Tutorial on SPIN and PROMELA

(as part of the lecture "model checking", WS 2012/13)

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Outline

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1. Overview
2. Repetition
   - Channel systems
   - Guarded command languages
3. ProMeLa
4. SPIN

SPIN overview

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- one of the most prominent tools for formal verification of distributed software systems
- developed by Gerald Holzmann at Bell Labs (beginning in 1980)
- awarded the prestigious System Software Award 2001 by the ACM
- Primer and Reference Manual [Hol03]

SPIN main features

- modeling language of SPIN is called ProMeLa (**Pro**cess **Me**ta **La**nguage) $\rightarrow$ the name SPIN stands for **S**imple **P**roMeLa **In**terpreter

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- main features of SPIN: 1) on-the-fly verifier for safety and liveness properties and 2) on-the-fly LTL model checking
- properties can be specified as 1) invariants (using assertions), 2) LTL formula, 3) Büchi automaton, or 4) never claims (omega regular)

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The model checker SPIN

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- featuring nondeterminism (language features and interleaving processes)
- semantics based on program graphs (and hence transition systems)

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Channel systems

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representation of data-dependent parallel systems with

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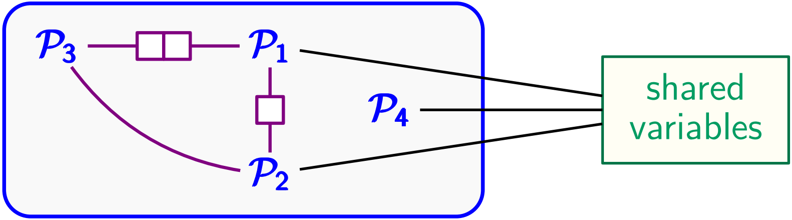

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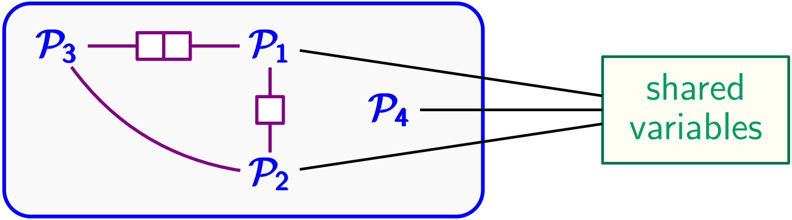
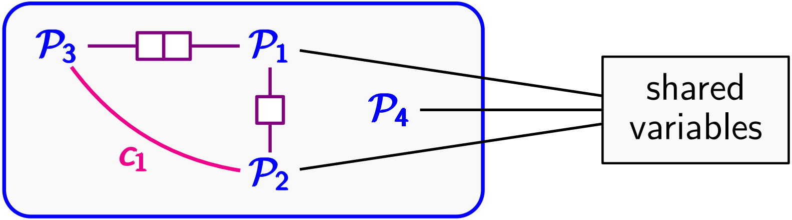


channel types: synchronous or FIFO

Channel systems

representation of data-dependent parallel systems with

- communication over shared variables
- synchronous message passing $\longleftarrow$ capacity **0**
- asynchronous message passing



channel types: synchronous or FIFO

$\uparrow$

no buffer (read/write simultaneously)

representation of data-dependent parallel systems with

- communication over shared variables
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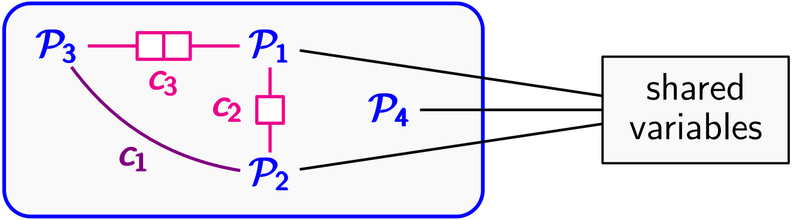
- asynchronous message passing $\longleftarrow$ capacity $\geqslant$ **1**



channel types: synchronous or FIFO

capacity = number of buffer cells

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formalization through program graphs for $\mathcal{P}_1, \ldots, \mathcal{P}_n$

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- with conditional transitions $\ell_i \xhookrightarrow{g:\alpha} \ell_i'$ (as before)
- and communication actions

$\ell_i \xhookrightarrow{c!v} \ell_i'$ sending value v via channel c

$\ell_i \xhookrightarrow{c?x} \ell_i'$ receiving a value for variable x via c

Interleaving for program graphs

... modeling parallel systems with processes communicating via shared variables

Interleaving for program graphs

program graph $\mathcal{P}_1$
$(Loc_1, \ldots, \hookrightarrow_1, \ldots)$

program graph $\mathcal{P}_2$
$(Loc_2, \ldots, \hookrightarrow_2, \ldots)$

Interleaving for program graphs

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interleaving operator

$$\mathcal{P}_1 \,|||\, \mathcal{P}_2 \;=\; (Loc_1 \times Loc_2, \ldots, \hookrightarrow, \ldots)$$

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$$\frac{\ell_1 \overset{g:\alpha}{\hookrightarrow}_1 \ell_1'}{\langle \ell_1, \ell_2 \rangle \overset{g:\alpha}{\hookrightarrow} \langle \ell_1', \ell_2 \rangle}$$

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$$\frac{\ell_1 \xhookrightarrow{g:\alpha}_1 \ell_1'}{\langle \ell_1, \ell_2 \rangle \xhookrightarrow{g:\alpha} \langle \ell_1', \ell_2 \rangle} \qquad \frac{\ell_2 \xhookrightarrow{g:\alpha}_2 \ell_2'}{\langle \ell_1, \ell_2 \rangle \xhookrightarrow{g:\alpha} \langle \ell_1, \ell_2' \rangle}$$

Example: interleaving for PG

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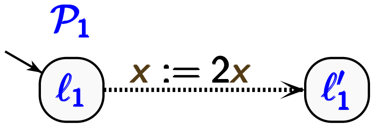
$\mathcal{P}_1$

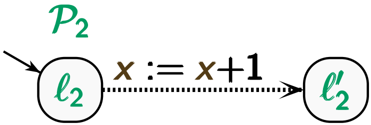
$$\to \ell_1 \xrightarrow{x := 2x} \ell_1'$$

$\mathcal{P}_2$

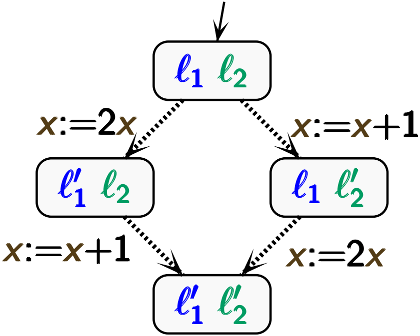
$$\to \ell_2 \xrightarrow{x := x+1} \ell_2'$$

Example: interleaving for PG





PG $\mathcal{P}_1 \,|||\, \mathcal{P}_2$



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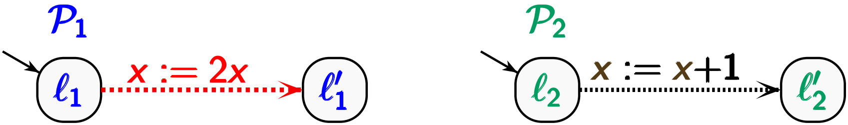

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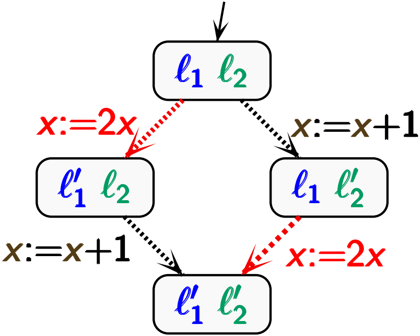

Example: interleaving for PG

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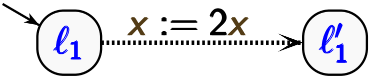
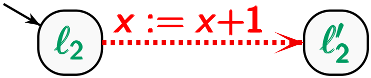


$\mathcal{P}_2$



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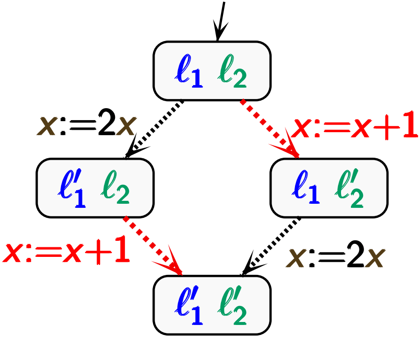

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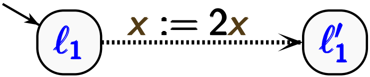
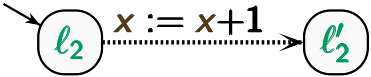


$\mathcal{P}_2$



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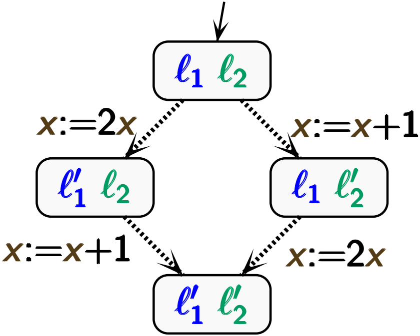
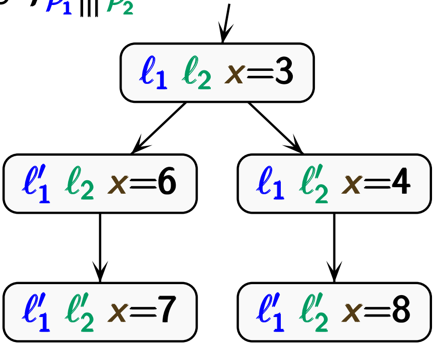


TS $\mathcal{T}_{\mathcal{P}_1 \,|||\, \mathcal{P}_2}$



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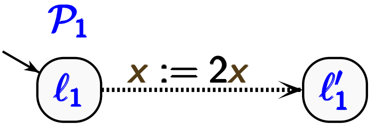

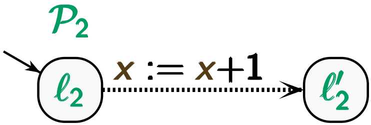

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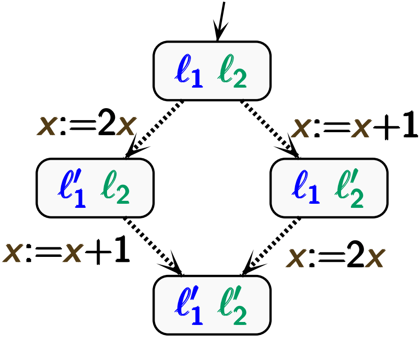

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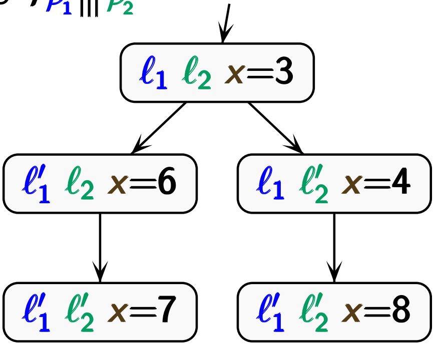

note: $\mathcal{T}_{\mathcal{P}_1} \,|||\, \mathcal{T}_{\mathcal{P}_2} \neq \mathcal{T}_{\mathcal{P}_1 \,|||\, \mathcal{P}_2}$

Mutual exclusion with semaphore

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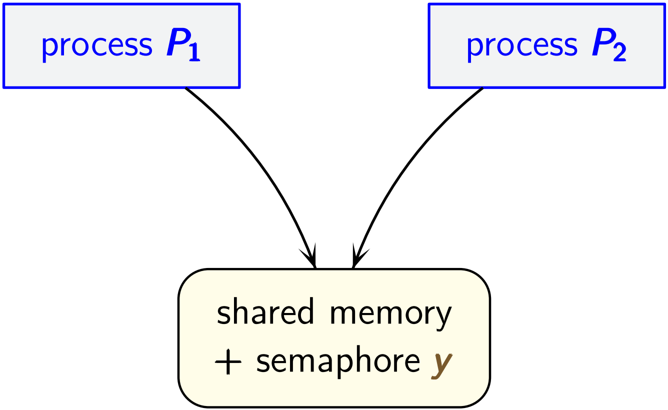

Mutual exclusion with semaphore

protocol for process P_i

```
LOOP FOREVER
    noncritical actions;
    AWAIT  y > 0 DO
           y:=y−1
    OD
    critical actions;
    y:=y+1
    END LOOP
```

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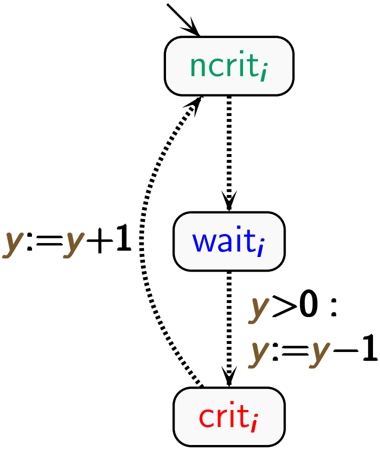
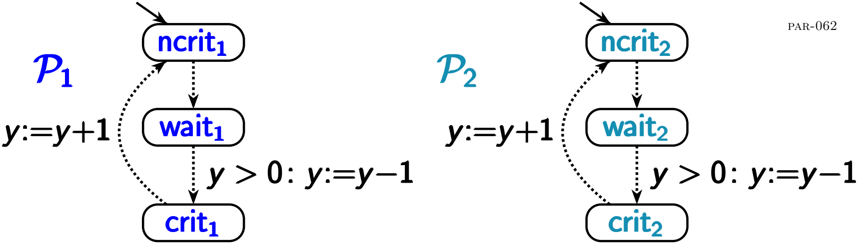
program graph $\mathcal{P}_i$




$\mathcal{P}_1$
ncrit$_1$
wait$_1$
crit$_1$
$y{:=}y{+}1$
$y > 0$: $y{:=}y{-}1$
$\mathcal{P}_2$
ncrit$_2$
wait$_2$
crit$_2$
$y{:=}y{+}1$
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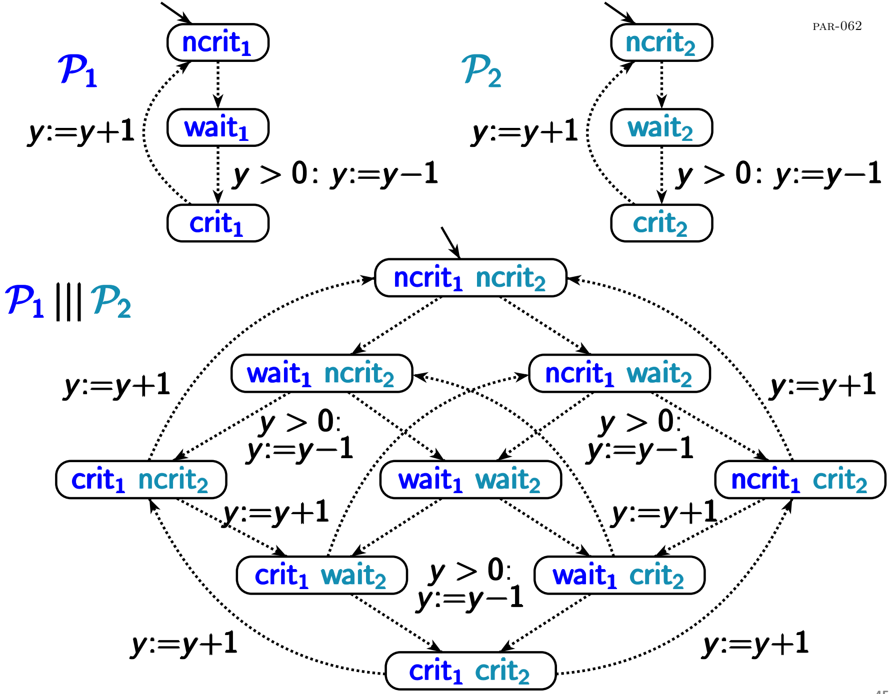
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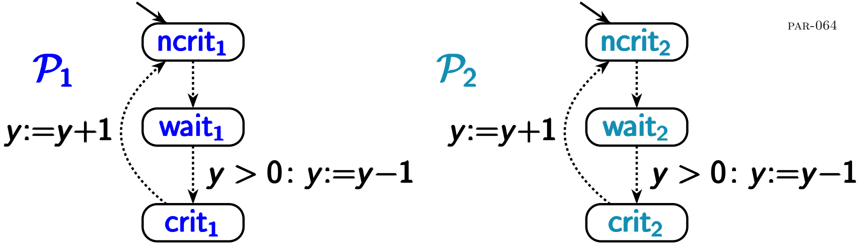
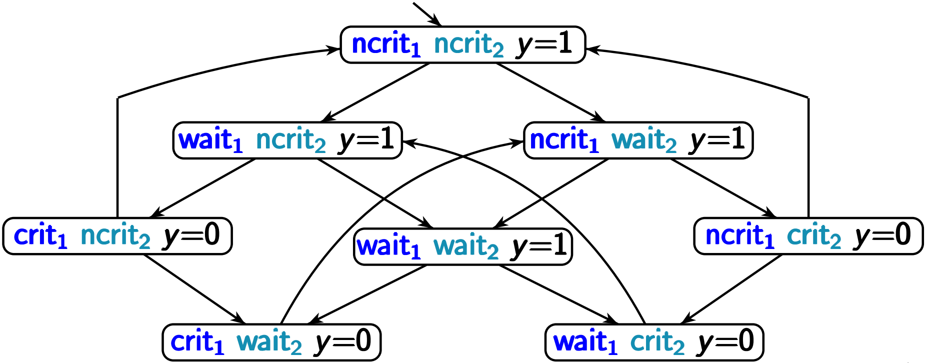
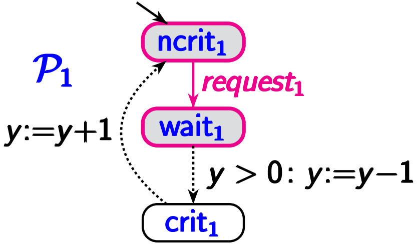
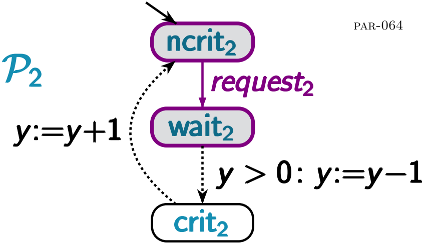


reachable fragment of the transition system $\mathcal{T}_{\mathcal{P}_1 ||| \mathcal{P}_2}$







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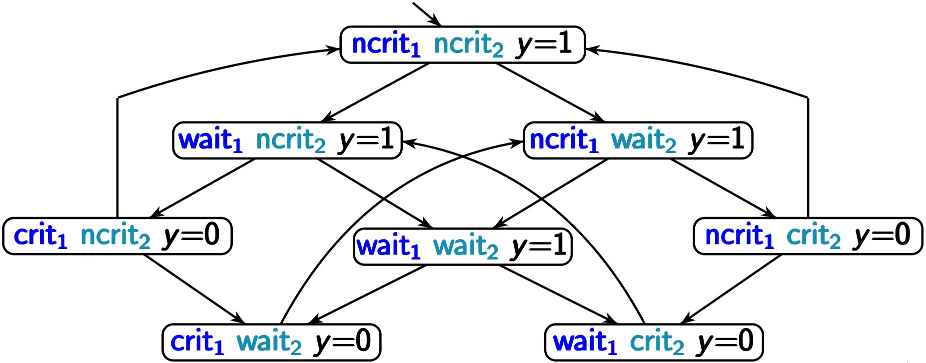
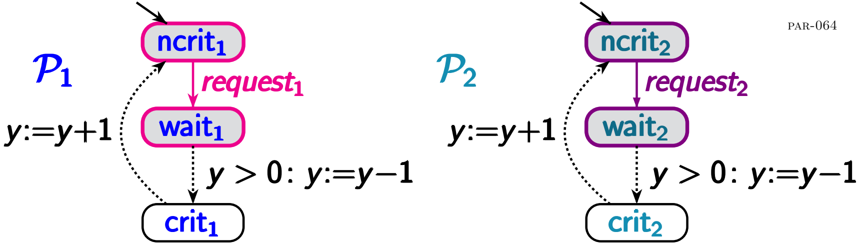
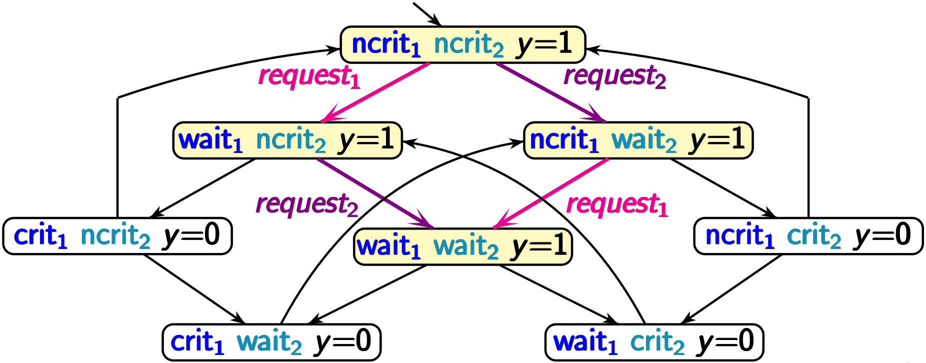
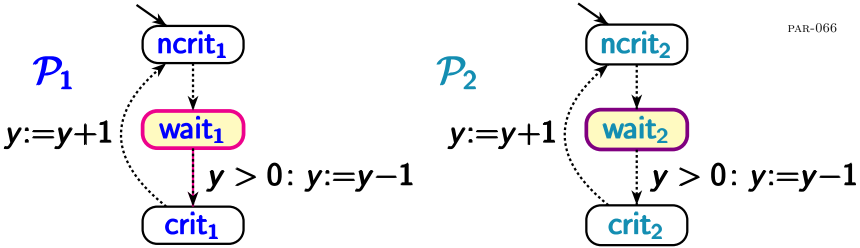


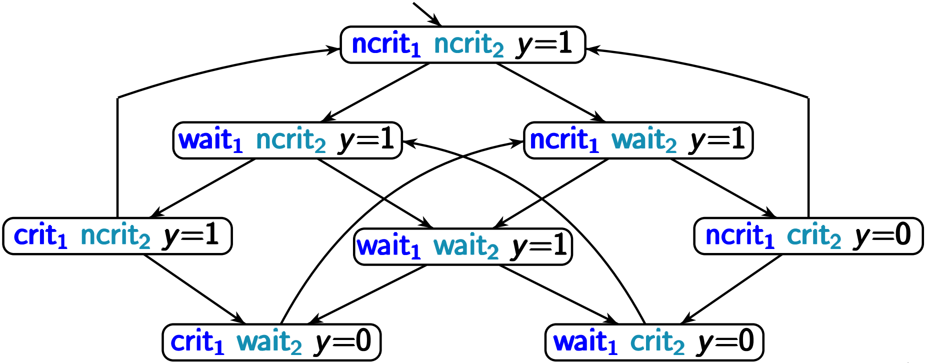


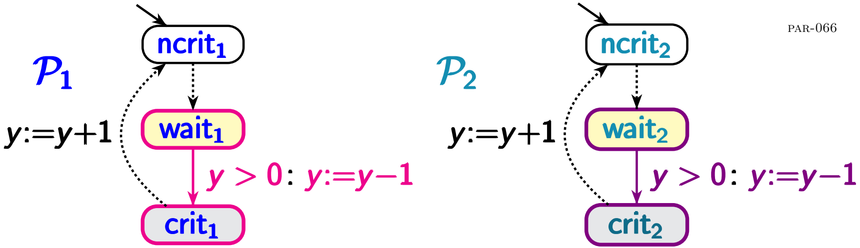
interleaving of the independent request actions





competition between the waiting processes





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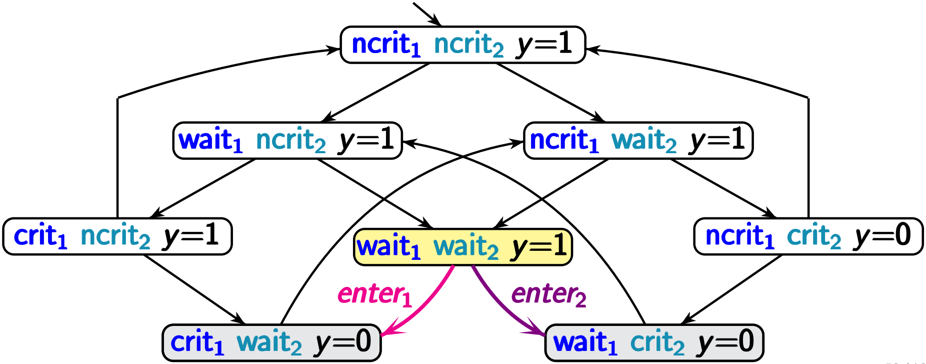

Peterson algorithm for mutual exclusion

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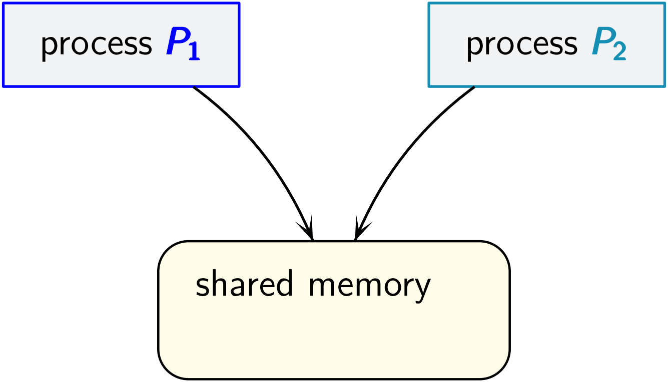

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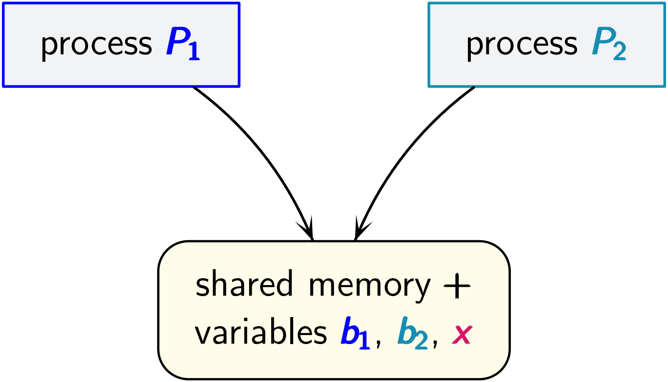

where b_1, $b_2 \in \{0, 1\}$ and $x \in \{1, 2\}$

Peterson algorithm for mutual exclusion

for competing processes P_1, P_2

with additional shared variables:

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protocol for P_1:

LOOP FOREVER

noncritical actions;

$b_1 := 1$; $x := 2$;

AWAIT $x{=}1 \vee \neg b_2$ DO critical section OD

$b_1 := 0$

END LOOP

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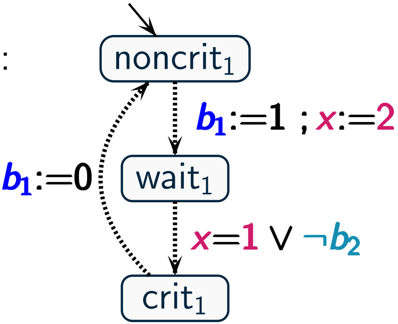

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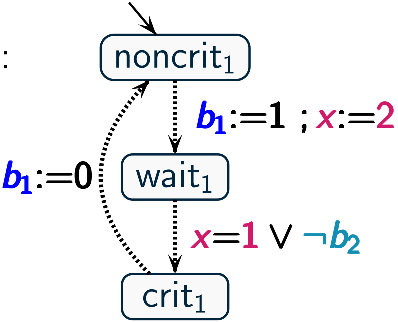

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symmetric protocol for P_2

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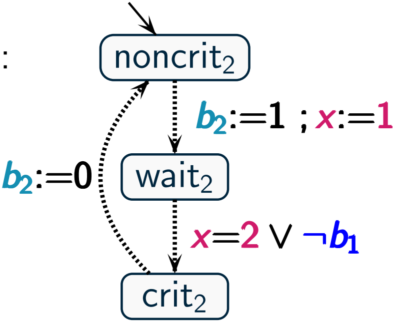
with additional shared variables:

- $b_1, b_2 \in \{0, 1\}$
- $x \in \{1, 2\}$



protocol for P_2:

LOOP FOREVER

noncritical actions;

atomic$\{b_2 := 1;\ \ x := 1\}$ $\longleftarrow$ atomic region

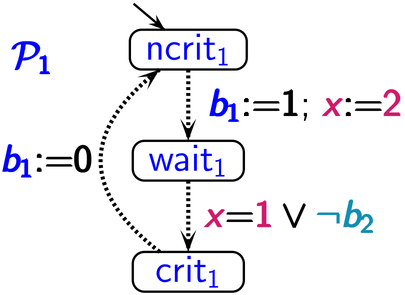
AWAIT $x{=}2 \vee \neg b_1$ DO critical section OD

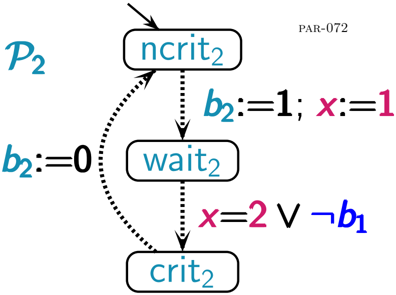
$b_2 := 0$

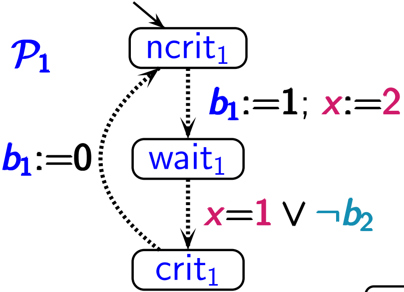
END LOOP

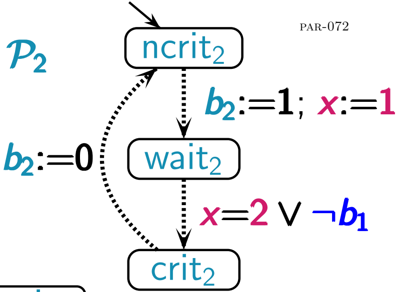
Program graph for Peterson algorithm

program graph for Peterson algorithm results from the interleaving of the program graphs for P_1, P_2

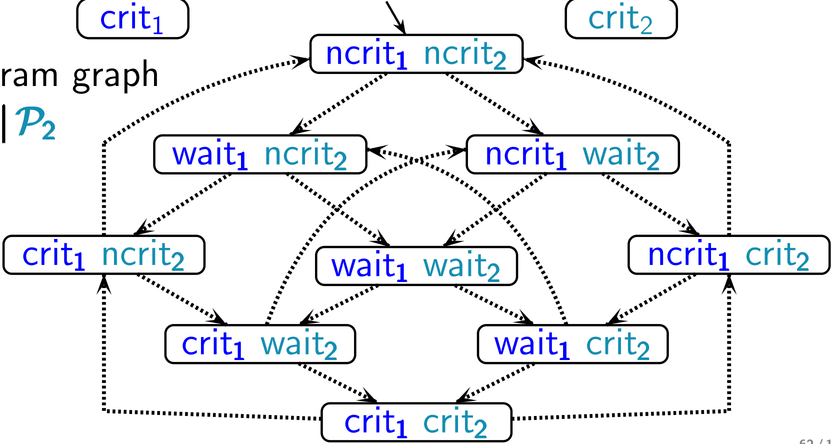

$\mathcal{P}_1$
ncrit_1
$b_1{:=}1;\ x{:=}2$
$b_1{:=}0$
wait_1
$x{=}1 \vee \neg b_2$
crit_1

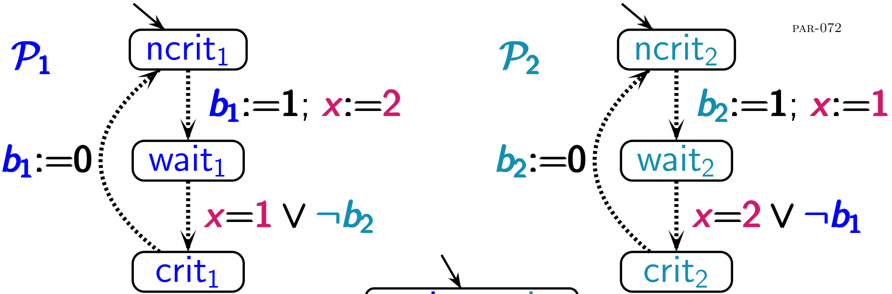

$\mathcal{P}_2$
ncrit_2
$b_2{:=}1;\ x{:=}1$
$b_2{:=}0$
wait_2
$x{=}2 \vee \neg b_1$
crit_2





program graph
$\mathcal{P}_1 \,|||\, \mathcal{P}_2$





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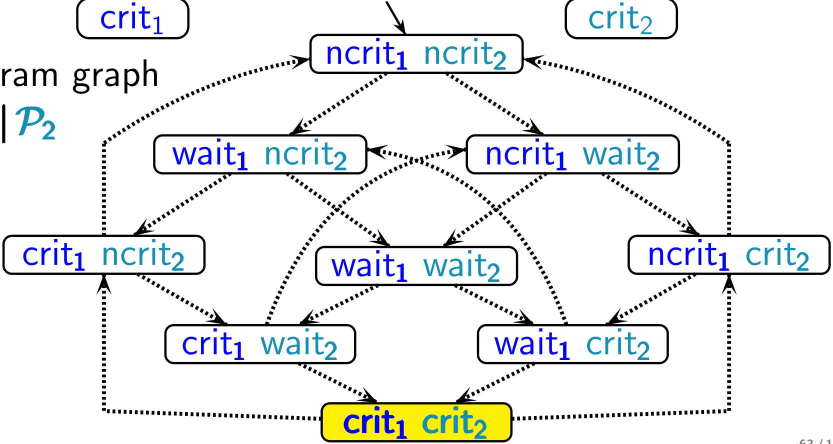
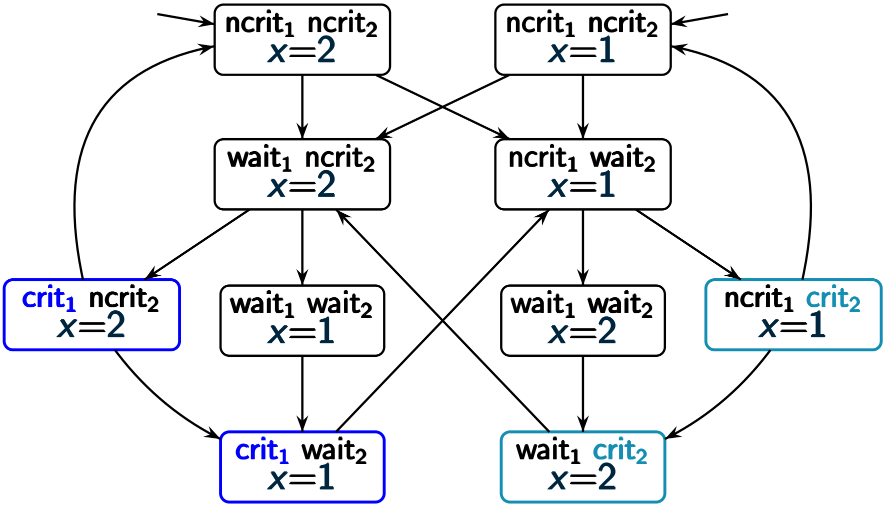
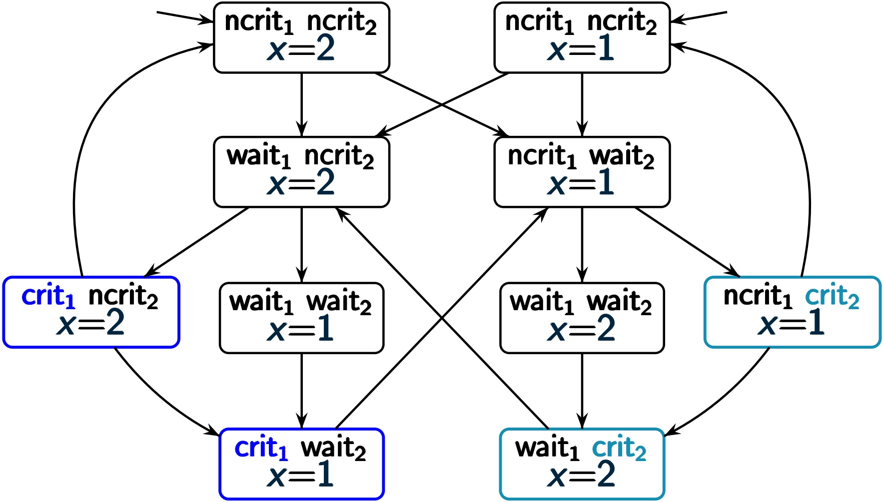


TS for the Peterson algorithm



value of b_i is given by $\mathbf{wait}_1 \vee \mathbf{crit}_i$

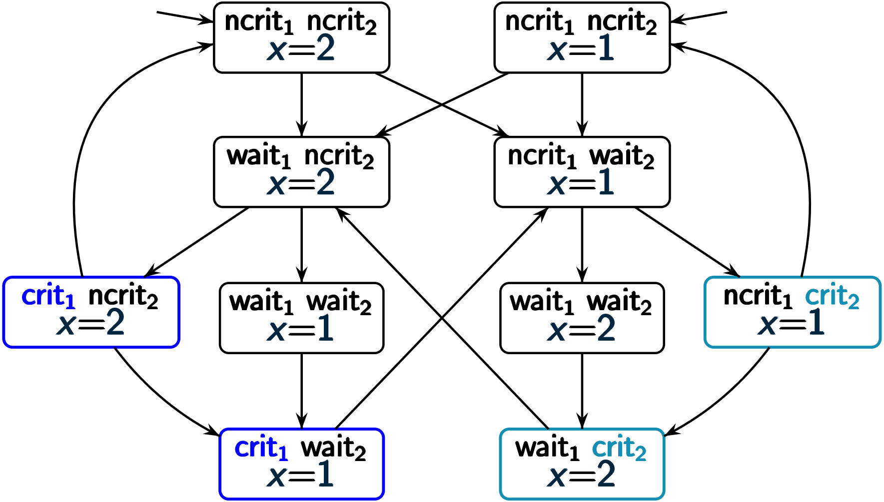
TS for the Peterson algorithm



value of b_i is given by **wait**$_1$ $\vee$ **crit**$_i$

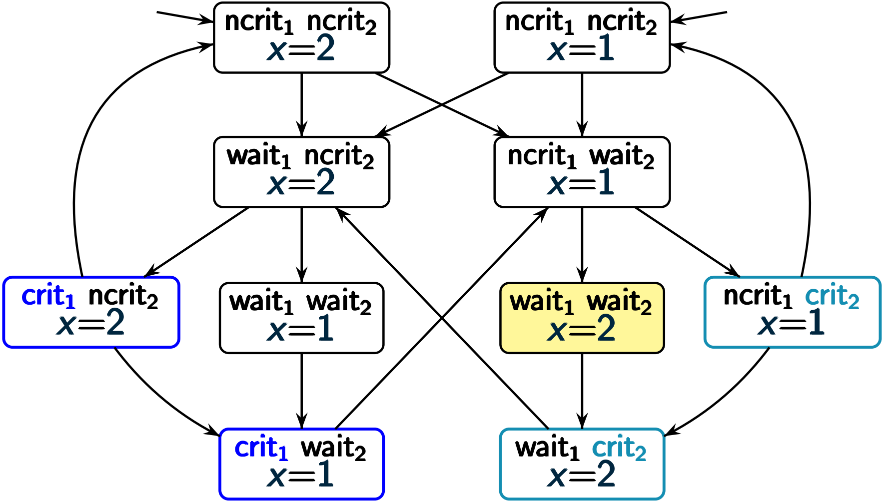
62 states are unreachable

TS for the Peterson algorithm



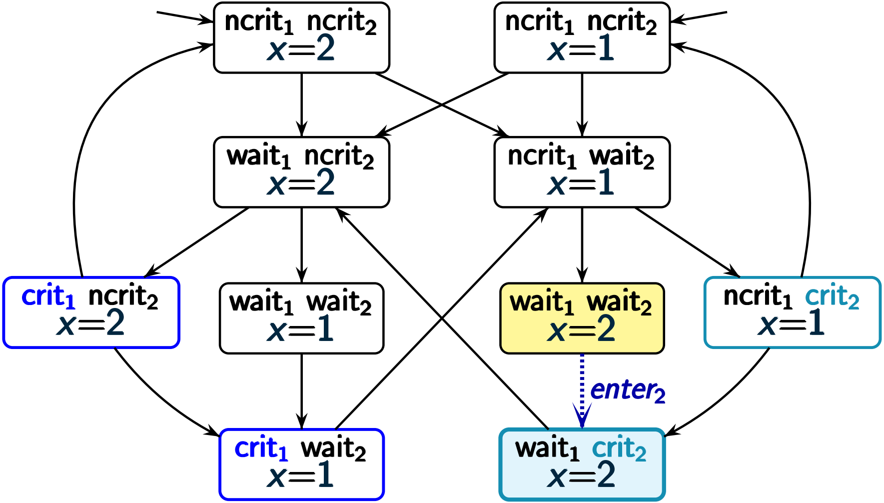
mutual exclusion property is satisfied as
no state $\langle\, crit_1, crit_2, x = \ldots \,\rangle$ is reachable

TS for the Peterson algorithm



if both processes are waiting . . .

TS for the Peterson algorithm



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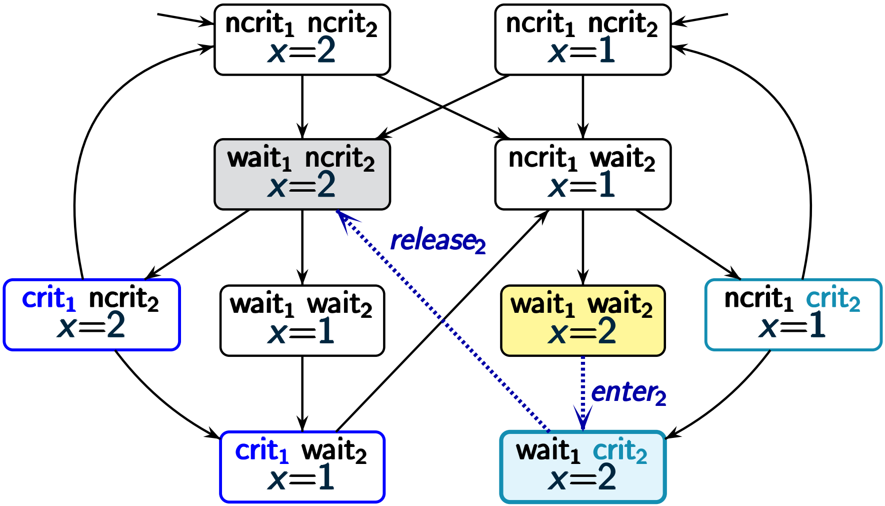

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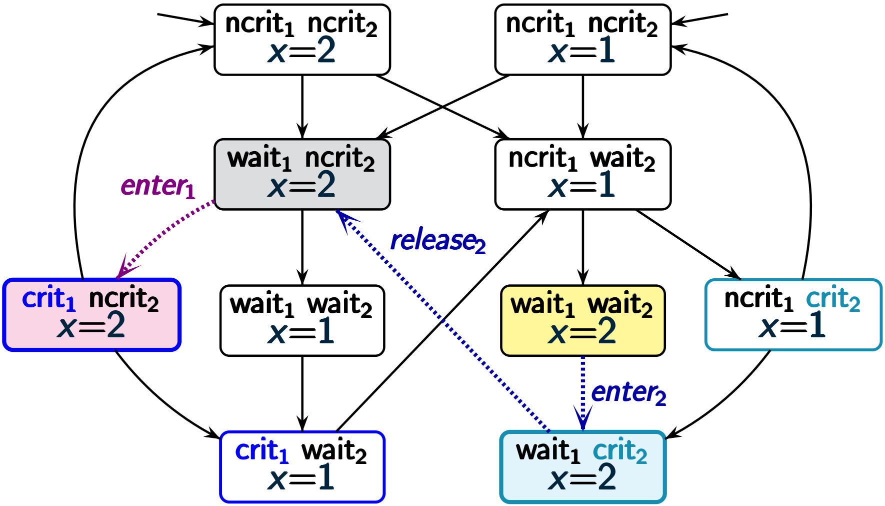
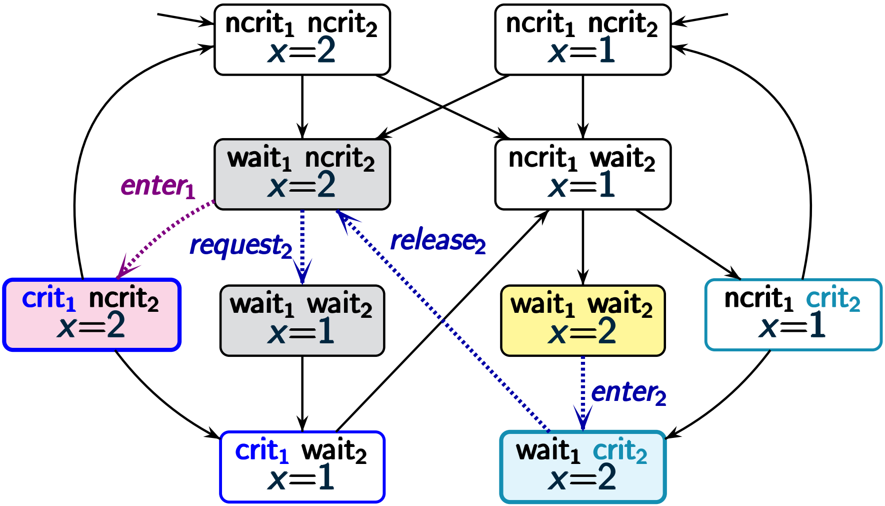


if both processes are waiting ...

TS for the Peterson algorithm



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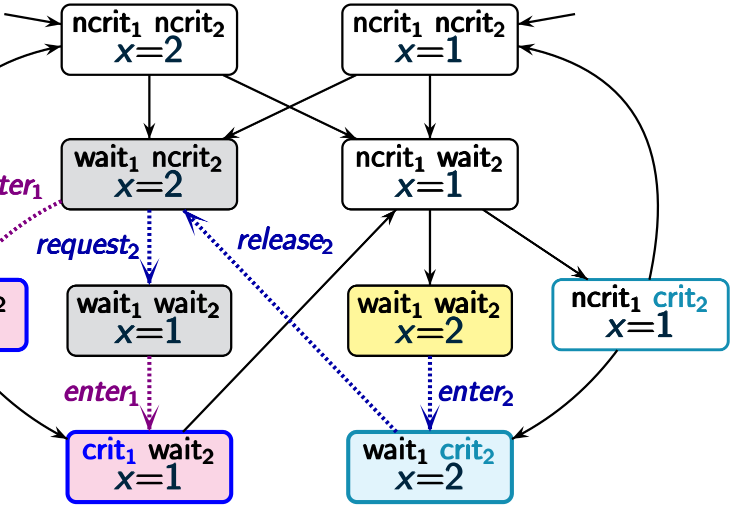

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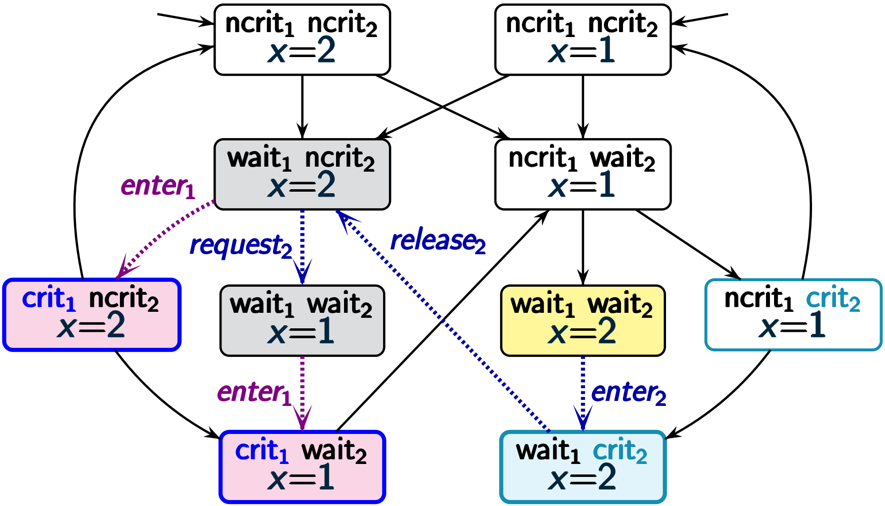

liveness: the process that waits longer will enter its critical section first

Outline

1. Overview
2. Repetition
   - Channel systems
   - Guarded command languages
3. ProMeLa
4. SPIN

Guarded Command Language (GCL)

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- high-level modeling language that contains features of imperative languages and nondeterministic choice

by Dijkstra, ca. 1975

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$$\boxed{\text{GCL-program}}$$
$$\Downarrow$$
$$\boxed{\text{program graph}}$$
$$\Downarrow$$
$$\boxed{\text{transition system}}$$

by Dijkstra, ca. 1975

Guarded Command Language (GCL)

guarded command $g \Rightarrow \textit{stmt}$

g	:	guard, i.e., Boolean condition on the program variables
$\textit{stmt}$	:	statement

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repetitive command/loop:

`DO` $::\ g \Rightarrow \mathit{stmt}$ `OD`

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repetitive command/loop:

$\texttt{DO} \; :: g \Rightarrow \mathit{stmt} \; \texttt{OD}$ $\longleftarrow$ $\boxed{\texttt{WHILE } g \texttt{ DO } \mathit{stmt} \texttt{ OD}}$

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repetitive command/loop:

$\texttt{DO} :: g \Rightarrow \mathit{stmt}\ \texttt{OD}$ $\longleftarrow$ $\texttt{WHILE}\ g\ \texttt{DO}\ \mathit{stmt}\ \texttt{OD}$

conditional command:

$$
\begin{array}{lll}
\texttt{IF} & :: & g \Rightarrow \mathit{stmt}_1 \\
 & :: & \neg g \Rightarrow \mathit{stmt}_2 \\
\texttt{FI} & &
\end{array}
$$

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$$\begin{array}{lll} \mathtt{IF} & :: & g \Rightarrow stmt_1 \\ & :: & \neg g \Rightarrow stmt_2 \\ \mathtt{FI} & & \end{array} \longleftarrow \begin{array}{l} \mathtt{IF}\ g \\ \quad \mathtt{THEN}\ stmt_1 \\ \quad \mathtt{ELSE}\ stmt_2 \\ \mathtt{FI} \end{array}$$

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repetitive command/loop:

DO :: $g \Rightarrow stmt$ OD $\longleftarrow$ WHILE g DO $stmt$ OD

conditional command:

```
IF ::  g ⇒ stmt1
   :: ¬g ⇒ stmt2
FI
```

$\longleftarrow$

```
IF g
   THEN stmt1
   ELSE stmt2
FI
```

symbol :: stands for the nondeterministic choice between enabled guarded commands

Guarded Command Language (GCL)

guarded command $g \Rightarrow \mathit{stmt}$ $\longleftarrow$ $\boxed{\text{enabled if } g \text{ holds}}$

repetitive command/loop:

$\texttt{DO} :: g \Rightarrow \mathit{stmt}\ \texttt{OD}$ $\longleftarrow$ $\boxed{\texttt{WHILE}\ g\ \texttt{DO}\ \mathit{stmt}\ \texttt{OD}}$

conditional command:

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GCL: nondeterministic choices between arbitrary guarded commands in DO … OD and IF … FI

Guarded Command Language (GCL)

modeling language with nondeterministic choice

$$
\begin{aligned}
\mathit{stmt} \stackrel{\text{def}}{=}\ & x := \mathit{expr} \quad \Big| \quad \mathit{stmt}_1 ; \mathit{stmt}_2 \quad \Big| \\
& \texttt{DO} :: g_1 \Rightarrow \mathit{stmt}_1 \ \ \ldots \ \ :: g_n \Rightarrow \mathit{stmt}_n \ \texttt{OD} \\
& \texttt{IF} :: g_1 \Rightarrow \mathit{stmt}_1 \ \ \ldots \ \ :: g_n \Rightarrow \mathit{stmt}_n \ \texttt{FI} \\
& \quad \vdots
\end{aligned}
$$

where x is a typed variable and expr an expression of the same type

Guarded Command Language (GCL)

modeling language with nondeterministic choice

$$\mathit{stmt} \stackrel{\text{def}}{=} x := \mathit{expr} \;\; \Big| \;\; \mathit{stmt}_1 ; \mathit{stmt}_2 \;\; \Big|$$

$$\texttt{DO} :: g_1 \Rightarrow \mathit{stmt}_1 \;\; \ldots \;\; :: g_n \Rightarrow \mathit{stmt}_n \; \texttt{OD}$$

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$$\vdots$$

semantics of a GCL-program: program graph

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$$\vdots$$

semantics of a GCL-program: program graph

- locations are statements
- plus auxiliary location for termination

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$$\mathtt{DO} :: g_1 \Rightarrow stmt_1 \;\ldots\; :: g_n \Rightarrow stmt_n \;\mathtt{OD}$$
$$\vdots$$

conditional transition for assignment:

$$x := expr \xrightarrow{true:\alpha} exit$$

where α has the effect of "$x := expr$"

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analogously: multiple assignments in an atomic step

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$$\mathit{stmt} \stackrel{\text{def}}{=} x := \mathit{expr} \quad \big| \quad \mathit{stmt}_1 ; \mathit{stmt}_2 \quad \big|$$
$$\texttt{DO} :: g_1 \Rightarrow \mathit{stmt}_1 \quad \ldots \quad :: g_n \Rightarrow \mathit{stmt}_n \ \texttt{OD}$$
$$\vdots$$

two SOS-rules for the PG-semantics of
sequential composition

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$$stmt \stackrel{\text{def}}{=} x := expr \quad | \quad stmt_1 ; stmt_2 \quad |$$

$$\text{DO} :: g_1 \Rightarrow stmt_1 \quad \ldots \quad :: g_n \Rightarrow stmt_n \ \text{OD}$$

$$\vdots$$

$$\frac{stmt_1 \xhookrightarrow{g:\alpha} stmt_1'}{stmt_1 ; stmt_2 \xhookrightarrow{g:\alpha} stmt_1' ; stmt_2}$$

$$exit \neq stmt_1'$$

Guarded Command Language (GCL)

modeling language with nondeterministic choice

$$stmt \stackrel{\text{def}}{=} x := expr \;\Big|\; stmt_1; stmt_2 \;\Big|$$

$$\texttt{DO} :: g_1 \Rightarrow stmt_1 \;\; \ldots \;\; :: g_n \Rightarrow stmt_n \;\texttt{OD}$$

$$\vdots$$

$$\frac{stmt_1 \xrightarrow{g:\alpha} stmt_1'}{stmt_1; stmt_2 \xrightarrow{g:\alpha} stmt_1'; stmt_2}$$

$$\frac{stmt_1 \xrightarrow{g:\alpha} exit}{stmt_1; stmt_2 \xrightarrow{g:\alpha} stmt_2}$$

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$$stmt \stackrel{\text{def}}{=} x := expr \quad | \quad stmt_1 ; stmt_2 \quad |$$

$$\mathtt{IF} :: g_1 \Rightarrow stmt_1 \quad \ldots \quad :: g_n \Rightarrow stmt_n \ \mathtt{FI}$$

$$\vdots$$

single SOS-rule for the PG-semantics of
conditional statements

Guarded Command Language (GCL)

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$$stmt \stackrel{\text{def}}{=} x := expr \;\mid\; stmt_1; stmt_2 \;\mid$$
$$\texttt{IF} :: g_1 \Rightarrow stmt_1 \;\ldots\; :: g_n \Rightarrow stmt_n \;\texttt{FI}$$
$$\vdots$$

Let $cstmt$ be an `IF` –`FI` -statement as above.

$$\frac{stmt_i \xhookrightarrow{h:\alpha} stmt'}{cstmt \xhookrightarrow{g_i \wedge h:\alpha} stmt'}$$

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 & & \;\;\vdots
\end{array}
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SOS-rules for the PG-semantics of loops

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$$\vdots$$

Let *loop* be a DO –OD -statement as above.

$$\frac{\mathit{stmt}_i \xhookrightarrow{h:\alpha} \mathit{stmt}'}{\mathit{loop} \xhookrightarrow{g_i \wedge h:\alpha} \mathit{stmt}'; \mathit{loop}}$$

$\mathit{exit}; \mathit{loop} \mathrel{\widehat{=}} \mathit{loop}$

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Let *loop* be a DO –OD -statement as above.

$$\frac{stmt_i \xrightarrow{h:\alpha} stmt'}{loop \xrightarrow{g_i \wedge h:\alpha} stmt'; loop} \qquad \frac{f = \neg g_1 \wedge \ldots \wedge \neg g_n}{loop \xrightarrow{f:skip} exit}$$

Outline

1. Overview
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   - Channel systems
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3. **ProMeLa**
4. SPIN

ProMeLa: general structure of a ProMeLa model

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  e.g., **chan** *ch* $=$ [5] **of** $\{T_1, T_2, \ldots, T_k\};$

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Data types (for global and local variables)

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- basic data types:

boolean	1 Bit	`bool` *flag* = *true*;
bytes	8 Bit	`byte` *answer* = 42;
shorts	16 Bit	`short` *value* = 7;
integer	32 Bit	`int` *i* = 99;

Data types (for global and local variables)

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- structured data types:

arrays	**int** *myarray*[12];
records	**typedef** *myrec*{**int** r_1; **int** r_2; }

Things to know about variables and data types

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- default **initial value is 0**
- expressions include most **arithmetic**, **relational** and **logical operators** of C

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The modeling language ProMeLa

Channel declarations:

$\texttt{chan}$ *name* $=$ [*capacity*] $\texttt{of}$ $\{T_1, T_2, \ldots, T_k\}$;

name	:	name of the channel
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T_i, $1 \leq i \leq k$	:	type of transmittable data (tuples)

The modeling language ProMeLa

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Communication:

- synchronous message passing $\longleftarrow$ *capacity* **0**
- asynchronous message passing $\longleftarrow$ *capacity* $\geqslant 1$

The modeling language ProMeLa

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Communication actions:

- sending: $\mathit{name}!\mathit{expr}_1, \mathit{expr}_2, \ldots, \mathit{expr}_k;$
- receiving: $\mathit{name}?x_1, x_2, \ldots, x_k;$

Things to know about channels

The modeling language ProMeLa

Things to know about channels

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rule for a **lossy write**:
$$\frac{}{c!expr \xrightarrow{full(c):skip} exit}$$

ProMeLa: general structure of a ProMeLa model

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ProMeLa model consists of...

- type declarations,
  e.g., $\textit{\textbf{mtype}} = \{\textit{MSG}, \textit{ACK}\};$
- global variables declarations,
  e.g., $\texttt{\textbf{bool}}\ \textit{flag} = \textit{true};$
- channel declarations,
  e.g., $\texttt{\textbf{chan}}\ \textit{ch} = [5]\ \texttt{\textbf{of}}\ \{T_1, T_2, \ldots, T_k\};$
- process declarations,
  e.g., $\texttt{\textbf{proctype}}\ \textit{Sender}(\textit{args})\{\ldots\};$
- the init process (optional),e.g., $\texttt{\textbf{init}}\ (\textit{args})\{\ldots\};$

ProMeLa: general structure of a ProMeLa model

ProMeLa model consists of...

- process declarations,
  e.g., **proctype** *Sender*(*args*){...};
- the init process (optional),e.g., **init** (*args*){...};

Processes

The modeling language ProMeLa

Processes

$$\mathit{proc} ::= [\texttt{active}]\ \texttt{proctype}\ \mathit{name}(\mathit{args})\{\mathit{stmt}\}$$

$$\mathit{stmt} ::= x := \mathit{expr} \mid \mathit{stmt}_1 ; \mathit{stmt}_2 \mid \dots \mid$$

$$\texttt{DO} :: g_1 \Rightarrow \mathit{stmt}_1 \dots :: g_n \Rightarrow \mathit{stmt}_n\ \texttt{OD} \mid$$

$$\texttt{IF} :: g_1 \Rightarrow \mathit{stmt}_1 \dots :: g_n \Rightarrow \mathit{stmt}_n\ \texttt{FI}$$

active	:	marks the process active
name	:	name of the process
args	:	process parameter variables
stmt	:	statement

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Things to know about processes

- there can be **more than one** process

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- processes **execute concurrently**

The modeling language ProMeLa

Things to know about processes

- there can be **more than one** process
- initially: `init` **process** and **all `active` processes** (together at least one)
- creation **at any point inside the model** using the **`run`** statement (max. 255 processes)
- processes **execute concurrently**
- process termination: control flow **reaches `exit` location**
- program termination: **all processes** reached their **`exit` location**

The modeling language ProMeLa

Statements

$$\begin{array}{rl} stmt ::= & x := expr \;\Big|\; stmt_1 ; stmt_2 \;\Big|\; \ldots \;\Big| \\ & \texttt{DO} :: g_1 \Rightarrow stmt_1 \ldots :: g_n \Rightarrow stmt_n \; \texttt{OD} \;\Big| \\ & \texttt{IF} :: g_1 \Rightarrow stmt_1 \ldots :: g_n \Rightarrow stmt_n \; \texttt{FI} \end{array}$$

The modeling language ProMeLa

Statements

$$\mathit{stmt} ::= x := \mathit{expr} \;\Big|\; \mathit{stmt}_1 ; \mathit{stmt}_2 \;\Big|\; \ldots \;\Big|$$
$$\texttt{DO} :: g_1 \Rightarrow \mathit{stmt}_1 \ldots :: g_n \Rightarrow \mathit{stmt}_n \;\texttt{OD} \;\Big|$$
$$\texttt{IF} :: g_1 \Rightarrow \mathit{stmt}_1 \ldots :: g_n \Rightarrow \mathit{stmt}_n \;\texttt{FI}$$

where g_i are guards, i.e., boolean expressions:

$$\mathit{bexpr} ::= x \odot \mathit{expr} \;\Big|\; c!\mathit{expr} \;\Big|\; c?x \;\Big|\; \ldots \;\Big|$$
$$\neg \mathit{bexpr} \;\Big|\; \mathit{bexpr}_1 \sim \mathit{bexpr}_2$$

with $\odot \in \{<, \leq, =, \geq, >\}$ and $\sim \in \{\wedge, \vee, \rightarrow, \ldots\}$

Simple statements

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Simple statements

skip statement:	**skip**	***true***
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The modeling language ProMeLa

Simple statements

skip statement:	`skip`	***true***
goto statement:	**goto** ℓ	***true***
assignments:	$x := expr$	***true***
expressions:	$expr$	$expr \neq 0$
run statement:	**run** $P()$	if possible
sending/ receiving:	$ch!expr$, $ch?x$	if enabled

The modeling language ProMeLa

Simple statements

skip statement:	**skip**	***true***
goto statement:	**goto** ℓ	***true***
assignments:	$x := \mathit{expr}$	***true***
expressions:	expr	$\mathit{expr} \neq 0$
run statement:	**run** $P()$	if possible
sending/ receiving:	$\mathit{ch}!\mathit{expr}$, $\mathit{ch}?x$	if enabled
atomic statements:	**atomic**$\{\mathit{stmt}\}$	first statement

Simple statements

skip statement:	`skip`	*true*
goto statement:	`goto` ℓ	*true*
assignments:	$x := \mathit{expr}$	*true*
expressions:	*expr*	$\mathit{expr} \neq 0$
run statement:	`run` $P()$	if possible
sending/ receiving:	$\mathit{ch}!\mathit{expr}$, $\mathit{ch}?x$	if enabled
atomic statements:	`atomic`$\{\mathit{stmt}\}$	first statement
$\vdots$	$\vdots$	$\vdots$
printf statement:	`printf ...`	*true*
assert statement:	`assert`(bexpr)	*true*

Conditional commands

$$
\begin{array}{lcrcl}
\texttt{IF} & :: & g_1 & \Rightarrow & \mathit{stmt}_1 \\
 & & & \vdots & \\
 & :: & g_n & \Rightarrow & \mathit{stmt}_n \\
 & :: & \texttt{else} & \Rightarrow & \mathit{stmt}_0 \\
\texttt{FI} & & & &
\end{array}
$$

Conditional commands

$$
\begin{array}{lll}
\texttt{IF} & :: & g_1 \Rightarrow \mathit{stmt}_1 \\
 & & \vdots \\
 & :: & g_n \Rightarrow \mathit{stmt}_n \\
 & :: & \texttt{else} \Rightarrow \mathit{stmt}_0 \\
\texttt{FI} & &
\end{array}
$$

two-step semantics!

possible interleaving between evaluation of guard g_i and the execution of statement stmt_i

The modeling language ProMeLa

Conditional commands

$$
\begin{array}{lrrcl}
\texttt{IF} & :: & g_1 & \Rightarrow & \mathit{stmt}_1 \\
 & & & \vdots & \\
 & :: & g_n & \Rightarrow & \mathit{stmt}_n \\
 & :: & \textbf{else} & \Rightarrow & \mathit{stmt}_0 \\
\texttt{FI} & & & &
\end{array}
$$

two-step semantics!
possible interleaving between evaluation of guard g_i and the execution of statement stmt_i

Things to know about if-statements

- **nondeterministic choice** between enabled guards
- **else** case if **none of the guards** is enabled
- if-statement is **executable** if there is **at least one** enabled guard and **blocked otherwise**

Loop commands

$$
\begin{array}{lll}
\texttt{DO} & :: \quad g_1 & \Rightarrow \textit{stmt}_1 \\
 & & \vdots \\
 & :: \quad g_n & \Rightarrow \textit{stmt}_n \\
 & :: \ \texttt{else} & \Rightarrow \textit{stmt}_0 \\
\texttt{OD} & &
\end{array}
$$

Loop commands

$$
\begin{array}{lrl}
\texttt{DO} & :: \quad g_1 & \Rightarrow \mathit{stmt}_1 \\
 & & \vdots \\
 & :: \quad g_n & \Rightarrow \mathit{stmt}_n \\
 & :: \ \mathbf{\texttt{else}} & \Rightarrow \mathit{stmt}_0 \\
\texttt{OD} & &
\end{array}
$$

again two-step semantics and loop statement has **blocking semantics**, meaning that the loop exits on **`break`** only!

Loop commands

$$\begin{array}{lllll} \texttt{DO} & :: & g_1 & \Rightarrow & stmt_1 \\ & & & \vdots & \\ & :: & g_n & \Rightarrow & stmt_n \\ & :: & \texttt{else} & \Rightarrow & stmt_0 \\ \texttt{OD} & & & & \end{array}$$

again two-step semantics and loop statement has **blocking semantics**, meaning that the loop exits on **`break`** only!

standard GCL semantics:

$$\frac{f = \neg g_1 \wedge \ldots \wedge \neg g_n}{loop \xhookrightarrow{f:skip} exit}$$

ProMeLa semantics:

$$\frac{break \xhookrightarrow{true:skip} exit}{loop \xhookrightarrow{g_i:skip} exit}$$

$(stmt_i = break)$

Loop commands

$$
\begin{array}{lllcl}
\texttt{DO} & :: & g_1 & \Rightarrow & \mathit{stmt}_1 \\
 & & & \vdots & \\
 & :: & g_n & \Rightarrow & \mathit{stmt}_n \\
 & :: & \texttt{else} & \Rightarrow & \mathit{stmt}_0 \\
\texttt{OD} & & & &
\end{array}
$$

again two-step semantics and loop statement has **blocking semantics**, meaning that the loop exits on **break** only!

Things to know about do-statements

- **nondeterministic choice** between enabled guards
- **else** case if **none of the guards** is enabled
- do-statement is **executable** if there is **at least one** enabled guard and **blocked otherwise**

Nondeterminism occurs because of

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- the choice of different possible actions within each process (**`IF`** ... **`FI`** and **`DO`** ... **`OD`**)

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- non-deterministic scheduling of processes (interleaving). Use **atomic**{*stmt*$_1$; ...; *stmt*$_n$} statements to avoid interleaving.

The modeling language ProMeLa

Nondeterminism occurs because of

- the choice of different possible actions within each process (`IF` ... `FI` and `DO` ... `OD`)
- non-deterministic scheduling of processes (interleaving). Use `atomic`{$stmt_1$; ...; $stmt_n$} statements to avoid interleaving.

Things to know about atomic regions

- execution in a **single step** instead of interleaved
- executable if the **first statement** is executable
- atomicity is **broken** if **any** of the statements is **blocking**

Example: ProMeLa model of Petersons algorithm

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bool $b1, b2$;
int x;
bool $incrit1, incrit2$;

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$\texttt{bool}\ b1, b2;$
$\texttt{int}\ x;$
$\texttt{bool}\ incrit1, incrit2;$

$\texttt{active proctype}\ p1()\{$
$\quad \texttt{DO}$
$\qquad :: \texttt{atomic}\{b1 = true; x = 2\};$
$\qquad \texttt{IF}$
$\qquad\quad :: \texttt{atomic}\{(b2 == false \,||\, x == 1) \Rightarrow incrit1 = true\};$
$\qquad\qquad \texttt{atomic}\{incrit1 = false; b1 = false\};$
$\qquad \texttt{FI}$
$\quad \texttt{OD}$
$\}$

Example: ProMeLa model of Petersons algorithm

```
bool b1, b2;
int x;
bool incrit1, incrit2;

active proctype p1(){
  DO
    :: atomic{b1 = true; x = 2};
    IF
      :: atomic{(b2 == false || x == 1) ⇒ incrit1 = true};
        atomic{incrit1 = false; b1 = false};
    FI
  OD
}

active proctype p1(){ ... symmetric ... }
```

Outline

The model checker SPIN

will be part of the lecture in January 2013

E.W. Dijkstra.
A Discipline of Programming.
Prentice-Hall, 1976.

G. Holzmann.
The SPIN Model Checker, Primer and Reference Manual.
Addison Wesley, 2003.