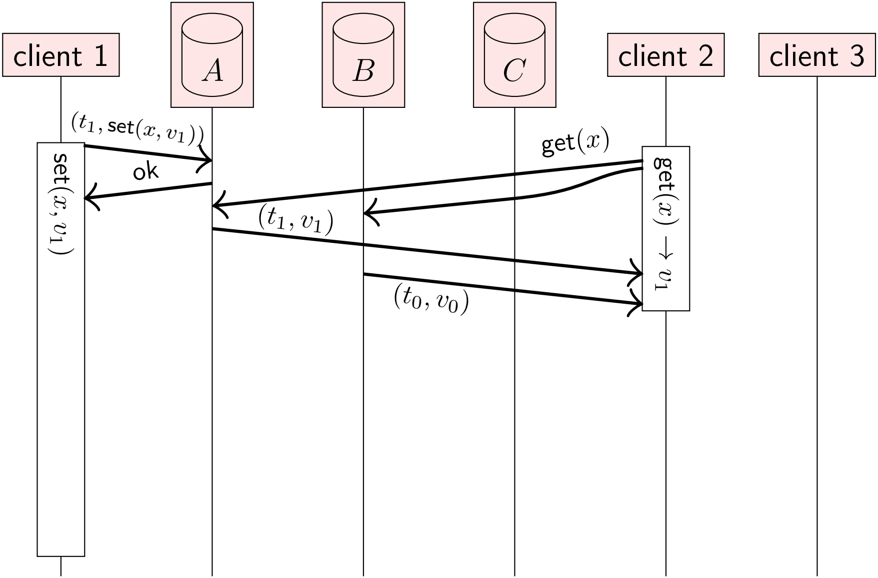

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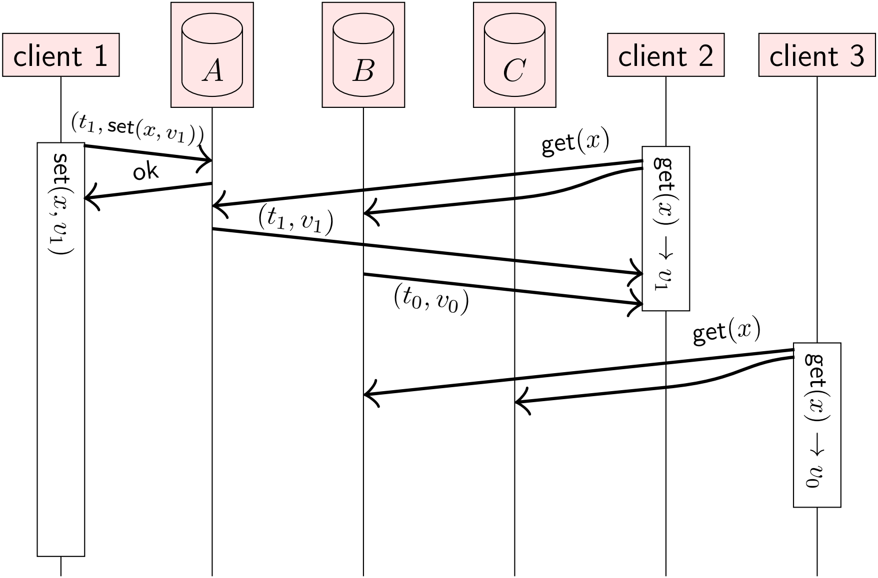

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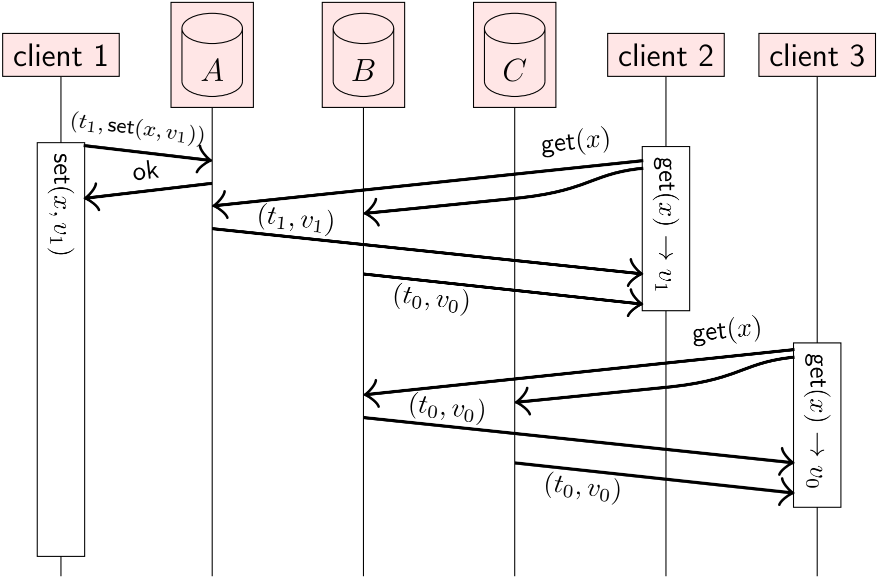

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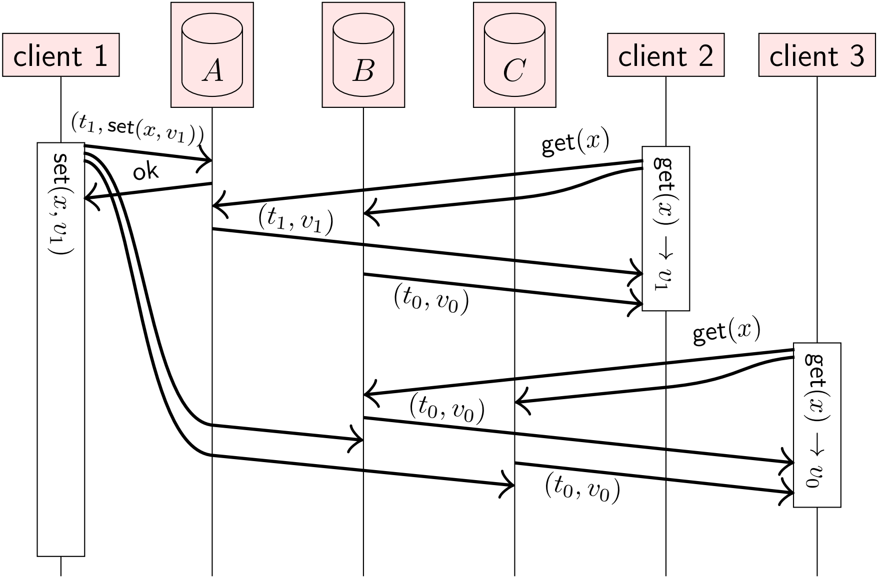

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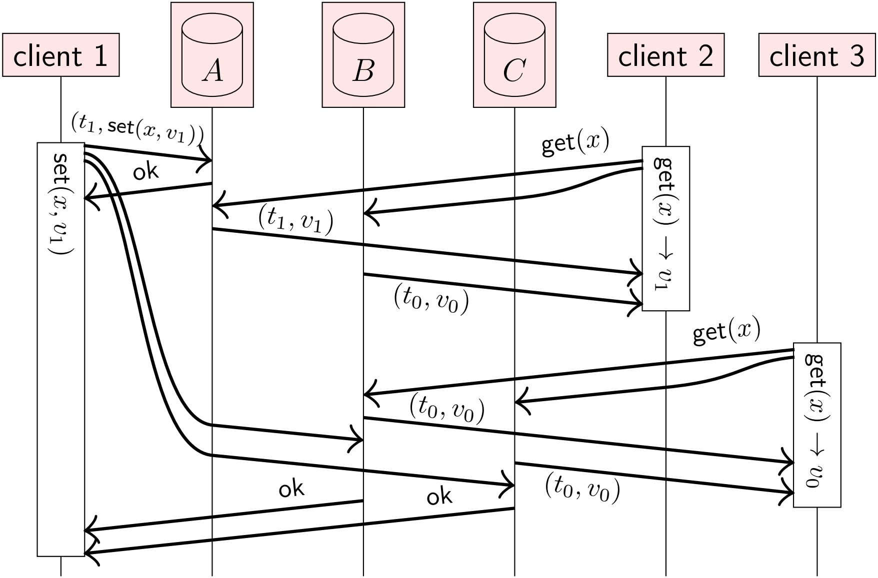

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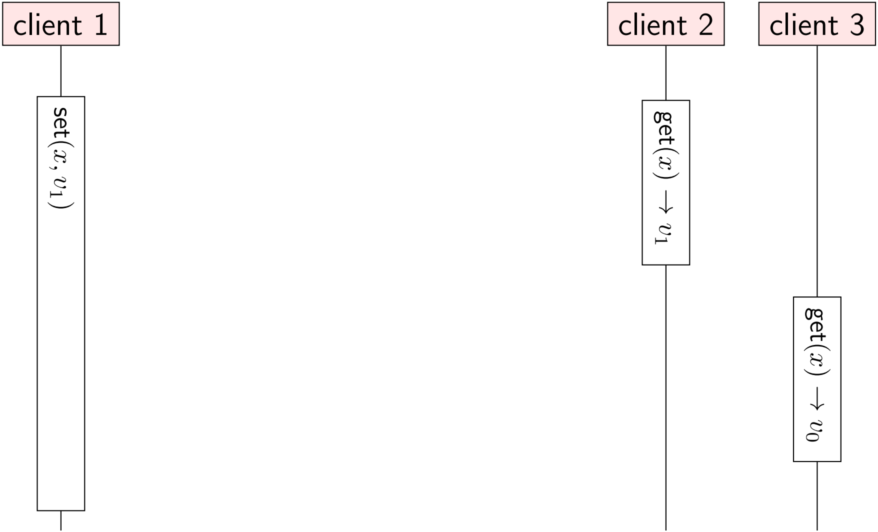

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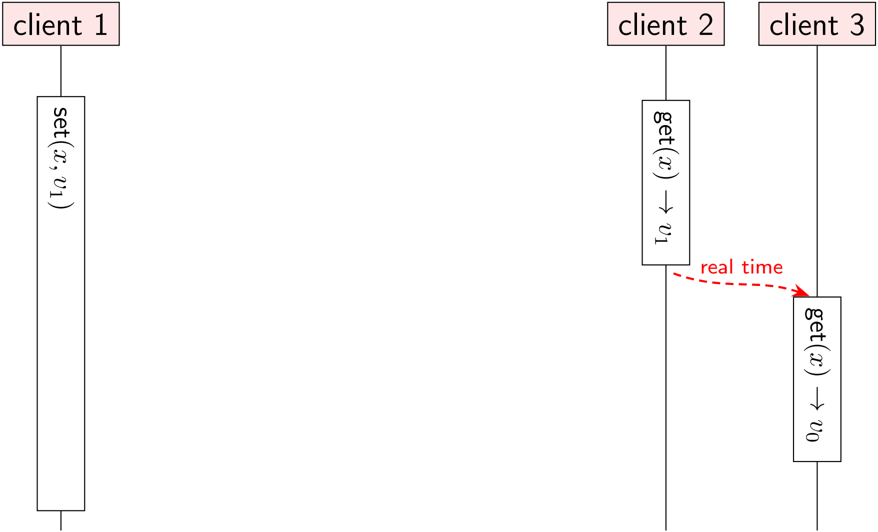

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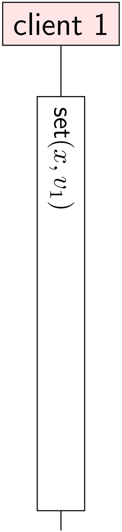
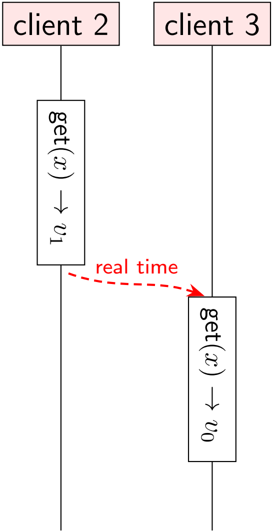


- Client 2's operation finishes before client 3's operation starts
- Linearizability therefore requires client 3's operation to observe a state no older than client 2's operation
- This example violates linearizability because v_0 is older than v_1



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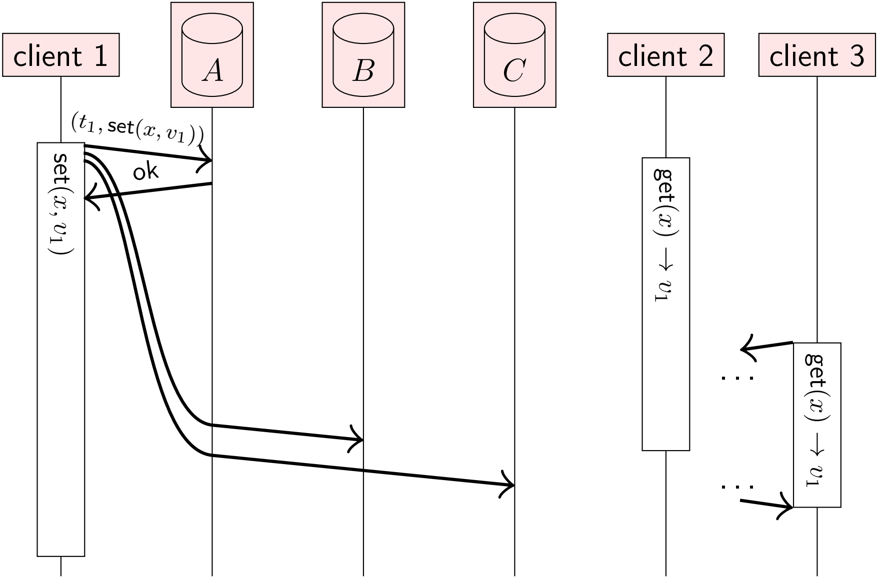

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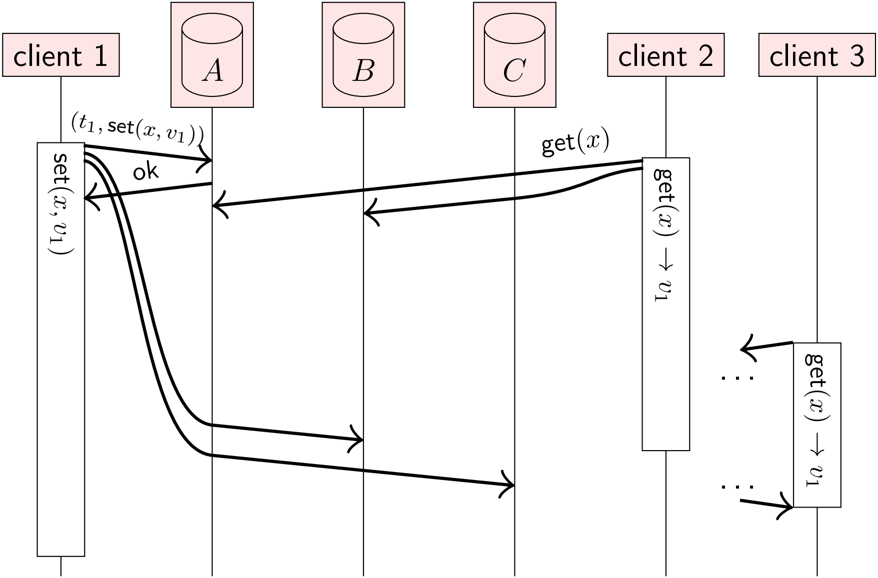

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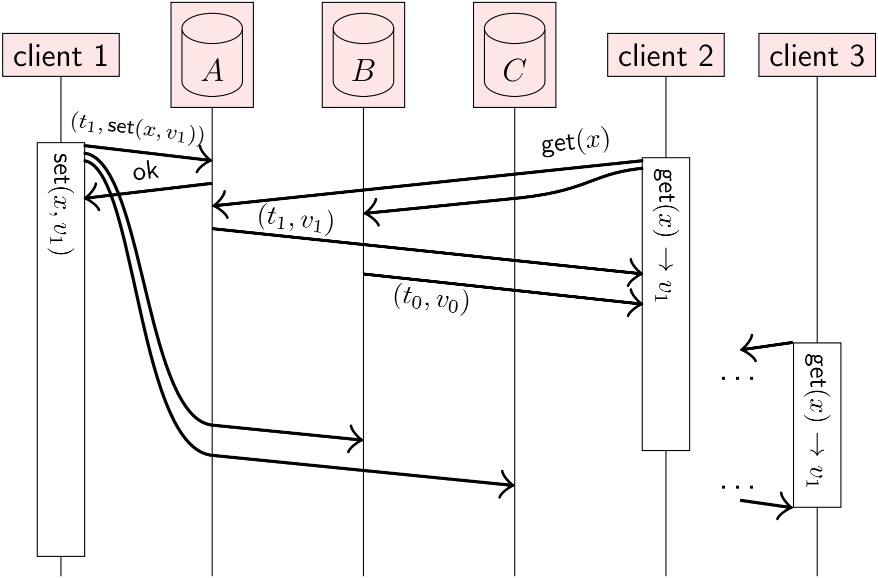

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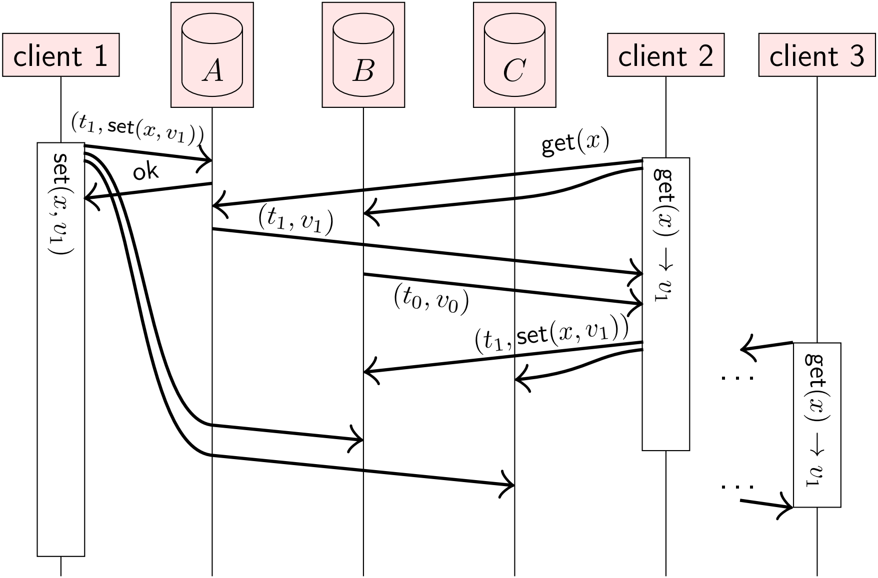

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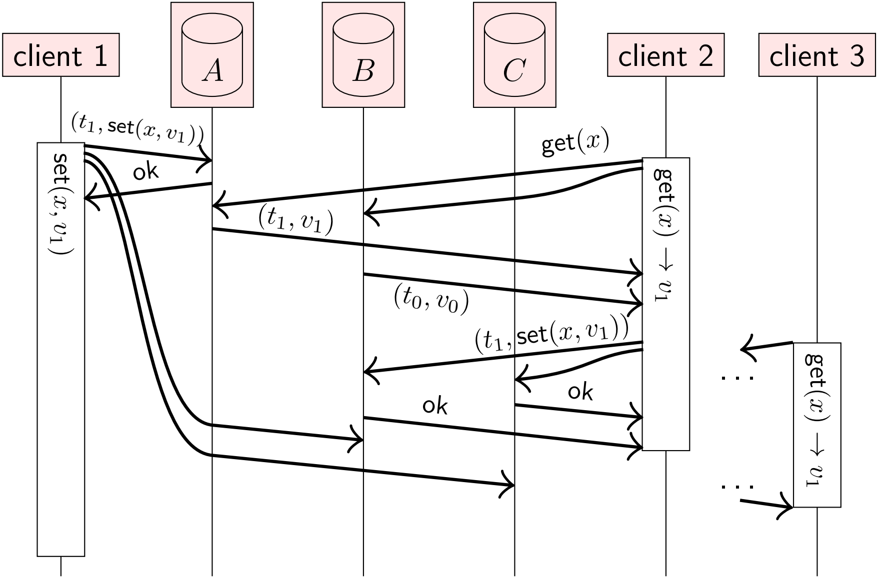

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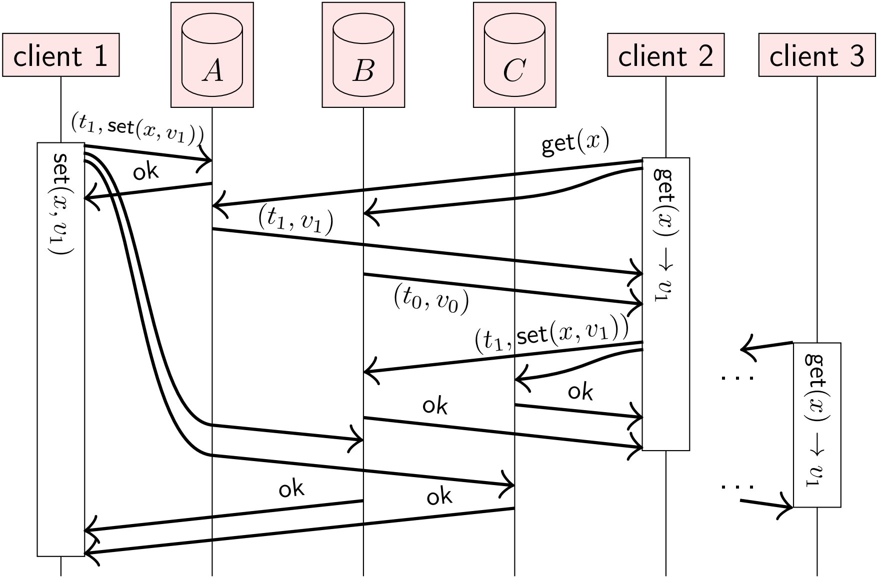

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- Can we implement **linearizable** compare-and-swap in a distributed system?
- **Yes:** total order broadcast to the rescue again!

Linearizable compare-and-swap (CAS)

on request to perform get(x) **do**
    total order broadcast (get, x) and wait for delivery
end on

on request to perform CAS(x, old, new) **do**
    total order broadcast $(\text{CAS}, x, old, new)$ and wait for delivery
end on

on delivering (get, x) by total order broadcast **do**
    return $localState[x]$ as result of operation get(x)
end on

on delivering $(\text{CAS}, x, old, new)$ by total order broadcast **do**
    $success :=$ false
    if $localState[x] = old$ **then**
        $localState[x] := new;\ success :=$ true
    end if
    return $success$ as result of operation CAS(x, old, new)
end on

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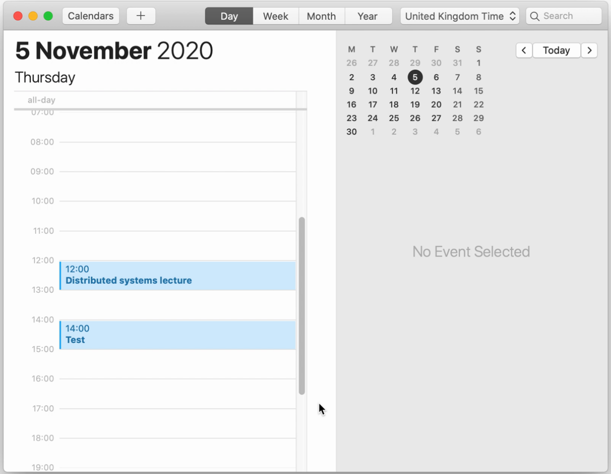
Eventual consistency: a weaker model than linearizability. Different trade-off choices.


Calendars
Day
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5 November 2020
Thursday
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07:00
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Distributed systems lecture
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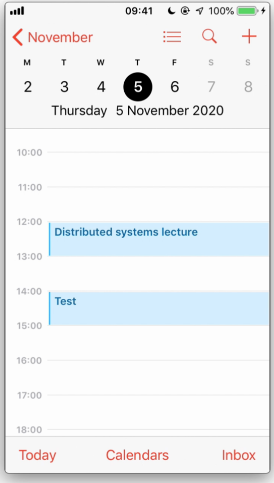
Today
No Event Selected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Test
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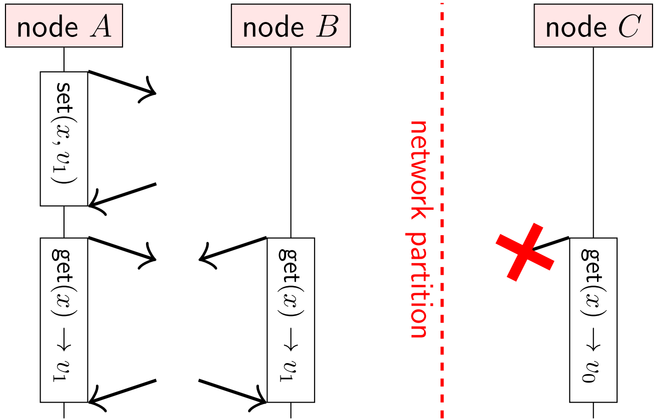
Today
Calendars
Inbox

The CAP theorem

A system can be either strongly **Consistent** (linearizable) or **Available** in the presence of a network **Partition**



C must either wait indefinitely for the network to recover, or return a potentially stale value

Eventual consistency

Replicas process operations based only on their local state.

If there are no more updates, **eventually** all replicas will be in the same state. (No guarantees how long it might take.)

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- Does not require waiting for network communication
- Causal broadcast (or weaker) can disseminate updates
- Concurrent updates $\Longrightarrow$ **conflicts** need to be resolved

Summary of minimum system model requirements

Problem	Must wait for communication	Requires synchrony
atomic commit	all participating nodes	partially synchronous

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Problem	**Must wait for communication**	**Requires synchrony**
atomic commit	all participating nodes	partially synchronous
consensus, total order broadcast, linearizable CAS	quorum	partially synchronous
linearizable get/set	quorum	asynchronous

strength of assumptions

Lecture 8

Concurrency control in applications

Collaboration and conflict resolution

Nowadays we use a lot of **collaboration software**:

- **Examples:** calendar sync (last lecture), Google Docs, ...

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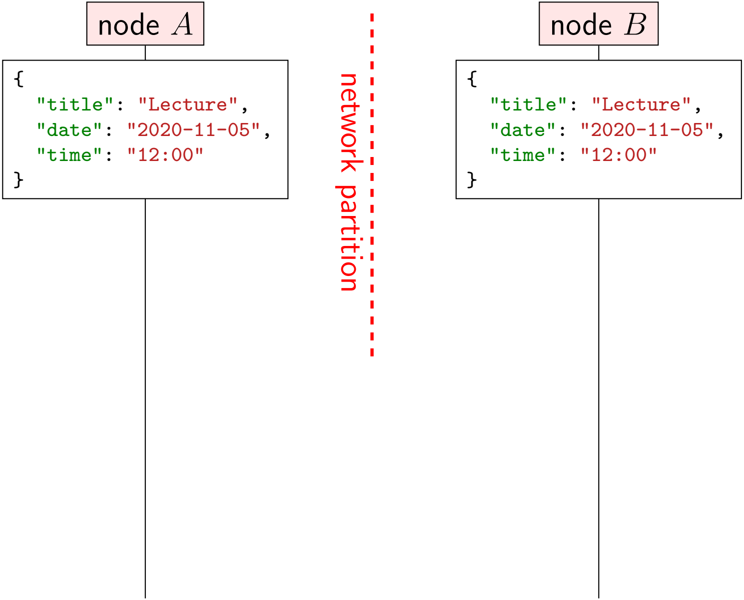
Families of **algorithms**:

- Conflict-free Replicated Data Types (**CRDTs**)
  - Operation-based
  - State-based
- Operational Transformation (**OT**)

Conflicts due to concurrent updates



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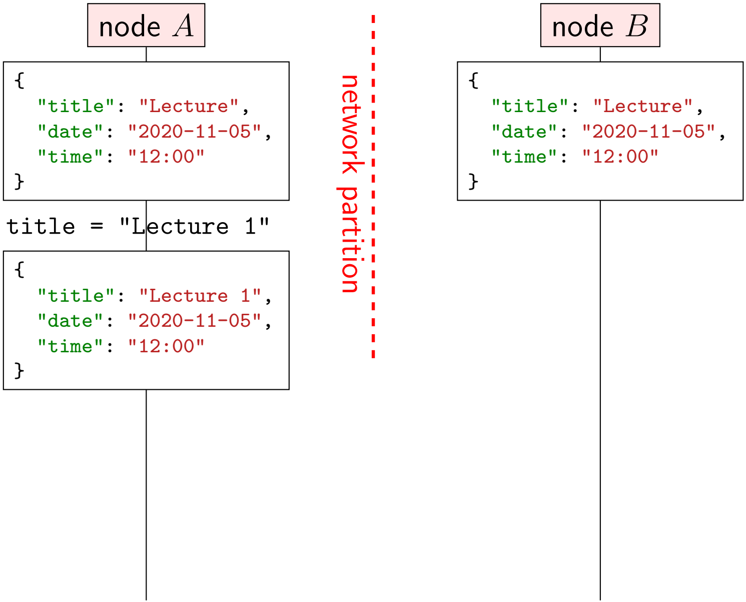

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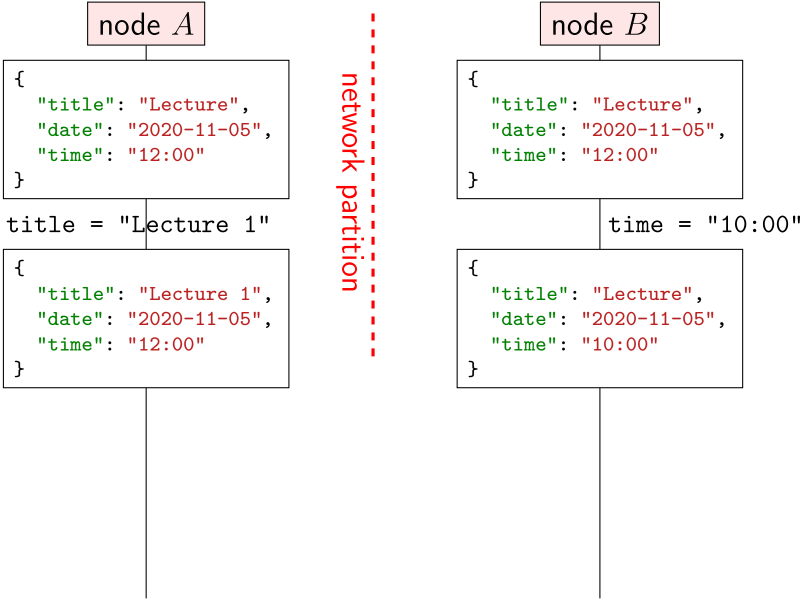

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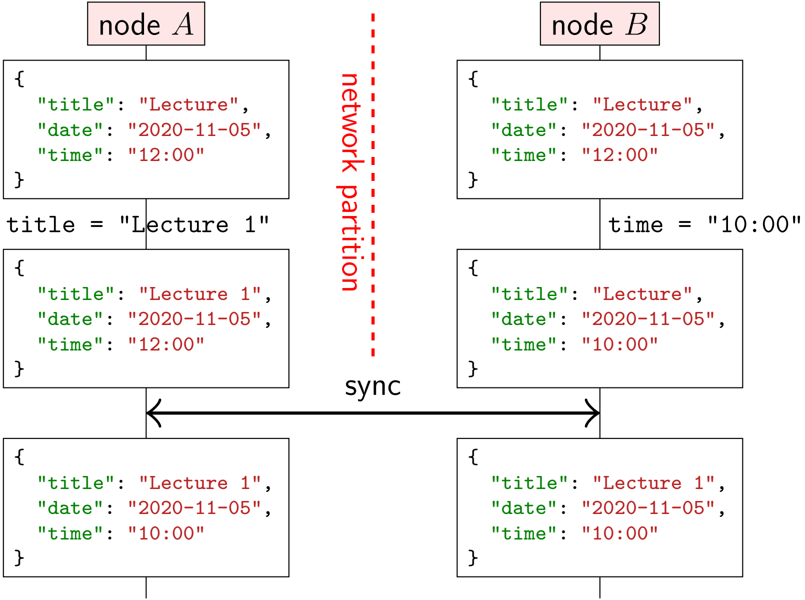

Operation-based map CRDT

on initialisation **do**
  $values := \{\}$
end on

on request to read value for key k **do**
  if $\exists t, v.\ (t, k, v) \in values$ **then return** v **else return** null
end on

on request to set key k to value v **do**
  $t := \mathrm{newTimestamp}()$ ▷ globally unique, e.g. Lamport timestamp
  broadcast (set, t, k, v) by reliable broadcast (including to self)
end on

on delivering (set, t, k, v) by reliable broadcast **do**
  $previous := \{(t', k', v') \in values \mid k' = k\}$
  if $previous = \{\} \lor \forall (t', k', v') \in previous.\ t' < t$ **then**
    $values := (values \setminus previous) \cup \{(t, k, v)\}$
  end if
end on

Operation-based CRDTs

Reliable broadcast may deliver updates in any order:

- broadcast $(\text{set}, t_1, \text{"title"}, \text{"Lecture 1"})$
- broadcast $(\text{set}, t_2, \text{"time"}, \text{"10:00"})$

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CRDT algorithm implements this:

- Reliable broadcast ensures every operation is eventually delivered to every (non-crashed) replica
- Applying an operation is **commutative**: order of delivery doesn't matter

State-based map CRDT

The operator $\sqcup$ merges two states s_1 and s_2 as follows:

$$s_1 \sqcup s_2 = \{(t, k, v) \in (s_1 \cup s_2) \mid \nexists (t', k', v') \in (s_1 \cup s_2).\ k' = k \wedge t' > t\}$$

on initialisation **do**
  $\mathit{values} := \{\}$
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on request to read value for key k **do**
  if $\exists t, v.\ (t, k, v) \in \mathit{values}$ **then return** v **else return** null
end on

on request to set key k to value v **do**
  $t := \mathrm{newTimestamp}()$ ▷ globally unique, e.g. Lamport timestamp
  $\mathit{values} := \{(t', k', v') \in \mathit{values} \mid k' \neq k\} \cup \{(t, k, v)\}$
  broadcast values by best-effort broadcast
end on

on delivering V by best-effort broadcast **do**
  $\mathit{values} := \mathit{values} \sqcup V$
end on

State-based CRDTs

Merge operator $\sqcup$ must satisfy: $\forall s_1, s_2, s_3 \ldots$

- **Commutative**: $s_1 \sqcup s_2 = s_2 \sqcup s_1$.
- **Associative**: $(s_1 \sqcup s_2) \sqcup s_3 = s_1 \sqcup (s_2 \sqcup s_3)$.
- **Idempotent**: $s_1 \sqcup s_1 = s_1$.

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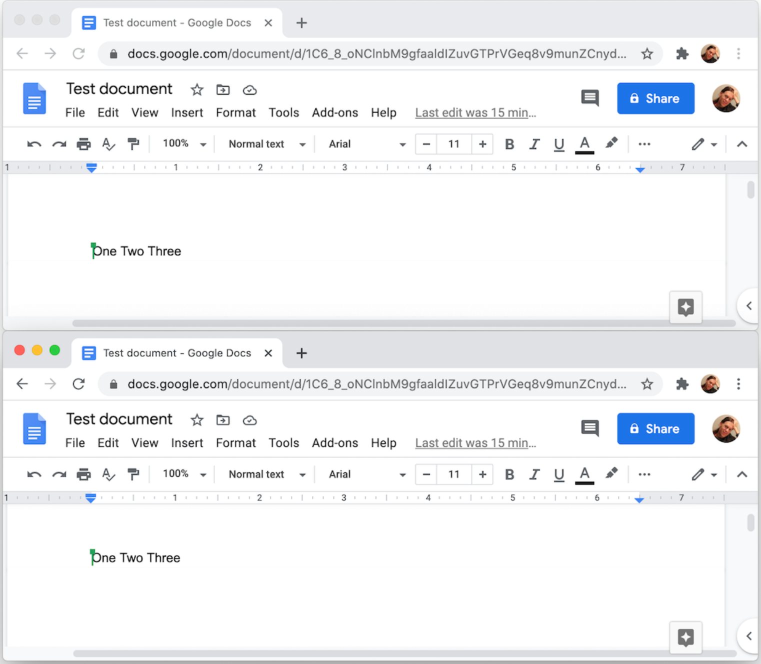
Not necessarily uses broadcast:

- Can also merge concurrent updates to replicas e.g. in quorum replication, anti-entropy, ...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Test document
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Test document - Google Docs
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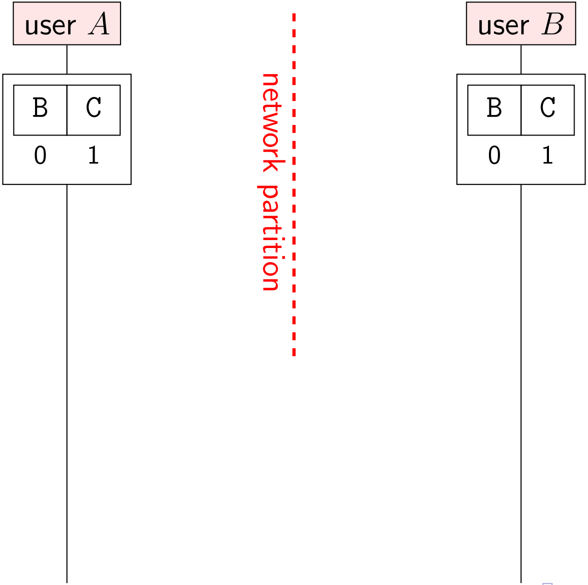
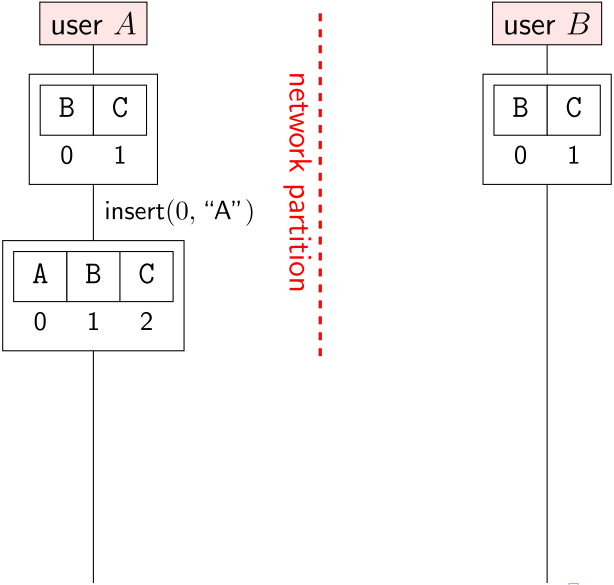
One Two Three

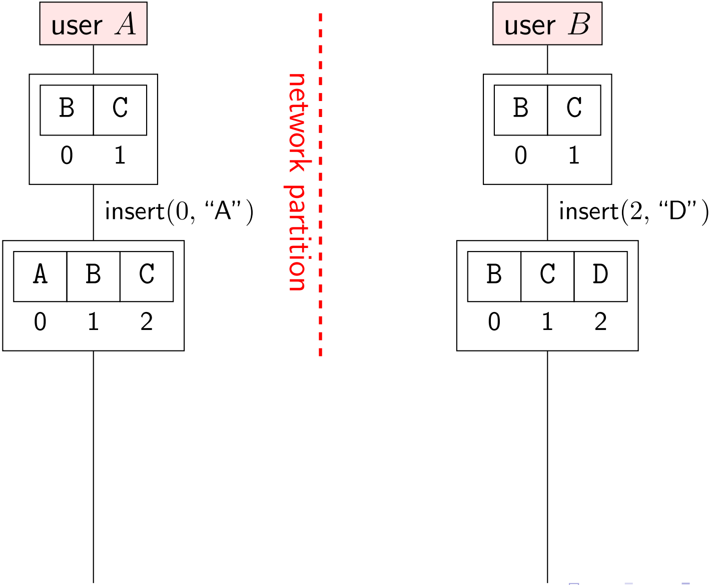
Collaborative text editing: the problem



Collaborative text editing: the problem



Collaborative text editing: the problem



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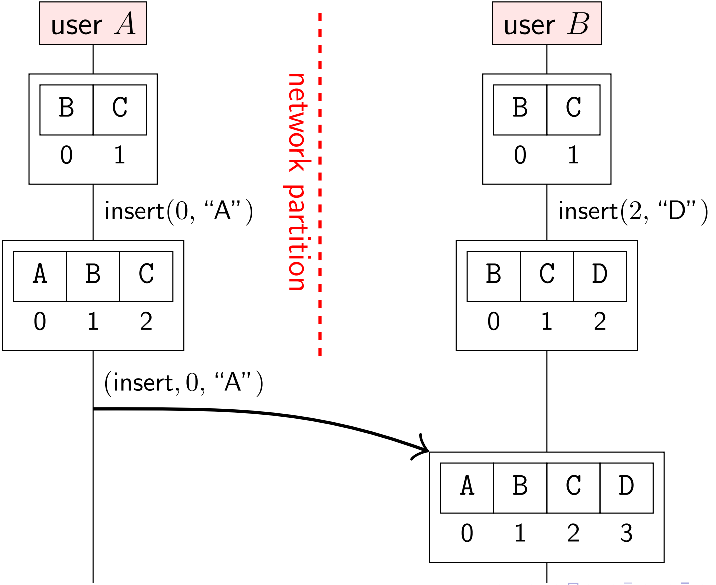
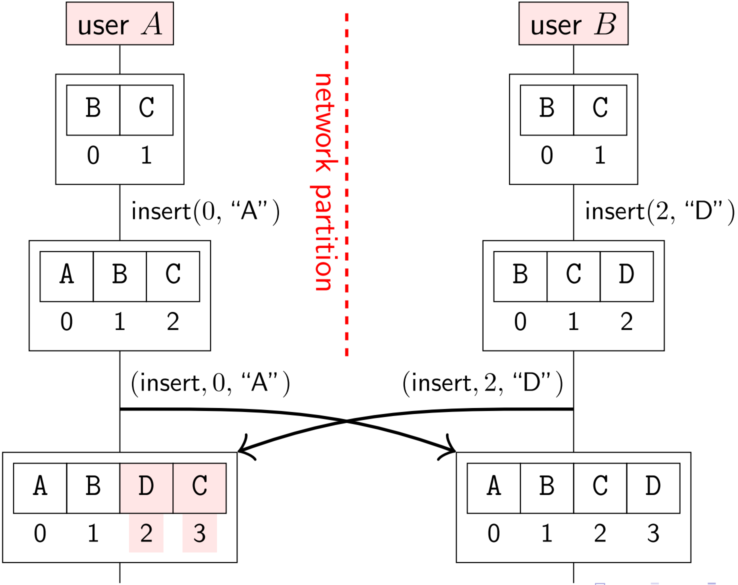
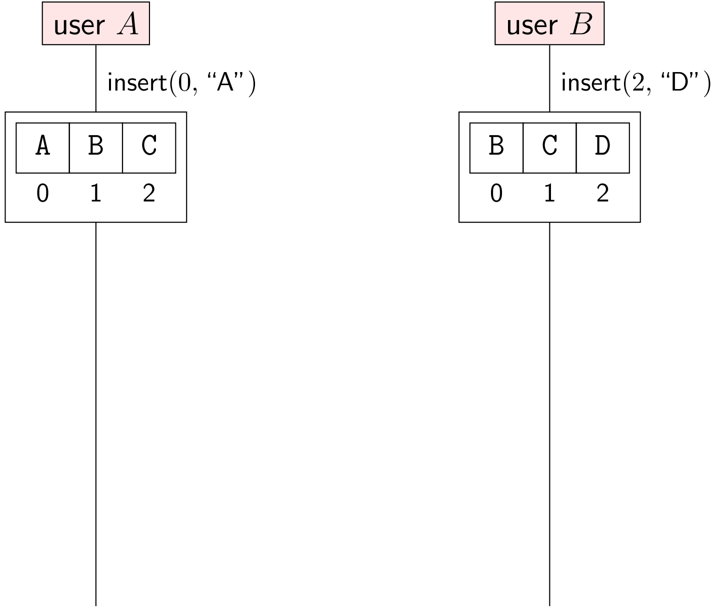


Collaborative text editing: the problem



Operational transformation



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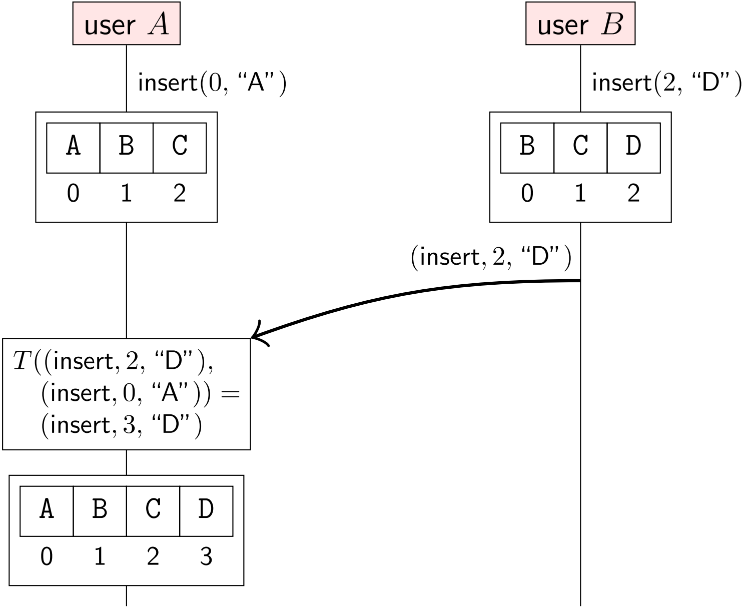

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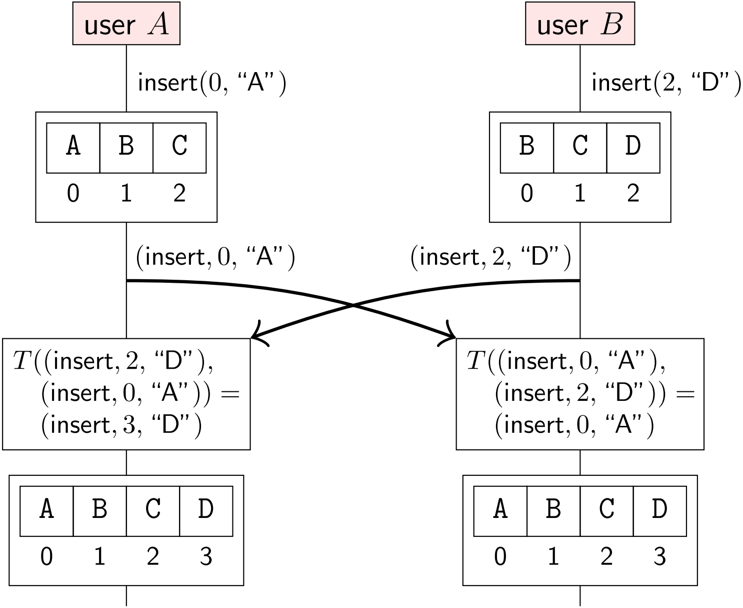
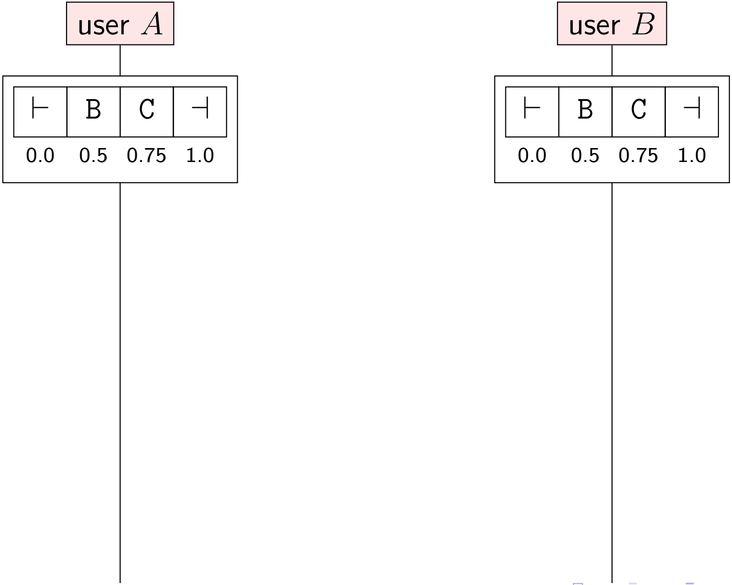


Text editing CRDT



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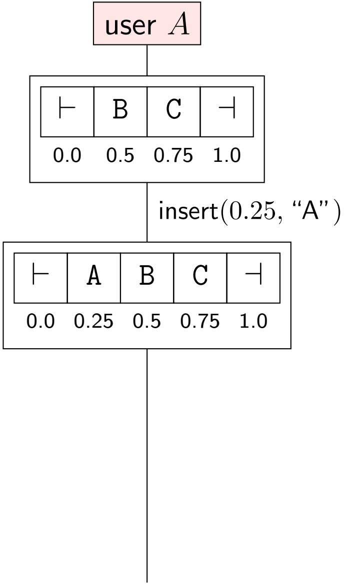

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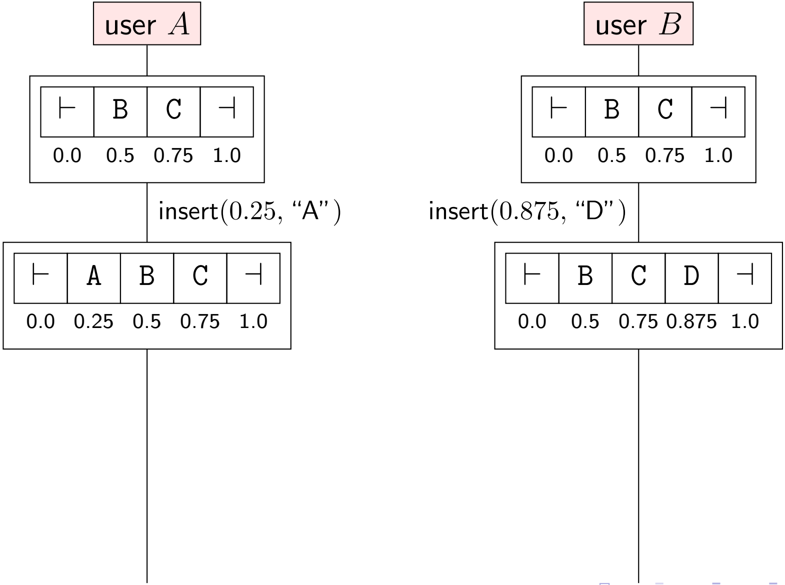

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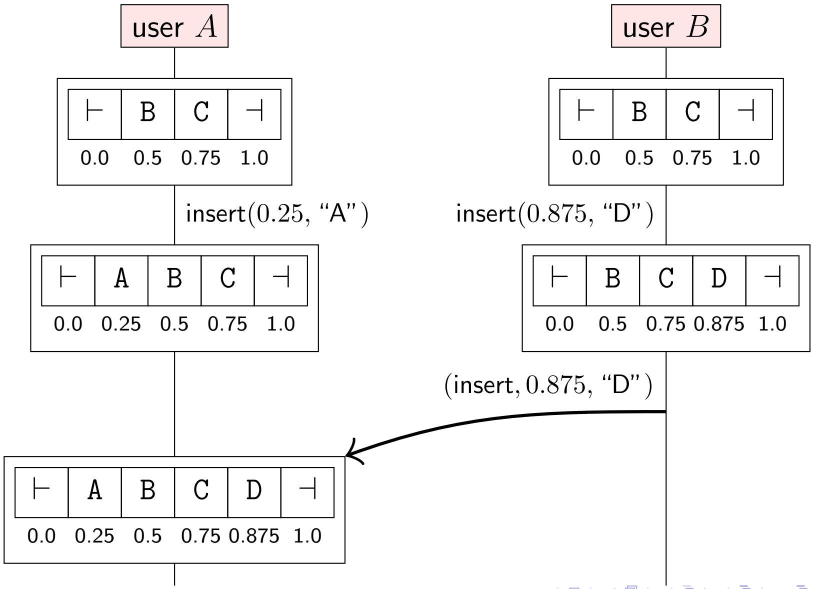

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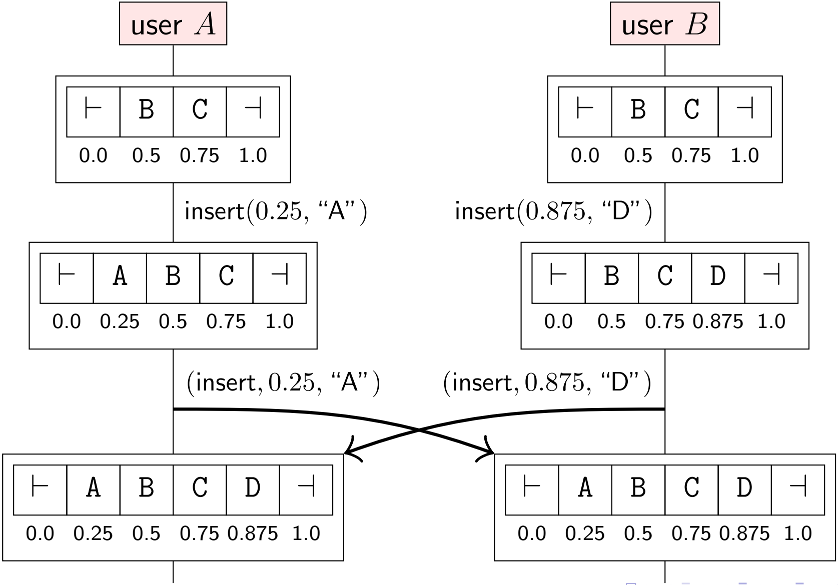

Operation-based text CRDT (1/2)

function $\textsc{ElementAt}(chars, index)$
  $min =$ the unique triple $(p, n, v) \in chars$ such that
    $\nexists (p', n', v') \in chars.\ p' < p \vee (p' = p \wedge n' < n)\}$
  if $index = 0$ **then return** min
  else return $\textsc{ElementAt}(chars \setminus \{min\}, index - 1)$
end function

on initialisation **do**
  $chars := \{(0, \text{null}, \vdash),\ (1, \text{null}, \dashv)\}$
end on

on request to read character at index $index$ **do**
  let $(p, n, v) := \textsc{ElementAt}(chars, index + 1)$; **return** v
end on

on request to insert character v at index $index$ at node $nodeId$ **do**
  let $(p_1, n_1, v_1) := \textsc{ElementAt}(chars, index)$
  let $(p_2, n_2, v_2) := \textsc{ElementAt}(chars, index + 1)$
  broadcast $(\text{insert}, (p_1 + p_2)/2, nodeId, v)$ by causal broadcast
end on

Operation-based text CRDT (2/2)

on delivering (insert, p, n, v) by causal broadcast **do**
$$chars := chars \cup \{(p, n, v)\}$$
end on

on request to delete character at index $index$ **do**
let $(p, n, v) := \textsc{ElementAt}(chars, index + 1)$
broadcast (delete, p, n) by causal broadcast
end on

on delivering (delete, p, n) by causal broadcast **do**
$$chars := \{(p', n', v') \in chars \mid \neg(p' = p \wedge n' = n)\}$$
end on

- Use causal broadcast so that insertion of a character is delivered before its deletion
- Insertion and deletion of different characters commute

Google's Spanner

A database system with millions of nodes, petabytes of data, distributed across datacenters worldwide

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- Two-phase commit for cross-shard atomicity

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The interesting bit: read-only transactions require **no locks**!

Consistent snapshots

A read-only transaction observes a **consistent snapshot**:
If $T_1 \rightarrow T_2$ (e.g. T_2 reads data written by T_1)...

- Snapshot reflecting writes by T_2 also reflects writes by T_1
- Snapshot that does not reflect writes by T_1 does not reflect writes by T_2 either

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- Each read-write transaction T_w has commit timestamp t_w
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- Every value is tagged with timestamp t_w of transaction that wrote it (not overwriting previous value)
- Read-only transaction T_r has snapshot timestamp t_r
- T_r ignores values with $t_w > t_r$; observes most recent value with $t_w \leq t_r$

Obtaining commit timestamps

Must ensure that whenever $T_1 \rightarrow T_2$ we have $t_1 < t_2$.

- Physical clocks may be **inconsistent with causality**

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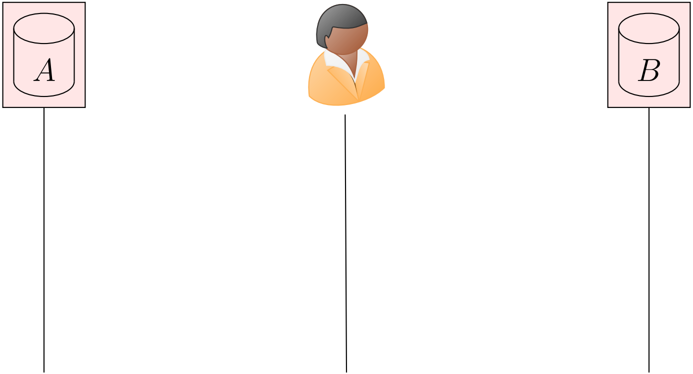

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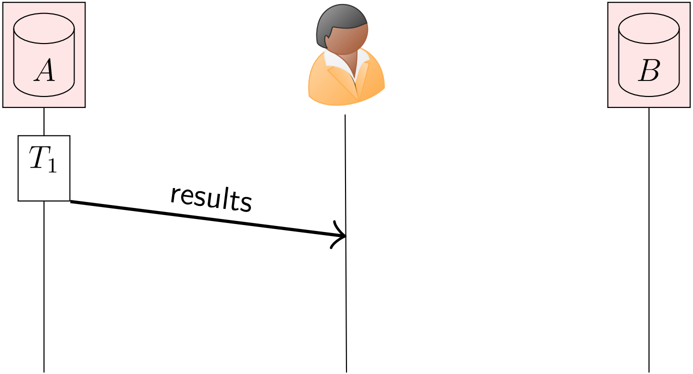

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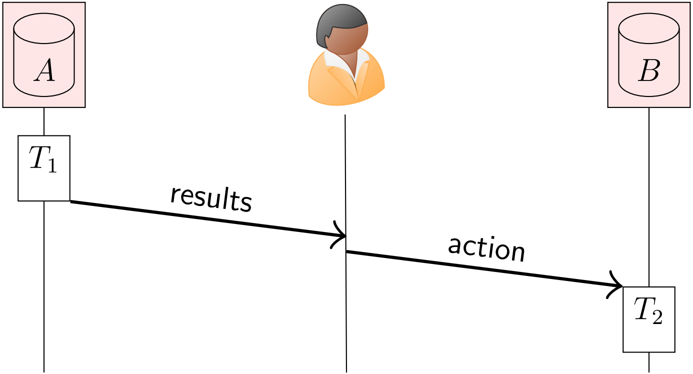
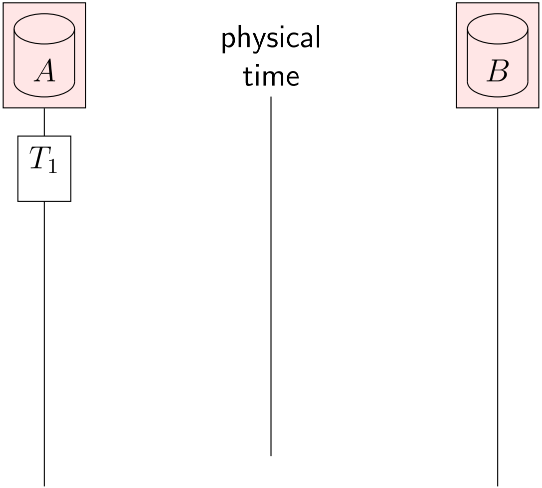
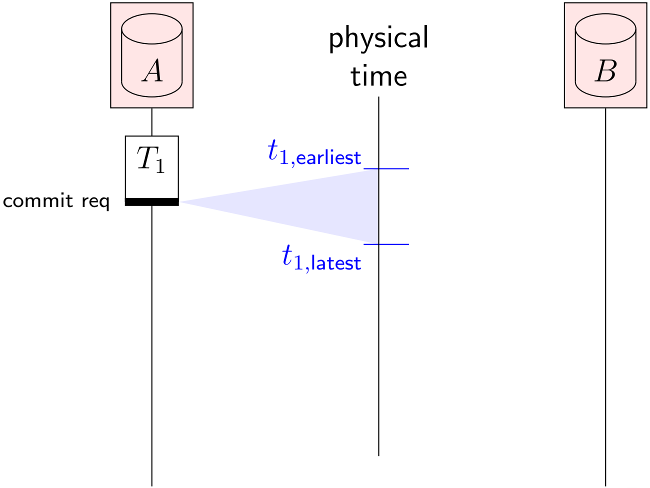


TrueTime: explicit physical clock uncertainty



TrueTime: explicit physical clock uncertainty

Spanner's TrueTime clock returns $[t_{\text{earliest}}, t_{\text{latest}}]$.
True physical timestamp must lie within that range.



TrueTime: explicit physical clock uncertainty

Spanner's TrueTime clock returns $[t_{\text{earliest}}, t_{\text{latest}}]$.
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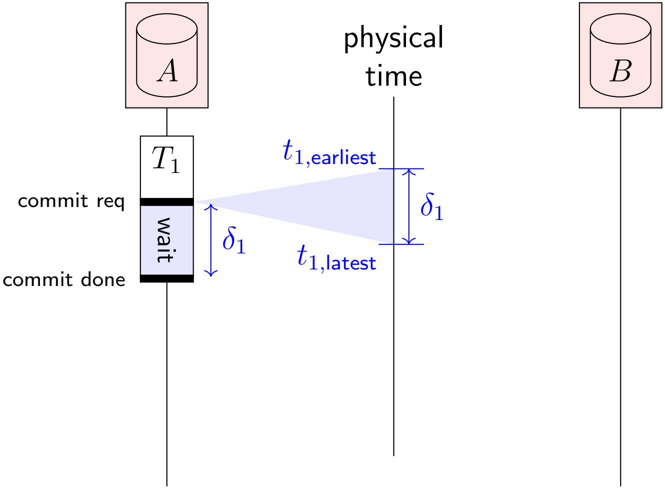
On commit, wait for uncertainty $\delta_i = t_{i,\text{latest}} - t_{i,\text{earliest}}$.



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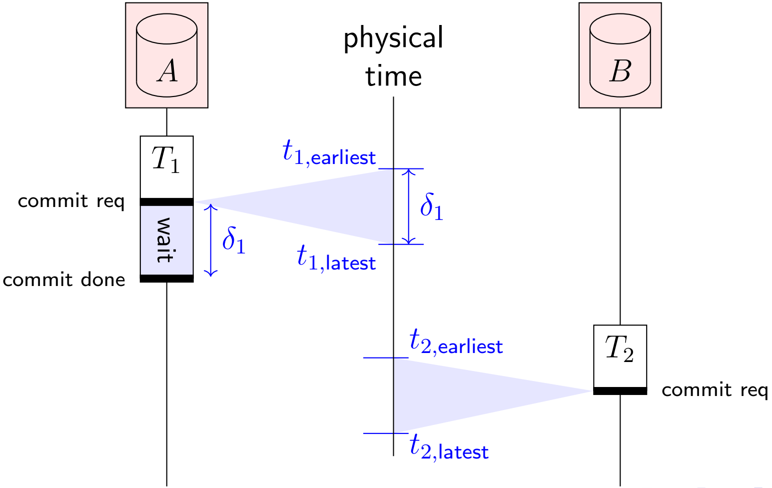

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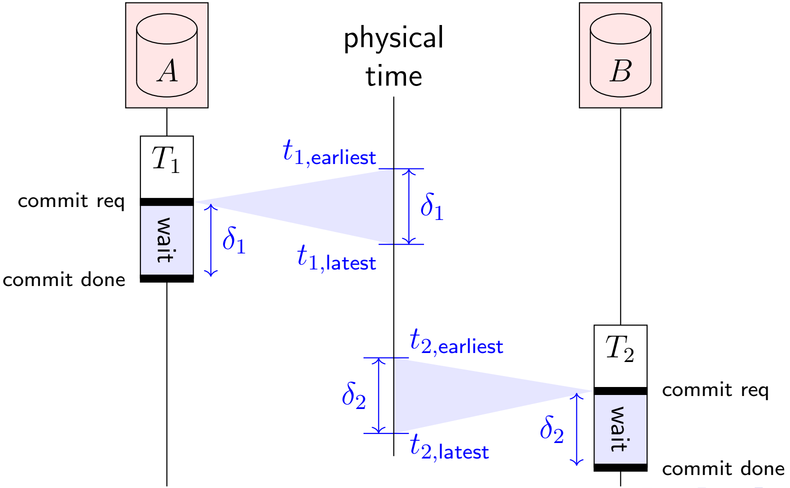

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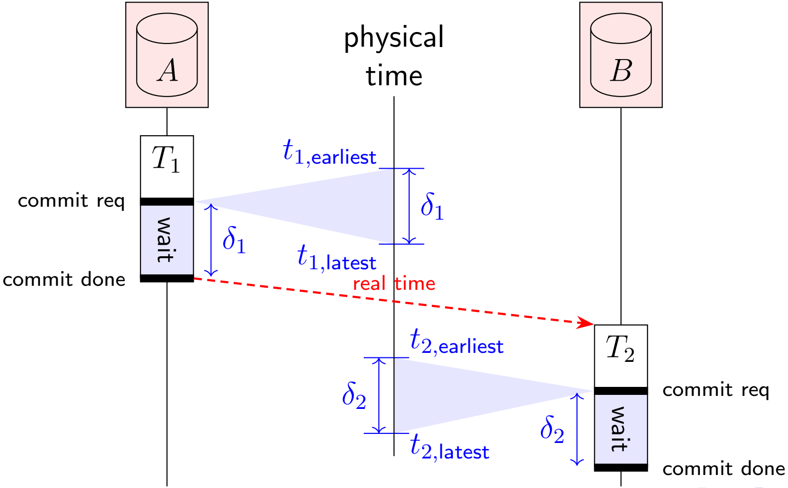
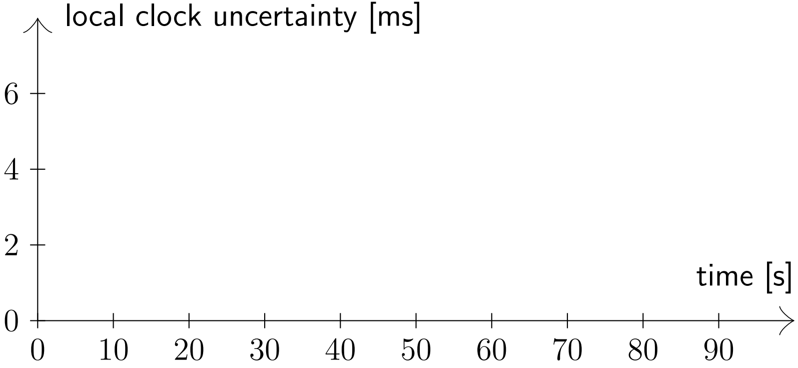


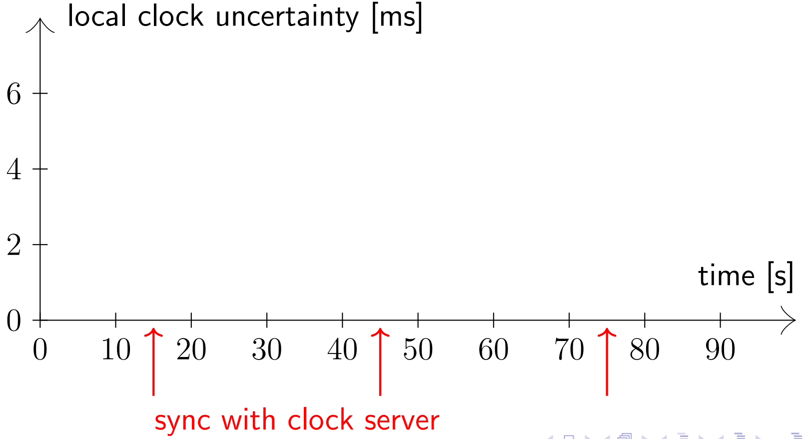
Determining clock uncertainty in TrueTime

Clock servers with **atomic clock** or **GPS receiver** in each datacenter; servers report their clock uncertainty.



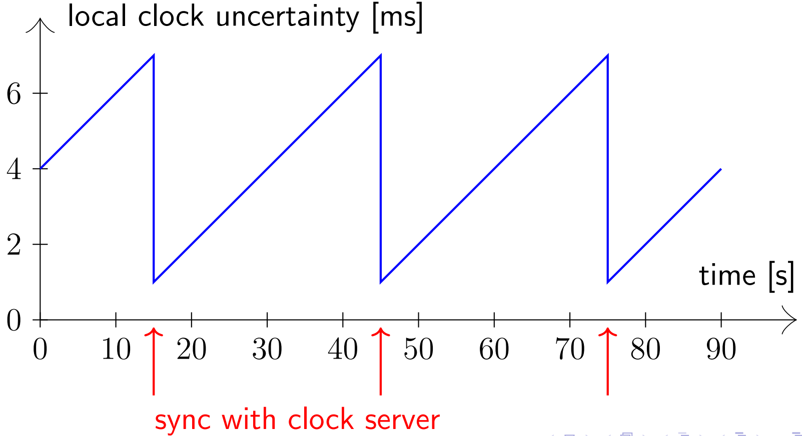
Determining clock uncertainty in TrueTime

Clock servers with **atomic clock** or **GPS receiver** in each datacenter; servers report their clock uncertainty.
Each node syncs its quartz clock with a server every 30 sec.



Determining clock uncertainty in TrueTime

Clock servers with **atomic clock** or **GPS receiver** in each datacenter; servers report their clock uncertainty.
Each node syncs its quartz clock with a server every 30 sec.
Between syncs, assume worst-case drift of 200ppm.



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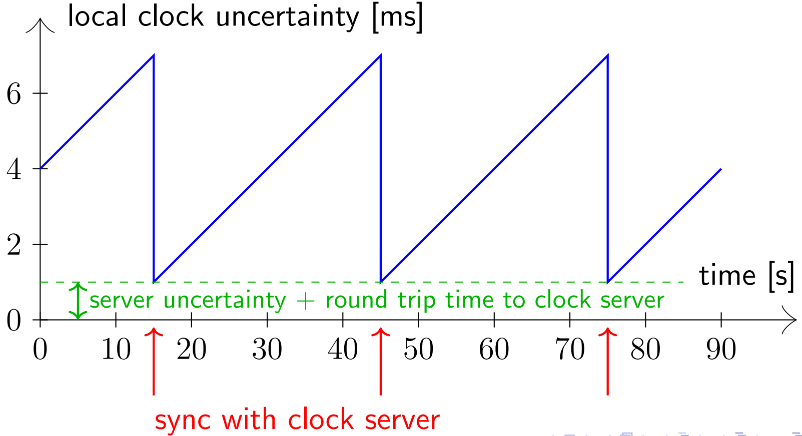

That's all, folks!

Any questions? Email mk428@cst.cam.ac.uk!

Summary:

- Distributed systems are everywhere
- You use them every day: e.g. web apps
- Key goals: availability, scalability, performance
- Key problems: concurrency, faults, unbounded latency
- Key abstractions: replication, broadcast, consensus
- No one right way, just trade-offs