Distributed Systems
Principles and Paradigms

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Chapter 06: Synchronization

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Clock Synchronization

- Physical clocks
- Logical clocks
- Vector clocks

Physical clocks

Problem

Sometimes we simply need the exact time, not just an ordering.

Solution

Universal Coordinated Time (UTC):

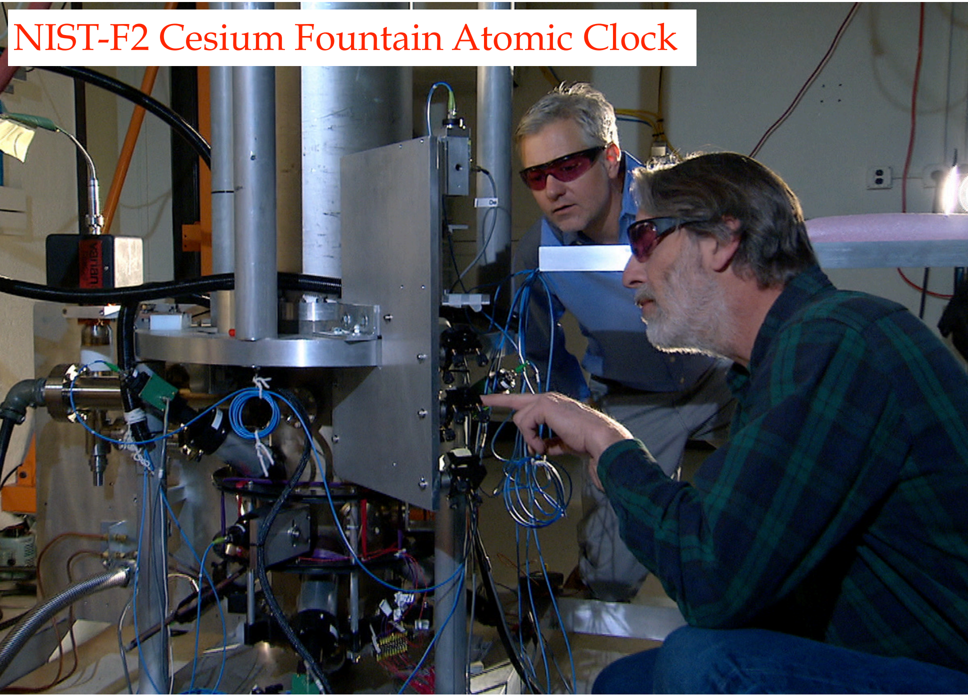
- Based on the number of transitions per second of the cesium 133 atom (pretty accurate). 1 second = 9 192 631 770 hyperfine transitions
- At present, the real time is taken as the average of some 50 cesium-clocks around the world.
- Introduces a leap second from time to time to compensate that days are getting longer.

Note

UTC is broadcast through short wave radio and satellite. Satellites can give an accuracy of about ± 0.5 ms.

see: https://www.timeanddate.com/time/how-do-atomic-clocks-work.html

NIST-F2 Cesium Fountain Atomic Clock



Physical clocks

clock drift

Problem

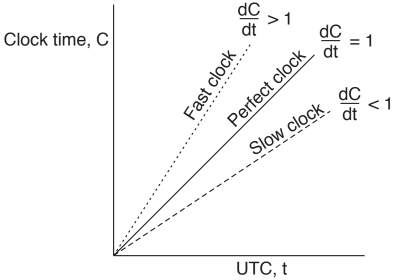
Suppose we have a distributed system with a UTC-receiver somewhere in it $\Rightarrow$ we still have to distribute its time to each machine.

Basic principle

- Every machine has a timer that generates an interrupt H times per second.
- There is a clock in machine p that ticks on each timer interrupt. Denote the value of that clock by $C_p(t)$, where t is UTC time.
- Ideally, we have that for each machine p, $C_p(t) = t$, or, in other words, $dC/dt = 1$.

Physical clocks

idea:
total drift per time unit = 2.rho
total drift after n time units = 2.rho.n
if 2.rho.n <= delta (maximum allowed error)
then synchronize every n <= delta / (2.rho) time units



In practice: $1-\rho \leq \frac{dC}{dt} \leq 1+\rho$.

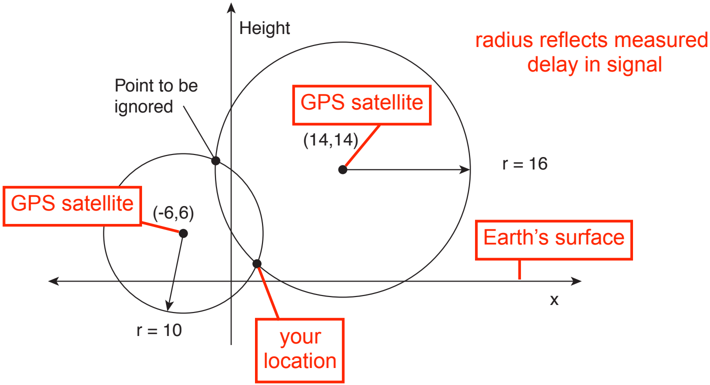
Goal

Never let two clocks in any system differ by more than δ time units $\Rightarrow$ synchronize at least every $\delta/(2\rho)$ seconds.

Global positioning system

Basic idea

You can get an accurate account of time as a side-effect of GPS.



Global positioning system

each GPS satellite is equiped with it own very precise and sophisticated atomic clock

Problem

Assuming that the clocks of the satellites are accurate and synchronized:

- It takes a while before a signal reaches the receiver
- The receiver's clock is definitely out of synch with the satellite

message delay must be computed also and included in the calculation of local position and time

time flows slower in space than on Earth's surface (really!!) General Relativity effects must be taken into account!

Global positioning system

Principal operation

- Δ_r: unknown deviation of the receiver's clock.
- x_r, y_r, z_r: unknown coordinates of the receiver.
- T_i: timestamp on a message from satellite i
- $\Delta_i = (T_{now} - T_i) + \Delta_r$: measured delay of the message sent by satellite i.
- Measured distance to satellite i: $c \times \Delta_i$
  (c is speed of light)
- Real distance is

$$d_i = c\Delta_i - c\Delta_r = \sqrt{(x_i - x_r)^2 + (y_i - y_r)^2 + (z_i - z_r)^2}$$

Observation

4 satellites $\Rightarrow$ 4 equations in 4 unknowns (with Δ_r as one of them)

Clock synchronization principles

absolute time UTC

Time Servers keep their clocks synchronized through atomic clocks

Principle I

Every machine asks a time server for the accurate time at least once every $\delta/(2\rho)$ seconds (Network Time Protocol).

Note

Okay, but you need an accurate measure of round trip delay, including interrupt handling and processing incoming messages.

messages are not instantaneous

Clock synchronization principles

Principle II

relative time

Let the time server scan all machines periodically, calculate an average, and inform each machine how it should adjust its time relative to its present time.

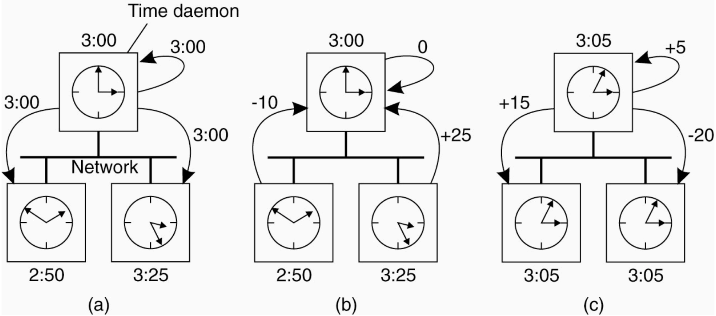
Note

Okay, you'll probably get every machine in sync. You don't even need to propagate UTC time.

Fundamental

You'll have to take into account that setting the time back is never allowed ⇒ smooth adjustments.

causes software to crash,
solution: slow down machine clock



Time daemon
3:00
3:00
3:00
3:00
Network
2:50
3:25
(a)
3:00
0
-10
+25
2:50
3:25
(b)
3:05
+5
+15
-20
3:05
3:05
(c)

The Happened-before relationship

with Logical (Software) Clocks absolute time is irrelevant
peers agreeing on an ordering of messages is enough
goal: all messages are seen in the same order by all peers

Problem

We first need to introduce a notion of ordering before we can order anything.

The happened-before relation

- If a and b are two events in the same process, and a comes before b, then $a \rightarrow b$.
- If a is the sending of a message, and b is the receipt of that message, then $a \rightarrow b$
- If $a \rightarrow b$ and $b \rightarrow c$, then $a \rightarrow c$

Note

This introduces a partial ordering of events in a system with concurrently operating processes.

Logical clocks

this is as trivial as an integer counter

Problem

How do we maintain a global view on the system's behavior that is consistent with the happened-before relation?

Solution

Attach a timestamp $C(e)$ to each event e, satisfying the following properties:

- **P1** If a and b are two events in the same process, and $a \rightarrow b$, then we demand that $C(a) < C(b)$.
- **P2** If a corresponds to sending a message m, and b to the receipt of that message, then also $C(a) < C(b)$.

Problem

How to attach a timestamp to an event when there's no global clock $\Rightarrow$ maintain a consistent set of logical clocks, one per process.

one integer counter per process

Logical clocks

also called Lamport Clocks
(after Leslie Lamport)
https://en.wikipedia.org/wiki/Leslie_Lamport

Solution

Each process P_i maintains a local counter C_i and adjusts this counter according to the following rules:

1: For any two successive events that take place within P_i, C_i is incremented by 1. e.g., event = sending a message

2: Each time a message m is sent by process P_i, the message receives a timestamp $ts(m) = C_i$.

3: Whenever a message m is received by a process P_j, P_j adjusts its local counter C_j to $\max\{C_j, ts(m)\}$; then executes step 1 before passing m to the application.

note 2 steps in reception:
1- message received and placed in queue
2- message removed from queue and passed to Pj

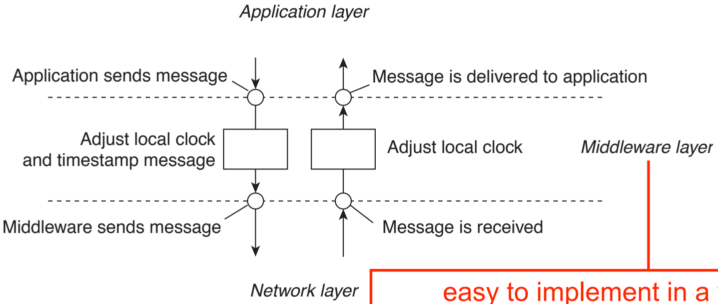
Notes

- Property P1 is satisfied by (1); Property P2 by (2) and (3).
- It can still occur that two events happen at the same time. Avoid this by breaking ties through process IDs.

Logical clocks – example

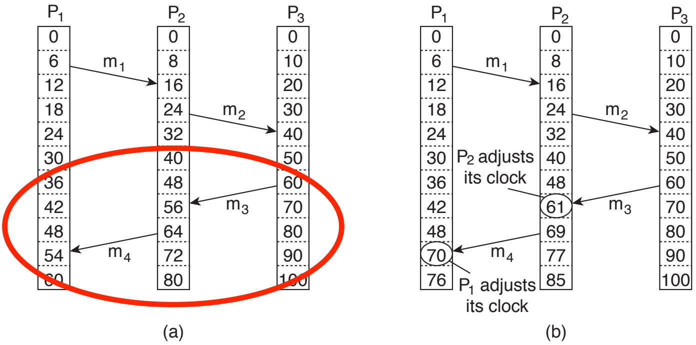
Note

Adjustments take place in the middleware layer



easy to implement in a way that is transparent to programmers: let a middleware hide it

Logical clocks – example



without

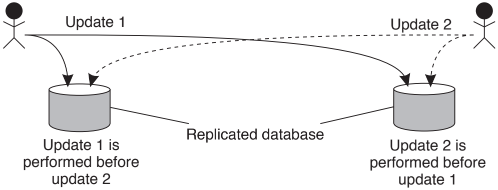
with

Example: Totally ordered multicast

Problem

We sometimes need to guarantee that concurrent updates on a replicated database are seen in the same order everywhere:

- P_1 adds \$100 to an account (initial value: \$1000)
- P_2 increments account by 1%
- There are two replicas



Result

In absence of proper synchronization:
replica #1 $\leftarrow$ \$1111, while replica #2 $\leftarrow$ \$1110.

replica1	replica2
up1,up2	up1,up2 (ok)
up1,up2	up2,up1 (wrong)
up2,up1	up1,up2 (wrong)
up2,up1	up2,up1 (ok)

Example: Totally ordered multicast

first part of reception

meaning: messages placed in queue ordered by timestamps => priority queue

Solution

- Process P_i sends timestamped message msg_i to all others. The message itself is put in a local queue $queue_i$.
- Any incoming message at P_j is queued in $queue_j$, according to its timestamp, and acknowledged to every other process.

P_j passes a message msg_i to its application if:

second part of reception

(1) msg_i is at the head of $queue_j$
(2) for each process P_k, there is a message msg_k in $queue_j$ with a larger timestamp.

note: only do this for real messages, acks at the head of the queue are discarded immediately

Note

We are assuming that communication is reliable and FIFO ordered.

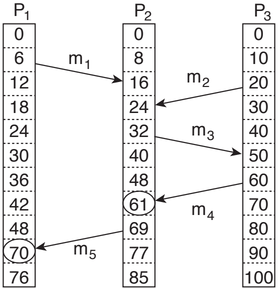
no network failures

if P sends m1 and then m2, any other process will receive m1 first and only then m2

Vector clocks

Observation

Lamport's clocks do not guarantee that if $C(a) < C(b)$ that a causally preceded b



Observation

Event a: m_1 is received at $T = 16$;
Event b: m_2 is sent at $T = 20$.

even though C(a) < C(b)
the events are not related

Note

We cannot conclude that a causally precedes b.

Vector clocks

Solution

- Each process P_i has an array $VC_i[1..n]$, where $VC_i[j]$ denotes the number of events that process P_i knows have taken place at process P_j.
- When P_i sends a message m, it adds 1 to $VC_i[i]$, and sends VC_i along with m as vector timestamp $vt(m)$. Result: upon arrival, recipient knows P_i's timestamp.
- When a process P_j delivers a message m that it received from P_i with vector timestamp $ts(m)$, it

  (1) updates each $VC_j[k]$ to $\max\{VC_j[k], ts(m)[k]\}$
  (2) increments $VC_j[j]$ by 1.

Question

What does $VC_i[j] = k$ mean in terms of messages sent and received?

Causally ordered multicasting

Observation

We can now ensure that a message is delivered only if all causally preceding messages have already been delivered.

Adjustment

P_i increments $VC_i[i]$ only when sending a message, and P_j "adjusts" VC_j when receiving a message (i.e., effectively does not change $VC_j[j]$).

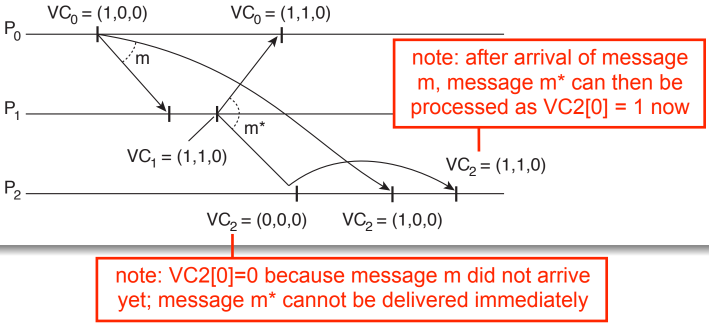
P_j postpones delivery of m until:

- $ts(m)[i] = VC_j[i] + 1$. Pj knows all messages from Pi, plus the current (+1)
- $ts(m)[k] \leq VC_j[k]$ for $k \neq i$.

for the other processes, Pj knows at least as much as Pi

Causally ordered multicasting

Example



Example

Take $VC_2 = [0,2,2]$, $ts(m) = [1,3,0]$ from P_0. What information does P_2 have, and what will it do when receiving m (from P_0)?

Mutual exclusion

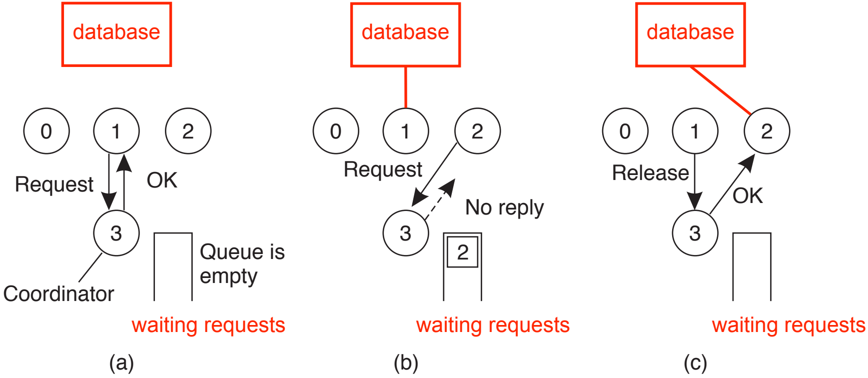
Problem

A number of processes in a distributed system want exclusive access to some resource.

Basic solutions

- Via a centralized server.
- Completely decentralized, using a peer-to-peer system.
- Completely distributed, with no topology imposed.
- Completely distributed along a (logical) ring.

Mutual exclusion: centralized



Decentralized mutual exclusion

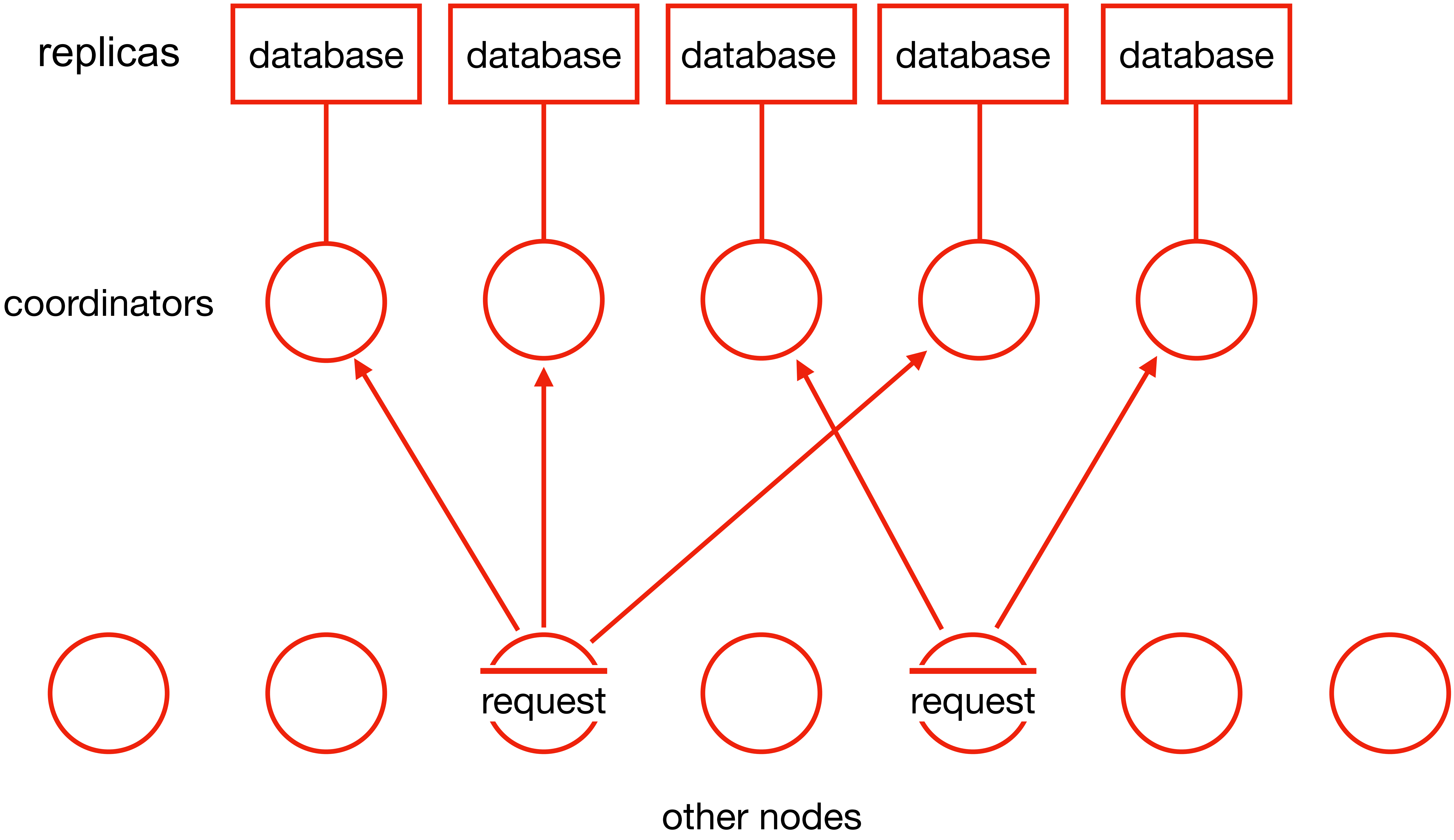
Principle

Assume every resource is replicated n times, with each replica having its own coordinator $\Rightarrow$ access requires a majority vote from $m > n/2$ coordinators. A coordinator always responds immediately to a request.

Assumption

When a coordinator crashes, it will recover quickly, but will have forgotten about permissions it had granted.

this can result in a failure as other clients may contact these coordinators and have access to the resource, breaking the mutual exclusion of the original client


replicas
database
database
database
database
database
coordinators
request
request
other nodes

Decentralized mutual exclusion

Issue

How robust is this system? Let $p = \Delta t / T$ denote the probability that a coordinator crashes and recovers in a period Δt while having an average lifetime $T \Rightarrow$ probability that k out m coordinators reset:

$$P[\text{violation}] = p_v = \underbrace{\sum_{k=2m-n}^{n}}_{} \binom{m}{k} p^k (1-p)^{m-k}$$

With $p = 0.001$, $n = 32$, $m = 0.75n$, $\underline{p_v < 10^{-40}}$

limit corresponds to minimum condition for majority

m > n/2 <=> 2m-n > 0

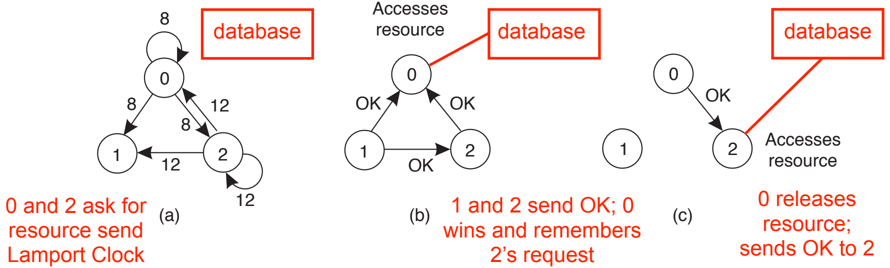
note: probability of multiple coordinators down is very low thus algorithm is robust **but** involves exchange of many messages

Mutual exclusion Ricart & Agrawala

Principle

The same as Lamport except that acknowledgments aren't sent. Instead, replies (i.e. grants) are sent only when

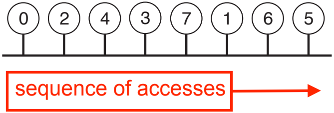
- The receiving process has no interest in the shared resource; or
- The receiving process is waiting for the resource, but has lower priority (known through comparison of timestamps).
- In all other cases, reply is deferred, implying some more local administration.



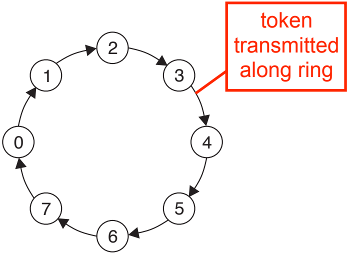
Mutual exclusion: Token ring algorithm

Essence

Organize processes in a *logical* ring, and let a token be passed between them. The one that holds the token is allowed to enter the critical region (if it wants to).



(a)



(b)

Mutual exclusion: comparison

n - number of nodes
m - number of coordinators
k - number of tries

Algorithm	# msgs	Delay	Problems
Centralized	3	2	Coordinator crash
Decentralized	3mk, k = 1,2,...	2 m	Starvation, low eff.
Distributed	2 (n – 1)	2 (n – 1)	Crash of any process
Token ring	1 to ∞	0 to n – 1	Lost token, proc. crash

Election algorithms

Principle

An algorithm requires that some process acts as a coordinator. The question is how to select this special process dynamically.

Note

In many systems the coordinator is chosen by hand (e.g. file servers). This leads to centralized solutions $\Rightarrow$ single point of failure.

Question

If a coordinator is chosen dynamically, to what extent can we speak about a centralized or distributed solution?

Question

Is a fully distributed solution, i.e. one without a coordinator, always more robust than any centralized/coordinated solution?

Election by bullying

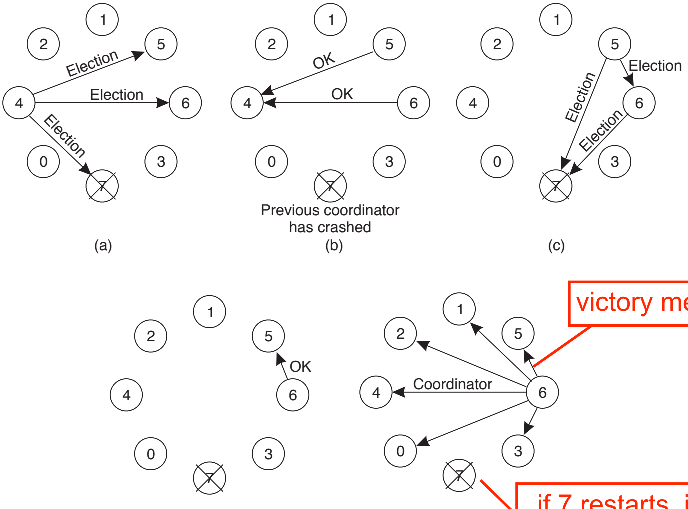
Principle

Each process has an associated priority (weight). The process with the highest priority should always be elected as the coordinator.
How do we find the heaviest process?

- Any process can just start an election by sending an election message to all other processes (assuming you don't know the weights of the others).
- If a process P_{heavy} receives an election message from a lighter process P_{light}, it sends a take-over message to P_{light}. P_{light} is out of the race.
- If a process doesn't get a take-over message back, it wins, and sends a victory message to all other processes.

Election by bullying

note: OK = “take over” message



(a) (b) (c) (d) (e)

victory messages

if 7 restarts, it initiates a new election and wins

why is this called the “Bullying Algorithm” ?

Election in a ring

Principle

priority = id

Process priority is obtained by organizing processes into a (logical) ring. Process with the highest priority should be elected as coordinator.

- Any process can start an election by sending an election message to its successor. If a successor is down, the message is passed on to the next successor.
- If a message is passed on, the sender adds itself to the list. When it gets back to the initiator, everyone had a chance to make its presence known.
- The initiator sends a coordinator message around the ring containing a list of all living processes. The one with the highest priority is elected as coordinator.

the initiator knows the election message did a full turn because it sees its own id in it