Consistent Detection of Global Predicates in Asynchronous Systems with Crash Faults

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joint work with

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Motivation

"We are looking for software which also works in very large distributed systems."

Overview

- Recap: observation in (fault-free) asynchronous systems (7 slides).
- Recap: modalities *possibly* and *definitely* (2 slides).
- Observation in asynchronous systems with crash faults (5 slides).
- Modalities *negotiably* and *discernibly* (4 slides).
- Base idea of detection algorithms (6 slides).

Asynchronous systems

- Set of n application processes $p_1, \ldots, p_n$ connected by a communication network.
- Communication by message passing using $send$ and $receive$ commands.
- Messages can take arbitrarily long.
- Processes can be arbitrarily slow.
- Very weak assumptions $\rightarrow$ very realistic model.

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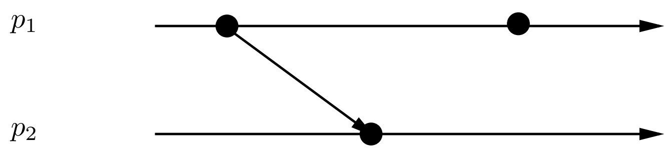
Observation in asynchronous systems

- Distributed computation in which events occur.
- For every relevant event, a *control message* is broadcast to a set of monitor processes .



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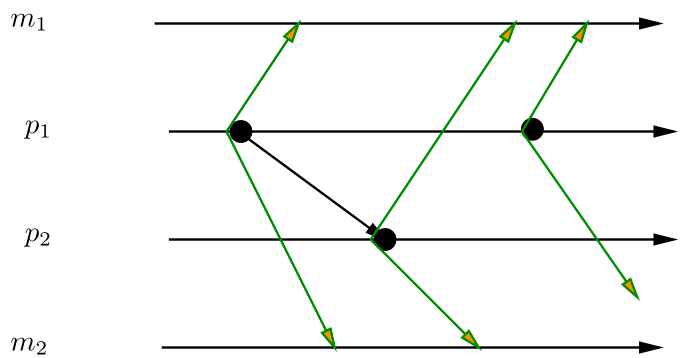


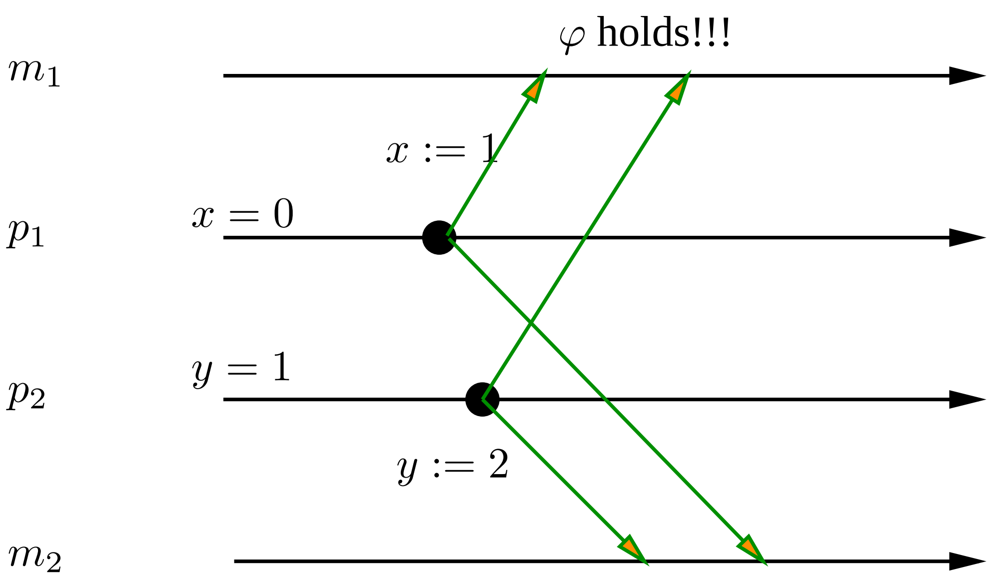
- Global state = "cut" through the diagram.
- Monitors construct a sequence of global states $\Sigma = S_1, S_2, \ldots$
- Σ is called an *observation*.

Predicate detection

- Given predicate φ on global states.
- Devise an algorithm with:
  - (safety) no false detections of φ.
  - (liveness) if φ holds, it is eventually detected.
- Naive approach: monitors check every S_i for φ.

Difficulties of observation

- Detection predicate is $\varphi \equiv x = y$
- "φ holds?" is not observer-invariant!



Lattice of all global states

- Look at set of all (possibly) global states.
- Take relation on how one set evolves from another by executing a single event.

$\Rightarrow$ Lattice of global states.

- Observation is a path through the lattice.

Lattice example

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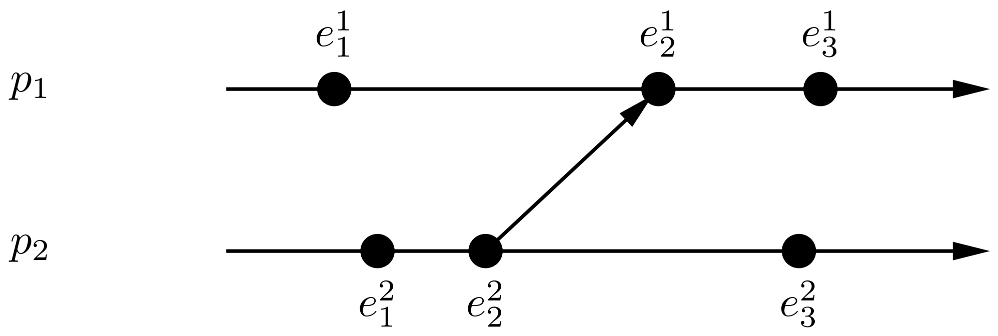

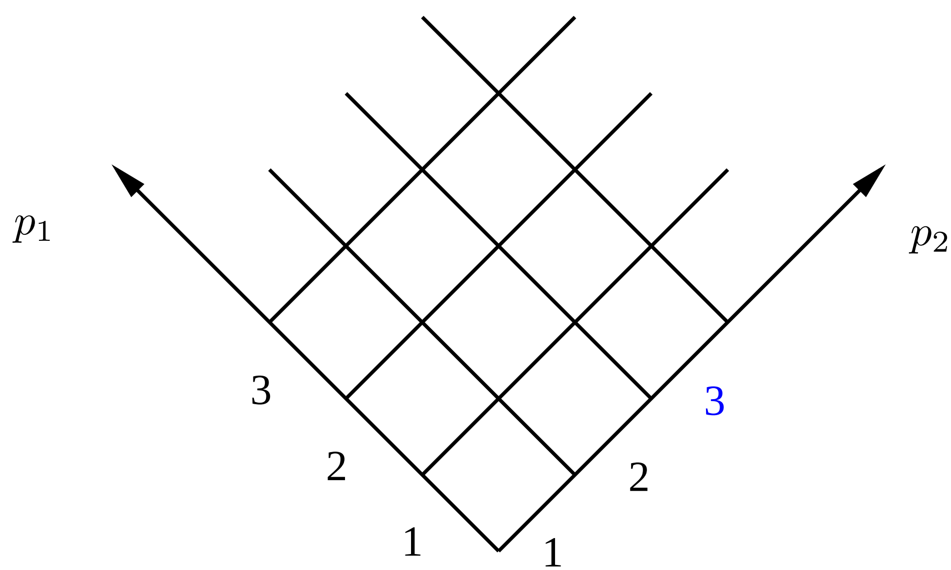

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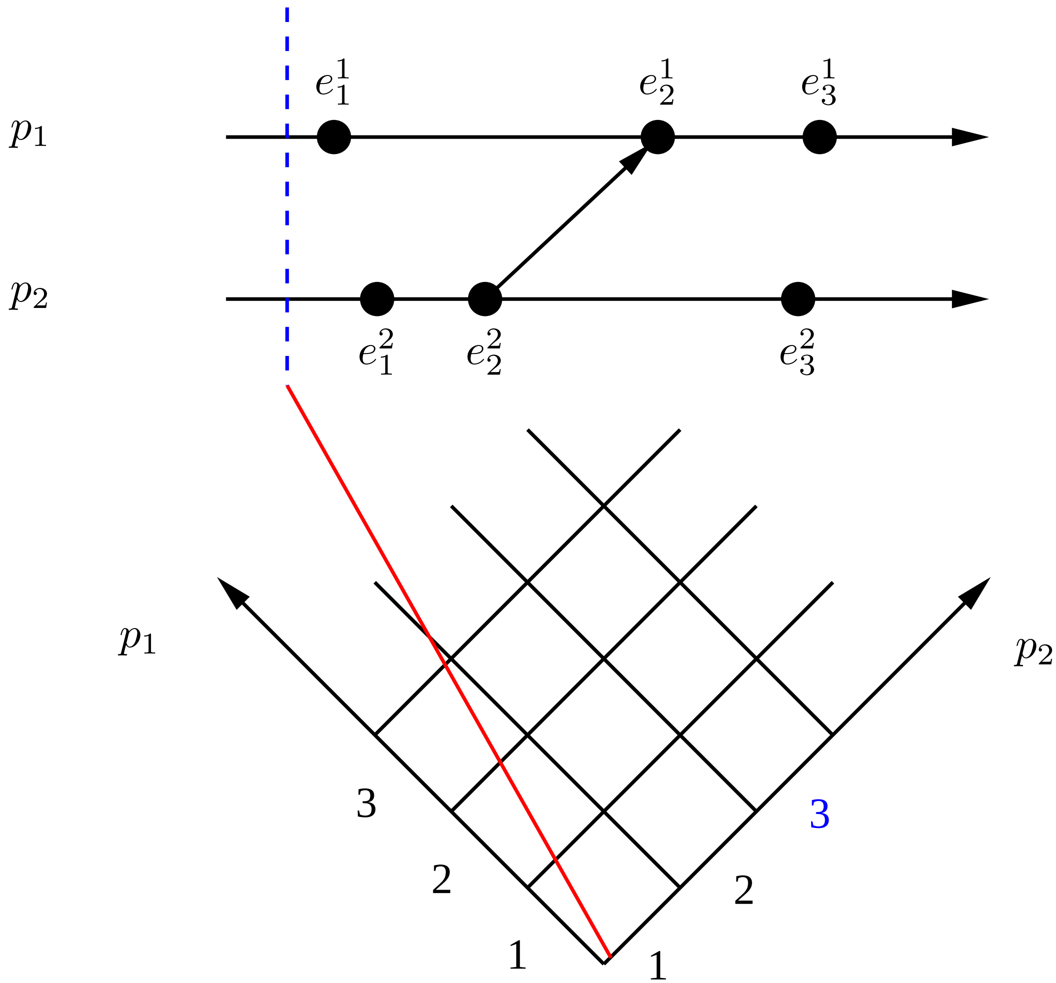

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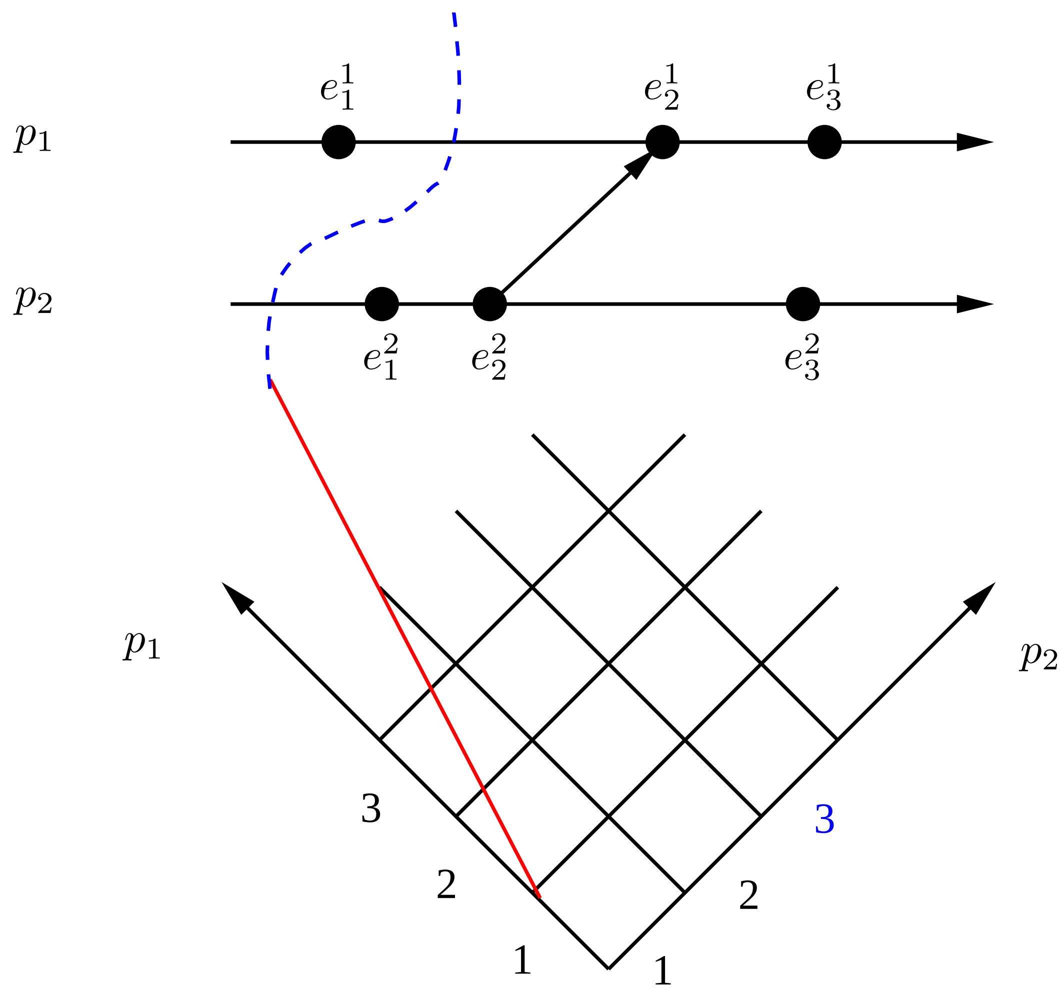

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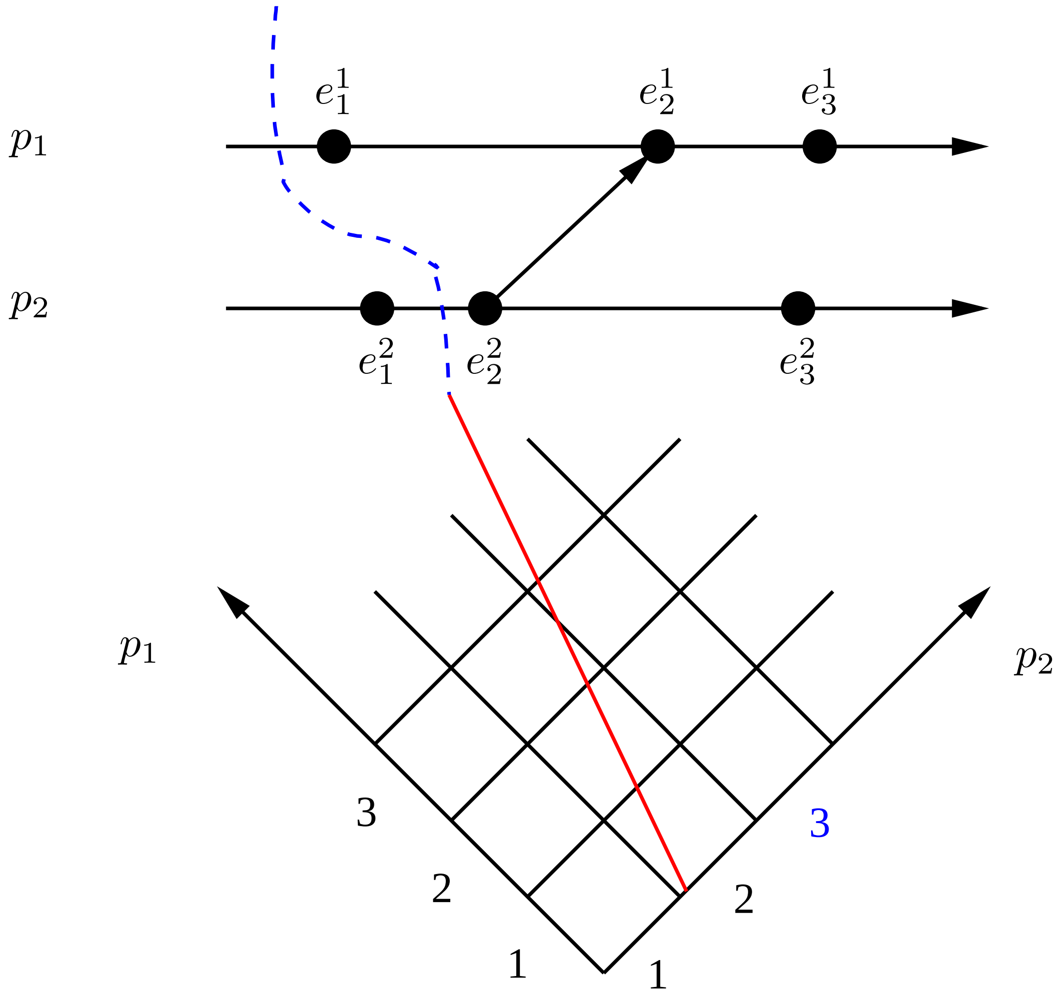

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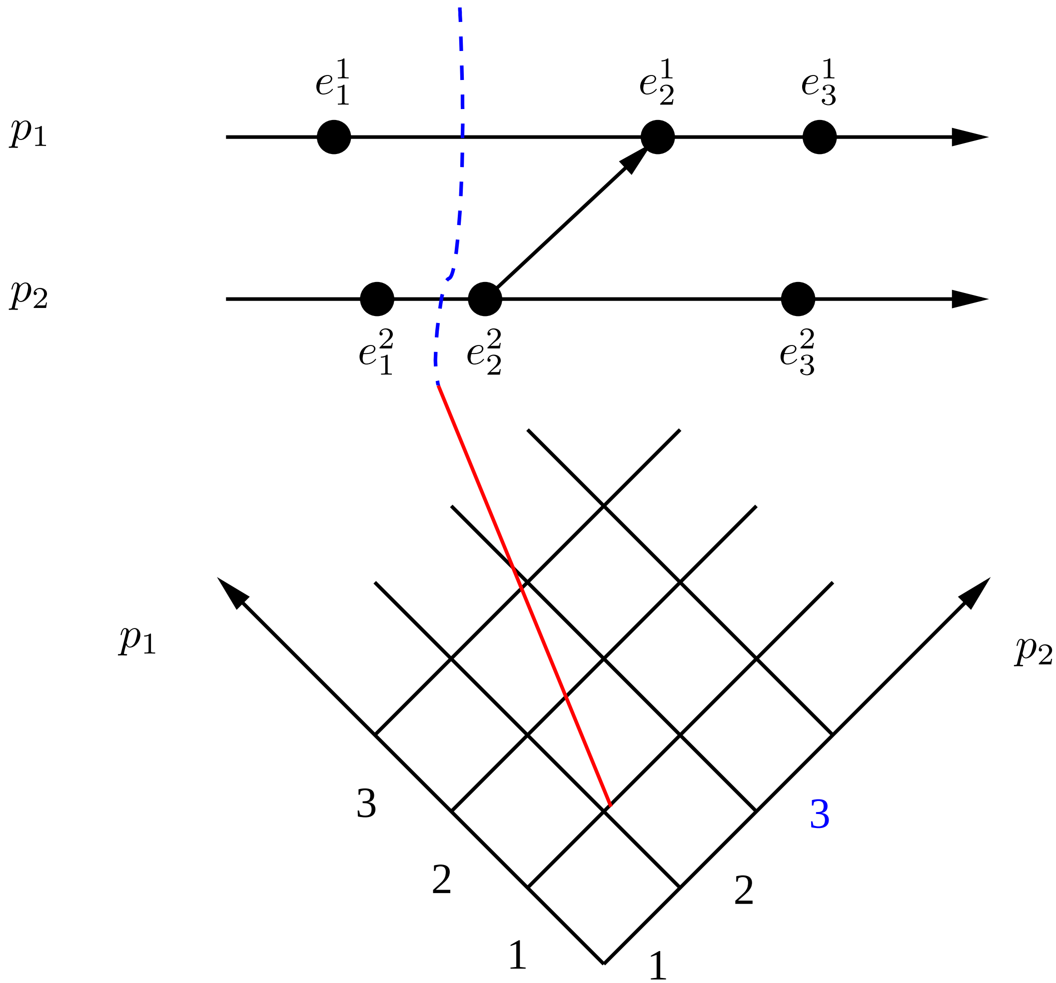

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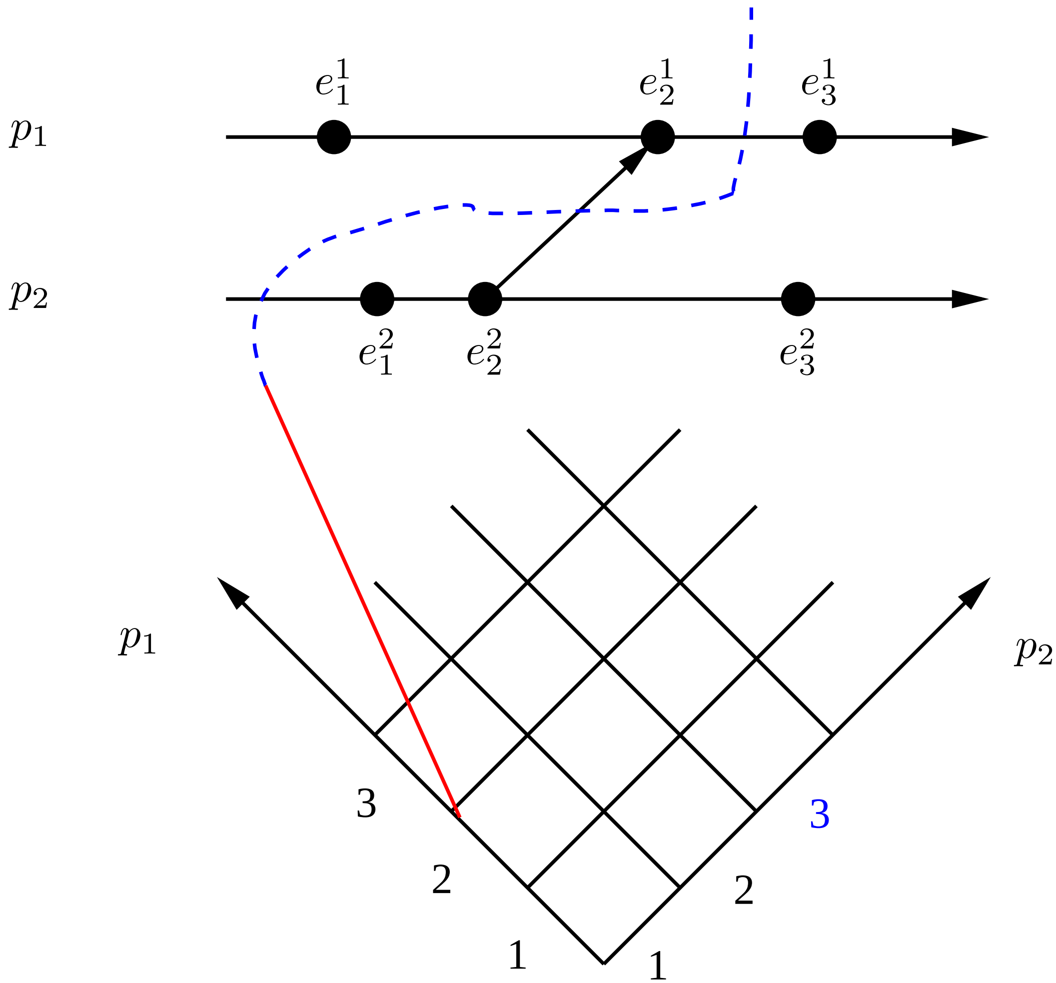

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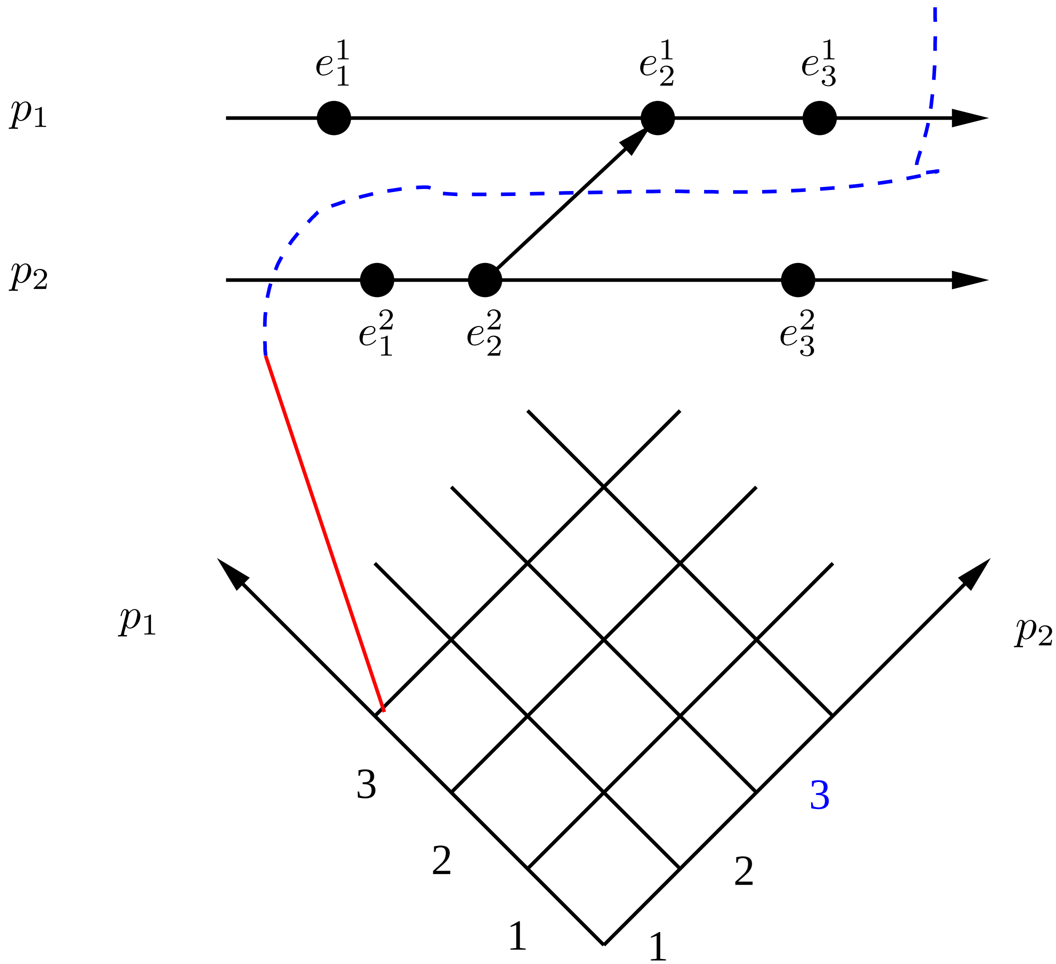

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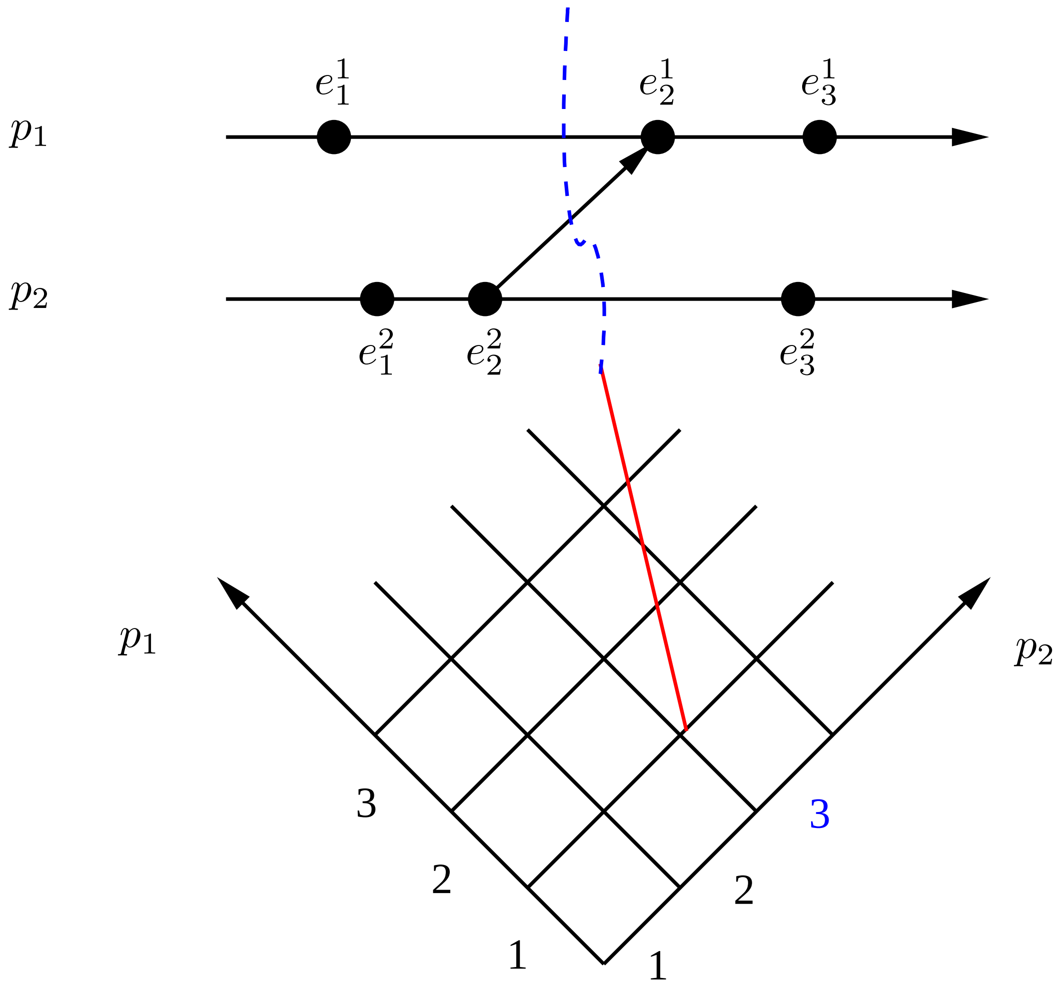

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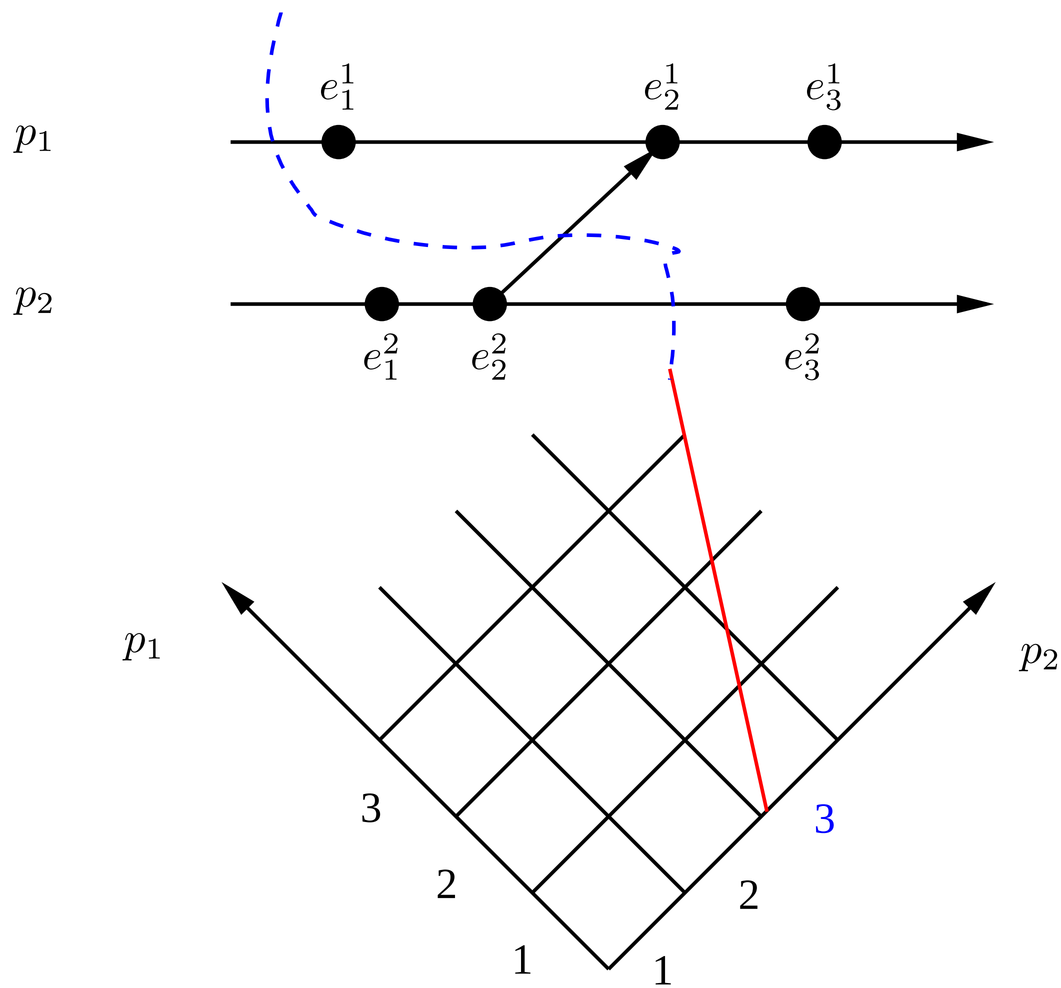

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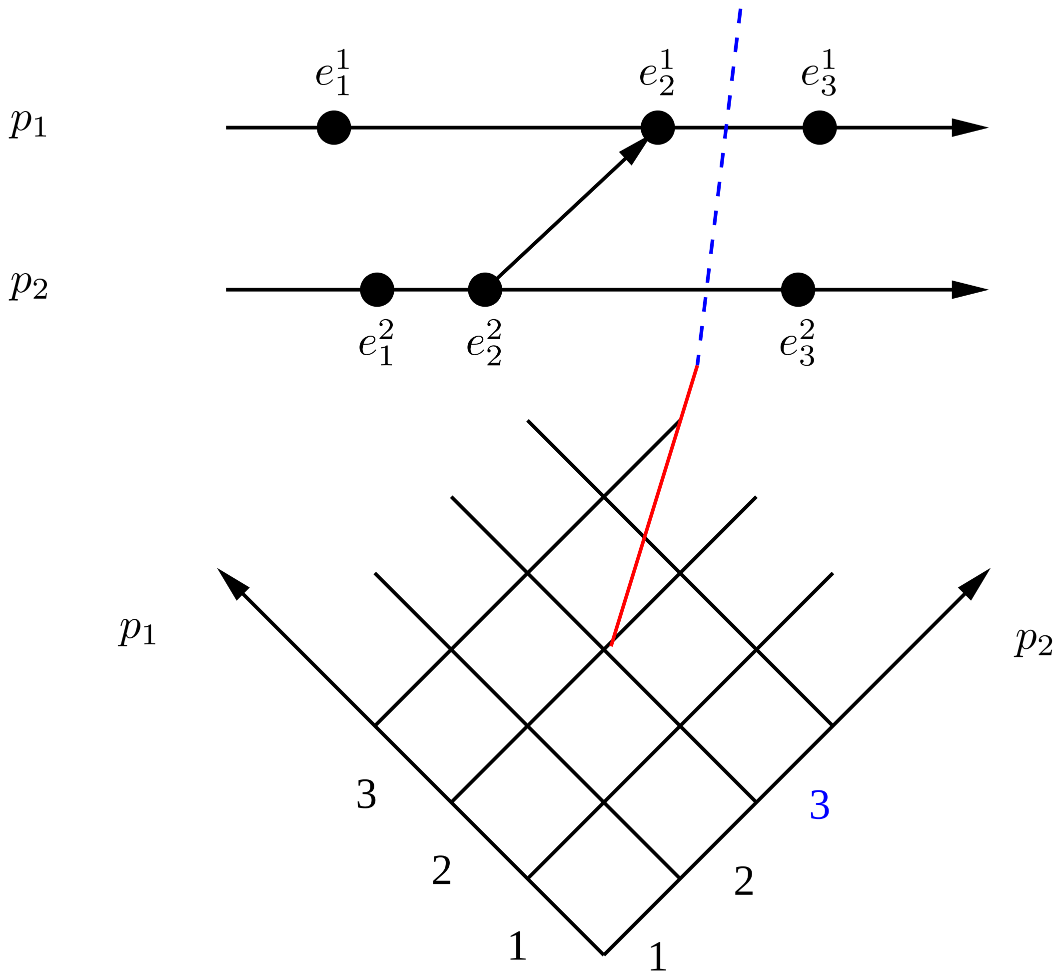

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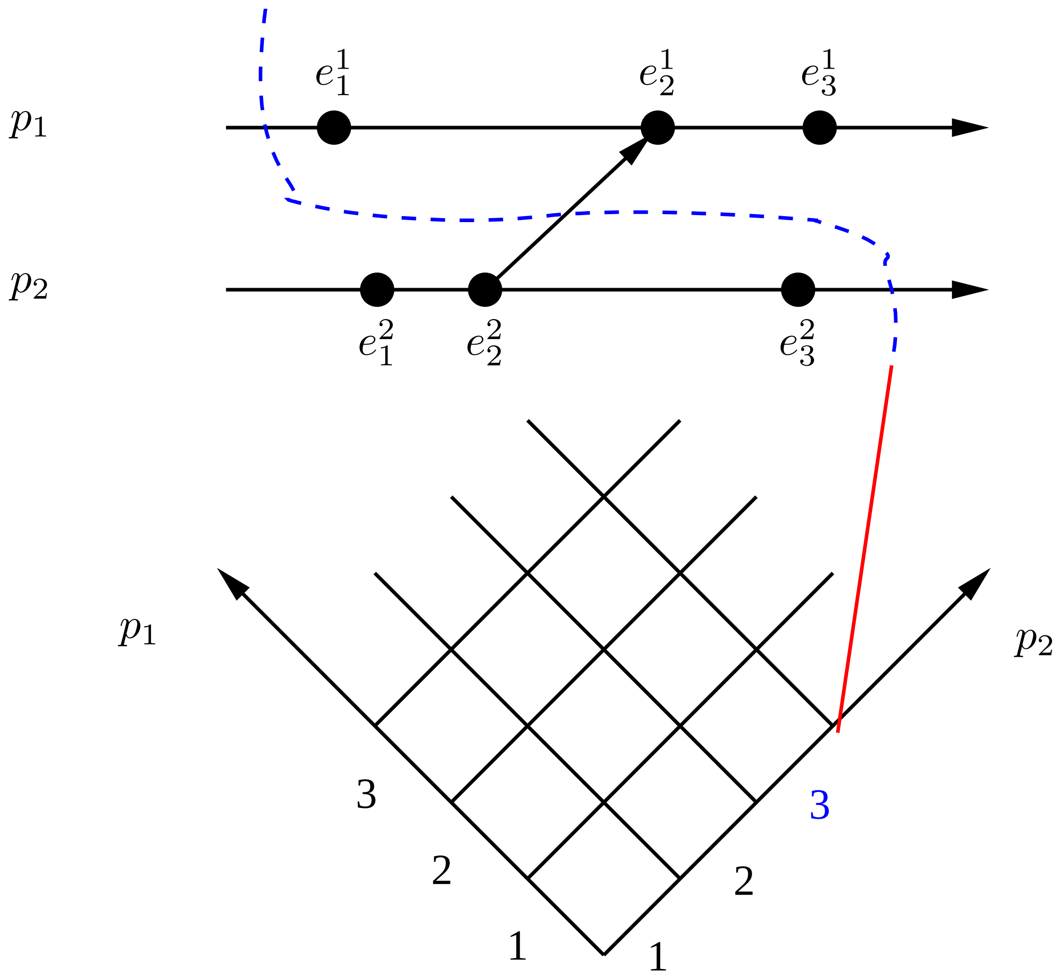

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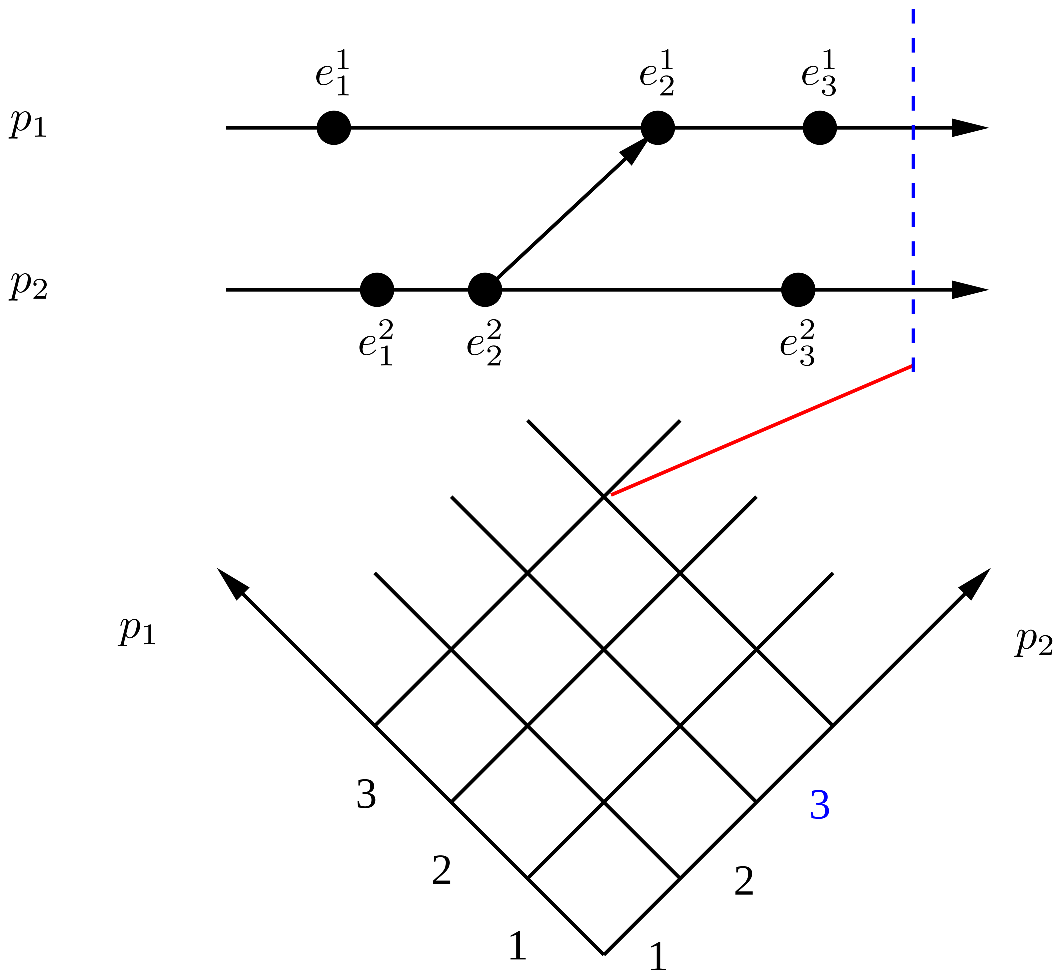

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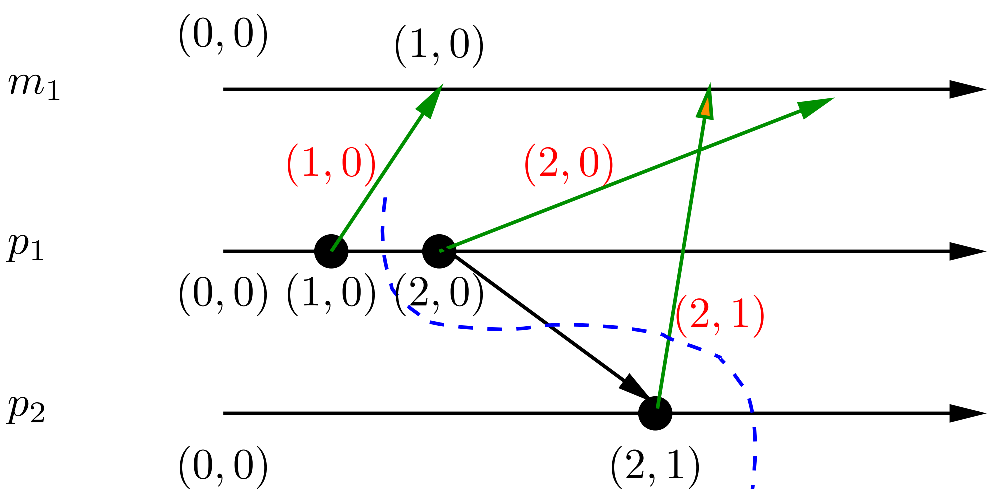
Consistent and inconsistent states

- Consistent state = respects causality
- Construct vector of local sequence numbers.
- Delay causally dependent control messages.



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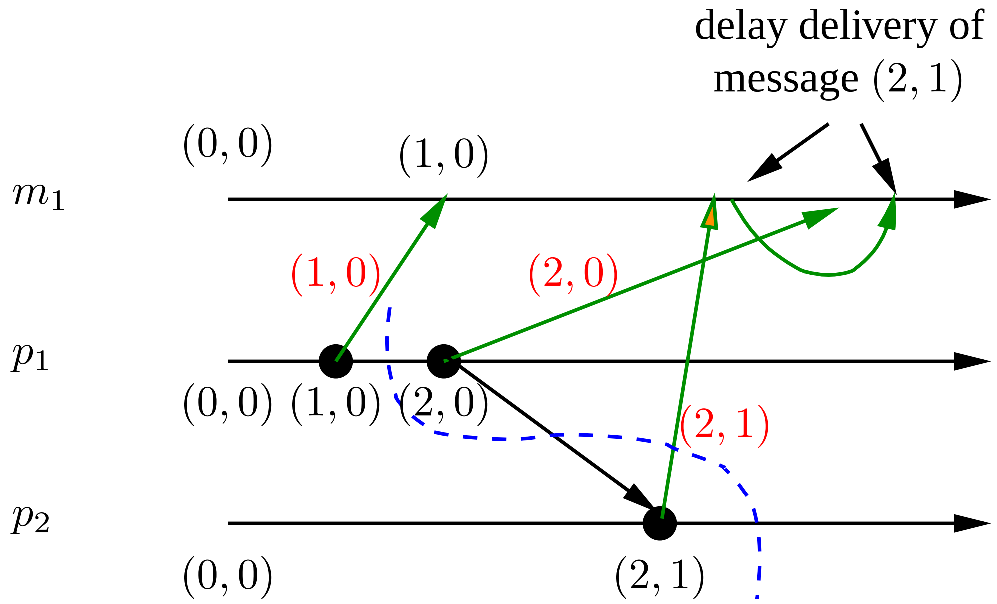

Modalities *possibly* and *definitely*

- Define observer-invariant notions:
  - $possibly(\varphi)$ holds iff there exists an observer which could see φ.
  - $definitely(\varphi)$ holds iff all observers at some time see φ.
- Observers construct and traverse state lattice to detect *possibly* or *definitely*.
- Safety requirement $\Box\varphi$: observers schould never detect $possibly(\neg\varphi)$.
- Liveness requirement $\Diamond\varphi$: detection of $definitely(\varphi)$ sufficient for validation.

Fault tolerance issues start here!

Faulty asynchronous systems

- Fault assumption = precise description about how and which components may fail.
- crash fault assumption = at most t processes simply stop executing steps.
- For the moment: restrict crash faults to application processes only (monitors always stay alive).
- Now study: predicate detection in asynchronous systems with crash faults.
- Only other work: Garg and Mitchell [3].

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New types of predicates

- Predicate up_i refers to functional state of p_i.
- Can be used in predicates:
  - Process p_i crashed after 4th event:

$$\neg up_i \wedge ec_i = 4$$

  - Every process either commits or crashes:

$$\forall i : \neg up_i \vee commit_i = 1$$

  - Process p_i is waiting for a message from a crashed process:

$$j \in waiting_i \wedge \neg up_j$$

Failure detection

- Every monitor must manipulate up_i so that:
  - (safety) never $\neg up_i$ if p_i has not crashed.
  - (liveness) if p_i crashes, eventually truthify $\neg up_i$.
- This is impossible in asynchronous systems (FLP [2]).
- Terminology: failure detectors *suspect* and *rehabilitate* application processes.

Implementable failure detectors

- Can ensure liveness, but cannot avoid false suspicions.
- Best we can do: a non-crashing process is not permanently suspected [4].
- For observation purposes: add causality information to suspicions:
  - "m_j suspects p_i after event e_k on p_i."
  - "m_j rehabilitates p_i after event e_k on p_i."
- Assume: between two events at most one suspicion and rehabilitation.

Lattice over extended state space

- Treat up_i as a variable on p_i.
- Suspicion/rehabilitation is a simple state change of p_i.

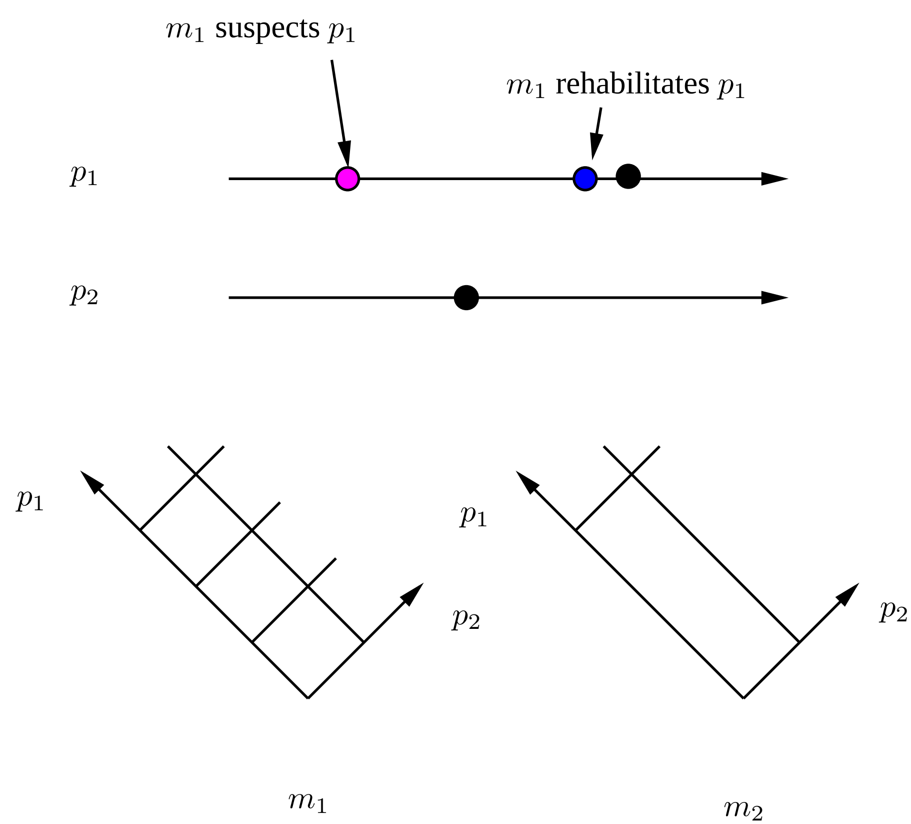
$\Rightarrow$ Extended state space.

- Change of up in consistent states yields again consistent states.

$\Rightarrow$ Integration of suspicions/rehabilitations into state lattice yields new lattice (over extended state space).

Per monitor lattice

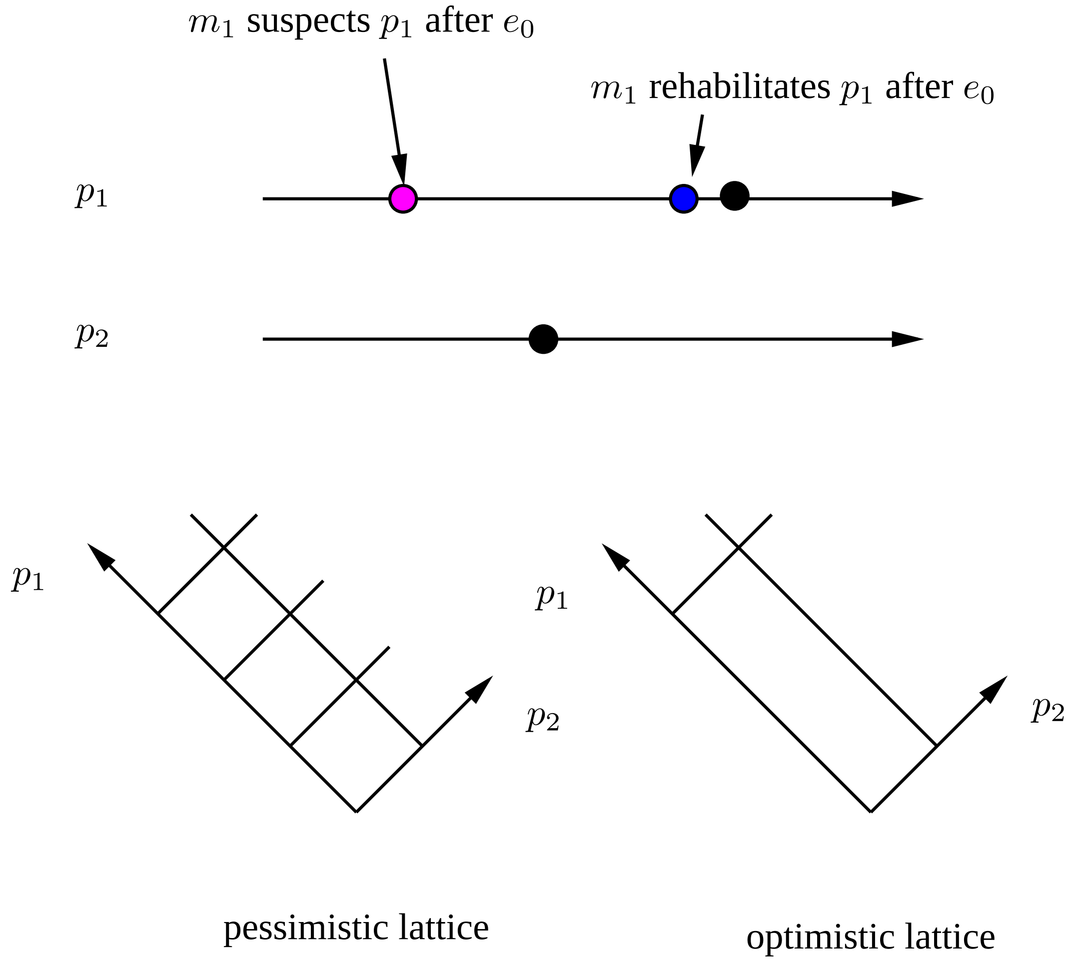
- Due to false suspicions monitors construct different state lattices.
- *possibly/definitely* not observer-invariant.



Global failure detector semantics

- Problem: false suspicions.
- Solution: define "global" failure detector semantics.
- p_i is suspected after e_k iff . . .
  - (pessimistic) $\exists$ a monitor which suspects p_i after e_k.
  - (optimistic) $\forall$ monitors suspect p_i after e_k.
- Can define pessimistic and optimistic state lattice.

Optimistic/pessimistic state lattice example



New modalities

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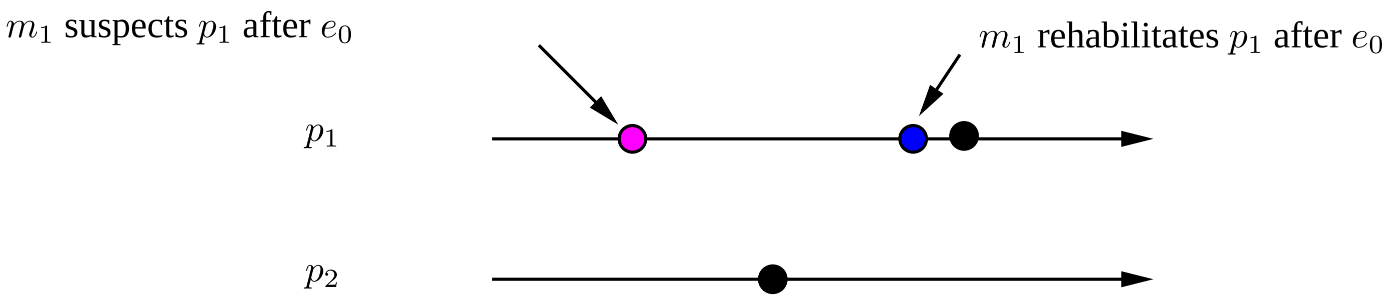
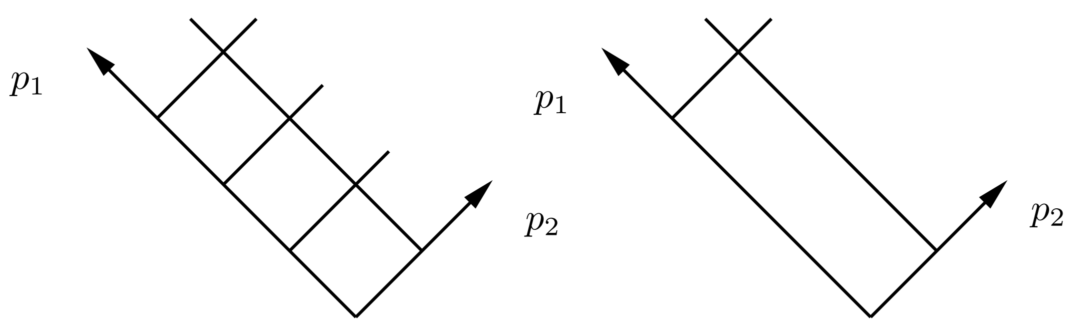
- Given predicate φ on extended state space.
- $negotiably(\varphi)$ holds iff $possibly(\varphi)$ holds on pessimistic state lattice.
- $discernibly(\varphi)$ holds iff $definitely(\varphi)$ holds on optimistic state lattice.





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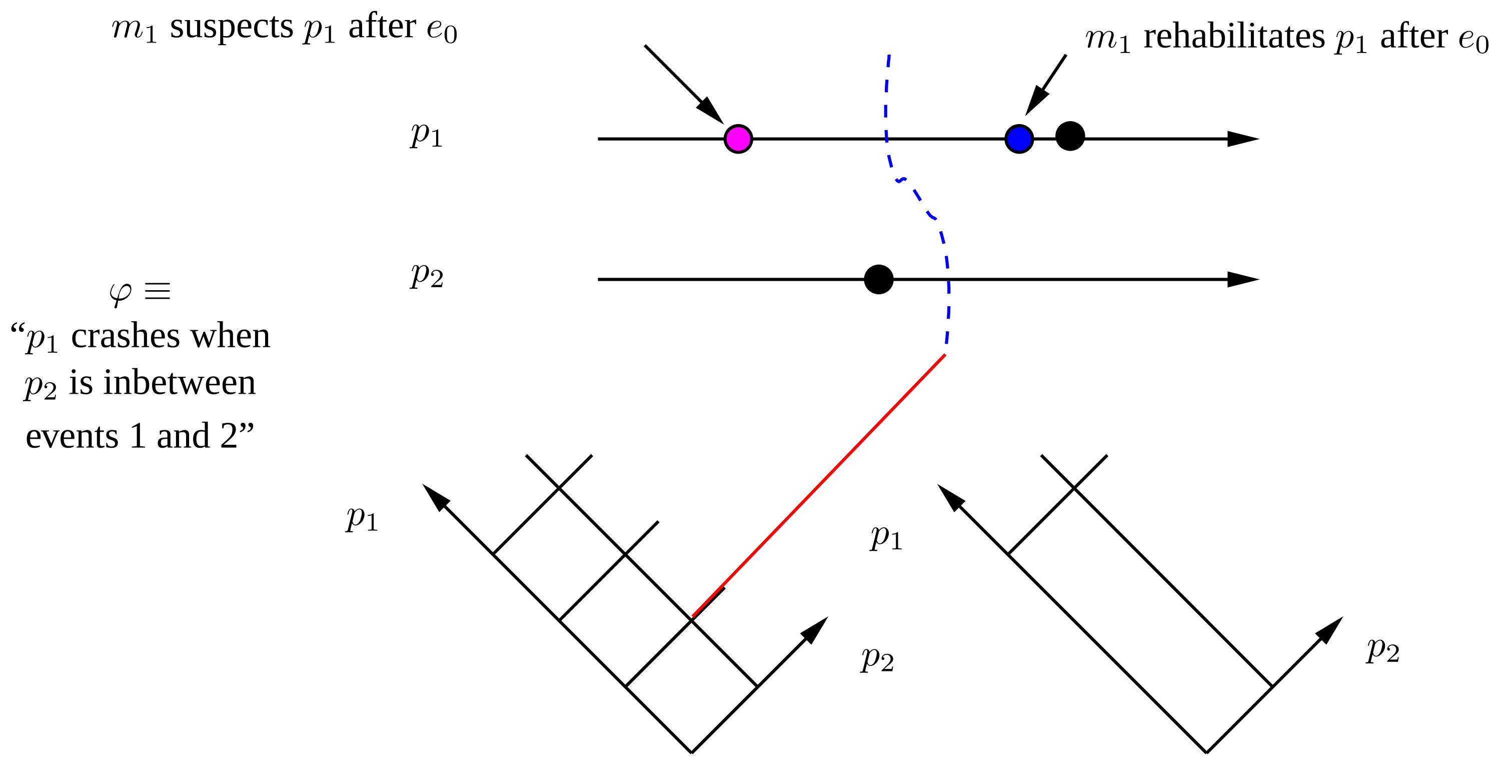

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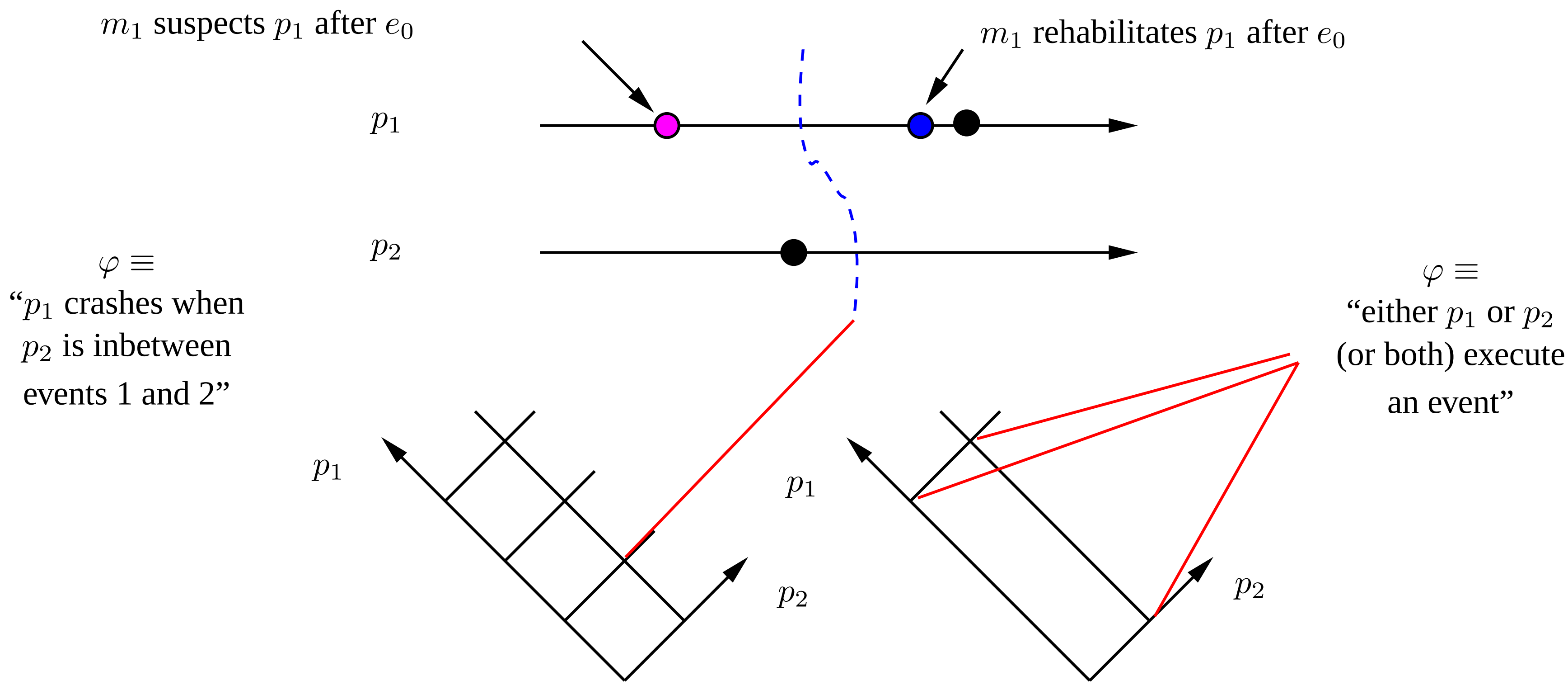


Intuition behind new modalities

- Intuition of optimistic/pessimistic network protocols:
  - pessimistic: be careful all the time, take immediate action.

  $\Rightarrow$ use *negotiably* to trigger action.
  - optimistic: go ahead and hope for the best.

  $\Rightarrow$ use *discernibly* to ignore spurious suspicions.

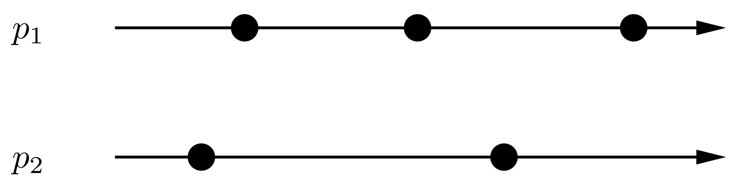
- Understandable in analogy to *possibly*/*definitely*:
  - Safety requirement $\Box\varphi$: take action if $negotiably(\neg\varphi)$ is detected.
  - Liveness requirement $\Diamond\varphi$: validated if $discernibly(\varphi)$ is detected.

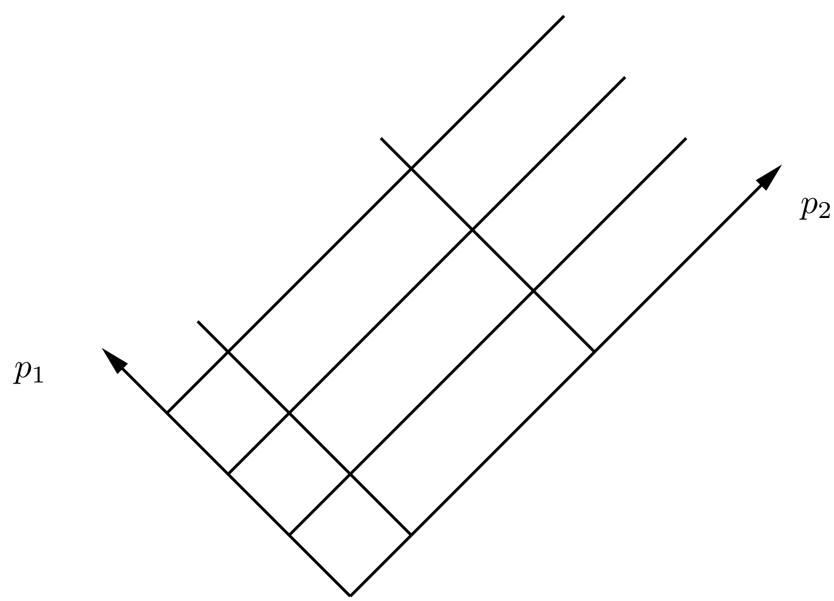
Detection algorithms

- Let monitors broadcast their suspicions to all other monitors.
- Eventually all monitor lattices converge.
- Can then do $possibly/definitely$ detection in observer invariant state lattices (use standard algorithms).

Lattice convergence example

- No use starting detection on “unfinished” lattice!





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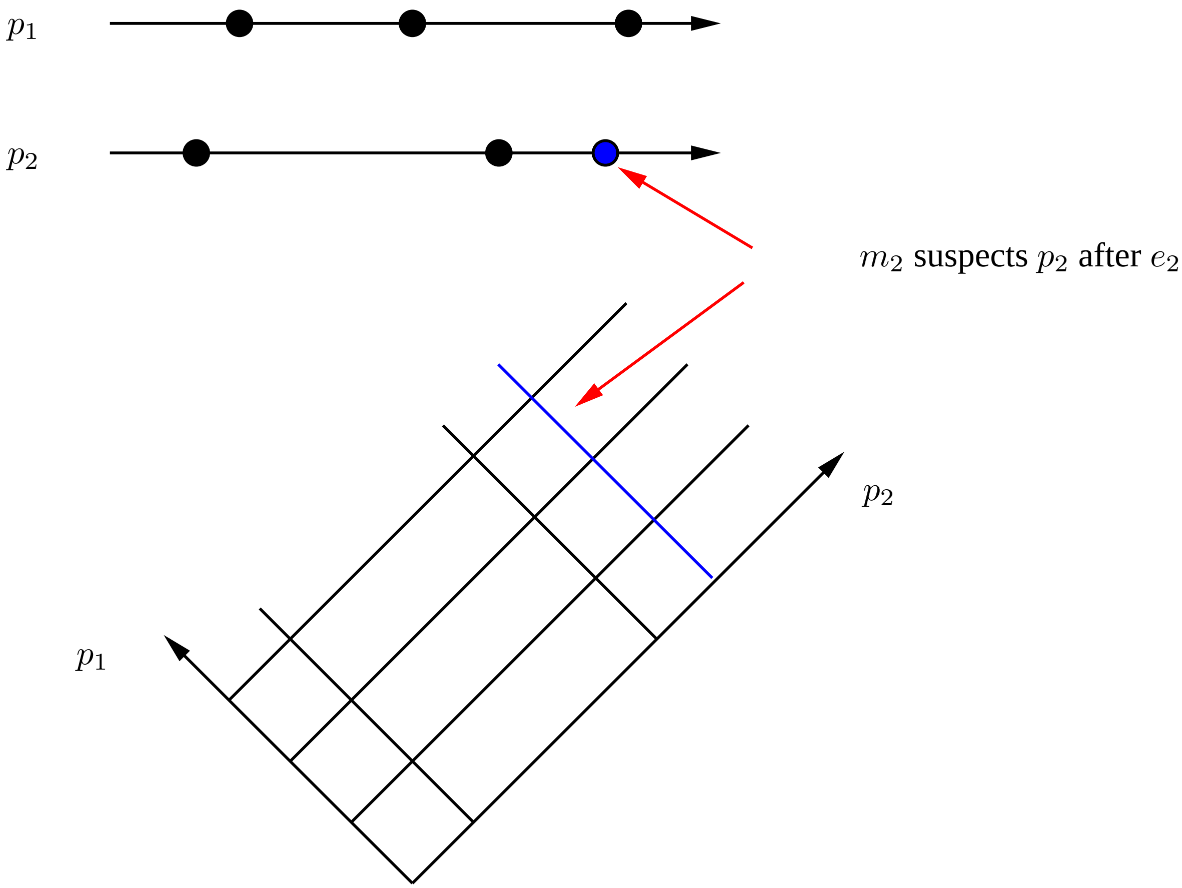

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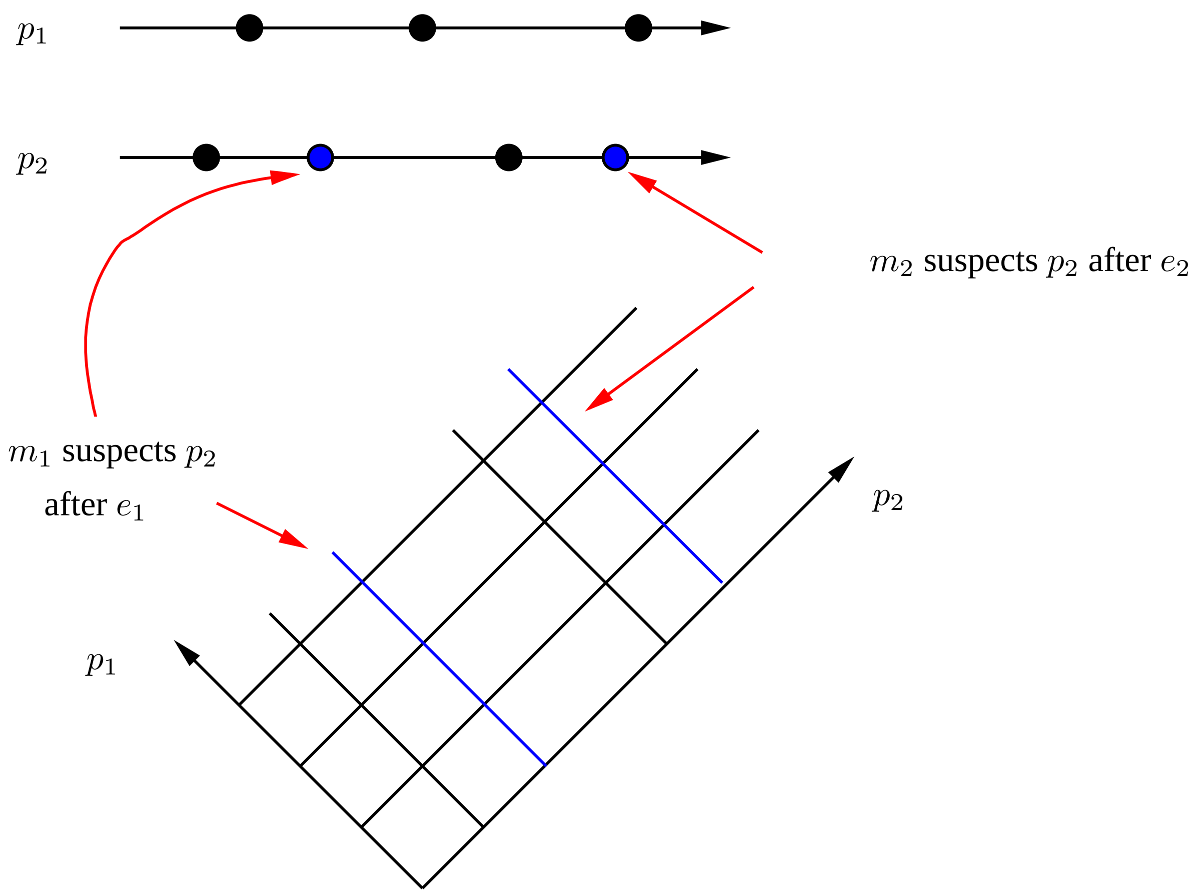

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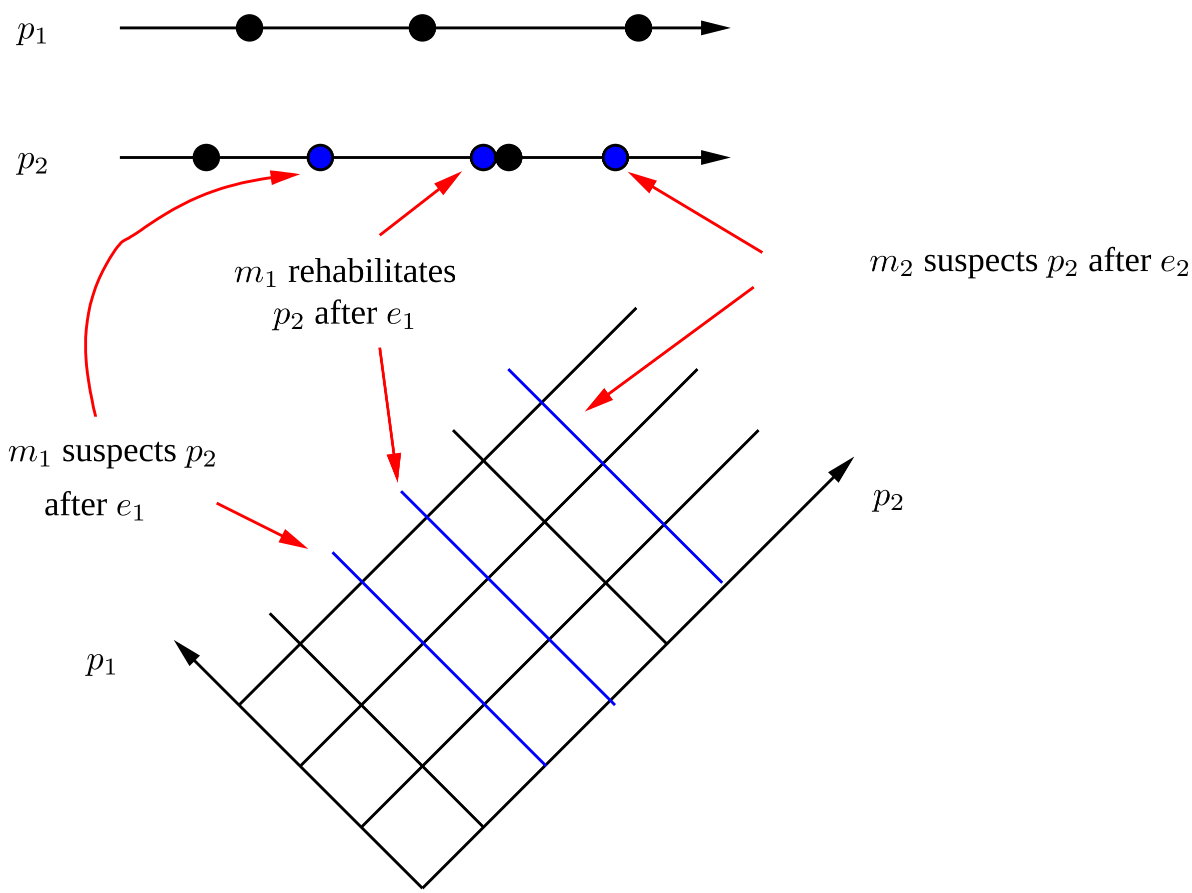
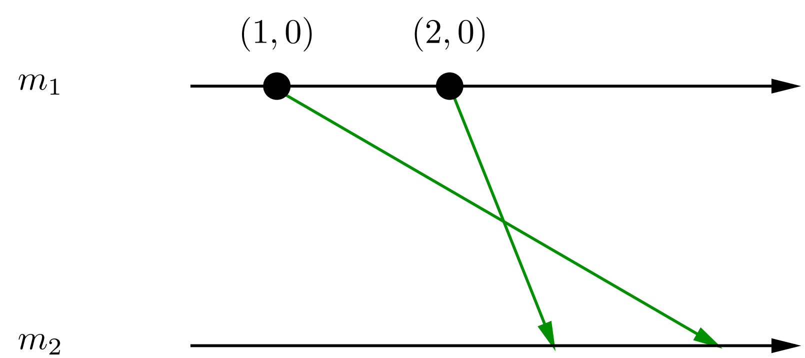


Causal broadcast of failure detector info

- Idea: causally broadcast failure detector events.
- You'll always get the "next one".



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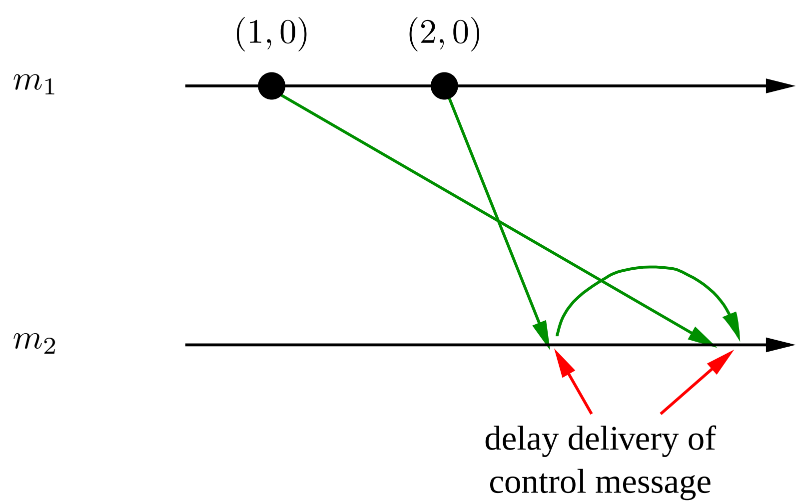
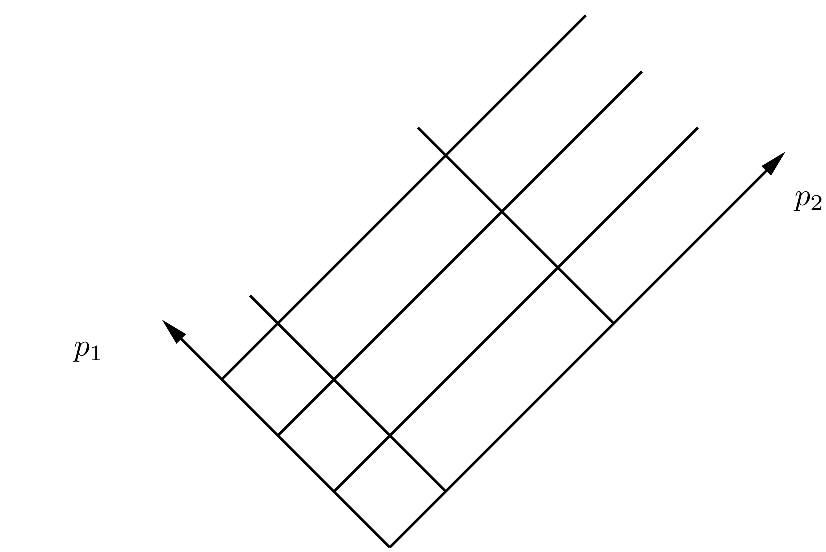


Settled region

- Causal broadcast of failure detector messages is useful!
- Monitors piggy back coordinates of most recent global state they have seen: per monitor stable region.
- Take intersection of all monitor regions: globally stable region.
- Steadily expand stable region, extract optimistic/pessimistic data and do $possibly/definitely$ detection on it.

Settled region example



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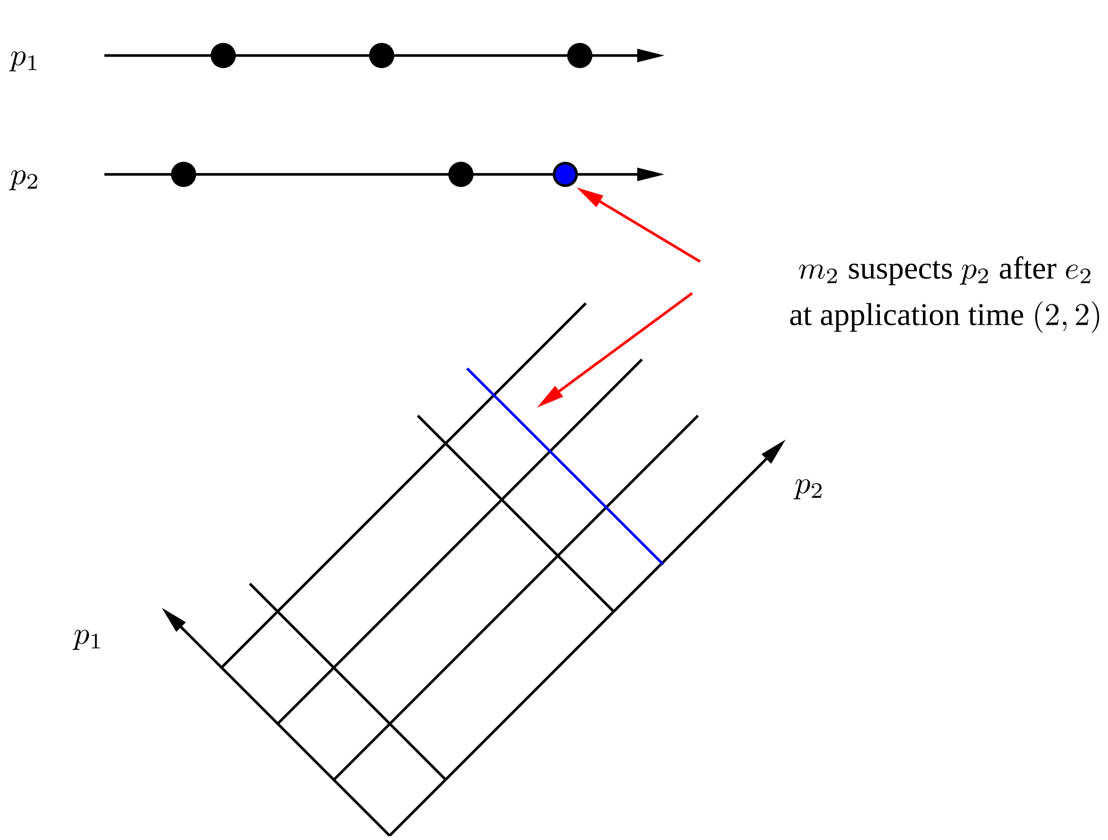

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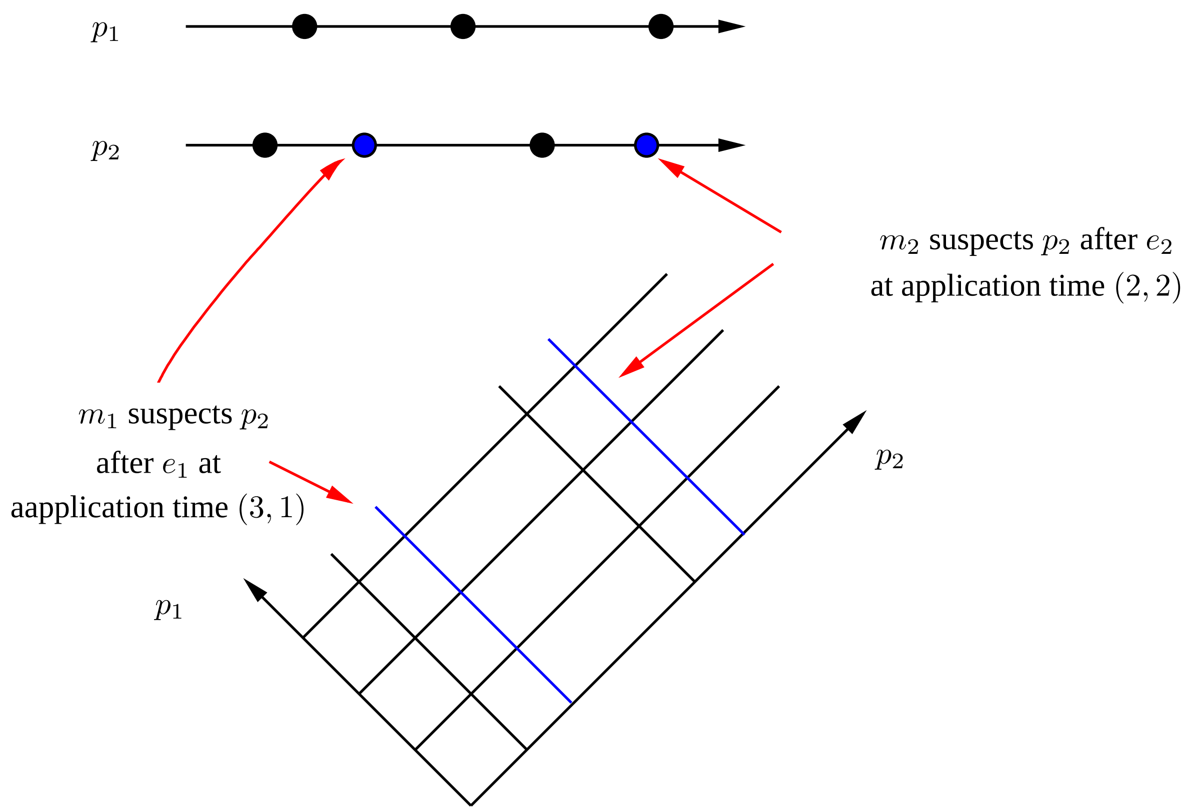

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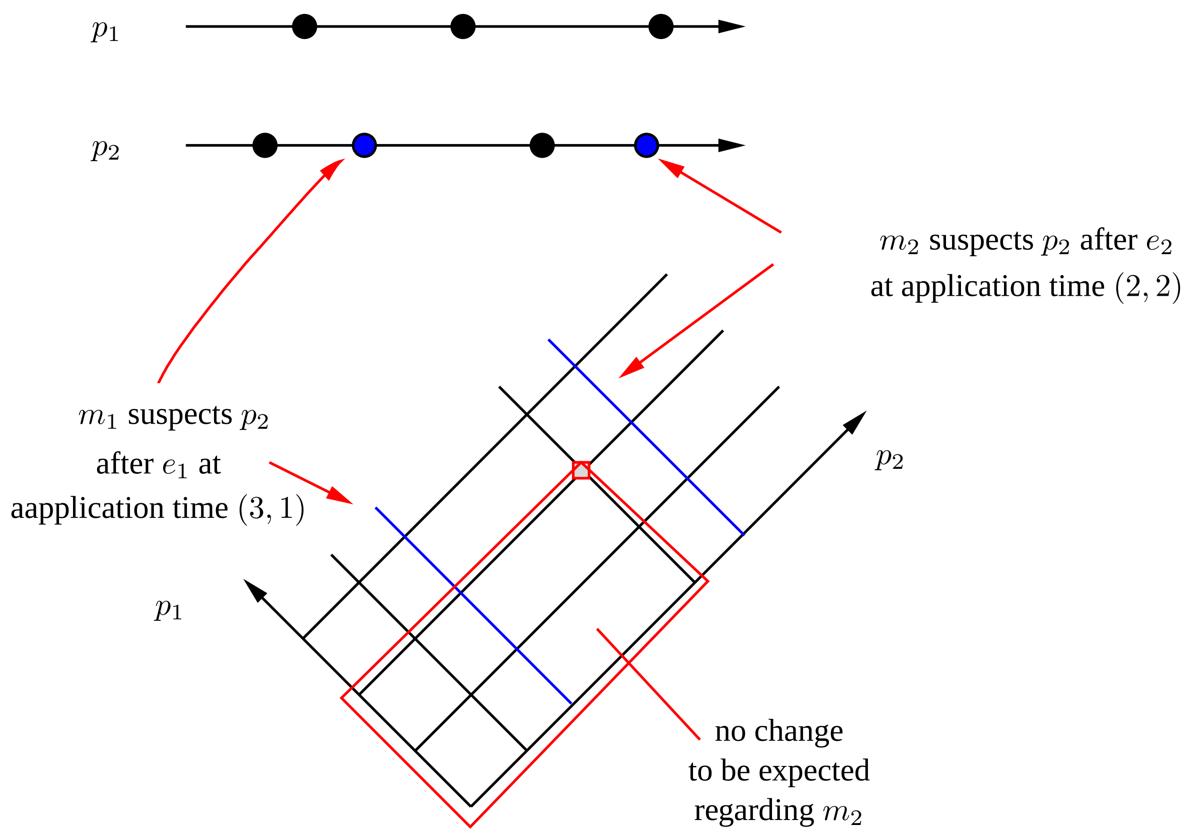

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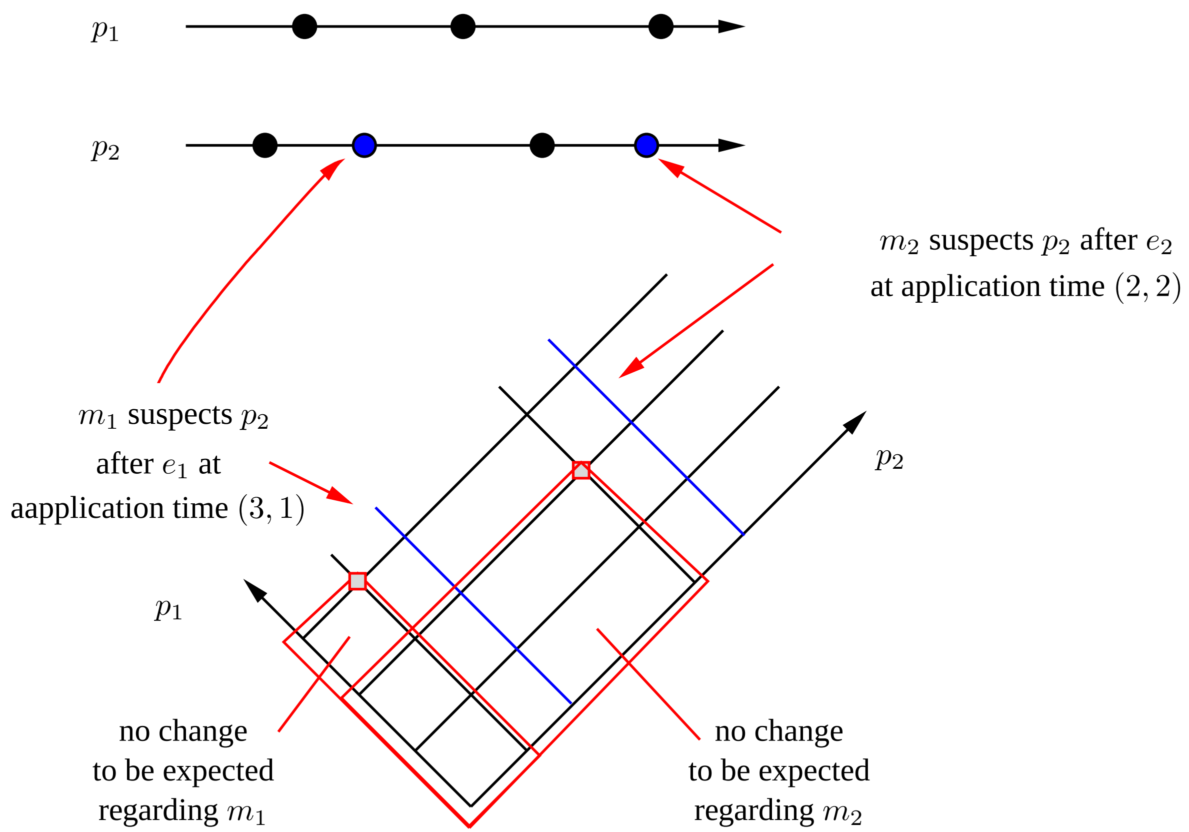

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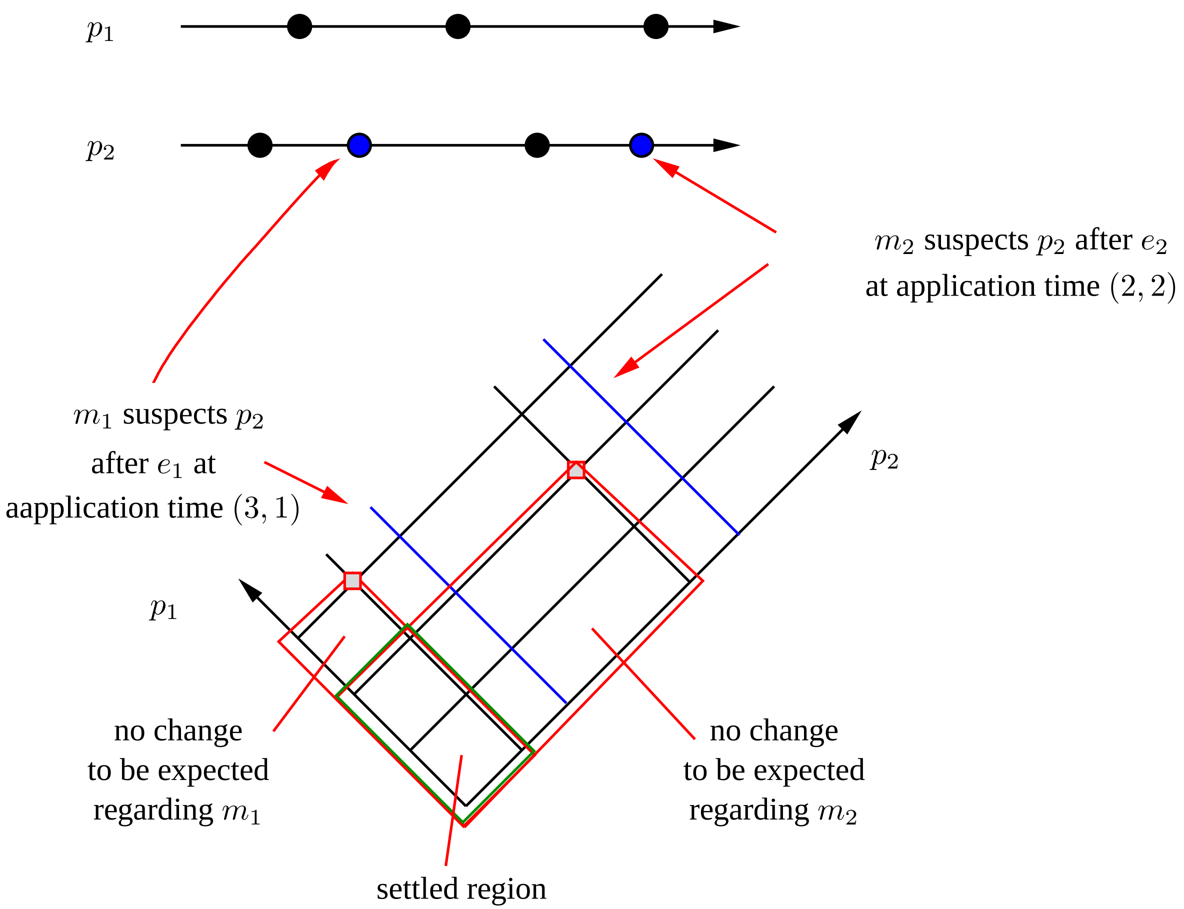

Advanced topics

- Algorithm works under assumption that no monitors fail.
- If monitors can fail, detection becomes harder:
  - Can still detect *negotiably* without a stable region.
  - Detection *discernibly* impossible, because accurate failure detection is needed.
  - A weaker variant (*t-discernably*) can be detected at the price of having a majority of correct monitors.

Complexity and restricted predicates

- Complexity:
  - general predicate detection is NP-complete [1].
  - Our detection algorithms are only wrappers around possibility/definitely detection.
  - Study restricted classes of predicates.
- Perfect failure detectors available:
  - No false suspicions.
  - Optimistic/pessimistic lattice are the same.
- Perfect failure detectors and crash predicates:
  - Predicates are stable.
  - $possibly{=}definitely \rightarrow negotiably{=}discernibly$

Overview of results

- First work to deal with general predicates in faulty systems.
- Observation modalities $negotiably$ and $discernibly$. . .
  - do not solve all problems in crash-affected systems.
  - reflects by their definition the inherent problem of crash failure detection.
  - can be understood in analogy to $possibly$ and $definitely$.
  - can be detected in asynchronous systems, even if monitors may crash.
- Still a lot of work to do.

References

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[2] Michael J. Fischer, Nancy A. Lynch, and Michael S. Paterson. Impossibility of distributed consensus with one faulty process. *Journal of the ACM*, 32(2):374–382, April 1985.

[3] Vijay K. Garg and J. Roger Mitchell. Distributed predicate detection in a faulty environment. In *Proceedings of the 18th IEEE International Conference on Distributed Computing Systems (ICDCS98)*, 1998.

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Acknowledgements

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