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)

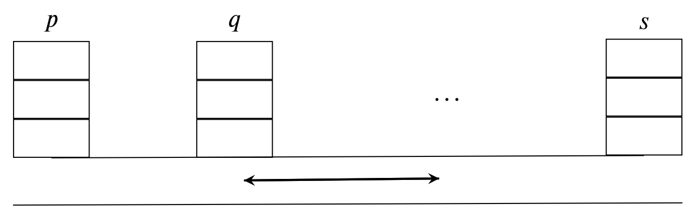
1.1.1 How to make systems tolerate faults

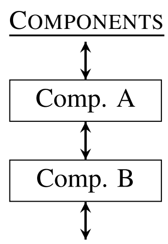
- PREVENTION
- TOLERANCE
  - Replication/Redundancy
  - Recovery
- REMOVAL
- FORECASTING/PREDICTION

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





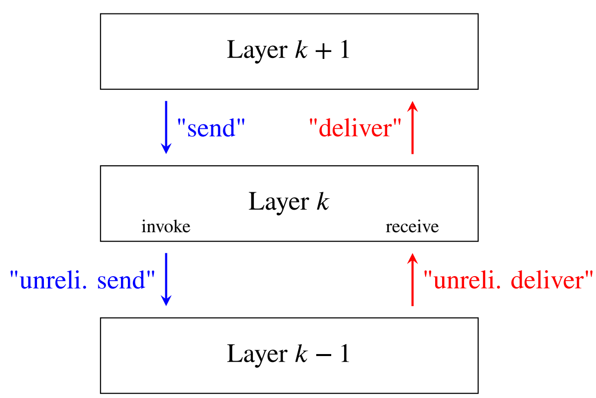
EVENTS for Component c:

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

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

upon $\langle b$, *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: $\langle jh, handle \mid job \rangle$
Indication: $\langle jh, confirm \mid job \rangle$
Properties:
Every job submitted for handling is eventually confirmed.

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

upon ...
upon ...

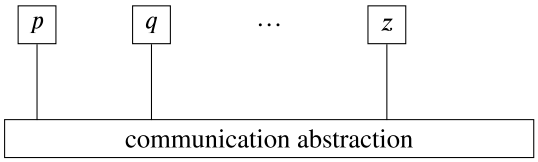
Implementation (asynchronized) JOBHANDLER
State
$buf \leftarrow \emptyset$
upon $\langle jh, handle \mid job \rangle$ do
$buf \leftarrow buf \cup \{job\}$
trigger $\langle jh, confirm \mid job \rangle$

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

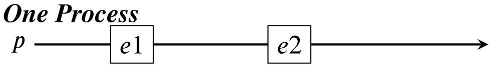
Events:
$\langle sl.send \mid q, m \rangle$
$\langle sl.deliver \mid p, m \rangle$
Properties:
Reliable delivery:
If a correct process sends a message m to a correct process q then q eventually delivers m
No creation:
If process q delivers some m from process p then p has sent m to q
At-most-once delivery: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

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

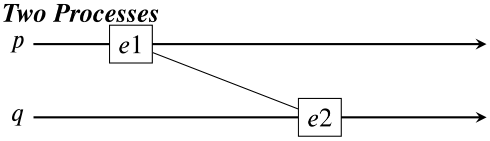
INIT:
$\mathbb{D} \leftarrow \emptyset$
upon $\langle pl.send \mid q, m \rangle$ do
  trigger $\langle sl, send \mid q, m \rangle$
  upon $\langle sl.deliver \mid p, m \rangle$ do
    if $(p, m) \notin \mathbb{D}$ then
      $\mathbb{D} \leftarrow \mathbb{D} \cup \{(p, m)\}$
      trigger $\langle pl.deliver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

2.4 Timing Assumptions

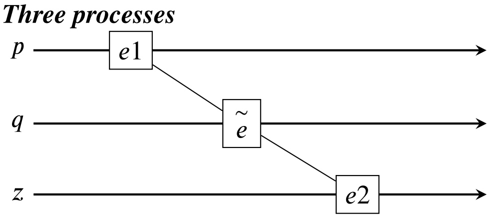
- **Asynchronous model** (*Logical Timing*)
  - ***One Process***

    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

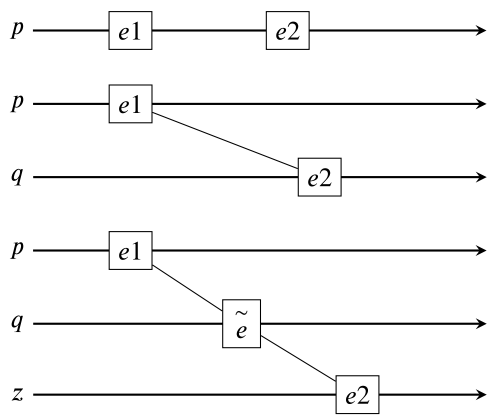
3 Timing Assumptions - March 3, 2020

3.1 Asynchronous System

Logical clock creates a logical time

- Each process p keeps a logical clock lp (initially 0)
- When an event e on p occurs, then $lp \leftarrow lp + 1$
- When p sends a message m to q, then p attaches a timestamp $ts(m) = lp$ to m
- When p receives a message m' with $ts(m')$, then p sets $lp \leftarrow max\{lp, ts(m')\} + 1$

3.1.1 Happens-before relation



In each of these we can say that $e1$ happens before $e2$

3.1.2 Lemma

$e1$ occurs at p at lp
$e2$ occurs at q at lq
$\Rightarrow e1 \rightarrow e2$, then $lp < lq$, but not the other way round!

3.2 Synchronous System

<u>**EITHER:**</u>

- Assume every process has access to a real-time clock (***RTC***)

<u>**OR:**</u>

- Synchronous computation (bounds on computation time)
- Synchonous communication (bounds on message-transmission time)

CAREFUL! when synchrony, assumptions are needed for safety properties

3.3 Partially Synchronous Model

- Synchronous most of the time
- When asynchronous, must not violate safety
  Formally captured by abstraction of an eventually synchonous system.
- Initial period of asynchrony
- After some point in time (unknown to algorithm), system is synchonous

NOTE: Abstract model will remain synchronous forever after sync-point. In practice, periods of synchrony and asynchrony alternate.

3.4 Abstracting Time

DEFINITION: Perfect Failure Detecture $\mathbb{P}$
EVENT: $\langle \mathbb{P}.\mathit{Crash} \mid p \rangle$ denotes that process p has crashed.
PROPERTIES:

STRONG COMPLETENESS:
Eventually every process that has crashed is detected by all correct processes.

STRONG ACCURACY:
For any process p, if p detects that q crashed, then q has crashed.

Formally, all processes are either alive forever or they crash and stop.
Suppose a notion of time in $\mathbb{N}$:

$C : \mathbb{N} \to \Pi$, $C(t)$ denotes the processes that are live at time t.
$F : \mathbb{N} \to \Pi$, $F(t)$ denotes the proceses that are faulty (crashed) at time t.

$p \in F(t)$, then $\forall t' \geq t : \; p \in F(t')$ (crashes are irreversible)

$\mathbb{F} = \bigcup_{t \geq 0} F(t)$, set of all faulty processes
$\mathbb{C} = \Pi \setminus \mathbb{F}$, set of all correct processes

Strong Completeness:
$\exists t : \forall p \in \mathbb{F}, \forall q \in \mathbb{C} : \exists t' \geq t : \langle \mathbb{P}.\mathit{Crash} \mid p \rangle$ occurs on process q at time t'.
Strong Accuracy:
$\forall q \in \mathbb{C}$ if $\langle \mathbb{P}.\mathit{Crash} \mid p \rangle$ occurs on process q at time t then $p \in F(t)$.

3.4.1 Implementing $\mathbb{P}$

Initialization:
start timer Δ
alive $\leftarrow \Pi$
detected $\leftarrow \emptyset$

upon timeout do for all $p \in \Pi$ do
if $p \notin alive \wedge p \notin detected$ then trigger $\langle \mathbb{P}.Crash \mid p \rangle$
detected $\leftarrow$ detected $cup\{p\}$
start timer with Δ
alive $\leftarrow \emptyset$
send msg [PING] to all $p \in \Pi$

upon receive msg. [PING] from p do
send msg [PONG] to p

upon receiving [PONG] from p do
alive $\leftarrow$ alive $\cup\{p\}$

DEFINITION: Leader Election
EVENT: $\langle le.leader \mid p \rangle$, elects p to be leader
PROPERTIES (Eventual Leadership):
Eventually, some process l is elected leader by every correct process
ACCURACY:
If a process is elected leader then all previously elected leaders have crashed.

DEFINITION: Eventually Perfect Failure Detector
EVENTS:
$\langle \diamond\mathbb{P}.Suspect \mid p \rangle$, process p is suspected.
$\langle \diamond\mathbb{P}.Restore \mid p \rangle$, process p is thought to be alive.
PROPERTIES
STRONG COMPLETENESS:
Eventually, every process that has crashed is suspected by every correct process
EVENTUAL STRONG ACCURACY:
Eventually, every process that has crashed is suspected permanently by every correct process.

Model	Processes	Timing	
fail-stop	crash-stop	synchronous	$\langle \mathbb{P} \rangle$
fail-noisy	crash-stop	partially synchronous	$\langle \diamond\mathbb{P} \rangle$, $N > 2F$
fail-silent	crash-stop	asynchronous	$N > 2F$

4 4th Lecture - March 4, 2020

4.1 sub