CAAL
Concurrency Workbench Aalborg Edition

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MOTIVATION

- At Aalborg University we teach a courses on reactive systems and concurrency theory, based on Milner's CCS.

Existing tools for analysing processes described in CCS.

- Concurrency Workbench (CWB)
- Concurrency Workbench New Century (CWB-NC)
- Tool for the Analysis of Process Algebras (TAPAs)
- pseuCo (Java to CCS)
- CCS in Maude and in Haskell (experiential)

RELATED WORK

There exist various other tools, typically using a superclass of CCS, of industrial strength. To mention some:

- FDR3
- mCRL2
- CADP
- LTSmin
- PRISM

CAAL lacks the power of those above, but focuses on

- usability,
- use of graphical aids, and
- aims at use in education.

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CCS SYNTAX

The collection of CCS expressions $\mathcal{P}$ is given by the grammar:

$$P, Q ::= K \;\Big|\; \alpha.P \;\Big|\; P + Q \;\Big|\; P \mid Q \;\Big|\; P[f] \;\Big|\; P \setminus L \;\Big|\; 0$$

where K is a process constant (name), α is an action, L a set of labels, and f is a relabelling function.

- A process is guarded if all occurrences of process constants are under the scope of action prefixing.

Example of semantics (SOS rules):

$$a.b.0 + c.0 \xrightarrow{a} b.0$$

$$a.b.0 \mid c.0 \xrightarrow{a} b.0 \mid c.0$$

$$a.0 \mid \overline{a}.0 \xrightarrow{\tau} 0 \mid 0$$

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STRONG BISIMULATION

Definition (Bisimulation)

A binary relation $\mathcal{R}$ over the set of states of an LTS is a bisimulation if and only if whenever $s \mathcal{R} t$ and α is an action:

$$\text{if } s \xrightarrow{\alpha} s' \text{ then } t \xrightarrow{\alpha} t' \text{ s.t. } s' \mathcal{R} t', \text{ and}$$
$$\text{if } t \xrightarrow{\alpha} t' \text{ then } s \xrightarrow{\alpha} s' \text{ s.t. } s' \mathcal{R} t'.$$

Two states s and t are *strongly bisimilar*, written $s \sim t$, iff there is a bisimulation that relates them.

WEAK BISIMULATION

We write $s \stackrel{\alpha}{\Rightarrow} s'$ if

- $\alpha \neq \tau$ and $s(\stackrel{\tau}{\rightarrow})^* \circ \stackrel{\alpha}{\rightarrow} \circ (\stackrel{\tau}{\rightarrow})^* s'$ or
- $\alpha = \tau$ and $s(\stackrel{\tau}{\rightarrow}^*)s'$.

Definition (Weak Bisimulation)

A binary relation $\mathcal{R}$ over the set of states of an LTS is a weak bisimulation if and only if whenever $s \mathcal{R} t$ and α is an action:

$$\text{if } s \stackrel{\alpha}{\Rightarrow} s' \text{ then } t \stackrel{\alpha}{\Rightarrow} t' \text{ s.t. } s' \mathcal{R} t' \text{ and}$$
$$\text{If } t \stackrel{\alpha}{\Rightarrow} t' \text{ then } s \stackrel{\alpha}{\Rightarrow} s' \text{ s.t. } s' \mathcal{R} t'.$$

Two states s and t are *weakly bisimilar*, written $s \approx t$, iff there is a weak bisimulation that relates them.

BISIMULATION GAME

Given two states s and t:

- Attacker aims to show $s \not\sim t$; defender aims to show $s \sim t$.
- Configurations of the game are pairs (s, t).

1. Attacker selects a transition, $s \xrightarrow{\alpha} s'$ from s (or t).
2. Defender matches with transition from t (or s), $t \xrightarrow{\alpha} t'$.
3. The pair (s', t') forms next configuration and the round repeats.

- Attacker wins if defender is unable to match action.
- Defender wins if attacker is unable to select any action.
- Defender also wins if the play is infinite (or the same configuration has been seen twice).

Theorem

Attacker has a winning strategy from (s, t) iff $s \not\sim t$.

HML SYNTAX WITH RECURSIVE VARIABLES

$$\phi ::= tt \mid ff \mid \phi_1 \wedge \phi_2 \mid \phi_1 \vee \phi_2 \mid \langle\alpha\rangle\phi \mid [\alpha]\phi \mid \langle\langle\alpha\rangle\rangle\phi \mid [[\alpha]]\phi \mid X$$

where X is a variable declared as either a minimum fixed point

$$X \overset{\min}{=} \phi$$

or a maximum fixed point

$$X \overset{\max}{=} \phi\,.$$

- Note: CAAL allows for more than one variable but they may not be mutually recursive.

Example

$$X \overset{\max}{=} [a]X \wedge \langle b\rangle tt$$

HML-GAME

Given state s and formula ϕ:

- Attacker aims to show $s \not\models \phi$; defender aims to show $s \models \phi$.
- Configurations consist of process and formula pairs (s, ϕ).

- Attacker picks a successor from $\phi_1 \wedge \phi_2$, $[a]\phi_1$, or $[[a]]\phi_1$
- Defender picks a successor from $\phi_1 \vee \phi_2$, $\langle a \rangle \phi_1$, or $\langle\langle a \rangle\rangle \phi_1$
- In (s, X) the variable X unfolds to its definition.

- Attacker wins in (s, ff) or any infinite play in *min* context.
- Defender wins in (s, tt) or any infinite play in *max* context.
- Either player loses if stuck.

Theorem
Attacker has a universal winning strategy from (s, ϕ) iff $s \not\models \phi$.

DISTINGUISHING FORMULA

Theorem (Hennessy and Milner)

Let P and Q be guarded CCS processes. Then:

$$P \sim Q \text{ if and only if } P \models \phi \Leftrightarrow Q \models \phi$$

for all ϕ without the modalities $\langle\langle\alpha\rangle\rangle$ and $[[\alpha]]$. And

$$P \approx Q \text{ if and only if } P \models \phi \Leftrightarrow Q \models \phi$$

for all ϕ without the modalities $\langle\alpha\rangle$ and $[\alpha]$.

- Hence, if $s \not\sim t$ (or $s \not\approx t$) there is a distinguishing formula ϕ such that $s \models \phi$ and $t \not\models \phi$.

PROBLEMS

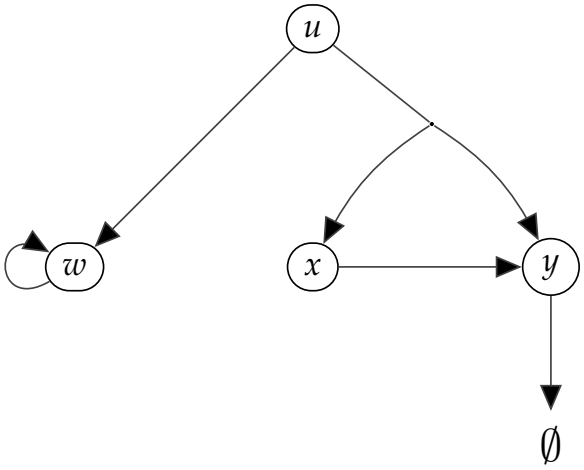
- Given two CCS processes, decide if they are strongly/weakly bisimilar.
- Given a CCS process P and a formula ϕ, decide if $P \models \phi$.
- If two processes are not bisimilar, find a distinguishing formula.
- If two processes are not bisimilar or a formula does not hold, play bisimulation/model checking games and win against the user.

DEPENDENCY GRAPHS

Definition (Dependency Graph)

A dependency graph is a pair (V, E) where V is a finite set of nodes and $E \subseteq V \times \mathcal{P}(V)$ is a finite set of hyperedges. A hyperedge is a pair (v, T) where v is the source and $T \subseteq V$ is the target set.

$$V = \{u, w, x, y\}, E = \{(y, \emptyset), (x, \{y\}), (u, \{x, y\}), (u, \{w\}), (w, \{w\})\}$$



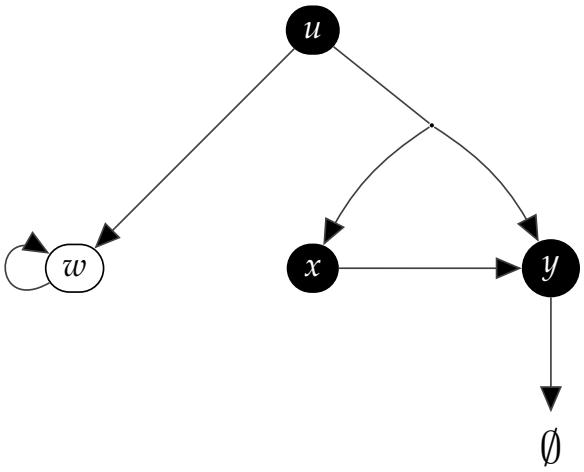
ASSIGNMENTS

Assignment is a function $A : V \to \{0, 1\}$.

Definition (Pre-fixed-point Assignment)

A *pre-fixed-point assignment* A satisfies that whenever $(v, T) \in E$ such that for all $v' \in T$ we have $A(v') = 1$ then also $A(v) = 1$.

There is a minimum pre-fixed-point assignment A_{min}.



ALGORITHMS FOR A_{min} [LIU AND SMOLKA]

- Global Iteration over all nodes.
  1. Initialize all nodes to 0.
  2. Relax the assignment by iterating over all edges until no change is needed.

- Local 'on-the-fly' algorithm.
  1. Explore the hyperedges in a forward and backward manner.
  2. Terminate as soon as the value for the source node is known.

ENCODING TO DEPENDENCY GRAPH

To determine whether $s \sim t$, $s \approx t$ or $s \models \phi$.

1. Construct a dependency graph rooted at v.
2. Compute $A_{min}(v)$.
3. The value $A_{min}(v)$ determines the result.

Remark: this approach can give conclusive results even for infinite-state systems (if we use the local algorithm).

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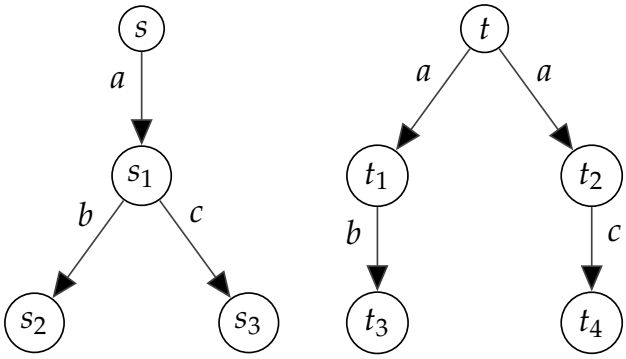
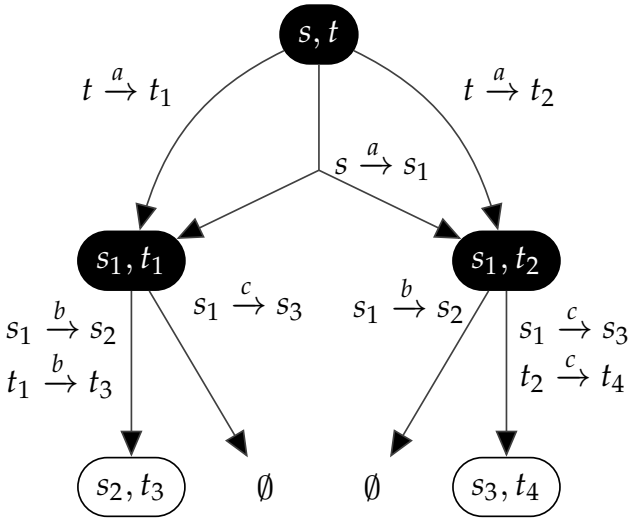
BISIMULATION ENCODING

Determining whether $s \sim t$.





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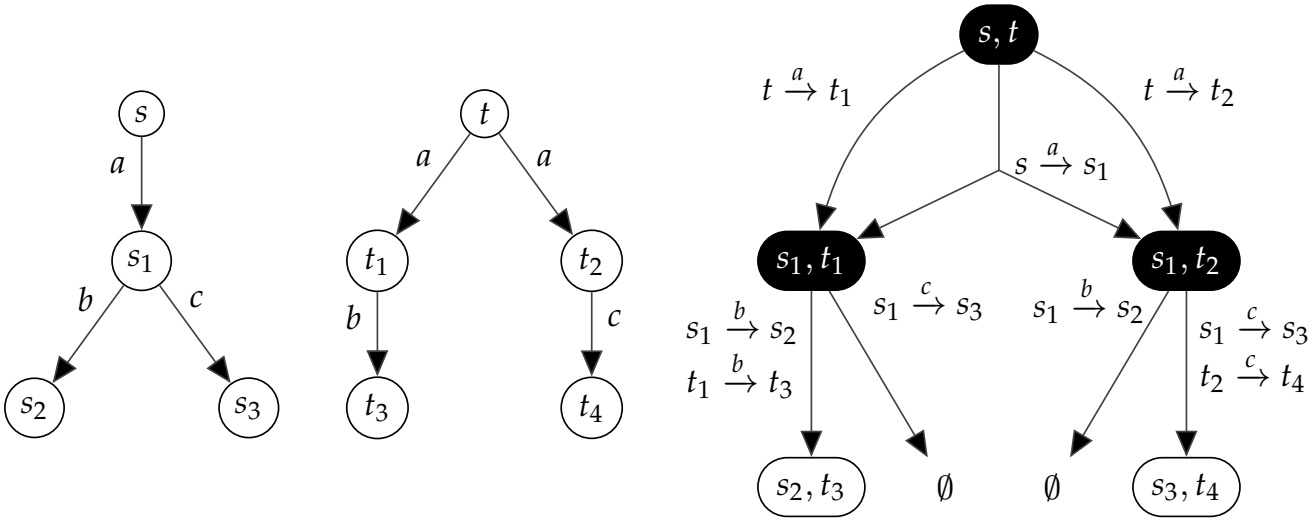
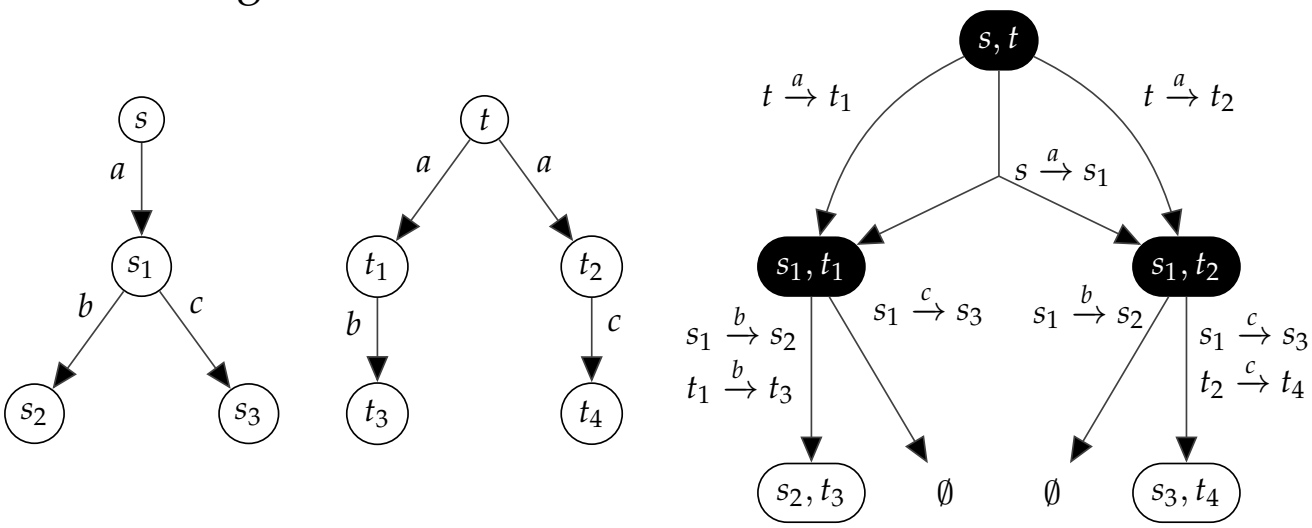


Same graph used by bisimulation game.

BISIMULATION ENCODING

Determining whether $s \sim t$.



Distinguishing Formula: $\phi = DF((s,t))$
$s \models \phi$ and $t \not\models \phi$

BISIMULATION ENCODING

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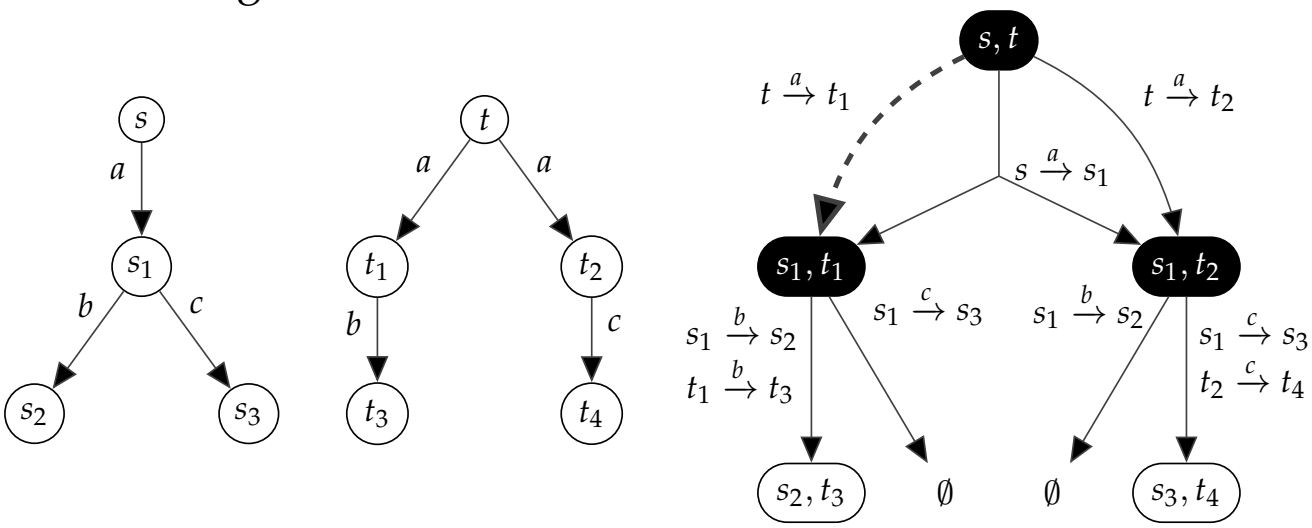
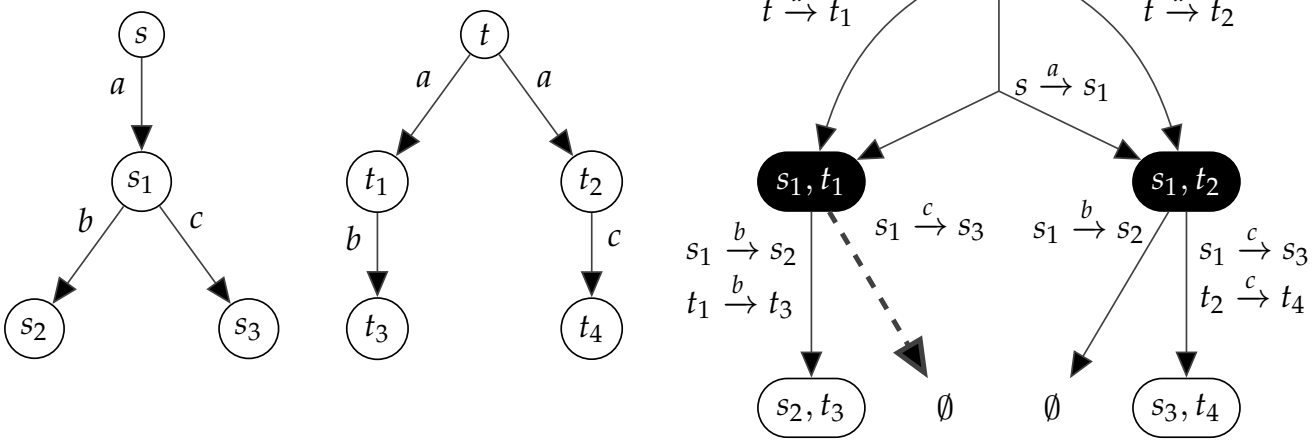


Distinguishing Formula: $\phi = [a]DF((s_1, t_1))$
$s \models \phi$ and $t \not\models \phi$

BISIMULATION ENCODING

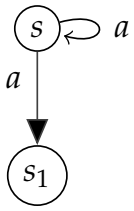
Determining whether $s \sim t$.



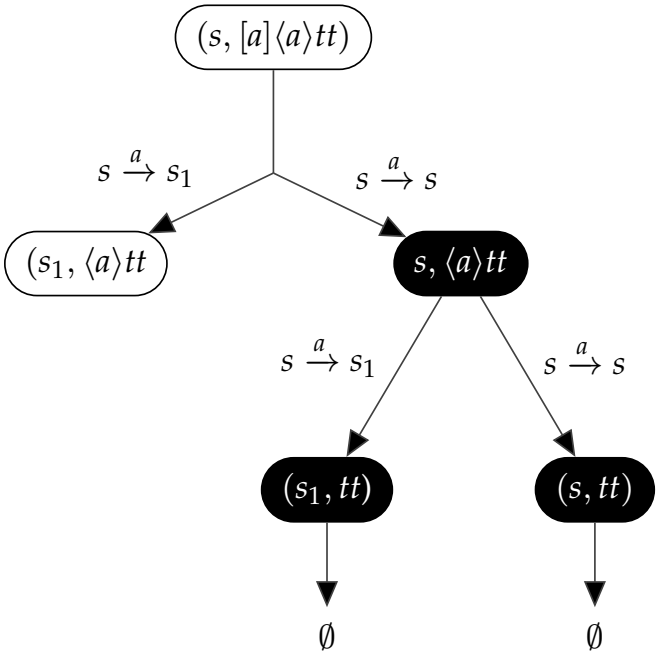
Distinguishing Formula: $\phi = [a]\langle c \rangle tt$
$s \models \phi$ and $t \not\models \phi$

MODEL CHECKING

Determining whether $s \models \phi$.

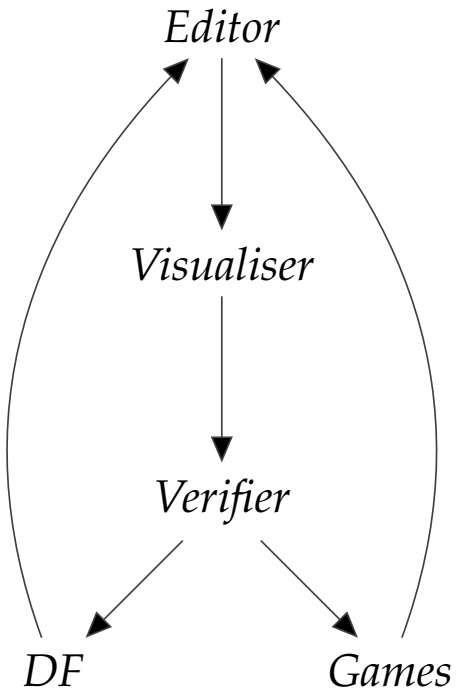


$$\phi = [a]\langle a\rangle tt$$



Same graph used by model checking game.

TOOL IMPLEMENTATION

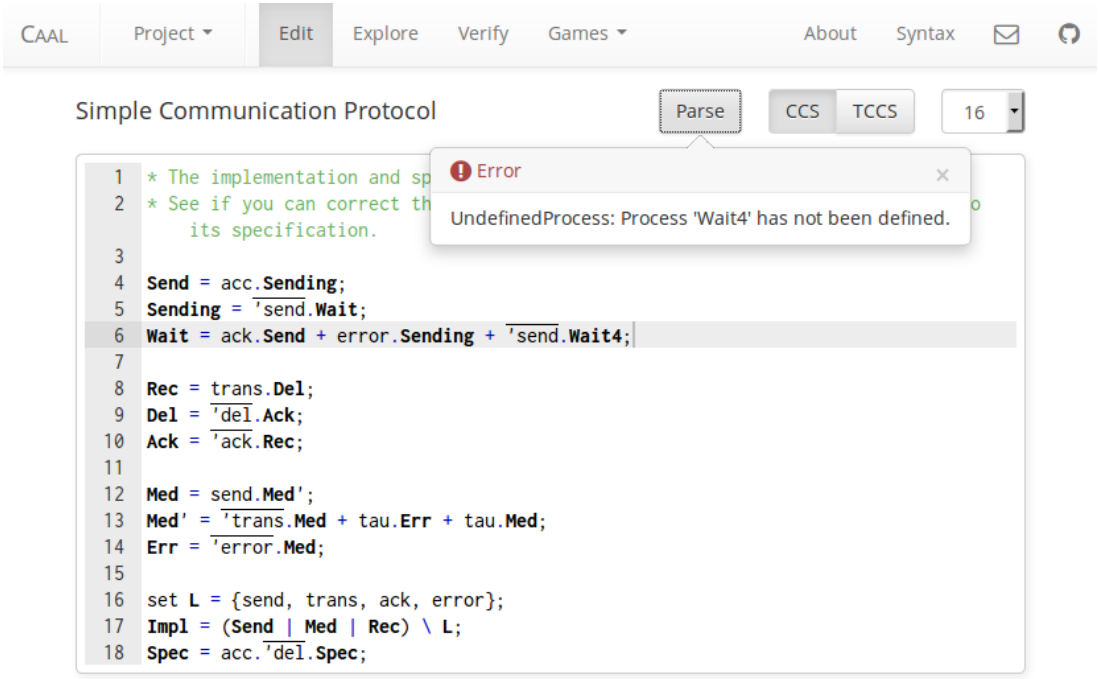


- Cross platform web based tool running in browser.
- Written in JavaScript.

`http://caal.cs.aau.dk`

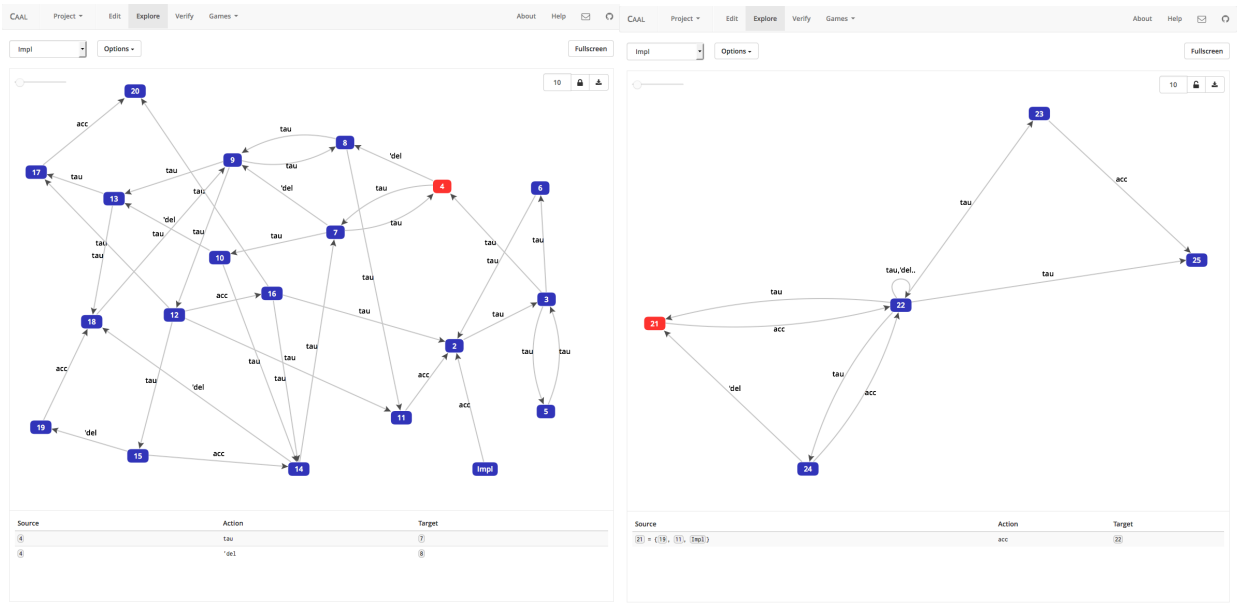
EDITOR

- Syntax highlighting for CCS and discrete timed CCS.



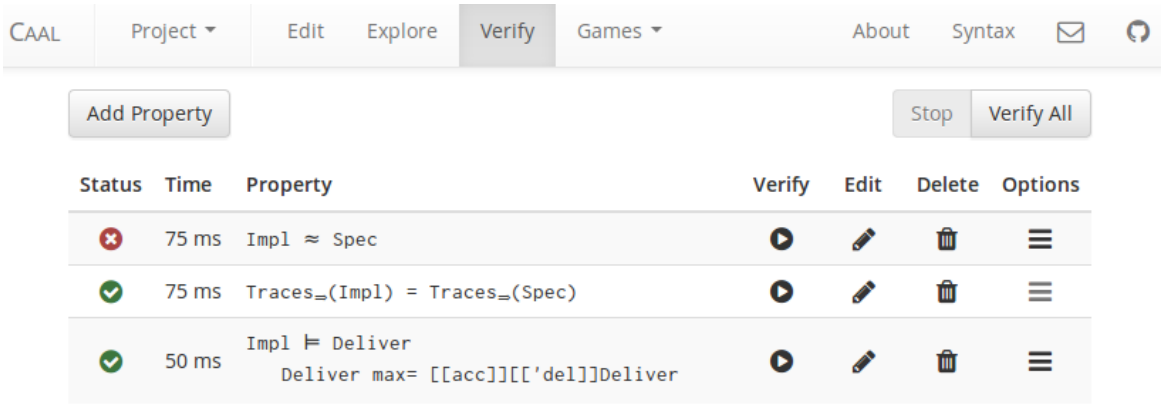
VISUALIZER

- Visualize labelled transition system. Custom state horizon.
- Bisimulation collapse.



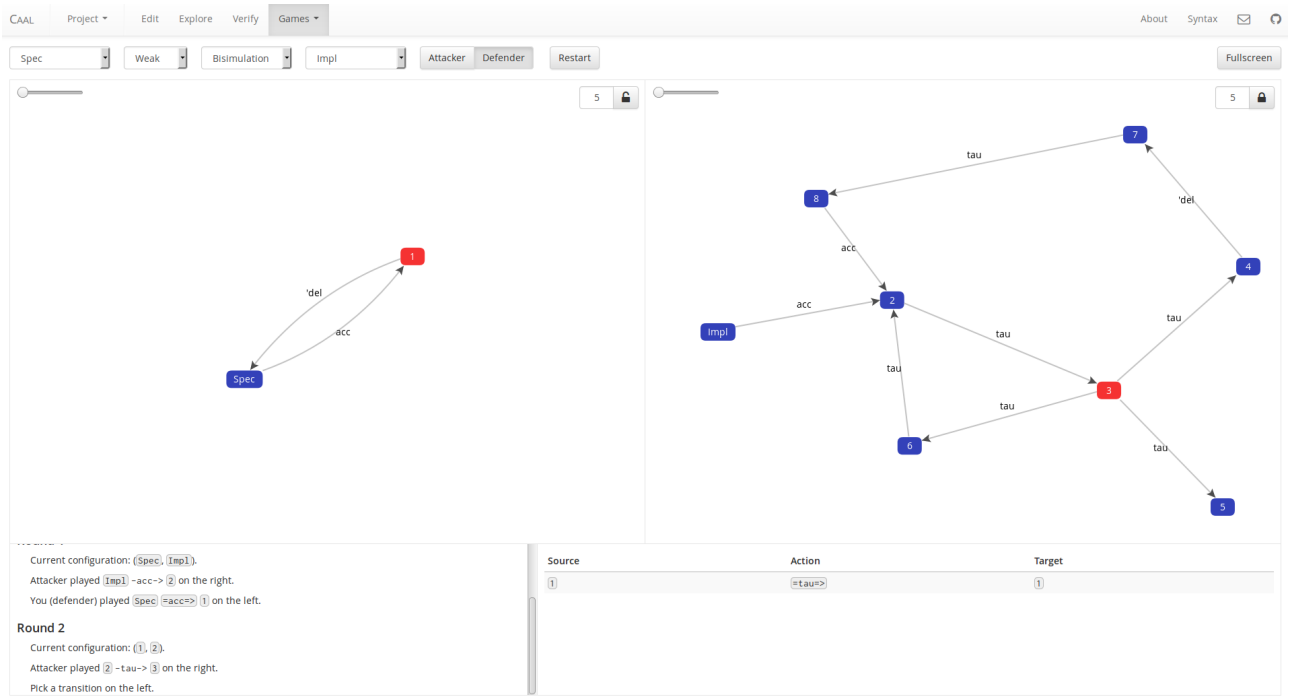
VERIFIER

- Preorders: trace inclusion and simulation.
- Equivalences: trace, simulation, and bisimulation.
- Both strong/weak and timed/untimed variants.
- Model checking of recursive HML formulae.
- Debugging options: distinguishing formulae, games.



GAMES

- Bisimulation and HML game.
- Play against a computer (and loose).



DEMO

CONCLUSION

CAAL is a graphical tool for the use in teaching about reactive systems.

- CAAL is trivial to run in any modern browser.
- Supports CCS and HML syntax including discrete time.
- Offers equivalence and model checking of CSS/TCCS.
- Focuses on usability rather than speed.
- Includes intuitive debugging using distinguishing formulae and games.

Current work.

- Verification-as-a-service.
- Performance optimisations.
- Parallelisation of fixed-point computation.

BIBLIOGRAPHY

[1] J.R. Andersen, M.M. Hansen, and N. Andersen. CAAL 2.0: Equivalences, preorders and games for CCS and TCCS. Master's thesis, Aalborg University, 2015.

[2] J.K. Wortmann, S.R. Olesen, and S. Enevoldsen. CAAL 2.0: Recursive HML, distinguishing formulae, equivalence collapses and parallel fixed-point computations. Master's thesis, Aalborg University, 2015.