Distributed algorithms

Prof R. Guerraoui
lpdwww.epfl.ch

Exam: Written
Reference: Book - Springer Verlag –
http://lpd.epfl.ch/site/education/da
- Introduction to Reliable (and Secure) Distributed Programming -

Algorithms (History)

- **M. Al-Khawarizmi ~9th century: inventor of the zero, the decimal system, Arithmetic and Algebra**

- **A. Turing: all machines are equal**

What is an algorithm?

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

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**
- **Birman, Schneider, Toueg – Cornell – (this course) ~90's**

In short

- **We study algorithms for *distributed* systems**
- **A new way of thinking about algorithms and their complexity**
- **Whereas a centralized algorithm is the soul of a computer, a distributed algorithm is the soul of a *society* of computers**

Important

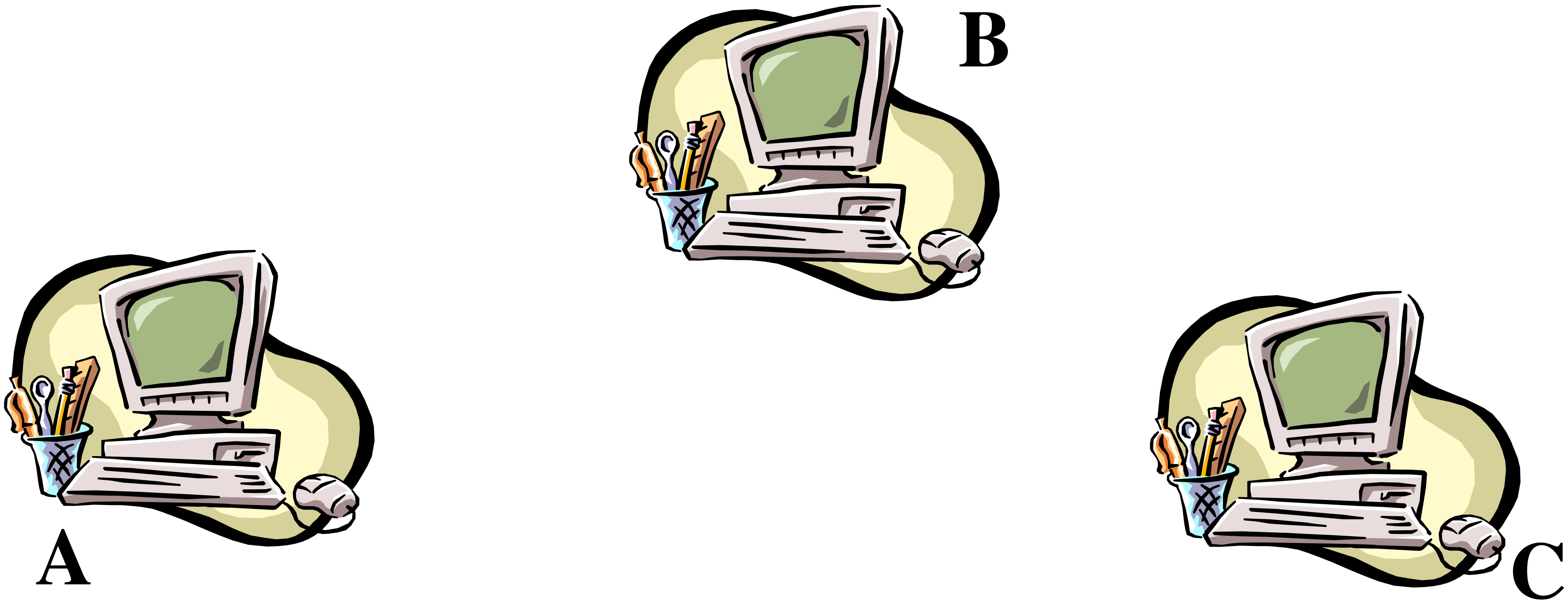
- **This course is complementary to the course (concurrent algorithms)**

- **We study here *message passing* based algorithms whereas the other course focuses on *shared memory* based algorithms**

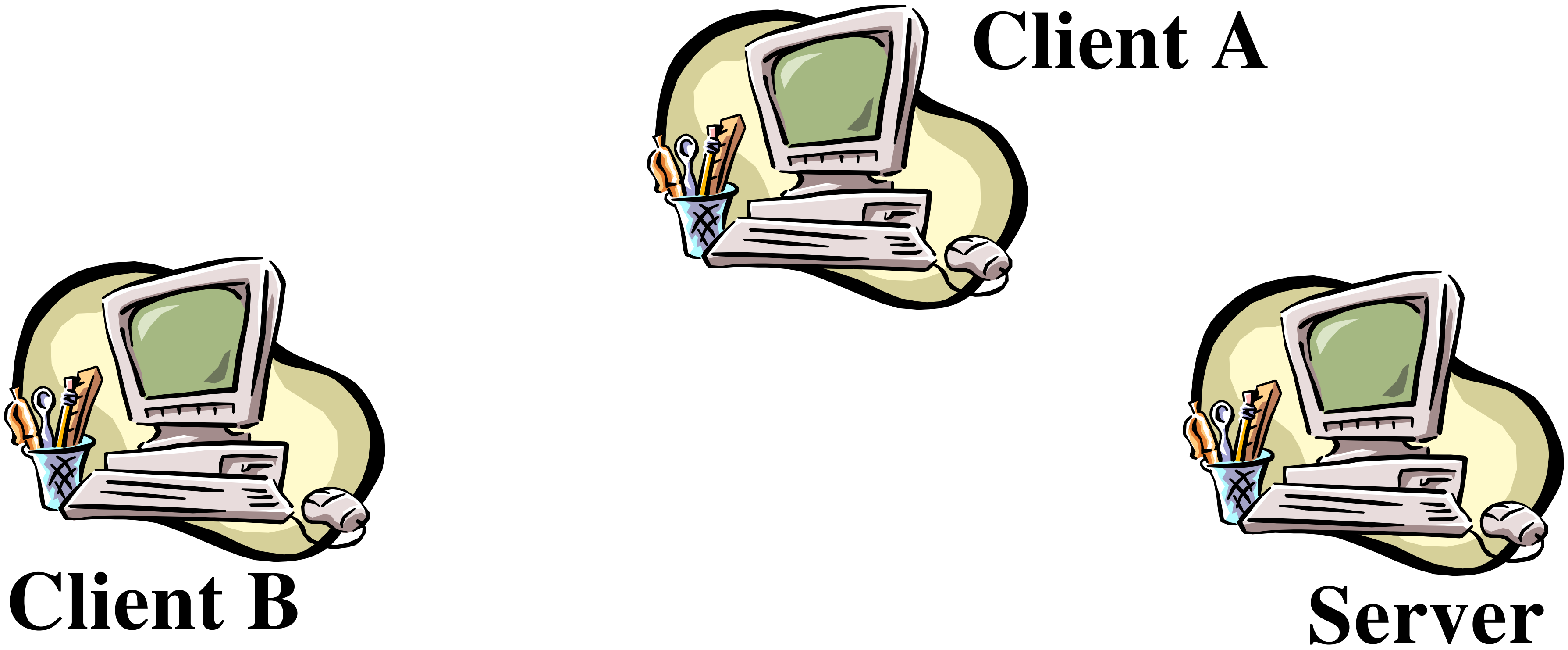
Overview

- (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



Multiple servers (genuine distribution)

Server B

Server A

Server C

Applications

- **Traffic control**
- **Finances: e-transactions, e-banking, stock-exchange**
- **Reservation systems**
- **Pretty much everything on the cloud**

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**

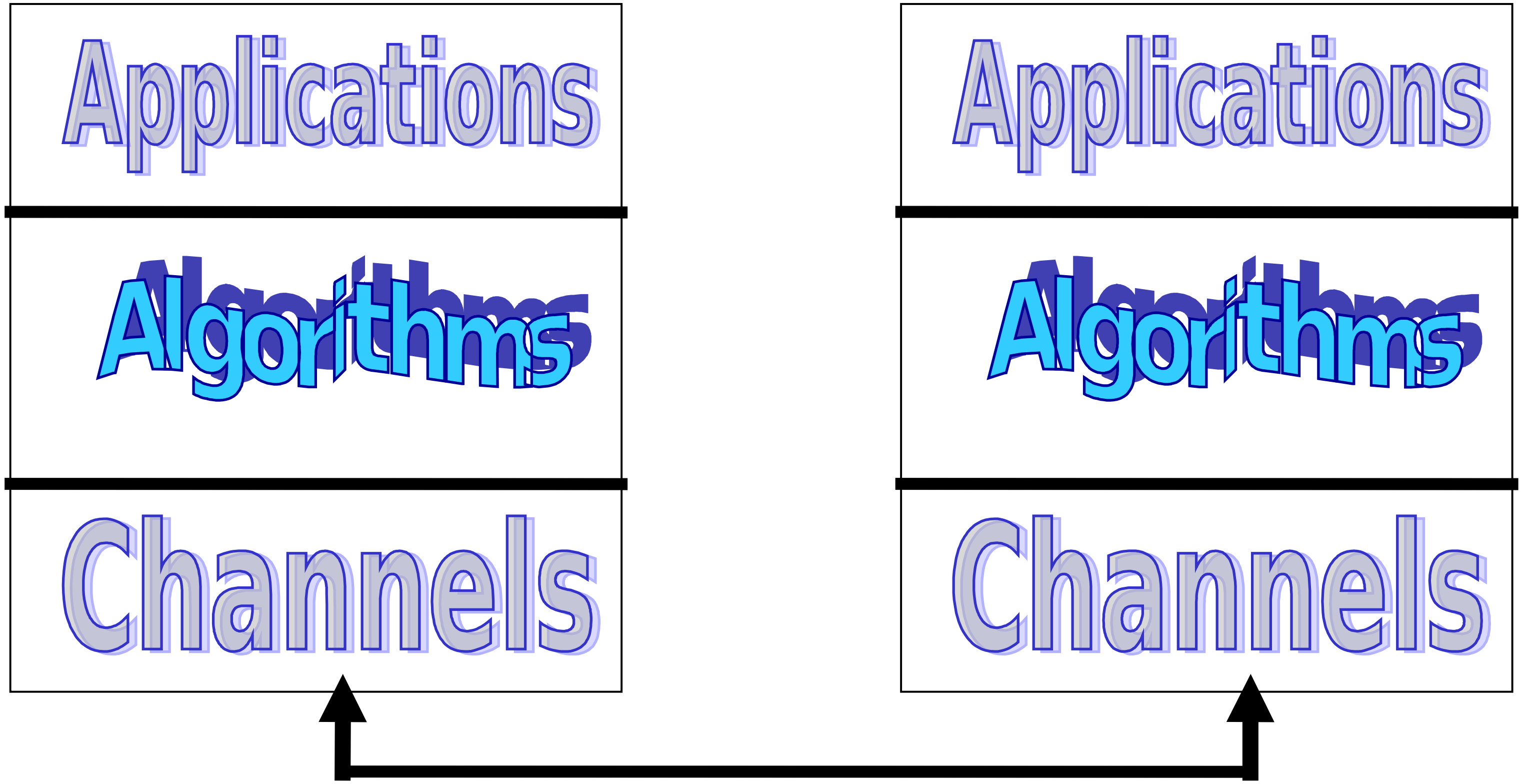
Overview

- **(1) *Why?* Motivation**

- **(2) *Where?* Between the network and the application**

- **(3) *How?* (3.1) Specifications, (3.2) assumptions, and (3.3) algorithms**

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
Leader election
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 by 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

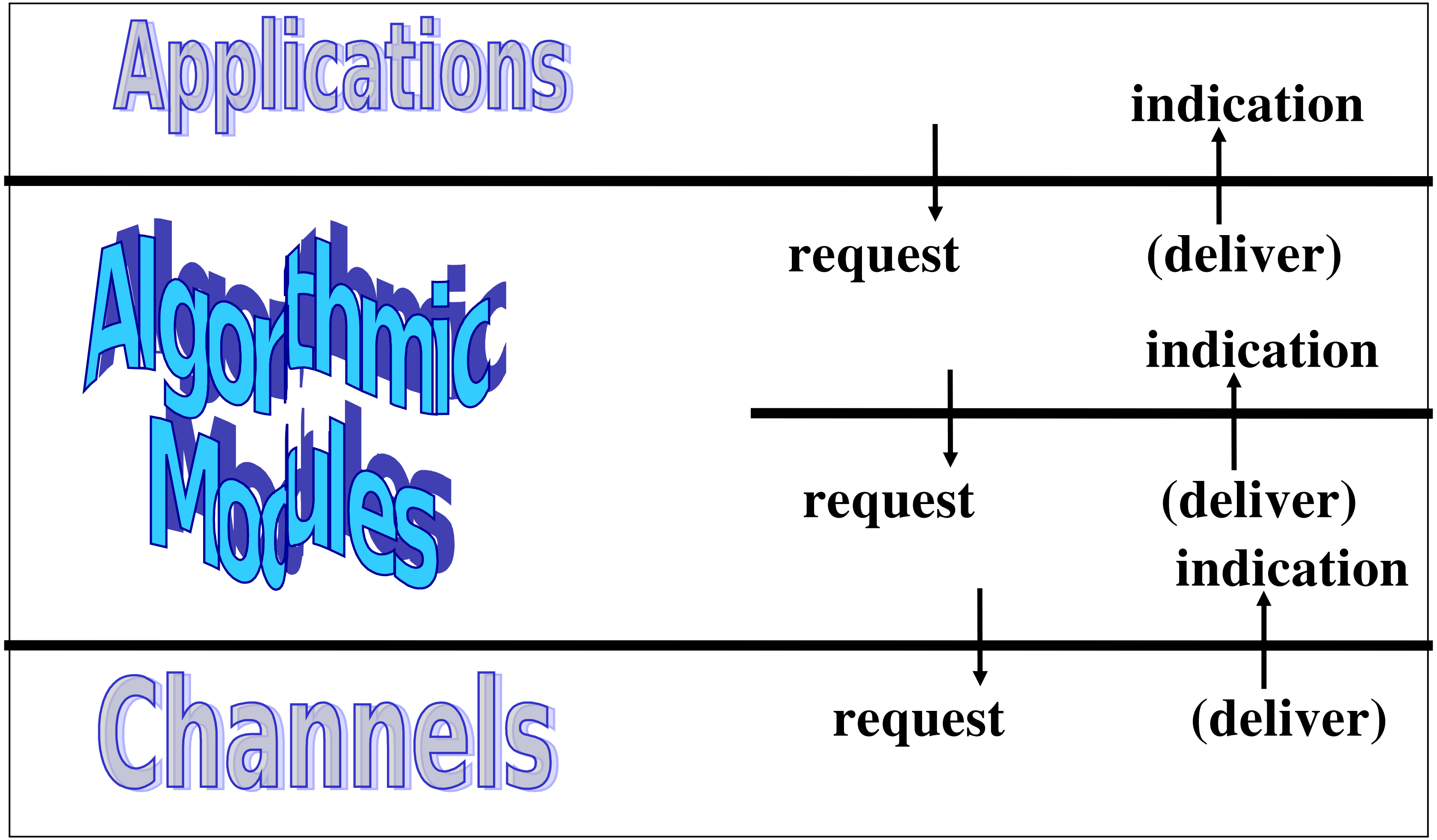
Processes

- **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)**
- **NB. 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 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



Overview

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

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?**

Overview

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

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**

Overview

- **(1) *Why?* Motivation**

- **(2) *Where?* Between the network and the application**

- **(3) *How?* (3.1) Specifications, (3.2) assumptions, and (3.3) 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**
  - **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)**

  Many models are in between

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/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 ∉ 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

Reliable FIFO links

- **Ensures properties PL1 to PL3 of perfect links**
- ***FIFO.*** **The messages are delivered in the same order they were sent.**

Algorithm (fl1)

- ✓ **Implements: Reliable FIFO links (fp2p).**
- ✓ **Uses: Reliable links (pp2p).**
- ✓ **Relies on acknowledgements messages.**
- ✓ **Acknowledgements are control messages.**

Algorithm (fl1)

- upon event <init> do
  - nb_acks[*] := 0
  - nb_sent[*] := 0

- upon event <fp2pSend, dest, m> do
  - wait nb_acks[dest] = nb_sent[dest]
  - nb_sent[dest] := nb_sent[dest]+1
  - trigger <p2pSend, dest, m>

Algorithm (fl1)

- upon event <pp2pDeliver, src, m> do
  - trigger <pp2pSend, src, ack>
  - trigger <fp2pDeliver, src, m>

- upon event <pp2pDeliver, src, ack> do
  - nb_ack[src] := nb_ack[src]+1

Algorithm (fl2)

- Implements: Reliable FIFO links (fp2p).
- Uses: Reliable links (pp2p).
- Relies on sequence numbers attached to each message.

- upon event <init> do
  - seq_nb[*] := 0
  - next[*] := 0

Algorithm (fl2)

- upon event <fp2pSend, dest, m> do
  - fifo_m := (seq_nb[dest], m)
  - trigger <pp2pSend, dest, fifo_m)>
  - seq_nb[dest] := seq_nb[dest]+1

- upon event <pp2pDeliver, src, (sn,m)> do
  - wait next[src] = sn
  - trigger <fp2pDeliver, src, m>
  - next[src] := next[src]+1

(fl1) vs. (fl2)

- (fl1) uses 2 messages per applicative message.
- (fl1) artificially limits bandwidth if latency is high.

- (fl2) increases the size of messages.
- Sequence numbers in (fl2) have an unbounded size.

Algorithm (fl3)

- Implements: Reliable FIFO links (fp2p).
- Uses: Reliable links (pp2p).
- Combines acknowledgements and sequence numbers mechanisms.
- An acknowledgement is sent every ack_int messages received.
- The sequence numbers are reset when they reach ack_int x win_size.
- The sender has to block at the right moment.

Algorithm (fl3)

- upon event <init> do
  - seq_nb[*] := 0
  - next[*] := 0
  - ack_nb[*] := 0

Algorithm (fl3)

- **upon event <fp2pSend, dest, m> do**
  - **wait ack_nb[dest] x ack_int >**

    seq_nb[dest] – win_size x ack_int
  - **fifo_m := (seq_nb[dest] mod (win_size x ack_int), m)**
  - **trigger <pp2pSend, dest, fifo_m)>**
  - **seq_nb[dest] := seq_nb[dest]+1**

Algorithm (fl3)

- upon event <pp2pDeliver, src, (sn,m)> do
  - wait next[src] = sn
  - if (sn+1) mod ack_int = 0
    - trigger <pp2pSend, src, ack>
  - next[src] := (next[src]+1) mod (win_size x ack_int)
  - trigger <fp2pDeliver, src, m>

- upon event <pp2pDeliver, src, ack> do
  - ack_nb[src] := ack_nb[src]+1

Overview

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

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 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**

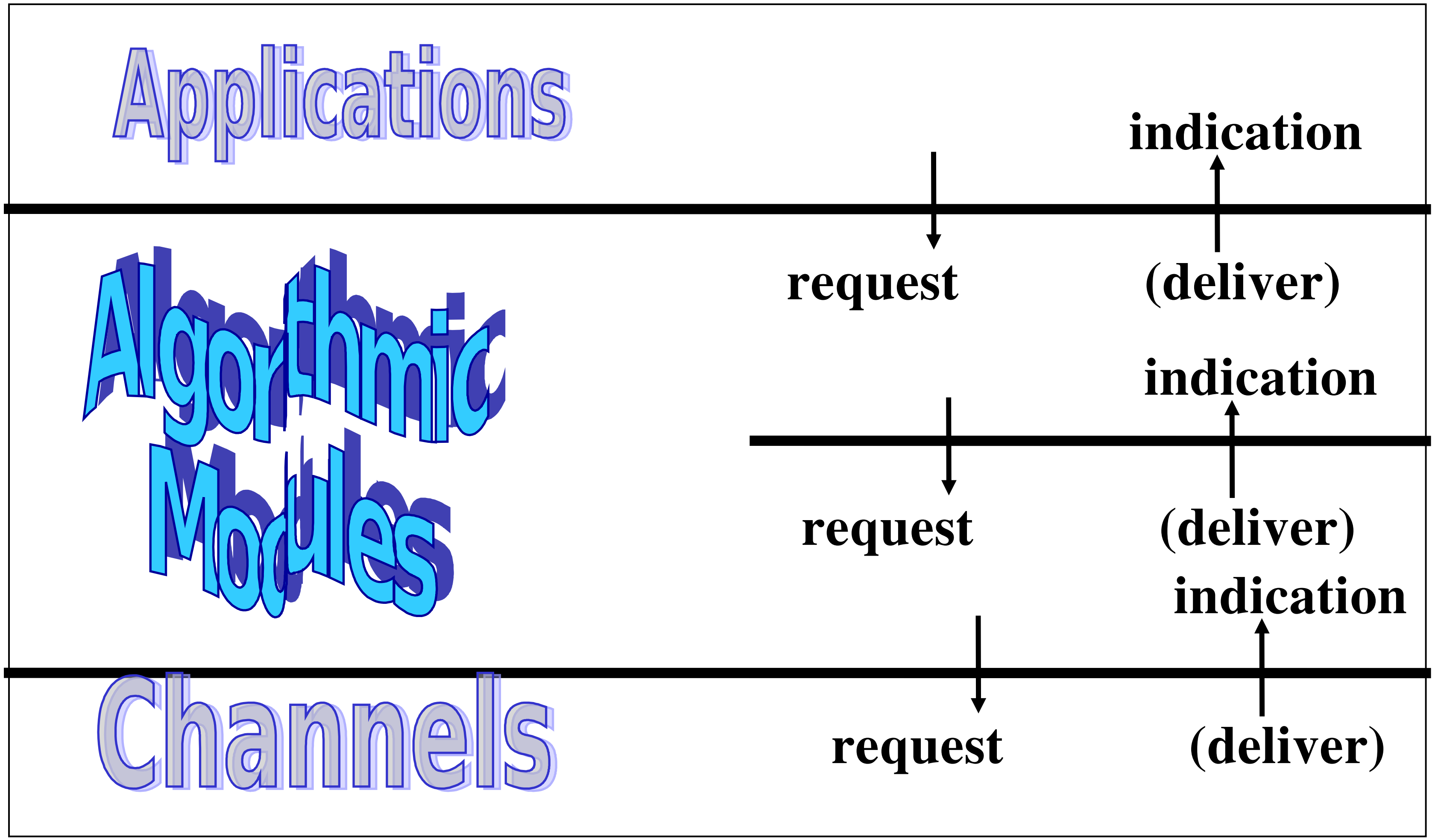
Eventually Synchronous: **the timing assumptions hold eventually**

Asynchronous: **no assumption**

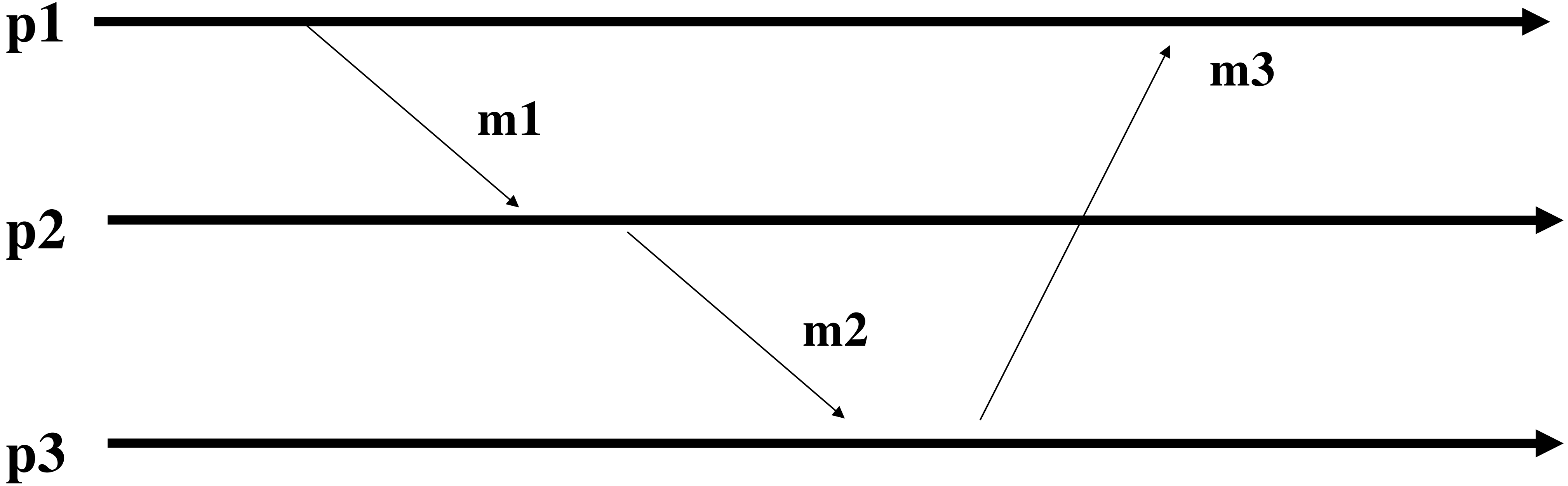
Overview

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

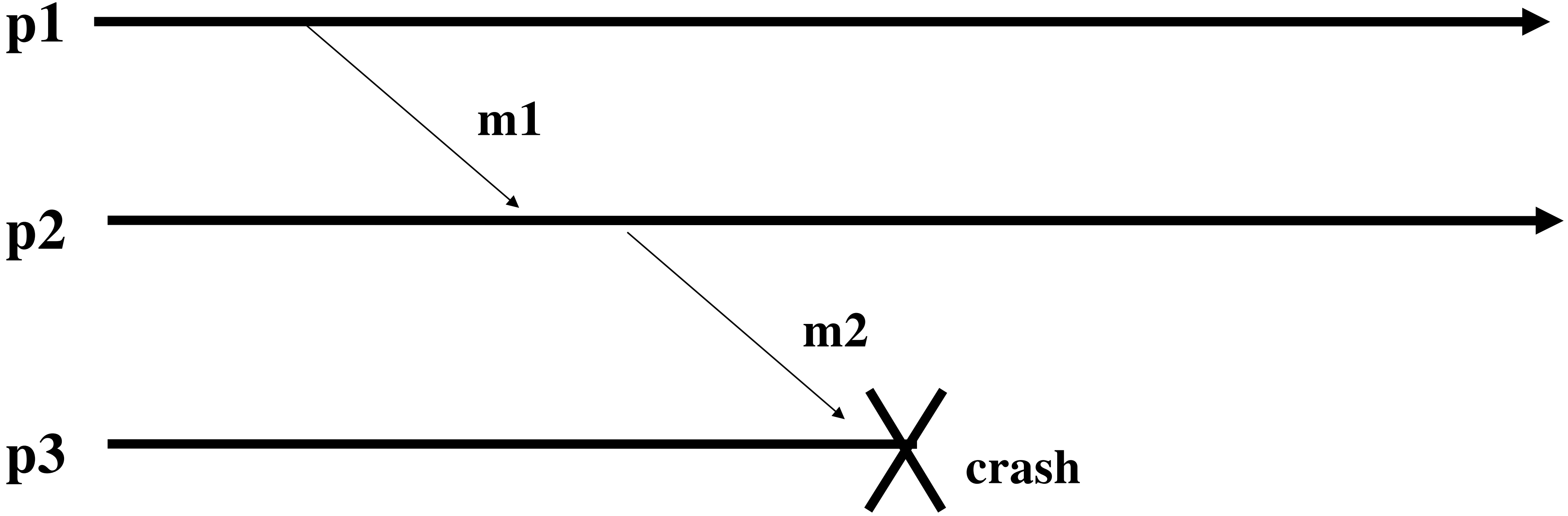
Algorithms
modules of a process



Algorithms



Algorithms



For every abstraction

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

Content of this course

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