
Principles of Distributed Computing

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Algorithms

- One processor
 - Reliable (no faults)
 - No communication
- No Concurrency
 - One step at a time
- Complexity
 - Step complexity
- Examples
 - Sorting (Quicksort, Mergesort, Heapsort)
 - Searching (Binary search)
 - Matrix mult. (Strassen's)
 - Primality testing

Distributed Systems

- Many processors
 - Faulty (crash, byzantine, etc.)
 - Communication over network
- Concurrent
 - Multiple steps at a time
- Complexity
 - Message complexity
 - Latency analysis
- Examples
 - Leader election
 - Consensus (Agreement)
 - Mutual exclusion (Dining Philosophers)
 - Atomic objects

History Lesson

- 1960's: Edsger W. Dijkstra
 - Concurrent operating systems
 - Semaphores
 - Dining Philosophers (mutual exclusion)
 - Self-stabilization (fault-recovery)
- 1970's: Leslie Lamport
 - Logical clocks (time and causality)
 - Replication
 - Byzantine Generals Problem (consensus)
 - "A distributed system is one in which the failure of a computer you didn't even know existed can render your own computer unusable."
- 1970's: Jim Gray
 - Transactions
 - Databases
- 1980's: Nancy Lynch
 - Fault tolerance
 - Timing (synchrony, asynchrony, partial synchrony)
 - Consensus
- 1990's: Birman, Schneider, Toueg
 - Failure detectors
 - Reliable broadcast
 - Totally-ordered broadcast
 - Causal broadcast
 - Group membership
 - View synchrony
- 2020's
 - Map Reduce, Google File System
 - Raft, Spanner
 - Spark
 - Bitcoin

Today's Lecture

- Big picture:
 - What is a distributed system?
 - Why build a distributed system?
- Components of a distributed system:
 - Processes (abstracting computers)
 - Channels (abstracting networks)
- Time & failure detectors

A distributed system

Node 1



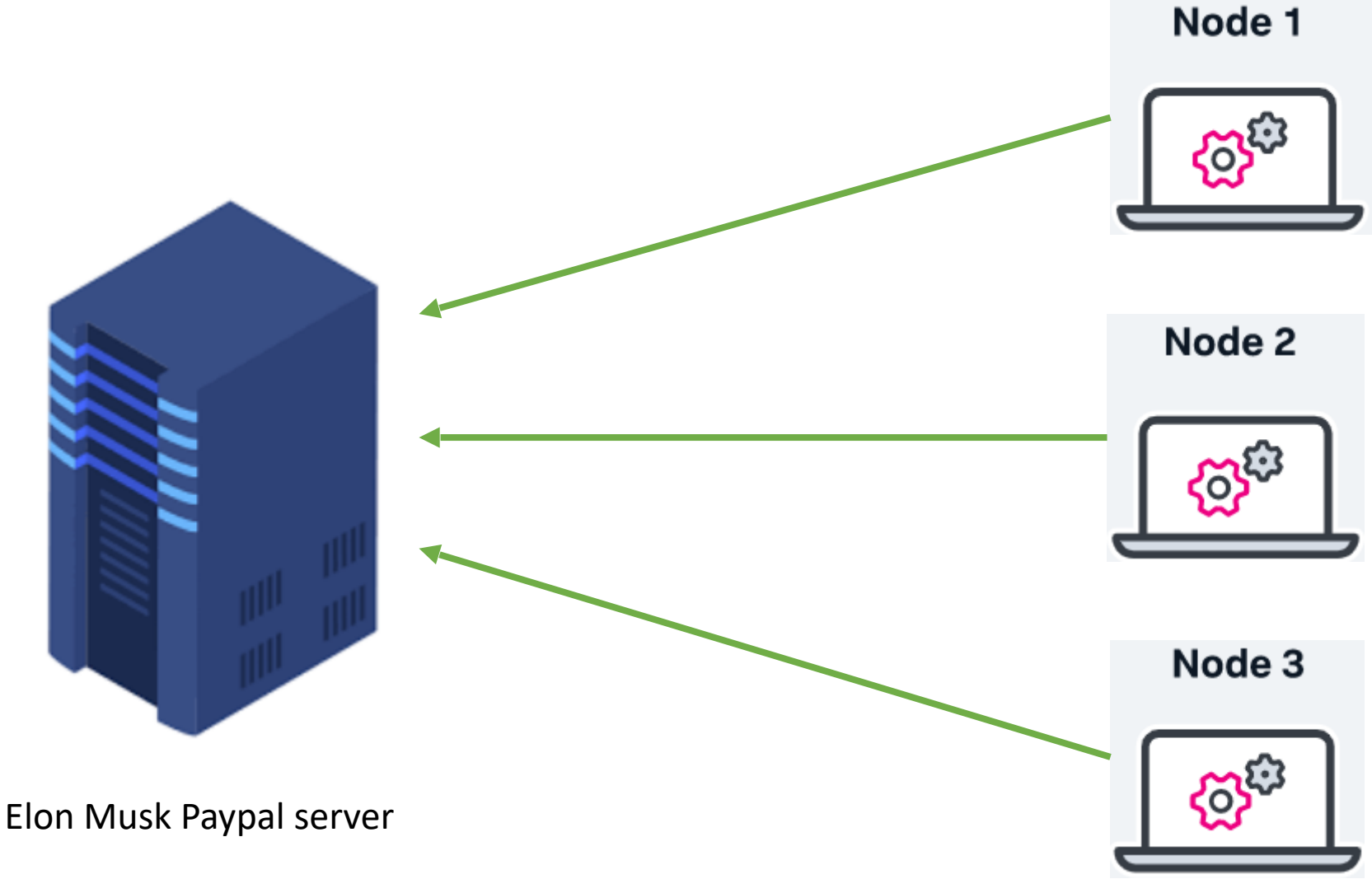
Node 2



Node 3

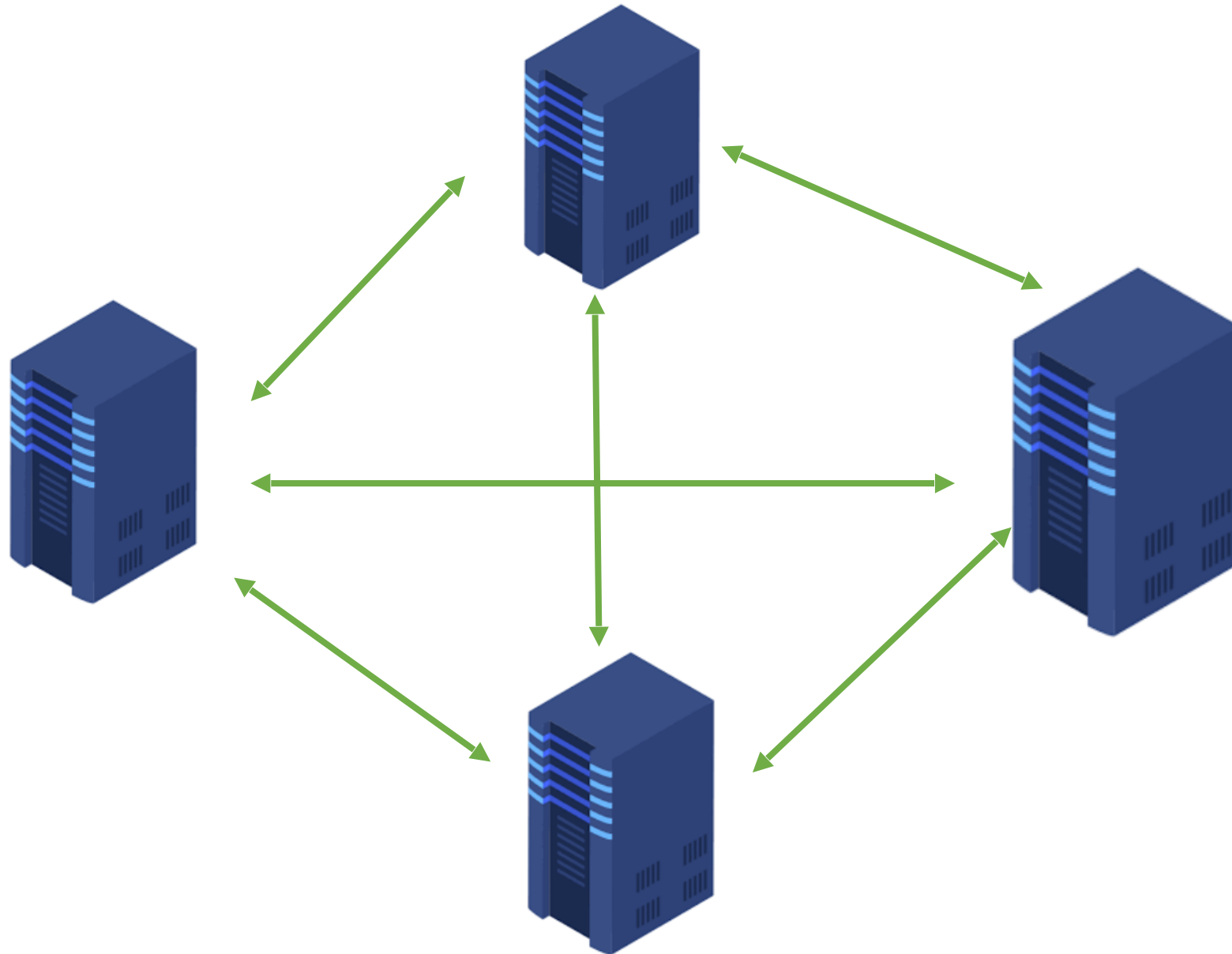


Client-server system



Elon Musk Paypal server

Multiple Servers



Why distributed systems?

- What are the advantages?

Distributed
Multi-server

vs.

Centralized
Client-server

Why distributed systems?

- What are the advantages?

Distributed
Multi-server

vs.

Centralized
Client-server

- High-availability / Fault-tolerance
- Locality, Responsiveness
- Concurrency / Parallelism -> Performance

Why not distributed systems?

- What are the disadvantages?

Distributed
Multi-server

vs.

Centralized
Client-server

Why not distributed systems?

- What are the disadvantages?

Distributed
Multi-server

vs.

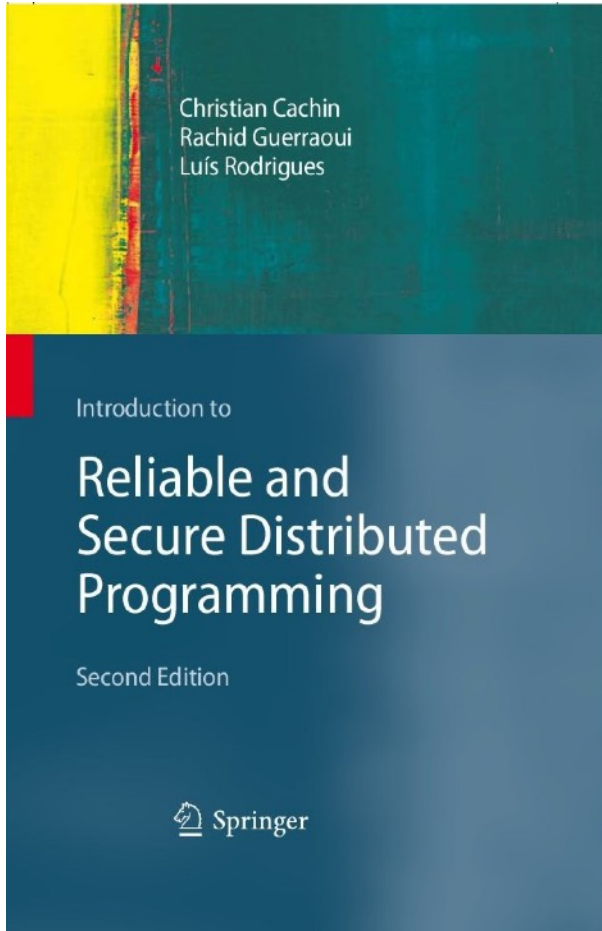
Centralized
Client-server

- Expensive (to have redundancy)
- Concurrency -> Interleaving -> Bugs
- Failures -> Incorrectness

Today's Lecture

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Textbook



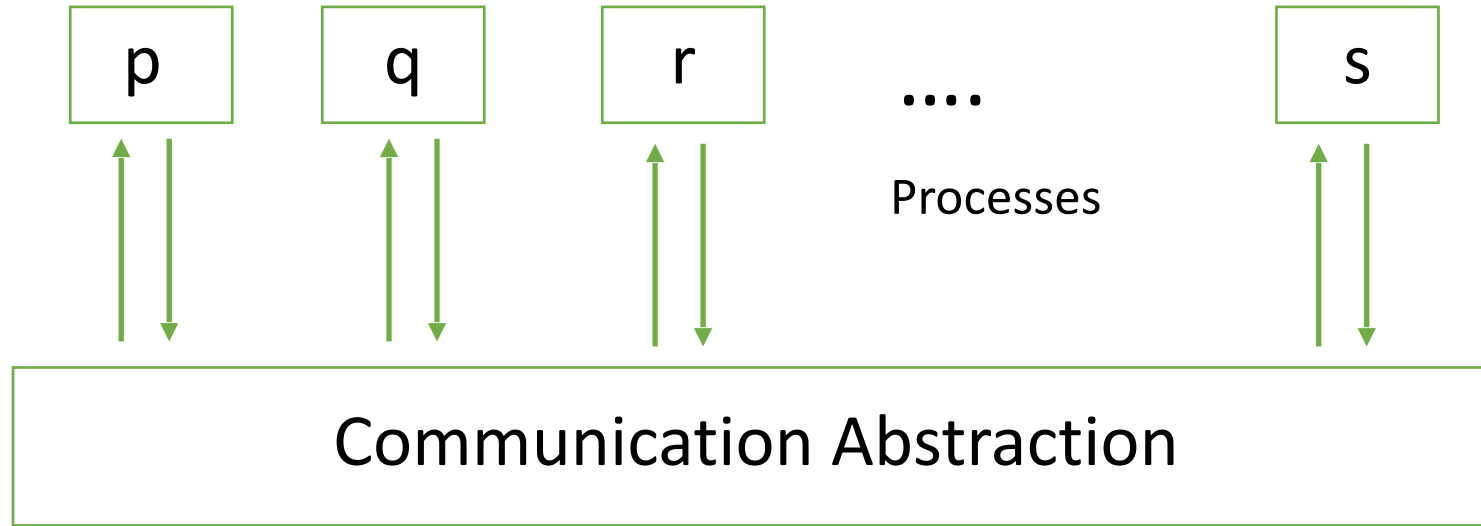
Introduction to Reliable and Secure Distributed Programming

C. Cachin, R. Guerraoui, L. Rodrigues

2nd ed. of "Introduction to Reliable Distributed Programming"

The new content covers Byzantine failures.

Distributed Programming

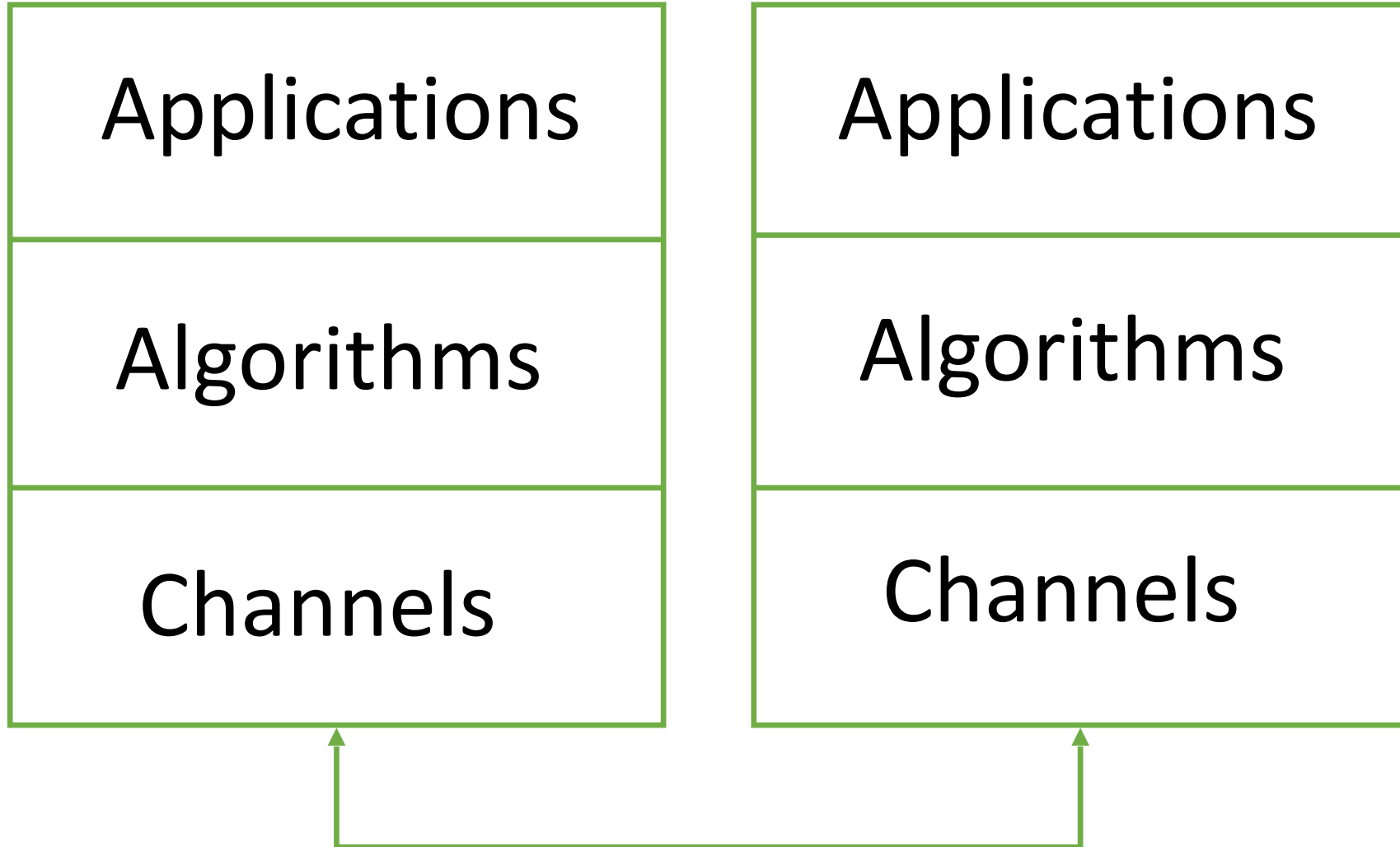


- System with N processes (also called replicas) $\Pi = \{p, q, r \dots\}$.
(Processes know each other.)
- Processes coordinate to implement the application

Programming abstractions

- Sequential programming
 - Array, record, list ...
- Concurrent programming
 - Thread, semaphore, monitor, ...
- Distributed programming
 - Reliable broadcast
 - Shared memory
 - Consensus
 - Atomic commit
 - ...

Distributed System

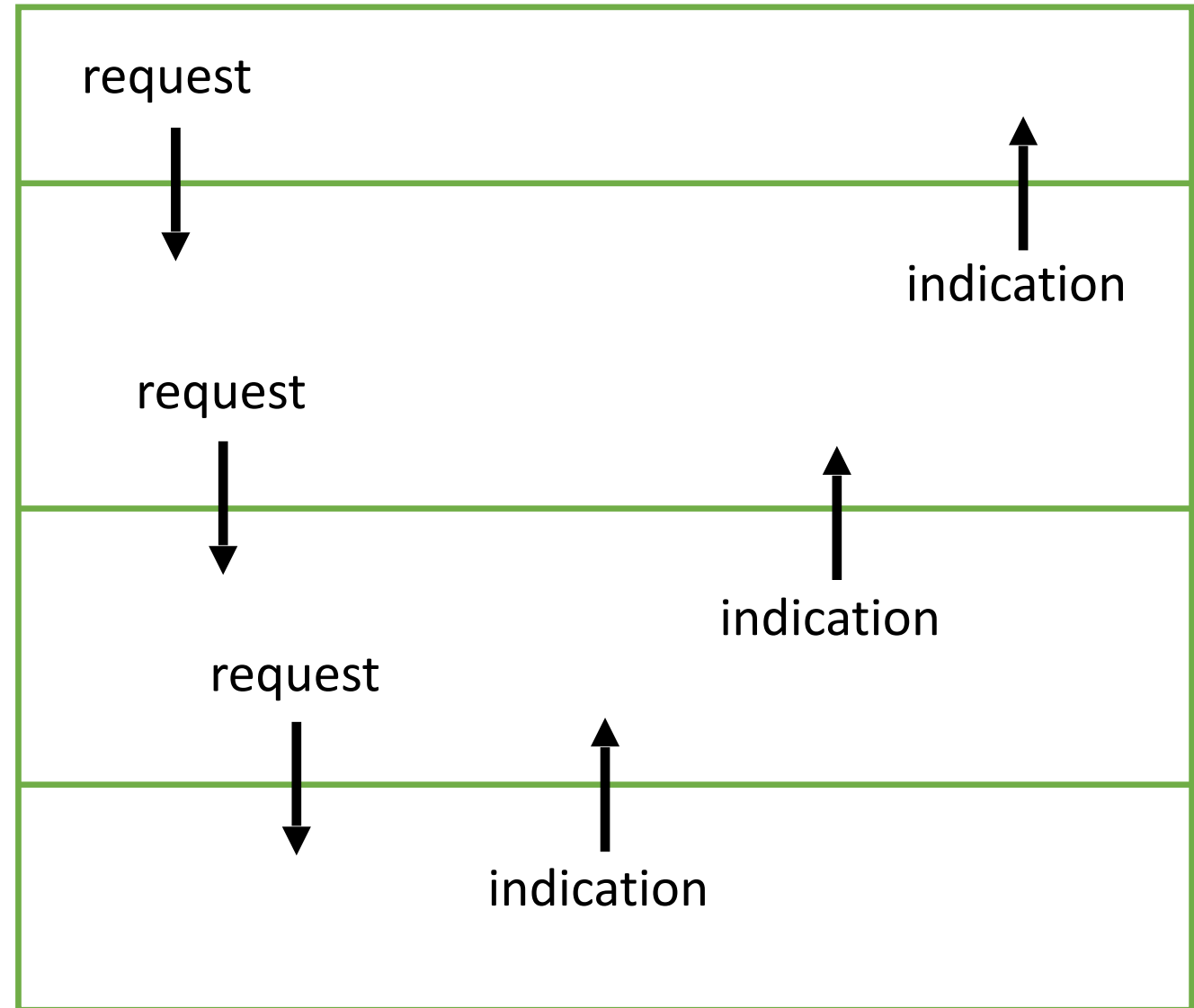


Modules of a process

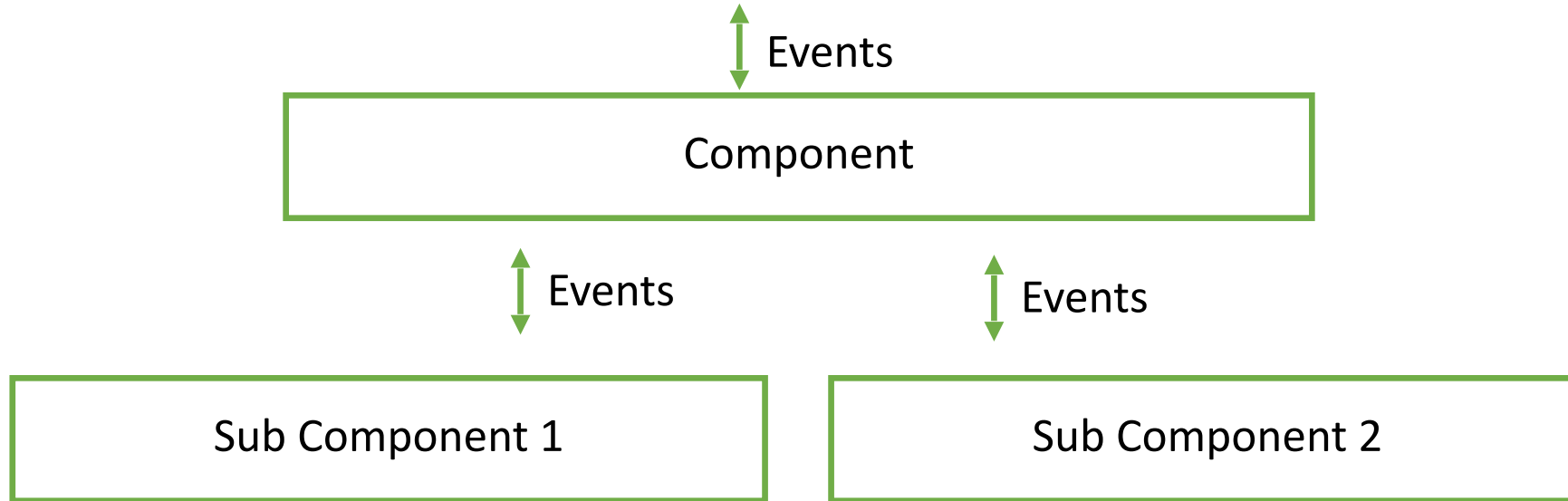
Applications

Algorithmic
Modules

Channels

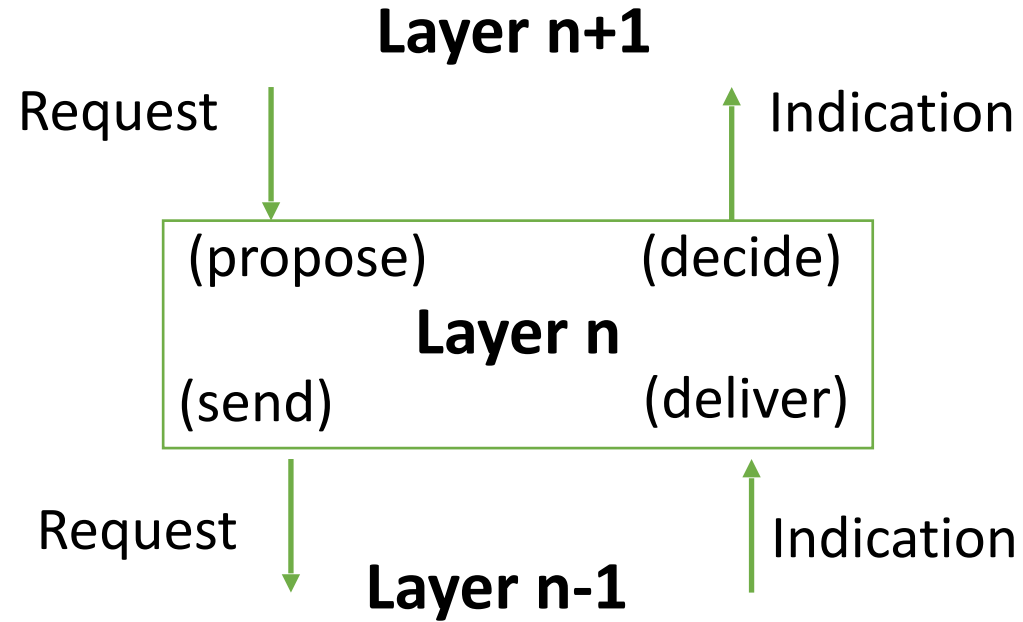


Layered Modular Architecture



- Every process is a tree of components.
 - Every component has a unique identifier.
 - There might be multiple instances of a component type.
- Modules communicate through events.

Programming with Events



- Asynchronous events
 - Request events flow downward
 - Indication (or Response) events flow upward

Reactive Programming

A component is implemented as a set of event handlers

```
upon event <component, Event (att1, att2 ...) > do  
  do something;  
trigger <component', Event' (att'1, att'2 ...) >;
```

The component is elided if the event is from/to the parent of current component.

Specification

What does a component provide?
Specification in terms of the interface events.

Example Components

- Reliable broadcast
 - Ensure that a message sent to a group of processes is received by all or none.
- Atomic commit
 - Ensure that the processes reach a common decision on whether to commit or abort a transaction.

Module Specification

- A module is defined by events and properties:

Reliable Broadcast

- Events
 - Request: $\langle \text{broadcast } (m) \rangle$
 - Indication: $\langle \text{deliver } (\text{src}, m) \rangle$
- Properties:
 - Validity
 - No Duplication
 - No creation
 - Agreement

Module Specification

- A module is defined by events and properties:

Atomic Commit

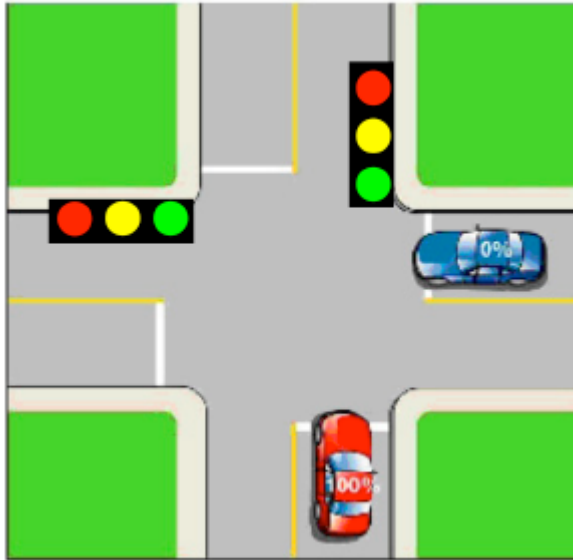
- Events
 - Request: $\langle \text{propose } (d) \rangle$ where d is either Commit or Abort
 - Indication: $\langle \text{decide } (d) \rangle$
- Properties:
 - Uniform Agreement
 - Integrity
 - Abort Validity
 - Commit Validity
 - Termination

Two Types of Properties

- **Safety** properties state that nothing bad ever happens.
- **Liveness** properties state that something good eventually happens.

Safety and Liveness

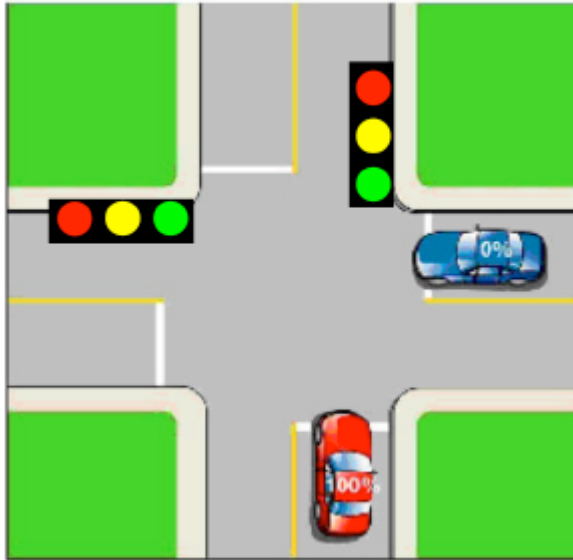
- Example: Traffic lights



- Only one direction gets a green light

Safety and Liveness

- Example: Traffic lights



- Eventually each direction gets a green light

Safety and Liveness

- Example: Reliable Broadcast
Eventually every message is delivered.

Safety and Liveness

- Example: Failure Detector

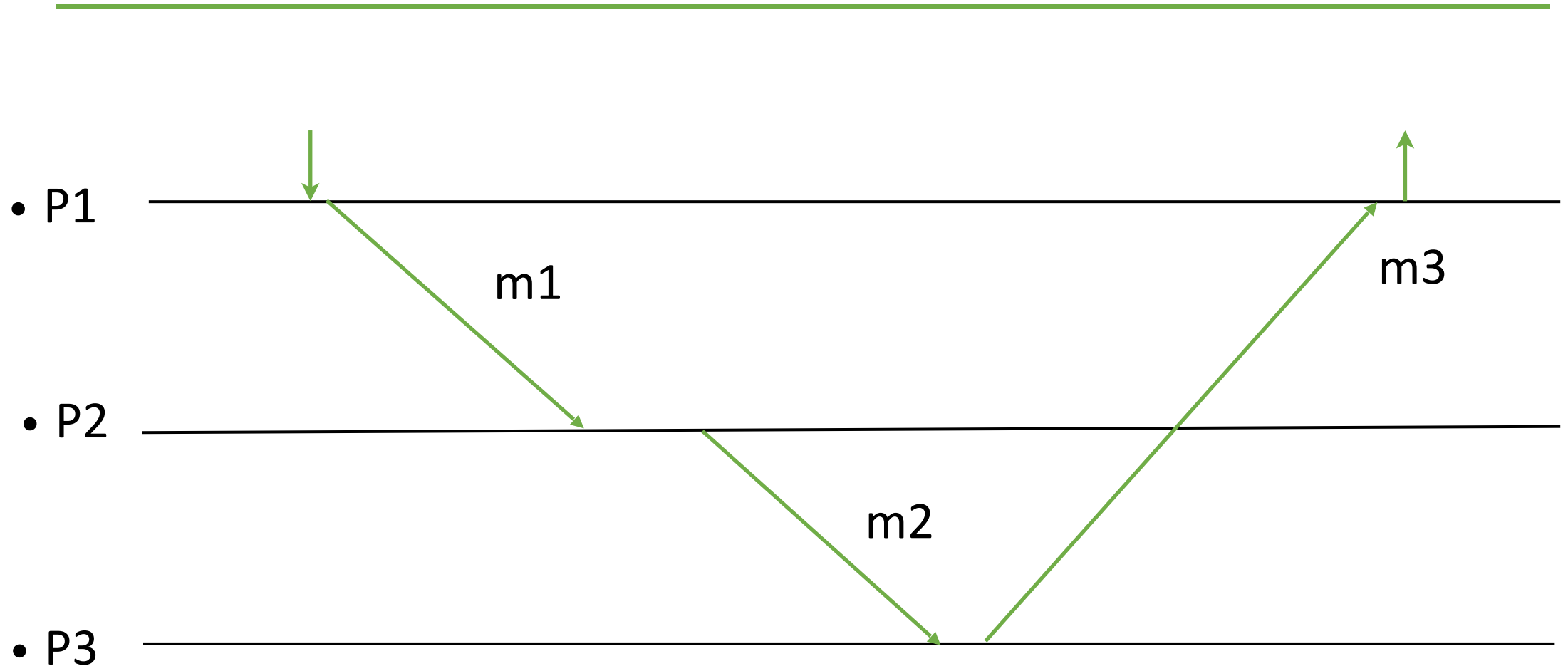
Strong Completeness: Eventually, every process that crashes is permanently suspected by every correct process.

Safety and Liveness

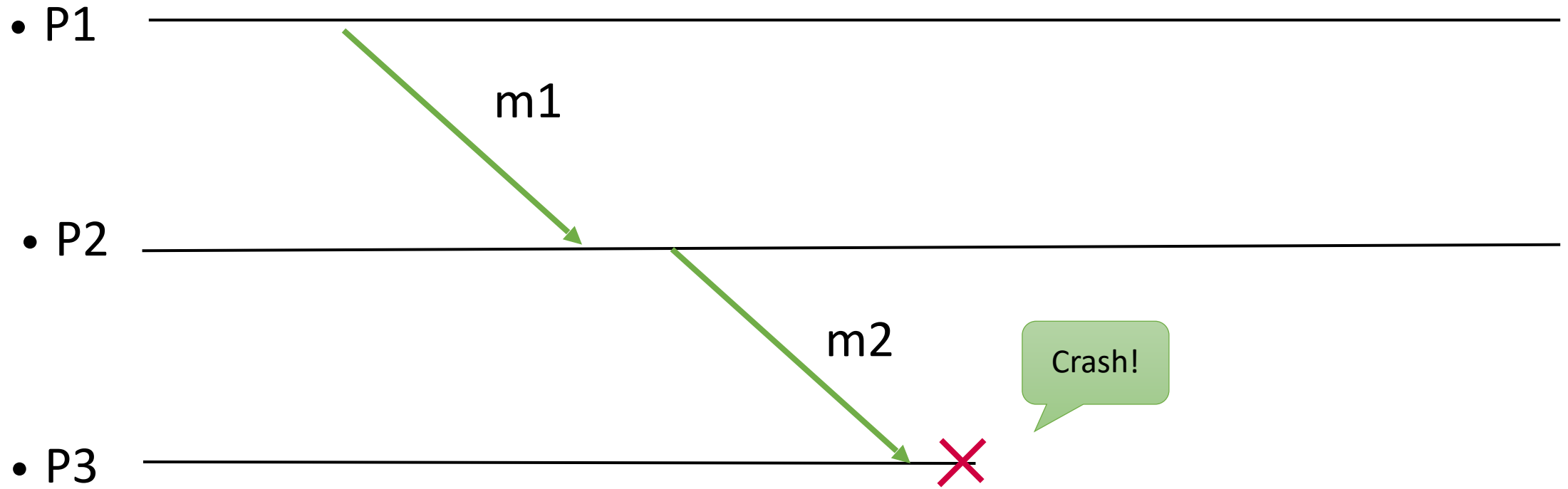
- Example: Failure Detector

Strong Accuracy: No process is suspected before it crashes.

Execution Traces



Execution Traces



Processes

Processes may fail:

- **Crash-stop**: The process takes no further process.
Simply a more specific case of emissions (dropping messages): If a process omits a message, then it omits all subsequent messages.
- **Arbitrary (Byzantine)**: The process can take arbitrary including malicious actions. For example, it can send misleading messages.

A process that does not fail is called **correct**.

A process that fails is called **incorrect**.

Processes

- By default, we assume crash-stop processes.
 - Processes fail only by crashing.
 - Processes do not recover.

Today's Lecture

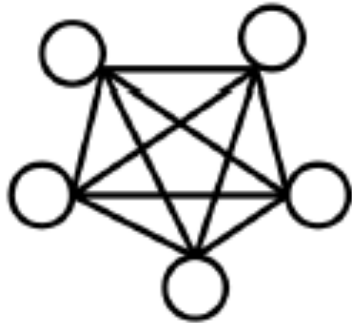
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 - Channels (abstracting networks)
 - Time & failure detectors
- Time & failure detectors

Channels

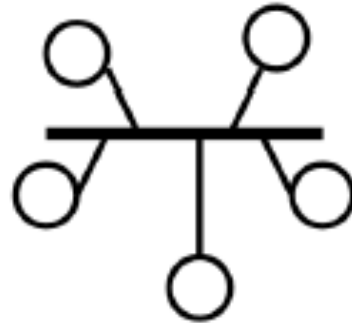
- Processes communicate by message passing through communication channels.
- We consider point-to-point channels.
- Messages are uniquely identified and the message identifier includes the sender's identifier.

Links

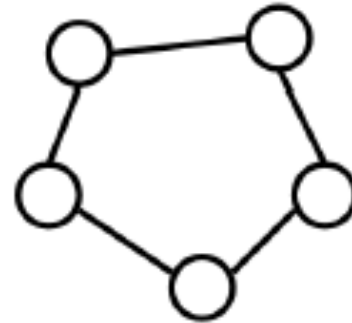
- Logically every process may communicate with every other process: (a)
- Physical implementation may differ: (b)-(d)



(a)



(b)



(c)



(d)

Channels

How reliable are the communication channels?

- Fair-loss links:
 - Messages may be lost, but is delivered with some small probability.
- Stubborn links:
 - Eventually messages delivered (infinitely often).
- Perfect links:
 - Eventually each message is delivered once.

Channel Specification

A channel module is defined by events and properties:

- Events
 - Request: send (dest, m)
 - Indication: deliver (src, m)
- Properties:
 - Reliability
 - No Duplication
 - Integrity
 - ...

Fair-loss links

- FL1. Fair-loss:
 - If a message is sent infinitely often by p_i to p_j , and neither p_i or p_j crash, then m is delivered infinitely often to p_j .
- FL2. Finite duplication:
 - If a message is sent a finite number of times by p_i to p_j , it is not delivered an infinite number of times to p_j .
- FL3. No creation:
 - No message is delivered unless it was sent.

Stubborn links

- SL1. Stubborn delivery.
 - If a correct process p_i sends a message m to a correct process p_j , then p_j delivers m , an infinite number of times.
- SL2. No creation:
 - No message is delivered unless it was sent.

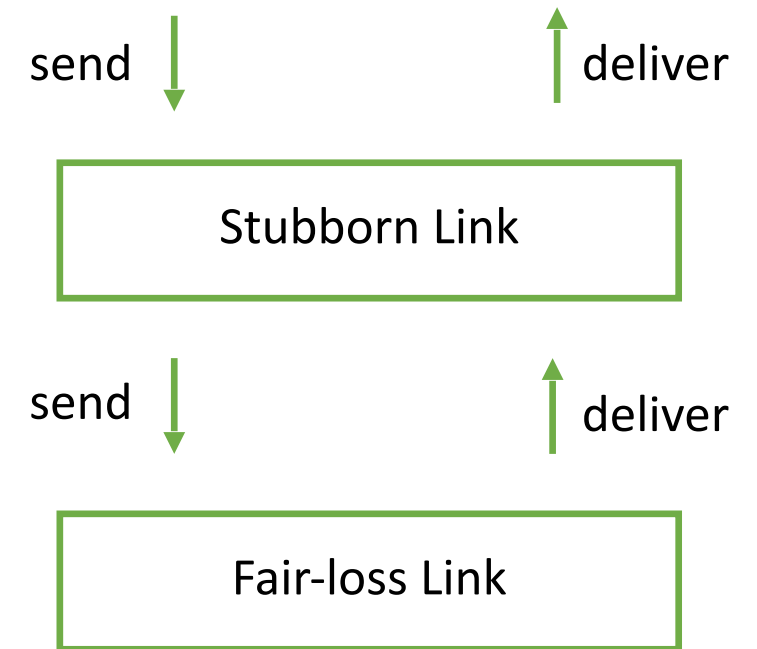
Algorithm (sl)

Implements: StubbornLinks (sl)

Uses: FairLossLinks (fl)

upon event <sl, send (dest, m)> **do**
 repeat forever
 trigger <fl, send (dest, m)>

upon event <fl, deliver (src, m)> **do**
 trigger <sl, deliver (src, m)>



Reliable (Perfect) links

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

Algorithm (pl)

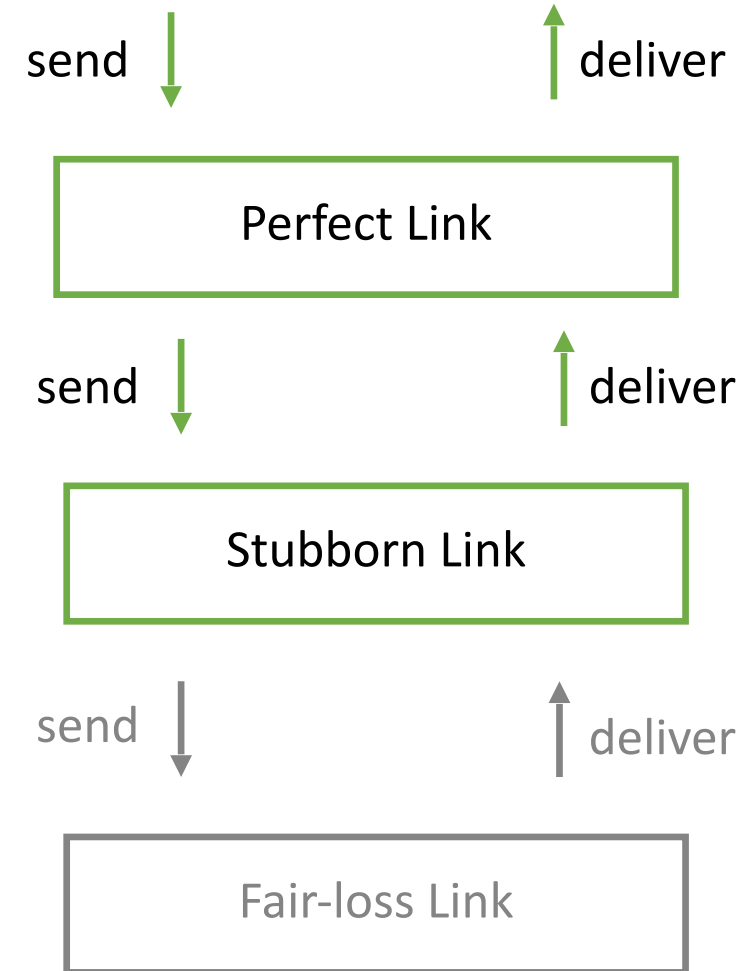
Implements: PerfectLinks (pl)

Uses: StubbornLinks (sl)

upon event < Init > **do** delivered := \emptyset

upon event < pl, send (dest, m) > **do**
 trigger < sl, send (dest, m) >

upon event < sl, deliver (src, m) > **do**
 if m \notin delivered **then**
 trigger < pl, deliver (src, m) >
 delivered := delivered \cup {m}



Reliable links

- We implicitly assume perfect links.
- Roughly speaking, reliable links ensure that messages exchanged between correct processes are not lost.

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 - Time & failure detectors
- Time & failure detectors

Time

- Local clocks:
 - Do processes have access to local clocks?
 - If so, are these clocks synchronized? Are these clocks accurate?
 - clock skew Difference between time
 - clock drift Difference between clock rate
- Communication channels:
 - How long does a message take to be delivered?

Models of Synchrony

Synchrony: perfectly synchronized rounds



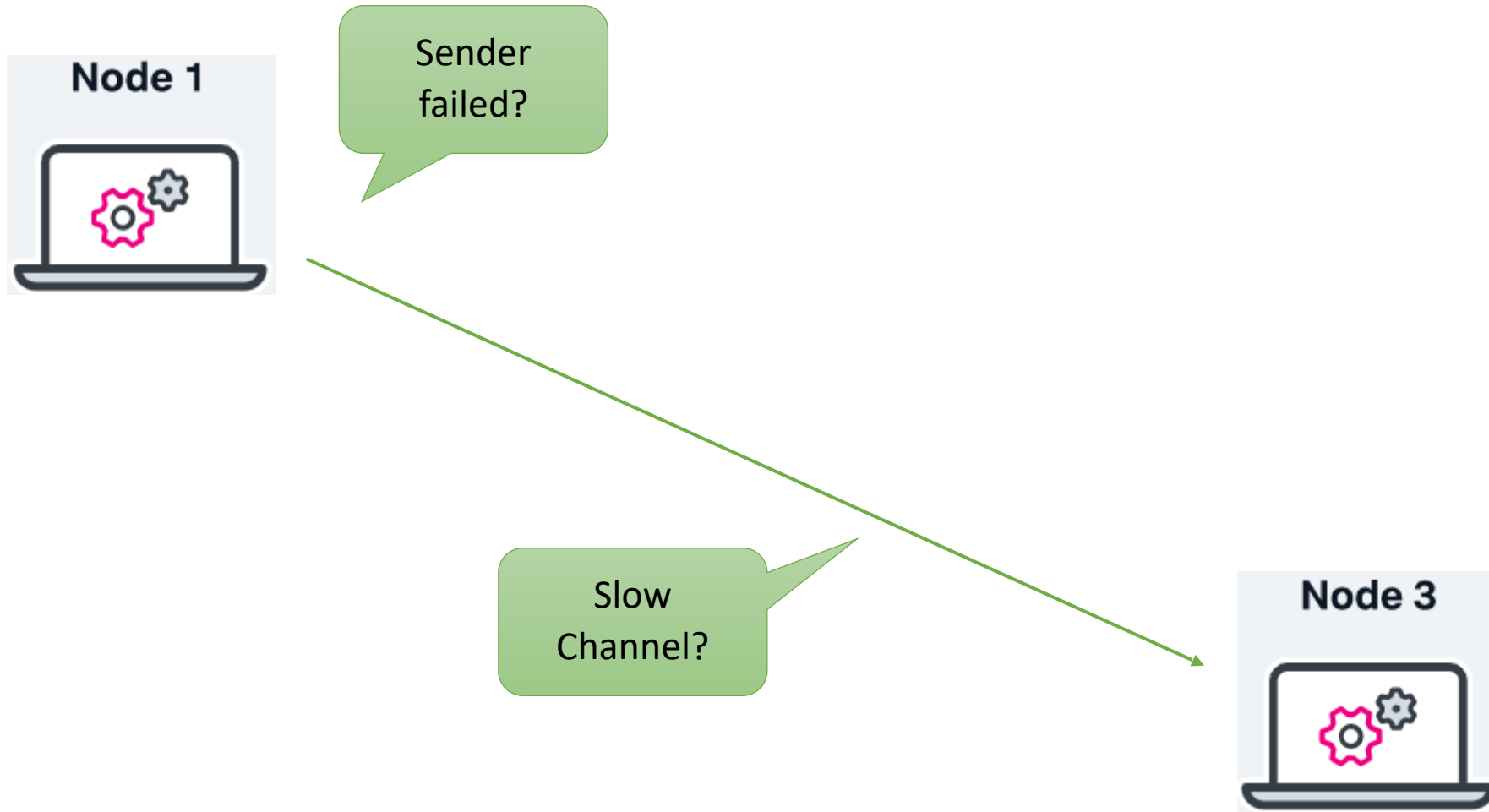
Partial Synchrony

Asynchrony: anything goes

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:**
 - Synchronous timing holds eventually.
- **Asynchronous:**
 - No assumptions, no clocks.

Time and Failure Detection



Failure Detector

- A failure detector is a distributed component that provides processes with suspicions about crashed processes.
- It is implemented using (i.e., it encapsulates) timing assumptions.
- According to the timing assumptions, the suspicions can be accurate or inaccurate.

Failure Detector

Failure detector component

- Events
 - Indication: $\langle \text{crash}(p) \rangle$
 - Indication: $\langle \text{restore}(p) \rangle$
- Properties:
 - Completeness
 - Accuracy

Failure Detector

- 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.

Failure Detector

Implementation:

- Processes periodically exchange heartbeat messages.
- A process sets a timeout based on worst case roundtrip of a message exchange.
- A process suspects another process if its times out is triggered.
- A process that receives a message from a suspected process revises its suspicion and increases its timeout.

Failure Detectors

Network model:

- Synchronous ->
- Eventual Synchronous ->
- Asynchronous ->

Guarantees:

Failure Detectors

Network model:

- Synchronous ->
- Eventual Synchronous ->
- Asynchronous ->

Guarantees:

Perfect FD

Failure Detectors

Network model:

- Synchronous ->
- Eventual Synchronous ->
- Asynchronous ->

Guarantees:

- Perfect FD
- Eventually Perfect FD

Failure Detectors

Network model:

- Synchronous ->
- Eventual Synchronous ->
- Asynchronous ->

Guarantees:

Perfect FD

Eventually Perfect FD

None!!

Protocol Design

Assumptions:

- Processes: crash-stop failures
- Channels: reliable channels
- Timing: perfect OR eventually perfect failure detectors

For every service:

- We develop algorithms for a crash-stop system with a perfect failure detector.
- We try to make a weaker assumptions and revisit the algorithms.

Cryptographic primitives

Dual goals of cryptography

- Confidentiality (encryption, not relevant here)
- Integrity
 - Hash functions
 - Message authentication codes (MAC)
 - Digital signatures

Hash functions

- Cryptographic hash function H maps inputs of arbitrary length to a short unique hash value.
- Collision-freedom: No process can find distinct values x and x' such that $H(x) = H(x')$

Message-Authentication Codes

- A MAC authenticates data between two processes
- It is based on a shared symmetric key, which is known only to the sender and to the receiver of a message, but to nobody else.
- For a message of its choice, the sender can compute an authenticator for the receiver. Given an authenticator and a message, the receiver can verify that the message has indeed been authenticated by the sender.
- Symmetric cryptographic can be computed and verified quickly.

Digital signatures

- Digital signatures are based on public-key cryptography (or asymmetric cryptography).
- The sender owns a private key that must remain secret; the public key is accessible to anyone. With the private key, the sender can produce a signature for a message.
- Everyone with access to the public key can verify that the signature on the message is valid.
- A signature scheme is more powerful than a MAC in the sense that if a relayed message is verified, only the owner of the private key can be the sender.
- Because of their underlying mathematical structure, asymmetric cryptography adds considerable computational overhead compared to symmetric cryptography.