

# Distributed Systems

The second half of *Concurrent and Distributed Systems*

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

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University of Cambridge

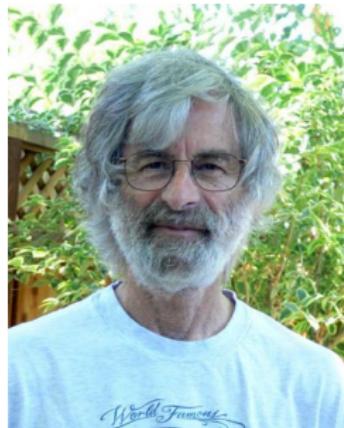
Computer Science Tripos, Part IB



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# A distributed system is...

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



# A distributed system is...

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

# Recommended reading

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

# Relationships with other courses

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

# Why make a system distributed?

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get data from a nearby node rather than one halfway round the world

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- ▶ **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

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⋮



## 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.

# 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.

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

This is hard.

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

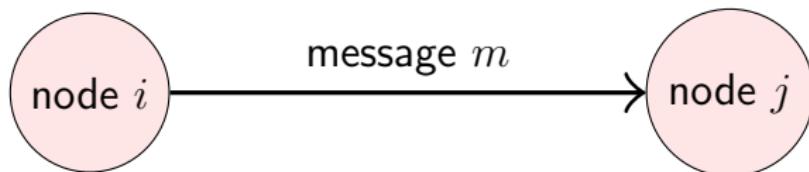
# Distributed Systems and Computer Networking

We use a simple abstraction of communication:



# Distributed Systems and Computer Networking

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Reality is much more complex:

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

# Hard drives in a van?!



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

High latency, high bandwidth!

# Latency and bandwidth

**Latency:** time until message arrives

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

# Latency and bandwidth

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**Bandwidth:** data volume per unit time

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

(Very rough numbers, vary hugely in practice!)

Concurrent and Distributed Systems

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

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## Concurrent and Distributed Systems

**Principal lecturer:** Dr David Greaves  
Martin Kleppmann

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

**Course code:** ConcDisSys

**Prerequisite course:** Object-Oriented Programming  
Operating Systems

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

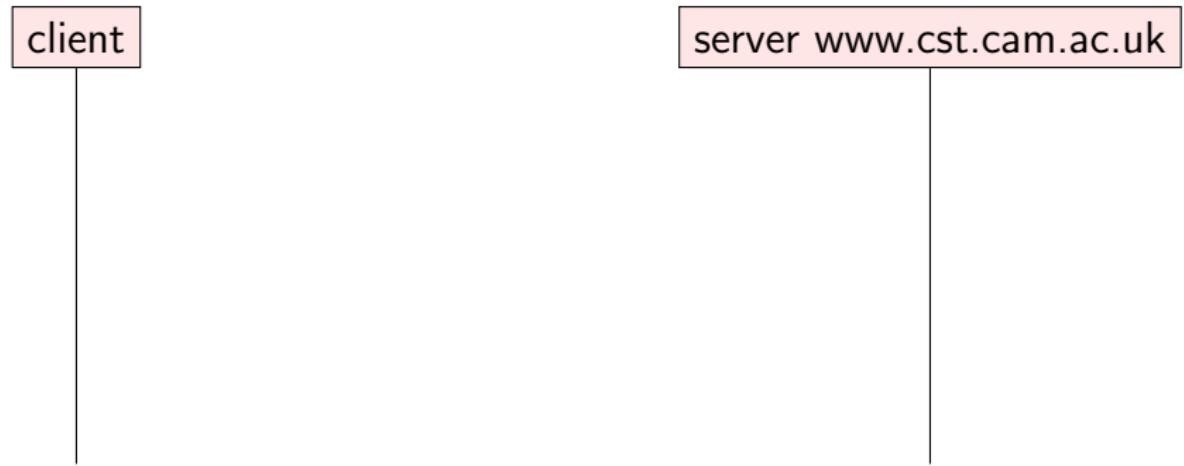
Related links

Course materials

Information for supervisors

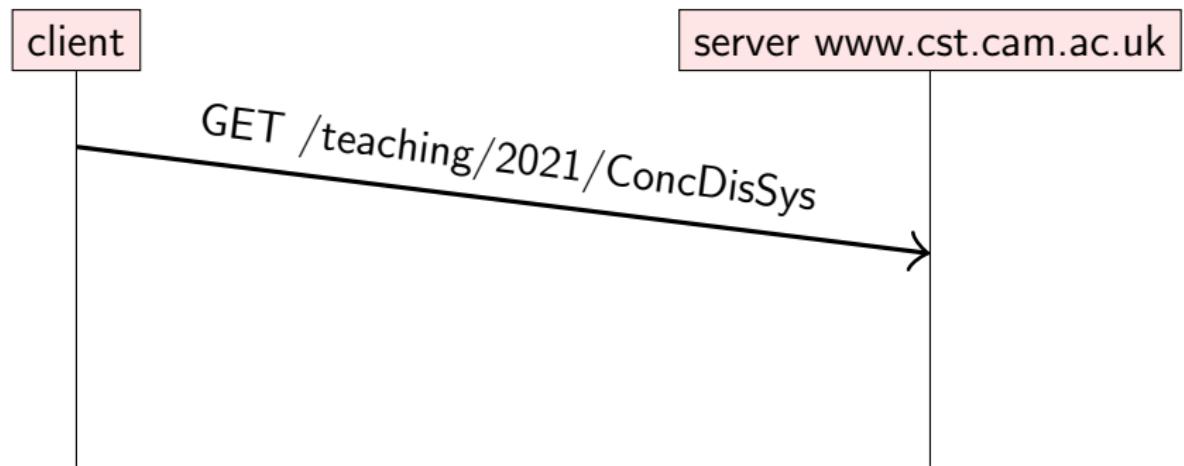
# Client-server example: the web

Time flows from top to bottom.



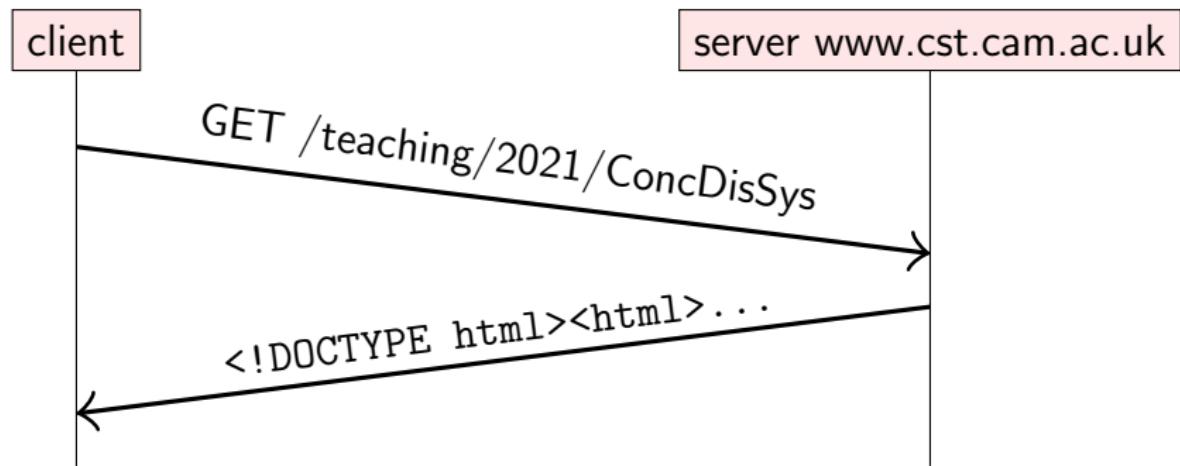
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Time flows from top to bottom.



Charles 4.5.6 - Session 1

Structure Sequence

Code	Method	Host	Path	Duration	Size	Sta...	In...
200	GET	www.cst.cam.ac.uk	/teaching/2021/ConcDisSys	111 ms	69.55 KB	Com...	

Filter: www.cst.cam.ac.uk  Focused

Overview Contents Summary Chart Notes

```
:path /teaching/2021/ConcDisSys
pragma no-cache
cache-control no-cache
upgrade-insecure-requests 1
user-agent Mozilla/5.0 (Macintosh; Intel Mac OS X 10_15_6) AppleWebKit/537.36 (KHTML, like Gecko) Chrome/85.0.4183...
accept text/html,application/xhtml+xml,application/xml;q=0.9,image/avif,image/webp,image/apng,*/*;q=0.8,application...
```

Headers Cookies Raw

```
1 <!DOCTYPE html>
2
3 <html xmlns="http://www.w3.org/1999/xhtml" lang="en"
4 dir="ltr"
5 xmlns:content="http://purl.org/rss/1.0/modules/content/"
6 xmlns:dc="http://purl.org/dc/terms/"
7 xmlns:foaf="http://xmlns.com/foaf/0.1/"
8 xmlns:og="http://ogp.me/ns#"
9 xmlns:rdfs="http://www.w3.org/2000/01/rdf-schema#"
10 xmlns:sioc="http://rdfs.org/sioc/ns#"
11 xmlns:sioc_type="http://rdfs.org/sioc/types#"
```

Headers Set Cookie Text Hex HTML Raw

GET https://www.cst.cam.ac.uk/profiles/cambridge/themes/cambridge\_theme/favicon.ico

Charles 4.5.6 - Session 1

Structure Sequence

Code	Method	Host	Path	Duration	Size	Sta...	In...
200	GET	www.cst.cam.ac.uk	/teaching/2021/ConcDisSys	111 ms	69.55 KB	Com...	

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```
:path /teaching/2021/ConcDisSys
pragma no-cache
cache-control no-cache
upgrade-insecure-requests 1
user-agent Mozilla/5.0 (Macintosh; Intel Mac OS X 10_15_6) AppleWebKit/537.36 (KHTML, like Gecko) Chrome/85.0.4183...
accept text/html,application/xhtml+xml,application/xml;q=0.9,image/avif,image/webp,image/apng,*/*;q=0.8,application/...
```

Headers Cookies Raw

```
1 <!DOCTYPE html>
2
3 <html xmlns="http://www.w3.org/1999/xhtml" lang="en"
4   dir="ltr"
5   xmlns:content="http://purl.org/rss/1.0/modules/content/"
6   xmlns:dc="http://purl.org/dc/terms/"
7   xmlns:foaf="http://xmlns.com/foaf/0.1/"
8   xmlns:og="http://ogp.me/ns#"
9   xmlns:rdfs="http://www.w3.org/2000/01/rdf-schema#"
10  xmlns:sioc="http://rdfs.org/sioc/ns#"
11  xmlns:siocType="http://rdfs.org/sioc/types#"
```

Headers Set Cookie Text Hex HTML Raw

GET https://www.cst.cam.ac.uk/profiles/cambridge/themes/cambridge\_theme/favicon.ico

request message

response message

Wi-Fi: en0

ip.addr == 128.232.132.21 Expression... +

No.	Time	Source	Destination	Protocol	Length	Info
2051	5.149927	192.168.1.231	128.232.132.21	TCP	78	59391 → 443 [SYN] Seq=0 Win=6...
2082	5.400527	192.168.1.231	128.232.132.21	TCP	78	59394 → 443 [SYN] Seq=0 Win=6...
2084	5.424557	128.232.132.21	192.168.1.231	TCP	74	443 → 59394 [SYN, ACK] Seq=0 ...
2085	5.424686	192.168.1.231	128.232.132.21	TCP	66	59394 → 443 [ACK] Seq=1 Ack=1...
2086	5.425139	192.168.1.231	128.232.132.21	TLSv1.3	616	Client Hello
2087	5.451977	128.232.132.21	192.168.1.231	TCP	66	443 → 59394 [ACK] Seq=1 Ack=5...
2088	5.451984	128.232.132.21	192.168.1.231	TLSv1.3	165	HelloRetryRequest, Change C...
2089	5.452089	192.168.1.231	128.232.132.21	TCP	66	59394 → 443 [ACK] Seq=551 Ack...
2090	5.452577	192.168.1.231	128.232.132.21	TLSv1.3	650	Change Cipher Spec, Client He...
2091	5.480436	128.232.132.21	192.168.1.231	TLSv1.3	343	ServerHello, Application Dat...
2092	5.480539	192.168.1.231	128.232.132.21	TCP	66	59394 → 443 [ACK] Seq=1135 Ac...
2094	5.490141	192.168.1.231	128.232.132.21	TLSv1.3	140	Application Data
2095	5.490245	192.168.1.231	128.232.132.21	TLSv1.3	158	Application Data

► Frame 2086: 616 bytes on wire (4928 bits), 616 bytes captured (4928 bits) on interface 0

► Ethernet II, Src: Apple\_b3:d7:02 (f0:18:98:b3:d7:02), Dst: ZyxelCom\_67:62:90 (8c:59:73:67:62:90)

► Internet Protocol Version 4, Src: 192.168.1.231, Dst: 128.232.132.21

► Transmission Control Protocol, Src Port: 59394, Dst Port: 443, Seq: 1, Ack: 1, Len: 550

► Transport Layer Security

No.	Time	Source	Destination	Protocol	Length	Info
0020	84 15 e8 02 01 bb a4 93 59 fd 8d 0c f2 57 80 18					.....Y....W..
0030	08 16 a5 d0 00 00 01 01 08 0a 99 7c 18 f0 6f b5					..... ..o.
0040	22 13 16 03 01 02 21 01 00 02 1d 03 03 f2 ad ef					".....!
0050	a6 1c bb 45 88 8f 2f 0a 2e 8d 33 5a 02 b8 ed 42					..E../. ..Z..B
0060	5d d9 f7 46 5b 48 6b 9b ce 94 87 ac 39 20 7b 4e					]..F[Hk.....9 {N
0070	e2 b0 ce 9e ca e6 cd 4c 2b 92 70 4e 38 19 5f e4					.....L + pN8_
0080	30 d7 2e 92 b6 70 90 9e 49 7a 05 17 79 a9 00 20					0...p..Iz..y..
0090	9a 9a 13 01 13 02 13 03 c0 2b c0 2f c0 2c c0 30					.....+/, .0
00a0	cc a9 cc a8 c0 13 c0 14 00 9c 00 9d 00 2f 00 35					...../5
00b0	01 00 01 b4 fa fa 00 00 00 00 00 16 00 14 00 00					.....
00c0	11 77 77 77 2e 63 73 74 2e 63 61 6d 2e 61 63 2e					www.cst.cam.ac.

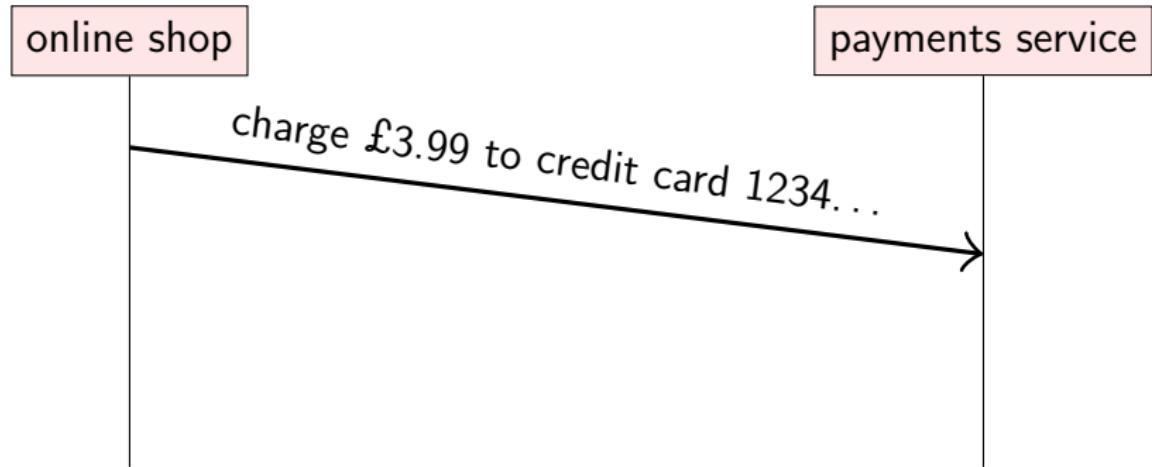
Transmission Control Protocol (tcp), 32 bytes

Packets: 2392 · Displayed: 87 (3.6%) · Dropped: 0 (0.0%) · Profile: Default

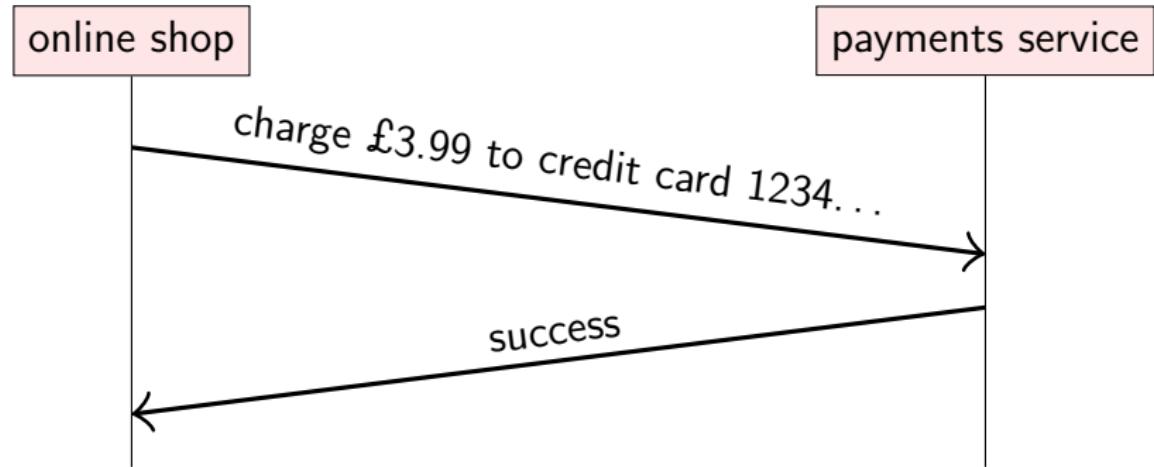
# Client-server example: online payments



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# 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()) {
    fulfillOrder();
}
```

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```



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

waiting

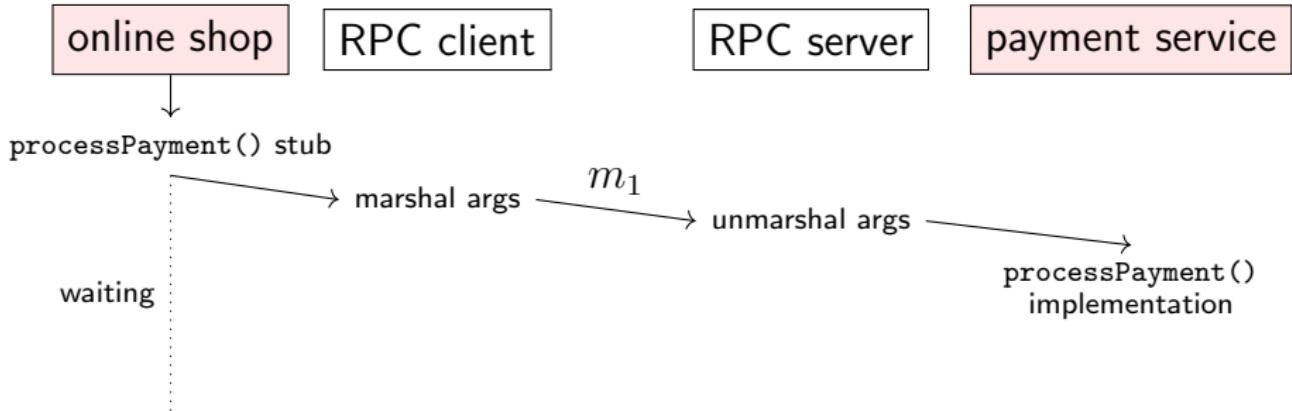
marshal args

$m_1$

unmarshal args

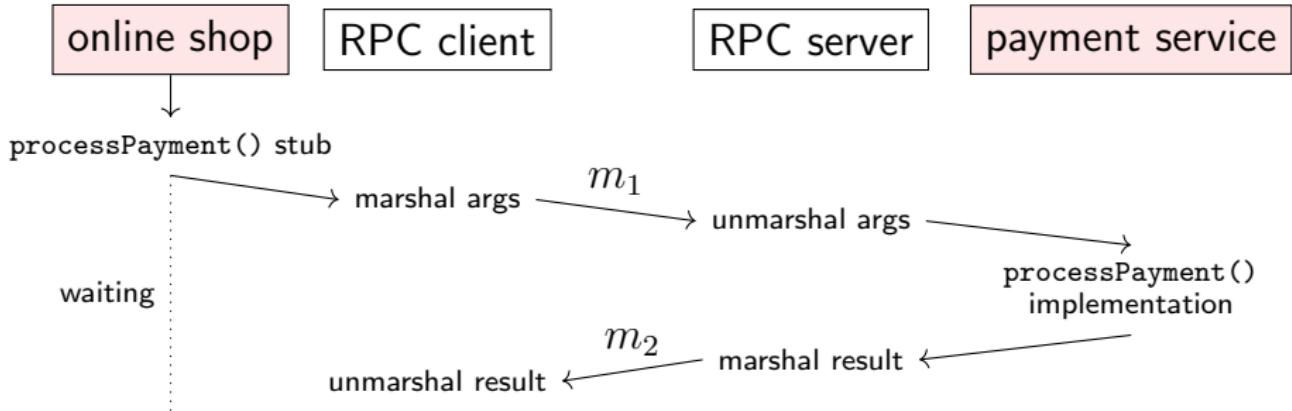
{  
  "request": "processPayment",  
  "card": {  
    "number": "1234567887654321",  
    "expiryDate": "10/2024",  
    "CVC": "123"  
  },  
  "amount": 3.99,  
  "currency": "GBP"  
}

$m_1 =$



$m_1 =$

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

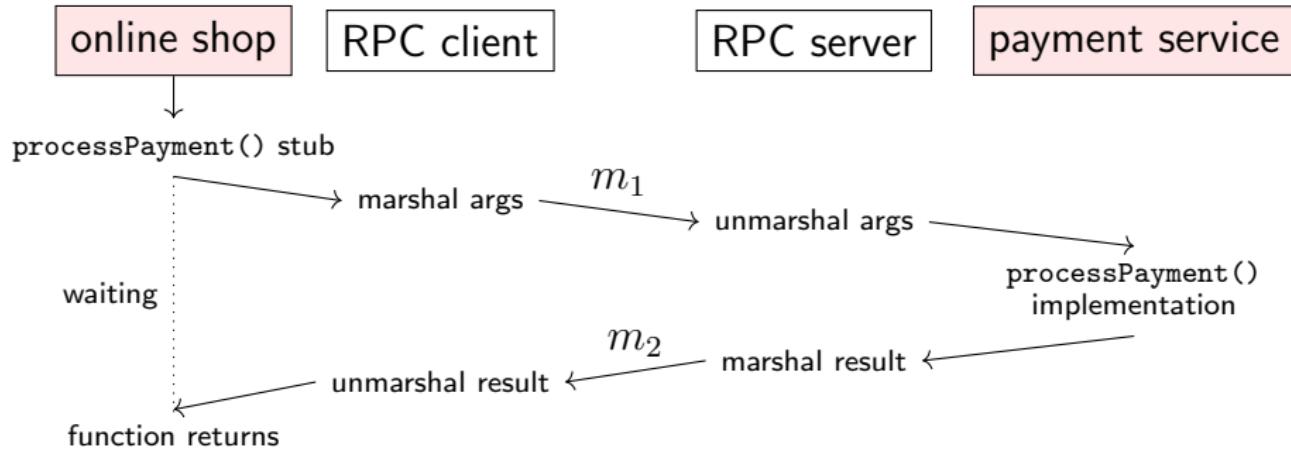


$m_1 =$

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

$m_2 =$

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



$$m_1 =$$

```
{  
  "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.

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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)
- ▶ Ajax in web browsers

# RPC/REST in JavaScript

```
let args = {amount: 3.99, currency: 'GBP', /*...*/};  
let request = {  
    method: 'POST',  
    body: JSON.stringify(args),  
    headers: {'Content-Type': 'application/json'}  
};  
  
fetch('https://example.com/payments', request)  
    .then((response) => {  
        if (response.ok) success(response.json());  
        else failure(response.status); // server error  
    })  
    .catch((error) => {  
        failure(error); // network error  
    });
```

# RPC in enterprise systems

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

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

# RPC in enterprise systems

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

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

Different services implemented in different languages:

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

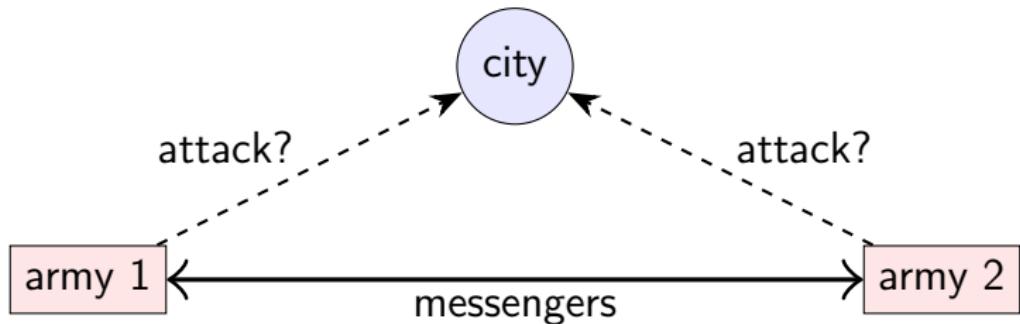
# gRPC IDL example

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

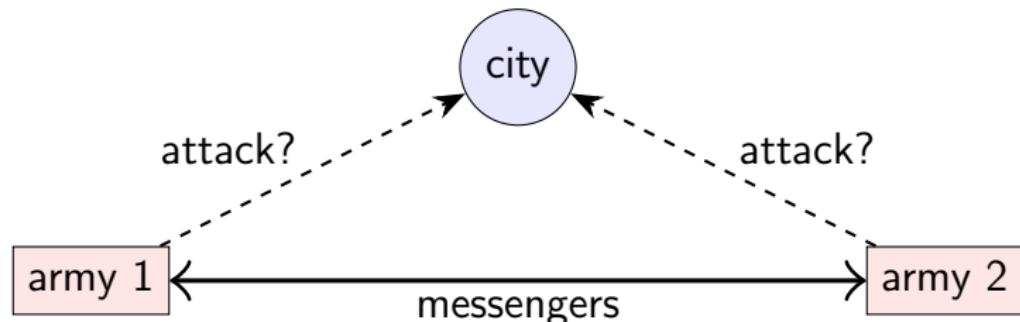
## Lecture 2

# Models of distributed systems

# The two generals problem



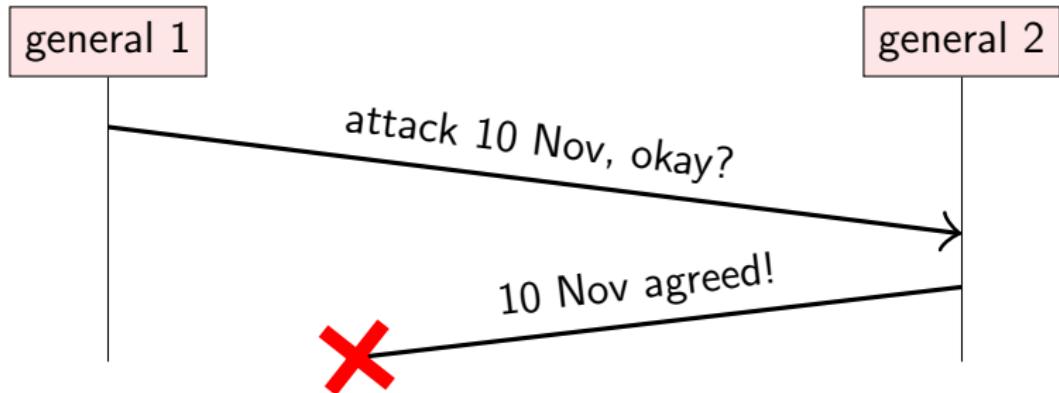
# The two generals problem



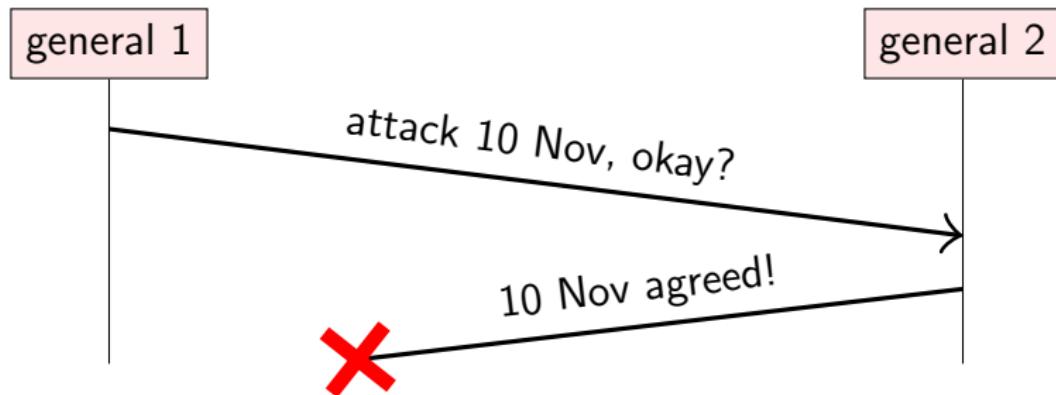
army 1	army 2	outcome
does not attack	does not attack	nothing happens
attacks	does not attack	army 1 defeated
does not attack	attacks	army 2 defeated
attacks	attacks	city captured

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

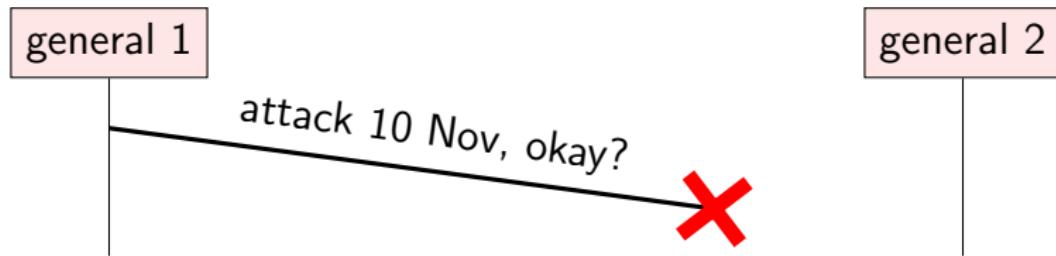
# The two generals problem



# The two generals problem



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



# How should the generals decide?

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

# How should the generals decide?

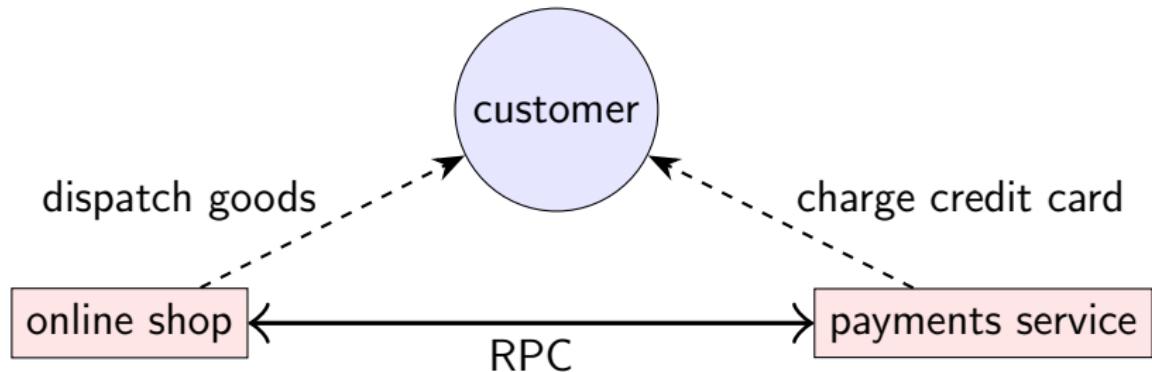
1. General 1 always attacks, even if no response is received?
  - ▶ Send lots of messengers to increase probability that one will get through
  - ▶ If all are captured, general 2 does not know about the attack, so general 1 loses
2. General 1 only attacks if positive response from general 2 is received?
  - ▶ Now general 1 is safe
  - ▶ But general 2 knows that general 1 will only attack if general 2's response gets through
  - ▶ Now general 2 is in the same situation as general 1 in option 1

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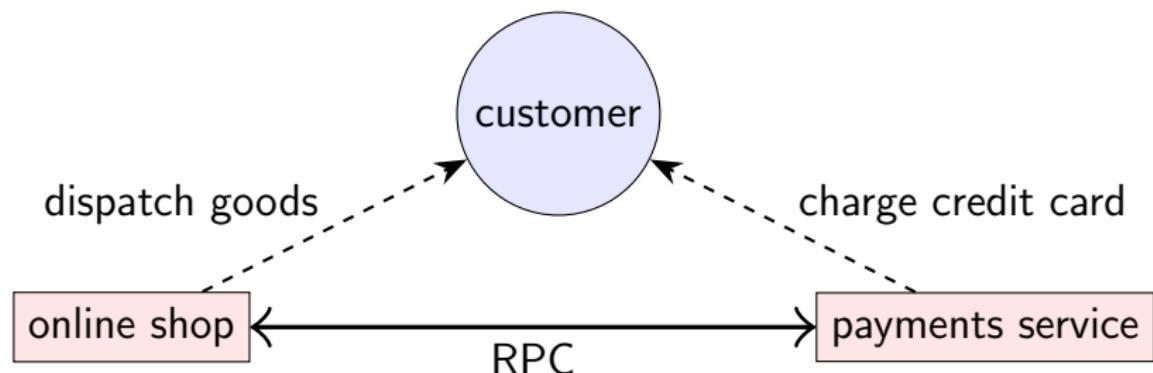
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  - ▶ But general 2 knows that general 1 will only attack if general 2's response gets through
  - ▶ Now general 2 is in the same situation as general 1 in option 1

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

# The two generals problem applied



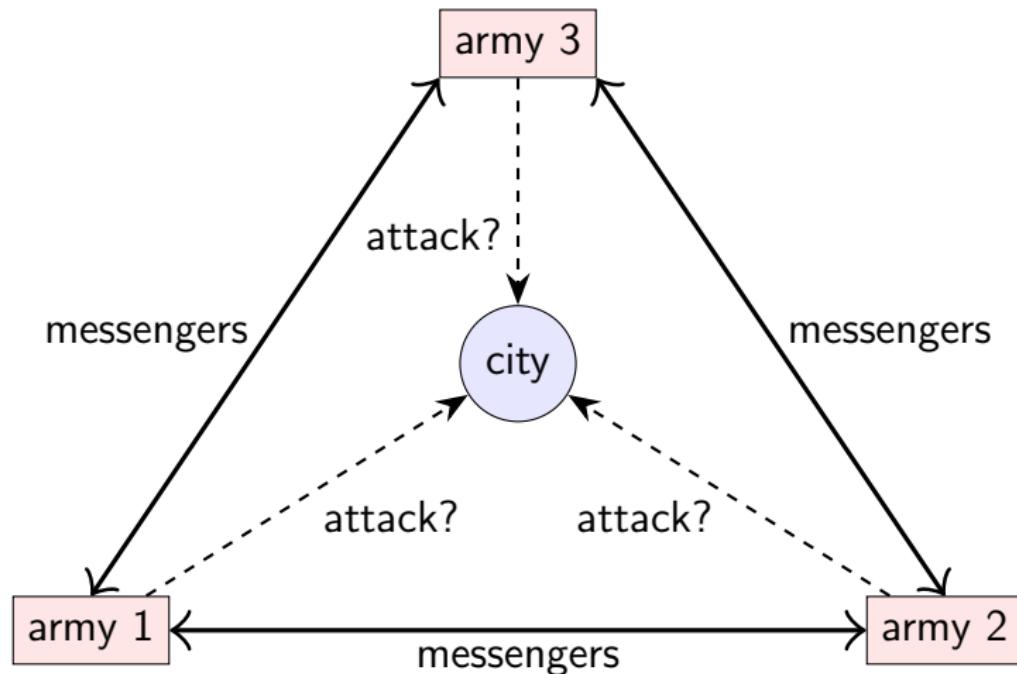
# The two generals problem applied



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

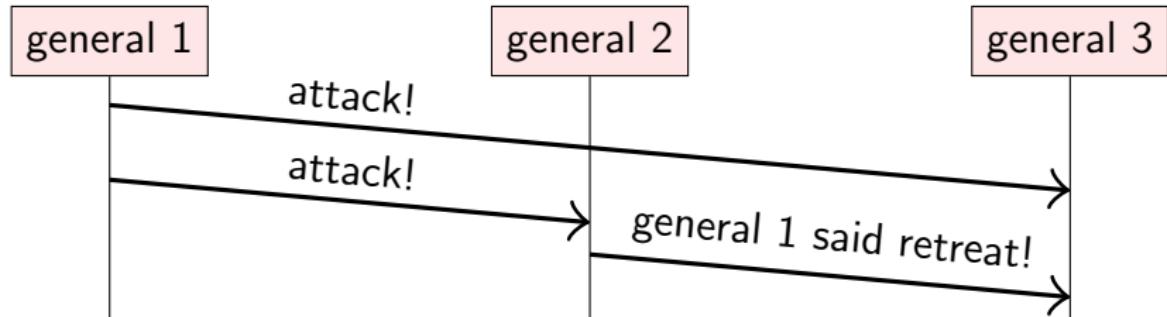
**Desired:** online shop dispatches *if and only if* payment made

# The Byzantine generals problem

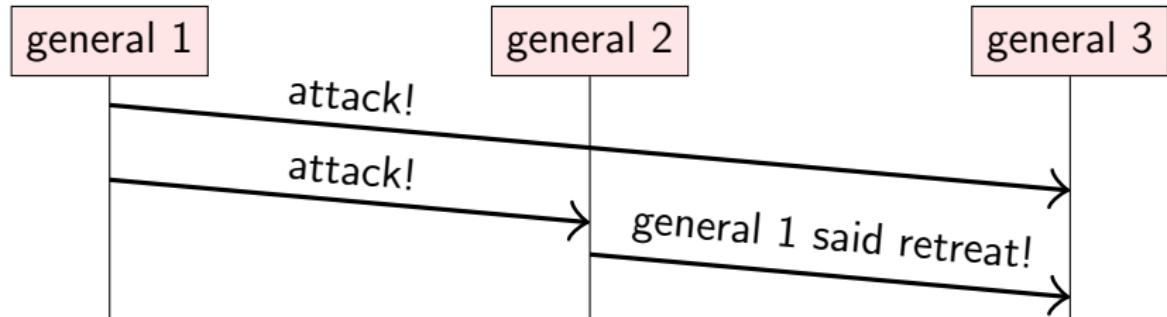


**Problem:** some of the generals might be traitors

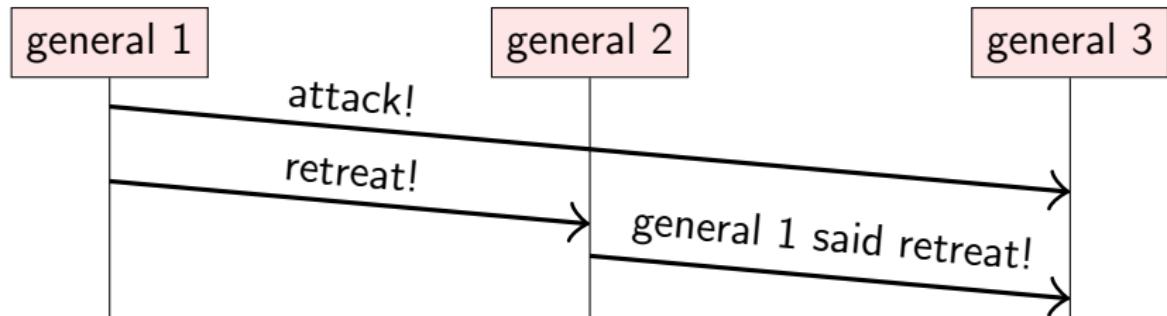
# Generals that might lie



# Generals that might lie



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



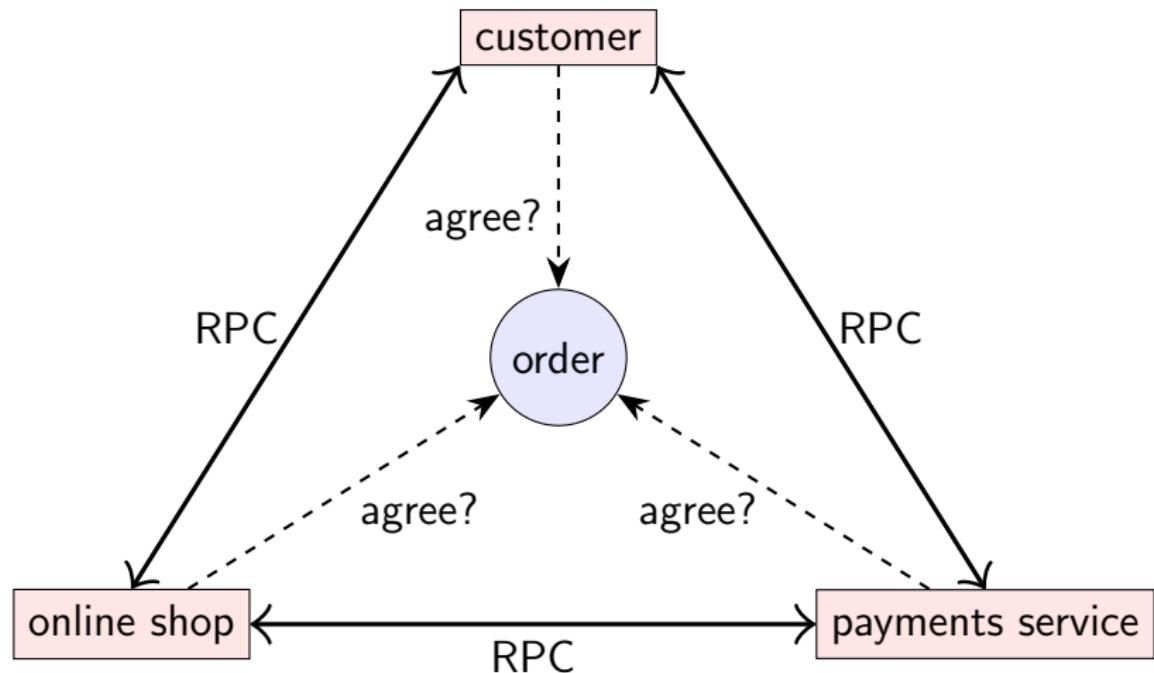
# The Byzantine generals problem

- ▶ Up to  $f$  generals might behave maliciously
- ▶ 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

- ▶ Up to  $f$  generals might behave maliciously
  - ▶ 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:

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- ▶ Byzantine generals problem: a model of node behaviour

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

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

Choice of models for each of these parts.

# Networks are unreliable



In the sea, sharks bite fibre optic cables

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

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

On land, cows step on the cables

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

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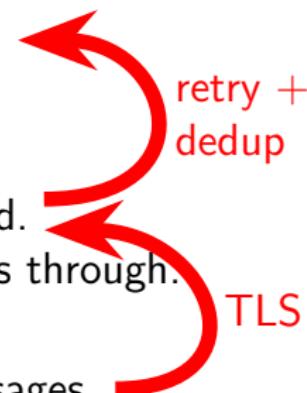
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A node may crash at any moment, losing its in-memory state.  
It may resume executing sometime later.
- ▶ **Byzantine** (fail-arbitrary):  
A node is faulty if it deviates from the algorithm.  
Faulty nodes may do anything, including crashing or malicious behaviour.

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

# System model: synchrony (timing) assumptions

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

- ▶ Operating system scheduling issues, e.g. priority inversion
- ▶ Stop-the-world garbage collection pauses
- ▶ Page faults, swap, thrashing

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

# System models summary

For each of the three parts, pick one:

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

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

# Availability

Online shop wants to sell stuff 24/7!

Service unavailability = downtime = losing money

Availability = uptime = fraction of time that a service is functioning correctly

- ▶ “Two nines” = 99% up = down 3.7 days/year
- ▶ “Three nines” = 99.9% up = down 8.8 hours/year
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**Service-Level Objective (SLO):**

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

**Service-Level Agreement (SLA):**

contract specifying some SLO, penalties for violation

# Achieving high availability: fault tolerance

**Failure:** system as a whole isn't working

**Fault:** some part of the system isn't working

- ▶ Node fault: crash (crash-stop/crash-recovery),  
deviating from algorithm (Byzantine)
- ▶ Network fault: dropping or significantly delaying messages

**Fault tolerance:**

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

**Single point of failure (SPOF):**

node/network link whose fault leads to failure

# Failure detectors

## **Failure detector:**

algorithm that detects whether another node is faulty

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

## **Problem:**

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

# Failure detection in partially synchronous systems

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

## Eventually perfect failure detector:

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

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

## Lecture 3

# Time, clocks, and ordering of events

# A detective story

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

Servers locked up and stopped responding.

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

What happened?

# Clocks and time in distributed systems

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

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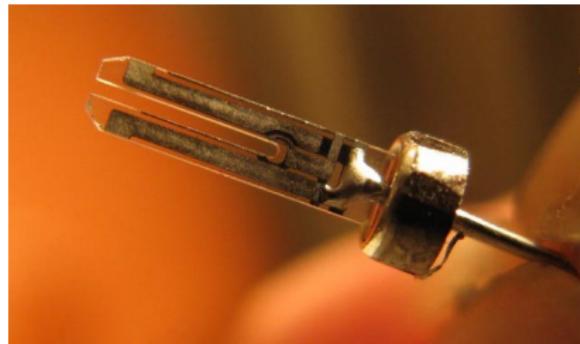
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**NB.** Clock in digital electronics (oscillator)  
≠ clock in distributed systems (source of **timestamps**)

# Quartz clocks

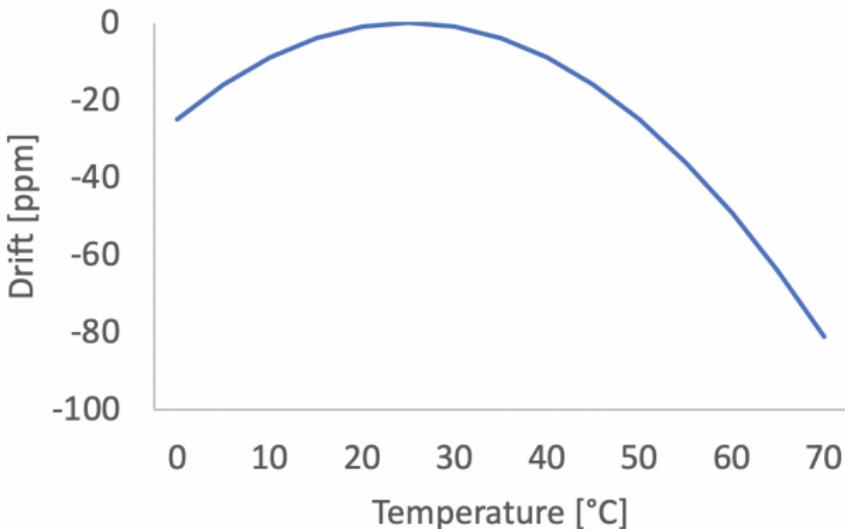
- ▶ Quartz crystal laser-trimmed to mechanically resonate at a specific frequency
- ▶ Piezoelectric effect: mechanical force  $\Leftrightarrow$  electric field
- ▶ Oscillator circuit produces signal at resonant frequency
- ▶ Count number of cycles to measure elapsed time



# 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

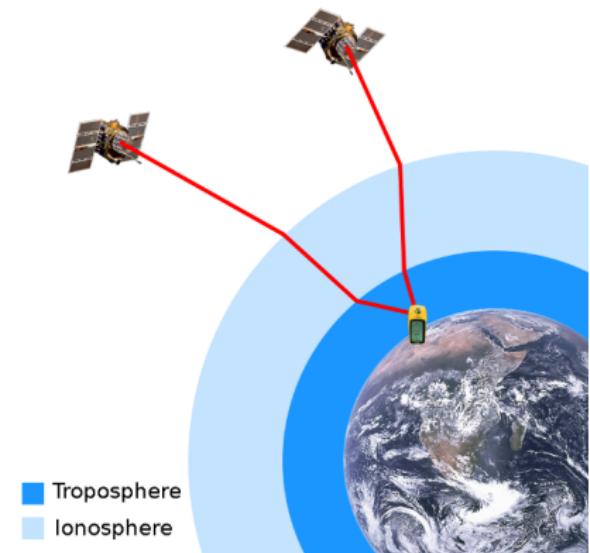
- ▶ Caesium-133 has a resonance ("hyperfine transition") at  $\approx 9$  GHz
- ▶ Tune an electronic oscillator to that resonant frequency
- ▶ 1 second = 9,192,631,770 periods of that signal
- ▶ Accuracy  $\approx 1$  in  $10^{-14}$  (1 second in 3 million years)
- ▶ Price  $\approx \text{£}20,000$ 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



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

# GPS as time source

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



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

# Coordinated Universal Time (UTC)

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



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



# Leap seconds

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

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

This is announced several months beforehand.



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

# How computers represent timestamps

Two most common representations:

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

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Conversion between the two requires:

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

# How most software deals with leap seconds

By ignoring them!



[https://www.flickr.com/  
photos/ru\\_boff/  
37915499055/](https://www.flickr.com/photos/ru_boff/37915499055/)

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



[https://www.flickr.com/  
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# Clock synchronisation

Computers track physical time/UTC with a quartz clock  
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**Clock skew**: difference between two clocks at a point in time

**Solution**: Periodically get the current time from a server that has a more accurate time source (atomic clock or GPS receiver)

Protocols: Network Time Protocol (**NTP**),  
Precision Time Protocol (**PTP**)



## Date &amp; Time

Search

## Date &amp; Time

## Time Zone

## Clock

 Set date and time automatically: Apple Europe (time.euro.apple.com.) 23/09/2020 11:03:48 

Sep 2020						
Mo	Tu	We	Th	Fr	Sa	Su
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	7	8	9	10	11



To set date and time formats, use Language & Region preferences. [Open Language & Region...](#)



Click the lock to prevent further changes.



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May contact multiple servers, discard outliers, average rest

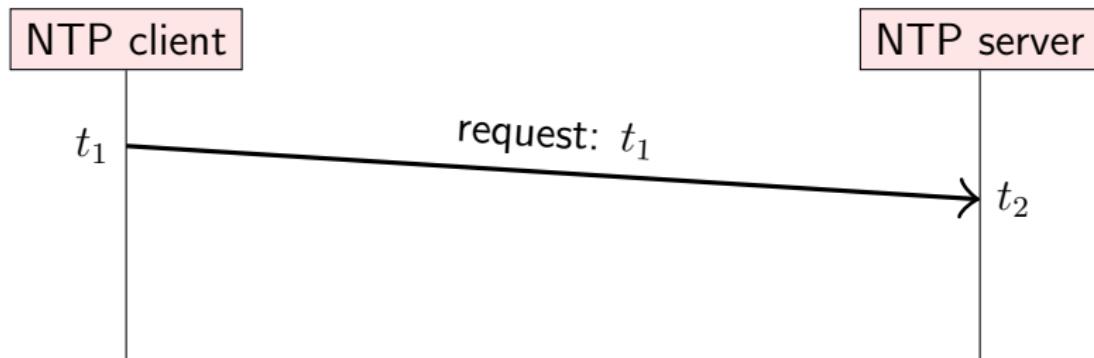
Makes multiple requests to the same server, use statistics to reduce random error due to variations in network latency

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

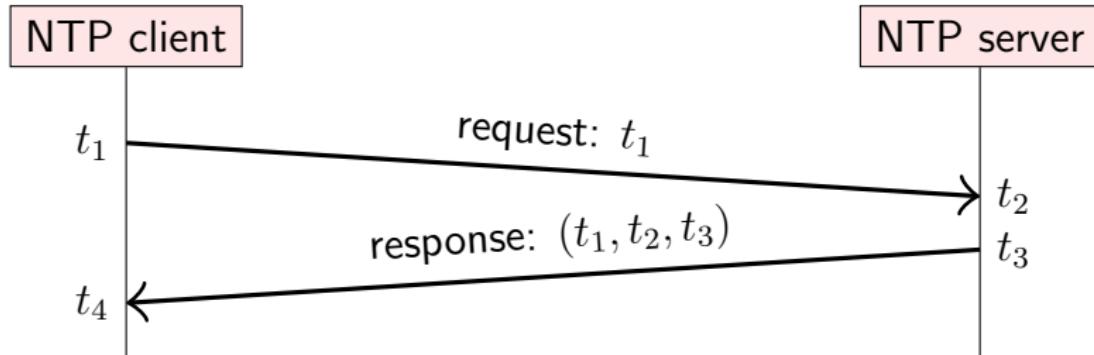
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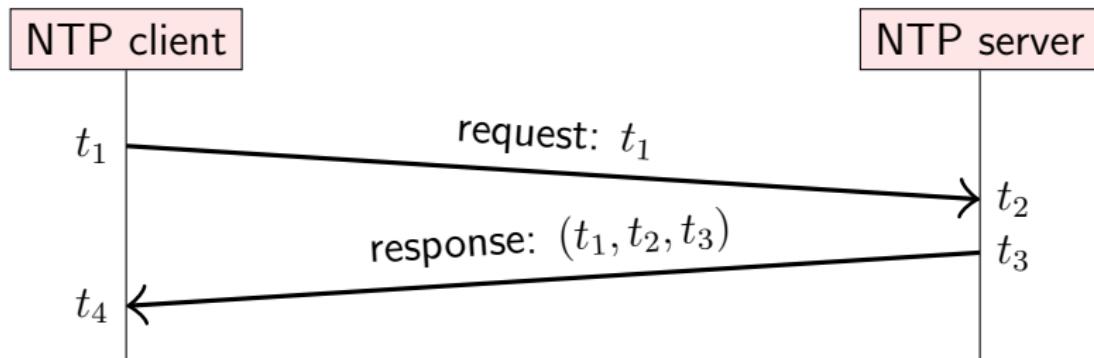
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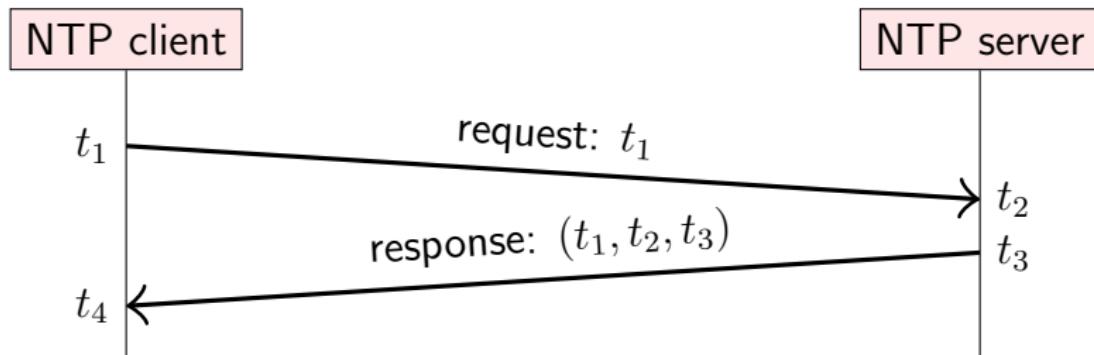


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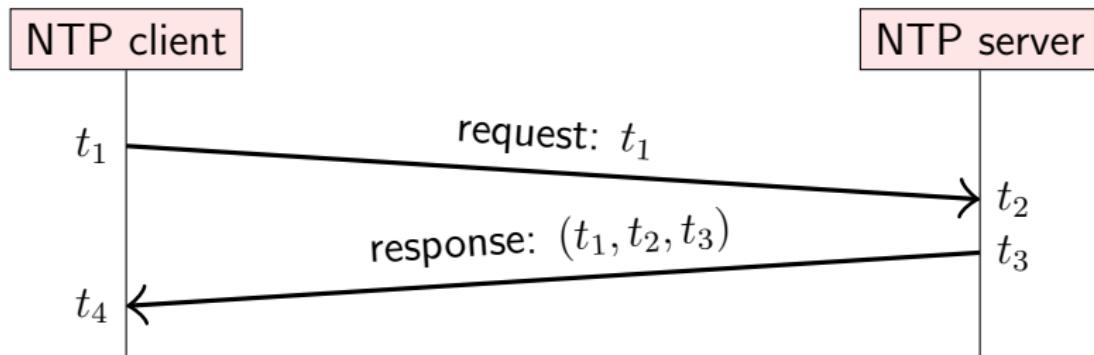
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Estimated clock skew:  $\theta = t_3 + \frac{\delta}{2} - t_4 = \frac{t_2 - t_1 + t_3 - t_4}{2}$

## Correcting clock skew

Once the client has estimated the clock skew  $\theta$ , 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  
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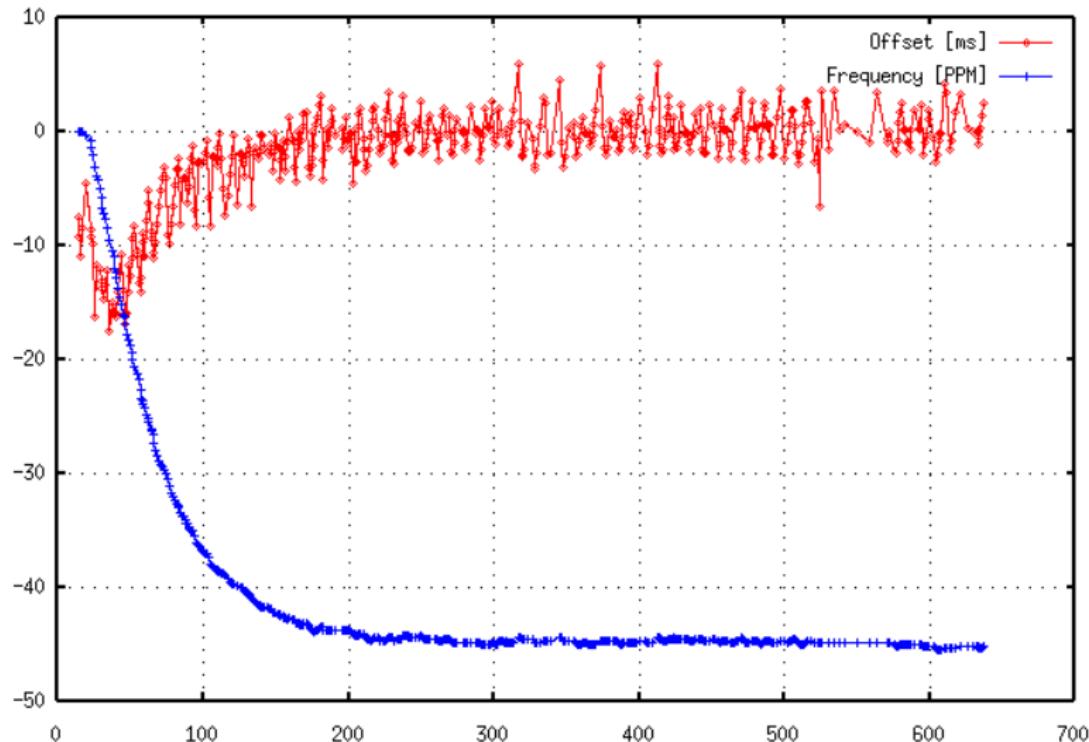
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- ▶ If  $|\theta| \geq 1,000$  s, **panic** and do nothing  
(leave the problem for a human operator to resolve)

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!
```

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long endTime = System.currentTimeMillis();
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// elapsedMillis may be negative!
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NTP client steps the clock during this

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NTP client steps the clock during this

// GOOD:

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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)

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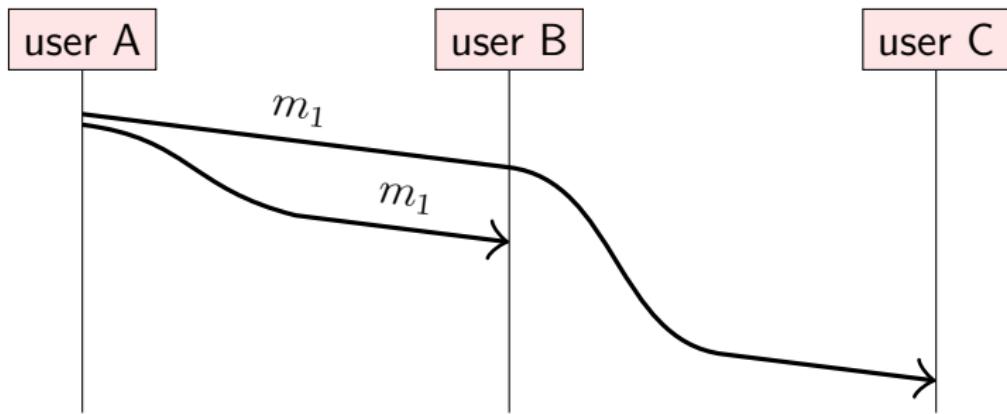
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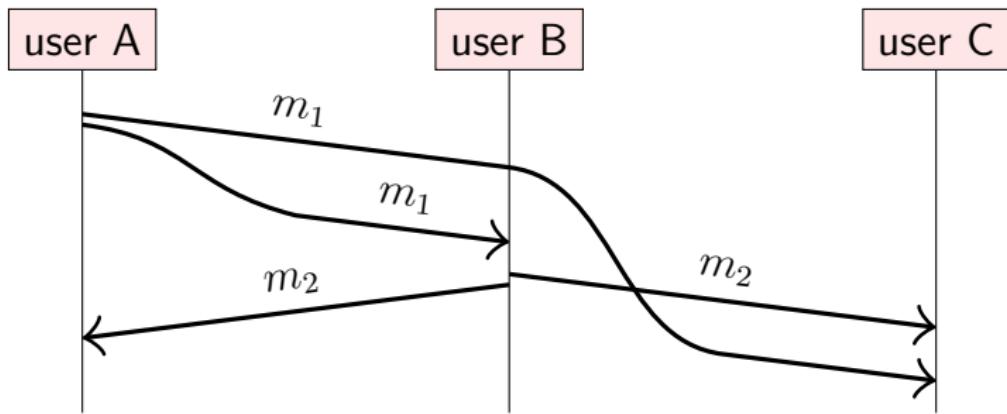
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# Ordering of messages



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

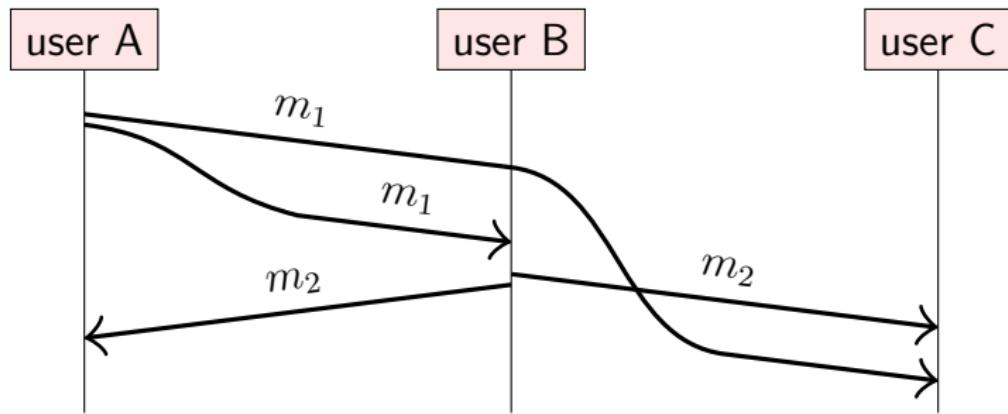
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$m_1$  = “A says: The moon is made of cheese!”

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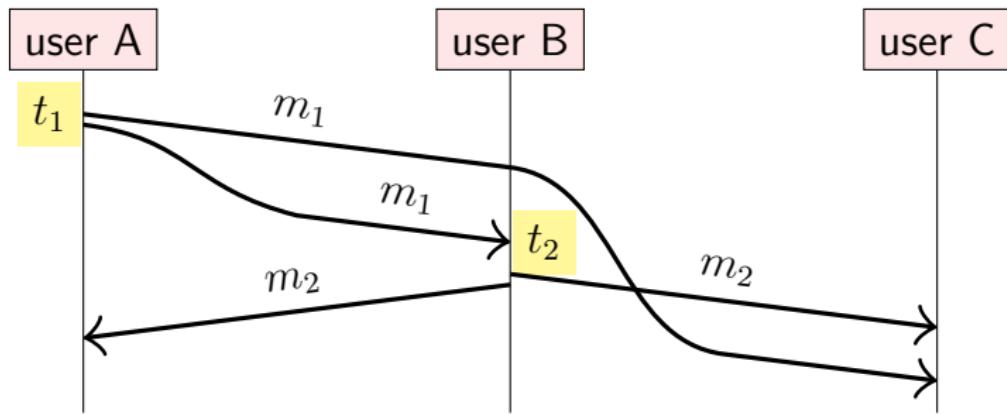


$m_1$  = "A says: The moon is made of cheese!"

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

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

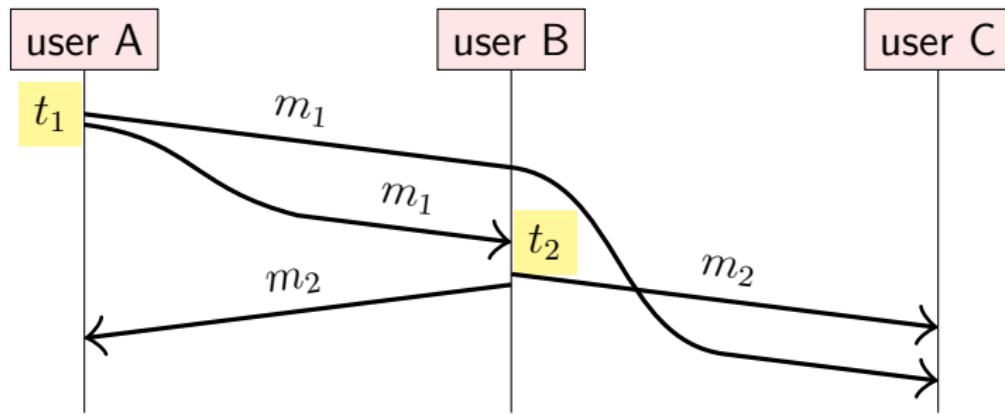
# Ordering of messages using timestamps?



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

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**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).

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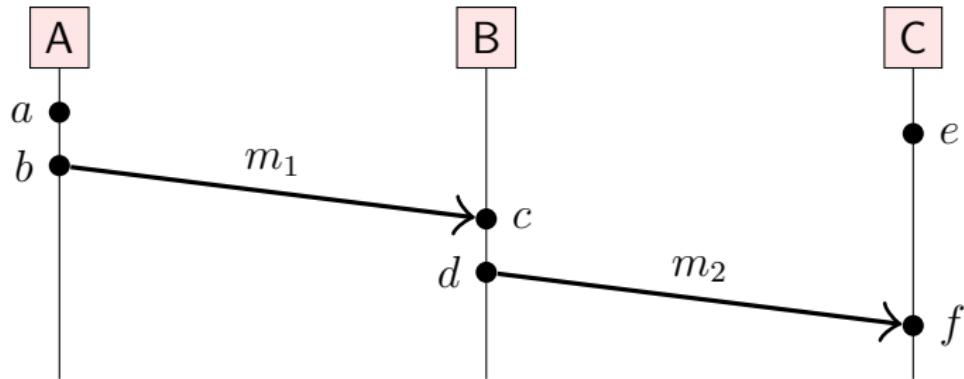
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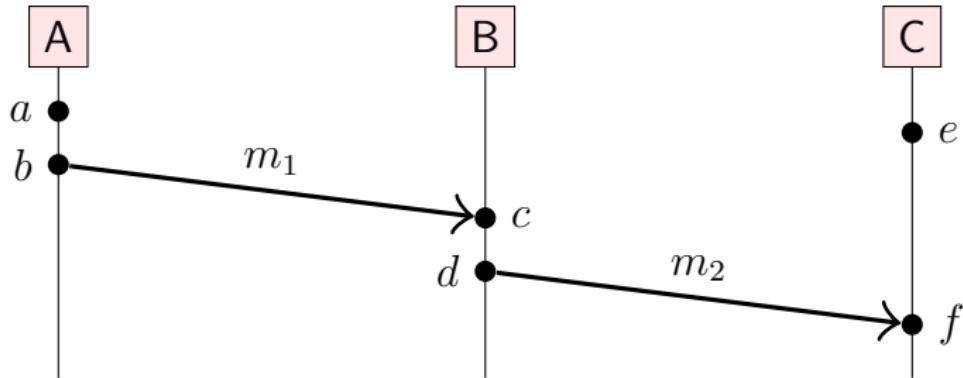
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The happens-before relation is a partial order: it is possible that neither  $a \rightarrow b$  nor  $b \rightarrow a$ . In that case,  $a$  and  $b$  are **concurrent** (written  $a \parallel b$ ).

# Happens-before relation example

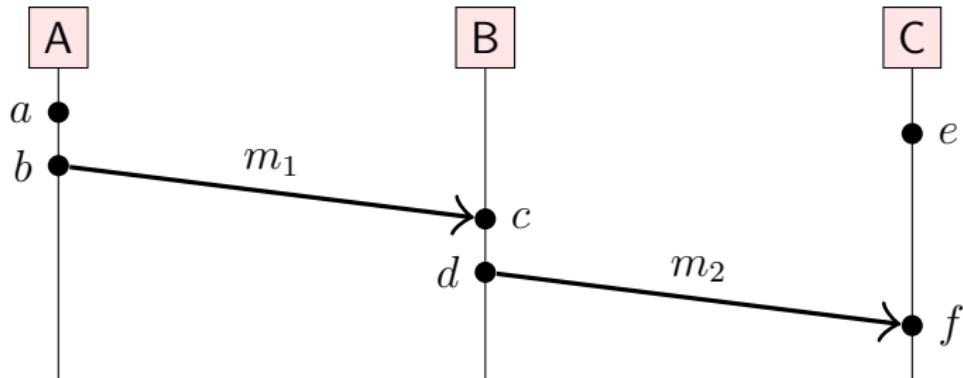


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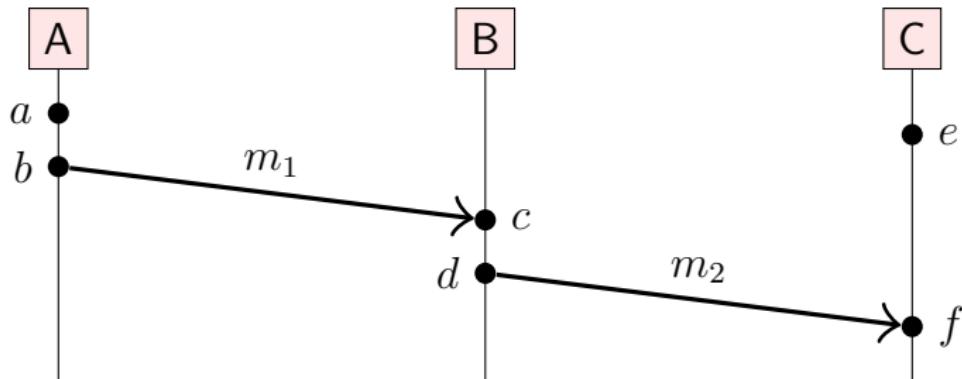
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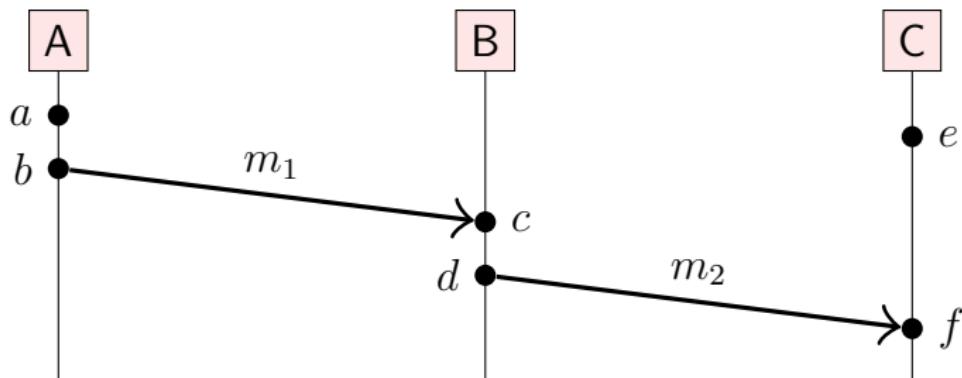
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- ▶  $a \parallel e$ ,  $b \parallel e$ ,  $c \parallel e$ , and  $d \parallel e$

# Causality

Taken from physics (relativity).

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

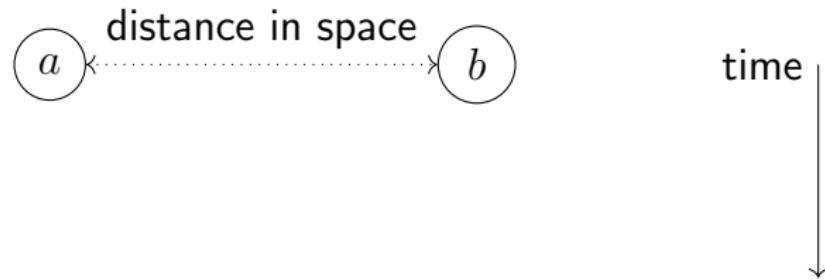
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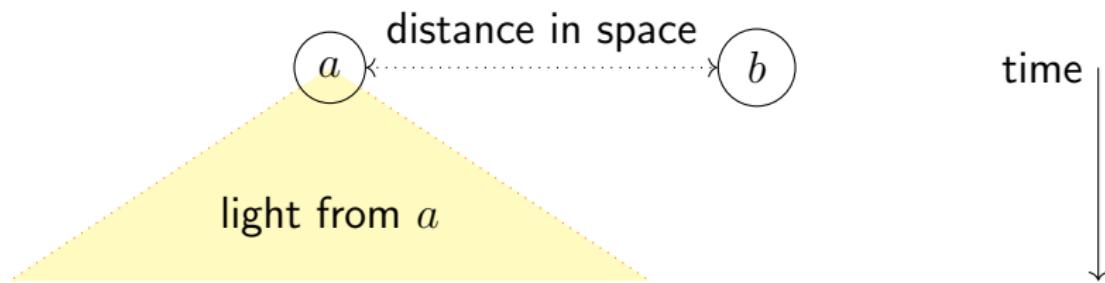


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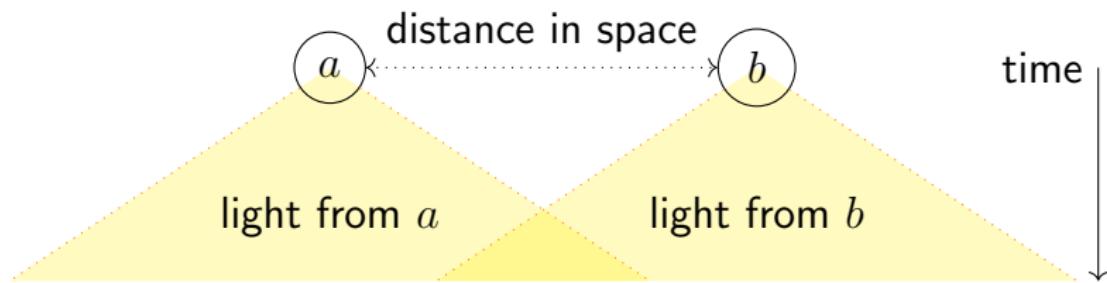


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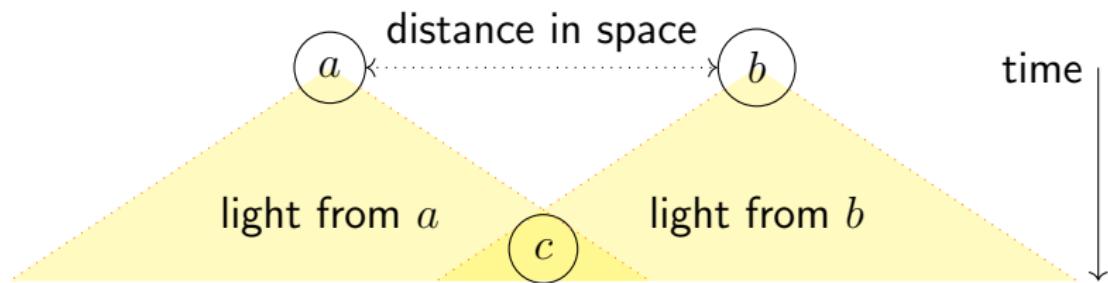


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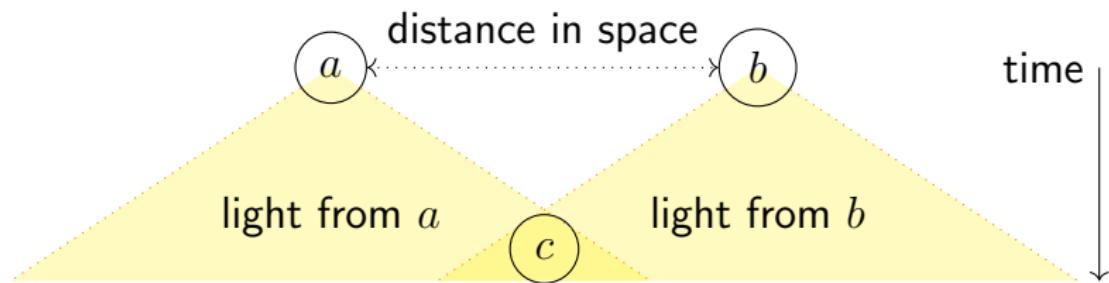


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Let  $\prec$  be a strict total order on events.

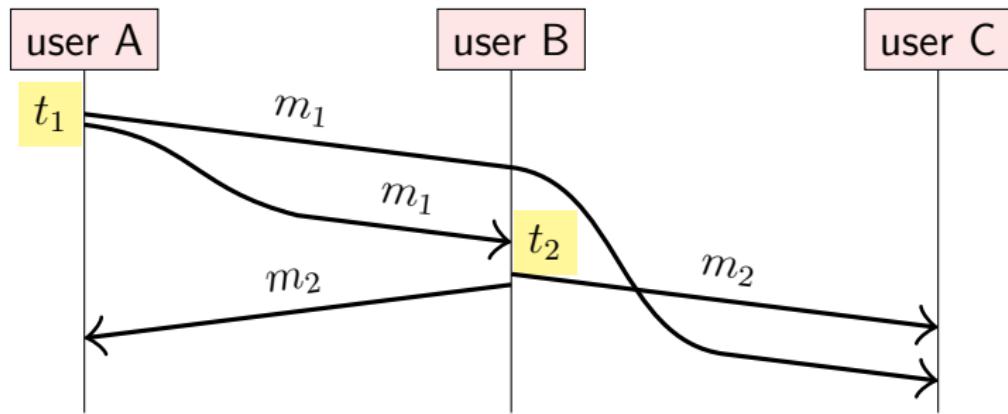
If  $(a \rightarrow b) \implies (a \prec b)$  then  $\prec$  is a **causal order** (or:  $\prec$  is “consistent with causality”).

NB. “causal”  $\neq$  “casual”!

## Lecture 4

# Broadcast protocols and logical time

# Physical timestamps inconsistent with causality



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

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

**Problem:** even with synced clocks,  $t_2 < t_1$  is possible.  
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## Logical vs. physical clocks

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We will look at two types of logical clocks:

- ▶ Lamport clocks
- ▶ Vector clocks

# Lamport clocks algorithm

**on** initialisation **do**

$t := 0$        $\triangleright$  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
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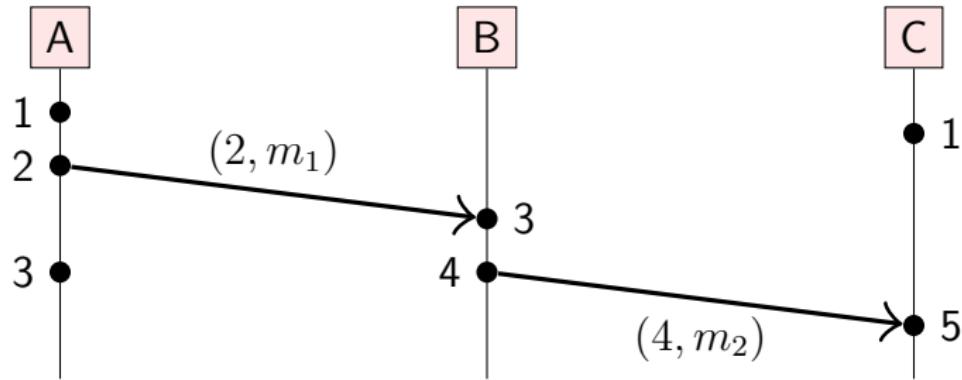
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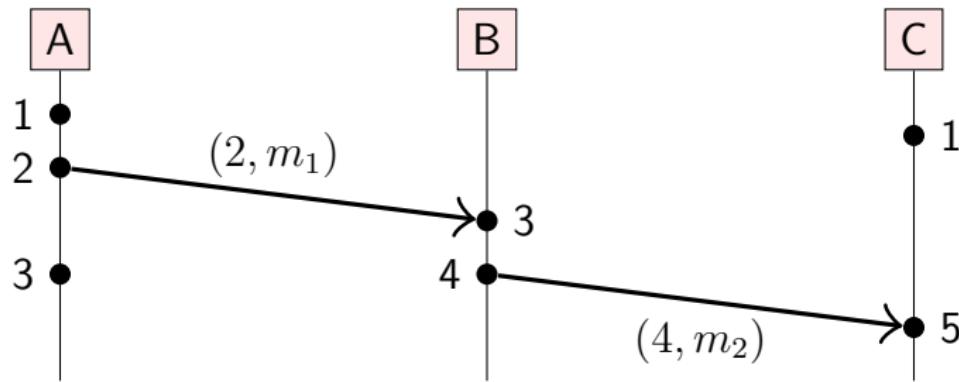
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# Lamport clocks example

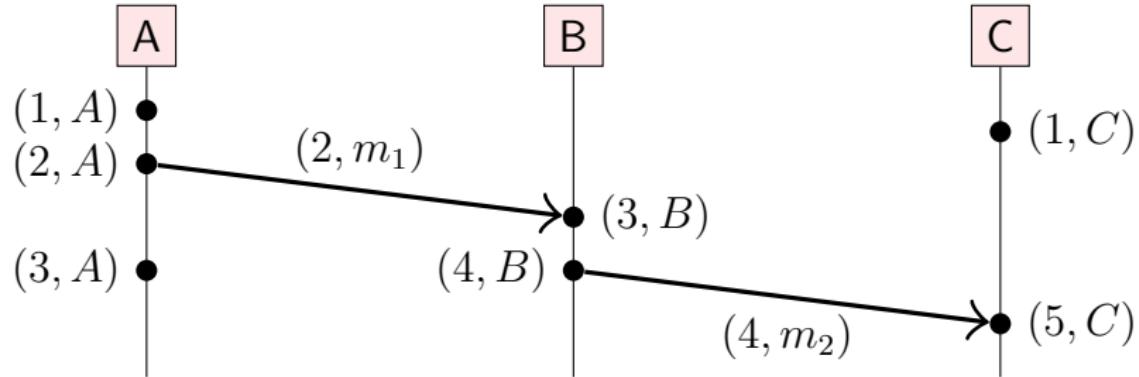


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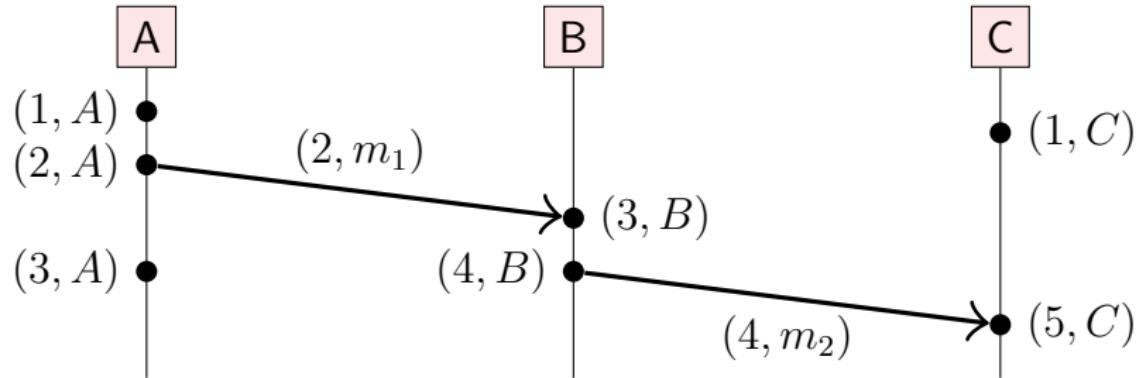
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Define a **total order**  $\prec$  using Lamport timestamps:

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

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**:

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

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- ▶ 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**

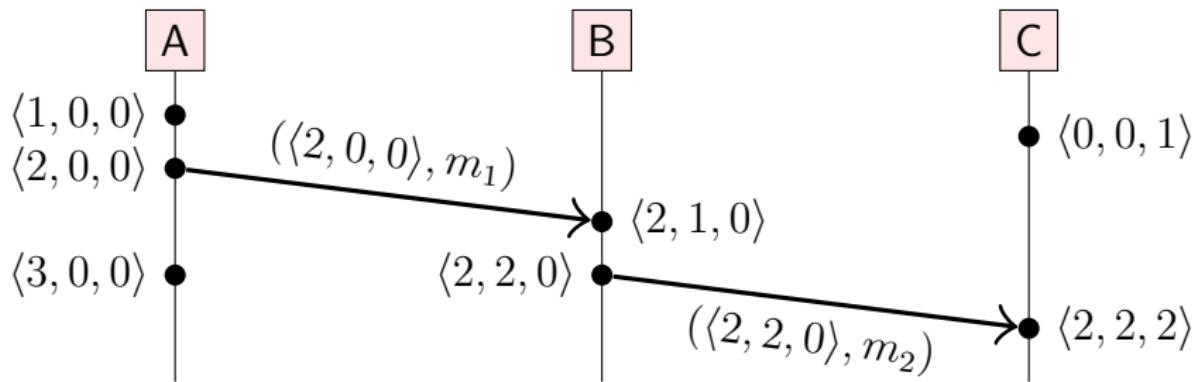
$T[j] := \max(T[j], T'[j])$  for every  $j \in \{1, \dots, n\}$

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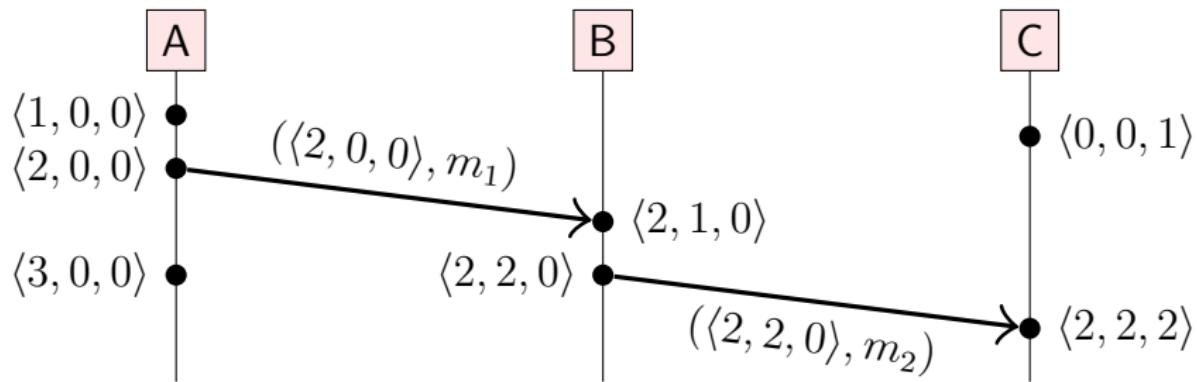
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The vector timestamp of an event  $e$  represents a set of events,  $e$  and its causal dependencies:  $\{e\} \cup \{a \mid a \rightarrow e\}$

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

# Vector clocks ordering

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

- ▶  $T = T'$  iff  $T[i] = T'[i]$  for all  $i \in \{1, \dots, n\}$
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$$V(a) \leq V(b) \text{ iff } (\{a\} \cup \{e \mid e \rightarrow a\}) \subseteq (\{b\} \cup \{e \mid e \rightarrow b\})$$

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

Properties of this order:

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

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

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Build upon system models from lecture 2:

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

# Receiving versus delivering

Node A:

Application

Node B:

Application

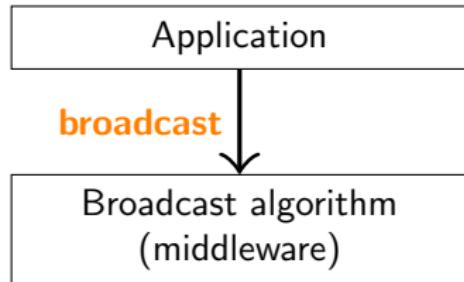
Broadcast algorithm  
(middleware)

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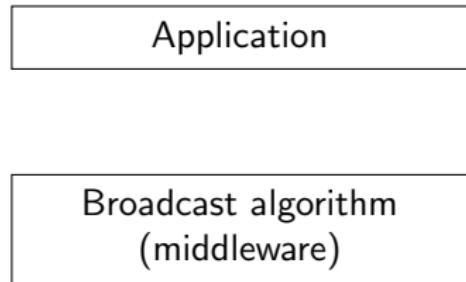
Network

# Receiving versus delivering

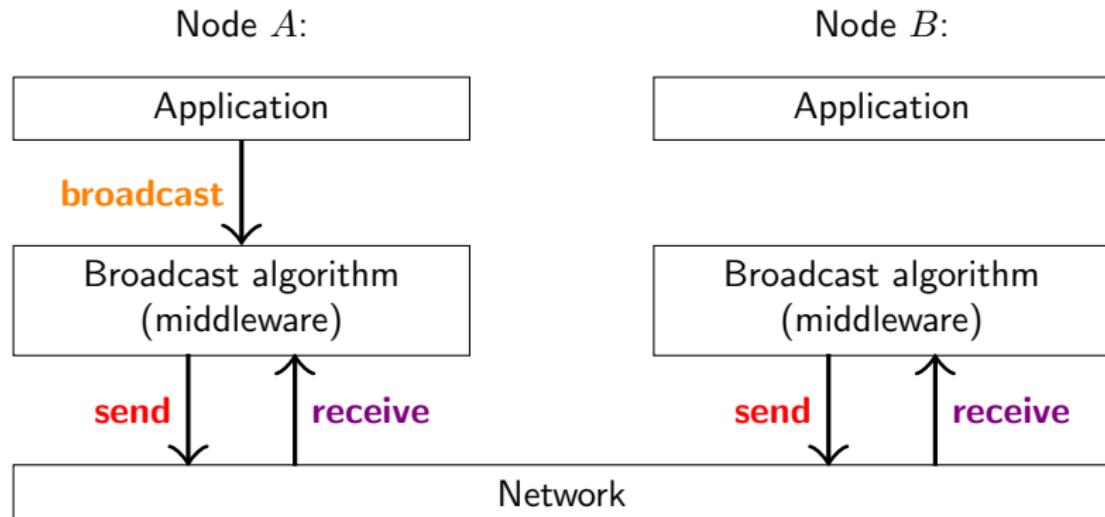
Node A:



Node B:

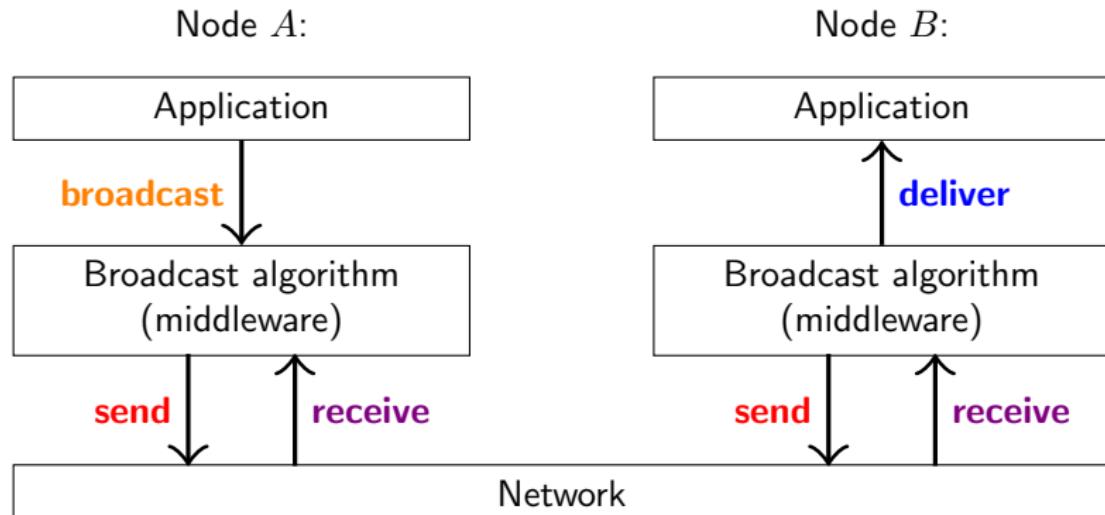


# Receiving versus delivering



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  $m_2$

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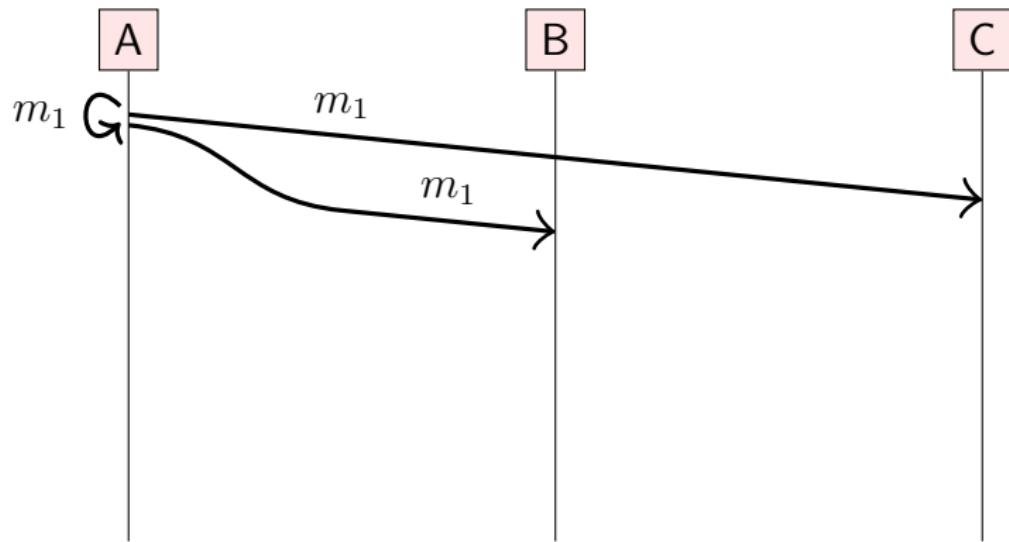
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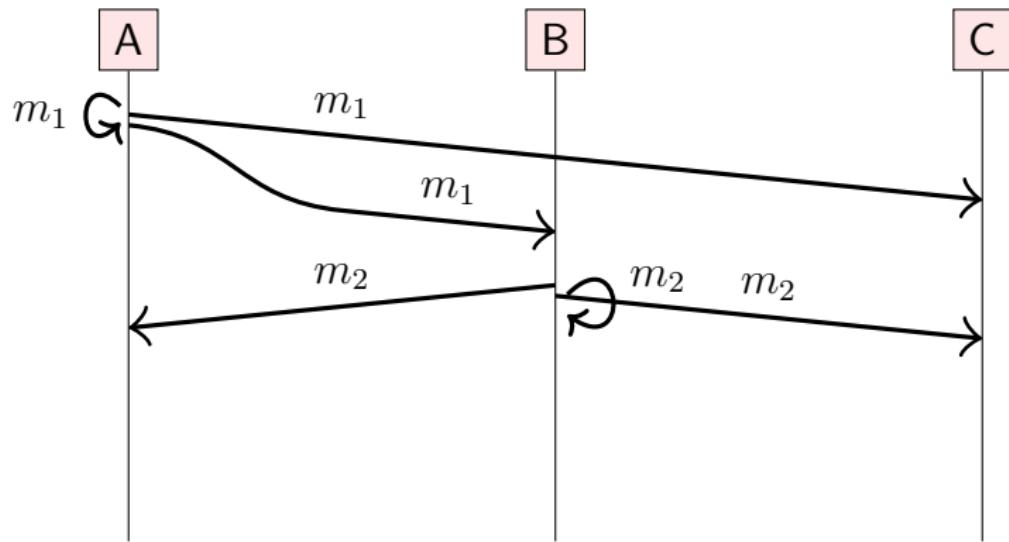
## FIFO-total order broadcast:

Combination of FIFO broadcast and total order broadcast

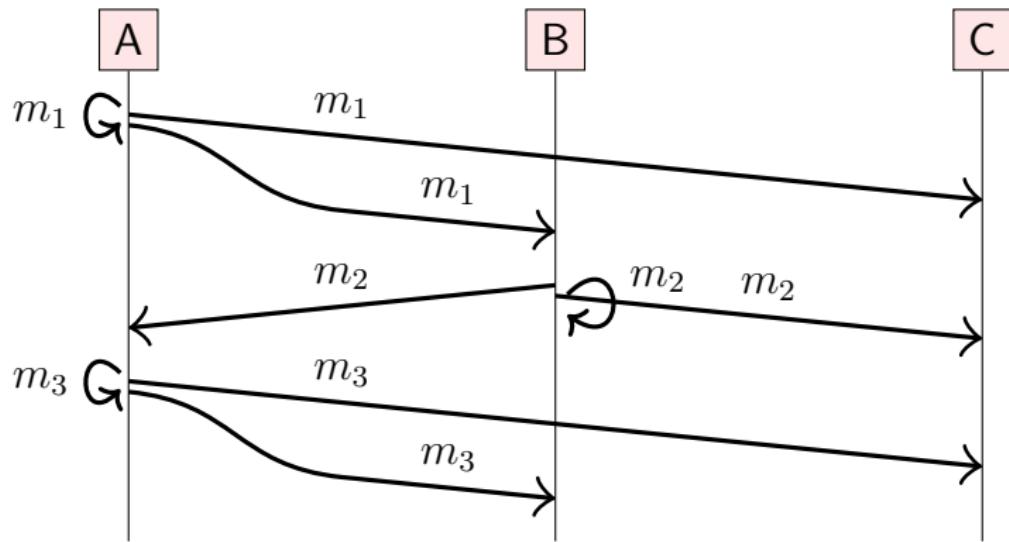
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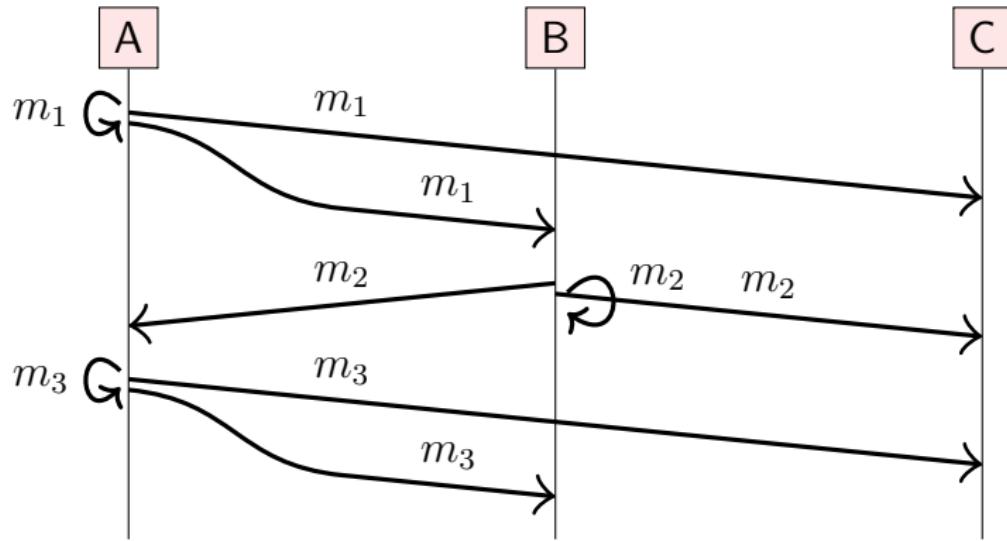
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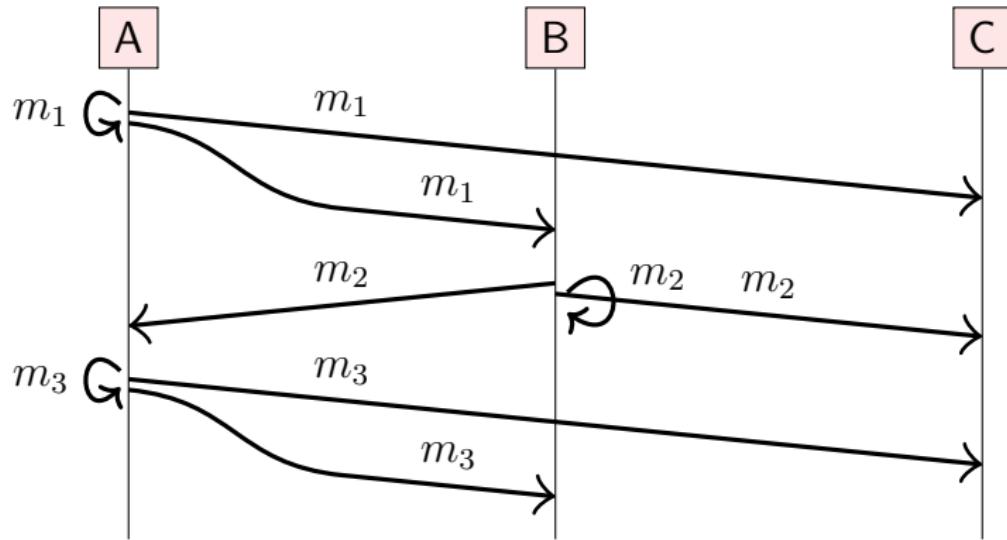
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Messages sent by the same node must be delivered in the order they were sent.

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

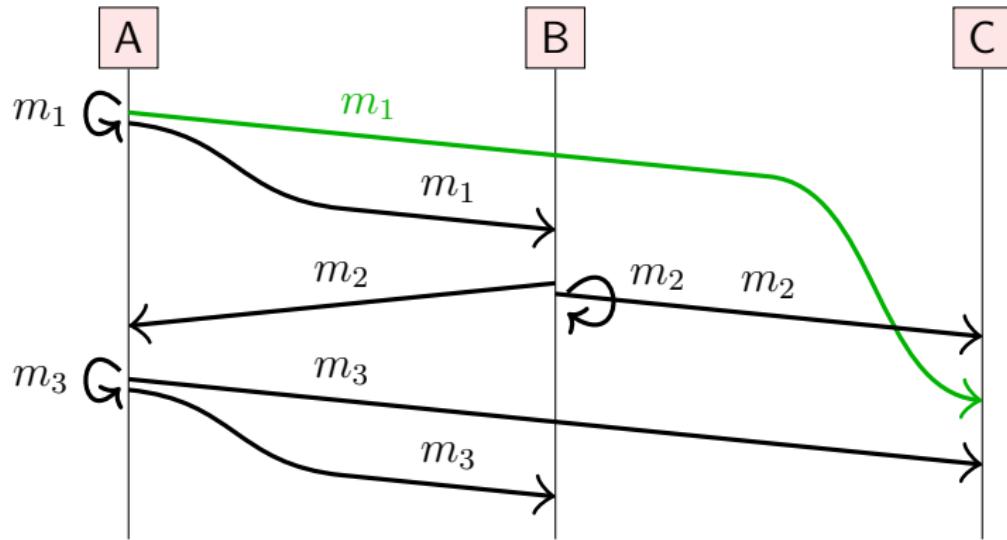
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Messages sent by the same node must be delivered in the order they were sent.

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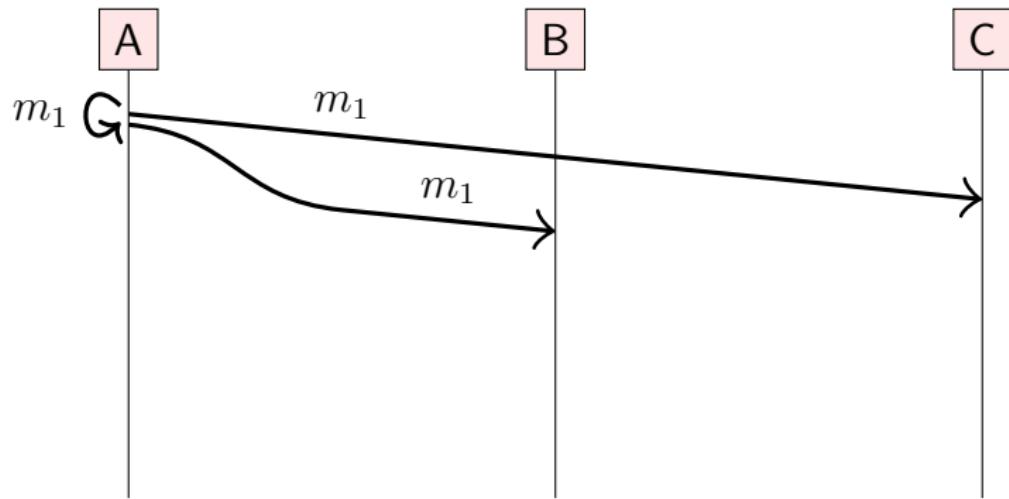
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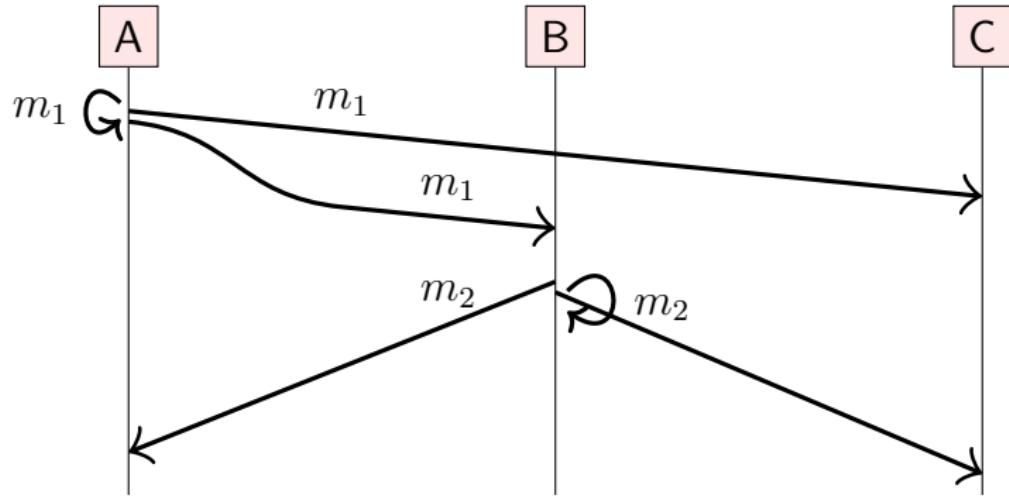
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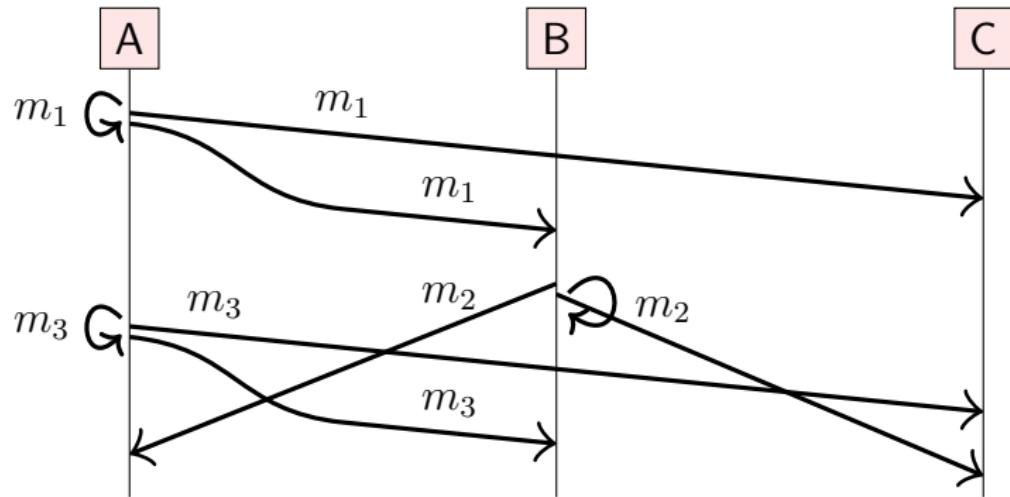
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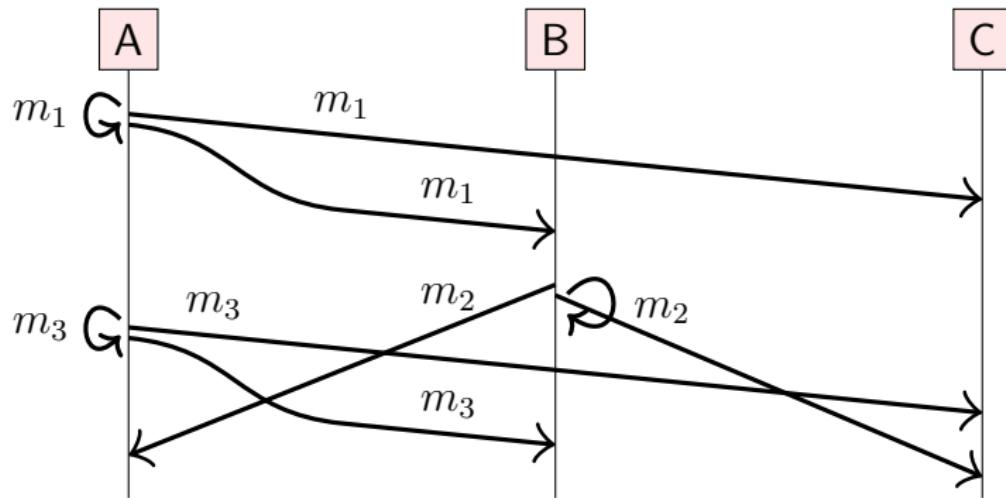
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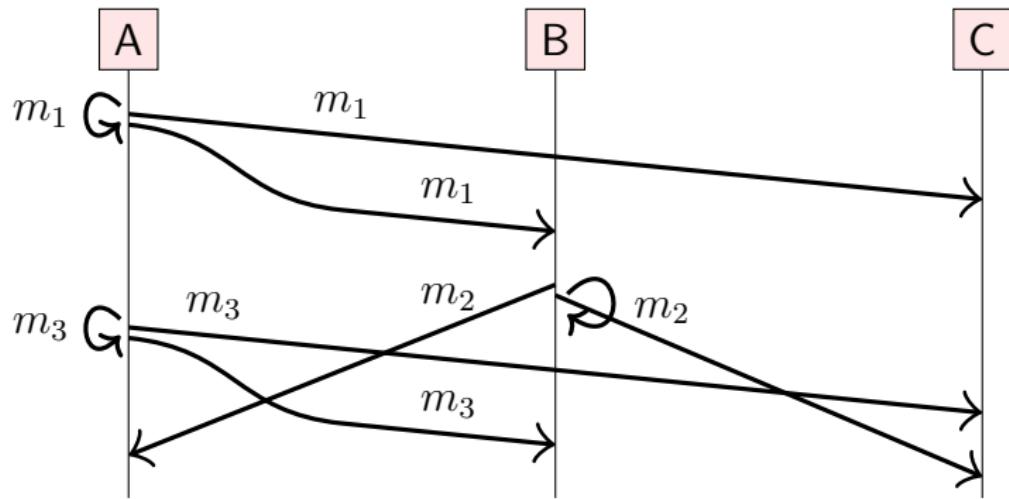


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Causally related messages must be delivered in causal order.  
Concurrent messages can be delivered in any order.

# Causal broadcast



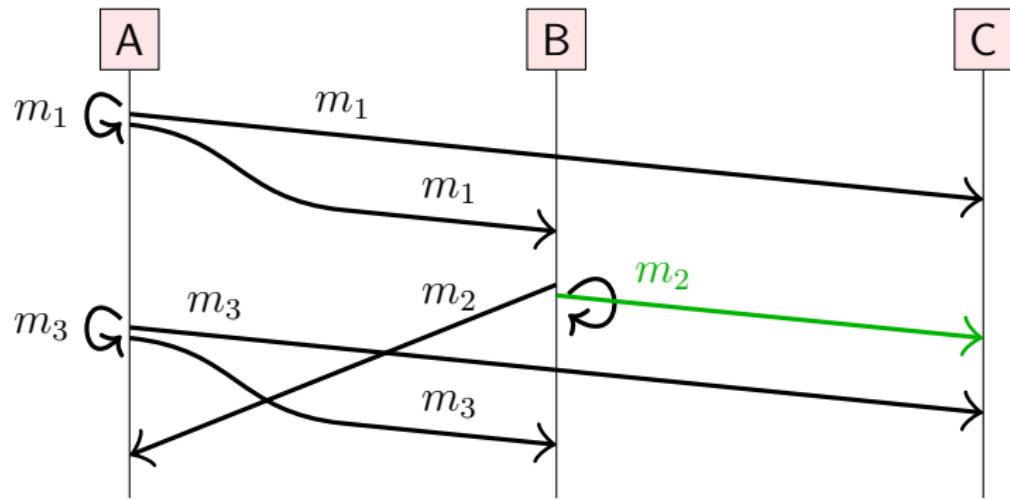
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Here:  $\text{broadcast}(m_1) \rightarrow \text{broadcast}(m_2)$  and

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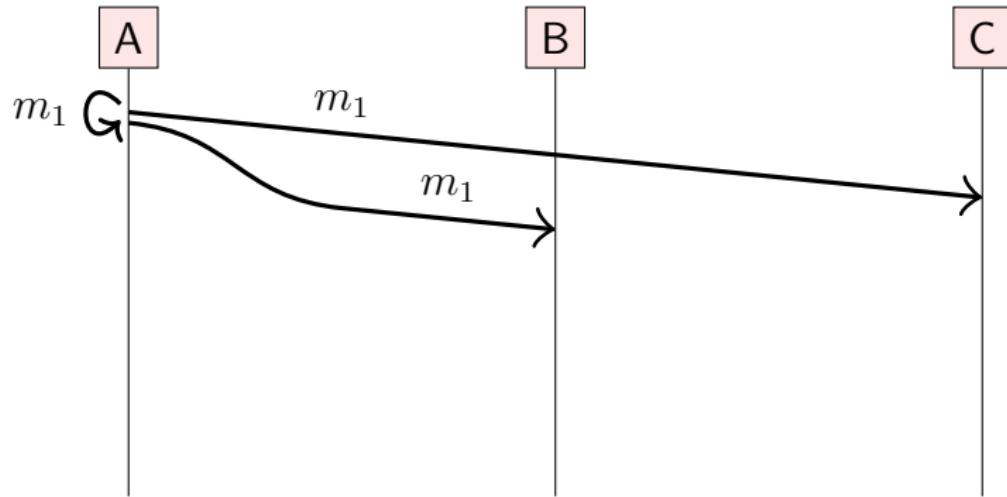
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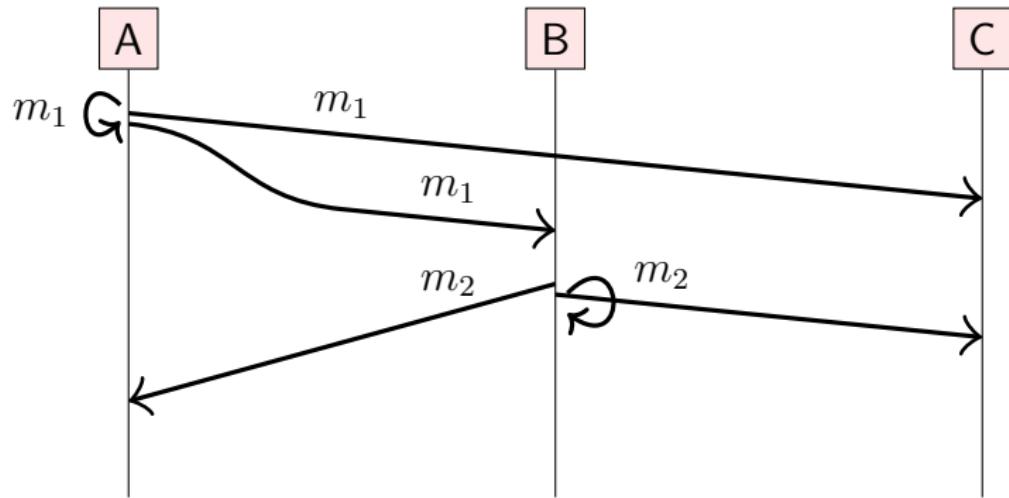
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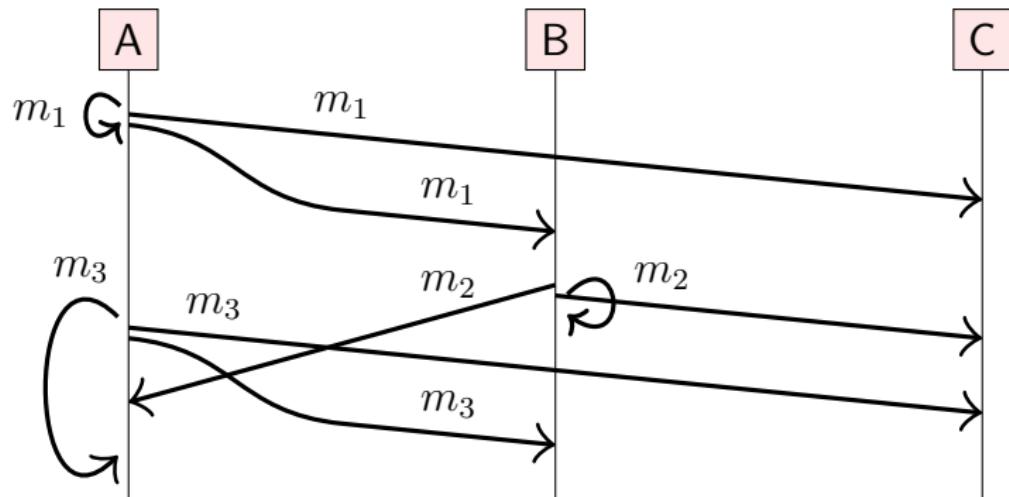
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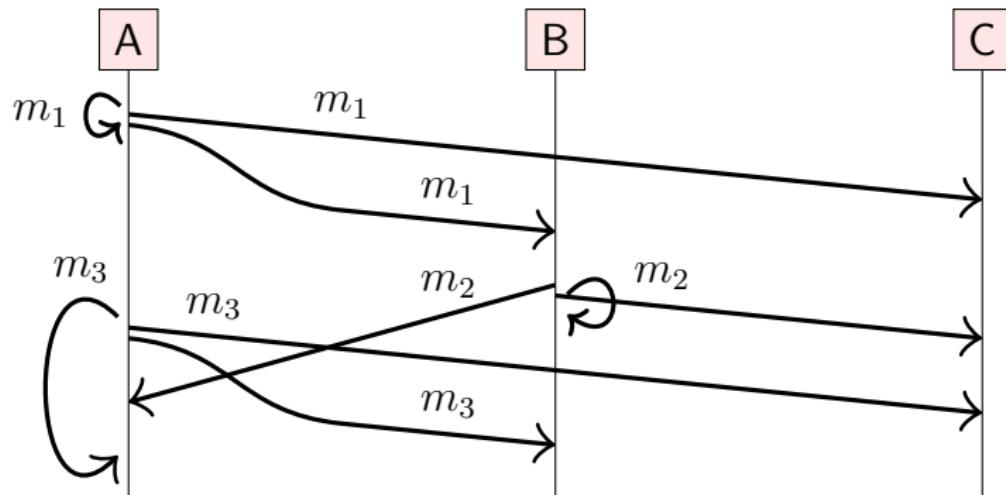
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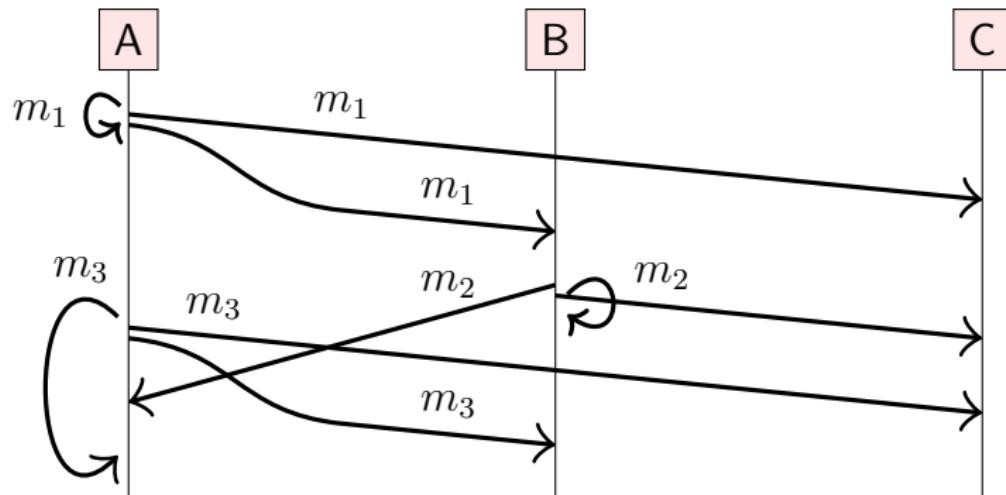


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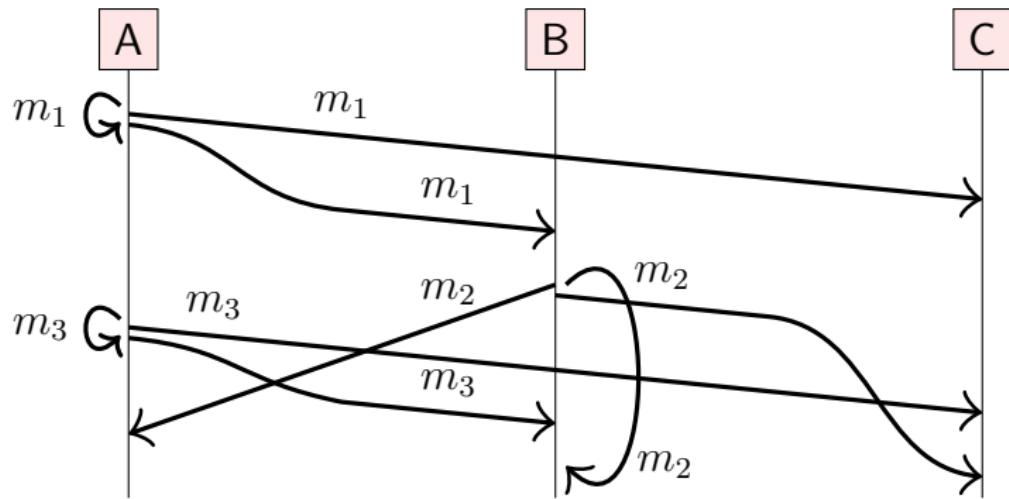
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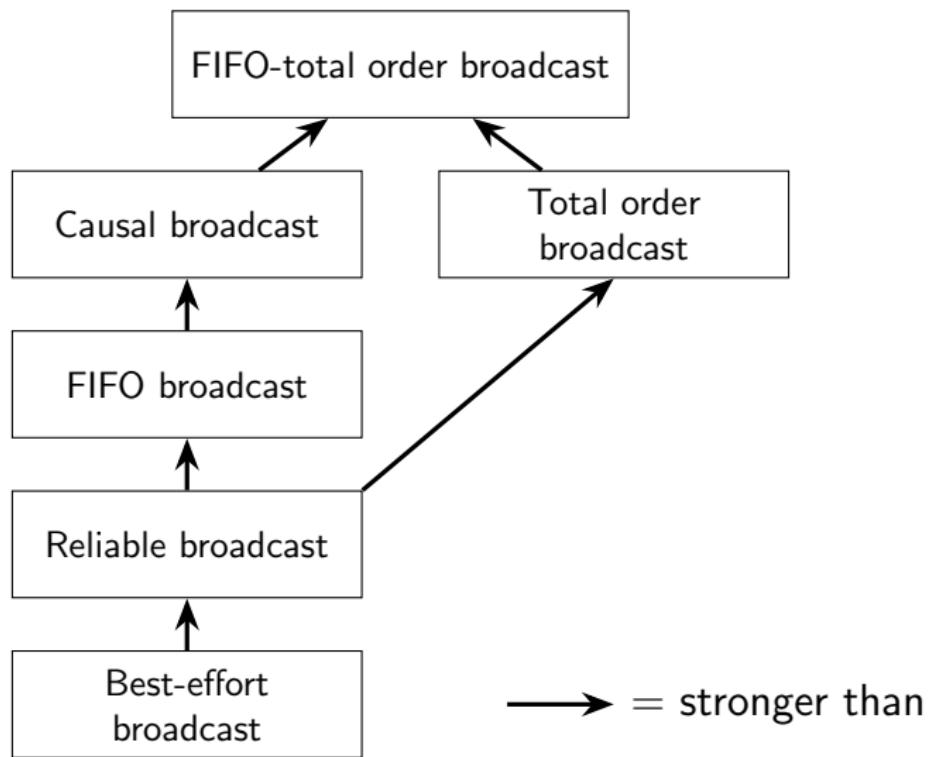
## Total order broadcast (2)



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

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# Relationships between broadcast models



# Broadcast algorithms

Break down into two layers:

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

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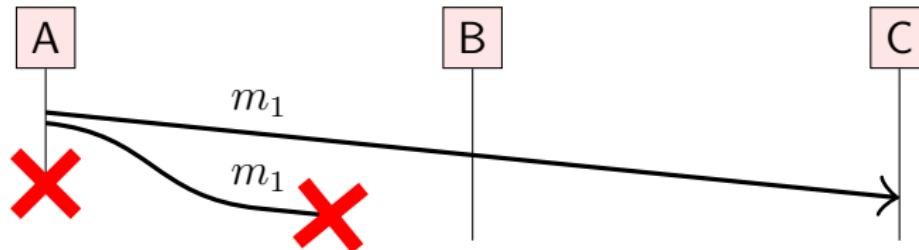
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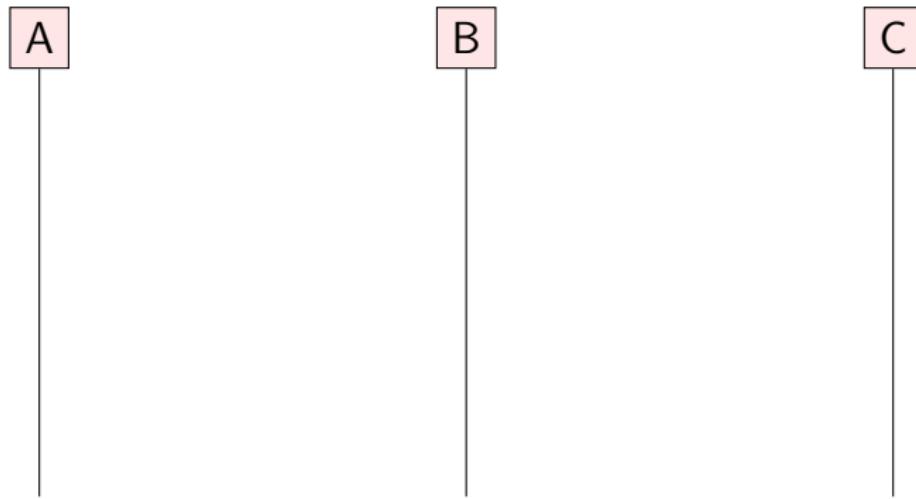
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- ▶ Use reliable links (retry + deduplicate)
- ▶ Problem: node may crash before all messages delivered



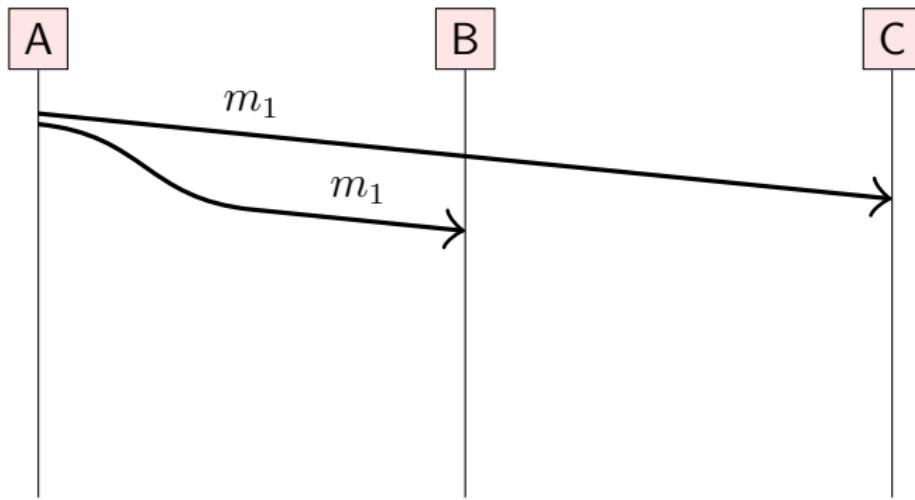
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Idea: the **first time** a node receives a particular message, it **re-broadcasts** to each other node (via reliable links).



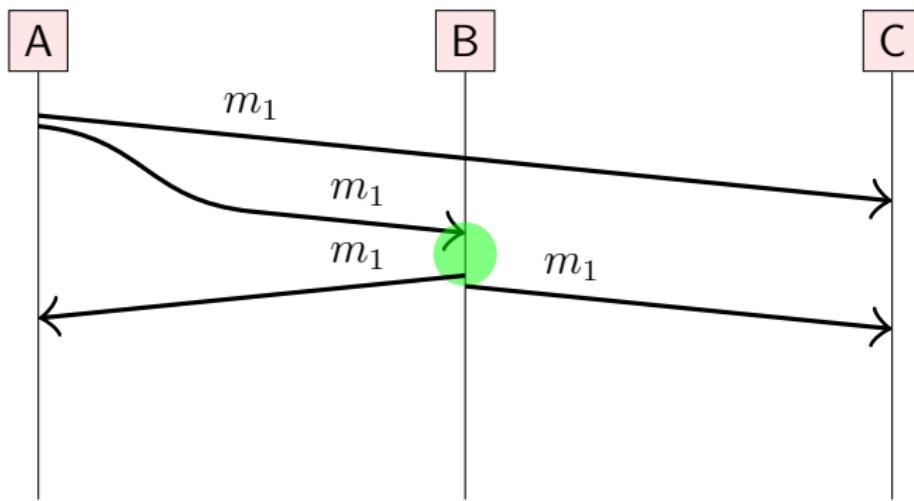
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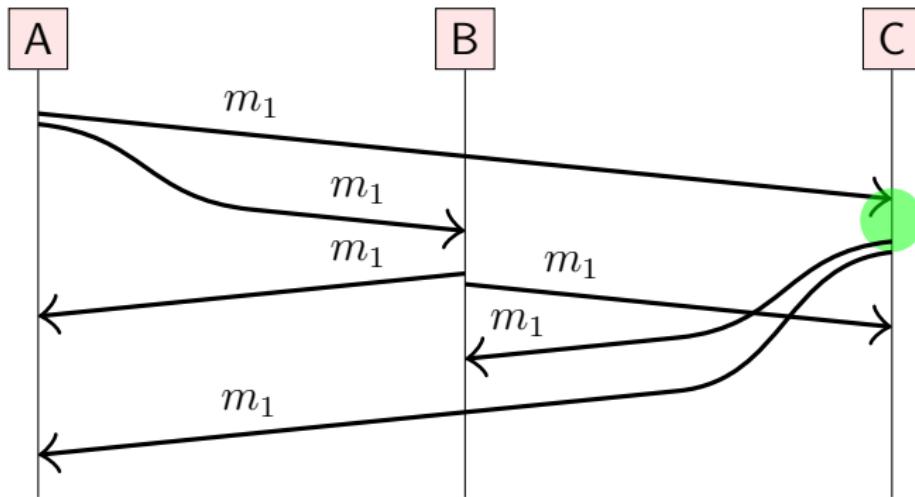
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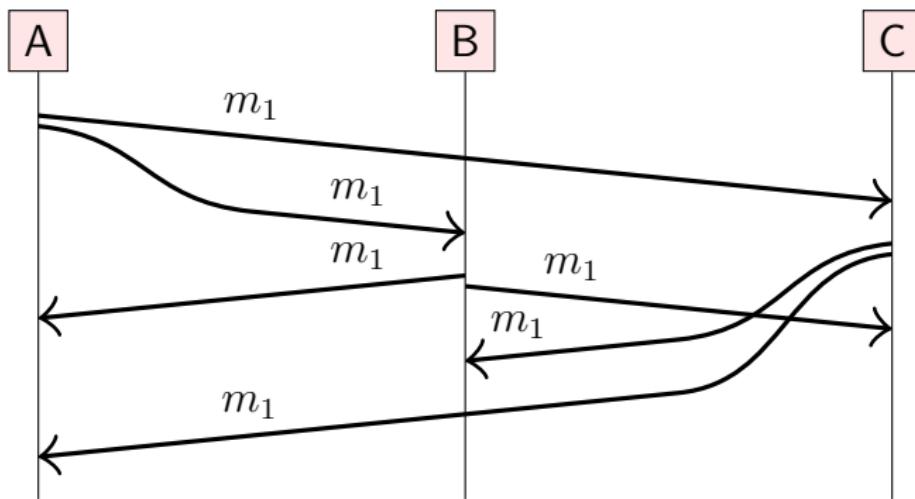
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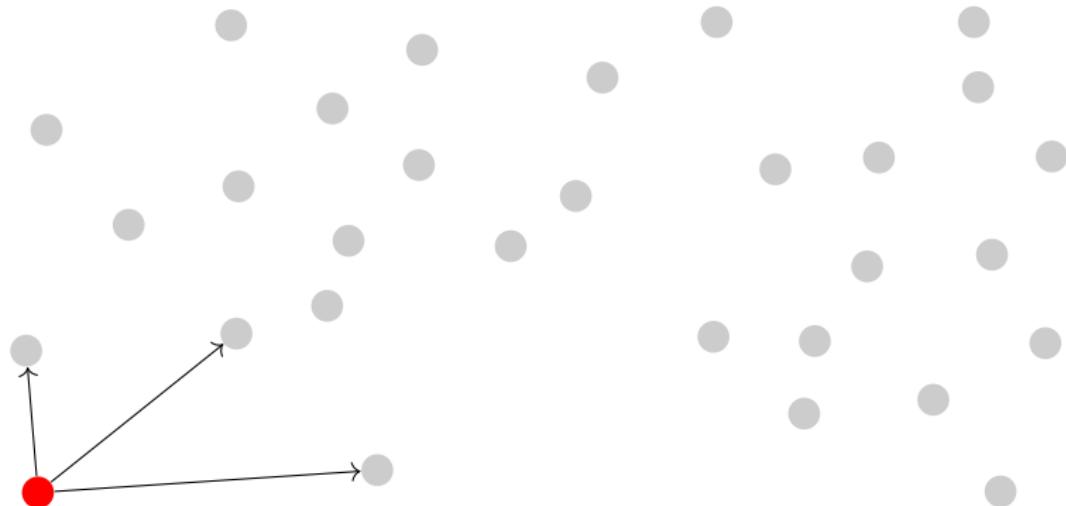


Reliable, but... up to  $O(n^2)$  messages for  $n$  nodes!

# Gossip protocols

Useful when broadcasting to a large number of nodes.

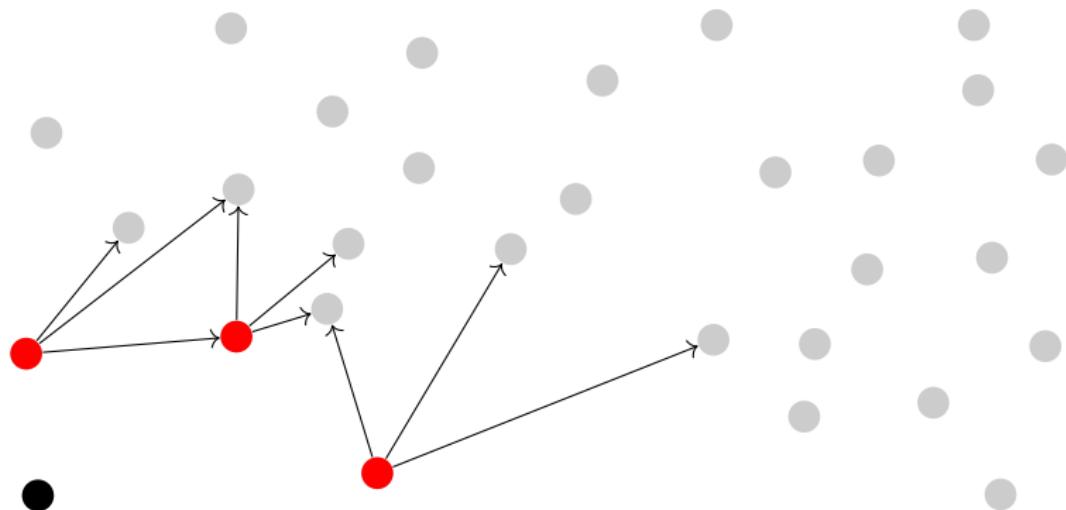
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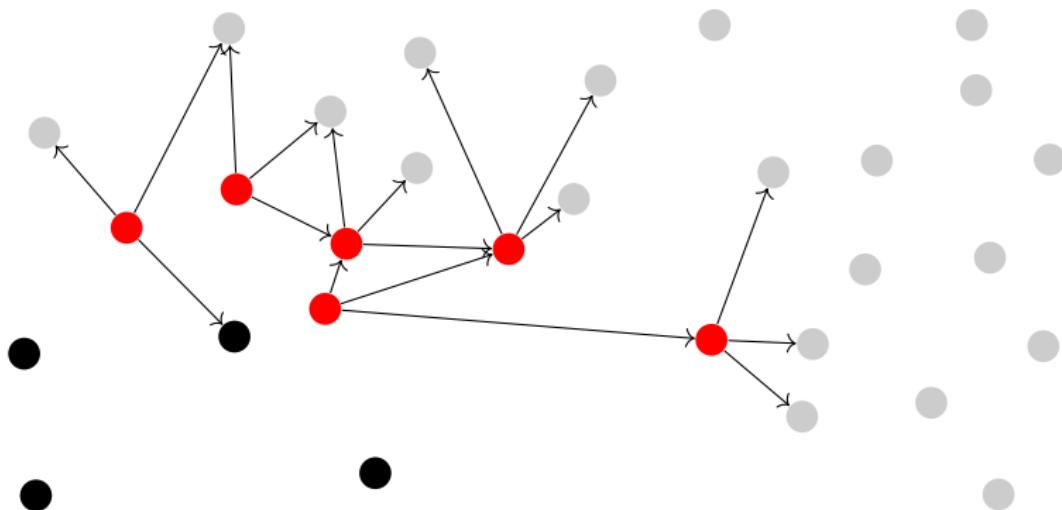
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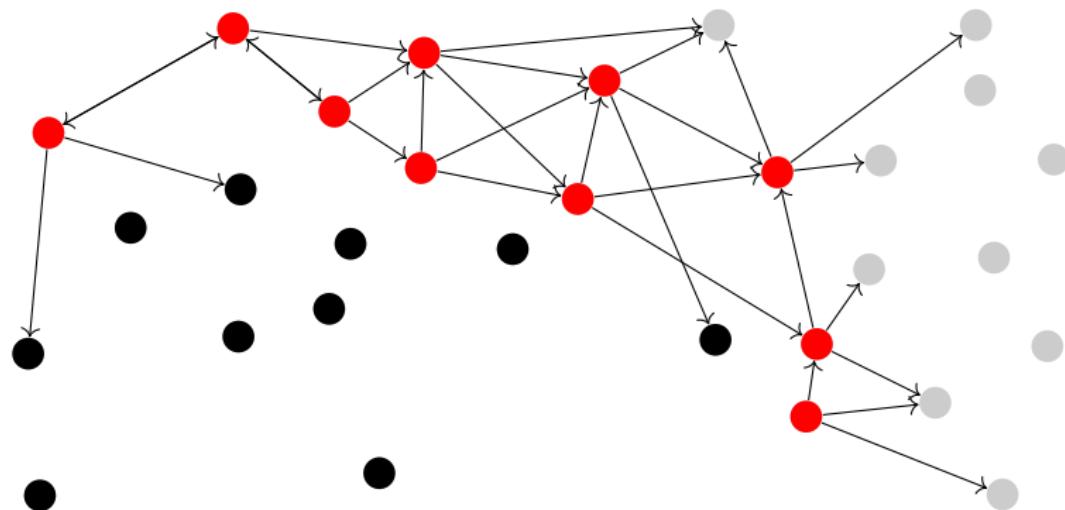
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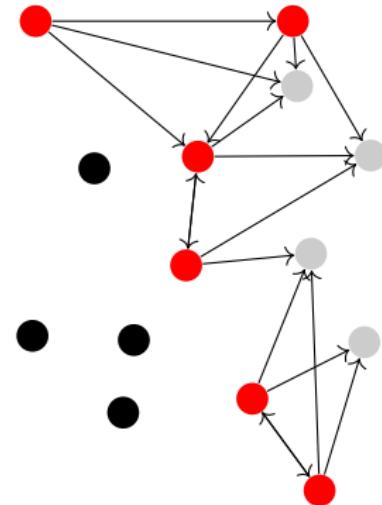
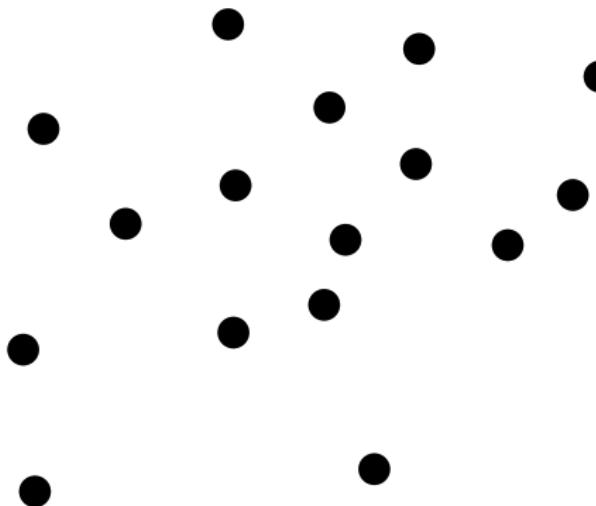
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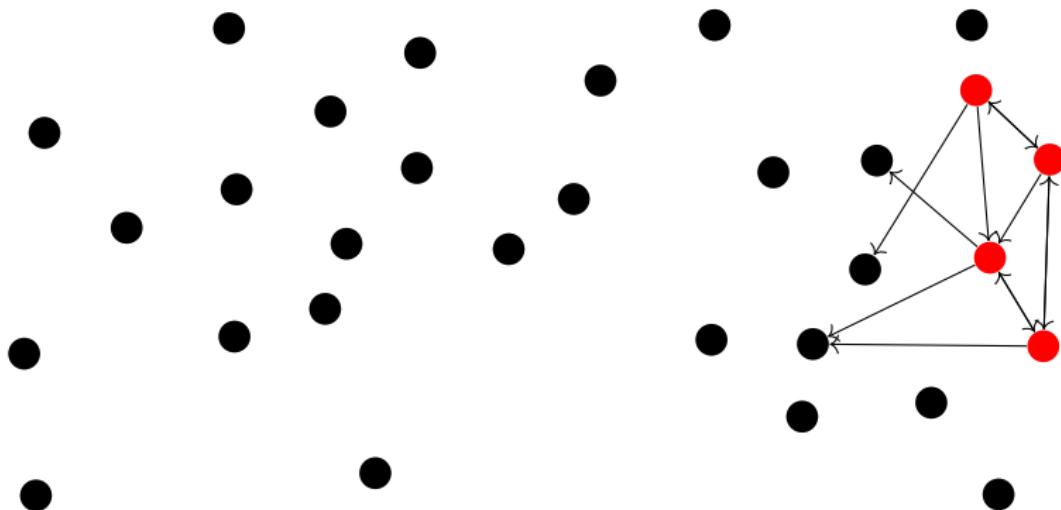
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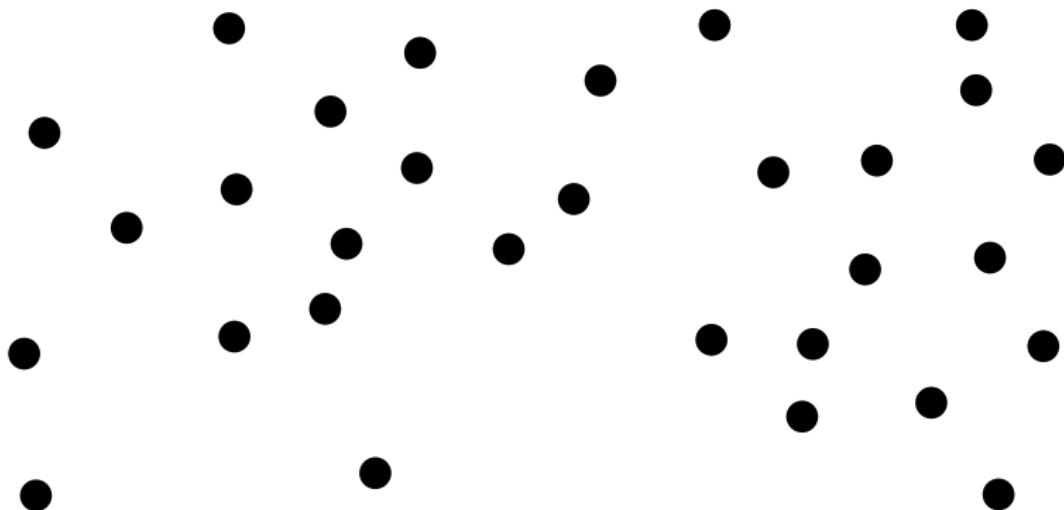
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Eventually reaches all nodes (with high probability).

# FIFO broadcast algorithm

**on** initialisation **do**

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

**end on**

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

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

$sendSeq := sendSeq + 1$

**end on**

**on** receiving  $msg$  from reliable broadcast at node  $N_i$  **do**

$buffer := buffer \cup \{msg\}$

**while**  $\exists sender, m.$   $(sender, delivered[sender], m) \in buffer$  **do**

deliver  $m$  to the application

$delivered[sender] := delivered[sender] + 1$

**end while**

**end on**

# Causal broadcast algorithm

**on** initialisation **do**

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

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

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$buffer := buffer \cup \{msg\}$

**while**  $\exists (sender, deps, m) \in buffer. deps \leq delivered$  **do**

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$buffer := buffer \setminus \{(sender, deps, m)\}$

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**end while**

**end on**

# Vector clocks ordering

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

- ▶  $T = T'$  iff  $T[i] = T'[i]$  for all  $i \in \{1, \dots, n\}$
- ▶  $T \leq T'$  iff  $T[i] \leq T'[i]$  for all  $i \in \{1, \dots, n\}$
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# Total order broadcast algorithms

**Single leader** approach:

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## **Lamport clocks** approach:

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

Lecture 5

# Replication

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- ▶ Keeping a copy of the same data on multiple nodes
- ▶ Databases, filesystems, caches, . . .
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Compare to **RAID** (Redundant Array of Independent Disks):  
replication within a single computer

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

## Retrying state updates

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

Like

12,300 people like this.

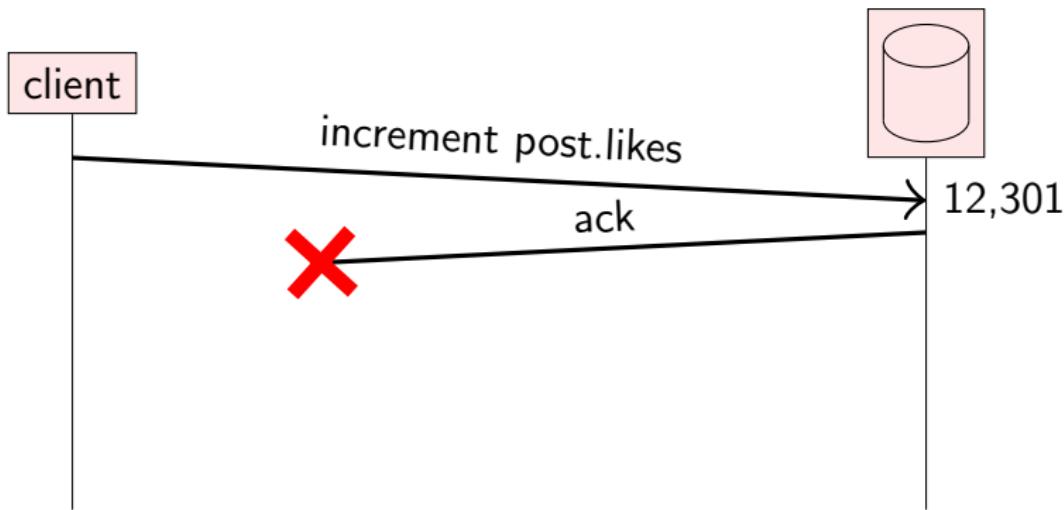


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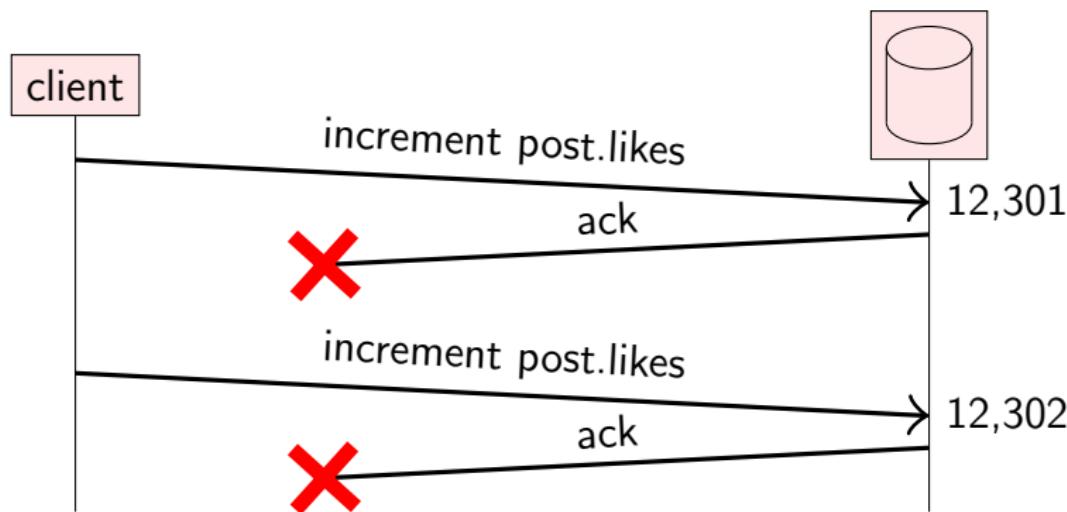


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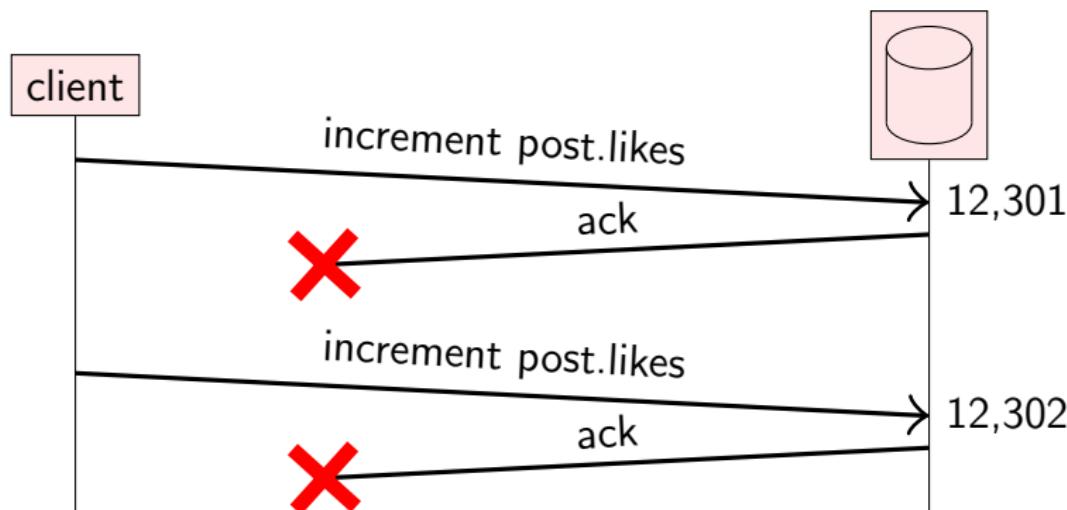


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Deduplicating requests requires that the database tracks which requests it has already seen (in stable storage)



TWEETS  
**6,219**

FOLLOWING  
**-20**

FOLLOWERS  
**24.1K**



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# 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 without deduplication.

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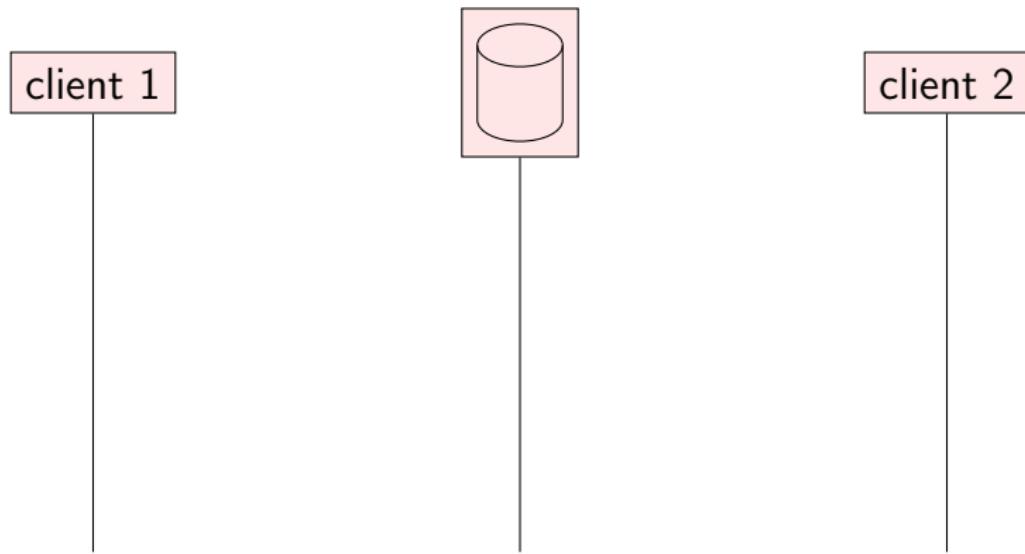
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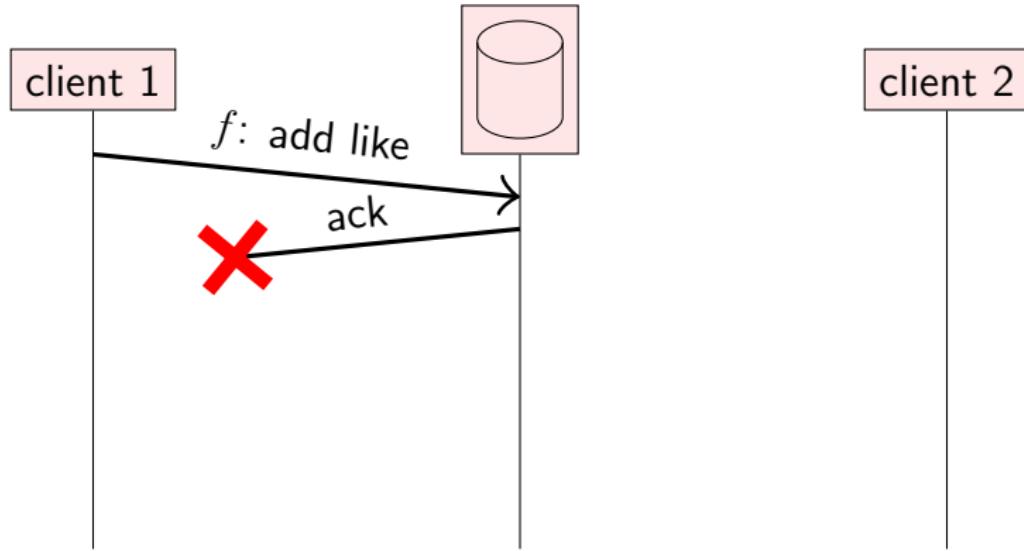
Choice of retry behaviour:

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

# Adding and then removing again

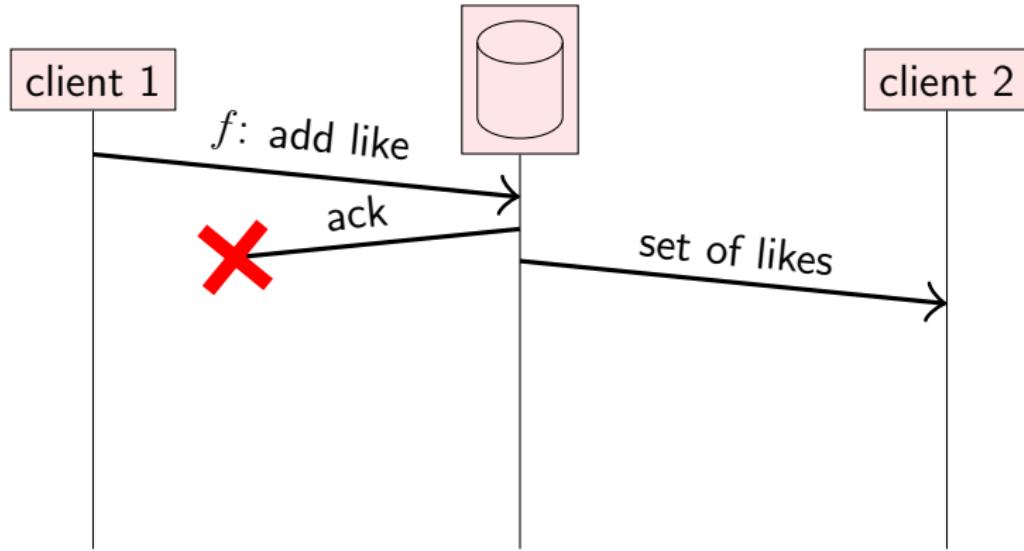


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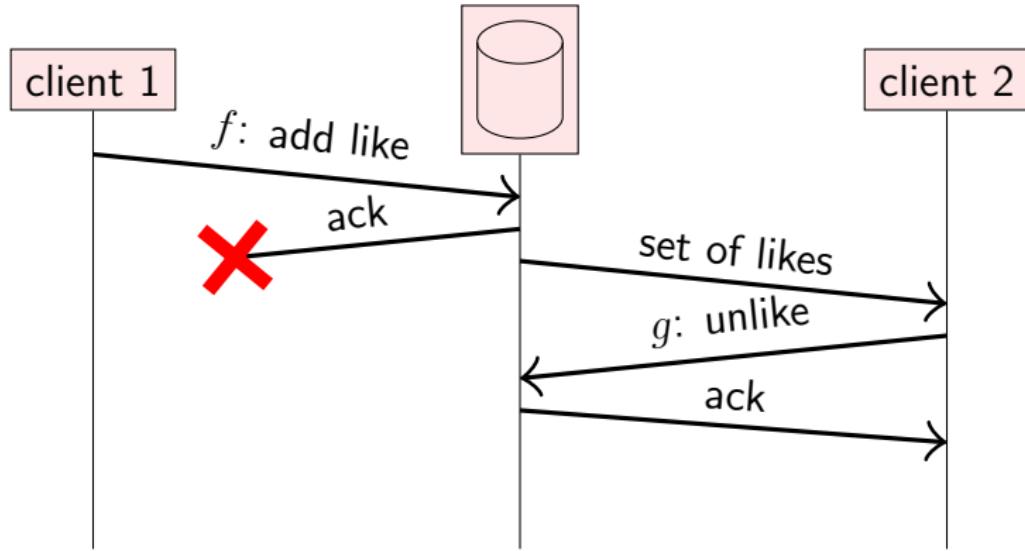
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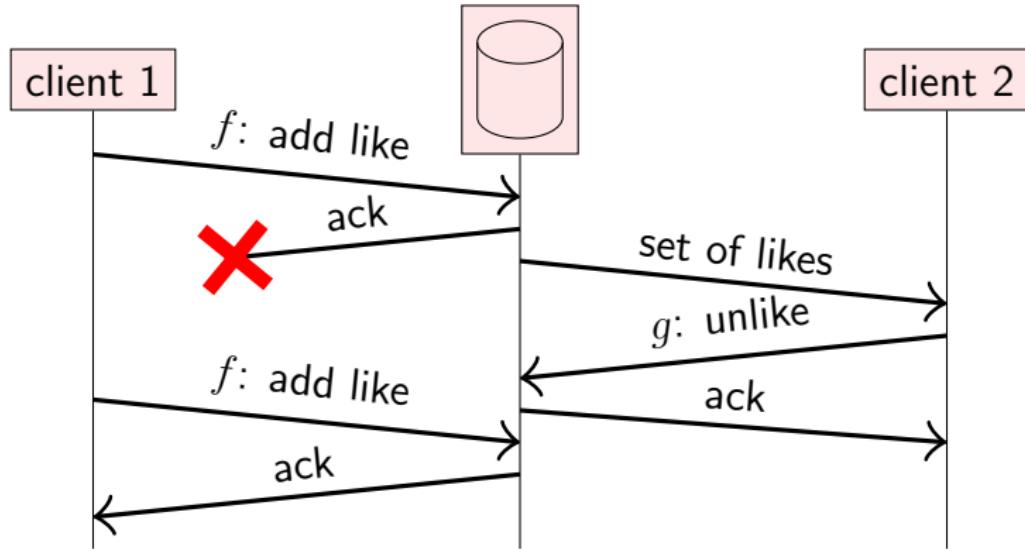
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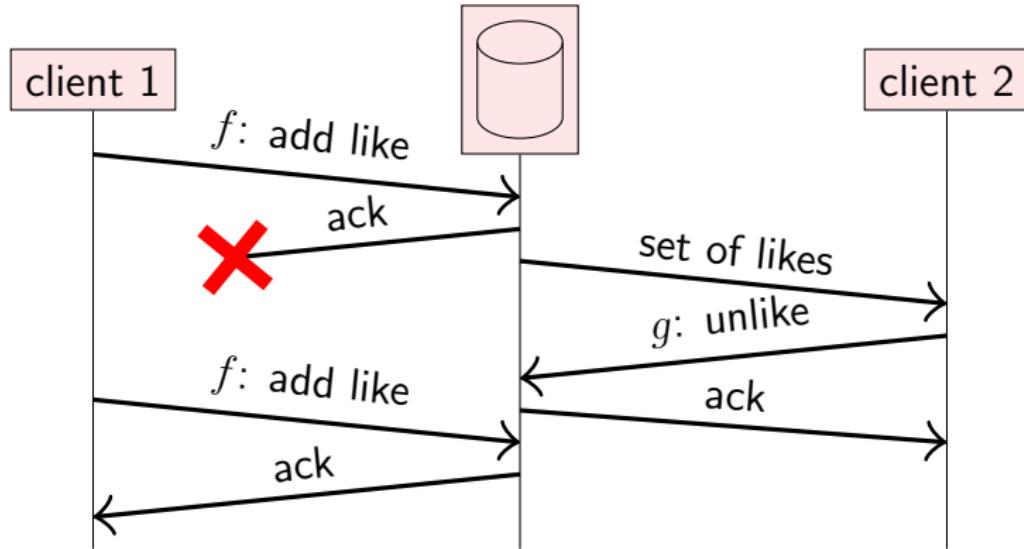
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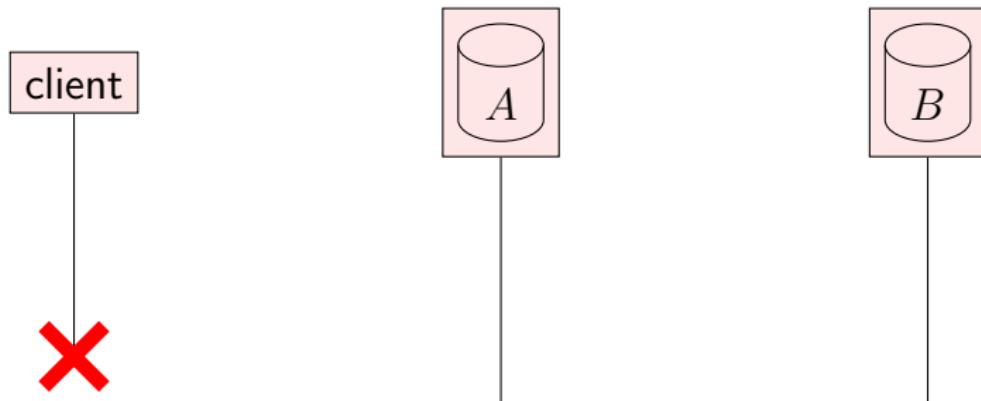


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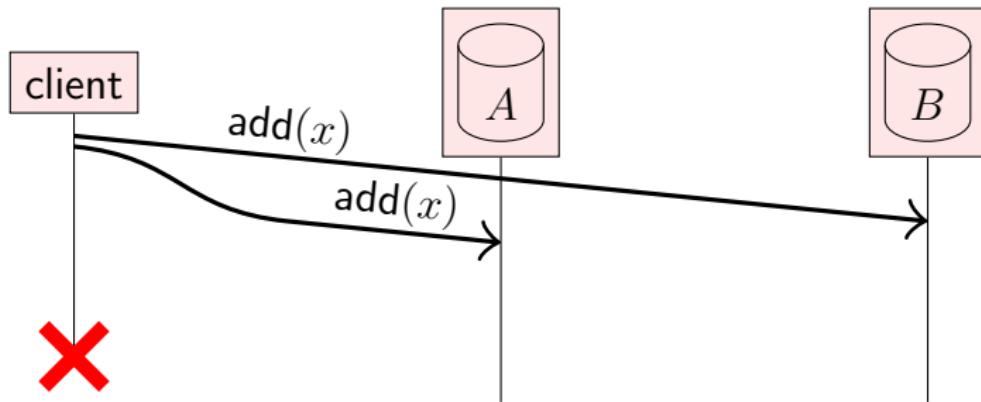
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**Idempotent?**  $f(f(x)) = f(x)$  but  $f(g(f(x))) \neq g(f(x))$

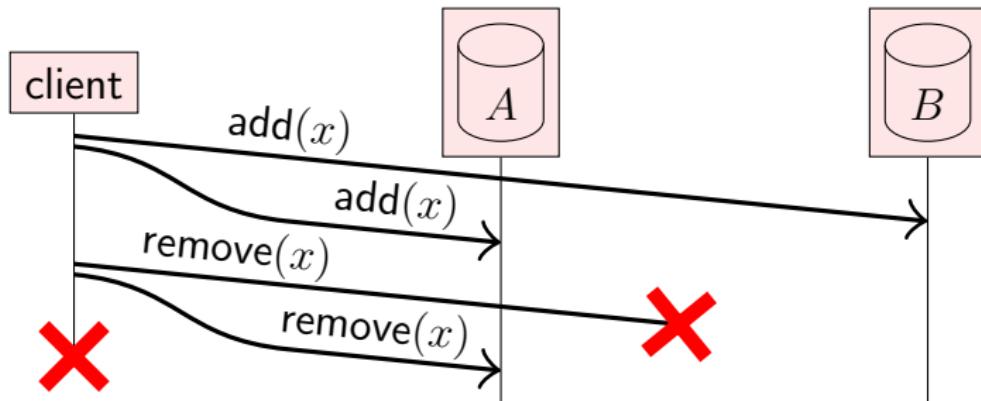
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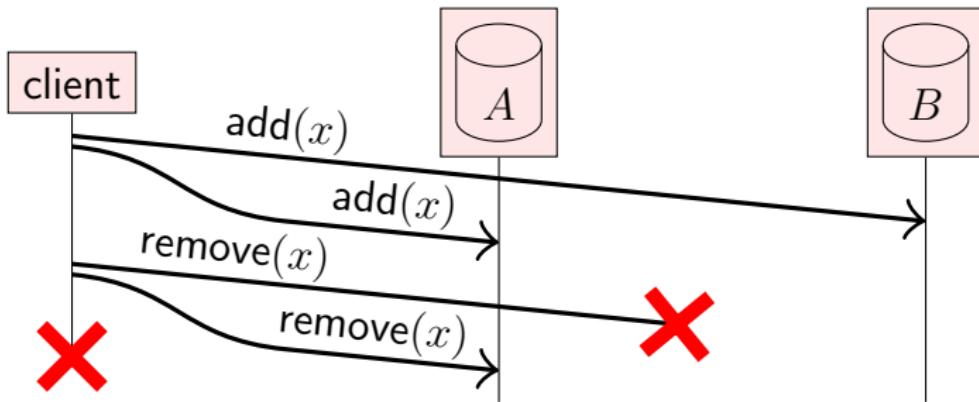
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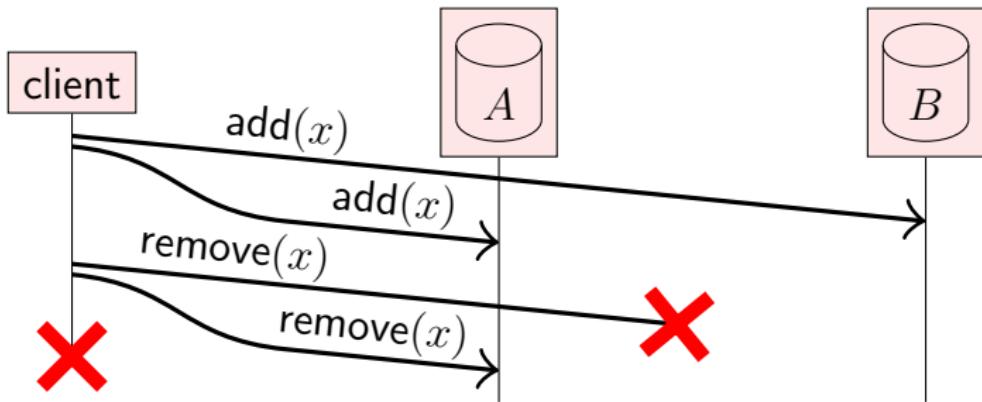


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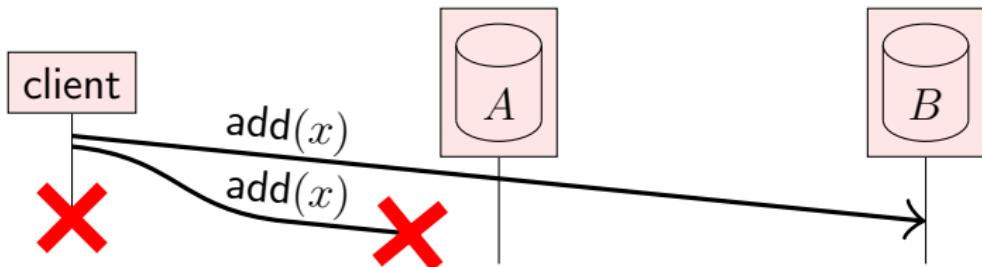


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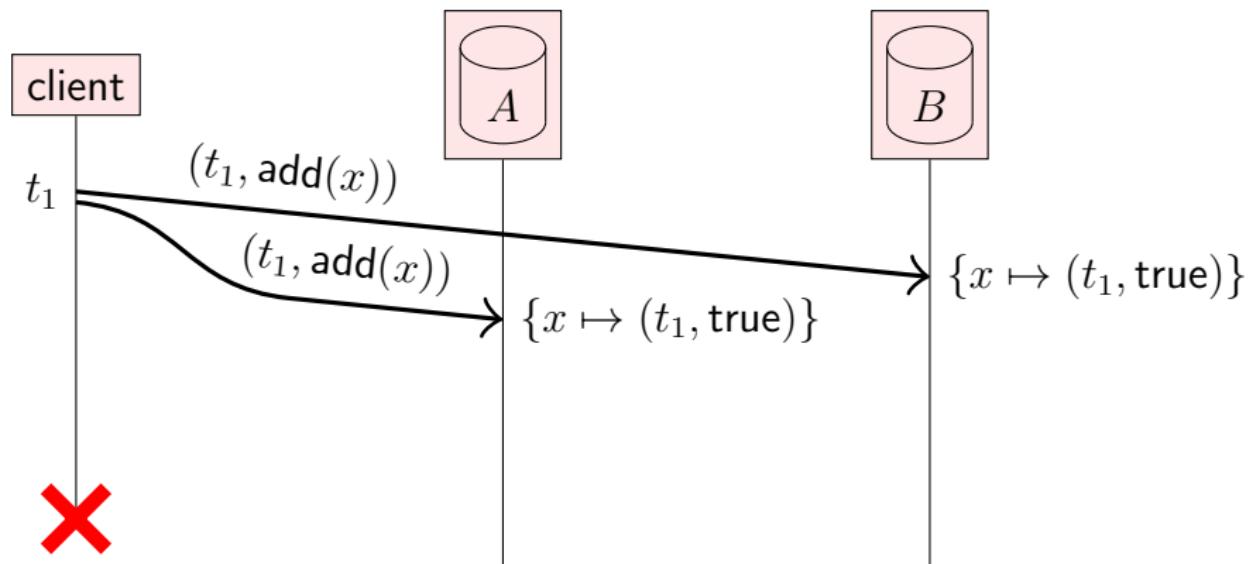
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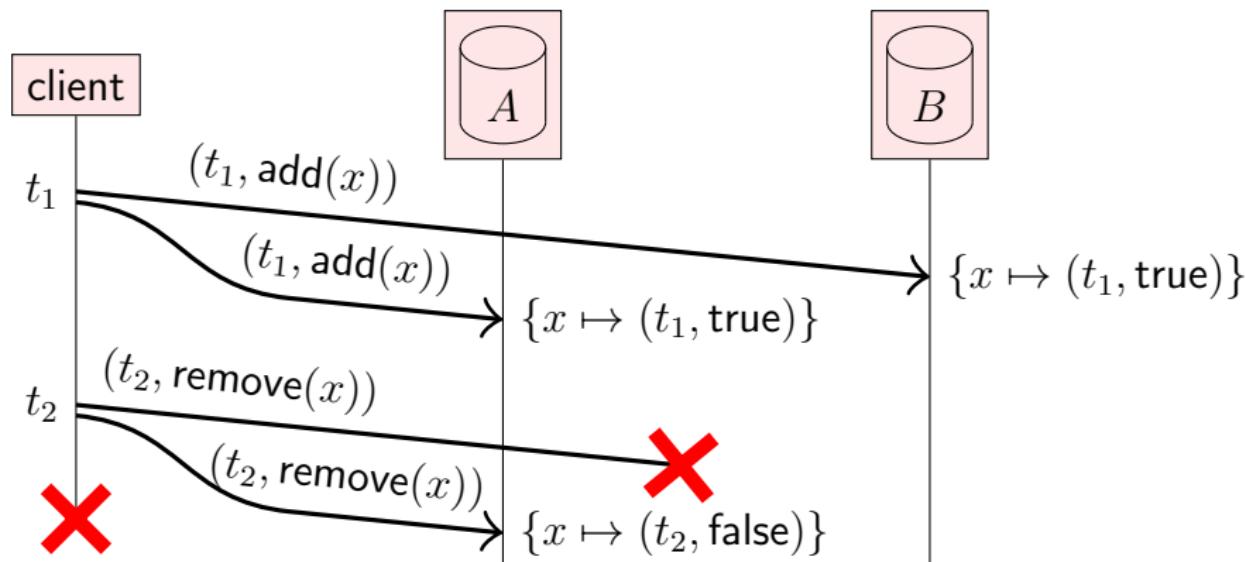
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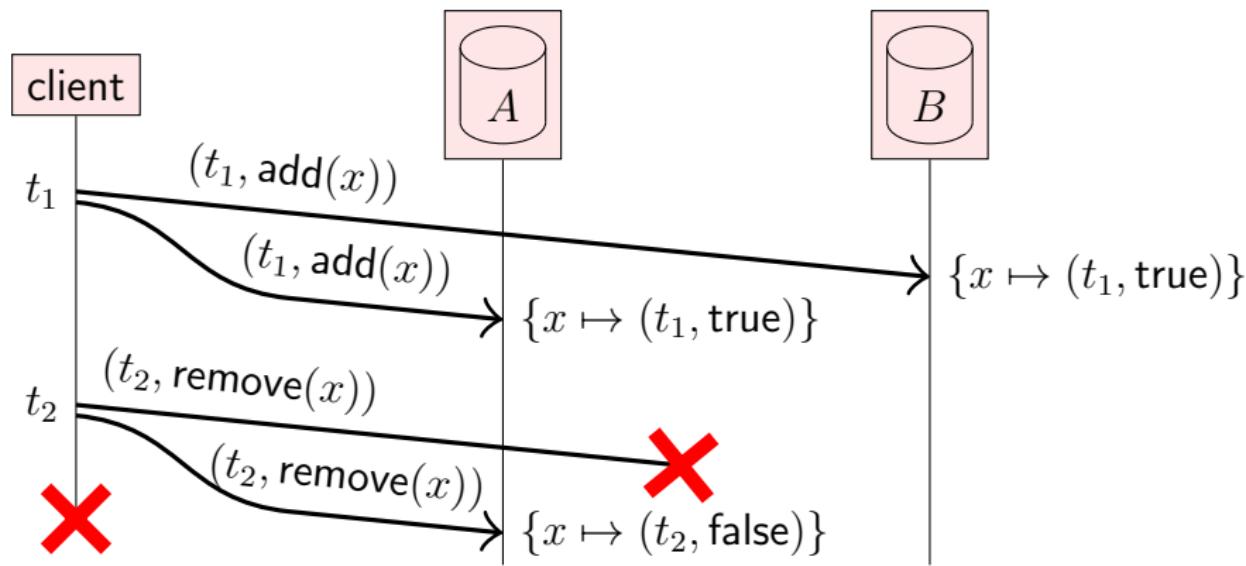
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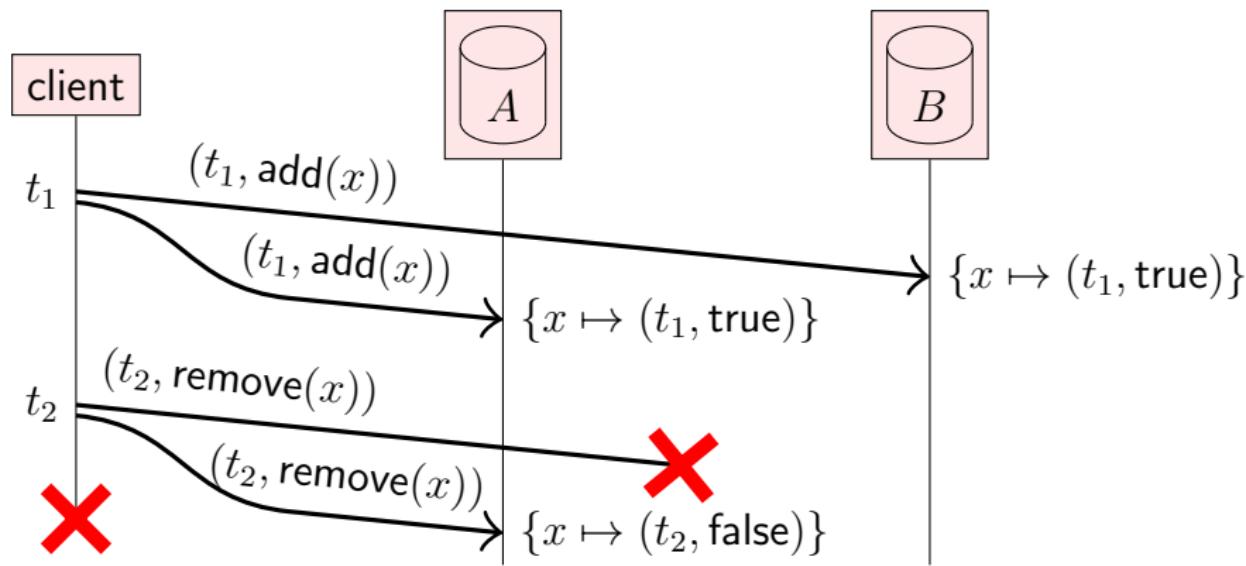


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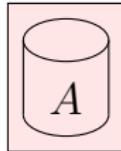
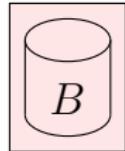


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Every record has **logical timestamp** of last write

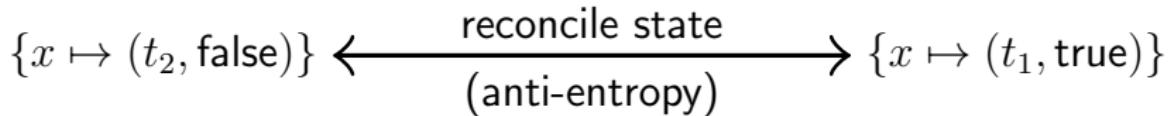
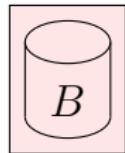
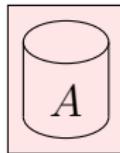
# Reconciling replicas

Replicas periodically communicate among themselves  
to check for any inconsistencies.

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

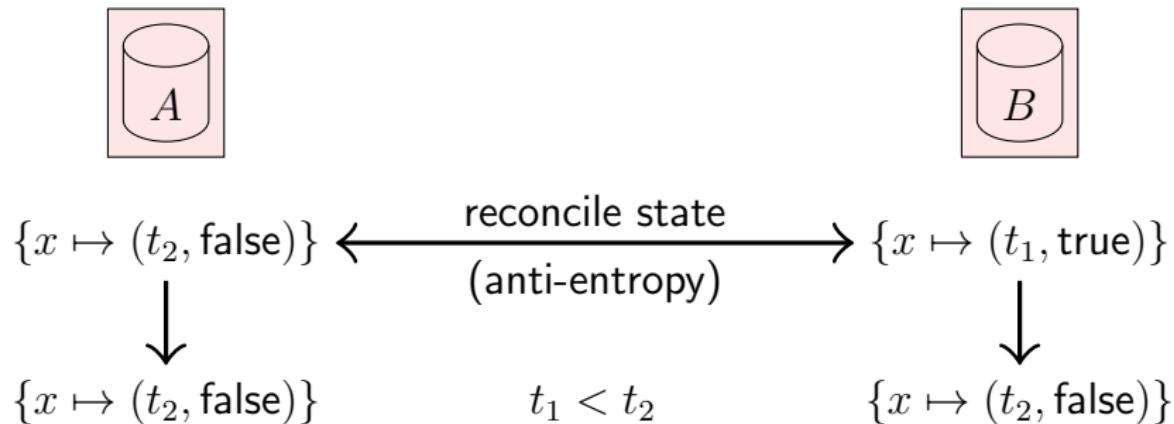
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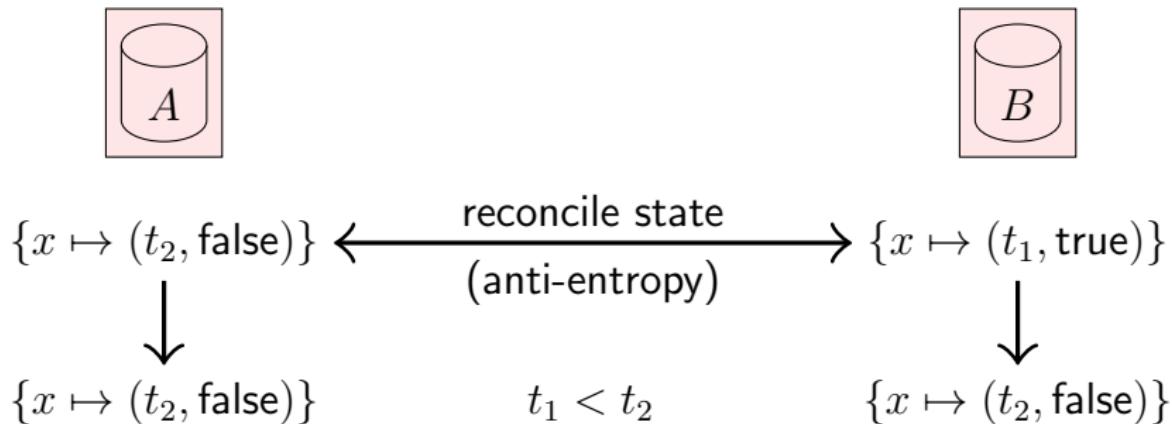
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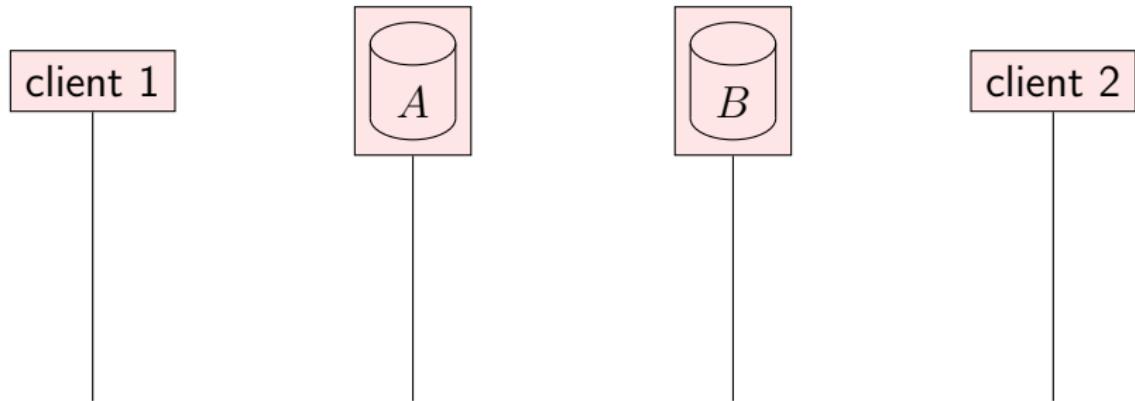
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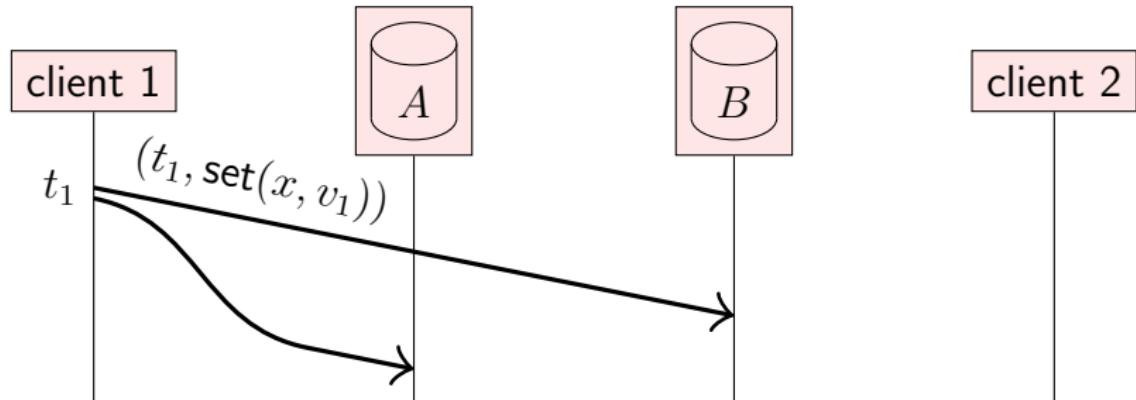


Propagate the record with the latest timestamp,  
discard the records with earlier timestamps  
(for a given key).

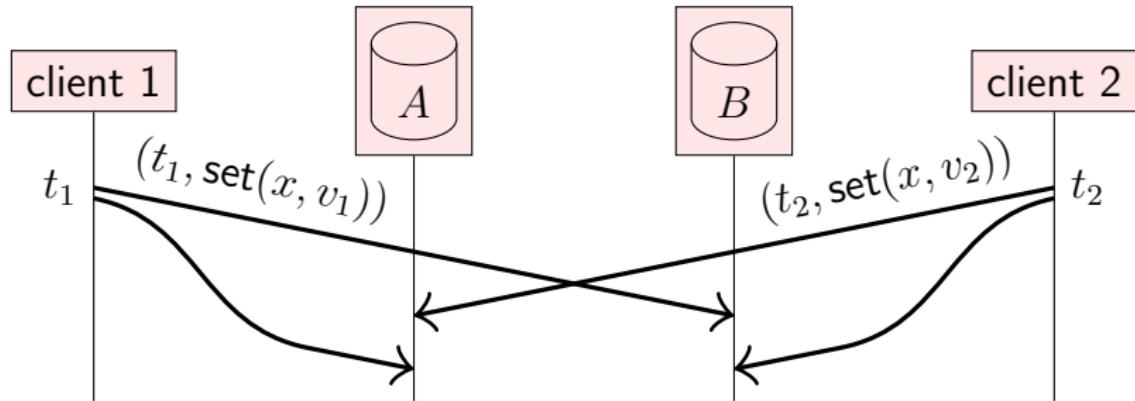
# Concurrent writes by different clients



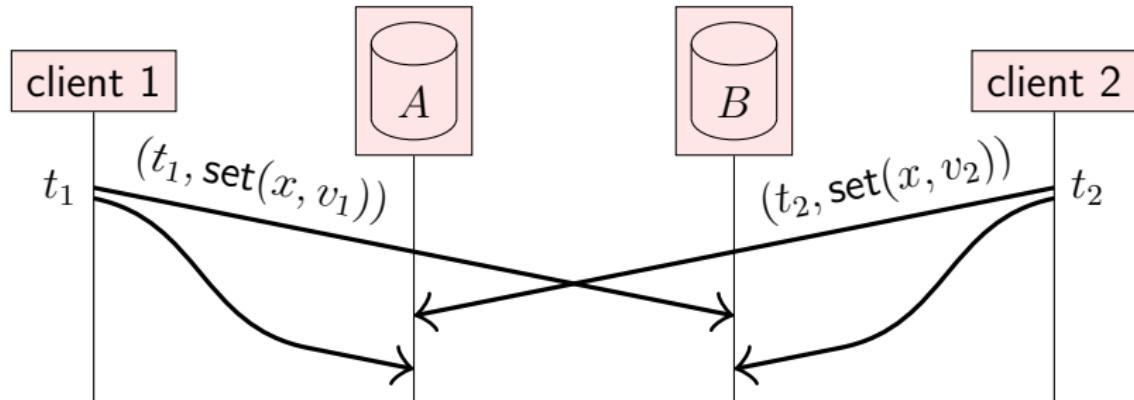
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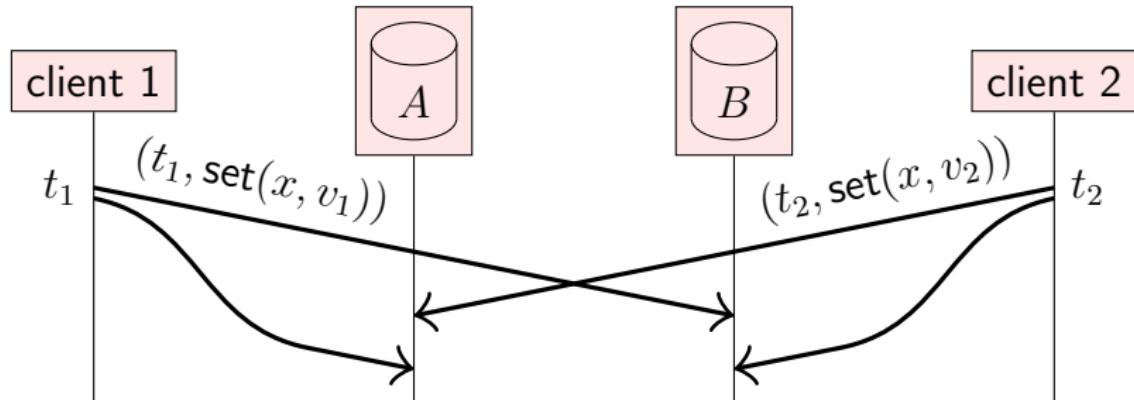
Two common approaches:

- ▶ **Last writer wins (LWW):**

Use timestamps with total order (e.g. Lamport clock)

Keep  $v_2$  and discard  $v_1$  if  $t_2 > t_1$ . Note: **data loss!**

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- ▶ **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

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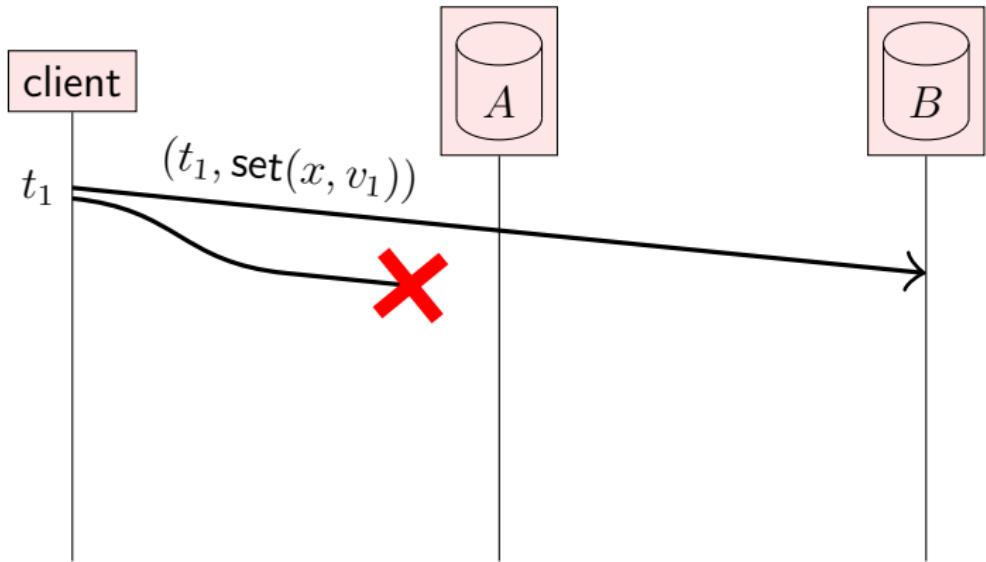
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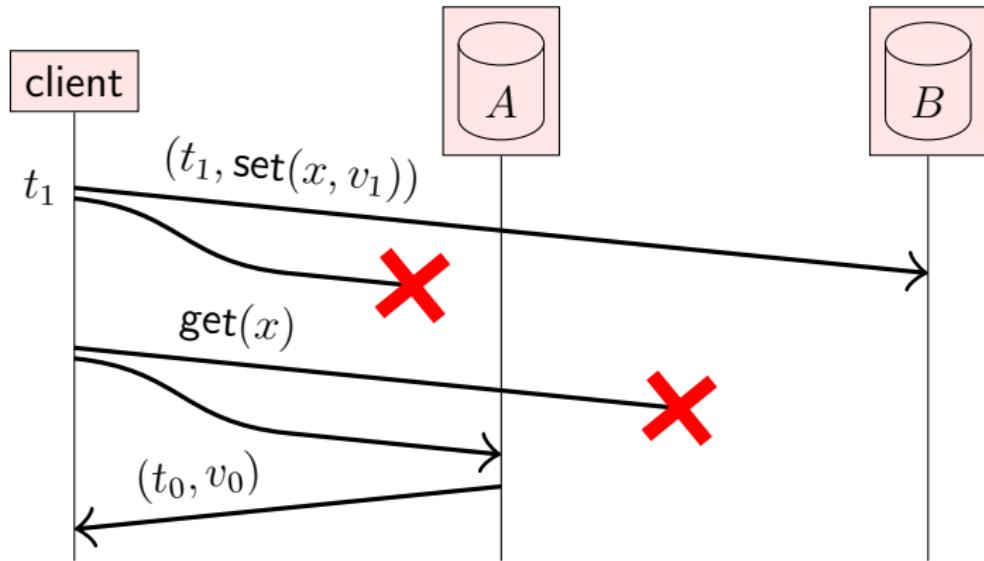
Example with  $p = 0.01$ :

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	$6 \cdot 10^{-74}$	$10^{-200}$

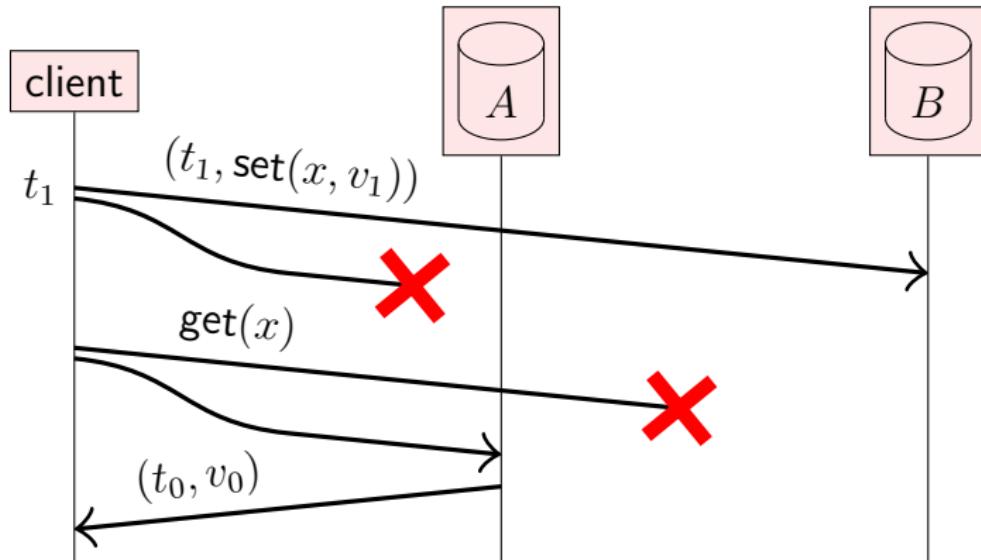
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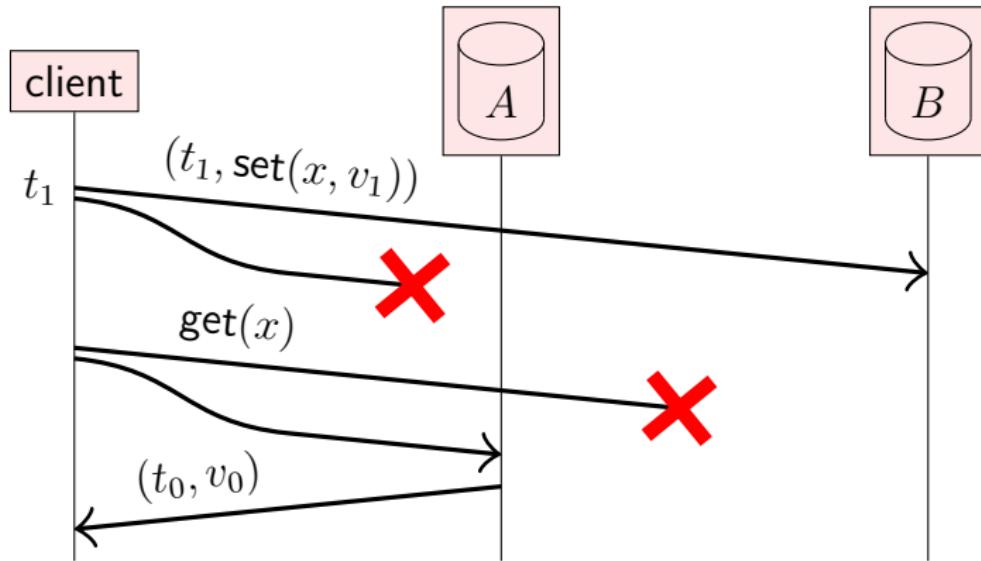


# Read-after-write consistency



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

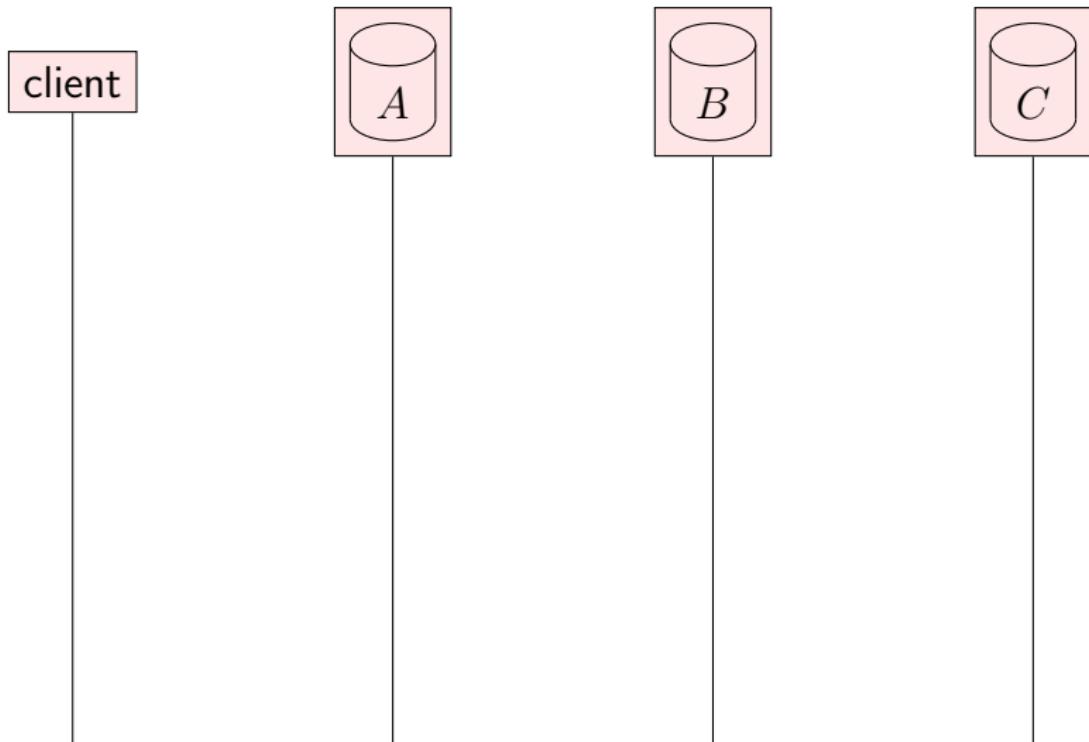
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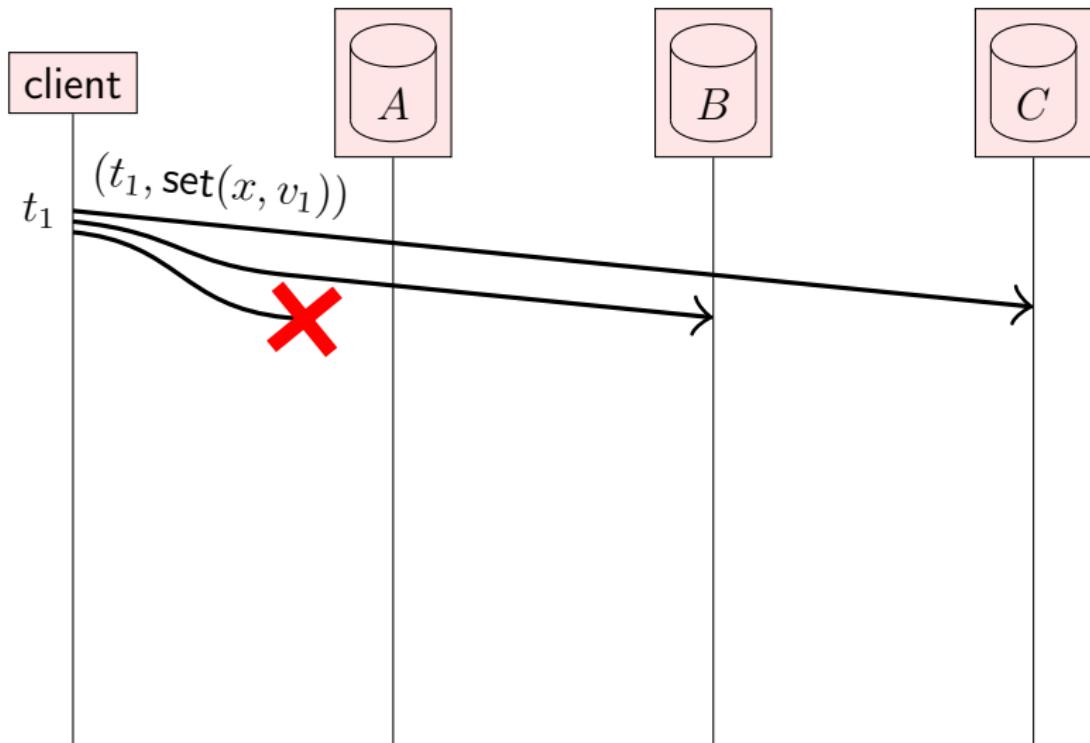
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Require writing to/reading from both replicas  $\implies$  cannot write/read if one replica is unavailable

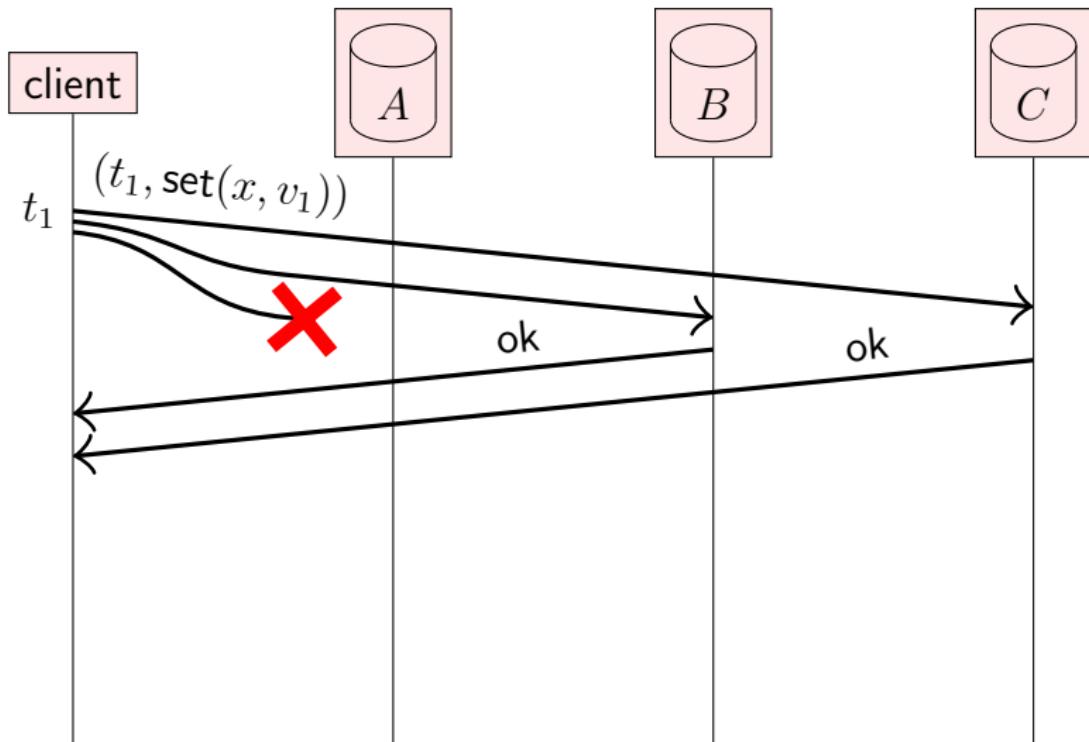
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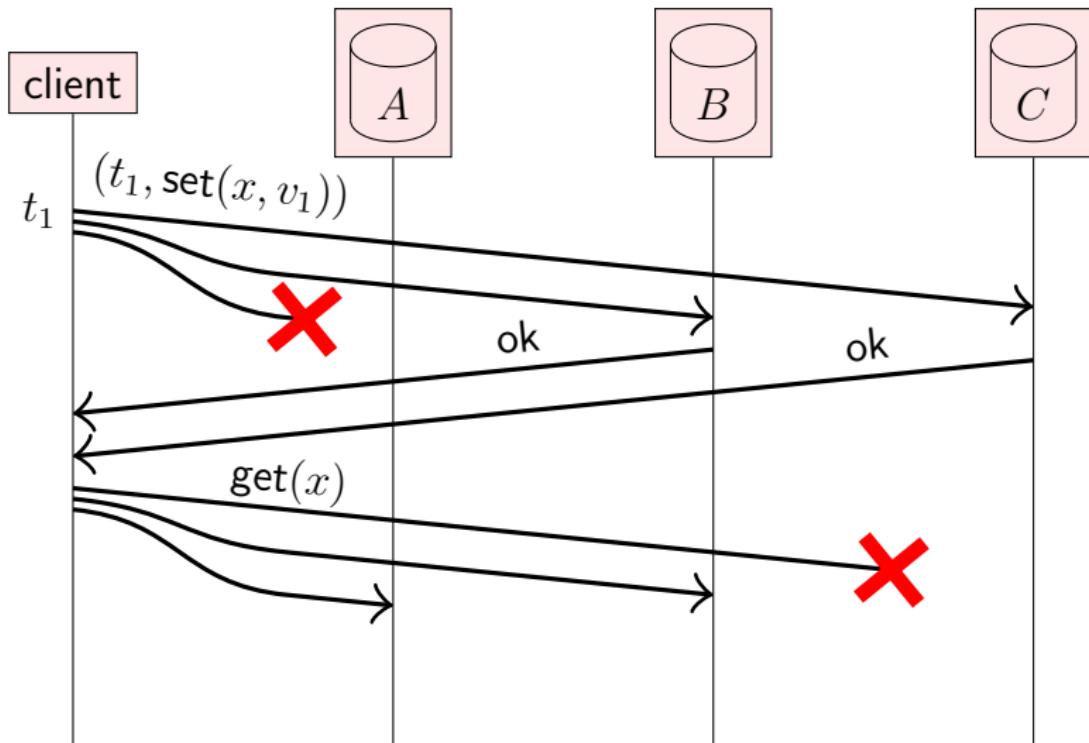


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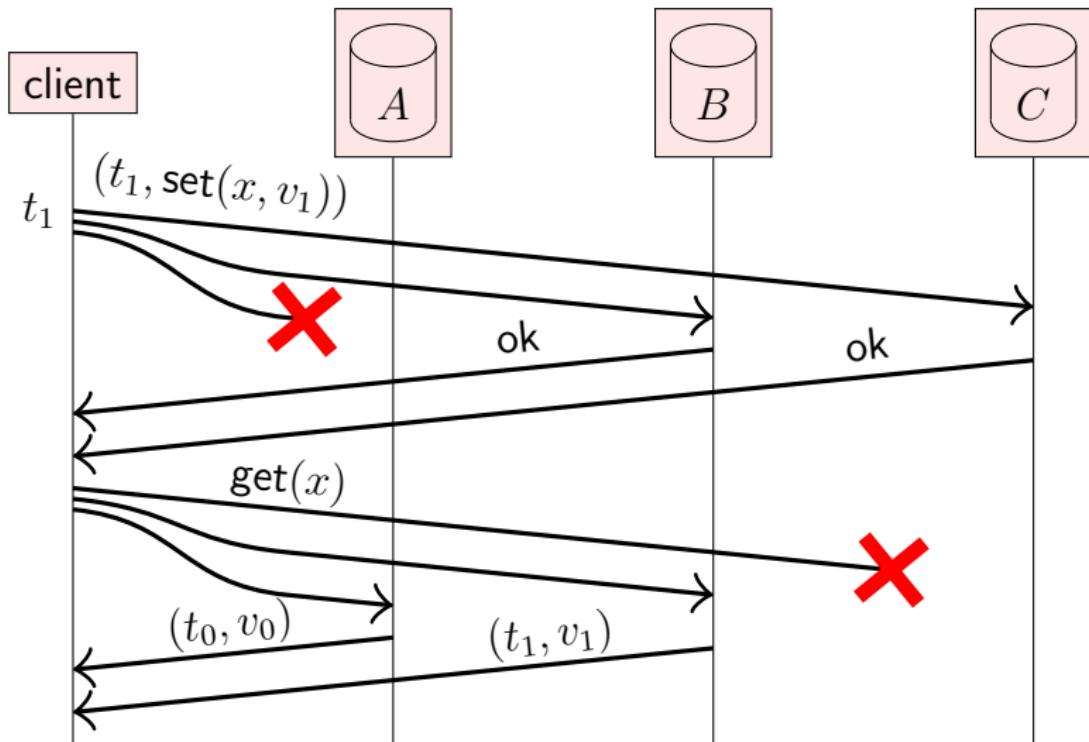
Write succeeds on  $B$  and  $C$

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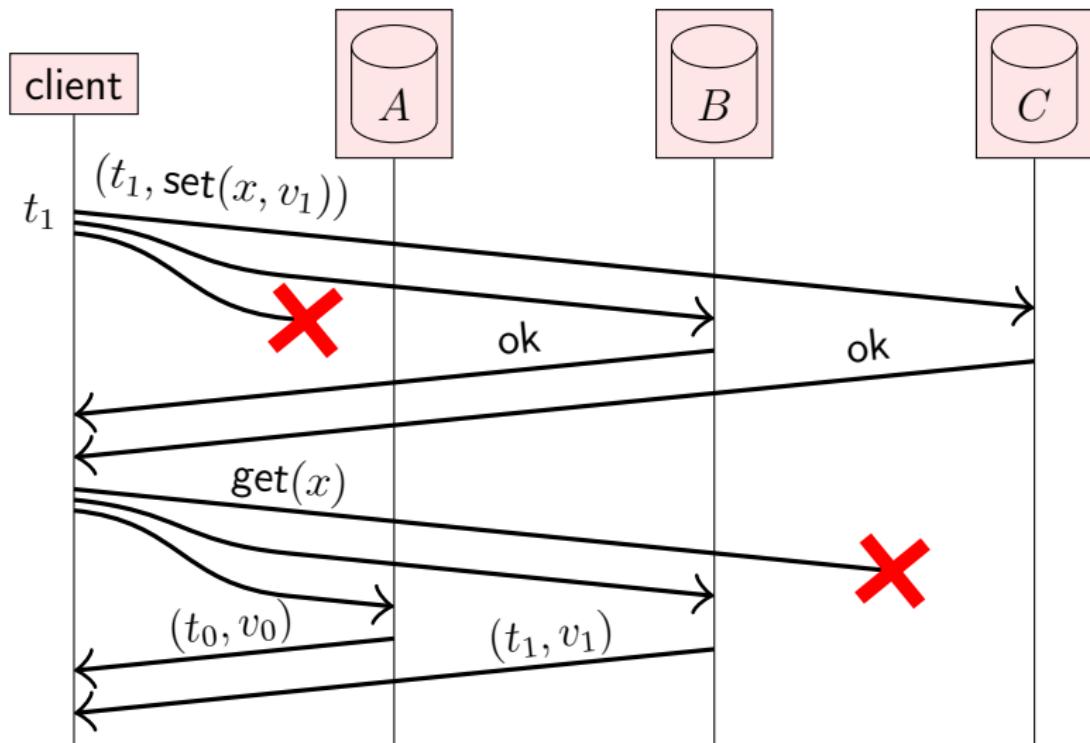
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Write succeeds on  $B$  and  $C$ ; read succeeds on  $A$  and  $B$   
Choose between  $(t_0, v_0)$  and  $(t_1, v_1)$  based on timestamp

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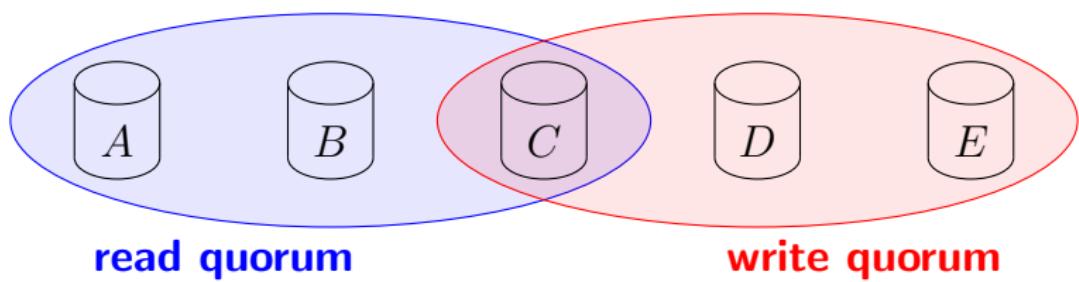
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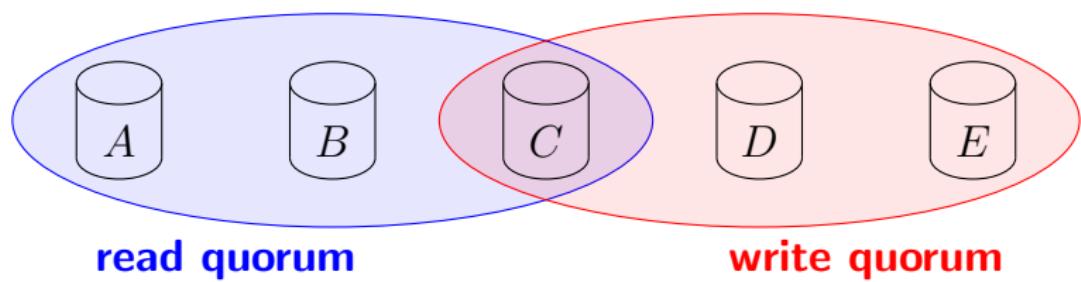
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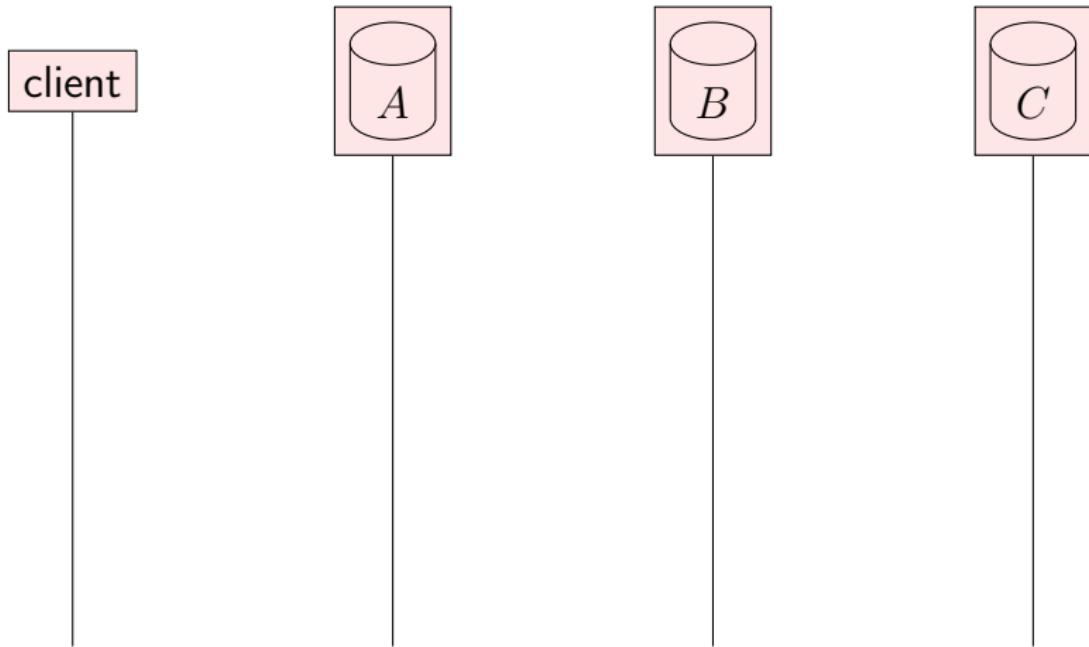
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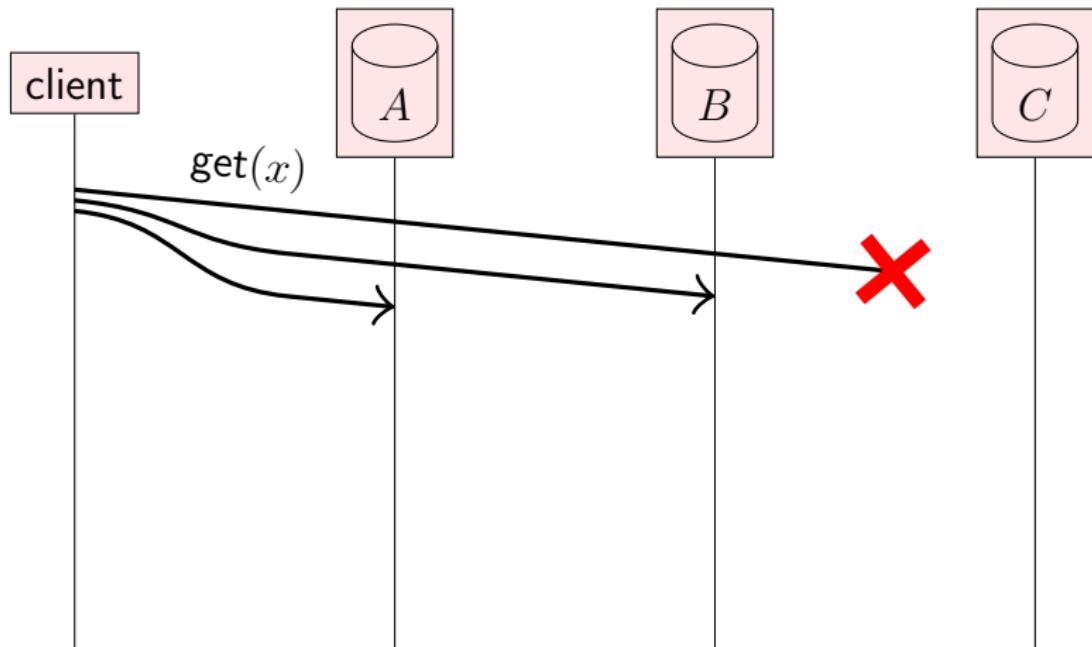
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- ▶ Typical:  $r = w = \frac{n+1}{2}$  for  $n = 3, 5, 7, \dots$  (majority)
- ▶ Reads can tolerate  $n - r$  unavailable replicas, writes  $n - w$



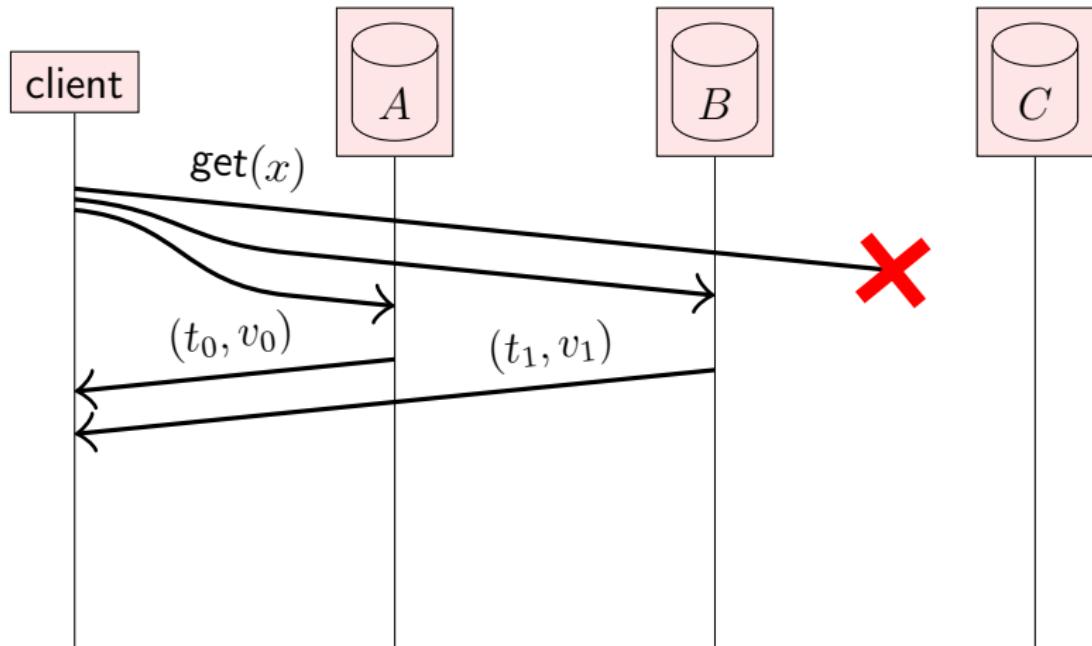
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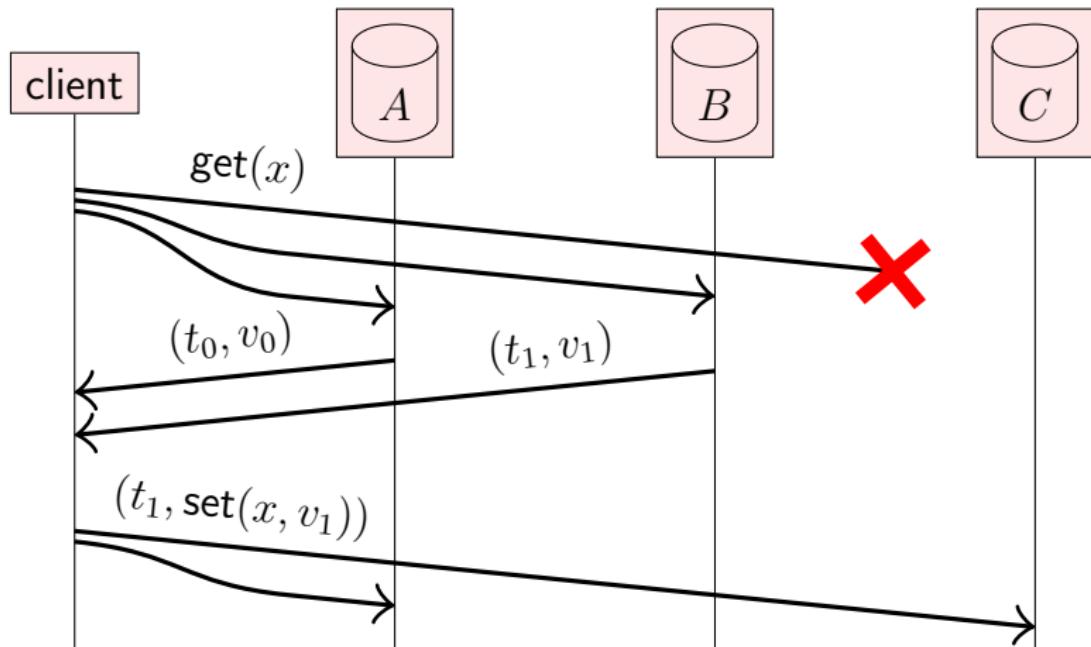


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Client helps **propagate**  $(t_1, v_1)$  to other replicas.

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

# 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!

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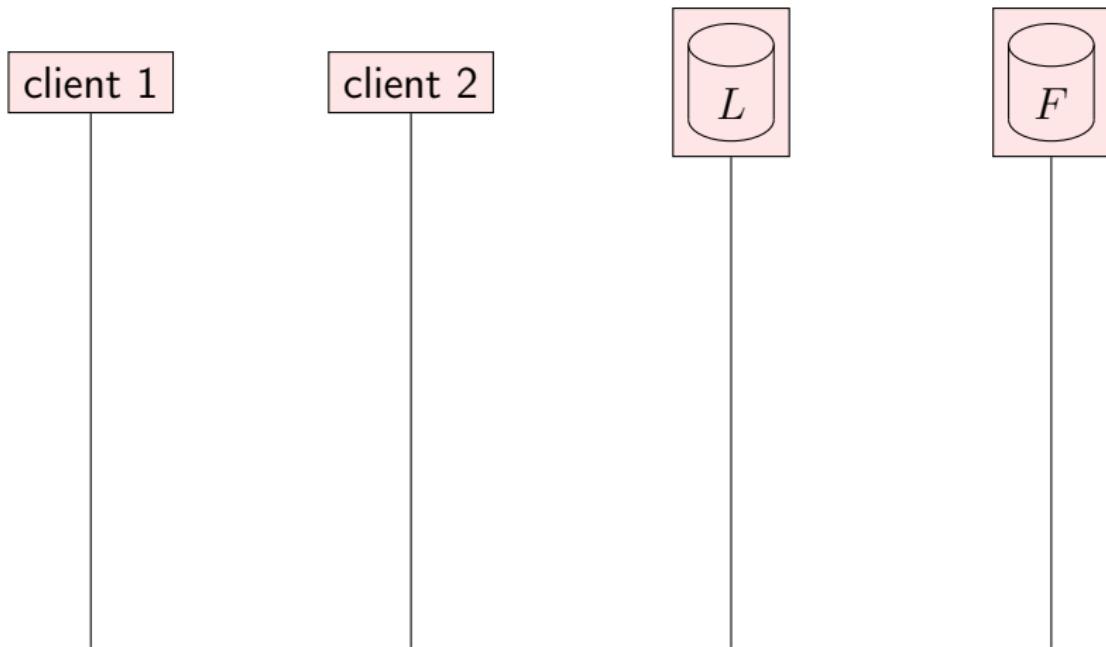
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- ▶ Need fault-tolerant total order broadcast: see lecture 6

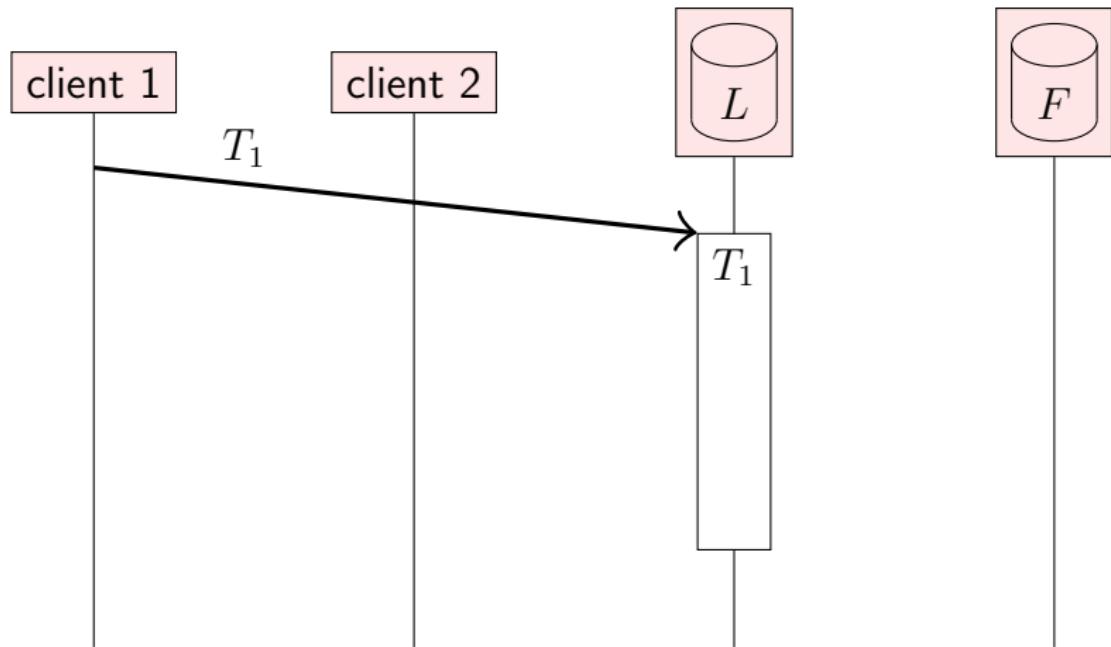
# Database leader replica

Leader database replica  $L$  ensures total order broadcast



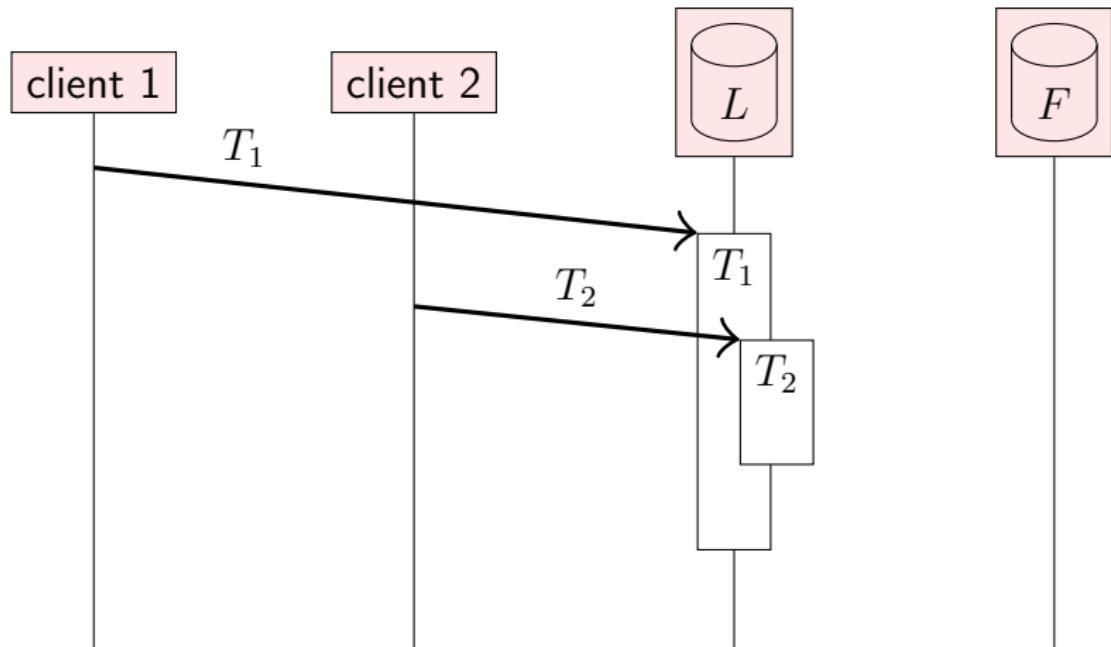
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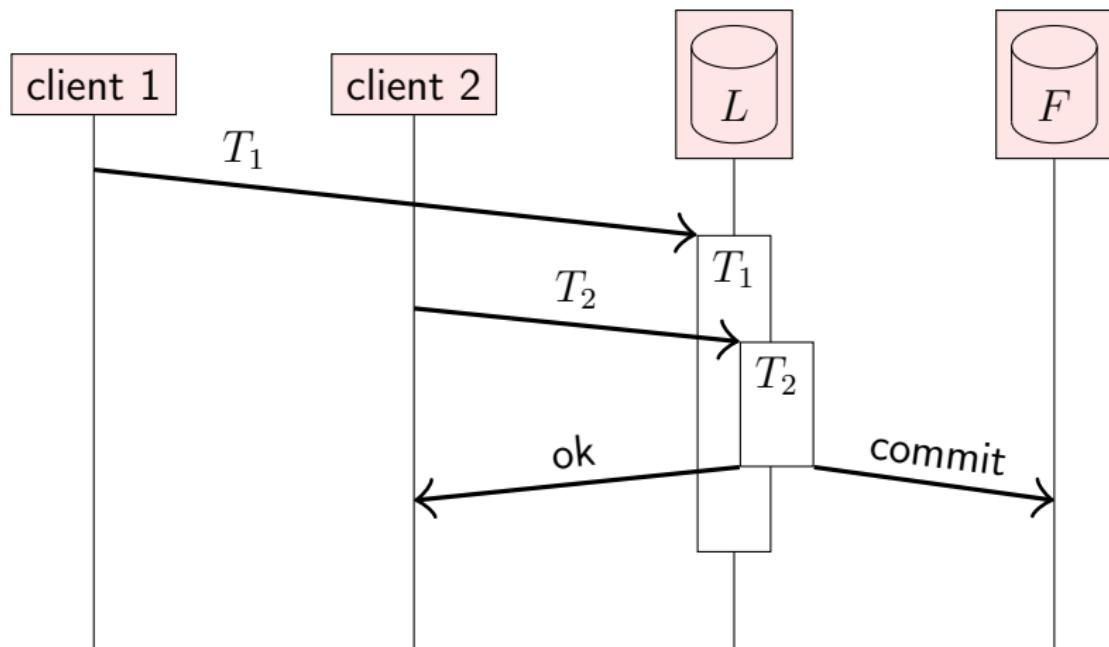
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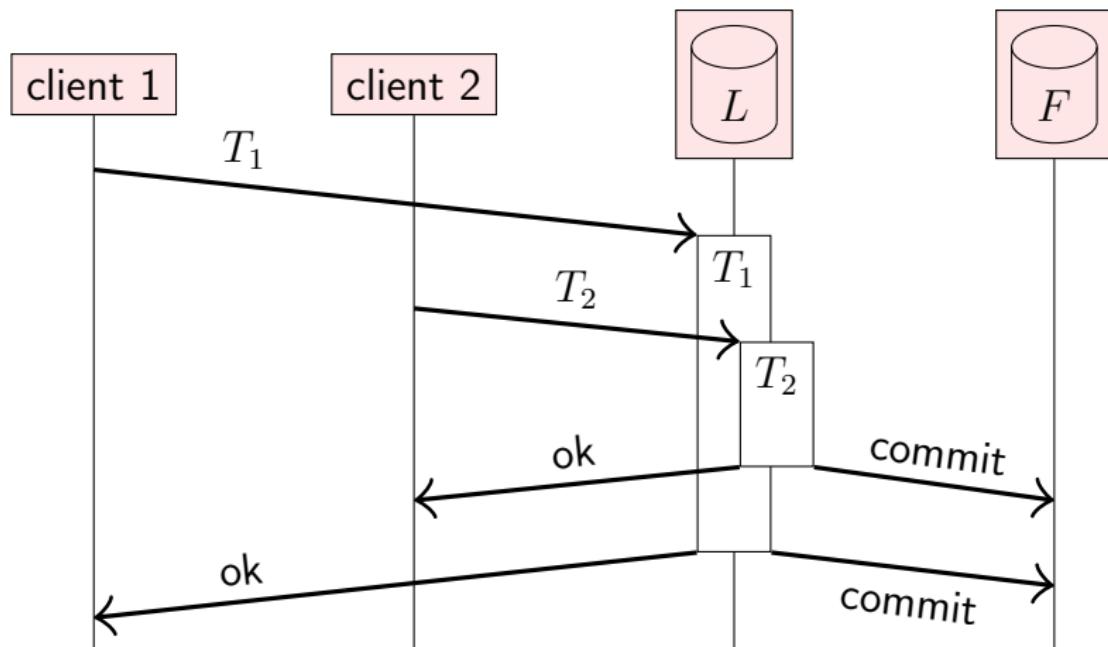
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best-effort	deterministic, commutative, idempotent, tolerates message loss

Lecture 6

# Consensus

## Fault-tolerant total order broadcast

Total order broadcast is very useful for state machine replication.

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

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

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

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

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

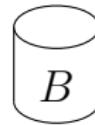
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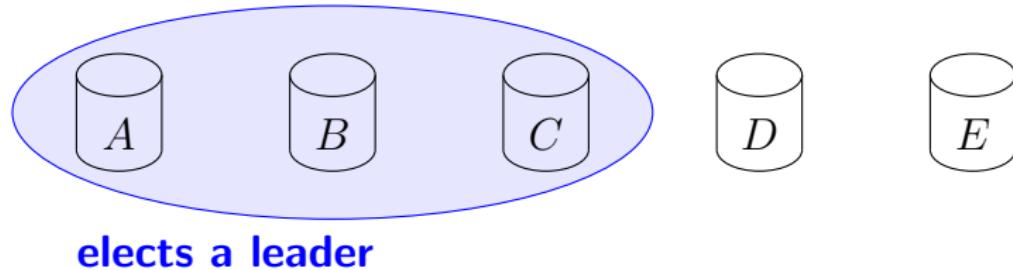
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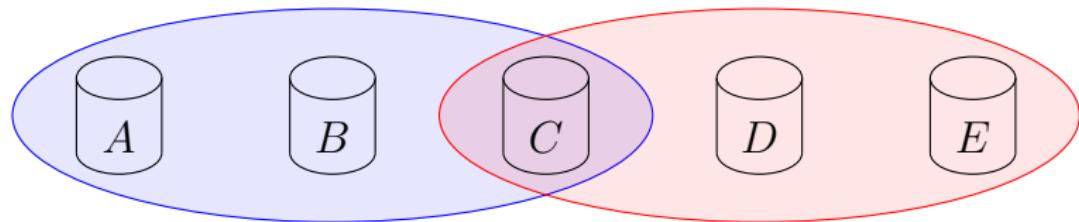
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elects a leader

cannot elect a different leader  
because *C* already voted

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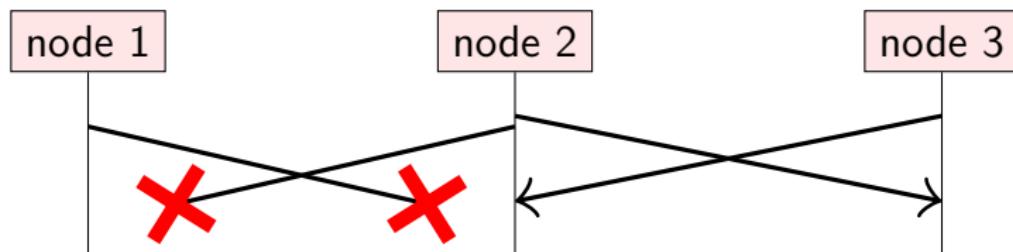
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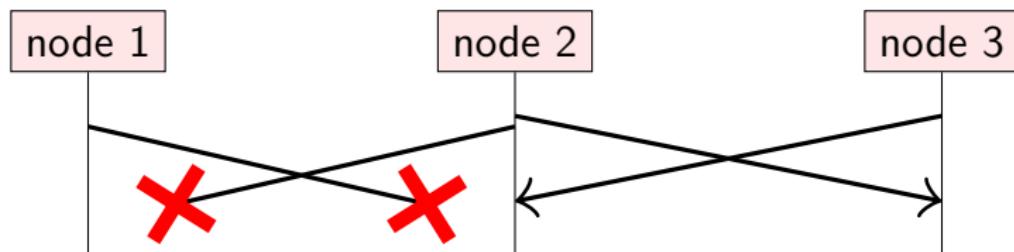
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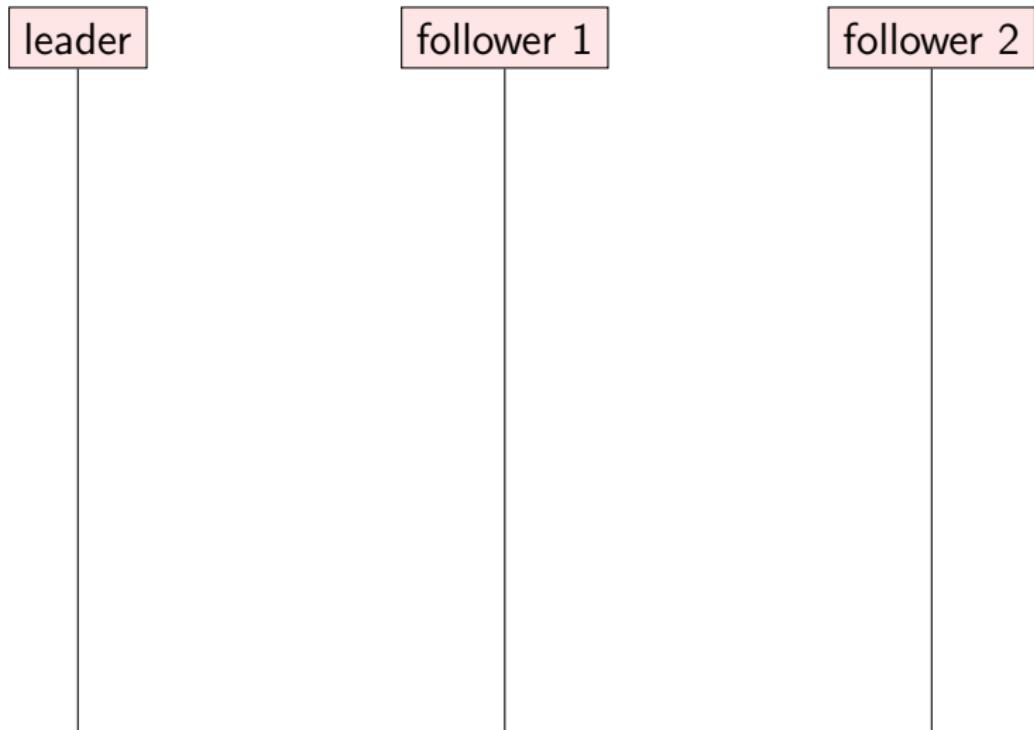


Nodes 2 and 3 may elect a new leader in term  $t + 1$ .

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

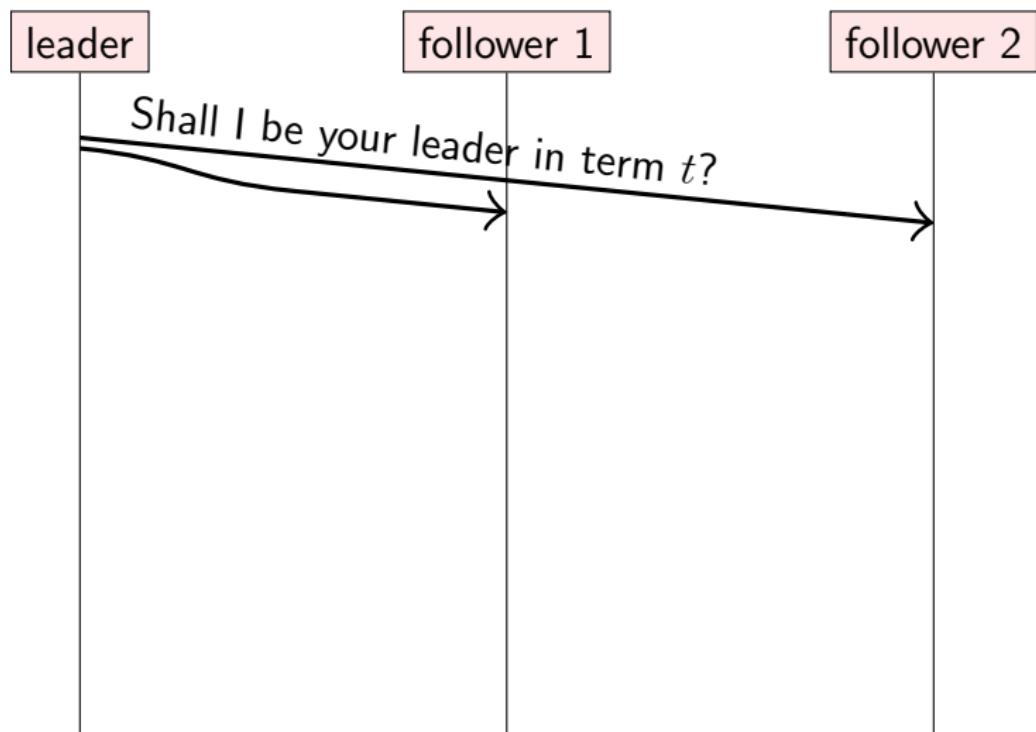
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For every decision (message to deliver), the leader must first get acknowledgements from a quorum.



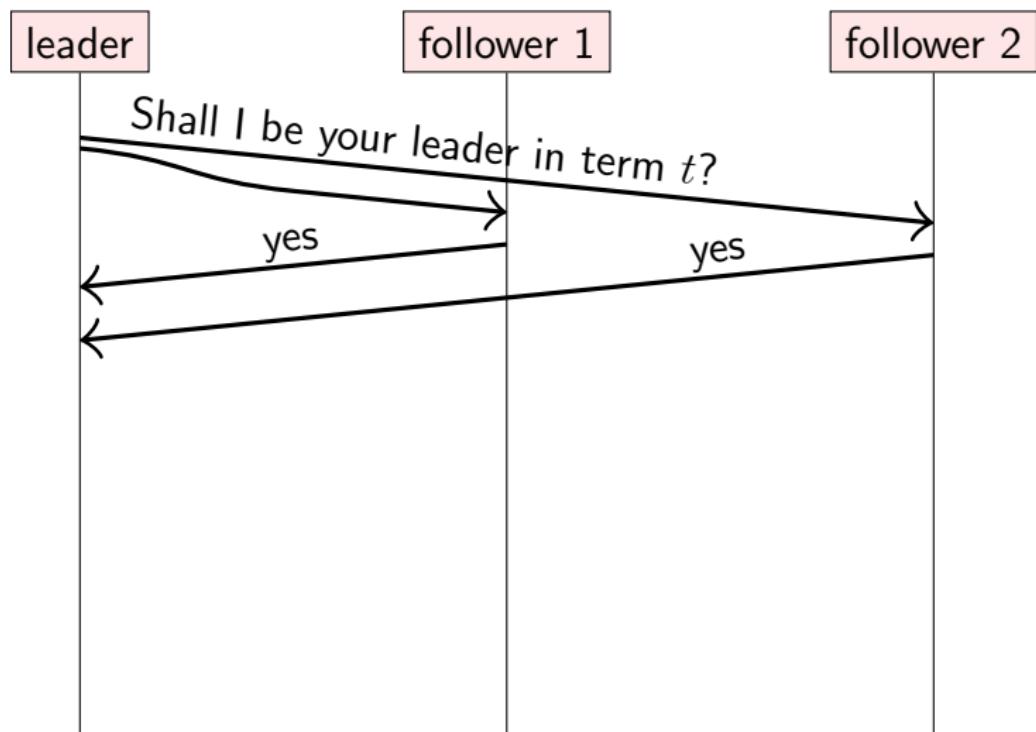
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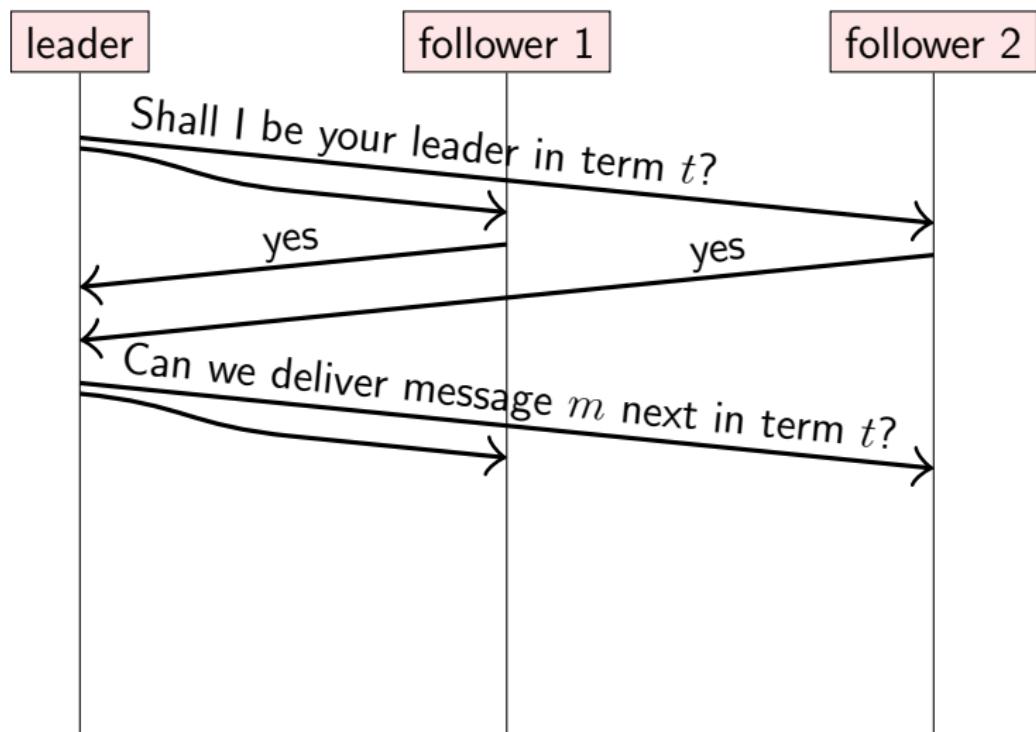
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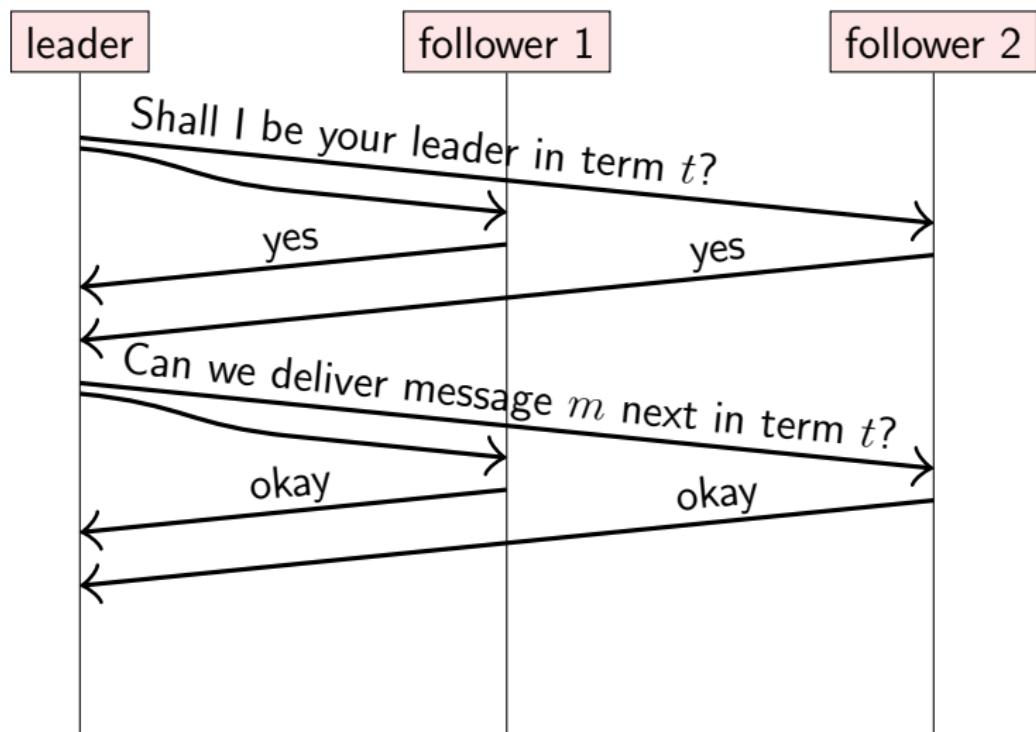
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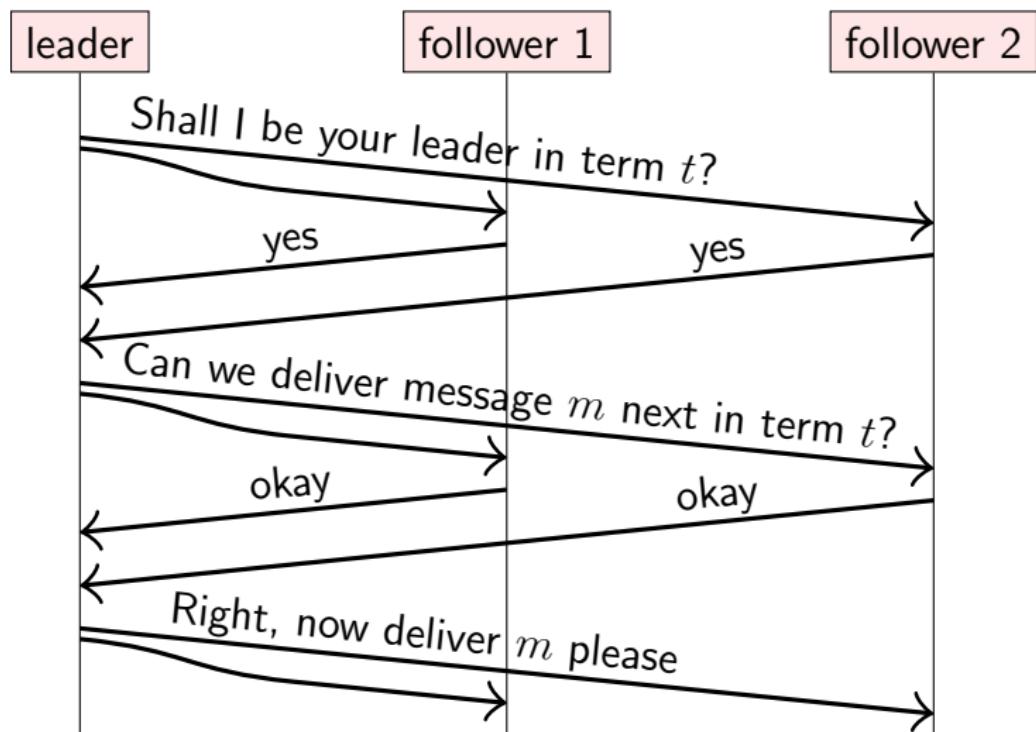
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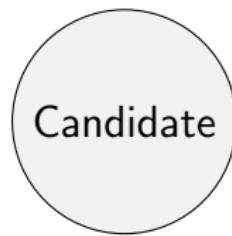
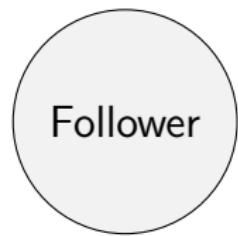


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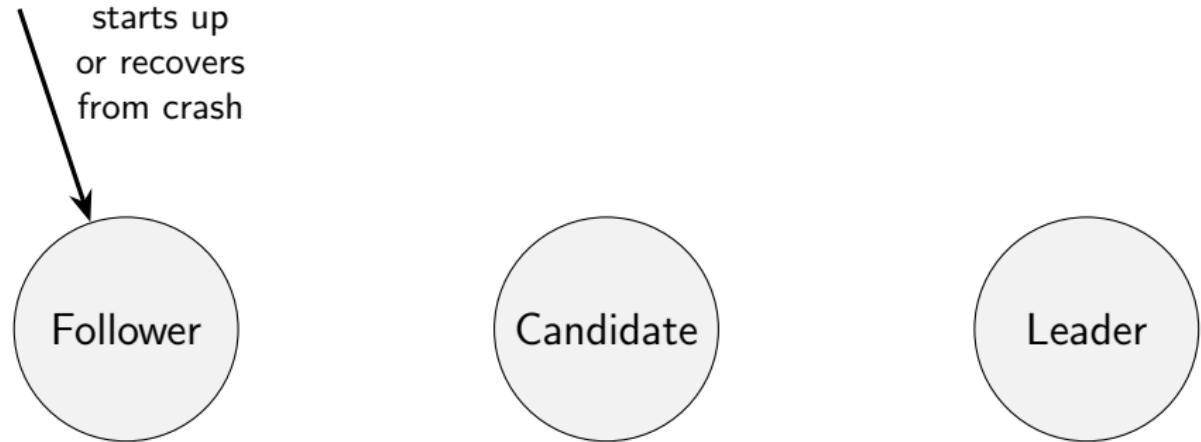
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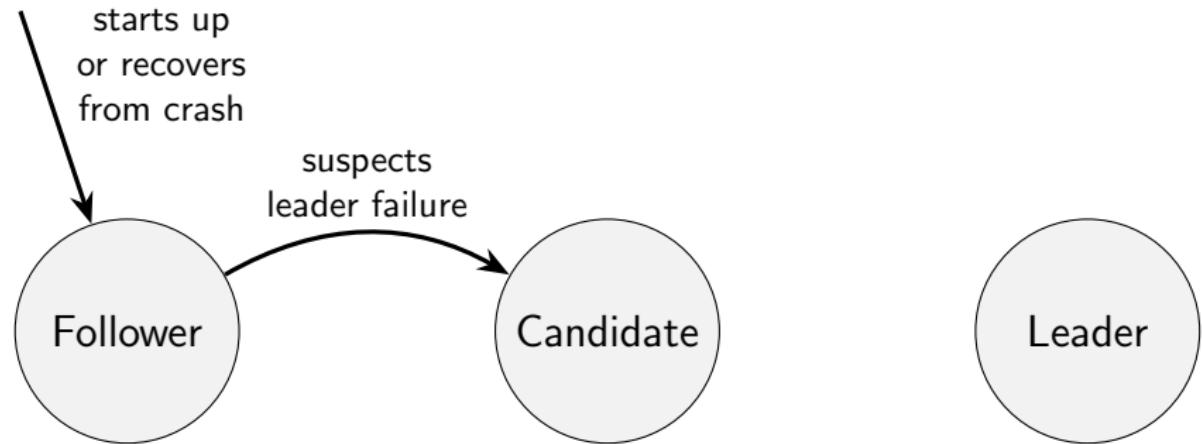
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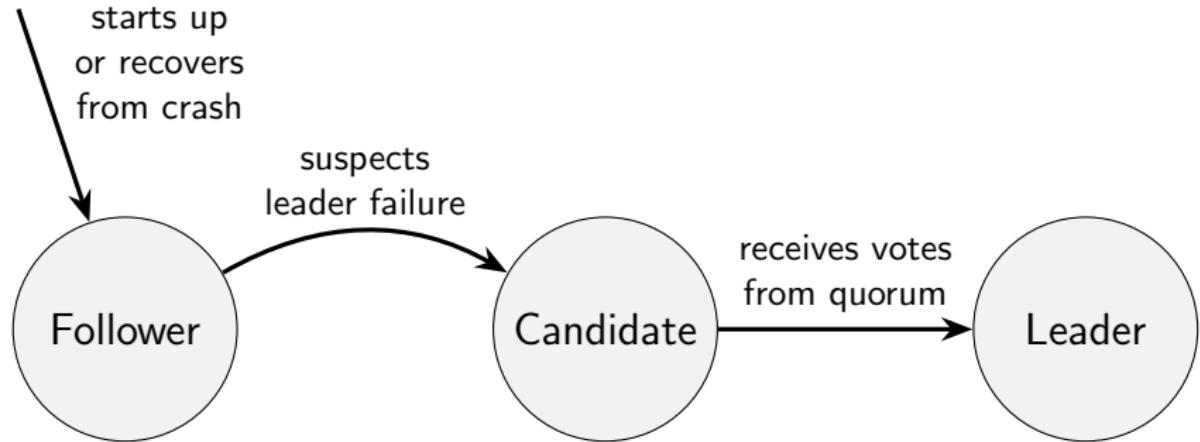
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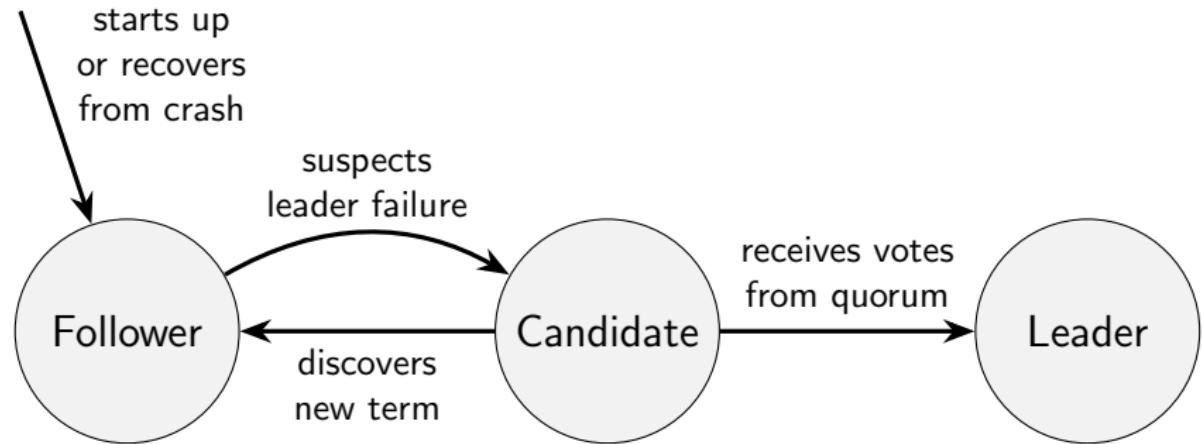
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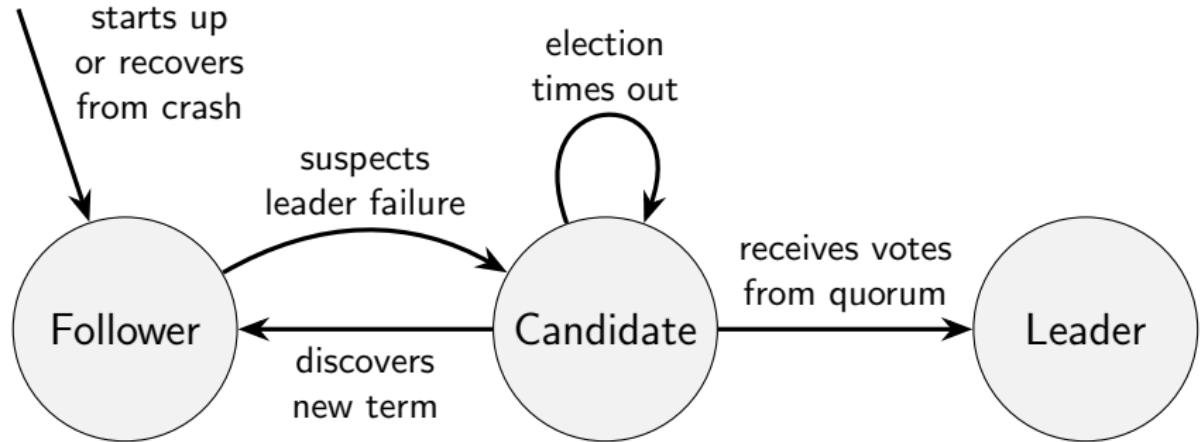
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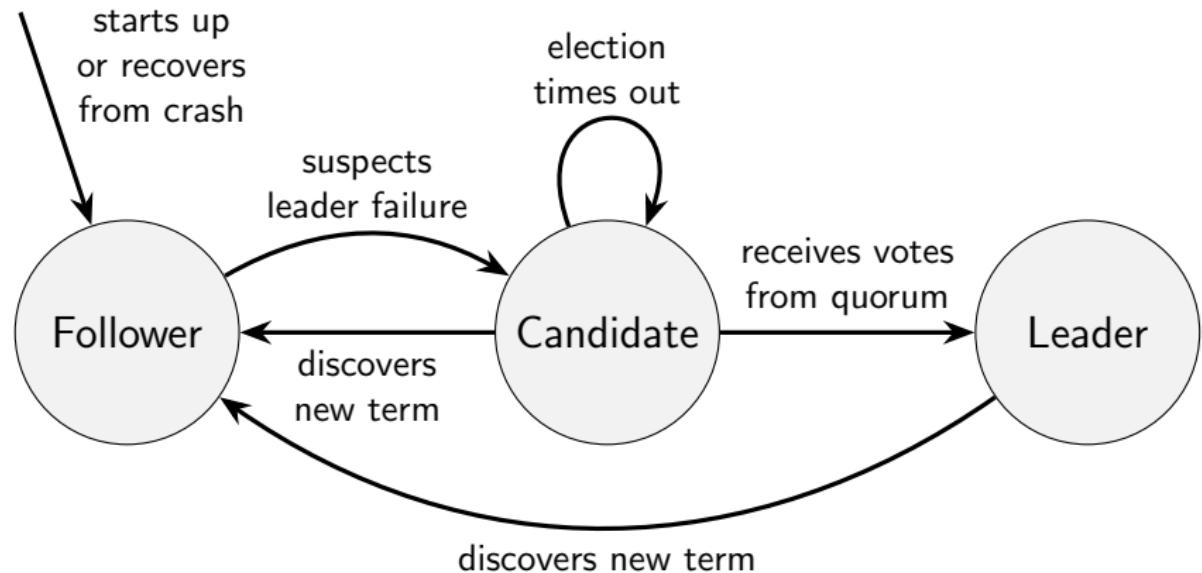
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# Raft (1/9): initialisation

**on** initialisation **do**

*currentTerm* := 0; *votedFor* := null

*log* := ⟨⟩; *commitLength* := 0

*currentRole* := follower; *currentLeader* := null

*votesReceived* := {}; *sentLength* := ⟨⟩; *ackedLength* := ⟨⟩

**end on**

**on** recovery from crash **do**

*currentRole* := follower; *currentLeader* := null

*votesReceived* := {}; *sentLength* := ⟨⟩; *ackedLength* := ⟨⟩

**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**

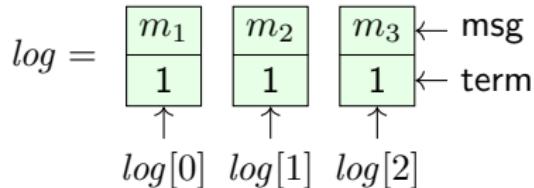
*msg* := (VoteRequest, *nodeId*, *currentTerm*, *log.length*, *lastTerm*)

**for each** *node* ∈ *nodes*: **send** *msg* to *node*

start election timer

**end on**

# Raft (1/9): initialisation



**on** initialisation **do**

*currentTerm := 0; votedFor := null*

*log := <>; commitLength := 0*

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**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 ∈ 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**

$myLogTerm := log[log.length - 1].term$   
 $logOk := (cLogTerm > myLogTerm) \vee$   
 $(cLogTerm = myLogTerm \wedge cLogLength \geq log.length)$

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

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

$currentTerm := cTerm$   
 $currentRole := \text{follower}$   
 $votedFor := cId$   
**send** (*VoteResponse*,  $nodeId$ ,  $currentTerm$ , true) to node  $cId$

**else**

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

**end if**

**end on**

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

c for candidate

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$(cTerm = currentTerm \wedge votedFor \in \{cId, \text{null}\})$

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

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$currentRole := \text{follower}$

$votedFor := cId$

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

**else**

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

**end if**

**end on**

## Raft (3/9): collecting votes

```
on receiving (VoteResponse, voterId, term, granted) at nodeId do
    if currentRole = candidate ∧ term = currentTerm ∧ granted then
        votesReceived := votesReceived ∪ {voterId}
        if |votesReceived| ≥ ⌈(|nodes| + 1)/2⌉ then
            currentRole := leader; currentLeader := nodeId
            cancel election timer
            for each follower ∈ nodes \ {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 from leader to followers

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

```
function REPLICATELOG(leaderId, followerId)
    i := sentLength[followerId]
    entries :=  $\langle \log[i], \log[i + 1], \dots, \log[\log.length - 1] \rangle$ 
    prevLogTerm := 0
    if i > 0 then
        prevLogTerm :=  $\log[i - 1].term$ 
    end if
    send (LogRequest, leaderId, currentTerm, i, prevLogTerm,
          commitLength, entries) to followerId
end function
```

# Raft (6/9): followers receiving messages

```
on receiving (LogRequest, leaderId, term, logLength, logTerm,  
          leaderCommit, entries) at node nodeId do  
    if term > currentTerm then  
      currentTerm := term; votedFor := null  
    end if  
    logOk := (log.length ≥ logLength)  
    if logOk ∧ (logLength > 0) then  
      logOk := (logTerm = log[logLength - 1].term)  
    end if  
  
    if term = currentTerm ∧ logOk then  
      currentRole := follower; currentLeader := leaderId  
      APPENDENTRIES(logLength, leaderCommit, entries)  
      ack := logLength + entries.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(logLength, leaderCommit, entries)
    if entries.length > 0  $\wedge$  log.length > logLength then
        if log[logLength].term  $\neq$  entries[0].term then
            log :=  $\langle \log[0], \log[1], \dots, \log[\logLength - 1] \rangle$ 
        end if
    end if
    if logLength + entries.length > log.length then
        for i := log.length - logLength to entries.length - 1 do
            append entries[i] to log
        end for
    end if
    if leaderCommit > commitLength then
        for i := commitLength to leaderCommit - 1 do
            deliver log[i].msg to the application
        end for
        commitLength := leaderCommit
    end if
end function
```

# Raft (8/9): leader receiving log acknowledgements

```
on receiving (LogResponse, follower, term, ack, success) at nodeId do
    if term = currentTerm ∧ currentRole = leader then
        if success = true ∧ ack ≥ 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
    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**  $\text{acks}(length) = |\{n \in \text{nodes} \mid \text{ackedLength}[n] \geq length\}|$

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

## Lecture 7

# Replica consistency

# “Consistency”

A word that means many different things in different contexts!

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

# “Consistency”

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- ▶ **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

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

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

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

Looks a bit similar to consensus?

# Atomic commit versus consensus

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

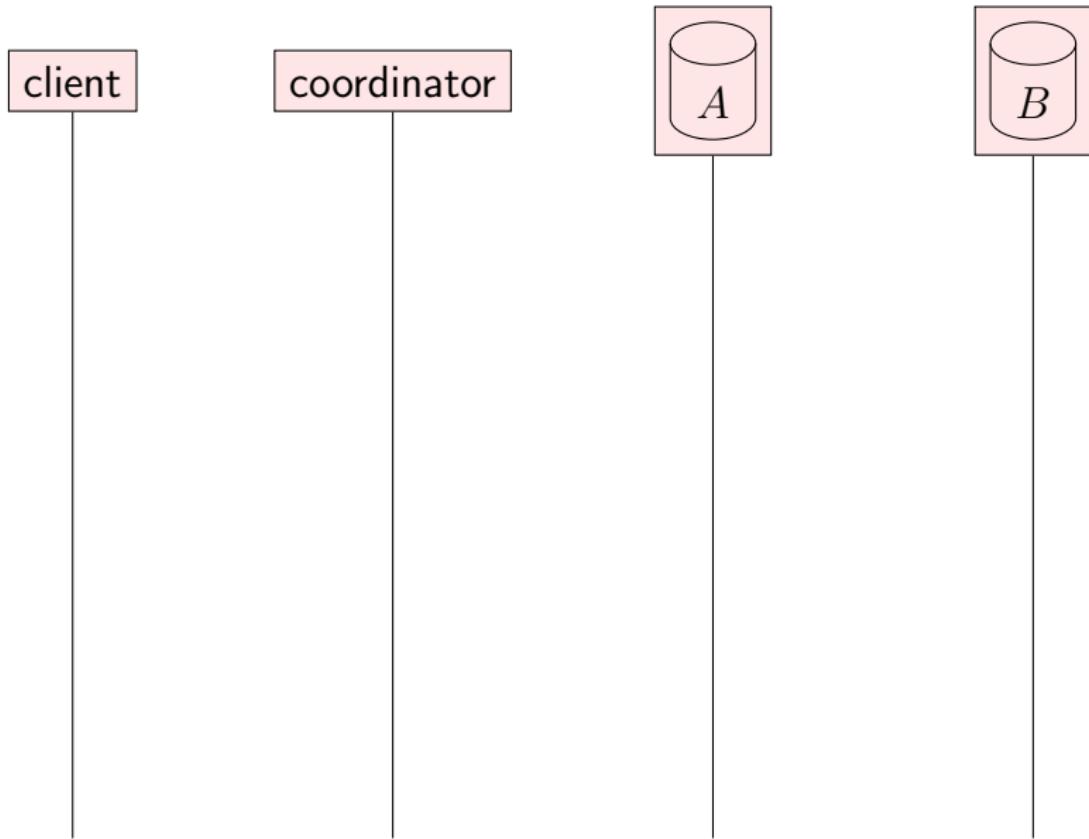
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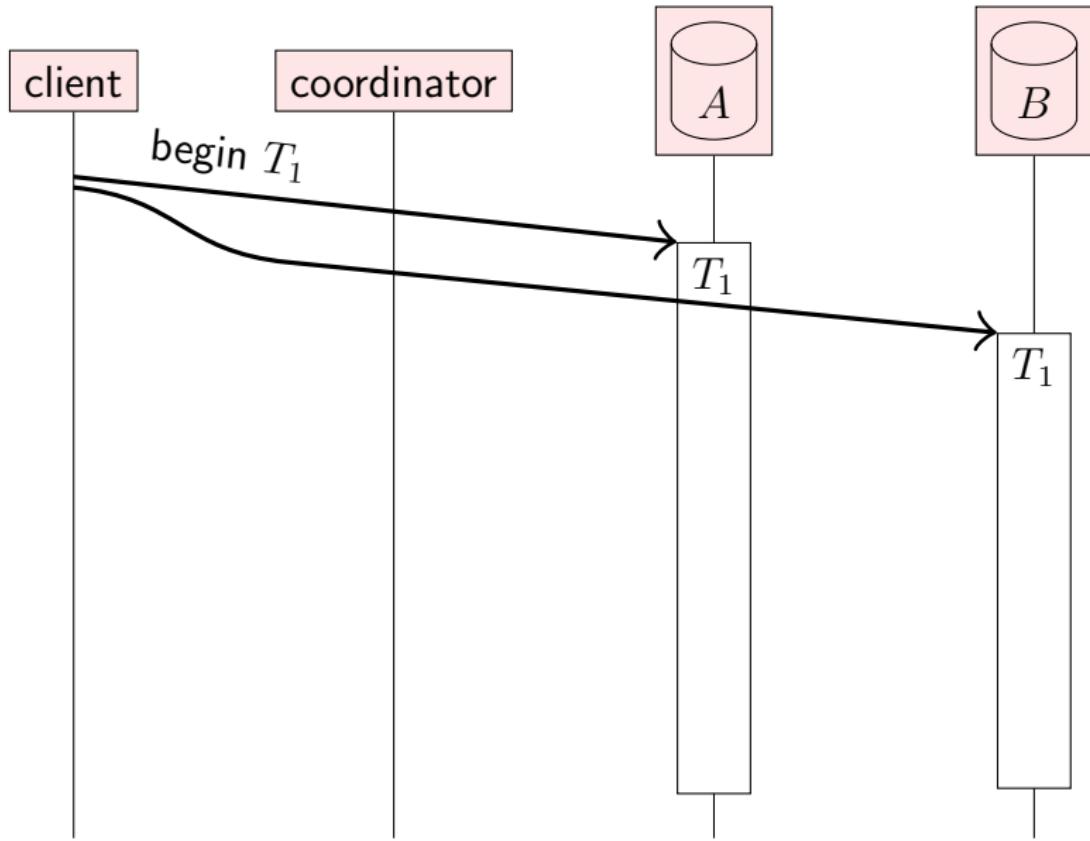
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Any one of the proposed values is decided	Must commit if all nodes vote to commit; must abort if $\geq 1$ nodes vote to abort
Crashed nodes can be tolerated, as long as a quorum is working	Must abort if a participating node crashes

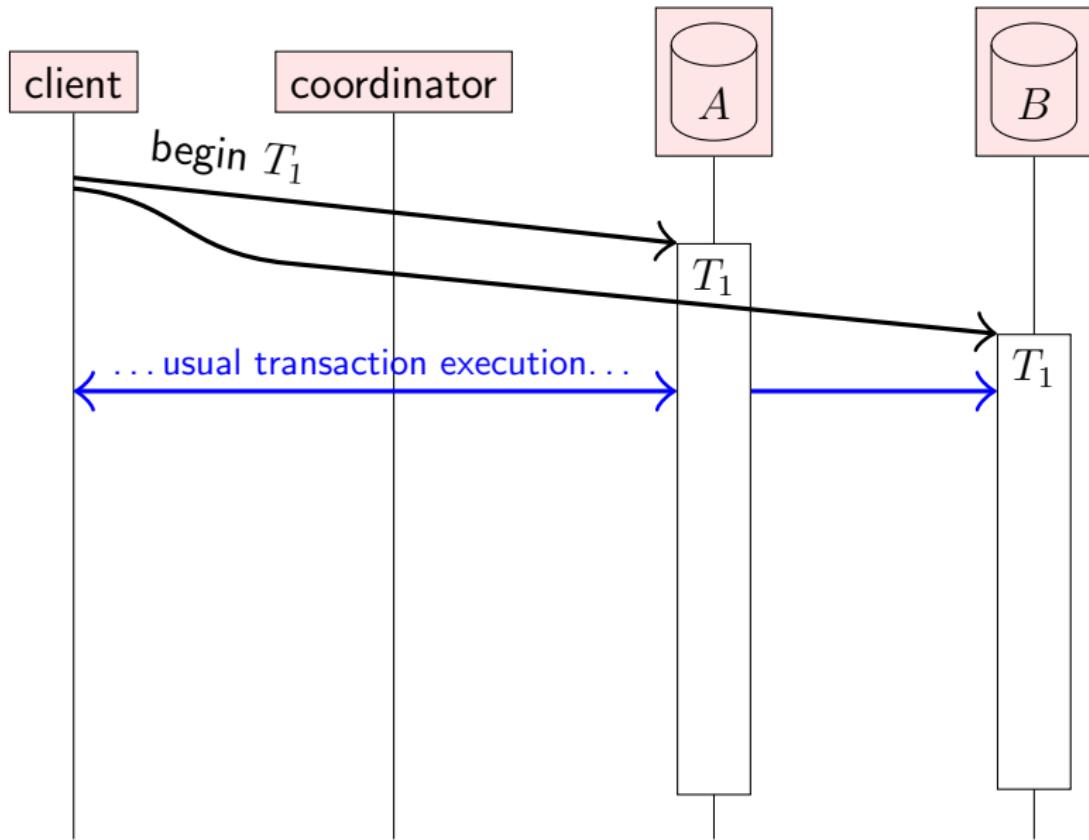
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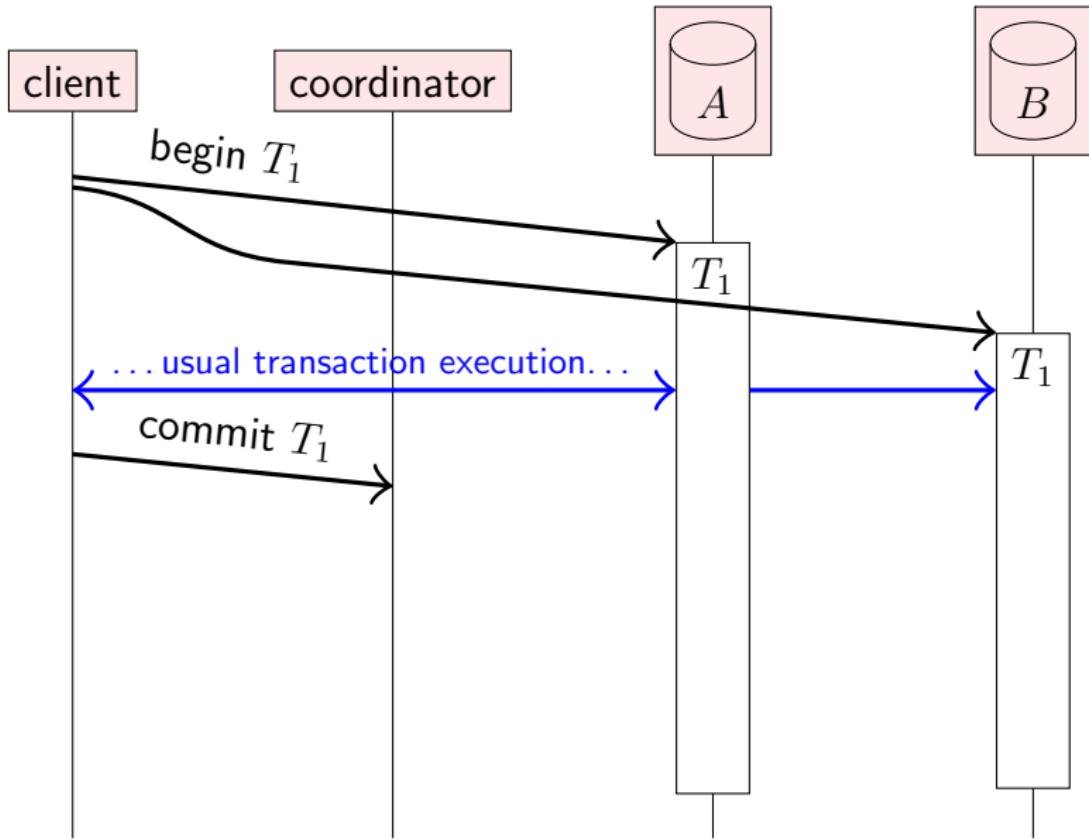
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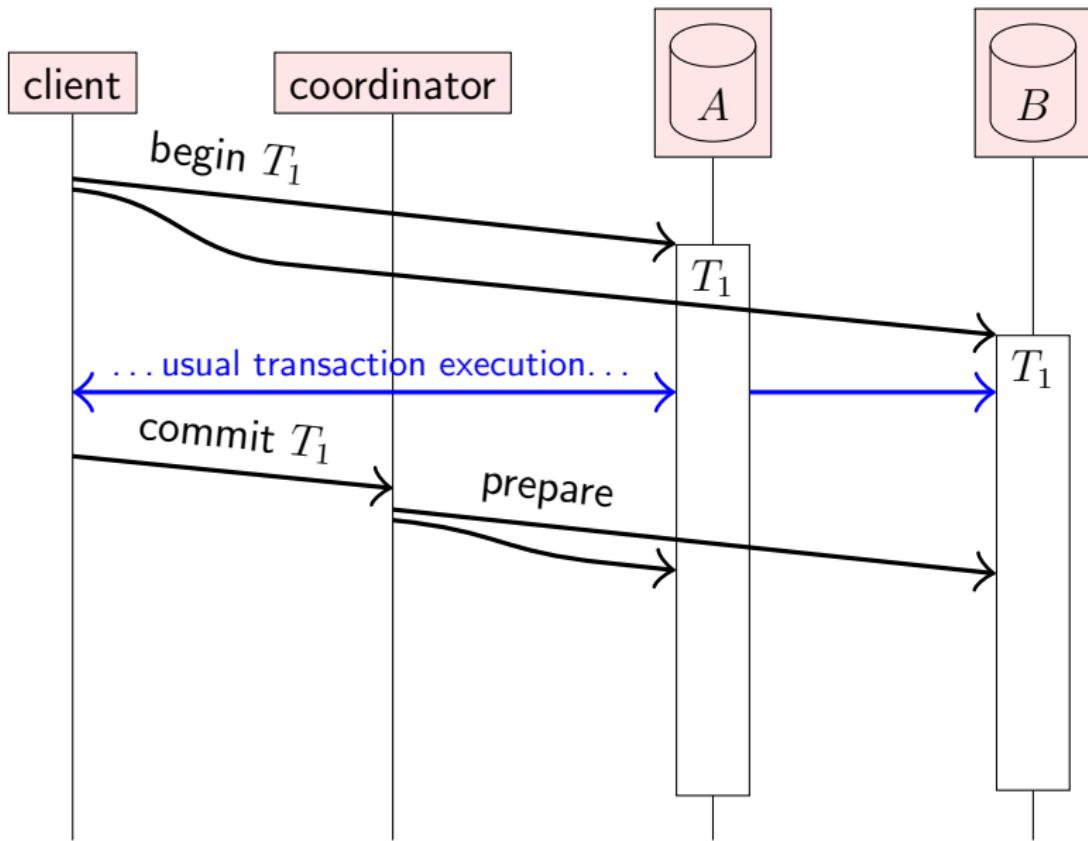
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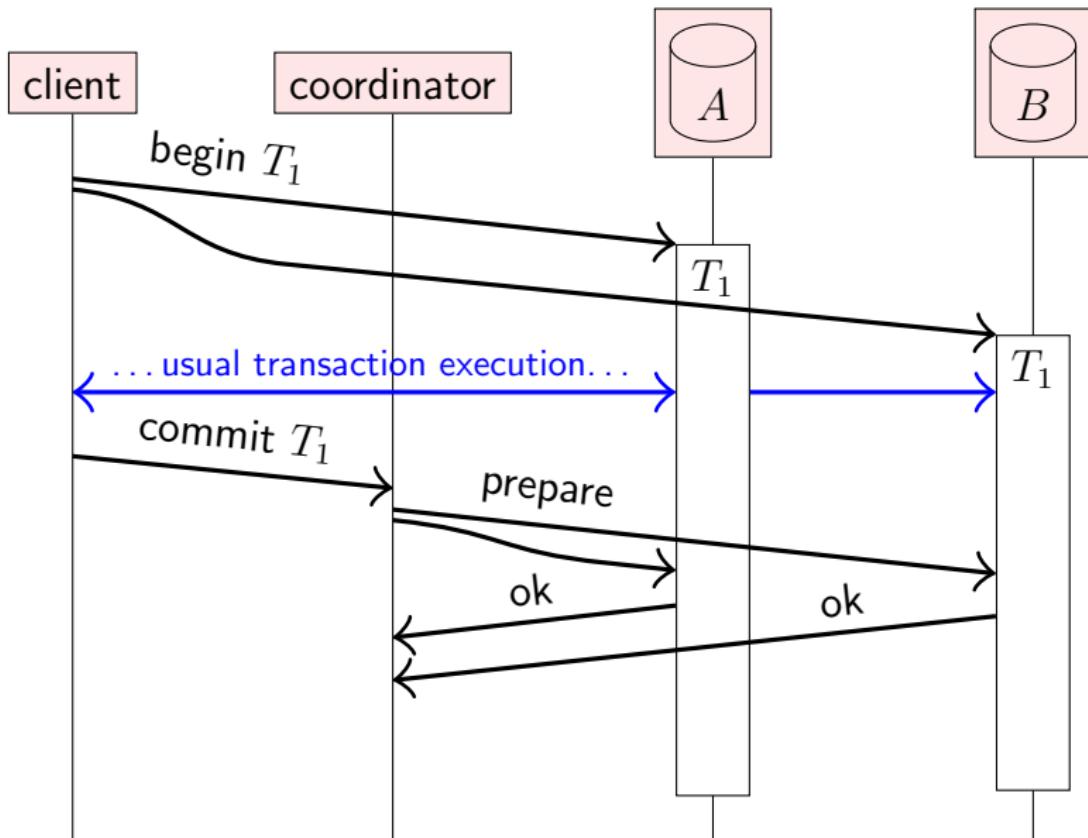
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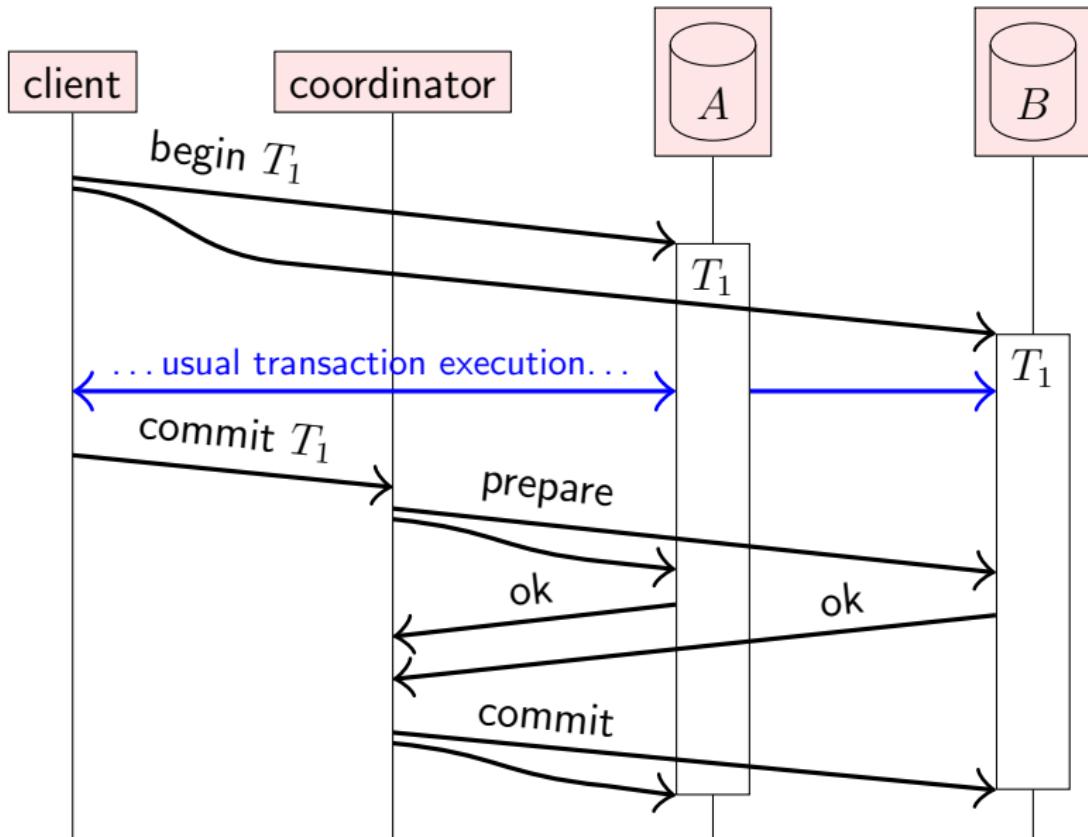
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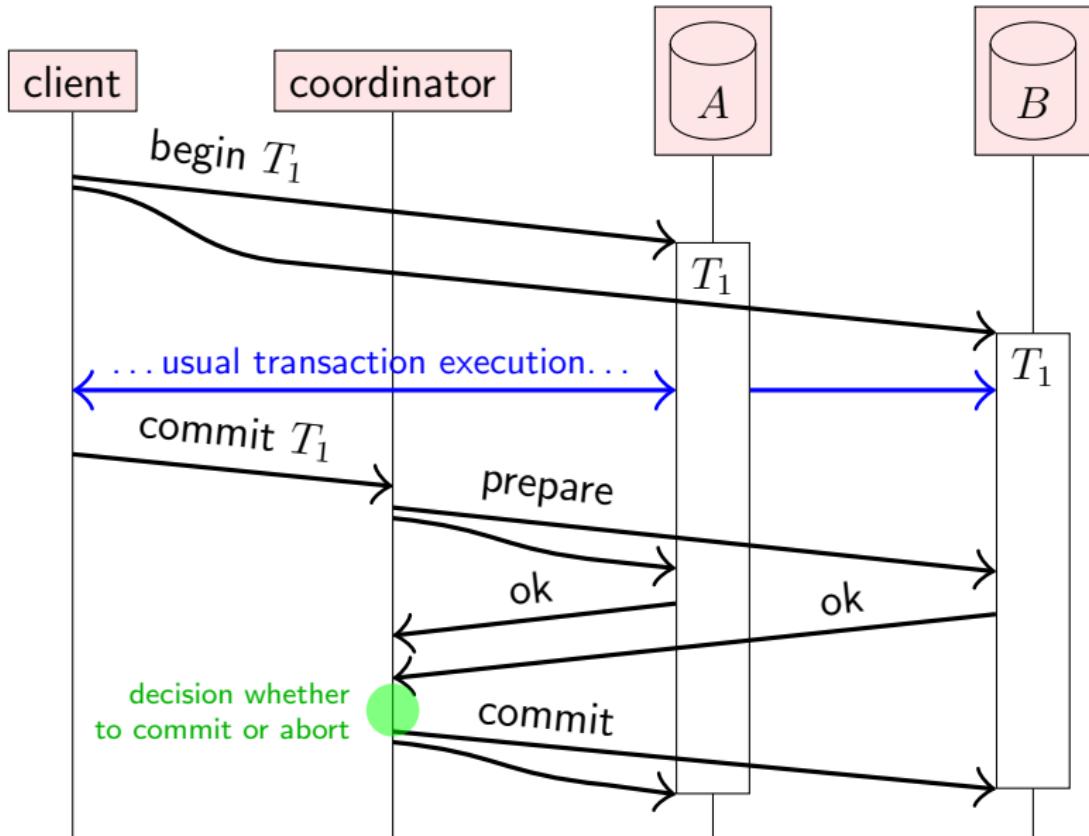
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- ▶ Algorithm is blocked until coordinator recovers

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

**on** initialisation for transaction  $T$  **do**

$commitVotes[T] := \{\}$ ;  $replicas[T] := \{\}$ ;  $decided[T] := \text{false}$

**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**

$replicas[T] := R$

$ok = \text{"is transaction } T \text{ able to commit on this replica?"}$

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,  $T, replicaId, \text{false}$ ) to  $replicas[T]$

**end for**

**end on**

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

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

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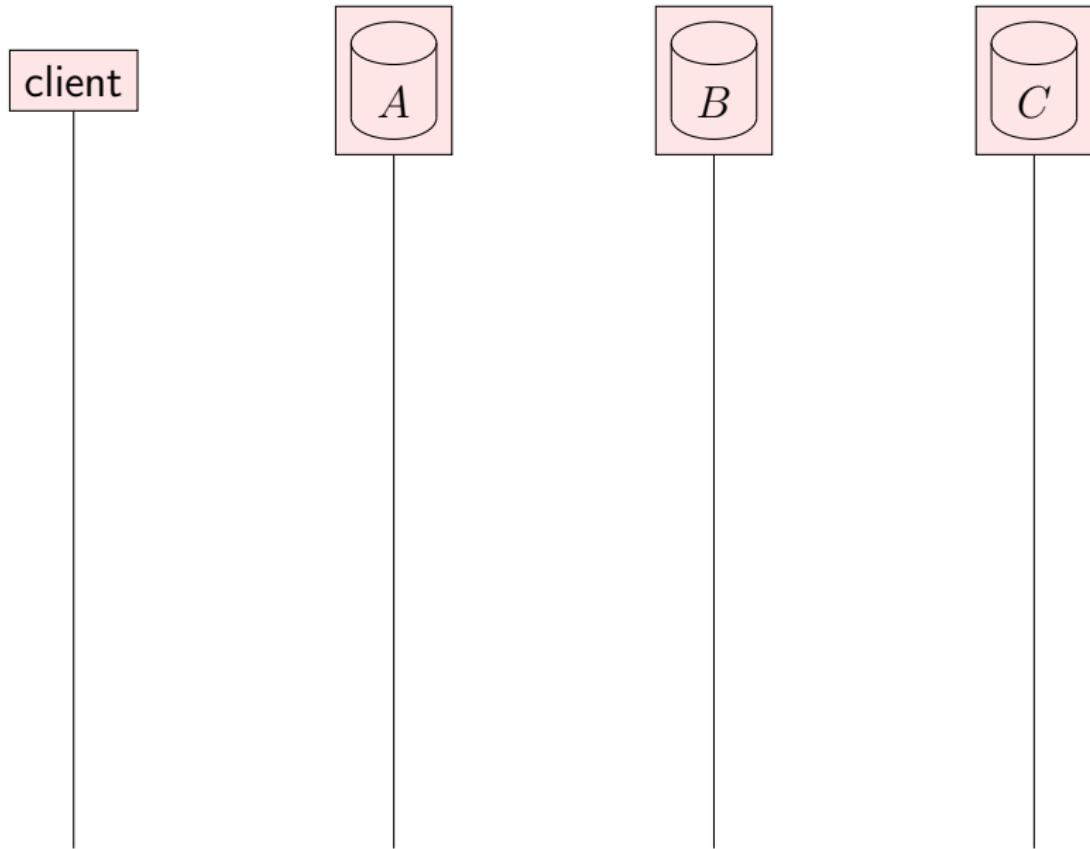
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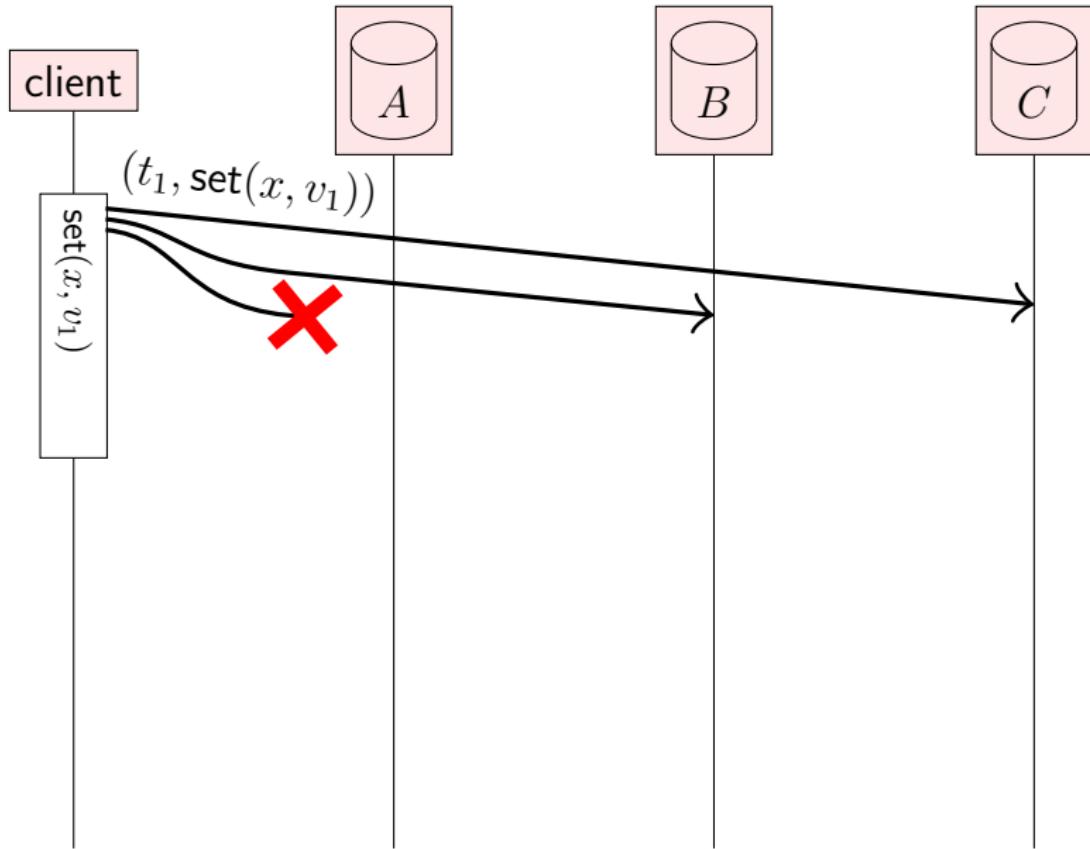
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Note: linearizability  $\neq$  serializability!

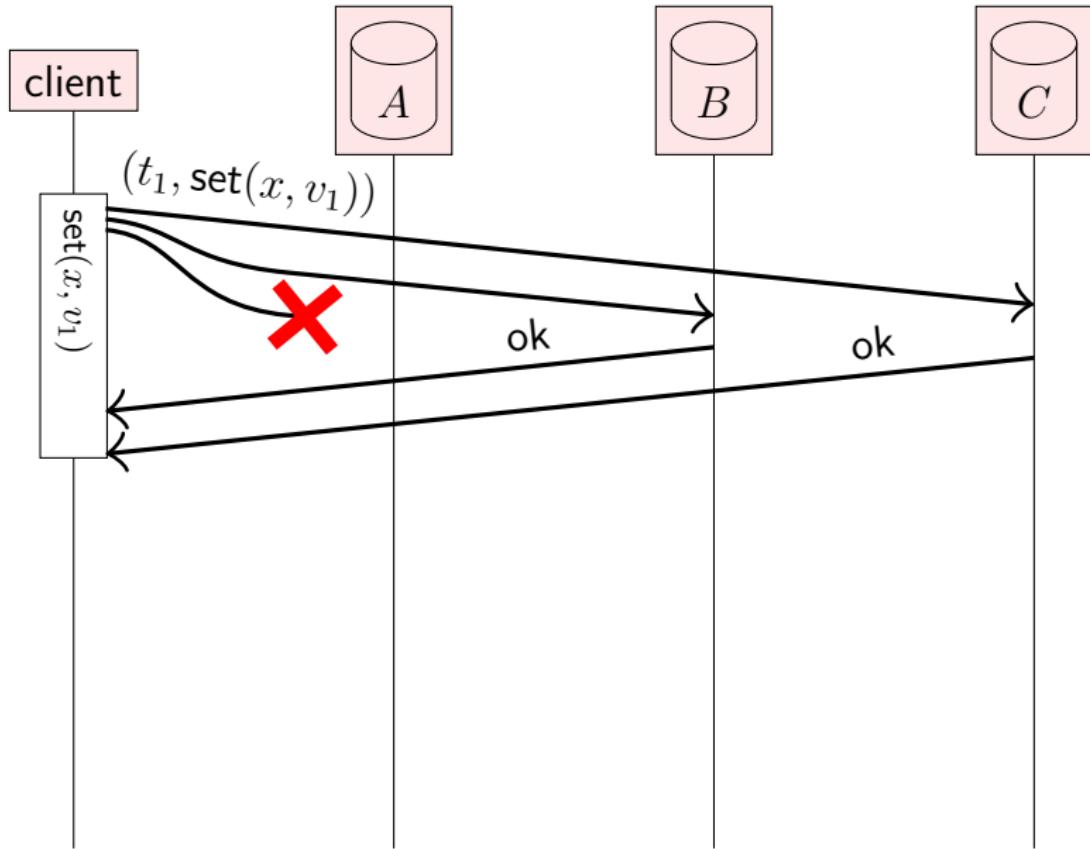
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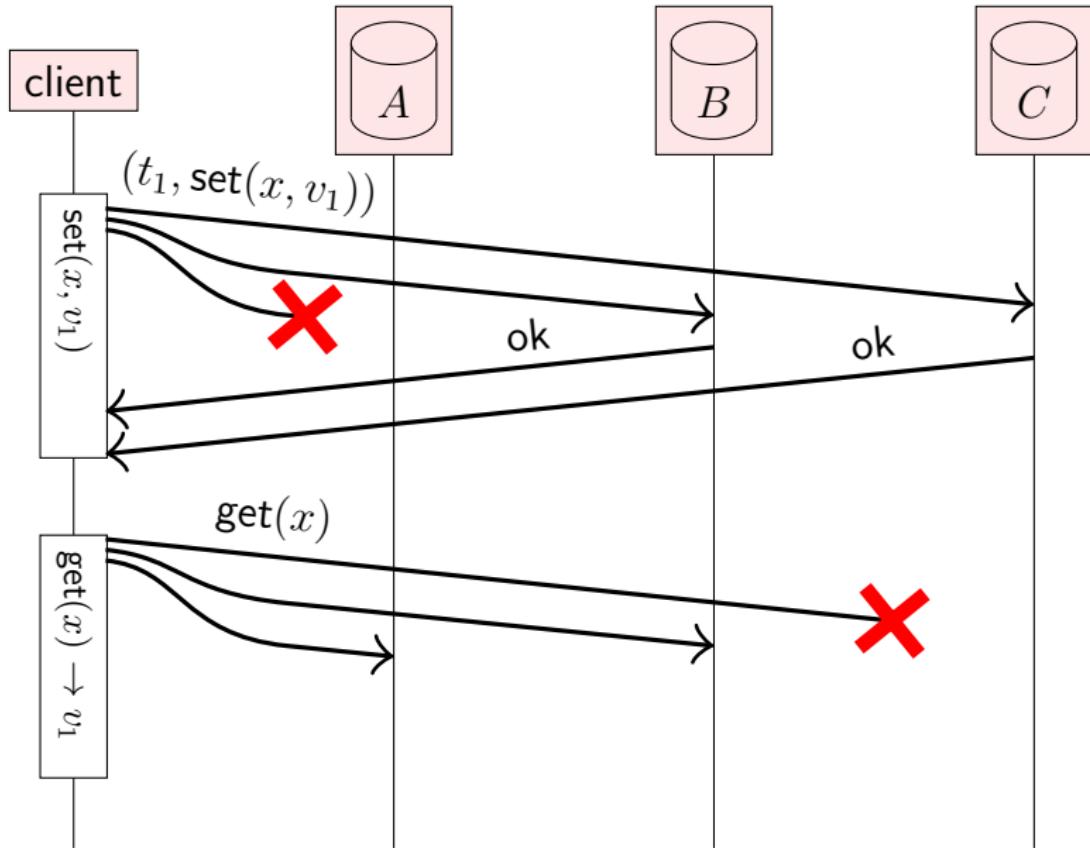
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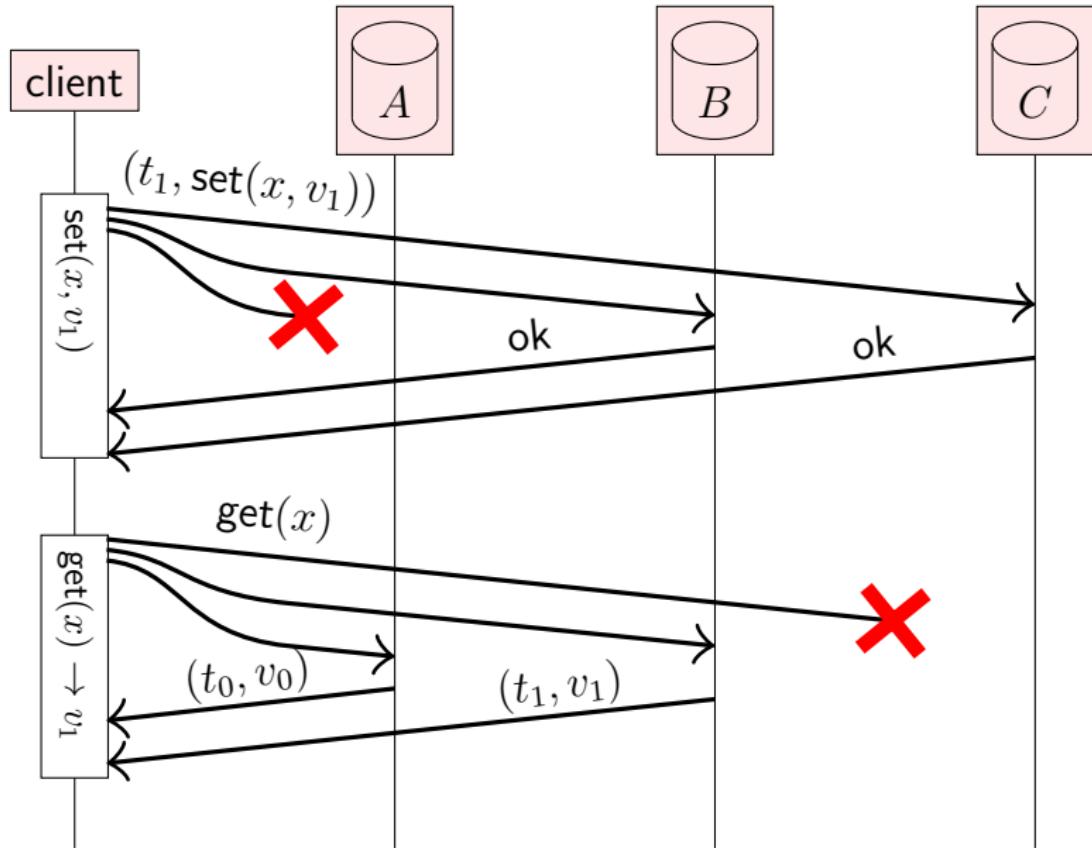
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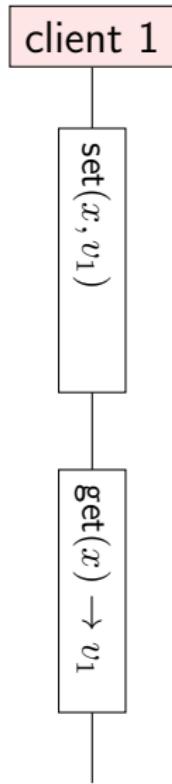
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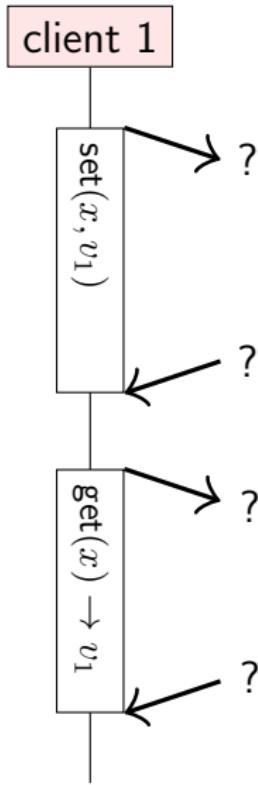


# From the client's point of view



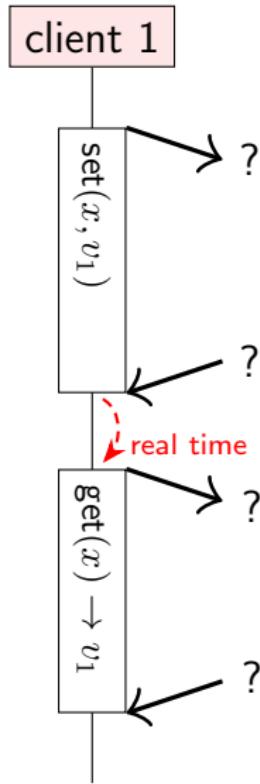
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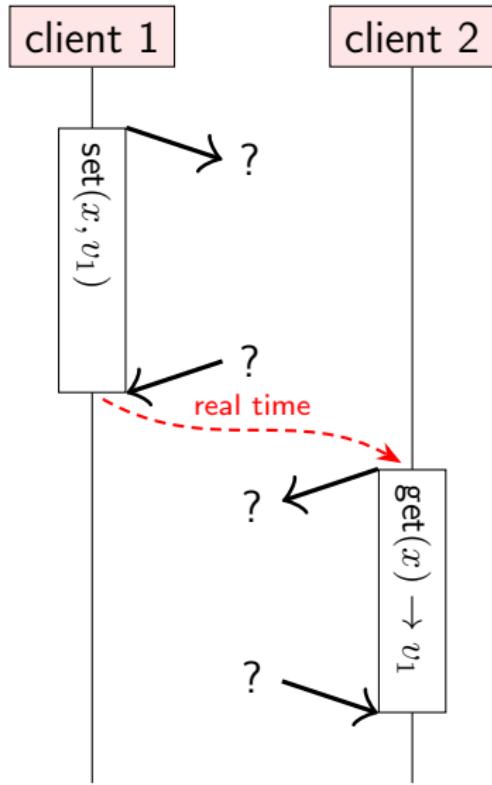
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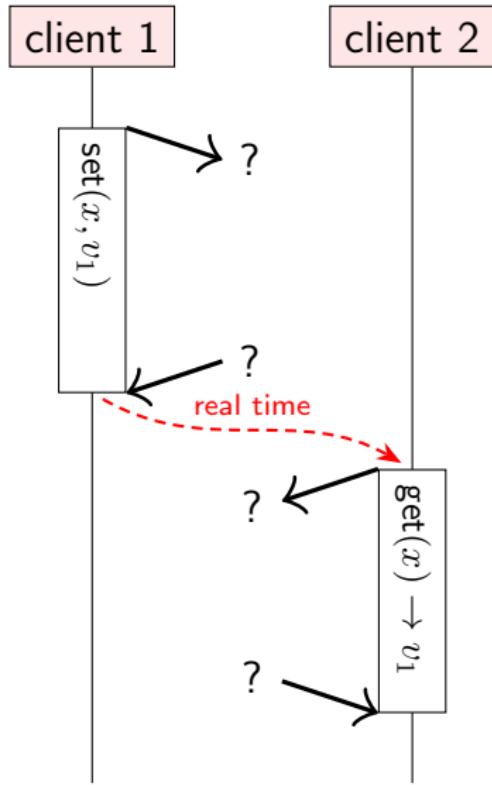
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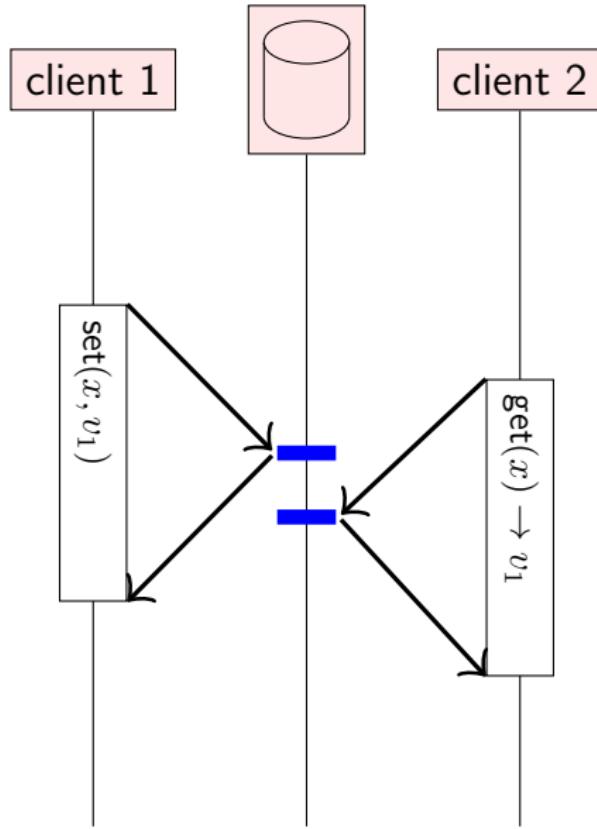
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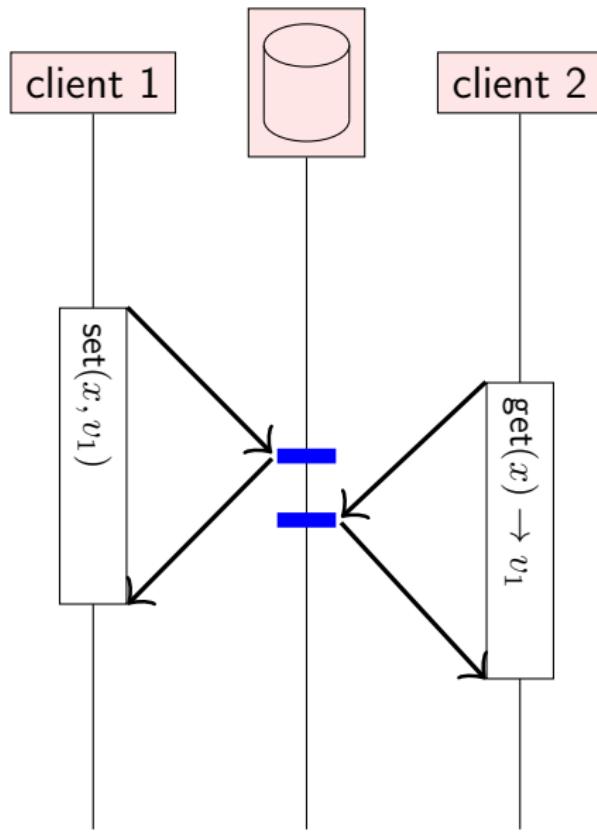
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- ▶ Even if the operations are on different nodes?
- ▶ **This is not happens-before:** we want client 2 to read value written by client 1, even if the clients have not communicated!

# Operations overlapping in time



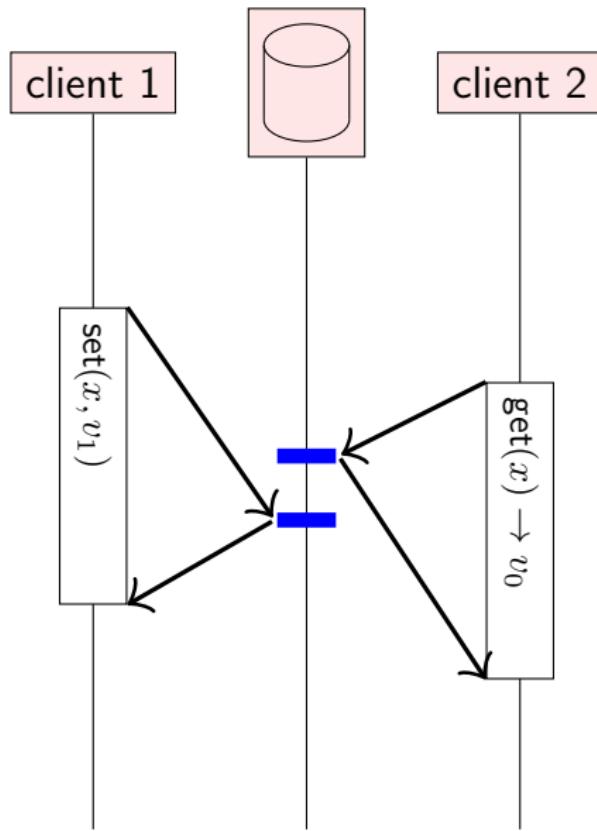
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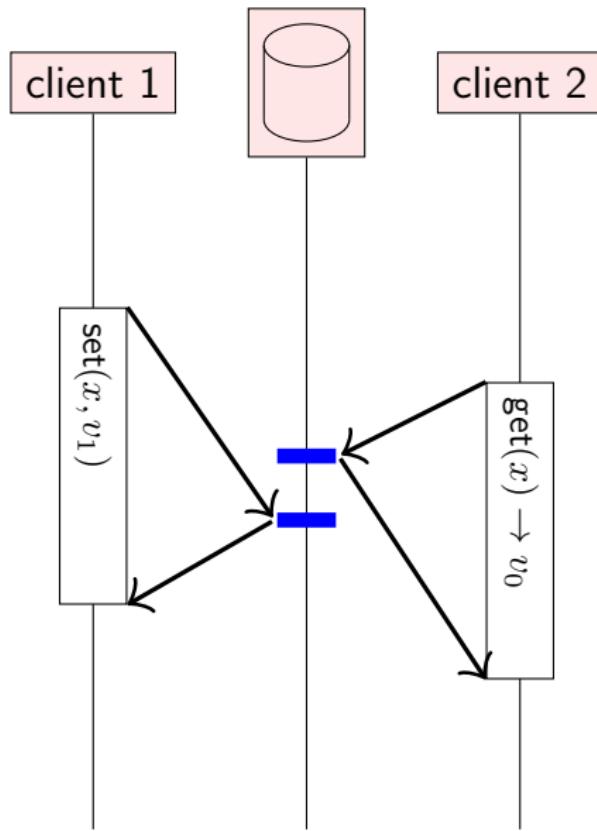
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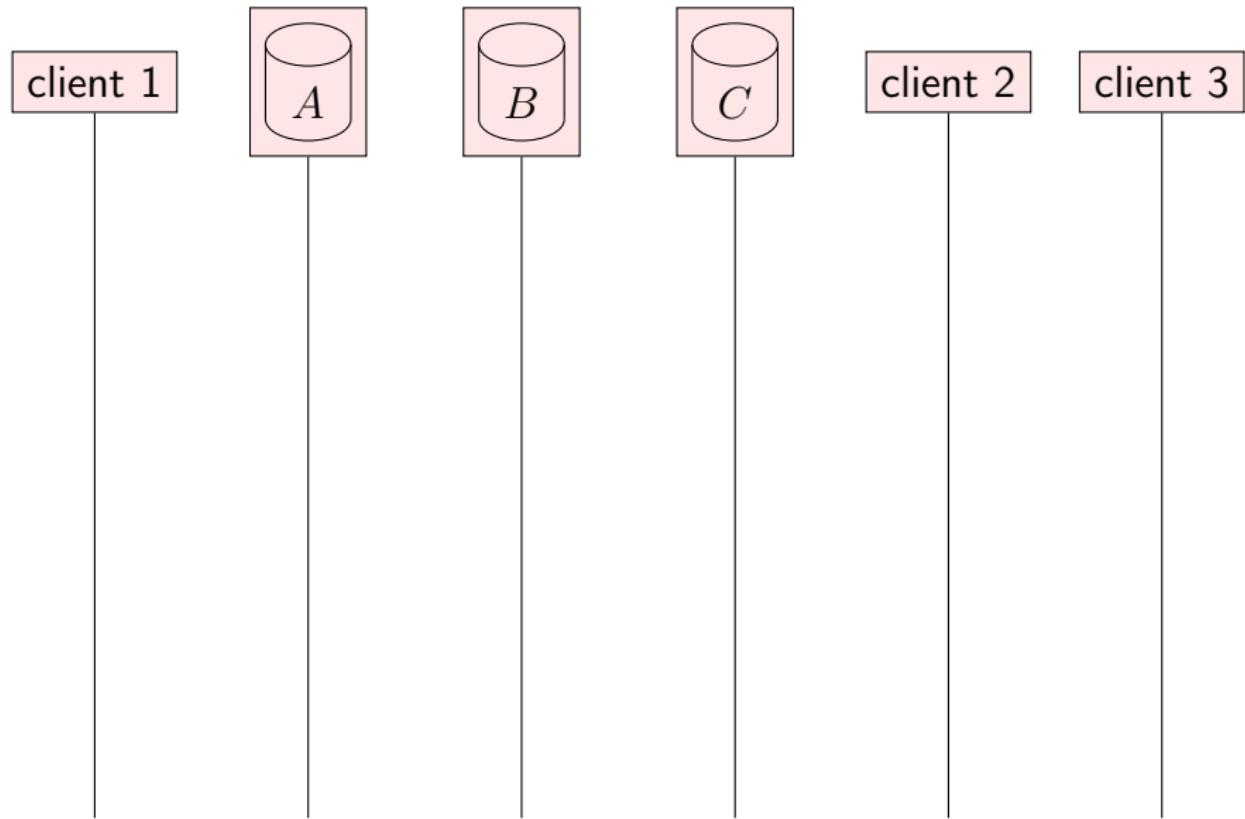
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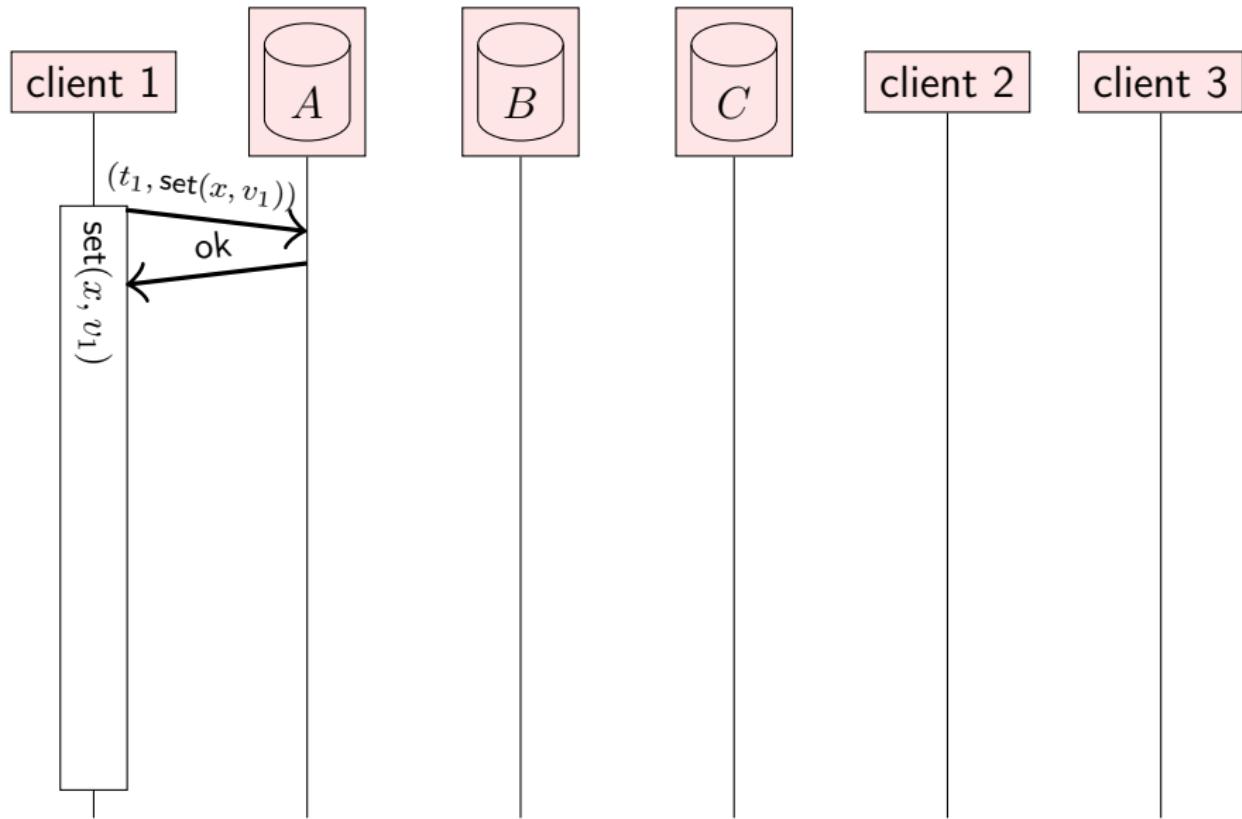


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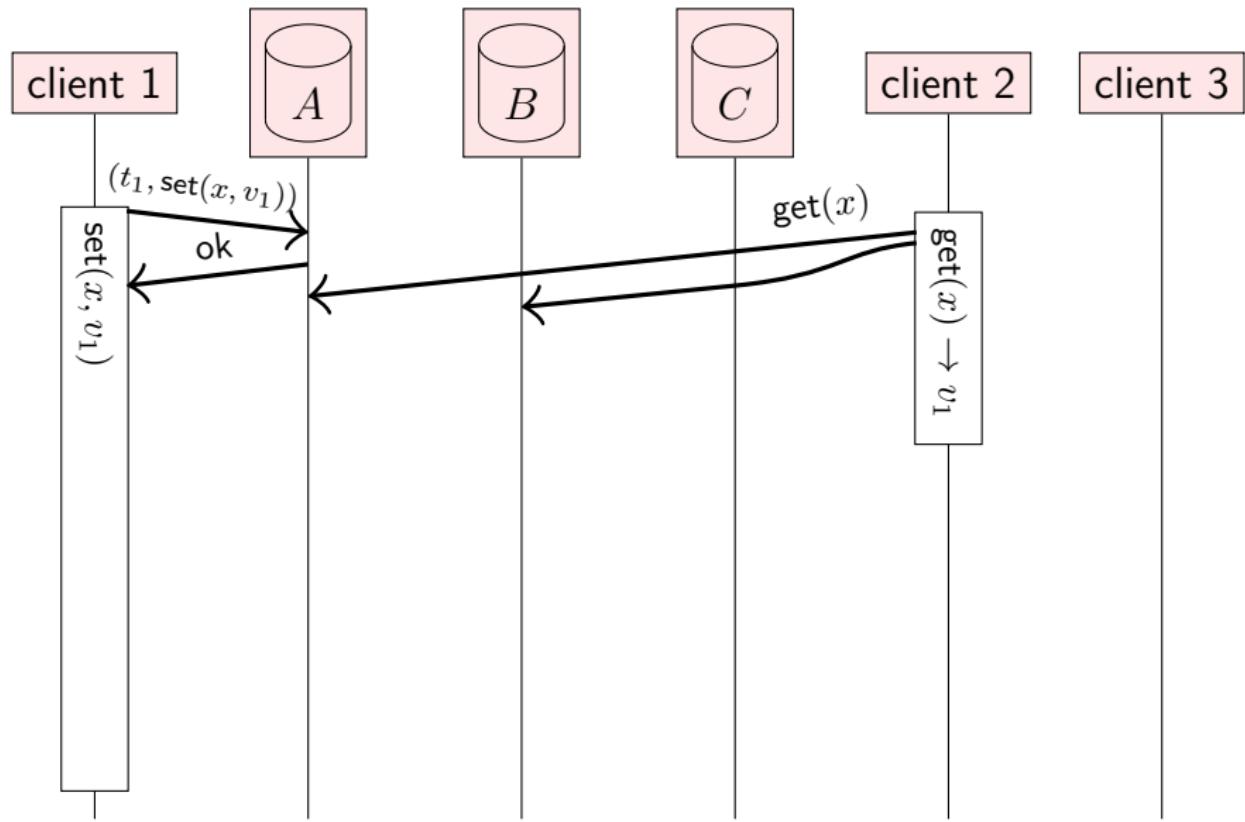
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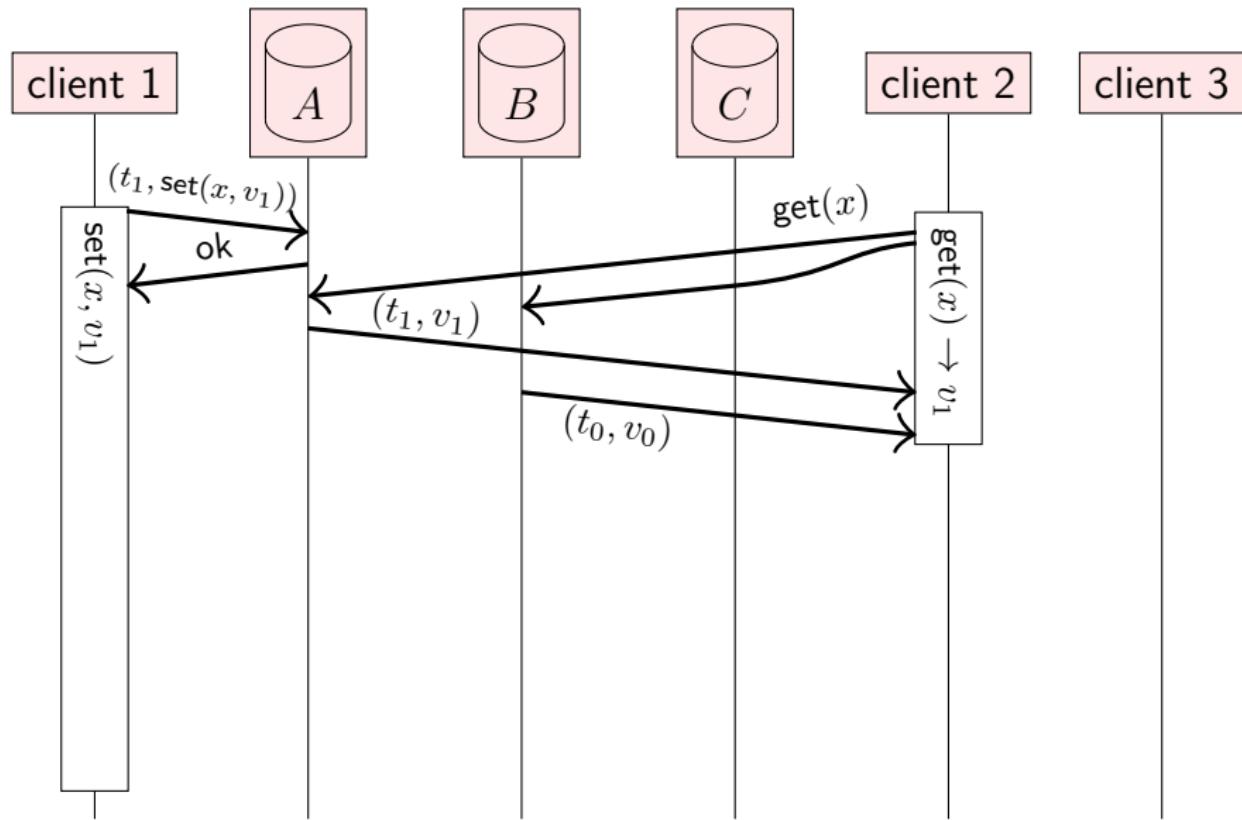
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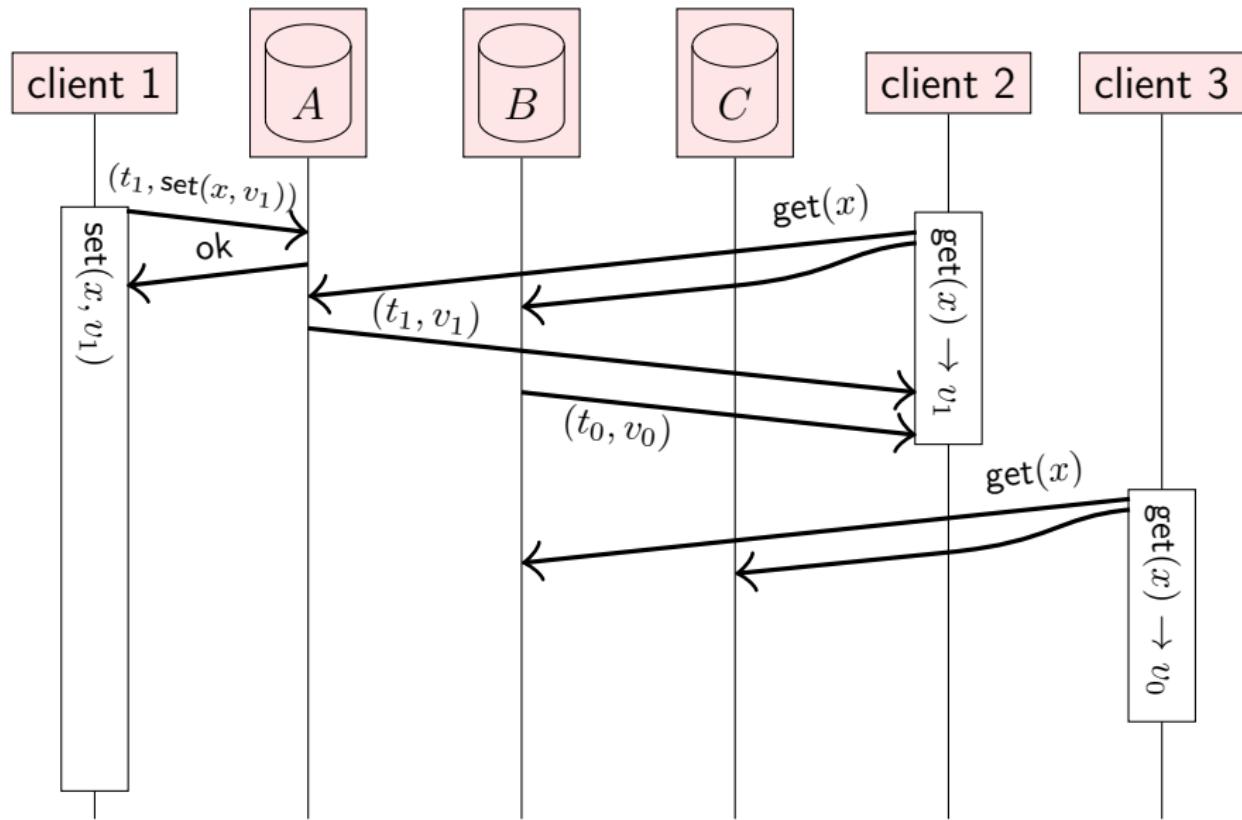
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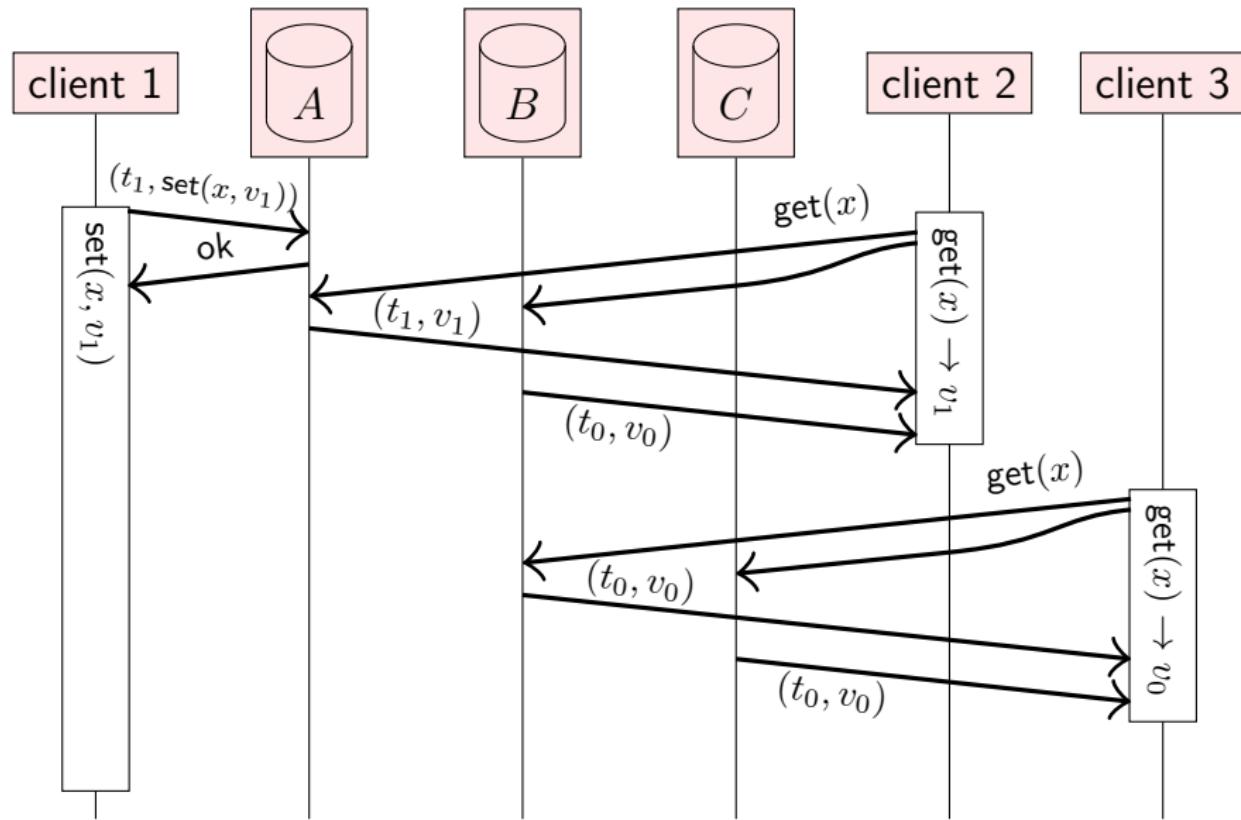
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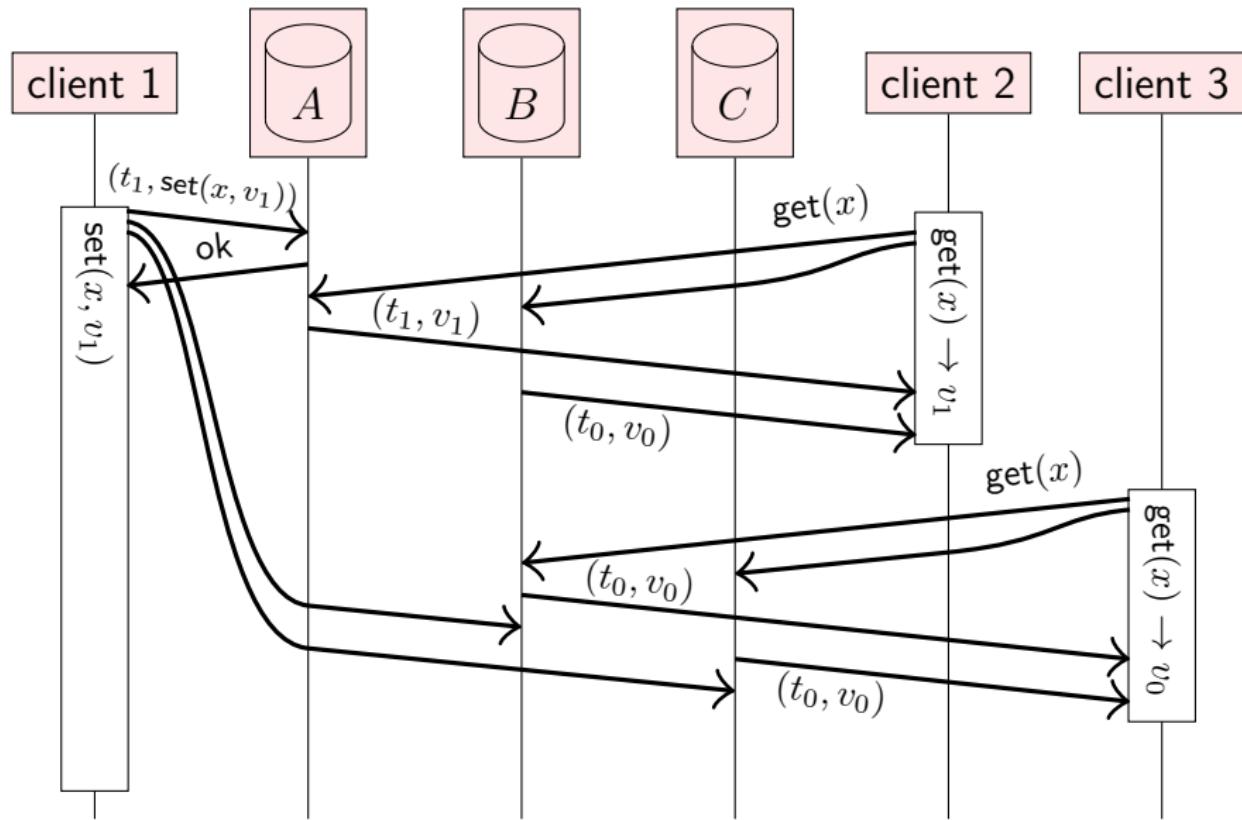
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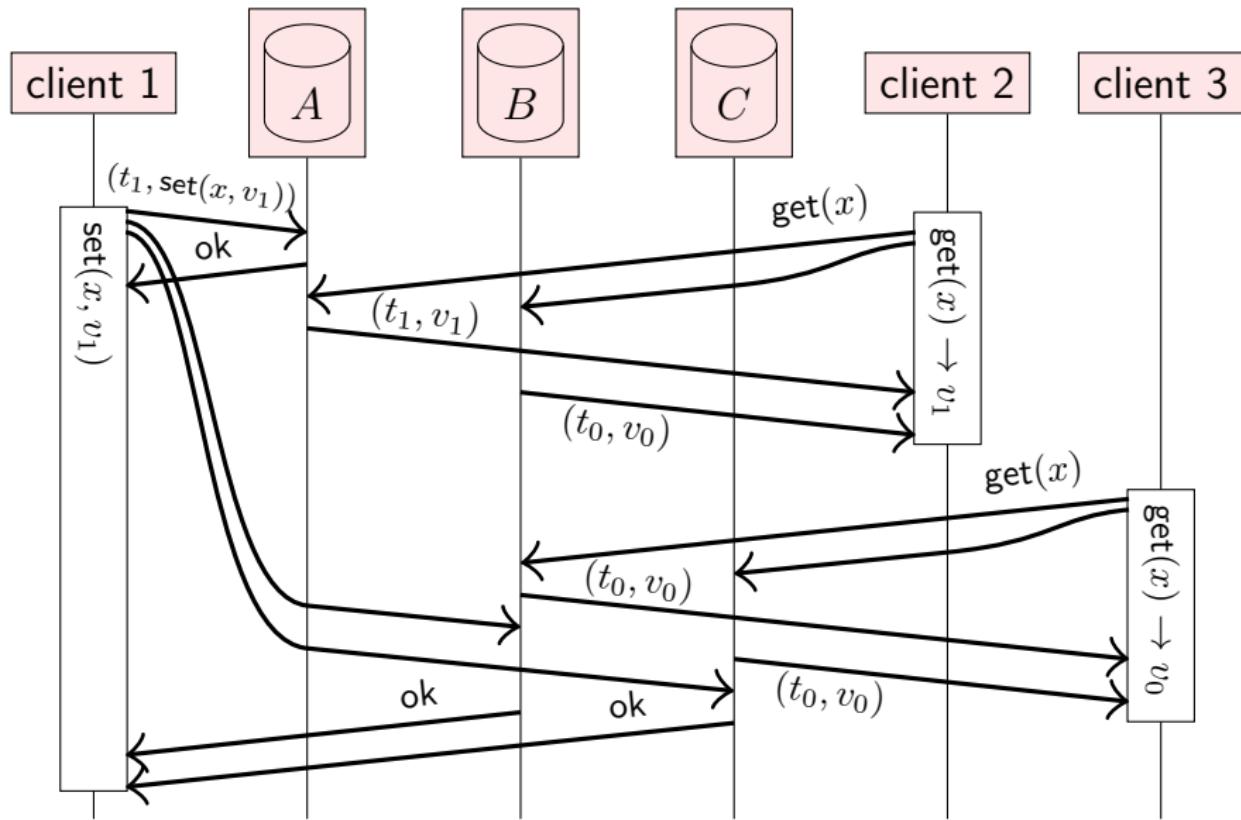
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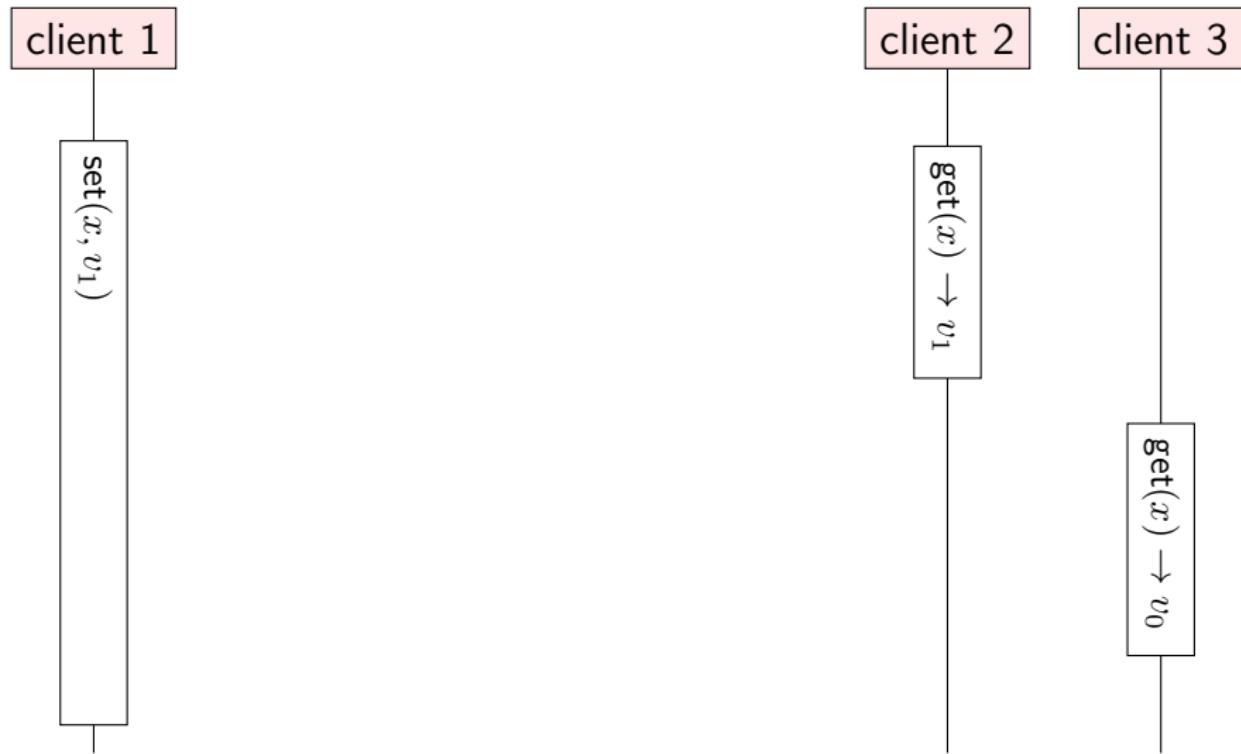
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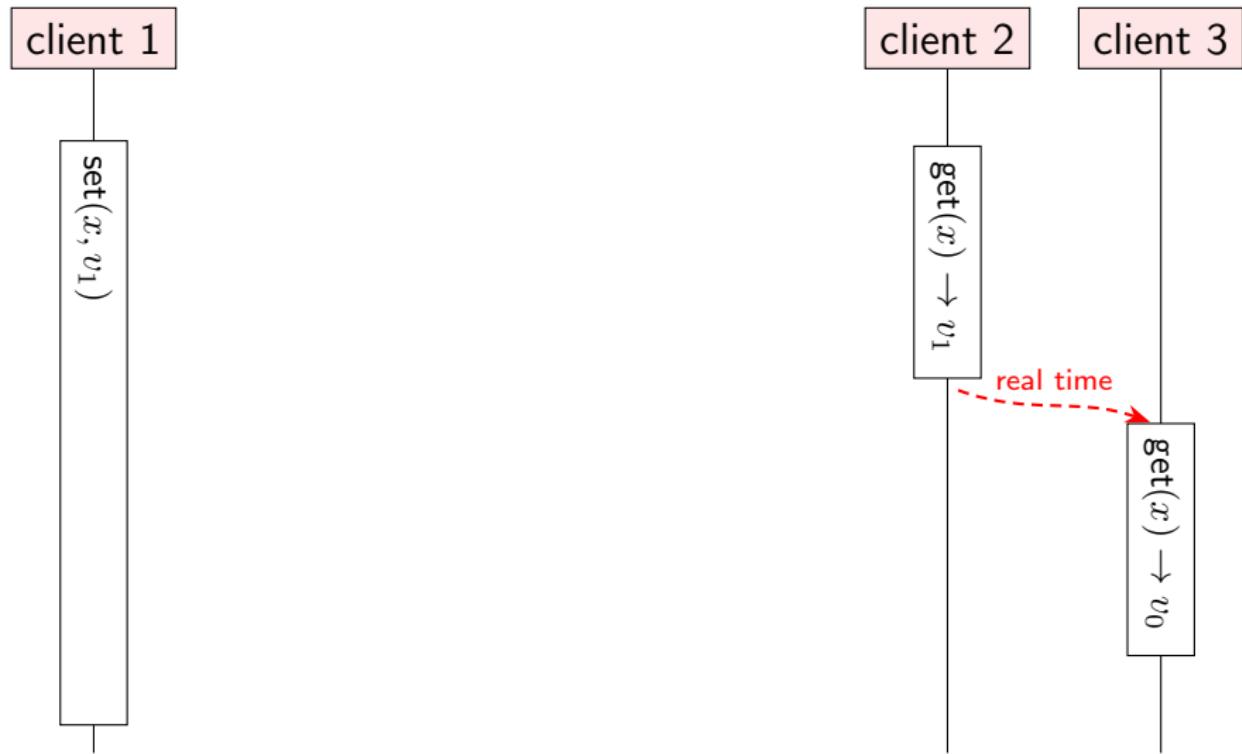
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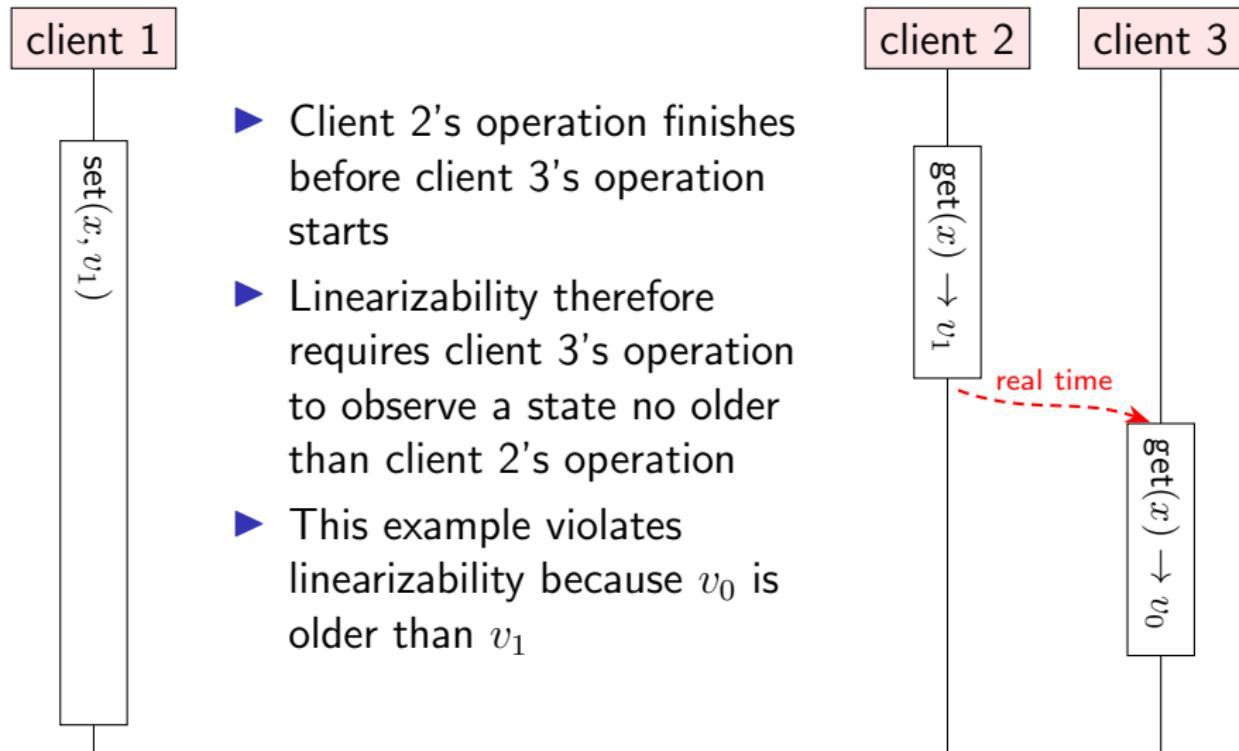
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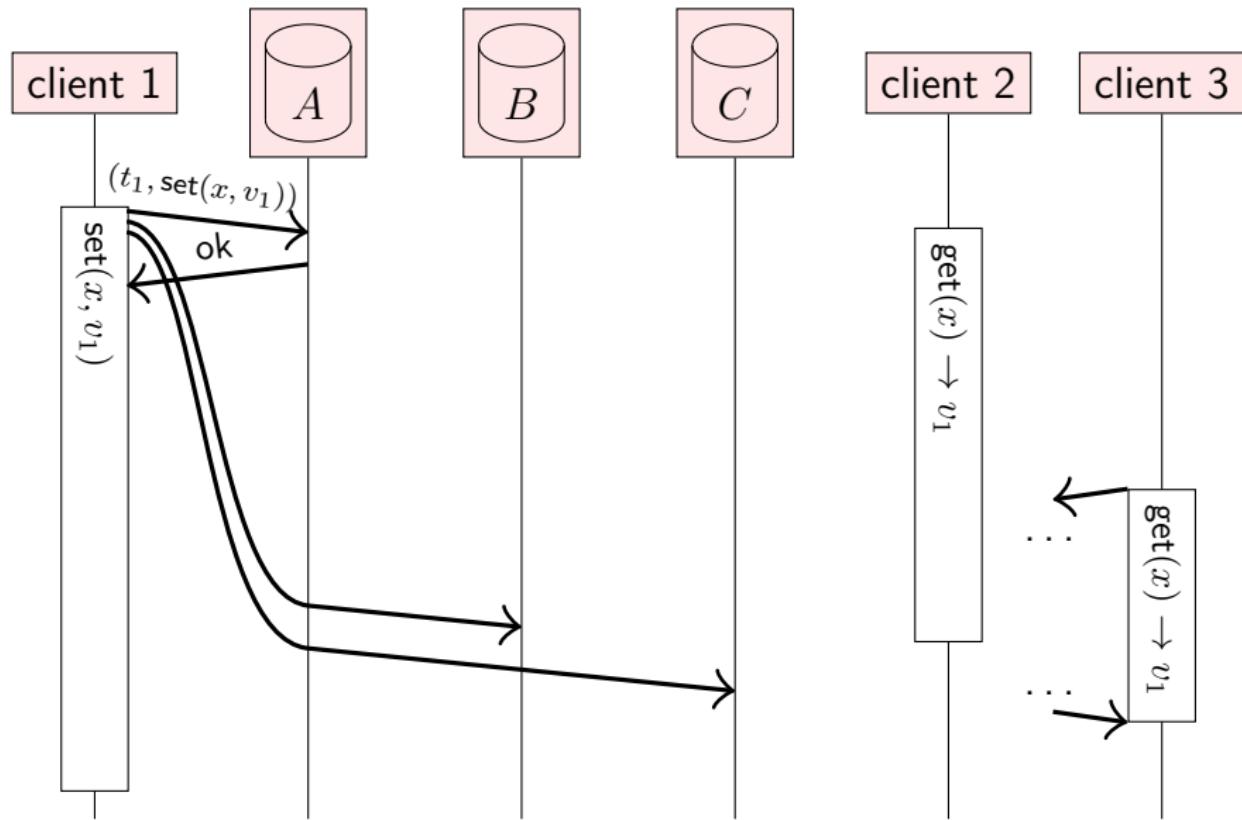
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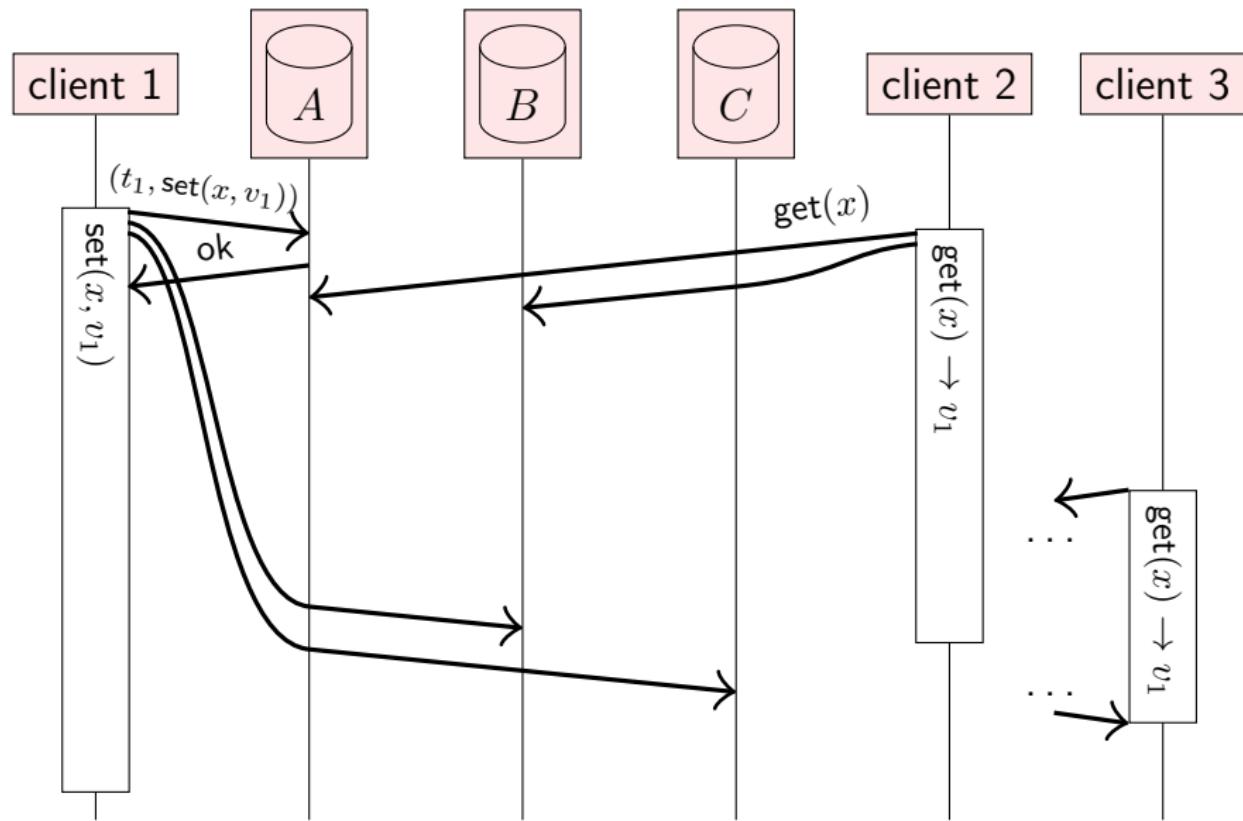
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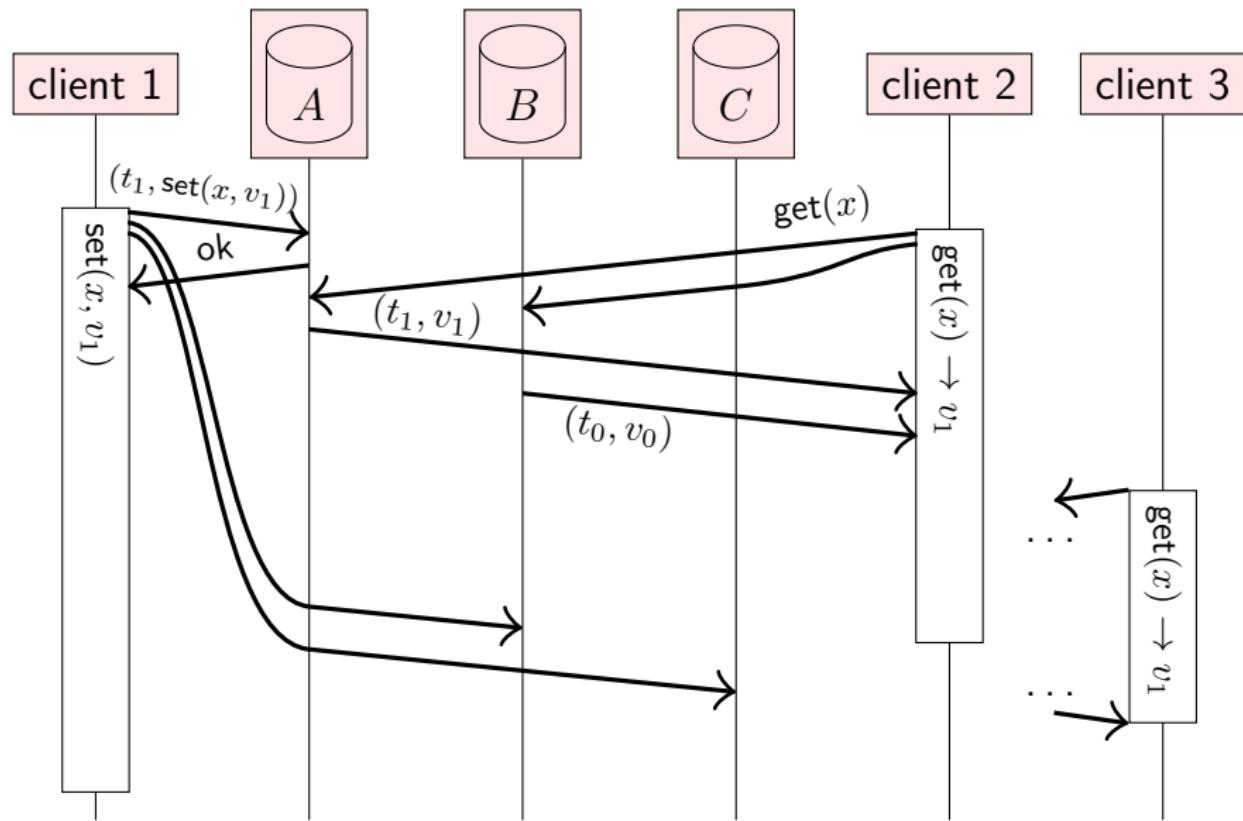
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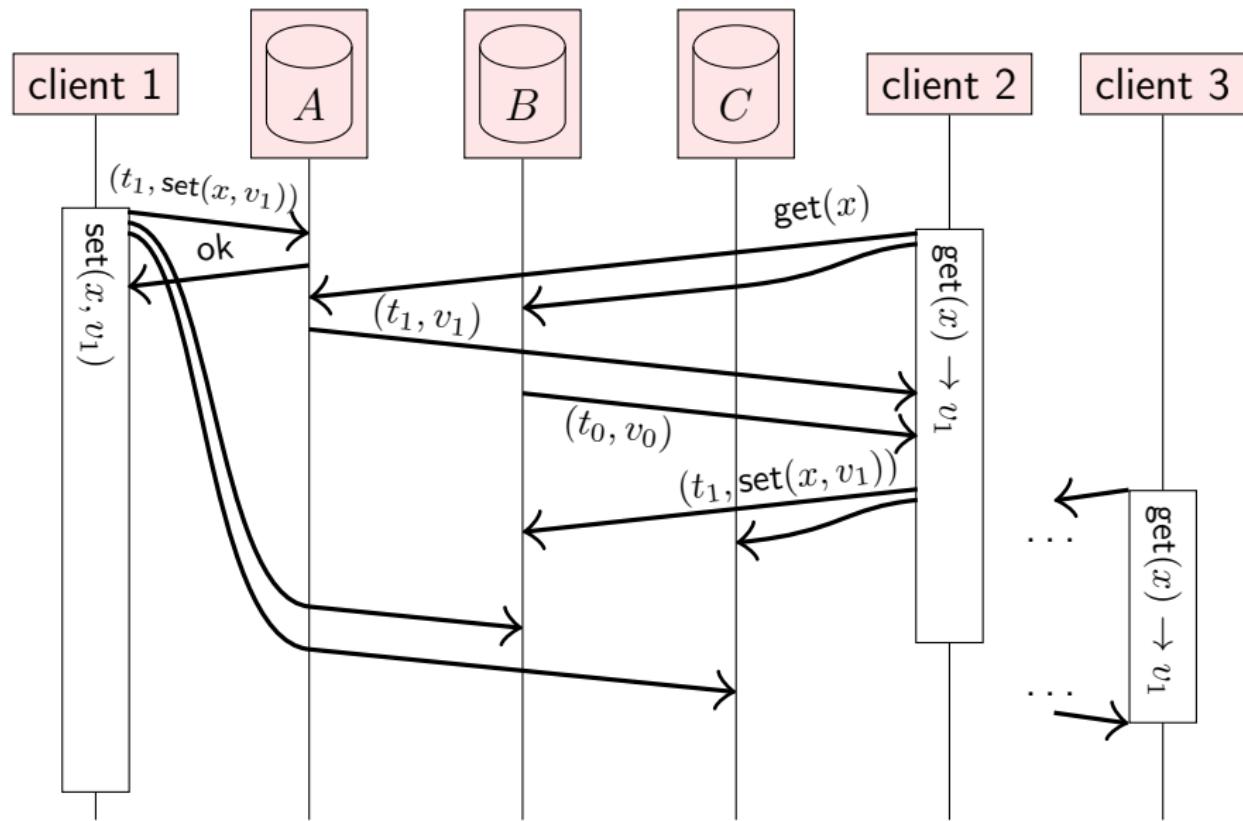
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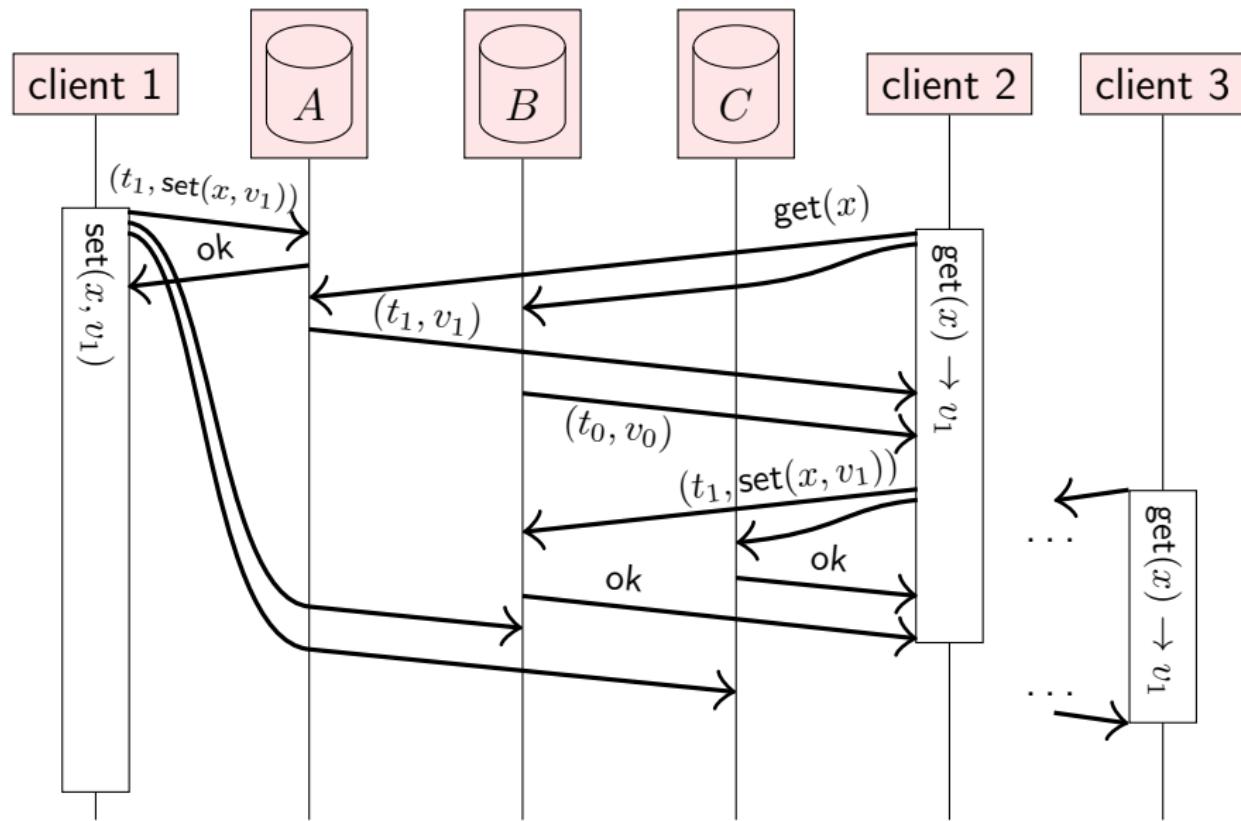
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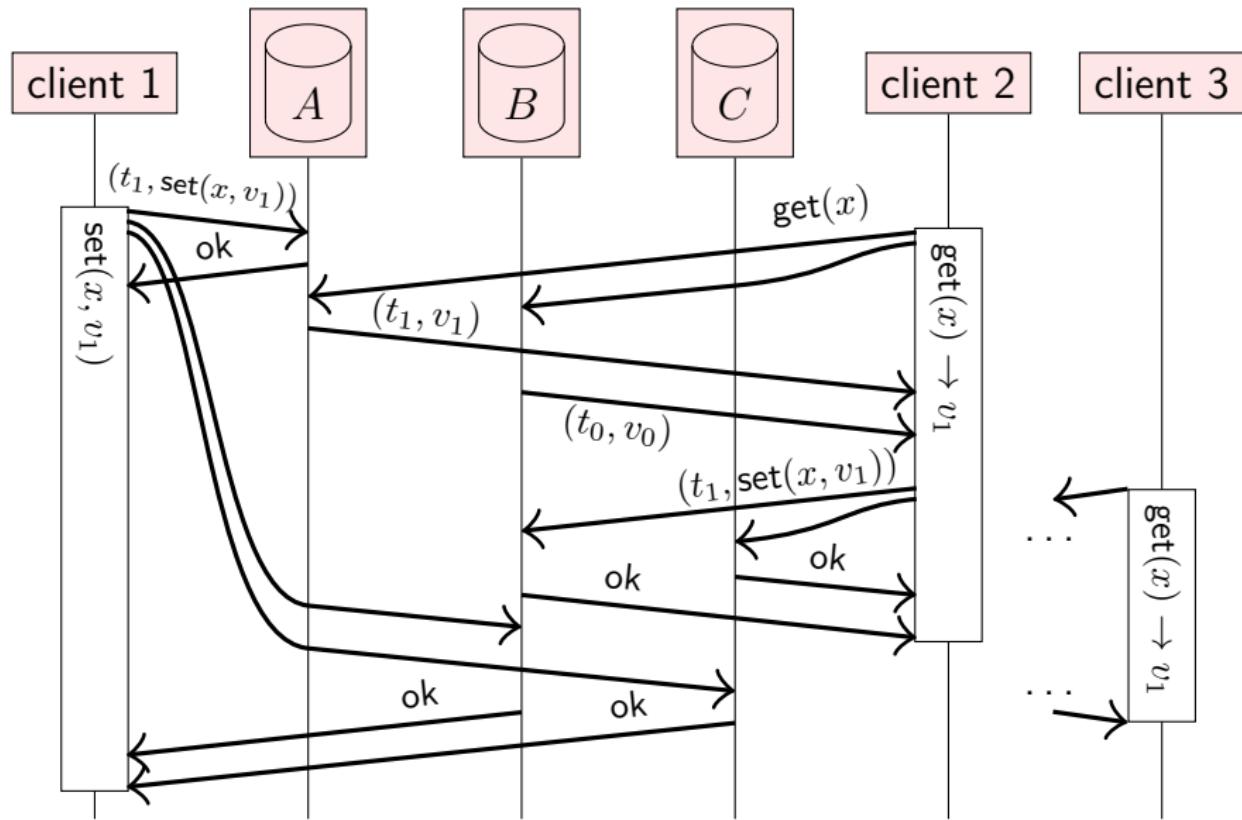
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What about an atomic **compare-and-swap** operation?

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- ▶ **Yes:** total order broadcast to the rescue again!

# Linearizable compare-and-swap (CAS)

**on** request to perform  $\text{get}(x)$  **do**

total order broadcast ( $\text{get}, x$ ) and wait for delivery

**end on**

**on** request to perform  $\text{CAS}(x, old, new)$  **do**

total order broadcast ( $\text{CAS}, x, old, new$ ) and wait for delivery

**end on**

**on** delivering ( $\text{get}, x$ ) by total order broadcast **do**

**return**  $localState[x]$  as result of operation  $\text{get}(x)$

**end on**

**on** delivering ( $\text{CAS}, x, old, new$ ) by total order broadcast **do**

*success* := false

**if**  $localState[x] = old$  **then**

$localState[x] := new$ ; *success* := true

**end if**

**return** *success* as result of operation  $\text{CAS}(x, old, new)$

**end on**

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Downsides:

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

Linearizability advantages:

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**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 12:00 Distributed systems lecture

13:00

14:00 14:00 Test

15:00

16:00

17:00

18:00

19:00

M T W T F S S  
26 27 28 29 30 31 1  
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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

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13:00

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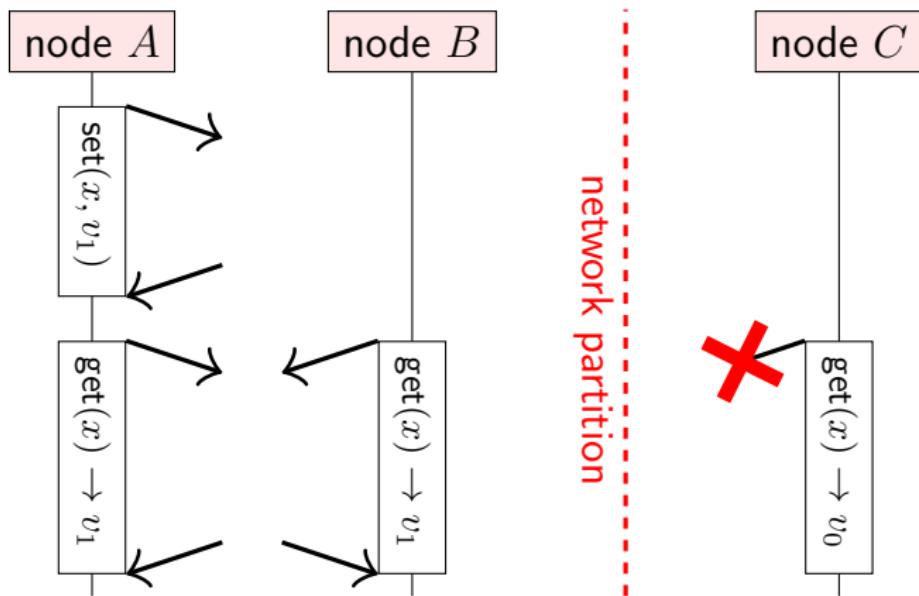
17:00

18:00

Today Calendars Inbox

# The CAP theorem

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



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

# Eventual consistency

Replicas process operations based only on their local state.

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

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## 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

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

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## Lecture 8

# Concurrency control in applications

# Collaboration and conflict resolution

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

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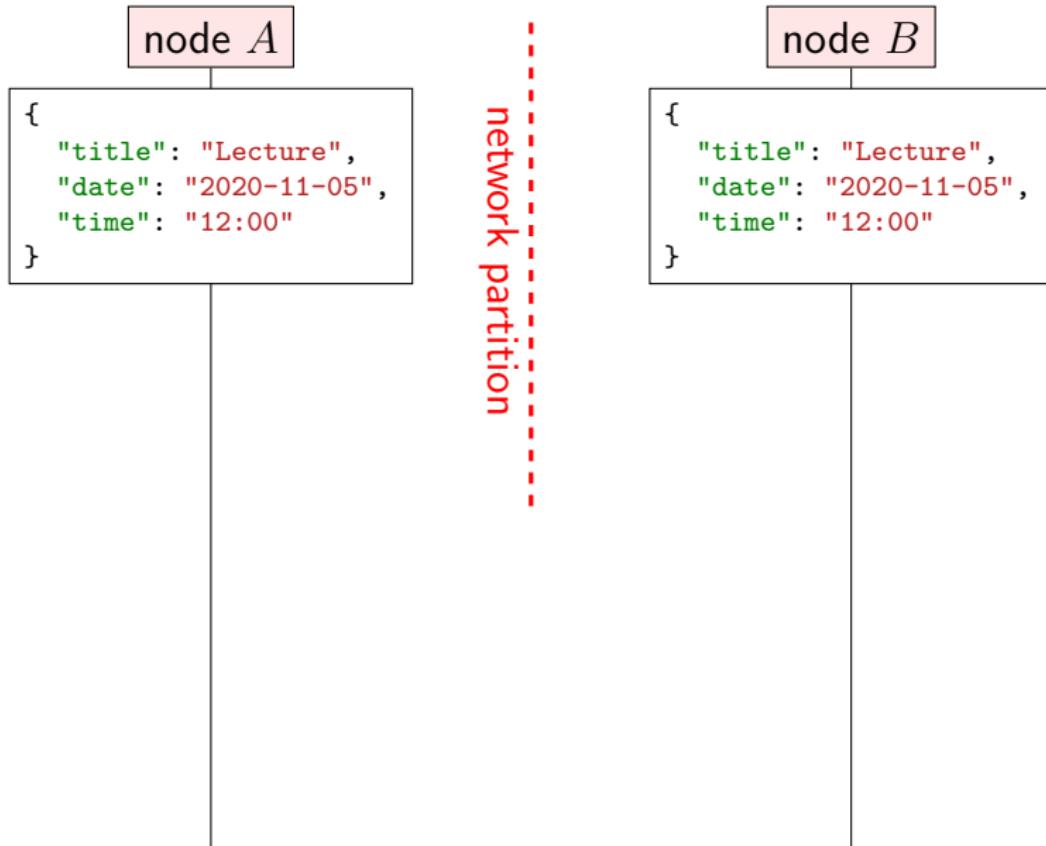
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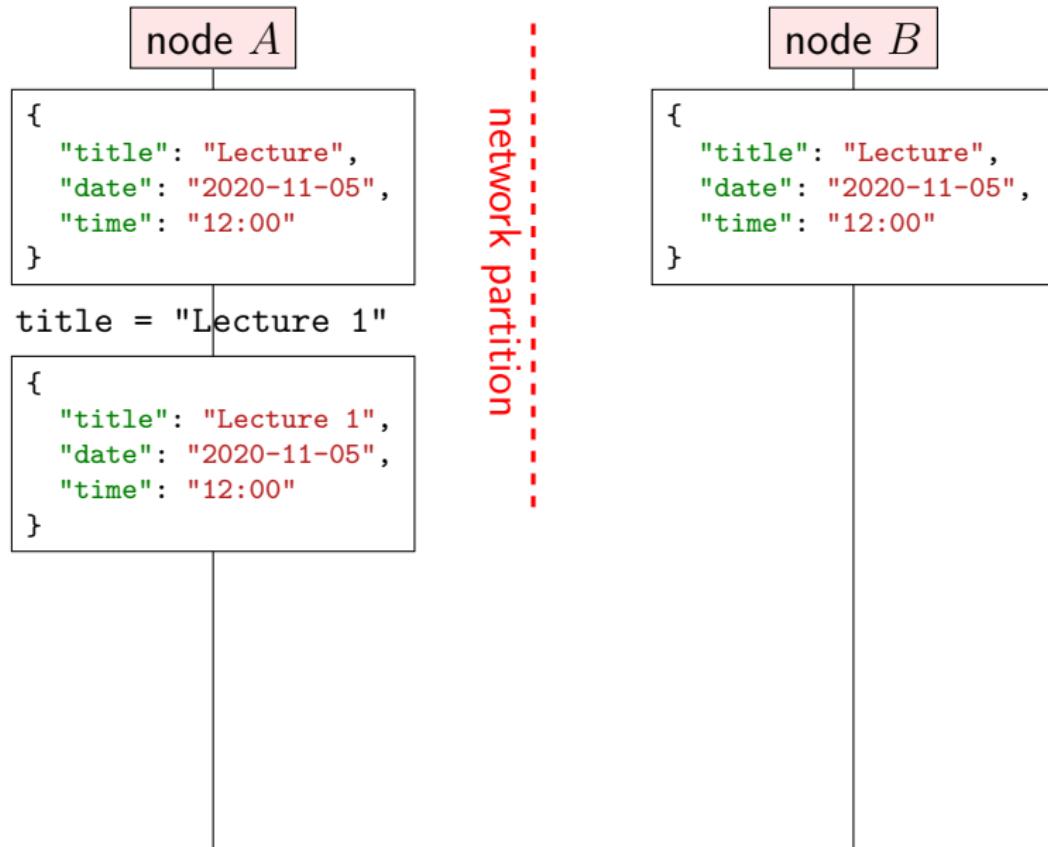
Families of **algorithms**:

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

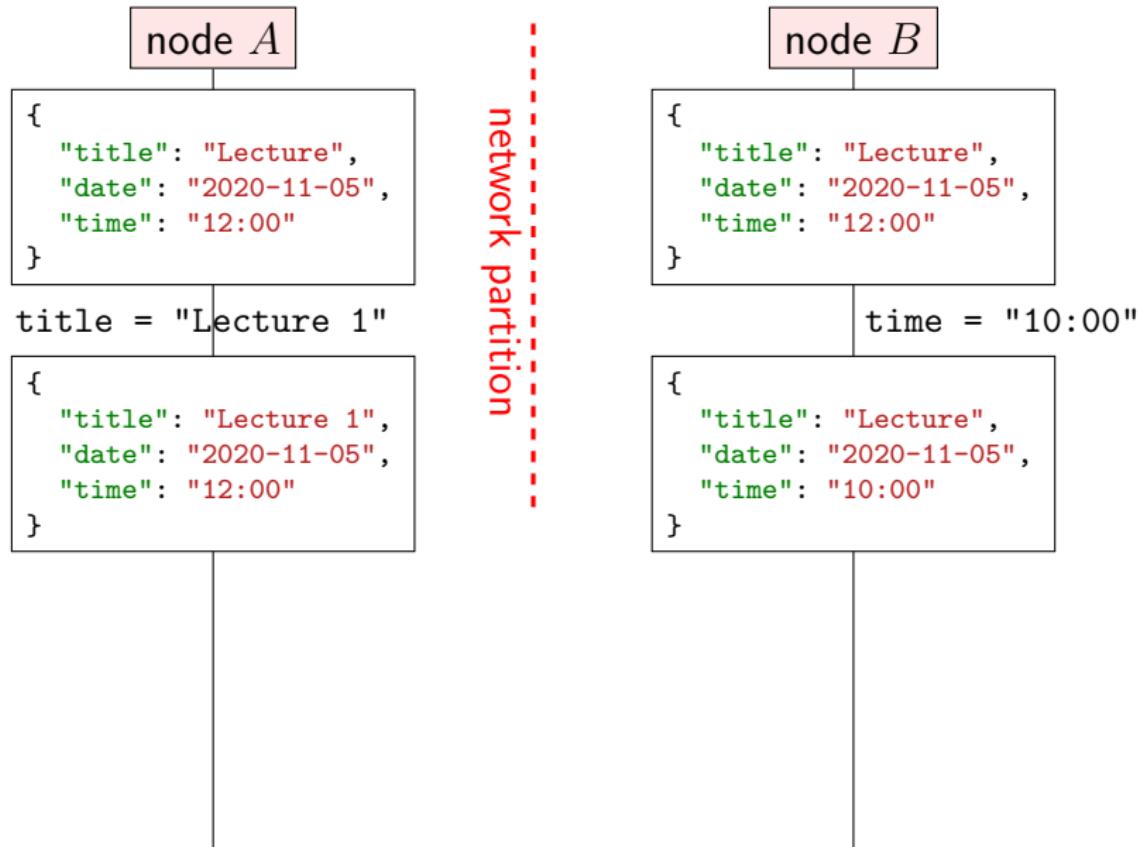
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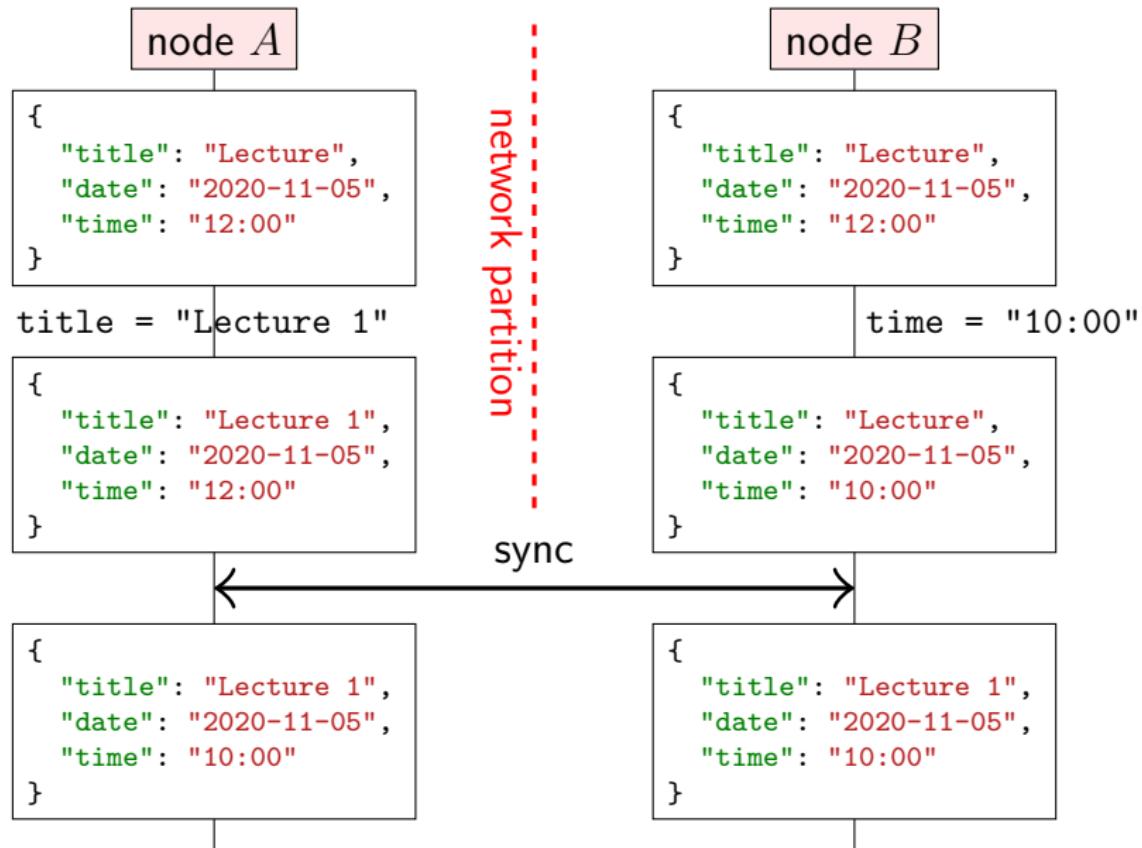
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# Operation-based map CRDT

**on** initialisation **do**

*values* := {}

**end on**

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

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

**end on**

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

*t* := 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* :=  $\{(t', k', v') \in \text{values} \mid k' = k\}$

**if** *previous* = {}  $\vee \forall (t', k', v') \in \text{previous}. t' < t$  **then**

*values* := (*values* \ *previous*)  $\cup \{(t, k, v)\}$

**end if**

**end on**

# Operation-based CRDTs

Reliable broadcast may deliver updates in any order:

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

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CRDT algorithm implements this:

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

# State-based map CRDT

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

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

**on** initialisation **do**

*values* := {}

**end on**

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

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

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

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

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

**broadcast** *values* by best-effort broadcast

**end on**

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

*values* := *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:**  $(s_1 \sqcup s_2) \sqcup s_3 = s_1 \sqcup (s_2 \sqcup s_3)$ .
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- ▶ Op-based CRDT typically has smaller messages
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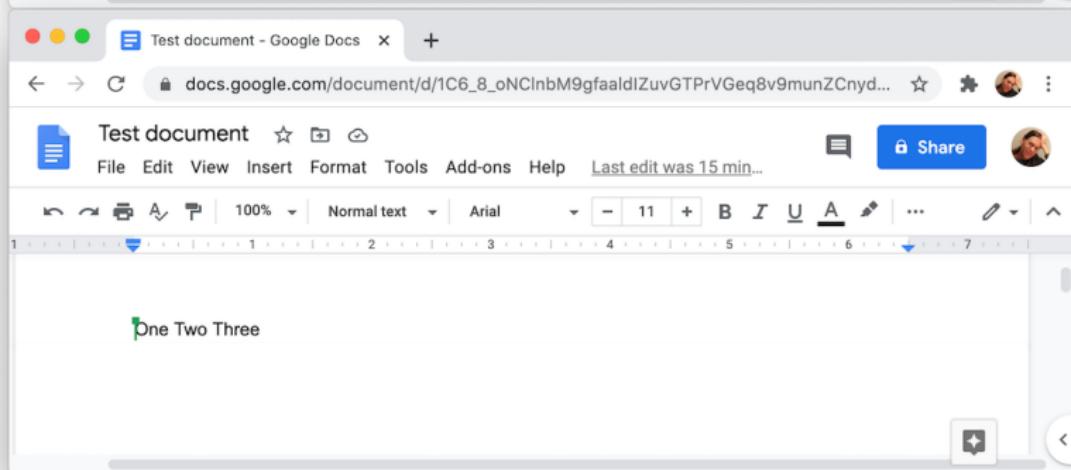
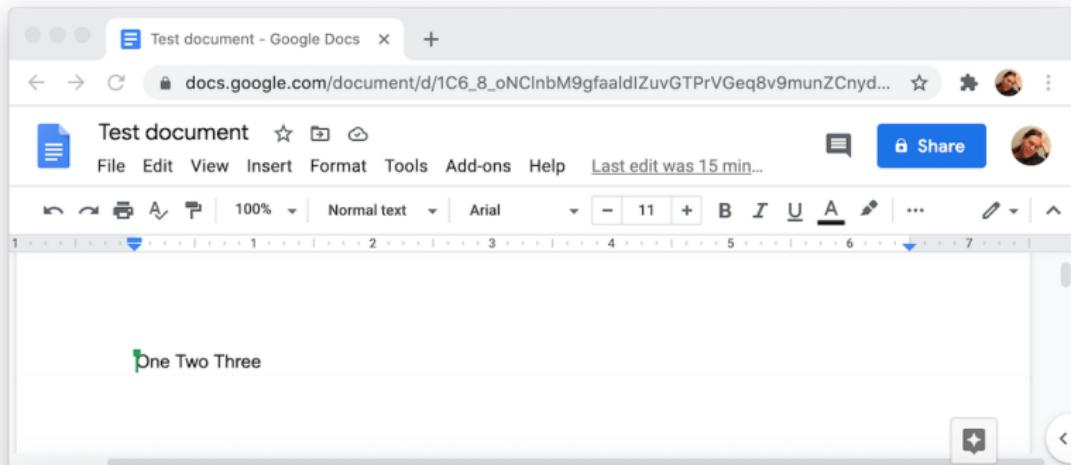
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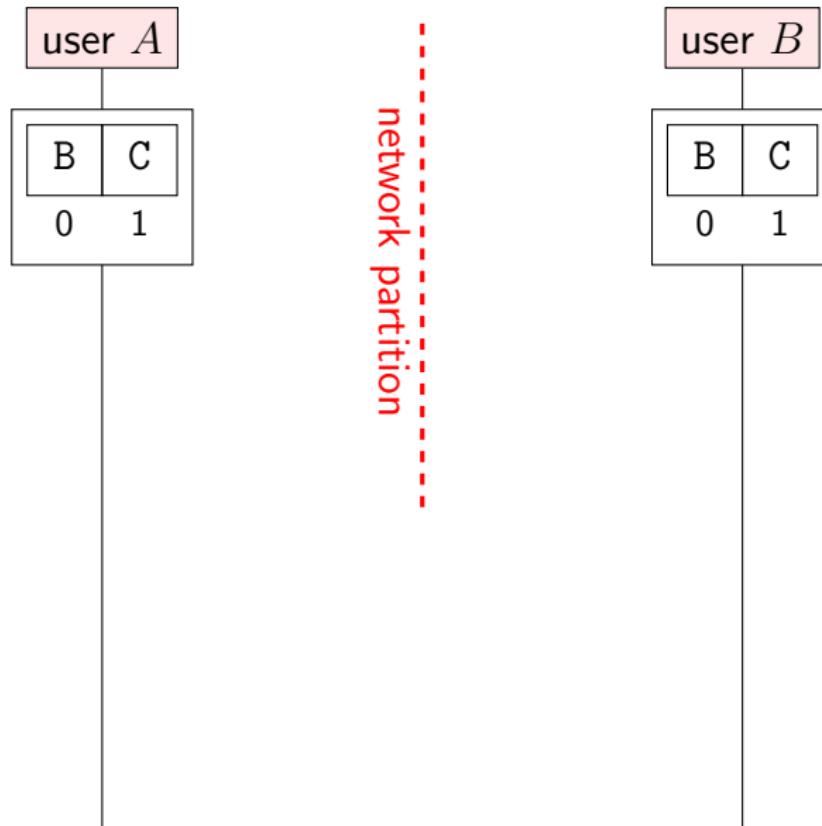
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Not necessarily uses broadcast:

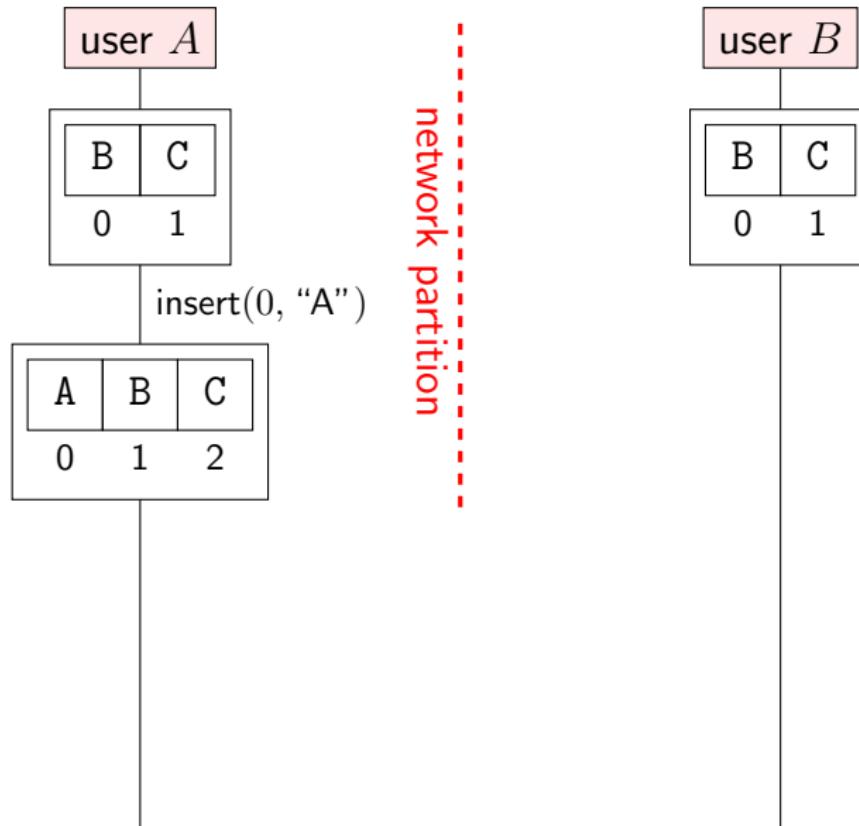
- ▶ Can also merge concurrent updates to replicas e.g. in quorum replication, anti-entropy, ...



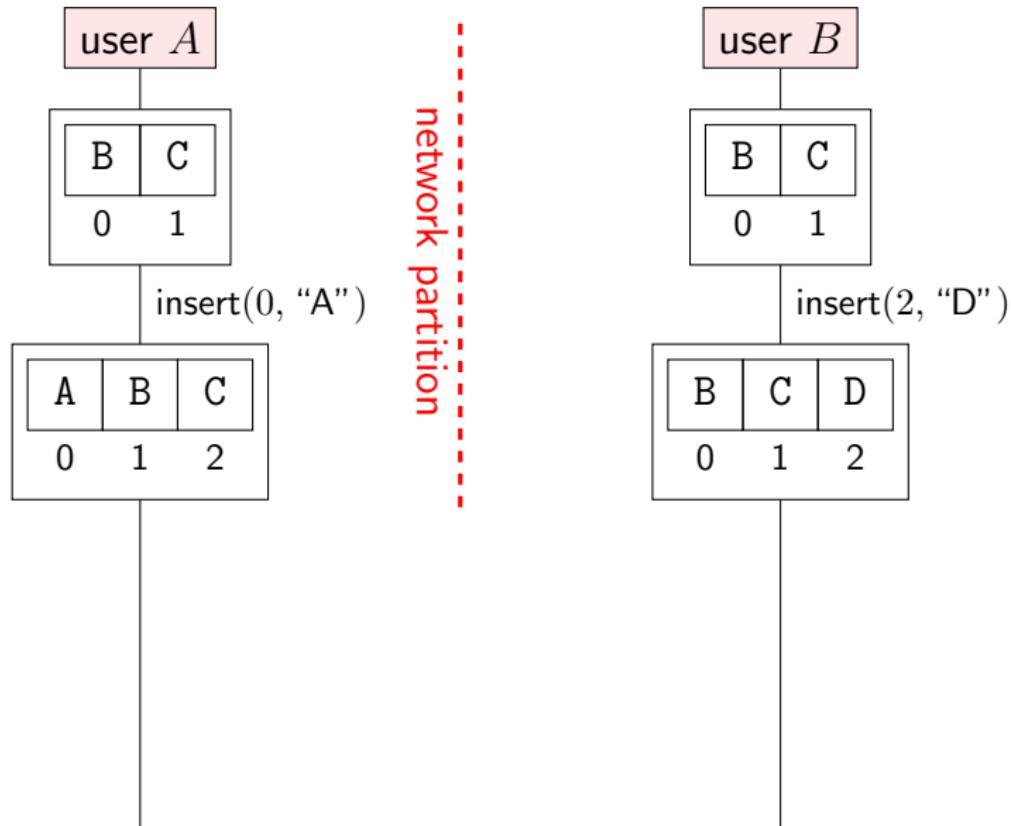
# Collaborative text editing: the problem



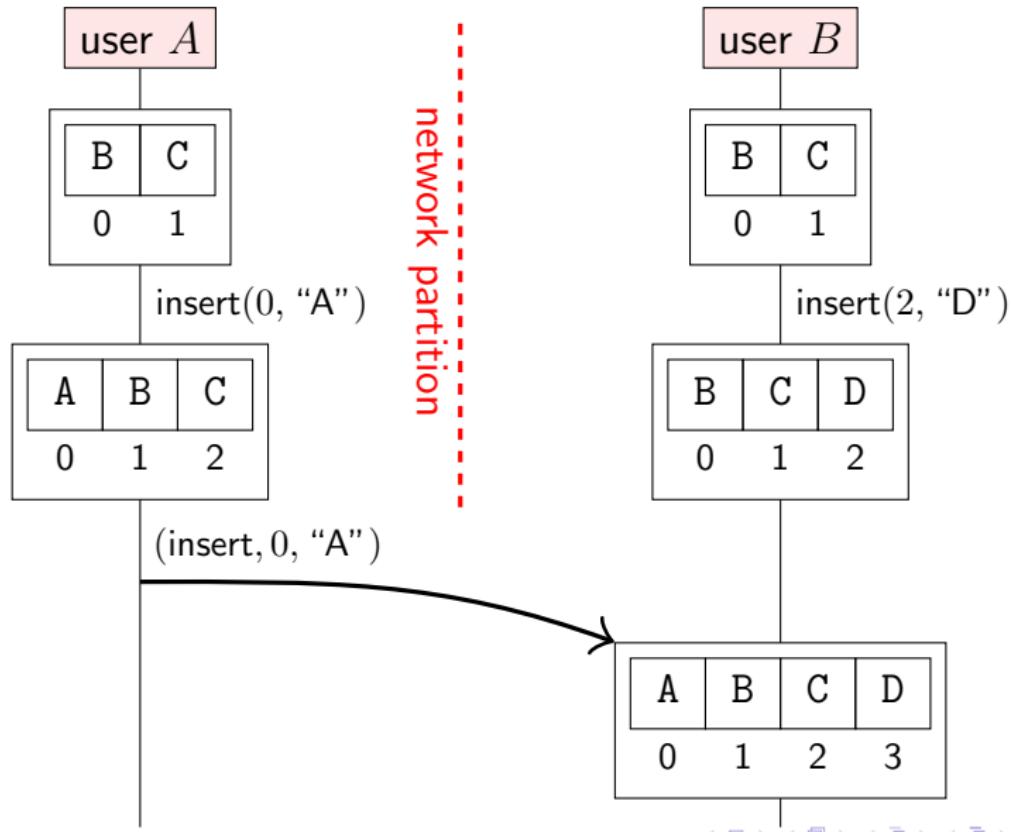
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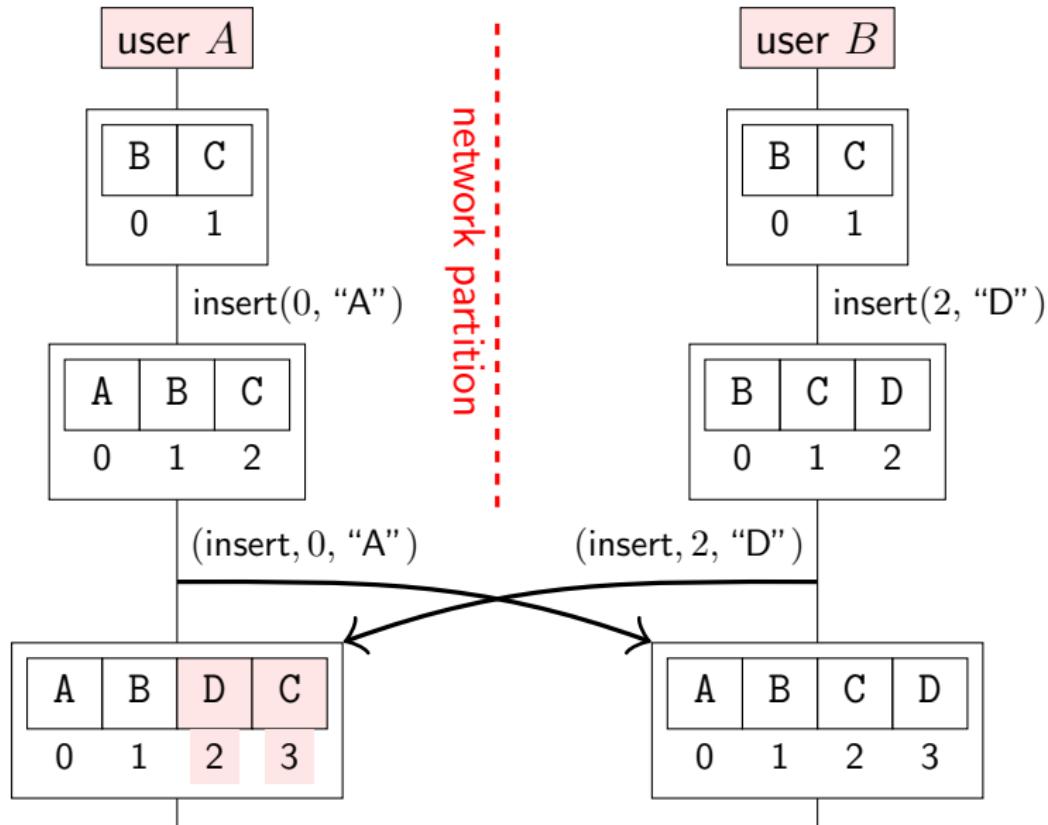
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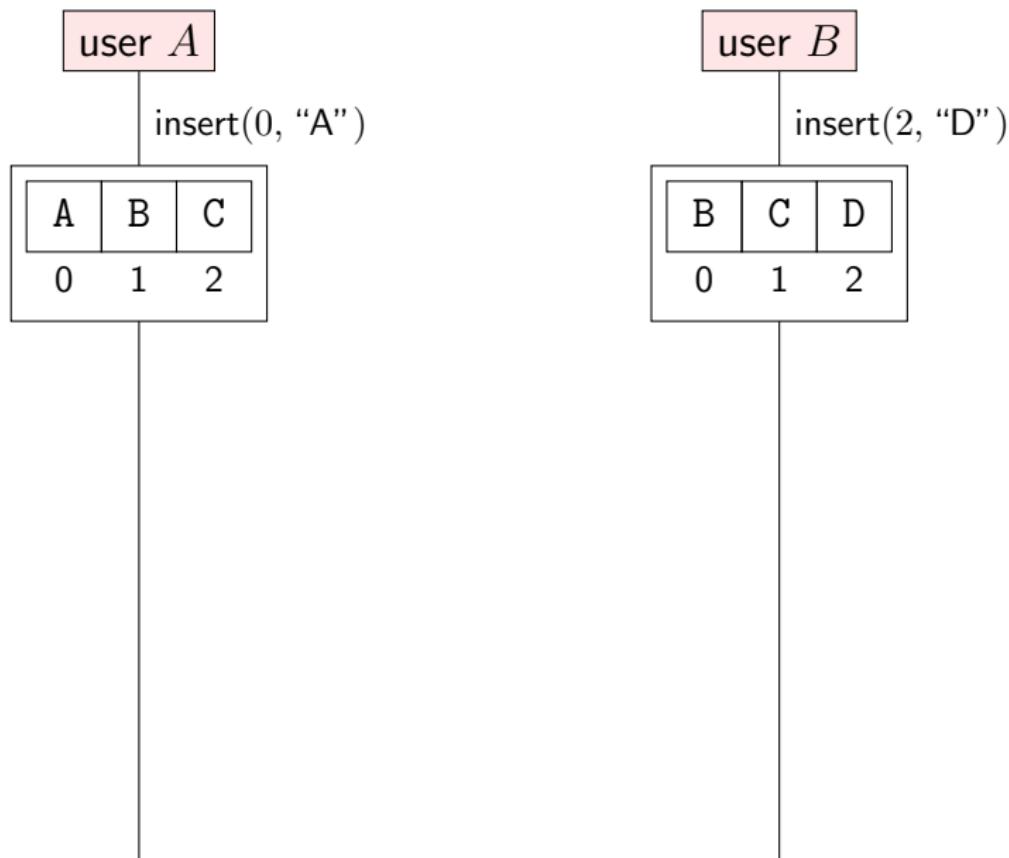
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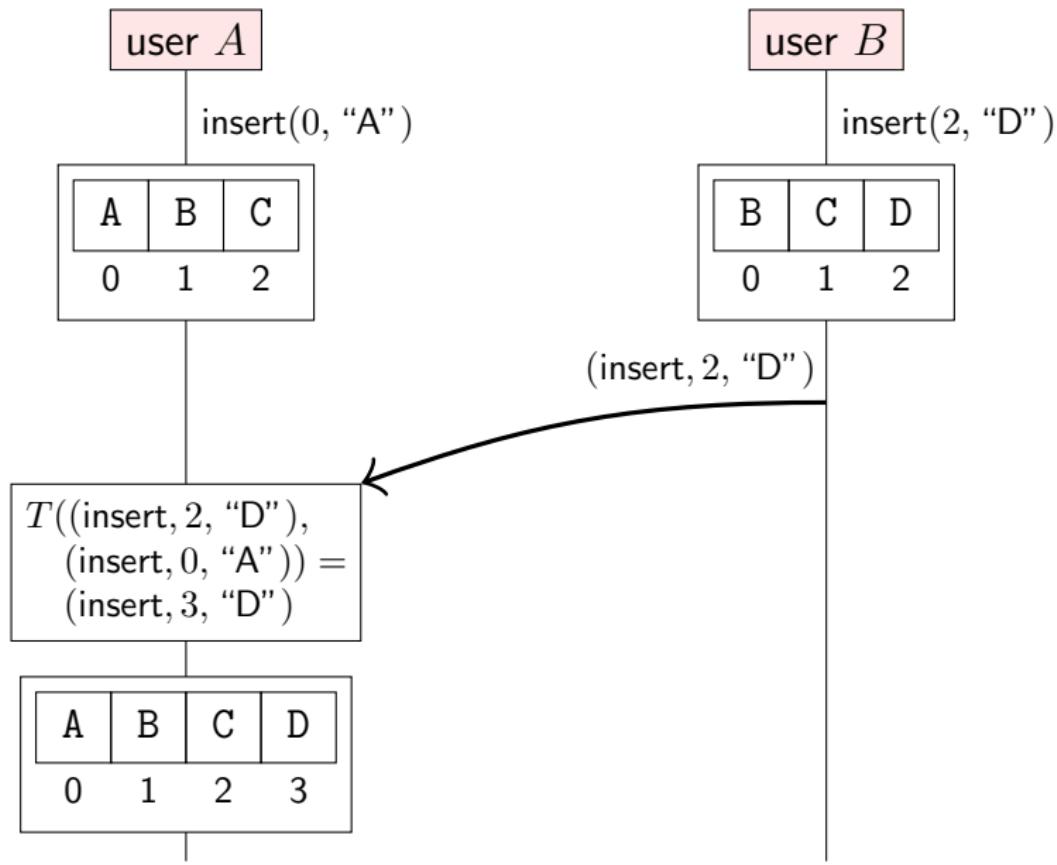
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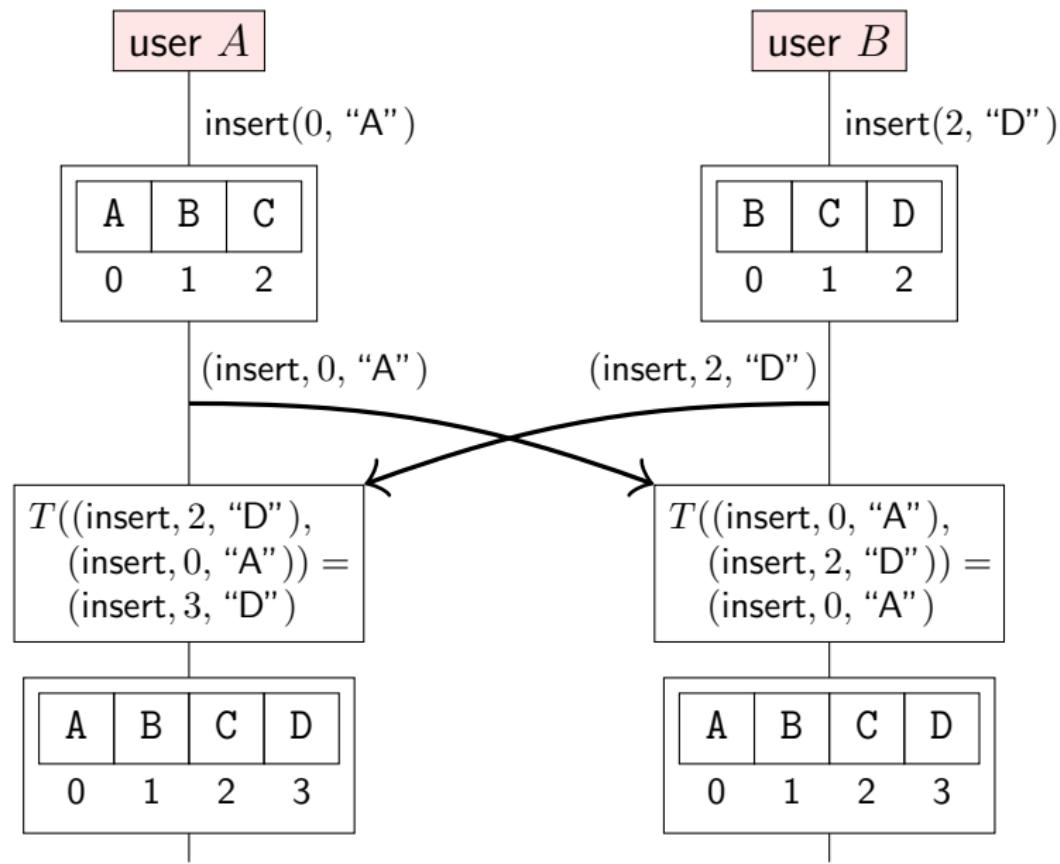
# Operational transformation



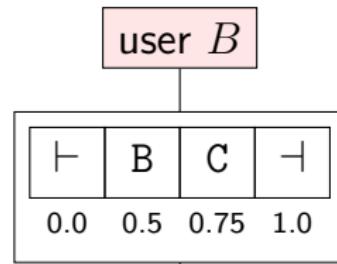
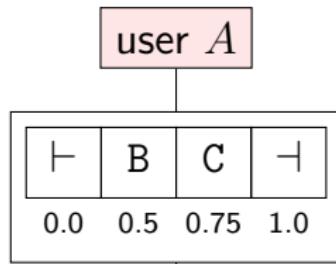
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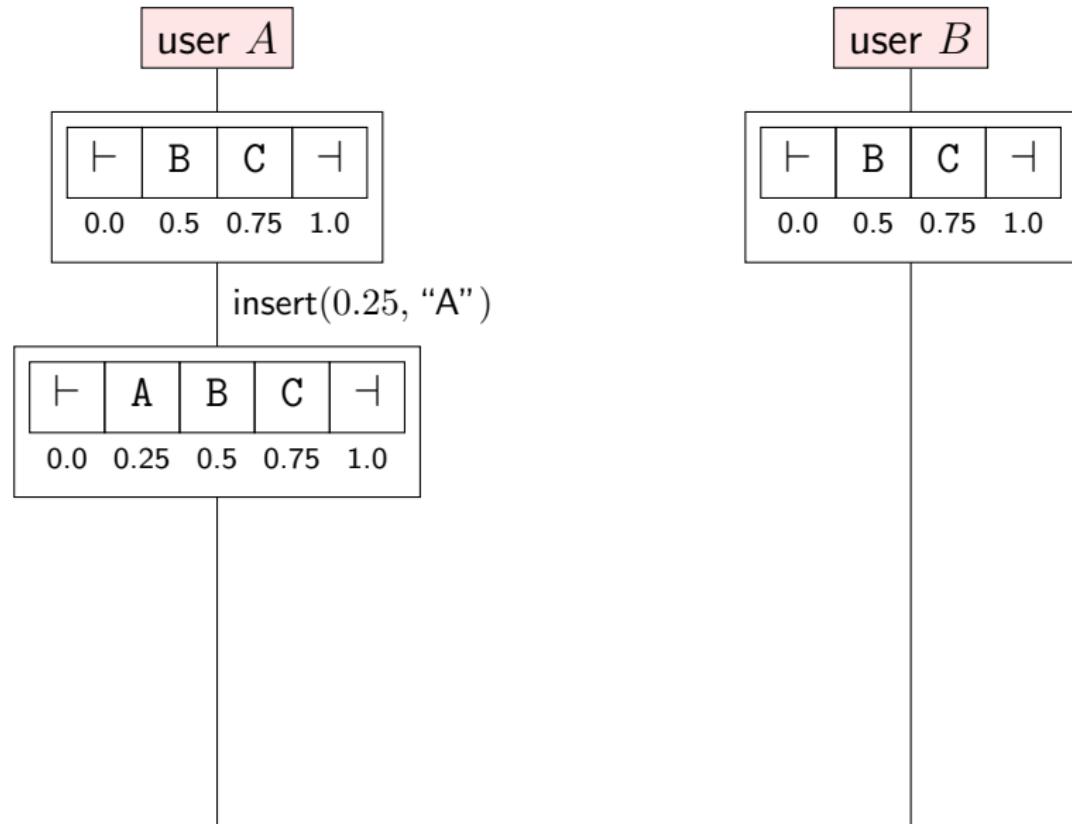
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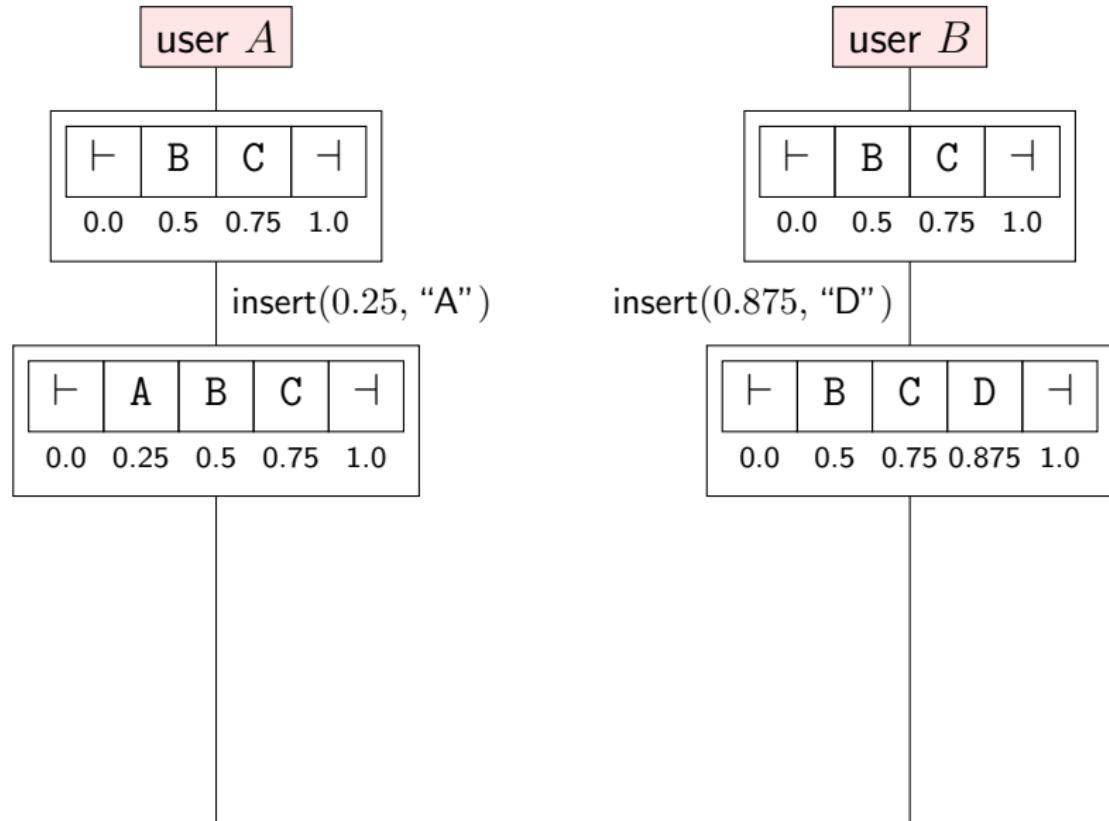
# Text editing CRDT



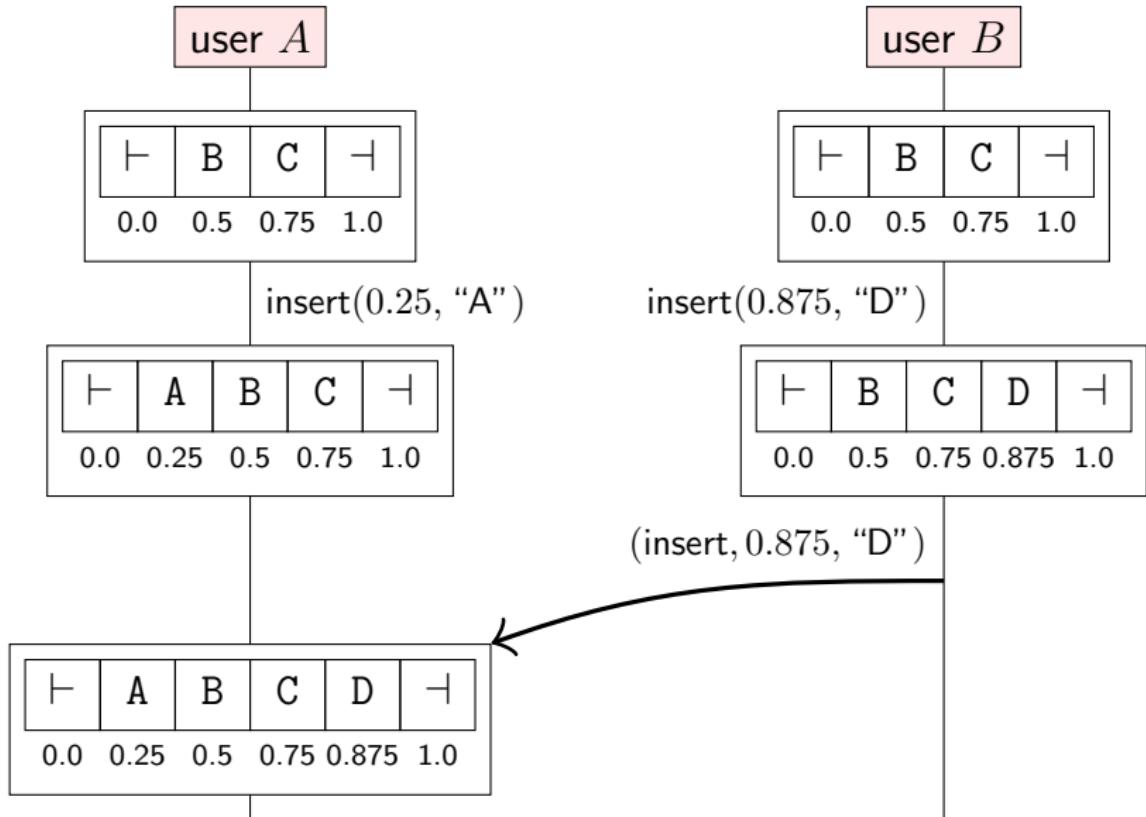
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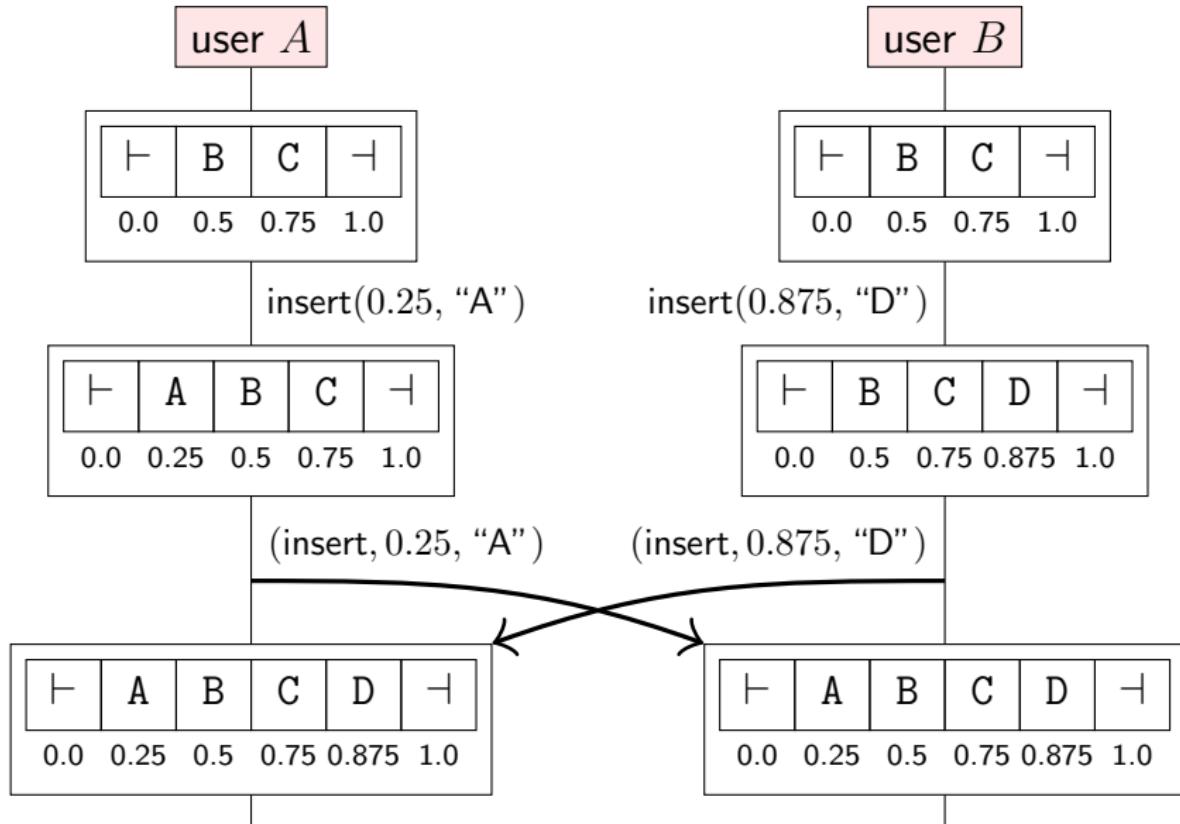
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# Operation-based text CRDT (1/2)

**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,  $(p_1 + p_2)/2$ , *nodeId*, *v*) by causal broadcast

**end on**

## Operation-based text CRDT (2/2)

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

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

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

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

# Google's Spanner

A database system with millions of nodes, petabytes of data,  
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The interesting bit: read-only transactions require **no locks!**

## Consistent snapshots

A read-only transaction observes a **consistent snapshot**:

If  $T_1 \rightarrow T_2$  (e.g.  $T_2$  reads data written by  $T_1$ )...

- ▶ Snapshot reflecting writes by  $T_2$  also reflects writes by  $T_1$
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- ▶ Read-only transaction  $T_r$  has snapshot timestamp  $t_r$
- ▶  $T_r$  ignores values with  $t_w > t_r$ ; observes most recent value with  $t_w \leq t_r$

## Obtaining commit timestamps

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

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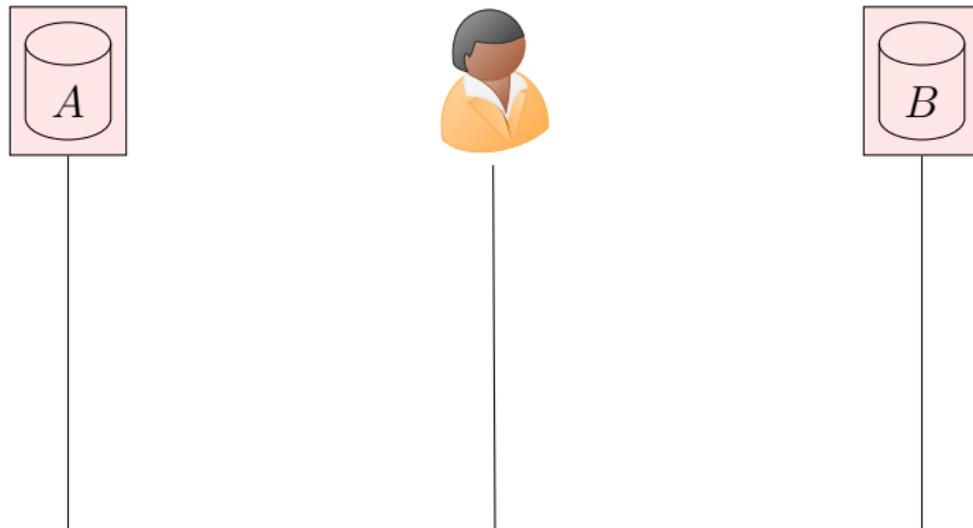
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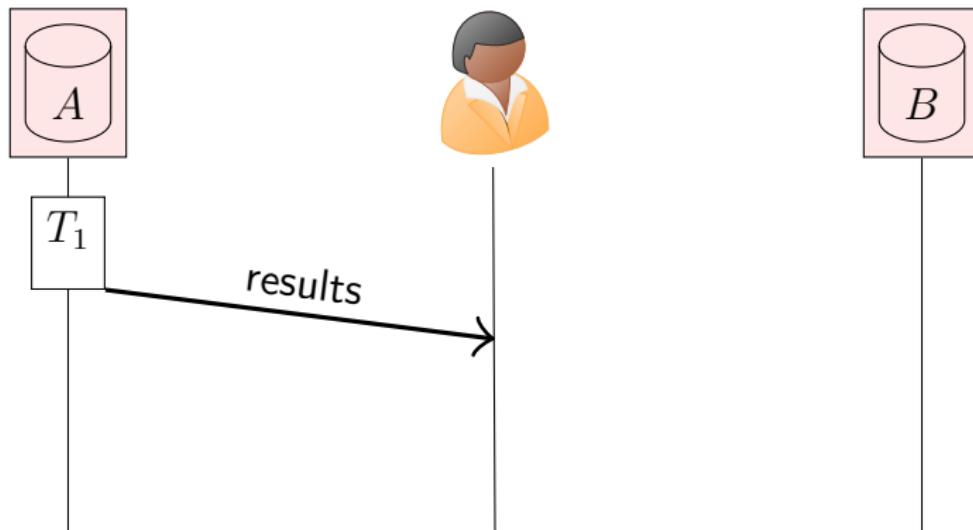
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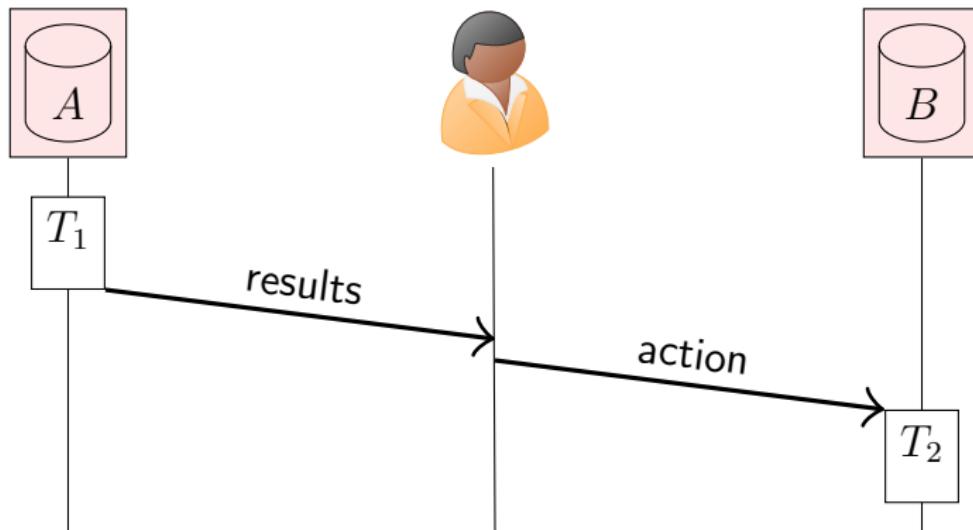
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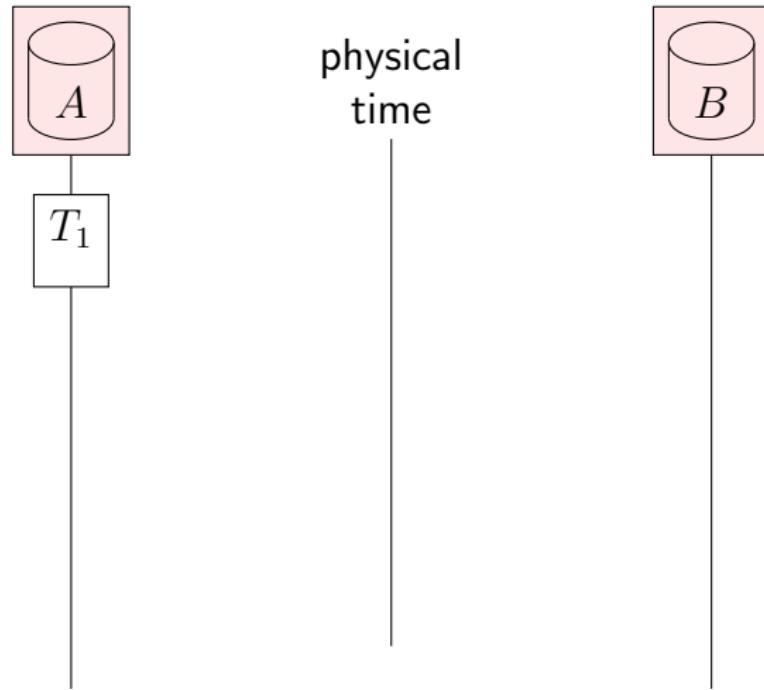
# Obtaining commit timestamps

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

- ▶ Physical clocks may be **inconsistent with causality**
- ▶ Can we use Lamport clocks instead?
- ▶ Problem: linearizability depends on **real-time order**, and logical clocks may not reflect this!



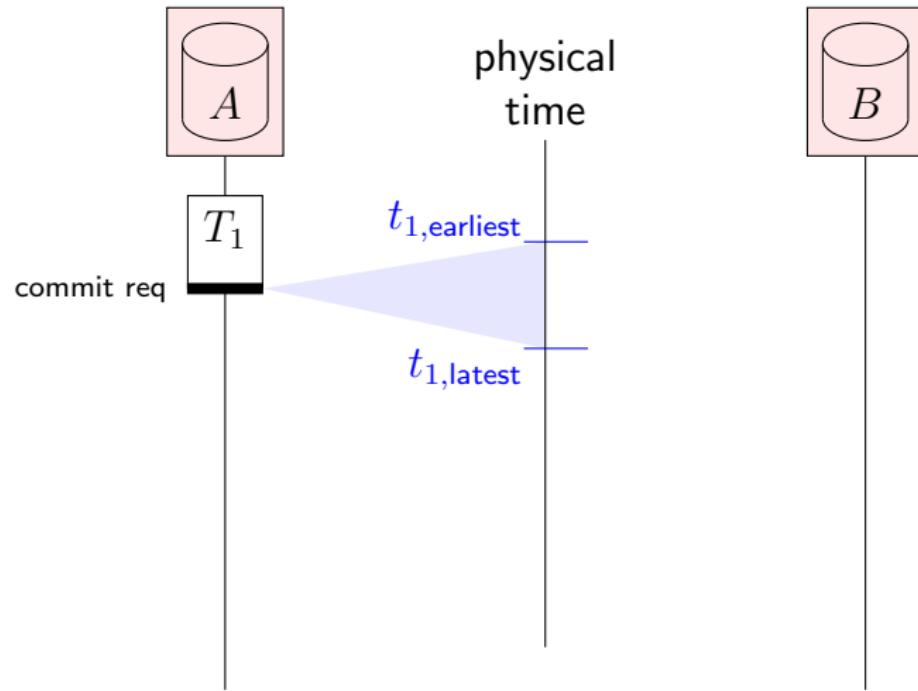
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True physical timestamp must lie within that range.

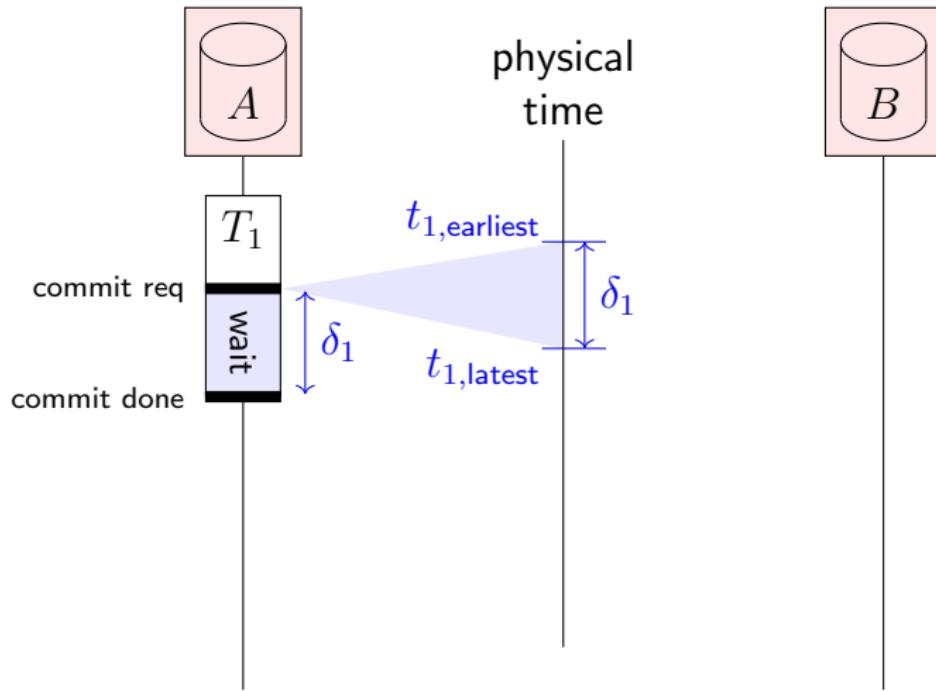


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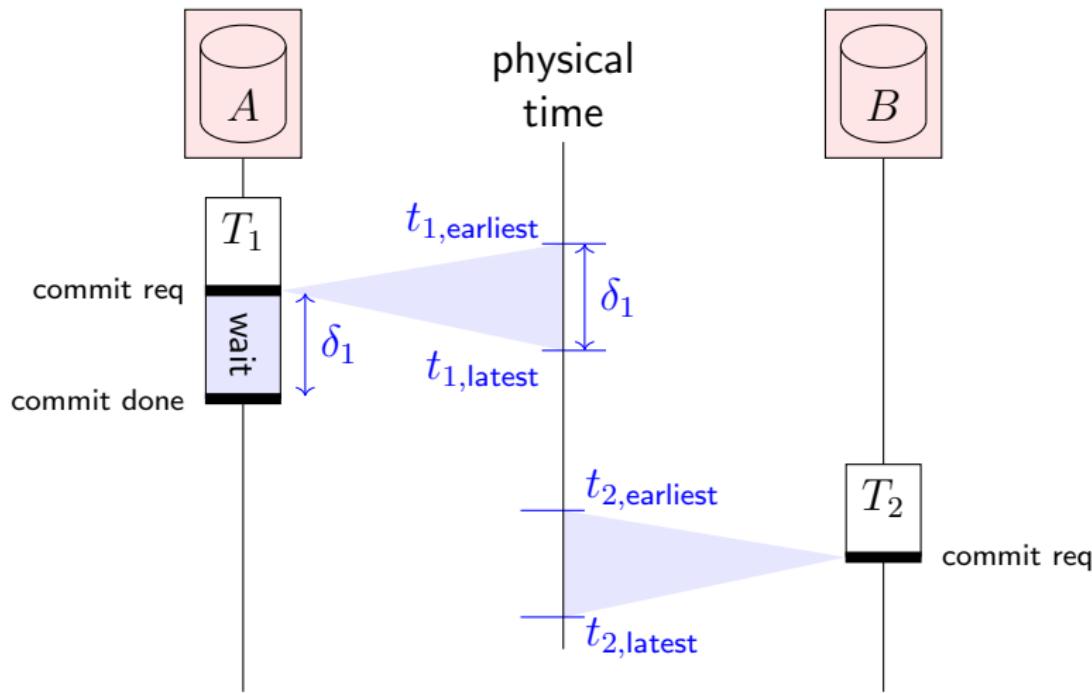


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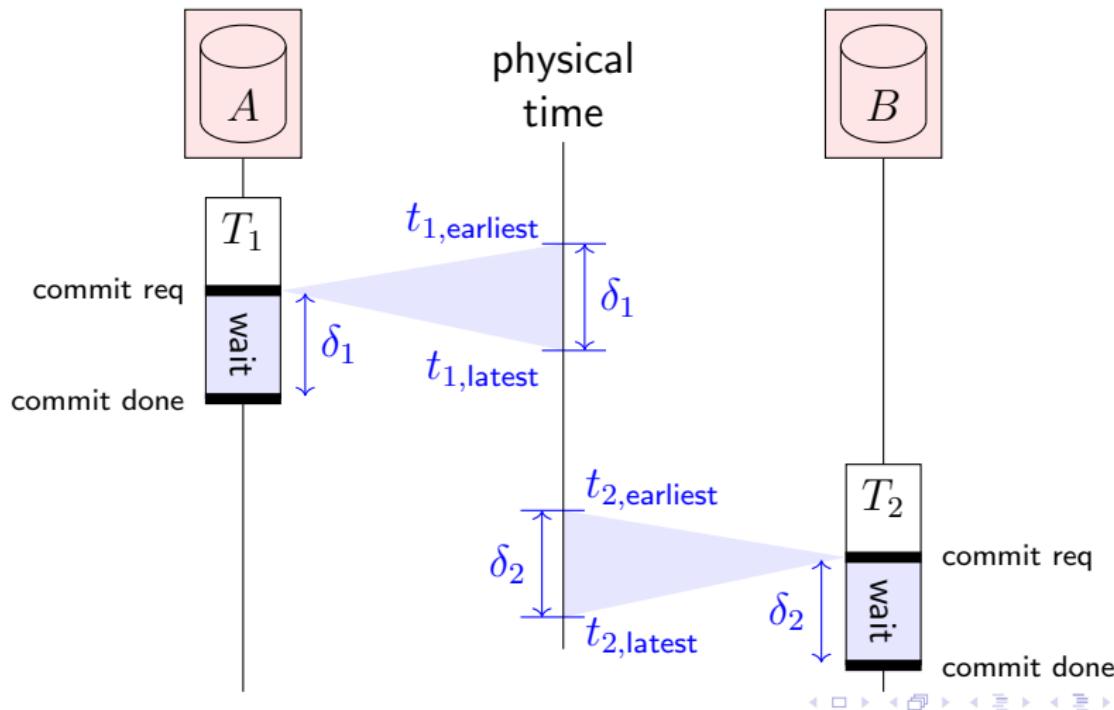


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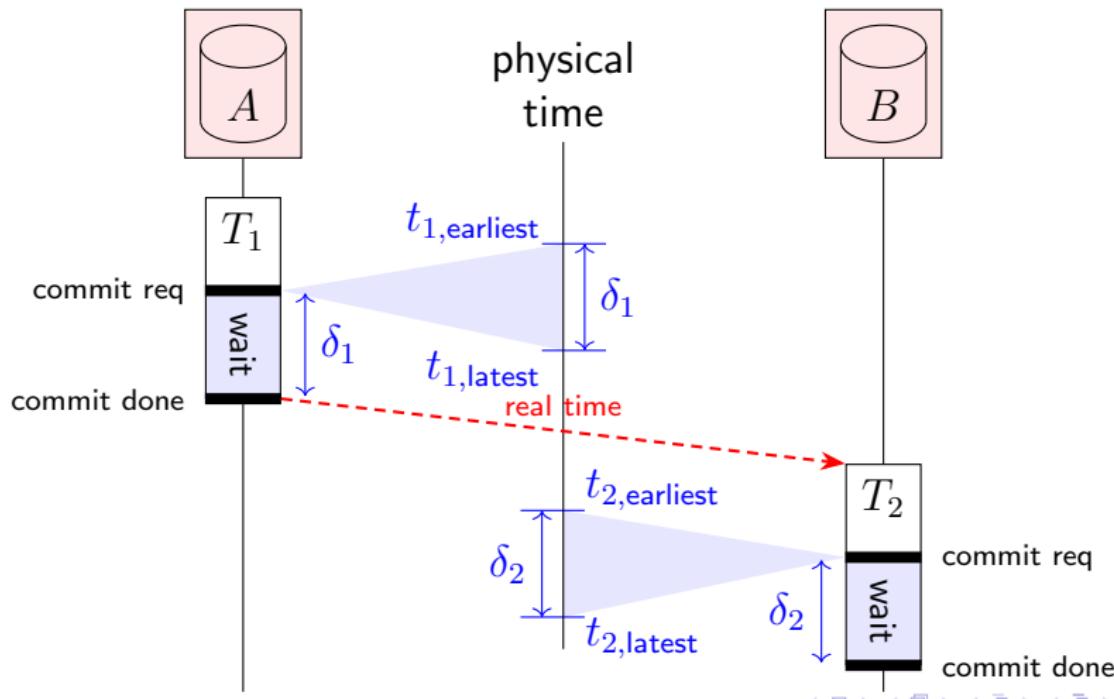


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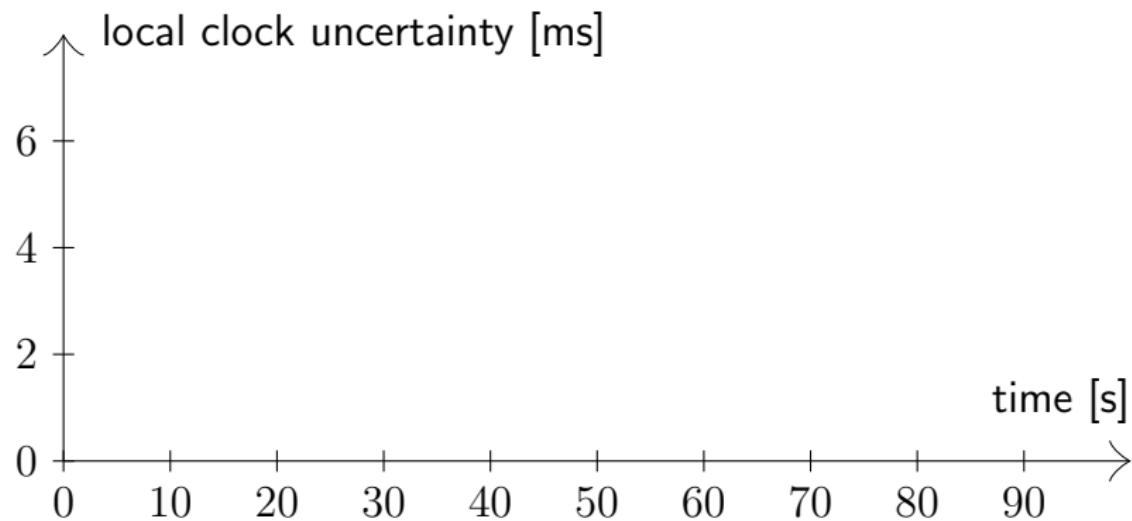
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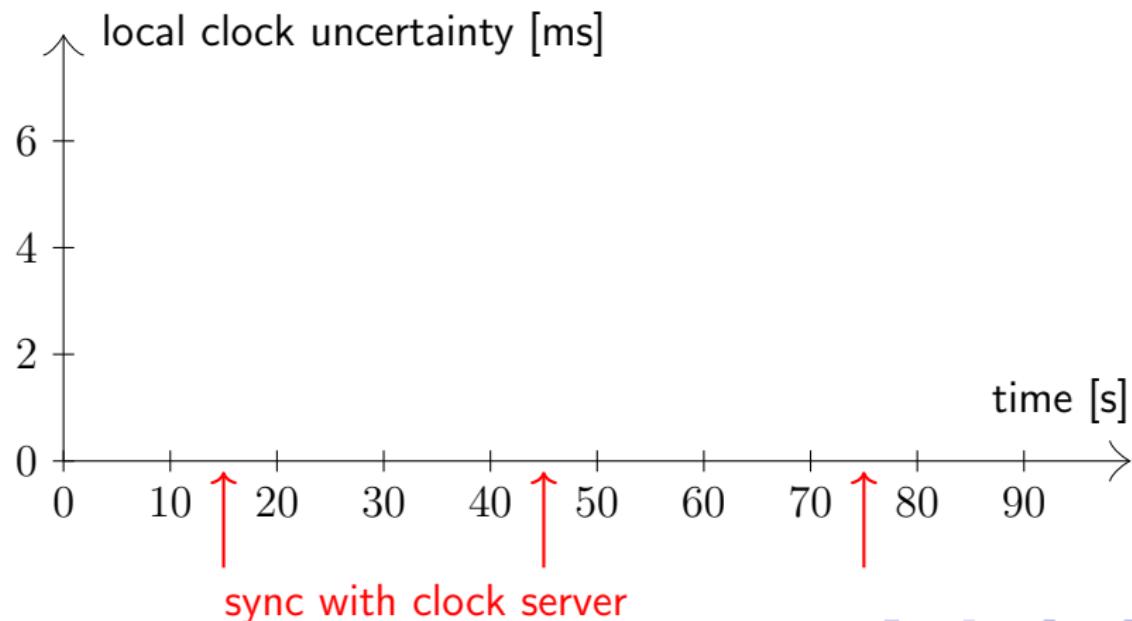
## Determining clock uncertainty in TrueTime

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



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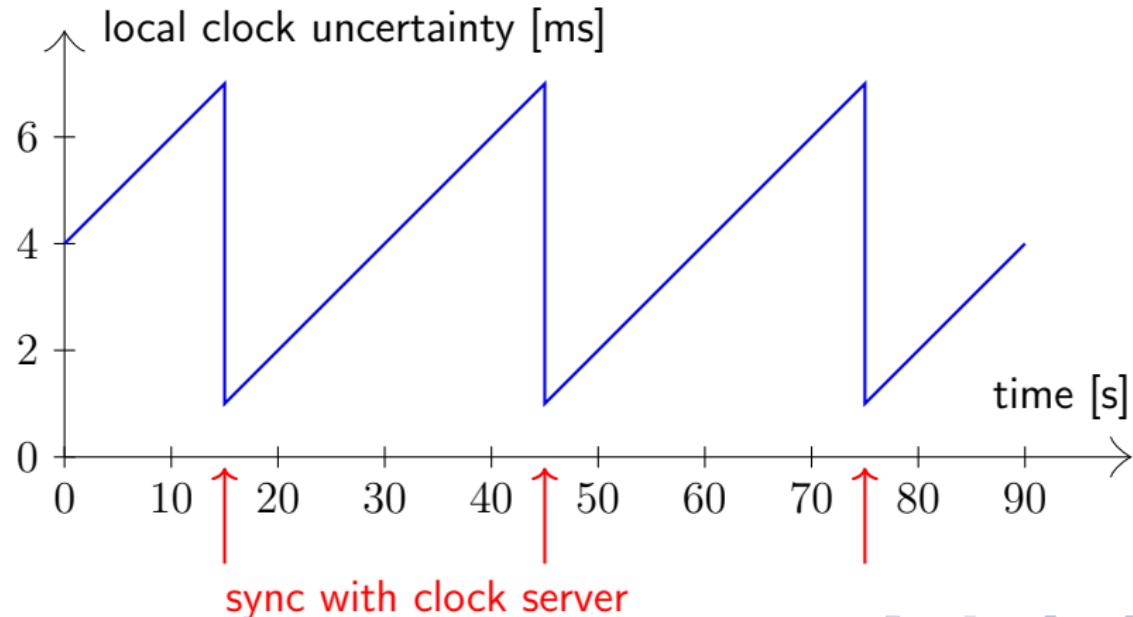
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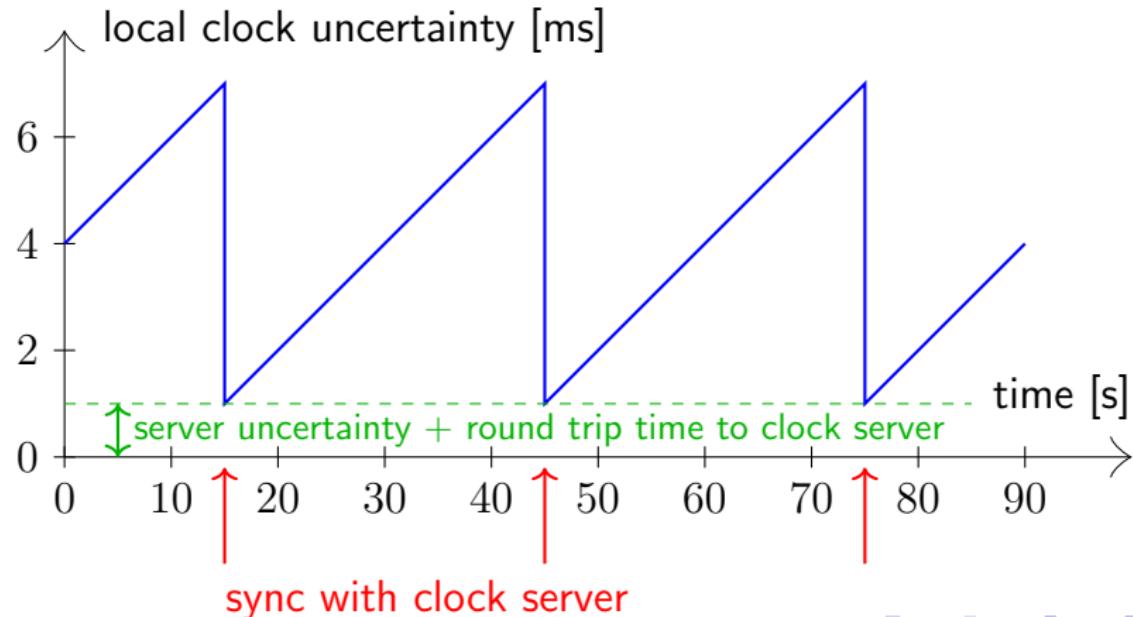
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# That's all, folks!

**Any questions?** Email [mk428@cst.cam.ac.uk](mailto:mk428@cst.cam.ac.uk)!

Summary:

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