Symbolic Implementation of Connectors in BIP

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Presentation outline

- BIP
- Connectors
- Boolean encoding
- Benchmarks

Motivation

Context: *Component-based* modelling, design and validation of embedded real-time systems.

Presently:

- A number of *coordination mechanisms* for concurrent systems: shared variables, semaphores, regions, etc.
- Ad-hoc use and analysis methodologies.

Our goal: *Unified framework* for component-based modelling and design

- allowing incremental description & correctness by construction
- encompassing heterogeneity
  - synchronous and asynchronous execution
  - event and data driven computation
  - centralised and distributed implementation

Component design by refinement

Three layers:

1. Component behaviour
2. Coordination
3. Data transfer

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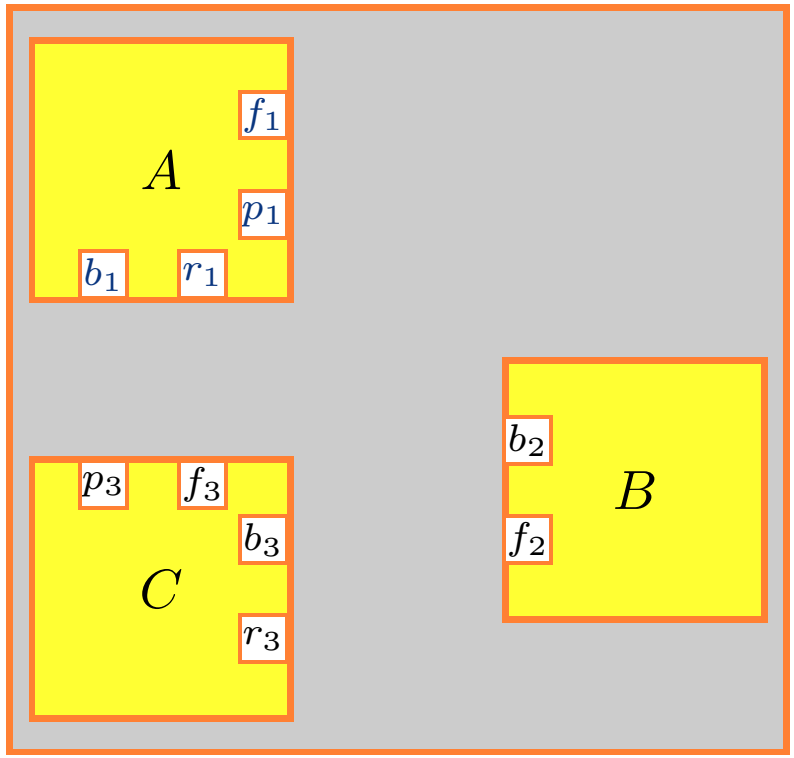

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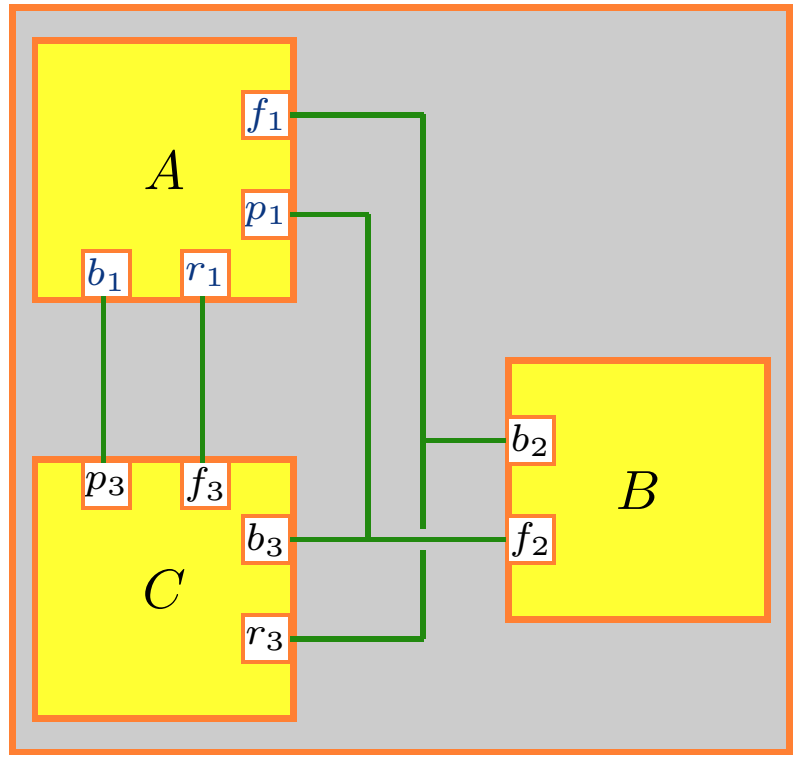

Component design by refinement

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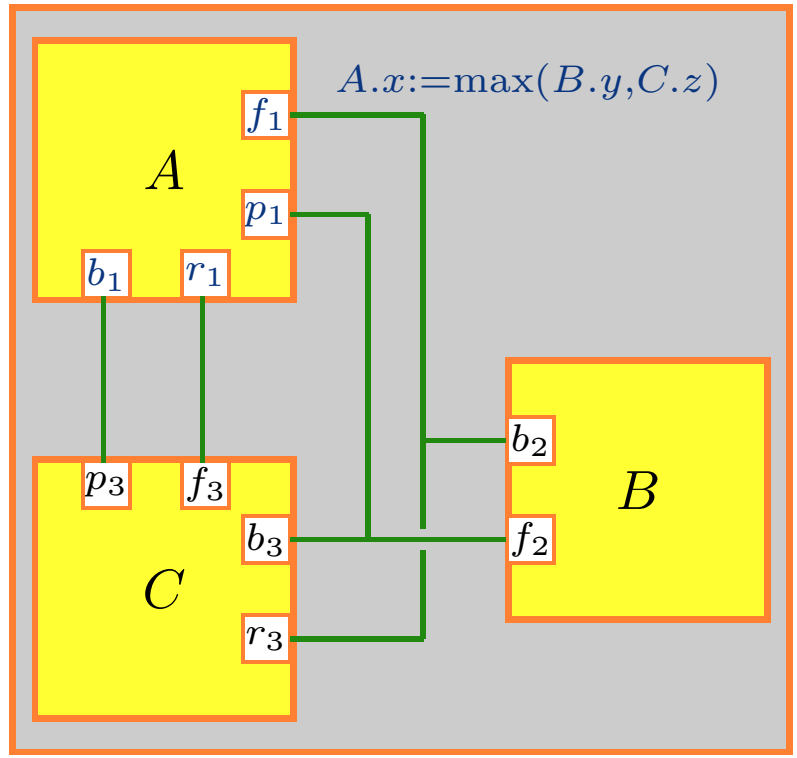
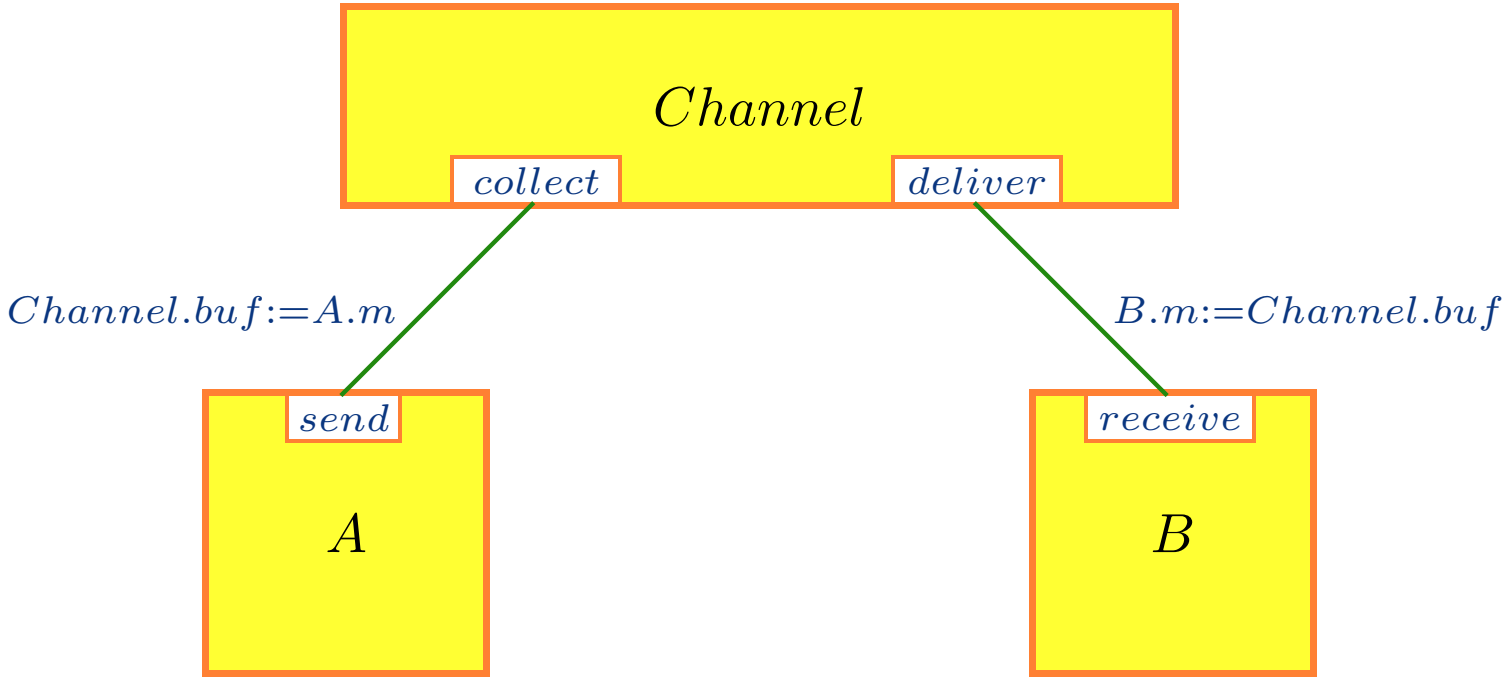


Unbuffered synchronous communication

(Not to confuse with synchronous *execution*!)



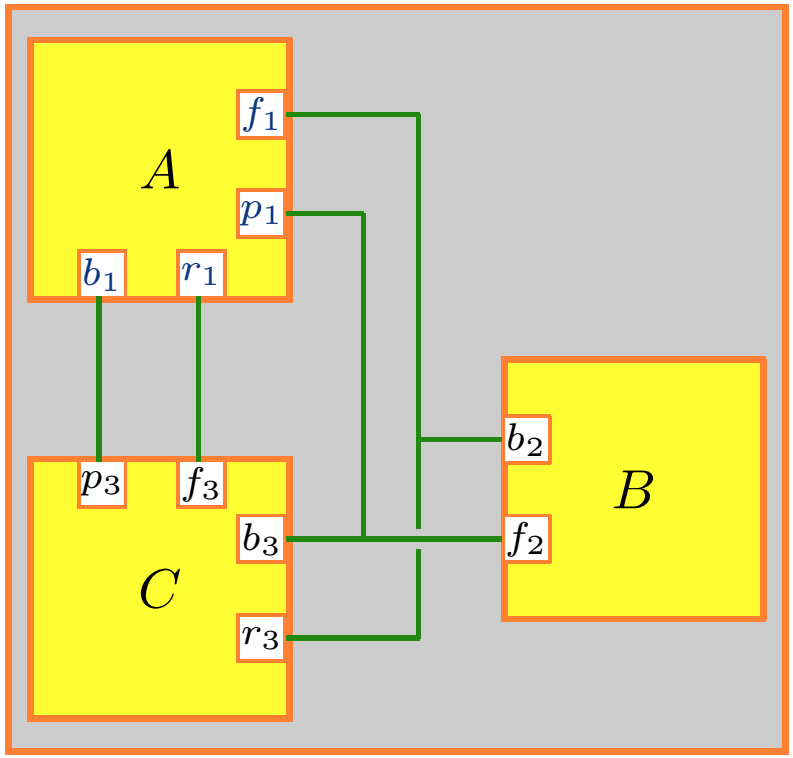
A sends a message m to B:

- Two synchronisations with the channel
- Each synchronisation allows a data transfer
- An explicit model of the channel behaviour

Scope of the basic model

Three layers:

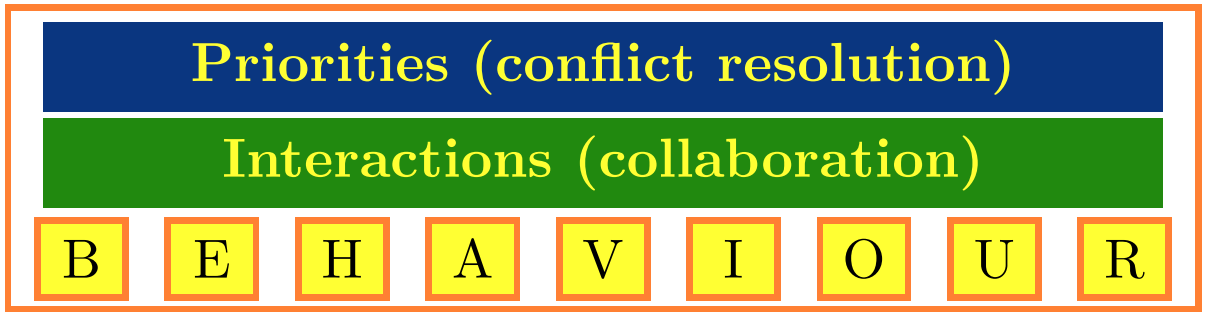
1. Component behaviour
2. Coordination
3. Data transfer



Interesting results already at this level, e.g.

- Analysis of synchronisation deadlocks
  - S. Bensalem, M. Bozga, J. Sifakis, T.-H. Nguyen. *D-Finder: A Tool for Compositional Deadlock Detection and Verification.* [CAV'09]
- Synthesis of glue for certain safety properties
  - S. Bliudze, J. Sifakis. *Synthesizing Glue Operators from Glue Constraints for the Construction of Component-Based Systems.* [Submitted to POPL'10]

Basic model of BIP

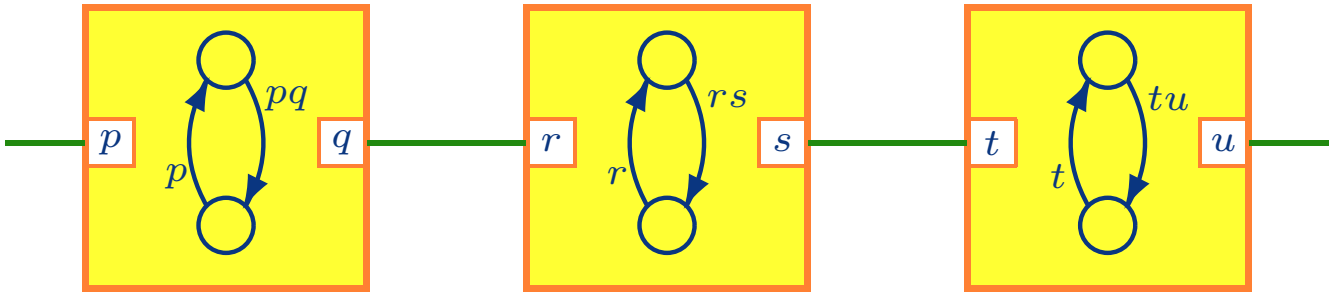


Layered component model

- **Behaviour** — labelled transition systems with **disjoint** sets of ports
- **Interaction** — set of interactions (interaction = set of ports)
- **Priorities** — strict partial order on interactions

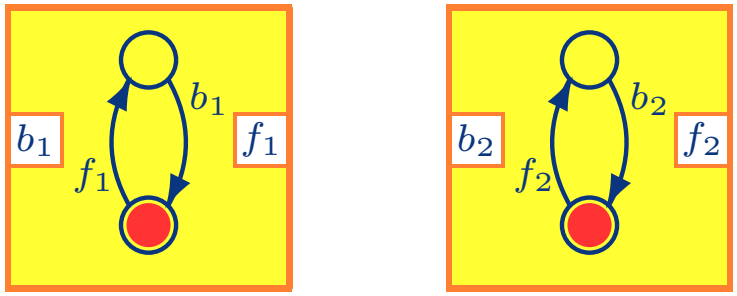
BIP: Examples

Modulo-8 counter:



Interactions: $\{p, pqr, pqrst, pqrstu\}$.

Mutual exclusion:



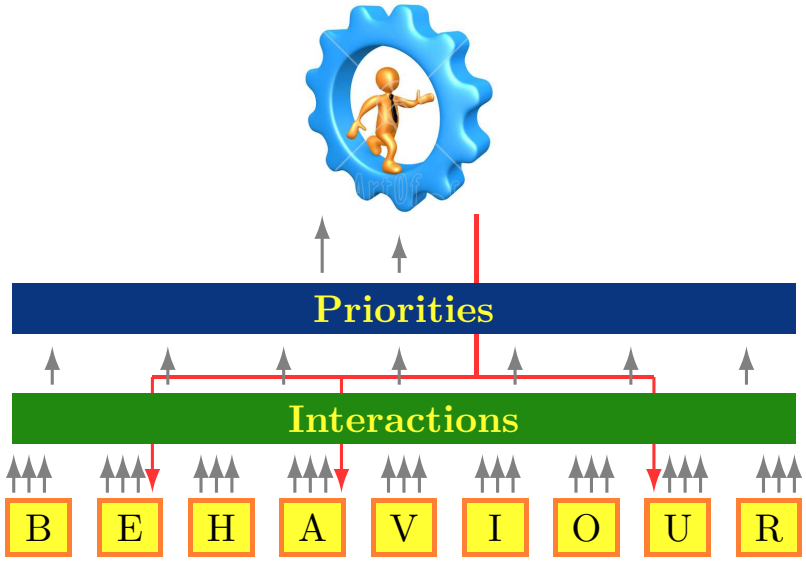
Interactions: $\{b_1, f_1, b_2, f_2\}$

Priority: $b_1 \prec f_2$, $b_2 \prec f_1$.

Implementation: Enumerative engine

Engine protocol:

1. Atoms notify the engine of their active ports.
2. The engine enumerates the allowed interactions;
3. Filters out low priority ones;
4. Picks one among those left;
5. Notifies the atoms.



Interaction model is a **set of sets** of ports ⇒ exponential complexity.

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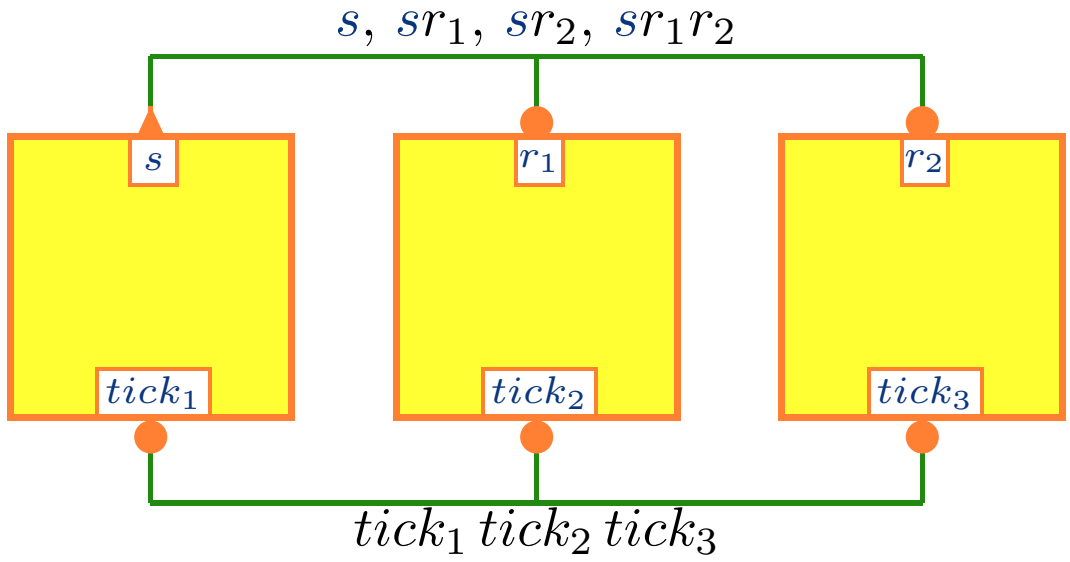
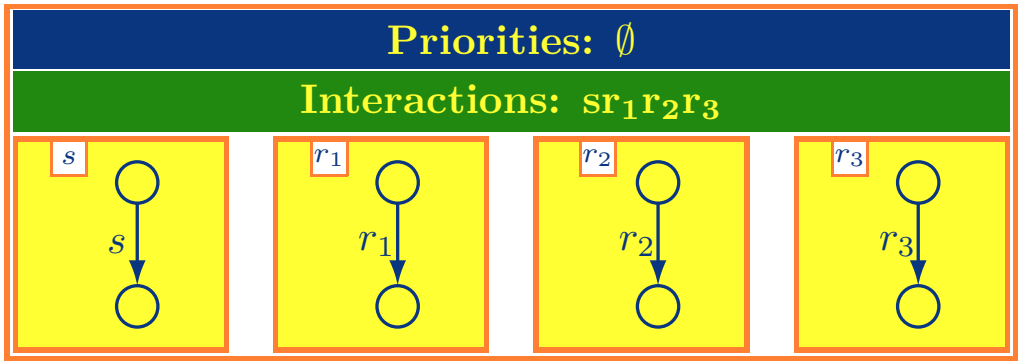
Basic connectors

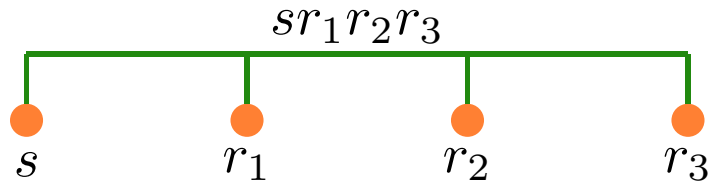
- A **connector** is a set of ports which can be involved in an interaction.
- Port attributes (**trigger** ▲, **synchron** ●) determine the synchronisation type.
- An **interaction** in a connector is a subset of ports such that either it contains a trigger or it is maximal.



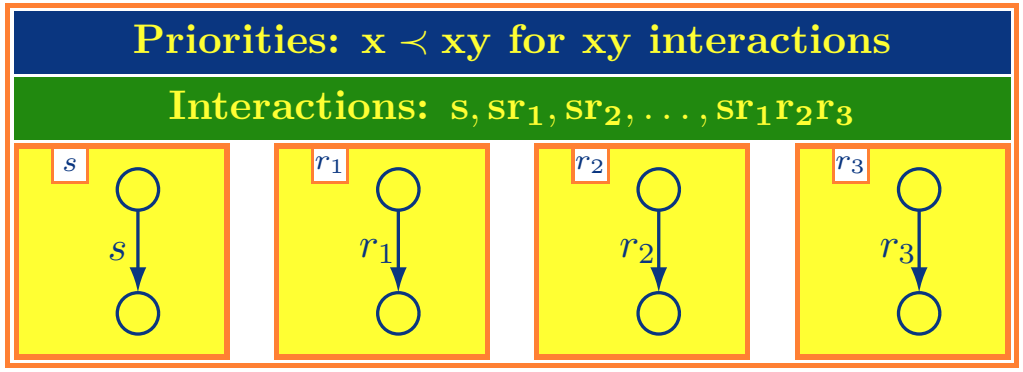
Interaction modelling: Flat connectors

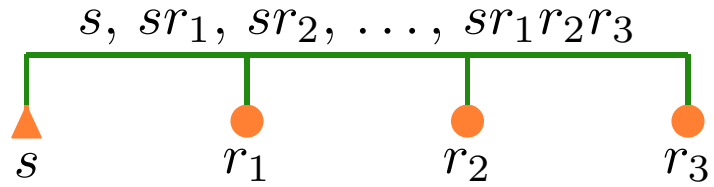
Rendezvous





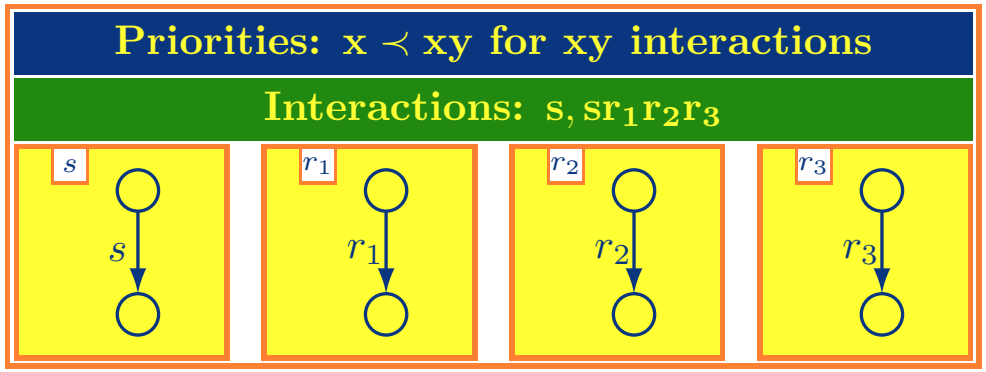
Broadcast

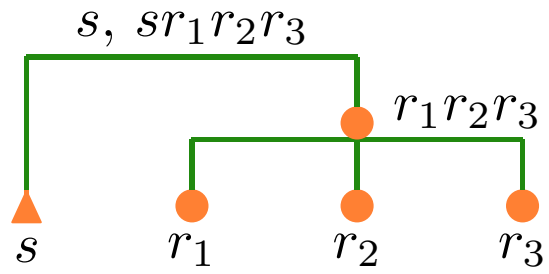




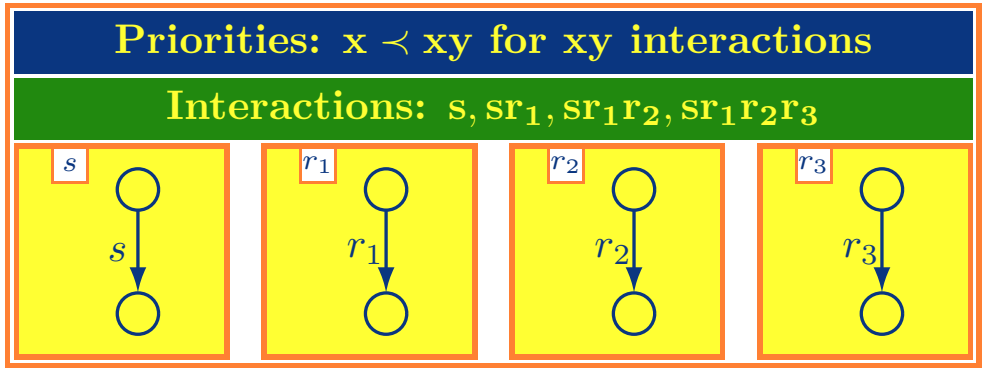
Interaction modelling: Hierarchical connectors

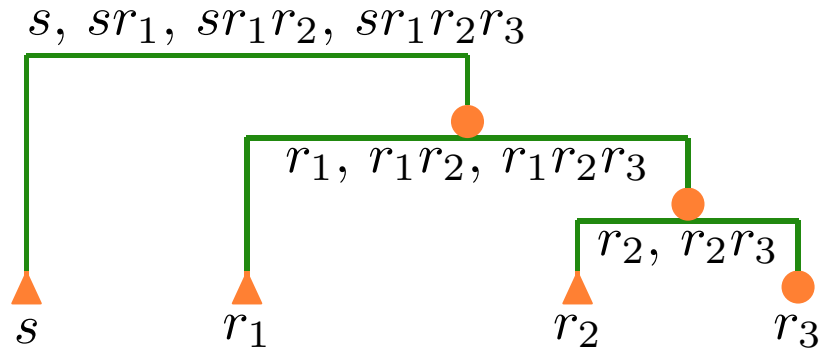
Atomic broadcast





Causality chain





The Algebra of Connectors, $\mathcal{AC}(P)$, introduced in [EMSOFT'07].

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Symbolic implementation

Motivation: Reduce Component/Engine protocol overhead.

Approach: Use boolean functions to pick the interaction to be executed.

- An interaction can be seen as a boolean valuation on ports:

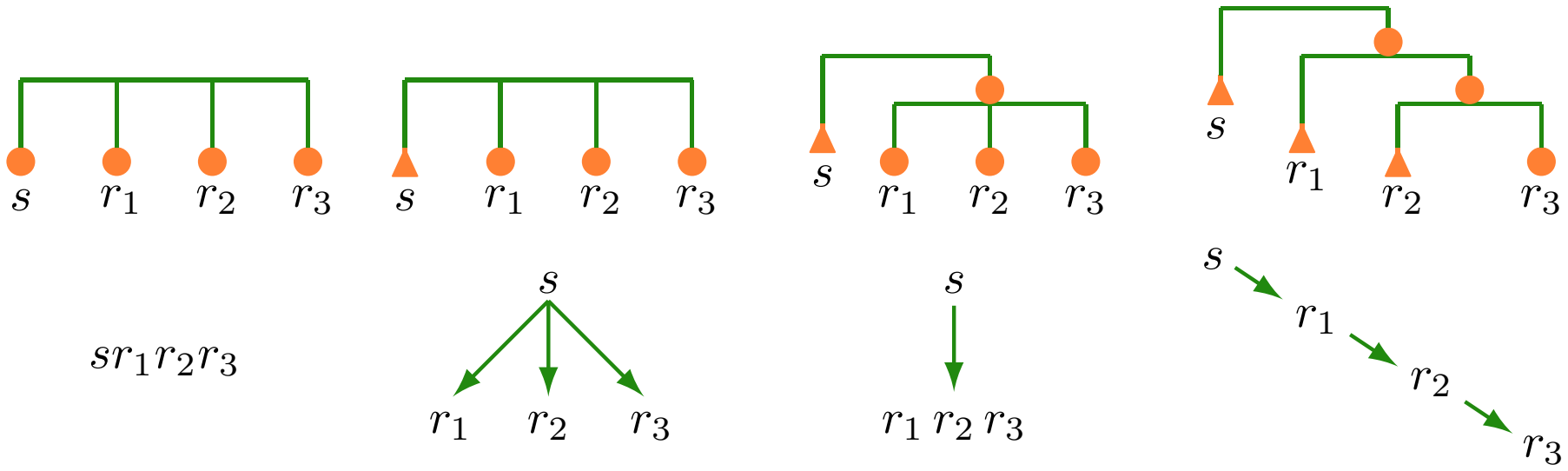
$$p_1 p_2 \quad \longleftrightarrow \quad \begin{pmatrix} p_1 & p_2 & p_3 & p_4 \\ 1 & 1 & 0 & 0 \end{pmatrix}$$

- Based on the connectors, priorities, and behaviour of components, compute a boolean formula φ on $P \cup Q$, such that

$$(a, q) \models \varphi \quad \Longleftrightarrow \quad a \text{ is enabled in } q\,.$$

- Implementation using existing BDD package.

Causal interaction trees



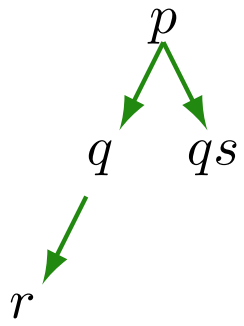
Rendezvous	*Broadcast*	*Atomic broadcast*	*Causal chain*
$sr_1r_2r_3$	s, sr_1, sr_2, ... sr_2r_3, $sr_1r_2r_3$	s, $sr_1r_2r_3$	s, sr_1, sr_1r_2, $sr_1r_2r_3$

Transformations are straightforward in both ways.

The Algebra of Causal Trees, $\mathcal{CT}(P)$, introduced in [FMCO'07].

Boolean representation of connectors

$\underline{p'[q'r][qs]}$:



Causal trees

$$\begin{aligned} true &\Rightarrow p\,, \\ q &\Rightarrow p\,, \\ r &\Rightarrow pq\,, \\ s &\Rightarrow pq \end{aligned}$$

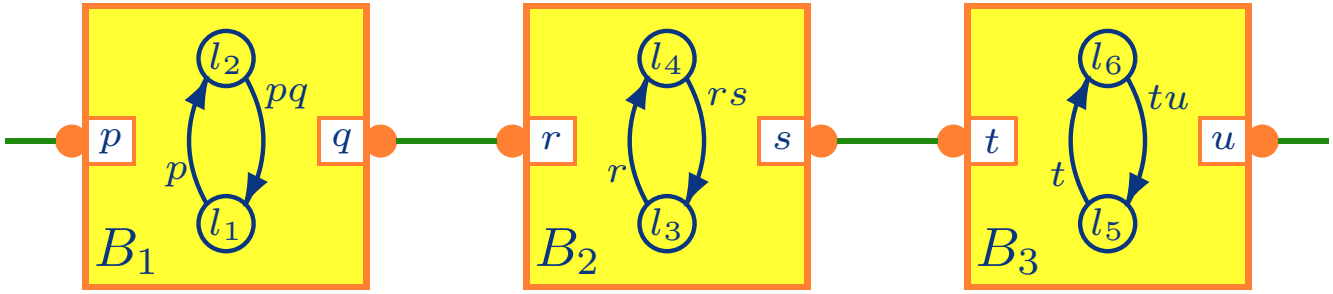
Causal rules

Notice that: $(q \Rightarrow p \vee ps) \equiv (q \Rightarrow p)$.

The corresponding boolean formula is

$$(true \Rightarrow p) \wedge (q \Rightarrow p) \wedge (r \Rightarrow pq) \wedge (s \Rightarrow pq) \equiv p\,q \vee p\,\overline{r}\,\overline{s}\,.$$

Boolean representation of atomic components



$$f_{B_1} = l_1\,\overline{l_2}\,p\,\overline{q} \vee \overline{l_1} l_2 p q \vee \overline{p}\,\overline{q}$$

$$f_B = (l_1\,\overline{l_2}\,p\,\overline{q} \vee \overline{l_1}\,l_2\,p\,q \vee \overline{p}\,\overline{q}) \wedge (l_3\,\overline{l_4}\,r\,\overline{s} \vee \overline{l_3}\,l_4\,r\,s \vee \overline{r}\,\overline{s}) \wedge (l_5\,\overline{l_6}\,t\,\overline{u} \vee \overline{l_5}\,l_6\,t\,u \vee \overline{t}\,\overline{u})$$

$$f_C = (p \vee qr \vee st \vee u) \wedge (q = r) \wedge (s = t)$$

Implementation: Symbolic engine*

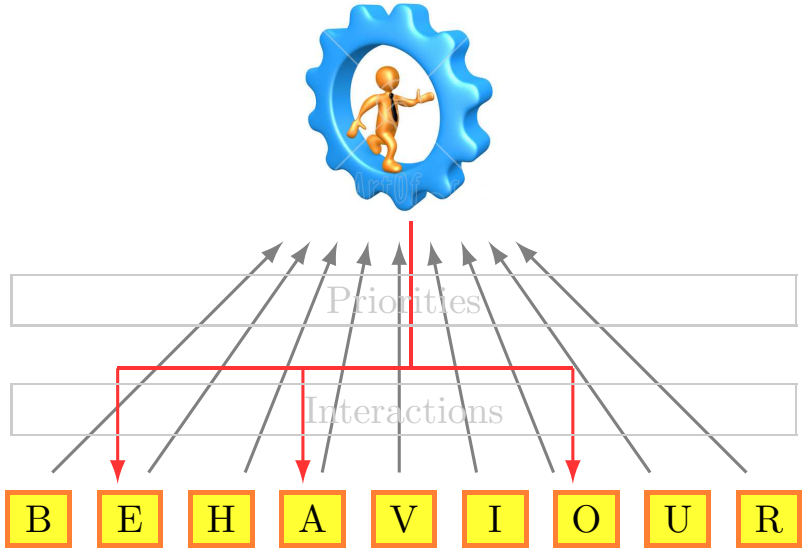
Initialization:

0. The engine precomputes functions

$f_B \in \mathbb{B}[\bigcup_{i=1}^{n} Q_i, P]$ — behaviour,

$f_C \in \mathbb{B}[P]$ — connectors,

$f_S = f_B \wedge f_C$.



Engine protocol:

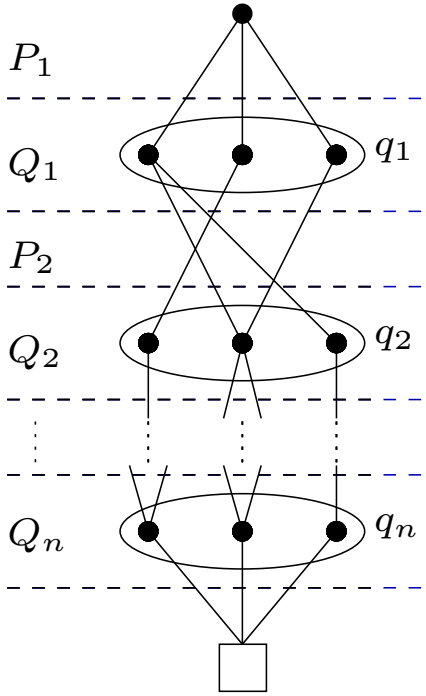
1. Atoms notify the engine of their current states q_i.
2. The engine picks any valuation a on P, such that

$$(a, q) \models f_S \wedge \bigwedge_{i=1}^{n} q_i$$

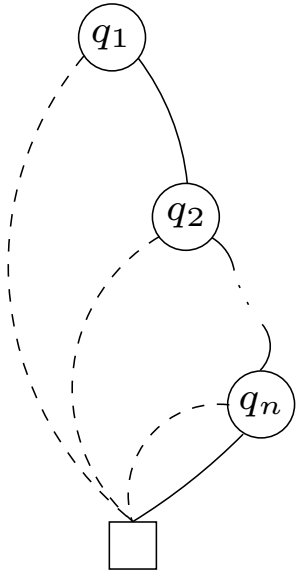
3. Notifies the atoms.

* Connectors only (for priorities see in the paper).

Complexity of the symbolic engine



$f_S = f_B \wedge f_C$



$\bigwedge_{i=1}^{n} q_i$

Complexity of the protocol:

- Conjunction $f_S \wedge \bigwedge_{i=1}^{n} q_i : O(|f_S|)$ (sic!)
- Selecting $a \models \ldots : O(n)$, where $n = |P \cup Q|$.

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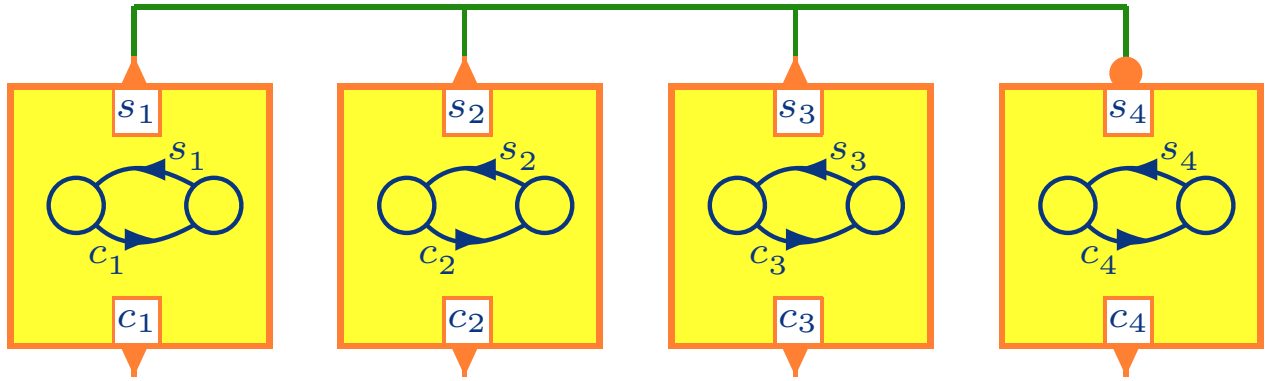
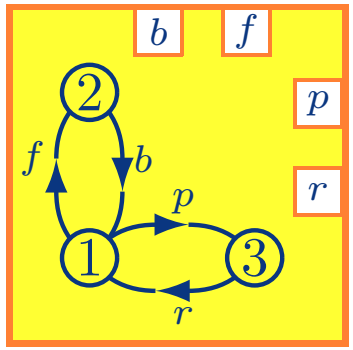
Benchmarks: Bus

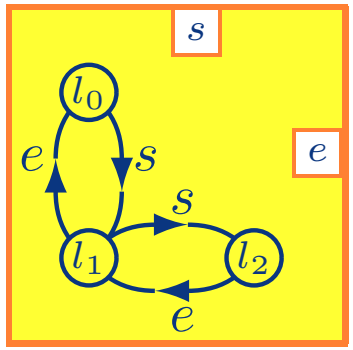


- N clusters
- "Sparse" connectors: $5N$
- Favours enumerative engine

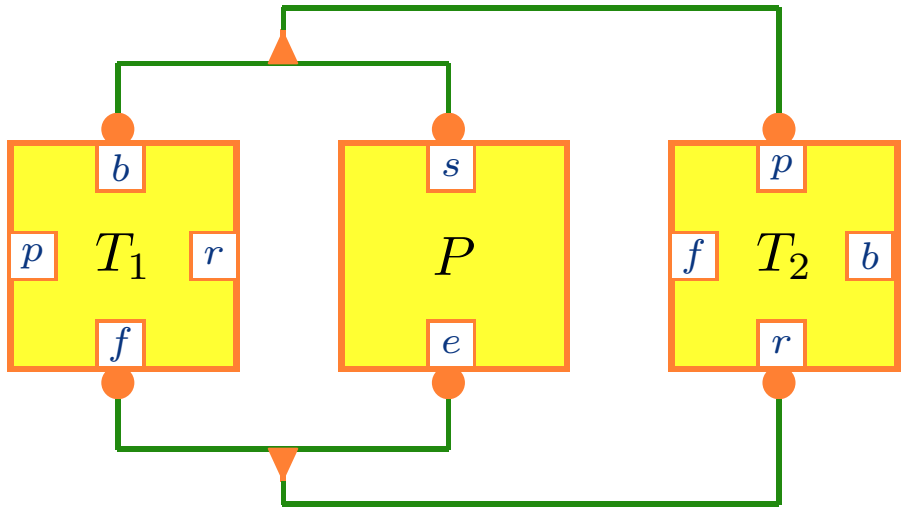
Benchmarks: Preemptable tasks



Task



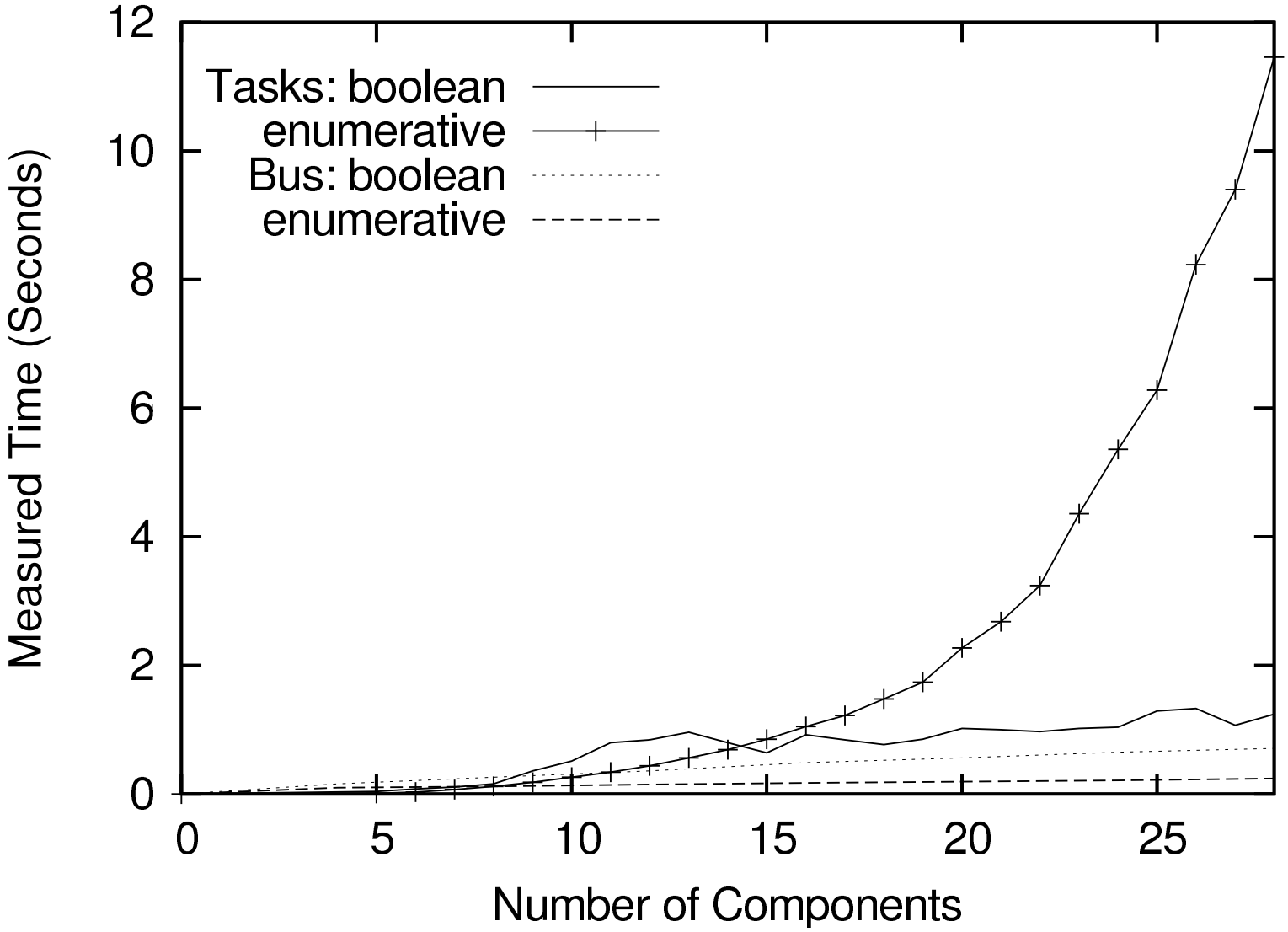
Processor



Connectors

- N Tasks, 4 Processors
- "Dense" connectors: $8N(N-1)$
- Favours symbolic engine

Benchmarks: Simulation results



Conclusion

- Symbolic engine implementation outperforms the enumerative one for "densly" connected systems.
  - How to characterize "dense"?
- BDD size linear in the number of components for both benchmarks.
  - Why? What about the general case?
  - Further optimizations, e.g. reordering components?
- Only one of the applications of the boolean representation:
  - Connector manipulation
  - Glue (connector & priority) synthesis

Thank you for your attention!

The Algebra of Interactions $\mathcal{AI}(P)$

Syntax: $x ::= 0 \mid 1 \mid p \mid x \cdot x \mid x + x \mid (x), \quad$ with $p \in P$

Axioms:

$+$	union	idempotent, associative, commutative, identity 0
$\cdot$	synchronisation	idempotent, associative, commutative, identity 1, absorbing 0
		distributes over union

Examples:

$$s + s\,r_1 + s\,r_2 + s\,r_1\,r_2 = s(1 + r_1)(1 + r_2) \quad \text{broadcast}$$

$$s + s\,r_1 + s\,r_1\,r_2 = s(1 + r_1(1 + r_2)) \quad \text{causality chain}$$

The Algebra of Interactions $\mathcal{AI}(P)$

Semantics: defined by the function $\|\cdot\| : \mathcal{AI}(P) \to 2^{2^P}$

$$
\begin{array}{lcl}
\|0\| & = & \emptyset, \\
\|1\| & = & \{\emptyset\}, \\
\|p\| & = & \Big\{\{p\}\Big\}, \text{ for any } p \in P, \\
\|x_1 + x_2\| & = & \|x_1\| \cup \|x_2\|, \text{ for any } x_1, x_2 \in \mathcal{AI}(P), \\
\|x_1 \cdot x_2\| & = & \Big\{a_1 \cup a_2 \,\Big|\, a_1 \in \|x_1\|, a_2 \in \|x_2\|\Big\}, \text{ for any } x_1, x_2 \in \mathcal{AI}(P)\,.
\end{array}
$$

The Algebra of Connectors $\mathcal{AC}(P)$

Syntax:

$$
\begin{array}{lcll}
s & ::= & [0] \mid [1] \mid [p] \mid [x] & (synchrons) \\
t & ::= & [0]' \mid [1]' \mid [p]' \mid [x]' & (triggers) \\
x & ::= & s \mid t \mid x \cdot x \mid x + x \mid (x) &
\end{array}
$$

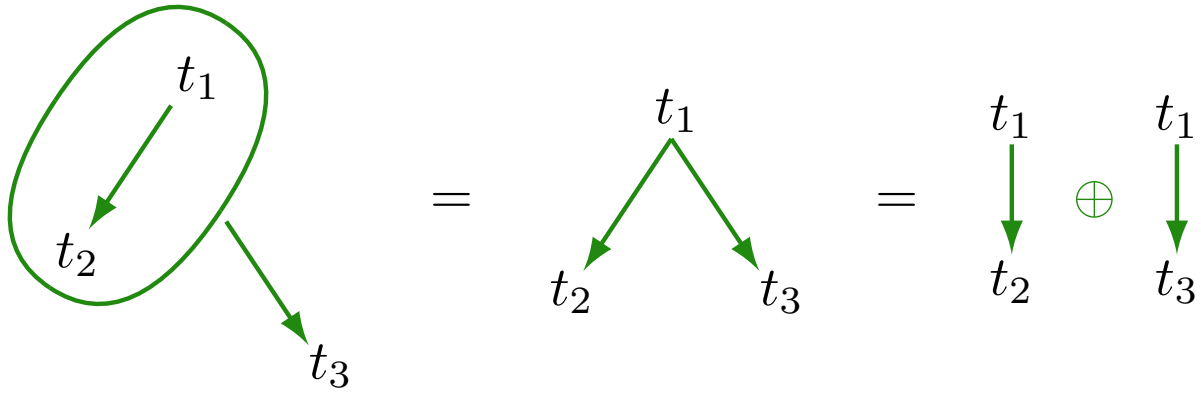
Operators:

$+$	union	idempotent, associative, commutative, identity $[0]$
$\cdot$	fusion	idempotent, associative, commutative, identity $[1]$
		distributes over union ($[0]$ is **not** absorbing)
$[\cdot]$, $[\cdot]'$	typing	(often denoted $[\cdot]^\alpha$ for some trigger/synchron typing α)

Semantics: is given by a function $|\cdot| : \mathcal{AC}(P) \rightarrow \mathcal{AI}(P)$.

$$|p'qr| \stackrel{def}{=} p(1+q)(1+r)$$

The Algebra of Causal Interaction Trees



Syntax: $t ::= a \,|\, t \to t \,|\, t \oplus t.$

Essential axioms:

$$
\begin{aligned}
(t_1 \to t_2) \to t_3 &= t_1 \to (t_2 \oplus t_3)\,, \\
t_1 \to (t_2 \oplus t_3) &= t_1 \to t_2 \;\oplus\; t_1 \to t_3\,, \\
(t_1 \oplus t_2) \to t_3 &= t_1 \to t_3 \;\oplus\; t_2 \to t_3\,.
\end{aligned}
$$

Semantics: $|\cdot| : \mathcal{C}T(P) \to \mathcal{A}I(P)$

$$
\begin{aligned}
|a| &= a\,, \\
|a \to t| &= a\Big(1 + |t|\Big)\,, \\
|t_1 \oplus t_2| &= |t_1| + |t_2| + |t_1|\,|t_2|
\end{aligned}
$$