Large-scale Distributed Systems

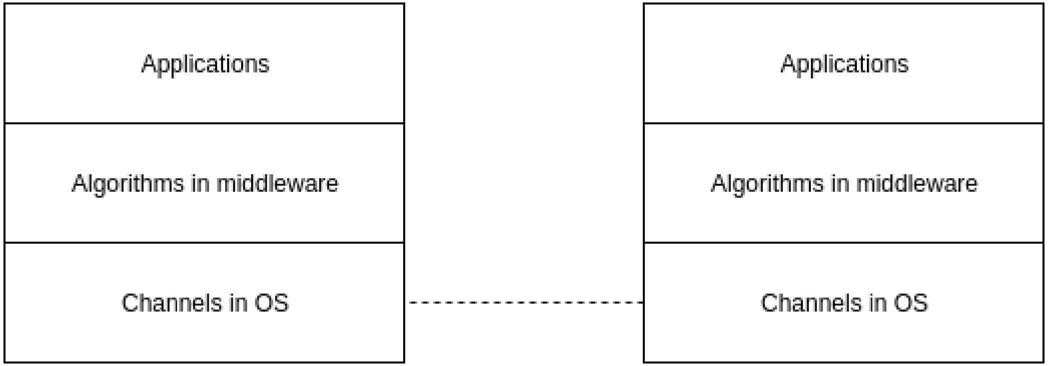
Lecture 2: Basic abstractions

Today

- Define basic abstractions that capture the fundamental characteristics of distributed systems.
    - We will later define more elaborate abstractions on top of those.
- Three main abstractions:
    - Process abstractions
    - Link abstractions
    - Timing abstractions
- A distributed system model = a combination of the three categories of abstractions.

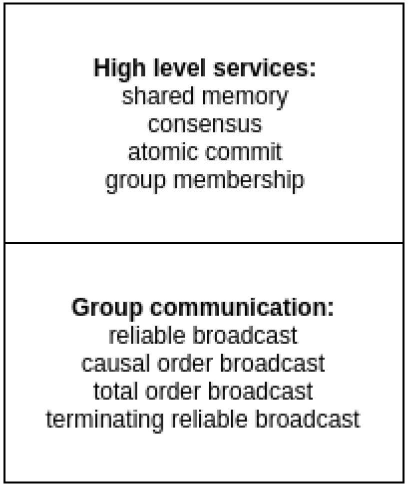
Need for distributed abstractions

- Core of any distributed system is a set of distributed algorithms.
    - Implemented as a middleware between network (OS) and the application.
- Reliable applications need underlying services stronger than transport protocols (e.g., TCP or UDP).



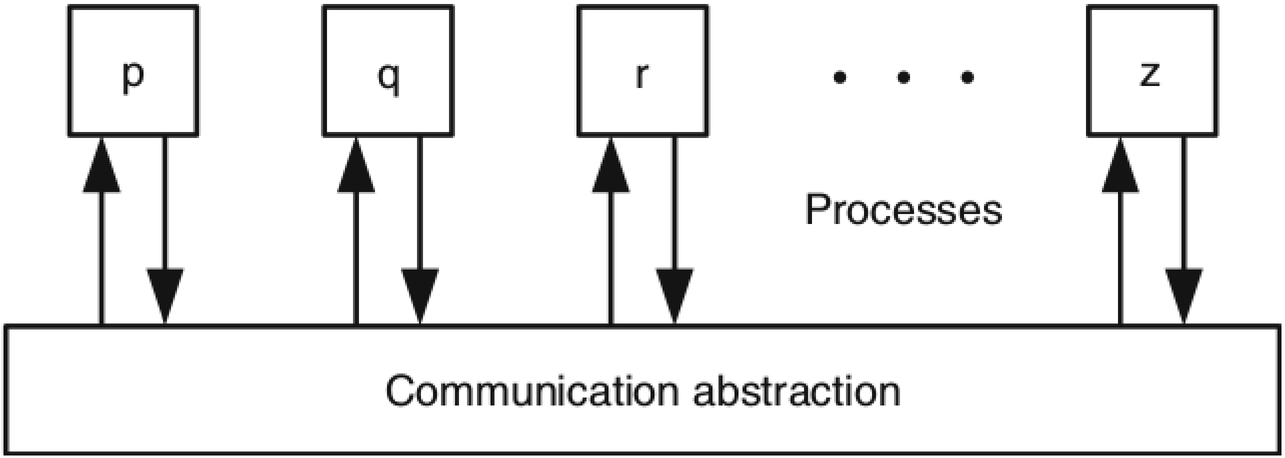
Network protocols are not enough

- Communication
  - Reliability guarantees (e.g. with TCP) are only offered for one-to-one communication (client-server).
  - How to do group communication?
- High-level services
  - Sometimes one-to-many communication is not enough.
  - Need reliable higher-level services.
- Strategy: build complex distributed systems in a bottom-up fashion, from simpler ones.



Distributed computation

Distributed computation



- A distributed algorithm is a distributed collection $\Pi = \{p, q, r, ...\}$ of N processes implemented by identical automata.
- The automaton at a process regulates the way the process executes its computation steps.
- Processes jointly implement the application.
  - Need for coordination.

Programming with events

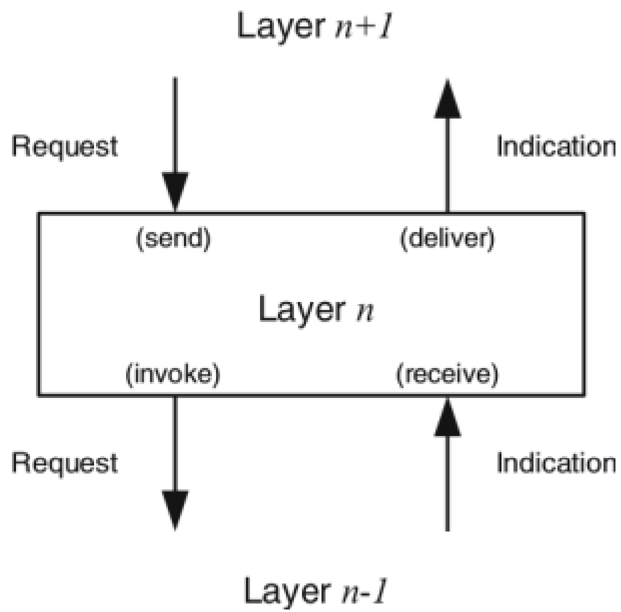
- Every process consists of modules or components.
  - Modules may exist in multiple instances.
  - Every instance has a unique identifier and is characterized by a set of properties.
- Asynchronous events represent communication or control flow between components.
  - Each component is constructed as a state-machine whose transitions are triggered by the reception of events.
  - Events carry information (sender, message, etc)
- Reactive programming model:

upon event $\langle\, co_1, Event_1 \mid att_1^1, att_1^2, \ldots \,\rangle$ **do**
  do something;
  trigger $\langle\, co_2, Event_2 \mid att_2^1, att_2^2, \ldots \,\rangle$; *// send some event*

upon event $\langle\, co_1, Event_3 \mid att_3^1, att_3^2, \ldots \,\rangle$ **do**
  do something else;
  trigger $\langle\, co_2, Event_4 \mid att_4^1, att_4^2, \ldots \,\rangle$; *// send some other event*

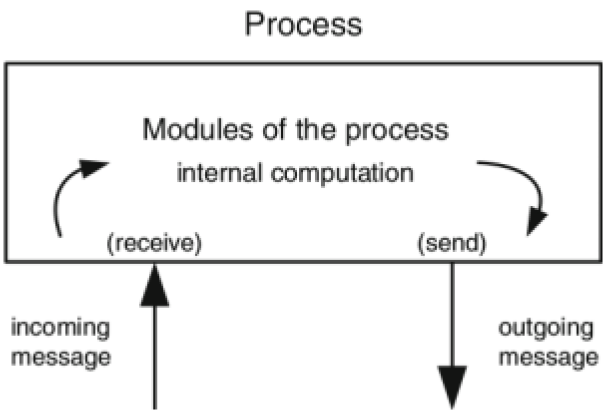
- Effectively, a distributed algorithm is described by a set of event handlers.

Layered modular architecture



- Components can be composed locally to build software stacks.
  - The top of the stack is the application layer.
  - The bottom of the stack the transport or network layer.
- Distributed programming abstraction layers are typically in the middle.
- We assume that every process executes the code triggered by events in a mutually exclusive way, without concurrently processing ≥ 2 events.

Execution



- The execution of a distributed algorithm is a sequence of steps executed by its processes.
- A process step consists in
  - receiving a message from another process,
  - executing a local computation,
  - sending a message to some process.
- Local messages between components are treated as local computation.
- We assume deterministic process steps (with respect to the message received and the local state prior to executing a step).

Liveness and safety

- Implementing a distributed programming abstraction requires satisfying its correctness in all possible executions of the algorithm.
  - i.e., in all possible interleaving of steps.
- Correctness of an abstraction is expressed in terms of liveness and safety properties.
  - Safety: properties that state that nothing bad ever happens.
    - A safety property is a property such that, whenever it is violated in some execution E of an algorithm, there is a prefix E' of E such that the property will be violated in any extension of E'.
  - Liveness: properties that state something good eventually happens.
    - A liveness property is a property such that for any prefix E' of E, there exists an extension of E' for which the property is satisfied.
- Any property can be expressed as the conjunction of safety property and a liveness property.

Correctness examples

Traffic lights at an intersection

- Safety: only one direction should have a green light.
- Liveness: every direction should eventually get a green light.

Correctness examples

TCP

- Safety: messages are not duplicated and received in the order they were sent.
- Liveness: messages are not lost.
  - i.e., messages are eventually delivered.

Assumptions

- In our abstraction of a distributed system, we need to specify the assumptions needed for the algorithm to be correct.

- A distributed system model includes assumptions on:
    - failure behavior of processes and channels
    - timing behavior of processes and channels

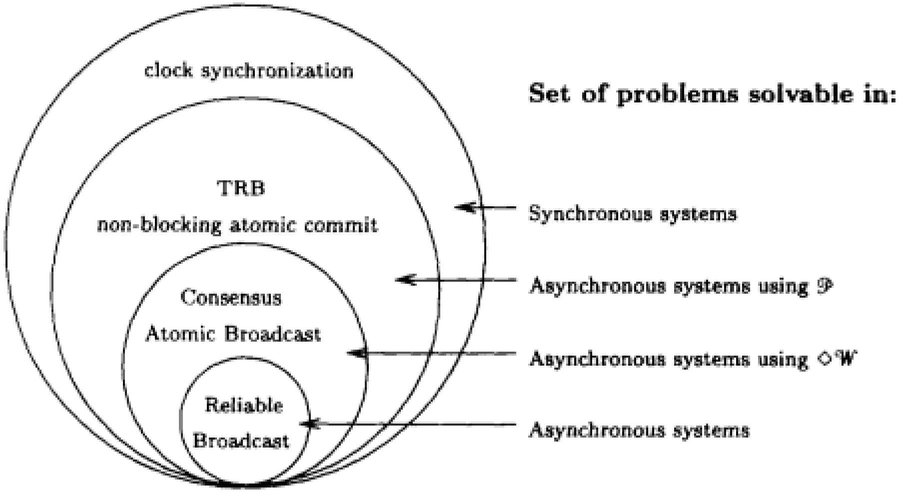


FIG. 9. Problem solvability in different distributed computing models.

Together, these assumptions define sets of solvable problems.

Process abstractions

Process failures

- Processes may fail in four different ways:
  - Crash-stop
  - Omissions
  - Crash-recovery
  - Byzantine / arbitrary
- Processes that do not fail in an execution are correct.

Crash-stop failures

- A process stops taking steps.
  - Not sending messages.
  - Not receiving messages.
- We assume the crash-stop process abstraction by default.
  - Hence, do not recover.
  - [Q] Does this mean that processes are not allowed to recover?

Omission failures

- Process omits sending or receiving messages.
  - Send omission: A process omits to send a message it has to send according to its algorithm.
  - Receive omission: A process fails to receive a message that was sent to it.
- Often, omission failures are due to buffer overflows.
- With omission failures, a process deviates from its algorithm by dropping messages that should have been exchanged with other processes.

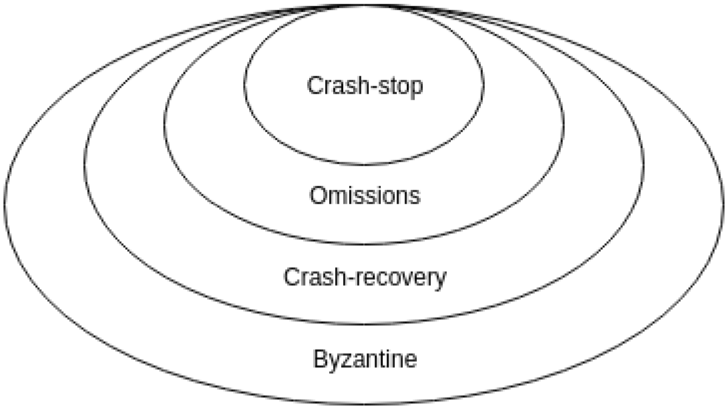
Crash-recovery failures

- A process might crash.
  - It stops taking steps, not receiving and sending messages.
- It may recover after crashing.
  - The process emits a `<Recovery>` event upon recovery.
- Access to stable storage:
  - May read/write (expensive) to permanent storage device.
  - Storage survives crashes.
  - E.g., save state to storage, crash, recover, read saved state, ...
- A failure is different in the crash-recovery abstraction:
  - A process is faulty in an execution if
    - It crashes and never recovers, or
    - It crashes and recovers infinitely often.
  - Hence, a correct process may crash and recover.

Byzantine failures

- A process may behave arbitrarily.
  - Sending messages not specified by its algorithm.
  - Updating its state as not specified by its algorithm.
- Might behave maliciously, attacking the system.
  - Several malicious nodes might collude.

Fault-tolerance hierarchy

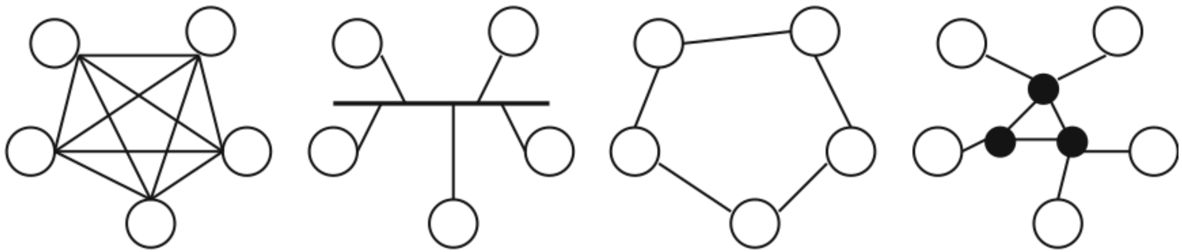


[Q] Explain how failure modes are special cases of one another.

Communication abstractions

Links

- Every process may logically communicate with every other process (a).
- The physical implementation may differ (b-d).



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

Link failures

- Fair-loss links
    - Channel delivers any message sent, with non-zero probability.
- Stubborn links
    - Channel delivers any message sent infinitely many times.
    - Can be implemented using fair-loss links.
- Perfect links (reliable)
    - Channel delivers any message sent exactly once.
    - Can be implemented using stubborn links.
    - By default, we assume the perfect links abstraction.
- [Q] What abstraction do UDP and TCP implement?

Stubborn links: interface

Module:

Name: StubbornPointToPointLinks, **instance** *sl*.

Events:

Request: $\langle$ *sl*, *Send* | q, m $\rangle$: Requests to send message m to process q.

Indication: $\langle$ *sl*, *Deliver* | p, m $\rangle$: Delivers message m sent by process p.

Properties:

SL1: *Stubborn delivery:* If a correct process p sends a message m once to a correct process q, then q delivers m an infinite number of times.

SL2: *No creation:* If some process q delivers a message m with sender p, then m was previously sent to q by process p.

[Q] Which property is safety/liveness/neither?

Perfect links: interface

Module:

Name: PerfectPointToPointLinks, **instance** *pl*.

Events:

Request: $\langle$ *pl*, *Send* | q, m $\rangle$: Requests to send message m to process q.

Indication: $\langle$ *pl*, *Deliver* | p, m $\rangle$: Delivers message m sent by process p.

Properties:

PL1: *Reliable delivery:* If a correct process p sends a message m to a correct process q, then q eventually delivers m.

PL2: *No duplication:* No message is delivered by a process more than once.

PL3: *No creation:* If some process q delivers a message m with sender p, then m was previously sent to q by process p.

[Q] Which property is safety/liveness/neither?

Perfect links: implementation

Implements:
PerfectPointToPointLinks, **instance** *pl*.

Uses:
StubbornPointToPointLinks, **instance** *sl*.

upon event $\langle$ *pl*, *Init* $\rangle$ **do**
delivered := $\emptyset$;

upon event $\langle$ *pl*, *Send* | q, m $\rangle$ **do**
trigger $\langle$ *sl*, *Send* | q, m $\rangle$;

upon event $\langle$ *sl*, *Deliver* | p, m $\rangle$ **do**
if $m \notin$ *delivered* **then**
delivered := *delivered* $\cup \{m\}$;
trigger $\langle$ *pl*, *Deliver* | p, m $\rangle$;

[Q] How does TCP efficiently maintain its `delivered` log?

Correctness of PL

- PL1. Reliable delivery
  - Guaranteed by the Stubborn link abstraction. (The Stubborn link will deliver the message an infinite number of times.)
- PL2. No duplication
  - Guaranteed by the log mechanism.
- PL3. No creation
  - Guaranteed by the Stubborn link abstraction.

Timing assumptions

Timing assumptions

- Timing assumptions correspond to the behavior of processes and links with respect to the passage of time. They relate to
  - different processing speeds of processes;
  - different speeds of messages (channels).
- Three basic types of system:
  - Asynchronous system
  - Synchronous system
  - Partially synchronous system

Asynchronous systems

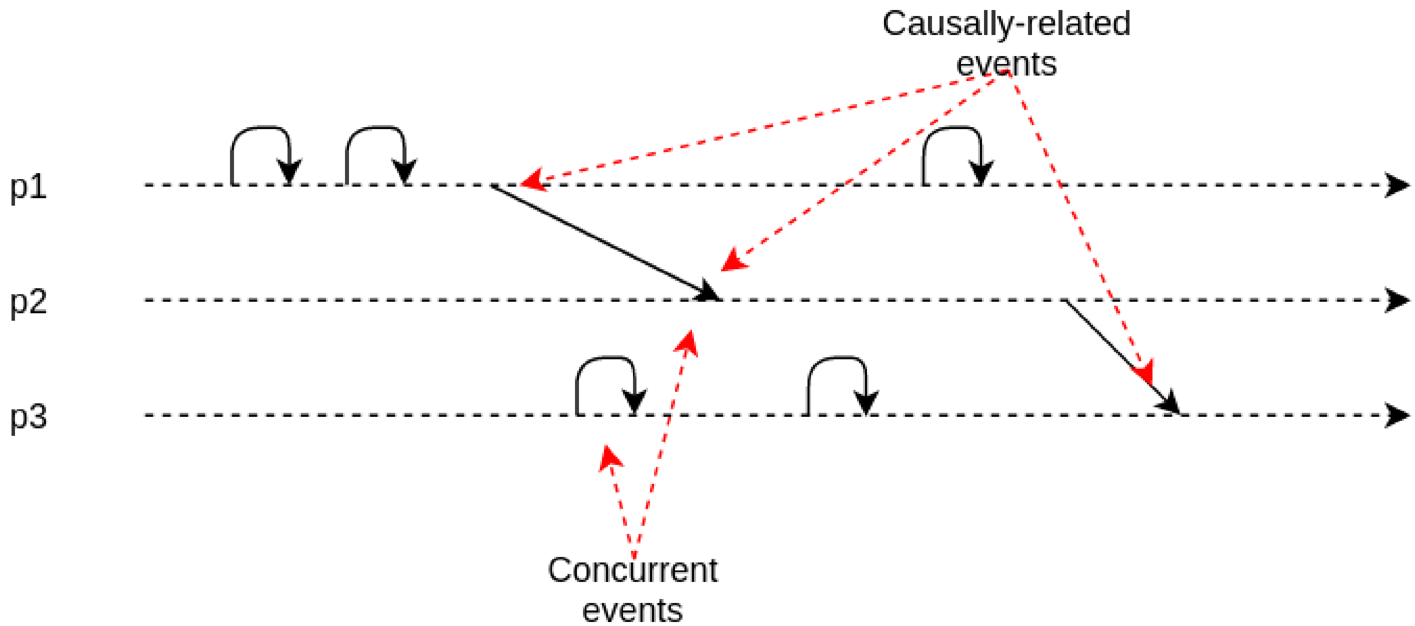
- No timing assumptions on processes and links.
  - Processes do not have access to any sort of physical clock.
  - Processing time may vary arbitrarily.
  - No bound on transmission time.
- But causality between events can still be determined.
  - How?

Causal order

The happened-before relation $e_1 \rightarrow e_2$ denotes that e_1 may have caused e_2. It is true in the following cases:

- FIFO order: e_1 and e_2 occurred at the same process p and e_1 occurred e_2;
- Network order: e_1 corresponds to the transmission of m at a process p and e_2 corresponds to its reception at a process q;
- Transitivity: if $e_1 \rightarrow e'$ and $e' \rightarrow e_2$, then $e_1 \rightarrow e_2$.

Causal order



Similarity of executions

- The view of p in E, denoted $E|p$ is the subsequence of process steps in E restricted to those of p
- Two executions E and F are similar w.r.t. to p if $E|p = F|p$.
- Two executions E and F are similar if $E|p = F|p$ for all processes p.

Computation theorem

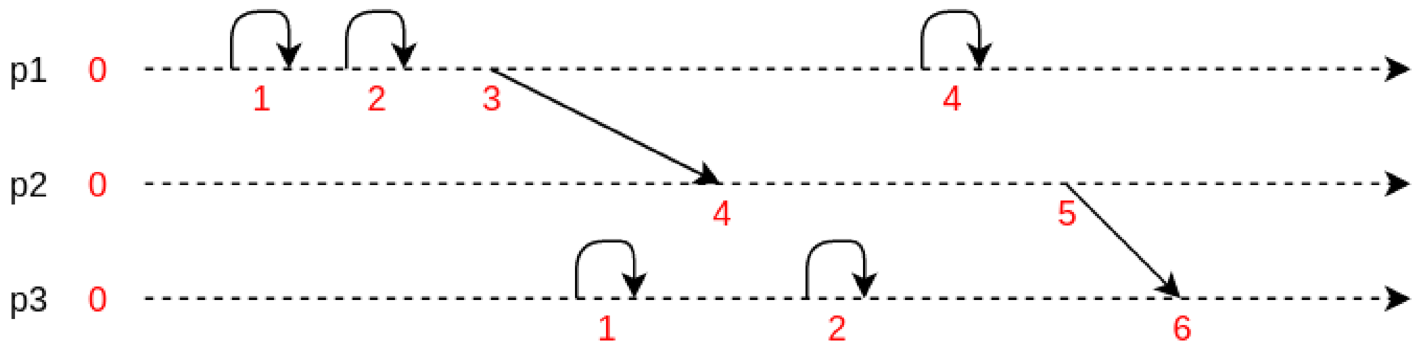
If two executions E and F have the same collection of events and their causal order is preserved, then E and F are similar executions.

Logical clocks

In an asynchronous distributed system, the passage of time can be measured with logical clocks:

- Each process has a local logical clock l_p, initially set a 0.
- Whenever an event occurs locally at p or when a process sends a message, p increments its logical clock.
  - $l_p := l_p + 1$
- When p sends a message event m, it timestamps the message with its current logical time, $t(m) := l_p$.
- When p receives a message event m with timestamp $t(m)$, p updates its logical clock.
  - $l_p := \max(l_p, t(m)) + 1$

Logical clocks



Clock consistency condition

Logical clocks capture cause-effect relations:

$$e_1 \rightarrow e_2 \Rightarrow t(e_1) < t(e_2)$$

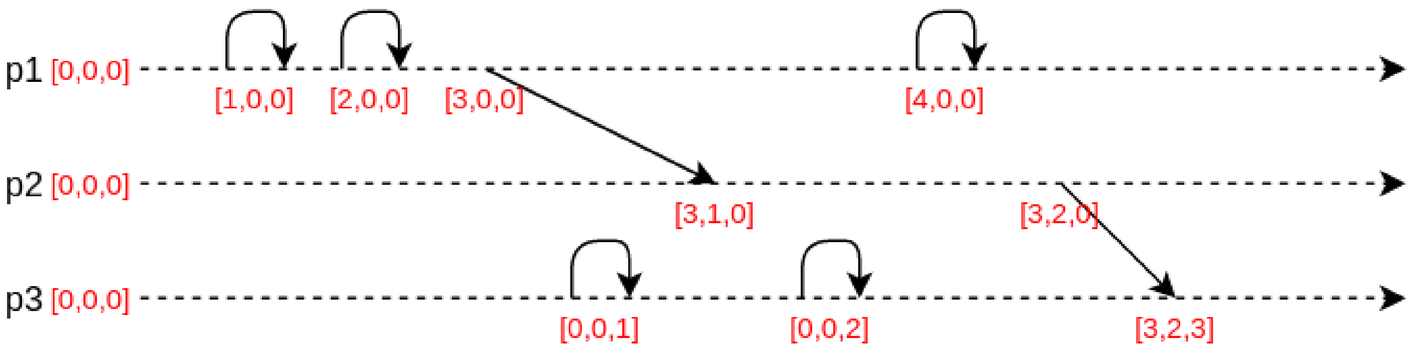
- If e_1 is the cause of e_2, then $t(e_1) < t(e_2)$.
    - Can you prove it?
- But not necessarily the opposite:
    - $t(e_1) < t(e_2)$ does not imply $e_1 \rightarrow e_2$.
    - e_1 and e_2 may be logically concurrent.

Vector clocks

Vector clocks fix this issue by making it possible to tell when two events cannot be causally related, i.e. when they are concurrent.

- Each process p maintains a vector V_p of N clocks, initially set at $V_p[i] = 0 \, \forall i$.
- Whenever an event occurs locally at p or when a process sends a message, p increments the p-th element of its vector clock.
  - $V_p[p] := V_p[p] + 1$
- When p sends a message event m, it piggybacks its vector clock as $V_m := V_p$.
- When p receives a message event m with the vector clock V_m, p updates its vector clock.
  - $V_p[p] := V_p[p] + 1$
  - $V_p[i] := \max(V_p[i], V_m[i])$, for $i \neq p$.

Vector clocks



Comparing vector clocks

- $V_p = V_q$
  - iff $\forall i \, V_p[i] = V_q[i]$.
- $V_p \leq V_q$
  - iff $\forall i \, V_p[i] \leq V_q[i]$.
- $V_p < V_q$
  - iff $V_p \leq V_q$ AND $\exists j \, V_p[j] < V_q[j]$
- V_p and V_q are logically concurrent.
  - iff NOT $V_p \leq V_q$ AND NOT $V_q \leq V_p$

Synchronous systems

Assumption of three properties:

- Synchronous computation
  - Known upper bound on the process computation delay.
- Synchronous communication
  - Known upper bound on message transmission delay.
- Synchronous physical clocks
  - Processes have access to a local physical clock;
  - Known upper bound on clock drift and clock skew.

[Q] Why studying synchronous systems? What services can be provided?

Partially synchronous systems

A partially synchronous system is a system that is synchronous most of the time.

- There are periods where the timing assumptions of a synchronous system do not hold.
- But the distributed algorithm will have a long enough time window where everything behaves nicely, so that it can achieve its goal.

[Q] Are there such systems?

Timing abstractions

Failure detection

- It is tedious to model (partial) synchrony.
- Timing assumptions are mostly needed to detect failures.
    - Heartbeats, timeouts, etc.
- We define failure detector abstractions to encapsulate timing assumptions:
    - Black box giving suspicions regarding node failures;
    - Accuracy of suspicions depends on model strength.

Implementation of failure detectors

A typical implementation is the following:

- Periodically exchange heartbeat messages;
- Timeout based on worst case message round trip;
- If timeout, then suspect node;
- If reception of a message from a suspected node, revise suspicion and increase timeout.

Perfect detector: interface

Assuming a crash-stop process abstraction, the perfect detector encapsulates the timing assumptions of a synchronous system.

Module:

Name: PerfectFailureDetector, **instance** $\mathcal{P}$.

Events:

Indication: $\langle\, \mathcal{P}, \mathit{Crash} \mid p \,\rangle$: Detects that process p has crashed.

Properties:

PFD1: *Strong completeness:* Eventually, every process that crashes is permanently detected by every correct process.

PFD2: *Strong accuracy:* If a process p is detected by any process, then p has crashed.

[Q] Which property is safety/liveness/neither?

Perfect detector: implementation

Implements:
PerfectFailureDetector, **instance** $\mathcal{P}$.

Uses:
PerfectPointToPointLinks, **instance** *pl*.

upon event $\langle\, \mathcal{P}, \mathit{Init} \,\rangle$ **do**
    $\mathit{alive} := \Pi$;
    $\mathit{detected} := \emptyset$;
    $\mathit{starttimer}(\Delta)$;

upon event $\langle\, \mathit{Timeout} \,\rangle$ **do**
    forall $p \in \Pi$ **do**
        if $(p \notin \mathit{alive}) \wedge (p \notin \mathit{detected})$ **then**
            $\mathit{detected} := \mathit{detected} \cup \{p\}$;
            trigger $\langle\, \mathcal{P}, \mathit{Crash} \mid p \,\rangle$;
        trigger $\langle\, \mathit{pl}, \mathit{Send} \mid p, [\text{HEARTBEATREQUEST}] \,\rangle$;
    $\mathit{alive} := \emptyset$;
    $\mathit{starttimer}(\Delta)$;

upon event $\langle\, \mathit{pl}, \mathit{Deliver} \mid q, [\text{HEARTBEATREQUEST}] \,\rangle$ **do**
    trigger $\langle\, \mathit{pl}, \mathit{Send} \mid q, [\text{HEARTBEATREPLY}] \,\rangle$;

upon event $\langle\, \mathit{pl}, \mathit{Deliver} \mid p, [\text{HEARTBEATREPLY}] \,\rangle$ **do**
    $\mathit{alive} := \mathit{alive} \cup \{p\}$;

Correctness

We assume a synchronous system:

- The transmission delay is bounded by some known constant.
- Local processing is negligible.
- The timeout delay Δ is chosen to be large enough such that
  - every process has enough time to send a heartbeat message to all,
  - every heartbeat message has enough time to be delivered,
  - the correct destination processes have enough time to process the heartbeat and to send a reply,
  - the replies have enough time to reach the original sender and to be processed.

Correctness:

- PFD1. Strong completeness
  - A crashed process p stops replying to heartbeat messages, and no process will deliver its messages. Every correct process will thus eventually detect the crash of p.
- PFD2. Strong accuracy
  - The crash of p is detected by some other process q only if q does not deliver a message from p before the timeout period.
  - This happens only if p has indeed crashed, because the algorithm makes sure p must have sent a message otherwise and the synchrony assumptions imply that the message should have been delivered before the timeout period.

Eventually perfect detector: interface

The eventually perfect detector encapsulates the timing assumptions of a partially synchronous system.

Module:

Name: EventuallyPerfectFailureDetector, **instance** $\diamond\mathcal{P}$.

Events:

Indication: $\langle\, \diamond\mathcal{P}, \mathit{Suspect} \mid p\,\rangle$: Notifies that process p is suspected to have crashed.

Indication: $\langle\, \diamond\mathcal{P}, \mathit{Restore} \mid p\,\rangle$: Notifies that process p is not suspected anymore.

Properties:

EPFD1: *Strong completeness:* Eventually, every process that crashes is permanently suspected by every correct process.

EPFD2: *Eventual strong accuracy:* Eventually, no correct process is suspected by any correct process.

Eventually perfect detector: impl.

Implements:
EventuallyPerfectFailureDetector, **instance** $\diamond\mathcal{P}$.

Uses:
PerfectPointToPointLinks, **instance** *pl*.

upon event $\langle\, \diamond\mathcal{P}, \mathit{Init}\,\rangle$ **do**
    $\mathit{alive} := \Pi$;
    $\mathit{suspected} := \emptyset$;
    $\mathit{delay} := \Delta$;
    $\mathrm{starttimer}(\mathit{delay})$;

upon event $\langle\, \mathit{Timeout}\,\rangle$ **do**
    if $\mathit{alive} \cap \mathit{suspected} \neq \emptyset$ **then**
        $\mathit{delay} := \mathit{delay} + \Delta$;
    forall $p \in \Pi$ **do**
        if $(p \notin \mathit{alive}) \wedge (p \notin \mathit{suspected})$ **then**
            $\mathit{suspected} := \mathit{suspected} \cup \{p\}$;
            trigger $\langle\, \diamond\mathcal{P}, \mathit{Suspect} \mid p\,\rangle$;
        else if $(p \in \mathit{alive}) \wedge (p \in \mathit{suspected})$ **then**
            $\mathit{suspected} := \mathit{suspected} \setminus \{p\}$;
            trigger $\langle\, \diamond\mathcal{P}, \mathit{Restore} \mid p\,\rangle$;
        trigger $\langle\, \mathit{pl}, \mathit{Send} \mid p, [\text{HEARTBEATREQUEST}]\,\rangle$;
    $\mathit{alive} := \emptyset$;
    $\mathrm{starttimer}(\mathit{delay})$;

upon event $\langle\, \mathit{pl}, \mathit{Deliver} \mid q, [\text{HEARTBEATREQUEST}]\,\rangle$ **do**
    trigger $\langle\, \mathit{pl}, \mathit{Send} \mid q, [\text{HEARTBEATREPLY}]\,\rangle$;

upon event $\langle\, \mathit{pl}, \mathit{Deliver} \mid p, [\text{HEARTBEATREPLY}]\,\rangle$ **do**
    $\mathit{alive} := \mathit{alive} \cup \{p\}$;

[Q] Show that this implementation is correct.

Leader election

- Failure detection captures failure behavior.
  - Detects failed processes.
- Leader election is an abstraction that also captures failure behavior.
  - Detects correct nodes.
  - But a single and same for all, called the leader.
- If the current leader crashes, a new leader should be elected.

Leader election: interface

Module:

Name: LeaderElection, **instance** *le*.

Events:

Indication: $\langle\, le, Leader \mid p\,\rangle$: Indicates that process p is elected as leader.

Properties:

LE1: *Eventual detection:* Either there is no correct process, or some correct process is eventually elected as the leader.

LE2: *Accuracy:* If a process is leader, then all previously elected leaders have crashed.

Leader election: implementation

Implements:
LeaderElection, **instance** *le*.

Uses:
PerfectFailureDetector, **instance** $\mathcal{P}$.

upon event $\langle$ *le*, *Init* $\rangle$ **do**
suspected := $\emptyset$;
leader := $\perp$;

upon event $\langle$ $\mathcal{P}$, *Crash* | p $\rangle$ **do**
suspected := *suspected* $\cup \{p\}$;

upon *leader* $\neq$ maxrank($\Pi \setminus$ *suspected*) **do**
leader := maxrank($\Pi \setminus$ *suspected*);
trigger $\langle$ *le*, Leader | *leader* $\rangle$;

[Q] Show that this implementation is correct.

[Q] Is LE a failure detector?

Distributed system models

Distributed system models

We define a distributed system model as the combination of (i) a process abstraction, (ii) a link abstraction, and (iii) a failure detector abstraction.

- Fail-stop (synchronous)
  - Crash-stop process abstraction
  - Perfect links
  - Perfect failure detector
- Fail-silent (asynchronous)
  - Crash-stop process abstraction
  - Perfect links
- Fail-noisy (partially synchronous)
  - Crash-stop process abstraction
  - Perfect links
  - Eventually perfect failure detector
- Fail-recovery
  - Crash-stop process abstraction
  - Stubborn links

The fail-stop distributed system model substantially simplifies the design of distributed algorithms.

References

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