

# The FLP Theorem

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# The Distributed Consensus Problem

# Faults

In this course we usually assumed that the participating processes and the network were completely reliable.

This is not the case with real systems, which are subject to a number of possible **faults**, such as process crashes, network partitioning, and lost, distorted, duplicated messages.

One can even consider more **Byzantine** types of failures, in which faulty processes might go completely haywire, perhaps even sending messages according to some malevolent plan.



# Consensus protocol

## Definition (Consensus protocol)

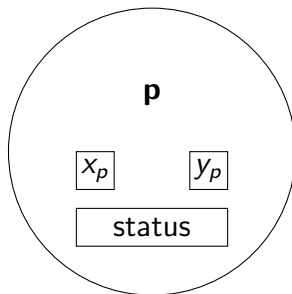
A **consensus protocol** is an asynchronous system of  $N$  processes ( $N \geq 2$ ). Each process  $p$  has a one-bit **input register**  $x_p$ , an **output register**  $y_p$  with values in  $\{\perp, 0, 1\}$  and an unbounded amount of internal storage.

**Initial states** prescribe fixed starting values for all but the input register; in particular, the output register starts with value  $\perp$ .

$p$  acts deterministically according to a **transition** function.

# Decision states

The states in which the output register has value 0 or 1 are distinguished as being **decision states**. The transition function cannot change the value of the output register once the process has reached a decision state; that is, the output register is “write-once”.



# Message system

A **message** is a pair  $(p, m)$ , where  $p$  is the name of the destination process and  $m$  is a “message value” from a fixed universe  $M$ .

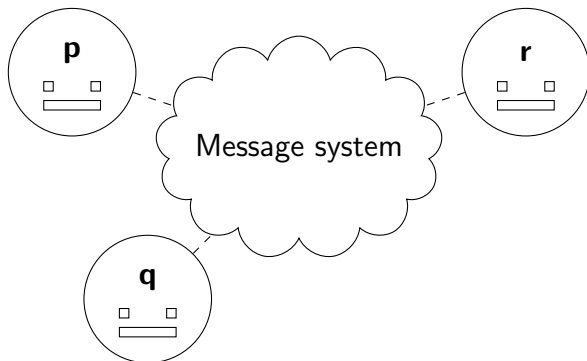
## Definition (Message system)

The **message system** maintains a multiset, called the **message buffer**, of messages that have been sent but not yet delivered. It supports two abstract operations:

- $\text{send}(p, m)$ : Places  $(p, m)$  in the message buffer.
- $\text{receive}(p)$ : Deletes some message  $(p, m)$  from the buffer and returns  $m$ , in which case we say  $(p, m)$  is **delivered**, or returns the special null marker  $\emptyset$  and leaves the buffer unchanged.

# Nondeterministic messaging

The message system acts nondeterministically, subject only to the condition that if `receive(p)` is performed infinitely many times, then every message  $(p, m)$  in the message buffer is eventually delivered.





# Configurations and steps

# Partial correctness

A configuration  $C$  has **decision value**  $v$  if some process  $p$  is in a decision state with  $y_p = v$ .

## Definition (Partial correctness)

A consensus protocol is **partially correct** if:

- 1 No accessible configuration has more than one decision value.
- 2 For each  $v \in \{0, 1\}$ , some accessible configuration has decision value  $v$ .

# Total correctness in spite of one fault

A process  $p$  is **nonfaulty** in run if it takes infinitely many steps, otherwise it is **faulty**.

A run is **admissible** if at most one process is faulty and all messages sent to nonfaulty processes are eventually received.

A run is **deciding** if some process reaches a decision state.

## Definition (Total correctness in spite of one fault)

A consensus protocol  $P$  is **totally correct in spite of one fault** if it is partially correct and every admissible run is deciding.

# Main result

Theorem (Fischer, Lynch, Paterson [FLP85])

*No consensus protocol is totally correct in spite of one fault.*

A configuration is **bivalent** if the set of decision values of configurations reachable from it has 2 elements. It is instead **0-valent** or **1-valent** according to the corresponding value.

Proof (sketch).

Given an initial bivalent configuration, we construct an admissible run that at each stage results in another bivalent configuration. □

# Lemma 1

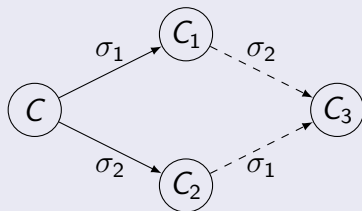
## Lemma

*Suppose that from some configuration  $C$ , the schedules  $\sigma_1, \sigma_2$  lead to configurations  $C_1, C_2$  respectively. If the sets of processes taking steps in  $\sigma_1$  and  $\sigma_2$ , respectively, are disjoint, then  $\sigma_2$  can be applied to  $C_1$  and  $\sigma_1$  can be applied to  $C_2$ , and both lead to the same configuration  $C_3$ .*

In other words: **schedules about disjoint processes commute with each other.**

# Proof of Lemma 1

Proof (Lemma 1).



Because the sets of processes are disjoint, an event in  $\sigma_1$  applicable to  $C$  is applicable to  $C_2$  as well.

Because of determinism, after all events are processed they must end up in the same state. □

# Lemma 2

Lemma

*P has a bivalent initial configuration.*

Proof (Lemma 2).



# Lemma 3

## Lemma

*Let  $C$  be a bivalent configuration of  $P$ , and let  $e = (p, m)$  be an event that is applicable to  $C$ . Let  $\mathcal{C}$  be the set of configurations reachable from  $C$  without applying  $e$ , and let  $\mathcal{D} = e(\mathcal{C}) = \{e(E) \mid E \in \mathcal{C} \text{ and } e \text{ is applicable to } E\}$ . Then,  $\mathcal{D}$  contains a bivalent configuration.*

In other words: given a bivalent configuration and an event  $e$  applicable to it, **we construct another bivalent configuration having  $e$  as the last applied event.**



# Proof of Lemma 3

Proof (Lemma 3).

Assume by contradiction that  $\mathcal{D}$  contains no bivalent configuration. We first show that  $\mathcal{D}$  contains both 0-valent and 1-valent configurations. □

# Proof of main result

Proof (main result).



# Bibliography



Michael J. Fischer, Nancy A. Lynch, and Michael S. Paterson, *Impossibility of distributed consensus with one faulty process*, Journal of the ACM (JACM) **32** (1985), no. 2, 374–382.