Verification of FIFO systems

and more specifically synchronizability

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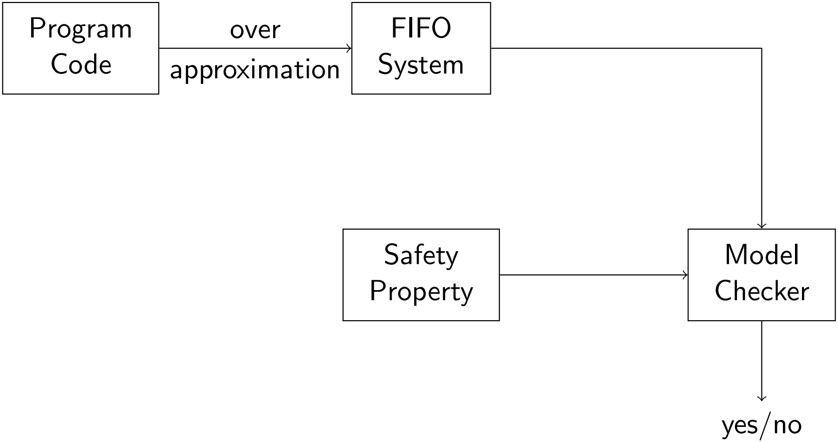
FIFO Queues are everywhere

```go
func prod(ch chan int) {
  for i := 0; i < 5; i++ {
    ch <- i // Send i to ch
  }
  close(ch) // No further values accepted at ch
}
func cons(ch1, ch2 chan int) {
  for {
    select {
    case x := <-ch1: print(x) // Either input from ch1
    case x := <-ch2: print(x) // or input from ch2
    }
  }
}
func main() {
  ch1, ch2 := make(chan int), make(chan int)
  go prod(ch1)
  go prod(ch2)
  cons(ch1, ch1)
}
```

Producer-Consumer in Go
From Lange, Ng, Toninho and Yoshida, ICSE'18

The Model-Checking Approach



ex: communication contracts, session types, ...

FIFO Systems: Definition

- a finite alphabet of messages
- a finite number of unbounded FIFO queues
- a finite parallel composition $P_1 || \dots || P_n$
- a process is a goto program with two basic atomic actions: queuing and dequeuing

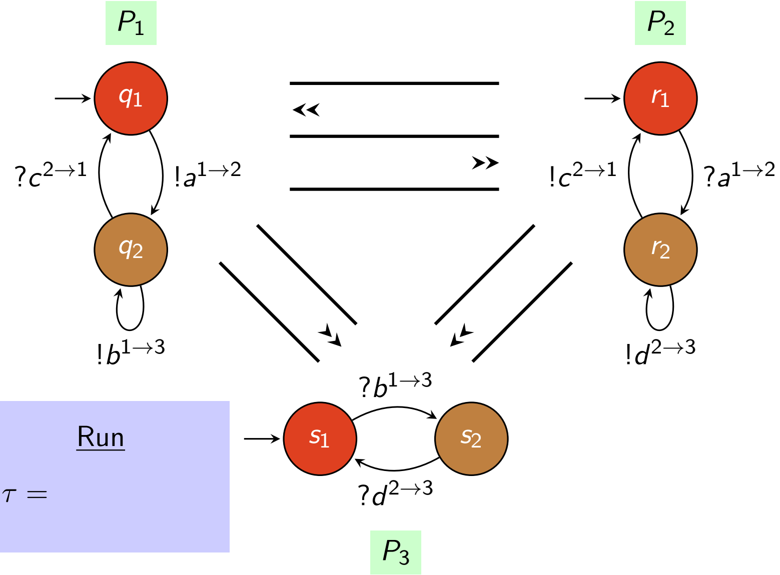
$$
\begin{array}{lcll}
P & ::= & q!a.P & \text{(enqueue a in q)} \\
 & | & q?a.P & \text{(dequeue a from q)} \\
 & | & P + P' & \text{(choice)} \\
 & | & X & \text{(goto)} \\
 & | & \text{rec } X.P & \text{(label)}
\end{array}
$$

Network Topology

- p2p : one queue per pair of processes
- mailbox : one queue per process
- binary system : p2p/mailbox with 2 processes

- general case: a process can queue/dequeue in all queues

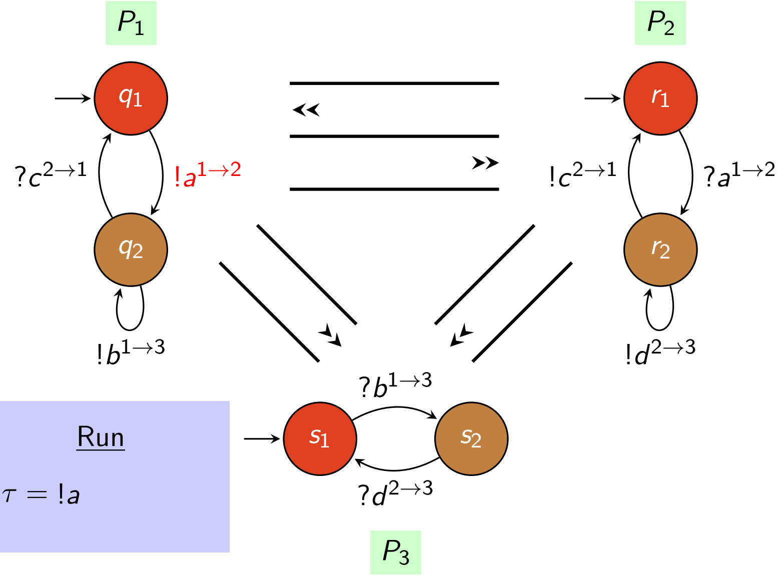
Example: a P2P System



Run

$\tau =$

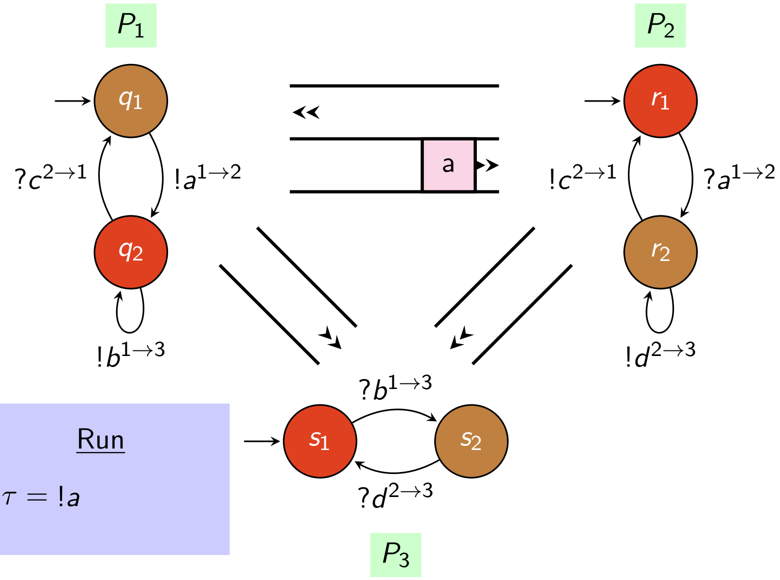
Example: a P2P System



Run

$\tau = !a$

Example: a P2P System



Run

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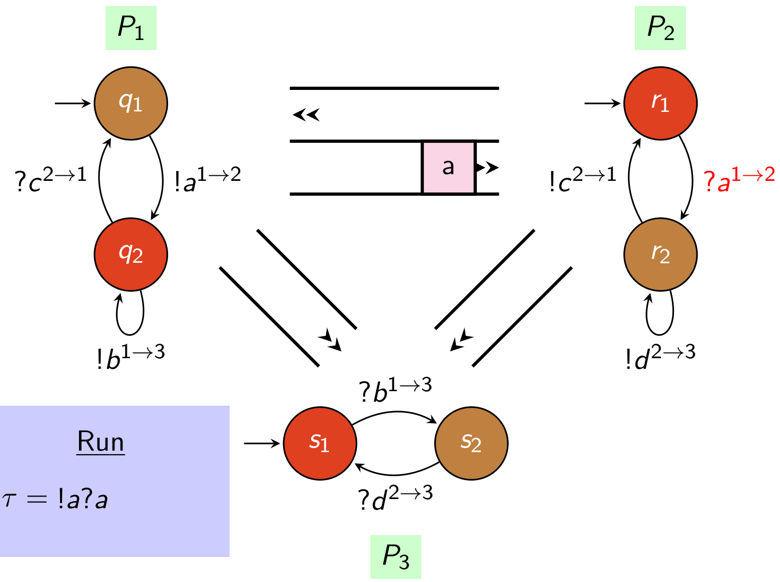
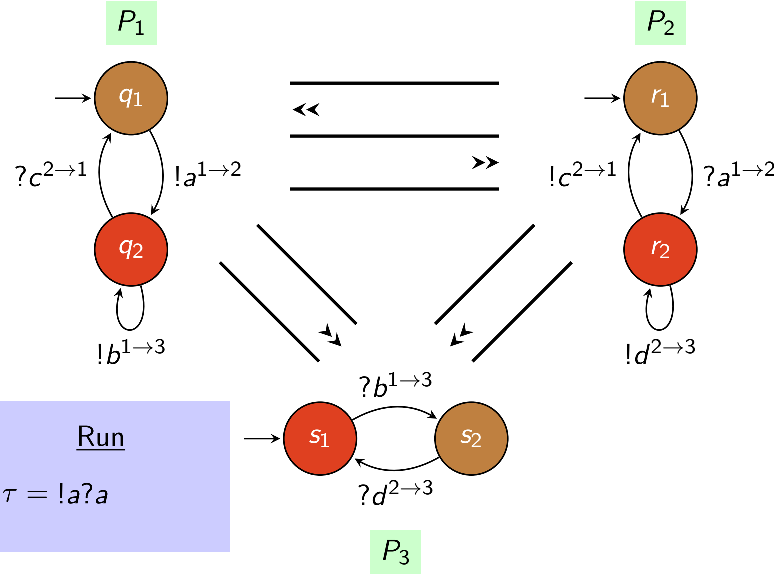


Run

$\tau = !a?a$

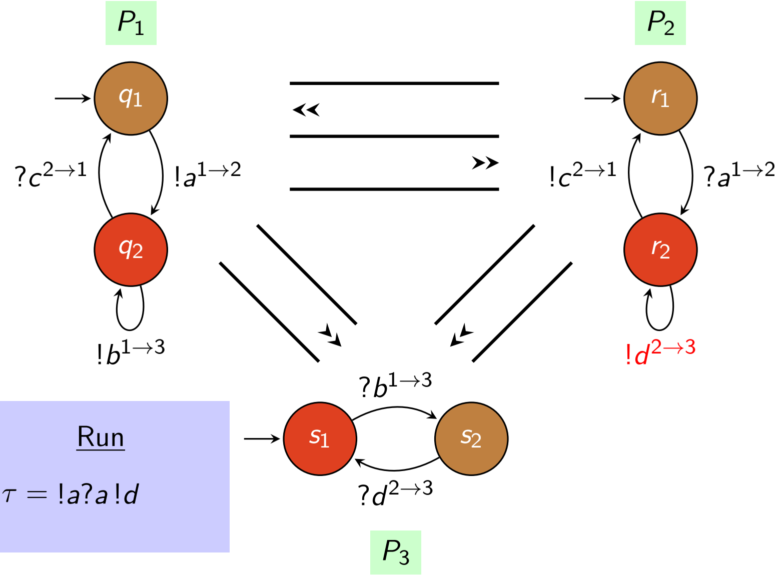
Example: a P2P System



Run

$\tau = !a?a$

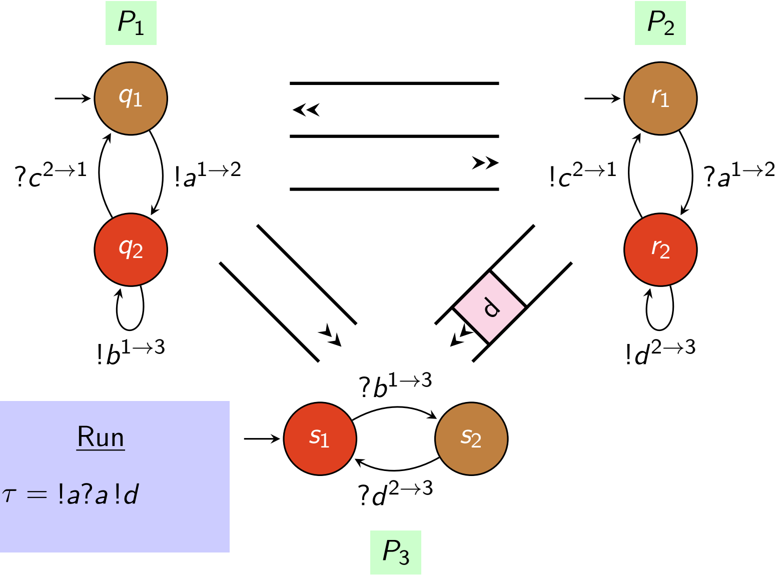
Example: a P2P System



Run

$\tau = \,!a?a\,!d$

Example: a P2P System



Run

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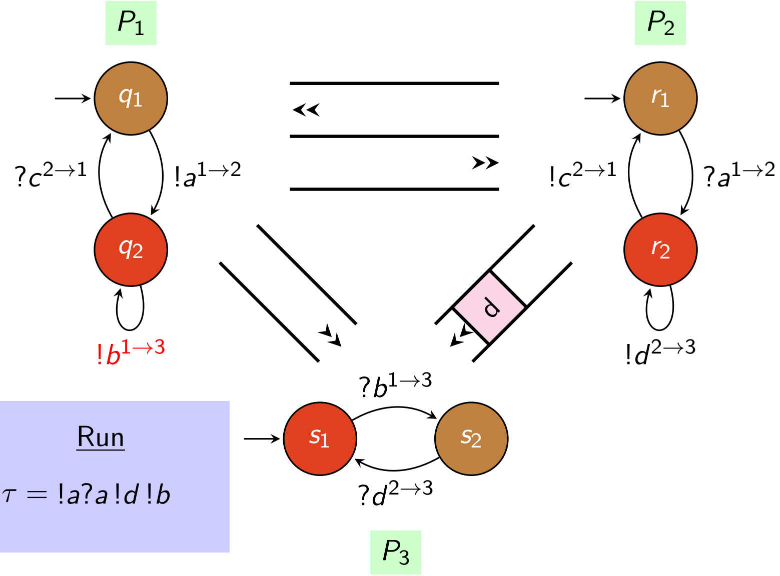
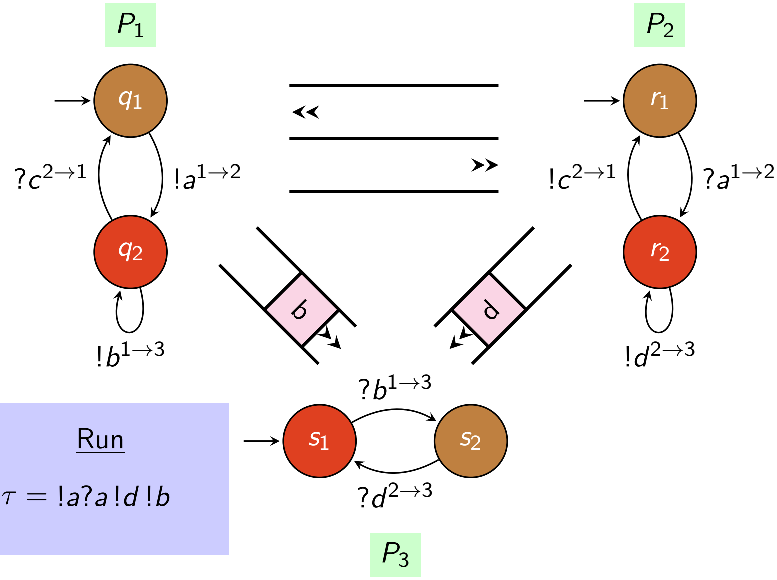


Run

$\tau = !a?a!d!b$

Example: a P2P System



Run

$\tau = !a?a!d!b$

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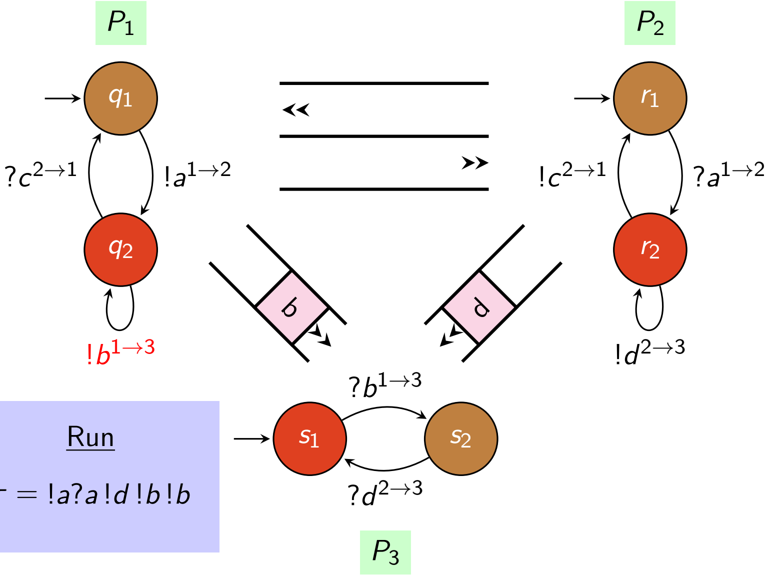

Run

$\tau = !a?a!d!b!b$

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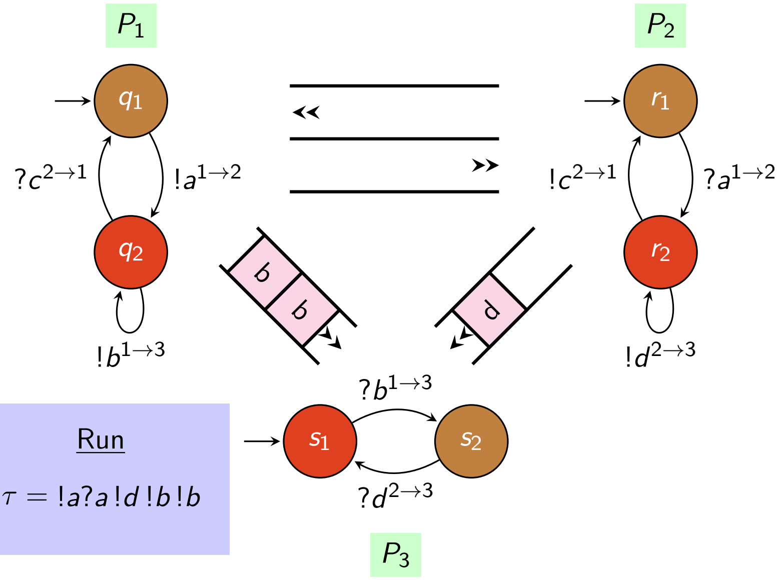
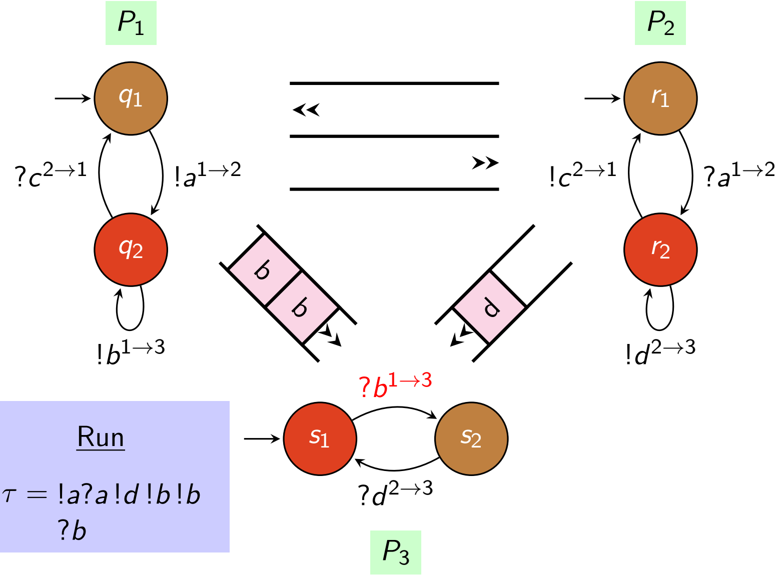


Run

$\tau = !a?a\,!d\,!b\,!b$

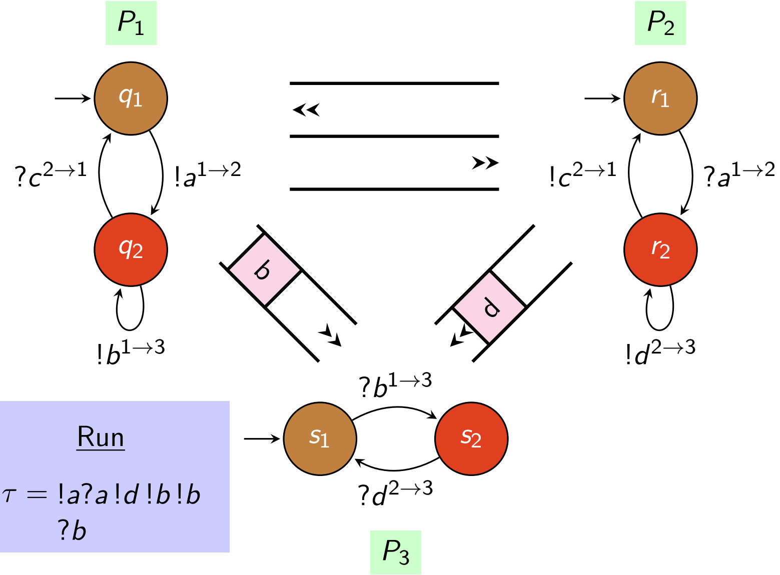
Example: a P2P System



<u>Run</u>

$\tau = !a?a!d!b!b$
$?b$

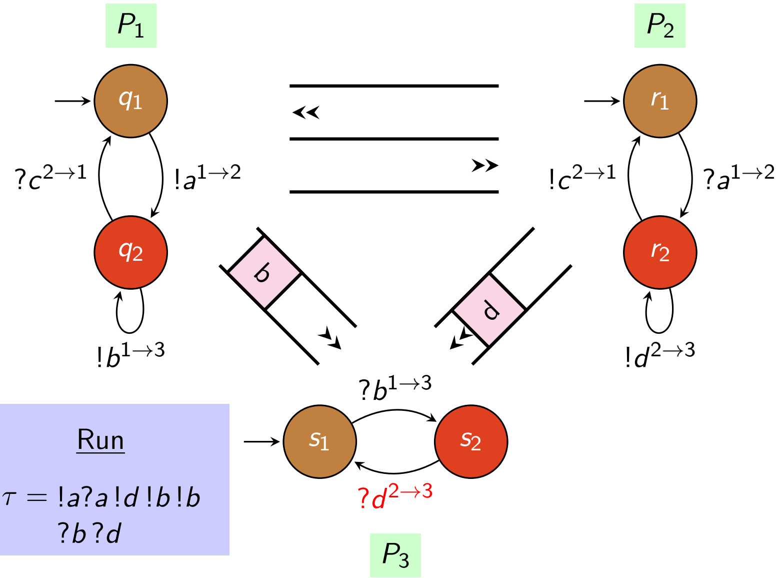
Example: a P2P System



Run

$\tau = !a?a!d!b!b$
$?b$

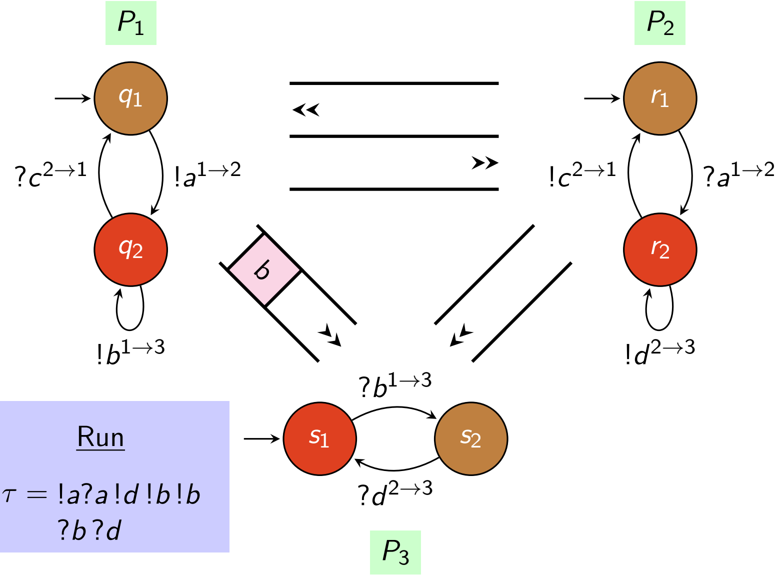
Example: a P2P System



<u>Run</u>

$\tau = \,!a?a\,!d\,!b\,!b\,?b\,?d$

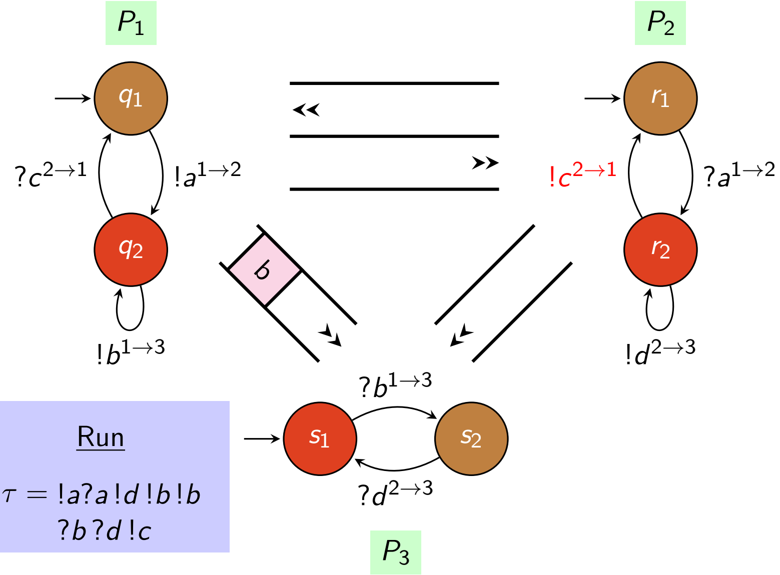
Example: a P2P System



Run

$\tau = \,!a?a\,!d\,!b\,!b\,?b\,?d$

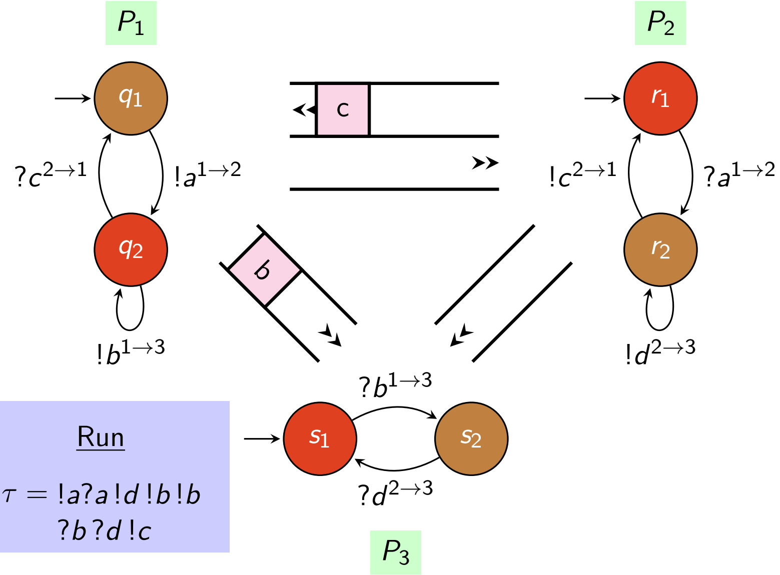
Example: a P2P System



Run

$\tau = !a?a!d!b!b$
$?b?d!c$

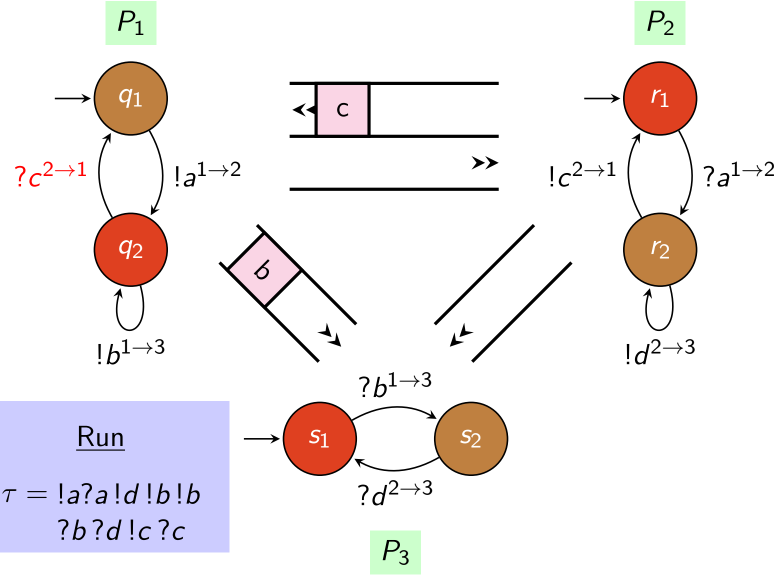
Example: a P2P System



<u>Run</u>

$\tau = \,!a?a\,!d\,!b\,!b$
$?b\,?d\,!c$

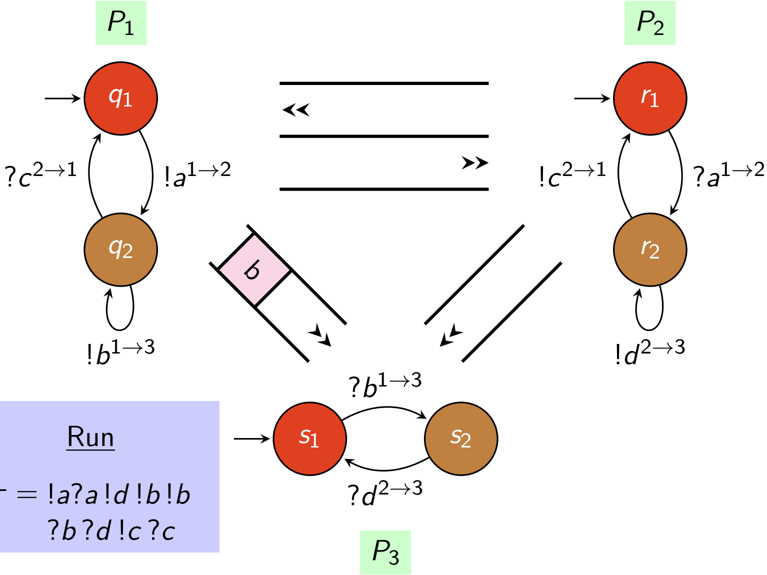
Example: a P2P System



Run

$\tau = \,!a\,?a\,!d\,!b\,!b$
$\quad ?b\,?d\,!c\,?c$

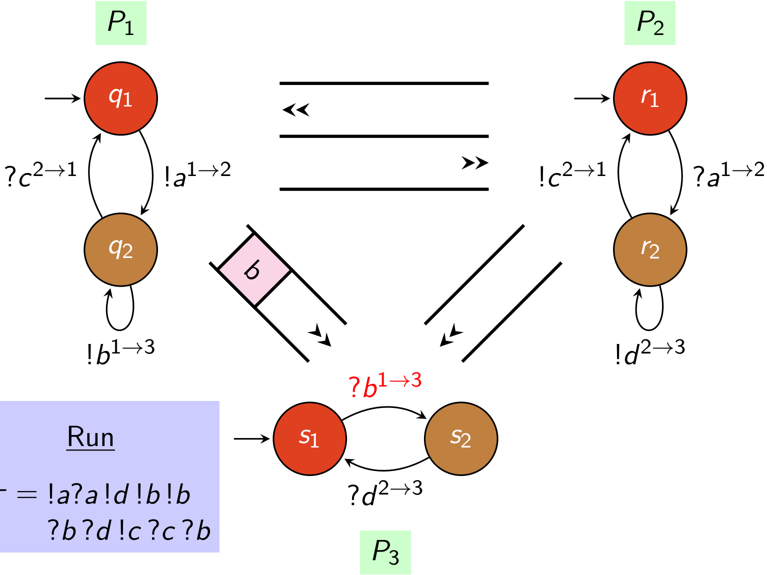
Example: a P2P System



<u>Run</u>

$$\tau = \,!a?a\,!d\,!b\,!b\;?b\,?d\,!c\,?c$$

Example: a P2P System



Run

$\tau = !a?a\,!d\,!b\,!b$
$\quad ?b\,?d\,!c\,?c\,?b$

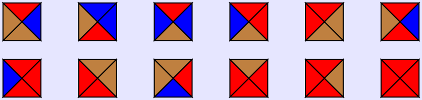
Verification Problems

- is there a bound on the size of the queues (for all runs) ?
- is there a run where a message is sent but never received?
- is there a run where a machine receives an unexpected message?
- is there a reachable configuration where all machines wait for messages but the queues are empty?
- ...

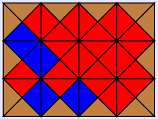
All these questions (and many others) are undecidable
[Brand Zafiropulo, JACM 1983]

Unary FIFO system and Tiling

Set of tiles



Solution



Unary FIFO system and Tiling

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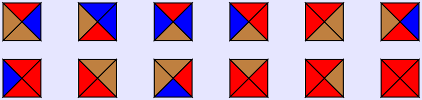

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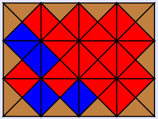
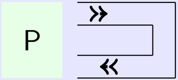


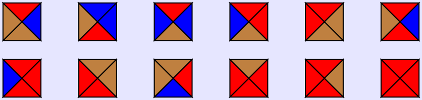
FIFO system



The process P guesses the solution

Unary FIFO system and Tiling

Set of tiles



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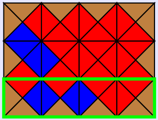
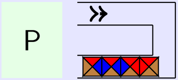


FIFO system

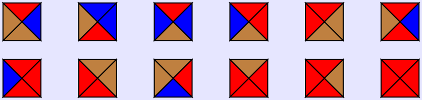


Guess first row and queue it

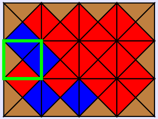
The process P guesses the solution

Unary FIFO system and Tiling

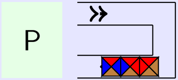
Set of tiles



Solution



FIFO system

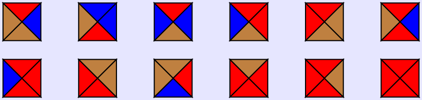


Guess tile above

The process P guesses the solution

Unary FIFO system and Tiling

Set of tiles



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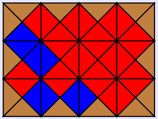
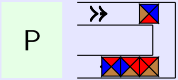


FIFO system



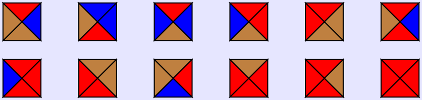
Guess tile above

and queue it

The process P guesses the solution

Unary FIFO system and Tiling

Set of tiles



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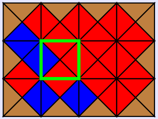

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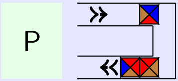
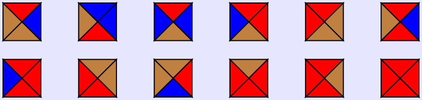


Guess tile above

The process P guesses the solution

Unary FIFO system and Tiling

Set of tiles



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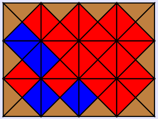

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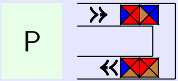


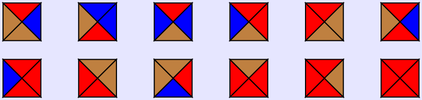
Guess tile above

and queue it

The process P guesses the solution

Unary FIFO system and Tiling

Set of tiles



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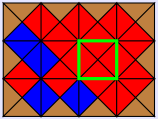

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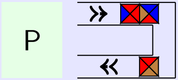
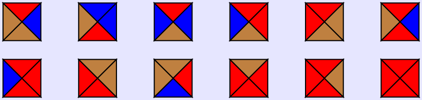


Guess tile above

The process P guesses the solution

Unary FIFO system and Tiling

Set of tiles



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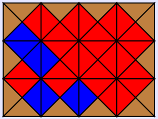

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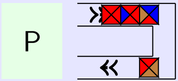


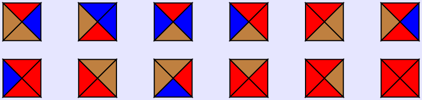
Guess tile above

and queue it

The process P guesses the solution

Unary FIFO system and Tiling

Set of tiles



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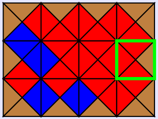

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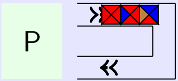
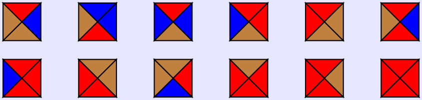


Guess tile above

The process P guesses the solution

Unary FIFO system and Tiling

Set of tiles



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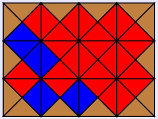

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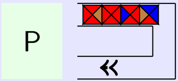


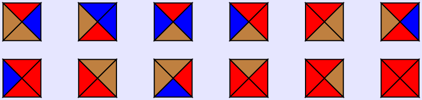
Guess tile above

and queue it

The process P guesses the solution

Unary FIFO system and Tiling

Set of tiles



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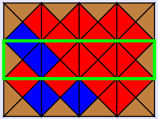

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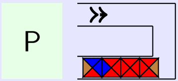
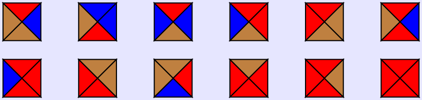


Start again
with the next row

The process P guesses the solution

Unary FIFO system and Tiling

Set of tiles



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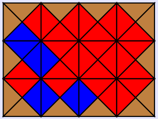
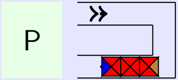


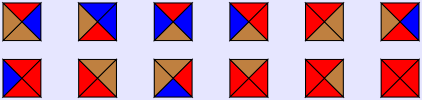
FIFO system



The process P guesses the solution

Unary FIFO system and Tiling

Set of tiles



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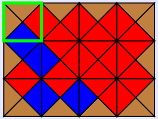
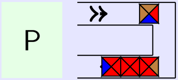


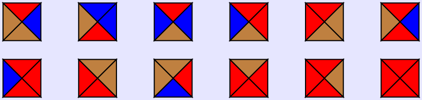
FIFO system



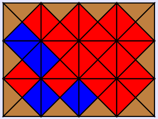
The process P guesses the solution

Unary FIFO system and Tiling

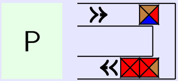
Set of tiles



Solution



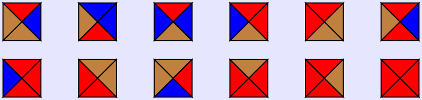
FIFO system



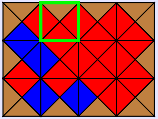
The process P guesses the solution

Unary FIFO system and Tiling

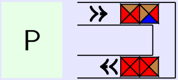
Set of tiles



Solution



FIFO system



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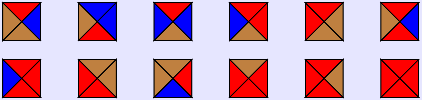
Set of tiles



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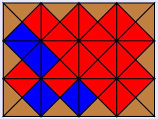
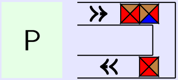


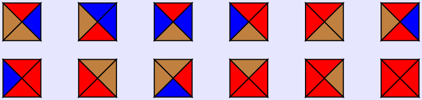
FIFO system



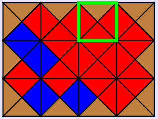
The process P guesses the solution

Unary FIFO system and Tiling

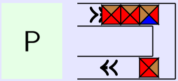
Set of tiles



Solution



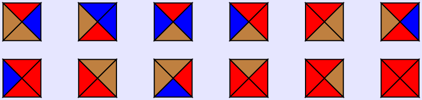
FIFO system



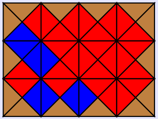
The process P guesses the solution

Unary FIFO system and Tiling

Set of tiles



Solution



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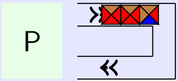
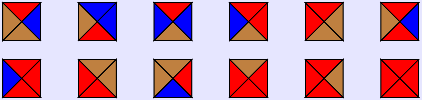


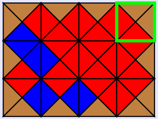
The process P guesses the solution

Unary FIFO system and Tiling

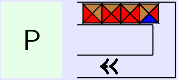
Set of tiles



Solution

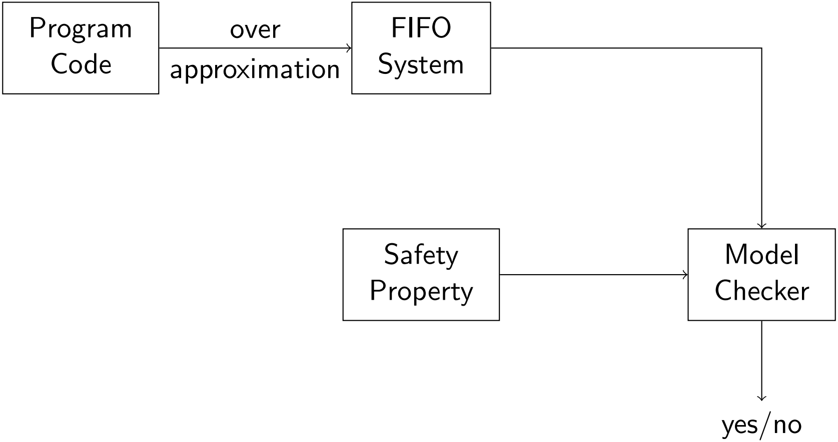


FIFO system



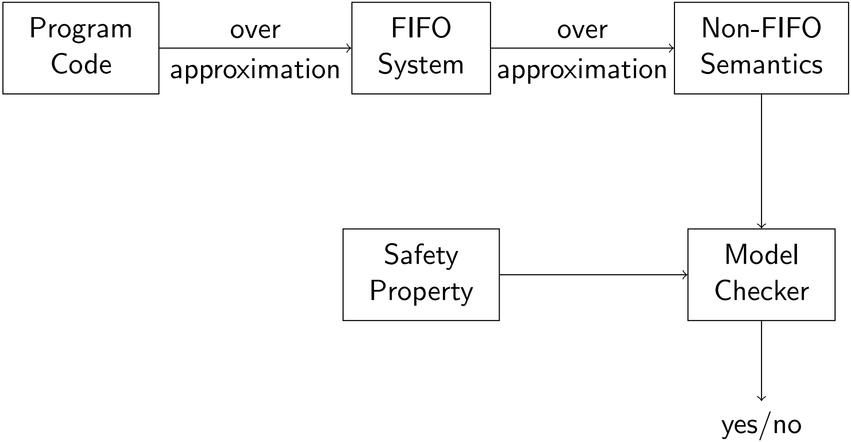
The process P guesses the solution

The Model-Checking Approach



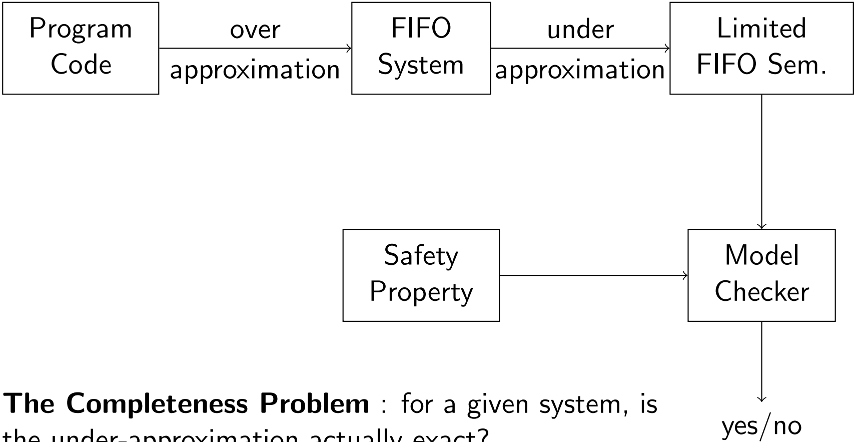
How does a model-checker work?

Solution 1: Second Over-Approximation



ex: Out-of-order (bag) semantics, Lossy semantics.
HIGH COMPLEXITY (non primitive recursive, non Ackermanian)

Solution 2: Under-Approximation

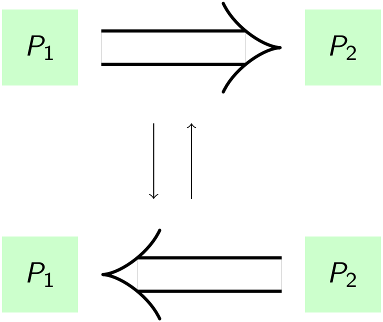


The Completeness Problem : for a given system, is the under-approximation actually exact?

Half-Duplex Semantics

Introduced by Cece and Finkel, CAV'97

H.D. Semantics : *block sending until no more incoming messages*



Safety Model-Checking in PTIME
Completeness Problem in PTIME

Note: Cece and Finkel only considered binary systems
Can be extended to any mailbox system [Germerie, Di Giusto and L., ICE'21].

Bounded Context-Switch Semantics

Introduced by Madhusudan, La Torre and Parlato, TACAS'08

Bounded Context Switch Semantics
switch at most k times from one process to another

Safety Model-Checking in 2EXPTIME
Completeness Problem not really addressed

Synchronous Semantics

a run is synchronous if it is of the form

$$!a_1?a_1!a_2?a_2\cdots!a_n?a_n$$

Synchronous Semantics : consider only synchronous runs.

Completeness could be

every run (that ends with empty buffers) is synchronous.

Decidable, but very limited!
e.g. for 2 processes, means half-duplex + "ping-pong".

Stating Completeness Differently

$$P_1 = 1!a \qquad P_2 = 1?a.2?b.1?c \qquad P_3 = 2!b.1!c$$

$P_1||P_2||P_3$ admits the non-synchronous run

$$1!a \cdot 2!b \cdot 1?a \cdot 2?b \cdot 1!c \cdot 1?c$$

BUT it also admits this *equivalent*, synchronous one

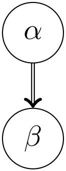
$$1!a \cdot \; 1?\mathrm{a} \; \cdot \; 2!\mathrm{b} \; \cdot 2?b \cdot 1!c \cdot 1?c$$

The synchronous semantics could be considered complete for $P_1||P_2||P_3$.

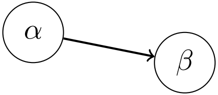
The *Happens Before* Partial Order

consider a run of the form $\cdots\alpha\cdots\beta\cdots$
α happens before β if

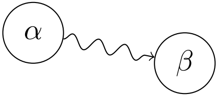
either process(α) = process(β)



or β is the reception matching
the send α



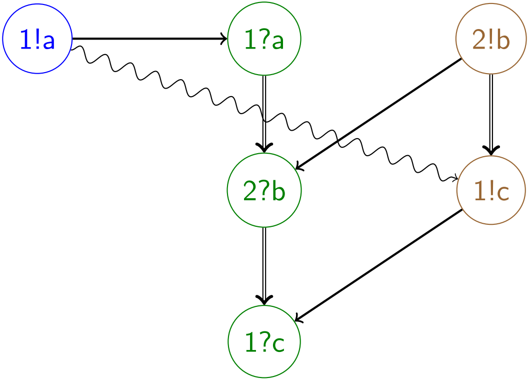
or buffer(α) = buffer(β)
and kind(α) = kind(β) ($\in \{!, ?\}$)

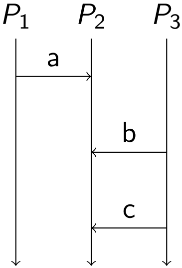


or a chain of such elementary steps

Traces (and Message Sequence Charts, MSC)

$$1!a \cdot 2!b \cdot 1?a \cdot 2?b \cdot 1!c \cdot 1?c$$





Back to the Completeness of the Synchronous Semantics

We say that

- a trace is ∃-synchronous if it admits a linearisation (i.e. a run) that is synchronous
- the synchronous semantics is complete for a system $P_1 || \cdots || P_n$ if all traces are ∃-synchronous

$\sim$ what we called *greedy systems* in ICE'21
(but we have a different treatment of orphan messages)

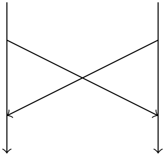
The **completeness problem** is decidable in PTIME
(for a fixed number of processes).
Regular **safety checking** is decidable in PTIME

Remarks:

- the session type discipline usually *enforces* greediness
- generalises half-duplex systems

Limitations

Many protocols are not $\exists$-synchronous, for instance



Actually, $\exists$-synchronous systems are a very light generalisation of half-duplex systems (see more in ICE'21)

How can we generalize this idea more significantly?

Bounded Semantics

Genest, Kuske, Muscholl. Fundam. Informaticae. 2007.

A run r is *k-bounded* ($k \geq 1$) if for all prefix r' and for all buffer i, $|r'|_{i!} - |r'|_{i?} \leq k$.

A trace is ∃-k-bounded if it admits a k-bounded linearisation.

(actually more general, we should only count messages that are eventually received)

Regular Safety Checking is in PSPACE.
The Completeness Problem (whether a system is ∃-k-bounded) is decidable in PSPACE.

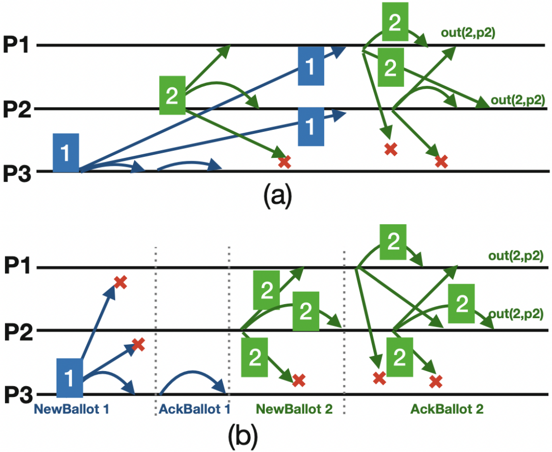
Remark: Genest et al only considered p2p systems.

Communication-Closed Protocols

Cezara Drăgoi *et al.* POPL'16 - CAV'19

messages are timestamped with a round number

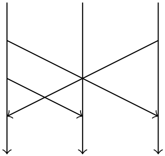
messages from older rounds are ignored



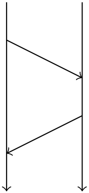
k-exchanges

a k-exchange is a MSC that admits a linearisation of the form

$$!a_1 \cdots !a_l \cdots ?b_1 \cdots ?b_m \text{ with } l, m \leq k.$$



a 3-exchange

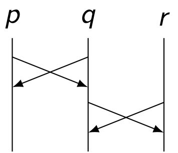


not a k-exchange
(for any k)

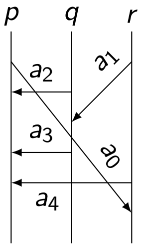
k-synchronous MSCs

Bouajjani, Enea, Ji and Qadeer, CAV'18

a MSC is k-synchronous if it is a concatenation of k-exchanges



a 2-synchronous MSC



(a)

not k-synchronous (for any k)

k-synchronous semantics

Bouajjani, Enea, Ji and Qadeer, CAV'18

a system is *k-synchronous* if all its MCSs (traces?) are k-synchronous

- Reachability is in PSPACE under the k-synchronous semantics
- The completeness problem (whether a system is k-synchronous) is in PSPACE

Proofs later cleaned and extended to p2p systems
see [Laversa, Di Giusto, L. FOSSACS'20].

The Need for a General Framework

∃-k-bounded, k-synchronous, are similar, but

- ∃-k-bounded only considered for p2p systems
  what about mailbox systems?
- the proofs are technical and hide similarities
  what is the key idea?
- both need to fix a k
  can we guess k? what about ∞-synchronous?

Known results:

- guessing k for ∃-k-bounded/p2p is undecidable
  [Genest, Kuske and Muscholl, Fundam. Inform. 2007]
- guessing k for k-synchronous/mailbox is in PSPACE
  [Di Giusto, Laversa, L., CIAA'21]

General Framework: our Proposal

joint work with Bollig, Finkel and Suresh. **Submitted.**

- a restricted FIFO semantics is a set of MSCs
  in other words, a set of graphs
- let's define it with a formula ϕ of a logic for graphs: MSO
- let's add another hypothesis: all MSCs that satisfy ϕ have tree-width at most k (for some fixed k)

- main result: safety checking and the completeness problems are in EXPTIME. The proof is half a page long.

- side contribution: we identified the ∞-synchronous semantics.
  Safety checking and completeness are
  - EXPTIME (PSPACE?) for mailbox systems
  - undecidable for p2p systems

Thank you!