Synthesizing Concurrent Programs using Answer Set Programming

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Related work

Automated Synthesis of Concurrent Programs

- E. M. Clarke and E. A. Emerson
  Design and Synthesis of Synchronization Skeletons Using Branching Temporal Logic
  Workshop on Logic of Program, Springer-Verlag, 1982
- Z. Manna and P. Wolper
  Synthesis of Communicating Process from Temporal Specifications
  ACM TOPLAS, 1984
- ...

Answer Set Programming

- S. Heymans, D. Van Nieuwenborgh and D. Vermeir
  Synthesis from Temporal Specifications using Preferred Answer Set Programming
  LNCS no. 3701, 2005
- ...

Overview

- Concurrent Programs
  - Syntax
  - Semantics
- Specification of Concurrent Programs
  - Behavioural properties
  - Structural properties
  - Symmetric Concurrent Programs
- Automated Synthesis of Concurrent Program

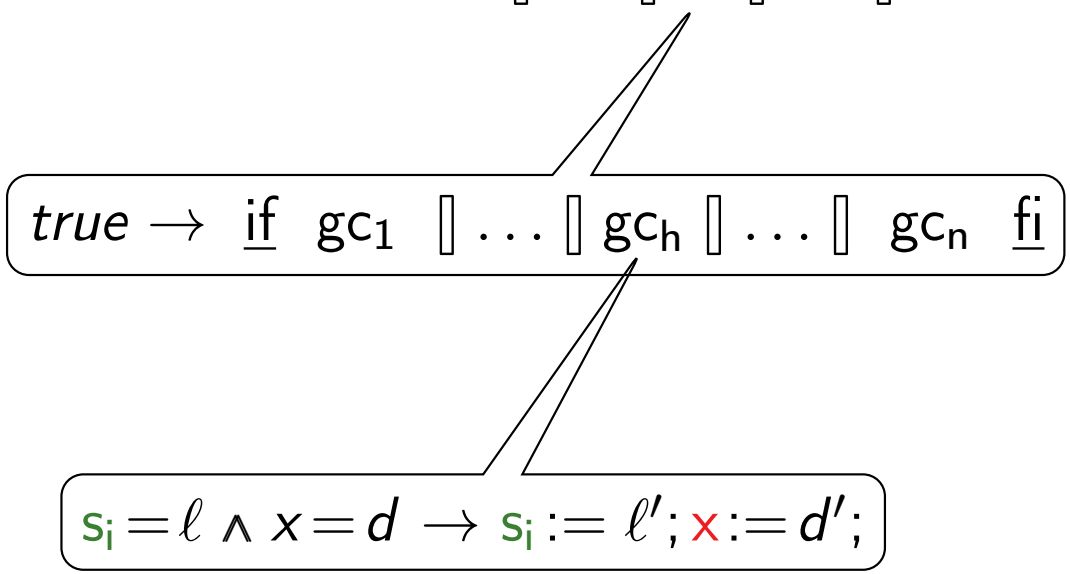
  based on Answer Set Programming
- Experimental Results

k-Process Concurrent Program

Syntax

* $P_1, \ldots, P_k$, *processes*
* $s_1, \ldots, s_k$, *local variables* ranging over a finite domain L
* x, a single *shared variable* ranging over a finite domain D

$s_1 := \ell_1; \ldots; s_k := \ell_k;\ x := d_0;\ \underline{\text{do}}\ P_1 \,[]\, \ldots \,[]\, P_i \,[]\, \ldots \,[]\, P_k\ \underline{\text{od}}$



where $\ell_1, \ldots, \ell_k, \ell, \ell' \in L$, and $d_0, d, d' \in D$.

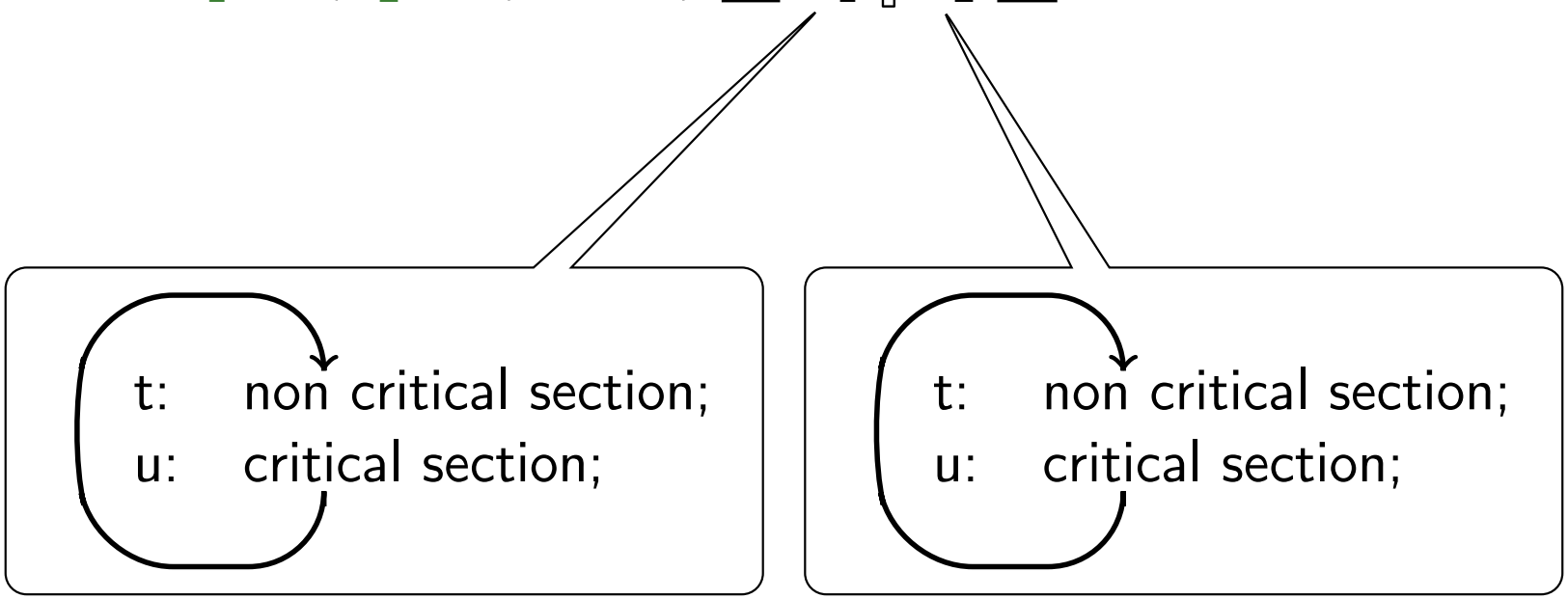
Example

Syntax

A 2-Process Concurrent Program C

- P_1, P_2, processes
- s_1, s_2, local variables ranging over $L = \{t, u\}$
- x, a single shared variable ranging over $D = \{0, 1\}$

C : $s_1 := t; s_2 := t;\ x := 0;\ \underline{\text{do}}\ P_1 \,[\!]\, P_2\ \underline{\text{od}}$



Example

Syntax

A 2-Process Concurrent Program C

- P_1, P_2, processes
- s_1, s_2, local variables ranging over $L = \{t, u\}$
- x, a single shared variable ranging over $D = \{0, 1\}$

$$C: \quad s_1 := t; s_2 := t; \; x := 0; \; \underline{\text{do}} \; P_1 \; [] \; P_2 \; \underline{\text{od}}$$

$$P_1: \; true \rightarrow \underline{\text{if}}$$
$$s_1 = t \wedge x = 0 \rightarrow s_1 := u; x := 0;$$
$$[] \; s_1 = u \wedge x = 0 \rightarrow s_1 := t; x := 1;$$
$$\underline{\text{fi}}$$

$$P_2: \; true \rightarrow \underline{\text{if}}$$
$$s_2 = t \wedge x = 1 \rightarrow s_2 := u; x := 1;$$
$$[] \; s_2 = u \wedge x = 1 \rightarrow s_2 := t; x := 0;$$
$$\underline{\text{fi}}$$

k-Process Concurrent Program

Semantics

A k-Process Concurrent Program C

* $P_1, \ldots, P_k$, processes
* $s_1, \ldots, s_k$, local variables ranging over a finite domain L
* x, a single *shared variable* ranging over a finite domain D

$$s_1 := \ell_1; \ldots; s_k := \ell_k;\ x := d_0;\ \underline{\text{do}}\ P_1 \,[]\, \ldots \,[]\, P_i \,[]\, \ldots \,[]\, P_k\ \underline{\text{od}}$$

The Kripke structure $\mathcal{K} = \langle S, S_0, R, \lambda \rangle$ associated with C:

* set of *states*: $S = L^k \times D$
* set of *initial states*: $S_0 = \{\langle \ell_1, \ldots, \ell_k, d_0 \rangle\}$
* total *transition relation*: $R \subseteq S \times S$
* total *labelling function*: $\lambda : S \to \mathcal{P}(Elem)$

Example

$$
\begin{array}{l}
s_1 := t;\ s_2 := t;\ x := 0; \\
\underline{\text{do}} \quad \begin{array}{l} true \rightarrow \underline{\text{if}} \\ \quad s_1 = t \wedge x = 0 \rightarrow s_1 := u; x := 0; \\ \quad [\!] \ s_1 = u \wedge x = 0 \rightarrow s_1 := t; x := 1; \\ \quad \underline{\text{fi}} \end{array} \\
\quad \| \\
\quad \begin{array}{l} true \rightarrow \underline{\text{if}} \\ \quad s_2 = t \wedge x = 1 \rightarrow s_2 := u; x := 1; \\ \quad [\!] \ s_2 = u \wedge x = 1 \rightarrow s_2 := t; x := 0; \\ \quad \underline{\text{fi}} \end{array} \quad \underline{\text{od}}
\end{array}
$$

Example (Cont'd)

$s_1 := t;\ s_2 := t;\ x := 0;$

$$\underline{\text{do}}\quad \begin{array}{l} true \rightarrow \underline{\text{if}} \\ \quad s_1 = t \wedge x = 0 \rightarrow s_1 := u; x := 0; \\ [\!] \ s_1 = u \wedge x = 0 \rightarrow s_1 := t; x := 1; \\ \quad \underline{\text{fi}} \end{array} \Bigg\| \begin{array}{l} true \rightarrow \underline{\text{if}} \\ \quad s_2 = t \wedge x = 1 \rightarrow s_2 := u; x := 1; \\ [\!] \ s_2 = u \wedge x = 1 \rightarrow s_2 := t; x := 0; \\ \quad \underline{\text{fi}} \end{array} \quad \underline{\text{od}}$$

$S_0 = \{\langle t, t, 0\rangle\}$

$\langle t, t, 0\rangle$

$S = \{\langle t, t, 0\rangle, \ldots\}$

$\lambda = \{\langle\langle t, t, 0\rangle, \{s_1 = t, s_2 = t, x = 0\}\rangle, \ldots\}$

Example (Cont'd)

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\begin{array}{l}
s_1 := t;\ s_2 := t;\ x := 0; \\
\underline{\text{do}} \quad \begin{array}{l} true \rightarrow \underline{\text{if}} \\ \quad s_1 = t \wedge x = 0 \rightarrow s_1 := u; x := 0; \\ [\!] \ s_1 = u \wedge x = 0 \rightarrow s_1 := t; x := 1; \\ \quad \underline{\text{fi}} \end{array} \\
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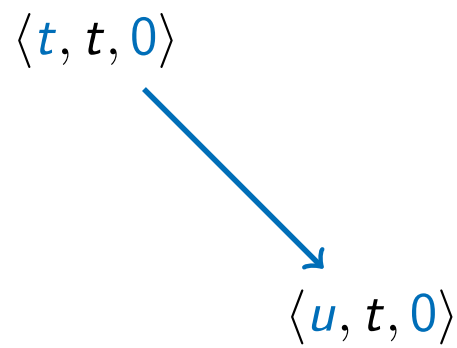
$S_0 = \{\langle t, t, 0\rangle\}$

$S = \{\langle t, t, 0\rangle, \langle u, t, 0\rangle, \ldots\}$

$R = \{\langle\langle t, t, 0\rangle, \langle u, t, 0\rangle\rangle, \ldots$



$\lambda = \{\langle\langle t, t, 0\rangle, \{s_1 = t, s_2 = t, x = 0\}\rangle, \ldots\}$

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\qquad \| \\
\begin{array}{l} true \rightarrow \underline{\text{if}} \\ \quad s_2 = t \wedge x = 1 \rightarrow s_2 := u; x := 1; \\ \quad [\!] \ s_2 = u \wedge x = 1 \rightarrow s_2 := t; x := 0; \\ \quad \underline{\text{fi}} \end{array} \quad \underline{\text{od}}
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$S_0 = \{\langle t, t, 0\rangle\}$

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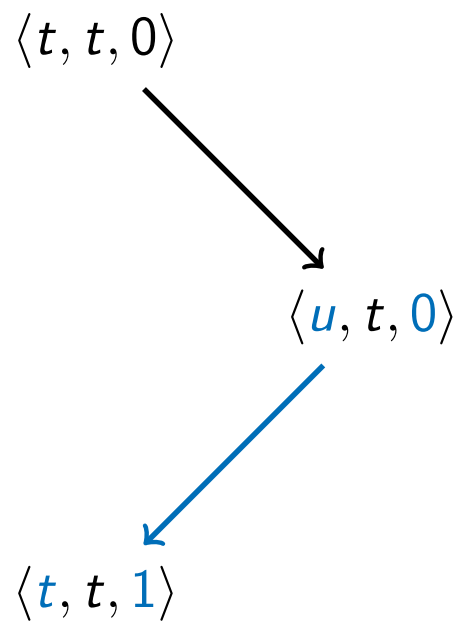
$R = \{\langle\langle t, t, 0\rangle, \langle u, t, 0\rangle\rangle, \langle\langle u, t, 0\rangle, \langle t, t, 1\rangle\rangle, \ldots$

$\lambda = \{\langle\langle t, t, 0\rangle, \{s_1 = t, s_2 = t, x = 0\}\rangle, \ldots\}$



Example (Cont'd)

$s_1 := t;\ s_2 := t;\ x := 0;$

$$\underline{\text{do}}\quad \begin{array}{l} \mathit{true} \rightarrow \underline{\text{if}} \\ \quad s_1 = t \wedge x = 0 \rightarrow s_1 := u; x := 0; \\ \quad [\!] \ s_1 = u \wedge x = 0 \rightarrow s_1 := t; x := 1; \\ \quad \underline{\text{fi}} \end{array} \quad \| \quad \begin{array}{l} \mathit{true} \rightarrow \underline{\text{if}} \\ \quad s_2 = t \wedge x = 1 \rightarrow s_2 := u; x := 1; \\ \quad [\!] \ s_2 = u \wedge x = 1 \rightarrow s_2 := t; x := 0; \\ \quad \underline{\text{fi}} \end{array} \quad \underline{\text{od}}$$

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$\langle\langle u, t, 0\rangle, \langle t, t, 1\rangle\rangle,$
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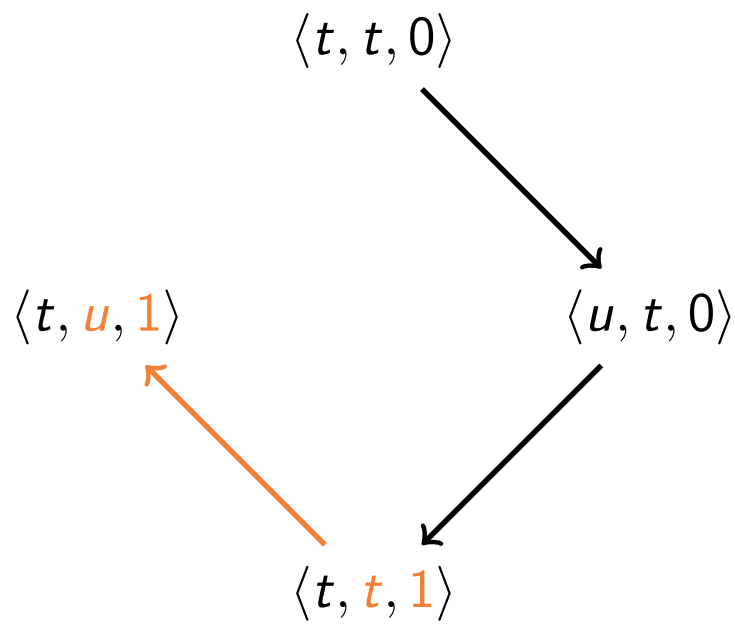

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\begin{array}{l}
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$$S_0 = \{\langle t, t, 0\rangle\}$$

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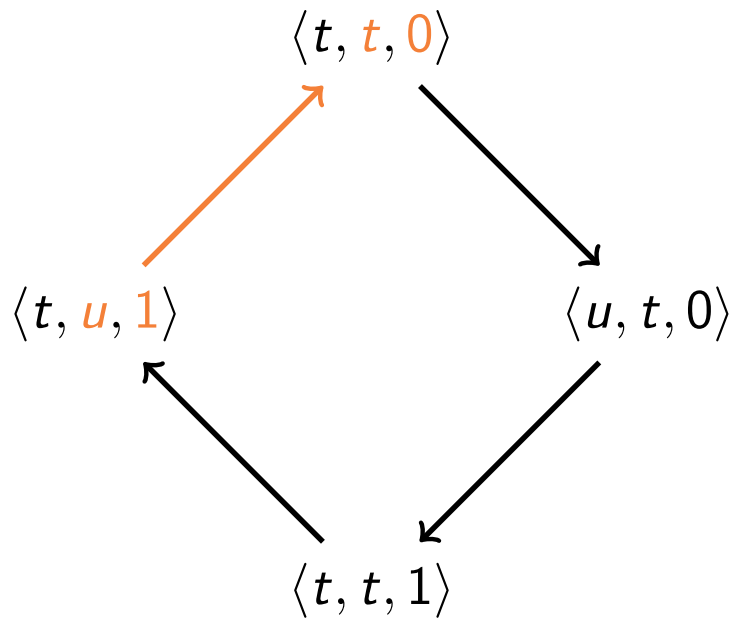
$$\lambda = \{\langle\langle t, t, 0\rangle, \{s_1 = t, s_2 = t, x = 0\}\rangle, \ldots\}$$



Specification: Behavioural Properties

Time dependant behavioural properties of Concurrent Programs:

- safety
- liveness

Specified in a Temporal Logic, i.e., Computation Tree Logic (CTL):

- path quantifiers: for all paths **A**, for some paths **E**
- temporal operators: eventually **F**, globally **G**, next **X**,....

> A k-Process Concurrent Program C satisfies a behavioural property φ iff
> the Kripke structure $\mathcal{K}$ associated with C satisfies φ.

Specification: Behavioural Properties

Computation Tree Logic

- Syntax: $\varphi ::= b \mid \neg\varphi \mid \varphi_1 \wedge \varphi_2 \mid \mathsf{EX}\,\varphi \mid \mathsf{EG}\,\varphi \mid \mathsf{E}[\varphi_1\,\mathsf{U}\,\varphi_2]$

  $\mathsf{AG}\varphi \equiv \neg\mathsf{EF}\neg\,\varphi$, etc.

- Semantics:

$$\left.\begin{array}{r}\text{Kripke structure } \mathcal{K}\\ \text{state } s\\ \text{formula } \varphi\end{array}\right\} \quad \mathcal{K}, s \models \varphi$$

recursively defined as follows:

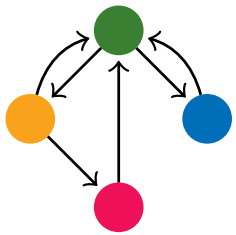
$\mathcal{K}, s \models b$	iff	$b \in \lambda(s)$
$\mathcal{K}, s \models \neg\,\varphi$	iff	$\mathcal{K}, s \models \varphi$ does not hold
$\mathcal{K}, s \models \varphi_1 \wedge \varphi_2$	iff	$\mathcal{K}, s \models \varphi_1$ and $\mathcal{K}, s \models \varphi_2$
$\mathcal{K}, s \models \mathsf{EX}\,\varphi$	iff	there exists $\langle s, t\rangle \in R$ such that $\mathcal{K}, t \models \varphi$
$\mathcal{K}, s \models \mathsf{EG}\,\varphi$	iff	there exists a path π such that $\pi_0 = s$ and for all $i \geq 0$, $\mathcal{K}, \pi_i \models \varphi$
$\mathcal{K}, s \models \mathsf{E}\,[\varphi_1\,\mathsf{U}\,\varphi_2]$	iff	there exists a path $\pi = \langle s, s_1, \ldots\rangle$ in $\mathcal{K}$ and $i \geq 0$ such that $\mathcal{K}, \pi_i \models \varphi_2$ and for all $0 \leq j < i$, $\mathcal{K}, \pi_j \models \varphi_1$

Specification: Behavioural Properties

Computation Tree Logic

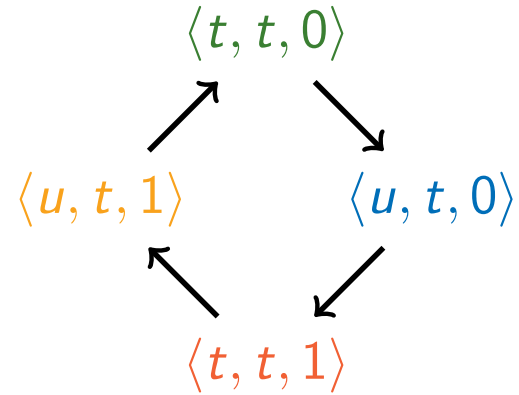
k-Process Concurrent Program satisfying p

M :



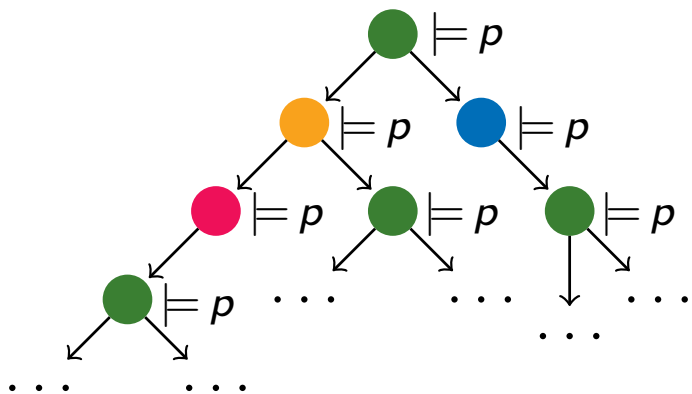
2-Process Concurrent Program satisfying mutual exclusion

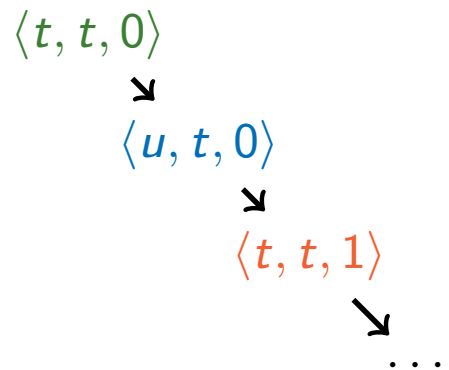
K :



$M, \bullet \models \mathsf{AG}\, p$

$K, \langle t, t, 0\rangle \models \mathsf{AG}\, \neg(\mathsf{s}_1 = u \wedge \mathsf{s}_2 = u)$





Specification: Structural Properties

Symmetric Program Structure

- local transition relation $T \subseteq L \times L$

  pattern of execution of each process P_i

- k-generating function $f: D \to D$ (permutation on the domain of x)

  global property of a concurrent program C

T and f define a Symmetric Program Structure $\Sigma = \langle f, T \rangle$

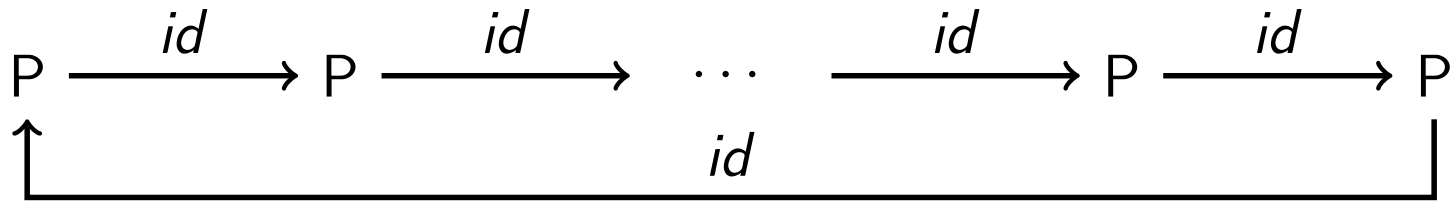
A k-Process Concurrent Program C satisfies Σ *iff*

1. each process $P_1, \ldots, P_k$ in C satisfies T, and
2. C satisfies f

Symmetric Concurrent Programs

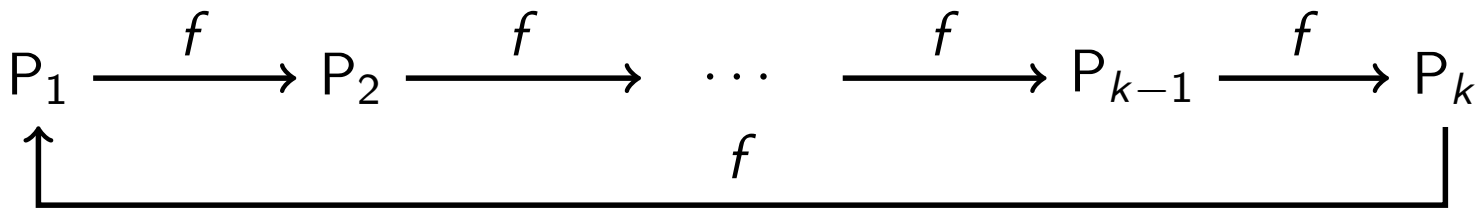
k-generating function f is

either the identity function id



(Dijkstra's semaphore)

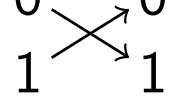
or a generator of a cyclic group $\{id, f, \ldots, f^{k-1}\}$ of order k



(Peterson's algorithm)

Example

A 2-Process Symmetric Concurrent Program for Mutual Exclusion

Symmetric program structure Σ: T :  f: 

$$true \rightarrow \underline{\text{if}} \;\; s_1 = t \wedge x = 0 \rightarrow s_1 := u \; ; \; x := 0 \; ;$$

$$[] \;\; s_1 = t \wedge x = 1 \rightarrow s_1 := t \; ; \; x := 1 \; ;$$

$$[] \;\; s_1 = u \wedge x = 0 \rightarrow s_1 := t \; ; \; x := 1 \; ; \; \underline{\text{fi}}$$

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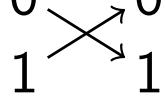
Symmetric program structure Σ: T :  f: 

$$true \rightarrow \underline{\text{if}} \;\; s_1 = t \wedge x = 0 \rightarrow s_1 := u \;;\; x := 0 \;;$$

$$true \rightarrow \underline{\text{if}} \;\; s_2 = t \wedge x = 1 \rightarrow s_2 := u \;;\; x := 1 \;;$$

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Example

A 2-Process Symmetric Concurrent Program for Mutual Exclusion

Symmetric program structure Σ: $T : t \rightleftarrows u$ $\circlearrowright$ $\quad f: \begin{matrix} 0 & 0 \\ 1 & 1 \end{matrix}$ (0 ↔ 0, 1 ↔ 1)

$$true \rightarrow \underline{\text{if}} \;\; s_1 = t \wedge x = 0 \rightarrow s_1 := u \;;\; x := 0 \;;$$

$$true \rightarrow \underline{\text{if}} \;\; s_2 = t \wedge x = 1 \rightarrow s_2 := u \;;\; x := 1 \;;$$

$$[] \;\; s_1 = t \wedge x = 1 \rightarrow s_1 := t \;;\; x := 1 \;;$$

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Example

A 2-Process Symmetric Concurrent Program for Mutual Exclusion

Symmetric program structure Σ: $T : t \rightleftarrows u$ $\circlearrowleft$ $\quad f: \begin{matrix} 0 & 0 \\ 1 & 1 \end{matrix}$ (crossed)

$$true \rightarrow \underline{\text{if}} \;\; s_1 = t \wedge x = 0 \rightarrow s_1 := u \;;\; x := 0 \;;$$

$$true \rightarrow \underline{\text{if}} \;\; s_2 = t \wedge x = 1 \rightarrow s_2 := u \;;\; x := 1 \;;$$

$$[] \;\; s_1 = t \wedge x = 1 \rightarrow s_1 := t \;;\; x := 1 \;;$$

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Synthesis of a Concurrent Programs

- automatically derive a k-concurrent program from a given specification:
  - Behavioural Properties
  - Structural Properties
- derive a program correct by construction

$$s_1 := \ell_1;\ s_2 := \ell_2;\ x := d_0;$$

$$\underline{\text{do}} \quad \begin{array}{l} \mathit{true} \rightarrow \underline{\text{if}} \\ \quad s_1 = ? \wedge x = ? \rightarrow s_1 := ?; x := ?; \\ [] \quad \ldots \\ [] \; s_1 = ? \wedge x = ? \rightarrow s_1 := ?; x := ?; \\ \quad \underline{\text{fi}} \end{array} \;\Big\|\; \begin{array}{l} \mathit{true} \rightarrow \underline{\text{if}} \\ \quad s_2 = ? \wedge x = ? \rightarrow s_2 := ?; x := ?; \\ [] \quad \ldots \\ [] \; s_2 = ? \wedge x = ? \rightarrow s_2 := ?; x := ?; \\ \quad \underline{\text{fi}} \end{array} \quad \underline{\text{od}}$$

Synthesis Problem

Given:

1. a CTL formula φ (Behavioural Property),
2. a Symmetric Program Structure $\Sigma = \langle f, T \rangle$ (Structural Property)

we look for a k-process concurrent program C such that

* for all $i > 0$ $f(P_i) = P_{(i \bmod k)+1}$, and
* C satisfies φ

> We guess P_1 satisfying T and we generate the set $P_2, \ldots, P_k$ using f such that the Kripke structure associated with C satisfies φ

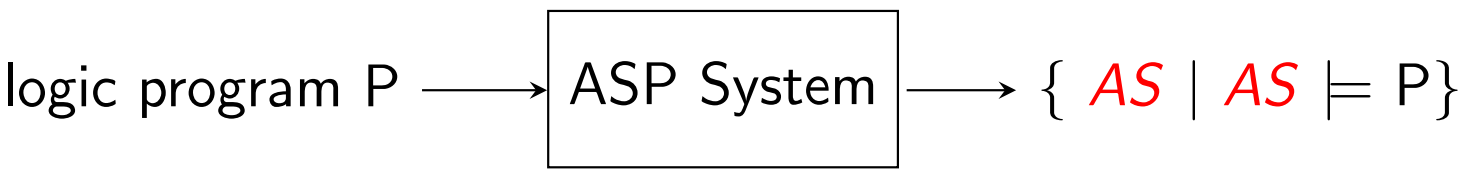
Answer Set Programming (ASP)

- knowledge representation and reasoning tool

  logic program $\Rightarrow$ encoding of a problem

  Answer Set $\Rightarrow$ solution of a problem

- guess & check
  - guess: rules for generate candidate solutions
  - check: rules for eliminate invalid candidates



ASP-based Synthesis Procedure

We reduce the derivation of a k-Process Concurrent Program to an answer set computation

$$\boxed{\varphi + \Sigma}$$

ASP-based Synthesis Procedure

We reduce the derivation of a k-Process Concurrent Program to an answer set computation

Encoding: a logic program Π encodes a *synthesis problem*.

Π is the union of:

- Π_φ, encoding Behavioural Properties φ
- Π_Σ, encoding Structural Properties Σ

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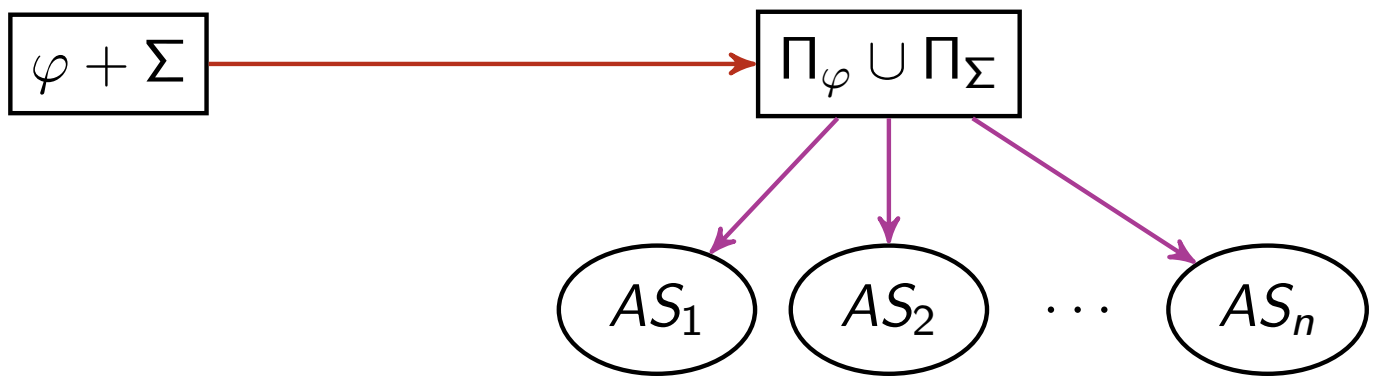

ASP-based Synthesis Procedure

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Encoding: a logic program Π encodes a *synthesis problem*.

Π is the union of:

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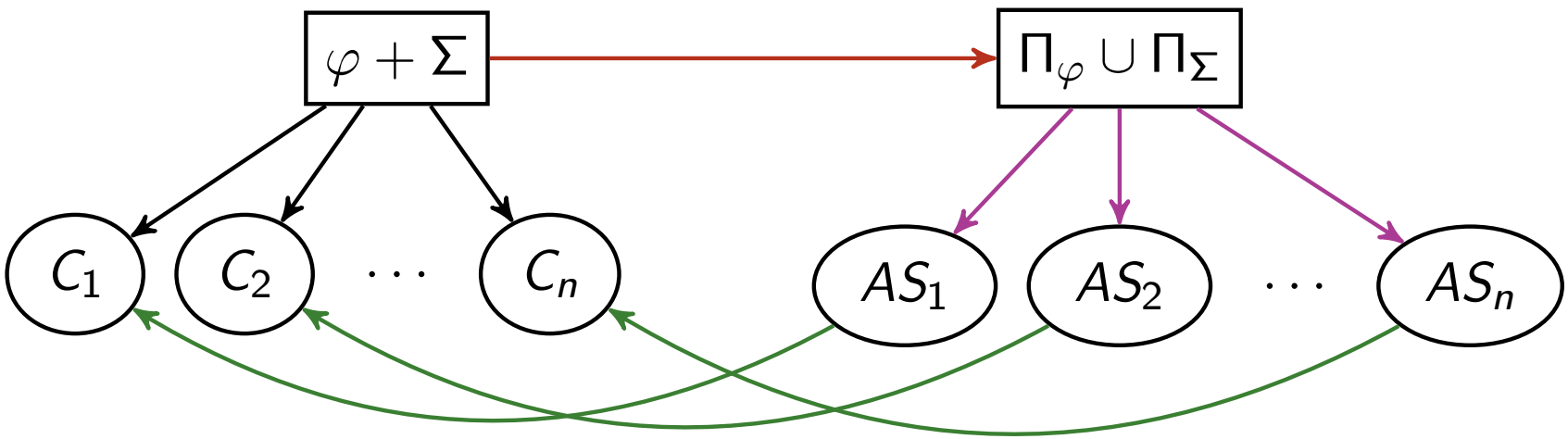
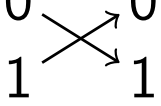
Decoding: answer sets $ans(\Pi) = \{AS_1, AS_2, ..., AS_n\}$ encode *solutions* of the synthesis problem



Example

Encoding

Symmetric program structure Σ: $T : t \rightleftarrows u$ f: 

Behavioural property: $\varphi = \mathsf{AG}\,\neg(\mathsf{s}_1 = u \wedge \mathsf{s}_2 = u)$

$\Pi = \{$

$\leftarrow not\ sat(s(t,t,0), n(ef(a(ap(s1,u), ap(s2,u))))).$

$sat(s(t,t,0), n(ef(a(ap(s1,u), ap(s2,u))))) \leftarrow$
$not\ sat(s(t,t,0), ef(a(ap(s1,u), ap(s2,u)))).$

$\ldots$

$sat(s(t,t,0), a(ap(s1,u), ap(s2,u))) \leftarrow$
$sat(s(t,t,0), ap(s1,u)), sat(s(t,t,0), ap(s2,u)).$

$\ldots$

$gc(1,X,0,Y,0) \vee gc(1,X,0,Y,1) \vee \ldots \leftarrow reachable(X,\_,0).$

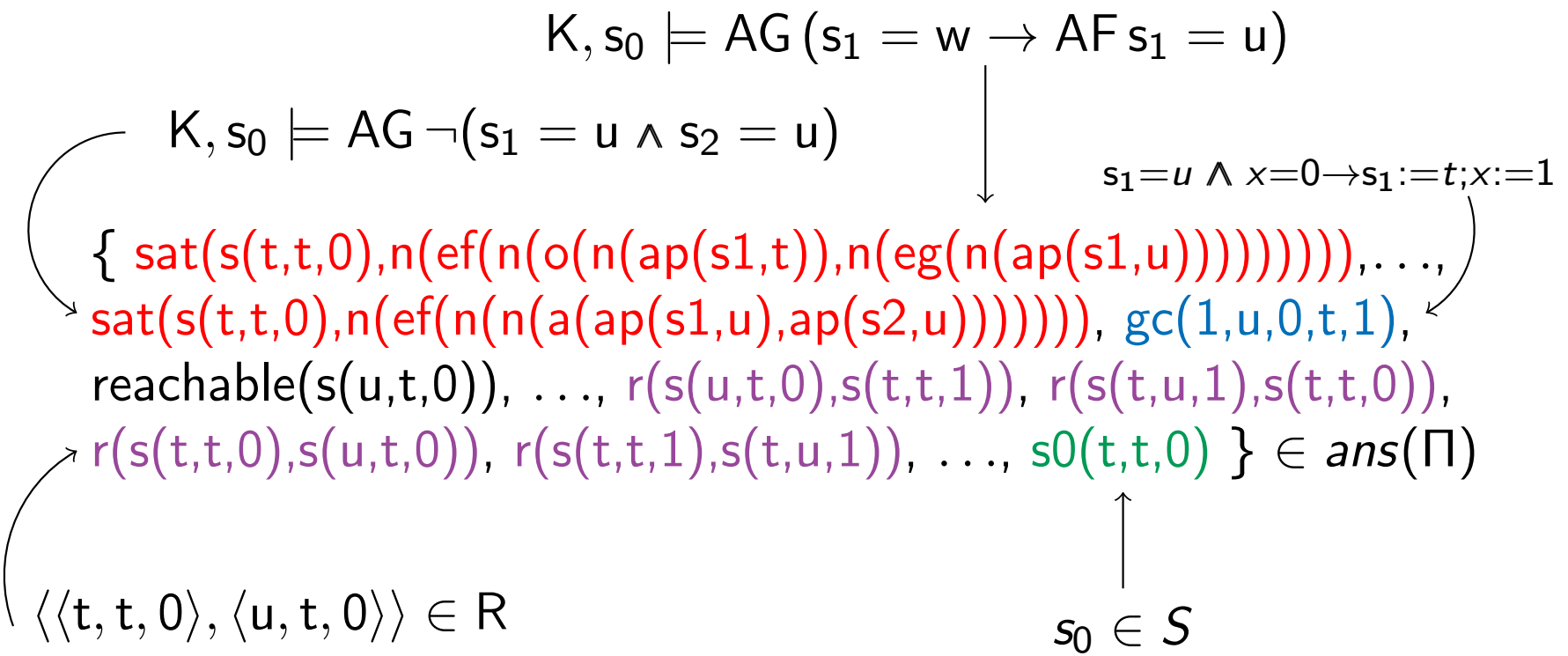
$\ldots$

$gc(2,u,f(1),t,f(0)) \leftarrow gc(1,u,0,t,1).$

$\}$

Example

Decoding



Correctness of Synthesis Procedure

Theorem (Correctness of Synthesis)

Let $\Pi = \Pi_\varphi \cup \Pi_\Sigma$. *be the logic program obtained from:*

1. *a CTL formula* φ, *and*
2. *a symmetric program structure* $\Sigma = \langle f, T \rangle$.

Then,

$$\left(\mathsf{s}_1 := \ell_0; \ldots; \mathsf{s}_k := \ell_0;\ x := d_0;\ \underline{\text{do}}\ P_1 \,[\!]\, \ldots \,[\!]\, P_k\ \underline{\text{od}}\right)\ \models\ \varphi$$

iff there exists an answer set AS *in* $ans(\Pi)$ *such that*

$\forall i \in \{1, \ldots, k\}$, $\forall \ell, \ell' \in L$, $\forall d, d' \in D$,

$\left(\mathsf{s}_i = \ell \wedge x = d \rightarrow \mathsf{s}_i := \ell'; x := d'\right)$ *is in* P_i *iff* $AS \models \mathsf{gc}(i, \ell, d, \ell', d')$

Experimental results

Examples

ME *Mutual Exclusion*: no two processes are in *use*
for all i, j in $\{1, \ldots, k\}$, with $i \neq j$,

$$\mathsf{AG}\,\neg(\mathsf{s}_i = u \wedge \mathsf{s}_j = u)$$

SF *Starvation Freedom*: if a process is waiting then it will enter in use
for all i in $\{1, \ldots, k\}$,

$$\mathsf{AG}\,(\mathsf{s}_i = w \rightarrow \mathsf{AF}\,\mathsf{s}_i = u)$$

BO *Bounded Overtaking*: while a process is waiting, any other process can exits from its critical section at most once
for all i, j in $\{1, \ldots, k\}$,

$$\mathsf{AG}\,((\mathsf{s}_i = w \wedge \mathsf{s}_j = u) \rightarrow \mathsf{AF}\,(\mathsf{s}_j = t \wedge \mathsf{A}[\neg(\mathsf{s}_j = u)\,\mathsf{U}\,\mathsf{s}_i = u]))$$

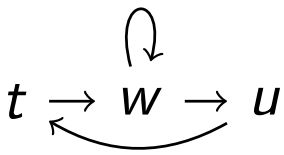
MR *Maximal Reactivity* (MR): if a process is waiting and all others are thinking then in the next state it will enter in use
for all i in $\{1, \ldots, k\}$,

$$\mathsf{AG}\,((\mathsf{s}_i = w \wedge \bigwedge_{j \in \{1,\ldots,k\} \setminus \{i\}} \mathsf{s}_j = t) \rightarrow \mathsf{EX}\,\mathsf{s}_i = u)$$

Experimental results

Synthesis of k-process concurrent programs

T :



id: $0 \longrightarrow 0$, $1 \longrightarrow 1$

f_1: $0 \longrightarrow 1$, $1 \longrightarrow 0$

f_2: $0 \longrightarrow 1$, $1 \longrightarrow 0$, $2 \longrightarrow 2$

f_3: $0 \longrightarrow 1$, $1 \longrightarrow 2$, $2 \longrightarrow 0$

Program	Satisfied Properties	$\lvert D\rvert$	f	$\lvert ans(\Pi)\rvert$	Time (sec)
mutex for 2 processes	*ME*	2	*id*	6	0.07
	ME	2	f_1	7	0.70
	ME, *SF*	2	f_1	3	0.71
	ME, *SF*, *BO*	2	f_1	3	1.44
	ME, *SF*, *BO*, *MR*	3	f_2	2	11.70
mutex for 3 processes	*ME*	2	*id*	5	0.95
	ME	2	f_1	10	0.87
	ME, *SF*	3	f_3	8	152.00
	ME, *SF*, *BO*	3	f_3	8	1700.00

Conclusions

- reduction of the design of a concurrent program to the design of its formal specification
- fully declarative solution (independent of the ASP solver)
- state space explosion problem
  - exploit CTL formulas symmetries,
  - exploit Kripke structures symmetries,
  - ...