Large-scale Data Systems

Lecture 2: Basic distributed abstractions

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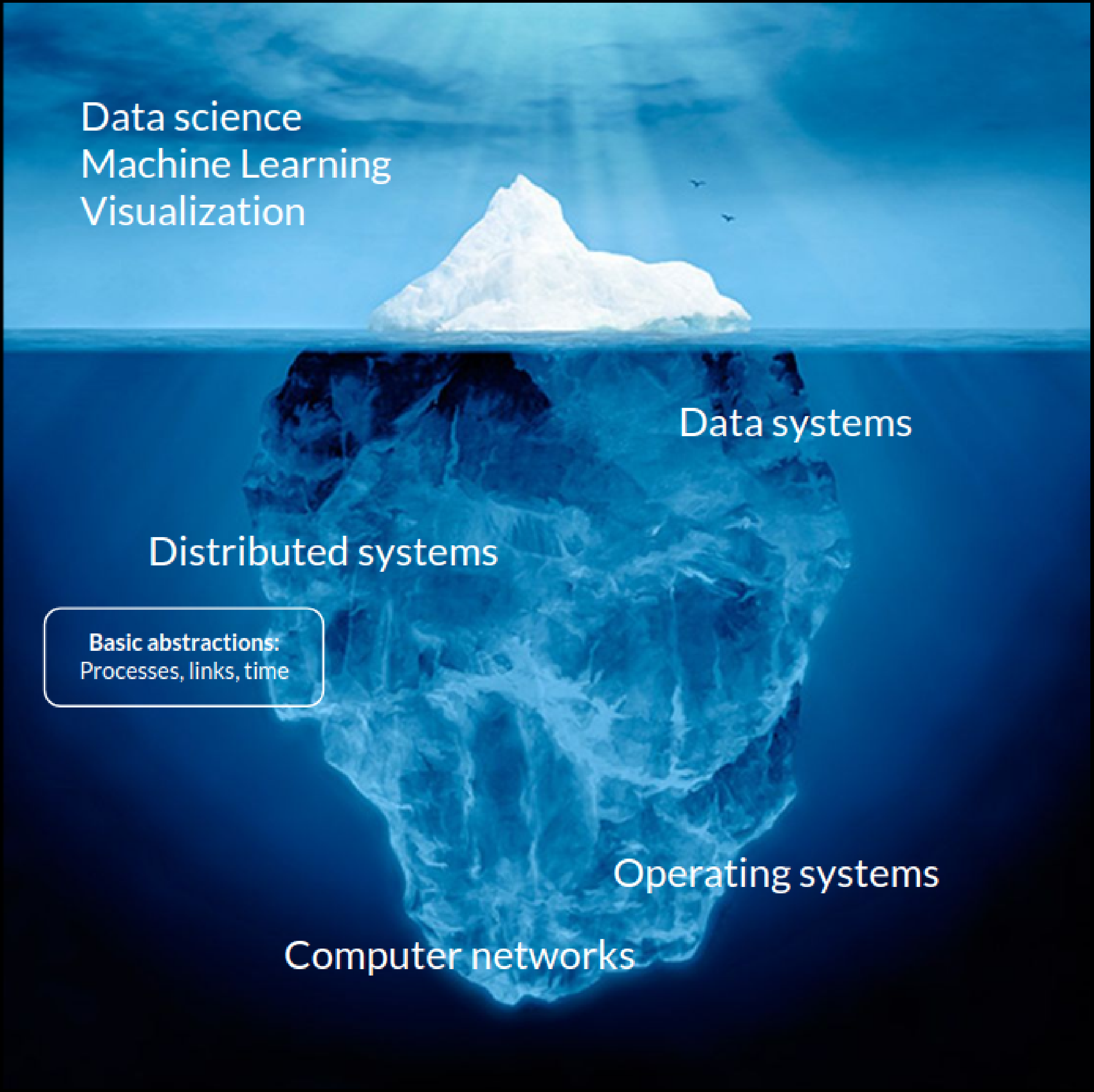
Today

- Define basic abstractions that capture the fundamental characteristics of distributed systems:
  - Process abstractions
  - Link abstractions
  - Timing abstractions
- A distributed system model = a combination of the three categories of abstractions.


Data science
Machine Learning
Visualization
Data systems
Distributed systems
Basic abstractions:
Processes, links, time
Operating systems
Computer networks

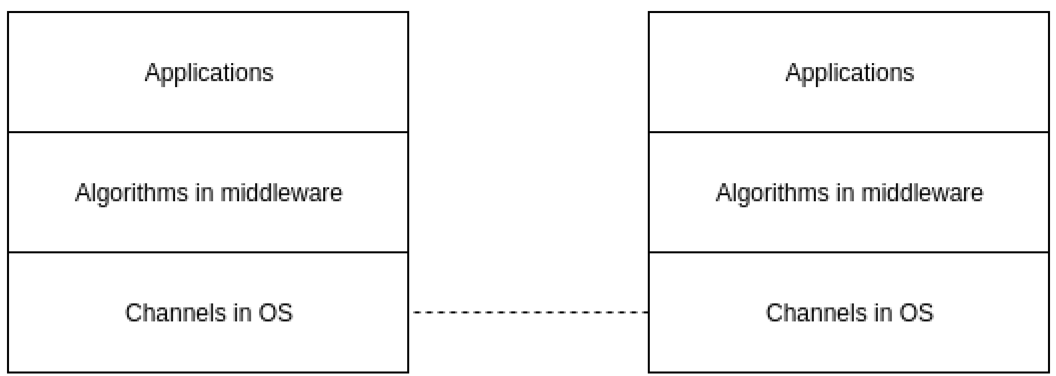
Why distributed abstractions?

Reliable distributed applications need underlying services stronger than transport protocols (e.g., TCP or UDP).

"All problems in computer science can be solved by another level of indirection" - David Wheeler.

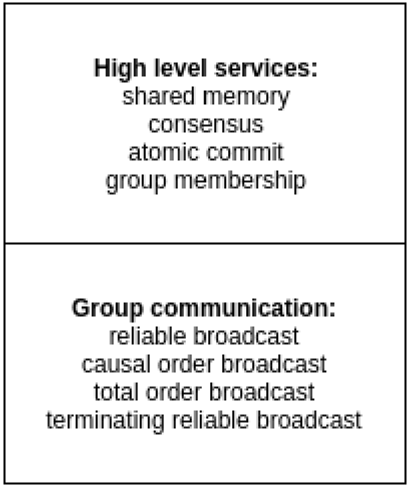
Distributed abstractions

- Core of any distributed system is a set of distributed algorithms.
- Implemented as a middleware between network (OS) and the application.



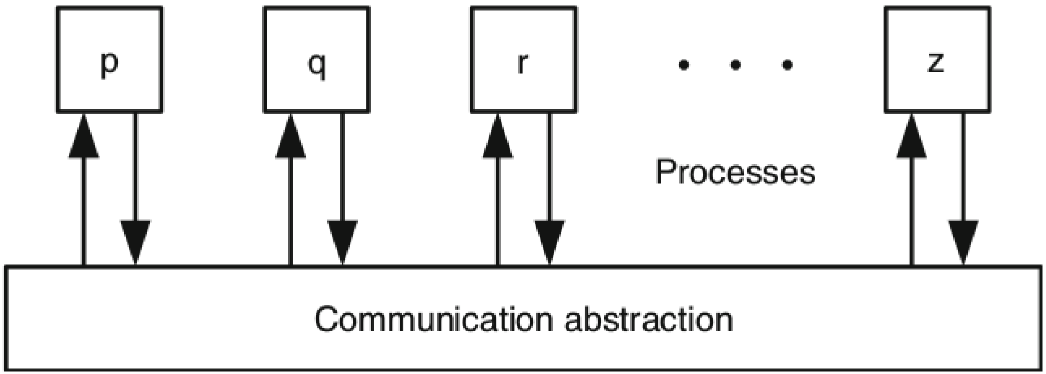
Network protocols are not enough

- 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 algorithms



- 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.

Event-driven programming

- 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)

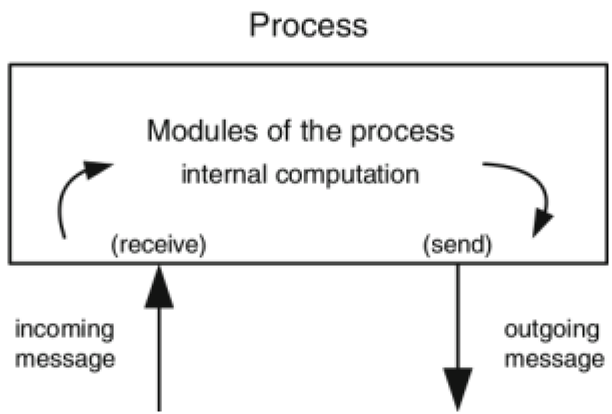
Reactive programming model

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*

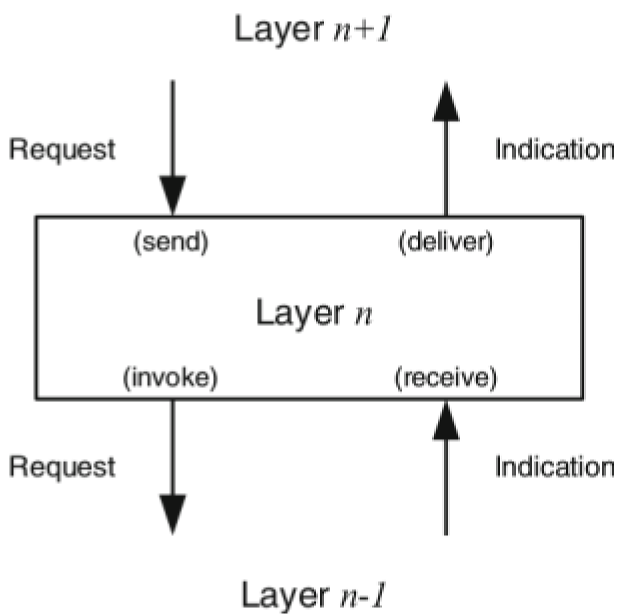
Effectively, a distributed algorithm is described by a set of event handlers.

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).

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.

Example: Job handler

Module 1.1: Interface and properties of a job handler

Module:

Name: JobHandler, **instance** *jh*.

Events:

Request: $\langle$ *jh*, *Submit* | *job* $\rangle$: Requests a job to be processed.

Indication: $\langle$ *jh*, *Confirm* | *job* $\rangle$: Confirms that the given job has been (or will be) processed.

Properties:

JH1: *Guaranteed response:* Every submitted job is eventually confirmed.

Algorithm 1.1: Synchronous Job Handler

Implements:
JobHandler, **instance** *jh*.

upon event $\langle$ *jh*, *Submit* | *job* $\rangle$ **do**
process(*job*);
trigger $\langle$ *jh*, *Confirm* | *job* $\rangle$;

Algorithm 1.2: Asynchronous Job Handler

Implements:

JobHandler, **instance** *jh*.

upon event $\langle$ *jh*, *Init* $\rangle$ **do**

buffer := $\emptyset$;

upon event $\langle$ *jh*, *Submit* | *job* $\rangle$ **do**

buffer := *buffer* $\cup$ {*job*};

trigger $\langle$ *jh*, *Confirm* | *job* $\rangle$;

upon *buffer* $\neq \emptyset$ **do**

job := selectjob(*buffer*);

process(*job*);

buffer := *buffer* $\setminus$ {*job*};

Module 1.2: Interface and properties of a job transformation and processing abstraction

Module:

Name: TransformationHandler, **instance** *th*.

Events:

Request: $\langle$ *th*, *Submit* | *job* $\rangle$: Submits a job for transformation and for processing.

Indication: $\langle$ *th*, *Confirm* | *job* $\rangle$: Confirms that the given job has been (or will be) transformed and processed.

Indication: $\langle$ *th*, *Error* | *job* $\rangle$: Indicates that the transformation of the given job failed.

Properties:

TH1: *Guaranteed response:* Every submitted job is eventually confirmed or its transformation fails.

TH2: *Soundness:* A submitted job whose transformation fails is not processed.

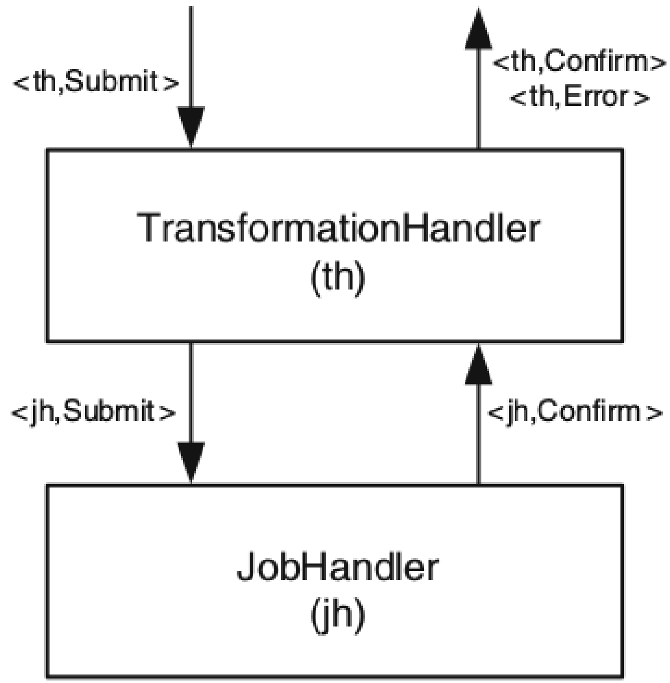


Figure 1.3: A stack of job-transformation and job-handler modules

Algorithm 1.3: Job-Transformation by Buffering

Implements:
TransformationHandler, **instance** *th*.

Uses:
JobHandler, **instance** *jh*.

```
upon event ⟨ th, Init ⟩ do
    top := 1;
    bottom := 1;
    handling := FALSE;
    buffer := [⊥]^M;

upon event ⟨ th, Submit | job ⟩ do
    if bottom + M = top then
        trigger ⟨ th, Error | job ⟩;
    else
        buffer[top mod M + 1] := job;
        top := top + 1;
        trigger ⟨ th, Confirm | job ⟩;

upon bottom < top ∧ handling = FALSE do
    job := buffer[bottom mod M + 1];
    bottom := bottom + 1;
    handling := TRUE;
    trigger ⟨ jh, Submit | job ⟩;

upon event ⟨ jh, Confirm | job ⟩ do
    handling := FALSE;
```

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.

Example 1: Traffic lights at an intersection

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

Example 2: 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

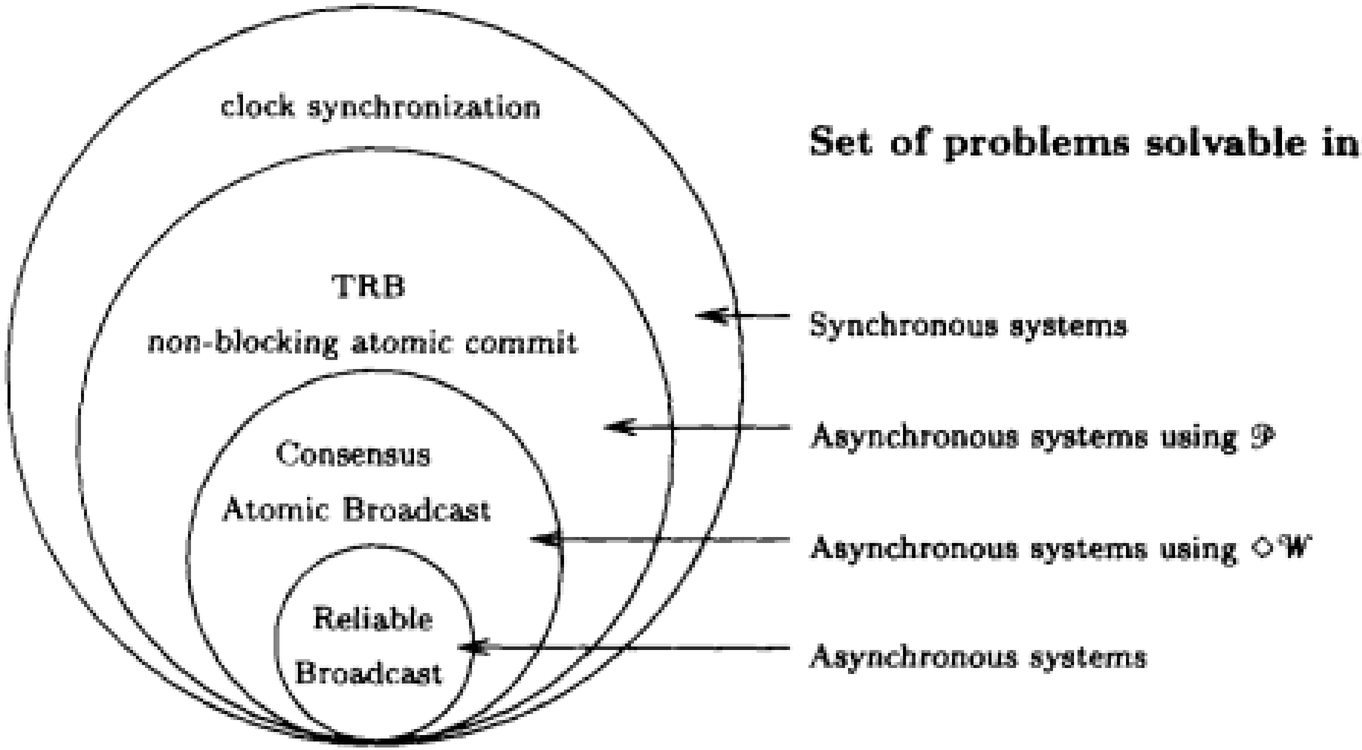


FIG. 9. Problem solvability in different distributed computing models.

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

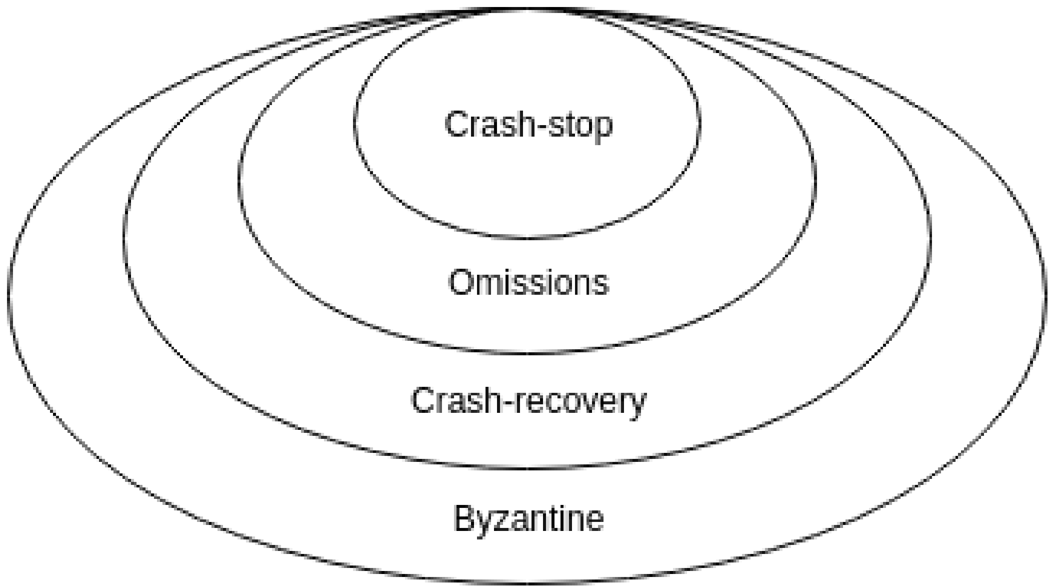
- Process omits sending or receiving messages.
  - Send omission: A process omits to send a message it has to send according to its algorithm.
  - Receive omission: A process fails to receive a message that was sent to it.
- Often, omission failures are due to buffer overflows.
- With omission failures, 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.

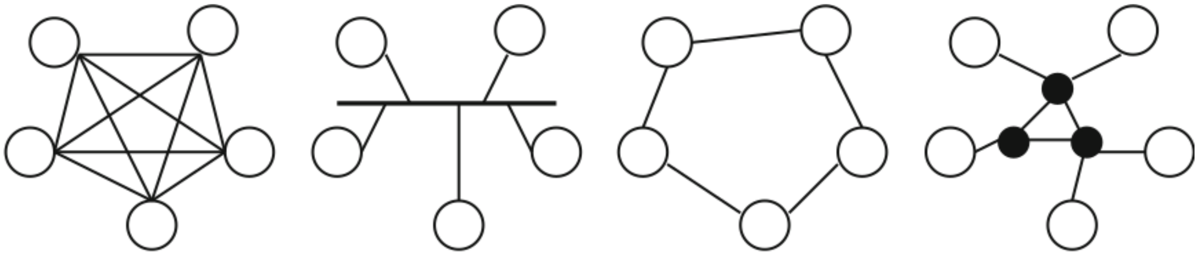


Fault-tolerance hierarchy

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.

Exercise
What abstraction do UDP and TCP implement?

Stubborn links (sl)

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.

Exercise

Which property is safety/liveness/neither?

Perfect links (pl)

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.

Exercise

Which property is safety/liveness/neither?

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 $\rangle$;

Exercise
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 abstractions

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

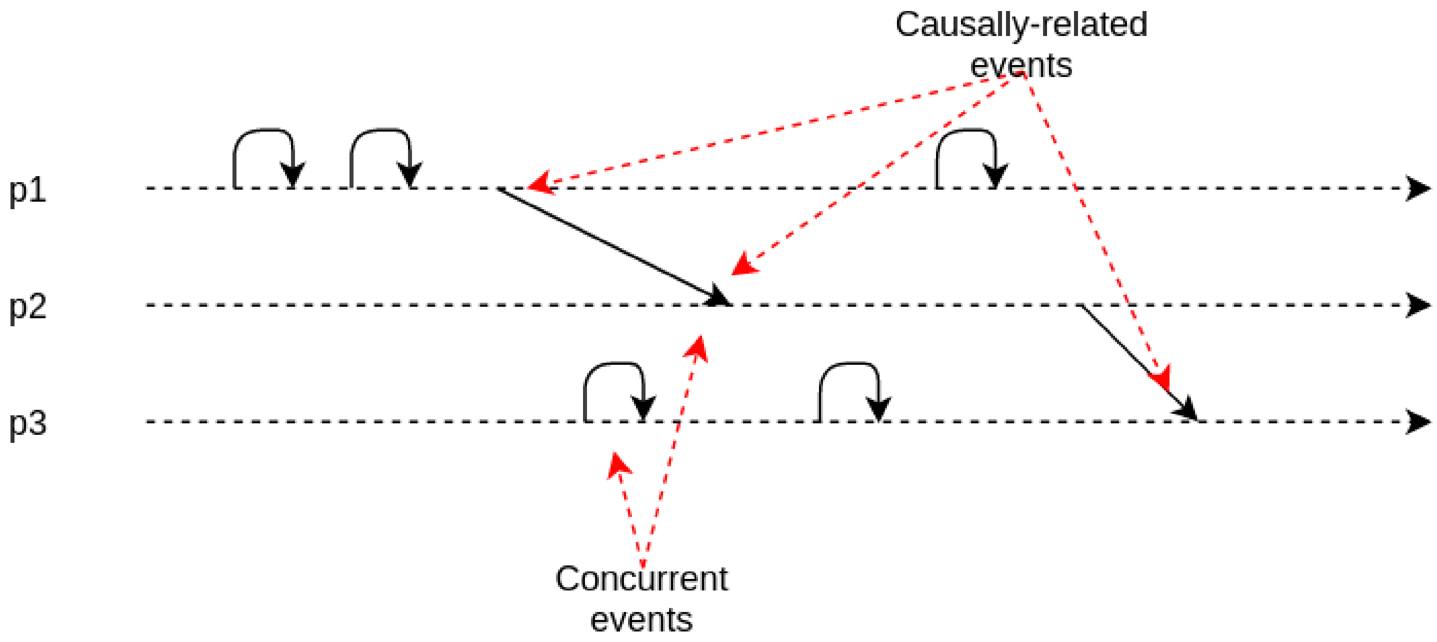
Asynchronous systems

- 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 before 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 $e_1 \rightarrow e_2$.


Causally-related events
p1
p2
p3
Concurrent events

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.

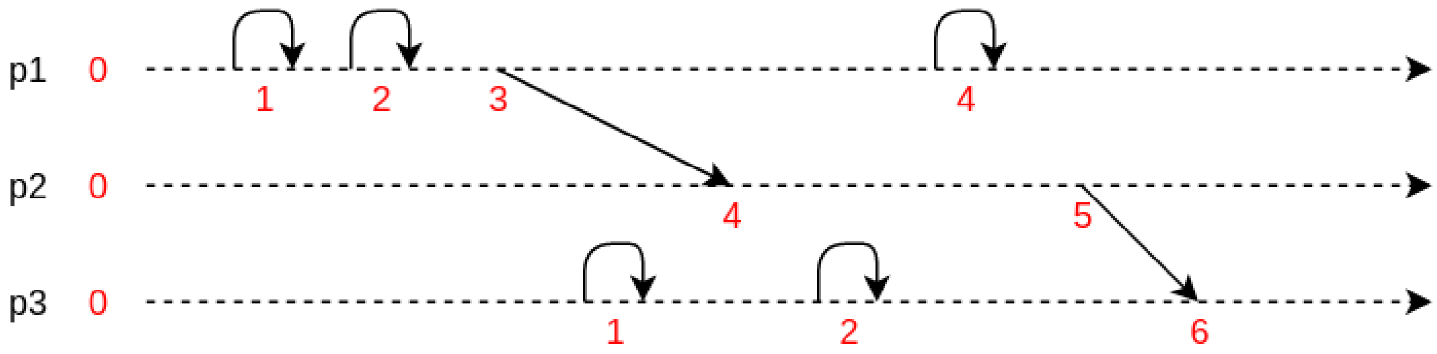
Computation theorem

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.
    - $l_p := \max(l_p, t(m)) + 1$


p1
0
1
2
3
4
p2
0
4
5
p3
0
1
2
6

Clock consistency condition

Logical clocks capture cause-effect relations:

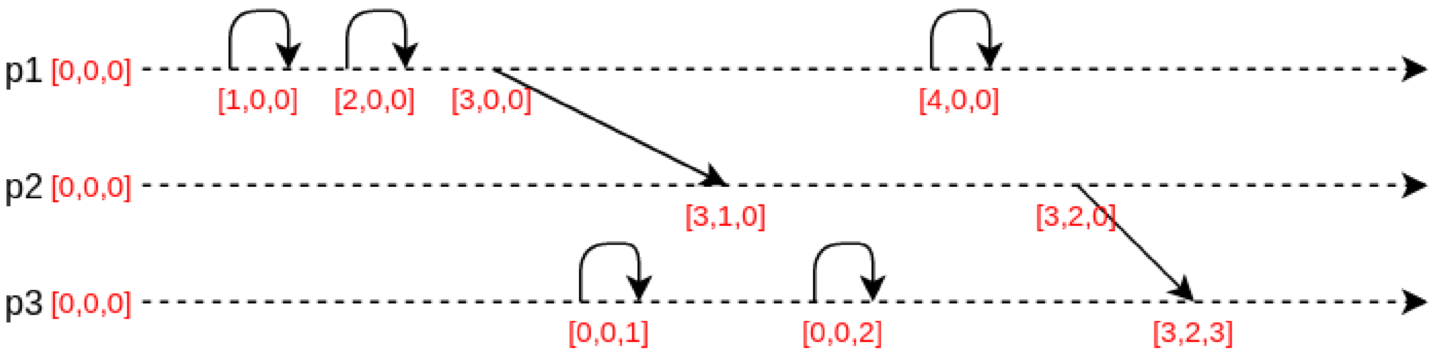
$$e_1 \to e_2 \Rightarrow t(e_1) < t(e_2)$$

- 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 $e_1 \to e_2$.
  - 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 $i \neq p$.


p1 [0,0,0]
[1,0,0]
[2,0,0]
[3,0,0]
[4,0,0]
p2 [0,0,0]
[3,1,0]
[3,2,0]
p3 [0,0,0]
[0,0,1]
[0,0,2]
[3,2,3]

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.

Exercise
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.

Exercise
Are there such systems?

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 hearbeat 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 ($\mathcal{P}$)

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.

Exercise
Which property is safety/liveness/neither?

```
Implements:
      PerfectFailureDetector, instance P.

Uses:
      PerfectPointToPointLinks, instance pl.

upon event ⟨ P, Init ⟩ do
      alive := Π;
      detected := ∅;
      starttimer(Δ);

upon event ⟨ Timeout ⟩ do
      forall p ∈ Π do
            if (p ∉ alive) ∧ (p ∉ detected) then
                  detected := detected ∪ {p};
                  trigger ⟨ P, Crash | p ⟩;
            trigger ⟨ pl, Send | p, [HEARTBEATREQUEST] ⟩;
      alive := ∅;
      starttimer(Δ);

upon event ⟨ pl, Deliver | q, [HEARTBEATREQUEST] ⟩ do
      trigger ⟨ pl, Send | q, [HEARTBEATREPLY] ⟩;

upon event ⟨ pl, Deliver | p, [HEARTBEATREPLY] ⟩ do
      alive := alive ∪ {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.

- 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 ($\diamond\mathcal{P}$)

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

Module:

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

Events:

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

Indication: $\langle\, \diamond\mathcal{P}$, *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.

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

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

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

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

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

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

Exercise
Show that this implementation is correct.

Leader election (le)

- 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.

Module:

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

Events:

Indication: $\langle$ *le*, *Leader* | 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.

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

Exercise

- Show that this implementation is correct.
- 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-recovery process abstraction
  - Stubborn links

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

The end.

References

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