Distributed Systems

Distributed State

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In computer systems two type of processes exist

- stochastic processes[1] and
- deterministic processes

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- **R** epeatable: The process can be invoked multiple times with the same input and produce the same output.

↪ In the literature instead of Repeatable, you will also find Responsible or even Relevant

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- R epeatable: The process can be invoked multiple times with the same input and produce the same output.
- T erminated: Given the same resources the process produces the same results in a determined time frame.

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Agenda

- Coordination
- Global State
- Mutual Exclusion

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What is required to make a distributed application behave deterministically?

Coordination in the Distributed System

Problem statement:

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Coordination and Synchronization

Coordination in the distributed systems allows to make the behavior of the system predictable and interactions causal by **ordering** them. The letter requires the introduction of a 'time line' in the system, which is known as **clock synchronization** among the nodes.

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Processes in a distributed systems require synchronization and coordination

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- in case a process is accessing shared resources
- the process needs interruption during its operation (*triggered events*).

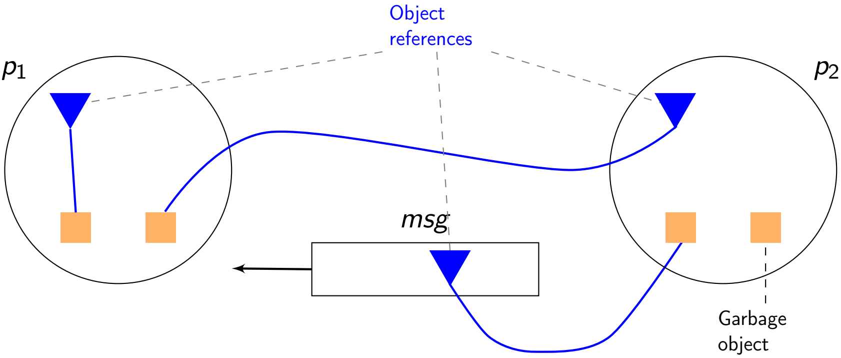
- Different nodes have individual clocks

↪ Without a clock and time synchronization processes in a distributed systems may behave erratically and coordination becomes difficult or even infeasible

Recap: Garbage Collection

How does garbage collection (GC) work?

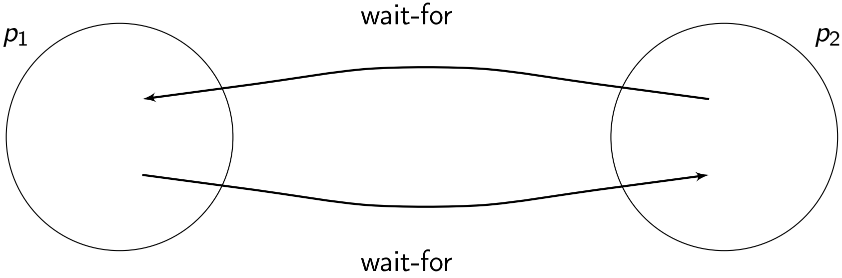
Global Properties: Garbage Collection



Recap: Deadlock

What is a deadlock?

Global Properties: Deadlock



Recap: Deadlock

When does a process termi-
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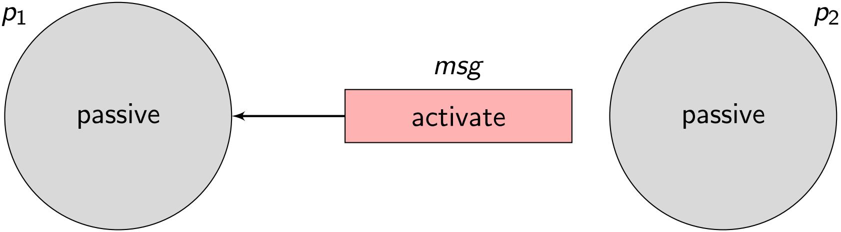
Global Properties: Termination



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What is necessary in order to assess the global state of a distributed application?

Happened-Before Relation

Problem statement

Is it possible to maintain a global view on the state of system's behavior wrt the **happened-before** relationship?

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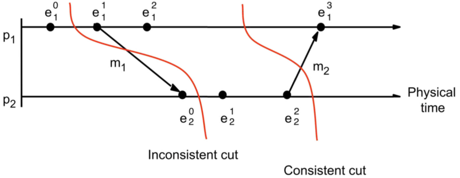
Is it possible to maintain a global view on the state of system's behavior wrt the **happened-before** relationship?

In other words:
If we introduce a cut C (a snapshot), can we guarantee

$$\forall e \in C : f \rightarrow e \Longrightarrow f \in C \ ?$$



Source: Coulouris et al, Distributed Systems, Pearson

Consistent Cuts

- A consistent cut requires a consistent global state of the distributed system
- The history of a process i is defined as $h(i) =< e_i^1, e_i^2, e_i^3, \ldots >$
- The global history H is the union of all histories of the involved processes
- A cut is a union of prefixes of process histories
- A run is a total ordering of all the events in a global history that is consistent with each local history's ordering
- A consistent run orders (serializes) the events in the global history H; to be consistent with the happened-before relation ($\rightarrow$) on H.

Global States

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- A **Global State** is stable: Once it has reached condition $\{true\}$ and it remains in that state for all states connected to that state.
- **Safety** is an assertion once an undesired state predicate evaluates to $\{false\}$ all other states S reachable from the starting state S_0 are `false` also.
- **Liveness** is an assertion to a desired state predicate to $\{true\}$ all other states reachable from S_o are `true` as well.

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Exclusive Resources for a Process

Problem statement:
For a process it might be necessary to have exclusive access to a resource. How this can be accomplished in a distributed system?

Examples:

- A process P wants to write to a file (storage) and has to make sure no other process is reading to that file yielding inconsistencies.
- A database is required to update a cell in a table (exclusive lock).
- A process P wants to remove by means of `rm -r d` the directory d recursively while guaranteeing that no other (remote) process P_j accesses any other file in the underlying directory structure.

We know this problem from the Operating Systems as entering a **critical section**:

Critical Sections

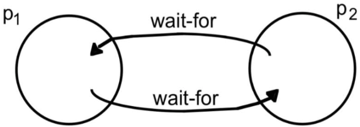
`enter()`	enter critical section – set up blocking
`accessResource()`	access shared resource in critical section
`exit()`	leave critical sections – free resource

Mutual Exclusion: Requirements

A distributed system has to conform to some essential requirements in order to provide **Mutual Exclusive** capabilities:

1. Safety: At most one process p may execute a critical section in a given time interval δt.
2. Liveness: A process p requests to enter the critical section and eventually succeeds.
3. Ordering: Request from processes p_i to enter the critical section follow the **happened-before** relationship.

$\hookrightarrow$ A distributed system not conforming to these requirements will experience deadlocks in process handling and eventually stalling of execution.



Source: Coulouris et al, Distributed Systems, Pearson

Mutual Exclusion: Solutions

Some possible architectures have been developed to cope with these requirements:

1. We provide a central service (*coordinator*) for resource allocation.
2. Nodes operate entirely decentralized on a peer-to-peer bases; thus no transitive dependencies exist.
3. Nodes operate entirely independent and distributed, without considering any topology dependencies; thus the intrinsic architecture has to guarantee for this.
4. Operations take place in or ordered manner; typically a logical ring; thus access rights are ordered in time (and by node).

Mutual Exclusion: Caveats

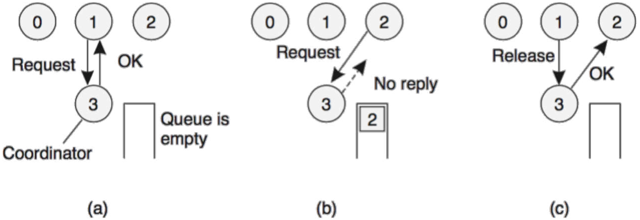
Due to the message (= information) transfer in the distributed system to synchronize activities, **mutual exclusion** is not free of costs:

- Message transfer consumes bandwidth and require processing for `entry()` and `exit()` operations in addition to operating with the resource.
- Operations at the client side to access the resource are significantly delayed.
- Access rates is limited given he concurrent access by clients entering the critical section.
- Throughput is limited by synchronization delay between two processes exiting an entering the critical section.

↪ A good system design require as little mutual exclusions as possible

Solution 1: Central locking

One dedicated node in the distributed system is assigned a coordinator tracking all unsatisfied and pending processes requests P_k in a **Queue**:



Source: Tanenbaum, Van Steen, Distributed Systems, Pearson

Let process 3 be the coordinator. Access to a resource is permitted only in case 3 has provided an Ok message.

(a) Process 1 requests access to a resource. Since no other process wants to access the same resource, coordinator 3 immediately permits this.
(b) Process 2 is asking for the same resource. 3 puts the request for process 2 in the queue, 2 is blocked.
(c) Once process 1 has released the resource and notified 3, 2 is informed about its permissive use.

Solution 2: Decentralized/local locking

In this scenario,

- all resources in the distributed system needs to be replicated n times having its own (local) coordinator,
- access permissions are given via a majority vote $m > n/2$ of local coordinators while
- responses from the local coordinator are given immediately.

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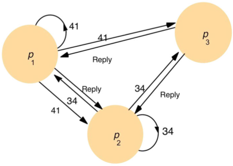
Consequences

- Amnesia of a coordinator: If a coordinator crashes it has lost all reported states. Even if the bookkeeping is done persistently, time sync operations are required; thus better scratch the entire state tables.
- Robustness of the distributed system: In order for the system to work, just a little over 50% of the coordinators need to vote – or are available. Assuming the availability of a coordinator process being 99.9% the probability of a dysfunctional distributed system is extremely small

Solution 3: Mutual exclusion according to Ricart & Agrawala

- We consider processes $p_1, p_2, ..., p_n$ providing mutual exclusion by means of
  - unique process identifiers (PID)
  - inter-process communication (IPC) between processes, and
  - Lamport clocks attached to each message.



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  - `released()`: outside the critical section
  - `wanted()`: trying to enter the critical section
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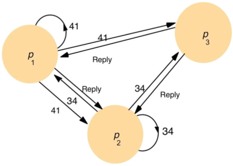

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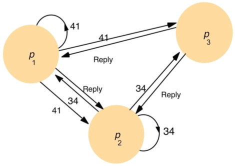

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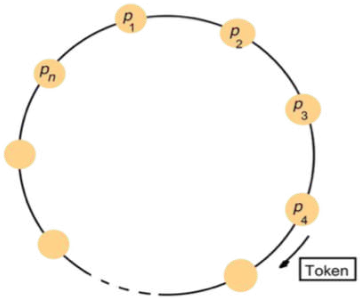
- A process states can be:
  - `released()`: outside the critical section
  - `wanted()`: trying to enter the critical section
  - `accessed()`: process is within the critical section
- A process in state `released()` immediately answers requests
- A process in state `accessed()` is blocked and does not reply to messages
- If more than one process is in state `wanted()`, the first one collecting $n-1$ replies is allowed to `accessed()`.

Solution 4: Token Ring based means

Exclusive access to a resource can be provided by possessing a particular message a **Token**:

- Processes needs be be logical ordered in a ring – irrespective of real network.
- A **Token** is passed around, permitting access to a critical section.
- Conditions Safety and Liveness are fulfilled.
- Ordering in time is not achieved and substituted by the logical process order.
- Significant consumption of bandwidth due to **Token** passing for every critical resource.
- Access delay of resources depend on the topology (= number of nodes) for the **Token** passing.



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Comparison of Solutions

Solution	Algorithm	#msgs per entry/exit	Delay entry (in msg times)	Caveats
1	centralized	3	2	coordinator crash
2	decentralized	$2mk + m$ $k = 1, 2, \ldots$	$2mk$	Starvation, low efficiency
3	distributed	$2 * (n - 1)$	$2 * (n - 1)$	Crash of any process
4	token ring	1 to ∞	0 *to* $n - 1$	Lost token, process crash

Table: Comparison of solutions for mutual exclusions in Distributed Systems

Important takeaway messages of this chapter

- Coordination in distributed systems is not trivial
- The happened-before relationship is crucial to assess the global state of a distributed system
- Different ways for mutual exclusion in distributed systems exist – each with its individual benefits and drawbacks