Algorithms and Distributed Systems
2023/2024
(Lecture One)

MIEI - Integrated Master in Computer Science and Informatics
MEI – Master in Computer Science and Informatics
Specialization block

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Based on slides from João Leitão

Lecture structure:

- Understand what is a distributed system.
- Modeling a distributed system.
    - General system model.
    - Fault model.
    - Timing assumption.
- Understanding the role of an algorithm.
    - Point-to-Point Communication Algorithms.
- The Broadcast Problem
    - Best effort broadcast.
    - Reliable broadcast.

What is a distributed system?

"A distributed system is a network that consists of autonomous computers that are connected using a distribution middleware. They help in sharing different resources and capabilities to provide users with a single and integrated coherent network." – Technopedia.

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“A distributed system is one in which the failure of a computer you didn’t even know existed can render your own computer unusable.”

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Note: our goal, as designers of distributed systems and distributed algorithms is to work to ensure that there are definitions that don't depend on failure!

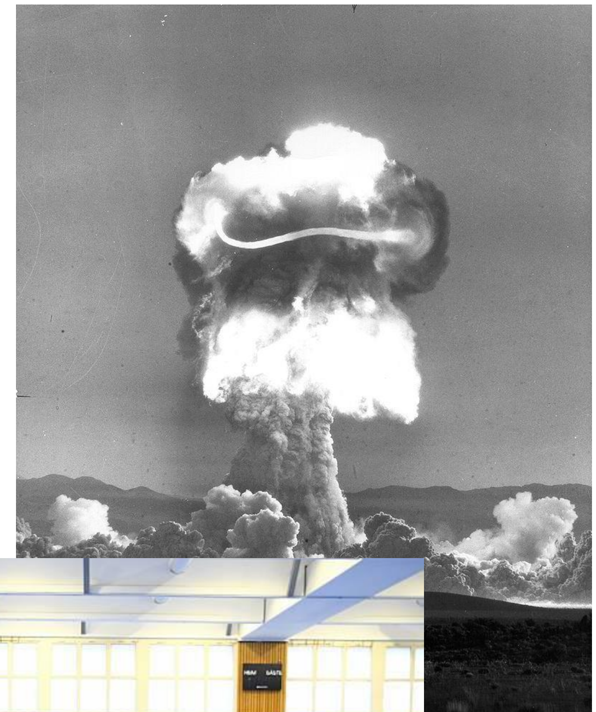
This might be a more honest answer!

What is a distributed system?

A more honest and focused answer:

A distributed system is composed by a set of **processes** that are interconnected through some **network** where processes seek to achieve some form of **cooperation** to execute tasks towards a **common goal**.

What is a distributed system?



Why do we want to distribute things anyways?

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- **Fault-Tolerance (also known as *dependability*):** If I use N machines to support my system and **f** (f < N) fail, then my system can still operate.

- **Concurrency (or more processing/storage power)**: If instead of using 1 machine to run my system, I use N machines (N >> 1) then I will have N times more resources and, hopefully, my system will be (close to) N times faster.

Challenges of Distributed Systems

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There are challenges inherent to all distributed systems:

- **Fault-Tolerance:** It is necessary to consider what you do when a machine fails or becomes unreachable (and they will).
- **Concurrency:** It is necessary to consider the possible orderings of events.
- **No global clock:** In other words, no way of synchronising via time.

Reasoning about Distributed Systems.

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- Uh oh...

The model of a distributed system

- Somewhat “less intelligent” example:
  - How do you reason about a car?

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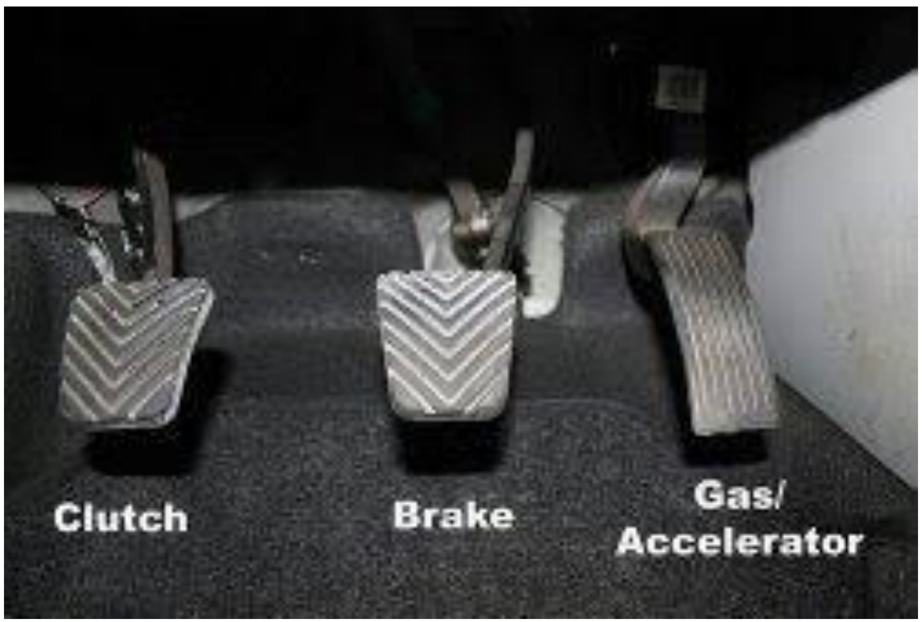

The model of a distributed system

Key insight:

We need **abstractions** for talking about all kinds of systems

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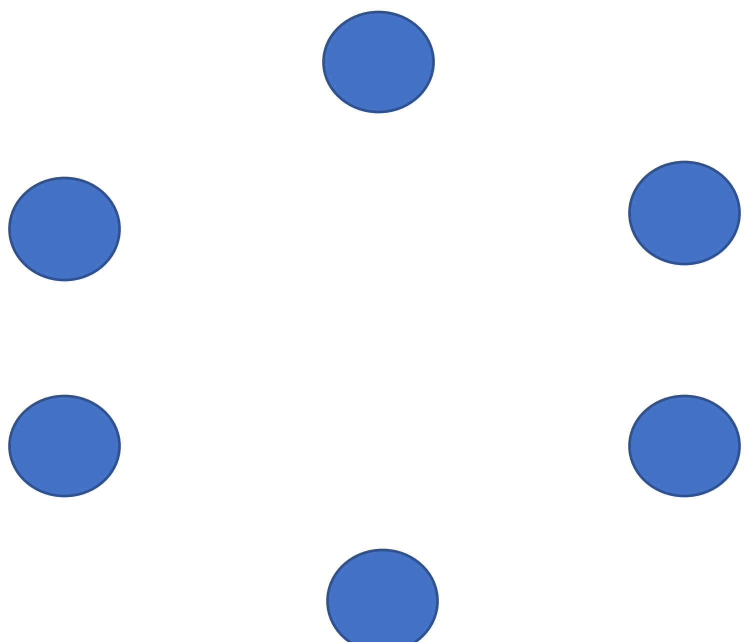

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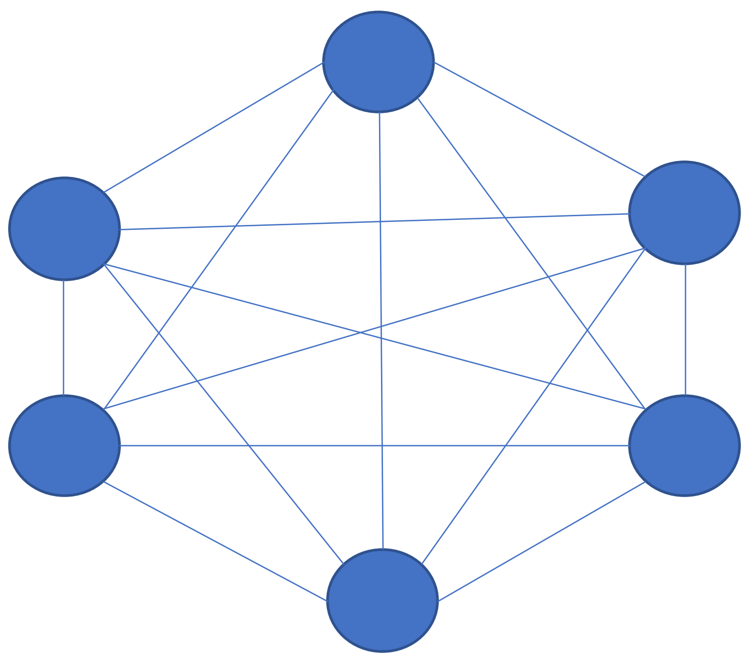
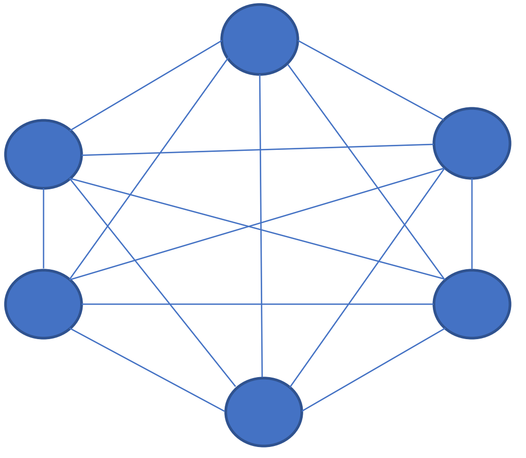


The model of a distributed system

More formally:

- Processes – computational elements:
  - Abstracts the notion of machine/node.
- Network – Graph **G=(V,E)**, in which **V** is the set of processes, **E** represents the communication channels (i.e., links) between pairs of processes.



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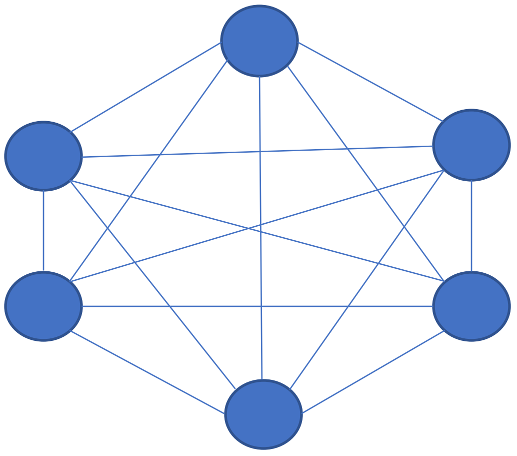
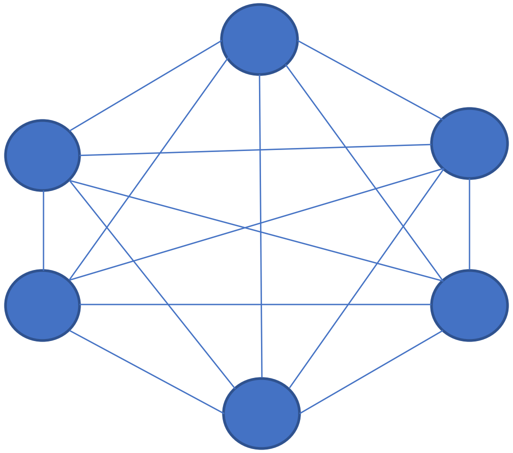
In general, we will consider a complete graph, where every process is connected to every other by a bidirectional link.



The model of a distributed system

- Processes are fully independent, meaning that they do not share memory in any way.
- But a clear requirement for cooperation is to exchange information… so how do processes exchange information among them?



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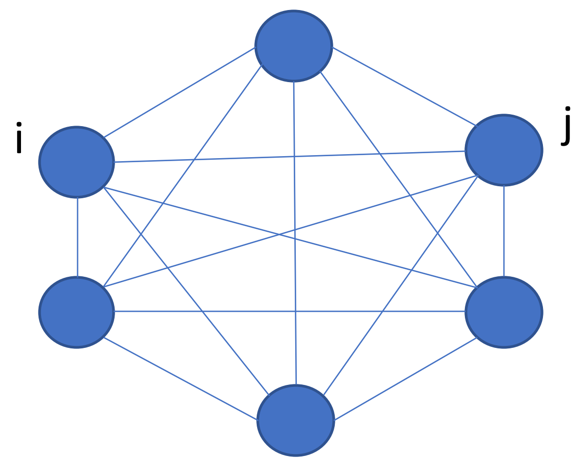

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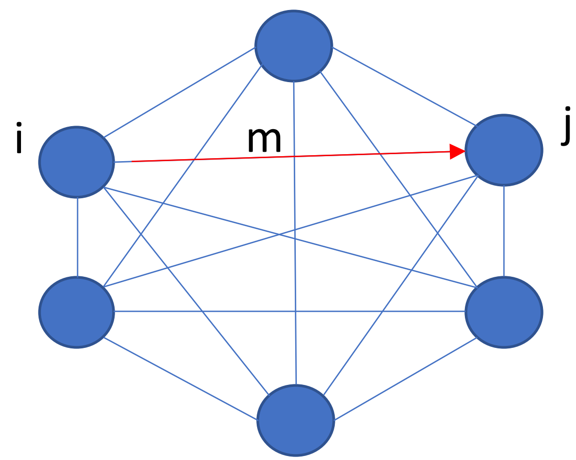
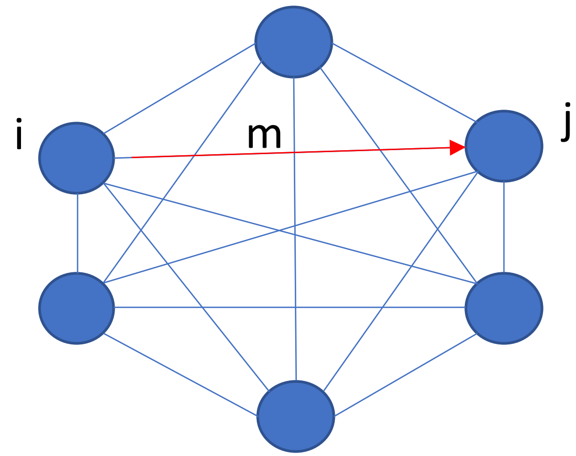


The model of a distributed system

More formally:

- Processes communicate through the exchange of Messages, belonging to an alphabet **M** plus the special symbol **null**, which captures a non-existent message.
- Notation: $\mathrm{send}_i(j, m, arg_1, arg_2, \ldots, arg_n)$
  - Process **i** send message **m** with arguments arg_1 to arg_n to process **j**.



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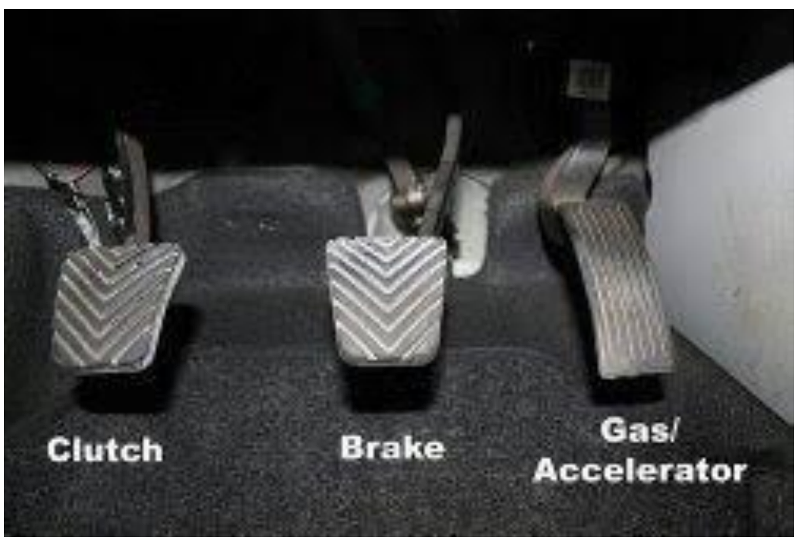

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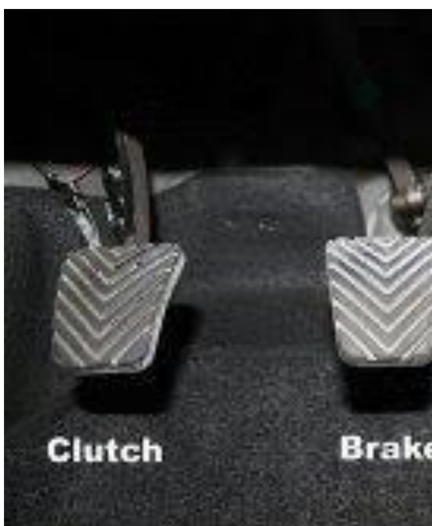

The model of a distributed system

- We are done right?
- Not quite...
- Some extra things must be considered.
  - Timing assumptions.
  - Internal model of the process.
  - (Process) Fault model.
  - Network model,

Examples

- Client-server web interactions
- Audio streaming
- Stock-exchange trading

Timing assumptions

Two fundamental models

Synchronous System:

- Assumes that there is a known *upper bound* to the time required to deliver a message through the network and for a process to make all computations related with the processing of the message.

Asynchronous System:

- There are *no assumptions* about the time required to deliver a message or process a message.

Timing assumptions

- This might look like not a big deal but, there are strong implications here:

    - In a synchronous system you can **detect** when a process fails (in some particular fault models).
    - In a synchronous system you can have protocols **evolve** in synchronous steps (Why is that?)
    - In an asynchronous system there are some problems that have **no solution**.

Timing assumptions

The “real world” is **asynchronous**, so why is it that we sometimes consider the synchronous model?

- The synchronous model is **easier** to reason about
- More **efficient** solutions can be devised in the synchronous model

Internal Model of the Process

- Each process has a unique identifier: $\mathbf{i} \in \mathbf{V}$
- Internally each process has (classical model):
  - states_i – set of (valid) states for process i
  - Inputs and outputs that are special state variables (which allow the process to get information from outside and export information to the outside)
  - init_i – initial state for process i
  - Fundamentally, a process is a **deterministic automaton**.

Beyond Synchrony and Asynchrony

- There is a (more) practical system model that in some sense stands between these two extremes.
- The **partially synchronous** model (or *eventually synchronous* model).
- In this model the system is considered to be **asynchronous,** but it is assumed that **eventually** (*meaning for sure at some time in the future - that is unknown*) the system will behave in a **synchronous** way for long enough (for something good to happen).

Transition between States

- Synchronous Model: Execution in rounds.
- Transition of the process (internal) state based on two functions:
  - $trans_i$: $states_i$ x [M U {null}] ^{V} --> $states_i$
  - $msgs_i$: $states_i$ --> [M U {null}] ^{V}
- In each round a process will:
  - Sends a message (potentially different) to <u>all processes</u>.
  - Receives a message from <u>all processes</u>.
  - Apply $trans_i$ over the received messages to determine its following state.

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Transition between States

- Synchronous Model: Execution in rounds.
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  - $trans_i$: $\mathbf{states_i \times [M \cup \{null\}]^V \text{-->} states_i}$
  - $msgs_i$: $states_i \text{-->} [M \cup \{null\}]^V$
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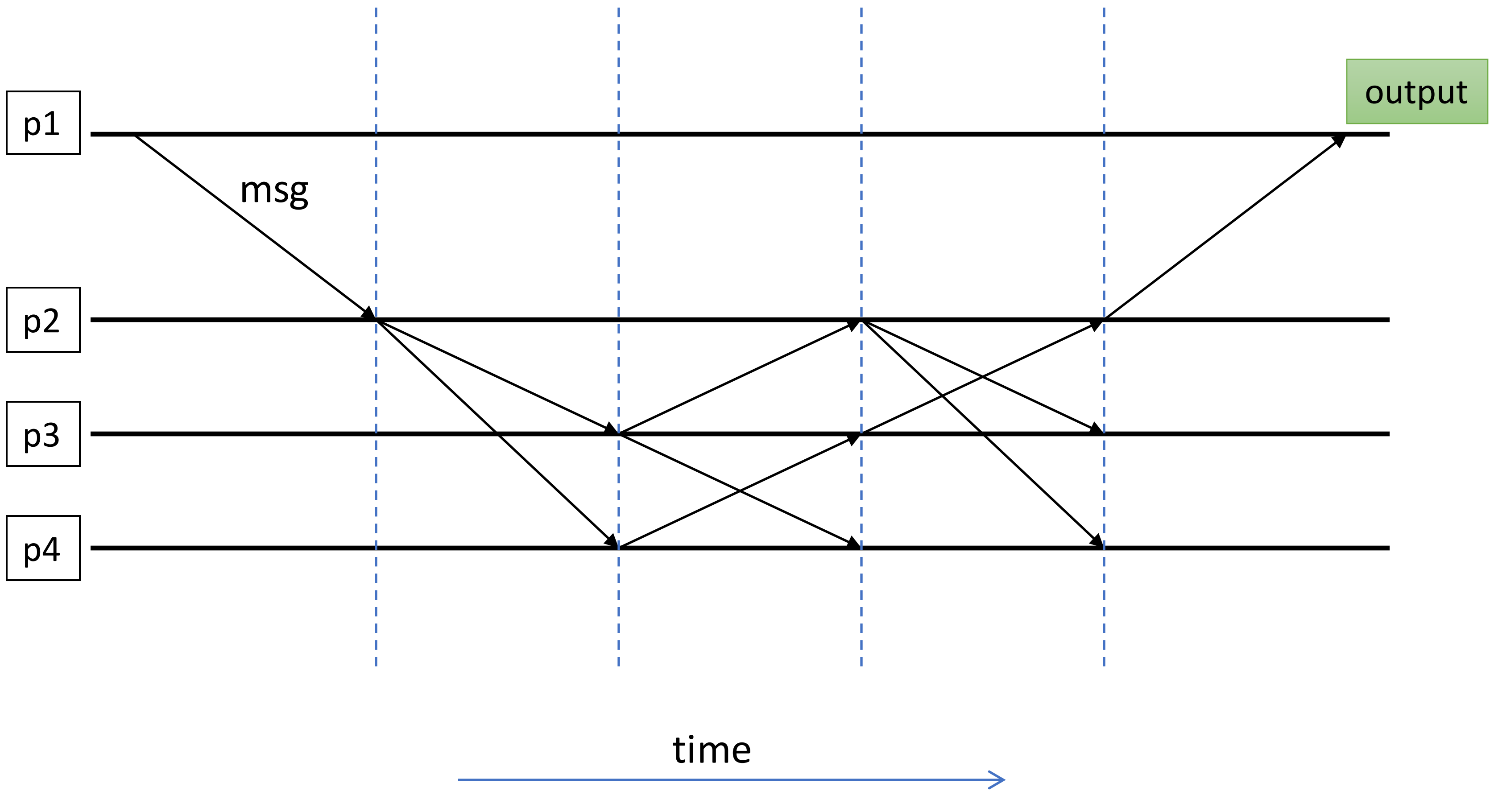
  - **Apply $trans_i$ over the received messages to determine its following state.**

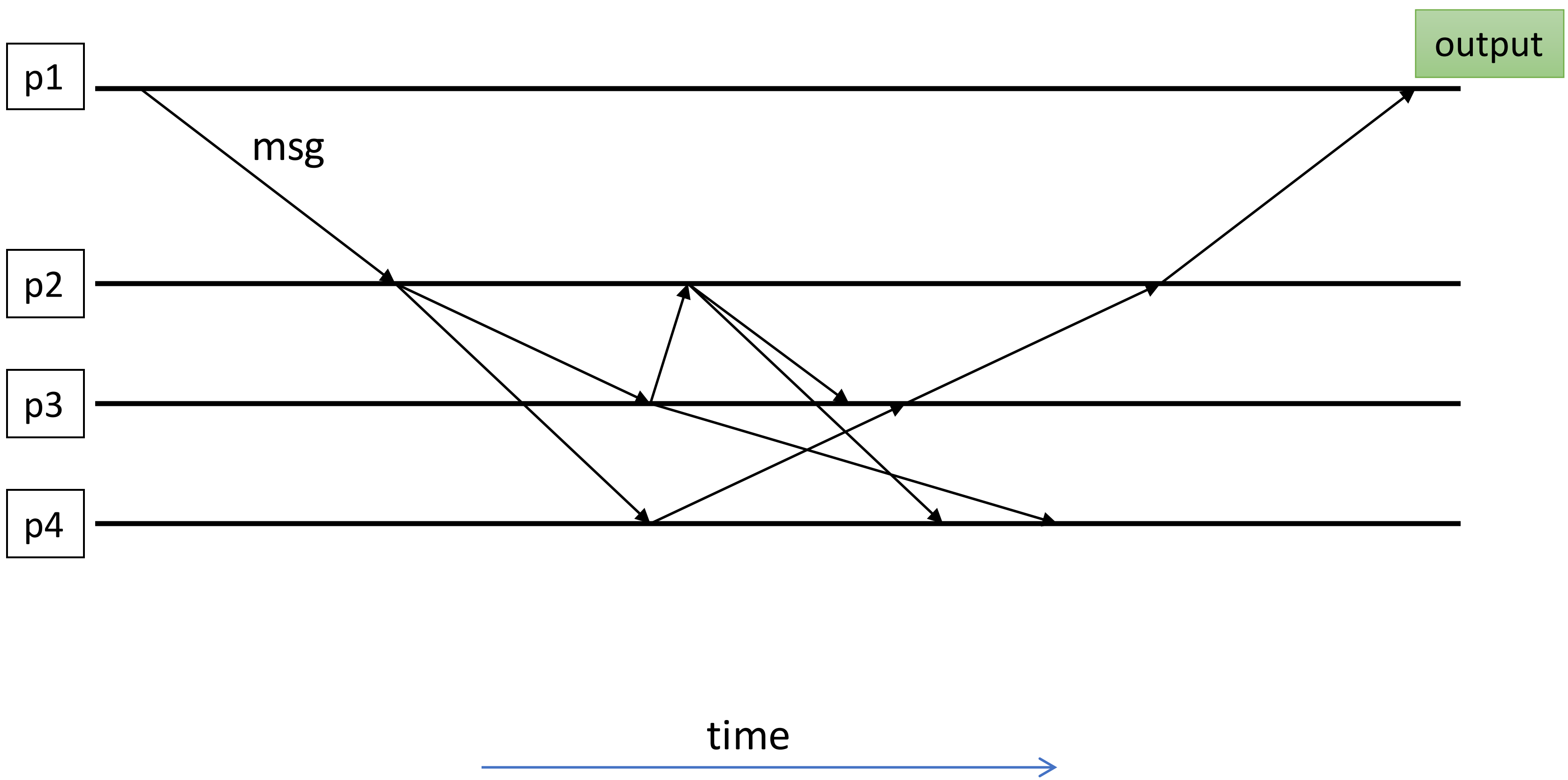
Transition between States

- Asynchronous Model: Execution is not based on rounds.
- Transition of the process state based on two functions:
  - $trans_i$: $states_i$ x M U {null} --> $states_i$
  - $msgs_i$: $states_i$ --> $\{M \cup \{null\}\}^V$
- Since there is no notion of rounds:
  - A transition of state is triggered by the reception of a single message (notice that the transition can be S --> S)
  - Transitioning to a state (even if the same) can trigger the generation (and transmission) of a new set of messages.

Example of an execution in the synchronous model:

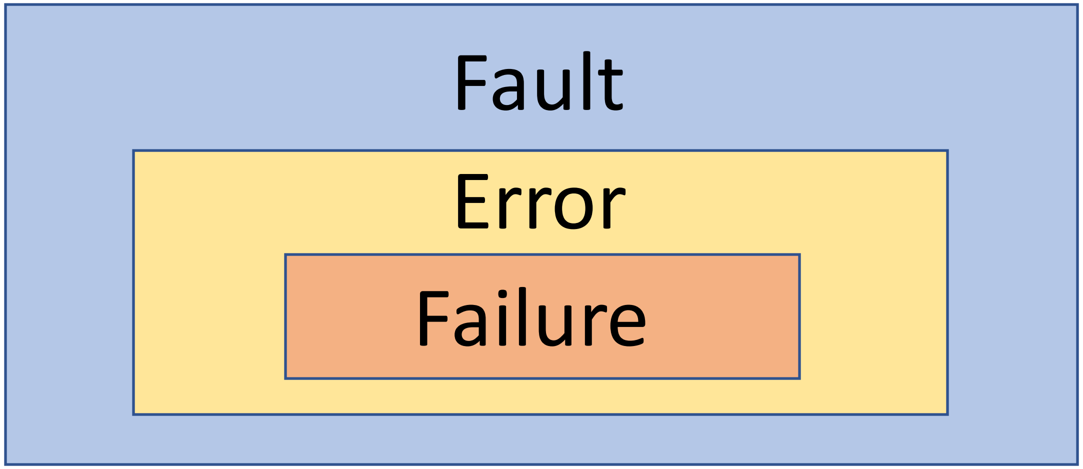


Example of an execution in the asynchronous model:



Fault Model

- Faults lead processes to deviate from their expected behavior.
- Classical Model:



- Example: Sector in the hard disk is damaged (fault); -> Sector is accessed (Error) -> File is lost (Failure)

Fault Model (cont.)

- This classical model usually has a recursive implication.
- The failure of a component of a process (or system) might imply a fault in another component (or different process in the system).
- Going back to the previous example, the failure of the file system (file damaged) might lead to a fault in the load of the operative system, which might result in the failure of the operative system.

Process Fault Model

- A process that never fails, is considered **correct.**
- **Correct processes** never deviate from their expected/prescribed behavior.
    - It executes the algorithm as expected and sends all messages defined by it.
- **Failed (or Faulty) processes** might deviate from their prescribed behavior in different ways.
    - The *unit of failure* is the process, meaning that when it fails, all its component fail at the same time.
- The (possible/considered) behaviors of a faulty process is defined by the process fault model.

Process Fault Models

- Crash Fault Model:
  - When a process fails it stops sending any messages (from that point onward).
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- Omission Fault Model:
  - A process that fails omits the transmission (or reception) of any number of messages (potentially not all of them).
- Fail-Stop Model:
  - Similar to the crash model, except that upon failure the process “notifies” all other processes of its own failure

    (only possible when considering a synchronous system).

Process Fault Models

- Byzantine (or Arbitrary) Fault Model:
  - A failed process might deviate from its protocol in any arbitrary way.
  - Examples:
    - Duplicate Messages;
    - Create invalid messages;
    - Modify values received from other processes.
  - Why is this relevant?
    - Can capture memory corruption;
    - Can capture software bugs;
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    - Can capture memory corruption;
    - Can capture software bugs;
    - A malicious attacker that controls a process.
  - This is not something that we will delve into here:
    - The **Confiabilidade de Sistemas Distríbuidos (CSD) course** deals with these challenges**.**

Network Model

- The Network Model captures the assumptions made concerning the **links** that interconnect processes.
- Namely it captures what can go wrong in the network regarding:
  - Messages sent between processes being lost.
  - Possibility of duplication of messages.
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Network Model

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The Network is usually not your friend.

Some of the weird phenomena in the network can be understood in the **Architectures and Protocols of Computer Networks (APRC)** course.

How to model the network?

We need abstractions like we had with the timing and fault models

In principle, we make a set of assumptions about the network operates

Some models ***closer*** to reality than others

Network Model (a starting point)

Fair Loss Model

- A model that captures the possibility of messages **being lost** (albeit in a fair way)
- Properties:
  - FL1 (Fair-Loss): Considering two correct processes ***i*** and ***j***; if ***i*** sends a message to ***j*** infinite times, then ***j*** delivers the message infinite times.
  - FL2 (Finite Duplication): Considering two correct processes ***i*** and ***j***; if ***i*** sends a message *m* to ***j*** a finite number of times, then ***j*** cannot deliver *m* infinite times.
  - FL3 (No Creation): If a correct process ***j*** delivers a message *m*, then *m* was sent to ***j*** by some process ***i.***

Network Model (moving on…)

Stubborn Model

- A stronger model that assumes that processes communicate in a stubborn way, to **prevent message loss**.
- Properties:
  - SL1 (Stubborn Delivery): Considering two correct processes ***i*** and ***j***; if ***i*** sends a message to ***j***, then ***j*** delivers the message an infinite number of times.
  - SL2 (No Creation): If a correct process ***j*** delivers a message *m*, then *m* was sent to ***j*** by some process ***i*.**

Network Model (better now)

<u>Perfect Link Model</u> (also called Reliable):

- A stronger model that assumes the links between processes are well-behaved.
- Properties:
  - PL1 (Reliable Delivery): Considering two correct processes ***i*** and ***j***; if ***i*** sends a message to ***j***, then ***j*** ***eventually*** delivers *m*.
  - PL2 (No Duplication): No message is delivered by a process more than once.
  - PL3 (No Creation): If a correct process ***j*** delivers a message *m*, then *m* was sent to ***j*** by some process ***i.***

How does all this fits in?

- Our typical network is more closely captured by the properties of the fair-loss model, however its frequent that we use the perfect link model… Why?

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  - The perfect link model makes it easier to reason about algorithms design...
  - ...but more importantly, these abstractions can be built on top of one another using **distributed algorithms.**

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- **What is this dark sorcery that you speak?**

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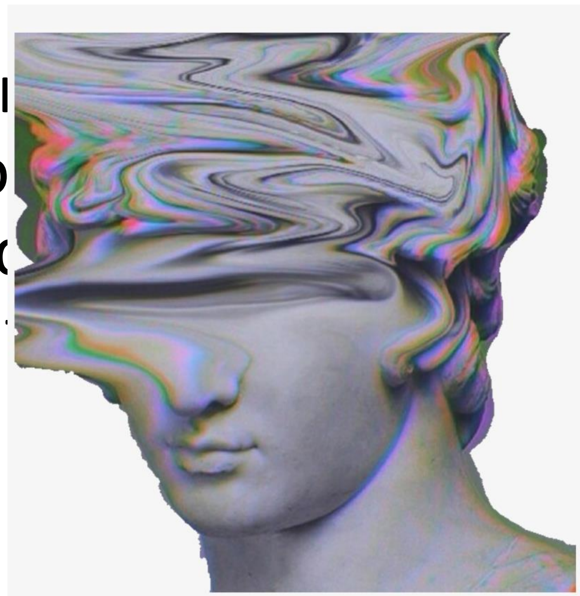

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- **Wait for the lab today to discover...**

How does al

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Don't forget that the perfect link abstraction does not state anything about time

Algorithms Specification and Properties

- Did you noticed that when discussing these network models (i.e., abstractions) I have defined them in terms of a set of properties?

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- **Algorithms** (that instantiate these abstractions) also provide a set of **properties** (if correct, those of the abstraction they implement).
- Why do we tend to think in terms of properties?

Algorithms Specification and Properties

- Did you noticed that when discussing these network models (i.e., abstractions) I have defined them in terms of a set of properties?
- **Algorithms** (that instantiate these abstractions) also provide a set of **properties** (if correct, those of the abstraction they implement).
- Why do we tend to think in terms of properties?
- Quick answer: Because algorithms are ***composable***, and the design of an algorithm depends on the underlying properties provided by other algorithms.

Algorithms Specification and Properties

What does these properties capture?

- The correctness criteria for the algorithm (and for any implementation of that algorithm).
- It defines restrictions to (all) valid executions of the algorithm.

Two fundamental types of properties:

- Safety
- Liveness

Safety Properties

Conditions that must be enforced at any (and all) point of the execution

- Intuitively, preventing *bad* things that should never happen.

Relevant aspects:

- The trace of an empty execution is always safe (do nothing and you shall do nothing wrong).
- The prefix of a trace that does not violate safety, will never violate safety.

Liveness Properties

Conditions that should be enforced at some point of an execution (but not necessarily always).

- Intuitively, good things that should happen eventually.

Relevant aspects:

- One can always extend the trace of an execution in a way that will respect liveness conditions (if you haven't done anything good yet, you might do it in the future).

Safety VS Liveness Properties

- Correct algorithms will have (most of the times) both Safety and Liveness properties.

- Some properties however are hard to classify within one of these classes, and they might mix aspects of safety and liveness
  - Usually, one can decompose these properties in simpler ones through conjunctions.

Modelling distributed systems

Models that handle:

- Networks
- Timing
- Faults

Currently, we do not have any constructions that actually **operate** within these models

Let's now start to think about concrete problems…

- Now that we have covered the rules of the game, we can start to think on how to solve problems (within a particular set of rules).

The Broadcast Problem

- Informally: A process needs to transmit the same message *m* to N other processes (where N is every process in the system including himself).

- *Let's assume that the complete set of processes in the system is known a-priori:* **π**
- *Let's assume we have access to the Perfect Point-to-Point Link Abstraction.*
- *Let's assume an asynchronous system (no rounds, no failure detection).*

The Broadcast Problem

- Wait... How do you specify an algorithm again?

- I have sort of told you before, through a deterministic automaton...

The Broadcast Problem

- Wait... How do you specify an algorithm again?
- I have sort of told you before, through a deterministic automaton...
- Ok let's simplify this...

The Anatomy of an Algorithm:

ALGORITHM

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You need an Interface for this to be used (think of APIs)

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Let’s use an event driven interface.

The Anatomy of an Algorithm:

Perfect Point-to-Point Link Algorithm

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The Anatomy of an Algorithm:

pp2pSend (p , m)

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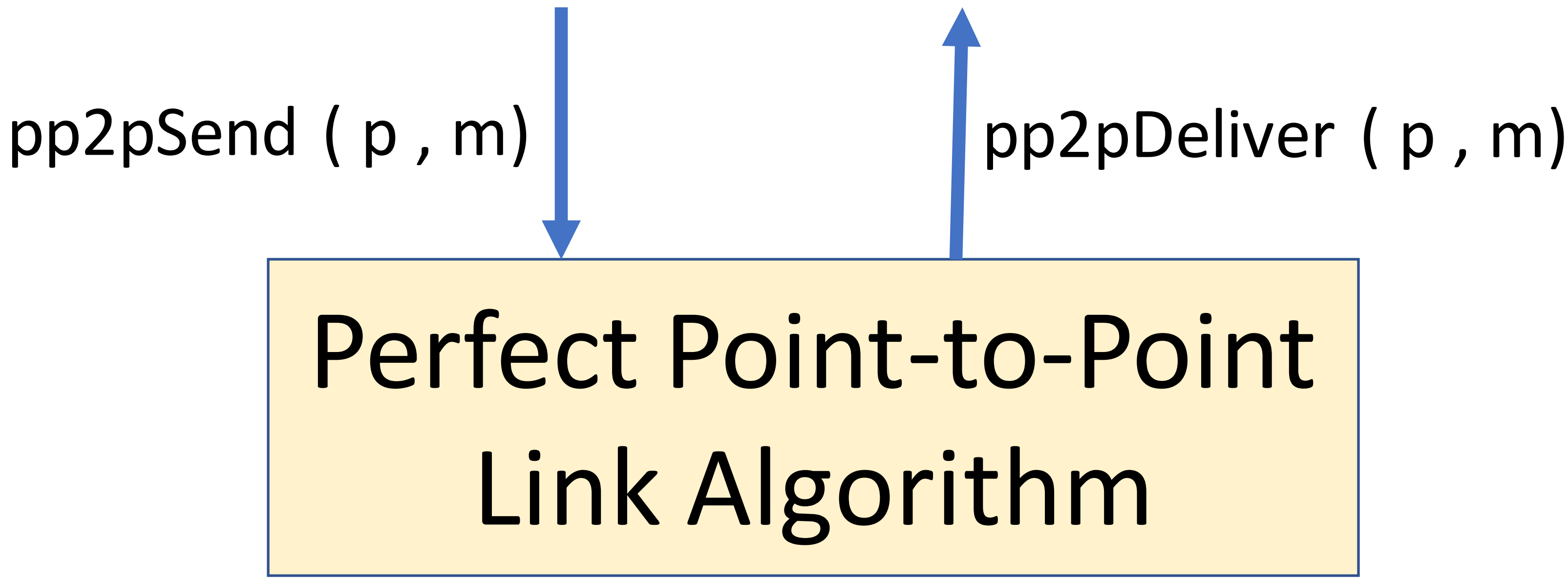

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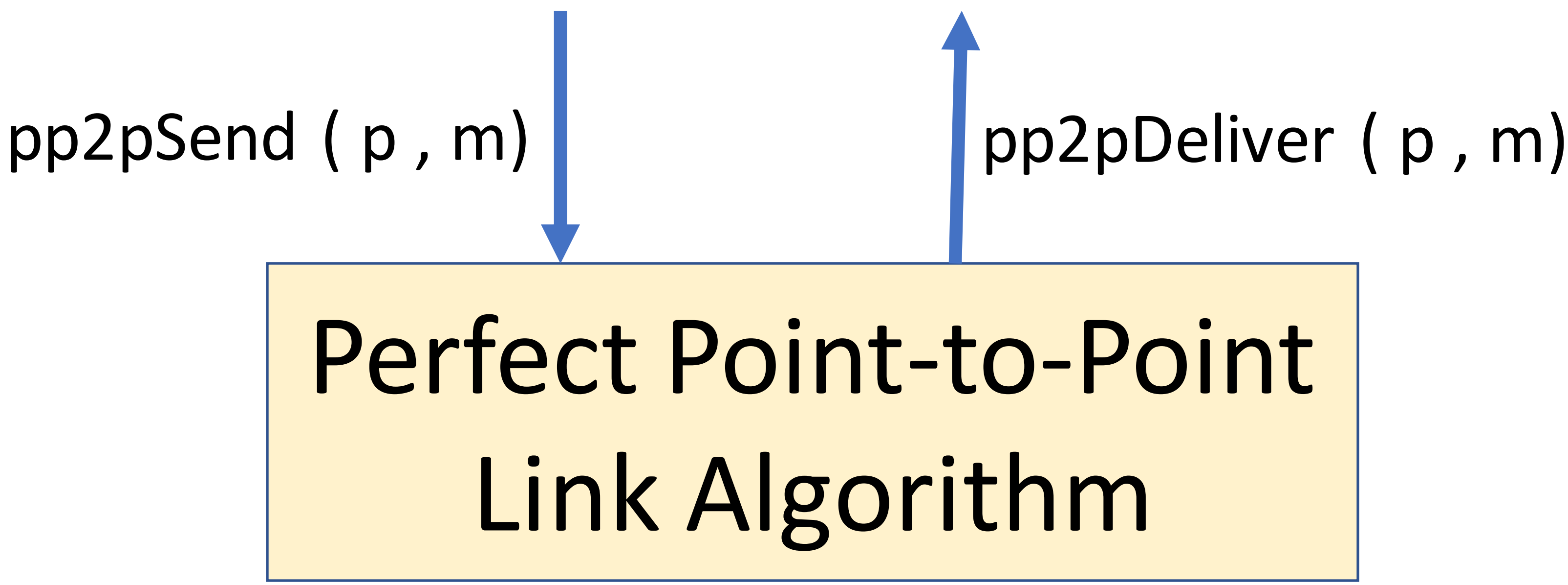
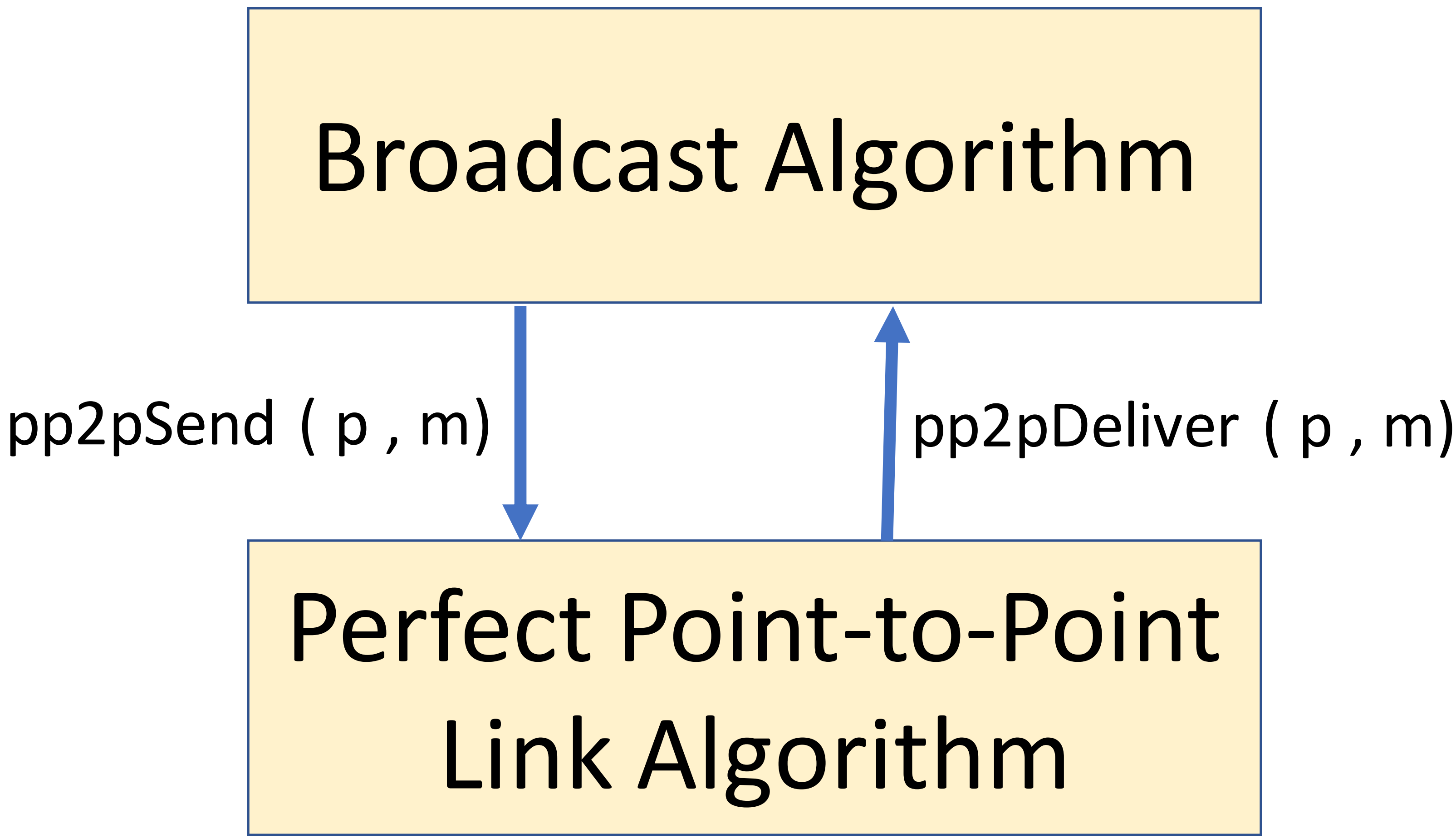
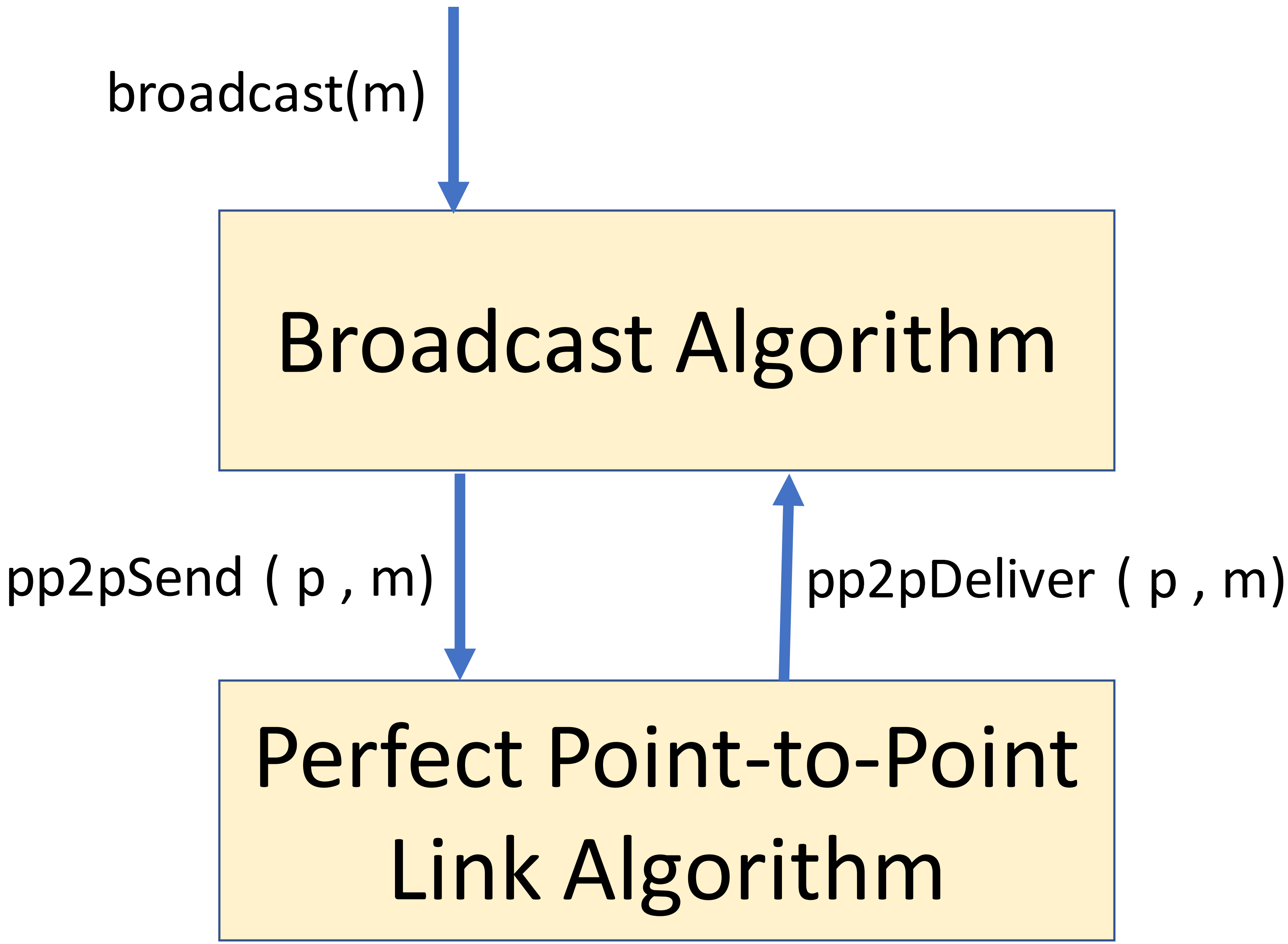


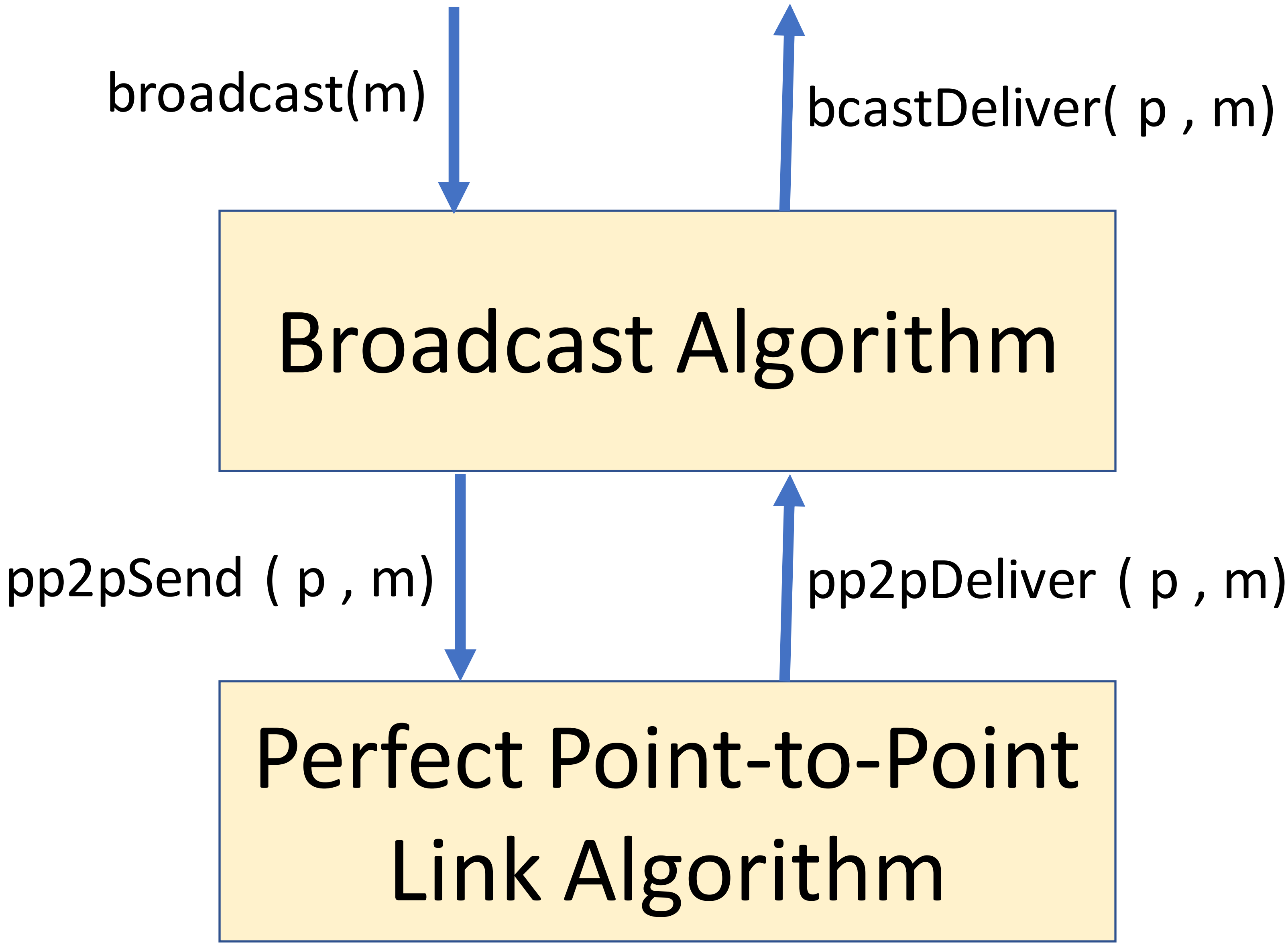
The Anatomy of an Algorithm:



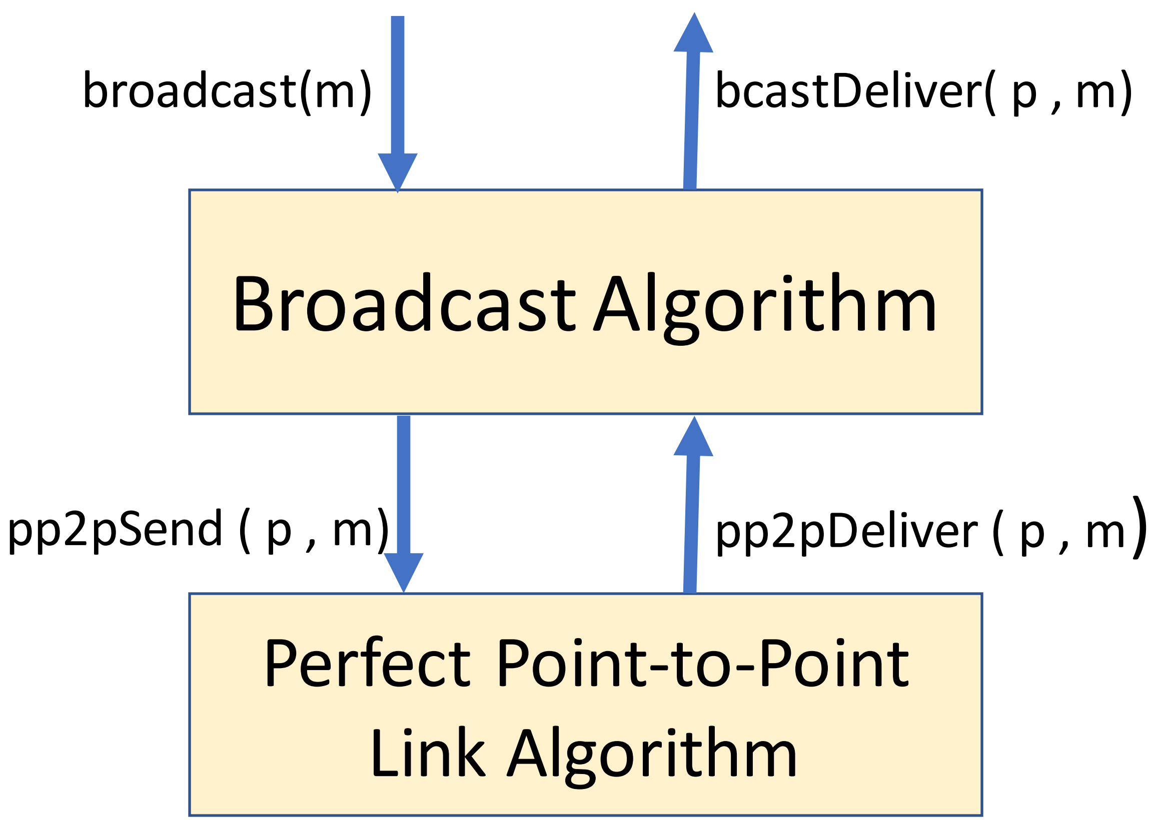
The Anatomy of an Algorithm:



The Anatomy of an Algorithm:



The Anatomy of an Algorithm:



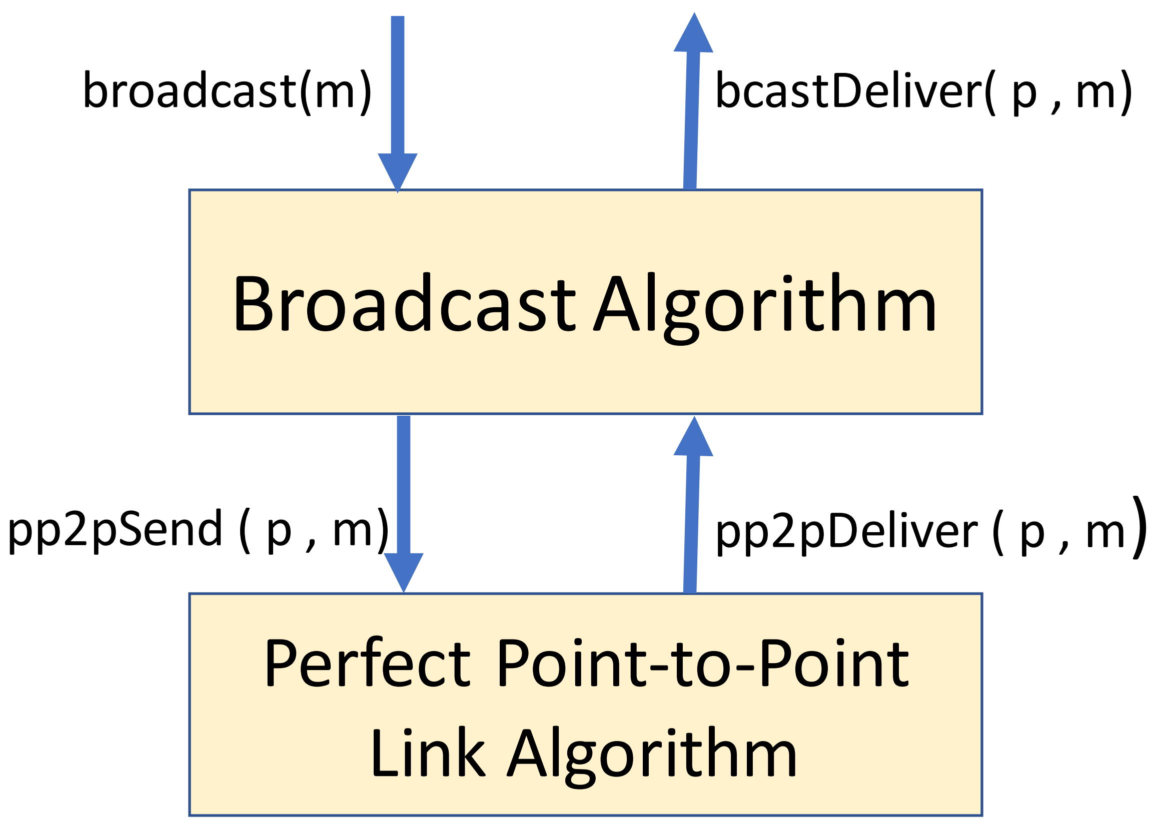
Now you specify what actions are performed when one of this events happen:

Upon broadcast(m) do:

…

…

The Anatomy of an Algorithm:



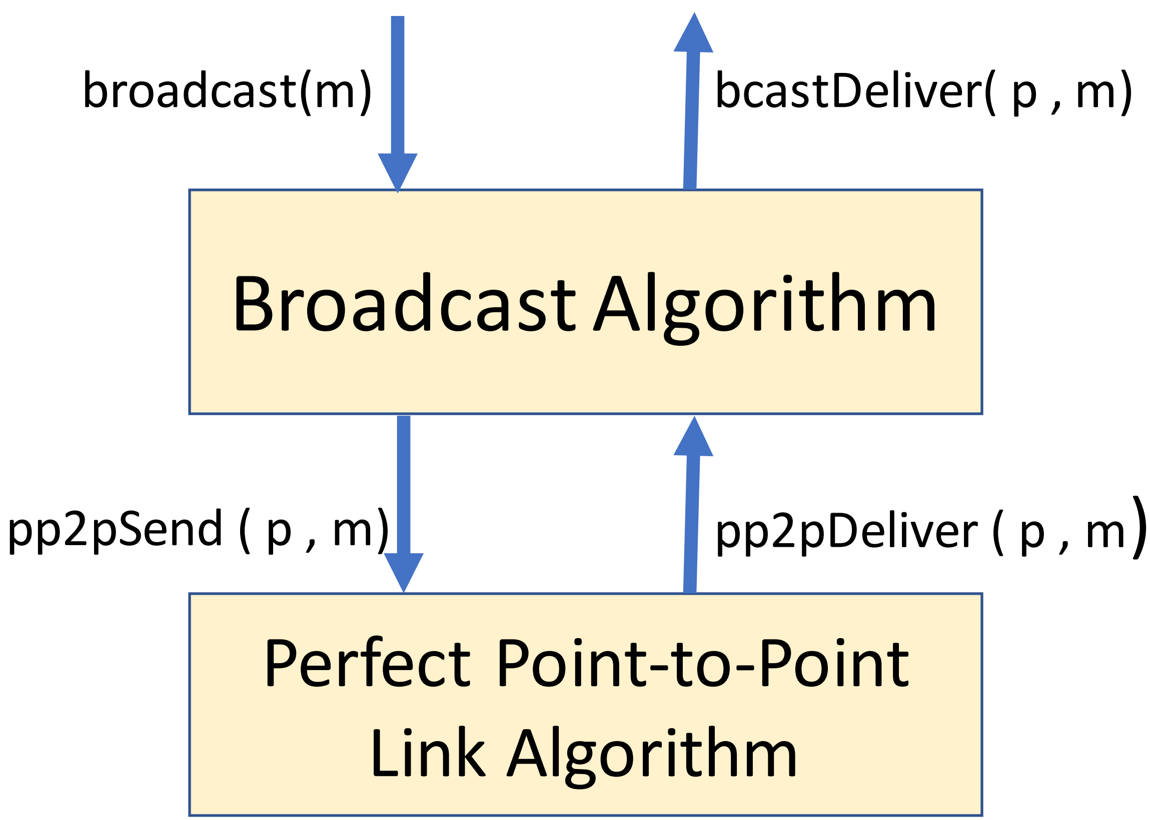
Now you specify what actions are performed when one of this events happen:

Upon broadcast(m) do:
…
…

You can trigger an event on other protocol:
Trigger pp2psend(p, m)

The Anatomy of an Algorithm:

There is a special event called **Init** where you can initialize the **local** state of the **algorithm**



Now you specify what happens when one of this events happen:

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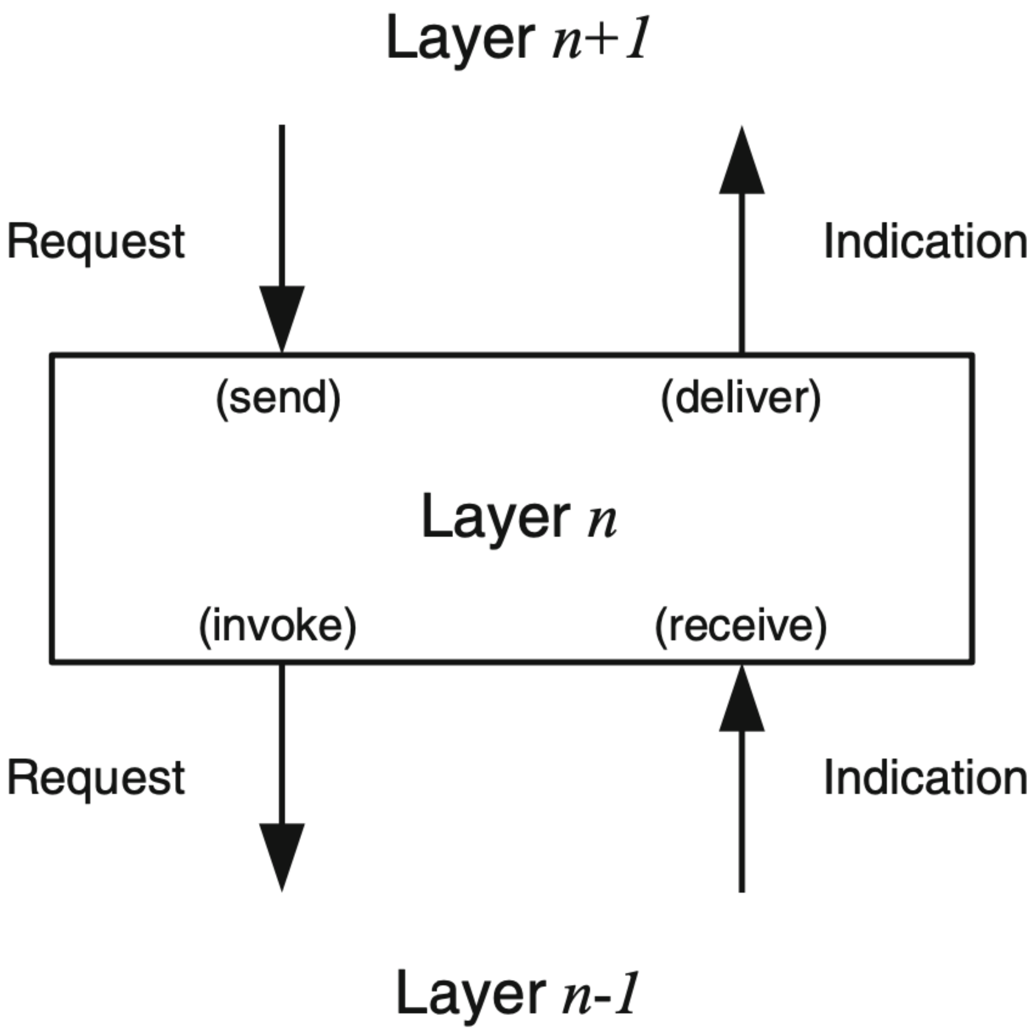
You can trigger an event on another protocol:

Trigger pp2psend(p, m);

Layering (Broadcasts)



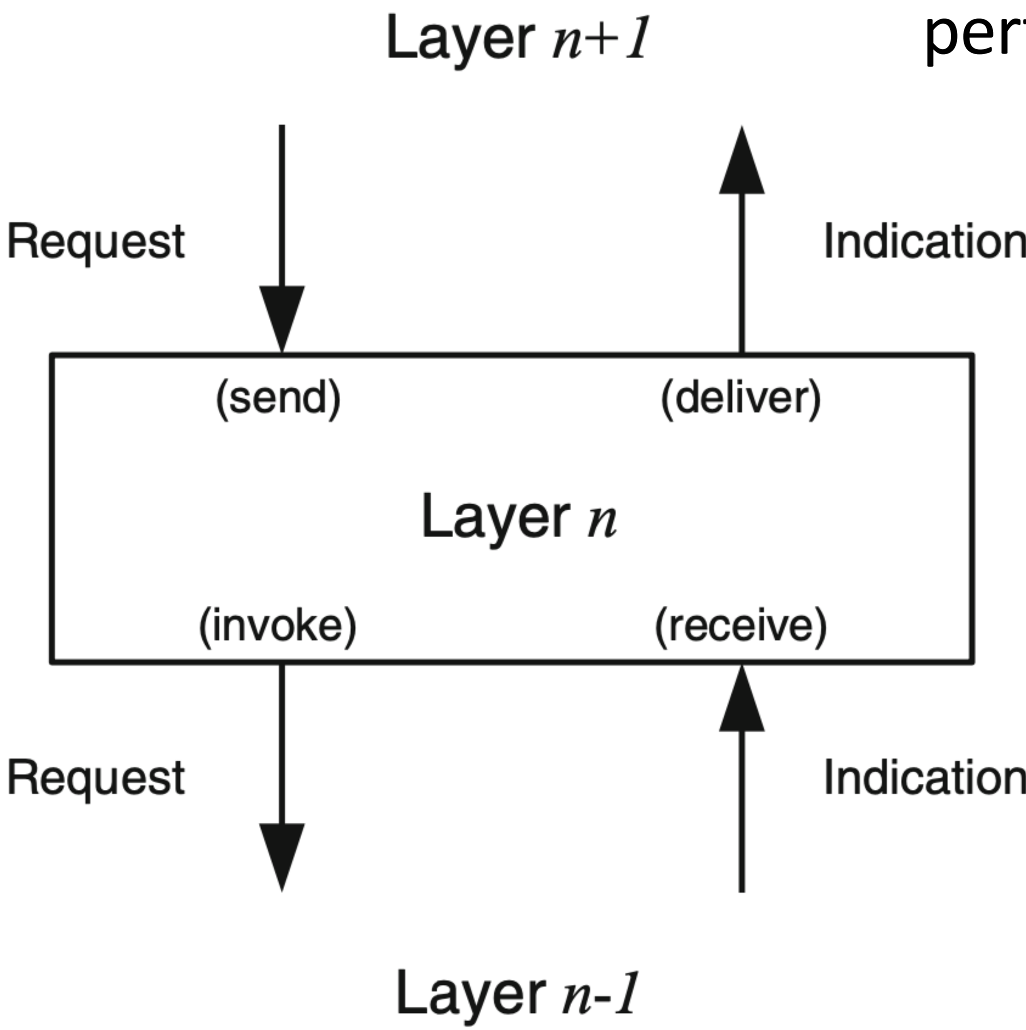
Two important distinctions:

- Requests

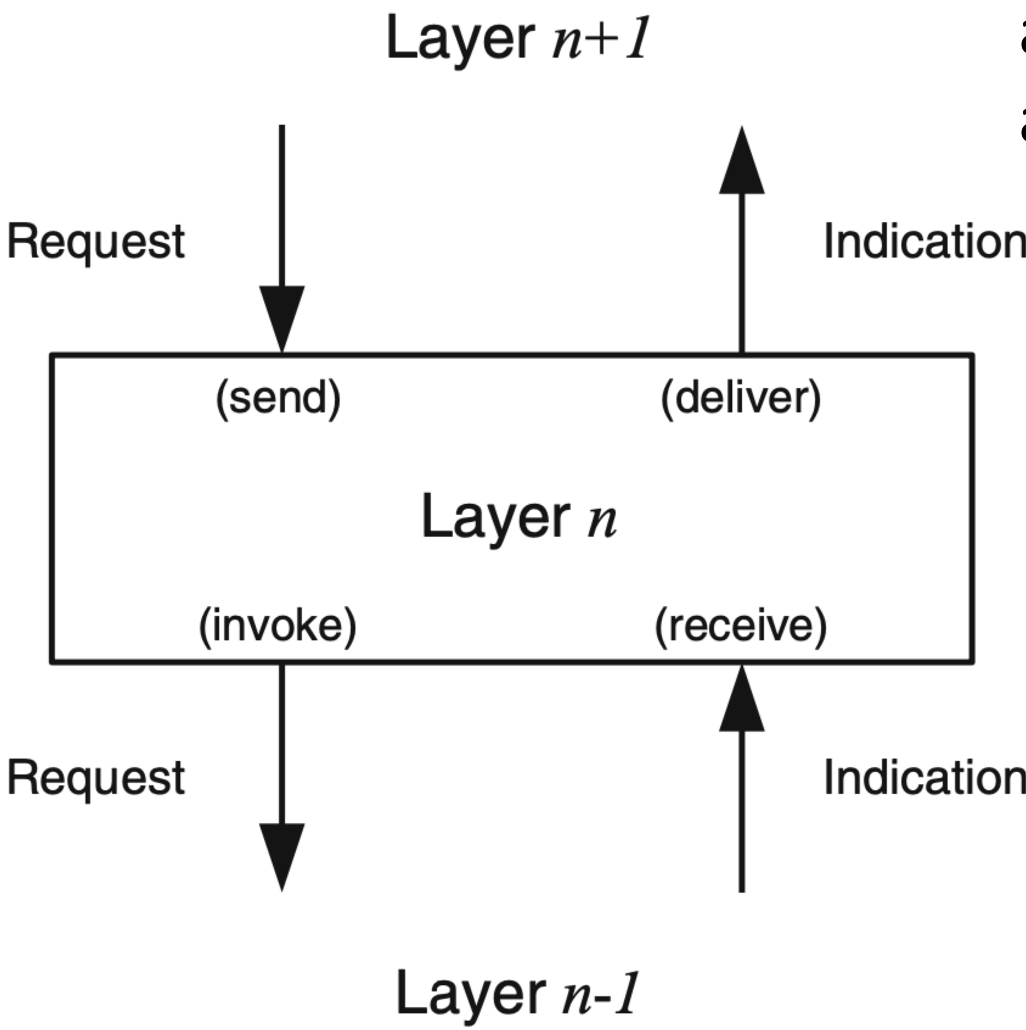
- Indications

Requests

Requests inform the *next* layered algorithm to perform some action.



Indications



Indications inform the *previous* layered algorithm that the action was performed.

Back to the Broadcast problem…

- What is the simplest solution that you can think of?

- **Think like this:**
  - I am a process; someone asks me to send a message to everyone (including me)
  - I know everyone already so basically what do I do?

Back to the Broadcast problem…

- What is the simplest solution that you can think of?

- **Solution:**

Just go ahead and send the message to everyone, one at a time. When you get one of these messages, you just deliver it to the upper layer.

Back to the Broadcast Problem:

Good… that works… (Sort of)

- That is the solution for the Best Effort Broadcast.
- Best Effort Broadcast:
  - BEB1 (Best-Effort validity): For any two correct processes ***i*** and ***j***, every message broadcasted by ***i*** is eventually delivered by ***j.***
  - BEB2: (No Duplication): No message is delivered more than once.
  - BEB3: (No Creation): If a correct process ***j*** delivers a message *m*, then *m* was **broadcast** by some process ***i.***

Best Effort Broadcast

State: (could be omitted)

Upon Init do: (could be omitted)

Upon bebBroadcast(m) **do**
    forall p $\in$ $\boldsymbol{\pi}$
        trigger pp2pSend(p, m);

Upon pp2pDeliver (p , m) **do**
    trigger bebDeliver(p, m);

Best Effort Broadcast

- Not so great right?
- What happens if a process fails while sending messages to all the other processes?

Best Effort Broadcast

- Not so great right?
- What happens if a process fails while sending messages to all the other processes?
- Answer not everyone gets the message…

Reliable Broadcast Problem

- Let's make this somewhat stronger and more interesting…
- Reliable Broadcast:
  - RB1 (Validity): If a correct process i broadcasts message m, then i eventually delivers the message.
  - RB2 (No Duplications): No message is delivered more than once.
  - RB3 (No Creation): If a correct process j delivers a message m, then m was broadcast to j by some process i.
  - RB4 (Agreement): If a message m is delivered by some correct process i, them m is eventually delivered by every correct process j.

How do you think we could solve this problem? Remember that we can use the Best Effort Broadcast Algorithm to solve this one…

- Let's make this somewhat stronger and more interesting…
- Reliable Broadcast:
  - RB1 (Validity): If a correct process i broadcasts message m, then i eventually delivers the message.
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Reliable Broadcast Problem

State:

delivered //set of message ids that were already delivered.

Upon Init **do**:

delivered $\longleftarrow$ {};

Upon rbBroadcast(m) **do**

trigger rbDeliver(m);

mid $\longleftarrow$ generateUniqueID(m);

delivered $\longleftarrow$ delivered U {mid};

trigger bebBroadcast({ mid, m });

Upon bebDeliver(p, { mid, m }) **do**

if (mid $\notin$ delivered) **then**

delivered $\longleftarrow$ delivered U {mid};

trigger rbDeliver(m);

trigger bebBroadcast(mid, m);

Reliable Broadcast Problem

In all fairness in the Literature: *Eager Reliable Broadcast*

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if (mid ∉ delivered) **then**

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trigger bebBroadcast(mid, m);

Why is this solution correct?

To show the correctness of the algorithm we must check each property individually. For each we have me make a (rational) argument that the algorithm enforces it.

- Reliable Broadcast:
  - RB1 (Validity): If a correct process i broadcasts message m, then i eventually delivers the message.
  - RB2 (No Duplications): No message is delivered more than once.
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```
Upon Init do:
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Upon rbBroadcast( m ) do
        trigger rbDeliver(m);
        mid ⟵ generateUniqueID(m);
        delivered ⟵ delivered U {mid};
        trigger bebBroadcast( { mid, m } );

Upon bebDeliver(p, { mid, m } ) do
        if ( mid ∉ delivered ) then
                delivered ⟵ delivered U {mid};
                trigger rbDeliver(m);
                trigger bebBroadcast(mid, m);
```

This solution consumes a lot of messages (not being nice for the network nor processors)!

In fact, it costs $O(|\pi|^2)$ total messages to execute.

Reliable Broadcast Problem

- Ideally we would design a Reliable Broadcast solution that resulted in $O(|\boldsymbol{\pi}|)$ messages
- See Lab 01!

Summary of Lecture

- Why are distributed systems required?
- The importance of abstractions
- Idealised models for describing distributed algorithms
- Concrete examples of broadcasting messages

<u>Quiz!!1!</u>

What do you remember?

Question 1

Which p2p link model allows for the loss of messages?

- Fair loss

- Stubborn

- Perfect

Answer 1

Which p2p link model allows for the loss of messages?

- **Fair loss**
- Stubborn
- Perfect

Question 2

In the synchronous model, it is impossible to tell when a process has failed?

- True
- False

Answer 2

In the synchronous model, it is impossible to tell when a process has failed?

- True
- **False**

Question 3

Which fault model allows a process to keep sending and delivering a subset of the messages it receives?

- Crash fault
- Omission fault
- Fail-stop

Answer 3

Which fault model allows a process to keep sending and delivering a subset of the messages it receives?

- Crash fault
- **Omission fault**
- Fail-stop