DS Summary

Chapter 1: Introduction

Loose Definition: A distributed system is a collection of interacting processes appearing as a single application to the end users.

Definition: A system where hardware and software components are located at netwrked computers, communicate and coordinate their actions ONLY by passing messages.

Grid Computing: A computational grid is a hardware and software infrastructure that provides dependable, consistent, pervasive, and inexpensive access to high-end computational capabilities.

Cloud Computing: Is grid computing plus virtualization, elasticity, and pay-as-you-go pricing.

Standalone system	Distributed system
Communication between processes possible through shared memory.	Communication between processes only through the network.
Global state possible through shared memory.	No global state.
Local operating system can be used to get a shared time value.	No global notion of time.
Local operating system offers primitives to safely share resources.	Synchonisation between processes through network communication only.
Failing processes easy to detect (communication is reliable).	(Partial) failures difficult to detect (because of unreliable communication).
Infrastructure known beforehand.	Infrastructure can vary dynamically (new servers/nodes can become available).
Components are located on the standalone machine.	Location of components can vary dynamically.
Local operating system enforces security.	Security threat due to distributed nature (possibly vulnerable communication link).

Developing distributed systems

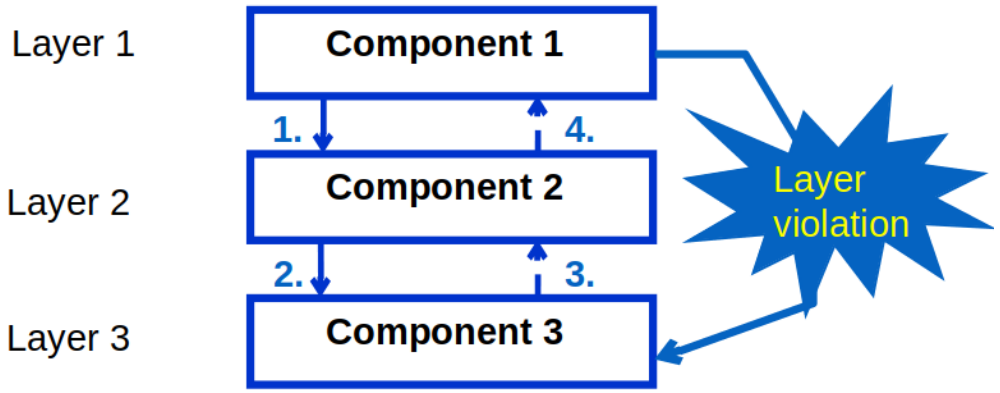
System Models

- **System models:** Capture non-functionals of the requirements related to distributed nature of the system.
- **Interaction models:** Can we give time guarantees on network communication/ process execution?
    - **Synchronous** system
    - **Asynchronous** system

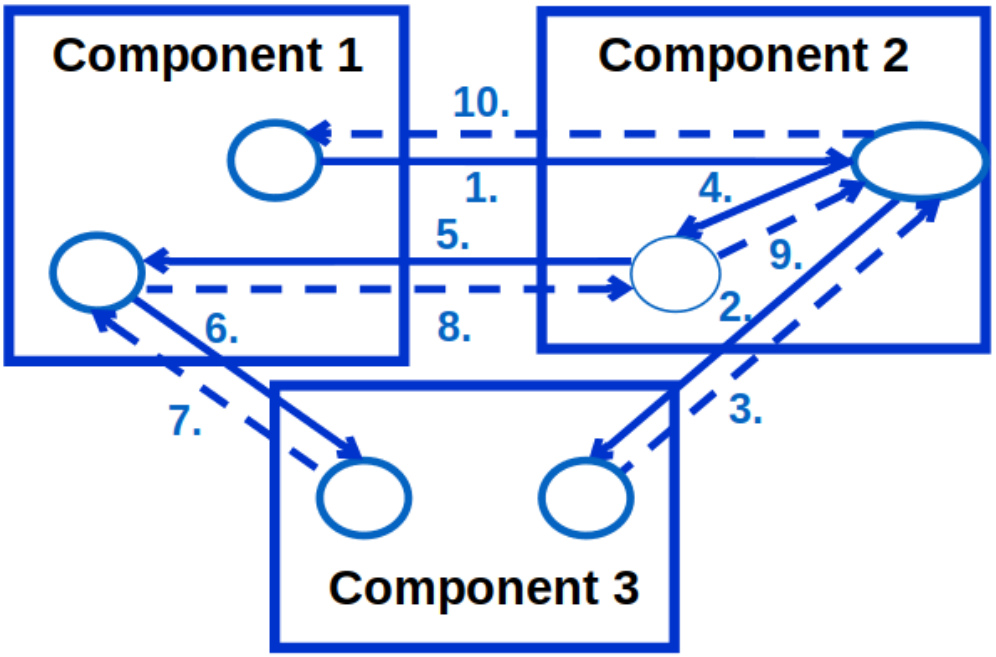
- **Failure models:** Which failures should the application cope with, how will we detect failures, and what will we do in case of failures?
  - **Process Omission failures:** a process does not fulfill a request.
  - **Channel Omission failures:** a communication link fails to deliver a message.
  - **Byzantine failures:** a process sends arbitrary messages.
  - **Timing failures:** a process violates its timing constraints.
    - **Solution:** heartbeat, timeout
- **Security models:** Who can do what in the system?
  - Interception of credentials
  - Impersonation
  - Copy, change, replay, create messages
  - **Solution:** encryption, authentication, authorization

Logical Architectures

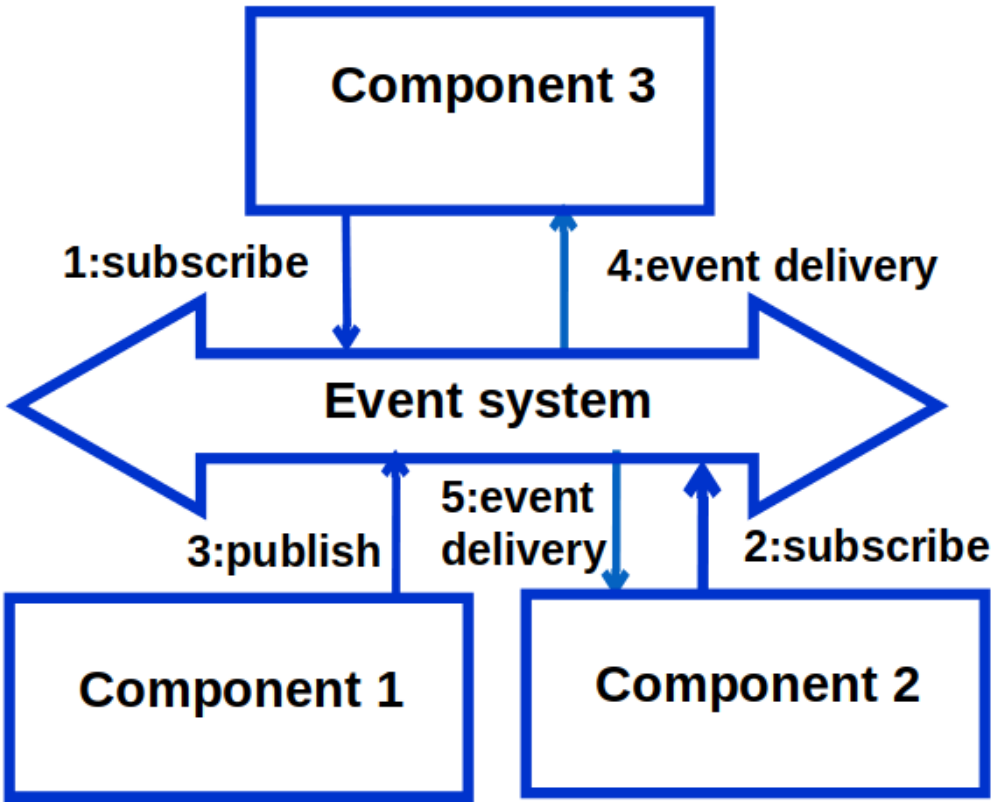
- **Layered architecture:** Each layer provides services to the layer above it and uses services from the layer below it.
  - **+**: Reduced number of interfaces, dependencies.
  - **+**: Easy replacement of a layer.
  - **-**: Possible duplication of functionality.



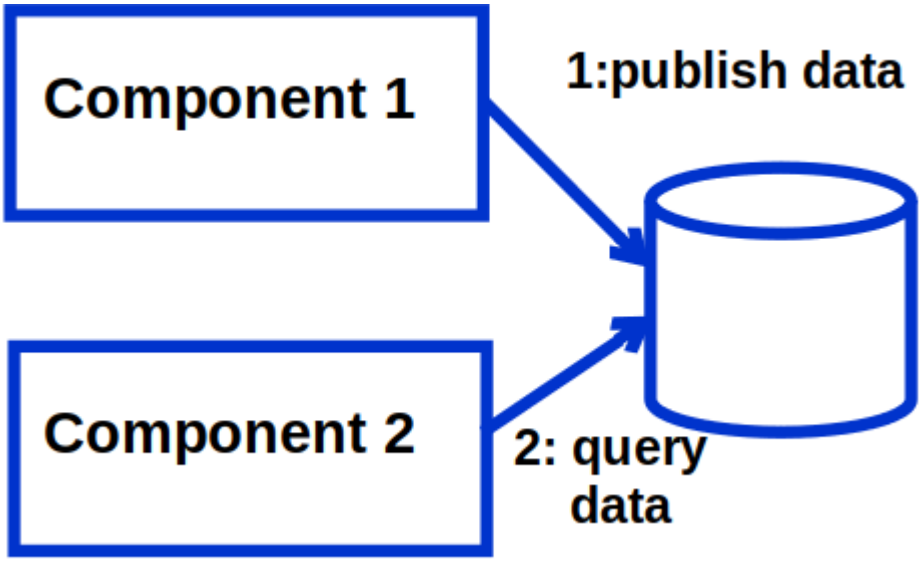
- **Object-based architecture:** Objects communicate by invoking methods on each other.
  - **+**: Encapsulation, reuse, flexibility.
  - **-**: Tight coupling, difficult to maintain.



- **Event-based architecture:** Components communicate by sending events. "publish-subscribe"
    - **+**: Decoupling, flexibility.
    - **-**: Difficult to understand, debug, maintain.

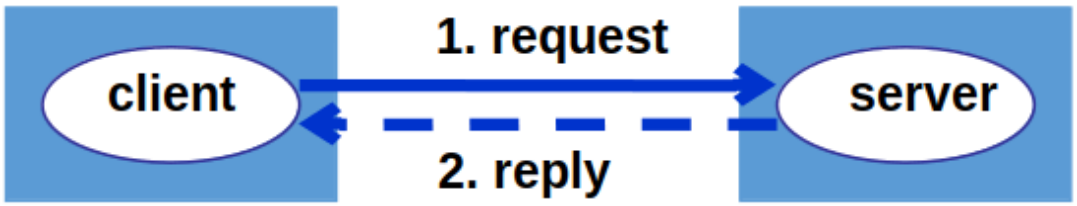


- **Data-centric architecture:** Components communicate by reading and writing shared data.
    - **+**: Decoupling, flexibility.
    - **-**: Possibly slow (central bottleneck, locking...).

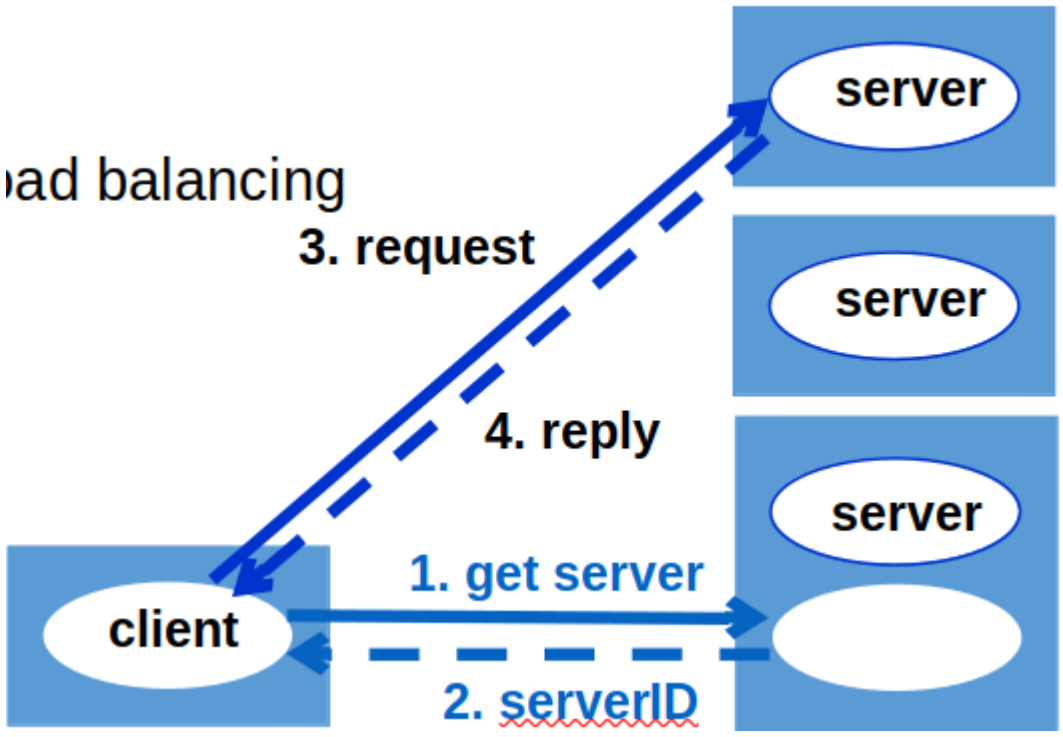


System Architectures

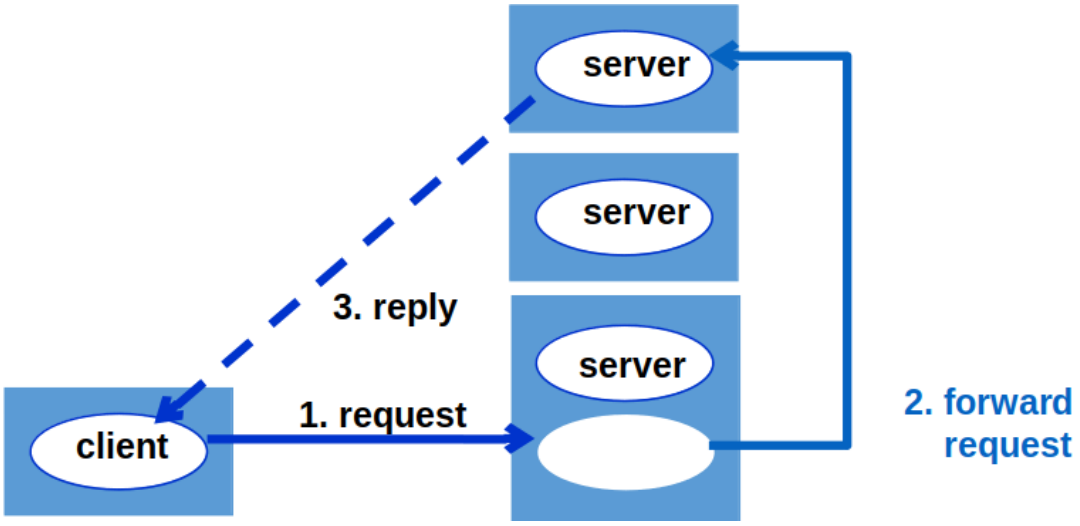
- **Client-server:** Client request services from server.



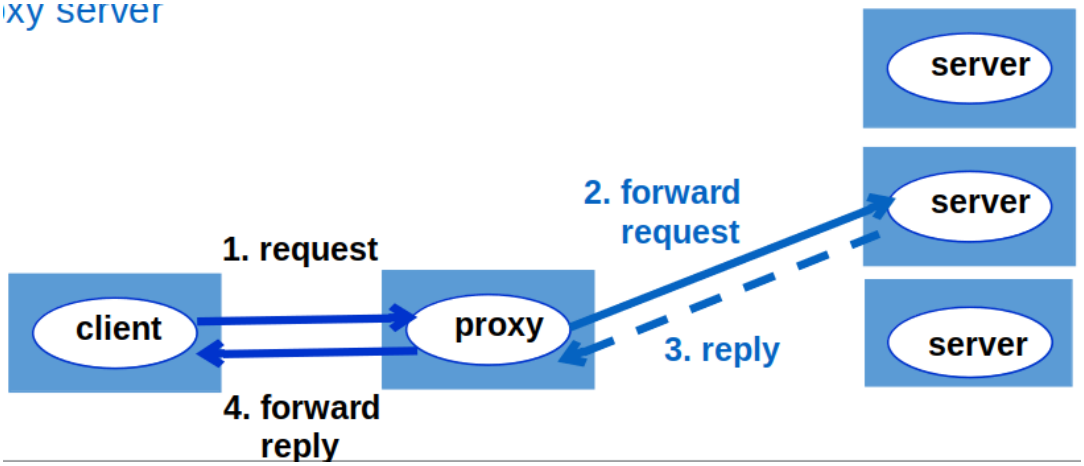
- **Client-multiple servers:** Client request services from multiple servers. (DNS based load balancing)



- **Client-multiple servers:** Client request services from multiple servers. (implicit server lookup)

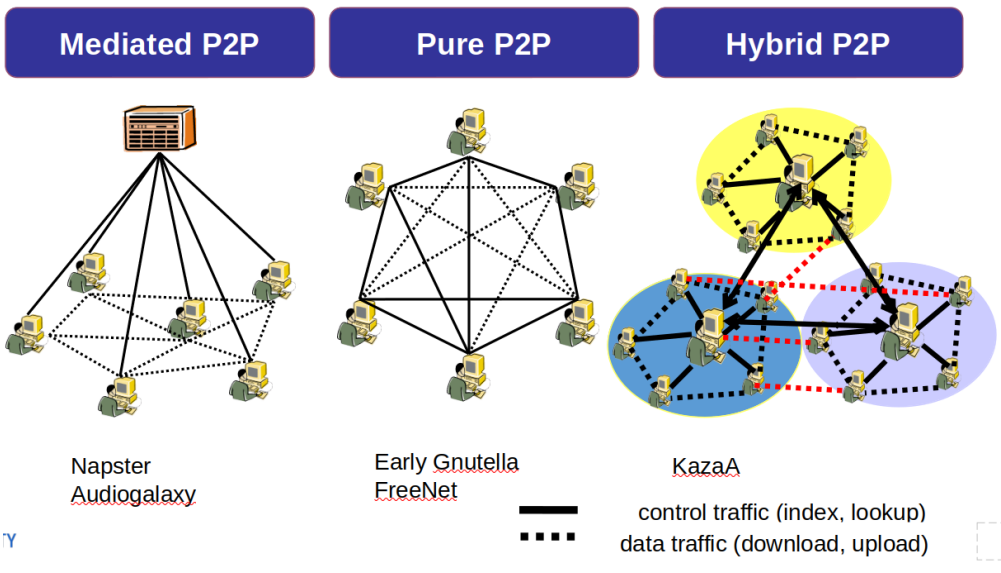


- **Proxy server:** Client request services from proxy server, which requests services from servers.



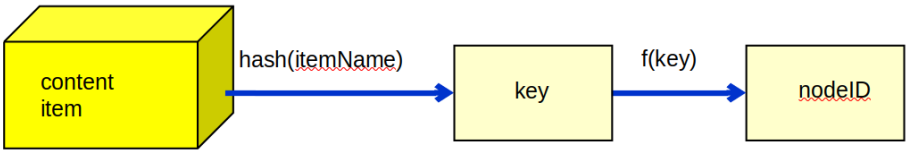
P2P Architectures

- **Unstructured P2P:** No organization, no central server.
  - Links have no other meaning that communication.
  - Unstructured search (flooding), this is resource consuming.



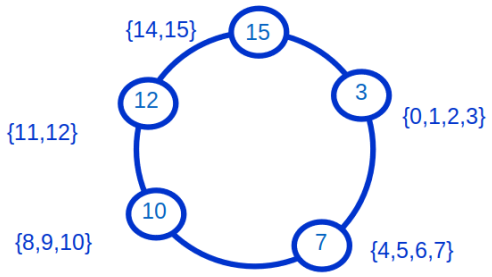
- **Structured P2P:** Organized, each node has a specific role.

- Logical link has relation to service offered.
- Structured search (DHT: Distributed hash table), this is efficient.
  Structured



Chord

each node has integer nodeID
e.g. consider 5 node network {nodeID}={3,7,10,12,15}
{key}={0 .. 15}



see chapter “P2P” for more details

Middleware

Role: Middleware is a software layer that provides a programming abstraction for distributed systems.

Services:

- **Naming service:** Associate logical names to remote entities.
- **Discovery and registration service:** Discover and register services.
- **Transaction service:** Support distributed (database) transactions.
- **Security service:** Provide security services.
- **Event service:** Support event-based communication.
- **Data replication service:** Replicate data for fault tolerance and optimize data access.
- **Persistence service:** Transparently offer data persistence.
- **Life cycle service:** Manage the life cycle of distributed objects.

Cap Theorem

CAP Theorem: In a distributed system, it is impossible to simultaneously guarantee all three of the following:

- **Consistency:** All read/write operations must result in a global consistent state.
- **Availability:** All requests on non-failing nodes must get a response.
- **Partition tolerance:** The system continues to operate despite network partitions.

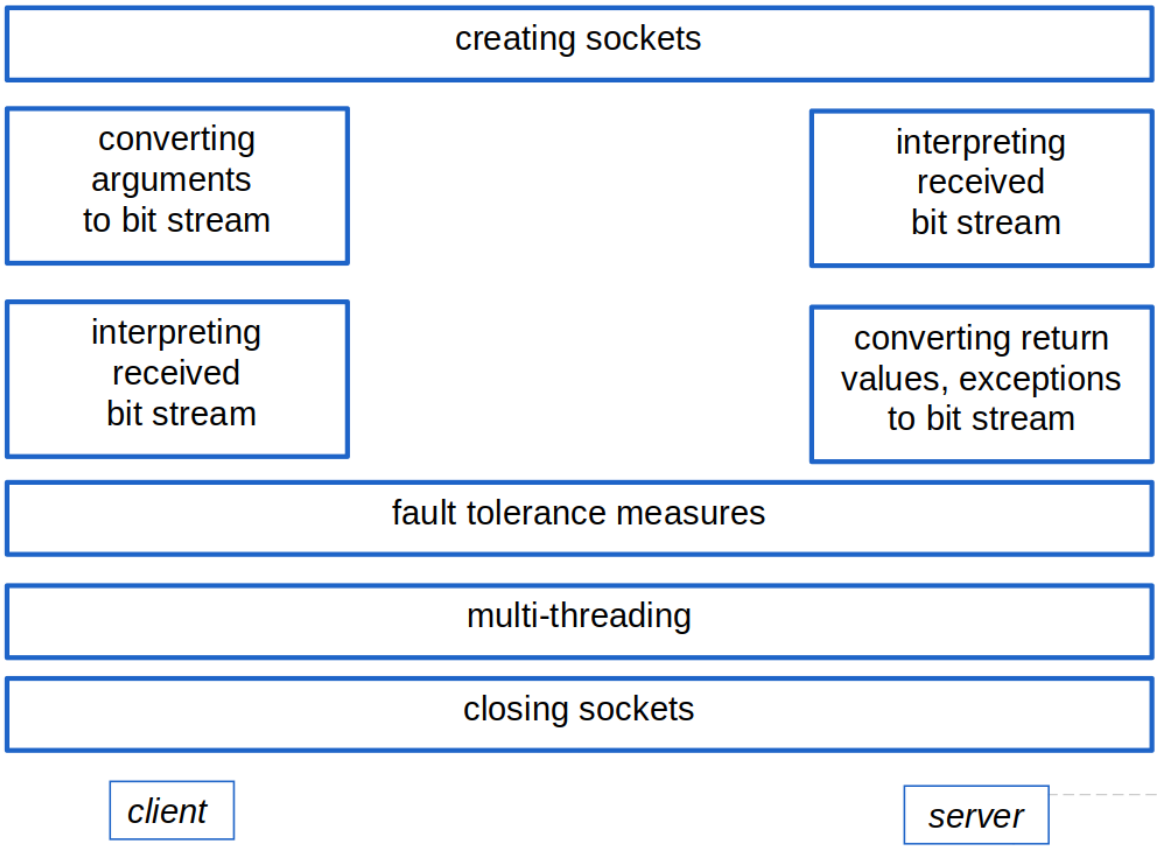
Strategies to avoid performance problems (just read this)

1. Keep complexity of client software as low as possible and put preferably as much as possible operations in the back-end.
2. Use caches when required, but the system should work perfectly as well without caches.
3. Make sure the system can reply fast to requests (i.e. avoid large-grain invocations, but split up in small-grain invocations).
4. To decouple systems, the use of queues is often useful (to easily add asynchronous processing).
5. Make sure the load balancing components work in a decent way (i.e. use appropriate load balancing algorithms).
6. Make sure to have very detailed log-files at all times (with different levels of details, to allow easy filtering), make it able to determine immediately the involved host, component, time stamps, and monitored values.
7. The detailed log-files should also contain failures, successful operations, response times and statistical processing should be done automatically (e.g. calculating averages, standard deviations, trends).
8. When the system runs, it should be able to cope with graceful shutdown of components (one by one).
9. The system should start up and work properly with zero-configuration: use good default values, use auto-discovery as much as possible.
10. To distribute load, make for instance use of a cluster management system or a cloud environment.

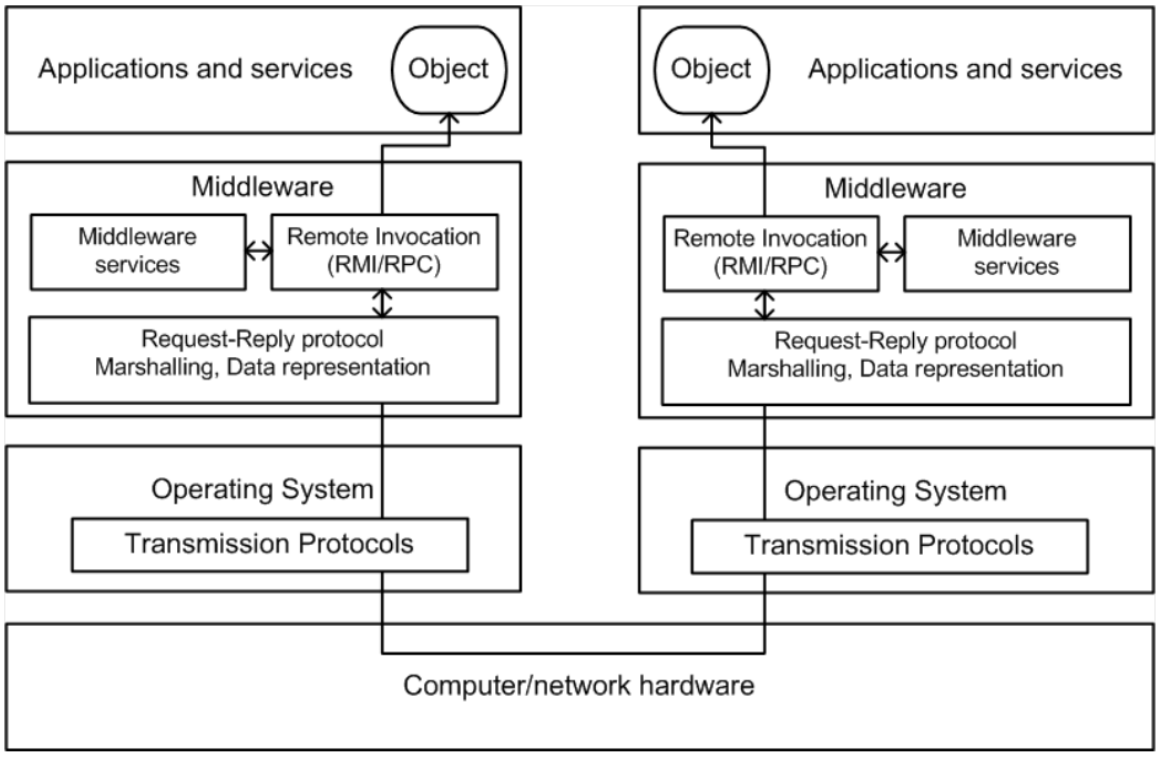
Chapter 2: Middleware

Remote Invocation

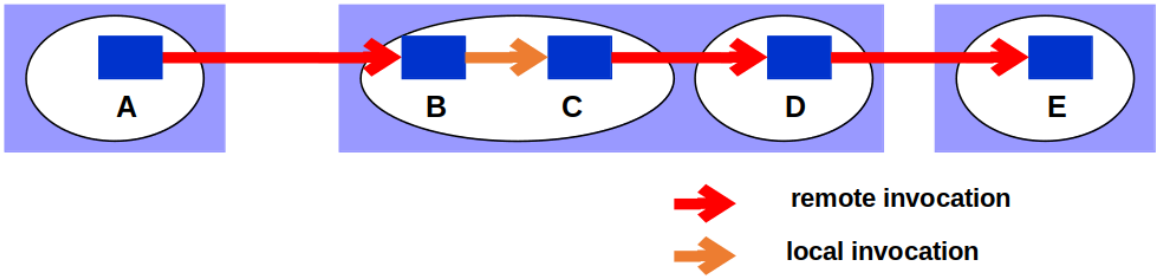
Requires:



Positioning:



Local and remote invocations:



Local invocation	Remote invocation
Use Object Reference Any public method remote interface	Use Remote Object Reference Limited access,

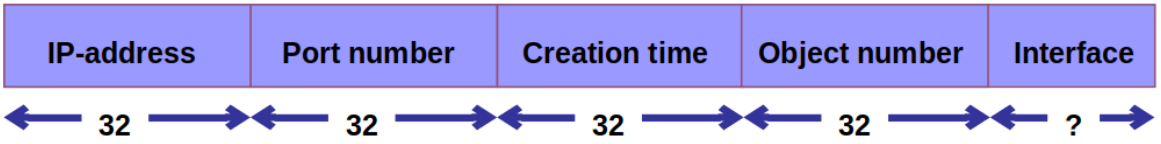
The goal of the remote invocation is to make the invocation of a method on a remote object look like a local invocation. This is done by the middleware. It hides:

- Locate/contact the remote object.
- Marshalling (convert parameters to byte stream).
- Fault tolerance measures.
- Communication details. But! The programmer must still be aware of the fact that the invocation is remote (network latency, possible failures). The typical approach is that the programmer has to catch exceptions that are thrown by the remote invocation.

Remote Object Reference (ROR)

Unique ID for objects in distributed systems. It is unique over time and space.

Host: Internet Address Process: Port number + process creation time Object: Object ID Object type: Interface ID



Fault Tolerance

Techniques:

- Retry-request messages
- Duplicate request filtering
- Retransmission of results
    - Re-execute call
    - History table of results -> retransmit reply

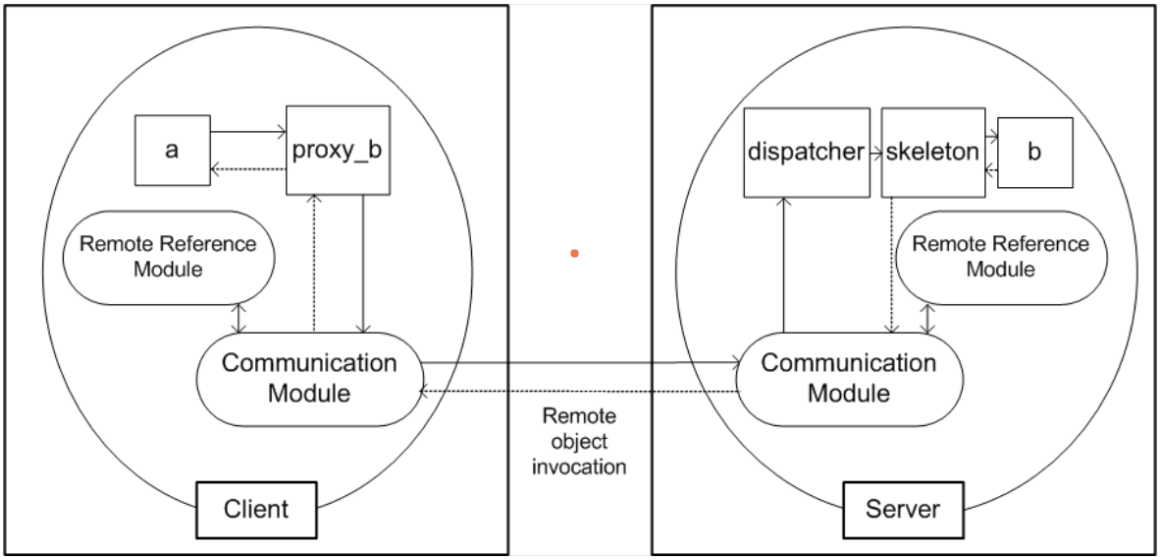
Invocation semantics:

- At most once

- At least once
- Exactly once

Retransmit request	Duplicate filtering	Re-execute call	Retransmit reply	Invocation semantics
NO	NA	NA	NA	*maybe*
YES	NO	YES	NO	*at-least-once*
YES	YES	NO	YES	*at-most-once*

RMI architecture



Request-reply (RR) protocol

Runs in the communication module. It is responsible for:

- send message to server object
- send back return value or exception info to requestor
- enforce appropriate invocation semantics

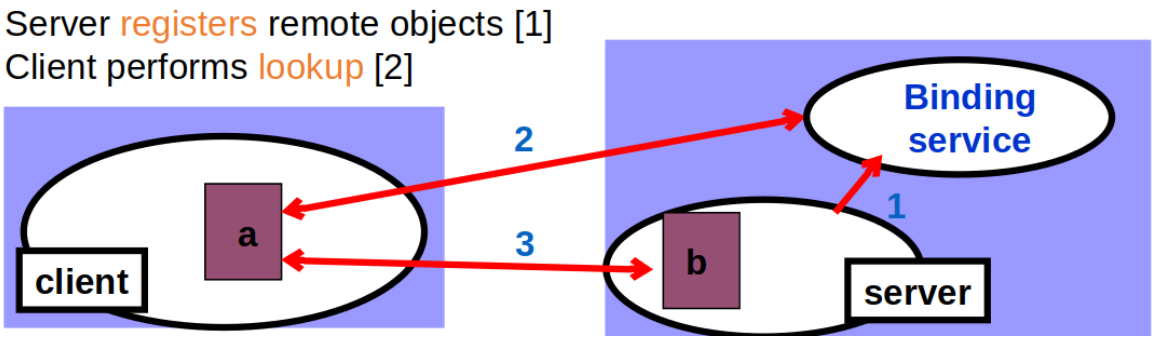
Duplicate Filtering Algorithm: The server keeps a history of the last N requests. If a request is received that is already in the history, the server sends back the result of the previous invocation.

Marshalling

Marshalling is the process of converting the parameters of a method call into a byte stream. The byte stream is sent over the network to the remote object. The remote object unmarshals the byte stream to get the parameters.

RMI binding service

The RMI binding service is a service that allows clients to look up remote objects by name. The binding service is a directory service that maps names to remote object references.



Middleware services

Naming service

Registration of object references with names. The names are structured in a hierarchy.

Trading service

Comparable to the naming service, but lets the objects be located by attributes also.

Event service

Publish-subscribe model. The event service allows objects to subscribe to events and to publish events.

Notification: Object that contains information about the event. Observer: decouple the object of interest from its subscribers.

Notification service

Extends the event service with filters. Notifications have a datatype, the consumers may use filters to specify events they are interested in. Proxies forwards notifications to consumers according to constraints specified in the filters.

Transaction service

A transaction is a sequence of operations that must be executed as a single unit. The transaction service provides the following properties:

- Atomicity: All operations in a transaction are executed or none.
- Consistency: A transaction transforms the system from one consistent state to another.

Persistence service

Automated storing and retrieving of objects.

Activation service

Activation: On demand execution of services to reduce server processes/threads. Activate objects when requests arrive. Passivate objects if in consistent state.

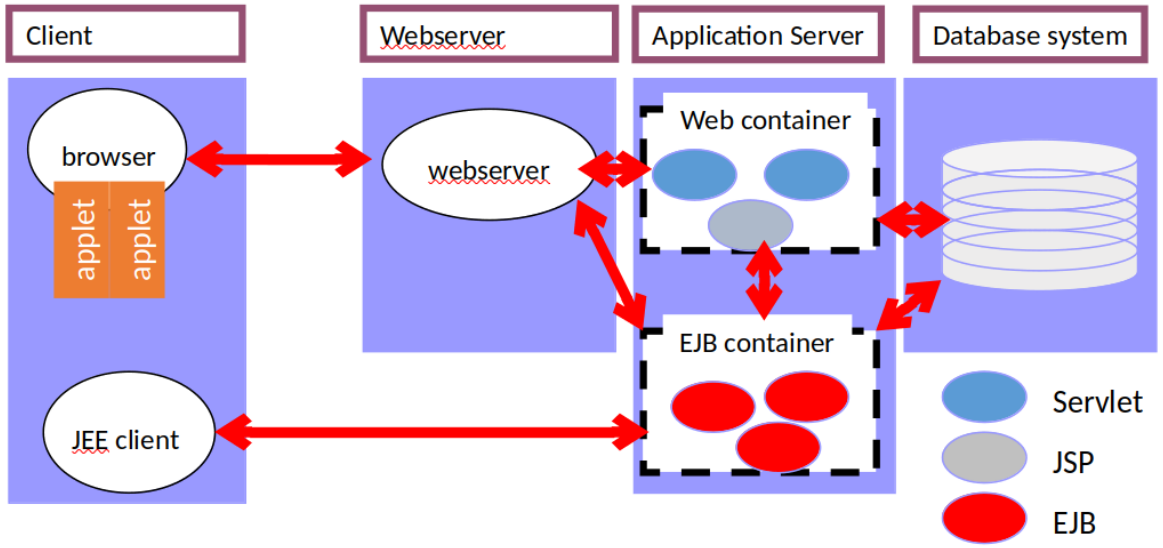
Activator: Keeps table of passive (activatable) objects. Activates objects on demand.

Load balancing service

Distribute the load over multiple servers. Often in combination with naming service.

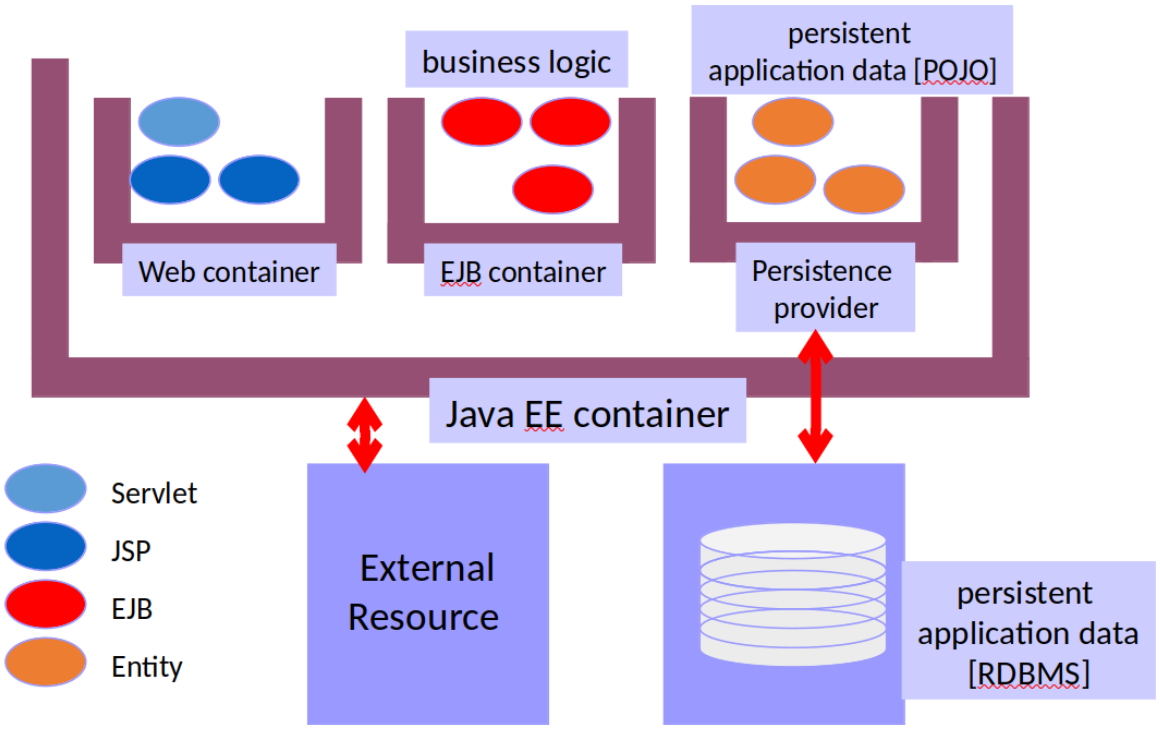
Chapter 3: Enterprise Applications

JEE-based applications (Java Enterprise Edition)



Web container services:
- component life cycle management
- handle communication with webserver HTTP <-> servlet
- session tracking

EJB container services:
- component life cycle management
- transaction service
- security handling
- resource pooling



Inversion of Control: Decisions taken at the server side, not the client side. The container provides transparent features.

Benefits

1. **Simplify the development of large, distributed applications.**
    1. The EJB container provides system-level services to enterprise beans.
    2. The bean developer can concentrate on solving business problems.
    3. The EJB container is responsible for system-level services such as transactions, management and security authentication.
2. **The client developer can focus on the presentation of the client.**
    1. Because the beans contain the business logic.
    2. The clients are thinner.
3. **Enterprise beans are portable/reusable components.**
    1. The application assembler can build new applications from existing beans.
    2. The applications can run on any compliant JEE server.

Chapter 4: Timing and synchronization

Physical clock synchronization

In distributed systems there is **no global state** notion. How can we be sure about event ordering when there is no global time notion?

There are two flavours of time:

- **Physical time:** Real time, related to solar time, this is important when a connection

to the "real" time is needed.
- **Logical time:** Time that is related to the order of events in the system. This is easier to implement.

Hardware clocks

A hardware clock is made up of a crystal oscillator and a counter. The counter is incremented by the oscillator at a fixed rate. The counter is read by the operating system.

Hardware clocks are not perfect. They drift and skew.

- The **drift rate** is the difference between the rate of the clock and the rate of the real time.
- The **skew** is the difference between the time of the clock and the real time.

The clock resolution is the smallest time interval that can be measured by the clock = 1/H. With H the amount of times the clock is updated per second.

A correct clock has a bounded drift rate and the monotonicity property. The clock is correct if the time it shows is always greater than the time it showed before.

External synchronization

There is an external "authoritative" process clock that is used to synchronize the clocks of the other processes. The authoritative process sends a message to the other processes with the time it has. The other processes adjust their clocks to the time of the authoritative process.

All the clocks have a bound skew that needs to be smaller than a predifined value.

$$\left|C_p(t) - C_{ext}(t)\right| \leq \Delta,\ \forall p \in \Pi$$

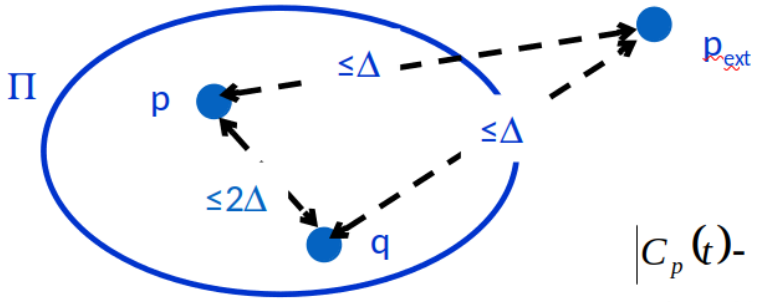
with pi the collection of clocks, without the external one.

Internal synchronization

Here the skew between any two clocks is bounded by a predefined value. The clocks are synchronized with each other. $\left|C_p(t) - C_q(t)\right| \leq \Delta,\ \forall p, q \in \Pi$ with pi the collection of clocks.

Obvious property

if P is externally synchronized with skew Δ,
then it is internally synchronized with skew 2Δ



$$
\begin{aligned}
&|C_p(t) - C_q(t)| \\
&= |C_p(t) - C_{ext}(t) + C_{ext}(t) - C_q(t)| \\
&\leq |C_p(t) - C_{ext}(t)| + |C_{ext}(t) - C_q(t)| \\
&\leq 2\Delta
\end{aligned}
$$

Client-server algorithm

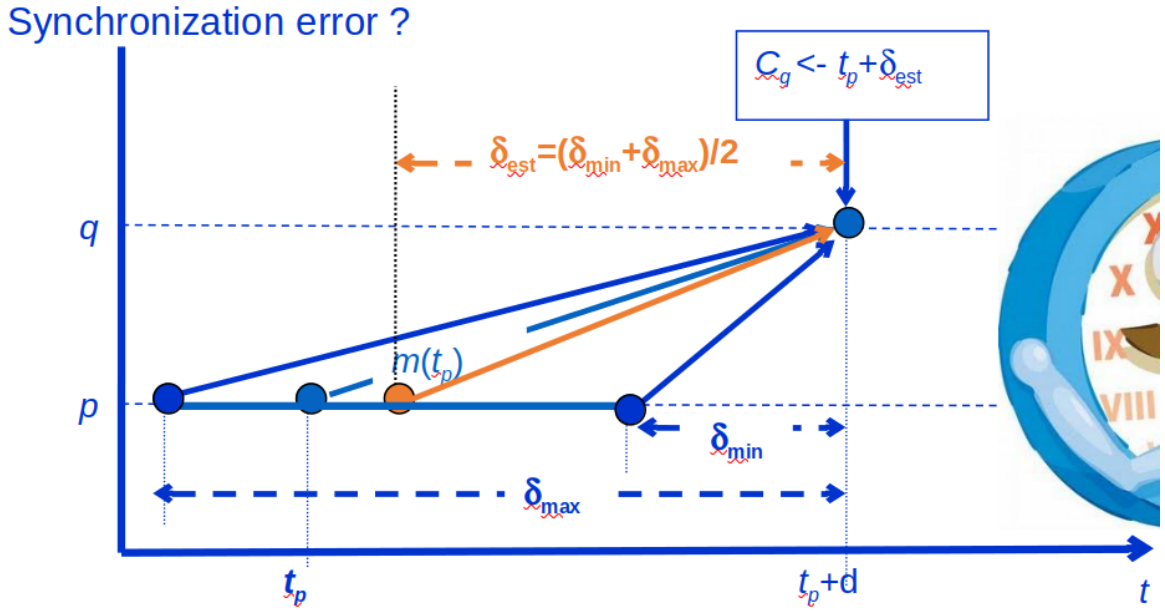
Here the meaning of the client server is that one process (p) has a better clock than the other process (q). **The goal of the synchronization is to minimize the skew between the clocks of p and q.**

The problem with this is that when p sends its current time to q, the time it takes for the message to arrive is not taken into account.

Synchronous system: Here the time it takes for a message to arrive is bounded by two bounds, δ_{max} and δ_{min}.

Estimate: $C_q = t_q + \frac{\delta_{min}+\delta_{max}}{2}$

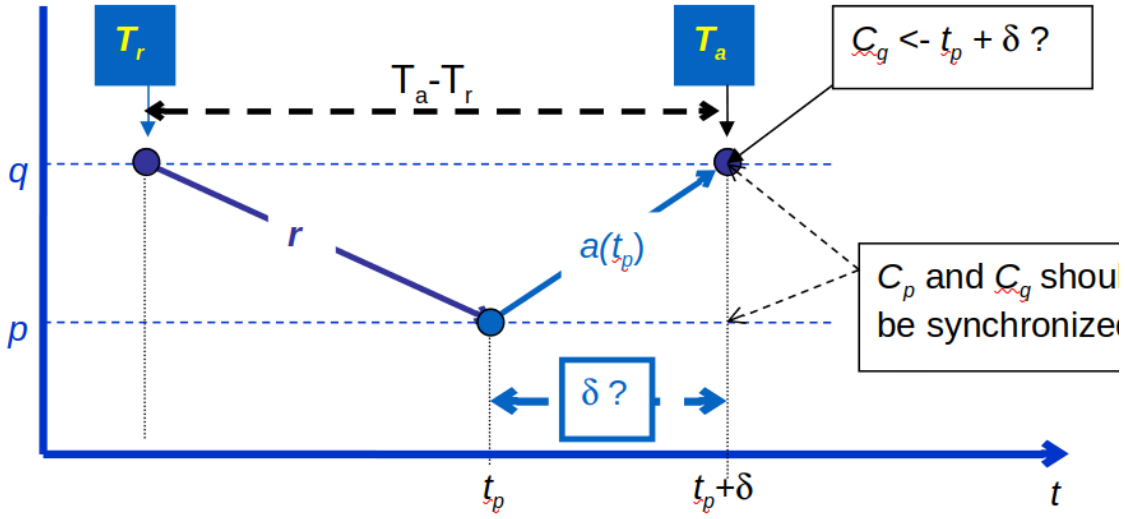
Worst case we will have a skew of $\frac{\delta_{max}-\delta_{min}}{2}$.

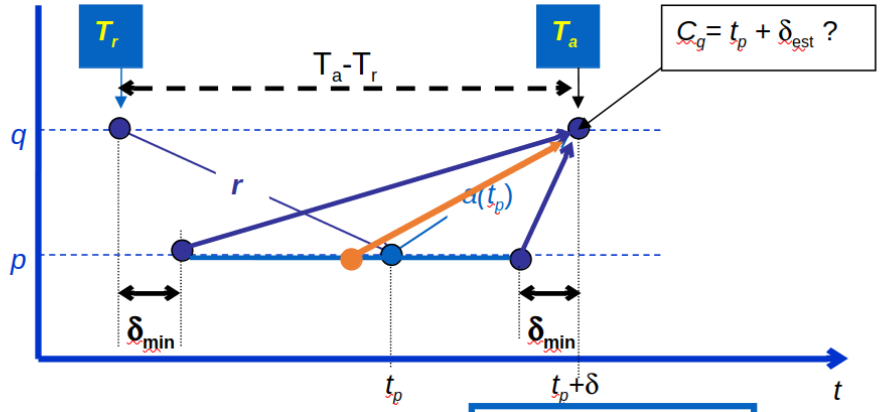


Asynchronous system: Here the time it takes for a message to arrive is not known, but we have an estimate of $\delta \approx RTT/2$. The RTT is the round trip time.

Cristian's algorithm (for asynchronous systems)

No upper bound for one way delay d
Suppose we have a lower bound δ_{min} (possibly 0)
Two messages involved:
- request (r)
- reply (a) : contains timestamp by time server





$\delta_{min} \leq \delta \leq T_a - T_r - \delta_{min}$

$\delta_{est} = (T_a - T_r)/2$

$C_q = t_p + \frac{T_a - T_r}{2}$

skew=$|C_q - C_p|$ = $|t_p + \delta_{est} - (t_p + \delta)|$
= $|\delta_{est} - \delta|$

$\max skew_{p,q} = \max|C_p - C_q| = \frac{T_a - T_r}{2} - \delta_{min}$

max skew for extreme values of δ

Peering algorithm: NTP (Network Time Protocol)

NTP is a protocol that is used to synchronize the clocks of computers over a network.

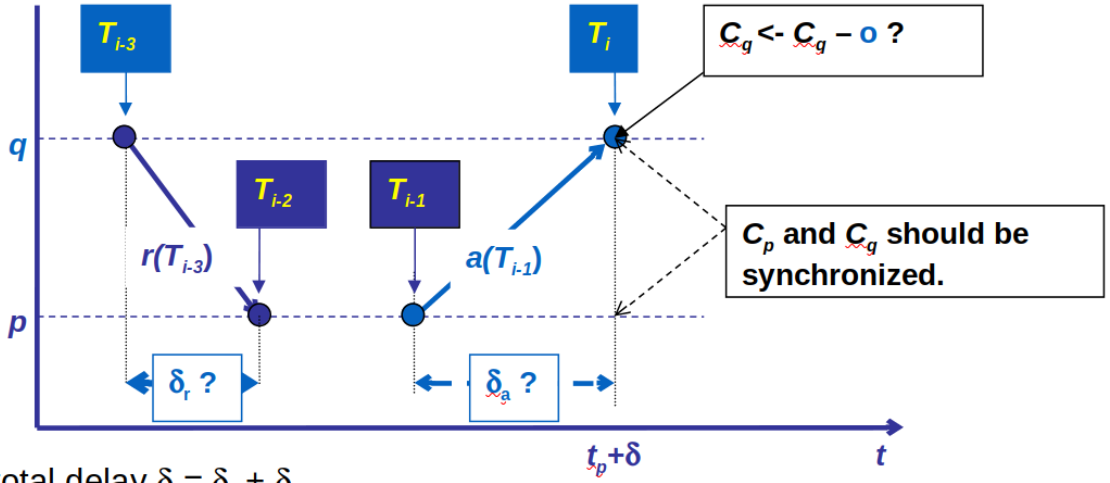
Network Time Protocol : asynchronous system

Clock skew between p and q : $C_q = C_p + o$

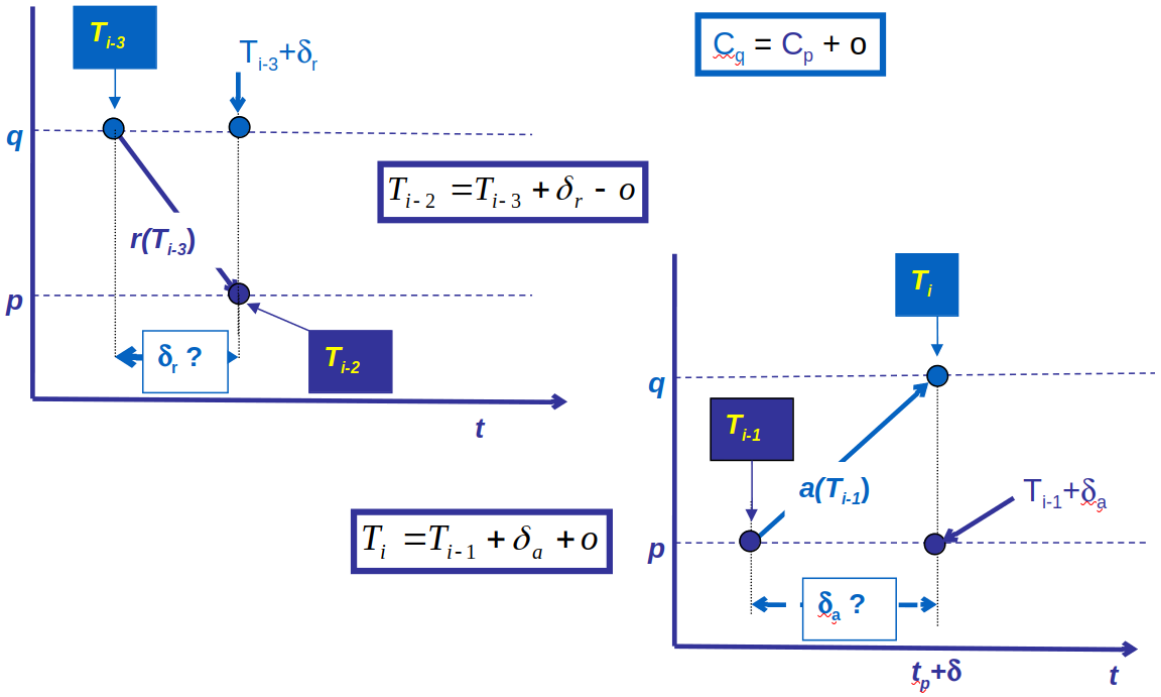
Two messages exchanged between p and q

- request (**r**)
- reply (**a**)

Time stamp info embedded in **a** and **r**



total delay $\delta = \delta_r + \delta_a$



maximum error = d/2

if <o,d> pairs are stored, o-values with lowest d's are most accurate

with d the delay = $\delta_r + \delta_a$.

NTP Modes

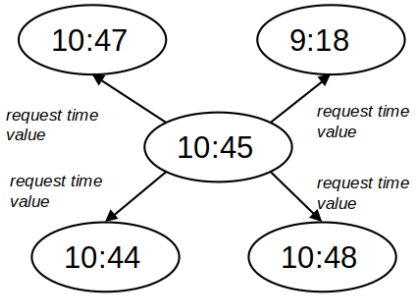
- **Multicast:** Used in high speed (low delay) LAN environments. The server multicasts the time to all clients. The clients then assume some average delay.

- **Procedure call:** Using Christian's algorithm. Better accuracy than multicast.
- **Symmetric:** Peering servers execute P2P algorithm. They collect 8 <o,d> pairs, using the optimal o based on minimal d. Used to achieve high accuracy.

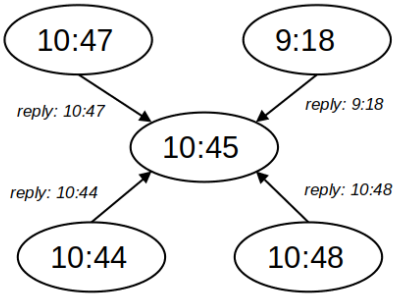
Peering algorithm: Berkeley algorithm

The peering processes elect time server. This coordinator actively polls its clients (participants).

1. Poll for participant time.
2. Use Christian's algorithm to measure RTT.
3. Calculate the average RTT.
    1. But neglect participants with RTT > RTTmax.
    2. If the time between the two is bigger than a certain threshold, the coordinator will not use the participant.
    3. Send the adjustment to the participant.
4. Elect a new coordinator if the current one fails.



1. coordinator requests time from participants

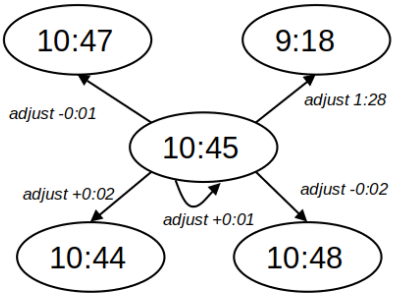


2. coordinator receives time values from participants

neglect 9:18
average:
/ 4 = 10:46

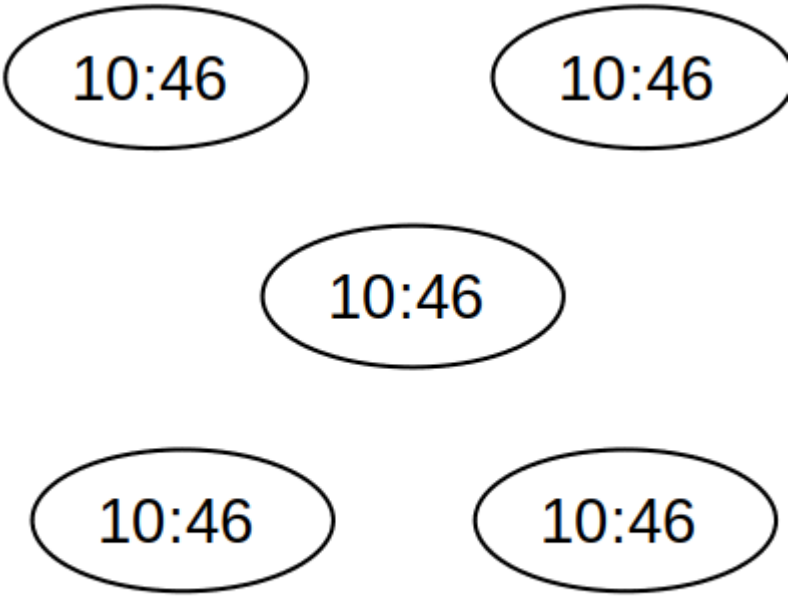
adjustments:
-0:01 for 10:47, -0:02 for 10:48,
+0:01 for 10:45, +0:02 for 10:44
+1:28 for 9:18

3. coordinator calculates time adjustments



4. coordinator sends time adjustments

SITY



5. updated clock values

To make sure you have no negative adjustments, you just add up until all corrections are positive.

Logical clocks

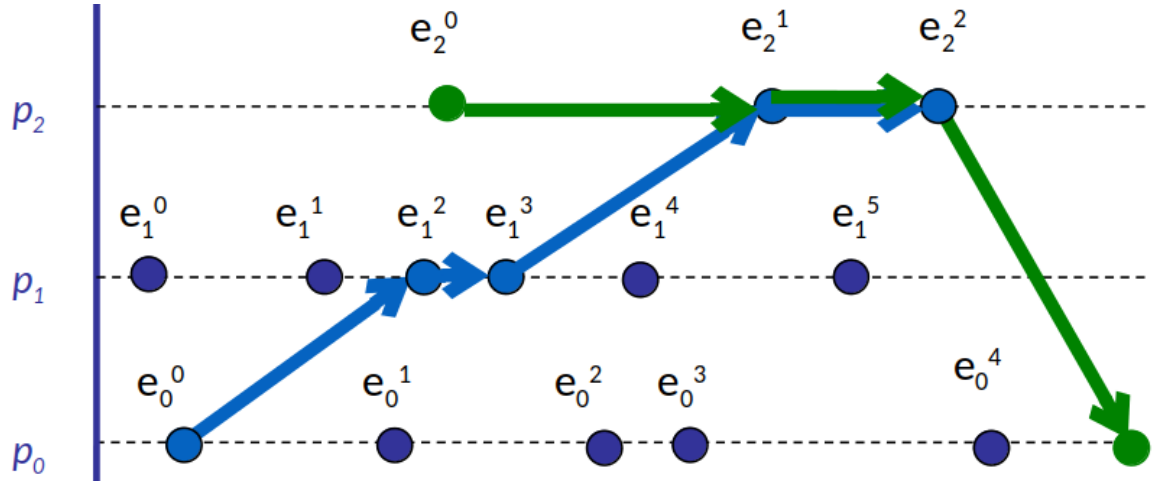
Logical clocks are used to order events in a distributed system. They are not related to physical time.

Event ordering is easy when the events happen in the same process. But when the events happen in different processes, it is more difficult.

How can we order events in a distributed system?

First some common sense about ordering events (->):

1. if both event belong to the same process, global ordering coincides with local ordering.
2. Sending a message happens before resceiving a message.
3. $(a \rightarrow b) AND (b \rightarrow c) \Rightarrow (a \rightarrow c)$



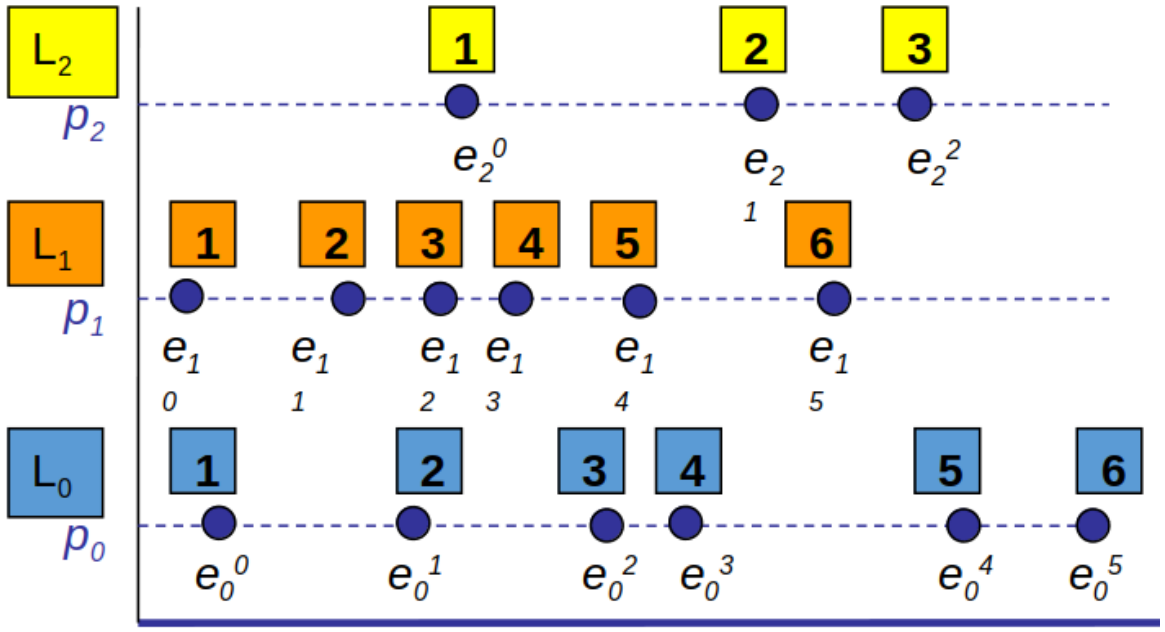
Events are **concurrent** if no chain of events can be found between the two events.

causality: $e \rightarrow e'$ doesn't mean that e causes e', it means that e' doesn't cause e.

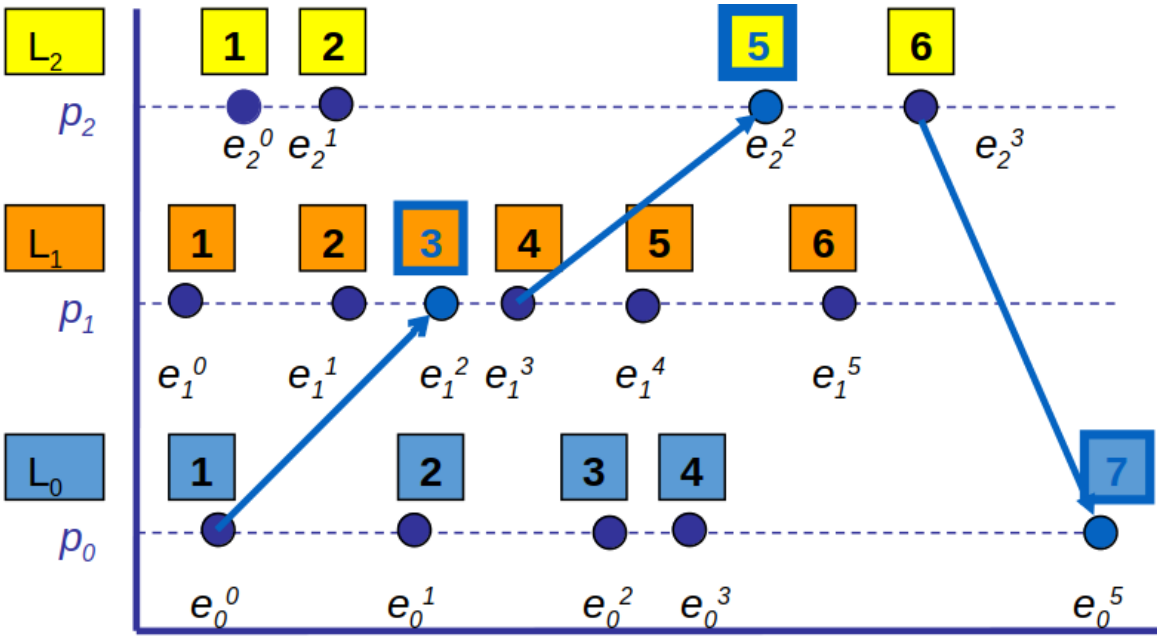
To really determine if e causes e', we need a clock.

Lamport's logical clocks

Each process p_i maintains a scalar L_i with initial value 0. This value is increased monotonically just before an event happens. If there is no communication between events, we have the following situation.



In situations where there is communication between events, we have the following situation. First the sender of the event sends the value of its clock to the receiver. The receiver then sets its clock to the maximum of its own clock and the received clock + 1. Creating the following:

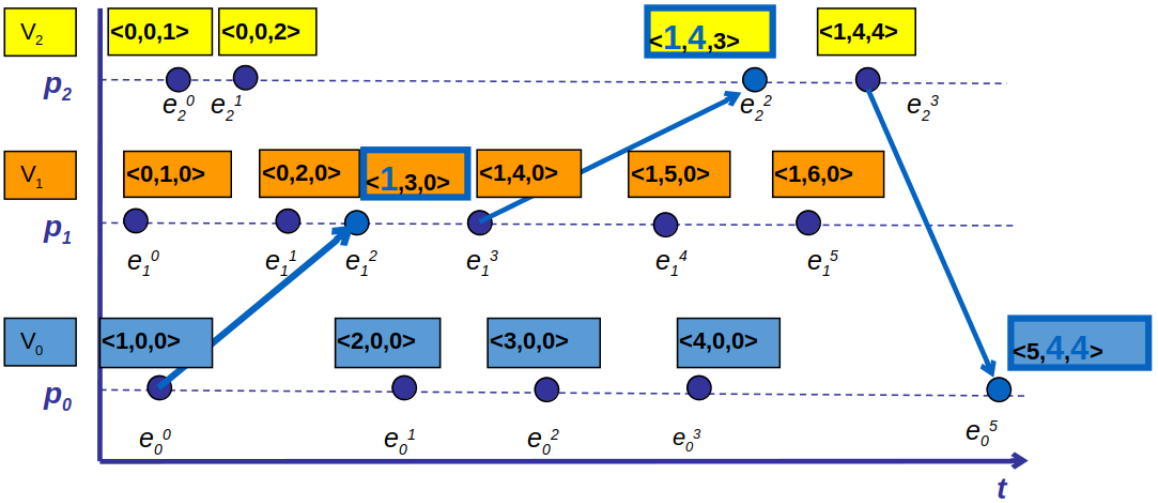


Lamport's clock just keeps track of the maximum amount of events seen at a process from any process in P.

Vector clocks

Keep track of the number of events seen from each process individually. Each process has a vector V_p of N elements.

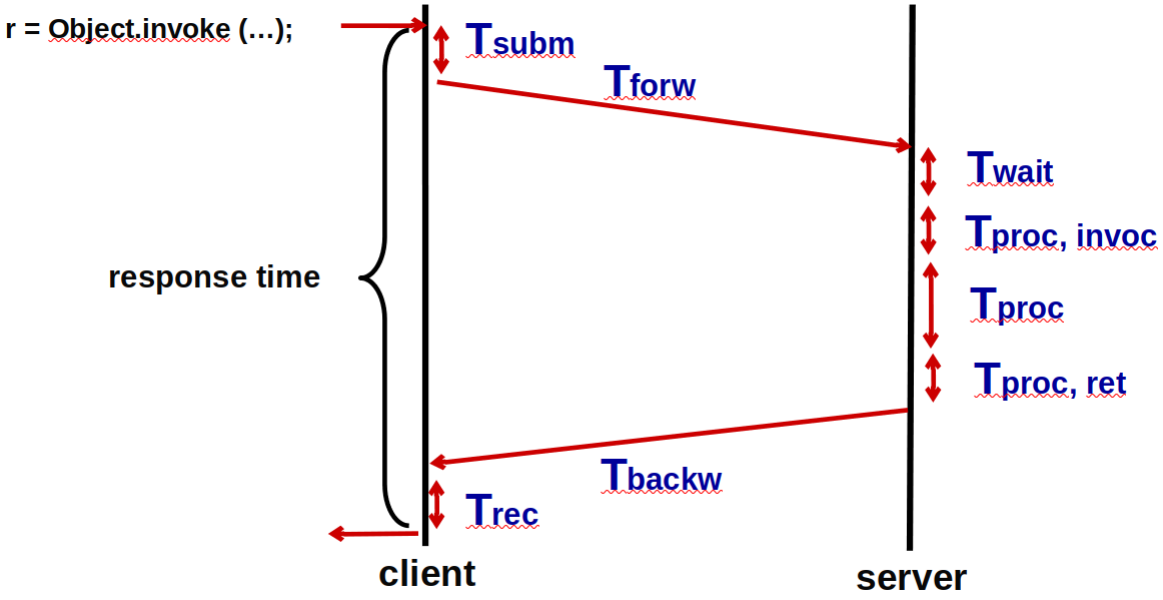
If an event has a clock value, indicating it has seen more events from every process than another event, THEN we are sure that the event has happened after the other event.



drawbacks: There is more data exchanged and the number of processes needs to be known.

Performance metrics

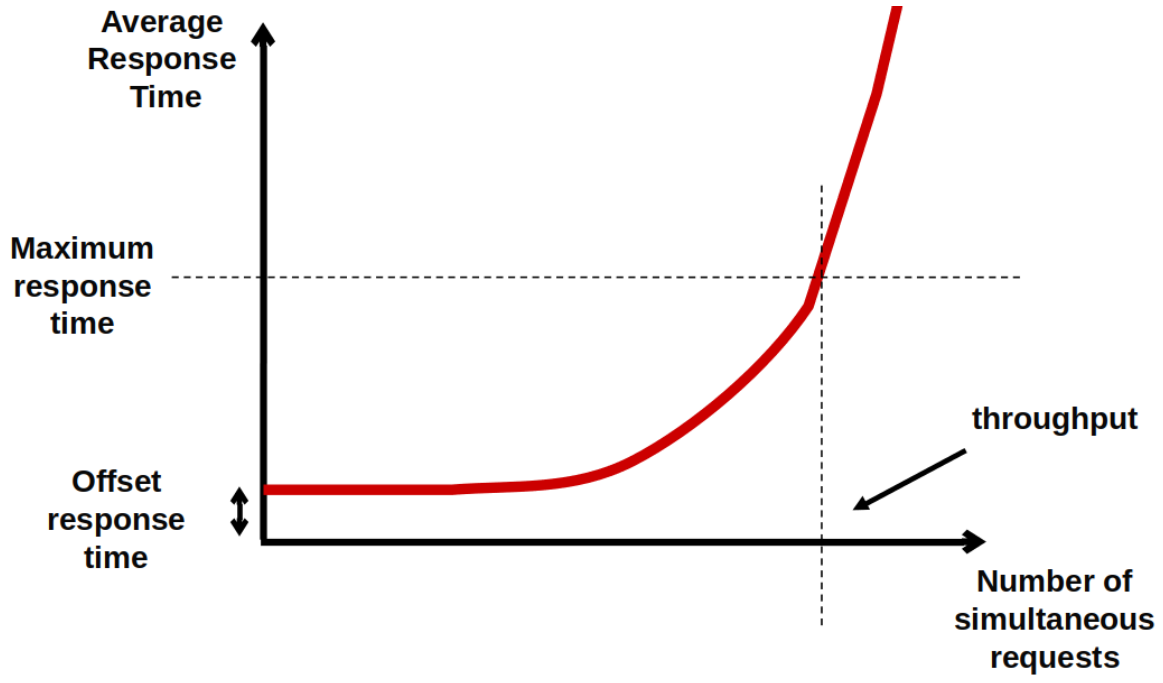
Response Time: A function of the number of simultaneous requests and the time it takes to process a request.



T_{wait} is the time spent in queue before a serving thread can be created. T_{forw}, T_{backw} are the delays of the sum of the link delays on the path from the client to the server and back. That **link delay** consists of the processing delay, queuing delay, transmission delay and propagation delay.

- **Processing delay:** The time it takes to process a request until the packet is assigned to the output queue.
- **Queuing delay:** The time it takes for the packet to wait in the queue.
- **Transmission delay:** The time it takes to transmit the packet over the link.
- **Propagation delay:** The time it takes for the packet to travel from the sender to the receiver.

Throughput: The maximum number of simultaneous requests per second.



Chapter 5: Coordination

In a distributed system, how to coordinate actions and the global state (shared variables)?

Failure detection

Unreliable failure detectors: Only hints about the failure of a process.

- **suspected:** The process is probably crashed.
- **unsuspected:** The process is probably alive.

Reliable failure detectors: Sure about crashing of a process.

- **failed:** The process has definitely crashed.
- **unsuspected:** The process is probably still alive.

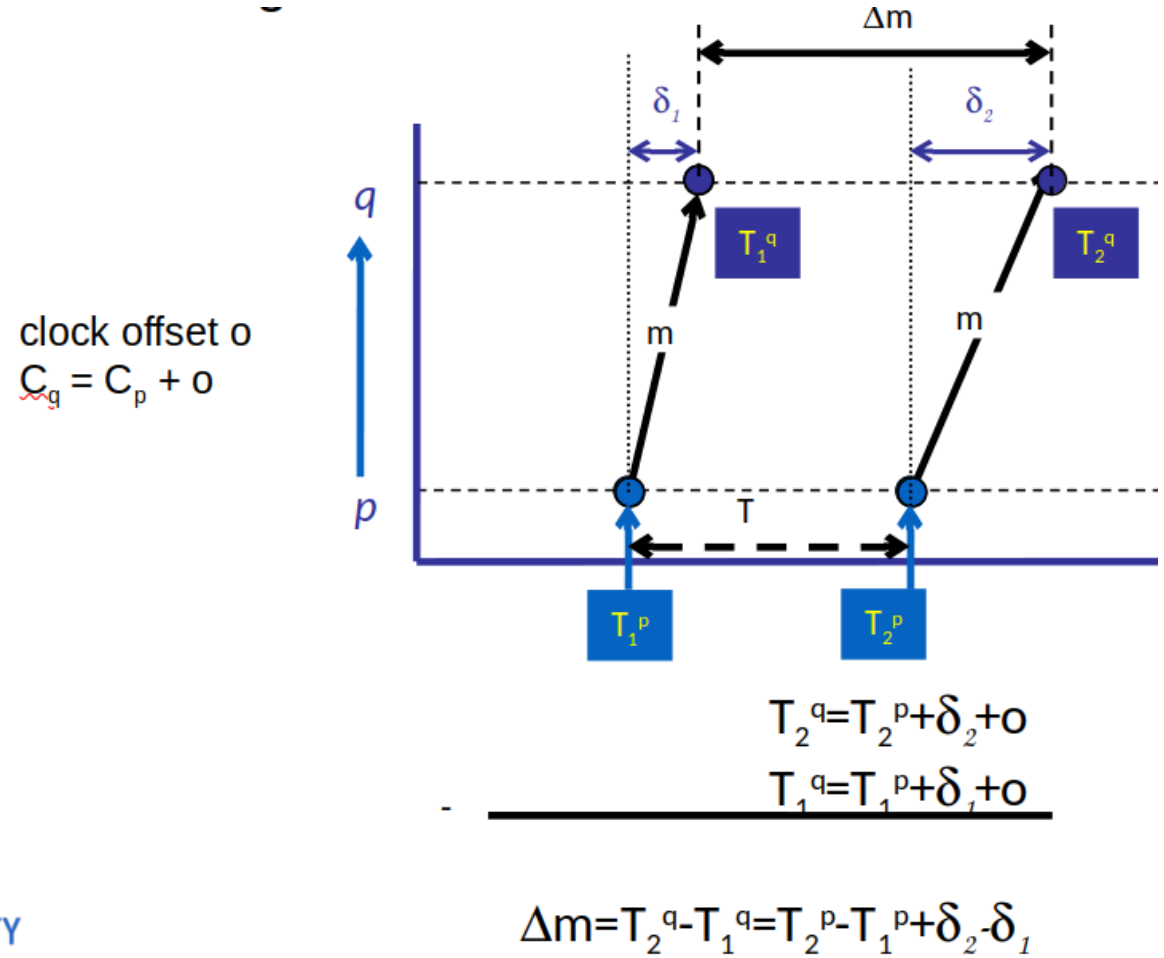
Algorithms

1. Hearth beat from p
2. Server polls p

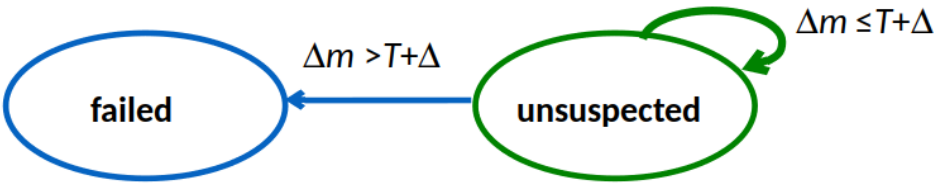
Hearth beat: p sends a message m to q every T seconds. q measures IAT of m : Δm.

Synchronous

The bounded network delay $\delta < \Delta$ and the message is delivered.



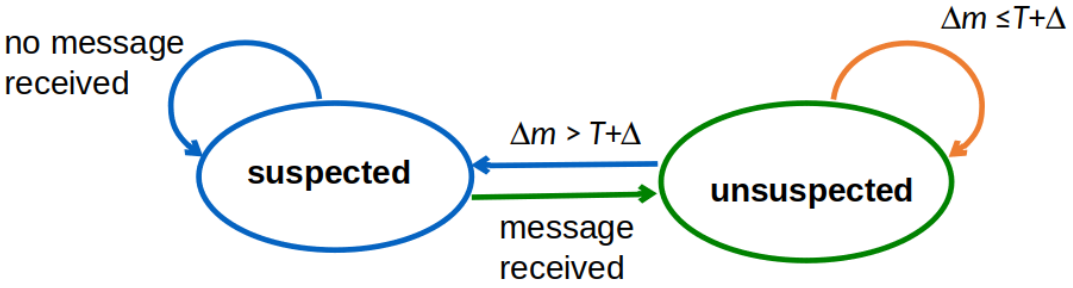
$\Delta m > T + \Delta$ -> p has crashed
$\Delta m \leq T + \Delta$ -> p WAS alive, but MIGHT have crashed since



Reliable failure detector

Asynchronous

Here we can make no assumption on network delay. Only suspicion if Δm becomes exceedingly large.



Unreliable failure detector

Δ ?

Δ >> too many unsuspected
Δ << too many suspected
sensible choice : set Δ in relation to network delay
- adapt dynamically
- e.g. $\Delta = 1.2\ \delta$

Mutual exclusion

Critical section: A part of the code that can only be executed by one process at a time.

The goal is to coordinate process access to shared resources.

In the distributed case, this can only be done by message passing.

Consider: N processes with NO shared variables. They access common resources in a critical section. It is an asynchronous system and all the processes can communicate with each other.

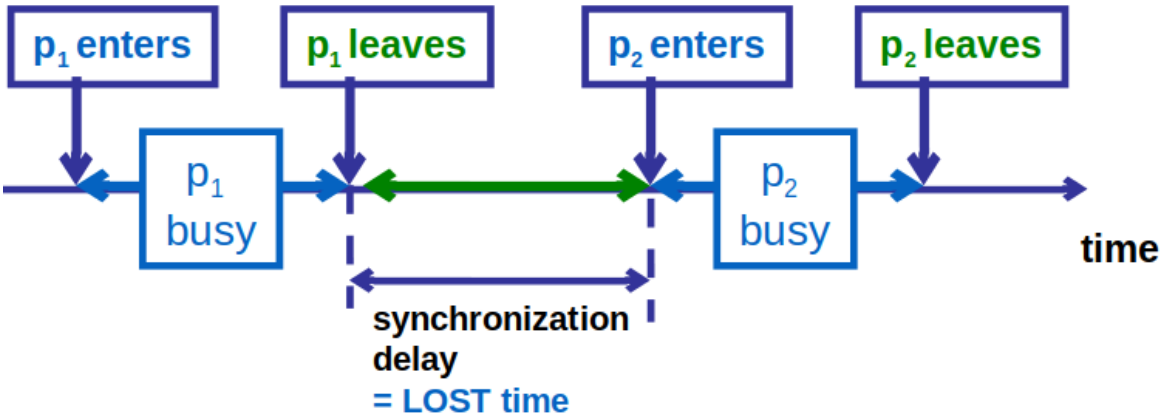
Failure model: They use reliable channels, there are no process failures and the processes are well-behaved (they have no bad intentions).

A Good solution should contain the following properties:

1. **Safety [REQUIRED]:** At most one process is in the critical section.
2. **Liveness [REQUIRED]:** If a process wants to enter the critical section, it will eventually do so.
3. **Fairness [BONUS]:** Use logical clock to order access requests.

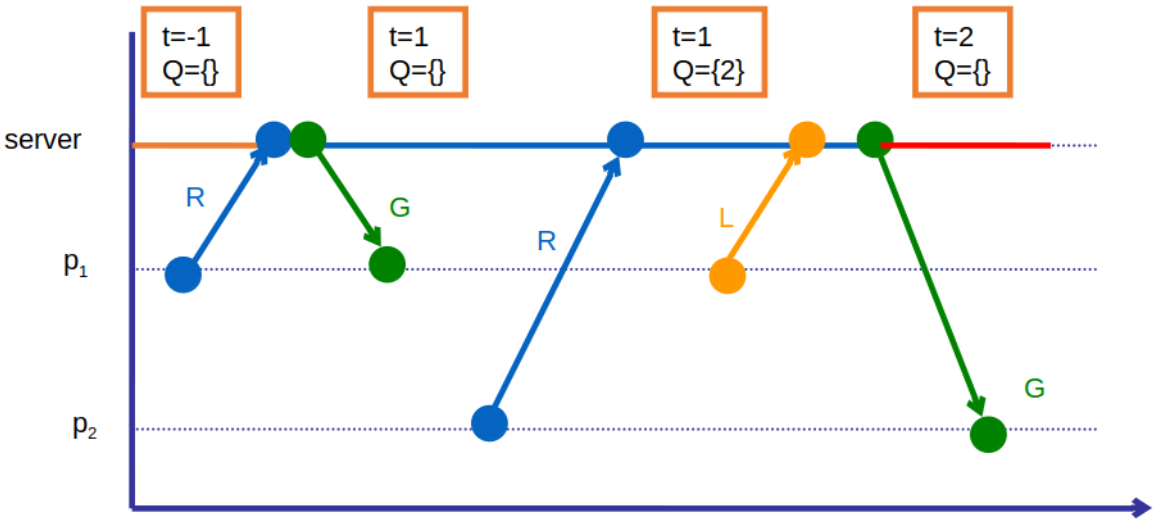
How will we quantify the solution quality? Evaluation metrics:

- **Bandwith consumption:** The number of messages sent.
- **Client delay:** The time it takes for a client to enter the critical section, measured in an **UNLOADED** system.
- **System throughput:** The number of processes that can enter the critical section in a given time period. However this depends on the resource access time. A derived measure is the:
    - **Synchonization delay** which is the time it takes for a process to enter the critical section, measured in a **LOADED** system.



Centralized algorithm

One process is the coordinator. The coordinator decides who can enter the critical section. This is easy to implement but not very scalable.



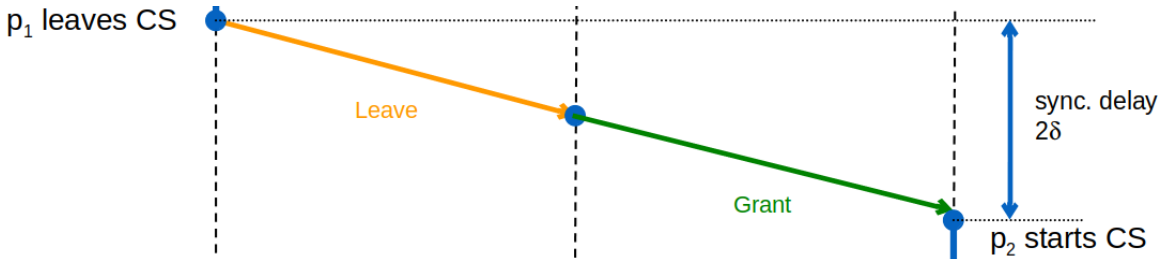
Algo OK?

- **Safety:** OK -> guarded by token variable

- **Liveness:** OK -> Request to enter: all processes eventually leave, each leave dequeues a message from Q. If oldest request is dequeued, every request eventually handled. Request to leave: no permission needed to leave.
- **Fairness:** OK -> FIFO queue

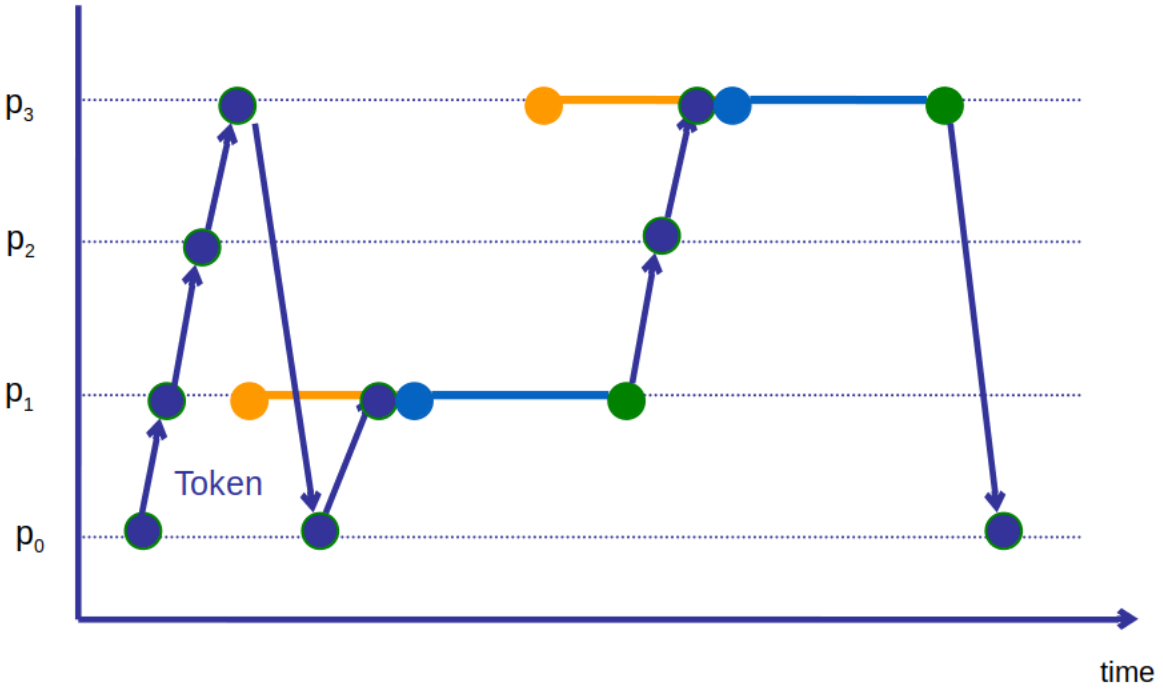
Algo efficiency?

Bandwith: 2 messages/enter, 1 message/leave **Client delay:** 2δ(=RTT)/enter, 0/leave
System throughput: 1/RTT



Ring-based algorithm

Processes are organized in a ring. The token is passed from process to process. The process that has the token can enter the critical section.



Algo OK?

- **Safety:** OK -> Process can only send the token if it has received the token.
- **Liveness:** OK -> Token circulates in the ring, no starvation.
- **Fairness:** Not guaranteed -> Process needs luck for early access, the order is not based on request time.

Algo efficiency?

Bandwith: Worst case: N messages, Best case: 1 message, Average case: $(N+1)/2$ messages.

Client delay: Worst case: $N\delta$, Best case: 0δ -> you just get the token, so no waiting, Average case: $N\delta/2$

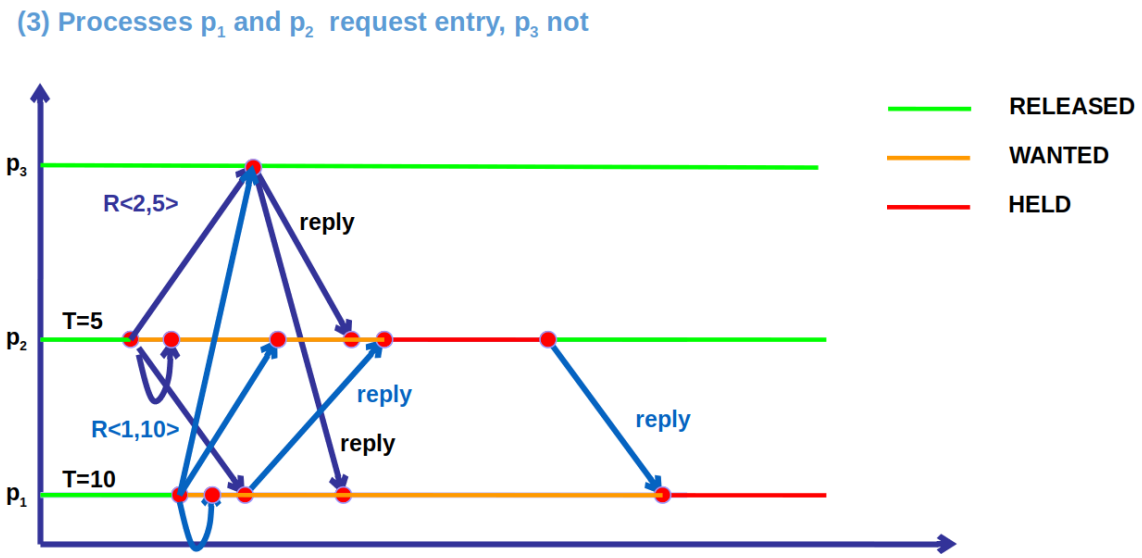
Synchonization delay: Worst case: $N\delta$, Best case: δ, Average case: $(N+1)\delta/2$

Multicast: Ricart-Agrawala algorithm

Processes send a request to all other processes. They can enter the critical section if they have received a reply from all other processes. They can use multicast to reduce bandwidth. Use a Lamport clock to order the requests.

Each process has:

- **State variable:** Released, wanted and Held.
- **Lamport clock:** To order requests.
- **Request queue:** To store pending requests. This queue is organized using the lamport clock, each request contains the following: <p, T>.



Algo OK?

- **Safety:** OK -> The proof shows that p and q cannot be executing simultaneously in the CS.
- **Liveness:** OK -> Every request is eventually handled. Meaning that every process will eventually receive (N-1) answers.
- **Fairness:** OK -> The order of the requests is based on the Lamport clock.

Algo efficiency?

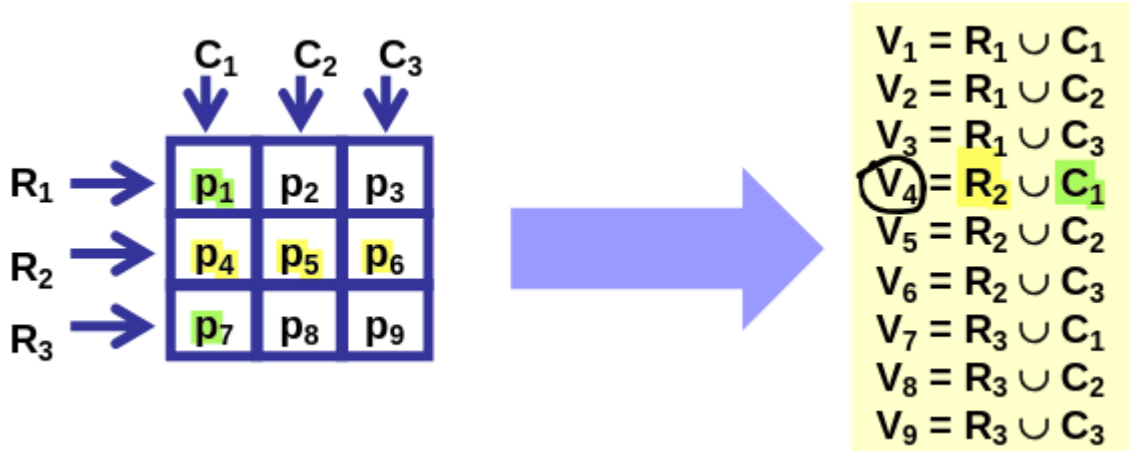
Bandwith: N(=1 if multicast is supported) messages/request, (N-1) message/reply. No message needed for leaving (= it is just the reply to the request of the following process that wants the CS).

Client delay: 2δ for enter, 0δ for leaving.

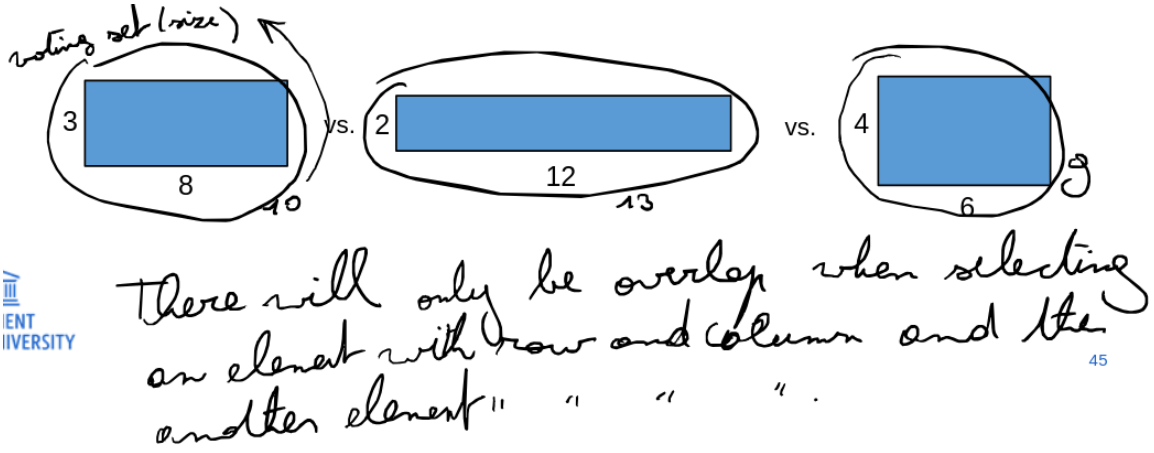
Synchonization delay: δ. The time it takes for a process to enter the critical section, measured in a **LOADED** system.

Multicast: Maekawa voting algorithm

Processes are organized in a grid. Each process can enter the critical section if it has received a reply from a majority of the processes in its column and row. This means that not all processes need to reply.



Voting set size:



Algo OK?

- **Safety:** OK -> The proof shows that p and q cannot be executing simultaneously in the CS.
- **Liveness:** Deadlock prone -> Use the Lamport clock to organize Q.
- **Fairness:** OK -> The order of the requests is based on the Lamport clock.

Algo efficiency?

Bandwith: K request messages, K reply messages. K release messages.

Client delay: 2δ for enter, 0δ for leaving.

Synchonization delay: 2δ. The release and reply message delays summed together.

Difference between Ricart-Agrawala and Maekawa

Maekawa:

- Additional state variable per process needed: Voting.
- Multicast request to enter to voting set only.
- Explicit leave needed, so voting processes can vote for other process.

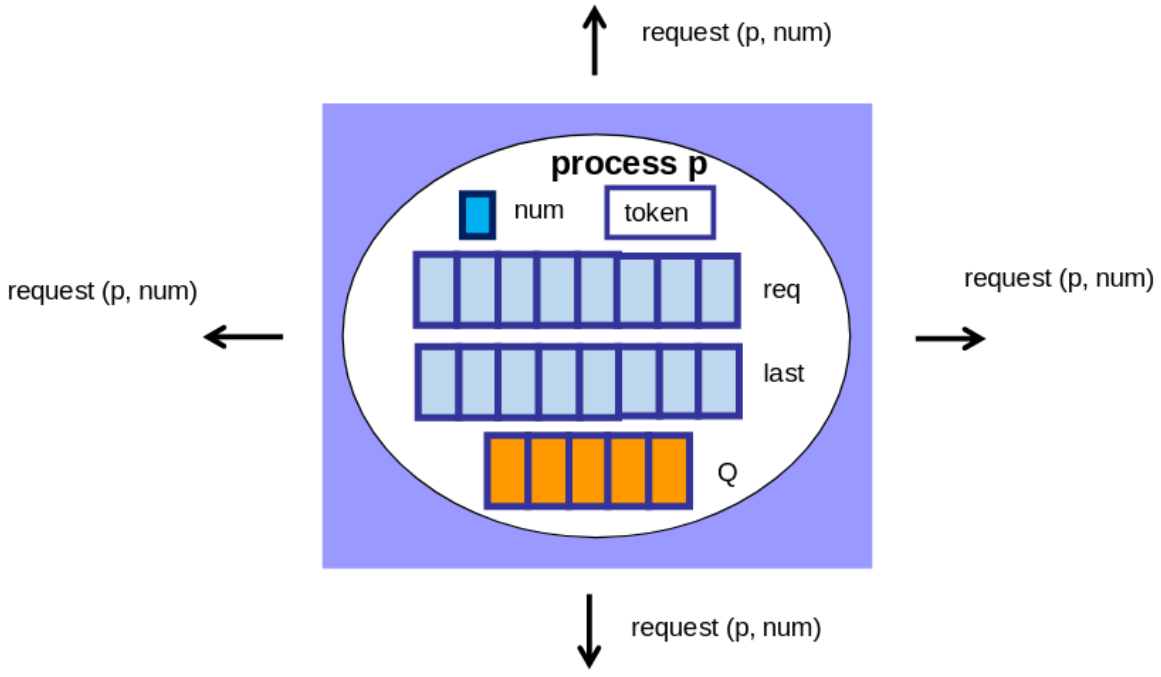
Needs also another type of message: **release**.

Summary of 4 algorithms

	Bandwidth enter()	leave()	Client delay enter()	leave()	Synchronization delay
Central server	2M	1M	2δ	0δ	2δ
Ring algorithm	constant		Nδ/2		(N+1)δ/2
Ricart-Agrawala	(2N-1)M	0M	2δ	0δ	1δ
Maekawa voting	2KM	KM	2δ	0δ	2δ

Suzuki-Kasami algorithm

Completed connected network of processes, token is passed between processes. The process that has the token can enter the critical section.



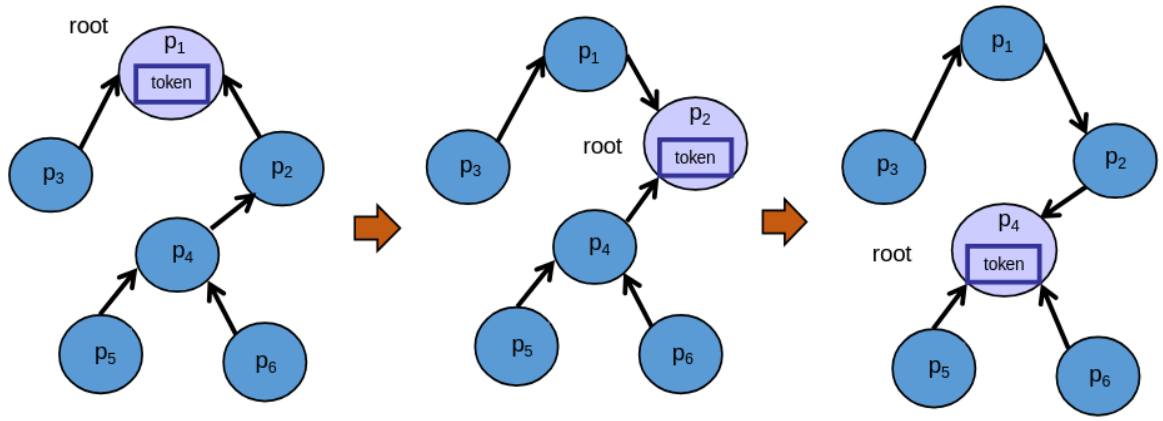
To enter the CS: N-1 messages with the request, receive 1 message with token = N messages.

Raymond's algorithm

Processes connected through tree topology, the token is passed between processes.

The process that holds the token is the root of the tree.

p_4 requests token :



Algorithm evaluation

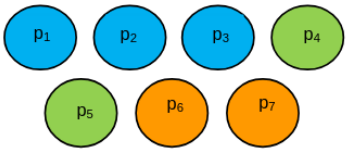
- Safety: only 1 token
- Deadlock: impossible, acyclic graph: if process *i* waits for process *j*, it is lower in the hierarchy and process *j* can not wait for process *i*
- Fairness: Q in order of arrival

Algorithm performance

average distance between two nodes in a tree = O(log n)
=> number of messages required = O(log n)

Group mutual exclusion

multiple processes (in a forum) join critical section simultaneously
each process 0 … N belongs to one of M distinct forums (M<N)



1. Centralized approach:
   - every forum elects a leader
   - mutual exclusion algorithm between the leaders
     - when a leader enters the CS
       - the leader notifies the other process in its forum
     - when the leader leaves the CS
       - other processes in its entry are denied further entry (to prevent starvation)
2. Distributed approach:
   - uses shared memory approach
   - every forum elects a leader
   - every leader guides processes in CS, and once leader leaves, other process are denied further entry (to guarantee fairness)

Election algorithms

Goal: Elect a coordinator in a distributed system.

Correctness requirements:

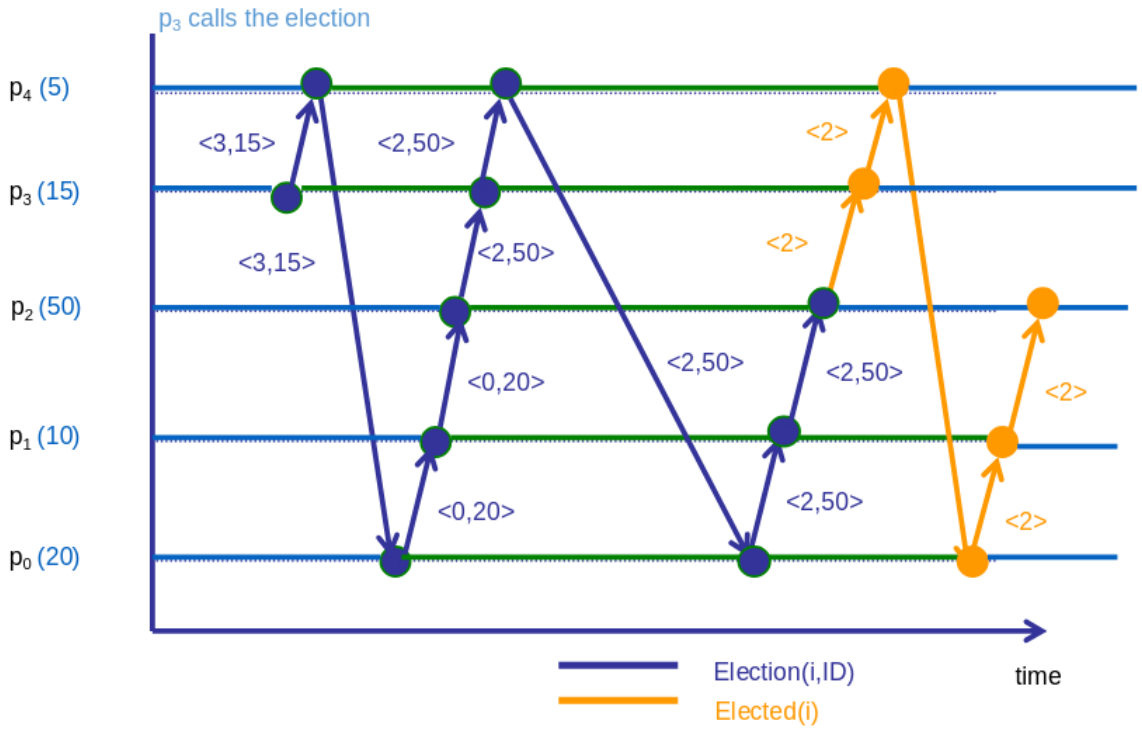
- **Safety [REQUIRED]:** Only one process is elected.
- **Liveness [REQUIRED]:** Eventually a process is elected.

Evaluation metrics:

- **Bandwith:** The number of messages sent in the election process.
- **Turn around time:** Time needed for election round.

Chang-Roberts: Ring-based algorithm

Processes are organized in a ring. The process with the highest ID is elected as the coordinator.

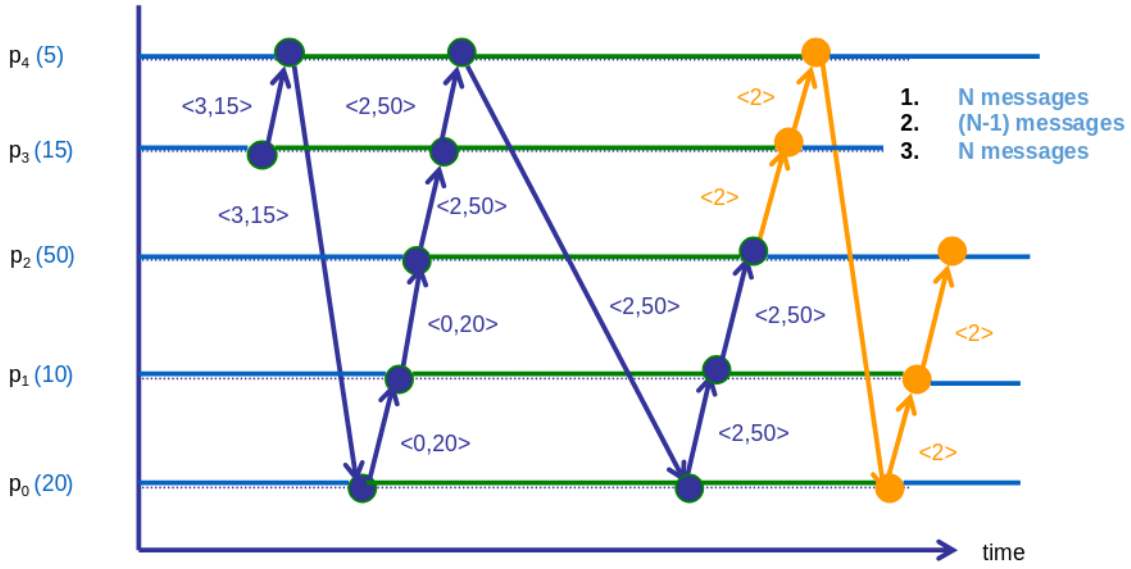


Algo OK?

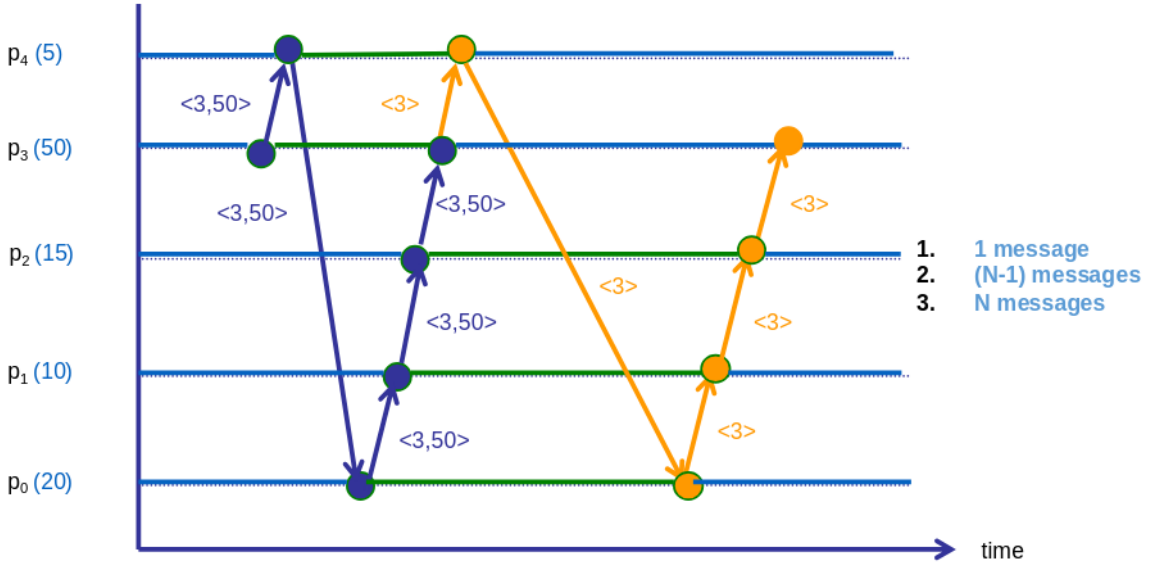
- **Safety:** OK -> Only one process is elected. But IDs need to be unique!
- **Liveness:** OK -> No failures, messages are allowed to circulate.

Algo efficiency?

Worst case : process with max ID is last process visited



Best case : process with max ID is process calling election



	min	max	average
bandwidth	2NM	(3N-1)M	(5N-1)M/2
turnaround time	2Nδ	(3N-1)δ	(5N-1)δ/2

Garcia-Molina: Bully algorithm

The **Garcia-Molina Bully Algorithm** is a distributed algorithm used for leader election in distributed systems. It ensures that the process with the highest ID becomes the leader. Here's a concise summary of how it works:

1. **Election Initiation**: When a process detects that the current leader has failed, it starts an election by sending election messages to all processes with higher IDs.
2. **Responses**:
    - If a higher-ID process responds, it takes over the election process by sending election messages to processes with IDs higher than its own.

    - If no higher-ID process responds, the initiating process declares itself the leader.

3. **Leader Announcement**: Once a leader is elected, it announces itself to all processes in the system.

The algorithm assumes that:

- Processes can communicate reliably.
- Every process knows the IDs of all other processes.
- Failure detection is available to identify leader failure.

Algo OK?

- **Safety:** OK if there is no process replacement.
- **Liveness:** OK -> messages delivered reliably.

Franklin's algorithm

Variant of Chang Roberts algorithm. It uses a bidirectional communication ring. Nodes are active or passive, initially all nodes are active. (We all know how it works).

Algo performance

$1 + \log_2 N$ are needed to elect an unique leader. $log_2 N$ are needed to elect a leader in a ring and then one round to announce the leader.

Peterson's algorithm

Peterson's algorithm, as explained in the slides, is a **variant of the Chang-Roberts Election Algorithm** that operates in a unidirectional ring topology, using **aliases** for leader election. It differs in how it determines the leader and handles communication in rounds.

Key Elements:

1. **Alias System:** Each process has an alias, which can change during the election process.
2. **Unidirectional Communication:** Processes communicate in one direction around the ring.
3. **Active and Passive Nodes:**
    - **Active nodes** participate in the election process.
    - **Passive nodes** only forward messages.

Algorithm Outline:

1. **Initialization:**
    - Initially, all nodes are active.
    - Each process `i` sends its alias to its successor and receives the alias from its predecessor.

2. **Round Logic:**
    - If a process receives an alias equal to its own, it becomes the leader.
    - If the received alias is different:
        - The process forwards the alias to its successor.
        - It also receives an alias from the predecessor of its predecessor.
    - The process updates its alias if:
        - The received alias is greater than the maximum of its own alias and the alias two steps behind.
        - Otherwise, the process becomes passive.
3. **Termination:**
    - When only one active process remains (i.e., it receives its own alias), it declares itself the leader.

Performance:

- Similar to **Franklin's algorithm**, it requires $1 + \log_2(N)$ rounds to elect a leader in a ring with N processes.
- Despite the unidirectional communication, the total number of messages exchanged is comparable to the bidirectional Franklin's algorithm.

This approach efficiently narrows down active participants while leveraging the alias system to identify a unique leader, demonstrating a robust adaptation of ring-based election protocols.

Dolev-Klawe-Rodeh algorithm

Same approach as Peterson's algorithm, but with a different way of updating the alias. It uses a special leader message to announce the leader.

Tree election algorithm

1. **Topology:** The processes form an acyclic graph (tree structure). Each node maintains:
    - A **list of child nodes** (can be empty).
    - A **parent link** (except for the root).
2. **Algorithm Outline:**
    - **Information Collection:**
        - Each node gathers the IDs of its child nodes.
        - Computes the maximum of its children's IDs and its own ID.
        - Passes this maximum value up to its parent node.
    - **Leader Identification:**
        - The root node collects all maximum values from its children.
        - Determines the leader by identifying the largest ID in the tree.
    - **Leader Announcement:**

        - The root node sends the leader ID back down to all nodes in the tree.

3. **Initialization:**
    - The algorithm is typically started by **leaf nodes**, which report their IDs up the tree.
4. **Key Properties:**
    - **Safety:** Ensures only one leader is elected (the node with the highest ID).
    - **Efficiency:** Communication complexity is proportional to the number of edges in the tree.
5. **Advantages:**
    - Suited for hierarchical or tree-structured systems.
    - Efficient for large systems where tree-based communication minimizes message overhead.

Echo algorithm with extinction

The **Echo Algorithm with Extinction** is a leader election algorithm designed for arbitrary networks and works by initiating and propagating "waves" of messages to identify a unique leader.

1. **Topology:** Works on **any** network graph, not restricted to a specific structure like a tree or ring.
2. **Algorithm Outline:**
    - **Wave Initiation:**
        - Multiple nodes may initiate a "wave" with a unique ID (typically their own).
        - Each wave is tagged with the ID of the initiating node.
    - **Message Propagation:**
        - Nodes forward wave messages to their neighbors.
        - If a node receives a wave with a higher ID than the one it is currently participating in, it switches to the higher ID and abandons the lower-ID wave.
        - If a node receives waves with lower IDs than its current wave, it drops those messages.
    - **Wave Completion:**
        - The wave with the largest ID propagates through the entire network.
        - Non-initiating nodes join the wave with the largest ID and ignore others.
    - **Leader Announcement:**
        - The node that initiated the wave with the largest ID is declared the leader.
3. **Key Properties:**

- **Extinction Mechanism:** Lower-ID waves are gradually "extinguished" as nodes only participate in waves with the highest ID encountered.
- **Safety:** Ensures only one leader (the node with the largest ID) is elected.
- **Liveness:** Guarantees all nodes eventually participate in the wave with the largest ID.

4. **Performance:**
   - Message complexity: At most $O(N \times E)$, where N is the number of nodes and E is the number of edges.
   - Efficient for dense or arbitrary networks where multiple waves need to be resolved.
5. **Advantages:**
   - Handles dynamic and arbitrary network topologies.
   - Robust to multiple simultaneous initiators.

The Echo Algorithm with Extinction ensures that the largest-ID wave completes, electing a single leader efficiently while minimizing the impact of redundant messages from smaller-ID waves.

Minimum spanning tree

Here we first make the MST using Kruskal, in the distributed case we need to know what nodes are in the same tree and whether an edge is an outgoing edge of the tree. Because of this, the nodes need to work together to find the least weight outgoing edge. When we have the MST, we can determine the node with the largest ID and elect that one as the leader.

Chapter 6: Distributed consensus with failures

Distributed consensus

Goal: Reach an agreement on a single value among a group of processes even though some of the processes may fail. All correct processes must agree on the same value at the end. A correct process is a process that didn't crash or misbehaved.

Important properties:

- **Agreement:** All correct processes must agree on the same value.
- **Validity:** If all processes decide for the same initial value, then all correct processes must decide for that value.
- **Termination:** All correct processes must eventually decide.

A **k-crash consensus algorithm*** is an algorithm that can reach consensus if at most k processes crash.

An assumption we will follow here is that the network topology is complete, it is always strongly connected, even when processes fail.

1-crash consensus problem

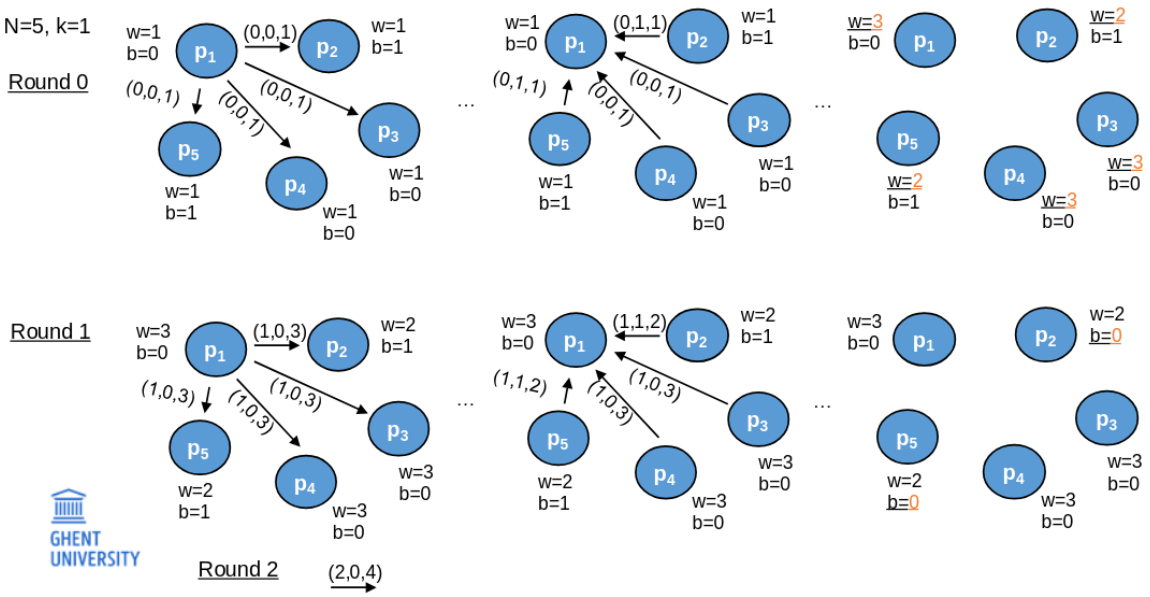
If processes cannot observe that other processes have crashed, then there is no termination algorithm for 1-crash consensus. **There is need for a probabilistic approach.**

In case of $k \geq N/2$: There is no probabilistic algorithm for k-crash consensus. The network can however be divided in two disjoint parts.

Bracha-Toueg algorithm

The Bracha-Toueg algorithm is a **probabilistic algorithm** for solving the k-crash consensus problem in a distributed system. It uses a **randomized approach** to reach consensus when one process may crash.

It assumes $k < N/2$, the message that is send each round contains (n, b, w), n is the round number, b is the value and w is the weight of the message.

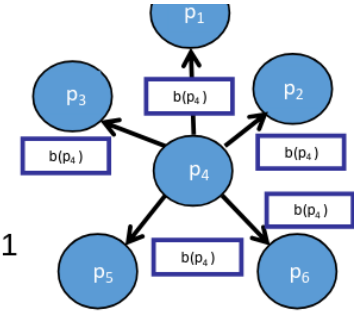


Algorithm evaluation

- when a process decides, all other correct processes are guaranteed to decide within two rounds (algorithm termination)
- if p waits for more than N-k messages, a deadlock can occur
- since p waits for N-k messages, it can only decide if:
- more than k processes have a weight > N/2
- N-k > k or k < N/2
- the algorithm terminates with probability one (Las Vegas algorithm, cfr next chapter)

Consensus with failure detection

k-crash consensus algorithm (k<N)



Algorithm outline

- each process randomly chooses a value 0 or 1
- proceeds in n rounds, n=0 .. N-1
- in round n, process p_n acts as coordinator
  - broadcasts its value (if not crashed)
  - each process waits for an incoming message from p_n:
    - if a message arrives: process adopts value of p_n
    - after time-out T: it suspects that p_n crashed
- after N rounds, each correct process decides
  - based on its current value

Evaluation

- after round i, all correct processes have the same value b
- then in the next rounds, all processes keep this value
- after round N, all correct processes decide for b

Algorithm type:

Rotating coordination algorithm

Chandra-Toueg algorithm

Assumes that failure detector is less accurate than in Bracha-Toueg. It works with acknowledgement messages. Works correctly if k < N/2.

Byzantine consensus

Byzantine processes may start to show strange behaviour.

Here the assumptions for the algorithms are:

- Processes are either correct or Byzantine.
- There is a complete network topology.

k-Byzantine consensus algorithm can cope with up to k Byzantine processes.

Chandra-Toueg Byzantine consensus algorithm

k-Byzantine consensus algorithm
Only possible if k< N/3

- correct processes need to be able to cope with k Byzantine processes
- can only collect votes from N-k processes
- among these N-k processes, k can be Byzantine
- N-2k votes from correct processes > k votes from Byzantine processes

$$\Rightarrow N-2k > k \text{ or } \boxed{k < N/3}$$

Similar to Bracha-Toueg crash consensus algorithm (section 6.4)

includes a verification phase of votes

- votes can not be trusted
- echoes votes to all processes
- only accepts if more than (N+k)/2 processes confirm

Clock synchronization with Byzantine processes

Byzantine processes can report wrong clock values

Makaney-Schneider algorithm

- proceeds in synchronization rounds
- in these rounds, each correct process:
  - collects clock values from all processes
  - discards values τ, for which fewer than N-k processes report a value in $[\tau - \delta, \tau + \delta]$
  - replaces all discarded and non-received values by an acceptable value
  - takes the average of these N values as its new clock value

Works only if k < N/3

Chapter 7: Anonymous networks

In previous chapters the assumption was that the processes had unique ID's. However this is not always the case.

1. No unique ID for all processes in heterogeneous settings.
2. Processes do not reveal ID for security reasons.
3. No transmission or storage of ID (to keep footprint low).

Probabilistic Algorithms

Property: impossibility of election in anonymous rings

=> Probabilistic approaches needed

Vegas algorithm:

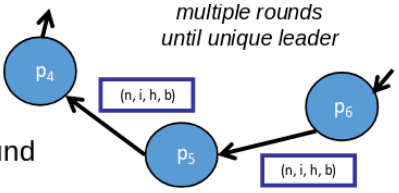
- may not terminate
- outcome is always correct

Monte Carlo:

- always terminates
- can be incorrect

Itai-Rodeh election algorithm

This is an adapted version of Chang-Roberts election algorithm. It is the Las Vegas algorithm for ring topologies.



Algorithm outline:

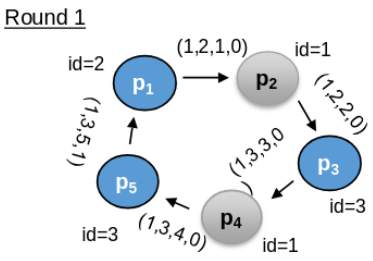
- each node generates random ID and passes this around
- in case there is one largest ID after round 1
  - node with this ID becomes the leader
- in case there are multiple largest IDs
  - next round with these nodes only
  - each node generates new random ID and passes this around
- until there is only one node with largest ID

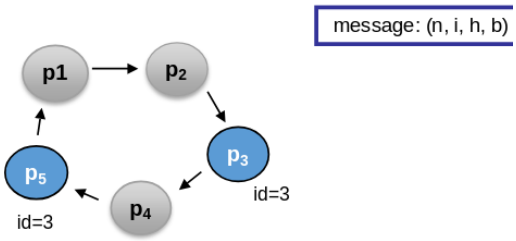
Algorithm keeps track of round numbers and hop count of messages:

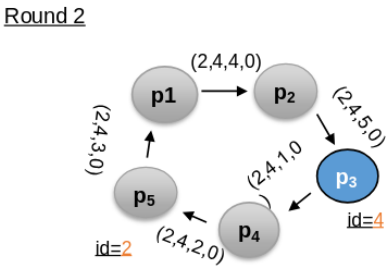
- messages from earlier rounds are ignored
- hop count is used to determine if message passed all nodes

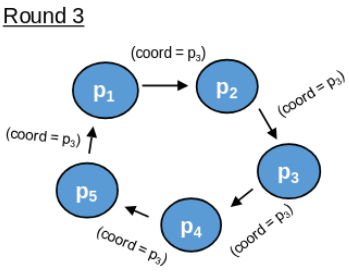
6

N=5









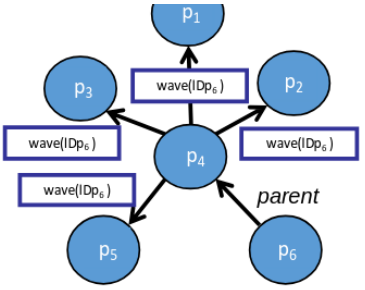
with n = election round, i = the largest ID seen so far, h = the amount of hops, b = boolean representing if there is a process also with that largest ID.

This algorithm terminates when a unique leader is identified. The size of the network N needs to be known in advance. The performance of the algorithm is O(N logN) messages. It is proven to be a Las Vegas algorithm because it is always correct and terminates with probability one.

Echo algorithm with extinction

Adapted version of echo election algorithm for anonymous networks

Outline:
- algorithm progresses in rounds
- all initiators are active at the start of the first round, non-initiators are passive
- at the start of every round, every process randomly selects an ID
- the echo algorithm with extinction is run
- round numbers are used to detect messages from earlier rounds
- a process becomes passive when it receives a message:
- with higher round number
- with same round number, but a higher ID



multiple rounds until unique leader

Number of nodes needs to be known in advance:
- each node reports the size of its subgraph in a wave message to its parent
- initiator checks if the number of nodes is indeed correct
  - otherwise it starts next round

Each active process at the start of an election round:
- selects a random ID from {1…N}
- starts wave, tagged with n (round number), ID_p, and s (=size of subtree)
- initially, n=1 and s=0
- 's=0' means not message to parent, 's!=0' reports size of subtree to parent

process p waits for wave message, tagged with round number n' and ID_j
- if n' > n, or n'=n and $ID_j > ID_p$: p marks sender as parent, changes to n' and wave j
- if n' < n, or n' = n and $ID_j < ID_p$: message is dropped
- if n' = n and $ID_j = ID_p$: sends message to parent once messages from all neighbours arrived

when wave completes, the initiator checks the reported network size
- if this is correct, this initiator becomes the leader
- otherwise, it starts the next round

Las Vegas algorithm

Itai-Rodeh ring size algorithm

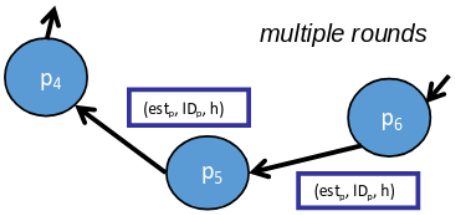
Computation of size of anonymous ring is impossible

Every probabilistic algorithm must allow for incorrect outcomes

⇒ there exists no Las Vegas algorithm for computing the ring size

⇒ only a Monte Carlo algorithm is possible

⇒ Itai-Rodeh ring size algorithm



Monte Carlo algorithm, but probability of incorrect outcome can be arbitrarily close to zero
(especially when IDs can be selected from a large domain)

Algorithm outline:
- each process p maintains an estimate est_p of the ring size
- initially est_p =2
- when the process discovers that its estimate is too conservative
  it moves to the next round
- in each round, the processes p randomly select an ID from {1 ..R}
  and send message (est_p, ID_p, h)
    - h = hop count, incremented every time a message is forwarded

p waits for (est, ID, h) :

- est < est_p : message is dropped
- est > est_p : p increases est_p , two options:
  - h < est: p sends (est, ID, h+1) and est_p = est
  - h = est : est_p = est + 1
- est = est_p : two options
  - h < est : p sends (est, ID, h+1)
- h = est : two options
  - ID != ID_p : est_p = est + 1
  - ID = ID_p : message dropped

Termination when no more messages are sent

at termination: est_p <= N for all processes

- estimate is only increased when a process is certain that the current estimate is too conservative
- only incorrect when too many random IDs are the same