1 Introduction - February 19, 2020

1.1 Defining Dependable Systems

QUOTES:

> *A distributed system is a system where a computer of which you did not know it exists can prevent you from getiing your job done.* - Leslie LAMPORT
>
> *There is perhaps a market for maybe five computers in the world.* - TJ WATSON

FAULT → ERROR → FAILURE
- Train delayed because of tree has fallen on the tracks
- Travelers reach destination too late
- Alice misses her exam

	FAULT	ERROR	FAILURE
Train:	Tree fallen	no train	delay for passengers
Journey:	Train delay	delay	reached destination 2h after intention
Exam:	arrival 2h late	missed time-slot	repeat exam

FAULT: cause of failure
ERROR: internal state of system, not according to specification
FAILURE: observable deviation of specification

FAULT examples:
- timing
- cables
- power supply
- messages lost
- data loss (solved with RAIDs)

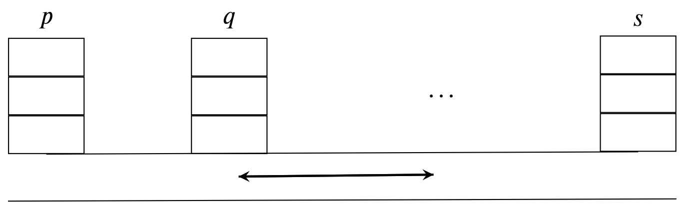
1.1.1 How to make systems tolerate faults

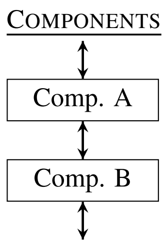
- PREVENTION
- TOLERANCE
  - Replication/Redundancy
  - Recovery
- REMOVAL
- FORECASTING/PREDICTION

SAFETY $\neq$ SECURITY
SAFETY is connected to loss of live/material due to accidents
SECURITY is connected to malicious intent

1.1.2 Defining distributed computation

Processes $\Pi = \{p, q, r, s \dots\}$
$\mid \Pi \mid = N$





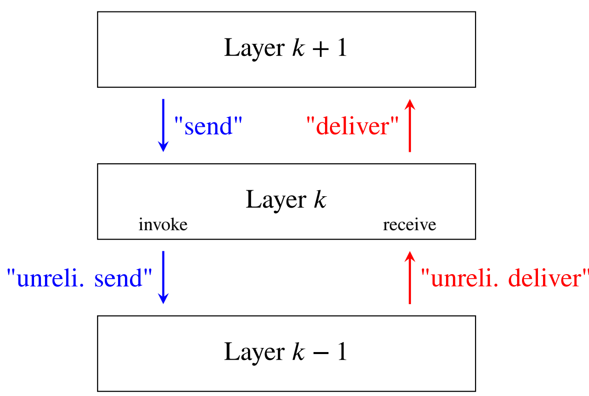
EVENTS for Component c:

$$\langle c, event \mid param_1, param_2 \ldots \rangle$$

upon $\langle c, ev_1 \mid param_1 \rangle$ do
  do something
  trigger $\langle b, \mathit{domore} \mid p \rangle$

upon $\langle b, \mathit{domore} \mid p \rangle$ do

1.1.3 Layered modules



Events either travel:
- upwards (red): indication
- downwards (blue): request

Events on a given layer may be:
- input events (IN)
- output events (OUT)

1.1.4 Module Jobhandler

Events:
Request: $\langle$*jh, handle* | *job*$\rangle$
Indication: $\langle$*jh, confirm* | *job*$\rangle$
Properties:
Every job submitted for handling is eventually confirmed.

Implementation (synchronized) JOBHANDLER
State
...
upon $\langle$*jh, handle* | *job*$\rangle$ do
"process job"
trigger $\langle$*jh, confirm* | *job*$\rangle$

upon ...
upon ...

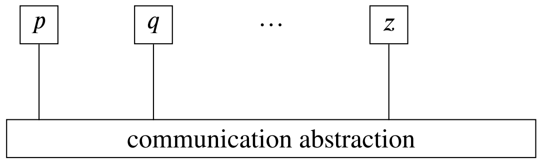
Implementation (asynchronized) JOBHANDLER
State
$buf \leftarrow \emptyset$
upon $\langle$*jh, handle* | *job*$\rangle$ do
$buf \leftarrow buf \cup \{job\}$
trigger $\langle$*jh, confirm* | *job*$\rangle$

upon $buf \neq \emptyset$ do
$job \leftarrow$ some element of buf
"process job"
$buf \leftarrow buf \setminus \{job\}$

1.2 Concurrency and Replication in Distributed Systems

2 Models and Abstructions - February 26, 2020

2.1 Processes and Protocols



- Set of Processes Π
  $|\ \Pi\ | = N$
- A process is an automaton
- A protocol is a set of processes

2.1.1 Execution

- Each computation step and every step of sending a message or receiving a message is an event
- An execution (history) is a sequence of all events of the processes as seen by a (hypothetical) global observer
- trace = execution

2.1.2 Properties

Used for specifying the abstractions:

- **Safety properties** (*something "bad" has not happened*)
  If a property P has been violated in some execution E, then there exists a prefix E' of E such that in every extension of E', property P is violated
- **Liveness properties** (*something "good" will happen in the future* [EVENTUALLY])
  Property P can be satisfied by some extension $\widetilde{E}$ of a given execution E

Safety or *Liveness* alone is not very useful. Only combination of both properties.

2.1.3 Process Failures

A process consists of different modules - if one of them fails the entire thing fails at once.

★ ***Crashes***
- *Omission failures* (*message sending and receiving events are omitted*)
- *Crash-Recovery Failure*
  - store(-) operation to write to stable storage
  - upon recovery, one can restore(-) data from this stable storage
- *Eavesdropping Fault*

★ ***Arbitrary Fault (Byzantine Fault)***

2.2 Cryptographic Abstraction

- ***Hash functions*** (SHA-256)
  $H : 0, 1^{\star} \rightarrow \{0, 1\}^k$
  - collision-free: difficult to find x, x' with $x \neq x'$ and $H(x) = H(x')$
- ***Message-Authentication-Code (MAC)*** (HMAC-SHA256)
  - *authentication*$(p, q, m) \rightarrow a$
  - *verifyAuth*$(p, q, m, a) \rightarrow$ YES/NO
- ***Digital Signatures*** (RSA, (EC)DSA)
  - *sign*$(p, m) \rightarrow s$
  - *verifySign*$(p, m, s) \rightarrow$ YES/NO

  ★ *Correctness*:
  $\forall m, p :$ *verifySign*$(p, m, sign(p, m))$ = YES

  ★ *Security*:
  $\forall m, p, s :$ *verifySign*(p, m, s) = NO, unless p has executed $sign(p, m) \rightarrow s$

2.3 Communication Abstraction

Every process can send messages to every other process.

2.3.1 Stubborn point-to-point links

Events:
$\langle sl.send \mid q, m \rangle$ { *send message m to process q*
$\langle sl.deliver \mid p, m \rangle$ { deliver a received message m from process p
Properties:
Stubborn delivery:
If a process sends a message m to process q, then m is infinitely often delivered at q.
No creation:
If some process q delivers some message m from p then process p has previously sent m to q.

2.3.2 Perfect point-to-point links

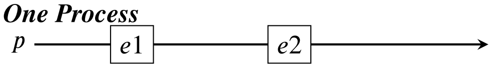
Events:
$\langle sl.send \mid q, m \rangle$
$\langle sl.deliver \mid p, m \rangle$
Properties:
Reliable delivery:
If a correct process sends a message m to a correct process q then q eventually delivers m
No creation:
If process q delivers some m from process p then p has sent m to q
At-most-once delivery:
Every message m is delivered at most once from p to q.

2.3.3 Alg. impl. perfect links (pl) from stubborn links (sl)

INIT:
$\mathbb{D} \leftarrow \emptyset$
upon $\langle pl.send \mid q, m\rangle$ do
  trigger $\langle sl, send \mid q, m\rangle$
  upon $\langle sl.deliver \mid p, m\rangle$ do
    if $(p, m) \notin \mathbb{D}$ then
      $\mathbb{D} \leftarrow \mathbb{D} \cup \{(p, m)\}$
      trigger $\langle pl.deliver \mid p, m\rangle$
      ...

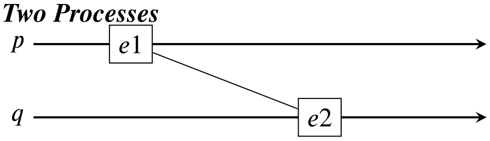
2.4 Timing Assumptions

- **Asynchronous model** (*Logical Timing*)
  - ***One Process***



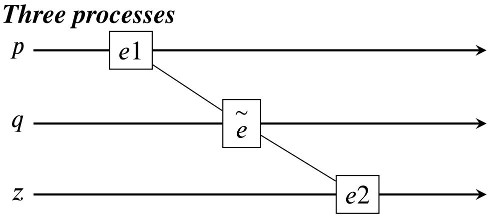
If $e2$ happened after $e1$ in one process, we know the sequence of events.

  - ***Two Processes***



If we know that $e1$ caused $e2$, we know that $e2$ happened after $e1$.

  - ***Three processes***



Transitivity holds across processes, so if $e1$ caused $\tilde{e}$ which cause $e2$, $e2$ happened after $e1$.

- Other time models exist

3 3rd Lecture - February 27, 2020

3.1 sub