CS256/Spring 2008 — Lecture #09

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Chapter 2

Invariance: Applications

Parameterized Programs

$$S:: \left[\begin{array}{l} \ell_0\text{: } \textbf{loop forever do} \\ \quad \left[\begin{array}{l} \ell_1\text{: } \textbf{noncritical} \\ \ell_2\text{: } \textbf{request } y \\ \ell_3\text{: } \textbf{critical} \\ \ell_4\text{: } \textbf{release } y \end{array}\right] \end{array}\right]$$

P^3: : [**local** y : **integer where** $y = 1$; $[S||S||S]$]
(with some renaming of labels of the S's.)

P^4: : [**local** y : **integer where** $y = 1$; $[S||S||S||S]$]

⋮

P^n: : ?

Mutual exclusion:

P^3: $\square(\neg(at\_\ell_3 \wedge at\_m_3) \ \wedge\ \neg(at\_\ell_3 \wedge at\_k_3) \wedge$
$\neg(at\_m_3 \wedge \text{at\_}k_3))$

P^4: $\square(\neg(\ldots) \ \wedge\ \ldots\ \wedge\ \neg(\ldots))$

P^n: ?

We want to deal with these programs,
i.e., programs with an arbitrary number of identical components, in a more uniform way.

Solution: parametrization

Syntax

Compound statements of variable size

cooperation: $\overset{M}{\underset{j=1}{||}} S[j] \quad : \quad [\ S[1] || \ldots || S[M]\ ]$

Selection: $\underset{j=1}{\overset{M}{\textbf{OR}}} S[j] \quad : \quad [\ S[1]\ \textbf{or}\ \ldots\ \textbf{or}\ S[M]\ ]$

$S[j]$ is a <u>parameterized statement</u>.

In what ways can j appear in S?

- explicit variable in expression

  $\ldots := j + \ldots$

- explicit subscript in array x

  $\ldots := x[j] + \ldots$ or $x[j] := \ldots$

- implicit subscript of all local variables in $S[j]$

  z stands for $z[j]$

- implicit subscript of all labels in $S[j]$

  ℓ_3 stands for $\ell_3[j]$

`Example:` Program PAR-SUM (Fig. 2.1)

(parallel sum of squares) $M \geq 1$

$$\begin{array}{ll} \textbf{in} & M\text{: } \textbf{integer where } M \geq 1 \\ & x \ \text{: } \textbf{array } [1..M] \textbf{ of integer} \\ \textbf{out} & z \ \text{: } \textbf{integer where } z = 0 \end{array}$$

$$\mathop{||}_{j=1}^{M} P[j] :: \begin{bmatrix} \textbf{local } y\text{: } \textbf{integer} \\ \ell_0\text{: } y := x[j] \\ \ell_1\text{: } z := z + y \cdot y \\ \ell_2\text{:} \end{bmatrix}$$

$$\boxed{z \ = \ x[1]^2 + x[2]^2 + \ldots + x[M]^2}$$

Program PAR-SUM-E (Fig. 2.2)

(Explicit subscripted parameterized statements of PAR-SUM)

$$
\begin{array}{ll}
\textbf{in} & M\colon \textbf{integer where } M \geq 1 \\
 & x\ \colon \textbf{array } [1..M] \textbf{ of integer} \\
\textbf{out} & z\ \colon \textbf{integer where } z = 0
\end{array}
$$

$$
\mathop{\Big\|}_{j=1}^{M} P[j] :: \left[\begin{array}{l}
\textbf{local } y[j]\colon\ \textbf{integer} \\
\ell_0[j]\colon\ y[j] := x[j] \\
\ell_1[j]\colon\ z := z + y[j] \cdot y[j] \\
\ell_2[j]\colon
\end{array}\right]
$$

We <u>write</u> the short version,

but we <u>reason</u> about this one.

Parameterized transition systems

The number M of processes is not fixed,
so there is an unbounded number of transitions.
To finitely represent these, we use
parameterization of transition relations.

`Example:` PAR-SUM

The unbounded number of transitions associated with ℓ_0 are represented by a single transition relation using parameter j:

$$\begin{aligned} \rho_{\ell_0}[j]: \quad & move(\ell_0[j], \ell_1[j]) \ \wedge \\ & y'[j] = x[j] \ \wedge \\ & pres(\{x, z\}) \end{aligned}$$

where $j = 1 \ldots M$.

Array Operations

Arrays (explicit or implicit) are treated as variables that range over functions:

$[1 \ldots M] \mapsto$ integers

Representation of array operations in transition relations:

- Retrieval: $y[k]$
  to retrieve the value of the kth element of array y

- Modification: $update(y, k, e)$
  the resulting array agrees with y on all i, $i \neq k$, and $y[k] = e$

Properties of *update*

$$update(y, k, e)[k] = e$$

$$update(y, k, e)[j] = y[j] \text{ for } j \neq k$$

<u>`Example:`</u> PAR-SUM

The proper representation of the transition relation for $\ell_0[j]$ is

$$\begin{aligned} \rho_0[j]: \quad & move(\ell_0[j],\ \ell_1[j]) \land \\ & y' = update(y,\ j,\ x[j]) \land \\ & pres(\{x, z\}) \end{aligned}$$

Parameterized Programs: Specification

Notation:

- $L_i = \{j \mid \ell_i[j] \in \pi\} \quad \subseteq \{1, \ldots, M\}$

  The set of indices of processes that currently reside at ℓ_i
- $N_i = |L_i|$

  The number of processes currently residing at ℓ_i

`Example:` $L_i = \{3, 5\}$ means $\ell_i[3], \ell_i[5] \in \pi$ and we have $N_i = 2$

Invariant:

$$\Box(N_i \geq 0)$$

Abbreviations:

$$\begin{aligned} L_{i_1,i_2,\ldots,i_k} &= L_{i_1} \cup L_{i_2} \cup \ldots \cup L_{i_k} \\ L_{i..j} &= L_i \cup L_{i+1} \cup \ldots \cup L_j \\ N_{i_1,i_2,\ldots,i_k} &= |L_{i_1,i_2,\ldots,i_k}| \\ N_{i..j} &= |L_{i..j}| \end{aligned}$$

Parameterized Programs: Specification (Con'd)

<u>`Example:`</u> Program MPX-SEM (Fig 2.3) $M \geq 2$
(multiple mutual exclusion by semaphores)
where

$$j \oplus_M 1 = (j \bmod M) + 1 = \begin{cases} j+1 & \text{if } j < M \\ 1 & \text{if } j = M \end{cases}$$

Elaboration for $M = 2$:
Program MPX-SEM-2 (Fig 2.4)

mutual exclusion: $\square \underbrace{\forall i, j \in [1..M] \,.\, i \neq j \,.\, \neg(at\_\ell_3[i] \;\wedge\; at\_\ell_3[j])}_{\psi}$

abbreviated as

$$\boxed{\square(N_3 \leq 1)}$$

i.e., the number of processes simultaneously residing at ℓ_3 is always less than or equal to 1.

Note: $\neg(at\_\ell_3[i] \wedge at\_\ell_3[j])$ can be expressed as $at\_\ell_3[i] + at\_\ell_3[j] \leq 1$.

Program MPX-SEM (Fig. 2.3)

$$
\begin{array}{ll}
\textbf{in} & M\text{: }\textbf{integer where } M \geq 2 \\
\textbf{local } y & \text{: }\textbf{array } [1..M] \textbf{ of integer} \\
& \qquad\qquad \textbf{where } y[1] = 1,\ y[j] = 0 \text{ for } 2 \leq j \leq M
\end{array}
$$

$$
\mathop{\Big|\Big|}_{j=1}^{M} P[j] :: \left[\begin{array}{l}
\ell_0\text{: } \textbf{loop forever do} \\
\qquad \left[\begin{array}{l}
\ell_1\text{: } \textbf{noncritical} \\
\ell_2\text{: } \textbf{request } y[j] \\
\ell_3\text{: } \textbf{critical} \\
\ell_4\text{: } \textbf{release } y[j \oplus_M 1]
\end{array}\right]
\end{array}\right]
$$

Program MPX-SEM-2 (Fig. 2.4)

local y: **array** [1..2] **of integer where** $y[1] = 1,\ y[2] = 0$

$$P[1] :: \left[\begin{array}{l} \ell_0[1]\text{: } \textbf{loop forever do} \\ \qquad \left[\begin{array}{l} \ell_1[1]\text{: } \textbf{noncritical} \\ \ell_2[1]\text{: } \textbf{request } y[1] \\ \ell_3[1]\text{: } \textbf{critical} \\ \ell_4[1]\text{: } \textbf{release } y[2] \end{array}\right] \end{array}\right]$$

$$||$$

$$P[2] :: \left[\begin{array}{l} \ell_0[2]\text{: } \textbf{loop forever do} \\ \qquad \left[\begin{array}{l} \ell_1[2]\text{: } \textbf{noncritical} \\ \ell_2[2]\text{: } \textbf{request } y[2] \\ \ell_3[2]\text{: } \textbf{critical} \\ \ell_4[2]\text{: } \textbf{release } y[1] \end{array}\right] \end{array}\right]$$

Parameterized Programs: Verification

Objective: prove $\{\varphi\}\tau[i]\{\varphi\}$ in a uniform way for all $i \in [1..M]$

Example: Program MPX-SEM (Fig 2.3) $M \geq 2$

Prove mutual exclusion:

$$\square(\underbrace{N_3 \leq 1}_{\varphi})$$

The assertion φ is not inductive, therefore we prove the invariance of

$$\varphi_1: \quad \forall j \,.\, y[j] \;\geq\; 0$$

$$\varphi_2: \quad \Big(N_{3,4} + \sum_{j=1}^{M} y[j]\Big) = \; 1$$

where $N_{3,4}$ = Number of processes currently residing at ℓ_3 or at ℓ_4

Example: Program MPX-SEM (Con't)

Then φ can be deducted by monotonicity:

$$\varphi_1 \ \wedge \ \varphi_2 \ \rightarrow \ \underbrace{N_3 \leq 1}_{\varphi}$$

since

$$\underbrace{N_3 \ \leq \ N_{3,4} \ = \ 1 - \sum_{j=1}^{M} y[j]}_{\varphi_2} \ \underbrace{\leq \ 1}_{\varphi_1}$$

- Proof of $\square(\underbrace{\forall j \,.\, y[j] \geq 0}_{\varphi_1})$

B1:

$$\underbrace{\ldots \ \wedge \ y[1] = 1 \ \wedge \ (\forall j \,.\, 2 \leq j \leq M \,.\, y[j] = 0)}_{\Theta}$$
$$\rightarrow \ \underbrace{\forall j \,.\, y[j] \geq 0}_{\varphi_1}$$

Note: $\forall j \,.\, y[j] \geq 0$ stands for $\forall j . i \leq j \leq M \,.\, y[j] \geq 0$

Example: Program MPX-SEM (Con't)

B2:

The only transitions that interfere with φ_1 are $\tau_{\ell_2}[i]$ and $\tau_{\ell_4}[i]$.

$$\begin{aligned}\rho_{\ell_2}[i]:\ & move(\ell_2[i], \ell_3[i]) \ \land\ y[i] > 0 \land \\ & y' = update(y, i, y[i]{-}1)\end{aligned}$$

$$\begin{aligned}\rho_{\ell_4}[i]:\ & move(\ell_4[i], \ell_0[i]) \land \\ & y' = update(y, i \oplus_M 1, y[i \oplus_M 1]{+}1)\end{aligned}$$

$\rho_{\ell_2}[i]$ implies

$$y[i] > 0 \ \land y'[i] = y[i] - 1 \ \land\ \forall j \,.\, j \neq i \,.\, y'[j] = y[j]$$

$\rho_{\ell_4}[i]$ implies

$$y'[i \oplus_M 1] = y[i \oplus_M 1] + 1 \ \land$$

$$\forall j (j \neq i \oplus_M 1)\ y'[j] = y[j]$$

We therefore have

$$\underbrace{\forall j \,.\, y[j] \geq 0}_{\varphi_1} \land \left\{ \begin{array}{c} \rho_{\ell_2}[i] \\ \rho_{\ell_4}[i] \end{array} \right\} \ \rightarrow\ \underbrace{\forall j \,.\, y'[j] \geq 0}_{\varphi'_1}$$

• Proof of $\square \underbrace{\left(N_{3,4} + \left(\sum_{j=1}^{M} y[j]\right) = 1\right)}_{\varphi_2}$

B1:

$$\underbrace{\begin{pmatrix} \pi = \{\ell_0[1], \ldots, \ell_0[M]\} \wedge \\ y[1] = 1 \ \wedge \ (\forall j \,.\, 2 \le j \le M \,.\, y[j] = 0) \end{pmatrix}}_{\Theta}$$

$$\rightarrow \ \underbrace{N_{3,4} + \left(\sum_{j=1}^{M} y[j]\right) = 1}_{\varphi_2}$$

B2: Verification conditions:

$\rho_{\ell_2}[i]$ implies:

$$N'_{3,4} = N_{3,4} + 1$$

$$\left(\sum_{j=1}^{M} y'[i]\right) = \left(\sum_{j=1}^{M} y[i]\right) - 1$$

$\rho_{\ell_4}[i]$ implies:

$$N'_{3,4} = N_{3,4} - 1$$

$$\left(\sum_{j=1}^{M} y'[i]\right) = \left(\sum_{j=1}^{M} y[i]\right) + 1$$

Therefore

$$\underbrace{N_{3,4} + \left(\sum_{j=1}^{M} y[i]\right) = 1}_{\varphi_2} \wedge \left\{ \begin{array}{c} \rho_{\ell_2}[i] \\ \rho_{\ell_4}[i] \end{array} \right\}$$

$$\rightarrow \underbrace{N'_{3,4} + \left(\sum_{j=1}^{M} y'[i]\right) = 1}_{\varphi'_2}$$

Parameterized Programs: Examples

<u>`Example:`</u> READERS-WRITERS (Fig 2.11)
(readers-writers with generalized semaphores)

where

$$\textbf{request}\ (y, c)\ =\ \langle \textbf{await}\ y \geq c;\ y := y - c\rangle$$

$$\textbf{release}\ (y, c)\ =\ \langle y := y + c\rangle$$

$$\square\ \underbrace{\forall i, j \in [1..M]\ .\ i \neq j\ .\ at\_\ell_6[i]\ \rightarrow\ \neg(at\_\ell_6[j]\ \vee\ at\_\ell_3[j])}_{\psi}$$

- φ_1 and φ_2 are inductive

  φ_1: $\quad y\ \geq\ 0$

  φ_2: $\quad N_{3,4} + M \cdot N_{6,7} + y\ =\ M$

- Therefore

  $$\underset{\varphi_1, \varphi_2}{N_{6,7} > 0\ \rightarrow\ (N_{6,7} = 1\ \wedge\ N_{3,4} = 0)}$$

  Thus,

  $$\square\,\psi$$

Program READ-WRITE(Fig. 2.11)

$$
\begin{array}{ll}
\textbf{in} & M\colon \textbf{integer where } M \geq 1 \\
\textbf{local } y & \colon \textbf{integer where } y = M
\end{array}
$$

$$
\mathop{\Big|\Big|}_{i=1}^{M} P[i] :: \left[\begin{array}{l}
\ell_0\colon \textbf{loop forever do} \\
\qquad \left[\begin{array}{l}
\ell_1\colon \textbf{noncritical} \\
\left[\begin{array}{ll}
R :: & \left[\begin{array}{l} \ell_2\colon \textbf{request } (y,1) \\ \ell_3\colon \textbf{read} \\ \ell_4\colon \textbf{release } (y,1) \end{array}\right] \\
\quad \textbf{or} & \\
W :: & \left[\begin{array}{l} \ell_5\colon \textbf{request } (y,M) \\ \ell_6\colon \textbf{write} \\ \ell_7\colon \textbf{release } (y,M) \end{array}\right]
\end{array}\right]
\end{array}\right]
\end{array}\right]
$$

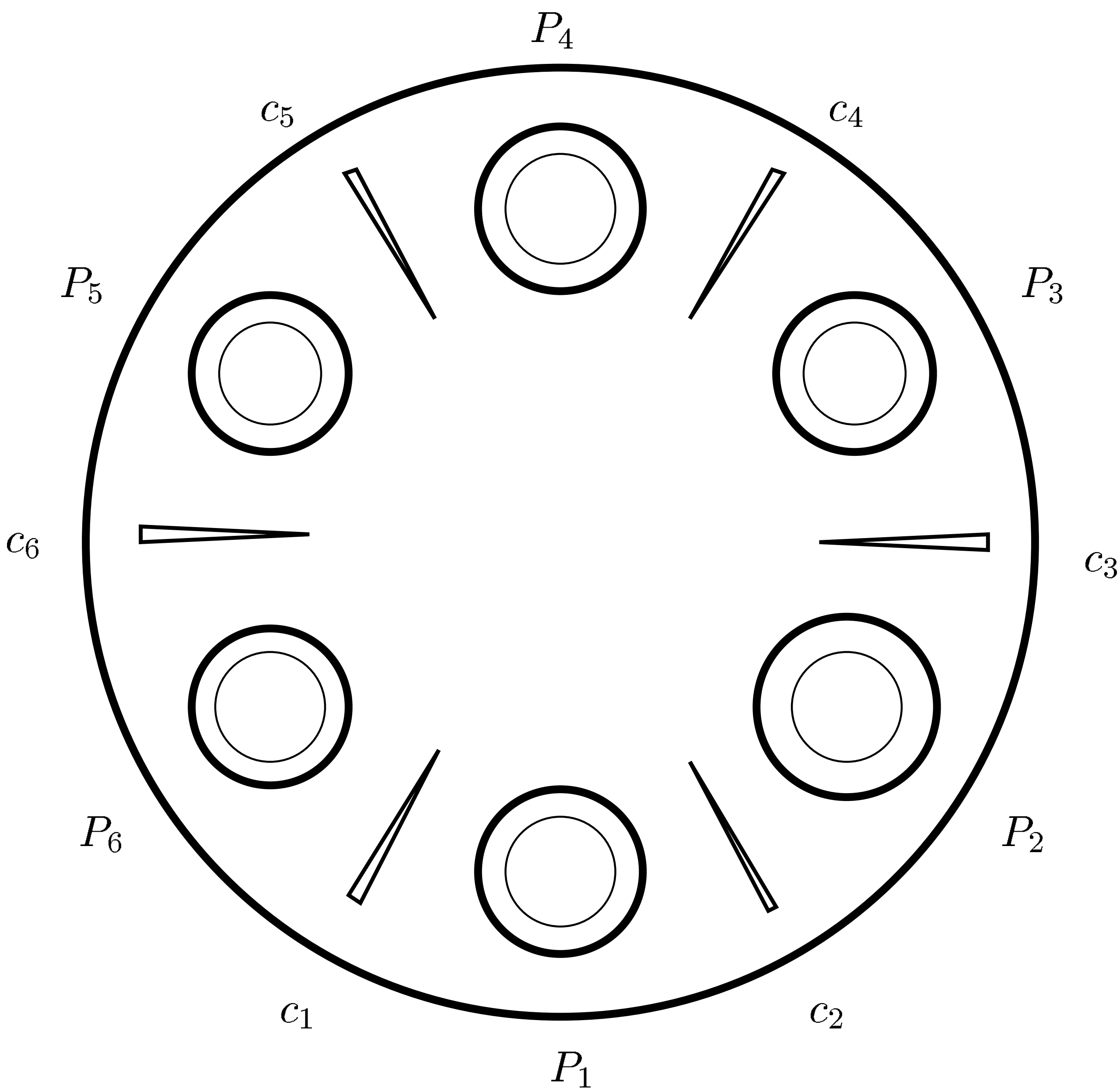
`Example:` **The Dining Philosophers Problem**

(multiple resource allocation)

Fig 2.14

- M philosophers are seated at a round table
- Each philosopher alternates between a "thinking" phase and "eating" phase
- M chopsticks, one between every two philosophers
- A philosopher needs 2 chopsticks (left & right) to eat

Dining philosophers setup (Fig. 2.14)



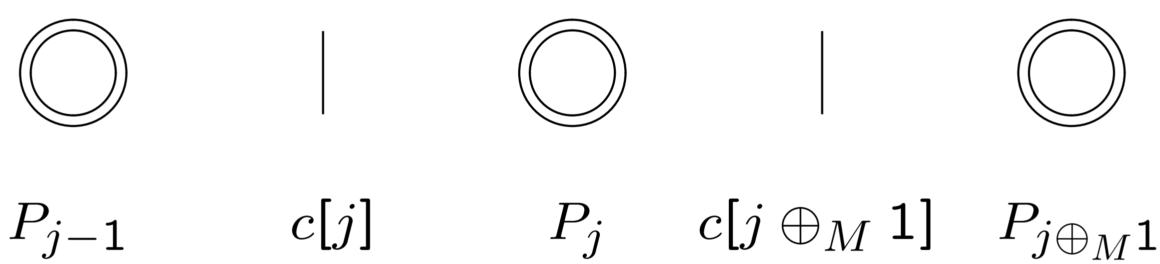
Program DINE (Fig. 2.15)
(A simple solution to the dining philosophers problem)

Philosopher P_i	-	process $P[i]$
"thinking" phase	-	noncritical
"eating" phase	-	critical

For philosopher j,

- $c[j]$ represents availability of left chopstick
  ($c[j] = 1$ iff chopstick is available)

- $c[j \oplus_M 1]$.............right chopstick



Program DINE (Fig. 2.15)

$$\begin{array}{ll}\textbf{in} & M\text{: }\textbf{integer where } M \geq 2 \\ \textbf{local } c & \text{: }\textbf{array } [1..M] \textbf{ of integer where } c = 1\end{array}$$

$$\overset{M}{\underset{j=1}{||}} P[j] :: \left[\begin{array}{l} \ell_0\text{: }\textbf{loop forever do} \\ \qquad \left[\begin{array}{l} \ell_1\text{: }\textbf{noncritical} \\ \ell_2\text{: }\textbf{request } c[j] \\ \ell_3\text{: }\textbf{request } c[j \oplus_M 1] \\ \ell_4\text{: }\textbf{critical} \\ \ell_5\text{: }\textbf{release } c[j] \\ \ell_6\text{: }\textbf{release } c[j \oplus_M 1] \end{array}\right] \end{array}\right]$$

Specification: Chopstick Exclusion

$$\square \underbrace{\forall j \in [1..M] \,.\, \neg(at\_\ell_4[j] \ \wedge \ at\_\ell_4[j \oplus_M 1])}_{\psi}$$

Mutual exclusion between every two adjacent philosophers

Proof:

- φ_0 and φ_1 are inductive

$$\varphi_0: \ \forall j \in [1..M] \,.\, c[j] \ \geq \ 0$$

$$\varphi_1: \ \forall j \in [1..M] \,.\, at\_\ell_{4..6}[j] \ + \ at\_\ell_{3..5}[j \oplus_M 1] \ + \ c[j \oplus_M 1] \ = \ 1$$

- Then,

$$at\_\ell_4[j] + at\_\ell_4[j \oplus_M 1]$$

$$\leq at\_\ell_{4..6}[j] + at\_\ell_{3..5}[j \oplus_M 1]$$

$$\underset{\varphi_1}{=} 1 - c[j \oplus_M 1] \ \underset{\varphi_0}{\leq} \ 1$$

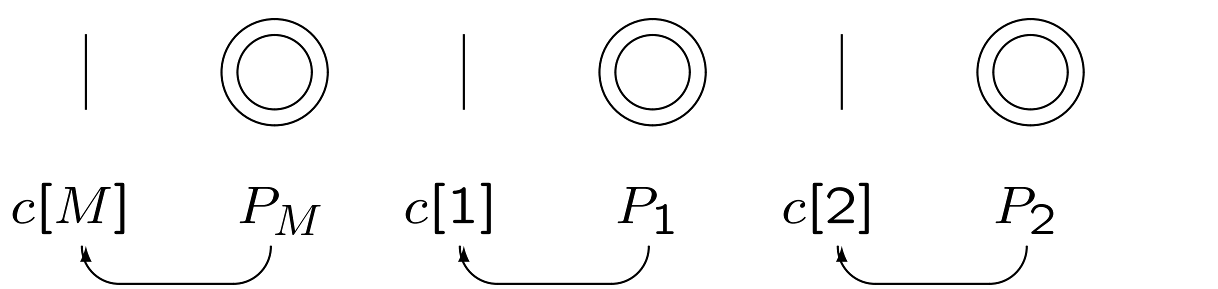
Chopstick Exclusion OK

Problem: possible deadlock ("starvation")

$P[1]$ ℓ_2: **request** $c[1]$; ℓ_3: **request** $c[2]$
$\uparrow$

.
.
.

$P[M]$ ℓ_2: **request** $c[M]$; ℓ_3: **request** $c[1]$
$\uparrow$



Solution: One Philosopher Excluded
(keeping the symmetry)

- Two-room philosophers' world (Fig 2.18)

  Philosophers are "thinking" at the library
  "eating" at the dining hall

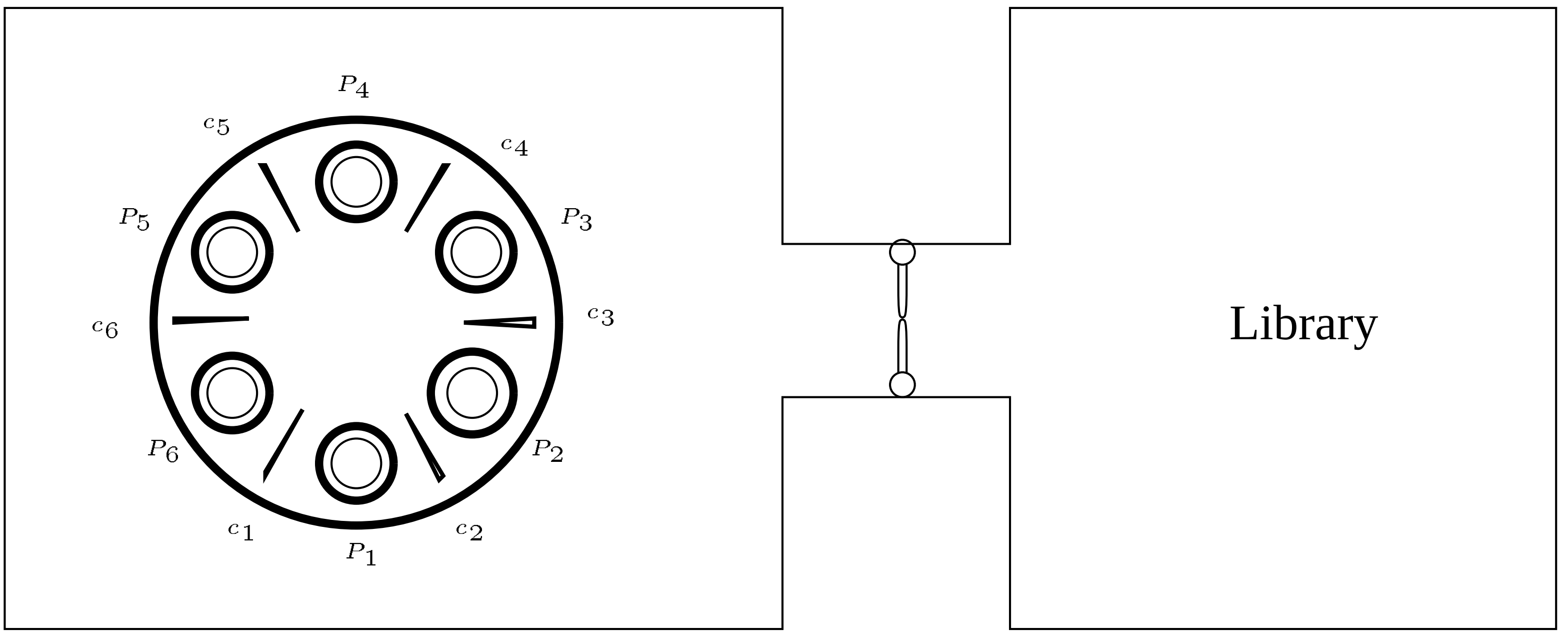
  When a philosopher finishes "eating"
  he returns to the library to "think"

- Program DINE-EXCL (Fig 2.17)

  Additional semaphore variable r
  "door keeper" (initally $r = M-1$)

  No more than $M-1$ philosophers are admitted to the dining hall at the same time.

Two-room philosopher's world (Fig. 2.18)



Program DINE-EXCL (Fig. 2.17)

$$
\begin{array}{lll}
\textbf{in} & M\textbf{: integer where } M \geq 2 \\
\textbf{local} & c\ \ \textbf{: array } [1..M] \textbf{ integer where } c = 1 \\
 & r\ \ \textbf{: integer where } r = M - 1
\end{array}
$$

$$
\overset{M}{\underset{j=1}{\big|\big|}} P[j] :: \left[\begin{array}{l}
\ell_0\textbf{: loop forever do} \\
\qquad \left[\begin{array}{l}
\ell_1\textbf{: noncritical} \\
\ell_2\textbf{: request } r \\
\ell_3\textbf{: request } c[j] \\
\ell_4\textbf{: request } c[j \oplus_M 1] \\
\ell_5\textbf{: critical} \\
\ell_6\textbf{: release } c[j] \\
\ell_7\textbf{: release } c[j \oplus_M 1] \\
\ell_8\textbf{: release } r
\end{array}\right]
\end{array}\right]
$$

Properties of DINE-EXCL:

- <u>chopstick exclusion</u>
  A safety property (in text)

- <u>starvation-free</u>
  progress (next book)

- <u>accessibility</u> $\ell_2[j] \Rightarrow \Diamond \ell_5[j]$
  progress (next book)

Chapter 3

Precedence

Proving Precedence Properties

nested waiting-for formulas

are of the form

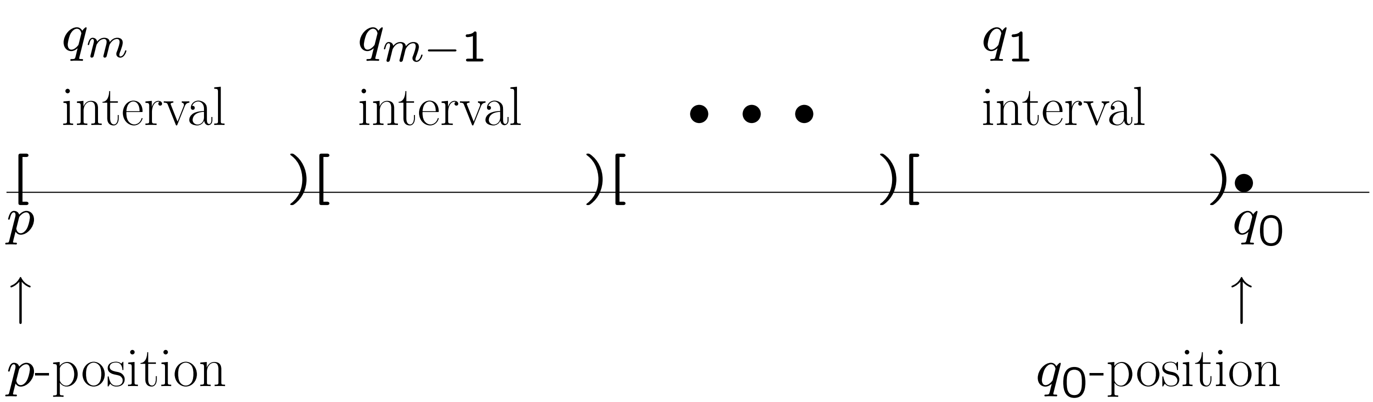
$$p \;\Rightarrow\; q_m \,\mathcal{W}\, (q_{m-1} \;\cdots\; (q_1 \,\mathcal{W}\, q_0) \ldots)$$

also written

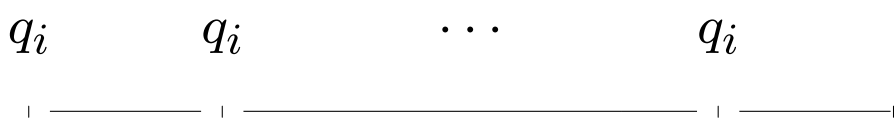
$$\boxed{p \;\Rightarrow\; q_m \,\mathcal{W}\, q_{m-1} \;\cdots\; q_1 \,\mathcal{W}\, q_0}$$

for assertions $p, q_0, q_1, \ldots, q_m$.

Models that satisfy these formulas

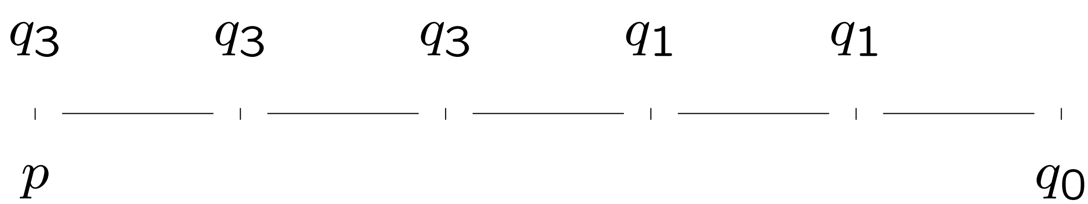


q_i-interval

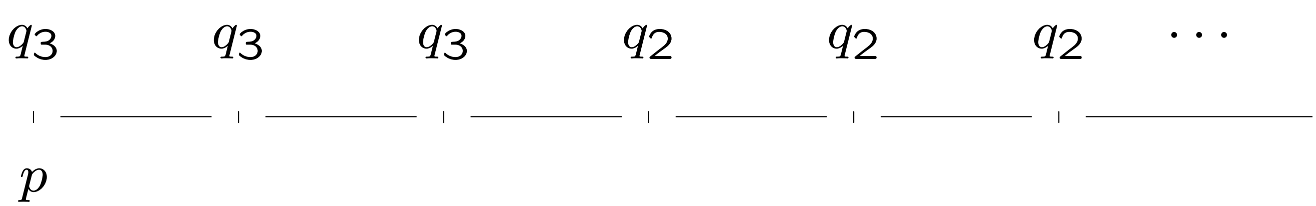


- May be empty

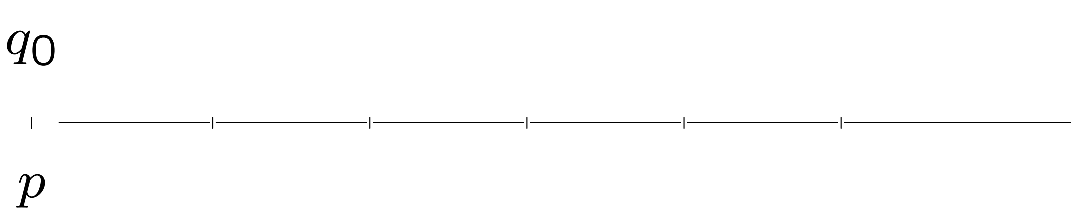
e.g. $p \Rightarrow q_3 \mathcal{W} q_2 \mathcal{W} q_1 \mathcal{W} q_0$



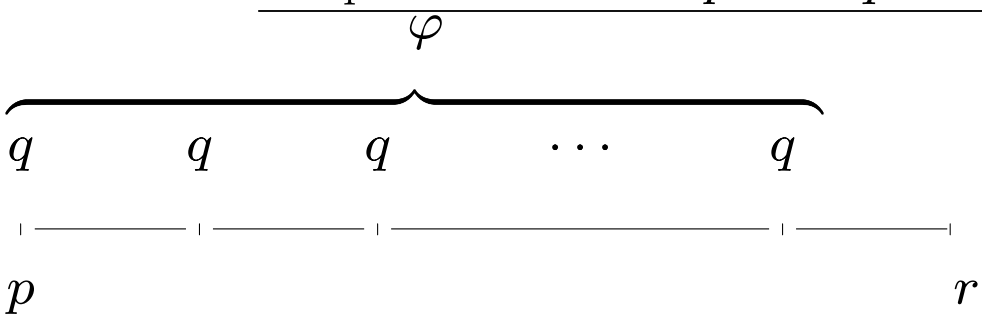
- May extend to infinity



Note: The following is OK



Simple Precedence: $p \Rightarrow q\,\mathcal{W}\,r$



can be reduced to first-order VCs by verification rule WAIT:

Rule wait (general waiting-for)

For assertions p, q, r, φ

W1. $p \rightarrow \varphi \vee r$

W2. $\varphi \rightarrow q$

W3. $\{\varphi\}\mathcal{T}\{\varphi \vee r\}$

$p \Rightarrow q\,\mathcal{W}\,r$

Recall: To show $P \Vdash \{\varphi\}\ \mathcal{T}\ \{\varphi \vee r\}$, we have to show that for every $\tau \in \mathcal{T}$

$$\rho_\tau \wedge \varphi \rightarrow \varphi' \vee r'$$

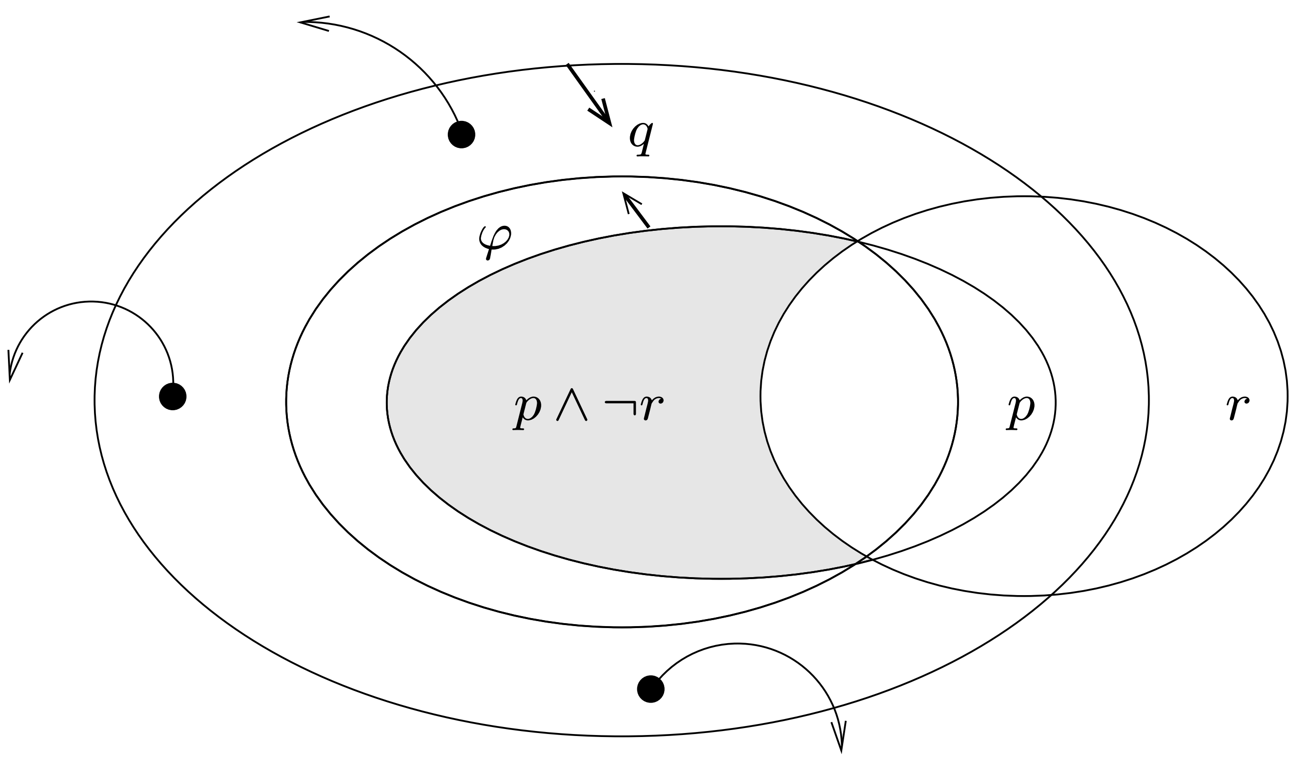
is P-state valid.

Intermediate Assertion φ

W1. $p \rightarrow \varphi \vee r$ "φ weakens $p \wedge \neg r$"

i.e., $p \wedge \neg r \rightarrow \varphi$

W2. $\varphi \rightarrow q$ "φ strengthens q"



Example: **Program mux-pet1 (Fig. 3.4)**

We proved mutual exclusion

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

Using invariants

$$\chi_0: \quad s = 1 \ \vee \ s = 2$$

$$\chi_1: \quad y_1 \ \leftrightarrow \ at\_\ell_{3..5}$$

$$\chi_2: \quad y_2 \ \leftrightarrow \ at\_m_{3..5}$$

$$\chi_3: \quad at\_\ell_3 \ \wedge \ at\_m_4 \ \rightarrow \ y_2 \ \wedge \ s = 1$$

$$\chi_4: \quad at\_\ell_4 \ \wedge \ at\_m_3 \ \rightarrow \ y_1 \ \wedge \ s = 2$$

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** $s = 1$

$$
P_1 :: \quad \ell_0 : \ \textbf{loop forever do} \begin{bmatrix} \ell_1 : & \textbf{noncritical} \\ \ell_2 : & (y_1,\ s) := (\text{T},\ 1) \\ \ell_3 : & \textbf{await } (\neg y_2) \vee (s \neq 1) \\ \ell_4 : & \textbf{critical} \\ \ell_5 : & y_1 := \text{F} \end{bmatrix}
$$

||

$$
P_2 :: \quad m_0 : \ \textbf{loop forever do} \begin{bmatrix} m_1 : & \textbf{noncritical} \\ m_2 : & (y_2,\ s) := (\text{T},\ 2) \\ m_3 : & \textbf{await } (\neg y_1) \vee (s \neq 2) \\ m_4 : & \textbf{critical} \\ m_5 : & y_2 := \text{F} \end{bmatrix}
$$

We want to prove simple precedence

$$\psi_2\colon \quad \underbrace{at\_\ell_3 \ \land \ at\_m_{0..2}}_{p} \ \Rightarrow \ \underbrace{\neg at\_m_4}_{q} \ \ \mathcal{W} \ \ \underbrace{at\_\ell_4}_{r}$$

We try to find an assertion φ such that
W1 – W3 of rule WAIT hold

Let

$$\varphi: \ at\_\ell_3 \land (at\_m_{0..2} \lor (at\_m_3 \land s = 2))$$

W1:

$$\underbrace{at\_\ell_3 \ \wedge \ at\_m_{0..2}}_{p} \ \rightarrow$$

$$\underbrace{at\_\ell_3 \ \wedge \ (at\_m_{0..2} \ \vee \ \cdots)}_{\varphi} \ \vee \ \underbrace{\cdots}_{r}$$

W2:

$$\underbrace{\cdots \ \wedge \ (at\_m_{0..2} \ \vee \ (at\_m_3 \ \wedge \ \cdots))}_{\varphi} \ \rightarrow \ \underbrace{\neg at\_m_4}_{q}$$

W3:

$$\rho_\tau \wedge \underbrace{at\_\ell_3 \ \wedge \ (at\_m_{0..2} \ \vee \ (at\_m_3 \ \wedge \ s = 2))}_{\varphi} \ \rightarrow$$

$$\underbrace{at'\_\ell_3 \ \wedge \ (at'\_m_{0..2} \ \vee \ (at'\_m_3 \ \wedge \ s' = 2))}_{\varphi'} \ \vee \ \underbrace{at'\_\ell_4}_{r'}$$

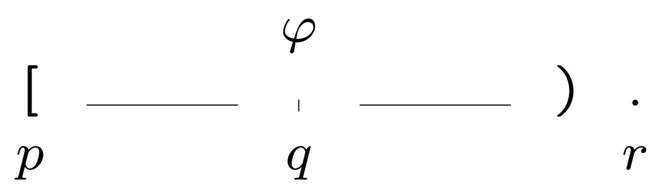
<u>Check:</u>

ℓ_3, m_2: OK

m_3: disabled (with the help of the invariant

$at\_\ell_{3..5} \leftrightarrow y_1$, we have $y_1 = \text{T}$).

Proving precedence properties:
Systematic derivation of intermediate assertions



Recall:

Rule WAIT (general waiting-for)

For assertions p, q, r, φ

W1. $p \rightarrow \varphi \vee r$

W2. $\varphi \rightarrow q$

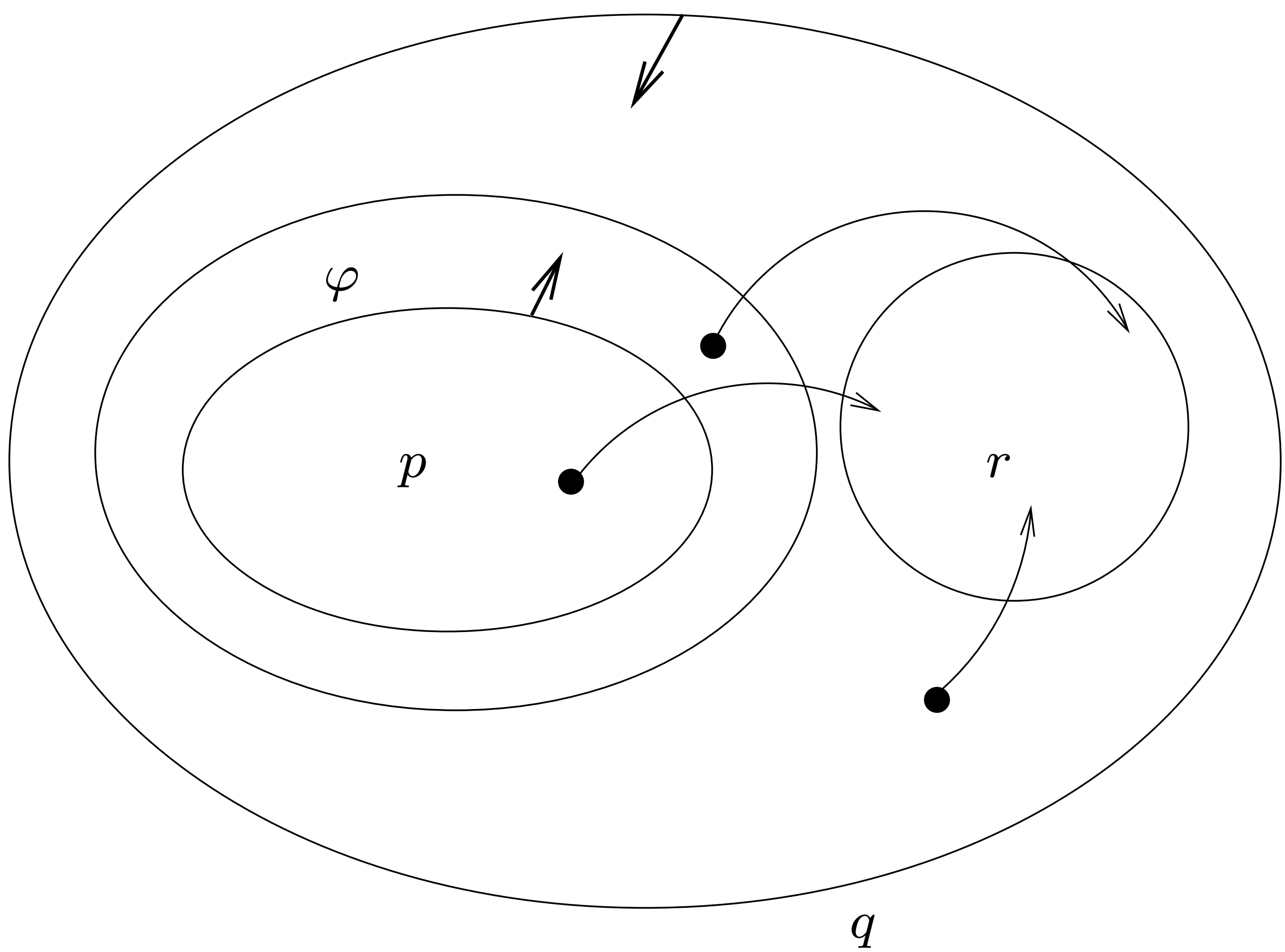
W3. $\{\varphi\}\mathcal{T}\{\varphi \vee r\}$

$$p \Rightarrow q \, \mathcal{W} \, r$$

How to find φ?

Escape Transition

Transition that leads to r-state.



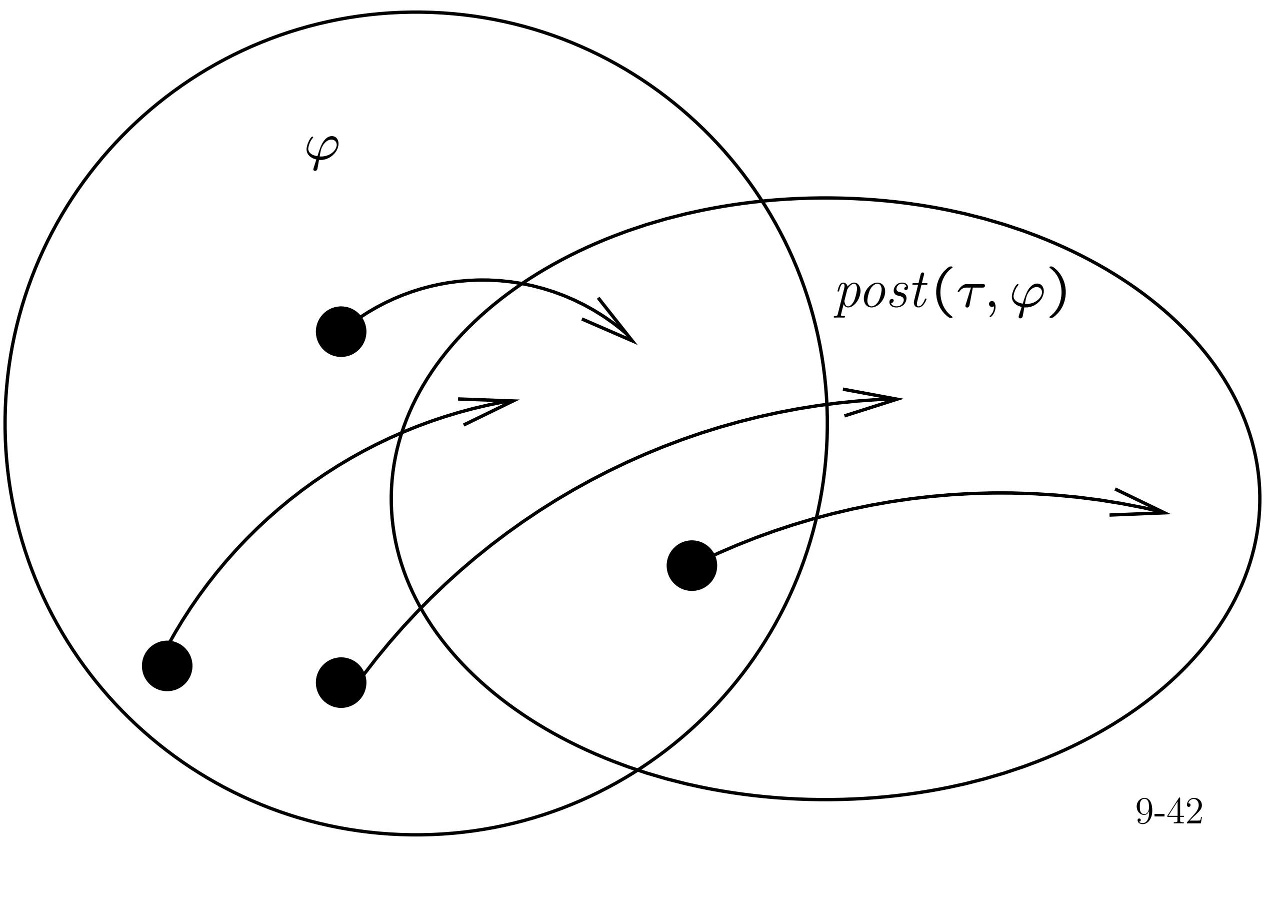
Forward propagation

Weaken $p \wedge \neg r$ until it becomes an assertion preserved under all nonescape transitions.

Based on postcondition:

$$\Psi(V) = post(\tau, \varphi): \;\; \exists V^0 . \varphi(V^0) \wedge \rho_\tau(V^0, V)$$

$post(\tau, \varphi)$ characterizes all states that are τ-successors of a φ-state.



Example: Postcondition

$V = \{x, y\}$,

$\rho_\tau : x' = x + y \wedge y' = x$,

$\Phi : x = y$

Then $post(\tau, \Phi)$ is given by

$$\exists x^0, y^0 : \underbrace{x^0 = y^0}_{\Phi(V^0)} \wedge \underbrace{x = x^0 + y^0 \wedge y = x^0}_{\rho_\tau(V^0, V)},$$

which can be simplified to

$\Psi : x = y + y$.

Forward Propagation: Algorithm

Φ_t - characterizes all states that can be reached from a $(p \wedge \neg r)$-state without taking an escape transition.

1. $\Phi_0 \; = \; p \wedge \neg r$
2. Repeat

   $\Phi_{k+1} = \Phi_k \vee post(\tau, \Phi_k)$

   for any non-escape transition τ

   Until

   $post(\tau, \Phi_t) \rightarrow \Phi_t$ [may use invariants]

   for all non-escape transitions τ

If this terminates (it may not), Φ_t is a good assertion to be used in rule WAIT.
Satisifies W1, W3, but check W2.

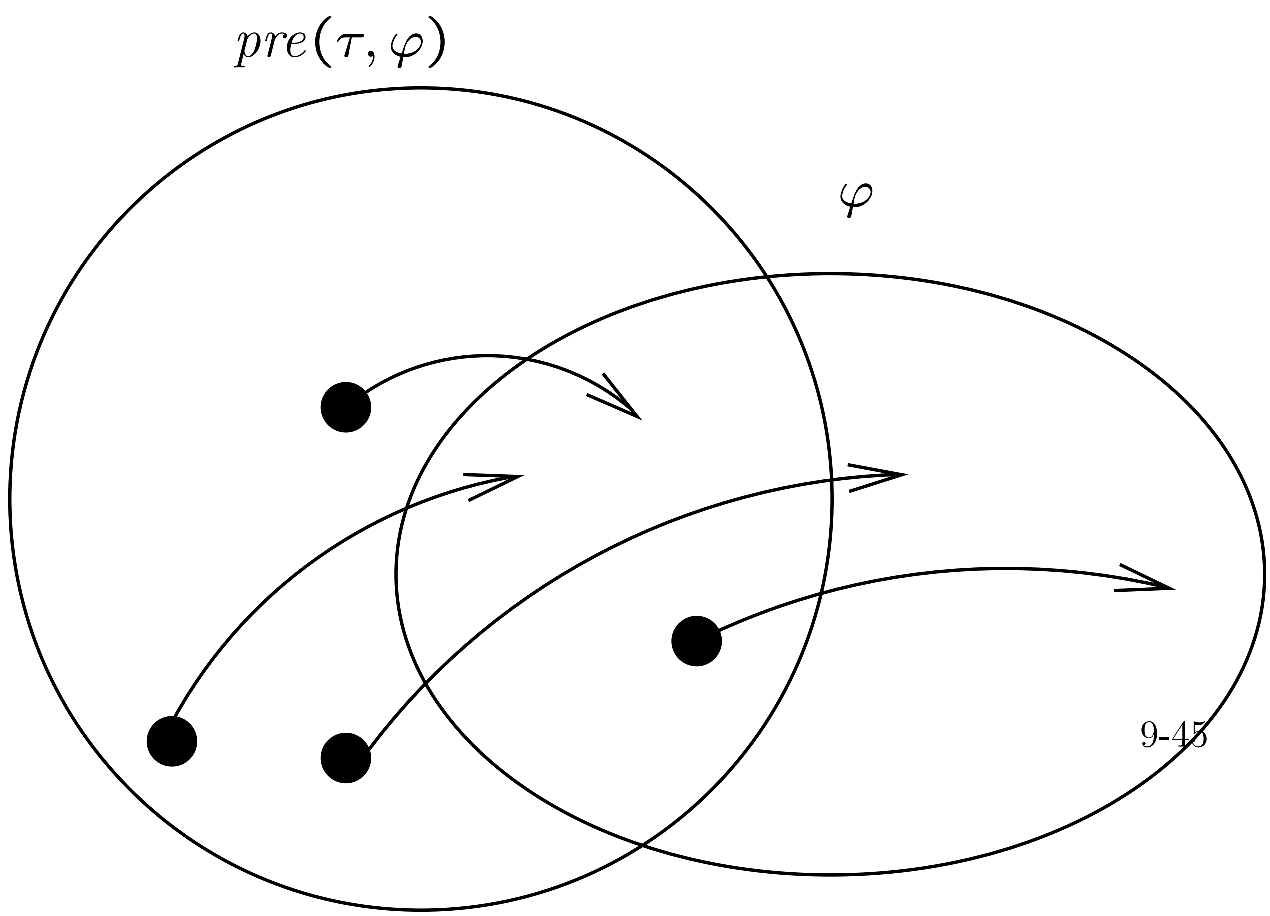
Backward propagation

Strengthen q until it becomes an assertion preserved under all nonescape transitions.

Based on precondition:

$$pre(\tau, \varphi): \ \ \forall V' \,.\, \rho_\tau(V, V') \rightarrow \varphi(V')$$

$pre(\tau, \varphi)$ characterizes all states all of whose τ-successors satisfy φ.



Example: Precondition

For Peterson's Algorithm, consider

$$\Gamma_0 : \underbrace{\neg at\_m_4}$$

and calculate $pre(m_3, \Gamma_0)$:

$$\forall V' : \underbrace{at\_m_3 \land (\neg y_1 \lor s \neq 2) \land at\_m_4{}' \land \cdots}_{\rho_{m_3}(V,V')} \rightarrow \underbrace{\neg at\_m_4{}'}_{\Gamma_0(V')}.$$

P-equivalent to

$$at\_m_3 \rightarrow (y_1 \land s = 2).$$

Backward Propagation: Algorithm

Γ_f - characterizes all states that can reach a q-state without taking an escape transition

1. $\Gamma_0 \; = \; q$
2. Repeat

   $\Gamma_{k+1} = \Gamma_k \wedge pre(\tau, \Gamma_k)$

   for any non-escape transition τ

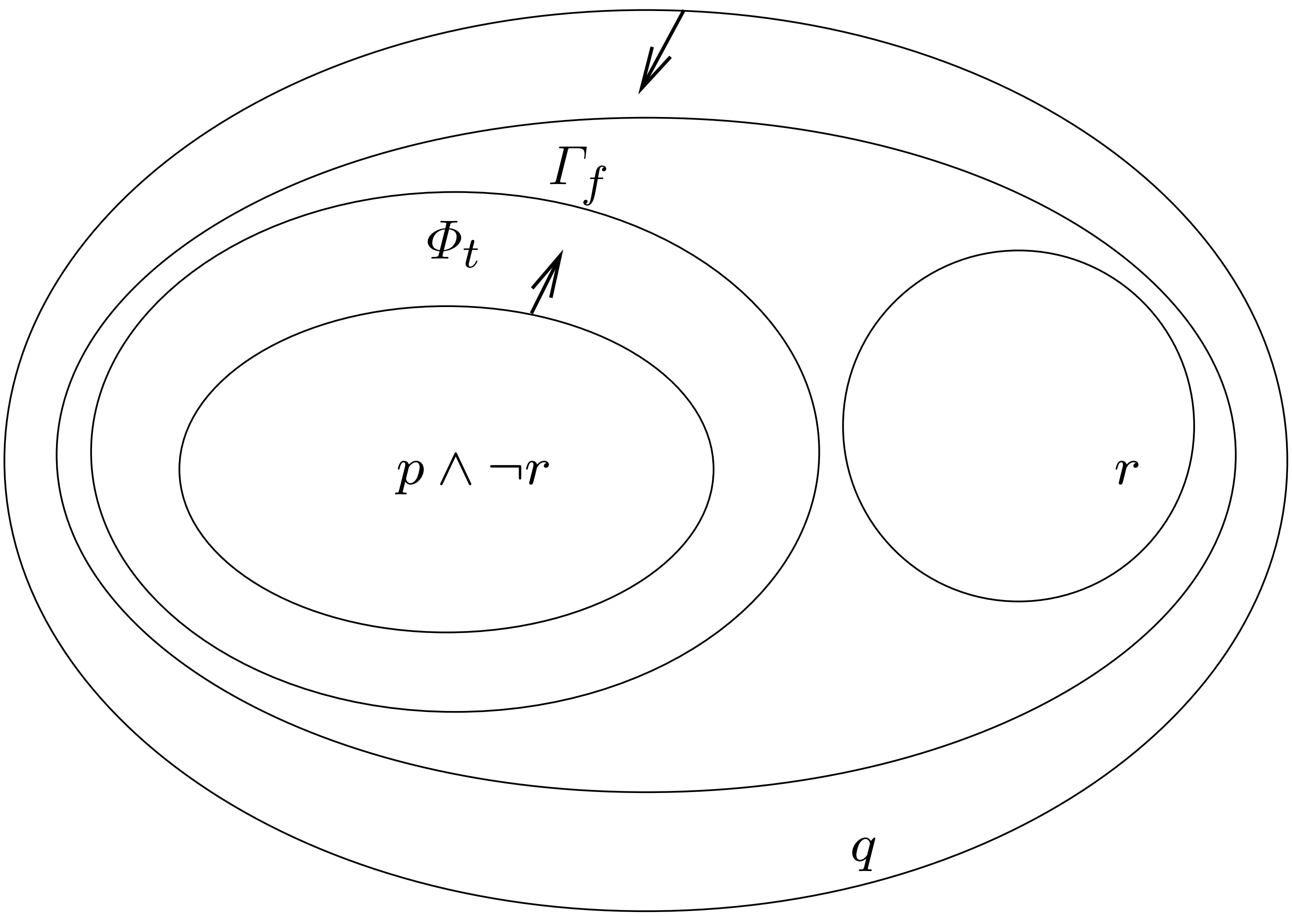
   Until

   $\Gamma_f \rightarrow pre(\tau, \Gamma_f)$ [may use invariants]

   for all non-escape transitions τ

If this terminates (it may not), Γ_f is a good assertion to be used in rule WAIT.
Satisfies W2, W3, but check W1.

Backward vs. Forward



If $p \Rightarrow q \; \mathcal{W} \; r$ is P-valid

$$\Phi_t \;\rightarrow\; \Gamma_f$$

is P-state valid.

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** $s = 1$

$$
P_1 :: \quad \ell_0 : \ \textbf{loop forever do} \begin{bmatrix} \ell_1 : & \textbf{noncritical} \\ \ell_2 : & (y_1,\ s) := (\text{T},\ 1) \\ \ell_3 : & \textbf{await}\ (\neg y_2) \vee (s \neq 1) \\ \ell_4 : & \textbf{critical} \\ \ell_5 : & y_1 := \text{F} \end{bmatrix}
$$

$||$

$$
P_2 :: \quad m_0 : \ \textbf{loop forever do} \begin{bmatrix} m_1 : & \textbf{noncritical} \\ m_2 : & (y_2,\ s) := (\text{T},\ 2) \\ m_3 : & \textbf{await}\ (\neg y_1) \vee (s \neq 2) \\ m_4 : & \textbf{critical} \\ m_5 : & y_2 := \text{F} \end{bmatrix}
$$

Example: Forward Propagation

$$\underbrace{at\_\ell_3 \wedge at\_m_{0..2}}_{p} \Rightarrow \underbrace{\neg at\_m_4}_{q} \;\mathcal{W}\; \underbrace{at\_\ell_4}_{r}$$

Start with

$$\Phi_0 : \; \underbrace{at\_\ell_3 \wedge at\_m_{0..2}}_{p}.$$

and calculate $post(m_2, \Phi_0)$:

$$\exists \underbrace{(\pi^0, y_1^0, y_2^0, s^0)}_{V^0} : \; \underbrace{(at\_\ell_3)^0 \wedge (at\_m_{0..2})^0}_{\Phi_0(V^0)} \wedge$$
$$\underbrace{(at\_m_2)^0 \wedge at\_m_3 \wedge ((at\_\ell_3)^0 \leftrightarrow at\_\ell_3) \wedge s = 2 \wedge \cdots}_{\rho_{m_2}(V^0, V)}$$

P-equivalent to

$$\Psi_1 : at\_\ell_3 \wedge at\_m_3 \wedge s = 2,$$

using the invariant $\varphi_1 : \; y_1 \leftrightarrow at\_\ell_{3..5}$.

Thus,

$$\Phi_1 : \; \underbrace{at\_\ell_3 \wedge at\_m_{0..2}}_{\Phi_0} \vee \underbrace{at\_\ell_3 \wedge at\_m_3 \wedge s = 2}_{\Psi_1},$$

Example: Forward Propagation (cont.)

i.e.,

$$\boxed{at\_\ell_3 \;\wedge\; (at\_m_{0..2} \;\vee\; (at\_m_3 \wedge s = 2))}$$

Φ_1 is preserved under all transitions except the escape transition ℓ_3, so the process converges.

Example: Backward Propagation

Start with

$$\Gamma_0 : \ \underbrace{\neg at\_m_4}_{q}.$$

We calculated $pre(m_3, \Gamma_0)$ above, which is P-equivalent to

$$\Delta_1 : \ at\_m_3 \rightarrow (y_1 \wedge s = 2).$$

Thus,

$$\Gamma_1 : \ \underbrace{\neg at\_m_4}_{\Gamma_0} \ \wedge \ \underbrace{at\_m_3 \rightarrow (y_1 \wedge s = 2)}_{\Delta_1}.$$

Consider transition τ_{m_2}, and calculate $pre(m_2, \Gamma_1)$:

$$\forall V' : \ \underbrace{at\_m_2 \wedge at\_m_3{}' \wedge y_1' = y_1 \wedge s' = 2 \wedge \cdots}_{\rho_{m_2}}$$
$$\rightarrow \underbrace{\neg at\_m_4{}' \ \wedge \ (at\_m_3{}' \rightarrow (y_1' \wedge s' = 2))}_{\Gamma_1'}.$$

P-equivalent to

$$\Delta_2 : \ at\_m_2 \rightarrow y_1.$$

Example: Backward Propagation (Cont'd)

Thus,

$\Gamma_2: \neg at\_m_4 \wedge (at\_m_3 \rightarrow s = 2) \wedge (at\_m_{2,3} \rightarrow y_1)$.

Considering transitions τ_{m_1}, τ_{m_0}, and τ_{m_5} leads to the following sequence:

$$\Gamma_3: \neg at\_m_4 \wedge (at\_m_3 \rightarrow s = 2) \wedge (at\_m_{1..3} \rightarrow y_1)$$

$$\Gamma_4: \neg at\_m_4 \wedge (at\_m_3 \rightarrow s = 2) \wedge (at\_m_{0..3} \rightarrow y_1)$$

$$\Gamma_5: \neg at\_m_4 \wedge (at\_m_3 \rightarrow s = 2) \wedge (at\_m_{0..3,5} \rightarrow y_1)$$

By the control invariant $at\_m_{0..5}$, Γ_5 can be simplified to

$$\Gamma_5: \neg at\_m_4 \ \wedge \ (at\_m_3 \rightarrow s = 2) \ \wedge \ y_1.$$

Example: Backward Propagation (Cont'd)

Calculating $pre(\ell_5, \Gamma_5)$,

$$\forall V' : \underbrace{at\_\ell_5 \wedge y_1' = \text{F} \wedge \cdots}_{\rho_{\ell_5}} \rightarrow \underbrace{\neg at\_m_4' \wedge (at\_m_3' \rightarrow s' = 2) \wedge y_1'}_{\Gamma_5'},$$

gives

$$\Delta_6 : \ at\_\ell_5 \rightarrow \text{F}.$$

Propagating $\Gamma_5 \wedge \Delta_6$ via τ_{ℓ_4} gives

$$\Delta_7 : \ at\_\ell_4 \rightarrow \text{F}.$$

Hence,

$$\boxed{\Gamma_7 : \ \neg at\_m_4 \wedge (at\_m_3 \rightarrow s = 2) \wedge at\_\ell_3,}$$

using the invariant $\varphi_1 : \ y_1 \leftrightarrow at\_\ell_{3..5}$ for simplifications. The assertion is preserved under all but the escape transitions, ending the process.