

Distributed Systems

University of Cambridge

Computer Science Tripos, Part IB

Michaelmas term 2025/26

<https://www.cst.cam.ac.uk/teaching/2526/ConcDisSys/>

Dr. Martin Kleppmann

martin.kleppmann@cst.cam.ac.uk

Distributed Systems

The second half of *Concurrent and Distributed Systems*

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

Dr. Martin Kleppmann

martin.kleppmann@cst.cam.ac.uk

University of Cambridge

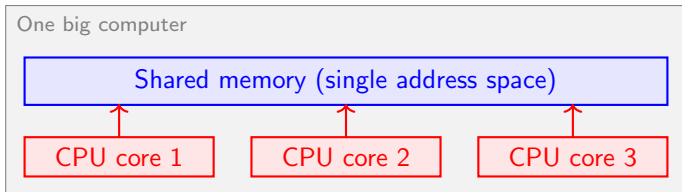
Computer Science Tripos, Part IB



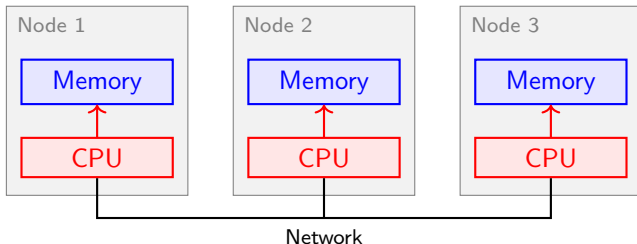
This work is published under a
Creative Commons BY-SA license.

Two models of concurrency

Shared-memory concurrency:



Message-passing distributed systems:



A distributed system is...

- ▶ Multiple “nodes” (computers, servers, phones, ...)
- ▶ communicating via an unreliable network
- ▶ trying to achieve some task together

A distributed system is...

- ▶ Multiple “nodes” (computers, servers, phones, ...)
- ▶ communicating via an unreliable network
- ▶ trying to achieve some task together

shared memory	distributed system
hardware fails ⇒ all threads stop	one machine fails ⇒ others continue running

A distributed system is...

- ▶ Multiple “nodes” (computers, servers, phones, ...)
- ▶ communicating via an unreliable network
- ▶ trying to achieve some task together

shared memory	distributed system
hardware fails ⇒ all threads stop	one machine fails ⇒ others continue running
reliable communication between CPU cores	unreliable network

A distributed system is...

- ▶ Multiple “nodes” (computers, servers, phones, ...)
- ▶ communicating via an unreliable network
- ▶ trying to achieve some task together

shared memory	distributed system
hardware fails ⇒ all threads stop	one machine fails ⇒ others continue running
reliable communication between CPU cores	unreliable network
locks, semaphores, atomic instructions (e.g. CAS)	only message-passing

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)
- ▶ **Cybersecurity** – Part IB Easter term
(web and internet security)
- ▶ **Cloud Computing** – Part II
(distributed systems for processing large amounts of data)

Why make a system distributed?

Why make a system distributed?

- ▶ **It's inherently distributed:**

e.g. sending a message from your mobile phone to your friend's phone

Why make a system distributed?

- ▶ **It's inherently distributed:**

e.g. sending a message from your mobile phone to your friend's phone

- ▶ **For better reliability:**

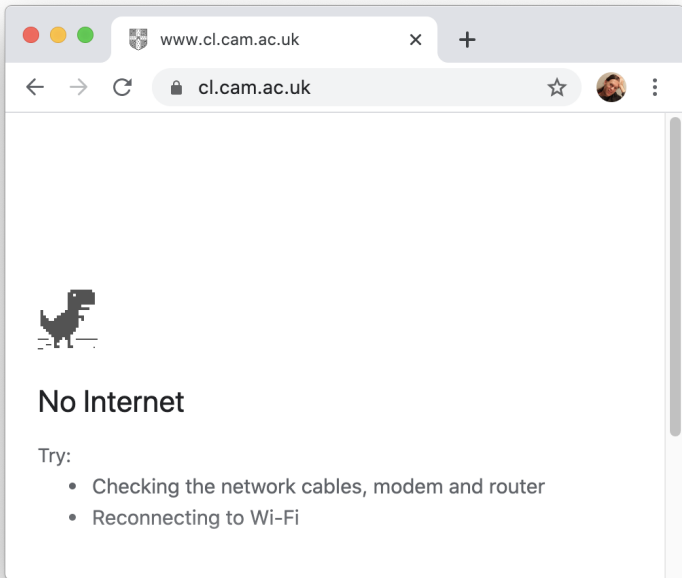
even if one node fails, the system as a whole keeps functioning

Why make a system distributed?

- ▶ **It's inherently distributed:**
e.g. sending a message from your mobile phone to your friend's phone
- ▶ **For better reliability:**
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

Why make a system distributed?

- ▶ **It's inherently distributed:**
e.g. sending a message from your mobile phone to your friend's phone
- ▶ **For better reliability:**
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



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 and without warning.

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 and without warning.

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?!

Theory and practice

Practice:

How can we achieve good performance in the common case?

Theory:

How can we guarantee correctness in all possible scenarios?

Theory and practice

Practice:

How can we achieve good performance in the common case?

Theory:

How can we guarantee correctness in all possible scenarios?

Build a system without understanding the theory?

- ▶ works fine for a while. . .
- ▶ but one day it fails catastrophically due to some weird edge case, and corrupts all your data 🤖

Theory and practice

Practice:

How can we achieve good performance in the common case?

Theory:

How can we guarantee correctness in all possible scenarios?


Build a system without understanding the theory?

- ▶ works fine for a while. . .
- ▶ but one day it fails catastrophically due to some weird edge case, and corrupts all your data 🤖

⚠ Distributed systems are notoriously hard to get right.
The theory helps us build robust systems.

Concurrent and Distributed Sys x +

← → ↻ ⓘ Not Secure | cst.cam.ac.uk/teaching/2021/ConcDisSys ☆ ⚙ 👤 ⋮

 UNIVERSITY OF CAMBRIDGE

Study at Cambridge

About the University

Research at Cambridge

Quick links ▾

Search 🔍

Department of Computer Science and Technology

Log in with Raven

HomeThe department ▾Initiatives ▾Research ▾Admissions ▾Current students ▾Job vacancies ➞Intranet

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

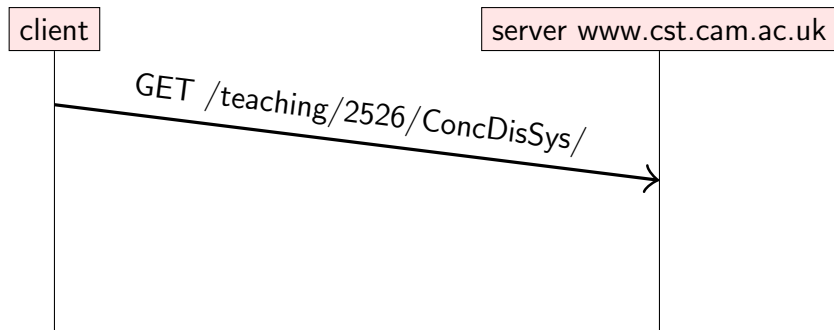
Time flows from top to bottom.

client

server www.cst.cam.ac.uk

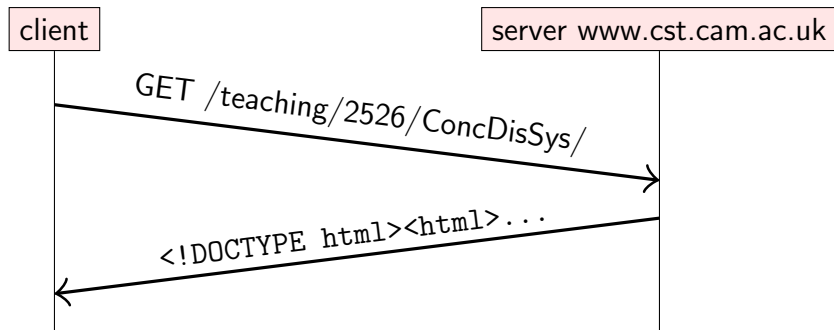
Client-server example: the web

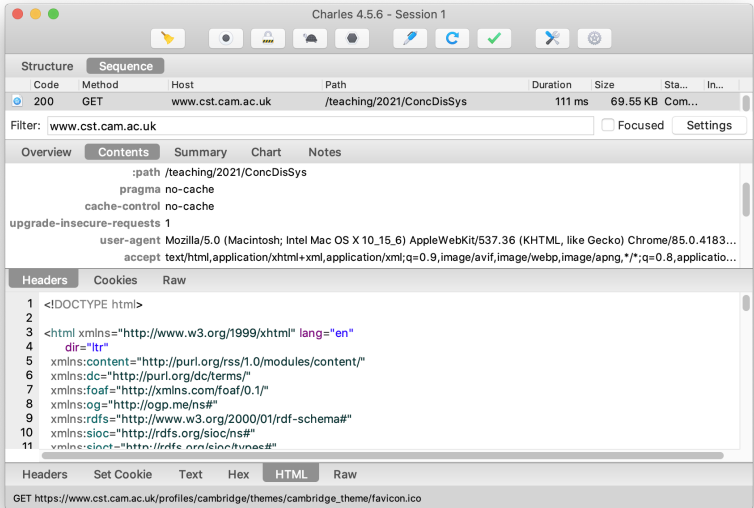
Time flows from top to bottom.

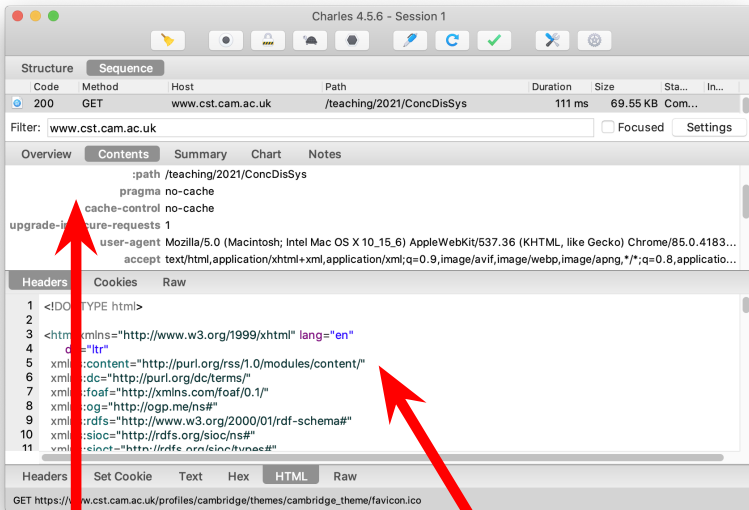


Client-server example: the web

Time flows from top to bottom.







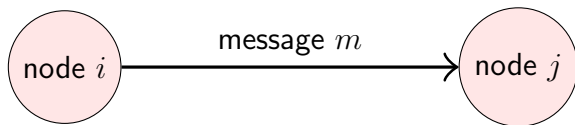
request message

response message

Abstracting over networking details

Network packets are too much low-level detail.

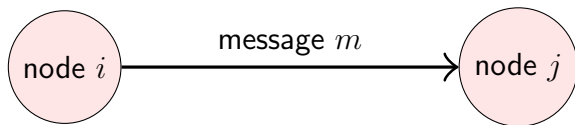
We use a simple abstraction of communication:



Abstracting over networking details

Network packets are too much low-level detail.

We use a simple abstraction of communication:



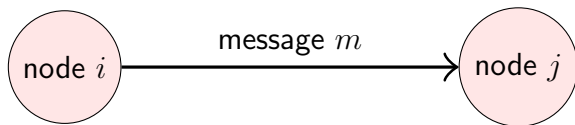
Reality is much more complex:

► **Node:**

server, desktop computer, phone, car, robot, sensor, ...

Abstracting over networking details

Network packets are too much low-level detail.
We use a simple abstraction of communication:

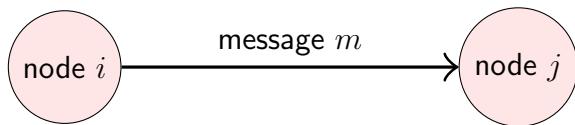


Reality is much more complex:

- ▶ **Node:**
server, desktop computer, phone, car, robot, sensor, ...
- ▶ **Various network operators:**
eduroam, home DSL, cellular data, coffee shop wifi, submarine cable, satellite. . .

Abstracting over networking details

Network packets are too much low-level detail.
We use a simple abstraction of communication:



Reality is much more complex:

- ▶ **Node:**
server, desktop computer, phone, car, robot, sensor, ...
- ▶ **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 datacenter: $\approx 100 \mu\text{s}$
- ▶ One continent to another: $\approx 100 \text{ ms}$
- ▶ Hard drives in a van: $\approx 1 \text{ day}$

Latency and bandwidth

Latency: time until message arrives

- ▶ In the same datacenter: $\approx 100 \mu\text{s}$
- ▶ One continent to another: $\approx 100 \text{ ms}$
- ▶ Hard drives in a van: $\approx 1 \text{ day}$

Bandwidth: data volume per unit time

- ▶ 4G cellular data: $\approx 10 \text{ Mbit/s}$
- ▶ Home broadband: $\approx 100 \text{ Mbit/s}$
- ▶ Hard drives in a van: $50 \text{ TB/box} \approx 1 \text{ Gbit/s}$
- ▶ In the same datacenter: $\approx 10 \text{ Gbit/s}$

(Very rough numbers, vary hugely in practice!)

Distributed Systems and Networking

networking	distributed systems
how to get data from A to B (packets, routing, ...)	how to achieve some goal by sending/receiving messages

Distributed Systems and Networking

networking	distributed systems
how to get data from A to B (packets, routing, ...)	how to achieve some goal by sending/receiving messages
"TCP is reliable" (dropped packets are automatically retransmitted)	any message can be lost (unplug the network cable ⇒ TCP timeout)



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
- ▶ “Five nines” = 99.999% up = down 5.3 minutes/year

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
- ▶ “Five nines” = 99.999% up = down 5.3 minutes/year

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, deadlock, ...
- ▶ Network fault: dropping or significantly delaying messages

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, deadlock, ...
- ▶ Network fault: dropping or significantly delaying messages

To increase availability: have fewer faults, or **tolerate** faults

Fault tolerance:

system as a whole continues working, despite faults
(up to some maximum number of faults)

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, deadlock, ...
- ▶ Network fault: dropping or significantly delaying messages

To increase availability: have fewer faults, or **tolerate** faults

Fault tolerance:

system as a whole continues working, despite faults
(up to some maximum number of faults)

Single point of failure (SPOF):

node/network link whose fault leads to failure

Fault tolerance is also useful for **software updates:**

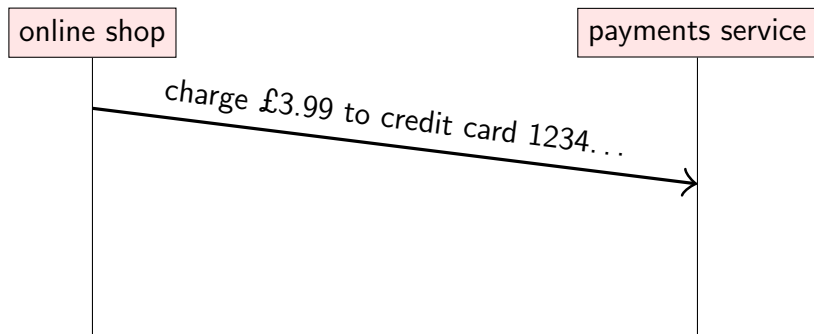
reboot one node at a time while continuing to serve users

Client-server example: online payments

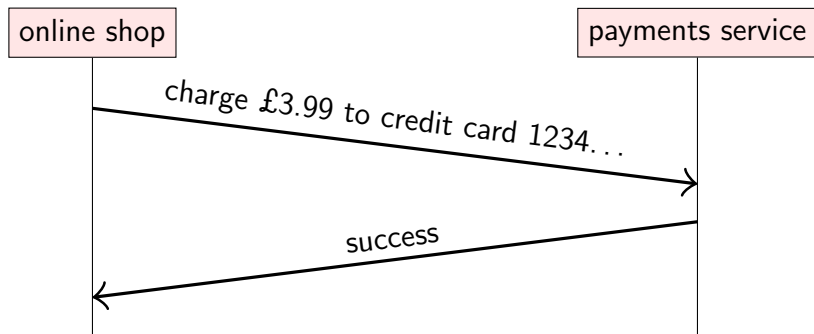
online shop

payments service

Client-server example: online payments



Client-server example: online payments



Remote Procedure Call (RPC) example

// 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();  
}
```

Remote Procedure Call (RPC) example

// 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();  
}
```



Implementation of this function is on another node!

online shop

RPC client

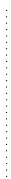
RPC server

payment service



processPayment() stub

waiting



online shop

RPC client

RPC server

payment service

processPayment() stub

marshal args

m_1

unmarshal args

waiting

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

$m_1 =$

online shop

RPC client

RPC server

payment service

processPayment() stub

marshal args

m_1

unmarshal args

processPayment()
implementation

waiting

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

$m_1 =$

online shop

RPC client

RPC server

payment service

processPayment() stub

waiting

marshal args

m_1

unmarshal args

processPayment()
implementation

unmarshal result

m_2

marshal result

$m_1 =$

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

$m_2 =$

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

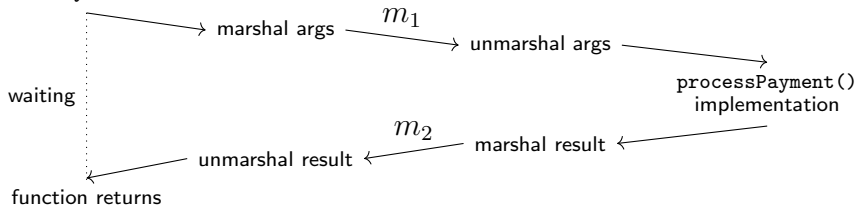
online shop

RPC client

RPC server

payment service

processPayment() stub



$m_1 =$

```
{
  "request": "processPayment",
  "card": {
    "number": "1234567887654321",
    "expiryDate": "10/2024",
    "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.

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.

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)
- ▶ JavaScript in web browsers making server requests (XMLHttpRequest, AJAX, fetch API, ...)

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.

(Server-to-server RPC within the same company)

RPC in enterprise systems

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

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

(Server-to-server RPC within the same company)

Different services implemented in different languages:

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

gRPC IDL example

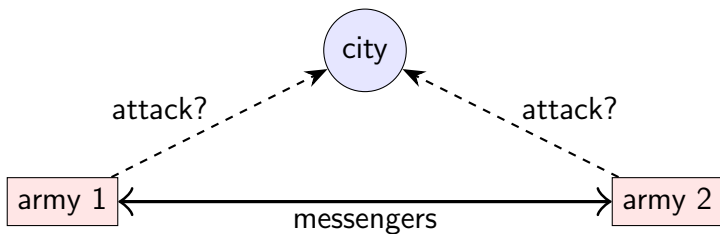
```
message PaymentRequest {  
  message Card {  
    string cardNumber = 1;  
    int32  expiryMonth = 2;  
    int32  expiryYear  = 3;  
    int32  CVC          = 4;  
  }  
  enum Currency { GBP = 1; USD = 2; }  
  
  Card      card      = 1;  
  int64     amount    = 2;  
  Currency  currency  = 3;  
}  
  
message PaymentStatus {  
  bool    success      = 1;  
  string  errorMessage = 2;  
}  
  
service PaymentService {  
  rpc ProcessPayment(PaymentRequest) returns (PaymentStatus) {}  
}
```

Models of distributed systems

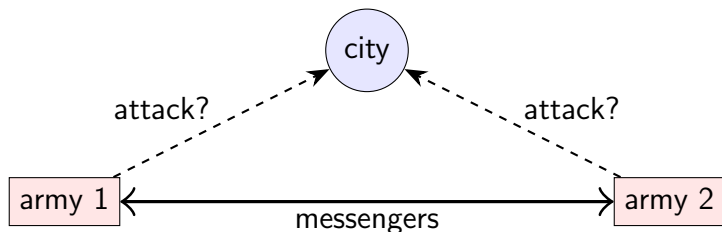
Dr. Martin Kleppmann
martin.kleppmann@cst.cam.ac.uk

University of Cambridge
Computer Science Tripos, Part IB

The two generals problem



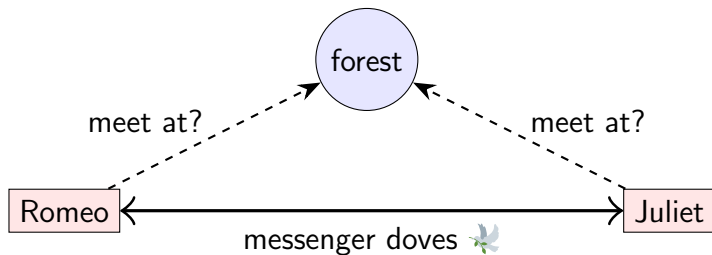
The two generals problem



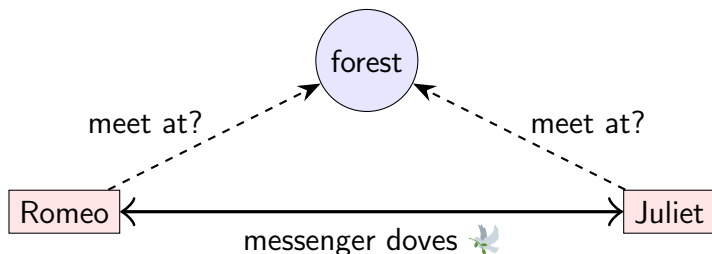
army 1	army 2	outcome
does not attack	does not attack	nothing happens
attacks	does not attack	army 1 defeated
does not attack	attacks	army 2 defeated
attacks	attacks	city captured

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

The Romeo and Juliet problem



The Romeo and Juliet problem



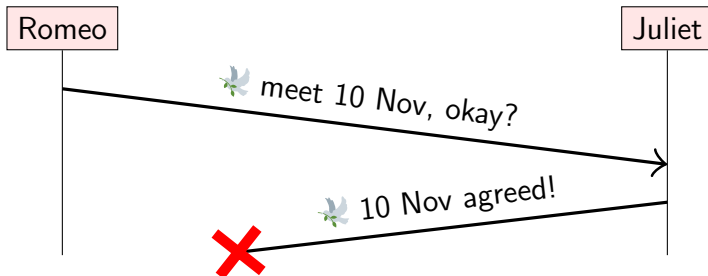
Romeo	Juliet	outcome
does not go	does not go	nothing happens
goes	does not go	Romeo gets desperate
does not go	goes	Juliet gets desperate
goes	goes	happy ever after

Desired: Romeo goes to the forest *if and only if* Juliet goes

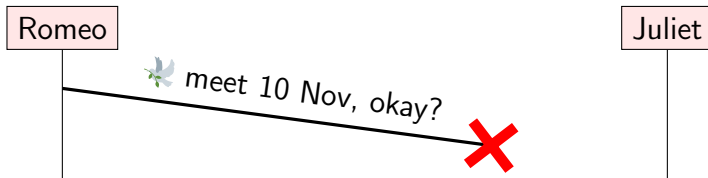
Reaching agreement with message loss



Reaching agreement with message loss



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



How should Romeo and Juliet decide?

1. Romeo always goes into the forest, even if no response is received
 - ▶ Send lots of messages to increase probability that one will get through
 - ▶ If all are lost, Juliet does not know about the meeting, so Romeo is alone

How should Romeo and Juliet decide?

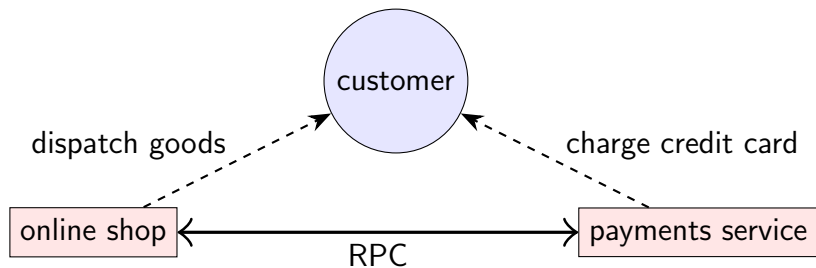
1. Romeo always goes into the forest, even if no response is received?
 - ▶ Send lots of messages to increase probability that one will get through
 - ▶ If all are lost, Juliet does not know about the meeting, so Romeo is alone
2. Romeo only goes into the forest if positive response from Juliet is received?
 - ▶ Now Romeo is safe
 - ▶ But Juliet knows that Romeo will only go if Juliet's response gets through
 - ▶ Now Juliet is in the same situation as Romeo in option 1

How should Romeo and Juliet decide?

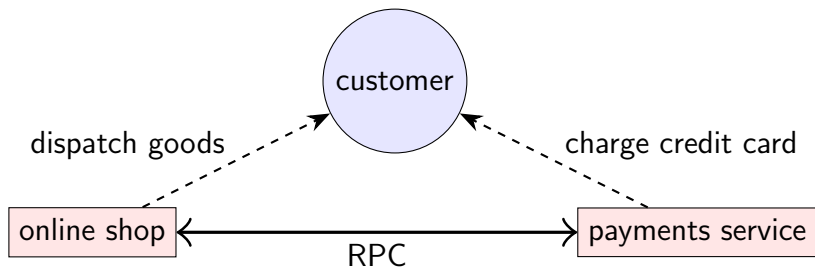
1. Romeo always goes into the forest, even if no response is received?
 - ▶ Send lots of messages to increase probability that one will get through
 - ▶ If all are lost, Juliet does not know about the meeting, so Romeo is alone
2. Romeo only goes into the forest if positive response from Juliet is received?
 - ▶ Now Romeo is safe
 - ▶ But Juliet knows that Romeo will only go if Juliet's response gets through
 - ▶ Now Juliet is in the same situation as Romeo in option 1

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

Two generals \neq online shopping

Analysing more carefully, we find that online shopping is not like the two generals after all.

Online shopping can use the following protocol:

Two generals \neq online shopping

Analysing more carefully, we find that online shopping is not like the two generals after all.

Online shopping can use the following protocol:

1. Try to charge customer's credit card

Two generals \neq online shopping

Analysing more carefully, we find that online shopping is not like the two generals after all.

Online shopping can use the following protocol:

1. Try to charge customer's credit card
2. If charge was successful, try dispatching goods

Two generals \neq online shopping

Analysing more carefully, we find that online shopping is not like the two generals after all.

Online shopping can use the following protocol:

1. Try to charge customer's credit card
2. If charge was successful, try dispatching goods
3. If dispatch was unsuccessful (e.g. out of stock):
refund the credit card payment

Two generals \neq online shopping

Analysing more carefully, we find that online shopping is not like the two generals after all.

Online shopping can use the following protocol:

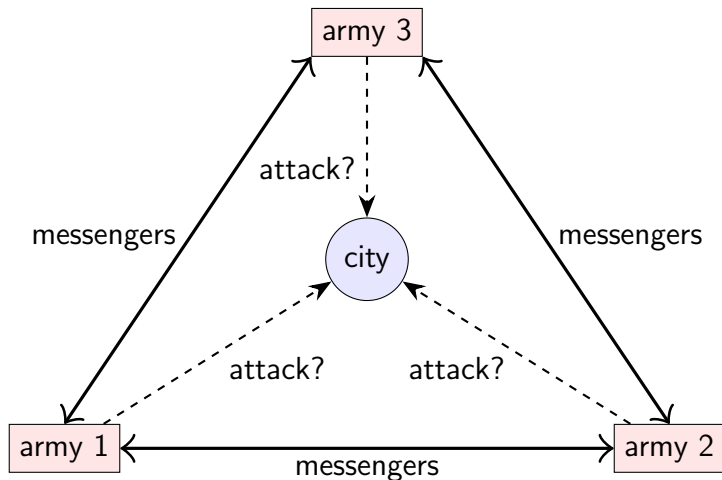
1. Try to charge customer's credit card
2. If charge was successful, try dispatching goods
3. If dispatch was unsuccessful (e.g. out of stock):
refund the credit card payment

The fact that one of the actions (payment) can be undone makes the problem solveable.

Defeat of an army cannot be undone.

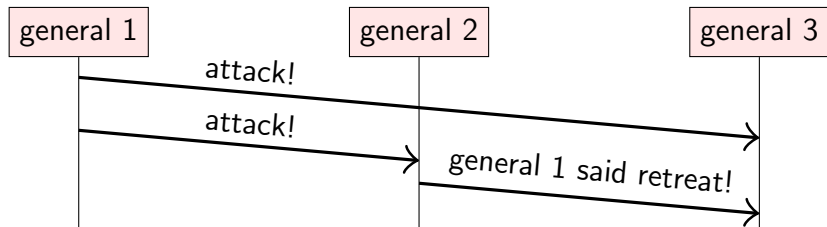
Dispatching goods cannot be undone.

The Byzantine generals problem

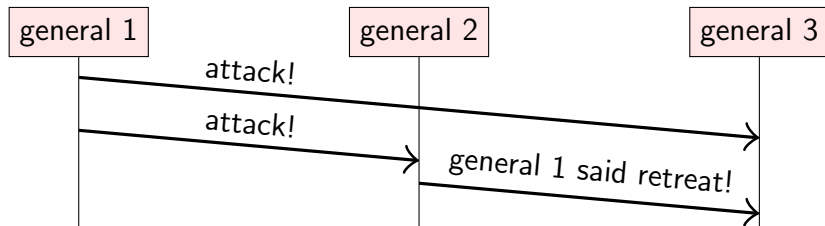


Problem: some of the generals might be traitors

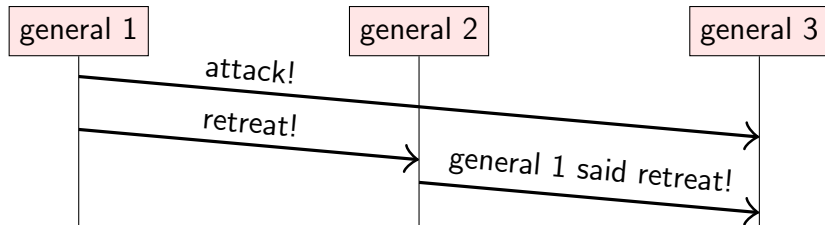
Generals who might lie



Generals who might lie



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



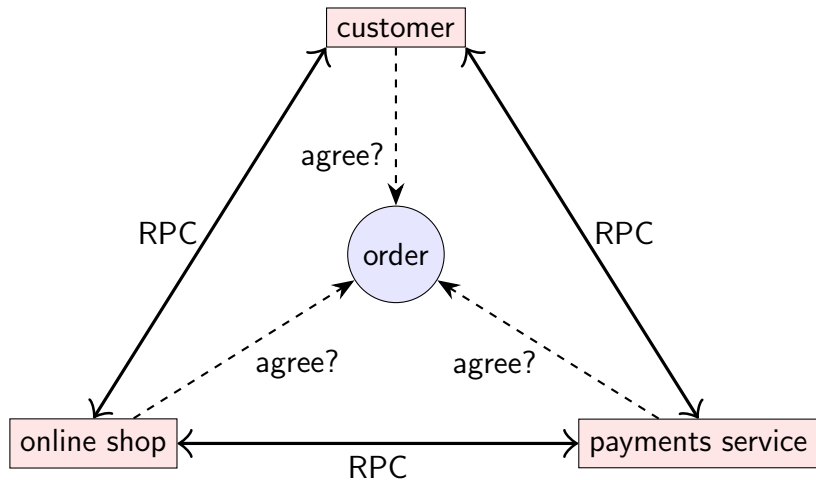
The Byzantine generals problem

- ▶ Each general is either *malicious* or *honest*
- ▶ Up to f generals might be malicious
- ▶ Honest generals don't know who the malicious ones are
- ▶ The malicious generals may collude
- ▶ Nevertheless, honest generals must agree on plan

The Byzantine generals problem

- ▶ Each general is either *malicious* or *honest*
 - ▶ Up to f generals might be malicious
 - ▶ Honest generals don't know who the malicious ones are
 - ▶ The malicious generals may collude
 - ▶ 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!

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!

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://www.theguardian.com/technology/2014/aug/14/>

google-undersea-fibre-optic-cables-shark-attacks

On land, cows step on the cables

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

System model: network behaviour

Assume bidirectional **point-to-point** communication between two nodes, with one of:

System model: network behaviour

Assume bidirectional **point-to-point** communication between two nodes, with one of:

- ▶ **Reliable** (perfect) links:
A message is received if and only if it is sent.
Messages may be reordered.

System model: network behaviour

Assume bidirectional **point-to-point** communication between two nodes, with one of:

- ▶ **Reliable** (perfect) links:

A message is received if and only if it is sent.

Messages may be reordered.

- ▶ **Fair-loss** links:

Messages may be lost, duplicated, or reordered.

If you keep retrying, a message eventually gets through.

System model: network behaviour

Assume bidirectional **point-to-point** communication between two nodes, with one of:

- ▶ **Reliable** (perfect) links:
A message is received if and only if it is sent.
Messages may be reordered.
- ▶ **Fair-loss** links:
Messages may be lost, duplicated, or reordered.
If you keep retrying, a message eventually gets through.
- ▶ **Arbitrary** links (active adversary):
A malicious adversary may interfere with messages
(eavesdrop, modify, drop, spoof, replay).

System model: network behaviour

Assume bidirectional **point-to-point** communication between two nodes, with one of:

- ▶ **Reliable** (perfect) links:
A message is received if and only if it is sent.
Messages may be reordered.
- ▶ **Fair-loss** links:
Messages may be lost, duplicated, or reordered.
If you keep retrying, a message eventually gets through.
- ▶ **Arbitrary** links (active adversary):
A malicious adversary may interfere with messages
(eavesdrop, modify, drop, spoof, replay).

Network partition: some links dropping/delaying all messages for extended period of time

System model: network behaviour

Assume bidirectional **point-to-point** communication between two nodes, with one of:

- ▶ **Reliable** (perfect) links:

A message is received if and only if it is sent.
Messages may be reordered.

- ▶ **Fair-loss** links:

Messages may be lost, duplicated, or reordered.
If you keep retrying, a message eventually gets through.

- ▶ **Arbitrary** links (active adversary):

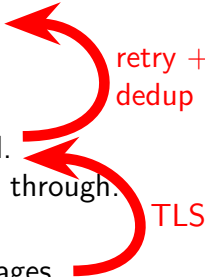
A malicious adversary may interfere with messages
(eavesdrop, modify, drop, spoof, replay).



Network partition: some links dropping/delaying all messages for extended period of time

System model: network behaviour

Assume bidirectional **point-to-point** communication between two nodes, with one of:

- ▶ **Reliable** (perfect) links:
A message is received if and only if it is sent.
Messages may be reordered.
 - ▶ **Fair-loss** links:
Messages may be lost, duplicated, or reordered.
If you keep retrying, a message eventually gets through.
 - ▶ **Arbitrary** links (active adversary):
A malicious adversary may interfere with messages
(eavesdrop, modify, drop, spoof, replay).
- 
- retry + dedup
- TLS

Network partition: some links dropping/delaying all messages for extended period of time

System model: node behaviour

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

- ▶ **Crash-stop** (fail-stop):

A node is faulty if it crashes (at any moment).

After crashing, it stops executing forever.

System model: node behaviour

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

- ▶ **Crash-stop** (fail-stop):

A node is faulty if it crashes (at any moment).

After crashing, it stops executing forever.

- ▶ **Crash-recovery** (fail-recovery):

A node may crash at any moment, losing its in-memory state. It may resume executing sometime later.

Data stored on disk survives the crash.

System model: node behaviour

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

- ▶ **Crash-stop** (fail-stop):
A node is faulty if it crashes (at any moment).
After crashing, it stops executing forever.
- ▶ **Crash-recovery** (fail-recovery):
A node may crash at any moment, losing its in-memory state. It may resume executing sometime later.
Data stored on disk survives the crash.
- ▶ **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: 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.

System model: 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.

- ▶ **Partially synchronous:**

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

System model: 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.

- ▶ **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

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

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!

Failure detectors

Failure detector:

algorithm that detects whether another node is faulty

Perfect failure detector:

labels a node as faulty if and only if it has crashed

Failure detectors

Failure detector:

algorithm that detects whether another node is faulty

Perfect failure detector:

labels a node as faulty if and only if it has crashed

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

Failure detectors

Failure detector:

algorithm that detects whether another node is faulty

Perfect failure detector:

labels a node as faulty if and only if it has crashed

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

Problem:

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

Failure detection and partial synchrony

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

Time, clocks, and ordering of events

Dr. Martin Kleppmann
martin.kleppmann@cst.cam.ac.uk

University of Cambridge
Computer Science Tripos, Part IB

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.:

- ▶ Schedulers, timeouts, failure detectors, retry timers

Clocks and time in distributed systems

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

- ▶ Schedulers, timeouts, failure detectors, retry timers
- ▶ Performance measurements, statistics, profiling

Clocks and time in distributed systems

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

- ▶ Schedulers, timeouts, failure detectors, retry timers
- ▶ Performance measurements, statistics, profiling
- ▶ Log files & databases: record when an event occurred

Clocks and time in distributed systems

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

- ▶ Schedulers, timeouts, failure detectors, retry timers
- ▶ Performance measurements, statistics, profiling
- ▶ Log files & databases: record when an event occurred
- ▶ Data with time-limited validity (e.g. cache entries)

Clocks and time in distributed systems

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

- ▶ Schedulers, timeouts, failure detectors, retry timers
- ▶ Performance measurements, statistics, profiling
- ▶ Log files & databases: record when an event occurred
- ▶ Data with time-limited validity (e.g. cache entries)
- ▶ Determining order of events across several nodes

Clocks and time in distributed systems

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

- ▶ Schedulers, timeouts, failure detectors, retry timers
- ▶ Performance measurements, statistics, profiling
- ▶ Log files & databases: record when an event occurred
- ▶ Data with time-limited validity (e.g. cache entries)
- ▶ Determining order of events across several nodes

We distinguish two types of clock:

- ▶ **physical clocks**: count number of seconds elapsed
- ▶ **logical clocks**: count events, e.g. messages sent

Clocks and time in distributed systems

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

- ▶ Schedulers, timeouts, failure detectors, retry timers
- ▶ Performance measurements, statistics, profiling
- ▶ Log files & databases: record when an event occurred
- ▶ Data with time-limited validity (e.g. cache entries)
- ▶ Determining order of events across several nodes

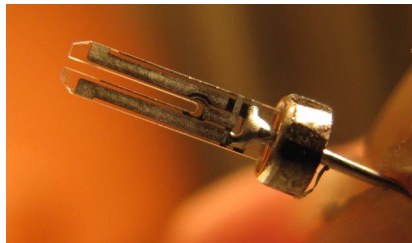
We distinguish two types of clock:

- ▶ **physical clocks**: count number of seconds elapsed
- ▶ **logical clocks**: count events, e.g. messages sent

NB. Clock in digital electronics (oscillator)
≠ clock in distributed systems (source of **timestamps**)

Quartz clocks

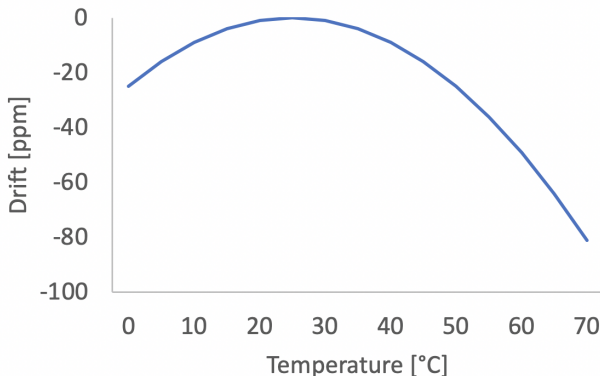
- ▶ Quartz crystal laser-trimmed to mechanically resonate at a specific frequency
- ▶ Piezoelectric effect: mechanical force \Leftrightarrow electric field
- ▶ Oscillator circuit produces signal at resonant frequency
- ▶ Count number of cycles to measure elapsed time



Quartz clock error: drift

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

Temperature significantly affects drift



Atomic clocks

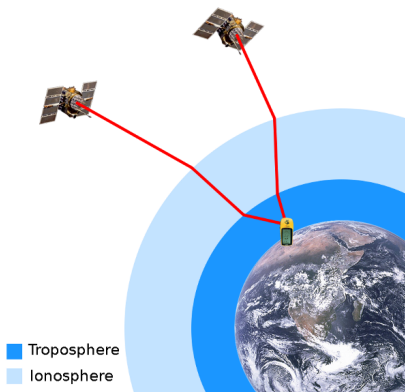
- ▶ Caesium-133 has a resonance (“hyperfine transition”) at ≈ 9 GHz
- ▶ Tune an electronic oscillator to that resonant frequency
- ▶ 1 second = 9,192,631,770 periods of that signal
- ▶ Accuracy ≈ 1 in 10^{-14} (1 second in 3 million years)
- ▶ Price \approx £20,000 (?)
(can get cheaper rubidium clocks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



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

International Atomic Time (TAI): 1 day is $24 \times 60 \times 60 \times 9,192,631,770$ periods of caesium-133's resonant frequency



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

International Atomic Time (TAI): 1 day is $24 \times 60 \times 60 \times 9,192,631,770$ periods of caesium-133's resonant frequency

Problem: speed of Earth's rotation is not constant



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

International Atomic Time (TAI): 1 day is $24 \times 60 \times 60 \times 9,192,631,770$ periods of caesium-133's resonant frequency

Problem: speed of Earth's rotation is not constant

Compromise: UTC is TAI with corrections to account for Earth rotation



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

International Atomic Time (TAI): 1 day is $24 \times 60 \times 60 \times 9,192,631,770$ periods of caesium-133's resonant frequency

Problem: speed of Earth's rotation is not constant

Compromise: UTC is TAI with corrections to account for Earth rotation

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: 2021-11-09T09:50:17+00:00

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: 2021-11-09T09:50:17+00:00

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/

How most software deals with leap seconds

By ignoring them!

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



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

How most software deals with leap seconds

By ignoring them!

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

30 June 2012: bug in Linux kernel caused livelock on leap second, causing many Internet services to go down



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

How most software deals with leap seconds

By ignoring them!

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

30 June 2012: bug in Linux kernel caused livelock on leap second, causing many Internet services to go down

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



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

Clock synchronisation

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

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

Clock synchronisation

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

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

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

Clock synchronisation

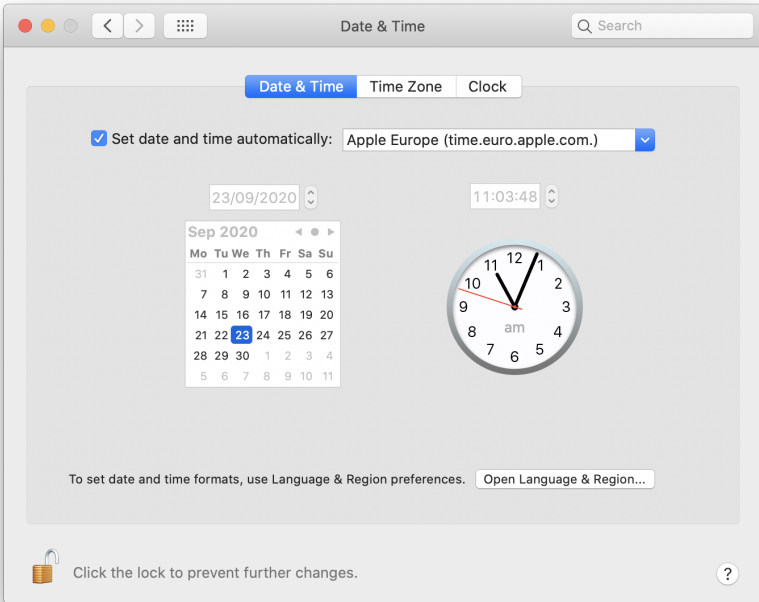
Computers track physical time/UTC with a quartz clock
(with battery, continues running when power is off)

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**)



Network Time Protocol (NTP)

Many operating system vendors run NTP servers,
configure OS to use them by default

Network Time Protocol (NTP)

Many operating system vendors run NTP servers, configure OS to use them by default

Hierarchy of clock servers arranged into **strata**:

- ▶ Stratum 0: atomic clock or GPS receiver
- ▶ Stratum 1: synced directly with stratum 0 device
- ▶ Stratum 2: servers that sync with stratum 1, etc.

Network Time Protocol (NTP)

Many operating system vendors run NTP servers, configure OS to use them by default

Hierarchy of clock servers arranged into **strata**:

- ▶ Stratum 0: atomic clock or GPS receiver
- ▶ Stratum 1: synced directly with stratum 0 device
- ▶ Stratum 2: servers that sync with stratum 1, etc.

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

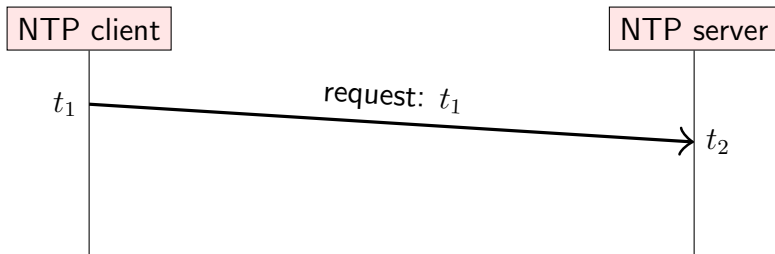
NTP client



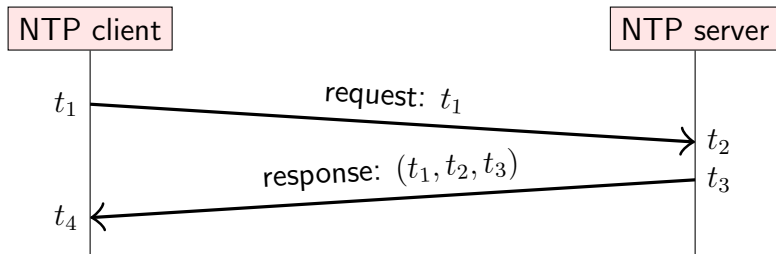
NTP server



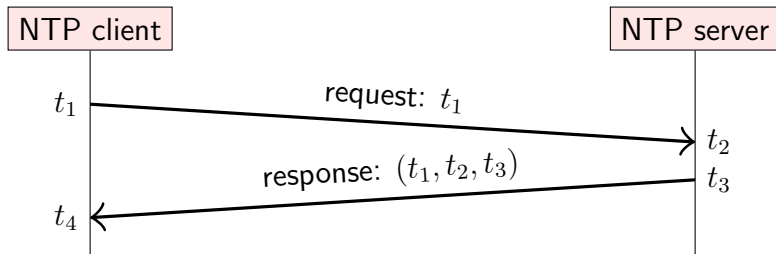
Estimating time over a network



Estimating time over a network

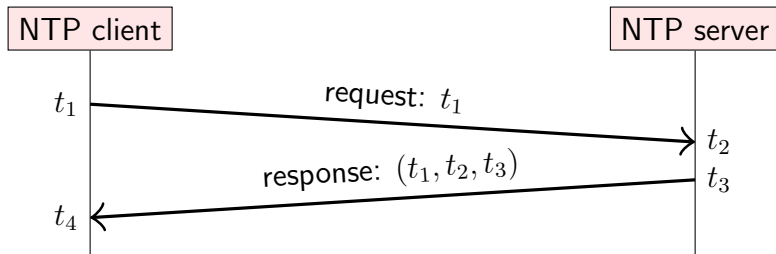


Estimating time over a network



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

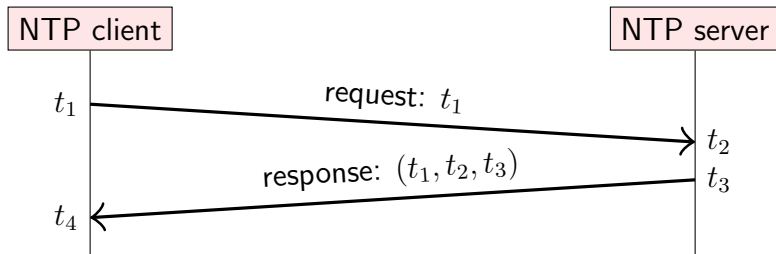
Estimating time over a network



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

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

Estimating time over a network



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

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

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

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 ≈ 5 minutes)

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 ≈ 5 minutes)
- ▶ If $125 \text{ ms} \leq |\theta| < 1,000$ s, **step** the clock:
suddenly reset client clock to estimated server timestamp

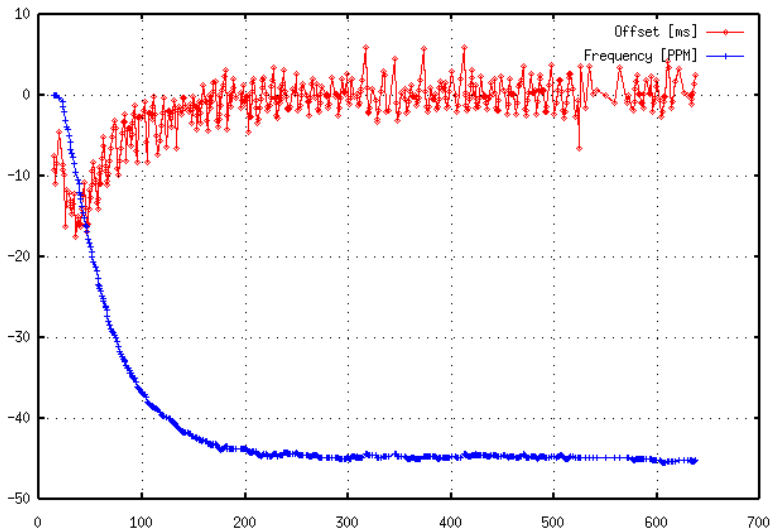
Correcting clock skew

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 ≈ 5 minutes)
- ▶ If $125 \text{ ms} \leq |\theta| < 1,000$ s, **step** the clock:
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!

Initial run of NTP 3.5f on HP L2000-44/2



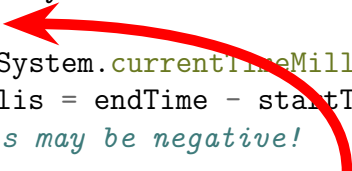
<http://www.ntp.org/ntpfaq/NTP-s-algo.htm>

Monotonic and time-of-day clocks

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

Monotonic and time-of-day clocks

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

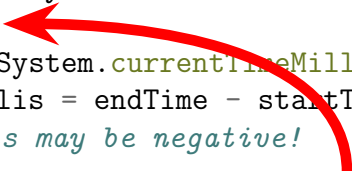


NTP client steps the clock during this

Monotonic and time-of-day clocks

// BAD:

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



NTP client steps the clock during this

// GOOD:

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

Monotonic and time-of-day clocks

Time-of-day clock:

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

Monotonic clock:

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

Monotonic and time-of-day clocks

Time-of-day clock:

- ▶ Time since a fixed date (e.g. 1 January 1970 epoch)
- ▶ May suddenly move forwards or backwards (NTP stepping), subject to leap second adjustments

Monotonic clock:

- ▶ Time since arbitrary point (e.g. when machine booted up)
- ▶ Always moves forwards at near-constant rate

Monotonic and time-of-day clocks

Time-of-day clock:

- ▶ Time since a fixed date (e.g. 1 January 1970 epoch)
- ▶ May suddenly move forwards or backwards (NTP stepping), subject to leap second adjustments
- ▶ Timestamps can be compared across nodes (if synced)

Monotonic clock:

- ▶ Time since arbitrary point (e.g. when machine booted up)
- ▶ Always moves forwards at near-constant rate
- ▶ Good for measuring elapsed time on a single node

Monotonic and time-of-day clocks

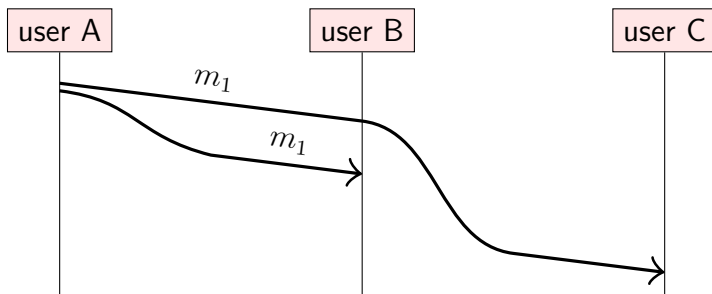
Time-of-day clock:

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

Monotonic clock:

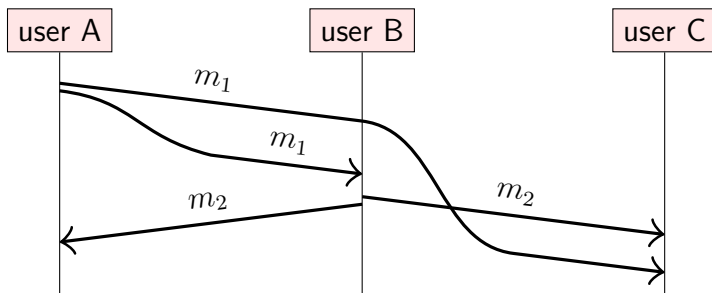
- ▶ Time since arbitrary point (e.g. when machine booted up)
- ▶ Always moves forwards at near-constant rate
- ▶ Good for measuring elapsed time on a single node
- ▶ Java: `System.nanoTime()`
- ▶ Linux: `clock_gettime(CLOCK_MONOTONIC)`

Ordering of messages



m_1 = "A says: The moon is made of cheese!"

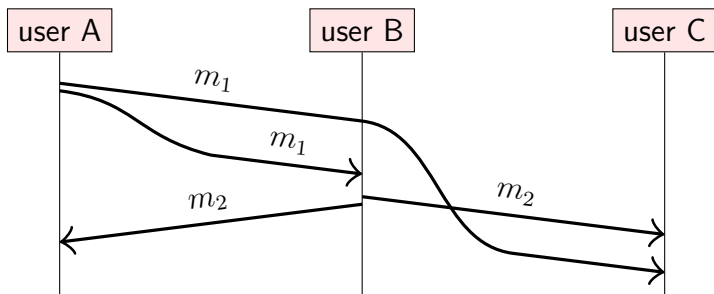
Ordering of messages



m_1 = "A says: The moon is made of cheese!"

m_2 = "B says: Oh no it isn't!"

Ordering of messages

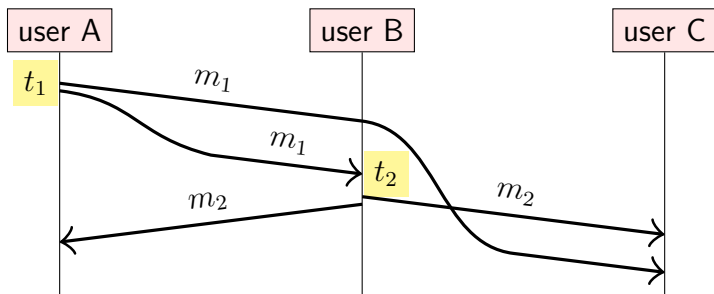


m_1 = "A says: The moon is made of cheese!"

m_2 = "B says: Oh no it isn't!"

C sees m_2 first, m_1 second,
even though logically m_1 **happened before** m_2 .

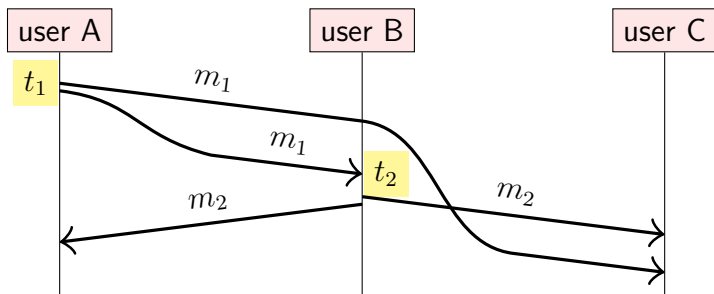
Ordering of messages using timestamps?



$m_1 = (t_1, \text{"A says: The moon is made of cheese!"})$

$m_2 = (t_2, \text{"B says: Oh no it isn't!"})$

Ordering of messages using timestamps?



$m_1 = (t_1, \text{"A says: The moon is made of cheese!"})$

$m_2 = (t_2, \text{"B says: Oh no it isn't!"})$

Problem: even with synced clocks, $t_2 < t_1$ is possible.
Timestamp order is inconsistent with expected order!

The happens-before relation

An **event** is something happening at one node (sending or receiving a message, or a local execution step).

We say event a **happens before** event b (written $a \rightarrow b$) iff:

The happens-before relation

An **event** is something happening at one node (sending or receiving a message, or a local execution step).

We say event a **happens before** event b (written $a \rightarrow b$) iff:

- ▶ a and b occurred at the same node, and a occurred before b in that node's local execution order; or

The happens-before relation

An **event** is something happening at one node (sending or receiving a message, or a local execution step).

We say event a **happens before** event b (written $a \rightarrow b$) iff:

- ▶ a and b occurred at the same node, and a occurred before b in that node's local execution order; or
- ▶ event a is the sending of some message m , and event b is the receipt of that same message m (assuming sent messages are unique); or

The happens-before relation

An **event** is something happening at one node (sending or receiving a message, or a local execution step).

We say event a **happens before** event b (written $a \rightarrow b$) iff:

- ▶ a and b occurred at the same node, and a occurred before b in that node's local execution order; or
- ▶ event a is the sending of some message m , and event b is the receipt of that same message m (assuming sent messages are unique); or
- ▶ there exists an event c such that $a \rightarrow c$ and $c \rightarrow b$.

The happens-before relation

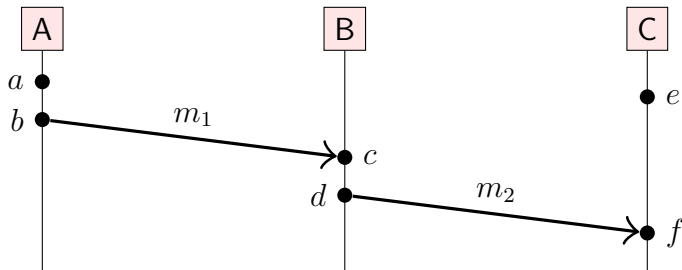
An **event** is something happening at one node (sending or receiving a message, or a local execution step).

We say event a **happens before** event b (written $a \rightarrow b$) iff:

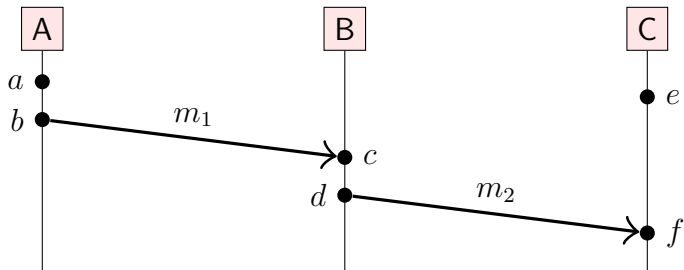
- ▶ a and b occurred at the same node, and a occurred before b in that node's local execution order; or
- ▶ event a is the sending of some message m , and event b is the receipt of that same message m (assuming sent messages are unique); or
- ▶ there exists an event c such that $a \rightarrow c$ and $c \rightarrow b$.

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

Happens-before relation example

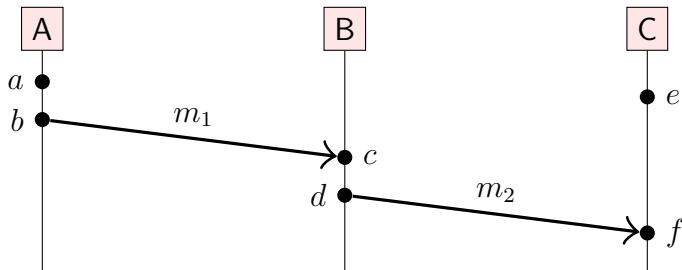


Happens-before relation example



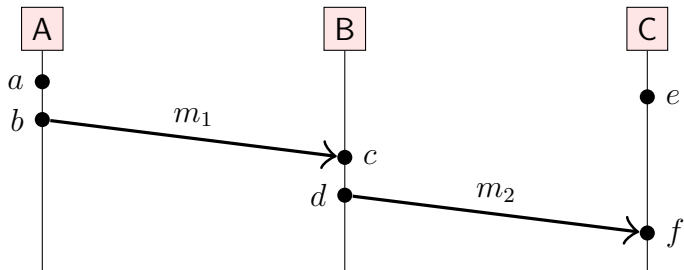
- ▶ $a \rightarrow b$, $c \rightarrow d$, and $e \rightarrow f$ due to node execution order

Happens-before relation example



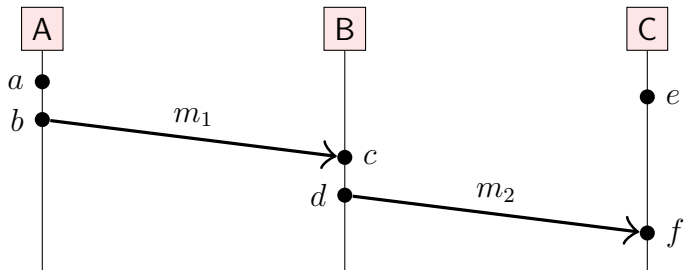
- ▶ $a \rightarrow b$, $c \rightarrow d$, and $e \rightarrow f$ due to node execution order
- ▶ $b \rightarrow c$ and $d \rightarrow f$ due to messages m_1 and m_2

Happens-before relation example



- ▶ $a \rightarrow b$, $c \rightarrow d$, and $e \rightarrow f$ due to node execution order
- ▶ $b \rightarrow c$ and $d \rightarrow f$ due to messages m_1 and m_2
- ▶ $a \rightarrow c$, $a \rightarrow d$, $a \rightarrow f$, $b \rightarrow d$, $b \rightarrow f$, and $c \rightarrow f$ due to transitivity

Happens-before relation example



- ▶ $a \rightarrow b$, $c \rightarrow d$, and $e \rightarrow f$ due to node execution order
- ▶ $b \rightarrow c$ and $d \rightarrow f$ due to messages m_1 and m_2
- ▶ $a \rightarrow c$, $a \rightarrow d$, $a \rightarrow f$, $b \rightarrow d$, $b \rightarrow f$, and $c \rightarrow f$ due to transitivity
- ▶ $a \parallel e$, $b \parallel e$, $c \parallel e$, and $d \parallel e$

Causality

Taken from physics (relativity).

- ▶ When $a \rightarrow b$, then a **might have caused** b .
- ▶ When $a \parallel b$, we know that a **cannot have caused** b .

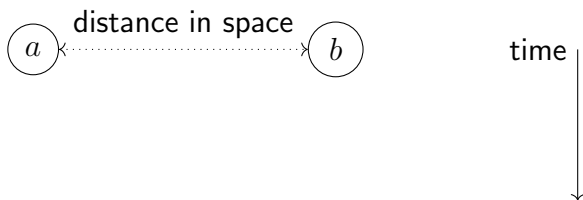
Happens-before relation encodes **potential causality**.

Causality

Taken from physics (relativity).

- ▶ When $a \rightarrow b$, then a **might have caused** b .
- ▶ When $a \parallel b$, we know that a **cannot have caused** b .

Happens-before relation encodes **potential causality**.

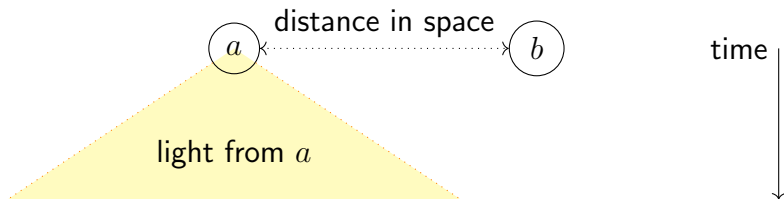


Causality

Taken from physics (relativity).

- ▶ When $a \rightarrow b$, then a **might have caused** b .
- ▶ When $a \parallel b$, we know that a **cannot have caused** b .

Happens-before relation encodes **potential causality**.

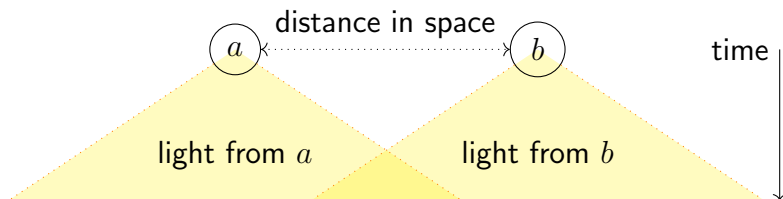


Causality

Taken from physics (relativity).

- ▶ When $a \rightarrow b$, then a **might have caused** b .
- ▶ When $a \parallel b$, we know that a **cannot have caused** b .

Happens-before relation encodes **potential causality**.

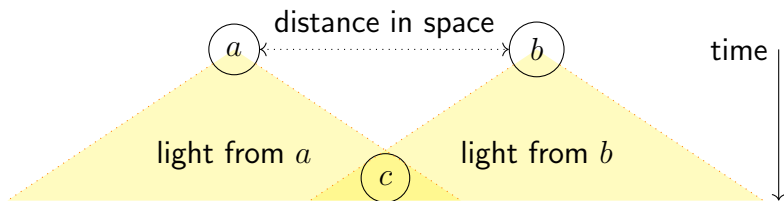


Causality

Taken from physics (relativity).

- ▶ When $a \rightarrow b$, then a **might have caused** b .
- ▶ When $a \parallel b$, we know that a **cannot have caused** b .

Happens-before relation encodes **potential causality**.

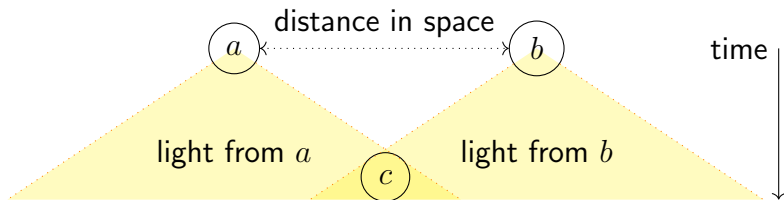


Causality

Taken from physics (relativity).

- ▶ When $a \rightarrow b$, then a **might have caused** b .
- ▶ When $a \parallel b$, we know that a **cannot have caused** b .

Happens-before relation encodes **potential causality**.



Let \prec be a strict total order on events.

If $(a \rightarrow b) \implies (a \prec b)$ then \prec is a **causal order**
(or: \prec is "consistent with causality").

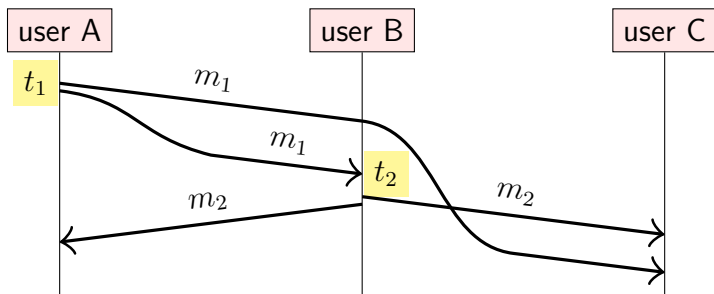
NB. "causal" \neq "casual"!

Broadcast protocols and logical time

Dr. Martin Kleppmann
martin.kleppmann@cst.cam.ac.uk

University of Cambridge
Computer Science Tripos, Part IB

Physical timestamps inconsistent with causality



$m_1 = (t_1, \text{"A says: The moon is made of cheese!"})$

$m_2 = (t_2, \text{"B says: Oh no it isn't!"})$

Problem: even with synced clocks, $t_2 < t_1$ is possible.
Timestamp order is inconsistent with expected order!

Logical vs. physical clocks

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

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

Logical vs. physical clocks

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

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

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

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

Logical vs. physical clocks

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

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

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

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

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

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

Properties of this scheme:

- ▶ If $a \rightarrow b$ then $L(a) < L(b)$

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

Properties of this scheme:

- ▶ If $a \rightarrow b$ then $L(a) < L(b)$
- ▶ However, $L(a) < L(b)$ does not imply $a \rightarrow b$

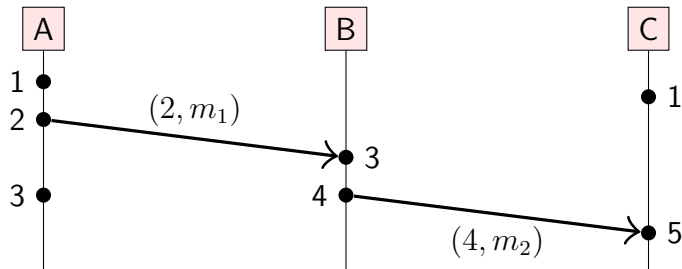
Lamport clocks in words

- ▶ 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

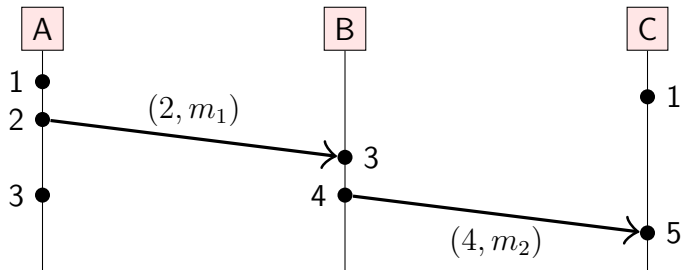
Properties of this scheme:

- ▶ If $a \rightarrow b$ then $L(a) < L(b)$
- ▶ However, $L(a) < L(b)$ does not imply $a \rightarrow b$
- ▶ Possible that $L(a) = L(b)$ for $a \neq b$

Lamport clocks example

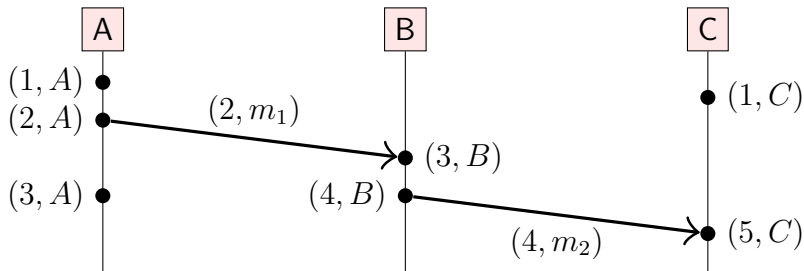


Lamport clocks example



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

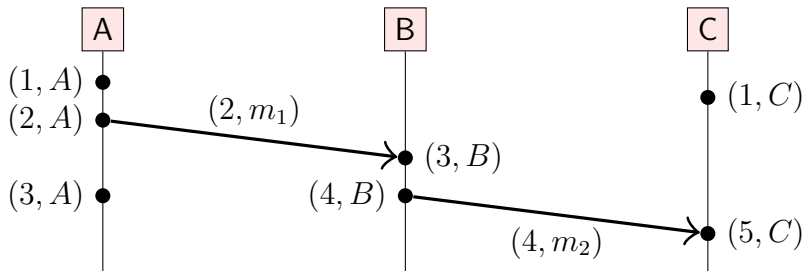
Lamport clocks example



Let $N(e)$ be the node at which event e occurred.

Then the pair $(L(e), N(e))$ **uniquely identifies** event e .

Lamport clocks example



Let $N(e)$ be the node at which event e occurred.

Then the pair $(L(e), N(e))$ **uniquely identifies** event e .

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

$$(a \prec b) \iff (L(a) < L(b) \vee (L(a) = L(b) \wedge N(a) < N(b)))$$

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

Vector clocks

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

If we want to detect which events are concurrent, we need **vector clocks**:

Vector clocks

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

If we want to detect which events are concurrent, we need **vector clocks**:

- ▶ Assume n nodes in the system, $N = \langle N_0, N_1, \dots, N_{n-1} \rangle$

Vector clocks

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

If we want to detect which events are concurrent, we need **vector clocks**:

- ▶ Assume n nodes in the system, $N = \langle N_0, N_1, \dots, N_{n-1} \rangle$
- ▶ Vector timestamp of event a is $V(a) = \langle t_0, t_1, \dots, t_{n-1} \rangle$
- ▶ t_i is number of events observed by node N_i

Vector clocks

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

If we want to detect which events are concurrent, we need **vector clocks**:

- ▶ Assume n nodes in the system, $N = \langle N_0, N_1, \dots, N_{n-1} \rangle$
- ▶ Vector timestamp of event a is $V(a) = \langle t_0, t_1, \dots, t_{n-1} \rangle$
- ▶ t_i is number of events observed by node N_i
- ▶ Each node has a current vector timestamp T
- ▶ On event at node N_i , increment vector element $T[i]$

Vector clocks

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

If we want to detect which events are concurrent, we need **vector clocks**:

- ▶ Assume n nodes in the system, $N = \langle N_0, N_1, \dots, N_{n-1} \rangle$
- ▶ Vector timestamp of event a is $V(a) = \langle t_0, t_1, \dots, t_{n-1} \rangle$
- ▶ t_i is number of events observed by node N_i
- ▶ Each node has a current vector timestamp T
- ▶ On event at node N_i , increment vector element $T[i]$
- ▶ Attach current vector timestamp to each message
- ▶ Recipient merges message vector into its local vector

Vector clocks algorithm

on initialisation at node N_i **do**

$T := \langle 0, 0, \dots, 0 \rangle$ ▷ 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**

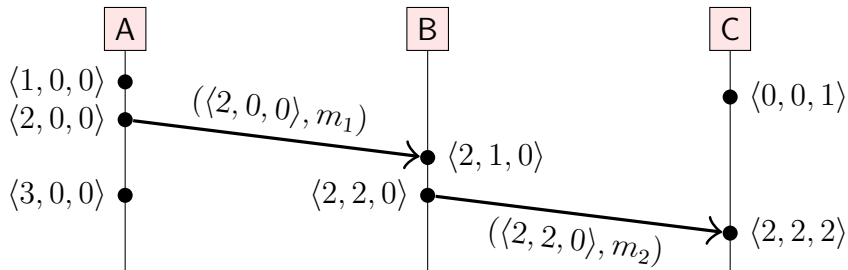
$T[j] := \max(T[j], T'[j])$ for every $j \in \{0, \dots, n-1\}$

$T[i] := T[i] + 1$; deliver m to the application

end on

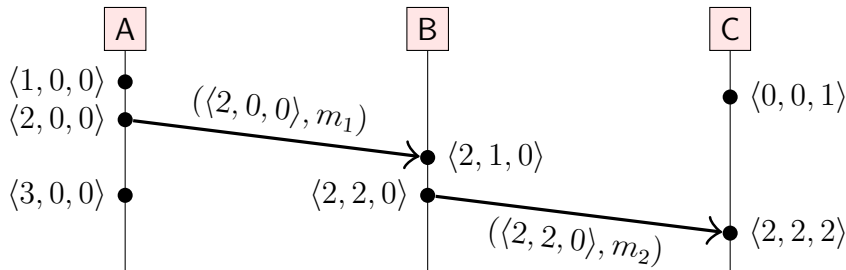
Vector clocks example

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



Vector clocks example

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



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 $i \in \{0, \dots, n-1\}$
- ▶ $T \leq T'$ iff $T[i] \leq T'[i]$ for all $i \in \{0, \dots, n-1\}$
- ▶ $T < T'$ iff $T \leq T'$ and $T \neq T'$
- ▶ $T \parallel T'$ iff $T \not\leq T'$ and $T' \not\leq T$

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 $i \in \{0, \dots, n-1\}$
- ▶ $T \leq T'$ iff $T[i] \leq T'[i]$ for all $i \in \{0, \dots, n-1\}$
- ▶ $T < T'$ iff $T \leq T'$ and $T \neq T'$
- ▶ $T \parallel T'$ iff $T \not\leq T'$ and $T' \not\leq T$

$$V(a) \leq V(b) \text{ iff } (\{a\} \cup \{e \mid e \rightarrow a\}) \subseteq (\{b\} \cup \{e \mid e \rightarrow b\})$$

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 $i \in \{0, \dots, n-1\}$
- ▶ $T \leq T'$ iff $T[i] \leq T'[i]$ for all $i \in \{0, \dots, n-1\}$
- ▶ $T < T'$ iff $T \leq T'$ and $T \neq T'$
- ▶ $T \parallel T'$ iff $T \not\leq T'$ and $T' \not\leq T$

$$V(a) \leq V(b) \text{ iff } (\{a\} \cup \{e \mid e \rightarrow a\}) \subseteq (\{b\} \cup \{e \mid e \rightarrow b\})$$

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

Broadcast (multicast) is **group communication**:

- ▶ One node sends message, all nodes in group deliver it

Broadcast protocols

Broadcast (multicast) is **group communication**:

- ▶ One node sends message, all nodes in group deliver it
- ▶ Set of group members may be fixed (static) or dynamic

Broadcast protocols

Broadcast (multicast) is **group communication**:

- ▶ One node sends message, all nodes in group deliver it
- ▶ Set of group members may be fixed (static) or dynamic
- ▶ If one node is faulty, remaining group members carry on

Broadcast protocols

Broadcast (multicast) is **group communication**:

- ▶ One node sends message, all nodes in group deliver it
- ▶ Set of group members may be fixed (static) or dynamic
- ▶ If one node is faulty, remaining group members carry on
- ▶ Note: concept is more general than IP multicast
(we build upon point-to-point messaging)

Broadcast protocols

Broadcast (multicast) is **group communication**:

- ▶ One node sends message, all nodes in group deliver it
- ▶ Set of group members may be fixed (static) or dynamic
- ▶ If one node is faulty, remaining group members carry on
- ▶ Note: concept is more general than IP multicast (we build upon point-to-point messaging)

Build upon system models from earlier lecture:

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

Broadcast protocols

Broadcast (multicast) is **group communication**:

- ▶ One node sends message, all nodes in group deliver it
- ▶ Set of group members may be fixed (static) or dynamic
- ▶ If one node is faulty, remaining group members carry on
- ▶ Note: concept is more general than IP multicast
(we build upon point-to-point messaging)

Build upon system models from earlier lecture:

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

Receiving versus delivering

Node A :

Application

Broadcast algorithm
(middleware)

Node B :

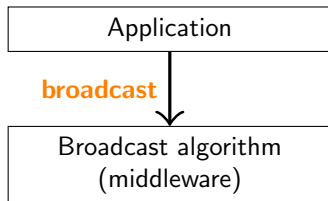
Application

Broadcast algorithm
(middleware)

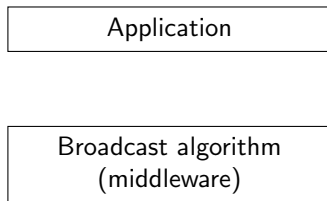
Network

Receiving versus delivering

Node *A*:

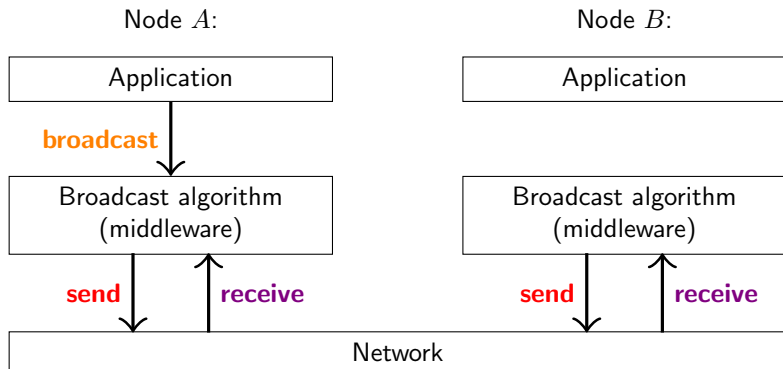


Node *B*:



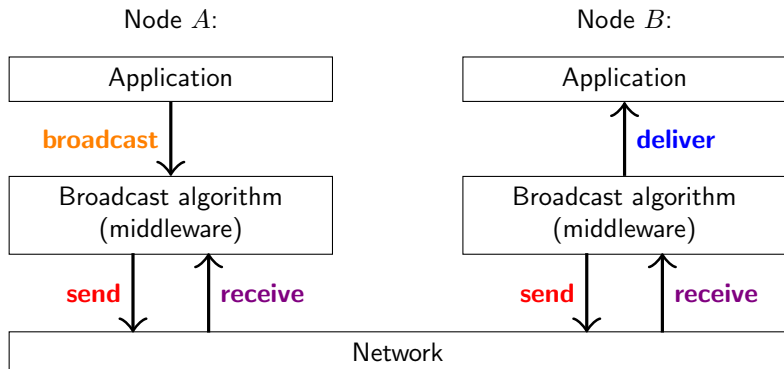
Network

Receiving versus delivering



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 $\text{broadcast}(m_1) \rightarrow \text{broadcast}(m_2)$, then m_1 must be delivered before m_2

Forms of reliable broadcast

FIFO broadcast:

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

Causal broadcast:

If $\text{broadcast}(m_1) \rightarrow \text{broadcast}(m_2)$ then m_1 must be delivered before m_2

Forms of reliable broadcast

FIFO broadcast:

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

Causal broadcast:

If $\text{broadcast}(m_1) \rightarrow \text{broadcast}(m_2)$ then m_1 must be delivered before m_2

Total order broadcast:

If m_1 is delivered before m_2 on one node, then m_1 must be delivered before m_2 on all nodes

Forms of reliable broadcast

FIFO broadcast:

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

Causal broadcast:

If $\text{broadcast}(m_1) \rightarrow \text{broadcast}(m_2)$ then m_1 must be delivered before m_2

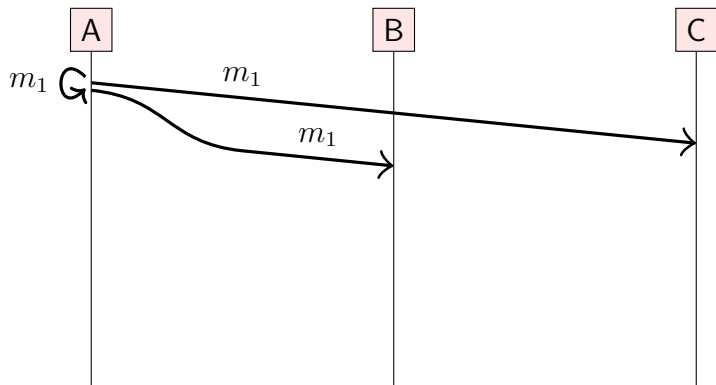
Total order broadcast:

If m_1 is delivered before m_2 on one node, then m_1 must be delivered before m_2 on all nodes

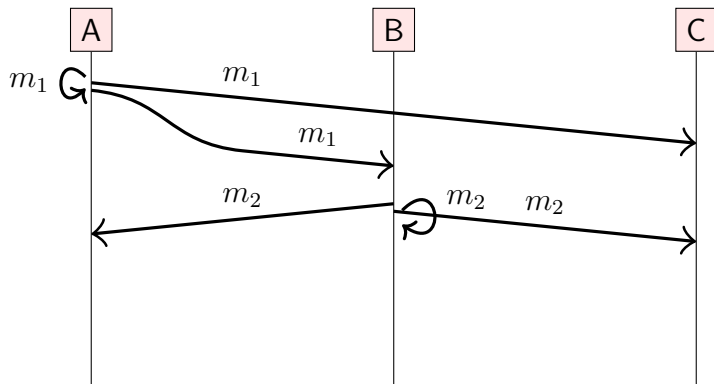
FIFO-total order broadcast:

Combination of FIFO broadcast and total order broadcast

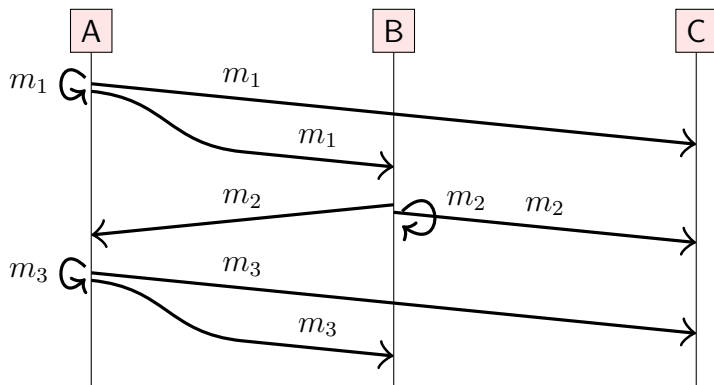
FIFO broadcast



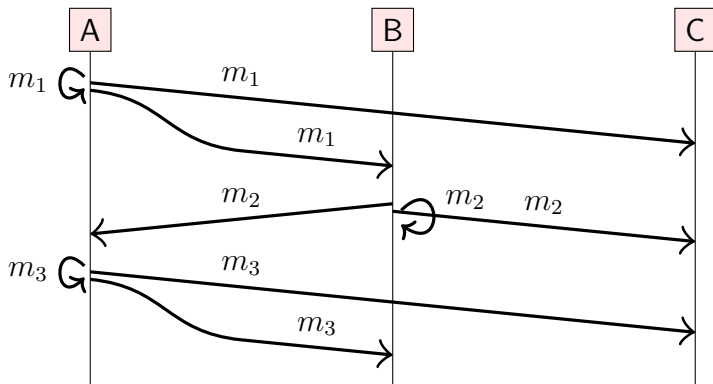
FIFO broadcast



FIFO broadcast



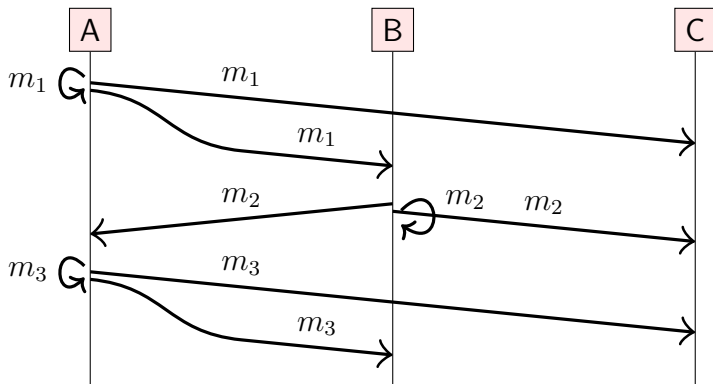
FIFO broadcast



Messages sent by the same node must be delivered in the order they were sent.

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

FIFO broadcast

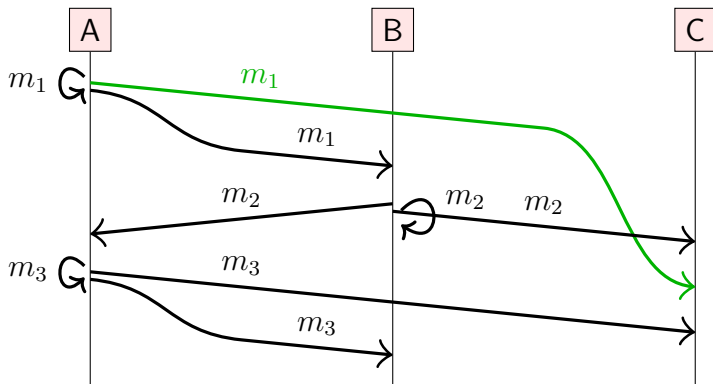


Messages sent by the same node must be delivered in the order they were sent.

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

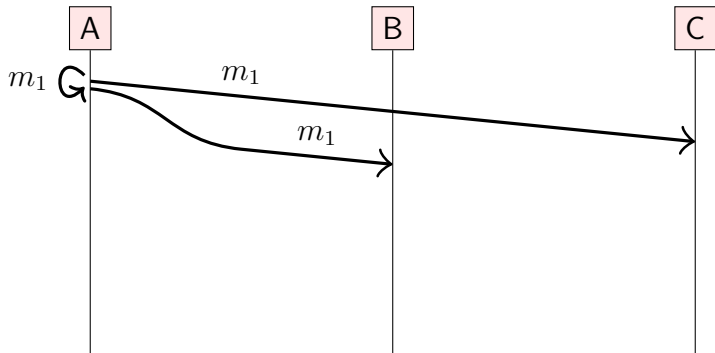


Messages sent by the same node must be delivered in the order they were sent.

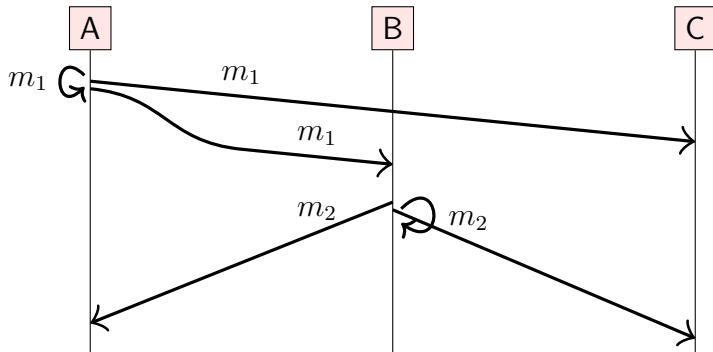
Messages sent by different nodes can be delivered in any order.

Valid orders: (m_2, m_1, m_3) or (m_1, m_2, m_3) or (m_1, m_3, m_2)

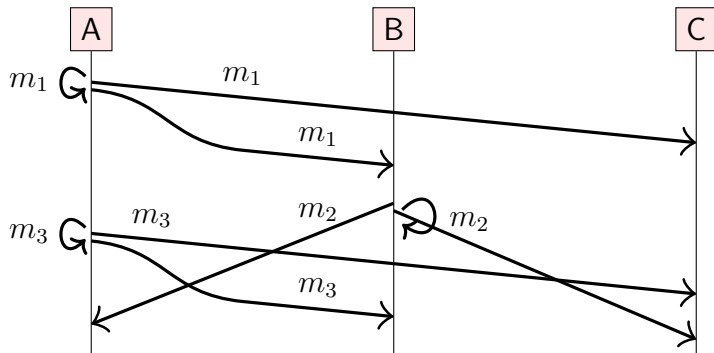
Causal broadcast



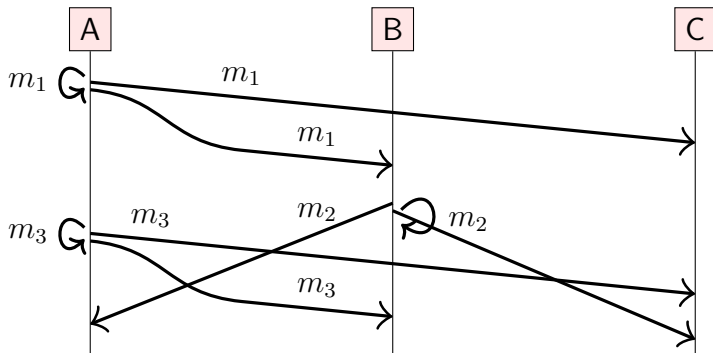
Causal broadcast



Causal broadcast

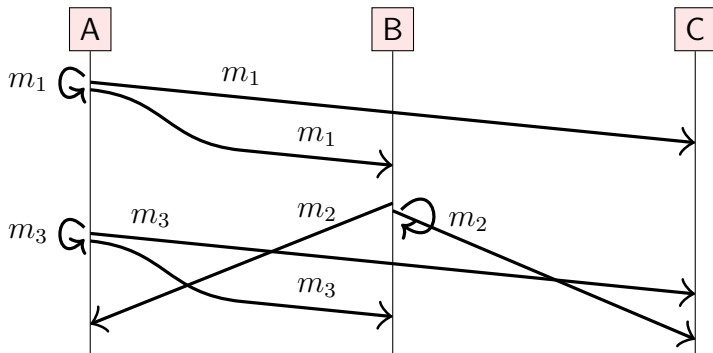


Causal broadcast



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

Causal broadcast

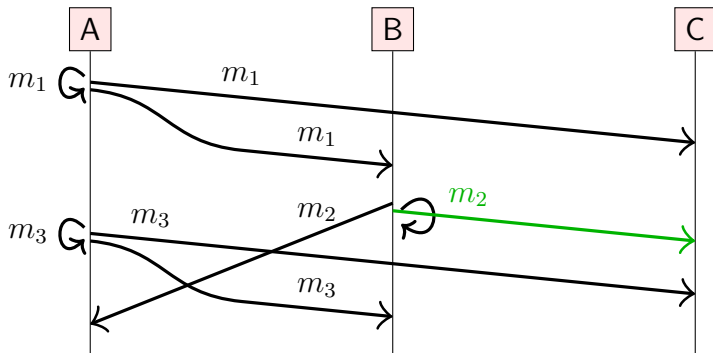


Causally related messages must be delivered in causal order.
Concurrent messages can be delivered in any order.

Here: $\text{broadcast}(m_1) \rightarrow \text{broadcast}(m_2)$ and
 $\text{broadcast}(m_1) \rightarrow \text{broadcast}(m_3)$

\Rightarrow valid orders are: (m_1, m_2, m_3) or (m_1, m_3, m_2)

Causal broadcast

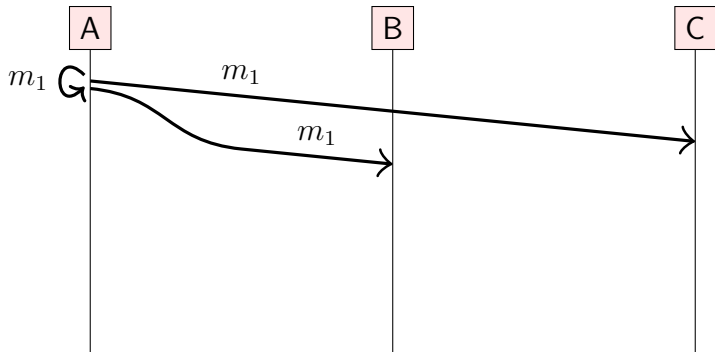


Causally related messages must be delivered in causal order.
Concurrent messages can be delivered in any order.

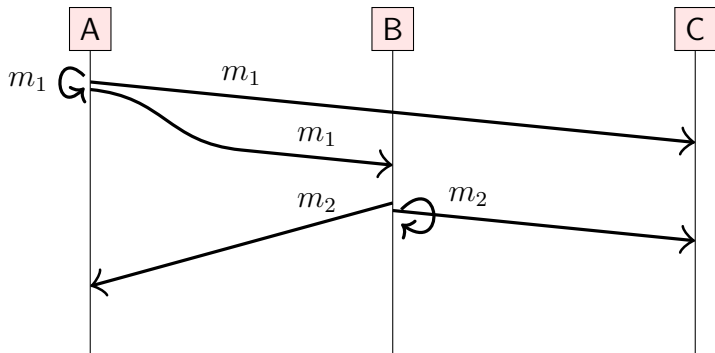
Here: $\text{broadcast}(m_1) \rightarrow \text{broadcast}(m_2)$ and
 $\text{broadcast}(m_1) \rightarrow \text{broadcast}(m_3)$

\Rightarrow valid orders are: (m_1, m_2, m_3) or (m_1, m_3, m_2)

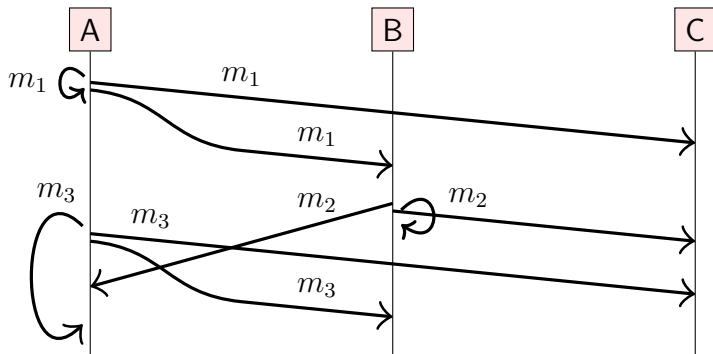
Total order broadcast (1)



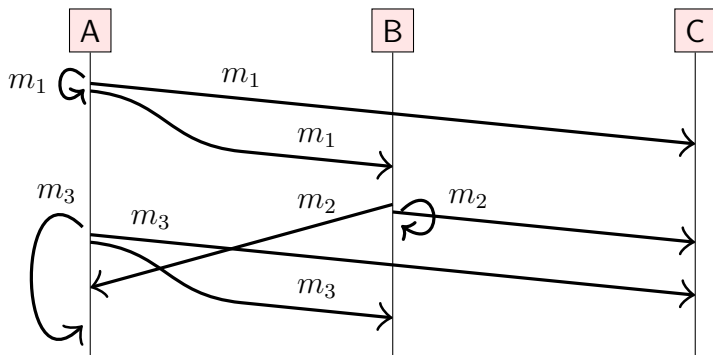
Total order broadcast (1)



Total order broadcast (1)

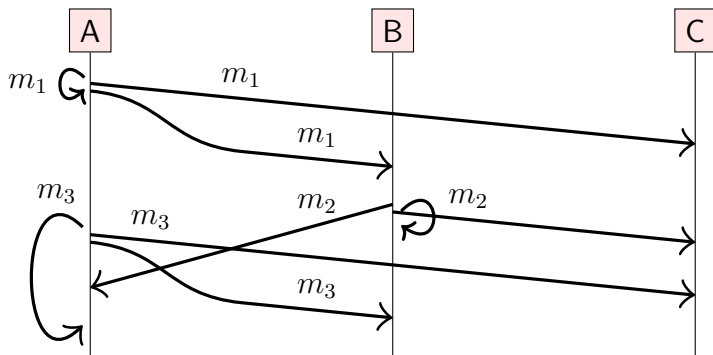


Total order broadcast (1)



All nodes must deliver messages in **the same** order
(here: m_1, m_2, m_3)

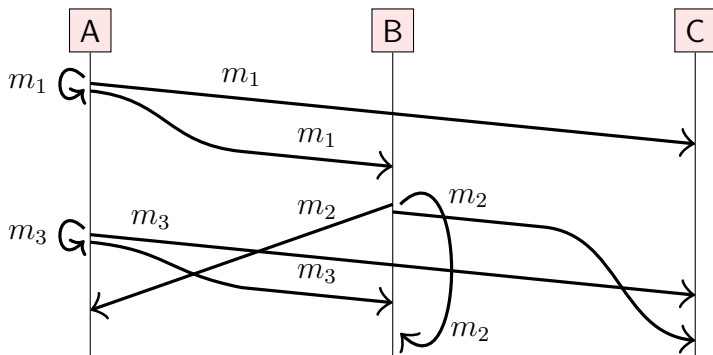
Total order broadcast (1)



All nodes must deliver messages in **the same** order
(here: m_1, m_2, m_3)

This includes a node's deliveries to itself!

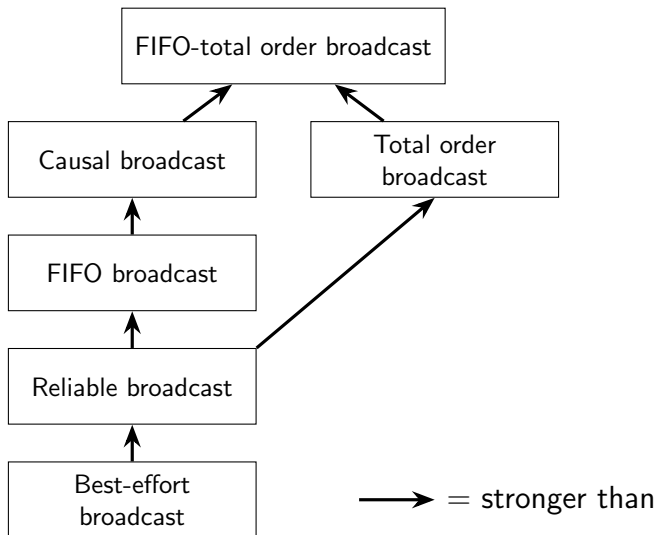
Total order broadcast (2)



All nodes must deliver messages in **the same** order
(here: m_1, m_3, m_2)

This includes a node's deliveries to itself!

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

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

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

- ▶ Use reliable links (retry + deduplicate)

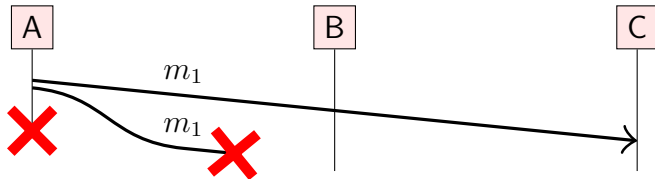
Broadcast algorithms

Break down into two layers:

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

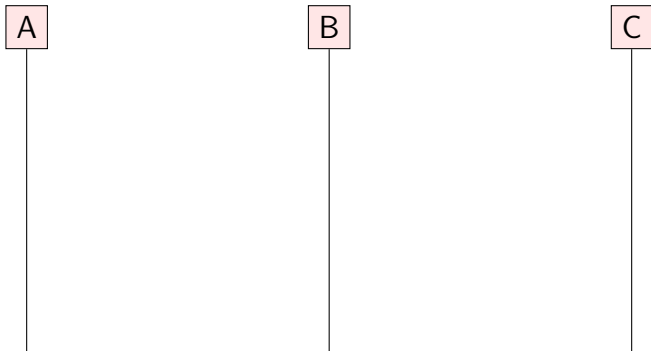
First attempt: **broadcasting node sends message directly** to every other node

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



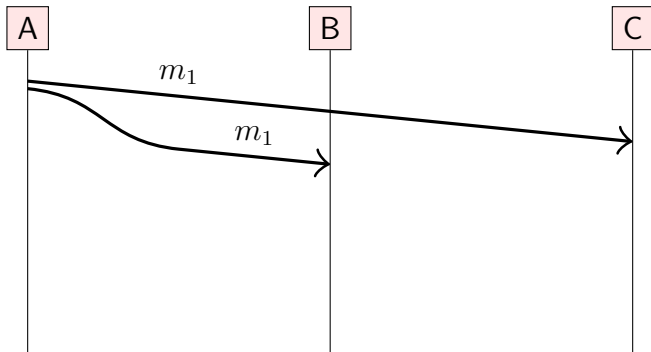
Eager reliable broadcast

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



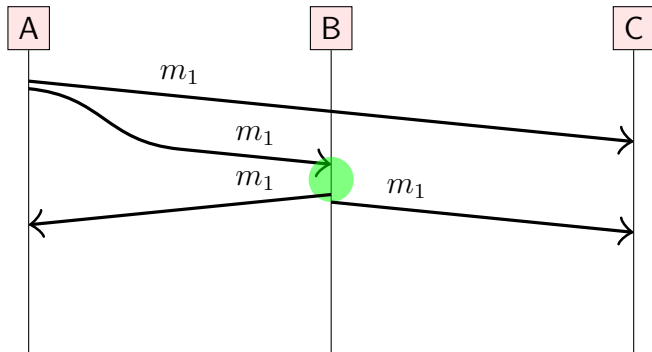
Eager reliable broadcast

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



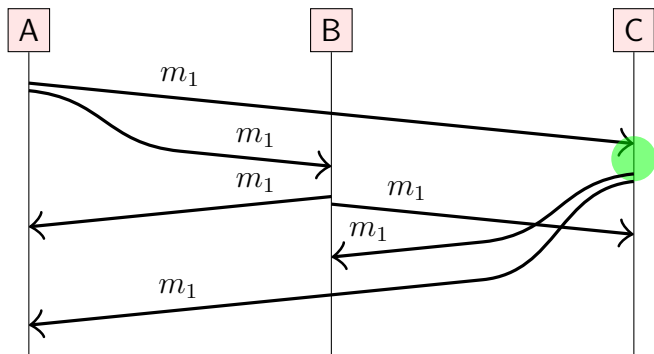
Eager reliable broadcast

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



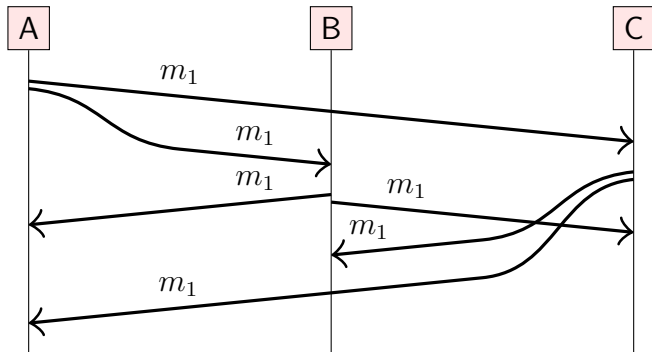
Eager reliable broadcast

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



Eager reliable broadcast

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

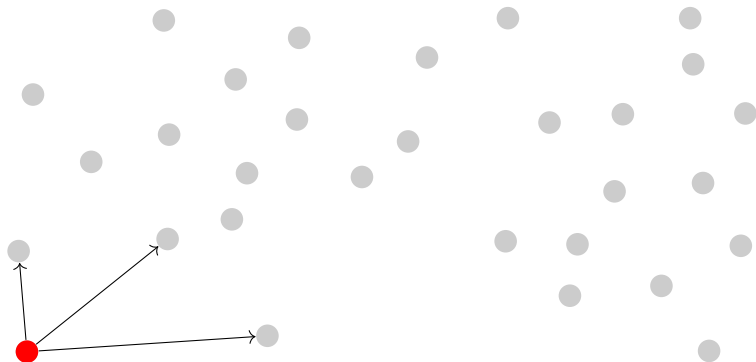


Reliable, but... up to $O(n^2)$ messages for n nodes!

Gossip protocols

Useful when broadcasting to a large number of nodes.

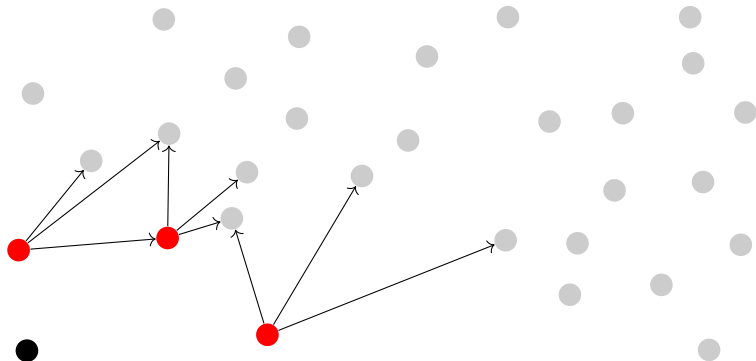
Idea: when a node receives a message for the first time,
forward it to 3 other nodes, chosen randomly.



Gossip protocols

Useful when broadcasting to a large number of nodes.

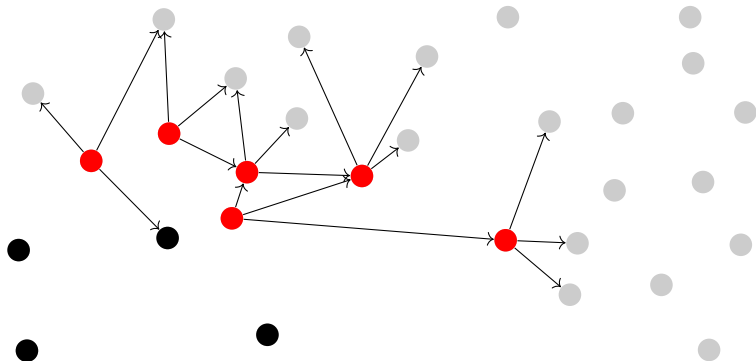
Idea: when a node receives a message for the first time,
forward it to 3 other nodes, chosen randomly.



Gossip protocols

Useful when broadcasting to a large number of nodes.

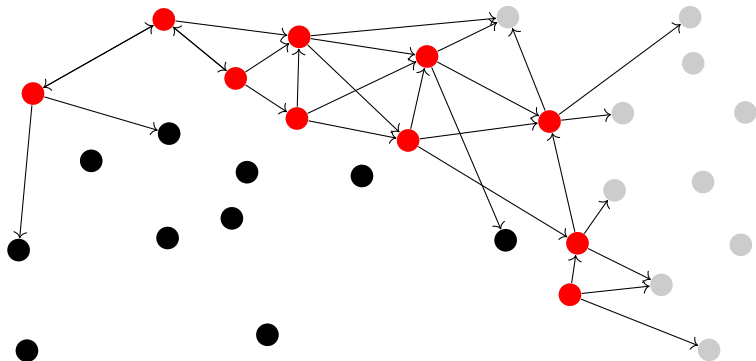
Idea: when a node receives a message for the first time,
forward it to 3 other nodes, chosen randomly.



Gossip protocols

Useful when broadcasting to a large number of nodes.

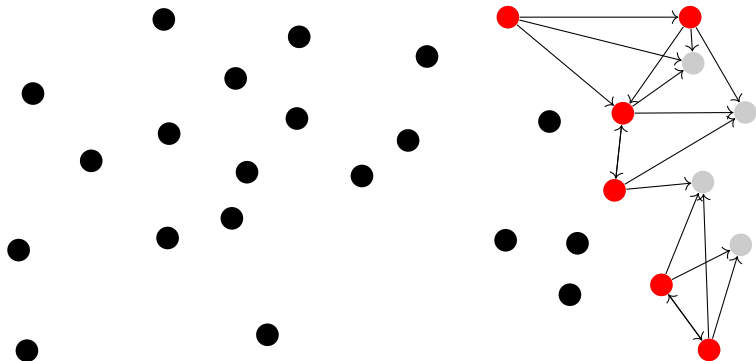
Idea: when a node receives a message for the first time, **forward it to 3 other nodes**, chosen randomly.



Gossip protocols

Useful when broadcasting to a large number of nodes.

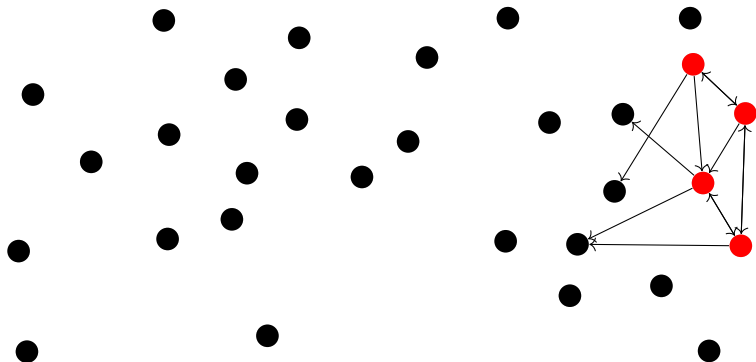
Idea: when a node receives a message for the first time, **forward it to 3 other nodes**, chosen randomly.



Gossip protocols

Useful when broadcasting to a large number of nodes.

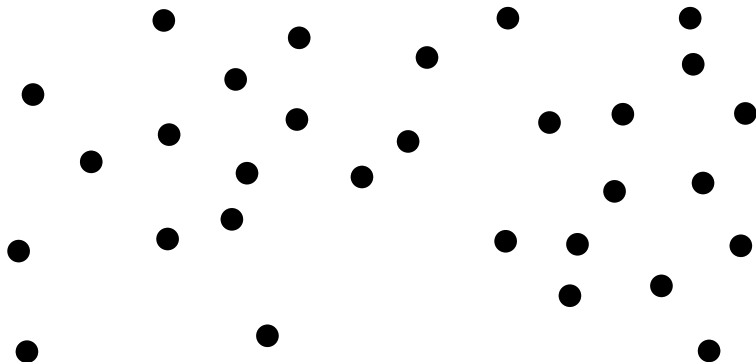
Idea: when a node receives a message for the first time,
forward it to 3 other nodes, chosen randomly.



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.



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**

$sendSeq := 0$; $delivered := \langle 0, 0, \dots, 0 \rangle$; $buffer := \{\}$

end on

on request to broadcast m at node N_i **do**

$deps := delivered$; $deps[i] := sendSeq$

send $(i, deps, m)$ via reliable broadcast

$sendSeq := sendSeq + 1$

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 $i \in \{0, \dots, n-1\}$
- ▶ $T \leq T'$ iff $T[i] \leq T'[i]$ for all $i \in \{0, \dots, n-1\}$
- ▶ $T < T'$ 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.

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.
- ▶ Problem: leader crashes \implies no more messages delivered
- ▶ Changing the leader safely is difficult

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.
- ▶ Problem: leader crashes \implies no more messages delivered
- ▶ Changing the leader safely is difficult

Lamport clocks approach:

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

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.
- ▶ Problem: leader crashes \implies no more messages delivered
- ▶ Changing the leader safely is difficult

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

Replication

Dr. Martin Kleppmann
martin.kleppmann@cst.cam.ac.uk

University of Cambridge
Computer Science Tripos, Part IB

Replication

- ▶ 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**

Replication

- ▶ 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**
- ▶ If some replicas are faulty, others are still accessible
- ▶ Spread load across many replicas

Replication

- ▶ 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**
- ▶ If some replicas are faulty, others are still accessible
- ▶ Spread load across many replicas
- ▶ Easy if the data doesn't change: just copy it
- ▶ We will focus on data changes

Replication

- ▶ 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**
- ▶ If some replicas are faulty, others are still accessible
- ▶ Spread load across many replicas
- ▶ Easy if the data doesn't change: just copy it
- ▶ We will focus on data changes

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

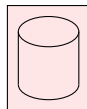
User A: The moon is not actually made of cheese!



Like

12,300 people like this.

client

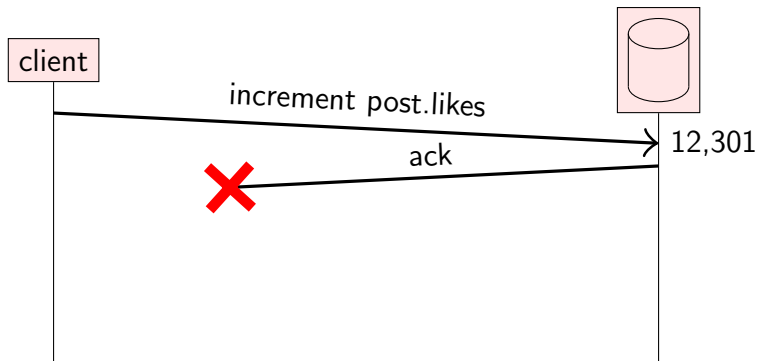


Retrying state updates

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




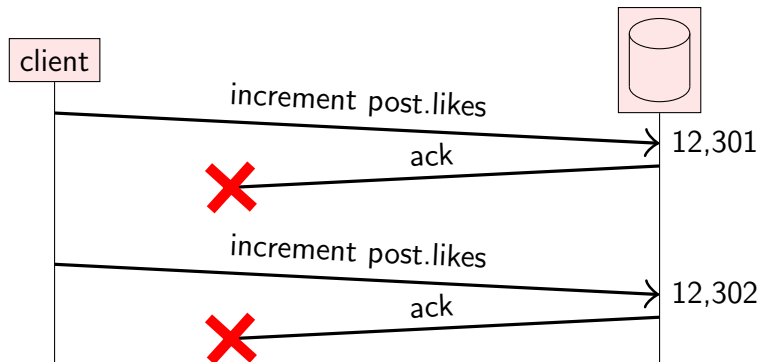
12,300 people like this.



Retrying state updates

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

 Like 12,300 people like this.

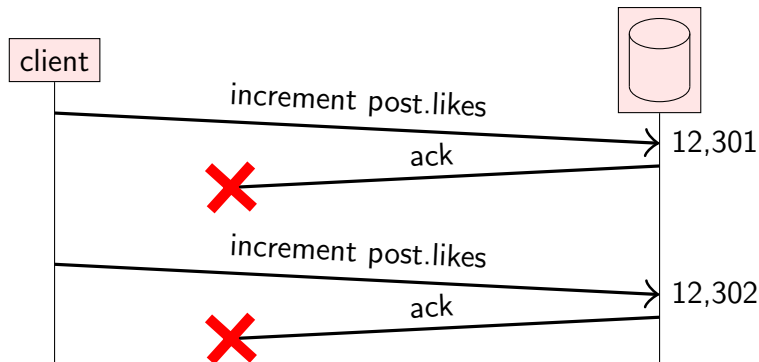


Retrying state updates

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



12,300 people like this.



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



TWEETS
6,219

FOLLOWING
-20

FOLLOWERS
24.1K



Follow

Лепра

@lepratorium



Добро пожаловать отсюда

Default City



Лепра @lepratorium · 2h

Викторианские советы

Часть 2 pic.twitter.com/21PraRYBaO

Details



Лепра @lepratorium · 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:** $f(\text{likeCount}) = \text{likeCount} + 1$
- ▶ **Idempotent:** $f(\text{likeSet}) = \text{likeSet} \cup \{\text{userID}\}$

Idempotent requests can be retried safely.

Idempotence

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

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

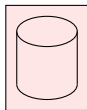
Idempotent requests can be retried safely.

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

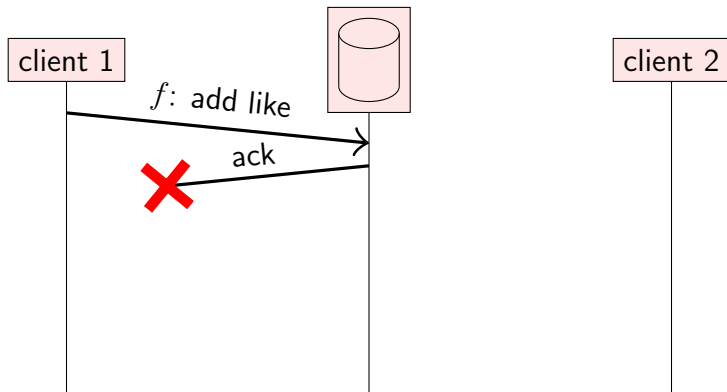
Adding and then removing again

client 1



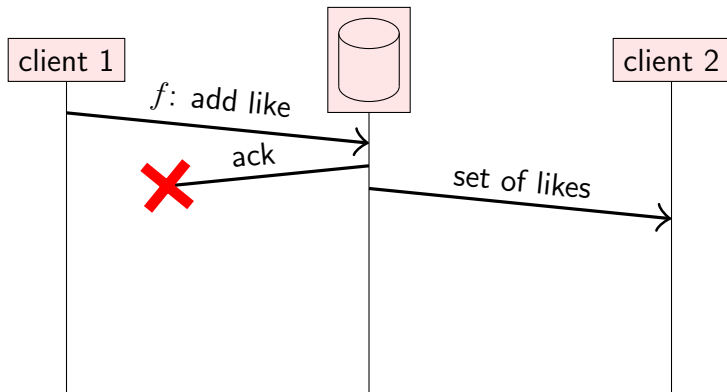
client 2

Adding and then removing again



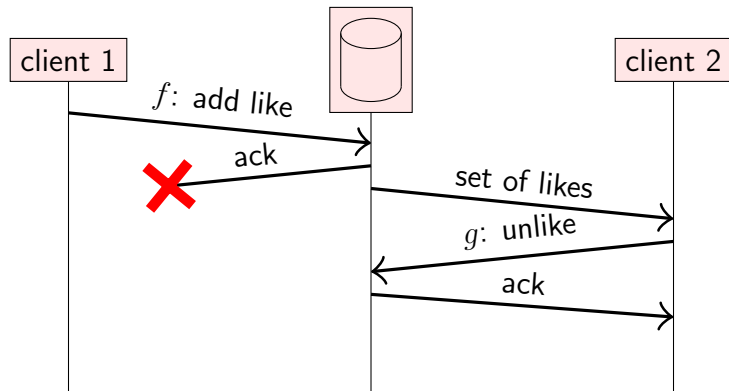
$$f(\text{likes}) = \text{likes} \cup \{\text{userID}\}$$

Adding and then removing again



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

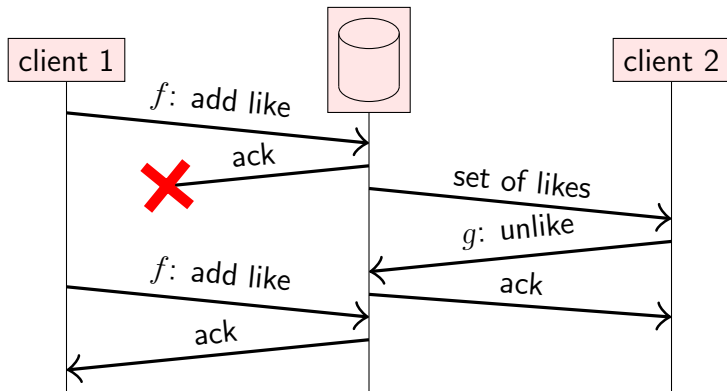
Adding and then removing again



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

$$g(\text{likes}) = \text{likes} \setminus \{\text{userID}\}$$

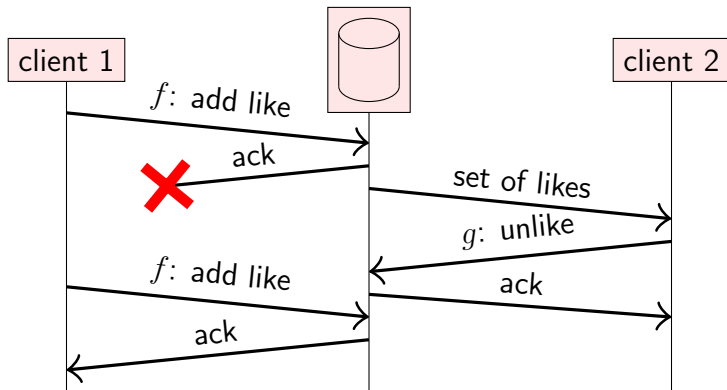
Adding and then removing again



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

$$g(\text{likes}) = \text{likes} \setminus \{\text{userID}\}$$

Adding and then removing again

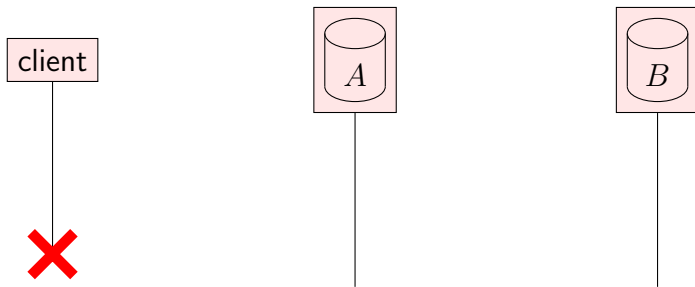


$$f(\text{likes}) = \text{likes} \cup \{\text{userID}\}$$

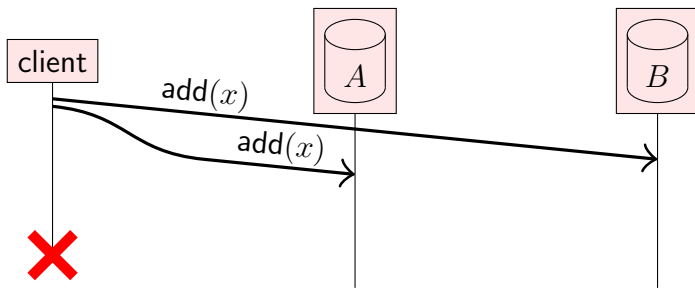
$$g(\text{likes}) = \text{likes} \setminus \{\text{userID}\}$$

Idempotent? $f(f(x)) = f(x)$ but $f(g(f(x))) \neq g(f(x))$

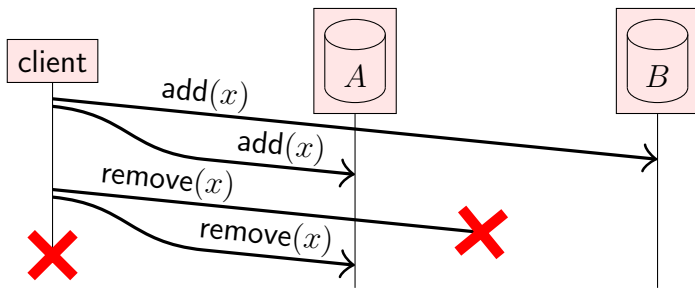
Another problem with adding and removing



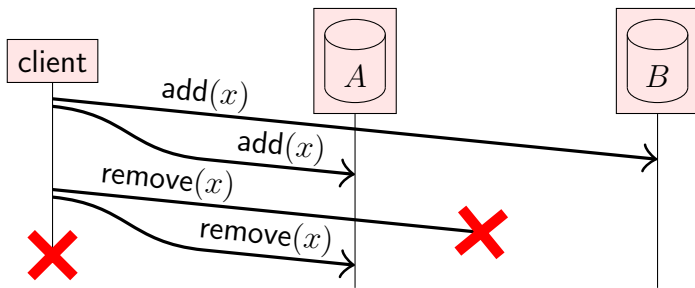
Another problem with adding and removing



Another problem with adding and removing

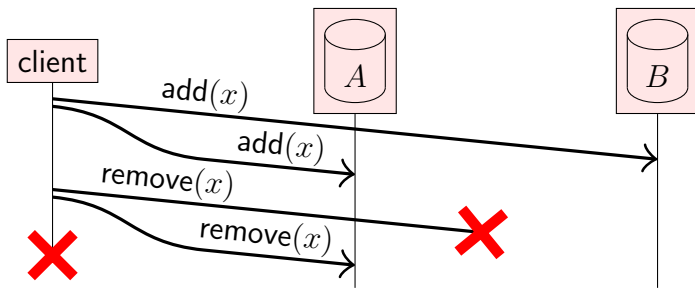


Another problem with adding and removing

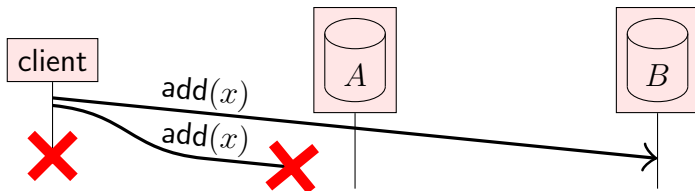


Final state ($x \notin A, x \in B$) is the same as in this case:

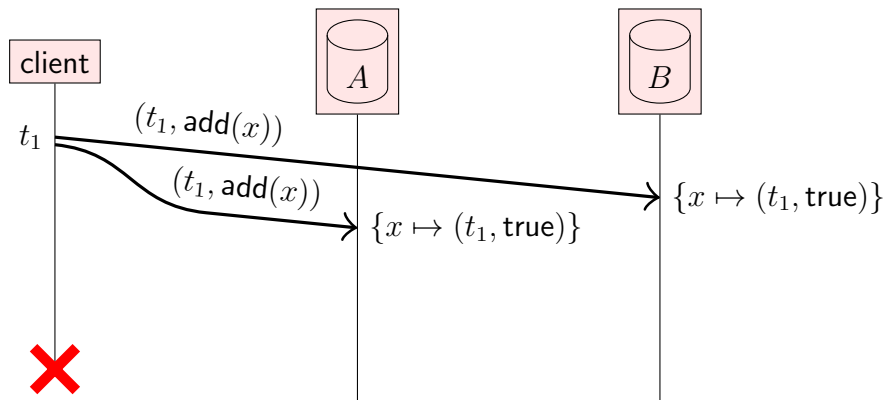
Another problem with adding and removing



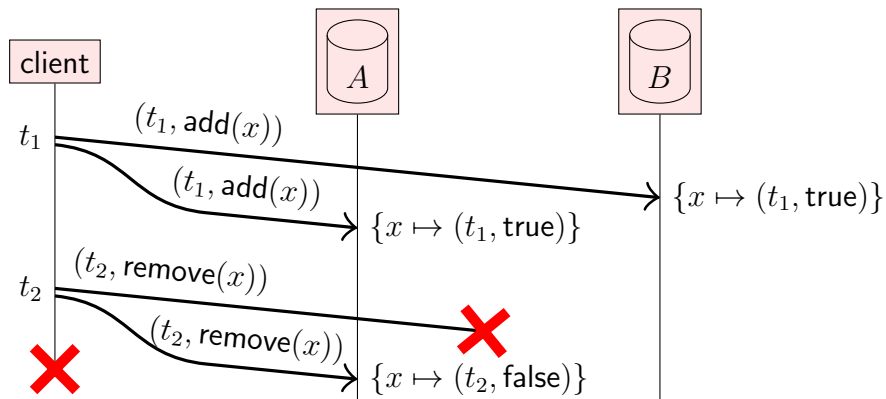
Final state ($x \notin A$, $x \in B$) is the same as in this case:



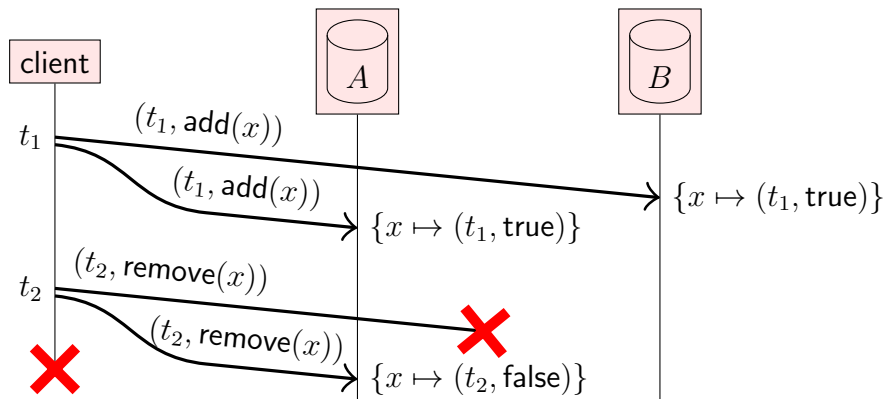
Timestamps and tombstones



Timestamps and tombstones

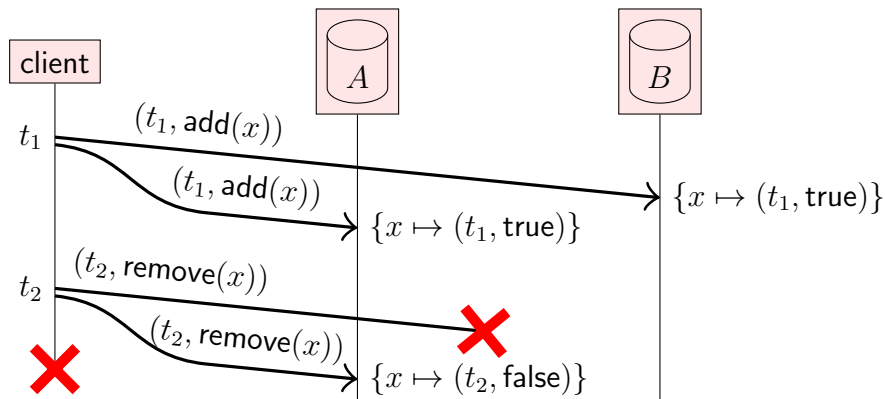


Timestamps and tombstones



“remove(x)” doesn’t actually remove x : it labels x with “false” to indicate it is invisible (a **tombstone**)

Timestamps and tombstones

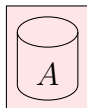
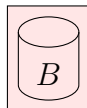


“remove(x)” doesn’t actually remove x : it labels x with “false” to indicate it is invisible (a **tombstone**)

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

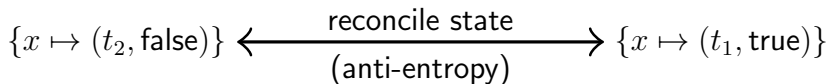
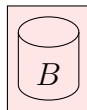
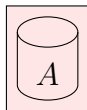
Reconciling replicas

Replicas periodically communicate among themselves to check for any inconsistencies.


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

$$\{x \mapsto (t_1, \text{true})\}$$

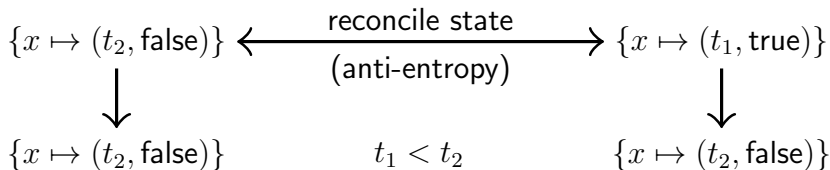
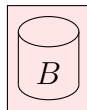
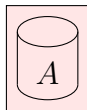
Reconciling replicas

Replicas periodically communicate among themselves to check for any inconsistencies.



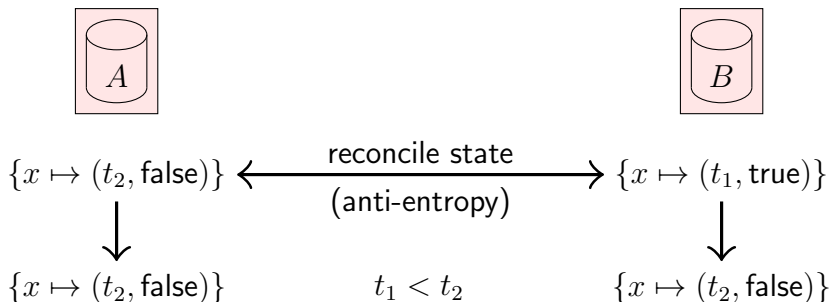
Reconciling replicas

Replicas periodically communicate among themselves to check for any inconsistencies.



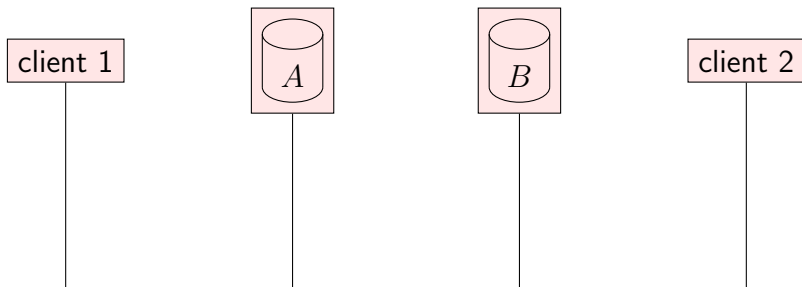
Reconciling replicas

Replicas periodically communicate among themselves to check for any inconsistencies.

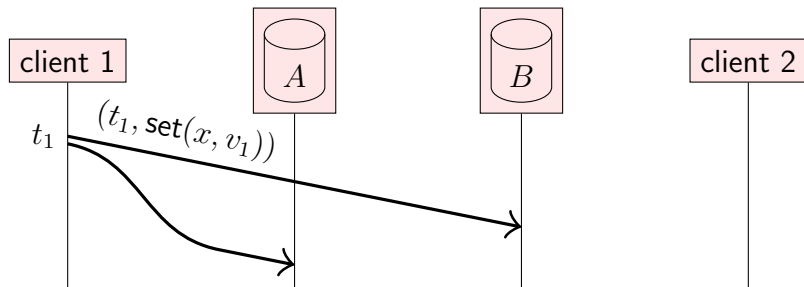


Propagate the record with the latest timestamp,
discard the records with earlier timestamps
(for a given key).

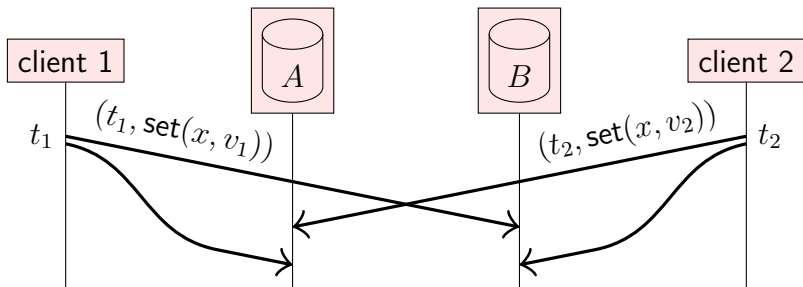
Concurrent writes by different clients



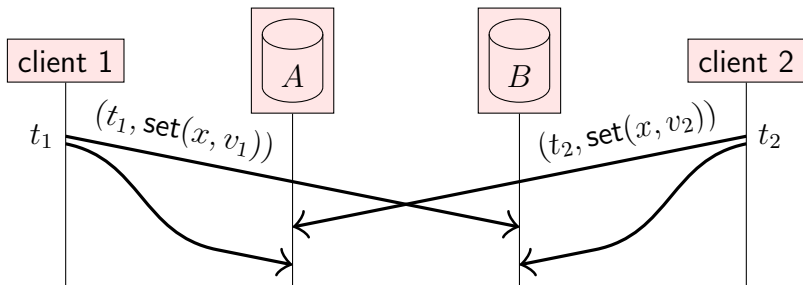
Concurrent writes by different clients



Concurrent writes by different clients



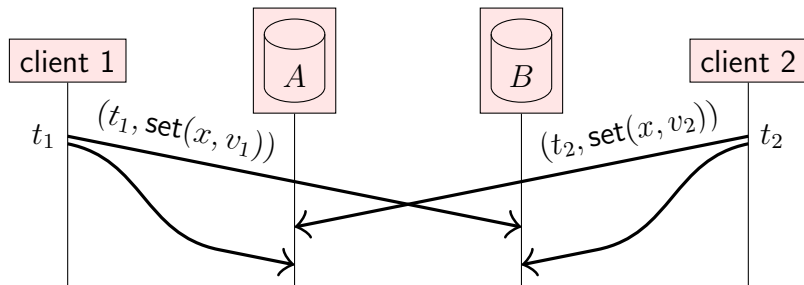
Concurrent writes by different clients



Two common approaches:

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

Concurrent writes by different clients



Two common approaches:

- ▶ **Last writer wins (LWW) register:**

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

- ▶ **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 $t_1 \parallel t_2$

Probability of faults

A replica may be **unavailable** due to network partition or node fault (e.g. crash, hardware problem).

Probability of faults

A replica may be **unavailable** due to network partition or node fault (e.g. crash, hardware problem).

Assume each replica has probability p of being faulty or unavailable at any one time, and that faults are independent.
(Not actually true! But okay approximation for now.)

Probability of faults

A replica may be **unavailable** due to network partition or node fault (e.g. crash, hardware problem).

Assume each replica has probability p of being faulty or unavailable at any one time, and that faults are independent.
(Not actually true! But okay approximation for now.)

Probability of **all** n replicas being faulty: p^n

Probability of ≥ 1 out of n replicas being faulty: $1 - (1 - p)^n$

Probability of faults

A replica may be **unavailable** due to network partition or node fault (e.g. crash, hardware problem).

Assume each replica has probability p of being faulty or unavailable at any one time, and that faults are independent.
(Not actually true! But okay approximation for now.)

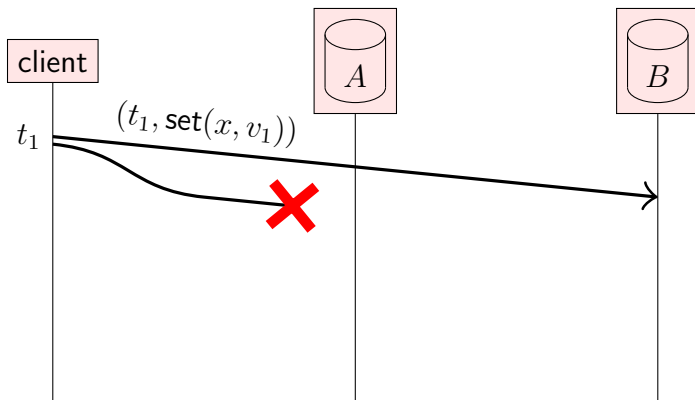
Probability of **all** n replicas being faulty: p^n

Probability of ≥ 1 out of n replicas being faulty: $1 - (1 - p)^n$

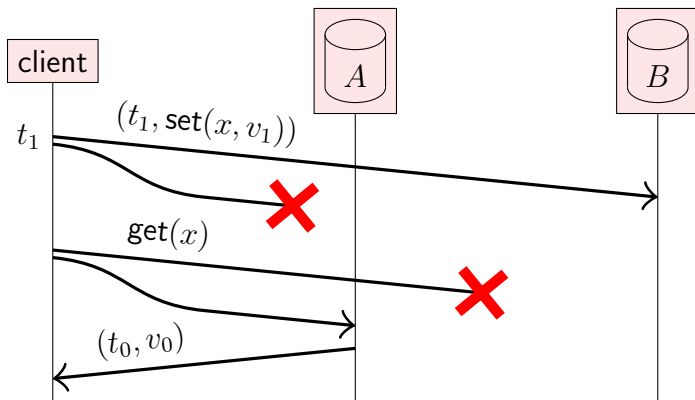
Example with $p = 0.01$:

replicas n	$P(\geq 1 \text{ faulty})$	$P(\geq \frac{n+1}{2} \text{ faulty})$	$P(\text{all } n \text{ faulty})$
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}

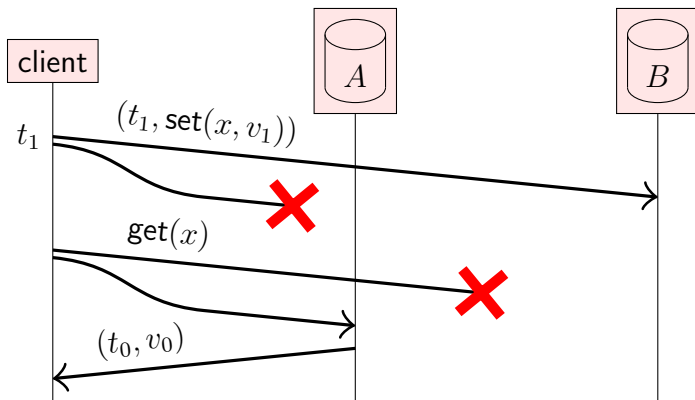
Read-after-write consistency



Read-after-write consistency

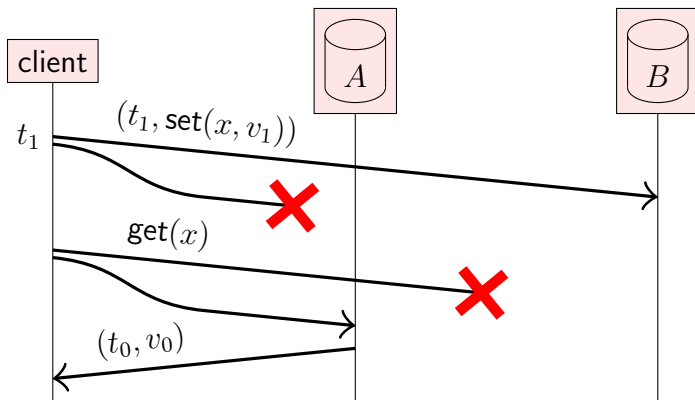


Read-after-write consistency



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

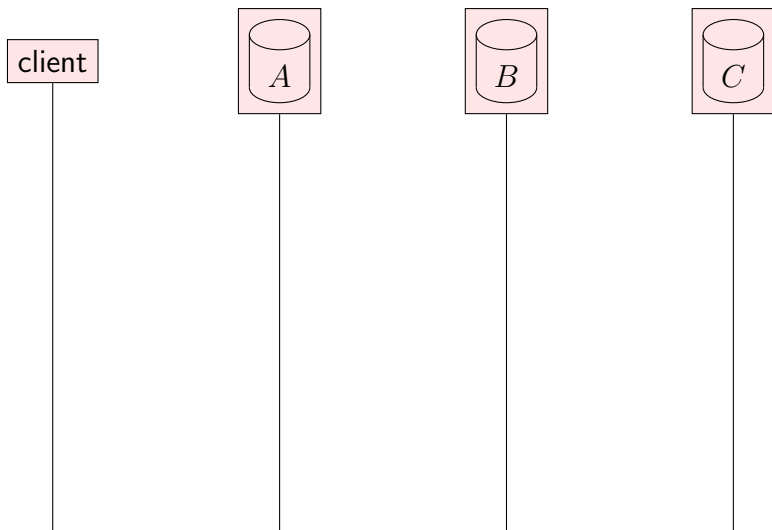
Read-after-write consistency



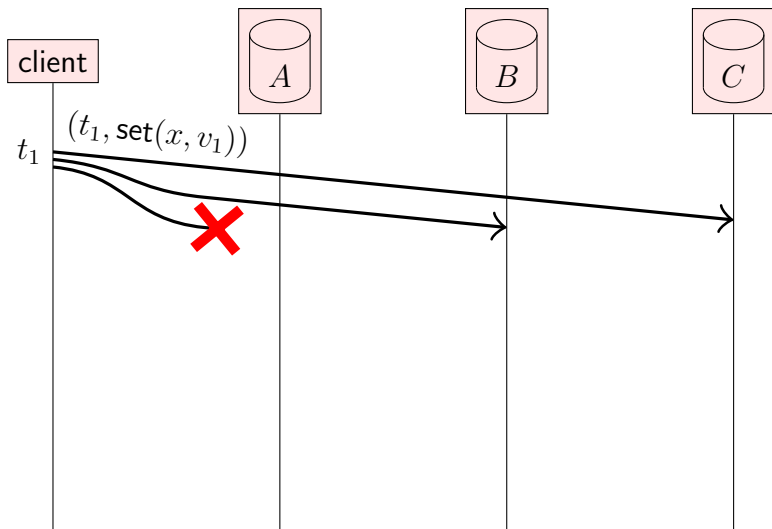
Writing to one replica, reading from another: client does not read back the value it has written

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

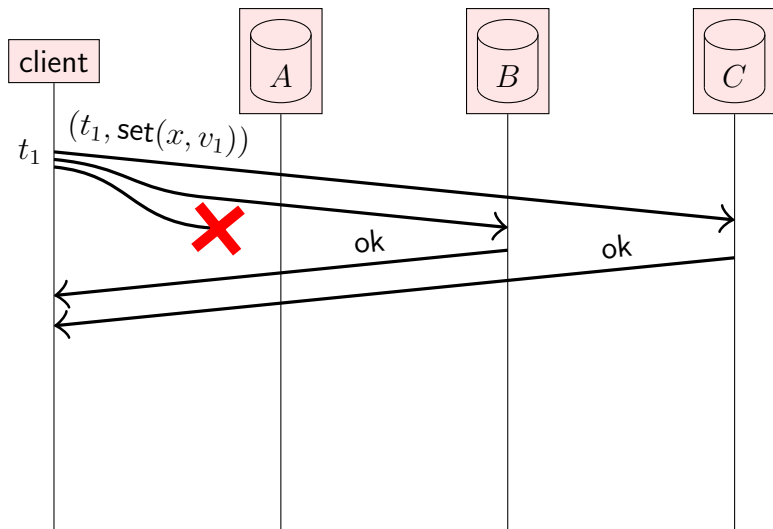
Quorum (2 out of 3)



Quorum (2 out of 3)

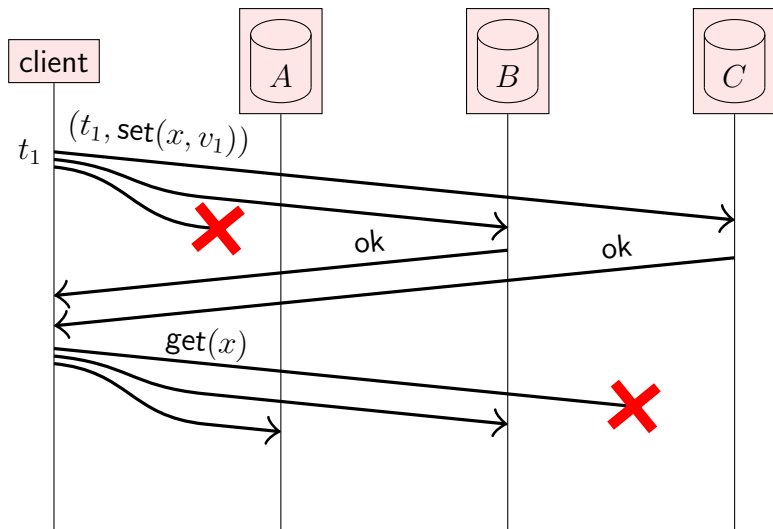


Quorum (2 out of 3)



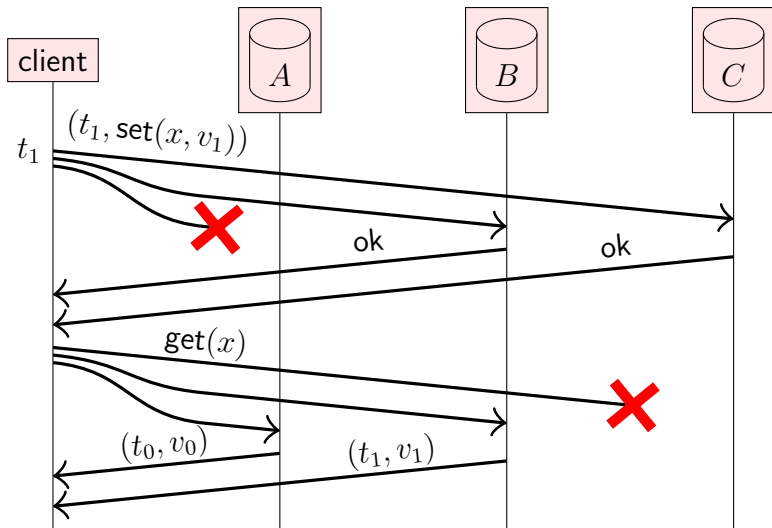
Write succeeds on B and C

Quorum (2 out of 3)



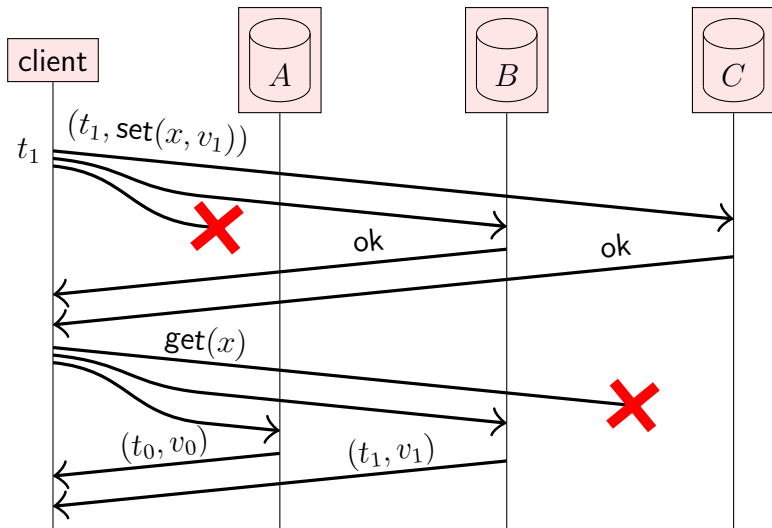
Write succeeds on B and C

Quorum (2 out of 3)



Write succeeds on B and C ; read succeeds on A and B

Quorum (2 out of 3)



Write succeeds on B and C ; read succeeds on A and B
Choose between (t_0, v_0) and (t_1, v_1) based on timestamp

Read and write quorums

In a system with n replicas:

- ▶ If a write is acknowledged by w replicas (**write quorum**),

Read and write quorums

In a system with n replicas:

- ▶ If a write is acknowledged by w replicas (**write quorum**),
- ▶ and we subsequently read from r replicas (**read quorum**),
- ▶ and $r + w > n$,

Read and write quorums

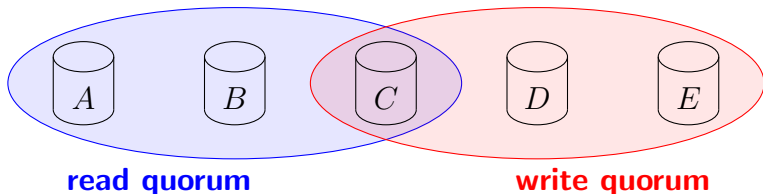
In a system with n replicas:

- ▶ If a write is acknowledged by w replicas (**write quorum**),
- ▶ and we subsequently read from r replicas (**read quorum**),
- ▶ and $r + w > n$,
- ▶ ...then the read will see the previously written value (or a value that subsequently overwrote it)

Read and write quorums

In a system with n replicas:

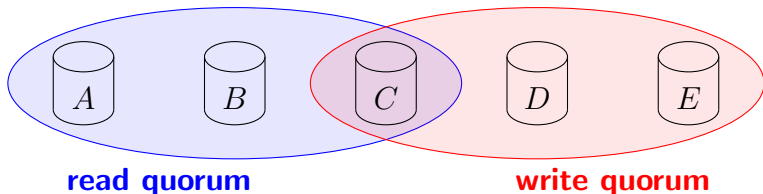
- ▶ If a write is acknowledged by w replicas (**write quorum**),
- ▶ and we subsequently read from r replicas (**read quorum**),
- ▶ and $r + w > n$,
- ▶ ...then the read will see the previously written value (or a value that subsequently overwrote it)
- ▶ Read quorum and write quorum share ≥ 1 replica



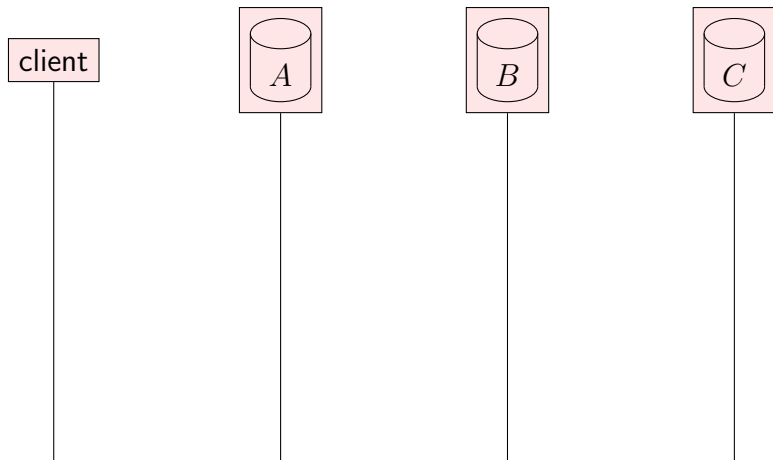
Read and write quorums

In a system with n replicas:

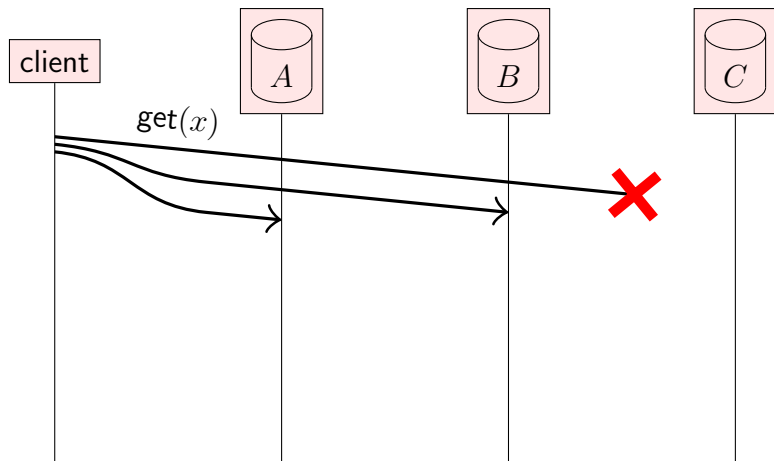
- ▶ If a write is acknowledged by w replicas (**write quorum**),
- ▶ and we subsequently read from r replicas (**read quorum**),
- ▶ and $r + w > n$,
- ▶ ... then the read will see the previously written value (or a value that subsequently overwrote it)
- ▶ Read quorum and write quorum share ≥ 1 replica
- ▶ Typical: $r = w = \frac{n+1}{2}$ for $n = 3, 5, 7, \dots$ (majority)
- ▶ Reads can tolerate $n - r$ unavailable replicas, writes $n - w$



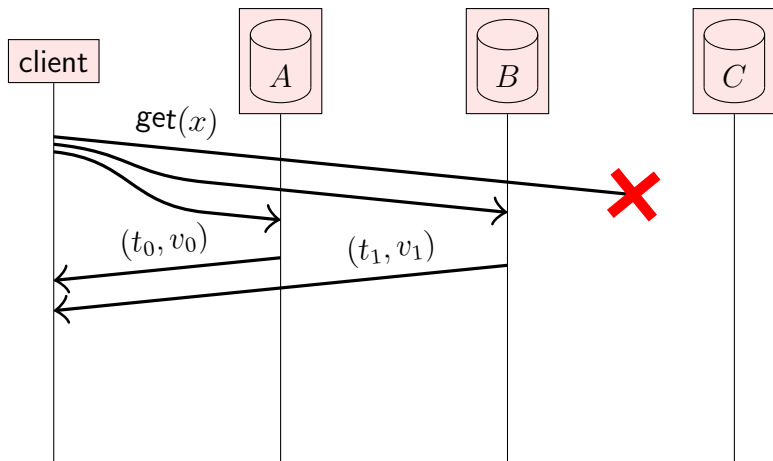
Read repair



Read repair

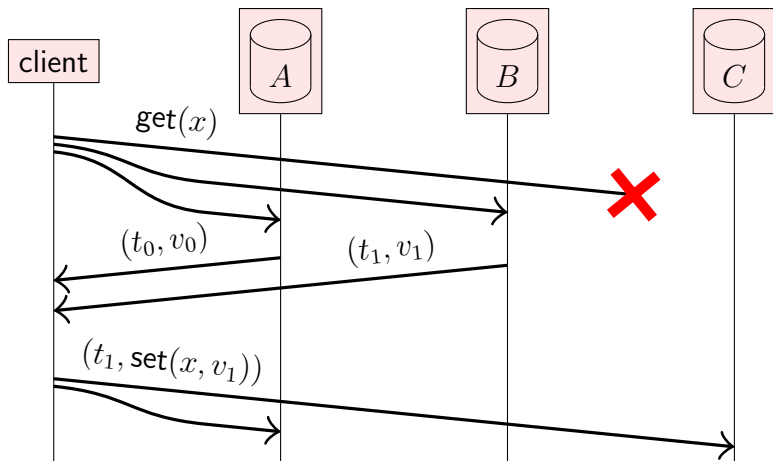


Read repair



Update (t_1, v_1) is more recent than (t_0, v_0) since $t_0 < t_1$.

Read repair



Update (t_1, v_1) is more recent than (t_0, v_0) since $t_0 < t_1$.
Client helps **propagate** (t_1, v_1) to other replicas.

State machine replication

So far we have used best-effort broadcast for replication.
What about stronger broadcast models?

State machine replication

So far we have used best-effort broadcast for replication.
What about stronger broadcast models?

Total order broadcast: every node delivers the **same messages** in the **same order**

State machine replication

So far we have used best-effort broadcast for replication.
What about stronger broadcast models?

Total order broadcast: every node delivers the **same messages** in the **same order**

State machine replication (SMR):

- ▶ FIFO-total order broadcast every update to all replicas
- ▶ Replica delivers update message: apply it to own state

State machine replication

So far we have used best-effort broadcast for replication.
What about stronger broadcast models?

Total order broadcast: every node delivers the **same messages** in the **same order**

State machine replication (SMR):

- ▶ FIFO-total order broadcast every update to all replicas
- ▶ Replica delivers update message: apply it to own state
- ▶ Applying an update is deterministic

State machine replication

So far we have used best-effort broadcast for replication.
What about stronger broadcast models?

Total order broadcast: every node delivers the **same messages** in the **same order**

State machine replication (SMR):

- ▶ FIFO-total order broadcast every update to all replicas
- ▶ Replica delivers update message: apply it to own state
- ▶ 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

State machine replication

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

on delivering u through FIFO-total order broadcast **do**
 update state using arbitrary deterministic logic!
end on

State machine replication

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

on delivering u through FIFO-total order broadcast **do**
 update state using arbitrary deterministic logic!
end on

Closely related ideas:

- ▶ Serializable transactions (execute in delivery order)

State machine replication

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

on delivering u through FIFO-total order broadcast **do**
 update state using arbitrary deterministic logic!
end on

Closely related ideas:

- ▶ Serializable transactions (execute in delivery order)
- ▶ Blockchains, distributed ledgers, smart contracts

State machine replication

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

on delivering u through FIFO-total order broadcast **do**
 update state using arbitrary deterministic logic!
end on

Closely related ideas:

- ▶ Serializable transactions (execute in delivery order)
- ▶ Blockchains, distributed ledgers, smart contracts

Limitations:

- ▶ Cannot update state immediately, have to wait for delivery through broadcast

State machine replication

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

```
on delivering  $u$  through FIFO-total order broadcast do  
    update state using arbitrary deterministic logic!  
end on
```

Closely related ideas:

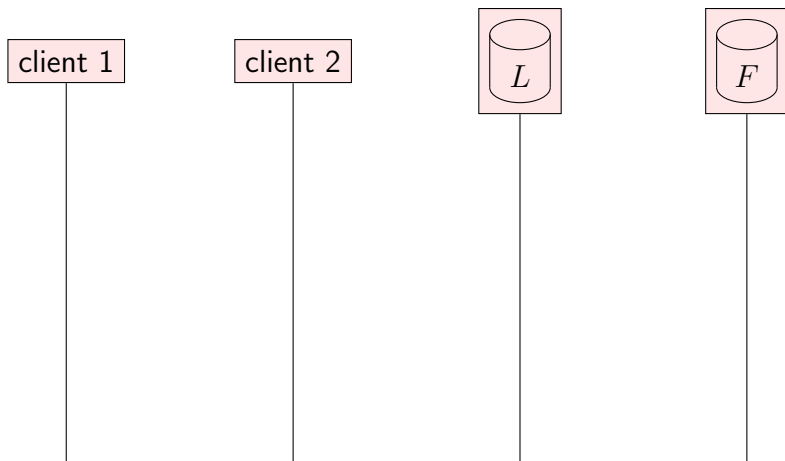
- ▶ Serializable transactions (execute in delivery order)
- ▶ Blockchains, distributed ledgers, smart contracts

Limitations:

- ▶ Cannot update state immediately, have to wait for delivery through broadcast
- ▶ Need fault-tolerant total order broadcast: see next lecture

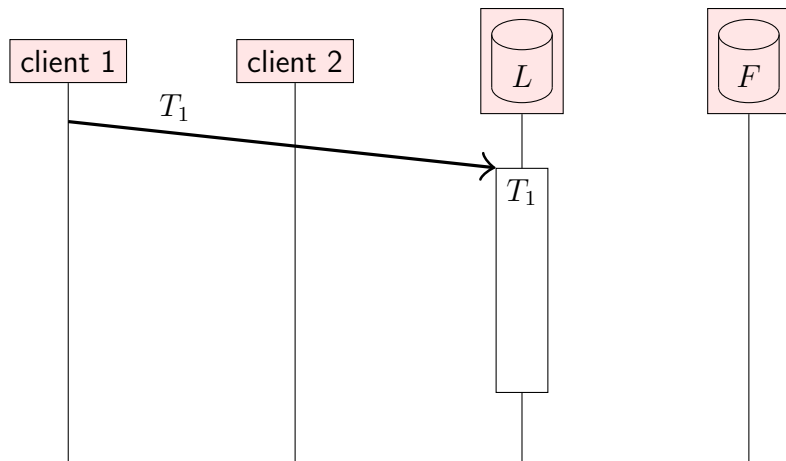
Database leader replica

Leader database replica L ensures total order broadcast



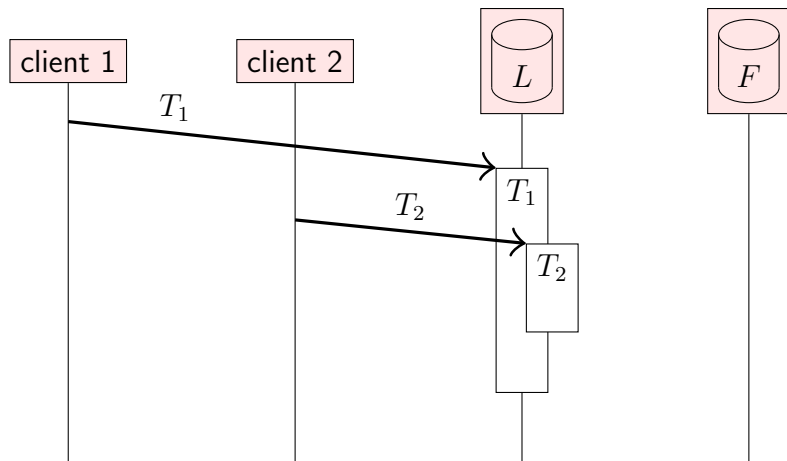
Database leader replica

Leader database replica L ensures total order broadcast



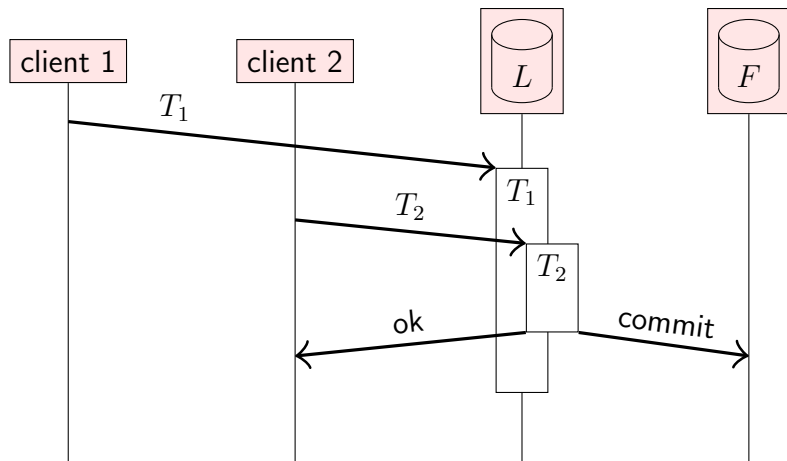
Database leader replica

Leader database replica L ensures total order broadcast



Database leader replica

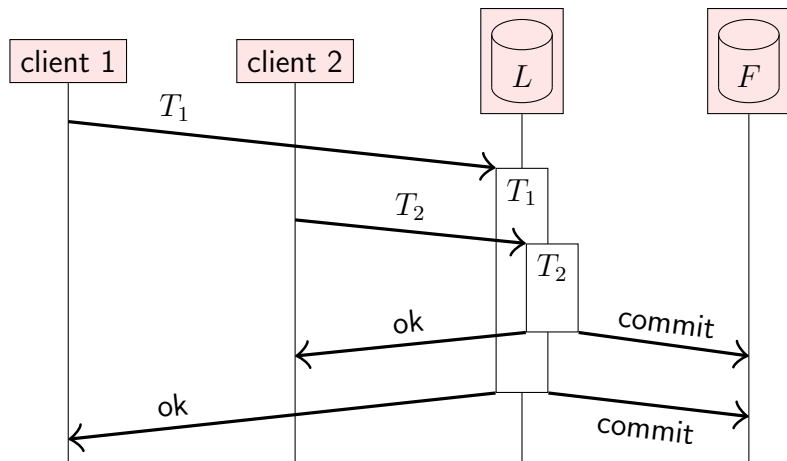
Leader database replica L ensures total order broadcast



Follower F applies transaction log in commit order

Database leader replica

Leader database replica L ensures total order broadcast



Follower F applies transaction log in commit order

Replication using causal (and weaker) broadcast

State machine replication uses (FIFO-)total order broadcast.
Can we use weaker forms of broadcast too?

Replication using causal (and weaker) broadcast

State machine replication uses (FIFO-)total order broadcast.
Can we use weaker forms of broadcast too?

If replica state updates are **commutative**, replicas can process updates in different orders and still end up in the same state.

Updates f and g are commutative if $f(g(x)) = g(f(x))$

Replication using causal (and weaker) broadcast

State machine replication uses (FIFO-)total order broadcast.
Can we use weaker forms of broadcast too?

If replica state updates are **commutative**, replicas can process updates in different orders and still end up in the same state.

Updates f and g are commutative if $f(g(x)) = g(f(x))$

broadcast	assumptions about state update function
total order	deterministic (SMR)

Replication using causal (and weaker) broadcast

State machine replication uses (FIFO-)total order broadcast.
Can we use weaker forms of broadcast too?

If replica state updates are **commutative**, replicas can process updates in different orders and still end up in the same state.

Updates f and g are commutative if $f(g(x)) = g(f(x))$

broadcast	assumptions about state update function
total order	deterministic (SMR)
causal	deterministic, concurrent updates commute

Replication using causal (and weaker) broadcast

State machine replication uses (FIFO-)total order broadcast.
Can we use weaker forms of broadcast too?

If replica state updates are **commutative**, replicas can process updates in different orders and still end up in the same state.

Updates f and g are commutative if $f(g(x)) = g(f(x))$

broadcast	assumptions about state update function
total order	deterministic (SMR)
causal	deterministic, concurrent updates commute
reliable	deterministic, all updates commute

Replication using causal (and weaker) broadcast

State machine replication uses (FIFO-)total order broadcast.
Can we use weaker forms of broadcast too?

If replica state updates are **commutative**, replicas can process updates in different orders and still end up in the same state.

Updates f and g are commutative if $f(g(x)) = g(f(x))$

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

Replica consistency

Dr. Martin Kleppmann
martin.kleppmann@cst.cam.ac.uk

University of Cambridge
Computer Science Tripos, Part IB

“Consistency”

A word that means many different things in different contexts!

“Consistency”

A word that means many different things in different contexts!

- ▶ **ACID**: a transaction transforms the database from one “consistent” state to another

“Consistency”

A word that means many different things in different contexts!

- ▶ **ACID**: a transaction transforms the database from one “consistent” state to another

Here, “consistent” = satisfying application-specific invariants

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

“Consistency”

A word that means many different things in different contexts!

- ▶ **ACID**: a transaction transforms the database from one “consistent” state to another

Here, “consistent” = satisfying application-specific invariants

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

- ▶ **Read-after-write consistency**

“Consistency”

A word that means many different things in different contexts!

- ▶ **ACID**: a transaction transforms the database from one “consistent” state to another

Here, “consistent” = satisfying application-specific invariants

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

- ▶ **Read-after-write consistency**
- ▶ **Replication**: replica should be “consistent” with other replicas

“Consistency”

A word that means many different things in different contexts!

- ▶ **ACID:** a transaction transforms the database from one “consistent” state to another

Here, “consistent” = satisfying application-specific invariants

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

- ▶ **Read-after-write consistency**
- ▶ **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**

Distributed transactions

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

- ▶ A transaction either **commits** or **aborts**
- ▶ If it commits, its updates are durable
- ▶ If it aborts, it has no visible side-effects

Distributed transactions

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

- ▶ 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
- ▶ If it aborts, it has no visible side-effects
- ▶ ACID consistency (preserving invariants) relies on atomicity

If the transaction updates data on multiple nodes, this implies:

- ▶ Either all nodes must commit, or all must abort

Distributed transactions

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

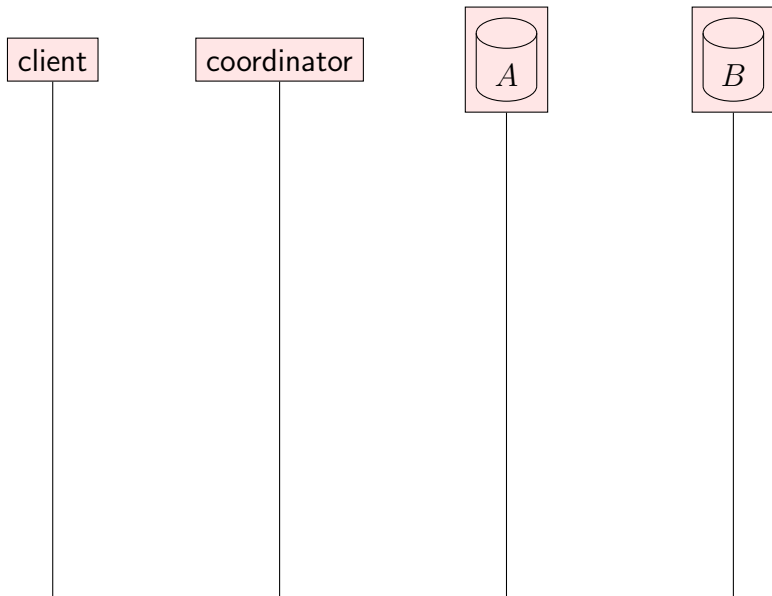
- ▶ A transaction either **commits** or **aborts**
- ▶ If it commits, its updates are durable
- ▶ If it aborts, it has no visible side-effects
- ▶ ACID consistency (preserving invariants) relies on atomicity

If the transaction updates data on multiple nodes, this implies:

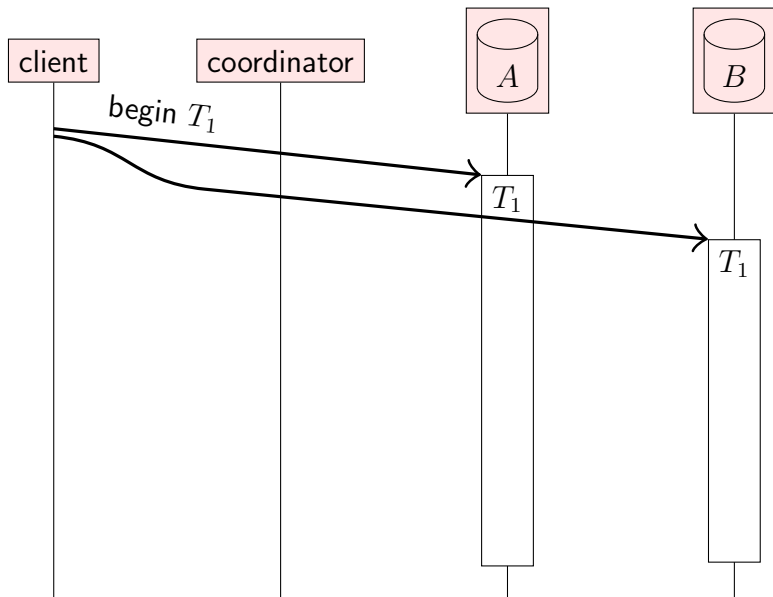
- ▶ Either all nodes must commit, or all must abort
- ▶ If any node crashes, all must abort

Ensuring this is the **atomic commitment** problem.

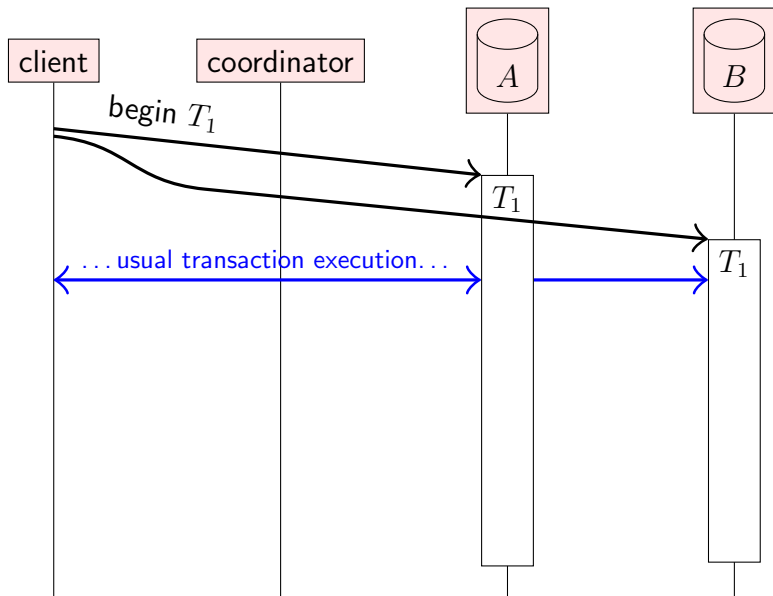
Two-phase commit (2PC)



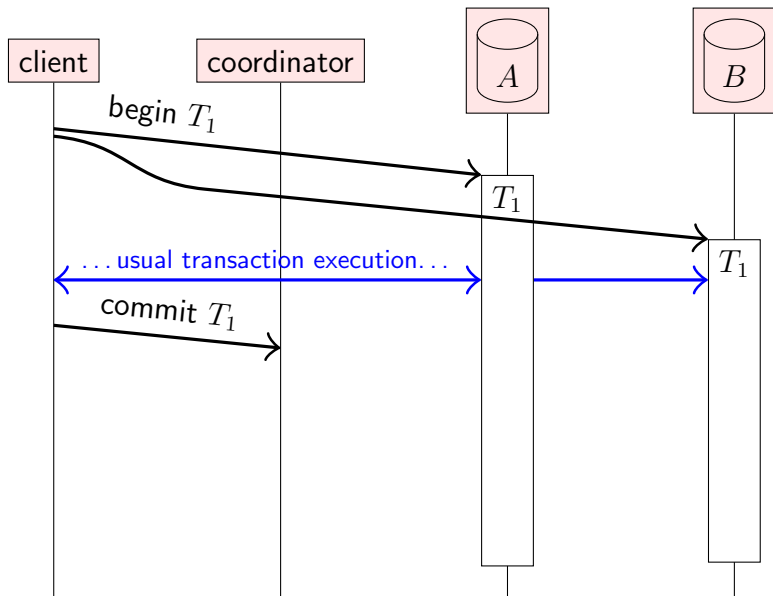
Two-phase commit (2PC)



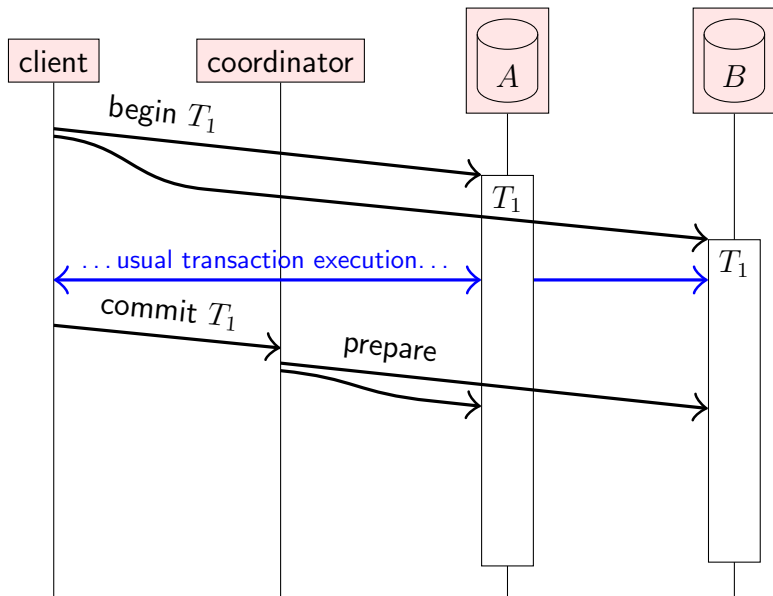
Two-phase commit (2PC)



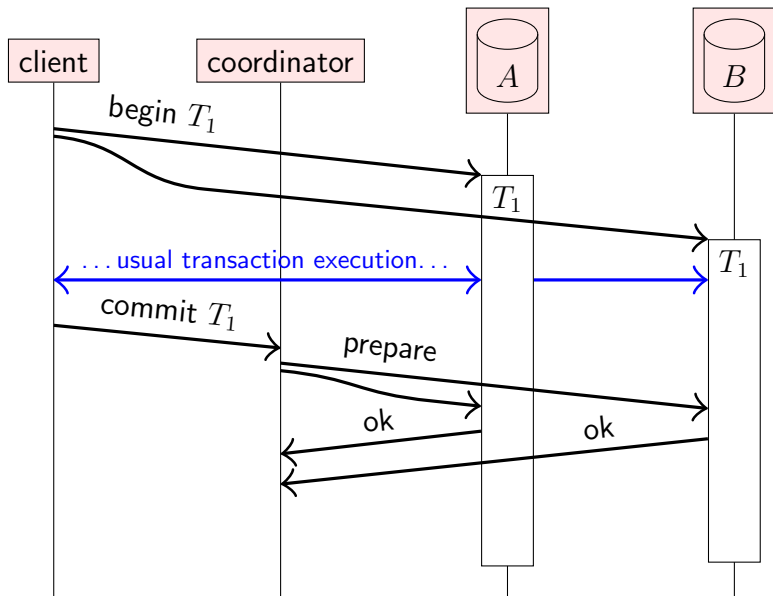
Two-phase commit (2PC)



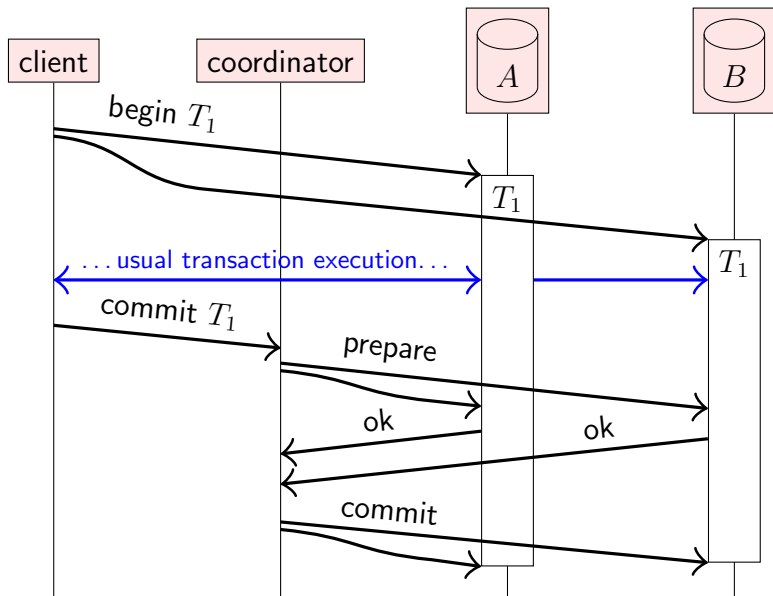
Two-phase commit (2PC)



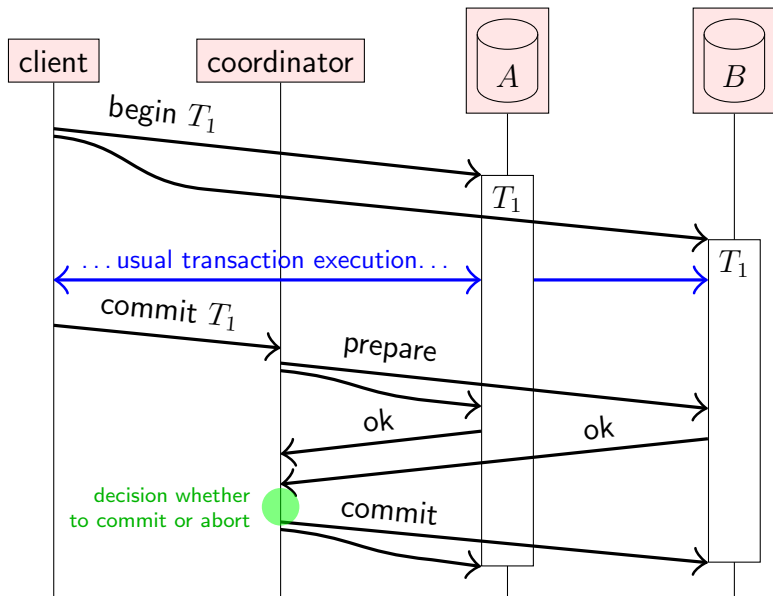
Two-phase commit (2PC)



Two-phase commit (2PC)



Two-phase commit (2PC)



The coordinator in two-phase commit

What if the coordinator crashes?

The coordinator in two-phase commit

What if the coordinator crashes?

- ▶ Coordinator writes its decision to disk
- ▶ When it recovers, read decision from disk and send it to replicas (or abort if no decision was made before crash)

The coordinator in two-phase commit

What if the coordinator crashes?

- ▶ Coordinator writes its decision to disk
- ▶ When it recovers, read decision from disk and send it to replicas (or abort if no decision was made before crash)
- ▶ **Problem:** if coordinator crashes after prepare, but before broadcasting decision, other nodes do not know what it has decided

The coordinator in two-phase commit

What if the coordinator crashes?

- ▶ Coordinator writes its decision to disk
- ▶ When it recovers, read decision from disk and send it to replicas (or abort if no decision was made before crash)
- ▶ **Problem:** if coordinator crashes after prepare, but before broadcasting decision, other nodes do not know what it has decided
- ▶ Replicas participating in transaction cannot commit or abort after responding “ok” to the *prepare* request (otherwise we risk violating atomicity)

The coordinator in two-phase commit

What if the coordinator crashes?

- ▶ Coordinator writes its decision to disk
- ▶ When it recovers, read decision from disk and send it to replicas (or abort if no decision was made before crash)
- ▶ **Problem:** if coordinator crashes after prepare, but before broadcasting decision, other nodes do not know what it has decided
- ▶ 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 (Prepare, T , R) to r

end on

on receiving (Prepare, T , R) at node $replicaId$ **do**

$replicas[T] := R$

$ok =$ "is transaction T able to commit on this replica?"

total order broadcast (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 (Vote, T , $replicaId$, false) to $replicas[T]$

end for

end on

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

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

Linearizability

Multiple nodes concurrently accessing replicated data.
How do we define “consistency” here?

Linearizability

Multiple nodes concurrently accessing replicated data.
How do we define “consistency” here?

The strongest option: **linearizability**

Linearizability

Multiple nodes concurrently accessing replicated data.
How do we define “consistency” here?

The strongest option: **linearizability**

- ▶ Informally: every operation takes effect **atomically** sometime after it started and before it finished

Linearizability

Multiple nodes concurrently accessing replicated data.
How do we define “consistency” here?

The strongest option: **linearizability**

- ▶ Informally: every operation takes effect **atomically** sometime after it started and before it finished
- ▶ All operations behave as if executed on a **single copy** of the data (even if there are in fact multiple replicas)

Linearizability

Multiple nodes concurrently accessing replicated data.
How do we define “consistency” here?

The strongest option: **linearizability**

- ▶ Informally: every operation takes effect **atomically** sometime after it started and before it finished
- ▶ All operations behave as if executed on a **single copy** of the data (even if there are in fact multiple replicas)
- ▶ Consequence: every operation returns an “up-to-date” value, a.k.a. “strong consistency”

Linearizability

Multiple nodes concurrently accessing replicated data.
How do we define “consistency” here?

The strongest option: **linearizability**

- ▶ Informally: every operation takes effect **atomically** sometime after it started and before it finished
- ▶ All operations behave as if executed on a **single copy** of the data (even if there are in fact multiple replicas)
- ▶ Consequence: every operation returns an “up-to-date” value, a.k.a. “strong consistency”
- ▶ Not just in distributed systems, also in shared-memory concurrency (memory on multi-core CPUs is not linearizable by default!)

Linearizability

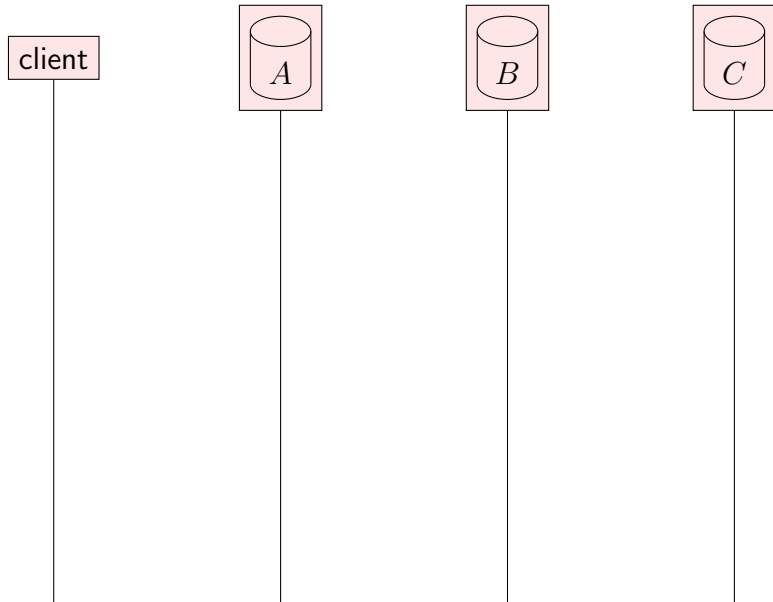
Multiple nodes concurrently accessing replicated data.
How do we define “consistency” here?

The strongest option: **linearizability**

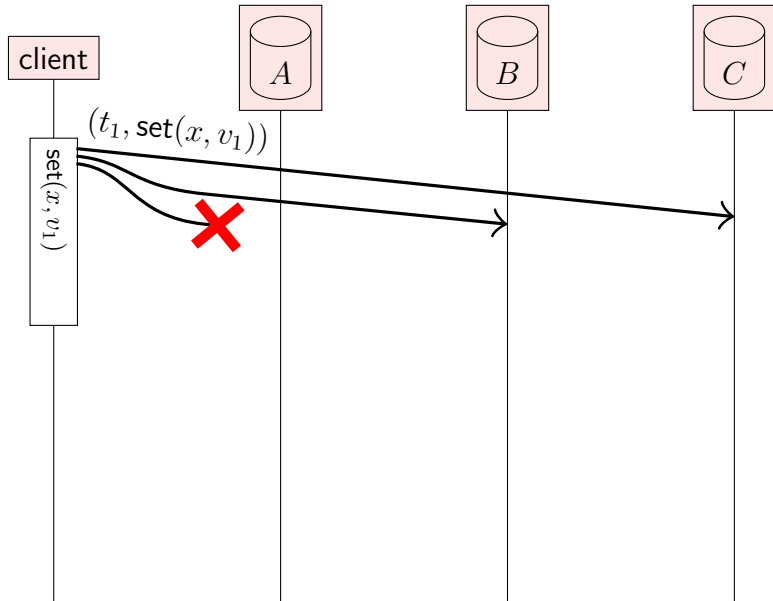
- ▶ Informally: every operation takes effect **atomically** sometime after it started and before it finished
- ▶ All operations behave as if executed on a **single copy** of the data (even if there are in fact multiple replicas)
- ▶ Consequence: every operation returns an “up-to-date” value, a.k.a. “strong consistency”
- ▶ Not just in distributed systems, also in shared-memory concurrency (memory on multi-core CPUs is not linearizable by default!)

Note: linearizability \neq serializability!

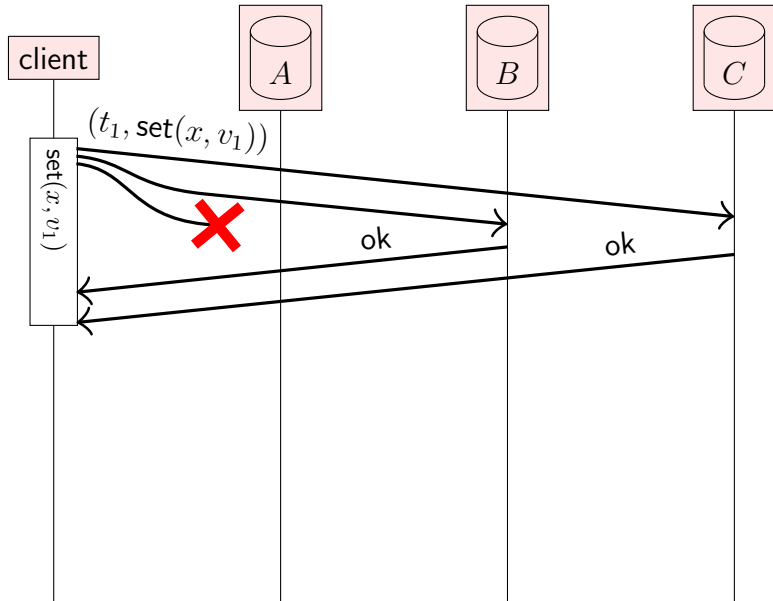
Read-after-write consistency revisited



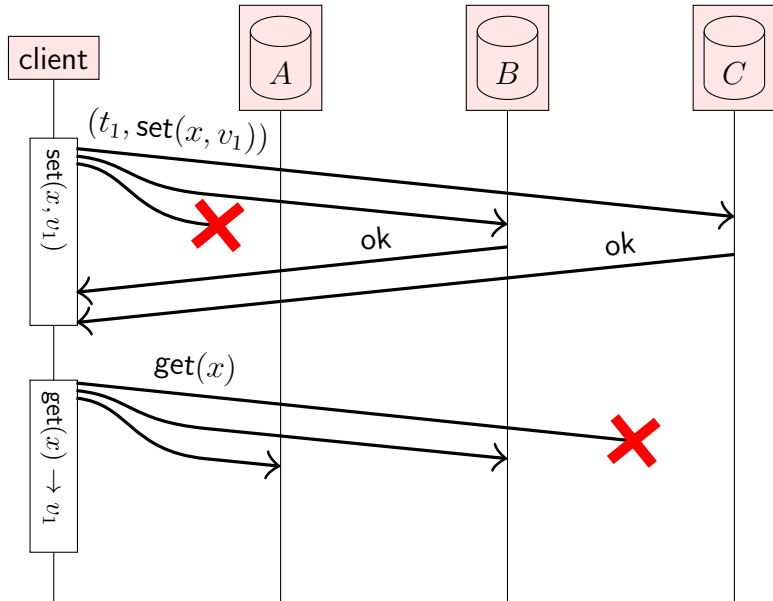
Read-after-write consistency revisited



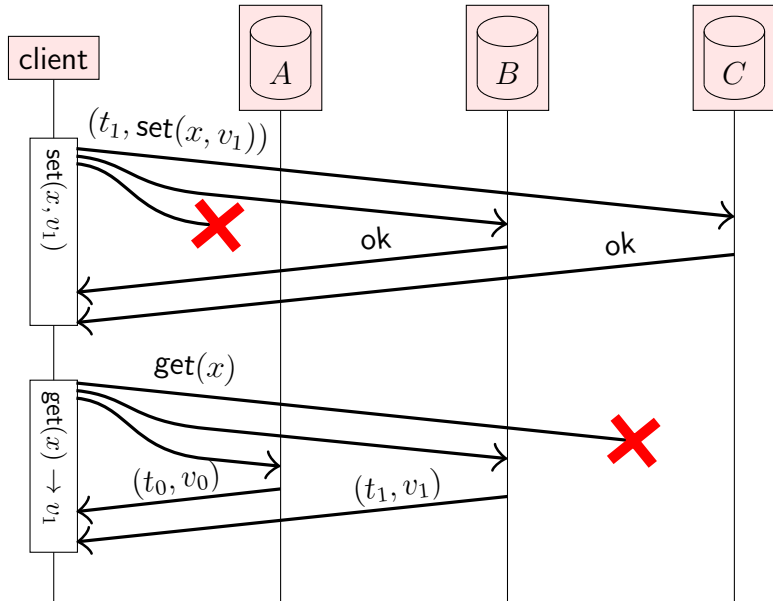
Read-after-write consistency revisited



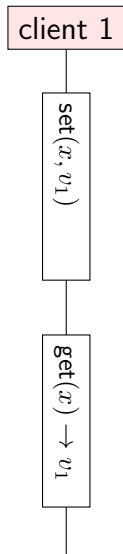
Read-after-write consistency revisited



Read-after-write consistency revisited

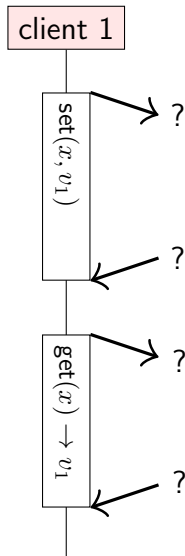


From the client's point of view



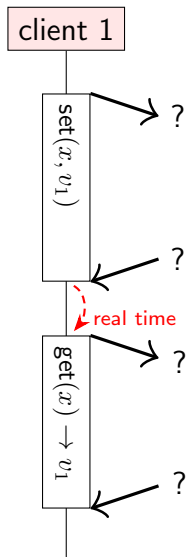
- Focus on client-observable behaviour: when and what an operation returns

From the client's point of view



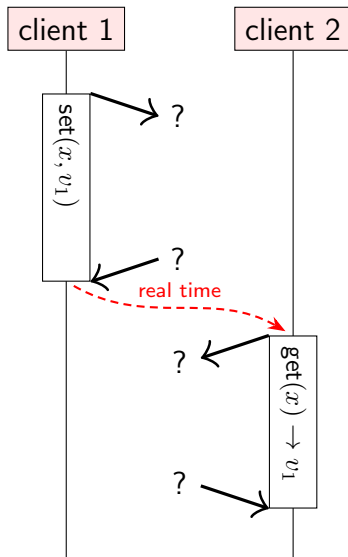
- ▶ Focus on client-observable behaviour: when and what an operation returns
- ▶ Ignore how the replication system is implemented internally

From the client's point of view



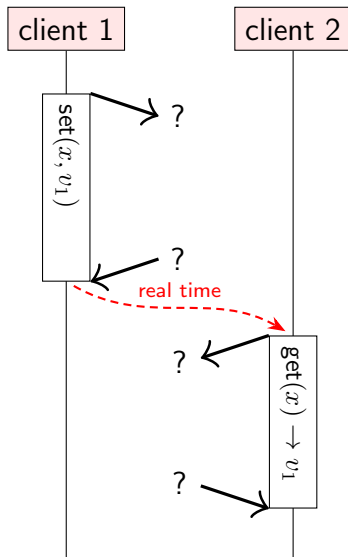
- ▶ Focus on client-observable behaviour: when and what an operation returns
- ▶ Ignore how the replication system is implemented internally
- ▶ Did operation *A* finish before operation *B* started?

From the client's point of view



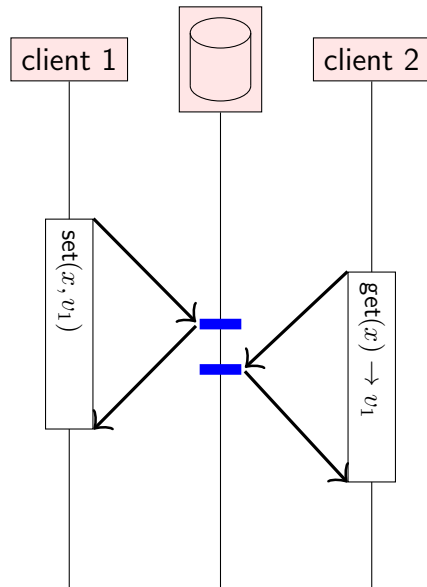
- ▶ Focus on client-observable behaviour: when and what an operation returns
- ▶ Ignore how the replication system is implemented internally
- ▶ Did operation *A* finish before operation *B* started?
- ▶ Even if the operations are on different nodes?

From the client's point of view



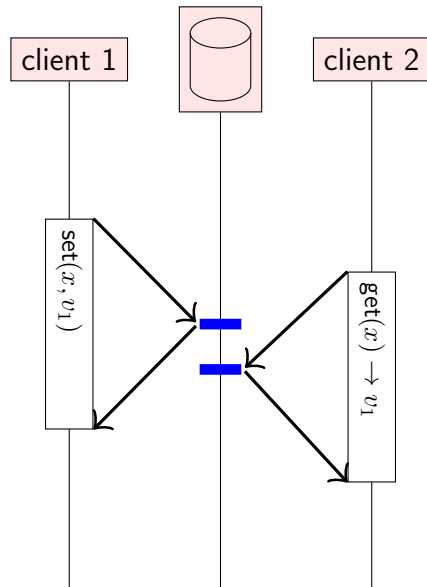
- ▶ Focus on client-observable behaviour: when and what an operation returns
- ▶ Ignore how the replication system is implemented internally
- ▶ Did operation *A* finish before operation *B* started?
- ▶ Even if the operations are on different nodes?
- ▶ **This is not happens-before:** we want client 2 to read value written by client 1, even if the clients have not communicated!

Operations overlapping in time



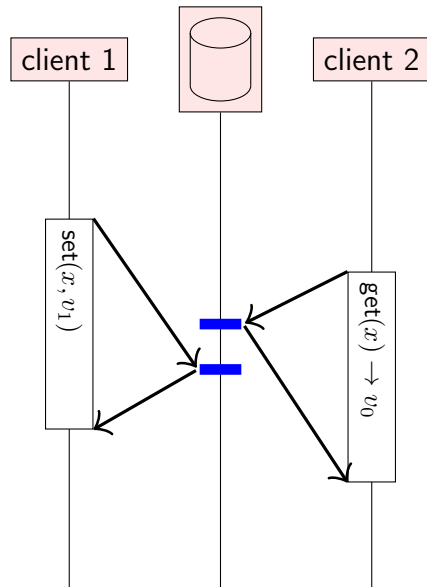
- ▶ Client 2's get operation overlaps in time with client 1's set operation

Operations overlapping in time



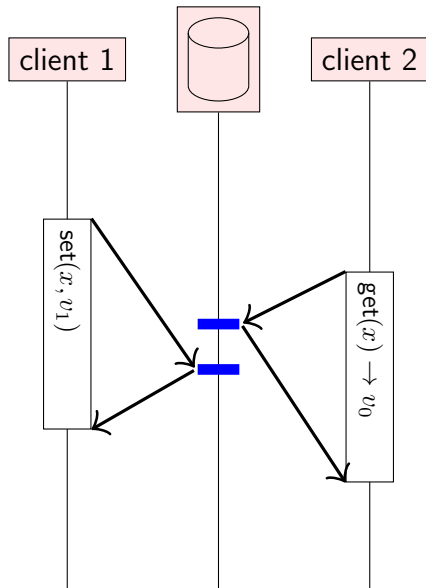
- ▶ Client 2's get operation overlaps in time with client 1's set operation
- ▶ Maybe the set operation takes effect first?

Operations overlapping in time



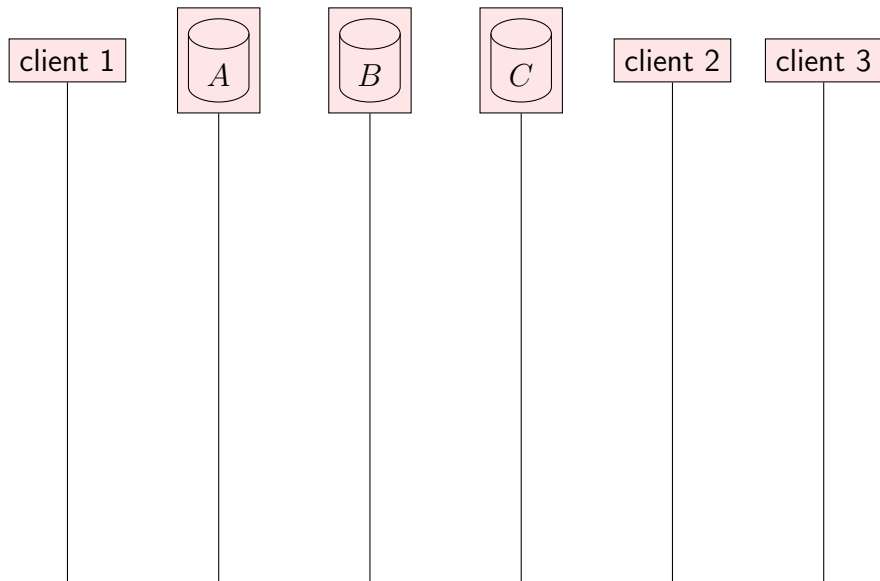
- ▶ Client 2's get operation overlaps in time with client 1's set operation
- ▶ Maybe the set operation takes effect first?
- ▶ Just as likely, the get operation may be executed first

Operations overlapping in time

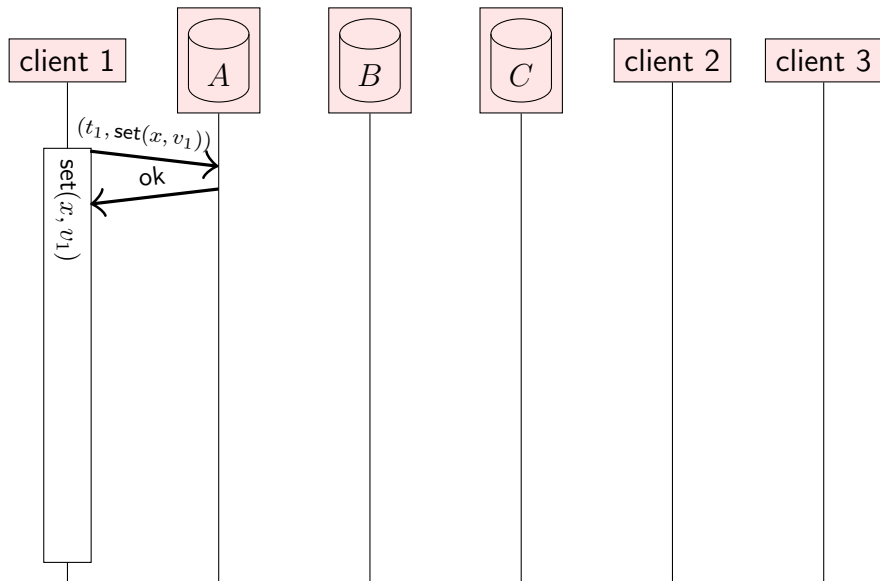


- ▶ Client 2's get operation overlaps in time with client 1's set operation
- ▶ Maybe the set operation takes effect first?
- ▶ Just as likely, the get operation may be executed first
- ▶ Either outcome is fine in this case

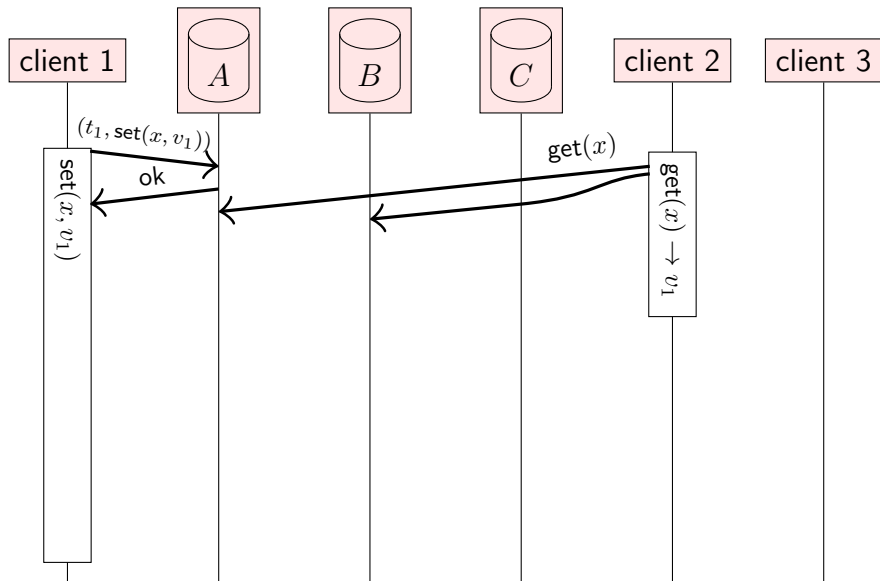
Not linearizable, despite quorum reads/writes



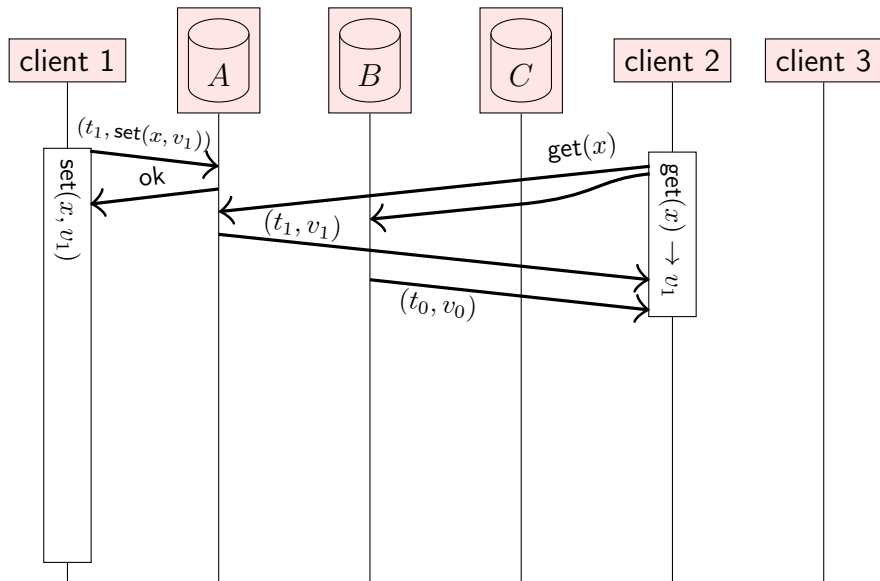
Not linearizable, despite quorum reads/writes



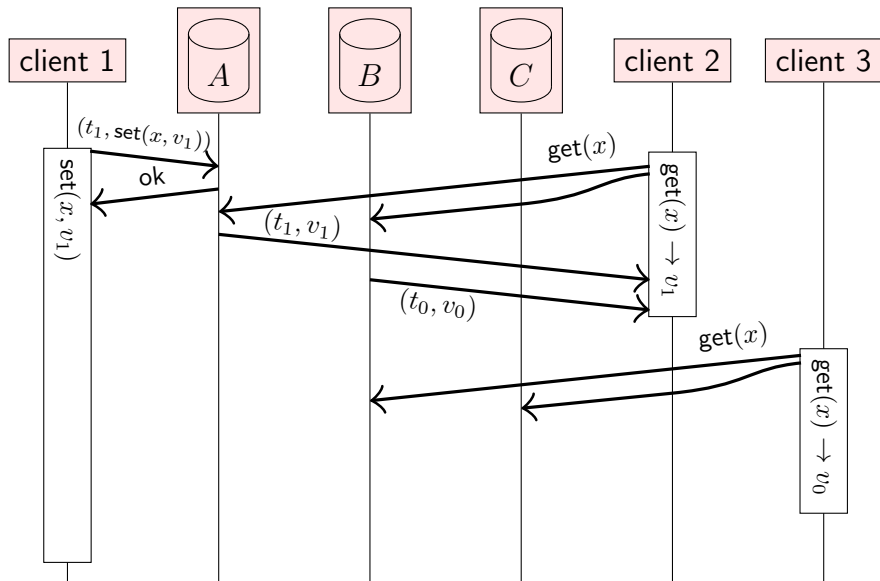
Not linearizable, despite quorum reads/writes



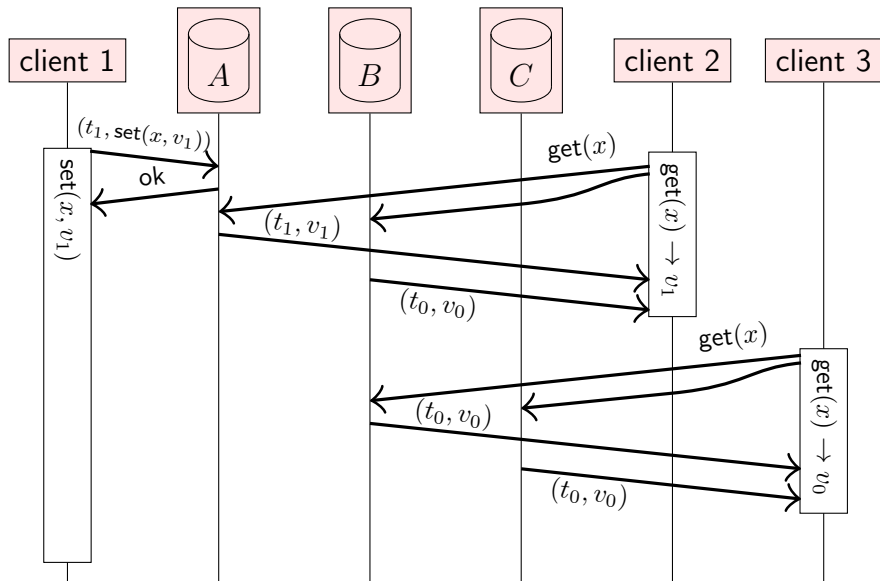
Not linearizable, despite quorum reads/writes



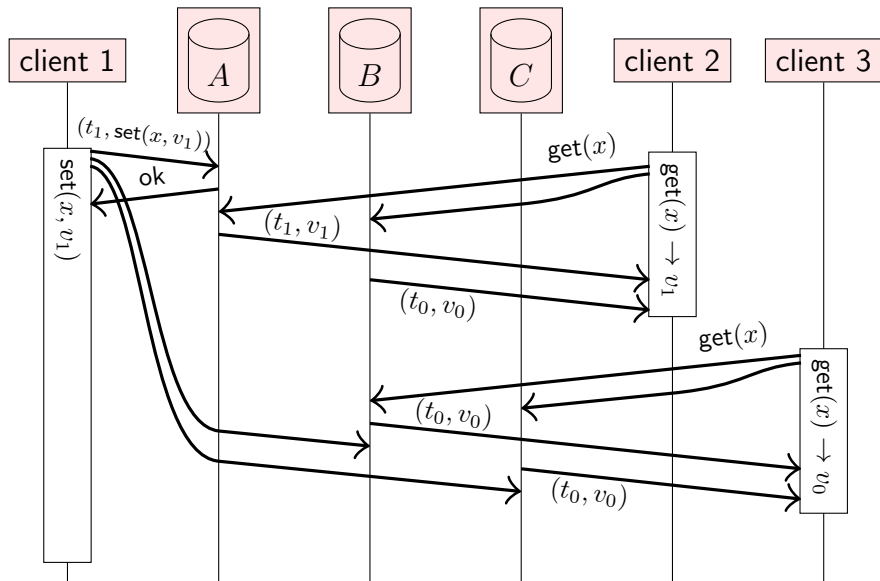
Not linearizable, despite quorum reads/writes



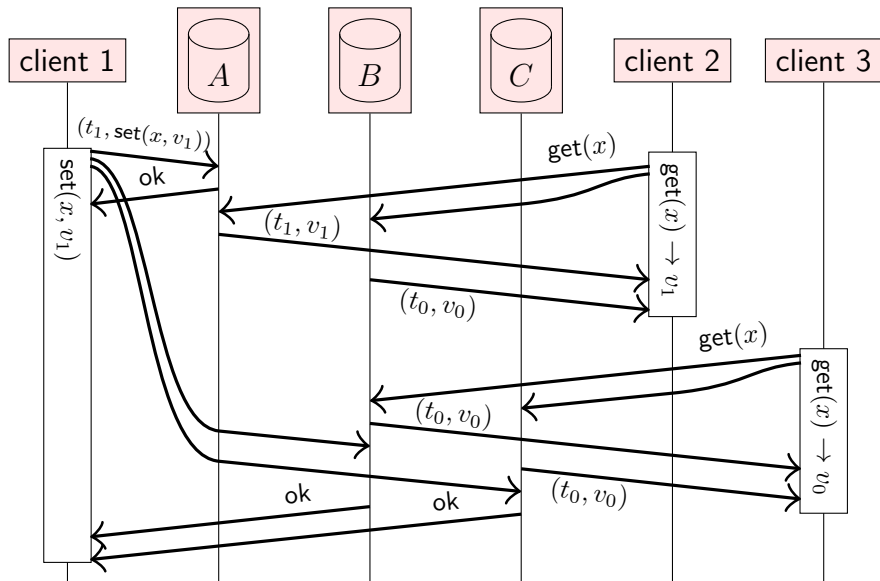
Not linearizable, despite quorum reads/writes



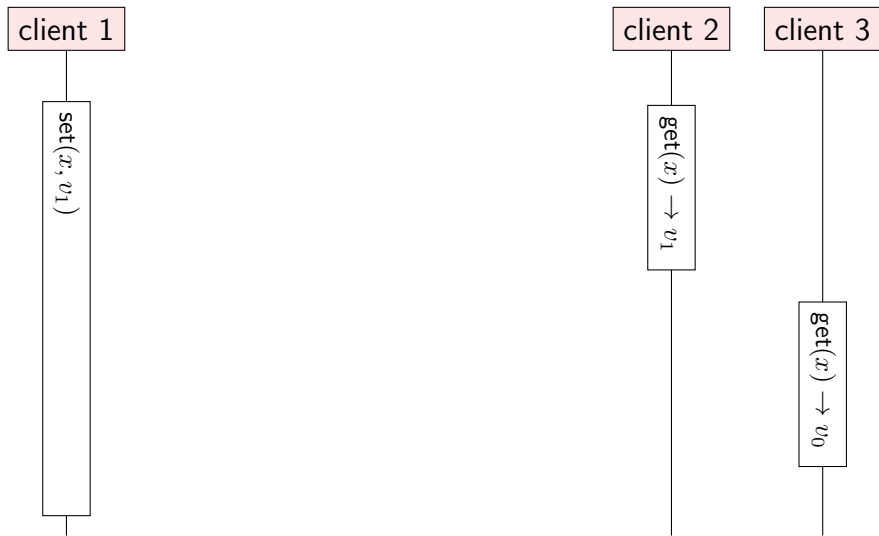
Not linearizable, despite quorum reads/writes



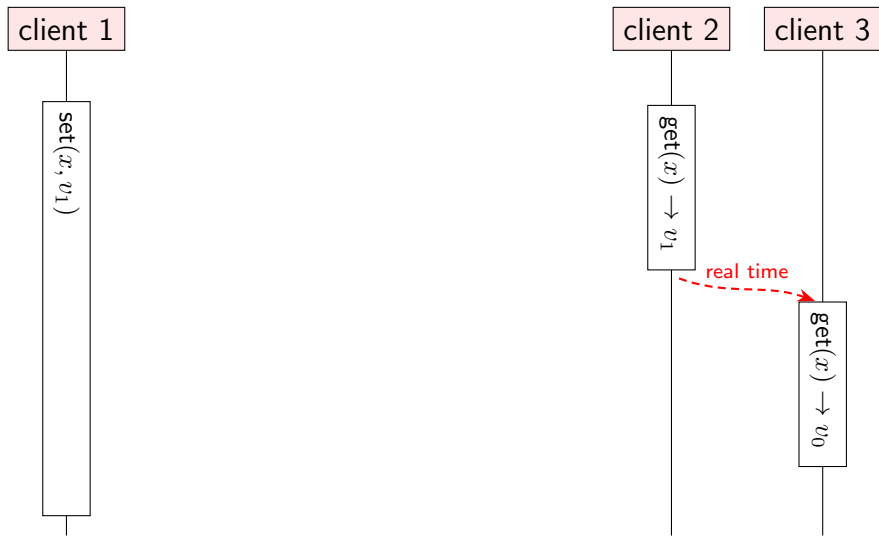
Not linearizable, despite quorum reads/writes



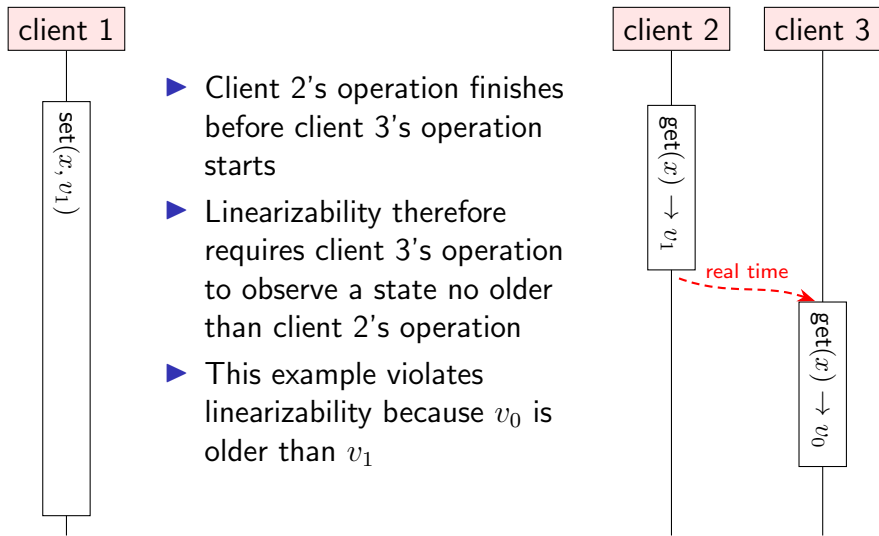
Not linearizable, despite quorum reads/writes



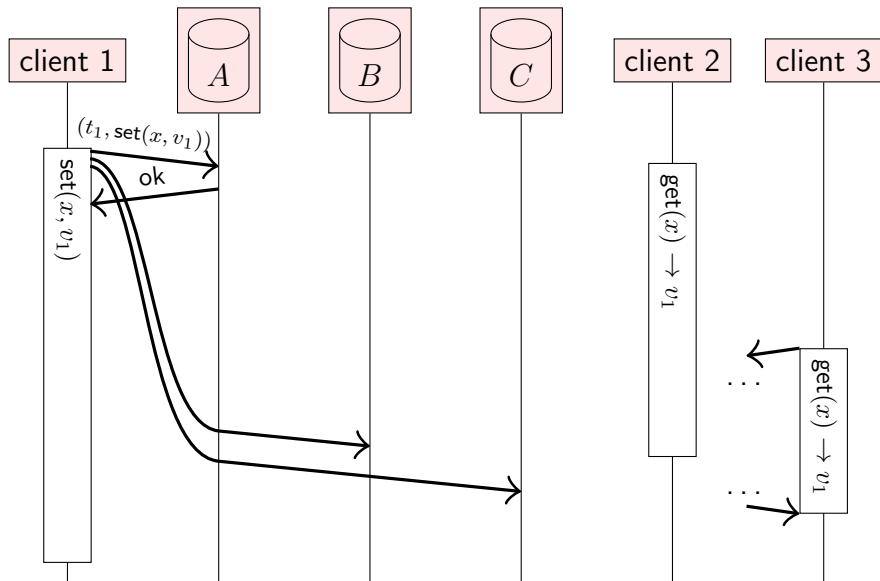
Not linearizable, despite quorum reads/writes



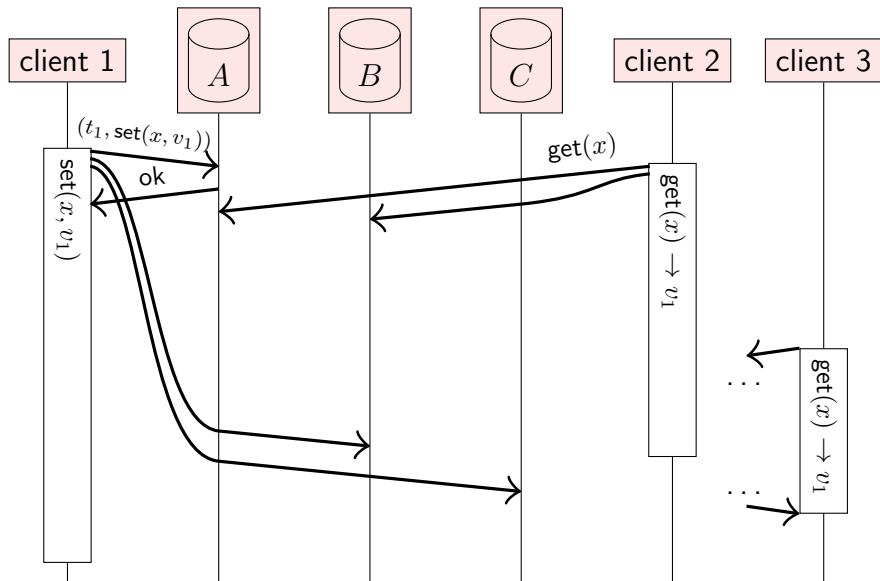
Not linearizable, despite quorum reads/writes



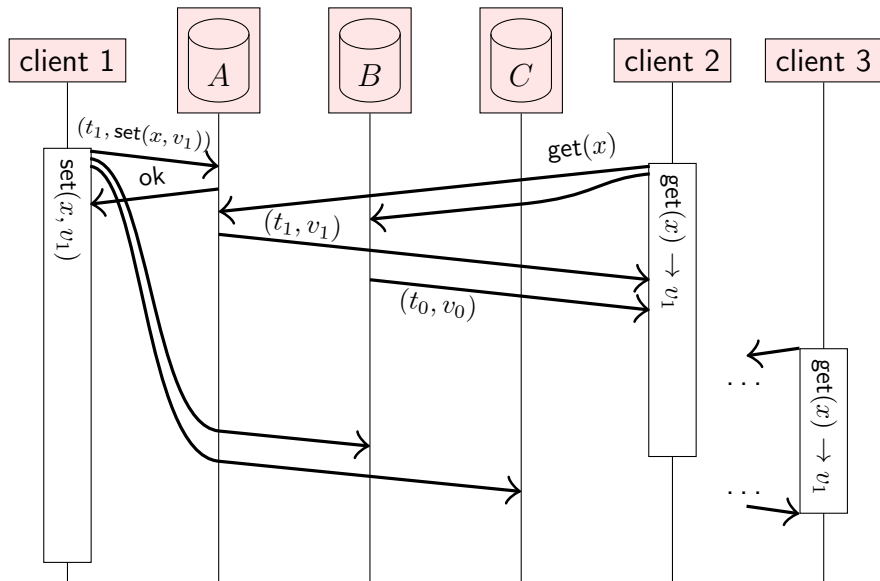
ABD: Making quorum reads/writes linearizable



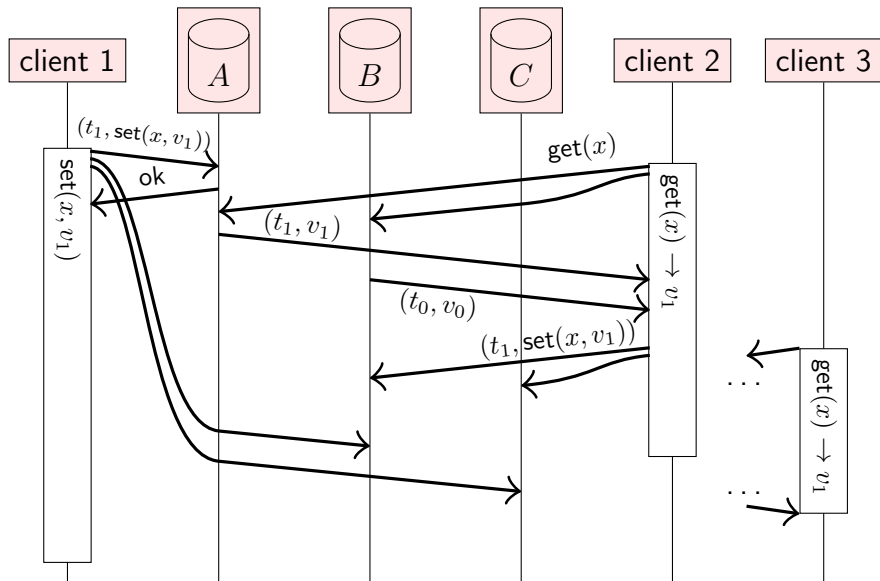
ABD: Making quorum reads/writes linearizable



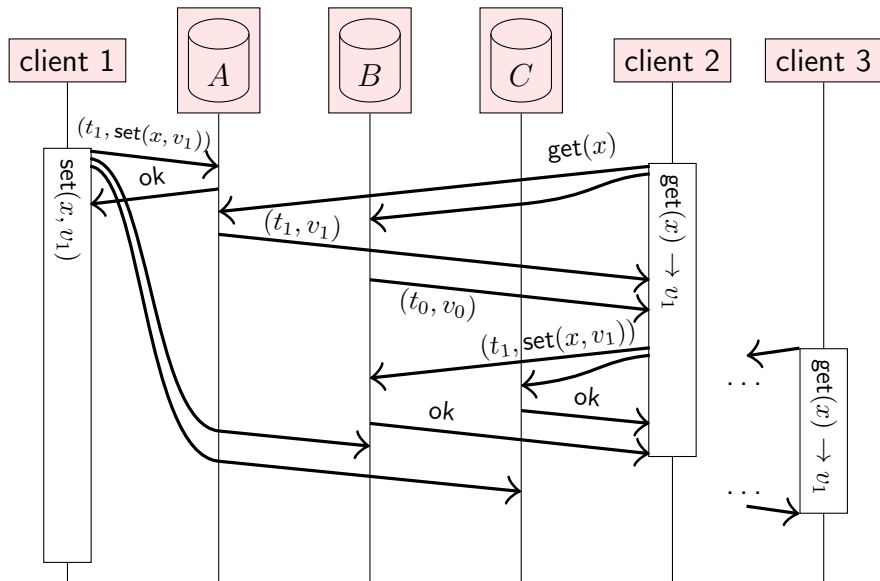
ABD: Making quorum reads/writes linearizable



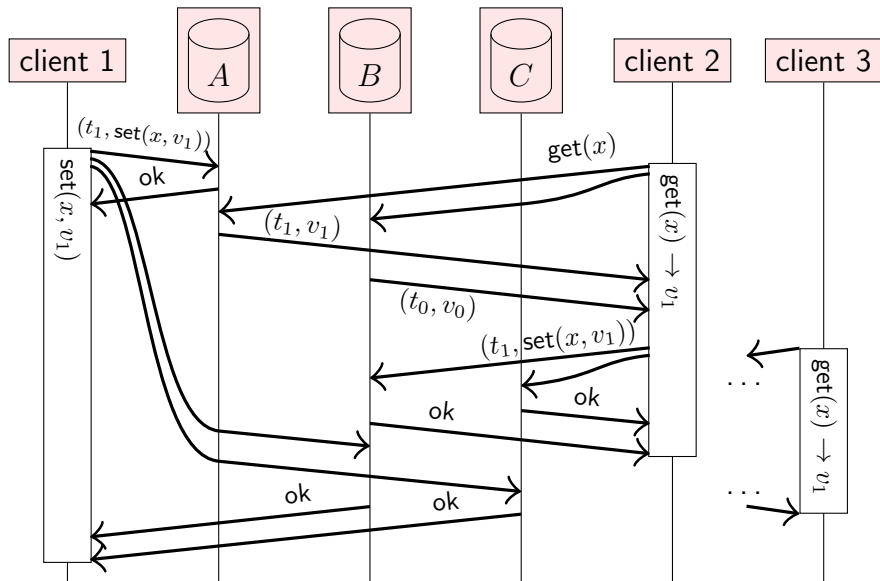
ABD: Making quorum reads/writes linearizable



ABD: Making quorum reads/writes linearizable



ABD: Making quorum reads/writes linearizable



Linearizability for different operations

This ensures linearizability of get (quorum read) and set (**blind write** to quorum)

Linearizability for different operations

This ensures linearizability of get (quorum read) and set (**blind write** to quorum)

- ▶ When an operation finishes, the value read/written is stored on a quorum of replicas
- ▶ Every subsequent quorum operation will see that value

Linearizability for different operations

This ensures linearizability of get (quorum read) and set (**blind write** to quorum)

- ▶ When an operation finishes, the value read/written is stored on a quorum of replicas
- ▶ Every subsequent quorum operation will see that value
- ▶ Multiple concurrent writes may overwrite each other

Linearizability for different operations

This ensures linearizability of get (quorum read) and set (**blind write** to quorum)

- ▶ When an operation finishes, the value read/written is stored on a quorum of replicas
- ▶ Every subsequent quorum operation will see that value
- ▶ Multiple concurrent writes may overwrite each other

What about an atomic **compare-and-swap** operation?

- ▶ $\text{CAS}(x, \text{oldValue}, \text{newValue})$ sets x to newValue iff current value of x is oldValue
- ▶ Previously discussed in shared-memory concurrency

Linearizability for different operations

This ensures linearizability of get (quorum read) and set (**blind write** to quorum)

- ▶ When an operation finishes, the value read/written is stored on a quorum of replicas
- ▶ Every subsequent quorum operation will see that value
- ▶ Multiple concurrent writes may overwrite each other

What about an atomic **compare-and-swap** operation?

- ▶ $\text{CAS}(x, \text{oldValue}, \text{newValue})$ sets x to newValue iff current value of x is oldValue
- ▶ Previously discussed in shared-memory concurrency
- ▶ Can we implement **linearizable** compare-and-swap in a distributed system?

Linearizability for different operations

This ensures linearizability of get (quorum read) and set (**blind write** to quorum)

- ▶ When an operation finishes, the value read/written is stored on a quorum of replicas
- ▶ Every subsequent quorum operation will see that value
- ▶ Multiple concurrent writes may overwrite each other

What about an atomic **compare-and-swap** operation?

- ▶ $\text{CAS}(x, \text{oldValue}, \text{newValue})$ sets x to newValue iff current value of x is oldValue
- ▶ Previously discussed in shared-memory concurrency
- ▶ 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 $\text{get}(x)$ **do**
 total order broadcast (get, x) and wait for delivery
end on

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

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

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

Consensus and total order broadcast

Dr. Martin Kleppmann
martin.kleppmann@cst.cam.ac.uk

University of Cambridge
Computer Science Tripos, Part IB

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?

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?

- ▶ **Manual failover:** a human operator chooses a new leader, and reconfigures each node to use new leader

Used in many databases! Fine for planned maintenance.

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?

- ▶ **Manual failover:** a human operator chooses a new leader, and reconfigures each node to use new leader

Used in many databases! Fine for planned maintenance.

Unplanned outage? Humans are slow, may take a long time until system recovers. . .

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?

- ▶ **Manual failover**: a human operator chooses a new leader, and reconfigures each node to use new leader

Used in many databases! Fine for planned maintenance.

Unplanned outage? Humans are slow, may take a long time until system recovers. . .

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

Consensus and total order broadcast

- ▶ Traditional formulation of consensus: several nodes want to come to **agreement** about a single **value**

Consensus and total order broadcast

- ▶ Traditional formulation of consensus: several nodes want to come to **agreement** about a single **value**
- ▶ In context of total order broadcast: this value is the **next message to deliver**

Consensus and total order broadcast

- ▶ Traditional formulation of consensus: several nodes want to come to **agreement** about a single **value**
- ▶ In context of total order broadcast: this value is the **next message to deliver**
- ▶ Once one node **decides** on a certain message order, all nodes will decide the same order

Consensus and total order broadcast

- ▶ Traditional formulation of consensus: several nodes want to come to **agreement** about a single **value**
- ▶ In context of total order broadcast: this value is the **next message to deliver**
- ▶ Once one node **decides** on a certain message order, all nodes will decide the same order
- ▶ Consensus and total order broadcast are formally equivalent

Consensus and total order broadcast

- ▶ Traditional formulation of consensus: several nodes want to come to **agreement** about a single **value**
- ▶ In context of total order broadcast: this value is the **next message to deliver**
- ▶ Once one node **decides** on a certain message order, all nodes will decide the same order
- ▶ Consensus and total order broadcast are formally equivalent

Common consensus algorithms:

- ▶ **Paxos**: single-value consensus
- ▶ **Multi-Paxos**: generalisation to total order broadcast

Consensus and total order broadcast

- ▶ Traditional formulation of consensus: several nodes want to come to **agreement** about a single **value**
- ▶ In context of total order broadcast: this value is the **next message to deliver**
- ▶ Once one node **decides** on a certain message order, all nodes will decide the same order
- ▶ Consensus and total order broadcast are formally equivalent

Common consensus algorithms:

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

Atomic commit versus consensus

Atomic commit	Consensus
Every node votes whether to commit or abort	One or more nodes propose a value

Atomic commit versus consensus

Atomic commit	Consensus
Every node votes whether to commit or abort	One or more nodes propose a value
Must commit if all nodes vote to commit; must abort if ≥ 1 nodes vote to abort	Any one of the proposed values is decided

Atomic commit versus consensus

Atomic commit	Consensus
Every node votes whether to commit or abort	One or more nodes propose a value
Must commit if all nodes vote to commit; must abort if ≥ 1 nodes vote to abort	Any one of the proposed values is decided
Must abort if a participating node crashes	Crashed nodes can be tolerated, as long as a quorum is working

How total order broadcast should behave

Properties of total order broadcast fall into two categories:

- ▶ **Safety:** *“nothing bad happens”*

- ▶ **Liveness:** *“something good eventually happens”*

How total order broadcast should behave

Properties of total order broadcast fall into two categories:

- ▶ **Safety:** *“nothing bad happens”*

1. Let N_1 and N_2 be two nodes that each deliver two messages m_1 and m_2 , and assume that N_1 delivers m_1 before m_2 . Then N_2 also delivers m_1 before m_2 .

- ▶ **Liveness:** *“something good eventually happens”*

How total order broadcast should behave

Properties of total order broadcast fall into two categories:

► **Safety:** *“nothing bad happens”*

1. Let N_1 and N_2 be two nodes that each deliver two messages m_1 and m_2 , and assume that N_1 delivers m_1 before m_2 . Then N_2 also delivers m_1 before m_2 .
2. If some node delivers a message m , then m was previously broadcast by some node.

► **Liveness:** *“something good eventually happens”*

How total order broadcast should behave

Properties of total order broadcast fall into two categories:

► **Safety:** *“nothing bad happens”*

1. Let N_1 and N_2 be two nodes that each deliver two messages m_1 and m_2 , and assume that N_1 delivers m_1 before m_2 . Then N_2 also delivers m_1 before m_2 .
2. If some node delivers a message m , then m was previously broadcast by some node.
3. A node does not deliver the same message more than once.

► **Liveness:** *“something good eventually happens”*

How total order broadcast should behave

Properties of total order broadcast fall into two categories:

► **Safety:** *“nothing bad happens”*

1. Let N_1 and N_2 be two nodes that each deliver two messages m_1 and m_2 , and assume that N_1 delivers m_1 before m_2 . Then N_2 also delivers m_1 before m_2 .
2. If some node delivers a message m , then m was previously broadcast by some node.
3. A node does not deliver the same message more than once.

► **Liveness:** *“something good eventually happens”*

4. If a node broadcasts a message m and does not crash, then eventually that node delivers m .

How total order broadcast should behave

Properties of total order broadcast fall into two categories:

► **Safety:** *“nothing bad happens”*

1. Let N_1 and N_2 be two nodes that each deliver two messages m_1 and m_2 , and assume that N_1 delivers m_1 before m_2 . Then N_2 also delivers m_1 before m_2 .
2. If some node delivers a message m , then m was previously broadcast by some node.
3. A node does not deliver the same message more than once.

► **Liveness:** *“something good eventually happens”*

4. If a node broadcasts a message m and does not crash, then eventually that node delivers m .
5. If one node delivers a message m , then every other node that does not crash eventually delivers m .

Consensus system models

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

Consensus system models

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

Why not asynchronous?

- ▶ **FLP result** (Fischer, Lynch, Paterson):

There is no deterministic consensus algorithm that is guaranteed to terminate in an asynchronous crash-stop system model.

Consensus system models

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

Why not asynchronous?

- ▶ **FLP result** (Fischer, Lynch, Paterson):
There is no deterministic consensus algorithm that is guaranteed to terminate in an asynchronous crash-stop system model.
- ▶ Paxos, Raft, etc. use clocks only used for timeouts/failure detector to ensure liveness. Safety does not depend on timing.

Consensus system models

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

Why not asynchronous?

- ▶ **FLP result** (Fischer, Lynch, Paterson):
There is no deterministic consensus algorithm that is guaranteed to terminate in an asynchronous crash-stop system model.
- ▶ Paxos, Raft, etc. use clocks only used for timeouts/failure detector to ensure liveness. Safety does not depend on timing.

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

Leader election

Multi-Paxos, Raft, etc. use a leader to sequence messages.

Leader election

Multi-Paxos, Raft, etc. use a leader to sequence messages.

- ▶ Use a **failure detector** (timeout) to determine suspected crash or unavailability of leader.
- ▶ On suspected leader crash, **elect a new one**.

Leader election

Multi-Paxos, Raft, etc. use a leader to sequence messages.

- ▶ Use a **failure detector** (timeout) to determine suspected crash or unavailability of leader.
- ▶ On suspected leader crash, **elect a new one**.
- ▶ Prevent **two leaders at the same time** (“split-brain”)!

Leader election

Multi-Paxos, Raft, etc. use a leader to sequence messages.

- ▶ Use a **failure detector** (timeout) to determine suspected crash or unavailability of leader.
- ▶ On suspected leader crash, **elect a new one**.
- ▶ Prevent **two leaders at the same time** (“split-brain”)!

Ensure ≤ 1 leader per **term**:

- ▶ Term is incremented every time a leader election is started

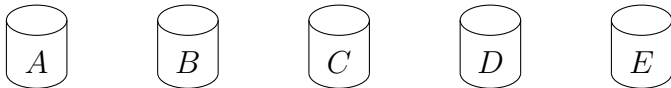
Leader election

Multi-Paxos, Raft, etc. use a leader to sequence messages.

- ▶ Use a **failure detector** (timeout) to determine suspected crash or unavailability of leader.
- ▶ On suspected leader crash, **elect a new one**.
- ▶ Prevent **two leaders at the same time** (“split-brain”)!

Ensure ≤ 1 leader per **term**:

- ▶ Term is incremented every time a leader election is started
- ▶ A node can only **vote once** per term
- ▶ Require a **quorum** of nodes to elect a leader in a term



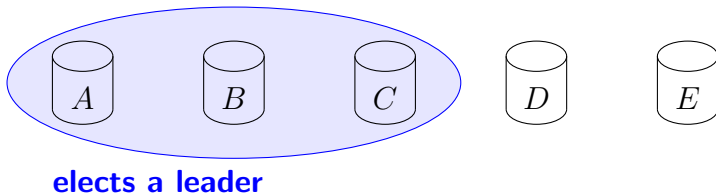
Leader election

Multi-Paxos, Raft, etc. use a leader to sequence messages.

- ▶ Use a **failure detector** (timeout) to determine suspected crash or unavailability of leader.
- ▶ On suspected leader crash, **elect a new one**.
- ▶ Prevent **two leaders at the same time** (“split-brain”)!

Ensure ≤ 1 leader per **term**:

- ▶ Term is incremented every time a leader election is started
- ▶ A node can only **vote once** per term
- ▶ Require a **quorum** of nodes to elect a leader in a term



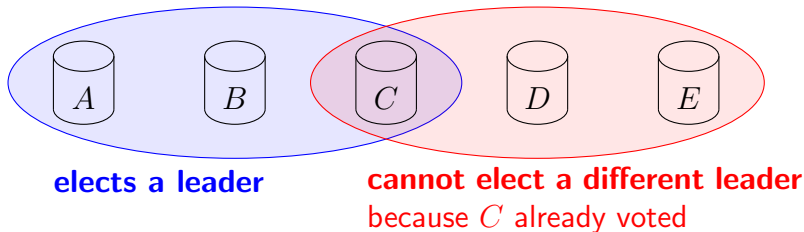
Leader election

Multi-Paxos, Raft, etc. use a leader to sequence messages.

- ▶ Use a **failure detector** (timeout) to determine suspected crash or unavailability of leader.
- ▶ On suspected leader crash, **elect a new one**.
- ▶ Prevent **two leaders at the same time** (“split-brain”)!

Ensure ≤ 1 leader per **term**:

- ▶ Term is incremented every time a leader election is started
- ▶ A node can only **vote once** per term
- ▶ Require a **quorum** of nodes to elect a leader in a term



Can we guarantee there is only one leader?

Can guarantee unique leader **per term**.

Can we guarantee there is only one leader?

Can guarantee unique leader **per term**.

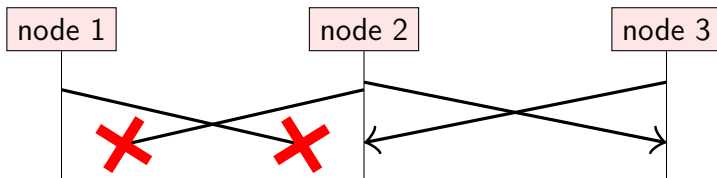
Cannot prevent having multiple leaders from different terms.

Can we guarantee there is only one leader?

Can guarantee unique leader **per term**.

Cannot prevent having multiple leaders from different terms.

Example: node 1 is leader in term t , but due to a network partition it can no longer communicate with nodes 2 and 3:



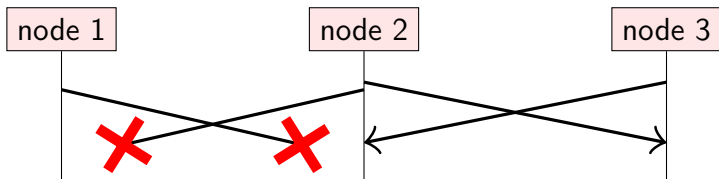
Nodes 2 and 3 may elect a new leader in term $t + 1$.

Can we guarantee there is only one leader?

Can guarantee unique leader **per term**.

Cannot prevent having multiple leaders from different terms.

Example: node 1 is leader in term t , but due to a network partition it can no longer communicate with nodes 2 and 3:

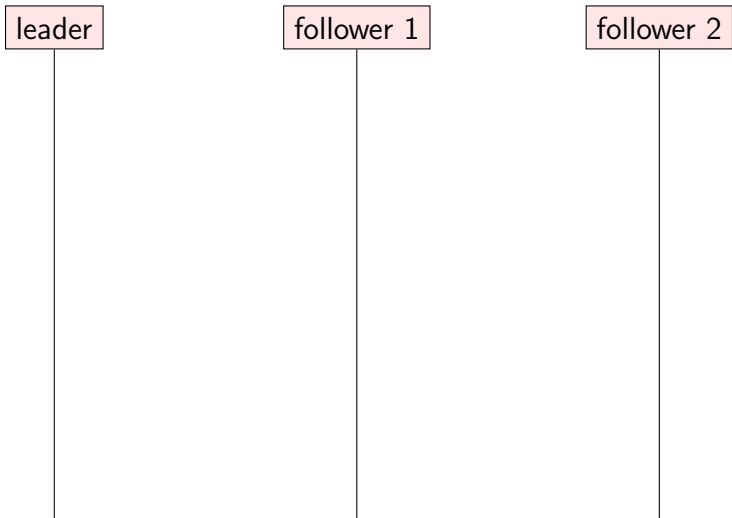


Nodes 2 and 3 may elect a new leader in term $t + 1$.

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

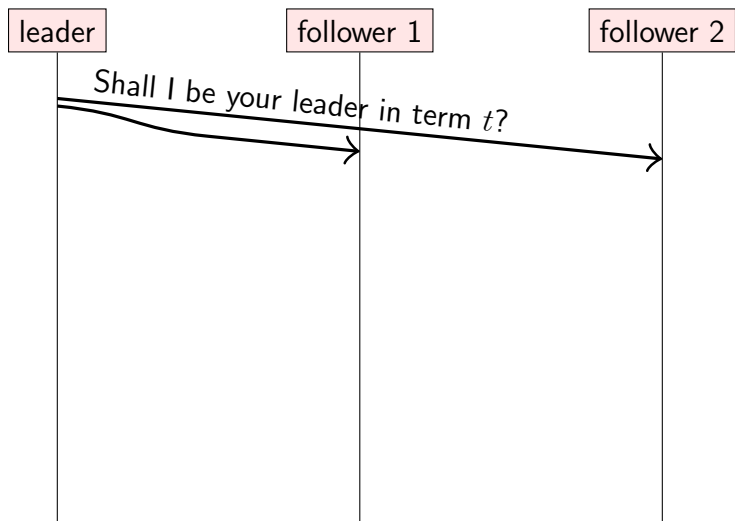
Checking if a leader has been voted out

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



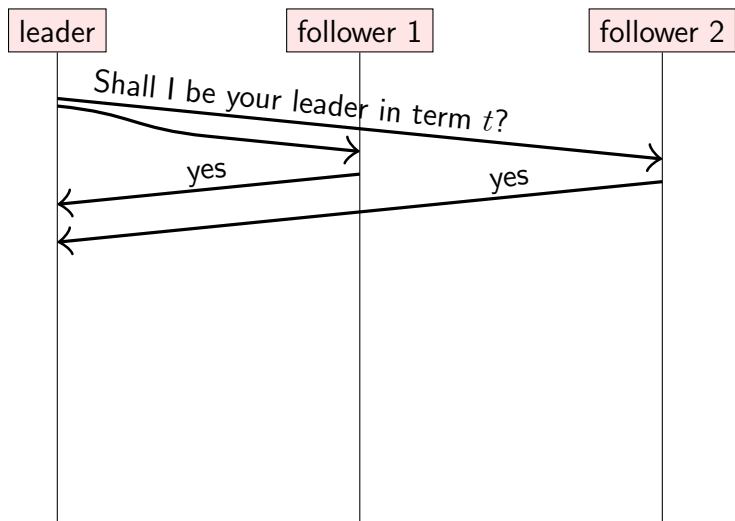
Checking if a leader has been voted out

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



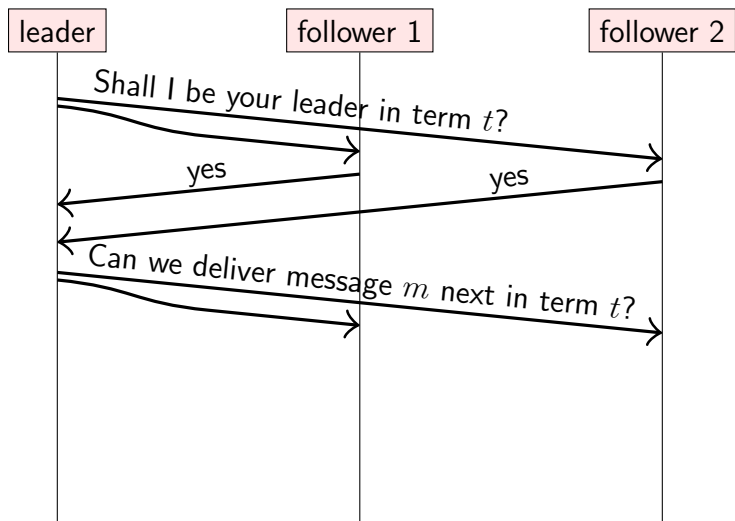
Checking if a leader has been voted out

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



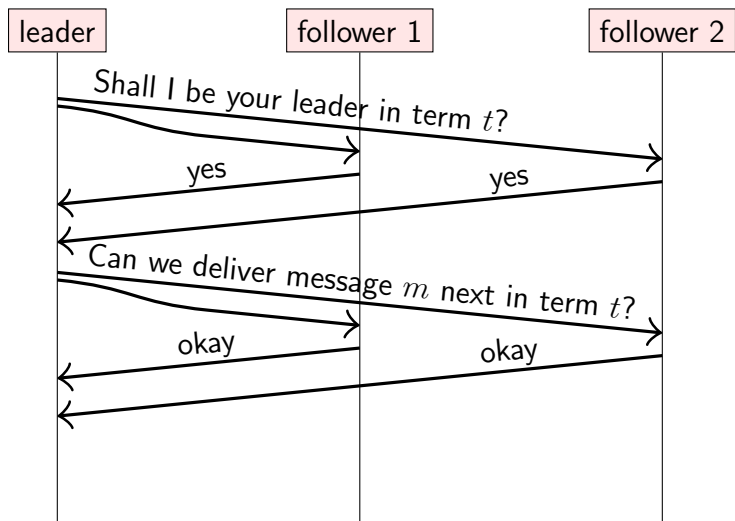
Checking if a leader has been voted out

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



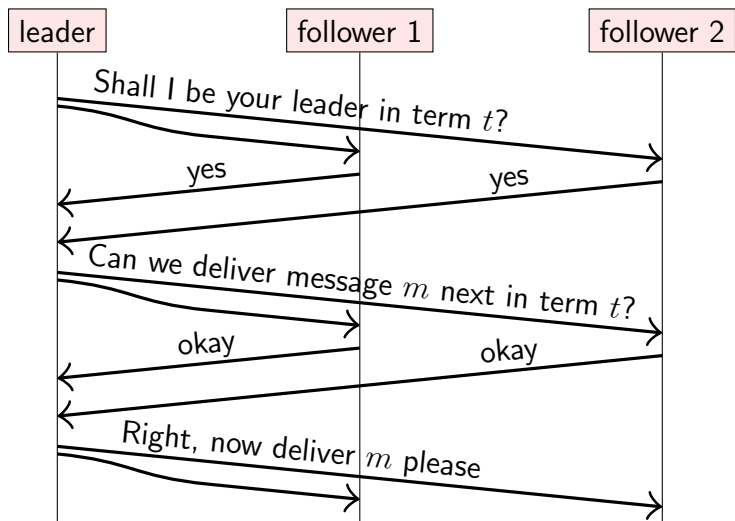
Checking if a leader has been voted out

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

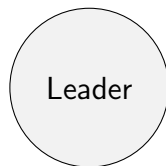
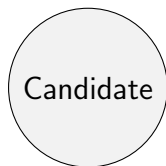
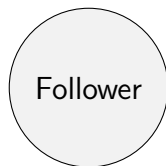


Checking if a leader has been voted out

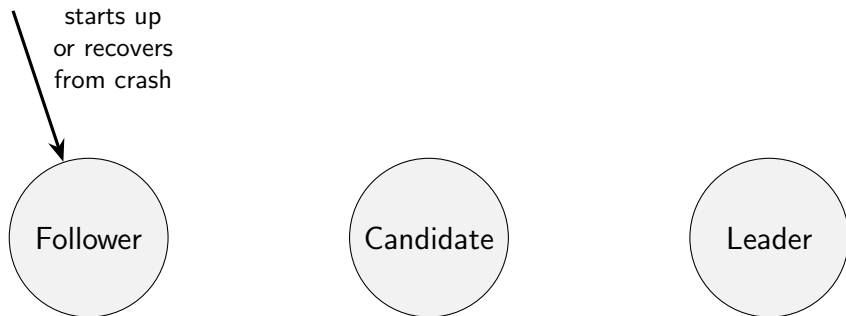
For every decision (message to deliver), the leader must first get acknowledgements from a quorum.



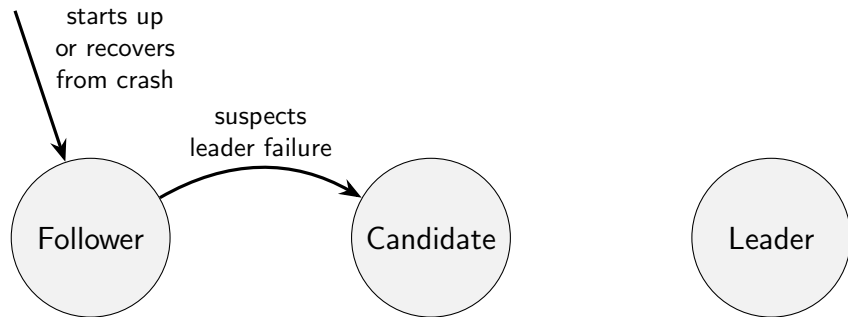
Node state transitions in Raft



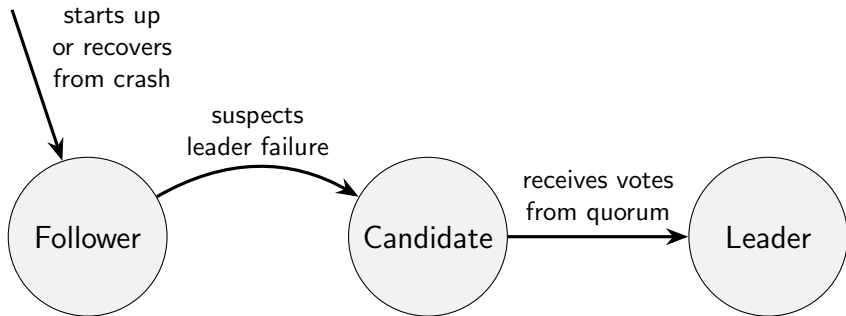
Node state transitions in Raft



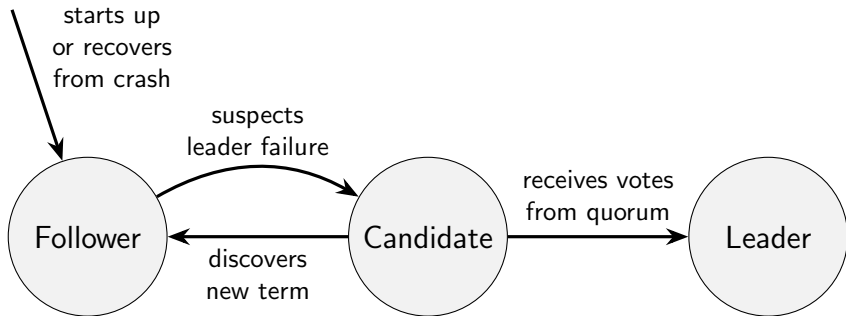
Node state transitions in Raft



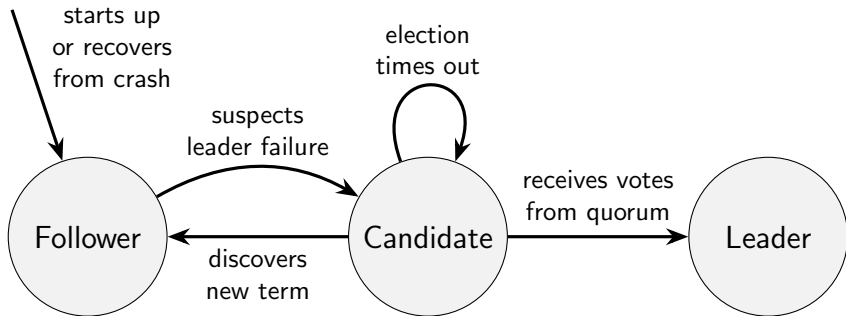
Node state transitions in Raft



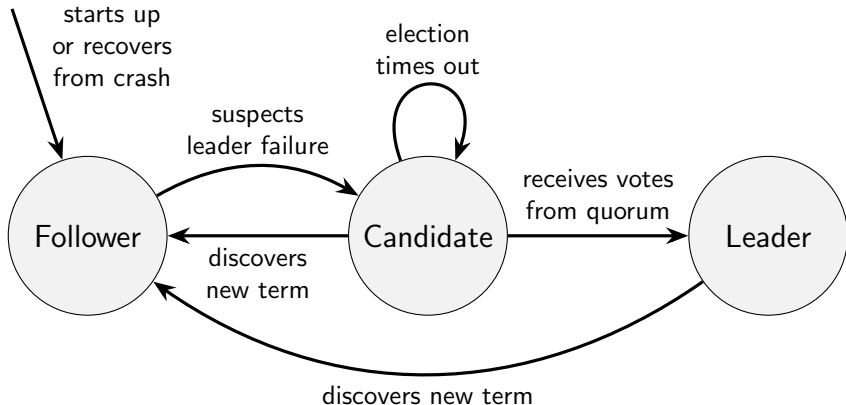
Node state transitions in Raft



Node state transitions in Raft



Node state transitions in Raft



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.length* - 1].term; **end if**

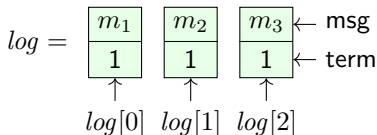
msg := (VoteRequest, *nodeId*, *currentTerm*, *log.length*, *lastTerm*)

for each *node* \in *nodes*: **send** *msg* to *node*

start election timer

end on

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** $lastTerm := log[log.length - 1].term$; **end if**

$msg := (VoteRequest, nodeId, currentTerm, log.length, lastTerm)$

for each $node \in nodes$: **send** msg to $node$

start election timer

end on

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

```
on receiving (VoteRequest,  $cId$ ,  $cTerm$ ,  $cLogLength$ ,  $cLogTerm$ )  
  at node  $nodeId$  do  
    if  $cTerm > currentTerm$  then  
       $currentTerm := cTerm$ ;  $currentRole := follower$   
       $votedFor := null$   
    end if  
     $lastTerm := 0$   
    if  $log.length > 0$  then  $lastTerm := log[log.length - 1].term$ ; end if  
     $logOk := (cLogTerm > lastTerm) \vee$   
       $(cLogTerm = lastTerm \wedge cLogLength \geq log.length)$   
  
    if  $cTerm = currentTerm \wedge logOk \wedge votedFor \in \{cId, null\}$  then  
       $votedFor := cId$   
      send (VoteResponse,  $nodeId$ ,  $currentTerm$ , true) to node  $cId$   
    else  
      send (VoteResponse,  $nodeId$ ,  $currentTerm$ , 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)  
  at node nodeId do  
    if cTerm > currentTerm then  
      currentTerm := cTerm; currentRole := follower  
      votedFor := null  
    end if  
    lastTerm := 0  
    if log.length > 0 then lastTerm := log[log.length - 1].term; end if  
    logOk := (cLogTerm > lastTerm) ∨  
             (cLogTerm = lastTerm ∧ cLogLength ≥ log.length)  
  
    if cTerm = currentTerm ∧ logOk ∧ votedFor ∈ {cId, null} then  
      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 (VoteResponse, voterId, term, granted) at nodeId do
  if currentRole = candidate  $\wedge$  term = currentTerm  $\wedge$  granted then
    votesReceived := votesReceived  $\cup$  {voterId}
    if |votesReceived|  $\geq \lceil (|nodes| + 1)/2 \rceil$  then
      currentRole := leader; currentLeader := nodeId
      cancel election timer
      for each follower  $\in$  nodes  $\setminus$  {nodeId} do
        sentLength[follower] := log.length
        ackedLength[follower] := 0
        REPLICATELOG(nodeId, follower)
      end for
    end if
  else if term > currentTerm then
    currentTerm := term
    currentRole := follower
    votedFor := 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 (msg : msg, term : currentTerm) to log
    ackedLength[nodeId] := log.length
    for each follower ∈ nodes \ {nodeId} do
      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 ∈ nodes \ {nodeId} do
      REPLICATELOG(nodeId, follower)
    end for
  end if
end do
```

Raft (5/9): replicating to followers

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

```
function REPLICATELOG(leaderId, followerId)  
  prefixLen := sentLength[followerId]  
  suffix :=  $\langle \log[\textit{prefixLen}], \log[\textit{prefixLen} + 1], \dots,$   
             $\log[\log.\textit{length} - 1] \rangle$   
  prefixTerm := 0  
  if prefixLen > 0 then  
    prefixTerm :=  $\log[\textit{prefixLen} - 1].\textit{term}$   
  end if  
  send (LogRequest, leaderId, currentTerm, prefixLen,  
        prefixTerm, commitLength, suffix) to followerId  
end function
```

Raft (6/9): followers receiving messages

```
on receiving (LogRequest, leaderId, term, prefixLen, prefixTerm,
              leaderCommit, suffix) at node nodeId do
  if term > currentTerm then
    currentTerm := term; votedFor := null
  end if
  if term = currentTerm then
    currentRole := follower; currentLeader := leaderId
    cancel election timer
  end if
  logOk := (log.length ≥ prefixLen) ∧
            (prefixLen = 0 ∨ log[prefixLen - 1].term = prefixTerm)
  if term = currentTerm ∧ logOk then
    APPENDENTRIES(prefixLen, leaderCommit, suffix)
    ack := prefixLen + suffix.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 APPENDENTRIES(prefixLen, leaderCommit, suffix)  
  if suffix.length > 0  $\wedge$  log.length > prefixLen then  
    index := min(log.length, prefixLen + suffix.length) - 1  
    if log[index].term  $\neq$  suffix[index - prefixLen].term then  
      log :=  $\langle$  log[0], log[1], ..., log[prefixLen - 1]  $\rangle$   
    end if  
  end if  
  
  if prefixLen + suffix.length > log.length then  
    for i := log.length - prefixLen to suffix.length - 1 do  
      append suffix[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 acks

```
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  
       $sentLength[follower] := ack$   
       $ackedLength[follower] := ack$   
      COMMITLOGENTRIES()  
    else if  $sentLength[follower] > 0$  then  
       $sentLength[follower] := sentLength[follower] - 1$   
      REPLICATELOG(nodeId, follower)  
    end if  
  else if  $term > currentTerm$  then  
     $currentTerm := term$   
     $currentRole := follower$   
     $votedFor := null$   
    cancel election timer  
  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 $\text{acks}(\text{length}) = |\{n \in \text{nodes} \mid \text{ackedLength}[n] \geq \text{length}\}|$

function COMMITLOGENTRIES

$\text{minAcks} := \lceil (|\text{nodes}| + 1)/2 \rceil$

$\text{ready} := \{len \in \{1, \dots, \text{log.length}\} \mid \text{acks}(len) \geq \text{minAcks}\}$

if $\text{ready} \neq \{\}$ $\wedge \max(\text{ready}) > \text{commitLength} \wedge$
 $\text{log}[\max(\text{ready}) - 1].\text{term} = \text{currentTerm}$ **then**

for $i := \text{commitLength}$ **to** $\max(\text{ready}) - 1$ **do**

 deliver $\text{log}[i].\text{msg}$ to the application

end for

$\text{commitLength} := \max(\text{ready})$

end if

end function

...and that was just the basic form of Raft!

A real implementation would need to do more:

- ▶ Efficient **log reconciliation** when $\neg \log Ok$
- ▶ Allow **reconfiguration**:
allow administrators to add or remove nodes, adjusting quorums accordingly
- ▶ Better **throughput**:
avoid having to do everything through the leader?
(some Paxos variants are less leader-centric)

...and that was just the basic form of Raft!

A real implementation would need to do more:

- ▶ Efficient **log reconciliation** when $\neg \log Ok$
- ▶ Allow **reconfiguration**:
allow administrators to add or remove nodes, adjusting quorums accordingly
- ▶ Better **throughput**:
avoid having to do everything through the leader?
(some Paxos variants are less leader-centric)

Going even further:

- ▶ Raft assumes all nodes are honest;
Byzantine consensus required for blockchains

Eventual Consistency

Dr. Martin Kleppmann
martin.kleppmann@cst.cam.ac.uk

University of Cambridge
Computer Science Tripos, Part IB

Eventual consistency

Linearizability advantages:

- ▶ Makes a distributed system behave as if it were non-distributed
- ▶ Simple for applications to use

Eventual consistency

Linearizability advantages:

- ▶ Makes a distributed system behave as if it were non-distributed
- ▶ Simple for applications to use

Downsides:

- ▶ **Performance** cost: lots of messages and waiting for responses

Eventual consistency

Linearizability advantages:

- ▶ Makes a distributed system behave as if it were non-distributed
- ▶ Simple for applications to use

Downsides:

- ▶ **Performance** cost: lots of messages and waiting for responses
- ▶ **Scalability** limits: leader can be a bottleneck

Eventual consistency

Linearizability advantages:

- ▶ Makes a distributed system behave as if it were non-distributed
- ▶ Simple for applications to use

Downsides:

- ▶ **Performance** cost: lots of messages and waiting for responses
- ▶ **Scalability** limits: leader can be a bottleneck
- ▶ **Availability** problems: if you can't contact a quorum of nodes, you can't process any operations

Eventual consistency

Linearizability advantages:

- ▶ Makes a distributed system behave as if it were non-distributed
- ▶ Simple for applications to use

Downsides:

- ▶ **Performance** cost: lots of messages and waiting for responses
- ▶ **Scalability** limits: leader can be a bottleneck
- ▶ **Availability** problems: if you can't contact a quorum of nodes, you can't process any operations

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

Calendars + Day Week Month Year United Kingdom Time Search

5 November 2020

Thursday

all-day

07:00

08:00

09:00

10:00

11:00

12:00

13:00

14:00

15:00

16:00

17:00

18:00

19:00

12:00
Distributed systems lecture

14:00
Test

M	T	W	T	F	S	S
26	27	28	29	30	31	1
2	3	4	5	6	7	8
9	10	11	12	13	14	15
16	17	18	19	20	21	22
23	24	25	26	27	28	29
30	1	2	3	4	5	6

No Event Selected

09:41 100%

< November

M T W T F S S

2 3 4 5 6 7 8

Thursday 5 November 2020

10:00

11:00

12:00

13:00

14:00

15:00

16:00

17:00

18:00

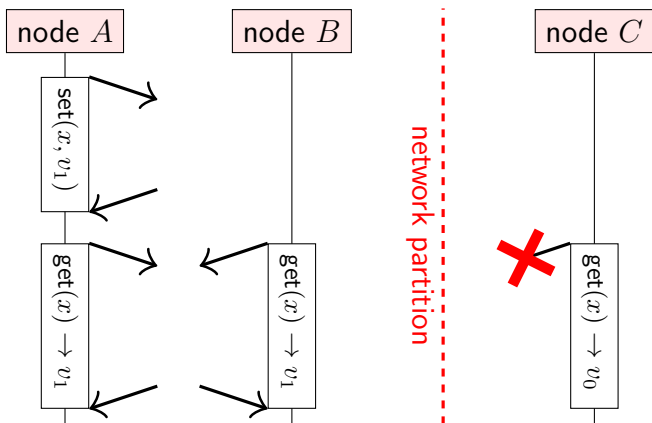
Distributed systems lecture

Test

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.)

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.)

Strong eventual consistency:

- ▶ **Eventual delivery:** every update made to one non-faulty replica is eventually processed by every non-faulty replica.

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.)

Strong eventual consistency:

- ▶ **Eventual delivery:** every update made to one non-faulty replica is eventually processed by every non-faulty replica.
- ▶ **Convergence:** any two replicas that have processed the same set of updates are in the same state (even if updates were processed in a different order).

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.)

Strong eventual consistency:

- ▶ **Eventual delivery:** every update made to one non-faulty replica is eventually processed by every non-faulty replica.
- ▶ **Convergence:** any two replicas that have processed the same set of updates are in the same state (even if updates were processed in a different order).

Properties:

- ▶ Does not require waiting for network communication
- ▶ Causal broadcast (or weaker) can disseminate updates

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.)

Strong eventual consistency:

- ▶ **Eventual delivery:** every update made to one non-faulty replica is eventually processed by every non-faulty replica.
- ▶ **Convergence:** any two replicas that have processed the same set of updates are in the same state (even if updates were processed in a different order).

Properties:

- ▶ Does not require waiting for network communication
- ▶ Causal broadcast (or weaker) can disseminate updates
- ▶ Concurrent updates \implies **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

↑
strength of assumptions

Summary of minimum system model requirements

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

↑
strength of assumptions

Summary of minimum system model requirements

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

Summary of minimum system model requirements

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
eventual consistency, causal broadcast, FIFO broadcast	local replica only	asynchronous

↑
strength of assumptions

Local-first software

End-user device is a full replica; servers are just for backup.

“Local-first”: a term introduced by me and my colleagues

<https://www.inkandswitch.com/local-first/>

Calendar app with cross-device sync is an example:

Local-first software

End-user device is a full replica; servers are just for backup.

“Local-first”: a term introduced by me and my colleagues

<https://www.inkandswitch.com/local-first/>

Calendar app with cross-device sync is an example:

- ▶ App works **offline** (can both read and modify data)
- ▶ **Fast**: no need to wait for network round-trip
- ▶ **Sync** with other devices when online
- ▶ **Real-time collaboration** with other users

Local-first software

End-user device is a full replica; servers are just for backup.

“Local-first”: a term introduced by me and my colleagues

<https://www.inkandswitch.com/local-first/>

Calendar app with cross-device sync is an example:

- ▶ App works **offline** (can both read and modify data)
- ▶ **Fast**: no need to wait for network round-trip
- ▶ **Sync** with other devices when online
- ▶ **Real-time collaboration** with other users
- ▶ **Longevity**: even if cloud service shuts down, you have a copy of your files on your own computer
- ▶ Supports **end-to-end encryption** for better security
- ▶ Simpler **programming model** than RPC
- ▶ **User control** and agency over their own data

Collaboration and conflict resolution

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

- ▶ **Examples:** calendar sync, text editors (Google Docs), spreadsheets, presentations, graphics apps. . .

Collaboration and conflict resolution

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

- ▶ **Examples:** calendar sync, text editors (Google Docs), spreadsheets, presentations, graphics apps. . .
- ▶ Several users/devices working on a shared file/document
- ▶ Each user device has local replica of the data

Collaboration and conflict resolution

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

- ▶ **Examples:** calendar sync, text editors (Google Docs), spreadsheets, presentations, graphics apps. . .
- ▶ Several users/devices working on a shared file/document
- ▶ Each user device has local replica of the data
- ▶ Update local replica optimistically, sync with others asynchronously (waiting for round trip is too slow)

Collaboration and conflict resolution

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

- ▶ **Examples:** calendar sync, text editors (Google Docs), spreadsheets, presentations, graphics apps. . .
- ▶ Several users/devices working on a shared file/document
- ▶ Each user device has local replica of the data
- ▶ Update local replica optimistically, sync with others asynchronously (waiting for round trip is too slow)
- ▶ **Challenge:** how to reconcile concurrent updates?

Collaboration and conflict resolution

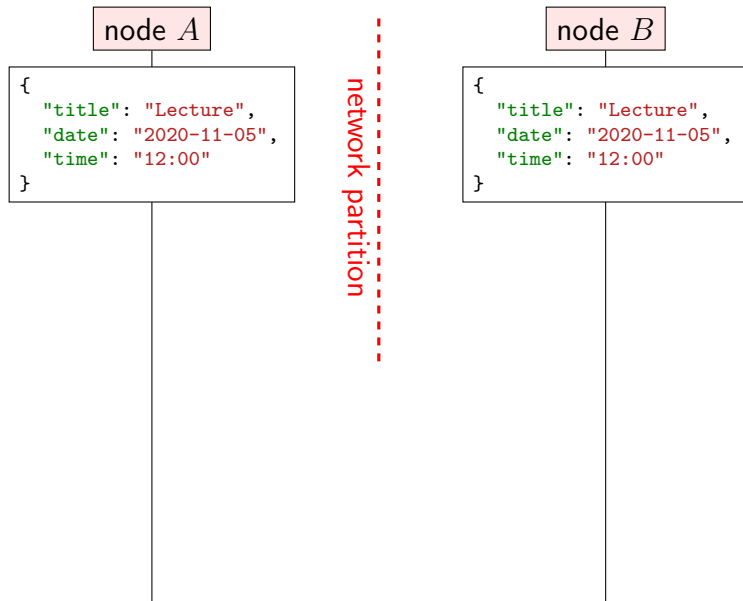
Nowadays we use a lot of **collaboration software**:

- ▶ **Examples:** calendar sync, text editors (Google Docs), spreadsheets, presentations, graphics apps. . .
- ▶ Several users/devices working on a shared file/document
- ▶ Each user device has local replica of the data
- ▶ Update local replica optimistically, sync with others asynchronously (waiting for round trip is too slow)
- ▶ **Challenge:** how to reconcile concurrent updates?

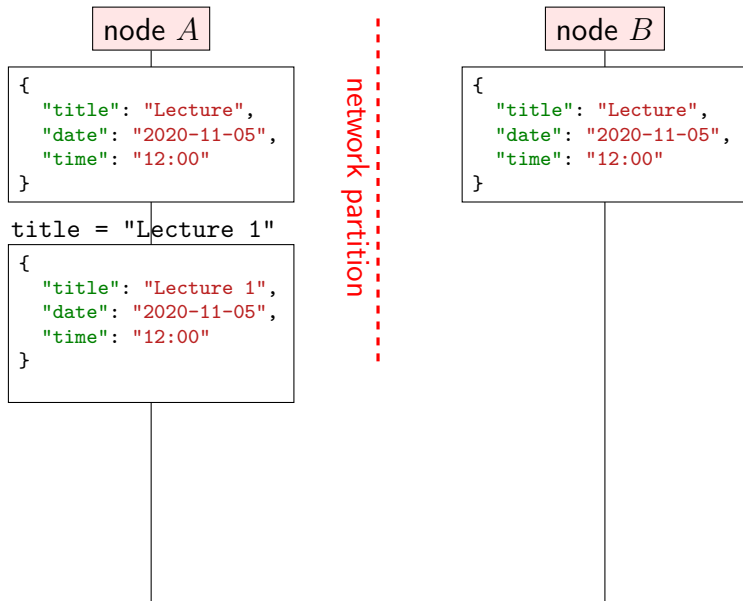
Families of **algorithms**:

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

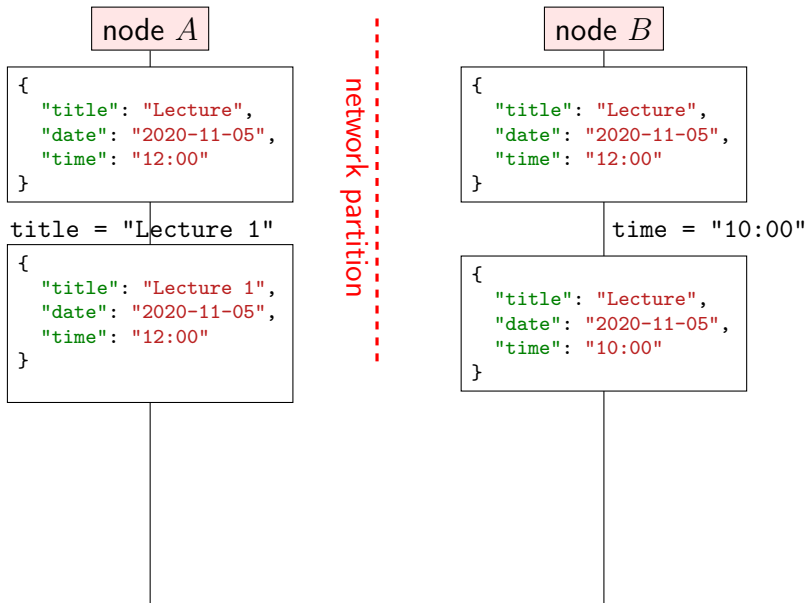
Conflicts due to concurrent updates



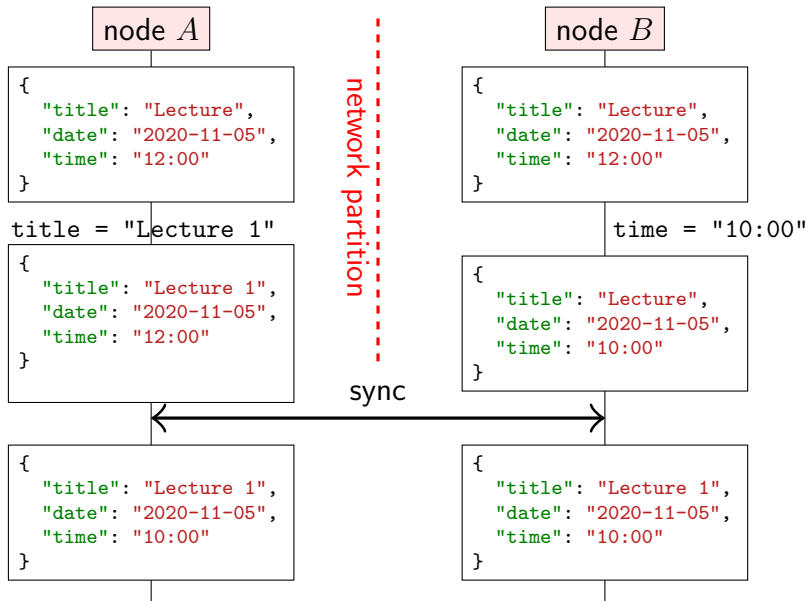
Conflicts due to concurrent updates



Conflicts due to concurrent updates



Conflicts due to concurrent updates



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**

$t := \text{newTimestamp}()$ \triangleright 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 $previous = \{\} \vee \forall (t', k', v') \in previous. t' < t$ **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 (set, t_1 , "title", "Lecture 1")
- ▶ broadcast (set, t_2 , "time", "10:00")

Operation-based CRDTs

Reliable broadcast may deliver updates in any order:

- ▶ broadcast (set, t_1 , "title", "Lecture 1")
- ▶ broadcast (set, t_2 , "time", "10:00")

Recall **strong eventual consistency**:

- ▶ **Eventual delivery:** every update made to one non-faulty replica is eventually processed by every non-faulty replica.
- ▶ **Convergence:** any two replicas that have processed the same set of updates are in the same state

Operation-based CRDTs

Reliable broadcast may deliver updates in any order:

- ▶ broadcast (set, t_1 , "title", "Lecture 1")
- ▶ broadcast (set, t_2 , "time", "10:00")

Recall **strong eventual consistency**:

- ▶ **Eventual delivery:** every update made to one non-faulty replica is eventually processed by every non-faulty replica.
- ▶ **Convergence:** any two replicas that have processed the same set of updates are in the same state

CRDT algorithm implements this:

- ▶ Reliable broadcast ensures every operation is eventually delivered to every (non-crashed) replica

Operation-based CRDTs

Reliable broadcast may deliver updates in any order:

- ▶ broadcast (set, t_1 , "title", "Lecture 1")
- ▶ broadcast (set, t_2 , "time", "10:00")

Recall **strong eventual consistency**:

- ▶ **Eventual delivery**: every update made to one non-faulty replica is eventually processed by every non-faulty replica.
- ▶ **Convergence**: any two replicas that have processed the same set of updates are in the same state

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**

values := {}

end on

on request to read value for key k **do**

if $\exists t, v. (t, k, v) \in \textit{values}$ **then return** v **else return** null

end on

on request to set key k to value v **do**

$t := \text{newTimestamp}()$ \triangleright globally unique, e.g. Lamport timestamp

$\textit{values} := \{(t', k', v') \in \textit{values} \mid k' \neq k\} \cup \{(t, k, v)\}$

broadcast \textit{values} by best-effort broadcast

end on

on delivering V by best-effort broadcast **do**

$\textit{values} := \textit{values} \sqcup V$

end on

State-based CRDTs

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

- ▶ **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:** $s_1 \sqcup s_1 = s_1$.

State-based CRDTs

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

- ▶ **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:** $s_1 \sqcup s_1 = s_1$.

State-based versus operation-based:

- ▶ Op-based CRDT typically has smaller messages
- ▶ State-based CRDT can tolerate message loss/duplication

State-based CRDTs

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

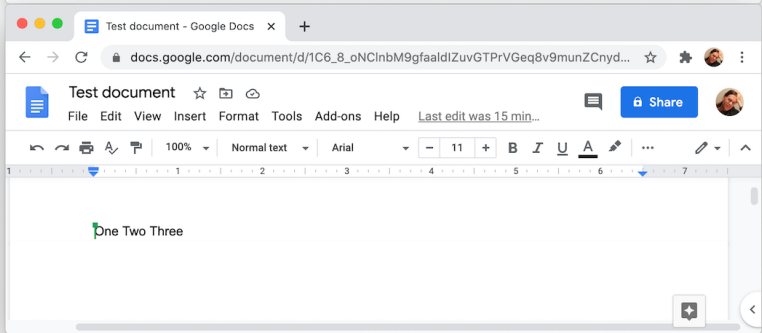
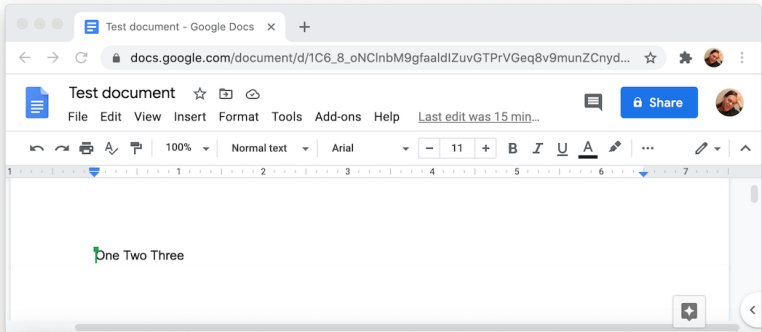
- ▶ **Commutative:** $s_1 \sqcup s_2 = s_2 \sqcup s_1$.
- ▶ **Associative:** $(s_1 \sqcup s_2) \sqcup s_3 = s_1 \sqcup (s_2 \sqcup s_3)$.
- ▶ **Idempotent:** $s_1 \sqcup s_1 = s_1$.

State-based versus operation-based:

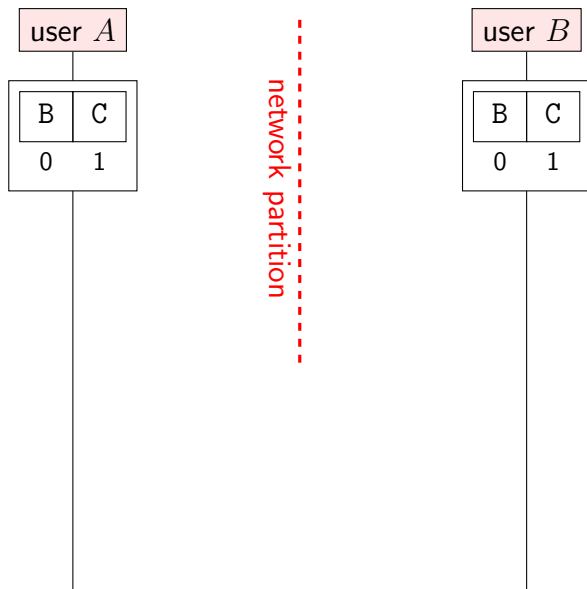
- ▶ Op-based CRDT typically has smaller messages
- ▶ State-based CRDT can tolerate message loss/duplication

Not necessarily uses broadcast:

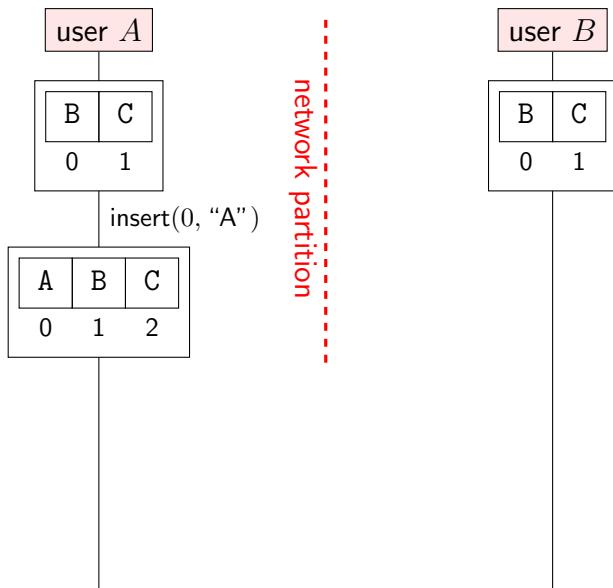
- ▶ Can also merge concurrent updates to replicas e.g. in quorum replication, anti-entropy, ...



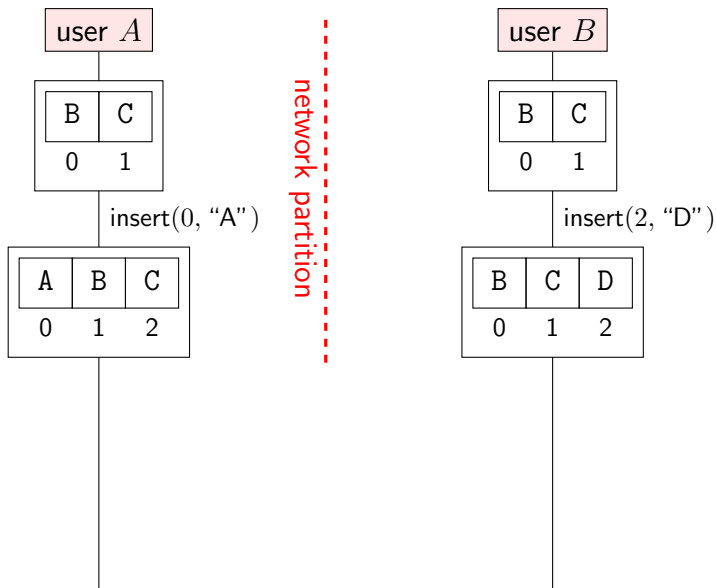
Collaborative text editing: the problem



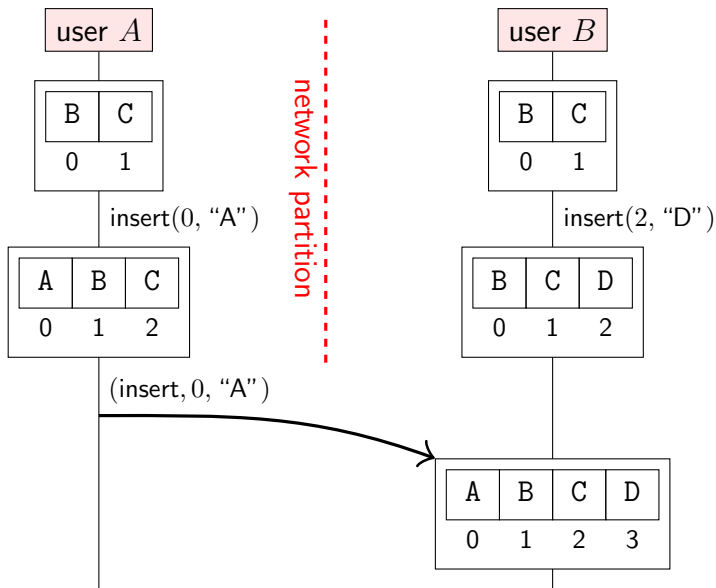
Collaborative text editing: the problem



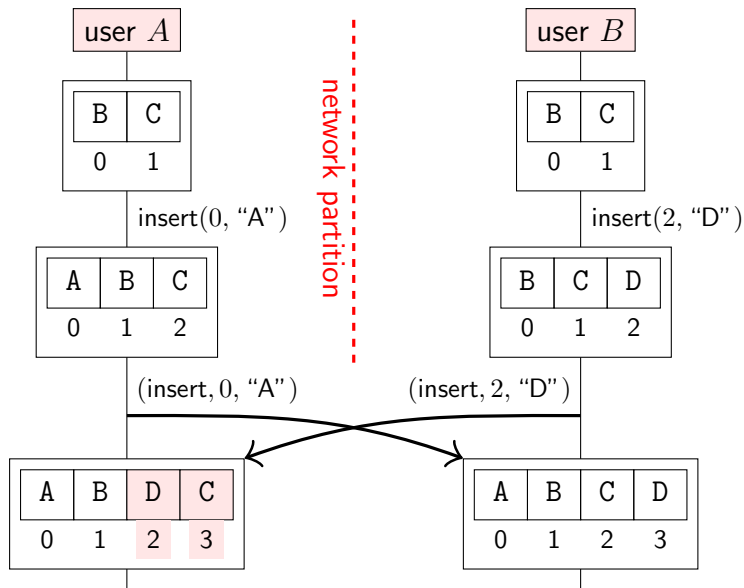
Collaborative text editing: the problem



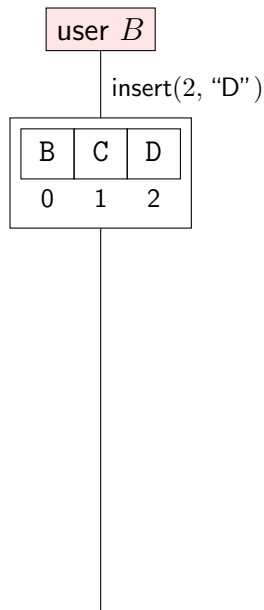
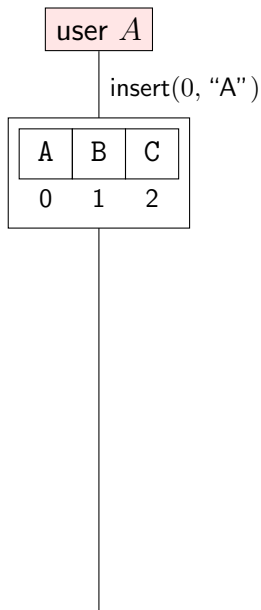
Collaborative text editing: the problem



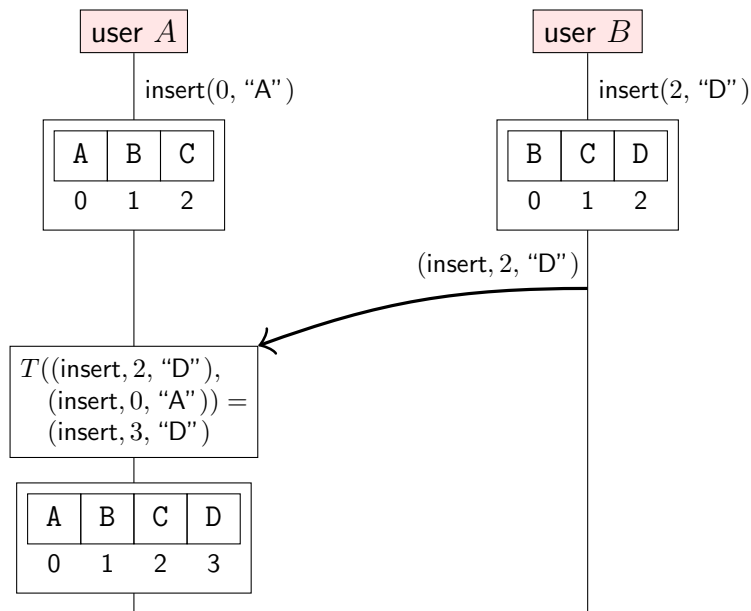
Collaborative text editing: the problem



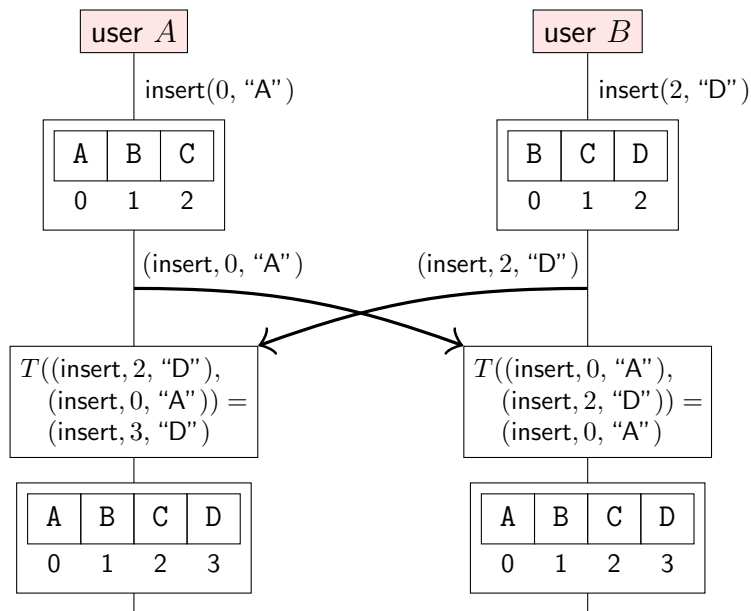
Operational transformation



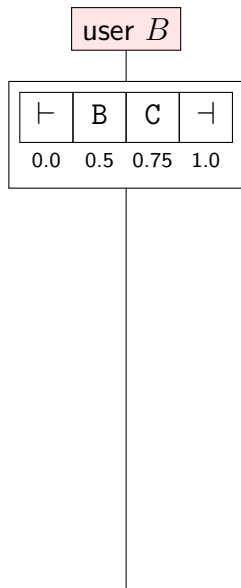
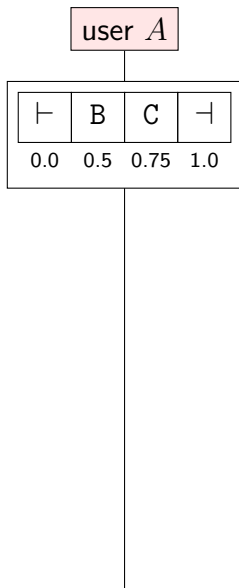
Operational transformation



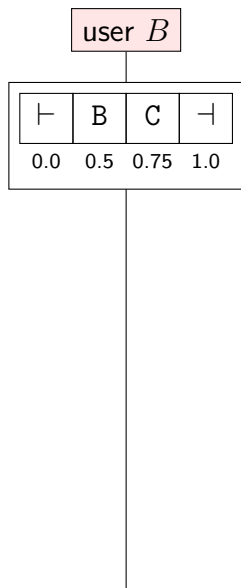
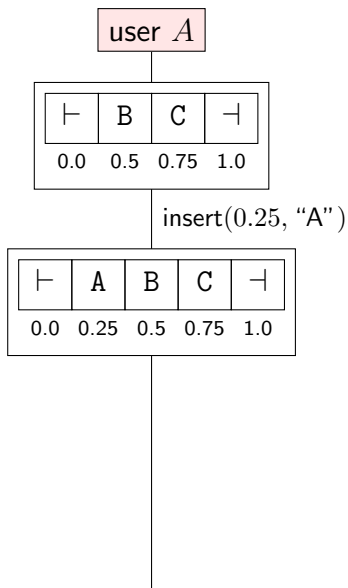
Operational transformation



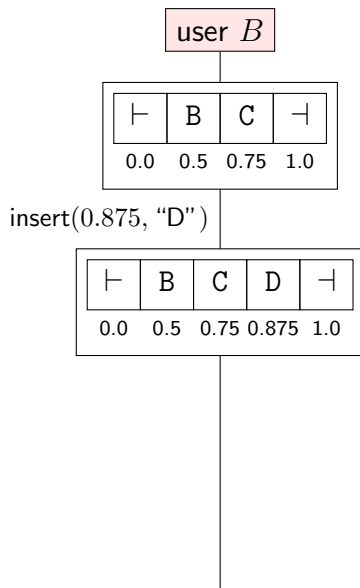
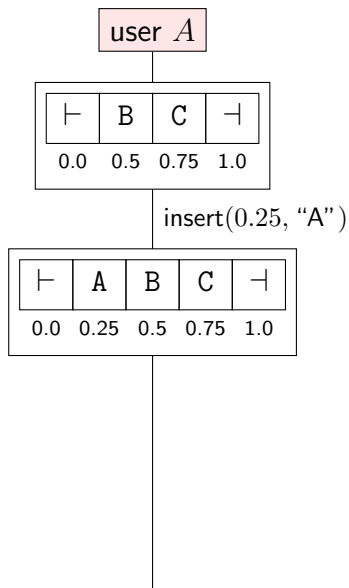
Text editing CRDT



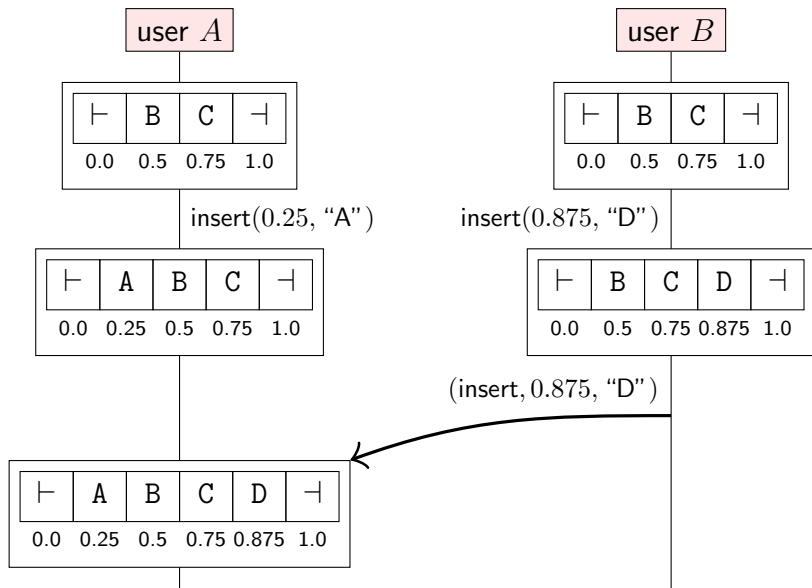
Text editing CRDT



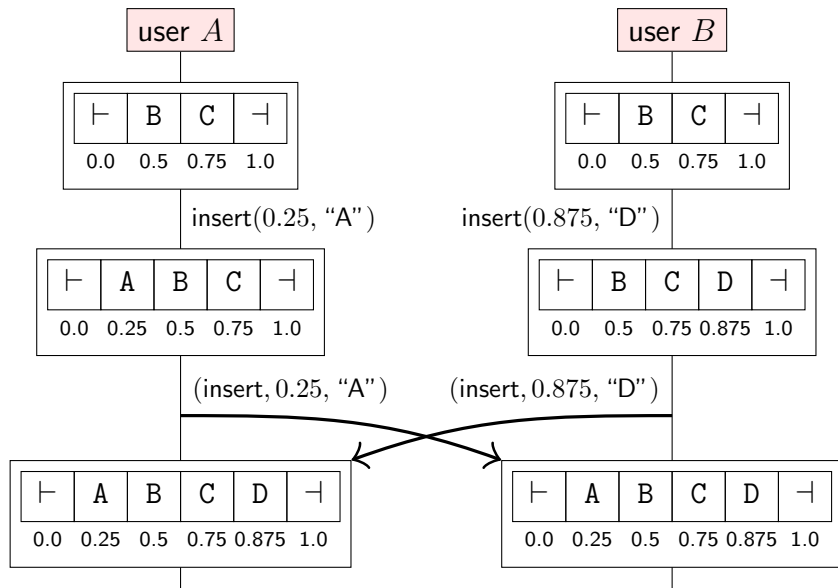
Text editing CRDT



Text editing CRDT



Text editing CRDT



Operation-based text CRDT (1/2)

function ELEMENTAT(*chars*, *index*)

min = the unique triple $(p, n, v) \in \text{chars}$ such that

$\nexists (p', n', v') \in \text{chars}. p' < p \vee (p' = p \wedge n' < n)$

if *index* = 0 **then return** *min*

else return ELEMENTAT(*chars* \ {*min*}, *index* - 1)

end function

on initialisation **do**

chars := {(0, null, ⊢), (1, null, ⊣)}

end on

on request to read character at index *index* **do**

let $(p, n, v) := \text{ELEMENTAT}(\text{chars}, \text{index} + 1)$; **return** *v*

end on

on request to insert character *v* at index *index* at node *nodeId* **do**

let $(p_1, n_1, v_1) := \text{ELEMENTAT}(\text{chars}, \text{index})$

let $(p_2, n_2, v_2) := \text{ELEMENTAT}(\text{chars}, \text{index} + 1)$

broadcast (insert, $(p_1 + p_2)/2, \text{nodeId}, v$) 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 $(p, n, v) := \text{ELEMENTAT}(chars, index + 1)$
 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

That's all, folks!

Any questions? Email martin.kleppmann@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