TÉCNICO LISBOA

Towards a dependable consensus: Basic abstractions

Highly dependable systems

Lecture 2

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Agenda

- Motivation: Dependable distributed systems
- Basic abstractions
  - processes
  - channels
  - timing assumptions
  - alternative timing abstractions:
    - failure detectors & leader election
  - Distributed system models

Dependable distributed systems

- Our society is critically dependent on a number of **inherently distributed** services, e.g.:
  - Traffic control
  - Finances:
    - e-transactions, e-banking, stock-exchange
  - Reservation systems
  - Pretty much everything on the cloud
- L. Lamport: “a distributed system is one that stops your application because a machine you have never heard from crashed” ~70’s

The optimistic view

- Concurrency => speed (load balancing)
- Partial failures => high availability

The pessimistic view

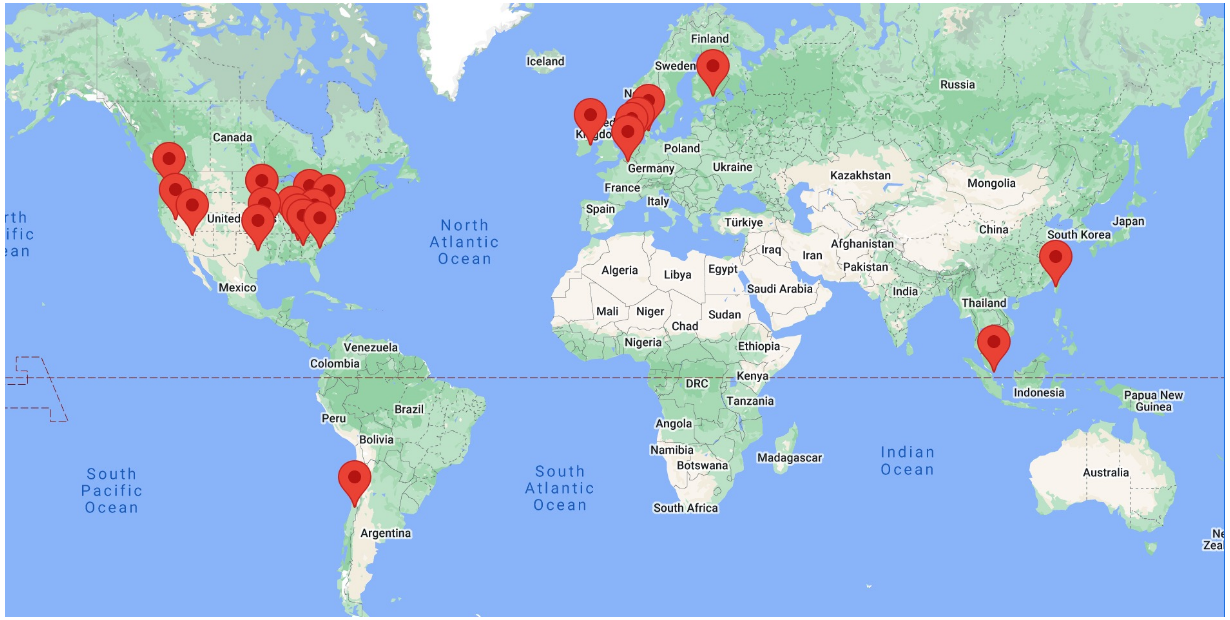
- Concurrency => different interleavings => incorrectness

- Partial failures => loss of state => incorrectness

Difficult to get right!

Distributed systems (Today: Google)

- Tens to hundreds of thousands of machines connected in each data center, 23 data centers in total
- A typical Google job can involve thousands of machines
  - GPT-3 took 405 GPU-years to train (on V100 GPUs)

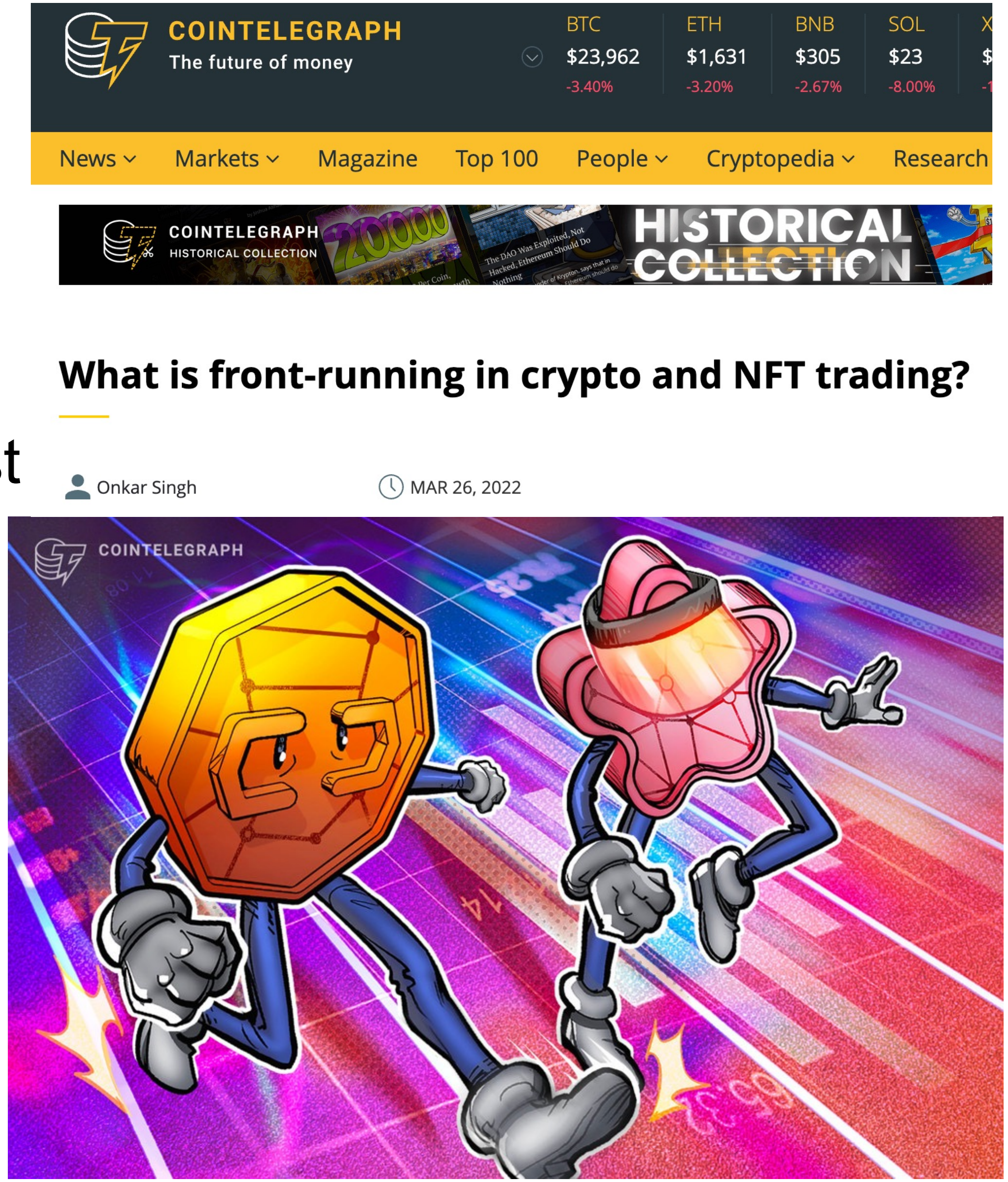


Failure is the norm, not the exception

- Tens of machines go down per day per data center
  - Due to power supply, hard drives, memory, etc.
- Need efficient algorithms to ensure **dependability** of distributed systems…
- …and abstractions to **mask complexity** from programmers!

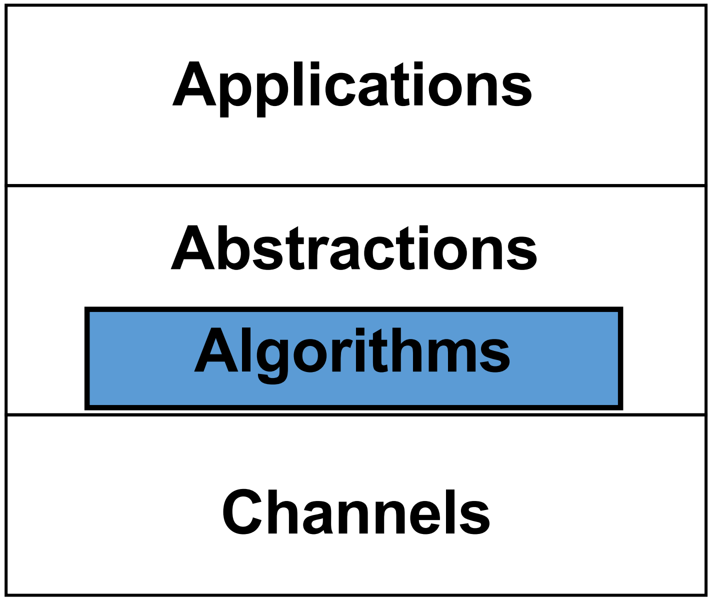
Blockchains introduce additional challenges

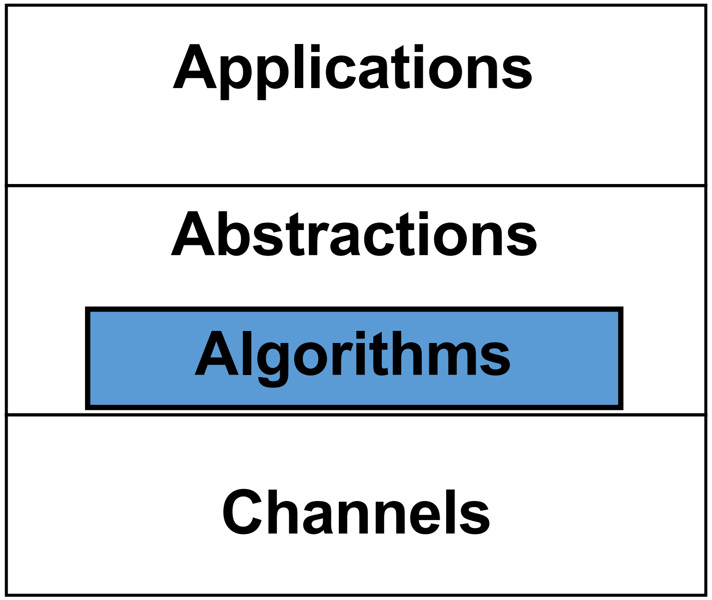
- Even in a fixed membership setting, machines fail or become unreachable
- Furthermore, need to reach consensus without having to trust a single entity or any individual participant
  - Adversarial setting - subset of machines may try to sway outcome (e.g., front running attacks try to reorder transactions)



The power of abstraction

- Complexity is masked via **abstractions** for building dependable services
- The network is too low level, even with additional help from protocols:
- Reliability guarantees (e.g., TCP) are only offered for communication among pairs of processes, i.e., *one-to-one* communication (*client-server*)





Abstractions for dependable computing

Reliable broadcast

Causal order broadcast

Shared memory

Consensus

Total order broadcast

Atomic commit

Leader election

Terminating reliable broadcast

……

- Several of you studied these abstractions (SD,DAD) **<u>in the benign (crash-stop) model</u>**
- In this course we will study (some of) them in the **Byzantine** fault model

Basic abstractions

- (1): *processes*
  (abstracting computers)
- (2): *channels*
  (abstracting networks)
- (3): *failure detectors/leader election*
  (abstracting time)
- … + *cryptographic primitives*
  (hashes, MACs, digital signatures)

Processes

- The distributed system is made of a finite set of N processes: each process models a sequential program
- Processes are denoted by $p_1,..p_N$ or p, q, r
- Processes have unique identities and know each other
- Every pair of processes is connected by a link through which the processes exchange messages

Processes

- A process executes a step at every tick of its local clock
- A step consists of:
  - Receiving a message
  - A local computation (local event), and
  - Sending a message
- One message is delivered from/sent to a process per step

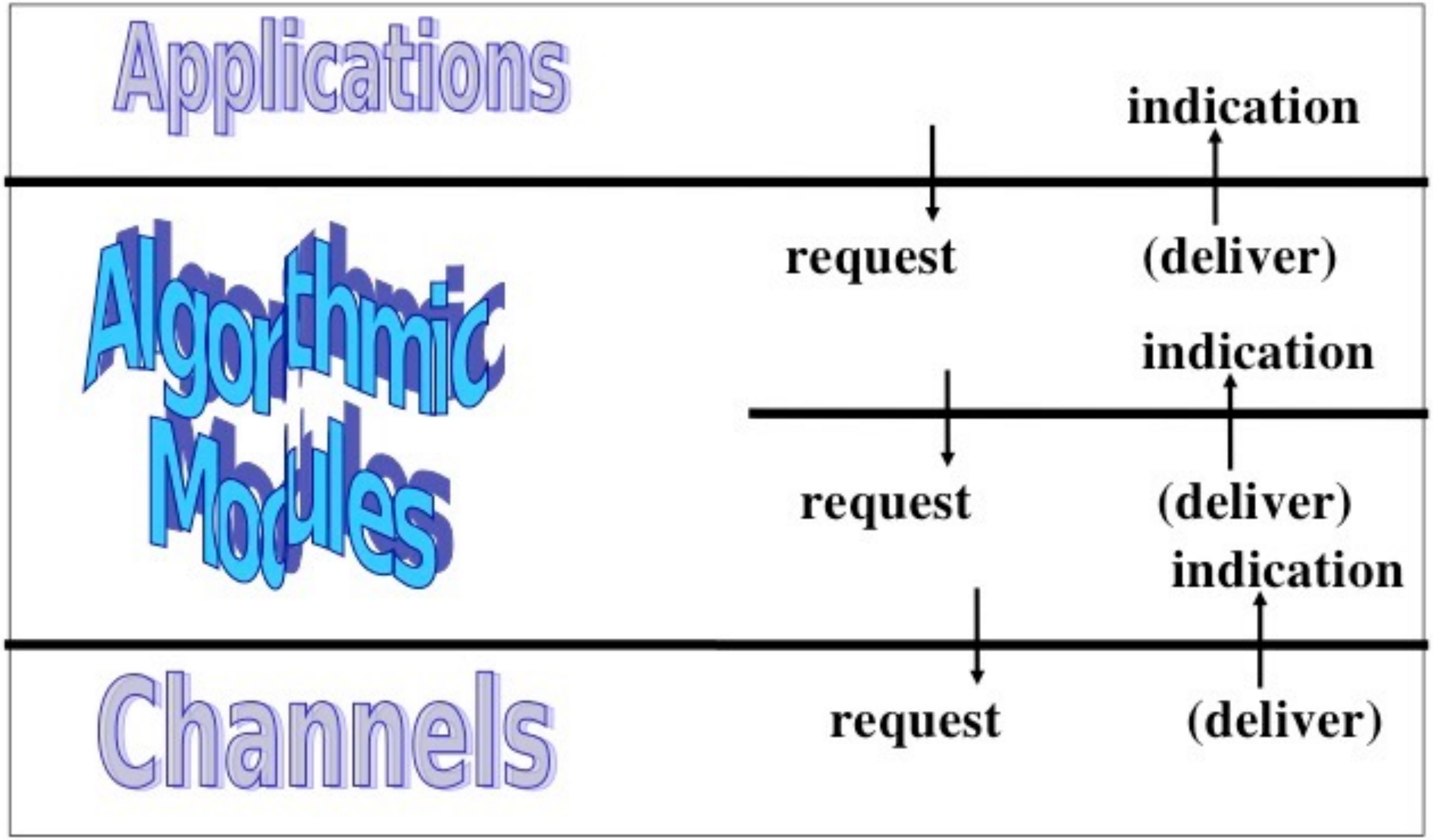
Processes

- The program of a process is made of a finite set of modules (or components) organized as a stack
- Modules within the same process interact by exchanging events
- **upon** event <Event1, att1, att2,..> do

  // . . .

  trigger <Event2, att1, att2,..>

Layering of process modules



Defining a distributed service

- *Specification*: What is the service supposed to do? i.e., correctness conditions over the set of outputs (expressed in terms of liveness + safety)
- *Model (assumptions)*: What is the system model, i.e., the power of the adversary and the capabilities of the network?
- *Algorithms*: How do we implement the service? Why does the algorithm work (proof)? What cost?

Liveness and safety

- *Safety* is a property which states that nothing bad should happen
- *Liveness* is a property which states that something good should happen (eventually)

Liveness and safety

- Example: Tell the truth
  - Having to say something is liveness
  - Not lying is safety

Recognizing safety and liveness

- Given a trace (sequence of outputs) of a distributed system
  - A safety property obeys:
    - If a finite trace does not obey the property, no extension of that trace obeys that property
  - A liveness property obeys:
    - A finite trace that does not obey the property can be extended so that the liveness property is upheld
- Any specification can be expressed in terms of liveness and safety properties

Specifications

- **Example 1: *reliable broadcast***
  - Ensure that a message sent to a group of processes is received by all nonfaulty processes or none

- **Example 2: *consensus***
  - Ensure that all nonfaulty processes reach a common decision among of set of proposed input values

Fault assumptions (model)

- A process either executes the algorithm assigned to it (steps) or fails
- A process is **correct** if it does not fail throughout its execution

- Two kinds of failures are mainly considered:
  - *Omissions:* the process omits to send messages it is supposed to send (distracted)
  - *Arbitrary:* the process sends messages it is not supposed to send (malicious or Byzantine)

- Other models exist in between

Crash-stop fault model

- Crash-stop: a more specific case of omissions
  - A process that omits a message to a process, omits all subsequent messages to all processes (permanent distraction): it crashes
- Also called “crash fault tolerance” (CFT)

Byzantine (arbitrary) faults

- A Byzantine faulty process may deviate in any conceivable way from the algorithm assigned to it:
  - due to both benign/unintentional faults, e.g., bugs
  - …as well as malicious faults: attacks, collusions
  - …and also omissions (i.e., encompasses the crash and similar models)
- To simplify reasoning:
  - unique adversary that coordinates actions of all faulty processes
- More expensive to tolerate than crashes:
  - Requires more replicas
  - cryptographic services
- Assume a maximum threshold (*f* out of N) of Byzantine processes

Abstracting Communication

- Processes communicate by message passing through communication channels

- Messages are uniquely identified (e.g., through <sender id, sequence number>)

Fair loss links (FLLs)

- *FLL1. Fair-loss*: If a message is sent infinitely often from correct process pi to correct process pj, then m is delivered infinitely often by pj

- *FLL2. Finite duplication:* If a message m is sent a finite number of times from a correct process pi to pj, m is delivered a finite number of times by pj

- *FLL3. No creation:* No message is delivered unless it was sent

Fair loss links abstraction

- This abstraction encodes a baseline guarantee from the network:
  - assume denial-of-service attacks do not last forever
  - with permanent network faults or DoS attacks of any possible duration it would be impossible to guarantee fair loss links

Stubborn links (SLs)

- *SL1. Stubborn delivery*: if a correct process pi sends a message m to a correct process pj, then pj delivers m an infinite number of times

- *SL2. No creation:* No message is delivered unless it was sent

Implementing Stubborn Links using FLL (in the crash fault model)

Implements: StubbornLinks (sp2p).

Uses: FairLossLinks (flp2p).

```
upon event <sp2pSend, dest, m> do
        while (true) do
                trigger <flp2pSend, dest, m>;

upon event <flp2pDeliver, src, m> do
        trigger <sp2pDeliver, src, m>;
```

Perfect (or Reliable) links

- *PL1. Validity*: If pi and pj are correct, then every message sent by pi to pj is eventually delivered by pj
- *PL2. No duplication:* No message is delivered (to a process) more than once
- *PL3. No creation:* No message is delivered unless it was sent

Implementing Perfect Links using SLs (in the crash fault model)

Implements: PerfectLinks (pp2p).

Uses: StubbornLinks (sp2p).

upon event <init> **do**

  delivered = { };

upon event <pp2pSend, dest, m> **do**

  trigger <sp2pSend, dest, m>;

upon event <sp2pDeliver, src, m> **do**

  if m $\notin$ delivered then

    trigger <pp2pDeliver, src, m>;

    delivered = delivered $\cup$ { m };

Authenticated perfect links

- Now we move to the Byzantine model – main challenge:
  - Byzantine processes may forge messages:
    - pretend that they were sent from any other process
  - <u>no creation</u> property of perfect/stubborn links can be endangered
  - Need to adapt specification and add machinery to the implementation
- <u>Solution:</u>
  - <u>**Authenticated Perfect Links**</u>

Authenticated perfect links

- *APL1. Reliable delivery*: If pi and pj are correct, then every message sent by pi to pj is eventually delivered by pj

- *APL2. No duplication:* No message is delivered (to a correct process) more than once

- *APL3. Authenticity:* if correct process pj delivers message m from correct process pi, then m was previously sent from pi to pj

Authenticated perfect links

- Rely on Message Authentication Codes (MACs) to eliminate forgery of messages
- Primitives for MACs:
  - MAC a 🡐 *authenticate*(send_proc p, rec_proc q, message m)
  - bool 🡐*verifyauth*(send_proc p, rec_proc q, message m, MAC a)
- Properties:
  - *verifyauth*(p, q, m, a) returns true **if and only if** p had previously invoked *authenticate*(p, q, m) and obtained a
  - only p can invoke *authenticate(p,…)*
  - only q can invoke *verifyauth(…,q,…)*

Authenticated perfect links using SLs

Implements: AuthenticatedPerfectLinks (alp2p).

Uses: StubbornLinks (sp2p).

upon event <init> **do**
    delivered = { };

upon event <alp2pSend, dest, m> **do**
    a = authenticate(*self,* dest,m);
    trigger <sp2pSend, dest, [m,a]>;

upon event <sp2pDeliver, src, m, a> **do**
    if verifyauth(src, self, m, a) && m ∉ delivered then
        trigger <alp2pDeliver, src, m>;
        delivered = delivered U { m };

Reliable/authenticated links

- We shall assume reliable/perfect links when dealing with crash-stop failure models, and
- Authenticated reliable/perfect links when considering byzantine processes

- These abstractions are often found in standard transport level protocols (e.g., TCP, TLS/SSL)
  - allows to simplify reasoning on complex services
  - for efficiency, it may be useful to assume weaker channels (e.g., fair-loss) and avoid redundant use of similar information at different layers
    - e.g., sequence numbers may be needed also by higher level layers

Timing assumptions

- *Synchronous:*
  - *Processing:* the time it takes for a process to execute a step is bounded and known
  - *Delays:* there is a known upper bound limit on the time it takes for a message to be received
  - *Clocks:* the drift between a local clock and the global real time clock is bounded and known

- *Eventually Synchronous:* the timing assumptions hold eventually

- *Asynchronous:* no timing assumptions

Abstracting time

- Many distributed algorithms rely on timing assumptions only to detect faulty processes:
  - e.g., timeouts are used to suspect crashed processes
- Alternative approaches to formulate timing assumptions:
  - assume an asynchronous model for what regards:
    - process speed, communication latency, clock skew
  - augment the system with oracles that encapsulate the timing assumptions
- **Failure detectors:**
  - oracles that provide information on which processes are faulty
- **Leader election:**
  - identify one process (leader) that is not faulty

Failure detection

- A failure detector module is defined by events and properties
- *Events*
  - Indication: <crash, p>
- Properties
  - Completeness: are faulty processes detected correctly?
  - Accuracy: can correct processes be suspected?

Failure detection

- *Perfect:*
  - *Strong Completeness:* Eventually, every process that crashes is permanently suspected by every correct process
  - *Strong Accuracy:* No process is suspected before it crashes
- *Eventually Perfect:*
  - *Strong Completeness*
  - *Eventual Strong Accuracy:* Eventually, no correct process is ever suspected

Eventually perfect failure detector

Implementation:

1. Processes periodically send heartbeat messages
2. A process sets a timeout based on worst case round trip of a message exchange
3. A process suspects another process if it times out on that process
4. A process that delivers a message from a suspected process revises its suspicion and doubles its timeout

- Can be implemented in an eventually synchronous system
  - Fully encapsulates synchrony/timing assumptions
  - Algorithms (like reliable broadcast and consensus) can be designed assuming asynchronous channels/processes

Failure detection for crash and arbitrary faults

- Failure detection for crash failures can be effectively implemented using timeouts:
- Detecting arbitrary failures is a more complex problem:
  - malicious processes may selectively behave according to the protocol
  - yet, badly violate its algorithm’s specification
  - detection of arbitrary failures is a difficult research problem
- Failure detectors are commonly employed only for detecting crash failures

Leader Election

- Identifies a correct process
- *Events*
  - Indication: <Leader, p>
- Properties
  - **Eventual detection**: Either there is no correct process, or some correct process is eventually elected as the leader
  - **Accuracy**: If a process is leader, then all previously elected leaders have crashed
    - ensures stability of the leader: only crash of current leader triggers change
    - indirectly precludes two processes to be leader at the same time

Leader Election using a Perfect f.d.

Implements: LeaderElection

Uses: PerfectFailureDetector P

upon event <init> **do**

  suspected:= empty set;

  curr_leader = null;

upon event <P, Crash, q> **do**

  add q to suspected

upon curr_leader != maxrank({processes not in suspected}) do

  curr_leader = maxrank({processes not in suspected})

  trigger <Leader, curr_leader>;

Eventual leader election

- Leader election is impossible to implement using an eventually perfect failure detector. Why?
  - if current leader is falsely suspected, a new leader **<u>must</u>** be elected to guarantee eventual detection
  - ….violating accuracy.
- Eventual leader election:
  - Eventual accuracy: there is a time after which every correct process trusts some correct process
  - Eventual agreement: there is a time after which no two correct processes trust different correct processes
- Useful abstraction in consensus algorithms (e.g., Paxos)

Eventual Leader Election using an Eventually Perfect f.d.

Implements: LeaderElection

Uses: EventualPerfectFailureDetector ◊P

upon event <init> **do**

    suspected:= empty set;

    curr_leader = null;

upon event <◊P, Suspect, q> **do**
    add q to suspected

upon event <◊P, Restore, q> **do**
    remove q from suspected

upon curr_leader != maxrank({processes not in suspected}) do

    curr_leader := maxrank({processes not in suspected})

    trigger <Leader, curr_leader>;

Byzantine Leader Election

- Timeliness of heartbeats messages is insufficient to detect arbitrary faults
- “Trust but verify” approach:
  - allow other processes to monitor actions of current leader
  - should the leader not achieve the desired goal after some time, it should be replaced by a new leader
    - definitions of “goal achievement” and “some time” are application dependent
      - applications can trigger a <Complain, p> event
    - in eventually synchronous systems, correct processes should successively increase the time between issuing complaints:
      - eventually give correct leaders enough time to achieve its goal

Byzantine Leader Election - specification

- Properties
  - **Eventual succession**: if more than f correct processes that trust some process p complain about p, then every correct process eventually trusts a different process than p
  - **Putsch resistance:** A correct process does not trust a new leader unless at least one correct process has complained against the previous leader
  - **Eventual agreement**: there is a time after which no two correct processes trust different processes

- Eventually every <u>correct</u> process trusts some process that appears to perform its task in the higher-level algorithm.
  - cannot require that every correct process eventually trusts a **correct** process… Why?

Rotating Byzantine Leader Election

- Uses authenticated perfect links
- Assumes number of processes, N, larger than 3 times the number, f, of (byzantine) faulty processes (N>3f)
- Algorithm advances in rounds, r
- Leader at round r is process having rank: r mod N
  - Locally generated Complaints for current leader are broadcast to all processes
  - When a process receives more than f Complaint messages it moves to the next round
    - At least one Complaint comes from a correct process

Rotating Byzantine Leader Election

- **Previous algorithm is incorrect. Why?**

- Problem:
  - only one complaint may come from a correct process, say p
  - the other f complaints may come from byzantine processes, which have sent the complaint only to p and not to the other processes

- In this case p changes leader, but the others do not!
  - Eventual agreement can be compromised

Rotating Byzantine Leader Election

- Leader at round r is process having rank: r mod N
  - Locally generated Complaints for current leader are broadcast
  - New round is triggered when a process receives more than 2f Complaint messages
    - prevents f byzantine processes to collude for a putsch
  - When a process receives more than f Complaint messages (and has not sent its Complaint), it also broadcasts
    - ensures that more than 2f Complaints are broadcast, when more than f Complaints are locally generated

Rotating Byzantine Leader Election

- Eventual succession.
  - if >f processes complain, all correct processes chime in
    - every correct process receives N-f>2f Complaint messages

Rotating Byzantine Leader Election

- Putsch resistance.
  - even colluding the f byzantine processes cannot overthrow the leader:
    - need at least f+1 Complaint messages
    - one Complaint message must come from correct process

Rotating Byzantine Leader Election

- Eventual agreement.
  - all correct processes must eventually stop complaining about a correct leader
    - assumption ➔ they increase (say double) the time between any two complaints
  - when all Complaint messages have been received, every correct process trusts the same process

Distributed system model

- Combination of:
  - process abstraction
  - link abstraction
  - failure-detector/leader-election abstraction

Distributed system models

- Some relevant combinations:
  - **Fail-stop:**
    - process abstraction: crash failure model
    - link abstraction: perfect
    - failure-detector/leader-election: perfect failure detector
  - **Fail-noisy:**
    - same as above but equipped with eventually perfect failure detection
  - **Fail-silent:**
    - as above but no failure-detection/leader-election oracle
  - **Fail-silent arbitrary:**
    - process abstraction: arbitrary failure model
    - link abstraction: authenticated perfect
    - failure-detector/leader-election: no
  - **Fail-noisy arbitrary**
    - as above but equipped with a byzantine eventual leader-detector

Acknowledgements

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