Synchronization

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Based on slides by Maarten Van Steen

What is the problem?

Two Generals' Problem (1/3)

- Two generals need to coordinate an attack.
  - Must agree on time to attack.
  - They will win only if they attack simultaneously.
  - Communicate through messengers.
  - Messengers may be killed on their way.

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- This problem is impossible to solve!

Two Generals' Problem (3/3)

- Applicability to distributed systems:
  - Two nodes need to agree on a value.
  - Communicate by messages using an unreliable channel.
- Agreement is a core problem.

Clock Synchronization

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- Physical clocks
- Logical clocks

Physical Clock

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  - Based on the number of transitions per second of the cesium 133 atom.
  - At present, the real time is taken as the average of some 50 cesium-clocks around the world.
- UTC is broadcast through short wave radio and satellite.

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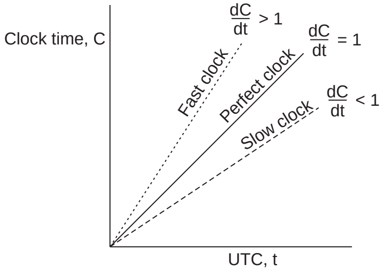
  - There is a clock in machine p that ticks on each timer interrupt. Denote the value of that clock by $C_p(t)$, where t is UTC time.
  - Ideally, we have that for each machine p, $C_p(t) = t$, or, in other words, $\frac{dC}{dt} = 1$.

Physical Clock (3/3)

- In practice: $1 - \rho \leq \frac{dC}{dt} \leq 1 + \rho$.
- Never let two clocks in any system differ by more than δ time units $\Rightarrow$ synchronize at least every $\delta/(2\rho)$ seconds.



Clock Synchronization

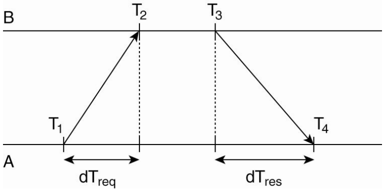
- Network Time Protocol (NTP)
- The Berkeley algorithm

Clock Synchronization - NTP

- Network Time Protocol (NTP)

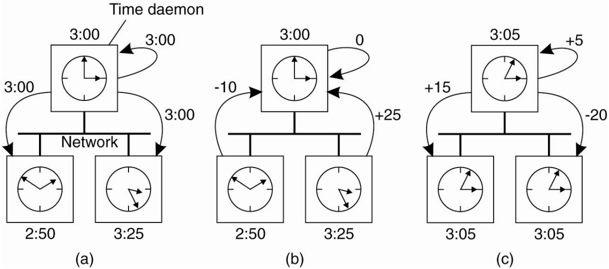
- Every machine asks a time server for the accurate time at least once every $\delta/(2\rho)$ seconds.

- You need an accurate measure of round trip delay, including interrupt handling and processing incoming messages.



Clock Synchronization - The Berkeley Algorithm

- The time daemon asks all the other machines for their clock values.
- The machines answer.
- The time daemon tells everyone how to adjust their clock.



Logical Clock

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  - If $a \rightarrow b$ and $b \rightarrow c$, then $a \rightarrow c$.
- If two events, a and b, happen in different processes that do not exchange messages, then $a \rightarrow b$ is not true, but neither is $b \rightarrow a$. These events are said to be concurrent.

Lamport Logical Clocks (1/4)

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  - 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 $C(a) < C(b)$.

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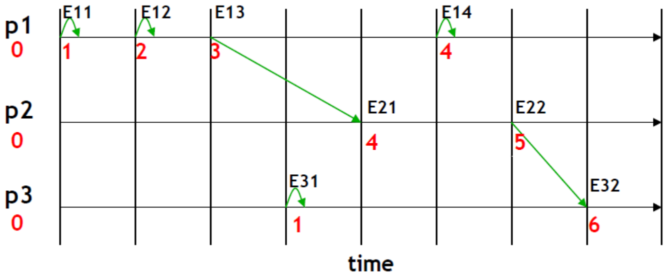
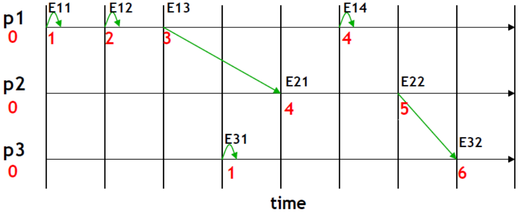
- Property P1 is satisfied by (1); Property P2 by (2) and (3).

Lamport Logical Clocks (3/4)



Lamport Logical Clocks (4/4)

- $a \to b$ implies $C(a) < C(b)$.
- $C(a) < C(b)$ does not necessarily imply $a \to b$.
- $C(E31) < C(E13)$, but $E31 \not\to E13$.



Example: Totally Ordered Multicast (1/2)

- 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)
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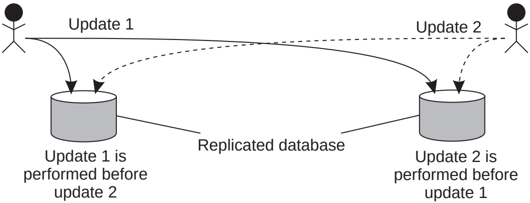

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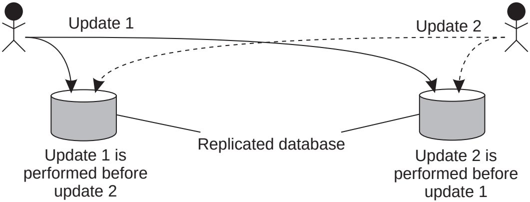
- In absence of proper synchronization:
  replica #1 $\leftarrow$ \$1111, while replica #2 $\leftarrow$ \$1110.



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- We are assuming that communication is reliable and FIFO ordered.

Shortcoming of Lamport Clocks

- Main shortcoming of Lamport's clocks:
  - $C(a) < C(b)$ does not necessarily imply $a \rightarrow b$
  - We cannot deduce causal dependencies from time stamps.

- Why?
  - Clocks advance independently or via messages.
  - There is no history as to where advances come from.

Vector Clocks (1/2)

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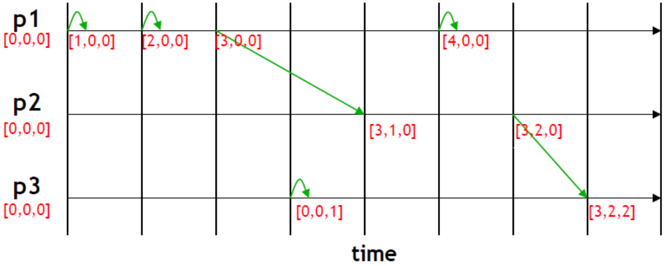
- $VC_i[j] = k$ tells us that P_i knows that P_j has sent k messages.

Vector Clocks (2/2)



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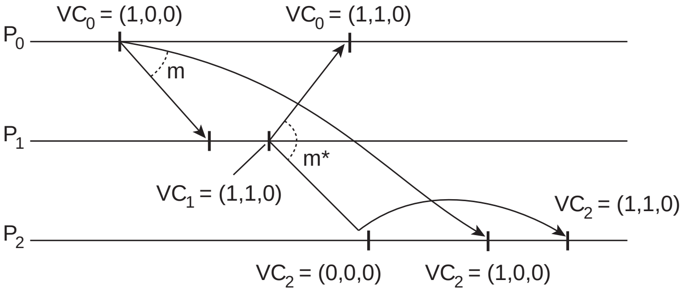
- P_i increments $VC_i[i]$ only when sending a message, and P_j adjusts VC_j when receiving a message.
- P_j postpones delivery of m until:
  - $ts(m)[i] = VC_j[i] + 1$.
  - $ts(m)[k] \leq VC_j[k]$ for $k \neq i$.

Example: Causally Ordered Multicasting (2/2)



Mutual Exclusion

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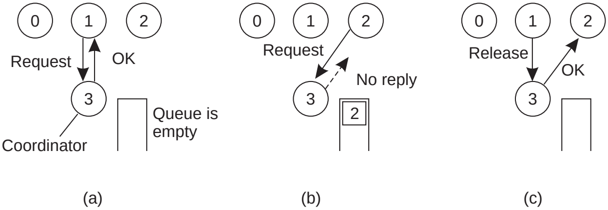
- A number of processes in a distributed system want exclusive access to some resource.
- Basic solutions:
  - Via a centralized server.
  - Decentralized algorithm.
  - Distributed algorithm, with no topology imposed.
  - Logical ring algorithm.

Mutual Exclusion
Centralized Model

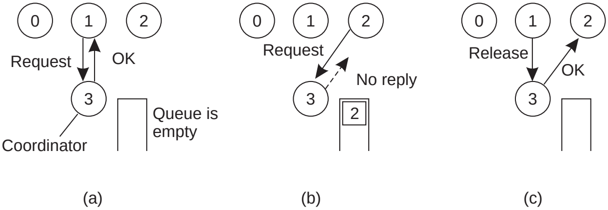
Centralized Algorithm

- Process 1 asks the coordinator for permission to access the shared resource. Permission is granted.



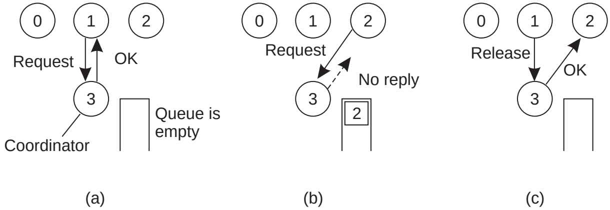
Centralized Algorithm

- Process 1 asks the coordinator for permission to access the shared resource. Permission is granted.
- Process 2 then asks permission to access the same resource. The coordinator does not reply.



Centralized Algorithm

- Process 1 asks the coordinator for permission to access the shared resource. Permission is granted.
- Process 2 then asks permission to access the same resource. The coordinator does not reply.
- When process 1 releases the resource, it tells the coordinator, which then replies to 2.



Mutual Exclusion
Decentralized Algorithm

Decentralized Algorithm (1/2)

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

Decentralized Algorithm (2/2)

- 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.
- Probability that k out m coordinators reset:

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

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

Mutual Exclusion
Distributed Algorithm

Distributed Algorithm (1/3)

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- When a process wants to access a shared resource:
  - It builds a message containing the name of the resource, its process number, and the current (logical) time.
  - It then sends the message to all other processes, conceptually including itself.
  - The sending of messages is assumed to be reliable.

Distributed Algorithm (2/3)

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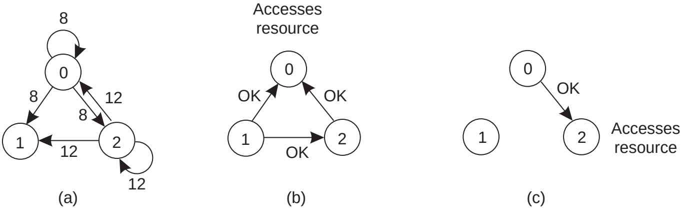
  - If the receiver already has access to the resource, it simply does not reply. Instead, it queues the request.
  - If the receiver wants to access the resource as well but has not yet done so, it compares the timestamp of the incoming message with the one contained in the message that it has sent everyone. The lowest one wins.

Distributed Algorithm (3/3)

- Two processes want to access a shared resource at the same moment.



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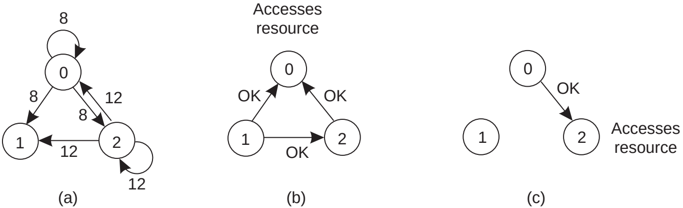

Distributed Algorithm (3/3)

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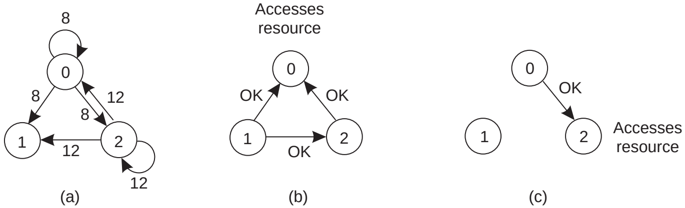
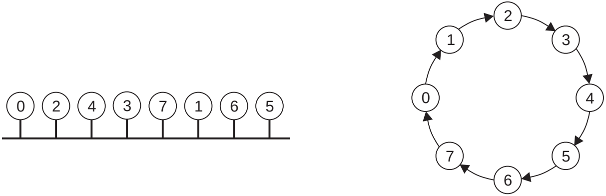
- When process 0 is done, it sends an OK also, so 2 can now go ahead.



Mutual Exclusion
Token Ring Algorithm

Token Ring Algorithm

- Organize processes in a logical ring.
- 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)

Election Algorithms

Election Algorithms

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

Election by Bullying (1/3)

- Each process has an associated priority (weight), and the process with the highest priority should always be elected as the coordinator.

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

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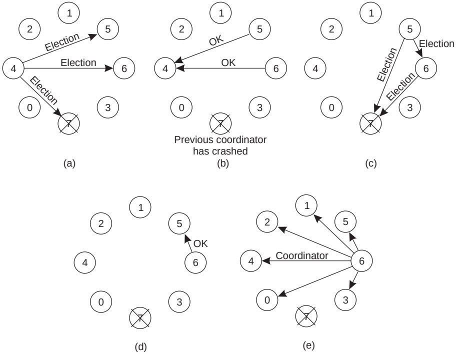
- If a process doesn't get a take-over message back, it wins, and sends a victory message to all other processes.

Election by Bullying (3/3)

- Process 4 holds an election.
- Processes 5 and 6 respond, telling 4 to stop.
- Now 5 and 6 each hold an election.
- Process 6 tells 5 to stop.
- Process 6 wins and tells everyone.



Election in a Ring (1/3)

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

Election in a Ring (2/3)

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- 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.

Election in a Ring (2/3)

- 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.

Election in a Ring (3/3)

- Does it matter if two processes initiate an election?
  - There is no problem with having two concurrent initiators.

Election in a Ring (3/3)

- Does it matter if two processes initiate an election?
  - There is no problem with having two concurrent initiators.
- What happens if a process crashes during the election?
  - Crashes during elections are permitted: you just start over again.

Summary

Summary

- Agreement in a distribute system
- Clocks: physical vs. logical
- Physical clocks: NTP, Berkeley
- Logical clocks: Happened-Before, Lamport, vector clocks
- Mutual exclusion: centralized, decentralized, distributed, ring-based
- Election: bullying, ring

Reading

- Chapter 6 of the Distributed Systems: Principles and Paradigms.

Questions?