CS256/Winter 2009 Lecture #14

Zohar Manna

Satisfiability over a finite-state program

<u>P-validity problem (of φ)</u>

Given a finite-state program P
and formula φ,

is φ P-valid?

i.e. do all P-computations satisfy φ?

<u>P-satisfiability problem (of φ)</u>

Given a finite-state program P
and formula φ

is φ P-satisfiable?

i.e., does there exist a P-computation which satisfies φ?

To determine whether φ is P-valid,
<u>it suffices</u> to apply an algorithm for
deciding if there is a P-computation
that satisfies $\neg\varphi$.

The Idea

To check P-satisfiability of φ,
we combine the tableau T_φ and the transition graph G_P into one product graph, called the behavior graph $\mathcal{B}_{(P,\varphi)}$, and search for paths

$$(s_0, A_0),\ (s_1, A_1),\ (s_2, A_2),\ \ldots$$

that satisfy the two requirements:

- $\sigma \vDash \varphi$:
  there exists a fulfilling path
  $\pi:\ A_0, A_1, \ldots$
  in the tableau T_φ such that $\varphi \in A_0$.

- σ is a P-computation:
  there exists a fair path
  $\sigma:\ s_0, s_1, \ldots$
  in the transition graph G_P.

State transition graph G_P: Construction

- Place as nodes in G_P all initial states s ($s \Vdash \Theta$)

- Repeat

  for some $s \in G_P,\ \tau \in \mathcal{T}$,
  add all its τ-successors s' to G_P
  if not already there,
  and add edges between s and s'.

  Until no new states or edges can be added.

If this procedure terminates, the system is finite-state.

Example: Program mux-pet1 (Fig. 3.4)

(Peterson's Algorithm for mutual exclusion)

local y_1, y_2: **boolean** **where** $y_1 = \text{F}, y_2 = \text{F}$
s : **integer** **where** $s = 1$

ℓ_0 : **loop forever do**

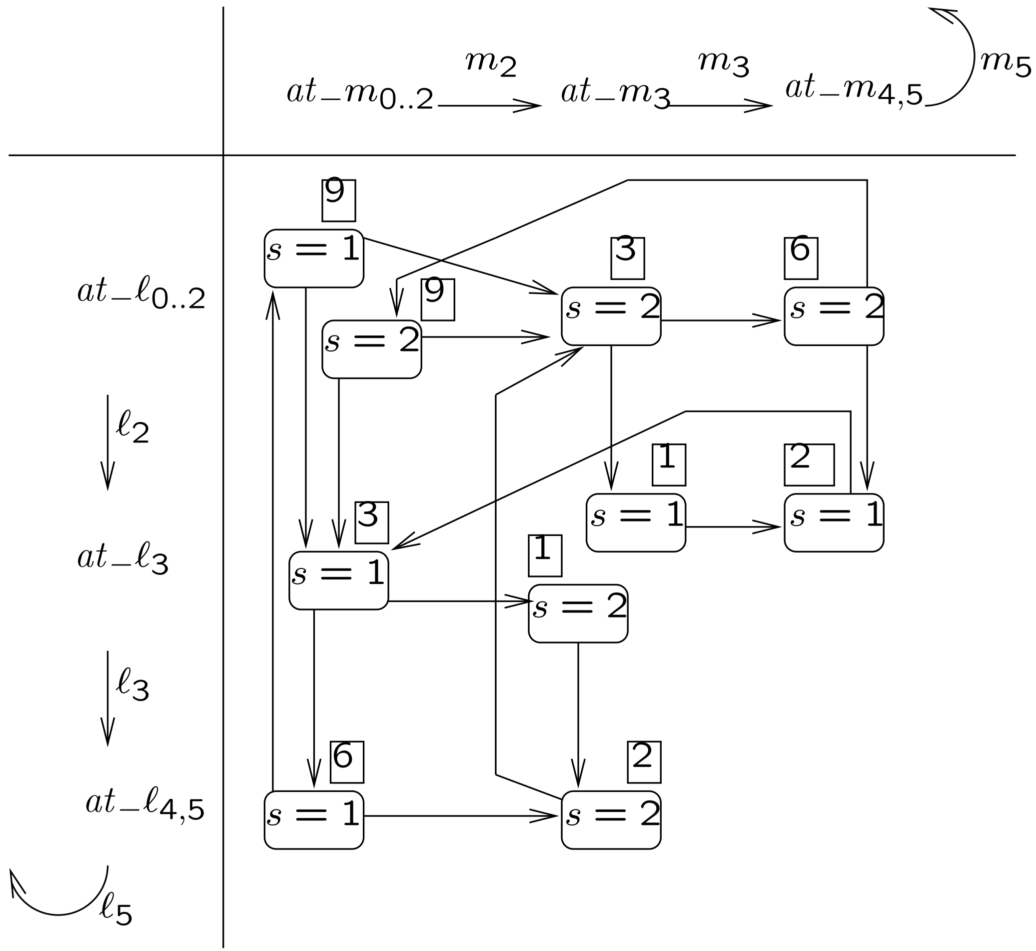
P_1 :: $\left[\begin{array}{ll} \ell_1: & \textbf{noncritical} \\ \ell_2: & (y_1,\ s) := (\text{T},\ 1) \\ \ell_3: & \textbf{await}\ (\neg y_2) \lor (s \neq 1) \\ \ell_4: & \textbf{critical} \\ \ell_5: & y_1 := \text{F} \end{array}\right]$

||

m_0 : **loop forever do**

P_2 :: $\left[\begin{array}{ll} m_1: & \textbf{noncritical} \\ m_2: & (y_2,\ s) := (\text{T},\ 2) \\ m_3: & \textbf{await}\ (\neg y_1) \lor (s \neq 2) \\ m_4: & \textbf{critical} \\ m_5: & y_2 := \text{F} \end{array}\right]$

Abstract state-transition graph for MUX-PET1



We use $y_1 \Leftrightarrow at\_\ell_{3..5}$
$y_2 \Leftrightarrow at\_m_{3..5}$

Some states have been lumped together:

a super-state labeled by $\boxed{i}$ represents i states

MUX-PET1 has 42 reachable states.

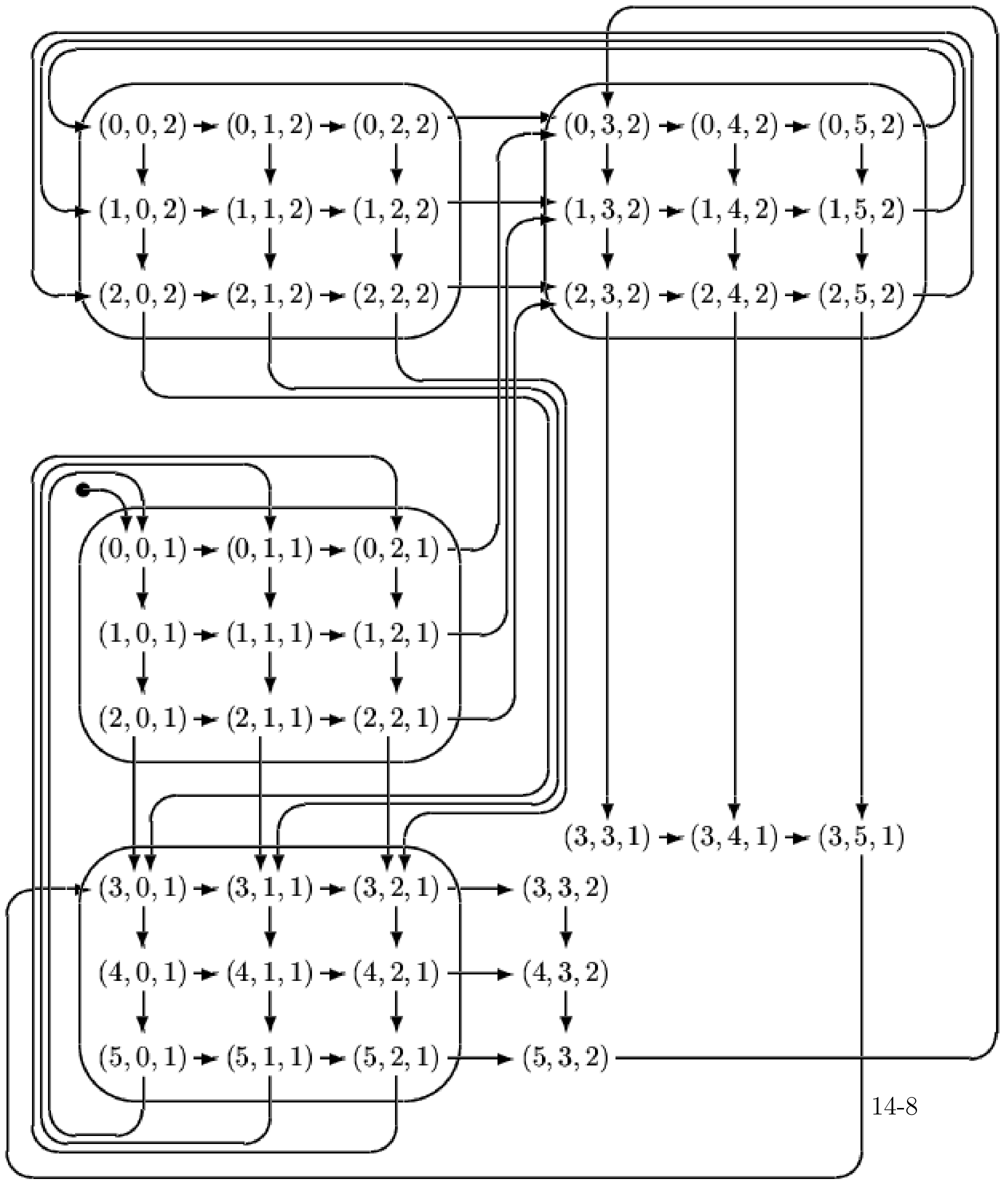
Based on this graph it is straightforward to check the properties

$\psi_1: \quad \Box\neg(at\_\ell_4 \wedge at\_m_4)$

$\psi_2: \quad \Box(at\_\ell_3 \wedge \neg at\_m_3 \rightarrow s = 1)$

$\psi_3: \quad \Box(at\_m_3 \wedge \neg at\_\ell_3 \rightarrow s = 2)$

MUX-PET1 Full state-transition graph (l_i, m_j, s)



Definitions

- For atom A, $\mathit{state}(A)$ is the conjunction of all state formulas in A
  (by R_{sat}, $\mathit{state}(A)$ must be satisfiable)

- For $A \in T_\varphi$,
  $\underline{\delta(A)}$ denotes the set of successors of A in T_φ

- atom A is <u>consistent</u> with state s
  if $s \Vdash \mathit{state}(A)$,

  i.e. s satisfies all state formulas in A.

- ϑ: $A_0, A_1, \ldots$ path in T_φ
  σ: $s_0, s_1, \ldots$ computation of P

  ϑ is a <u>trail</u> of T_φ over σ if
  A_j is consistent with s_j, for all $j \geq 0$

Behavior Graph

For finite-state program P and formula φ, we construct the (P, φ)-behavior graph

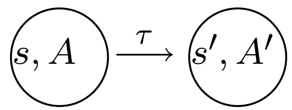
$$\mathcal{B}_{(P,\varphi)} \quad \approx \quad G_P \times T_\varphi^- \text{ (pruned)}$$

such that

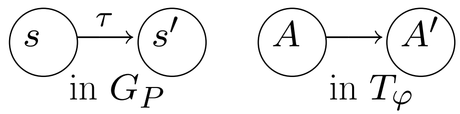
- <u>nodes</u> are labeled by (s, A)

  where s is a state from G_P and
  A is an atom from T_φ <u>consistent</u> with s.

- <u>edges</u>
  There is an edge

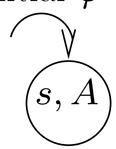


  if and only if $s' \in \tau(s)$ and $A' \in \delta(A)$



- <u>initial φ-node</u> $\quad (s, A)$

  if s is an initial state $(s \Vdash \Theta)$
  and A is an initial φ-atom $(\varphi \in A)$

  It is marked 

Algorithm behavior-graph

(constructing $\mathcal{B}_{(P,\varphi)}$)

- Place in $\mathcal{B}$ all initial φ-nodes (s, A)

  (s initial state of P,
  A initial φ-atom in T_φ^-
  A consistent with s)

- Repeat until no new nodes or new edges can be added:

  Let (s, A) be a node in $\mathcal{B}$
  $\tau \in \mathcal{T}$ a transition
  (s', A') a pair s.t.
  s' is a τ-successor of s
  $A' \in \delta(A)$ in pruned T_φ^-
  A' consistent with s'

  - Add (s', A') to $\mathcal{B}$, if not already there
  - Draw a τ-edge from (s, A) to (s', A'), if not already there

Example: Given FTS LOOP

$\Theta: \; x = 0$

$\mathcal{T} = \{\tau, \tau_I\}$

with τ_I (idling)

τ where ρ_τ: $x' = (x+1) mod 4$

$\mathcal{J}: \; \{\tau\}$

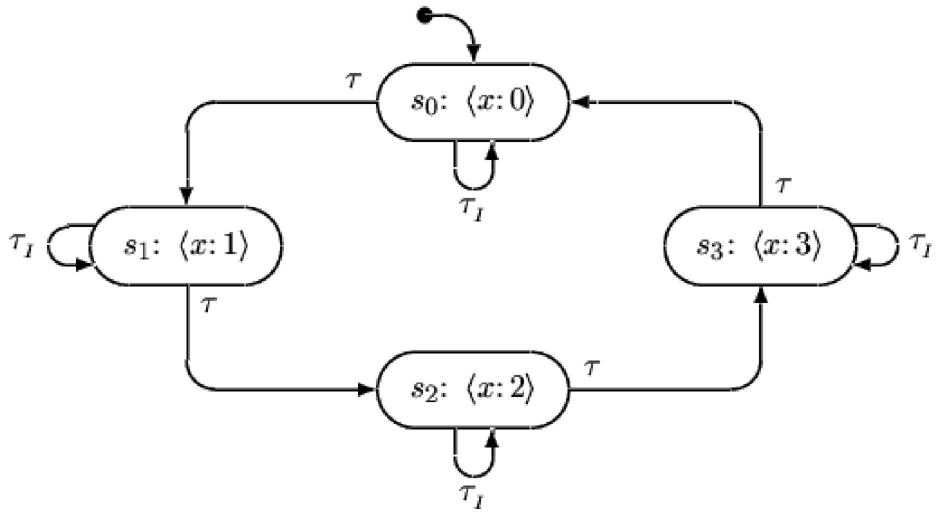
Check P-satisfiability of $\boxed{\psi_3\text{: } \Diamond \Box (x \neq 3)}$

state-transition graph G_{LOOP} (Fig 5.9)

pruned $T_{\psi_3}^-$ (Fig 5.8)

Behavior graph $\mathcal{B}_{(\text{LOOP},\psi_3)}$ (Fig 5.10)

Fig. 5.9. State-transition graph G_{LOOP}



Pruned tableau $T^{-}_{\psi_3}$ (Fig. 5.8)

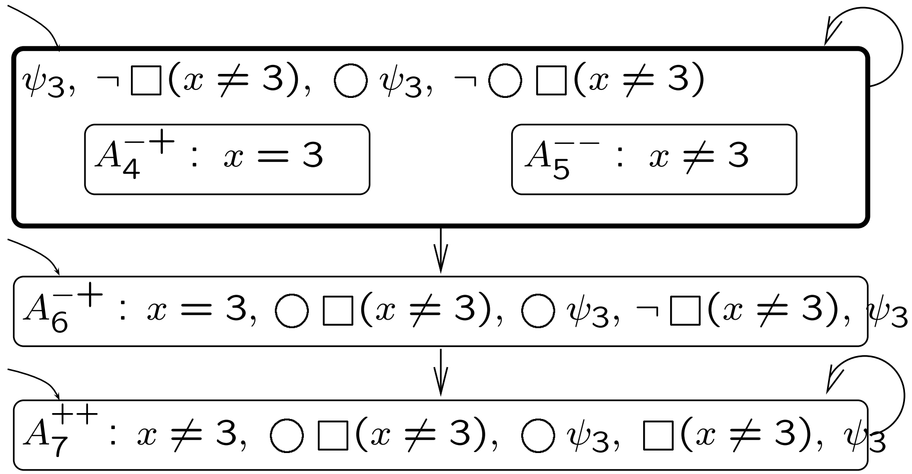
Eliminating

- MSCS's not reachable from an initial ψ_3-atom and
- non-fulfilling terminal MSCS's

Promising formulas:

$\diamond \Box(x \neq 3)$ promising $\Box(x \neq 3)$

$\neg \Box(x \neq 3)$ promising $(x = 3)$

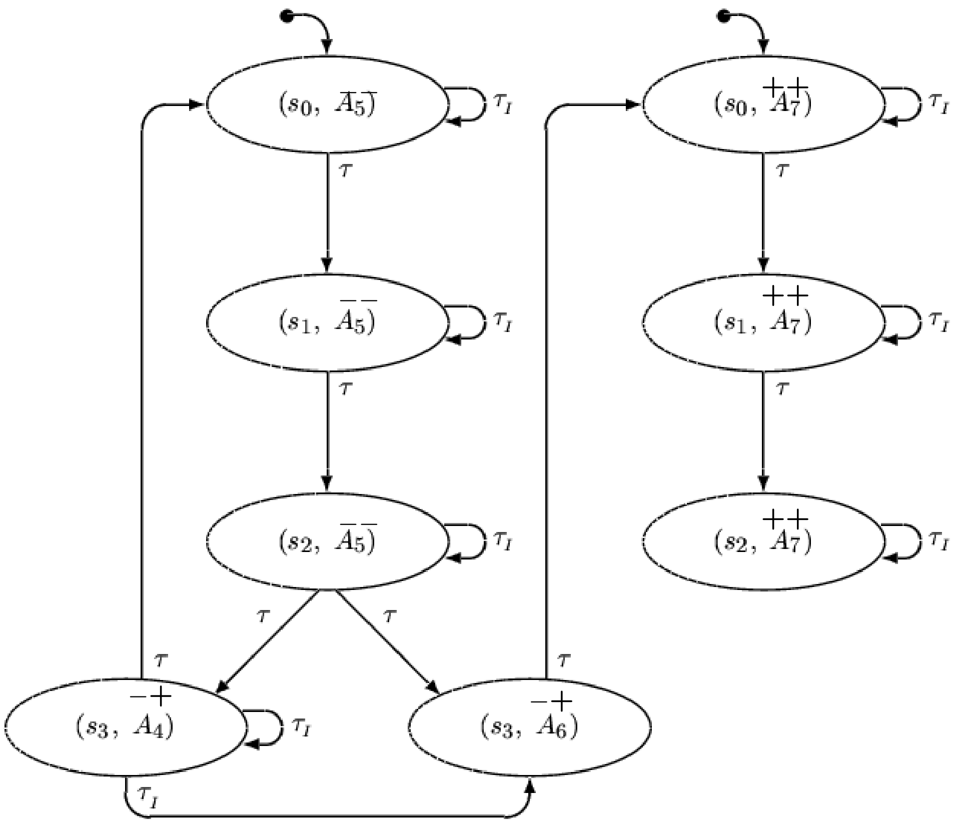


Two non-transient MSCS's:

$\{A_4^{-+}, A_5^{--}\}$ not fulfilling

$\{A_7^{++}\}$ fulfilling

Behavior graph $\mathcal{B}_{(\text{LOOP},\psi_3)}$ (Fig 5.10)



<u>`Example:`</u> Given FTS ONE:

Θ: $x = 0$

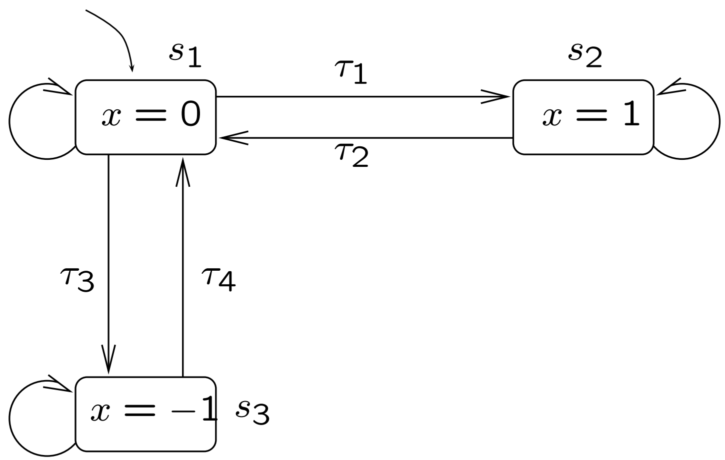
$\mathcal{T}$: $\{\tau_1, \tau_2, \tau_3, \tau_4, \tau_I\}$

with
$\rho_{\tau_1}: \quad x = 0 \wedge x' = 1$
$\rho_{\tau_2}: \quad x = 1 \wedge x' = 0$
$\rho_{\tau_3}: \quad x = 0 \wedge x' = -1$
$\rho_{\tau_4}: \quad x = -1 \wedge x' = 0$

$\mathcal{J}$: $\emptyset$

$\mathcal{C}$: $\{\tau_1, \tau_3\}$

Transition graph G_{ONE}



We want to know whether

$$\boxed{\varphi : \ \Box \Diamond (x = 1)}$$

is valid over ONE.

Check P-satisfiability of

$$\boxed{\neg\varphi : \ \underbrace{\Diamond \Box (x \neq 1)}_{\psi}}$$

$\Phi_{\psi}^{+} : \ \{\psi, \ \bigcirc \psi, \ \Box(x \neq 1), \ \bigcirc \Box (x \neq 1), \ x = 1\}$

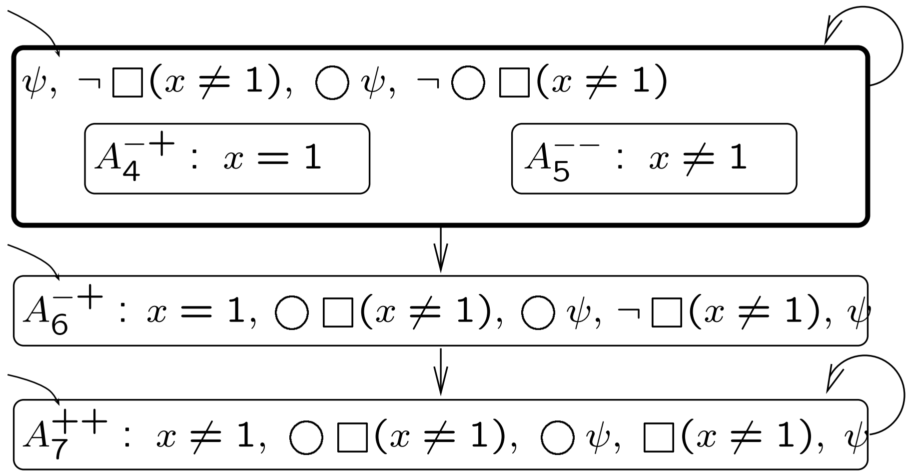
basic formulas: $\{\bigcirc \psi, \ \bigcirc \Box (x \neq 1), \ x = 1\}$

Promising formulas:

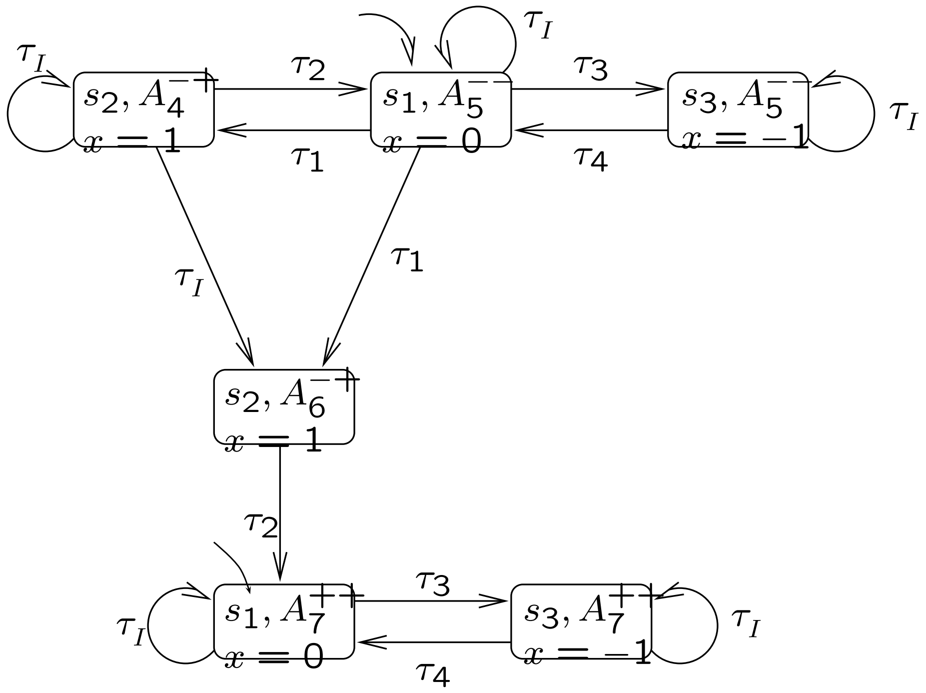
$\psi_1 : \psi = \Diamond \Box (x \neq 1)$ promising $r_1 : \ \Box (x \neq 1)$

$\psi_2 : \ \neg \Box (x \neq 1)$ promising $r_2 : \ x = 1$

Pruned tableau T_{ψ}^{-}



Behavior graph $\mathcal{B}_{(\text{ONE}, \Diamond \Box (x \neq 1))}$



Two non-transient MSCS's:

$\{(s_2, A_4^{-+}),\ (s_1, A_5^{--}),\ (s_3, A_5^{--})\}$: not fulfilling,

$\{(s_1, A_7^{++}), (s_3, A_7^{++})\}$: fulfilling

Paths of $\mathcal{B}_{(P,\varphi)}$

Claim 5.9 (paths of $\mathcal{B}_{(P,\varphi)}$)

The infinite sequence

$$\pi:\ \underbrace{(s_0, A_0)}_{\varphi\text{-initial}},\ (s_1, A_1),\ \ldots$$

is a path in $\mathcal{B}_{(P,\varphi)}$

iff

σ_π: $s_0, s_1, \ldots$ is a run of P
(i.e. computation of P less fairness)

ϑ_π: $A_0, A_1, \ldots$ is a trail of T_φ over σ_π
(i.e. A_j consistent with s_j, for all $j \geq 0$)

Example: In $\mathcal{B}_{(\text{LOOP},\psi_3)}$ (Fig. 5.10)

π: $\Big((s_0, A_5),\ (s_1, A_5),\ (s_2, A_5),\ (s_3, A_4)\Big)^\omega$

induces

σ_π: $(s_0, s_1, s_2, s_3)^\omega$ run of LOOP

ϑ_π: $(A_5, A_5, A_5, A_4)^\omega$ trail of T_{ψ_3} over σ_π

`Proposition 5.10` (P-satisfiability by path)

P has a computation satisfying φ

iff

there is an infinite φ-initialized path π in $\mathcal{B}_{(P,\varphi)}$ s.t.

σ_π is a P-computation (fair run of P)

ϑ is a fulfilling trail over σ_π

Searching for "good" paths in $\mathcal{B}_{(P,\varphi)}$

— not practical.

Definitions

For behavior graph $\mathcal{B}_{(P,\varphi)}$

- node (s', A') is a τ-successor of (s, A) if $\mathcal{B}_{(P,\varphi)}$ contains τ-edge connecting (s, A) to (s', A')
- transition τ is enabled on node (s, A) if τ is enabled on state s

Definitions (Con't)

For SCS $S \subseteq \mathcal{B}_{(P,\varphi)}$:

- Transition τ is taken in S if there exists two nodes $(s, A), (s', A') \in S$ s.t.
  (s', A') is a τ-successor of (s, A)

- S is $\begin{Bmatrix} \text{just} \\ \text{compassionate} \end{Bmatrix}$ if every $\begin{Bmatrix} \text{just} \\ \text{compassionate} \end{Bmatrix}$ transition $\tau \begin{Bmatrix} \in \mathcal{J} \\ \in \mathcal{C} \end{Bmatrix}$ is either taken in S or is disabled on $\begin{Bmatrix} \text{some node} \\ \text{all nodes} \end{Bmatrix}$ in S

- S is fair if it is both just and compassionate

- S is fulfilling if every promising formula $\psi \in \Phi_\psi$ is fulfilled by some atom A, s.t.
  $(s, A) \in S$ for some state s

- S is adequate if it is fair and fulfilling

Adequate SCS's

`Proposition 5.11` (adequate SCS and satisfiability)

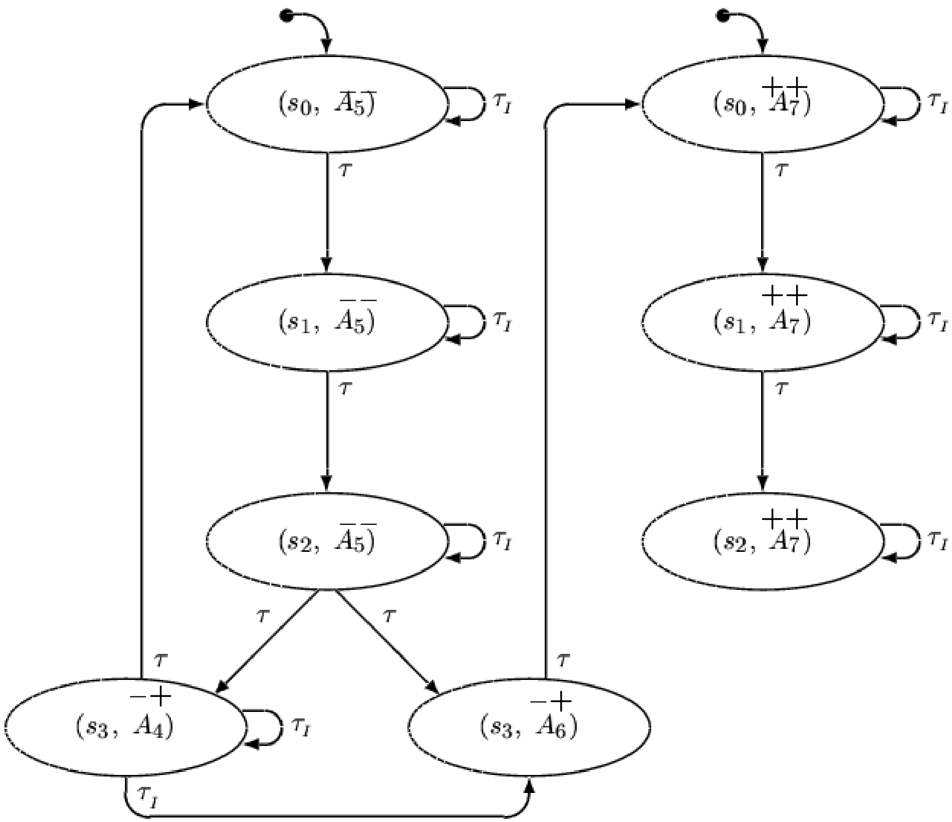
Given a finite-state program P and temporal formula φ.
φ is P-satisfiable
iff
$\mathcal{B}_{(P,\varphi)}$ has an adequate SCS

`Example:` Consider LOOP and

$$\psi_3 \colon \Diamond \Box (x \neq 3)$$

Is ψ_3 LOOP-satisfiable?
Check the SCS's in $\mathcal{B}_{(\text{LOOP},\psi_3)}$ (Fig. 5.10)

Behavior graph $\mathcal{B}_{(\text{LOOP},\psi_3)}$ (Fig 5.10)



Example (Con't)

- $\{ (s_0, A_5^{--}), (s_1, A_5^{--}), (s_2, A_5^{--}), (s_3, A_4^{-+}) \}$
  is fair but not fulfilling

- $\{ (s_0, A_7^{++})\}, \{(s_1, A_7^{++})\}, \{(s_2, A_7^{++})\}$

  each is fulfilling but not fair
  Not just with respect to transition τ

- $\{(s_3, A_6^{-+})\}$

  is neither fair (unjust toward τ) nor
  fulfilling (being transient)

No adequate subgraphs in $\mathcal{B}_{(\text{LOOP},\psi_3)}$

Therefore, by `proposition 5.11`, LOOP has no computation that satisfies ψ_3: $\Diamond \Box (x \neq 3)$

Example: Consider LOOP and

φ_3: $\square \diamond (x = 3)$

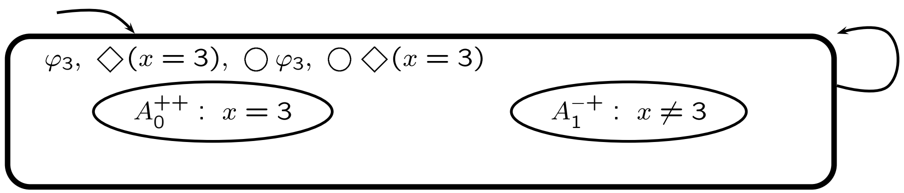
Is φ_3 LOOP-satisfiable?

Promising formulas :

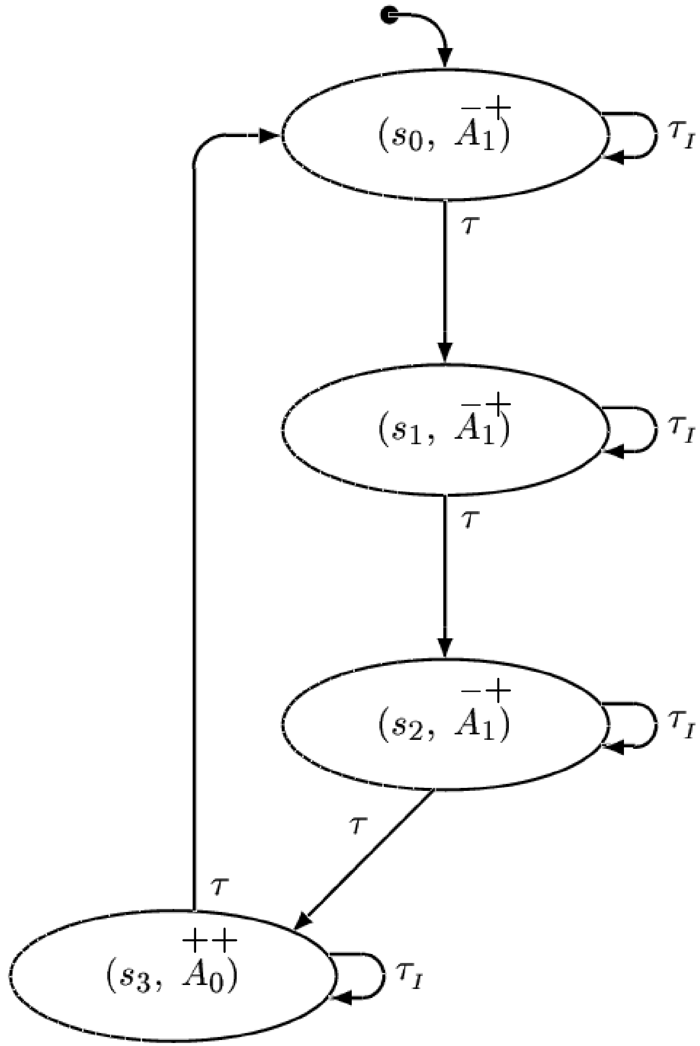
$$\diamond (x = 3) \ \text{promising} \ (x = 3)$$

$$\neg \square \diamond (x = 3) \ \text{promising} \ \neg \diamond (x = 3)$$

Pruned tableau T_{φ_3} (Fig. 5.6)



Behavior graph $\mathcal{B}_{(\text{LOOP},\varphi_3)}$ (Fig. 5.11)



$$S = \{\, (s_0, A_1^{-+}),\ (s_1, A_1^{-+}),\ (s_2, A_1^{-+}),\ (s_3, A_0^{++})\}$$

is an adequate subgraph:

fair (τ taken in S)

fulfilling

Therefore, by `proposition 5.11`, program LOOP has a computation satisfying φ_3: $\Box \Diamond (x = 3)$

The periodic computation σ: $(x{:}\,0, x{:}\,1, x{:}\,2, x{:}\,3)^\omega$ satisfies φ_3

From Atom Tableau T_φ to ω-Automaton $\mathcal{A}_\varphi$

For temporal formula φ, construct the ω-automaton

$$\mathcal{A}_\varphi :\ \langle \underbrace{N,\ N_0,\ E,}_{\substack{\text{Same as} \\ T_\varphi}}\ \mu,\ \mathcal{F}\rangle$$

where

- Node labeling μ:
  For node $n \in N$ labeled by atom A in T_φ,

  $$\mu(n) \ = \ state(A).$$

- Acceptance condition $\mathcal{F}$:

  Muller:

  $$\mathcal{F} \ = \ \{\text{SCS } S \mid S \text{ is fulfilling }\}$$

  Street:

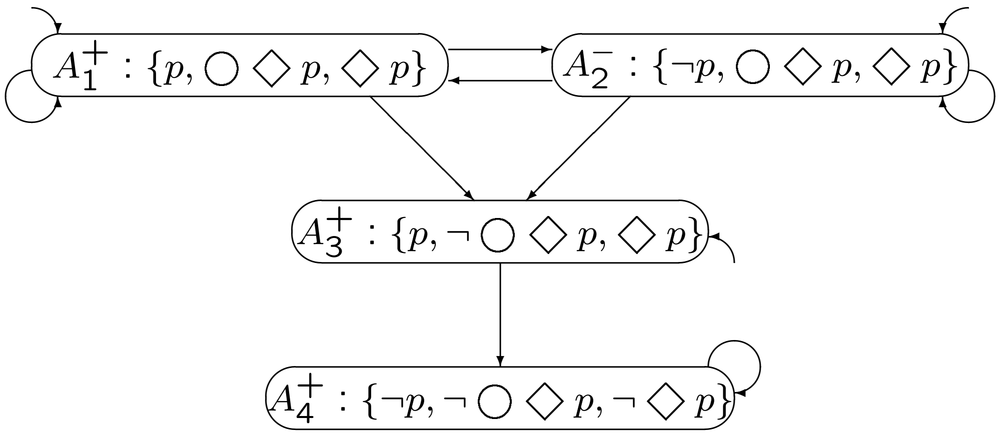
  $$\mathcal{F} \ = \ \{(P_\psi, R_\psi) \mid \psi \in \Phi_\varphi \text{ promises } r\},$$

  where

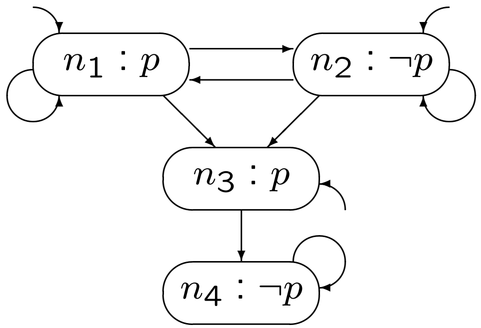
  $$\begin{aligned} P_\psi &= \{\ A \mid \neg\psi \in A\ \} \\ R_\psi &= \{\ A \mid r \in A\ \} \end{aligned}$$

Example: φ : $\diamond\, p$

Tableau T_φ:



Example: $\mathcal{A}_{\diamond p}$ from $T_{\diamond p}$



$$\begin{aligned}
\mathcal{F}_M &= \{\{n_1\}, \{n_1, n_2\}, \{n_4\}\} \\
\mathcal{F}_S &= \{(P_{\diamond p}, R_{\diamond p})\} \\
&= \{(\{n_4\}, \{n_1, n_3\})\} \\
&\approx \{(\{n_4\}, \{n_1\})\}
\end{aligned}$$

since no path can visit n_3 infinitely often

Abstraction

Abstraction = a method to verify infinite-state systems.

Idea:

	abstraction $\downarrow$	
Program P (infinite state)	$\longrightarrow$	Abstract program P^A (finite state)
Property φ	$\longrightarrow$	Abstract property φ^A
$P \models \varphi$?	$\longrightarrow$	$P^A \models \varphi^A$ $\downarrow$ model checking

We want to ensure that
if $P^A \models \varphi^A$ then $P \models \varphi$.

Abstraction (Cont'd)

How do we obtain such an abstraction function?

- 1) Abstract the domain to a finite-state one (*data abstraction*):
  For variables $\vec{x}$ ranging over domain D, find an abstract domain D^A and an abstraction function $\alpha : D \rightarrow D^A$.

- 2) From the data abstraction it is possible to compute an abstraction for the program and for the property such that
  if $P^A \models \varphi^A$ then $P \models \varphi$.

Example: Abstracting Bakery

Program MUX-BAK (infinite-state program)

$$
\begin{array}{l}
P_1 :: \left[\begin{array}{l}\textbf{loop forever do}\\ \left[\begin{array}{l}\ell_0 : \textbf{noncritical}\\ \ell_1 : y_1 := y_2 + 1\\ \ell_2 : \textbf{await } y_2 = 0 \lor y_1 \le y_2\\ \ell_3 : \textbf{critical}\\ \ell_4 : y_1 := 0\end{array}\right]\end{array}\right]\\
\|\\
P_2 :: \left[\begin{array}{l}\textbf{loop forever do}\\ \left[\begin{array}{l}m_0 : \textbf{noncritical}\\ m_1 : y_2 := y_1 + 1\\ m_2 : \textbf{await } y_1 = 0 \lor y_2 < y_1\\ m_3 : \textbf{critical}\\ m_4 : y_2 := 0\end{array}\right]\end{array}\right]
\end{array}
$$

Abstract domain: the boolean algebra over
$B = \{b_1, b_2, b_3 : \textbf{boolean}\}$,
with $b_1 : \; y_1 = 0$
$b_2 : \; y_2 = 0$
$b_3 : \; y_1 \le y_2$

Example: Abstracting Bakery (Cont'd)

Program MUX-BAK-ABSTR (finite-state program)

$$
\begin{array}{l}
P_1 :: \left[\begin{array}{l}\textbf{loop forever do}\\ \left[\begin{array}{l}\ell_0 : \textbf{noncritical}\\ \ell_1 : (b_1, b_3) := (\mathit{false}, \mathit{false})\\ \ell_2 : \textbf{await } b_2 \lor b_3\\ \ell_3 : \textbf{critical}\\ \ell_4 : (b_1, b_3) := (\mathit{true}, \mathit{true})\end{array}\right]\end{array}\right]\\
\|\\
P_2 :: \left[\begin{array}{l}\textbf{loop forever do}\\ \left[\begin{array}{l}m_0 : \textbf{noncritical}\\ m_1 : (b_2, b_3) := (\mathit{false}, \mathit{true})\\ m_2 : \textbf{await } b_1 \lor \neg b_3\\ m_3 : \textbf{critical}\\ m_4 : (b_2, b_3) := (\mathit{true}, b_1)\end{array}\right]\end{array}\right]
\end{array}
$$

This program can now be checked for mutual exclusion, bounded overtaking, response.

Show MUX-BAK-ABSTR $\models \Box \neg(at\_\ell_3 \land at\_m_3)$. Then it follows that MUX-BAK $\models \Box \neg(at\_\ell_3 \land at\_m_3)$.