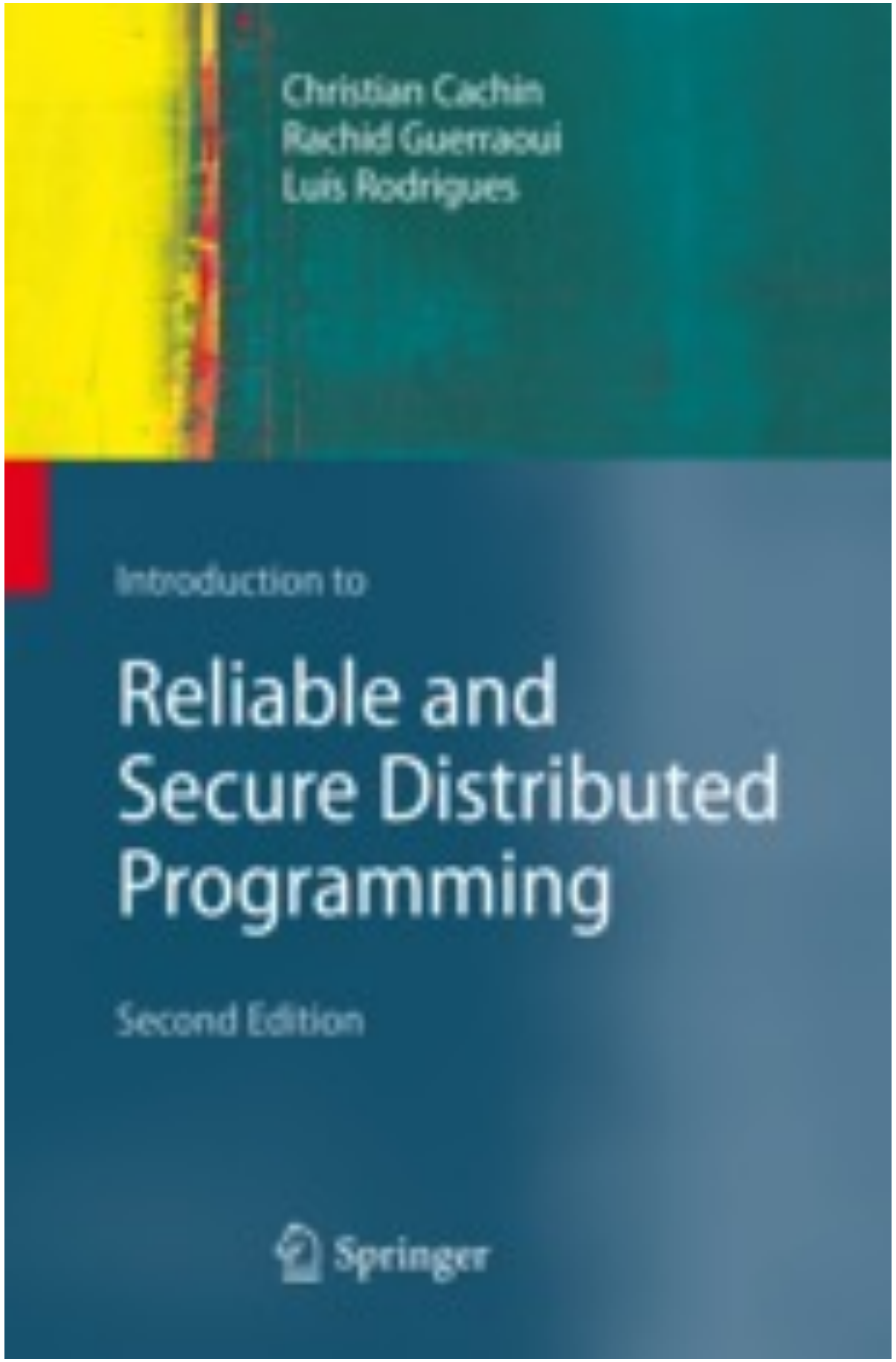
Distributed Algorithms

Prof R. Guerraoui

Exam 70% + Project 30%

Reference: Book - Springer Verlag

- ***Introduction to Reliable (and Secure) Distributed Programming –***


Christian Cachin
Rachid Guerraoui
Luís Rodrigues
Introduction to
Reliable and
Secure Distributed
Programming
Second Edition
Springer

The history of algorithms

- M. Al-Khawarizmi ~9th century: inventor of the zero, the decimal system, Arithmetic and Algebra
- A. Turing: one machine to rule them all

What is an algorithm?

- An ordered set of elementary instructions
- All execute on the same Turing machine
- Complexity measures the number of instructions (variables)

Really?

In short

- We study algorithms for ***distributed*** systems
- A new ***way*** of thinking about algorithms and their complexity

Distributed algorithms

- E. Dijkstra (concurrent os)~60's
- L. Lamport: "a distributed system is one that stops your application because a machine you have never heard from crashed" ~70's
- J. Gray (transactions) ~70's
- N. Lynch (consensus) ~80's

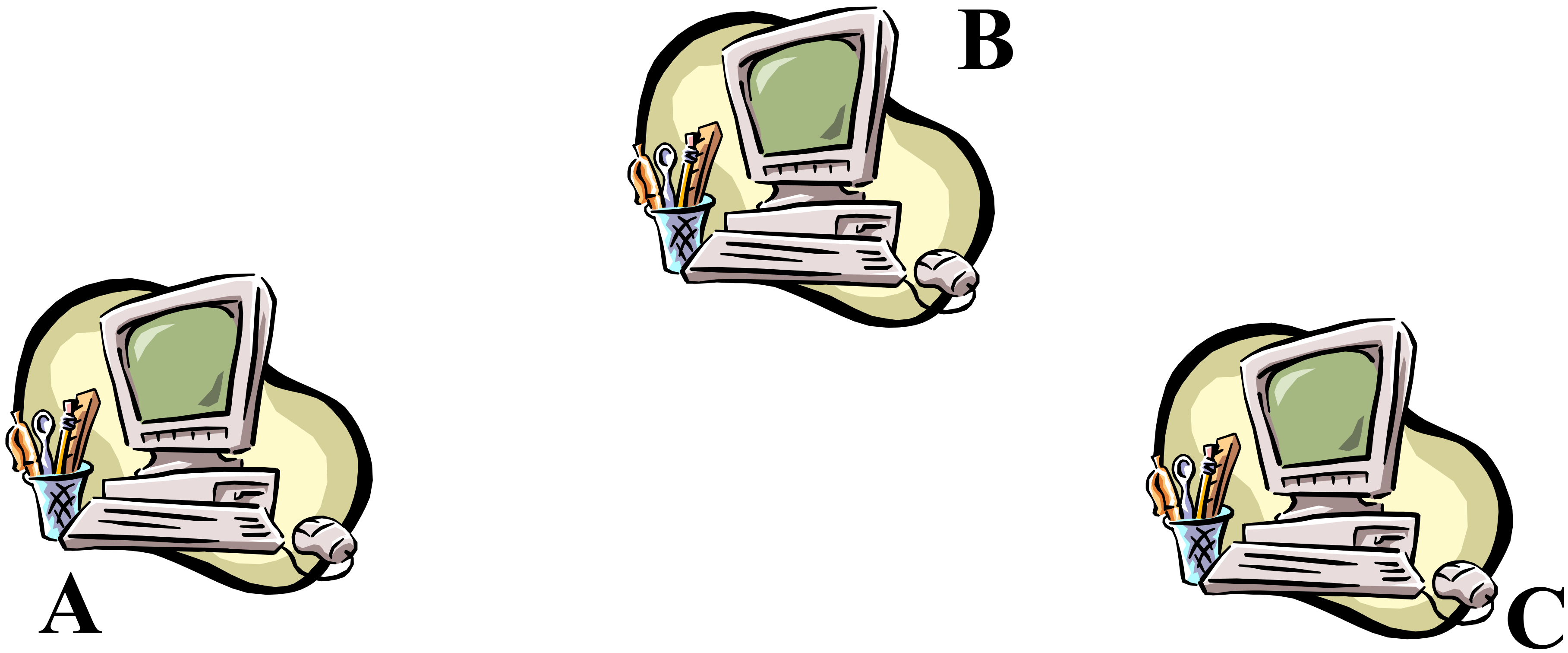
Warning

- This course is complementary to the course **concurrent algorithms**
- We study here ***message passing*** based algorithms whereas «the other» course focuses on ***shared memory*** based algorithms

Overview

- **(1)** ***Why?*** Motivation
- (2) ***Where?*** Between the network and the application
- (3) ***How?*** (3.1) Specifications, (3.2) assumptions, and (3.3) algorithms

A distributed system



Clients-server

Client A

Client B

Server

Multiple servers (genuine distribution – P2P - decentralization)

The optimistic view

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

The pessimistic view

- Concurrency (interleaving) => incorrectness
- Partial failures => incorrectness

Distributed algorithms (Today: Google)

- Hundreds of thousands of machines connected
- A Google job involves 2000 machines
- 10 machines go down per day

Satoshi Nakamoto (2008) Nick Szabo

2009: 0.005 $

2016: 600 $

2020: 10000 $

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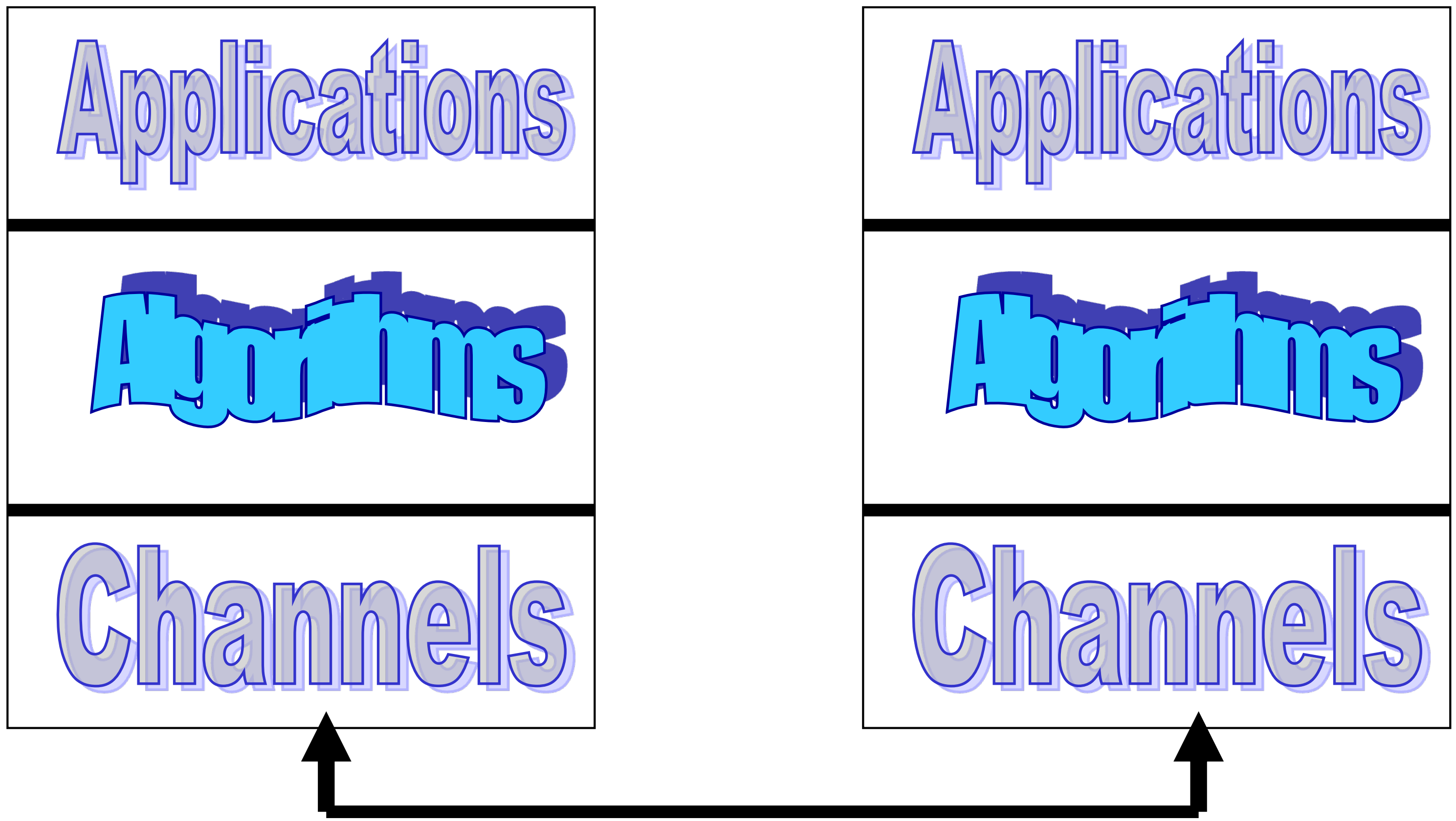
Distributed systems



Distributed systems

- The application needs underlying services for distributed interaction
- The network is not enough
  - Reliability guarantees (e.g., TCP) are only offered for communication among pairs of processes, i.e., *one-to-one* communication (*client-server*)

Content of this course

Reliable broadcast
Causal order broadcast
Shared memory
Consensus
Total order broadcast
Atomic commit
Terminating reliable broadcast
……

Reliable distributed services

- Example 1: ***reliable broadcast***
  - Ensure that a message sent to a group of processes is received (delivered) by all or none
- Example 2: ***atomic commit***
  - Ensure that the processes reach a common decision on whether to commit or abort a transaction

Underlying services

- (1): ***processes*** (abstracting computers)
- (2): ***channels*** (abstracting networks)
- (3): ***failure detectors*** (abstracting time)

Processes

- The distributed system is made of a finite set of ***processes***: each process models a ***sequential*** program
- Processes are denoted p1,..pN 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***

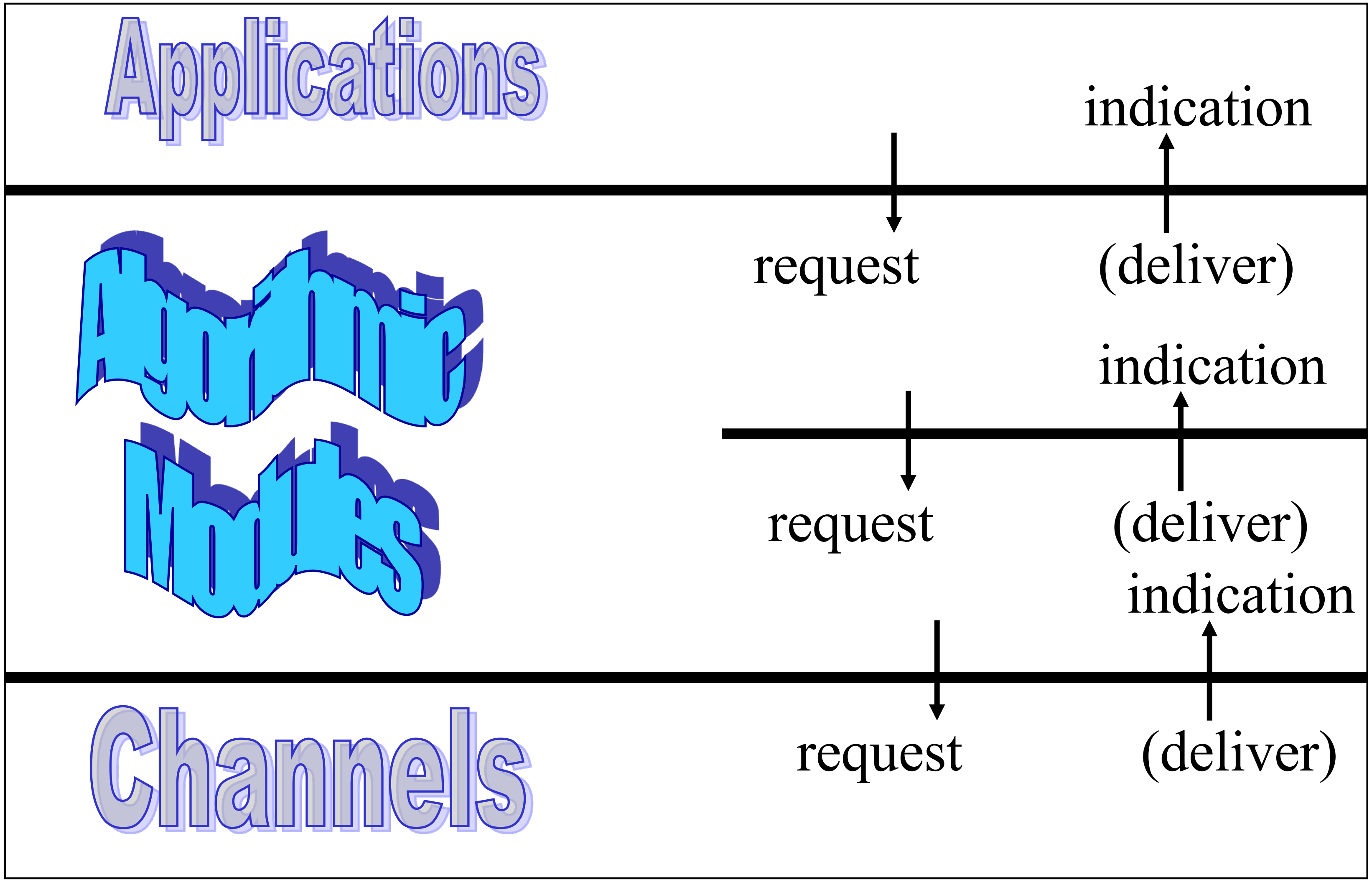
Processes

- A process executes a step at every tick of its local clock: a step consists of
  - A local computation (local event) and message exchanges with other processes (global event)

Processes

- The program of a process is made of a finite set of modules (or components) organized as a software stack
- Modules within the same process interact by exchanging events
- **upon event** < Event1, att1, att2,..> do
  - // something
  - **trigger** < Event2, att1, att2,..>

Modules of a process



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Approach

- ***Specifications***: What is the service? i.e., the problem ~ liveness + safety
- ***Assumptions***: What is the model, i.e., the power of the adversary?
- ***Algorithms***: How do we implement the service? Where are the bugs (proof)? What cost (complexity)?

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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
  - Any specification can be expressed in terms of liveness and safety properties (Lamport and Schneider)

Liveness and safety

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

Specifications

- Example 1: ***reliable broadcast***
  - Ensure that a message sent to a group of processes is received by all or none
- Example 2: ***atomic commit***
  - Ensure that the processes reach a common decision on whether to commit or abort a transaction

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Overview

- (1) ***Why?*** Motivation
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  - **3.2.1** Assumptions on processes and channels
  - 3.2.2 Failure detection

Processes

- A process either executes the algorithm assigned to it (steps) or fails
- 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)

Processes

- ***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

Processes

- By default, we shall assume a ***crash-stop*** model throughout this course; that is, unless specified otherwise: processes fail only by crashing (no recovery)

- A ***correct*** process is a process that does not fail (that does not crash)

Processes and channels

Processes communicate by message passing through ***communication channels***

Messages are ***uniquely identified*** and the message identifier includes the sender’s identifier

Fair-loss links

- ***FL1. Fair-loss***: If a message is sent infinitely often by pi to pj , and neither pi or pj crashes, then m is delivered infinitely often by pj
- ***FL2. Finite duplication:*** If a message m is sent a finite number of times by pi to pj, m is delivered a finite number of times by pj
- ***FL3. No creation:*** No message is delivered unless it was sent

Stubborn links

- ***SL1. Stubborn delivery***: if a process pi sends a message m to a correct process pj, and pi does not crash, then pj delivers m an infinite number of times
- ***SL2. No creation:*** No message is delivered unless it was sent

Algorithm (sl)

- **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>;

Reliable (Perfect) links

- ***Properties***
  - ***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

Algorithm (pl)

- **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>;
    - add m **to** delivered;

Reliable links

- We shall assume ***reliable links*** (also called perfect) throughout this course (unless specified otherwise)

- Roughly speaking, reliable links ensure that messages exchanged between correct processes are ***not lost***

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  - 3.2.1 Processes and links
  - **3.2.2** Failure Detection

Failure detection

- A ***failure detector*** is a distributed oracle 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 not

Failure detection

- A failure detector module is defined by events and properties
- ***Events***
  - Indication: <crash, p>
- ***Properties:***
  - Completeness
  - Accuracy

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

Failure detection

Algorithm:

- (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 timeouts that process
- (4) A process that delivers a message from a suspected process revises its suspicion and doubles its time-out

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 assumption

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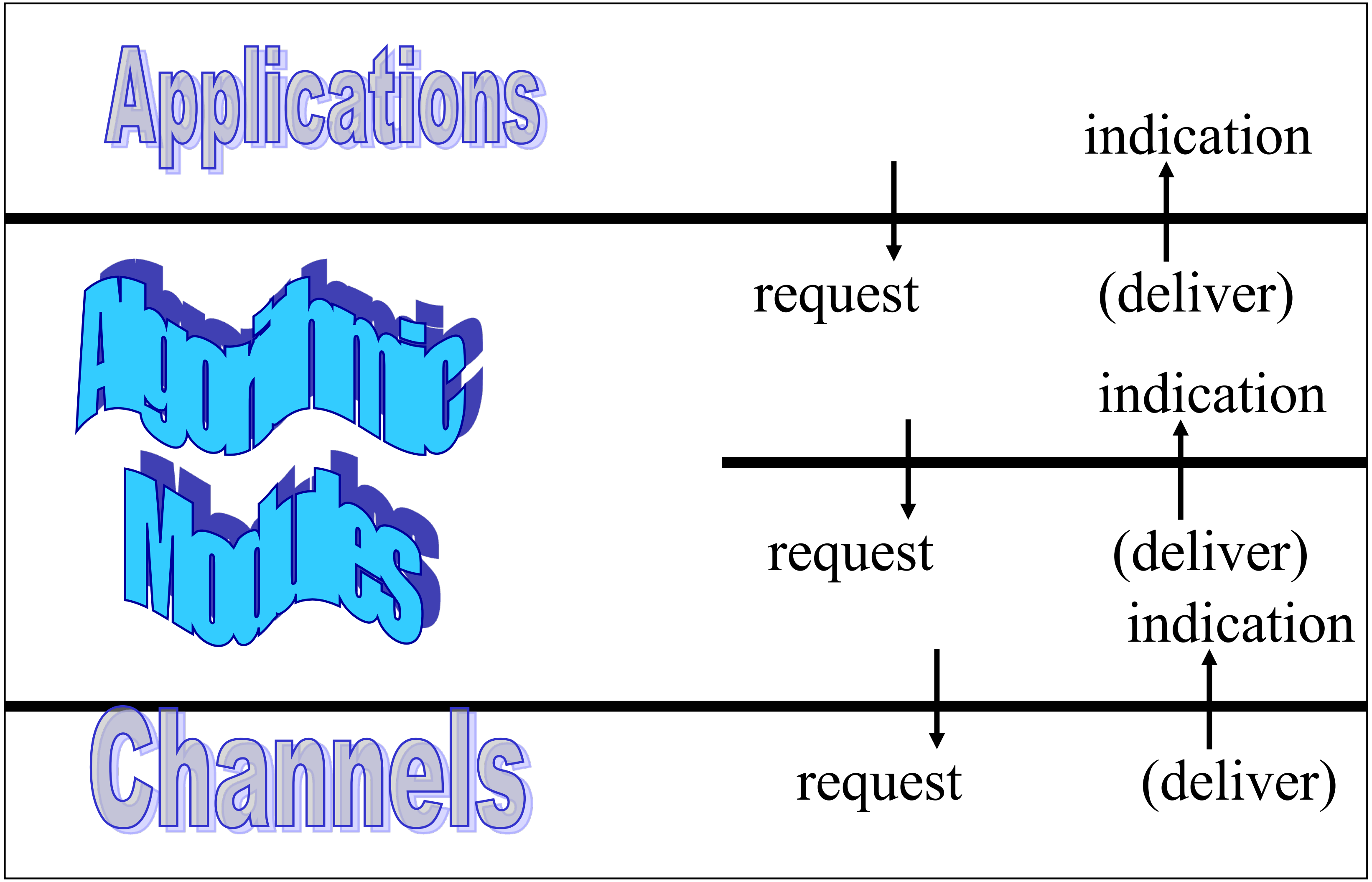
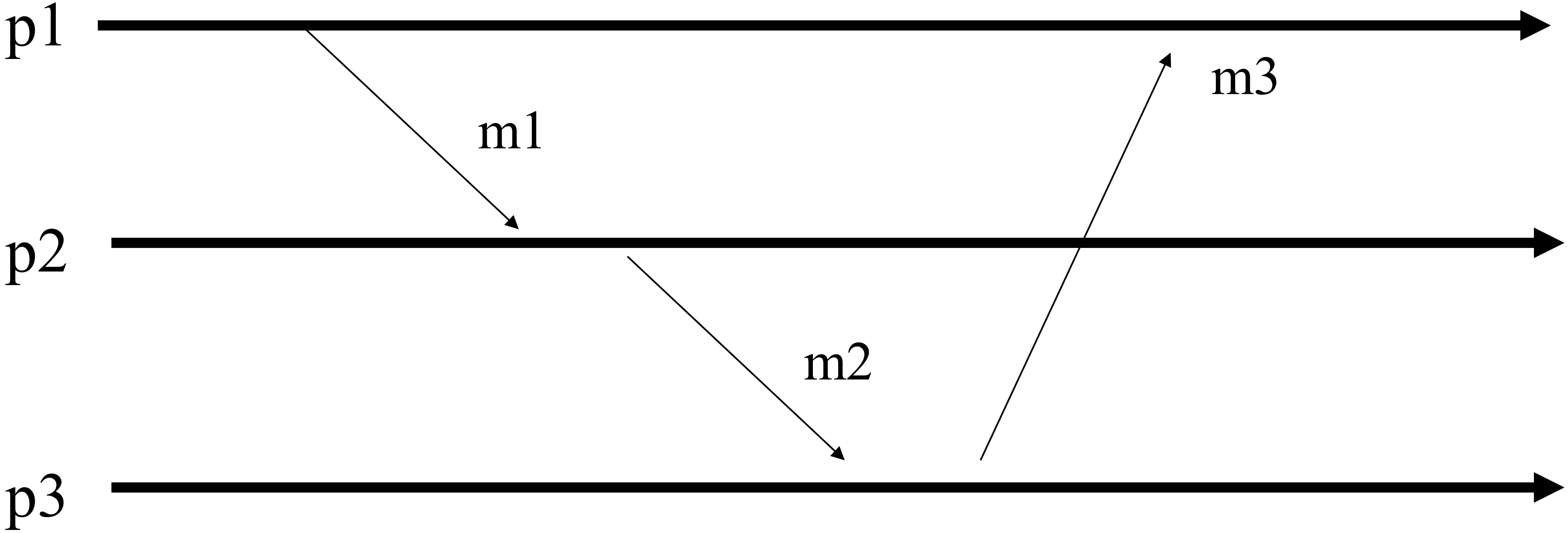
Algorithmic modules of a process



Algorithms (representation)



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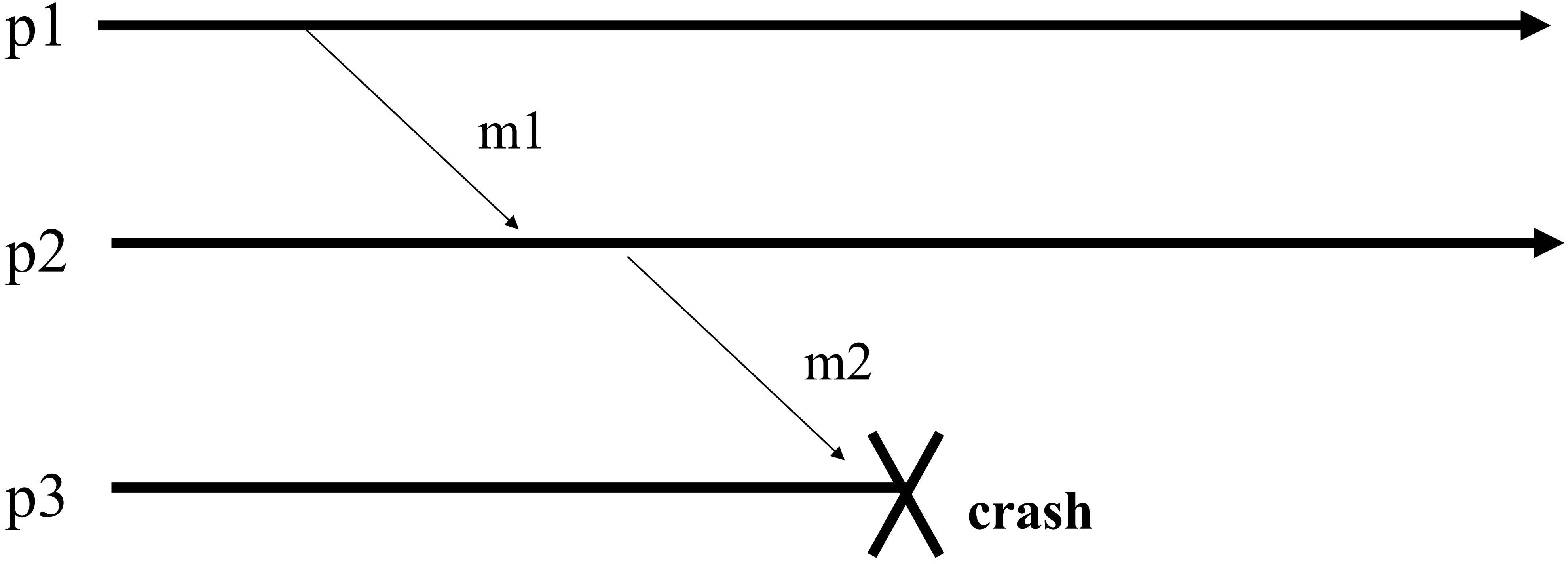

For every abstraction

- (A) We assume a crash-stop system with a perfect failure detector (fail-stop)
  - We design algorithms
- (B) We try to make a weaker assumption
  - We revisit the algorithms

Content of the course

Reliable broadcast
Causal order broadcast
Shared memory
Consensus
Total order broadcast
Atomic commit
Leader election
Terminating reliable broadcast
View synchronous broadcast