Slide 1

Distributed Systems (COMP9243)

Lecture 4: Synchronisation and Coordination (Part 1)

① Distributed Algorithms
② Time and Clocks
③ Global State
④ Concurrency Control

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Distributed Algorithms

Algorithms that are intended to work in a distributed environment

Used to accomplish tasks such as:

- ➜ Communication
- ➜ Accessing resources
- ➜ Allocating resources
- ➜ Consensus
- ➜ etc.

Synchronisation and coordination inextricably linked to distributed algorithms

- ➜ Achieved using distributed algorithms
- ➜ Required by distributed algorithms

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Synchronous vs Asynchronous Distributed Systems

Timing model of a distributed system

Affected by:

- ➜ Execution speed/time of processes
- ➜ Communication delay
- ➜ Clocks & clock drift

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Synchronous Distributed System:

Time variance is bounded

Execution : bounded execution speed and time

Communication : bounded transmission delay

Clocks : bounded clock drift (and differences in clocks)

Effect:

- ➜ Can rely on timeouts to detect failure
- ☑ Easier to design distributed algorithms
- ✗ Very restrictive requirements
  - Limit concurrent processes per processor Why?
  - Limit concurrent use of network Why?
  - Require precise clocks and synchronisation

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Asynchronous Distributed System:

Time variance is not bounded

Execution : different steps can have varying duration

Communication : transmission delays vary widely

Clocks : arbitrary clock drift

Effect:

- ➜ Allows no assumption about time intervals
- ✗ Cannot rely on timeouts to detect failure
- ✗ Most asynch DS problems hard to solve
- ✓ Solution for asynch DS is also a solution for synch DS
- ➜ Most real distributed systems are hybrid synch and asynch

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Evaluating Distributed Algorithms

Key Properties:

① **Safety:** Nothing bad happens

② **Liveness:** Something good eventually happens

General Properties:

- ➜ Performance
  - number of messages exchanged
  - response/wait time
  - delay, throughput: $1/(delay + executiontime)$
  - complexity: $O()$
- ➜ Efficiency
  - resource usage: memory, CPU, etc.
- ➜ Scalability
- ➜ Reliability
  - number of points of failure (low is good)

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Synchronisation and Coordination

Important:

Doing the right thing at the right time.

Two fundamental issues:

- ➜ Coordination (the right thing)
- ➜ Synchronisation (the right time)

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Coordination

Coordinate actions and agree on values.

Coordinate Actions:

- ➜ What actions will occur
- ➜ Who will perform actions

Agree on Values:

- ➜ Agree on global value
- ➜ Agree on environment
- ➜ Agree on state

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Synchronisation

Ordering of all actions

- ➜ Total ordering of events
- ➜ Total ordering of instructions
- ➜ Total ordering of communication
- ➜ Ordering of access to resources
- ➜ Requires some concept of time

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Main Issues

Time and Clocks: synchronising clocks and using time in distributed algorithms

Global State: how to acquire knowledge of the system's global state

Concurrency Control: coordinating concurrent access to resources

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Time and Clocks

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Time

Global Time:

- ➜ 'Absolute' time
  - Einstein says no absolute time
  - Absolute enough for our purposes
- ➜ Astronomical time
  - Based on earth's rotation
  - Not stable
- ➜ International Atomic Time (IAT)
  - Based on oscillations of Cesium-133
- ➜ Coordinated Universal Time (UTC)
  - Leap seconds
  - Signals broadcast over the world

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Local Time:

- Relative not 'absolute'
- Not synchronised to Global source

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Using Clocks in Computers

Timestamps:

- Used to denote at which time an event occurred

Synchronisation Using Clocks:

- Performing events at an exact time (turn lights on/off, lock/unlock gates)
- Logging of events (for security, for profiling, for debugging)
- Tracking (tracking a moving object with separate cameras)
- Make (edit on one computer build on another)
- Ordering messages

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Physical Clocks

Based on actual time:

- $C_p(t)$: current time (at UTC time t) on machine p
- Ideally $C_p(t) = t$
- ✗ Clock differences causes clocks to *drift*
- Must regularly synchronise with UTC

Computer Clocks:

- Crystal oscillates at known frequency
- Oscillations cause timer interrupts
- Timer interrupts update clock

Clock Skew:

- Crystals in different computers run at slightly different rates
- Clocks get out of sync
- Skew: instantaneous difference
- Drift: rate of change of skew

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Synchronising Physical Clocks

Internal Synchronisation:

- ➜ Clocks synchronise locally
- ➜ Only synchronised with each other

External Synchronisation:

- ➜ Clocks synchronise to an external time source
- ➜ Synchronise with UTC every δ seconds

Time Server:

- ➜ Server that has the correct time
- ➜ Server that calculates the correct time

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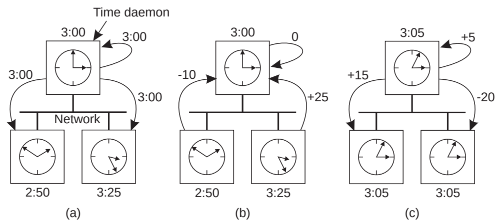
Berkeley Algorithm



Accuracy: 20-25 milliseconds

When is this useful?

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Cristian's Algorithm

Time Server:

- ➜ Has UTC receiver
- ➜ Passive

Algorithm:

- ➜ Clients periodically request the time
- ➜ Don't set time backward Why not?
- ➜ Take propagation and interrupt handling delay into account
  - $(T1 - T0)/2$
  - Or take a series of measurements and average the delay
- ➜ Accuracy: 1-10 millisec (RTT in LAN)

What is a drawback of this approach?

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Network Time Protocol (NTP)

Hierarchy of Servers:

- ➜ Primary Server: has UTC clock
- ➜ Secondary Server: connected to primary
- ➜ etc.

Synchronisation Modes:

Multicast: for LAN, low accuracy

Procedure Call: clients poll, reasonable accuracy

Symmetric: Between peer servers. highest accuracy

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Synchronisation:

- ➜ Estimate clock offsets and transmission delays between two nodes
- ➜ Keep estimates for past communication
- ➜ Choose offset estimate for lowest transmission delay
- ➜ Also determine unreliable servers
- ➜ Accuracy 1 - 50 msec

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Lamport

- ➜ Safety, Liveness
- ➜ Logical clocks and vector clocks
- ➜ Snapshots
- ➜ Byzantine generals
- ➜ Paxos consensus
- ➜ TLA+, LaTeX
- ➜ **Turing Award 2013**

Comments about his papers: Google: lamport my writings

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Logical Clocks

Event ordering is more important than physical time:

- ➜ Events (e.g., state changes) in a single process are ordered
- ➜ Processes need to agree on ordering of causally related events (e.g., message send and receive)

Local ordering:

- ➜ System consists of N processes $p_i, i \in \{1, \ldots, N\}$
- ➜ Local event ordering $\to_i$:

  If p_i observes e before e', we have $e \to_i e'$

Global ordering:

- ➜ Leslie Lamport's happened before relation $\to$
- ➜ Smallest relation, such that
  1. $e \to_i e'$ implies $e \to e'$
  2. For every message m, $send(m) \to receive(m)$
  3. Transitivity: $e \to e'$ and $e' \to e''$ implies $e \to e''$

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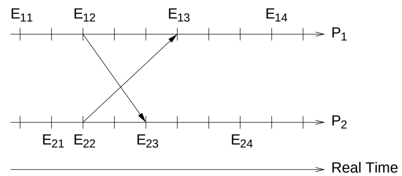
The relation $\to$ is a partial order:

- ➜ If $a \to b$, then a causally affects b
- ➜ We consider unordered events to be concurrent:

Example: $a \not\to b$ and $b \not\to a$ implies $a \parallel b$



- ➜ Causally related: $E_{11} \to E_{12}, E_{13}, E_{14}, E_{23}, E_{24}, \ldots$

  $E_{21} \to E_{22}, E_{23}, E_{24}, E_{13}, E_{14}, \ldots$
- ➜ Concurrent: $E_{11} \| E_{21}$, $E_{12} \| E_{22}$, $E_{13} \| E_{23}$, $E_{11} \| E_{22}$, $E_{13} \| E_{24}$, $E_{14} \| E_{23}, \ldots$

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Lamport's logical clocks:

- ➜ Software counter to locally compute the happened-before relation $\rightarrow$
- ➜ Each process p_i maintains a logical clock L_i
- ➜ Lamport timestamp:
  - $L_i(e)$: timestamp of event e at p_i
  - $L(e)$: timestamp of event e at process it occurred at

Implementation:

① Before timestamping a local event p_i executes $L_i := L_i + 1$

② Whenever a message m is sent from p_i to p_j:

- p_i executes $L_i := L_i + 1$ and sends L_i with m
- p_j receives L_i with m and executes $L_j := \max(L_j, L_i) + 1$ ($receive(m)$ is annotated with the new L_j)

Properties:

- ➜ $a \rightarrow b$ implies $L(a) < L(b)$
- ➜ $L(a) < L(b)$ does not necessarily imply $a \rightarrow b$

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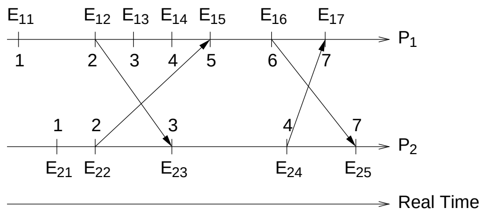
Example:



How can we order E_{13} and E_{23} ?

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Total event ordering:

- ➜ Complete partial to total order by including process identifiers
- ➜ Given local time stamps $L_i(e)$ and $L_j(e')$, we define global time stamps $\langle L_i(e), i\rangle$ and $\langle L_j(e'), j\rangle$
- ➜ Lexicographical ordering: $\langle L_i(e), i\rangle < \langle L_j(e'), j\rangle$ iff
  - $L_i(e) < L_j(e')$ or
  - $L_i(e) = L_j(e')$ and $i < j$

$E_{13} = 3, E_{24} = 4.$ Did E_{13} happen before E_{24}?

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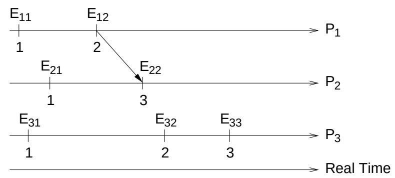
Vector Clocks

Main shortcoming of Lamport's clocks:

- ➜ $L(a) < L(b)$ does not imply $a \rightarrow b$
- ➜ We cannot deduce causal dependencies from time stamps:



- ➜ We have $L_1(E_{11}) < L_3(E_{33})$, but $E_{11} \not\rightarrow E_{33}$
- ➜ Why?
  - Clocks advance independently or via messages
  - There is no history as to where advances come from

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Vector clocks:

- At each process, maintain a clock for every other process
- I.e., each clock V_i is a vector of size N
- $V_i[j]$ contains i's knowledge about j's clock
- Events are timestamped with a vector

Implementation:

① Initially, $V_i[j] := 0$ for $i, j \in \{1, \ldots, N\}$
② Before p_i timestamps an event: $V_i[i] := V_i[i] + 1$
③ Whenever a message m is sent from p_i to p_j:

- p_i executes $V_i[i] := V_i[i] + 1$ and sends V_i with m
- p_j receives V_i with m and merges the vector clocks V_i and V_j:

$$V_j[k] := \begin{cases} \max(V_j[k], V_i[k]) + 1 & \text{, if } j = k \\ \max(V_j[k], V_i[k]) & \text{, otherwise} \end{cases}$$

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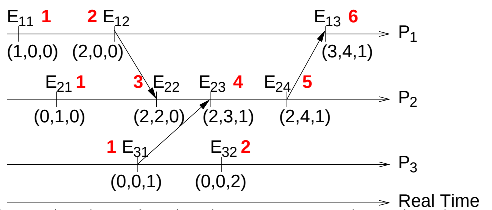
Properties:

- For all i, j, $V_i[i] \geq V_j[i]$
- $a \to b$ iff $V(a) < V(b)$ where
  - $V = V'$ iff $V[i] = V'[i]$ for $i \in \{1, \ldots, N\}$
  - $V \geq V'$ iff $V[i] \geq V'[i]$ for $i \in \{1, \ldots, N\}$
  - $V > V'$ iff $V \geq V' \wedge V \neq V'$
  - $V \| V'$ iff $V \not\geq V' \wedge V' \not\geq V$

Example:



- For $L_1(E_{12})$ and $L_3(E_{32})$, $2 = 2$ versus $(2, 0, 0) \neq (0, 0, 2)$

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GLOBAL STATE

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GLOBAL STATE

Determining global properties:

- Distributed garbage collection:
  Do any references exist to a given object?
- Distributed deadlock detection:
  Do processes wait in a cycle for each other?
- Distributed termination detection:
  Did a set of processes cease all activity? (Consider messages in transit!)
- Distributed checkpoint:
  What is a correct state of the system to save?

Consistent Cuts

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Determining global properties:

- ➜ We need to combine information from multiple nodes
- ➜ Without global time, how do we know whether collected local information is consistent?
- ➜ Local state sampled at arbitrary points in time surely is not consistent
- ➜ We need a criterion for what constitutes a globally consistent collection of local information

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Local history:

- ➜ N processes p_i, $i \in \{1, \ldots, N\}$
- ➜ For each p_i,
  - event: e_i^j local action or communication
  - history: $h_i^k = \langle e_i^0, e_i^1, \ldots e_i^k \rangle$
  - May be finite or infinite

Process state:

- ➜ s_i^k : state of process p_i immediately before event e_i^k
- ➜ s_i^k records all events included in the history h_i^{k-1}
- ➜ Hence, s_i^0 refers to p_i's initial state

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Global history and state:

- ➜ Using a total event ordering, we can merge all local histories into a global history:

$$H = \bigcup_{i=1}^{N} h_i$$

- ➜ Similarly, we can combine a set of local states $s_1, \ldots, s_N$ into a global state:

$$S = (s_1, \ldots, s_N)$$

- ➜ Which combination of local state is consistent?

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Cuts:

- ➜ Similar to the global history, we can define cuts based on k-prefixes:

$$C = \bigcup_{i=1}^{N} h_i^{c_i}$$

- ➜ $h_i^{c_i}$ is history of p_i up to and including event $e_i^{c_i}$
- ➜ The cut C corresponds to the state

$$S = (s_1^{c_1+1}, \ldots, s_N^{c_n+1})$$

- ➜ The final events in a cut are its frontier:

$$\{e_i^{c_i} \mid i \in \{1, \ldots, N\}\}$$

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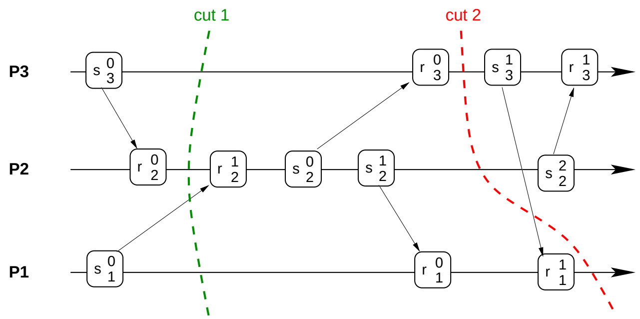

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Consistent cut:

- ➜ We call a cut consistent iff,

  for all events $e' \in C, e \to e'$ implies $e \in C$

- ➜ A global state is consistent if it corresponds to a consistent cut
- ➜ Note: we can characterise the execution of a system as a sequence of consistent global states

$$S_0 \to S_1 \to S_2 \to \cdots$$

Linearisation:

- ➜ A global history that is consistent with the happened-before relation $\to$ is also called a linearisation or consistent run
- ➜ A linearisation only passes through consistent global states
- ➜ A state S' is reachable from state S if there is a linearisation that passes thorough S and then S'

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CHANDY & LAMPORT'S SNAPSHOTS

- ➜ Determines a consistent global state
- ➜ Takes care of messages that are in transit
- ➜ Useful for evaluating stable global properties

Properties:

- ➜ Reliable communication and failure-free processes
- ➜ Point-to-point message delivery is ordered
- ➜ Process/channel graph must be strongly connected
- ➜ On termination,
  - processes hold only their local state components and
  - a set of messages that were in transit during the snapshot.

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Outline of the algorithm:

① One process initiates the algorithm by
- recording its local state and
- sending a marker message * over each outgoing channel

② On receipt of a marker message over incoming channel c,
- if local state not yet saved, save local state and send marker messages, or
- if local state already saved, channel snapshot for c is complete

③ Local contribution complete after markers received on all incoming channels

Result for each process:

- ➜ One local state snapshot
- ➜ For each incoming channel, a set of messages received after performing the local snapshot and before the marker came down that channel

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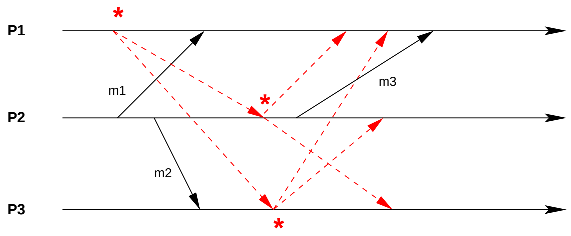

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SPANNER AND TRUETIME

Globally Distributed Database

- ➜ Want external consistency (linearisability)
- ➜ Want lock-free read transactions (for scalability)

WWGD? (what would Google do?)

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USE A GLOBAL CLOCK!

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EXTERNAL CONSISTENCY WITH A GLOBAL CLOCK

Data:

- ➜ versioned using timestamp

Read:

- ➜ Read operations performed on a *snapshot*
- ➜ Snapshot: latest version of data items <= given timestamp

Write:

- ➜ Each write operation (transaction actually) has unique timestamp
  - Timestamps must not overlap!
- ➜ Write operations are protected by locks
  - ➜ Means they don't overlap
- ➜ So get global time during the transaction
  - ➜ Means timestamps won't overlap

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BUT CLOCKS ARE NOT PERFECTLY SYNCHRONISED.

So transaction A could get the same timestamp as transaction B

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TRUE TIME

Add uncertainty to timestamps:

- ➜ TT.now(): current local clock value
- ➜ TT.now().earliest(), TT.now().latest: maximum skew of clock

Add delay to transaction:

- ➜ so timestamps can't possibly overlap
- ➜ `s = TT.now(); wait until TT.now().earliest > s.latest`

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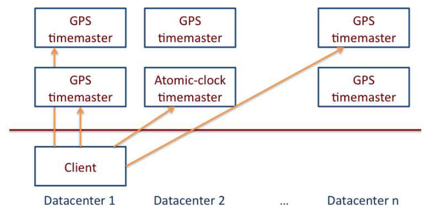
TRUETIME ARCHITECTURE



Compute reference [earliest, latest] = now ± ε

(from `http://research.google.com/archive/spanner-osdi2012.pptx`)

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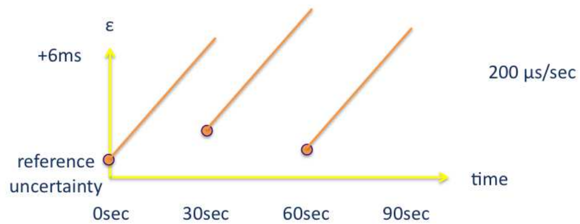
SYNCHRONISATION



(from `http://research.google.com/archive/spanner-osdi2012.pptx`)

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Concurrency

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Concurrency

Concurrency in a Non-Distributed System:

Typical OS and multithreaded programming problems

- ➜ Prevent *race conditions*
- ➜ Critical sections
- ➜ Mutual exclusion
  - Locks
  - Semaphores
  - Monitors
- ➜ Must apply mechanisms correctly
  - Deadlock
  - Starvation

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Concurrency in a Distributed System:

Distributed System introduces more challenges

- ➜ No directly shared resources (e.g., memory)
- ➜ No global state
- ➜ No global clock
- ➜ No centralised algorithms
- ➜ More concurrency

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Distributed Mutual Exclusion

- ➜ Concurrent access to distributed resources
- ➜ Must prevent race conditions during critical regions

Requirements:

① **Safety:** At most one process may execute the critical section at a time

② **Liveness:** Requests to enter and exit the critical section eventually succeed

③ **Ordering:** Requests are processed in happened-before ordering (also Fairness)

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Recall: Evaluating Distributed Algorithms

General Properties:

➜ Performance
- number of messages exchanged
- response/wait time
- delay
- throughput: $1/(delay + executiontime)$
- complexity: $O()$

➜ Efficiency
- resource usage: memory, CPU, etc.

➜ Scalability

➜ Reliability
- number of points of failure (low is good)

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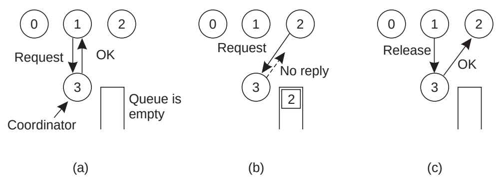
Method 1: Central Server

Simplest approach:

➜ Requests to enter and exit a critical section are sent to a lock server

➜ Permission to enter is granted by receiving a token

➜ When critical section left, token is returned to the server



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Properties:

➜ Number of message exchanged?

➜ Delay before entering critical section?

➜ Reliability?

➜ Easy to implement

➜ Does not scale well

➜ Central server may fail

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Method 2: Token Ring

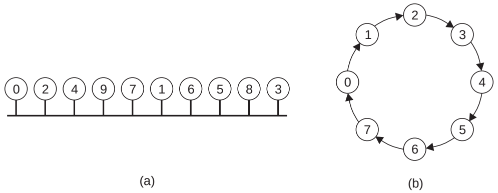
Implementation:

➜ All processes are organised in a logical ring structure

➜ A token message is forwarded along the ring

➜ Before entering the critical section, a process has to wait until the token comes by

➜ Must retain the token until the critical section is left



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Properties:

- ➜ Number of message exchanged?
- ➜ Delay before entering critical section?
- ➜ Reliability?
- ➜ Ring imposes an average delay of $N/2$ hops (limits scalability)
- ➜ Token messages consume bandwidth
- ➜ Failing nodes or channels can break the ring (token might be lost)

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Method 3: Using Multicasts and Logical Clocks

Algorithm by Ricart & Agrawala:

- ➜ Processes p_i maintain a Lamport clock and can communicate pairwise
- ➜ Processes are in one of three states:
  1. *Released:* Outside of critical section
  2. *Wanted:* Waiting to enter critical section
  3. *Held:* Inside critical section

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Process behaviour:

① If a process wants to enter, it

- multicasts a message $\langle L_i, p_i \rangle$ and
- waits until it has received a reply from every process

② If a process is in *Released*, it immediately replies to any request to enter the critical section

③ If a process is in *Held*, it delays replying until it is finished with the critical section

④ If a process is in *Wanted*, it replies to a request immediately only if the requesting timestamp is smaller than the one in its own request

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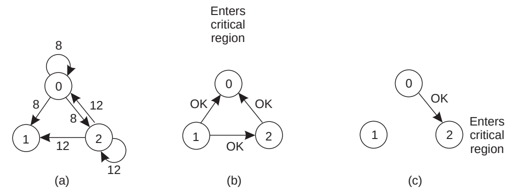

Properties:

- ➜ Number of message exchanged?
- ➜ Delay before entering critical section?
- ➜ Reliability?
- ➜ Multicast leads to increasing overhead (try using only subsets of peer processes)
- ➜ Susceptible to faults

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Mutual Exclusion: A Comparison

Messages Exchanged:

➜ Messages per entry/exit of critical section
- Centralised: 3
- Ring: $1 \rightarrow \infty$
- Multicast: $2(n-1)$

Delay:

➜ Delay before entering critical section
- Centralised: 2
- Ring: $0 \rightarrow n-1$
- Multicast: $2(n-1)$

Reliability:

➜ Problems that may occur
- Centralised: coordinator crashes
- Ring: lost token, process crashes
- Multicast: any process crashes

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Homework

➜ How would you use vector clocks to implement causal consistency?

➜ Could you use logical clocks to implement sequential consistency?

Hacker's edition:

➜ Modify the Ricart Agrawala mutual exclusion algorithm to only require sending to a subset of the processes.

➜ Can you modify the centralised mutual exclusion algorithm to tolerate coordinator crashes?

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Reading List

Optional

Time, Clocks, and the the Ordering of Events in a Distribted system Classic on Lamport clocks.

Distributed Snapshots: Determining Global States of Distributed Systems Chandy and Lamport algorithm.