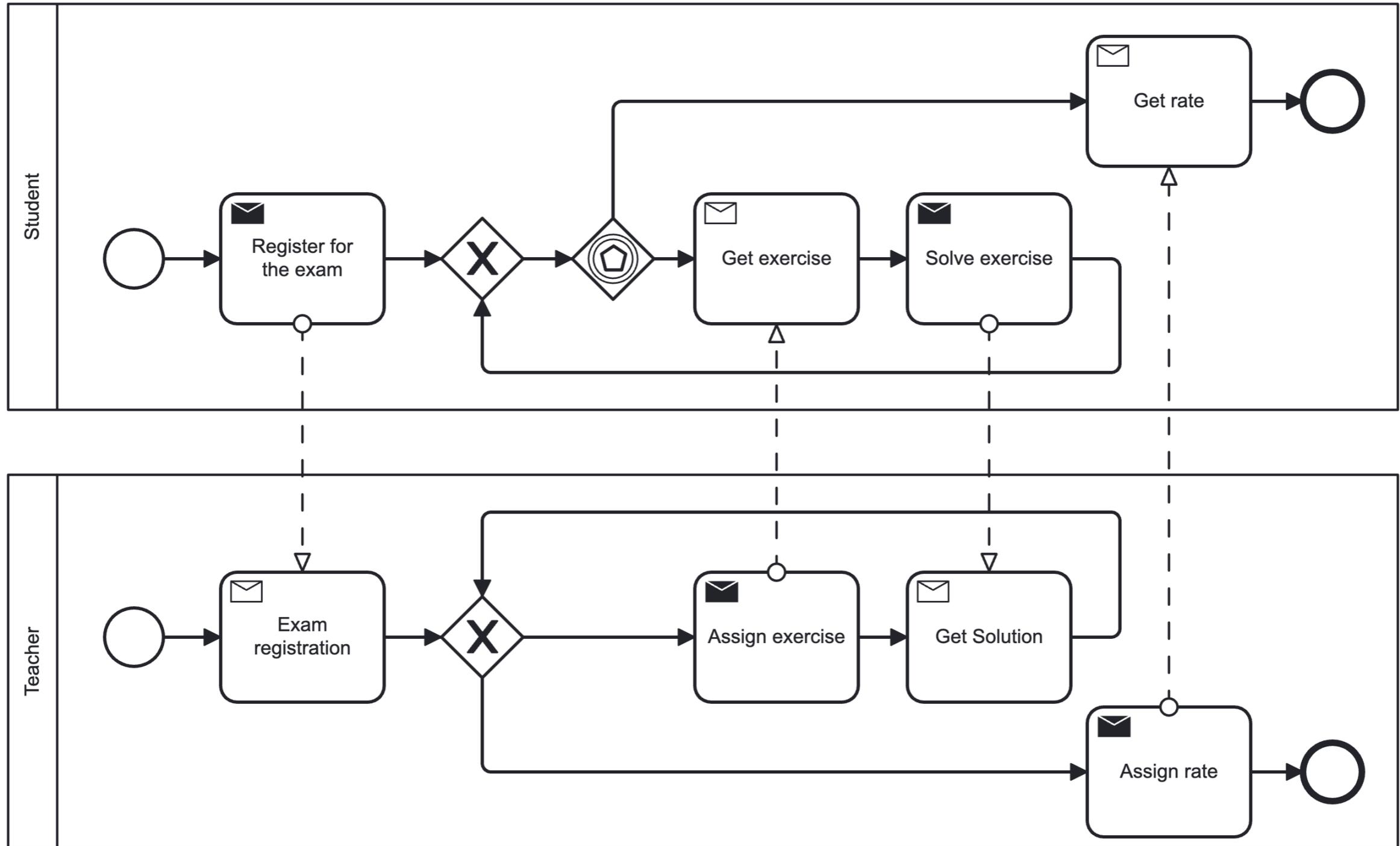




Pending exercises...

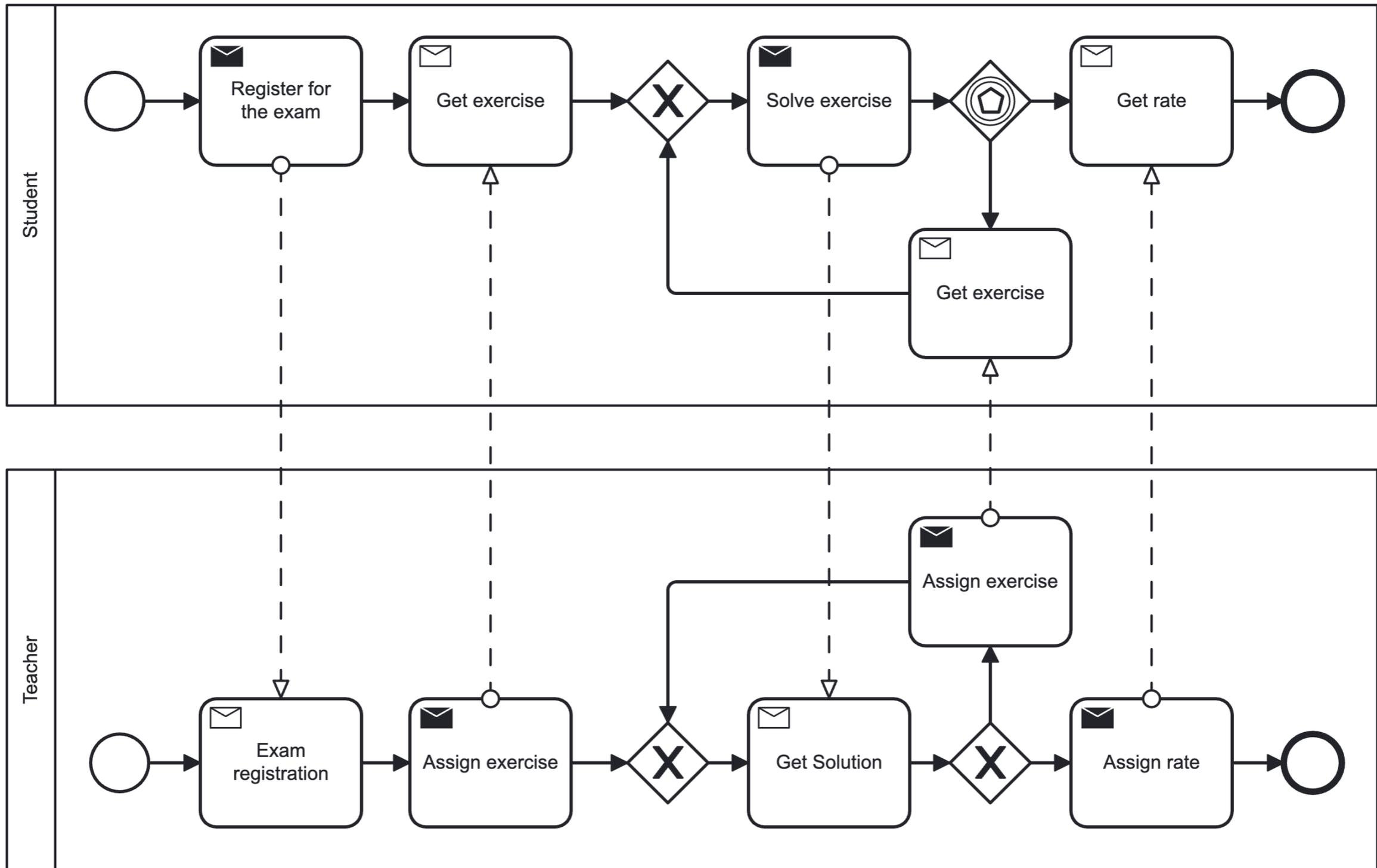
# Exercise

Modify the collaboration diagram to enforce the assignment of **at least one exercise**



# Solution?

Modify the collaboration diagram to enforce the assignment of **at least one exercise**



# Exercises

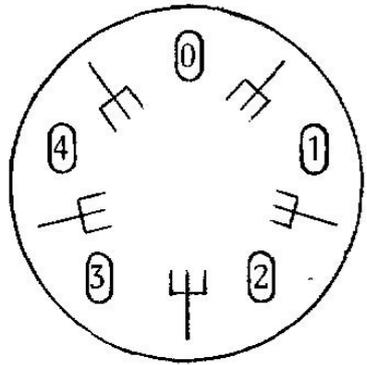
Search for EPC/BPMN diagram drawing software products.  
For each product found, annotate the following features:

- 1) which OS is supported? (Windows, Apple, Linux,...)
- 2) is it free? if not, describe its pricing.
- 3) is .epml/.bpmn format supported?
- 4) if you install the product, rate your user experience / usability (on the scale 1-5 stars)

**Send your findings to: [bruni@di.unipi.it](mailto:bruni@di.unipi.it)**

# Exercise: drawing tools



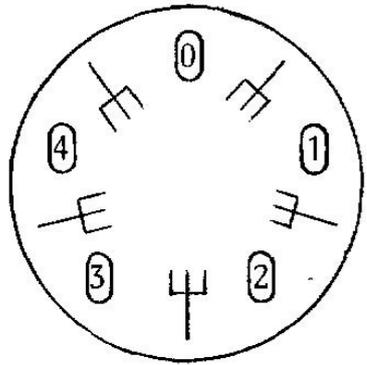


# Exercise:

# Dining philosophers

The problem is originally due to E.W. Dijkstra (and soon elaborated by T. Hoare) as an examination question on a synchronization problem where five computers competed for access to five shared tape drive peripherals.

It can be used to illustrate several important concepts in concurrency (mutual exclusion, deadlock, starvation)



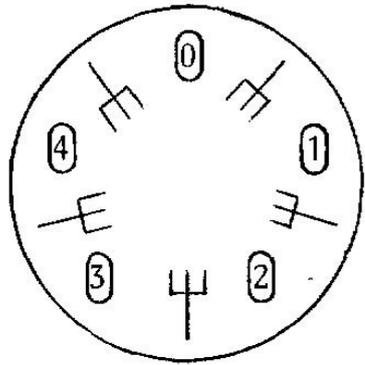
# Exercise:

## Dining philosophers

The life of a philosopher consists of an alternation of **thinking** and **eating**

**Five** philosophers are living in a house where a table is laid for them, each philosopher having his own place at the table

Their only problem (besides those of philosophy) is that the dish served is a very difficult kind of spaghetti, that has to be eaten with two forks. There are **two forks next to each plate**, so that presents no difficulty: as a consequence, however, no two neighbours may be eating simultaneously.



# Exercise:

## Dining philosophers

Design a net for representing the dining philosophers problem, then use WoPeD to compute the reachability graph

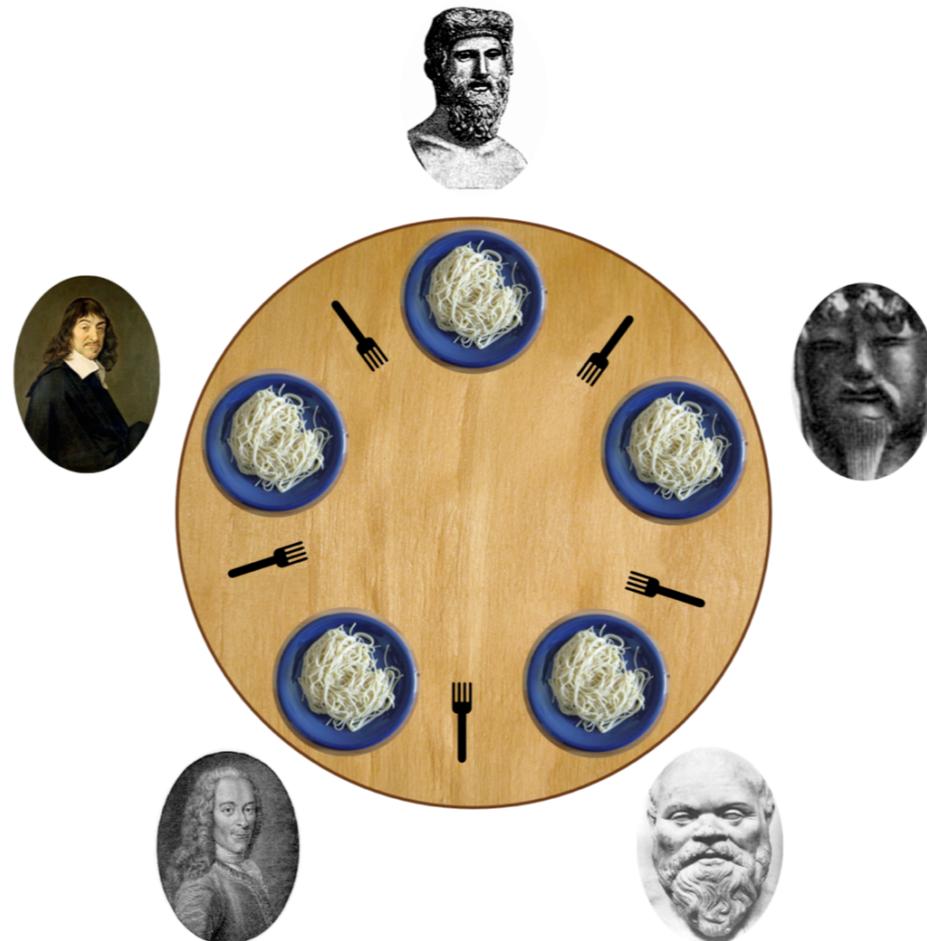
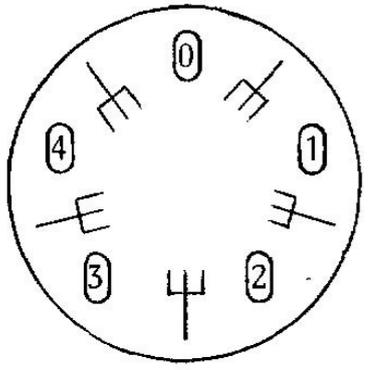
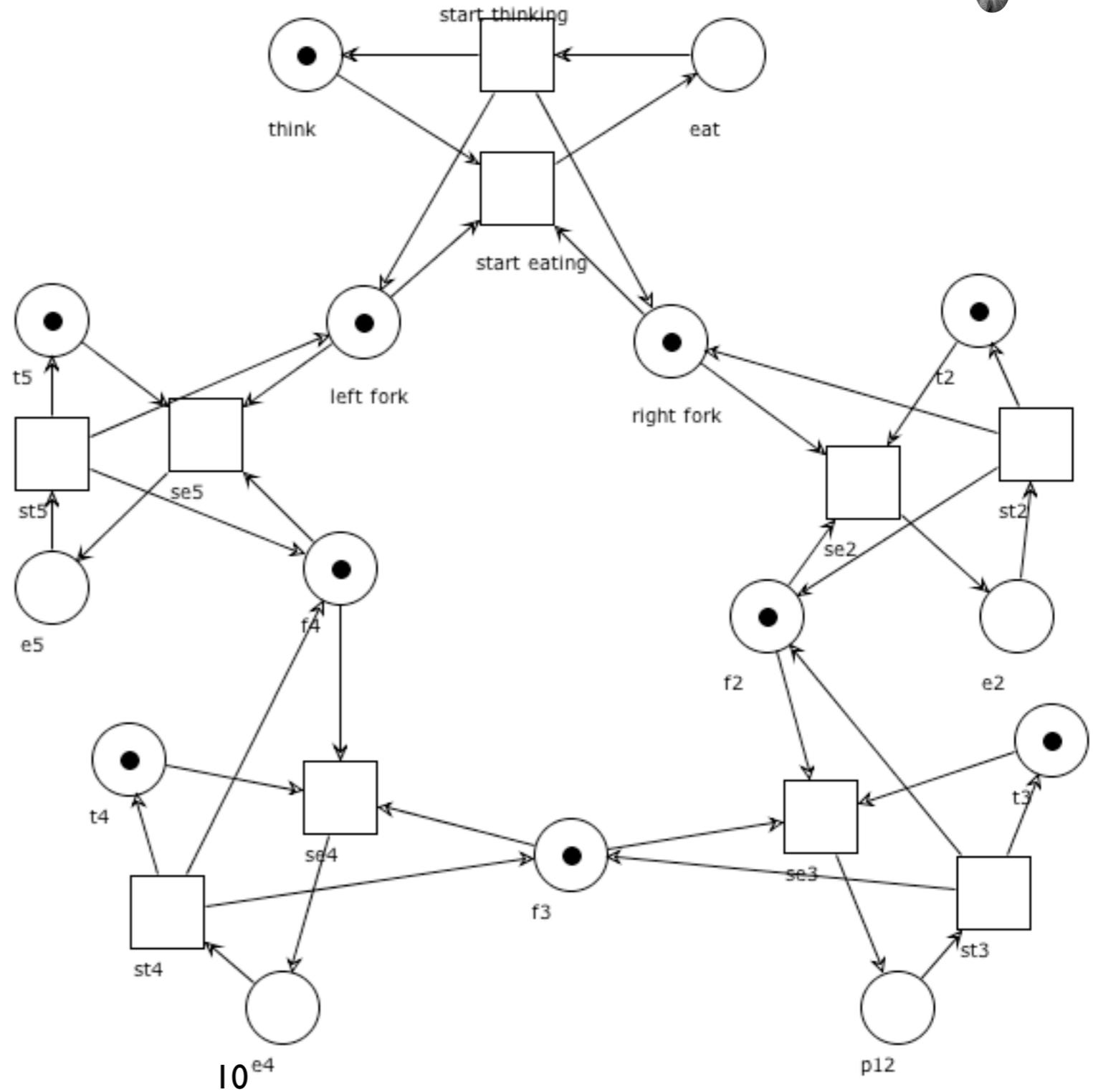
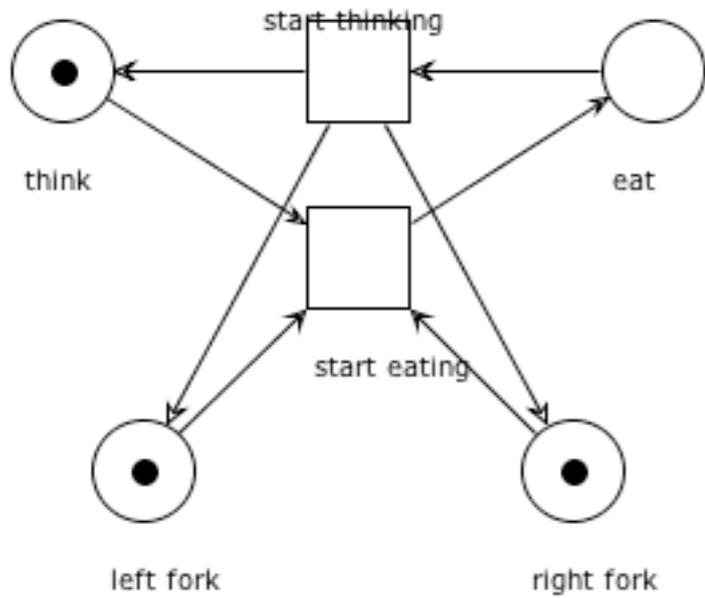
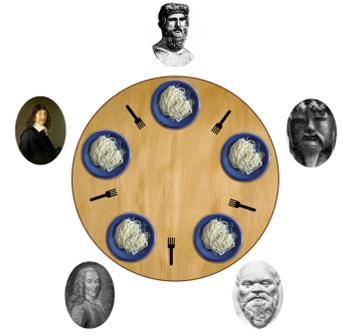


image taken from wikipedia  
philosophers clockwise from top:  
Plato, Konfuzius, Socrates,  
Voltaire and Descartes

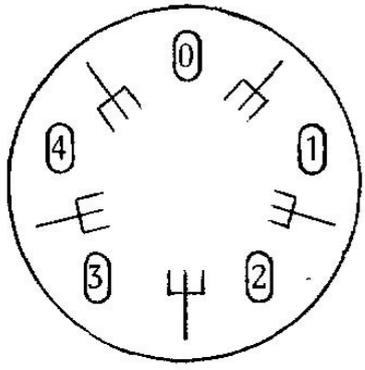


# Dining philosophers

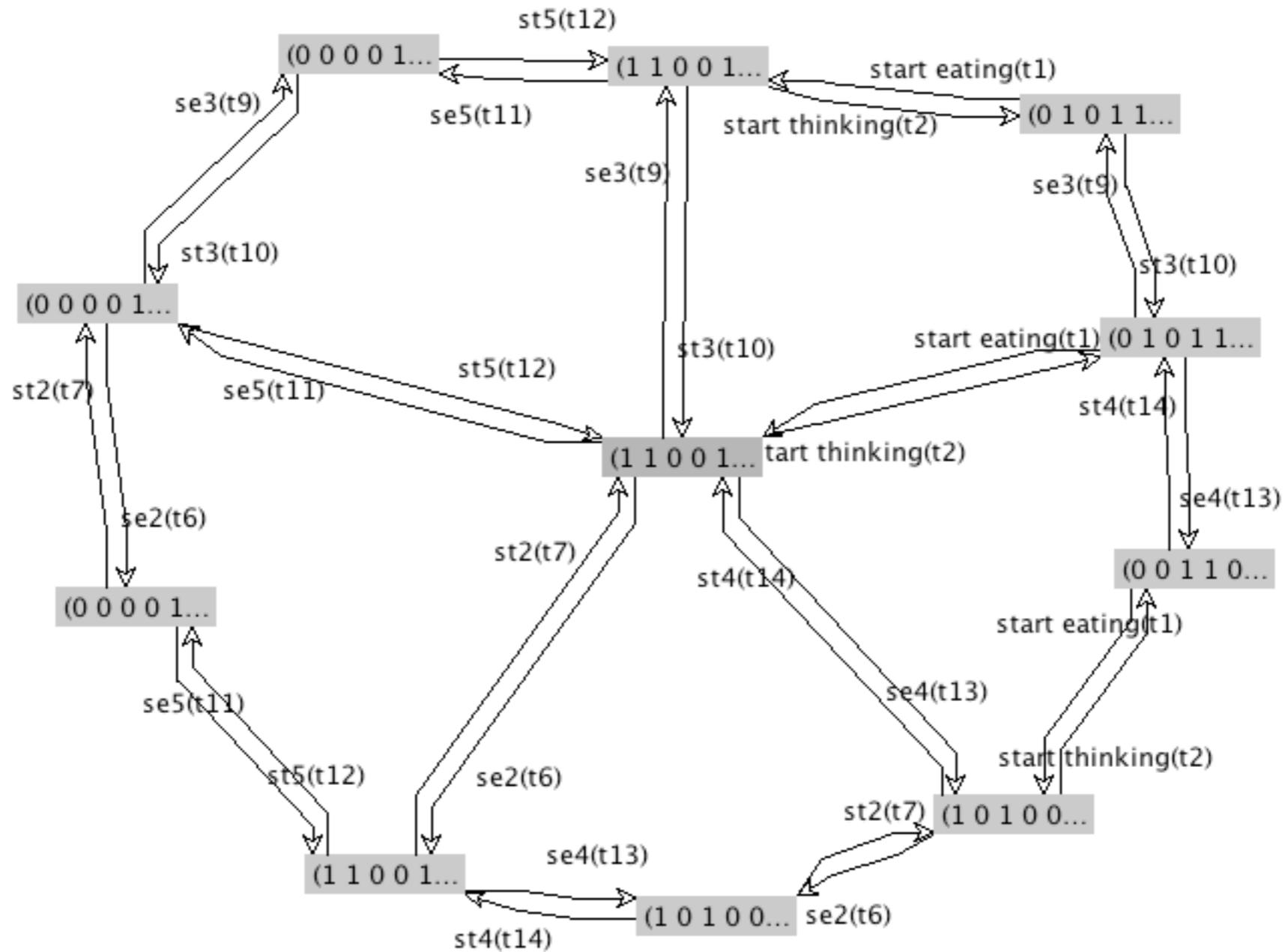
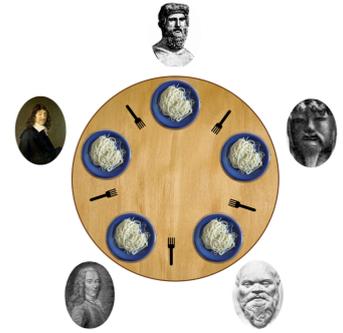


10<sup>e4</sup>

p12



# Dining philosophers



# Object


We give a matrix-based representation of Petri nets and their computations

Free Choice Nets (book, optional reading)

<https://www7.in.tum.de/~esparza/bookfc.html>

# Digression

Are you familiar with the following concepts?

Vector notation

$$[2 \quad 0 \quad 1] \cdot \begin{bmatrix} 0 \\ 3 \\ 2 \end{bmatrix} =$$

# Digression

Are you familiar with the following concepts?

Vector notation

$$[2 \quad 0 \quad 1] \cdot \begin{bmatrix} 0 & 1 \\ 3 & 4 \\ 2 & 2 \end{bmatrix} =$$

# Digression

Are you familiar with the following concepts?

Linear algebra

$$\begin{cases} 3x_1 + 2x_2 - 2x_3 = 0 \\ 6x_1 - 4x_2 = 0 \\ 9x_1 - 3x_3 = 0 \end{cases}$$

# Digression

Are you familiar with the following concepts?

Linear algebra

$$\begin{bmatrix} 3 & 2 & -2 \\ 6 & -4 & 0 \\ 9 & 0 & -3 \end{bmatrix} \cdot \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$

$$\begin{cases} 3x_1 + 2x_2 - 2x_3 = 0 \\ 6x_1 - 4x_2 = 0 \\ 9x_1 - 3x_3 = 0 \end{cases}$$

# Digression

Are you familiar with the following concepts?

Linear algebra

$$[x_1 \quad x_2 \quad x_3] \cdot \begin{bmatrix} 3 & 6 & 9 \\ 2 & -4 & 0 \\ -2 & 0 & -3 \end{bmatrix} = [0 \quad 0 \quad 0]$$

$$\begin{cases} 3x_1 + 2x_2 - 2x_3 = 0 \\ 6x_1 - 4x_2 = 0 \\ 9x_1 - 3x_3 = 0 \end{cases}$$

# Vectors: notation

Let  $E = \{e_1, e_2, \dots, e_n\}$  be a finite set of elements.

Any mapping  $v : E \rightarrow \mathbb{Q}$  (or to  $\mathbb{N}, \mathbb{Z}, \dots$ ) can be regarded as a vector:

$$\mathbf{v} = [v(e_1), v(e_2), \dots, v(e_n)]$$

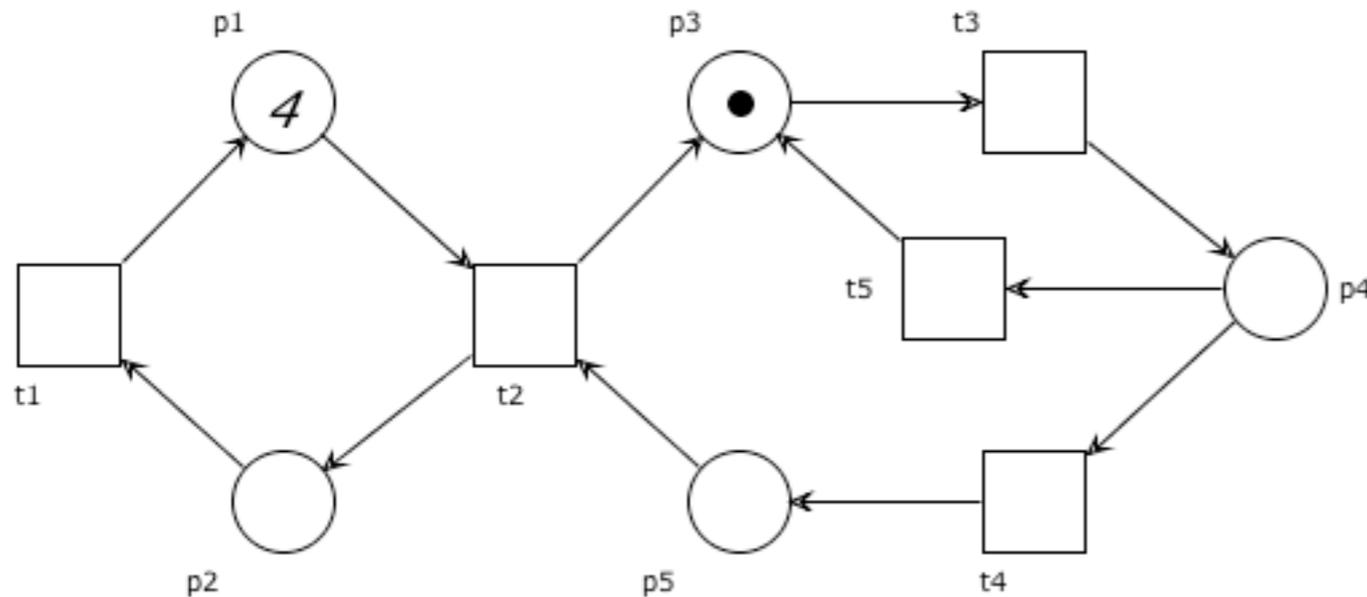
We **do not** use different symbols for row and column vectors:

$$\mathbf{v} = \begin{bmatrix} v(e_1) \\ v(e_2) \\ \vdots \\ v(e_n) \end{bmatrix}$$

# Marking as a vector

Any marking  $M : P \rightarrow \mathbb{N}$  corresponds to a vector:

$$M = [ M(p_1) \quad M(p_2) \quad \dots \quad M(p_n) ]$$



$$M_0 = [ 4 \quad 0 \quad 1 \quad 0 \quad 0 ]$$

# Vectors: notation

Let  $\mathbf{v}, \mathbf{w}$  be two vectors over  $E$

We write  $\mathbf{v} \leq \mathbf{w}$  if  $v(e) \leq w(e)$  for any  $e \in E$

We write  $\mathbf{v} < \mathbf{w}$  if  $v \leq w$  and  $v(e) < w(e)$  for some  $e \in E$

We write  $\mathbf{v} \prec \mathbf{w}$  if  $v(e) < w(e)$  for any  $e \in E$

We let  $\mathbf{0}$  denote any vector of any length whose entries are all 0

# Question time

$$3a + 2b \stackrel{?}{\subseteq} 2a + 3b + c$$

$$[3 \quad 2 \quad 0] \stackrel{?}{\leq} [2 \quad 3 \quad 1]$$

$$3a + 2b \stackrel{?}{\supseteq} 2a + 3b + c$$

$$[3 \quad 2 \quad 0] \stackrel{?}{\geq} [2 \quad 3 \quad 1]$$

$$a + 2b \stackrel{?}{\subset} 2a + 3b$$

$$[1 \quad 2 \quad 0] \stackrel{?}{<} [2 \quad 3 \quad 0]$$

$$[0 \quad 0 \quad 0] \stackrel{?}{\wedge} [2 \quad 0 \quad 1]$$

$$[0 \quad 0 \quad 0] \stackrel{?}{\wedge} [2 \quad 3 \quad 1]$$

# Question time

$$3a + 2b \stackrel{?}{\subseteq} 2a + 3b + c \quad \text{No} \quad [3 \ 2 \ 0] \stackrel{?}{\leq} [2 \ 3 \ 1]$$

$$3a + 2b \stackrel{?}{\supseteq} 2a + 3b + c \quad \text{No} \quad [3 \ 2 \ 0] \stackrel{?}{\geq} [2 \ 3 \ 1]$$

$$a + 2b \stackrel{?}{\subset} 2a + 3b \quad \text{Yes} \quad [1 \ 2 \ 0] \stackrel{?}{<} [2 \ 3 \ 0]$$

$$\text{No} \quad [0 \ 0 \ 0] \stackrel{?}{\wedge} [2 \ 0 \ 1]$$

$$\text{Yes} \quad [0 \ 0 \ 0] \stackrel{?}{\wedge} [2 \ 3 \ 1]$$

# Computation as a vector transformation

Linear transformations of vectors (spaces) can be expressed by matrix multiplication

Can we express Petri net computations by matrix multiplication?

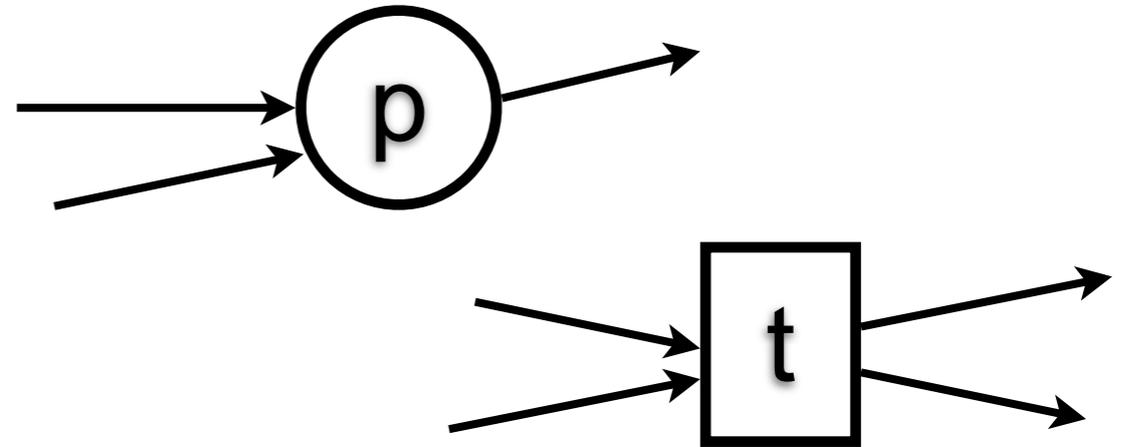
# Key point

The change of the numbers of tokens on a place  $p$  caused by the firing of the transition  $t$  does not depend on the current marking

It is entirely determined by the net  
(i.e., by the flow relation)

Let us have a look at the relative changes for every place and transition...

# Possible connections between $p$ and $t$

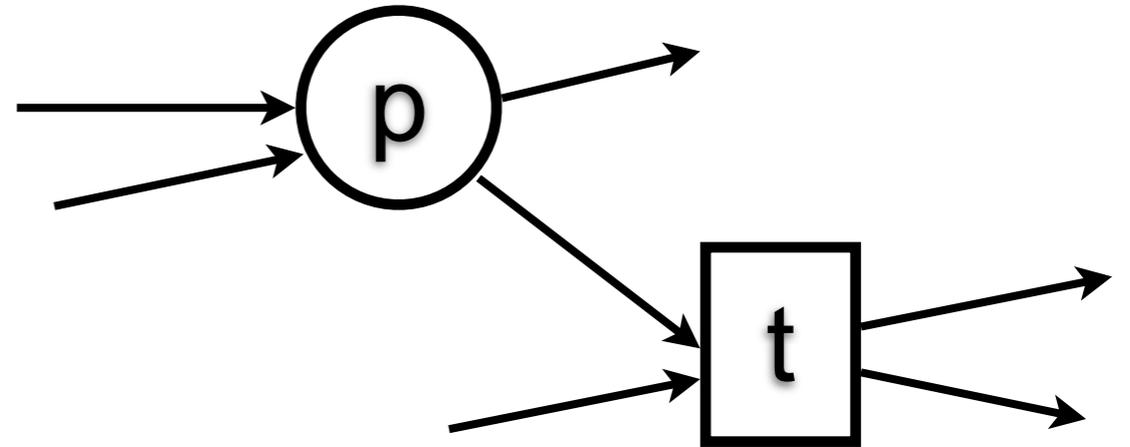


$(p, t) \notin F$  and  $(t, p) \notin F$

Place  $p$  and transition  $t$  are completely unrelated:

- $p$  has no influence on the enabling of  $t$
- firing  $t$  does not change the number of tokens in  $p$

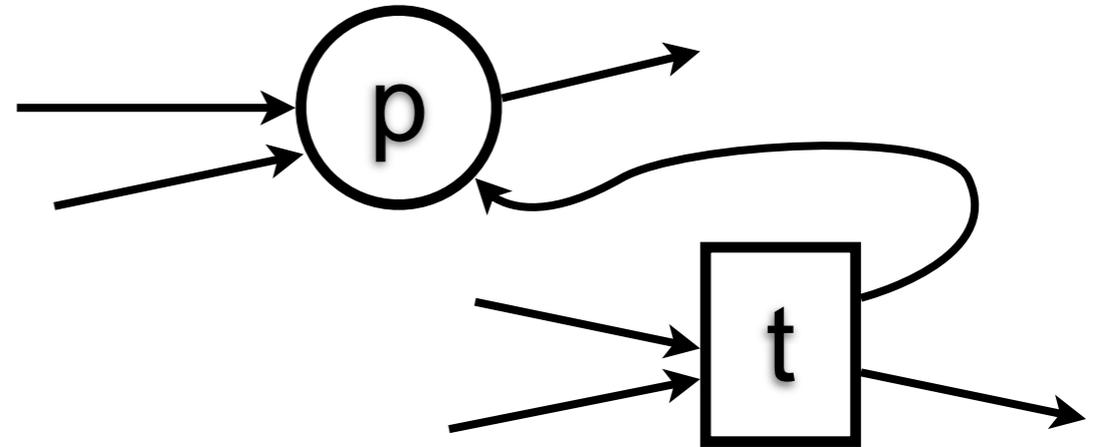
# Possible connections between $p$ and $t$



$(p, t) \in F$  and  $(t, p) \notin F$

- one token in  $p$  is needed to enable  $t$
- firing  $t$  reduces by one the number of tokens in  $p$

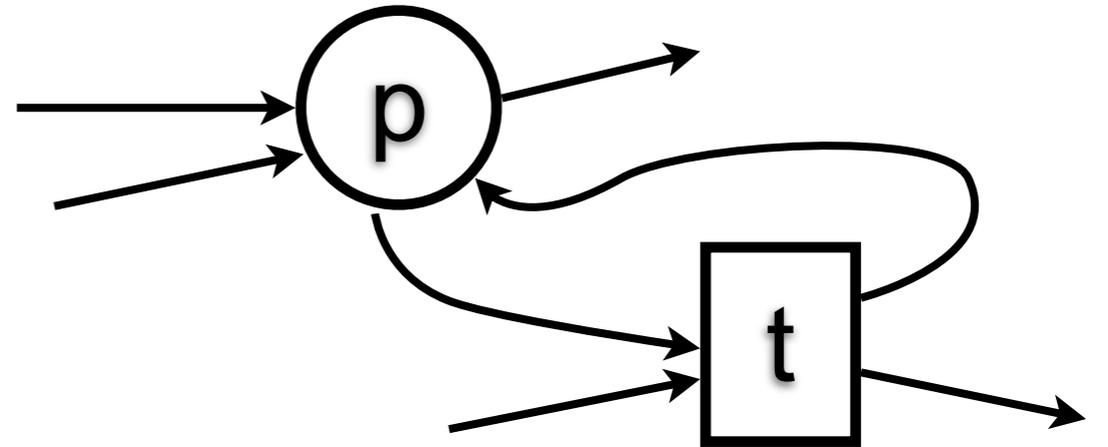
# Possible connections between $p$ and $t$



$(p, t) \notin F$  and  $(t, p) \in F$

- firing  $t$  increases by one the number of tokens in  $p$

# Possible connections between $p$ and $t$



$(p, t) \in F$  and  $(t, p) \in F$

- one token in  $p$  is needed to enable  $t$
- firing  $t$  does not change the number of tokens in  $p$

# Incidence matrix

Let  $N = (P, T, F)$  be a net.

Its **incidence matrix**  $\mathbf{N} : (P \times T) \rightarrow \{-1, 0, 1\}$  is defined as:

$$\mathbf{N}(p, t) = \begin{cases} -1 & \text{if } (p, t) \in F \wedge (t, p) \notin F \\ +1 & \text{if } (p, t) \notin F \wedge (t, p) \in F \\ 0 & \text{otherwise} \\ & ( (p, t) \notin F \wedge (t, p) \notin F \text{ or } (p, t) \in F \wedge (t, p) \in F ) \end{cases}$$

# Matrix view

m columns, one for each transition

n rows,  
one for  
each place

	$t_1$												
$p_1$													
$p_2$	-1												
$p_3$													
...													
	+1												
$p_n$													

# Matrix view

m columns, one for each transition

n rows,  
one for  
each place

	$t_1$	$t_2$											
$p_1$		+1											
$p_2$	-1												
$p_3$		+1											
...													
	+1												
$p_n$		-1											

# Matrix view

m columns, one for each transition

n rows,  
one for  
each place

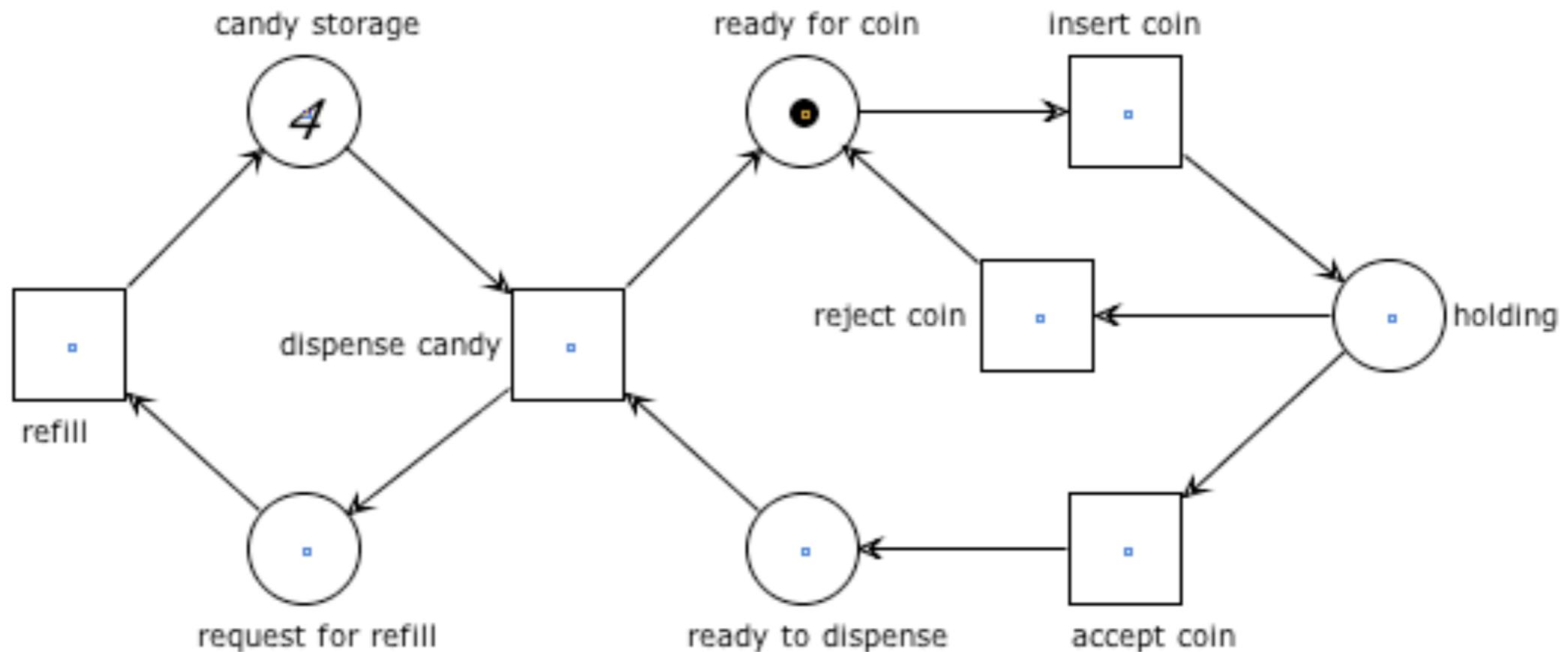
	$t_1$	$t_2$	$t_3$	...																
$p_1$		+1	-1																	
$p_2$	-1		+1																	
$p_3$		+1																		
			+1																	
...										...										
	+1																			
			-1																	
$p_n$		-1	+1																	



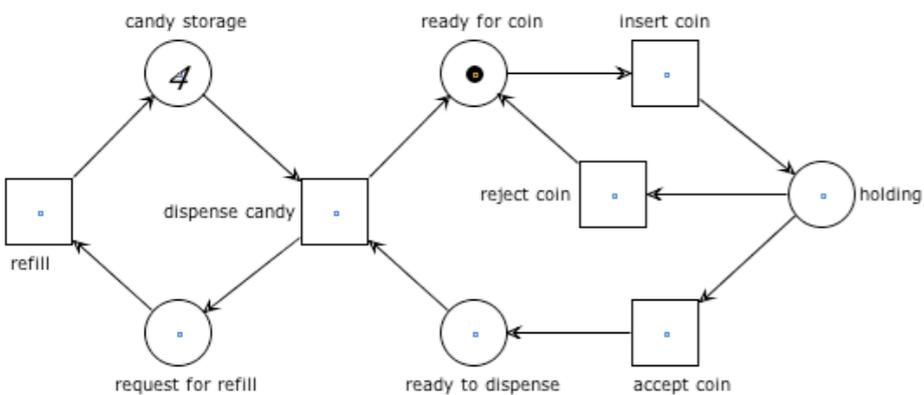




# Example: vending machine

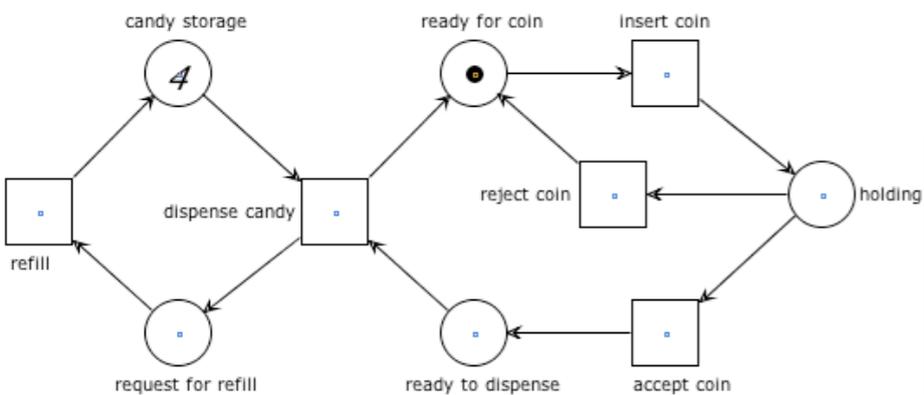


# Example: vending machine



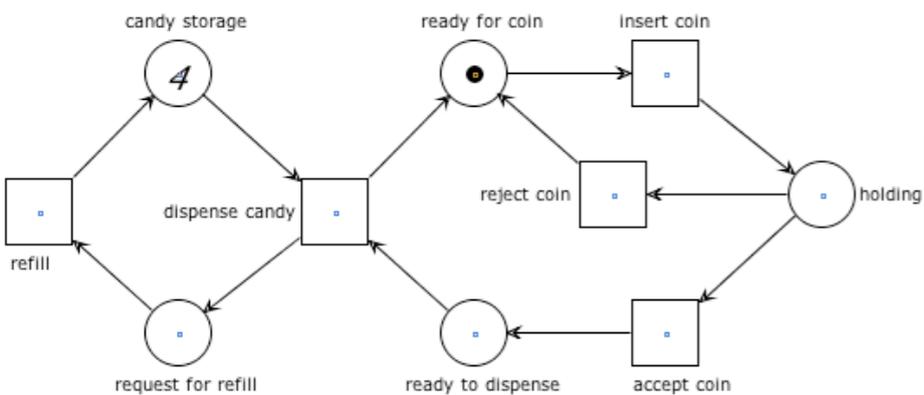
	refill $t_1$	dispense candy $t_2$	insert coin $t_3$	accept coin $t_4$	reject coin $t_5$
candy storage $p_1$					
request for refill $p_2$					
ready for coin $p_3$					
holding $p_4$					
ready to dispense $p_5$					

# Example: vending machine



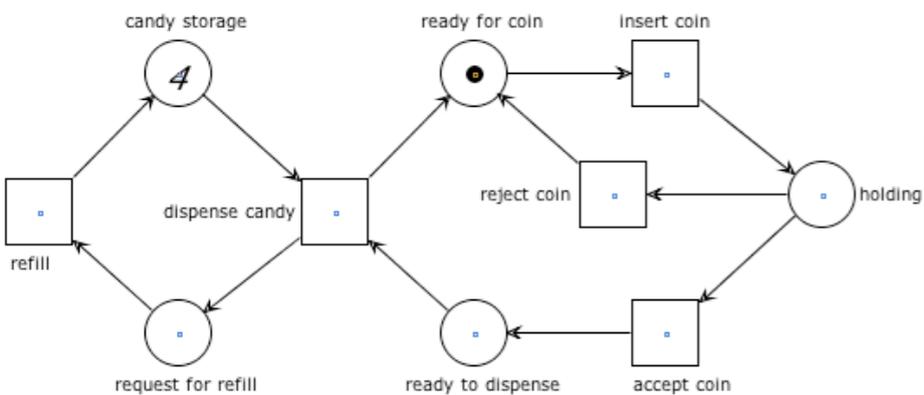
	refill $t_1$	dispense candy $t_2$	insert coin $t_3$	accept coin $t_4$	reject coin $t_5$
candy storage $p_1$	1				
request for refill $p_2$	-1				
ready for coin $p_3$					
holding $p_4$					
ready to dispense $p_5$					

# Example: vending machine



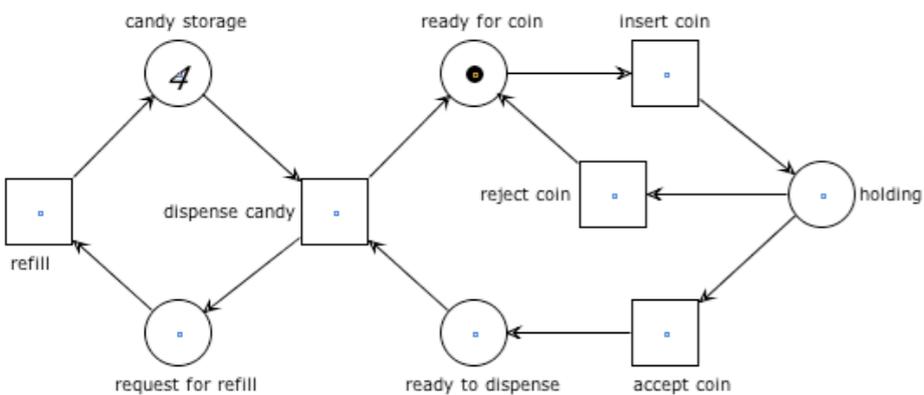
	refill $t_1$	dispense candy $t_2$	insert coin $t_3$	accept coin $t_4$	reject coin $t_5$
candy storage $p_1$	1	-1			
request for refill $p_2$	-1	1			
ready for coin $p_3$		1			
holding $p_4$					
ready to dispense $p_5$		-1			

# Example: vending machine



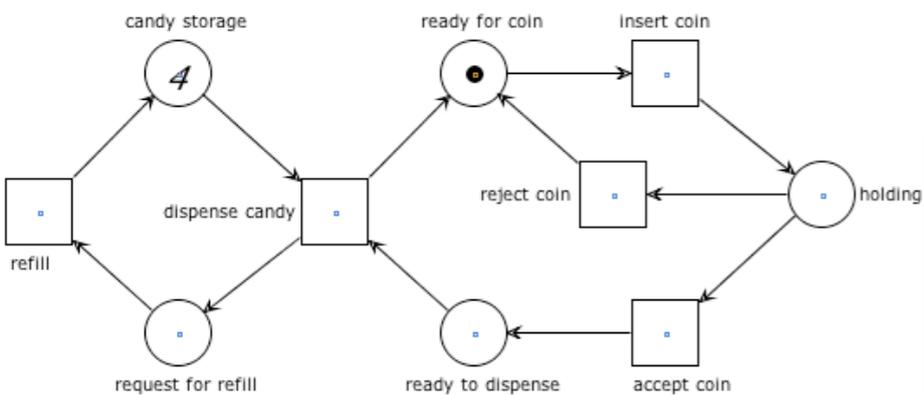
	refill $t_1$	dispense candy $t_2$	insert coin $t_3$	accept coin $t_4$	reject coin $t_5$
candy storage $p_1$	1	-1			
request for refill $p_2$	-1	1			
ready for coin $p_3$		1	-1		
holding $p_4$			1		
ready to dispense $p_5$		-1			

# Example: vending machine



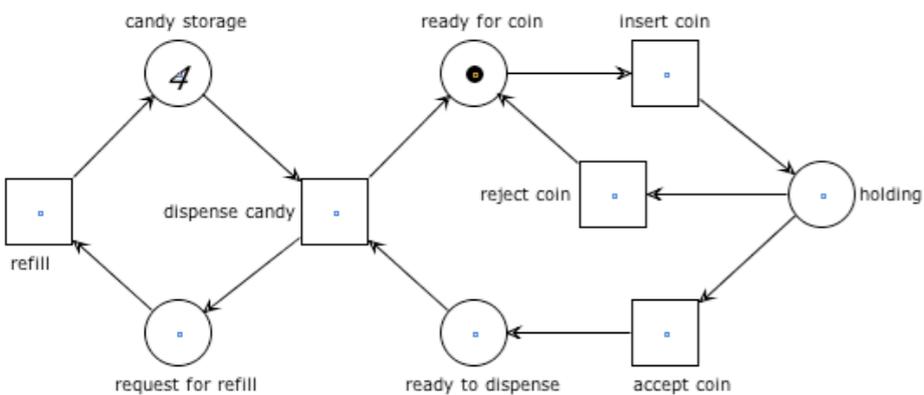
	refill $t_1$	dispense candy $t_2$	insert coin $t_3$	accept coin $t_4$	reject coin $t_5$
candy storage $p_1$	1	-1			
request for refill $p_2$	-1	1			
ready for coin $p_3$		1	-1		
holding $p_4$			1	-1	
ready to dispense $p_5$		-1		1	

# Example: vending machine



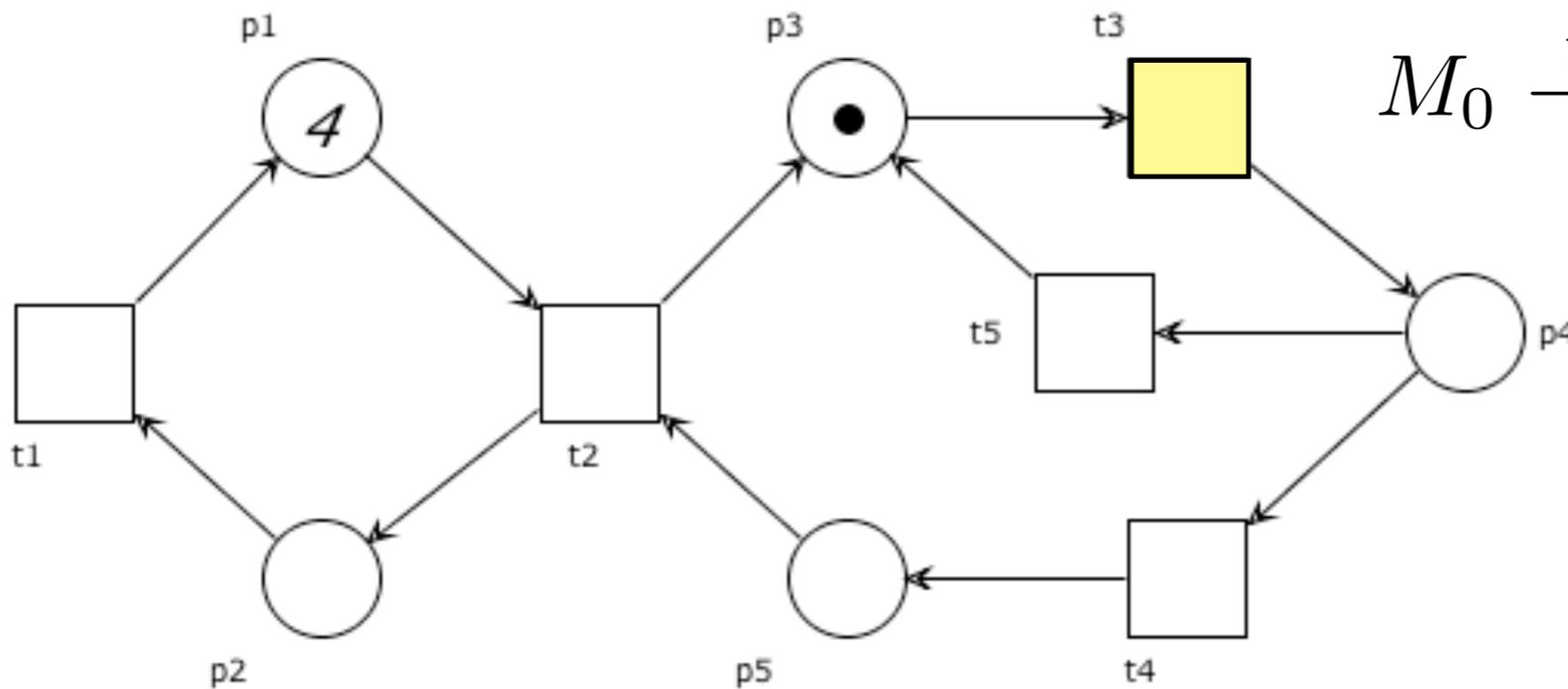
	refill $t_1$	dispense candy $t_2$	insert coin $t_3$	accept coin $t_4$	reject coin $t_5$
candy storage $p_1$	1	-1			
request for refill $p_2$	-1	1			
ready for coin $p_3$		1	-1		1
holding $p_4$			1	-1	-1
ready to dispense $p_5$		-1		1	

# Example: vending machine



	refill $t_1$	dispense candy $t_2$	insert coin $t_3$	accept coin $t_4$	reject coin $t_5$
candy storage $p_1$	1	-1	0	0	0
request for refill $p_2$	-1	1	0	0	0
ready for coin $p_3$	0	1	-1	0	1
holding $p_4$	0	0	1	-1	-1
ready to dispense $p_5$	0	-1	0	1	0

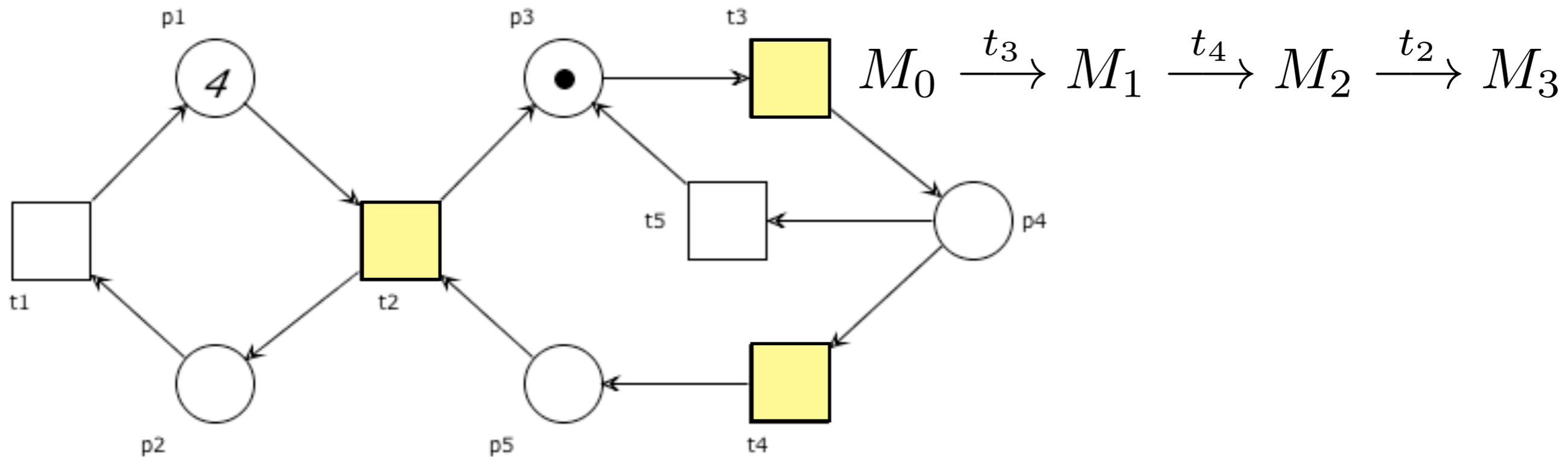
# Firing, in vector notation



$$M_0 \xrightarrow{t_3} M_1 = 4p_1 + p_4$$

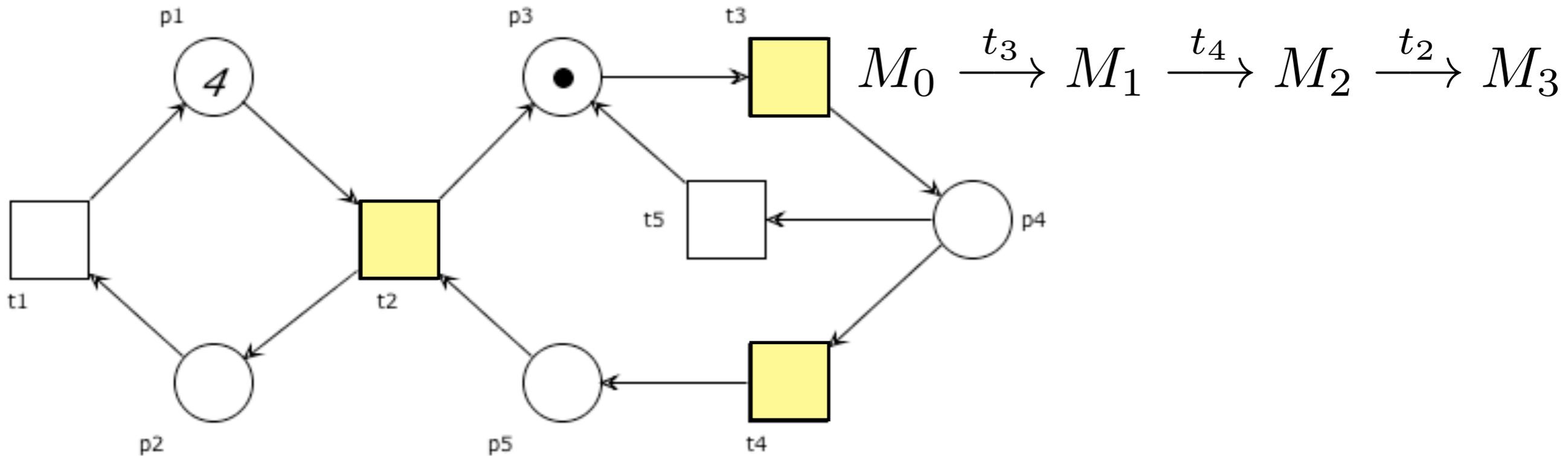
$$\begin{matrix} M_0 \\ \left[ \begin{array}{c} 4 \\ 0 \\ 1 \\ 0 \\ 0 \end{array} \right] \end{matrix}
 +
 \begin{matrix} t_3 \\ \left[ \begin{array}{c} 0 \\ 0 \\ -1 \\ 1 \\ 0 \end{array} \right] \end{matrix}
 =
 \begin{matrix} M_1 \\ \left[ \begin{array}{c} 4 \\ 0 \\ 0 \\ 1 \\ 0 \end{array} \right] \end{matrix}$$

# Firing, in vector notation



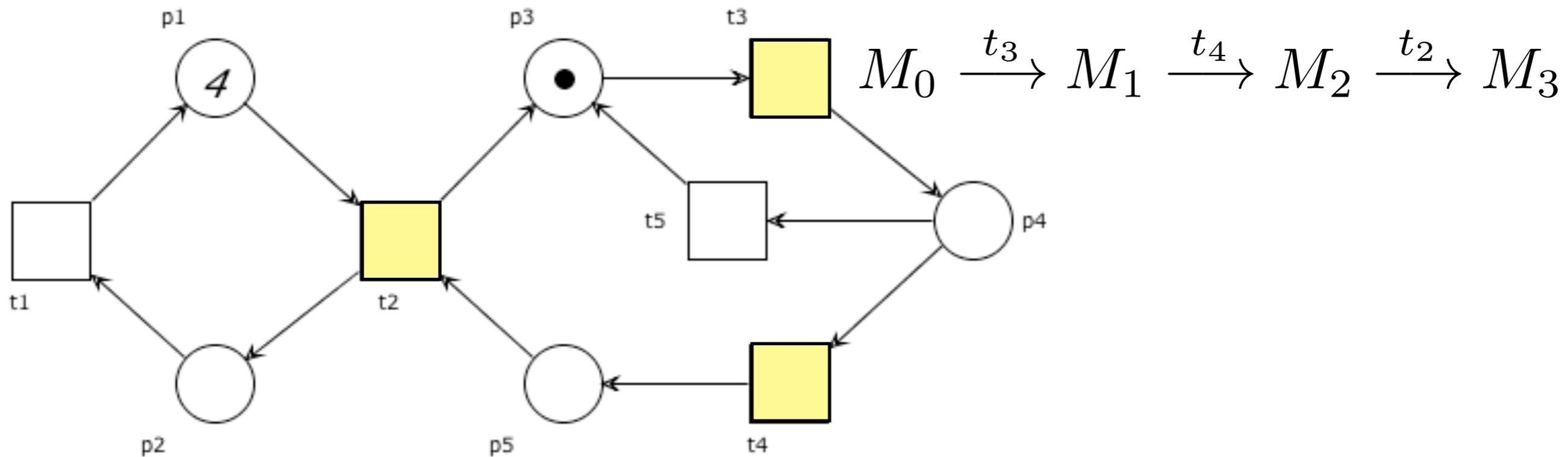
$$\begin{matrix} M_0 \\ \left[ \begin{array}{c} 4 \\ 0 \\ 1 \\ 0 \\ 0 \end{array} \right] \end{matrix} + \begin{matrix} t_3 \\ \left[ \begin{array}{c} 0 \\ 0 \\ -1 \\ 1 \\ 0 \end{array} \right] \end{matrix} = \begin{matrix} M_1 \\ \left[ \begin{array}{c} 4 \\ 0 \\ 0 \\ 1 \\ 0 \end{array} \right] \end{matrix}$$

# Firing, in vector notation



$$\begin{matrix} M_1 \\ \left[ \begin{array}{c} 4 \\ 0 \\ 0 \\ 1 \\ 0 \end{array} \right] \end{matrix} + \begin{matrix} t_4 \\ \left[ \begin{array}{c} 0 \\ 0 \\ 0 \\ -1 \\ 1 \end{array} \right] \end{matrix} = \begin{matrix} M_2 \\ \left[ \begin{array}{c} 4 \\ 0 \\ 0 \\ 0 \\ 1 \end{array} \right] \end{matrix}$$

# Firing, in vector notation



$$\begin{bmatrix} M_2 \\ 4 \\ 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} + \begin{bmatrix} t_2 \\ -1 \\ 1 \\ 1 \\ 0 \\ -1 \end{bmatrix} = \begin{bmatrix} M_3 \\ 3 \\ 1 \\ 1 \\ 0 \\ 0 \end{bmatrix}$$

# Products

Let  $\mathbf{x}, \mathbf{y}$  be two vectors of equal length  $n$  (written  $|\mathbf{x}| = |\mathbf{y}| = n$ )

We define their scalar product by

$$\mathbf{x} \cdot \mathbf{y} = \sum_{i=1}^n x_i y_i$$

$$\begin{bmatrix} x_1 & x_2 & \dots & x_n \end{bmatrix} \cdot \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix} = x_1 y_1 + x_2 y_2 + \dots + x_n y_n$$

# Products: example

$$\begin{bmatrix} 0 & 1 & -1 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 \\ 1 \\ 2 \\ 0 \\ 1 \end{bmatrix} =$$

# Products: example

$$\begin{bmatrix} 0 & 1 & -1 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 \\ 1 \\ 2 \\ 0 \\ 1 \end{bmatrix} = (0 \cdot 1) +$$

# Products: example

$$\begin{bmatrix} 0 & 1 & -1 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 \\ 1 \\ 2 \\ 0 \\ 1 \end{bmatrix} = (0 \cdot 1) + (1 \cdot 1) +$$

# Products: example

$$[ 0 \quad 1 \quad \boxed{-1} \quad 0 \quad 1 ] \cdot \begin{bmatrix} 1 \\ 1 \\ \boxed{2} \\ 0 \\ 1 \end{bmatrix} = (0 \cdot 1) + (1 \cdot 1) + (-1 \cdot 2) +$$

# Products: example

$$[ 0 \quad 1 \quad -1 \quad \boxed{0} \quad 1 ] \cdot \begin{bmatrix} 1 \\ 1 \\ 2 \\ \boxed{0} \\ 1 \end{bmatrix} = (0 \cdot 1) + (1 \cdot 1) + (-1 \cdot 2) + (0 \cdot 0) +$$

# Products: example

$$\begin{bmatrix} 0 & 1 & -1 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 \\ 1 \\ 2 \\ 0 \\ 1 \end{bmatrix} = (0 \cdot 1) + (1 \cdot 1) + (-1 \cdot 2) + (0 \cdot 0) + (1 \cdot 1)$$

# Products: example

$$[ 0 \quad 1 \quad -1 \quad 0 \quad 1 ] \cdot \begin{bmatrix} 1 \\ 1 \\ 2 \\ 0 \\ 1 \end{bmatrix} = (0 \cdot 1) + (1 \cdot 1) + (-1 \cdot 2) + (0 \cdot 0) + (1 \cdot 1) = 0 + 1 - 2 + 0 + 1$$

# Products: example

$$\begin{bmatrix} 0 & 1 & -1 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 \\ 1 \\ 2 \\ 0 \\ 1 \end{bmatrix} = (0 \cdot 1) + (1 \cdot 1) + (-1 \cdot 2) + (0 \cdot 0) + (1 \cdot 1) = 0 + 1 - 2 + 0 + 1 = 0$$

# Products

Let  $\mathbf{x}_1, \mathbf{x}_2, \dots, \mathbf{x}_k, \mathbf{y}$  be all vectors of equal length

Let  $X$  be a  $(k \times n)$ -matrix whose  $i$ -th row is  $\mathbf{x}_i$

We define the product  $X \cdot \mathbf{y}$  as the (column) vector where

$$(X \cdot \mathbf{y})_i = \mathbf{x}_i \cdot \mathbf{y}$$

$$\begin{bmatrix} \square & \square & \square & \square \\ \square & \square & \square & \square \\ \square & \square & \square & \square \\ \square & \square & \square & \square \end{bmatrix} \cdot \begin{bmatrix} \square \\ \square \\ \square \\ \square \end{bmatrix} = \begin{matrix} \text{rows} \\ \begin{bmatrix} \mathbf{x}_1 \\ \mathbf{x}_2 \\ \vdots \\ \mathbf{x}_k \end{bmatrix} \end{matrix} \cdot \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix} = \begin{bmatrix} \mathbf{x}_1 \cdot \mathbf{y} \\ \mathbf{x}_2 \cdot \mathbf{y} \\ \vdots \\ \mathbf{x}_k \cdot \mathbf{y} \end{bmatrix} \begin{bmatrix} \square \\ \square \\ \square \\ \square \end{bmatrix}$$

# Products: example

$$\begin{bmatrix} 1 & -1 & 0 & 0 & 0 \\ -1 & 1 & 0 & 0 & 0 \\ 0 & 1 & -1 & 0 & 1 \\ 0 & 0 & 1 & -1 & -1 \\ 0 & -1 & 0 & 1 & 0 \end{bmatrix} \cdot \begin{bmatrix} 1 \\ 1 \\ 2 \\ 0 \\ 1 \end{bmatrix} = \begin{bmatrix} 1 - 1 \\ -1 + 1 \\ 1 - 2 + 1 \\ 2 - 1 \\ -1 \end{bmatrix}$$

# Products: example

$$\begin{bmatrix} 1 & -1 & 0 & 0 & 0 \\ -1 & 1 & 0 & 0 & 0 \\ 0 & 1 & -1 & 0 & 1 \\ 0 & 0 & 1 & -1 & -1 \\ 0 & -1 & 0 & 1 & 0 \end{bmatrix} \cdot \begin{bmatrix} 1 \\ 1 \\ 2 \\ 0 \\ 1 \end{bmatrix} = \begin{bmatrix} 1 - 1 \\ -1 + 1 \\ 1 - 2 + 1 \\ 2 - 1 \\ -1 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \\ -1 \end{bmatrix}$$

# Products

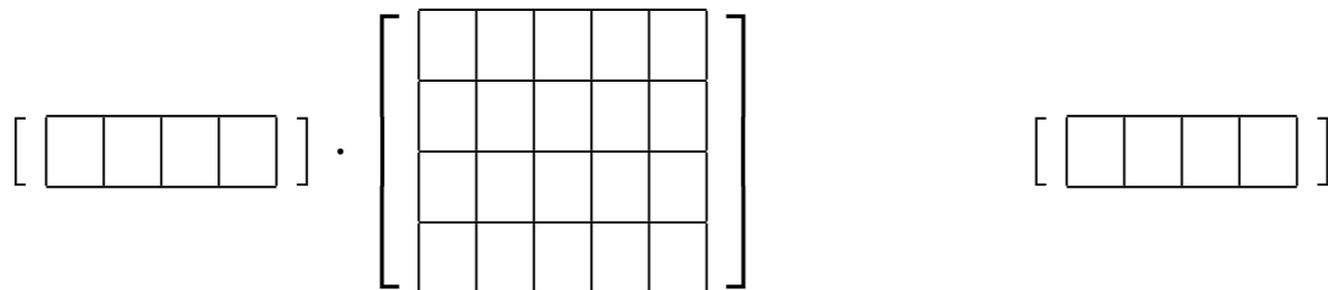
Let  $\mathbf{x}, \mathbf{y}_1, \mathbf{y}_2, \dots, \mathbf{y}_k$  be all vectors of equal length

Let  $Y$  be a  $(n \times k)$ -matrix whose  $i$ -th column is  $\mathbf{y}_i$

We define the product  $\mathbf{x} \cdot Y$  as the (row) vector where

$$(\mathbf{x} \cdot Y)_i = \mathbf{x} \cdot \mathbf{y}_i$$

$$[x_1 \ x_2 \ \dots \ x_n] \cdot \begin{matrix} \text{columns} \\ [y_1 \ y_2 \ \dots \ y_k] \end{matrix} = [x \cdot y_1 \quad x \cdot y_2 \quad \dots \quad x \cdot y_k]$$



# Vector perspective

Let  $P = \{ p_1, \dots, p_n \}$  and  $T = \{ t_1, \dots, t_m \}$

The net  $(P, T, F)$  can be seen as a matrix  $(n \times m)$

A marking is a vector of length  $n$

But we miss an ingredient:

can any firing sequence be seen as a vector?

# Parikh vectors of transition sequences

Let  $N = (P, T, F)$  be a net and  $\sigma \in T^*$  a finite sequence of transitions.

The **Parikh vector**

$$\vec{\sigma} : T \rightarrow \mathbb{N}$$

of  $\sigma$  maps every  $t \in T$  to the number of its occurrences in  $\sigma$ .

# Parikh vector of a firing

As a special case, for a sequence  $\sigma = t$  (one single transition):

$$\vec{t} = \begin{bmatrix} 0 & \dots & 0 & 1 & 0 & \dots & 0 \\ t_1 & & & t & & & t_m \end{bmatrix}$$

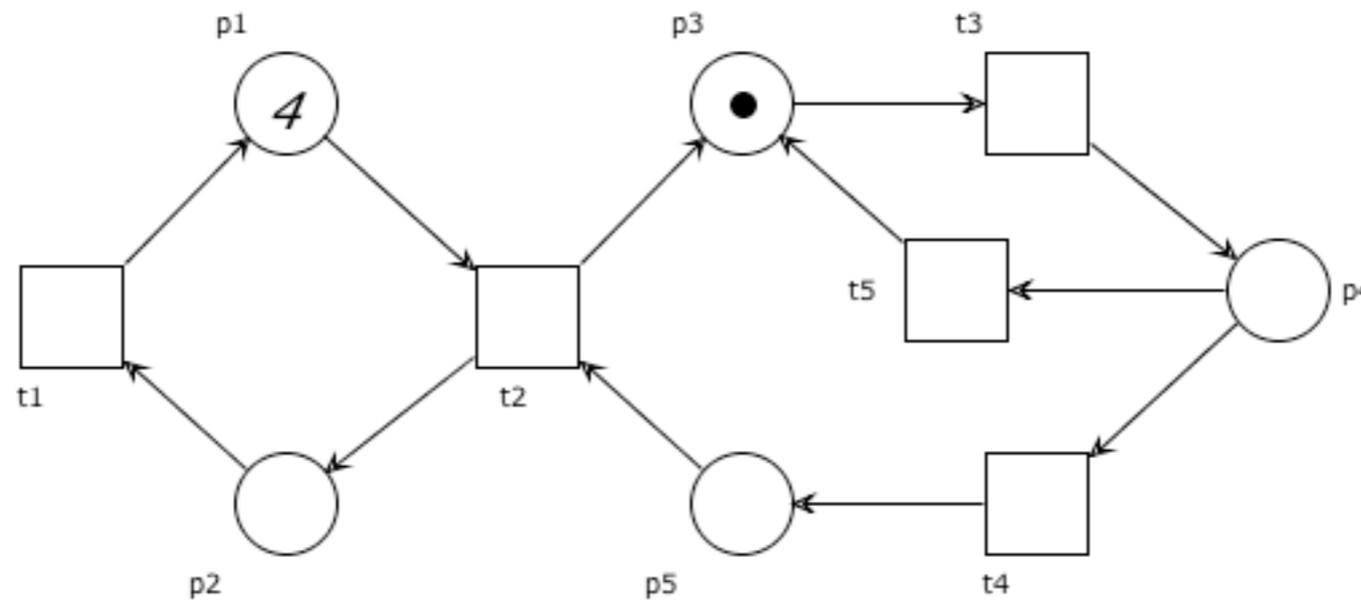
# Recursive definition of Parikh vector

$$\vec{\epsilon} = \mathbf{0}$$

$$\vec{t} = \begin{bmatrix} 0 & \dots & 0 & 1 & 0 & \dots & 0 \\ t_1 & & & t & & & t_m \end{bmatrix}$$

$$\vec{\sigma t} = \vec{\sigma} + \vec{t}$$

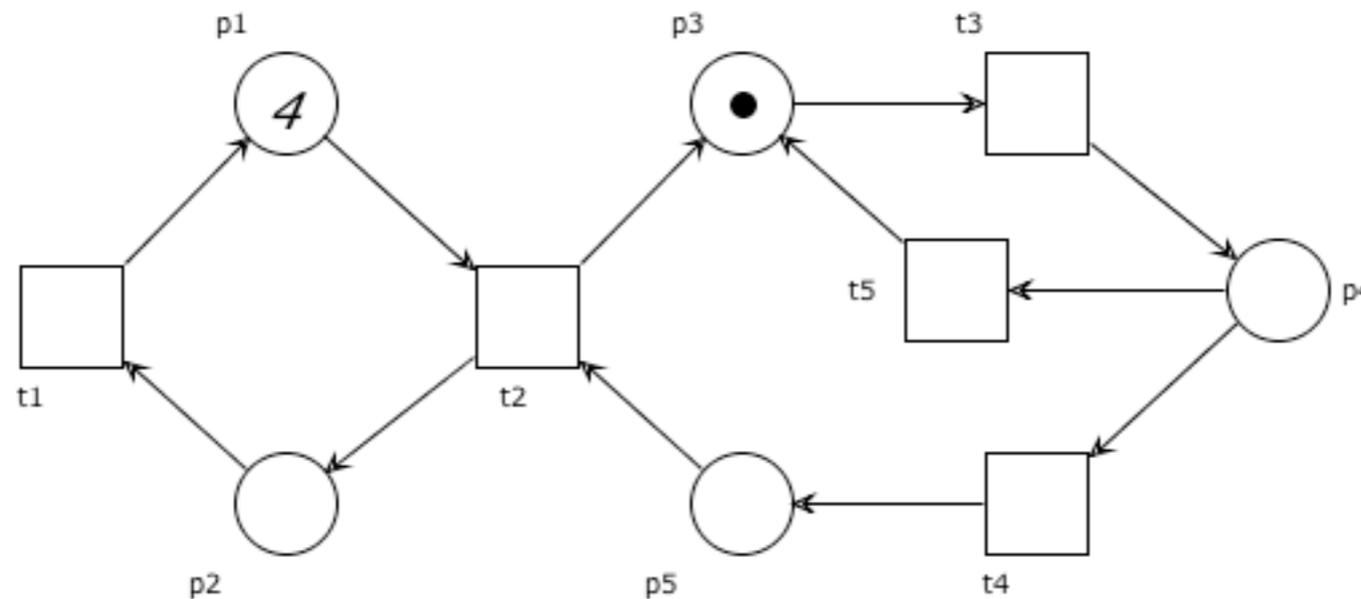
# Parikh vector: example



$$M_0 = 4p_1 + p_3$$

$$M_0 \xrightarrow{\sigma = t_3 t_5 t_3 t_4 t_2} 3p_1 + p_2 + p_3$$

# Parikh vector: example

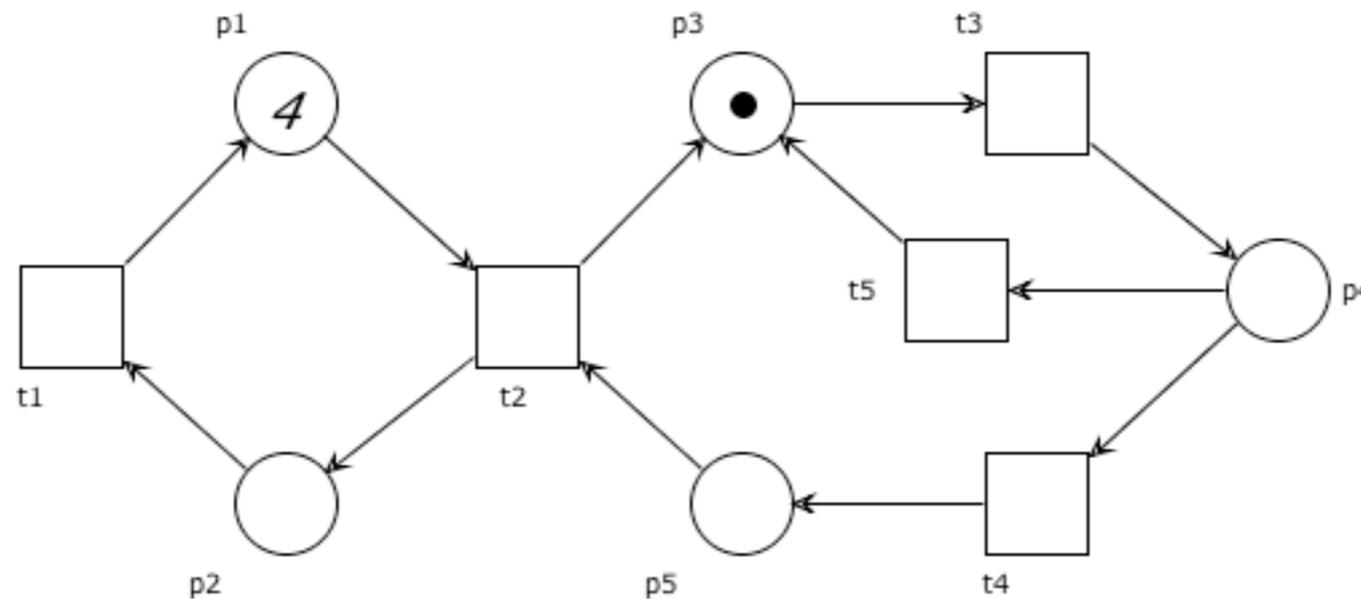


$$M_0 = 4p_1 + p_3$$

$$M_0 \xrightarrow{\sigma = t_3 t_5 t_3 t_4 t_2} 3p_1 + p_2 + p_3 \quad \vec{\sigma} = [0 \quad 1 \quad 2 \quad 1 \quad 1]$$

$$M_0 \xrightarrow{\sigma' = t_3 t_4 t_2 t_3 t_4 t_2 t_3 t_5 t_3} 2p_1 + 2p_2 + p_4$$

# Parikh vector: example



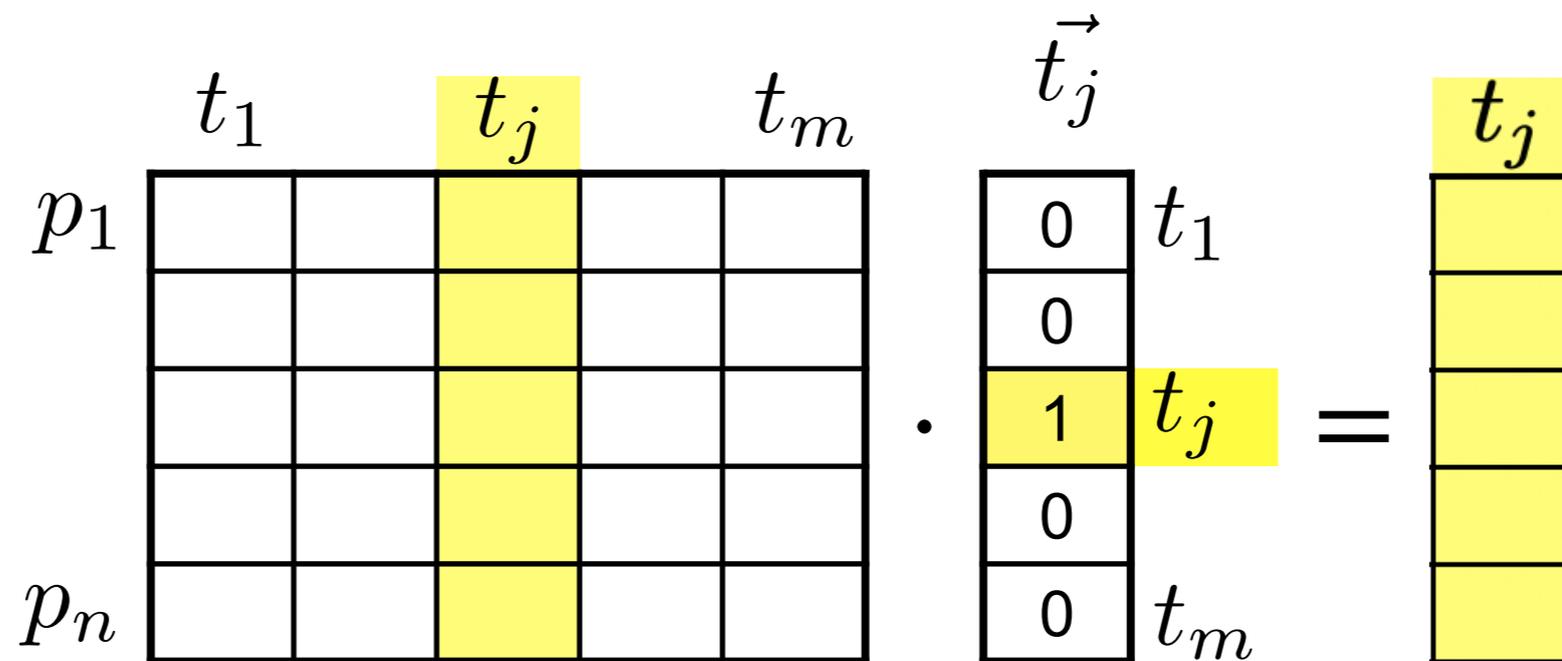
$$M_0 = 4p_1 + p_3$$

$$M_0 \xrightarrow{\sigma = t_3 t_5 t_3 t_4 t_2} 3p_1 + p_2 + p_3 \quad \vec{\sigma} = [0 \quad 1 \quad 2 \quad 1 \quad 1]$$

$$M_0 \xrightarrow{\sigma' = t_3 t_4 t_2 t_3 t_4 t_2 t_3 t_5 t_3} 2p_1 + 2p_2 + p_4 \quad \vec{\sigma}' = [0 \quad 2 \quad 4 \quad 2 \quad 1]$$

# First fact

$$\mathbf{N} \cdot \vec{t}_j = \mathbf{t}_j$$



# Second fact

$$\mathbf{N} \cdot \vec{t} = \mathbf{t}$$

If  $M \xrightarrow{t} M'$  then  $M' = M + \mathbf{t}$

# Consequence

$$\mathbf{N} \cdot \vec{t} = \mathbf{t}$$

If  $M \xrightarrow{t} M'$  then  $M' = M + \mathbf{t}$

If  $M \xrightarrow{t} M'$  then  $M' = M + \mathbf{N} \cdot \vec{t}$

# Marking equation lemma

**Lemma:** If  $M \xrightarrow{\sigma} M'$  then  $M' = M + \mathbf{N} \cdot \vec{\sigma}$

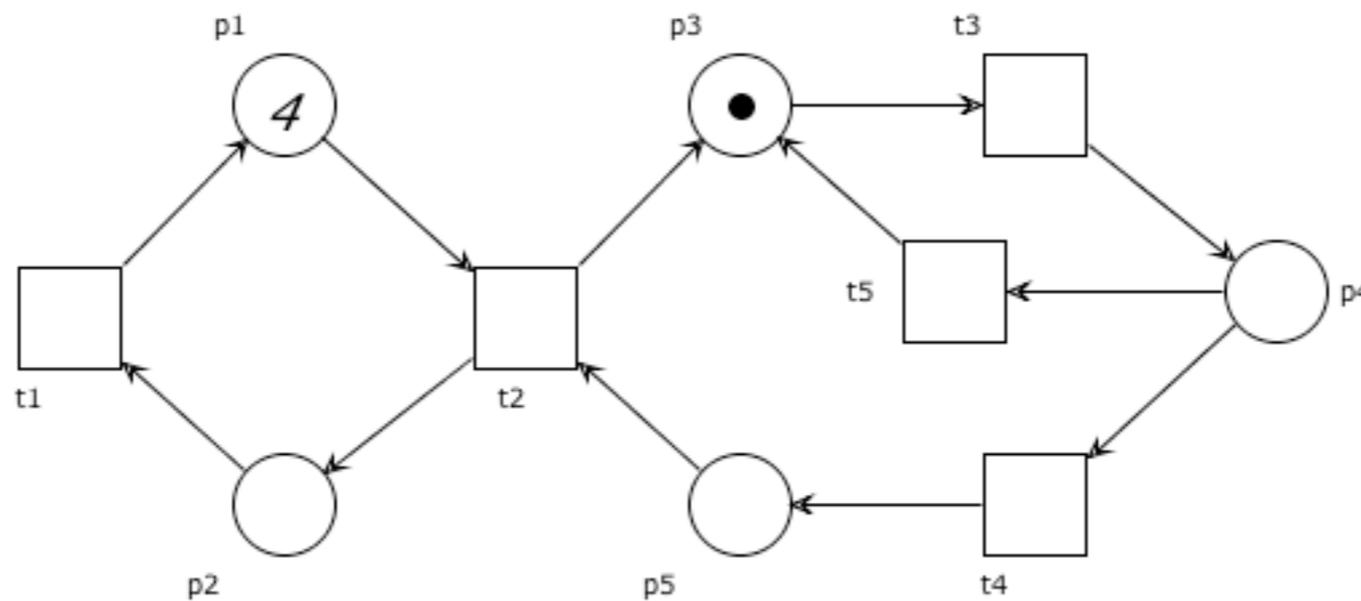
The proof is by induction on the length of  $\sigma$

**base** ( $\sigma = \epsilon$ ): and therefore  $M' = M$ . The equality holds trivially, because  $\vec{\sigma} = \mathbf{0}$

**induction** ( $\sigma = \sigma' t$  for some sequence  $\sigma'$  and transition  $t$ ):

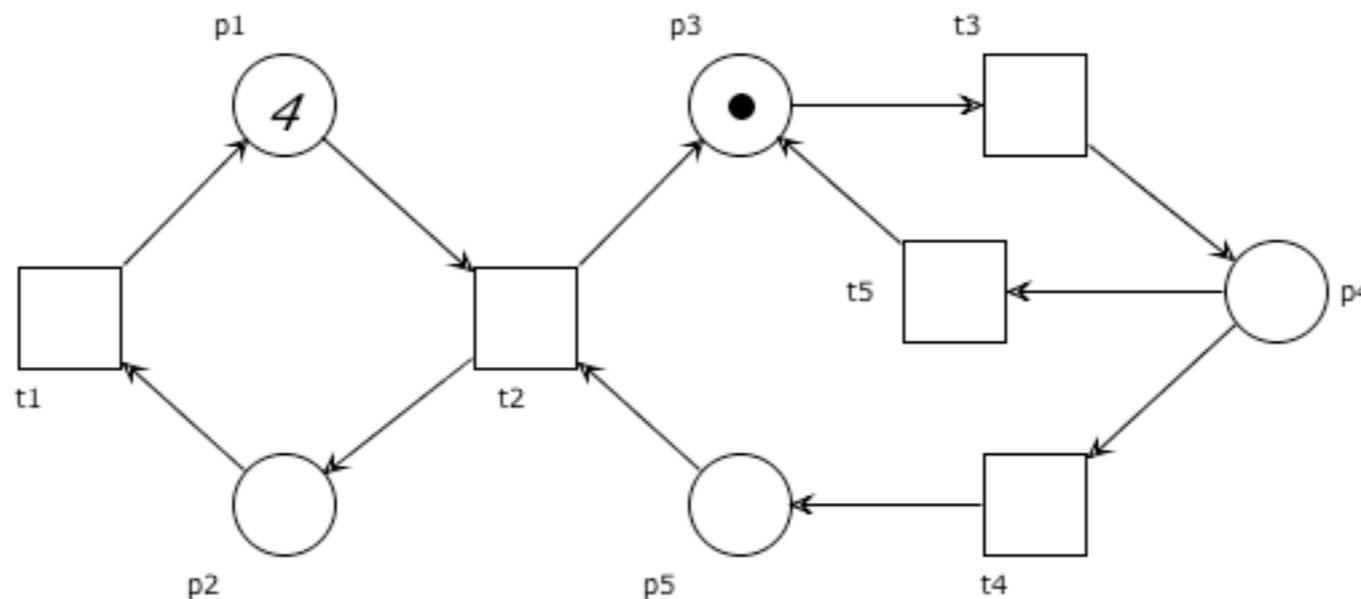
$$\begin{aligned} \text{Let } M \xrightarrow{\sigma'} M'' \xrightarrow{t} M'. \text{ We have: } M' &= M'' + \mathbf{t} \\ &= M'' + \mathbf{N} \cdot \vec{t} \\ \text{(inductive hyp. } M'' = M + \mathbf{N} \cdot \vec{\sigma}') &= M + \mathbf{N} \cdot \vec{\sigma}' + \mathbf{N} \cdot \vec{t} \\ &= M + \mathbf{N} \cdot (\vec{\sigma}' + \vec{t}) \\ &= M + \mathbf{N} \cdot \overrightarrow{(\sigma' t)} \\ &= M + \mathbf{N} \cdot \vec{\sigma} \end{aligned}$$

# Marking equation: example



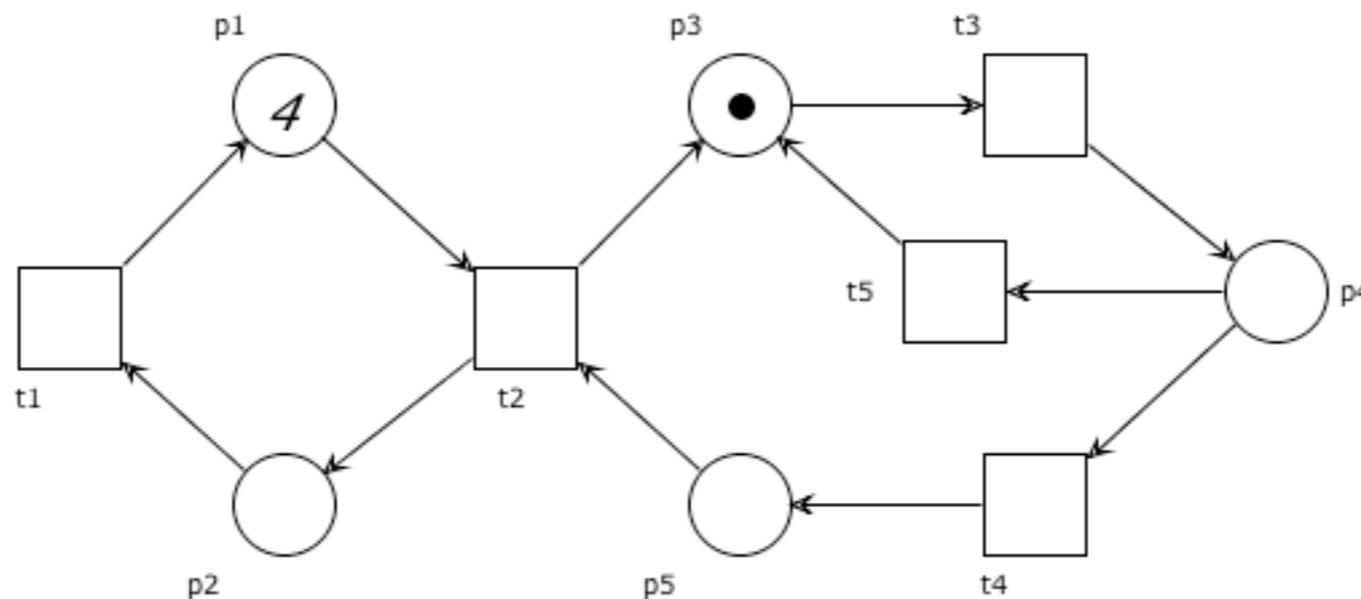
$$M_0 = [ 4 \quad 0 \quad 1 \quad 0 \quad 0 ]$$

# Marking equation: example



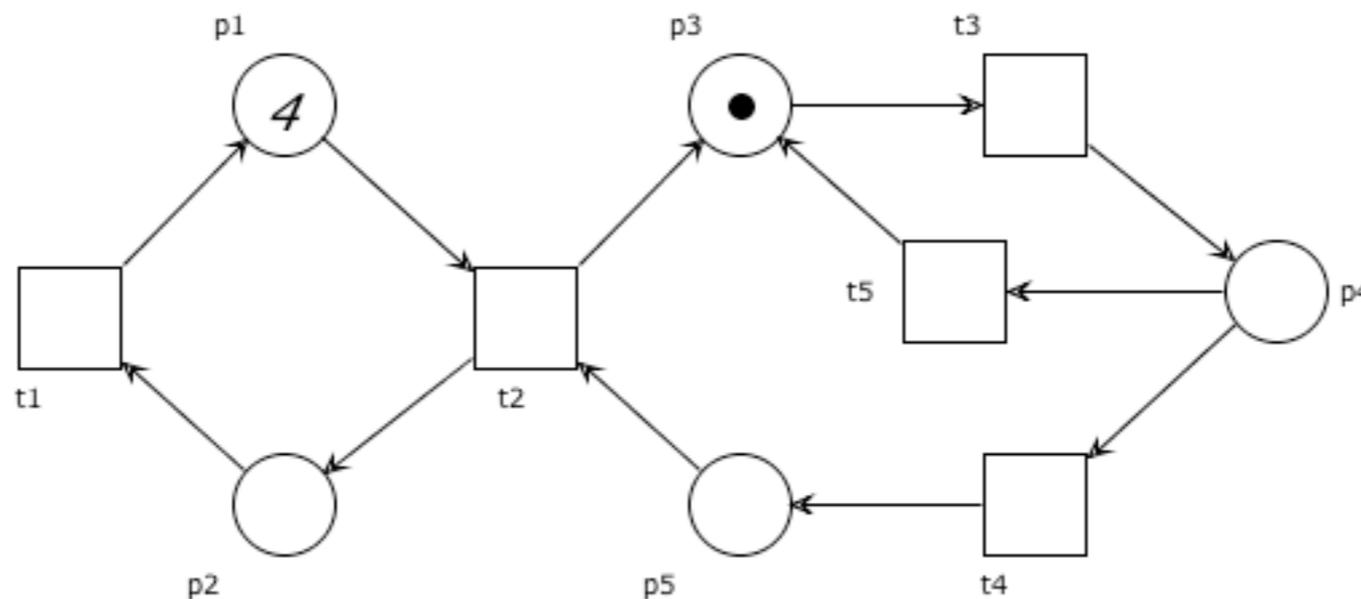
$$M_0 = [4 \quad 0 \quad 1 \quad 0 \quad 0] \quad \sigma = t_3 t_5 t_3 t_4 t_2$$

# Marking equation: example



$$M_0 = [4 \quad 0 \quad 1 \quad 0 \quad 0] \quad \sigma = t_3 t_5 t_3 t_4 t_2 \quad \vec{\sigma} = [0 \quad 1 \quad 2 \quad 1 \quad 1]$$

# Marking equation: example



$$M_0 = [4 \quad 0 \quad 1 \quad 0 \quad 0] \quad \sigma = t_3 t_5 t_3 t_4 t_2 \quad \vec{\sigma} = [0 \quad 1 \quad 2 \quad 1 \quad 1]$$

$$\begin{array}{c} M_0 \\ \left[ \begin{array}{c} 4 \\ 0 \\ 1 \\ 0 \\ 0 \end{array} \right] \end{array} + \begin{array}{c} N \\ \left[ \begin{array}{cccccc} 1 & -1 & 0 & 0 & 0 \\ -1 & 1 & 0 & 0 & 0 \\ 0 & 1 & -1 & 0 & 1 \\ 0 & 0 & 1 & -1 & -1 \\ 0 & -1 & 0 & 1 & 0 \end{array} \right] \end{array} \cdot \begin{array}{c} \vec{\sigma} \\ \left[ \begin{array}{c} 0 \\ 1 \\ 2 \\ 1 \\ 1 \end{array} \right] \end{array} = \begin{array}{c} \\ \left[ \begin{array}{c} 3 \\ 1 \\ 1 \\ 0 \\ 0 \end{array} \right] \end{array}$$

# Marking equation lemma: consequences

The marking reached by any occurrence sequence only depends on the number of occurrences of each transition

It does not depend on the order in which transitions occur

**Every fireable permutation of the same transitions leads to the same marking**

# Monotonicity lemma (1)

**Lemma:** If  $M \xrightarrow{\sigma} M'$  then  $M + L \xrightarrow{\sigma} M' + L$  for any  $L$

The proof is by induction on the length of  $\sigma$

**base** ( $\sigma = \epsilon$ ): the empty sequence is always enabled, at any marking

**induction** ( $\sigma = \sigma' t$  for some sequence  $\sigma'$  and transition  $t$ ):

Let  $M \xrightarrow{\sigma'} M'' \xrightarrow{t} M'$ .

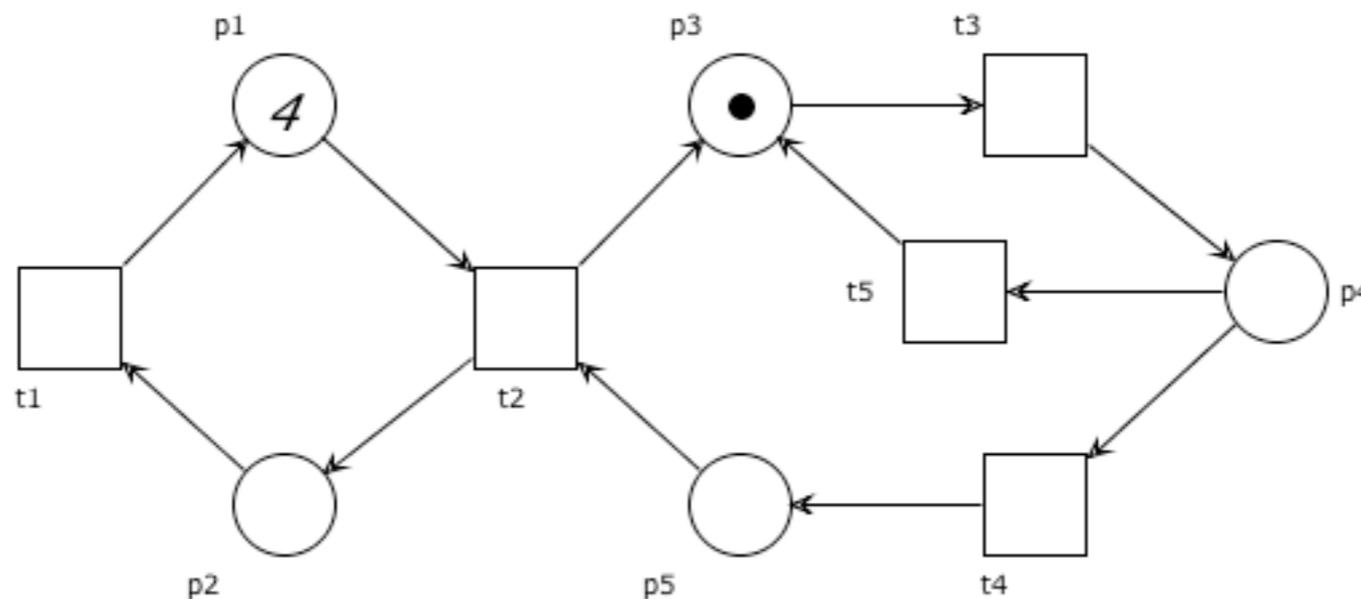
By the marking equation lemma:  $M' = M'' + \mathbf{N} \cdot \vec{t}$

By the induction hypothesis  $M + L \xrightarrow{\sigma'} M'' + L$

Moreover,  $M'' + L \xrightarrow{t}$  because  $M'' \xrightarrow{t}$ .

By the marking equation lemma:  $M'' + L \xrightarrow{t} M'' + L + \mathbf{N} \cdot \vec{t} = M' + L$

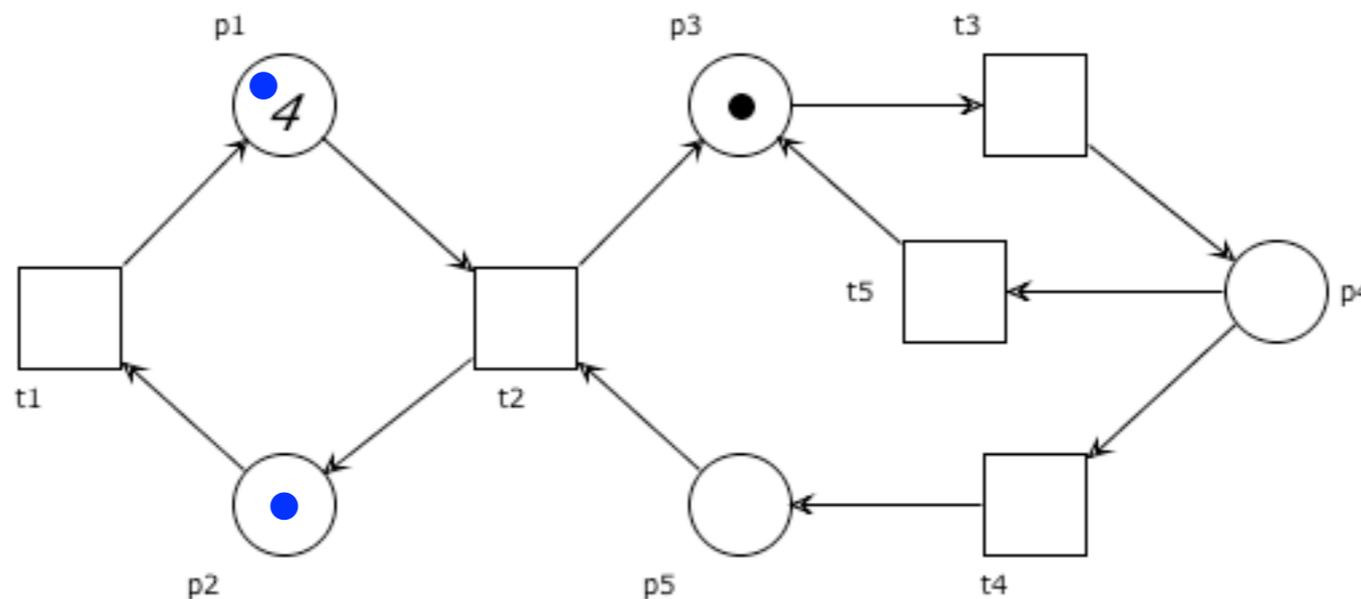
# Monotonicity lemma: example



$$M_0 = [4 \ 0 \ 1 \ 0 \ 0] \quad \sigma = t_3 t_5 t_3 t_4 t_2 \quad \vec{\sigma} = [0 \ 1 \ 2 \ 1 \ 1]$$

$$M = M_0 + N \cdot \vec{\sigma} = [3 \ 1 \ 1 \ 0 \ 0] \quad M_0 \xrightarrow{\sigma} M$$

# Monotonicity lemma: example



$$M_0 = [4 \quad 0 \quad 1 \quad 0 \quad 0] \quad \sigma = t_3 t_5 t_3 t_4 t_2 \quad \vec{\sigma} = [0 \quad 1 \quad 2 \quad 1 \quad 1]$$

$$M = M_0 + N \cdot \vec{\sigma} = [3 \quad 1 \quad 1 \quad 0 \quad 0] \quad M_0 \xrightarrow{\sigma} M$$

$$L = [1 \quad 1 \quad 0 \quad 0 \quad 0]$$

$$M_0 + L \xrightarrow{\sigma} M + L = [4 \quad 2 \quad 1 \quad 0 \quad 0]$$

# Monotonicity lemma, intuitively

If some activities can be done with less (resources),  
then the same activities can be done with more (resources)

If we perform activities with more resources than needed,  
then the additional resources are preserved

It also holds for infinite sequences...

# Reminder:

## infinite sequence

Let  $\sigma = t_1 t_2 \dots \in T^\omega$  be an infinite sequence of transitions.

We write  $M \xrightarrow{\sigma}$  if:

there is an infinite sequence of markings  $M_1, M_2, \dots$

with  $M = M_1$  and  $M_i \xrightarrow{t_i} M_{i+1}$  for  $1 \leq i$

(i.e.  $M = M_1 \xrightarrow{t_1} M_2 \xrightarrow{t_2} \dots$ )

**Proposition:**  $M \xrightarrow{\sigma}$  iff  $M \xrightarrow{\sigma'}$  for every prefix  $\sigma'$  of  $\sigma$

# Monotonicity lemma (2)

**Lemma:** If  $M \xrightarrow{\sigma}$  then  $M + L \xrightarrow{\sigma}$  for any  $L$

If  $\sigma$  is finite then the thesis follows from monotonicity lemma 1

If  $\sigma$  is infinite, then it suffices to prove that:

$M + L \xrightarrow{\sigma'}$  for any finite prefix  $\sigma'$  of  $\sigma$

Take any such prefix  $\sigma'$ . Then,  $M \xrightarrow{\sigma'}$  (because  $M \xrightarrow{\sigma}$ )

By the marking equation lemma,  $M \xrightarrow{\sigma'} M + \mathbf{N} \cdot \vec{\sigma}'$ .

By monotonicity lemma 1,  $M + L \xrightarrow{\sigma'} M + \mathbf{N} \cdot \vec{\sigma}' + L$

Hence  $M + L \xrightarrow{\sigma'}$

# Corollary

**Corollary:** If  $M \xrightarrow{\sigma} M'$  with  $M \subseteq M'$  then  $M \xrightarrow{\sigma\sigma\cdots}$

We need to show that every prefix of  $\sigma\sigma\cdots$  is enabled at  $M$ .  
Any such prefix take the form  $\sigma'' = \underbrace{\sigma \cdots \sigma}_n \sigma'$  with  $\sigma'$  a prefix of  $\sigma$ .

We prove that  $M \xrightarrow{\sigma''}$  by induction on  $n$ :

**base:**  $\sigma'' = \sigma'$  is a prefix of  $\sigma$  and  $M \xrightarrow{\sigma'}$  by Enabledness Prop.

**induction:** We assume that  $M \xrightarrow{\sigma''}$  and prove that  $M \xrightarrow{\sigma\sigma''}$ .

Let  $L = M' - M$ . By Monotonicity Lemma  $M + L \xrightarrow{\sigma''}$ .

Thus  $M \xrightarrow{\sigma} M + L \xrightarrow{\sigma''}$  and  $M \xrightarrow{\sigma\sigma''}$ .

# Boundedness Lemma

**Lemma:** If a system is bounded and  $M \in [M_0\rangle$  with  $M \supseteq M_0$ , then  $M = M_0$ .

Let  $M_0 \xrightarrow{\sigma} M$ .

By  $M \supseteq M_0$ , there exists a marking  $L$  with  $M = M_0 + L$ .

Let  $M_k = M_0 + k \cdot L$  for every  $k \in \mathbb{N}$ .

By the Monotonicity Lemma, we have:

$$M_0 \xrightarrow{\sigma} M_1 \xrightarrow{\sigma} M_2 \cdots$$

i.e.,  $M_k \in [M_0\rangle$  for any  $k \in \mathbb{N}$ .

Since the system is bounded, it must be  $L = \emptyset$ .

# Boundedness lemma: consequences

If we show that a marking  $M$  is reachable with

$$M \supset M_0$$

**then the system is not bounded**

# Repetition Lemma

**Lemma:** If  $M \xrightarrow{\sigma} M'$  and  $M \xrightarrow{\sigma\sigma\cdots}$ , then  $M \subseteq M'$ .

We proceed by contradiction.

Suppose  $M \not\subseteq M'$ , i.e., there exist  $k > 0, p \in P$  such that  $M'(p) = M(p) - k$ .

By the Marking Equation Lemma we have  $M' = M + \mathbf{N} \cdot \vec{\sigma}$ .

Therefore  $(\mathbf{N} \cdot \vec{\sigma})(p) = -k$ .

Let  $n = M(p) + 1$  and  $\sigma' = \underbrace{\sigma \cdots \sigma}_n$ .

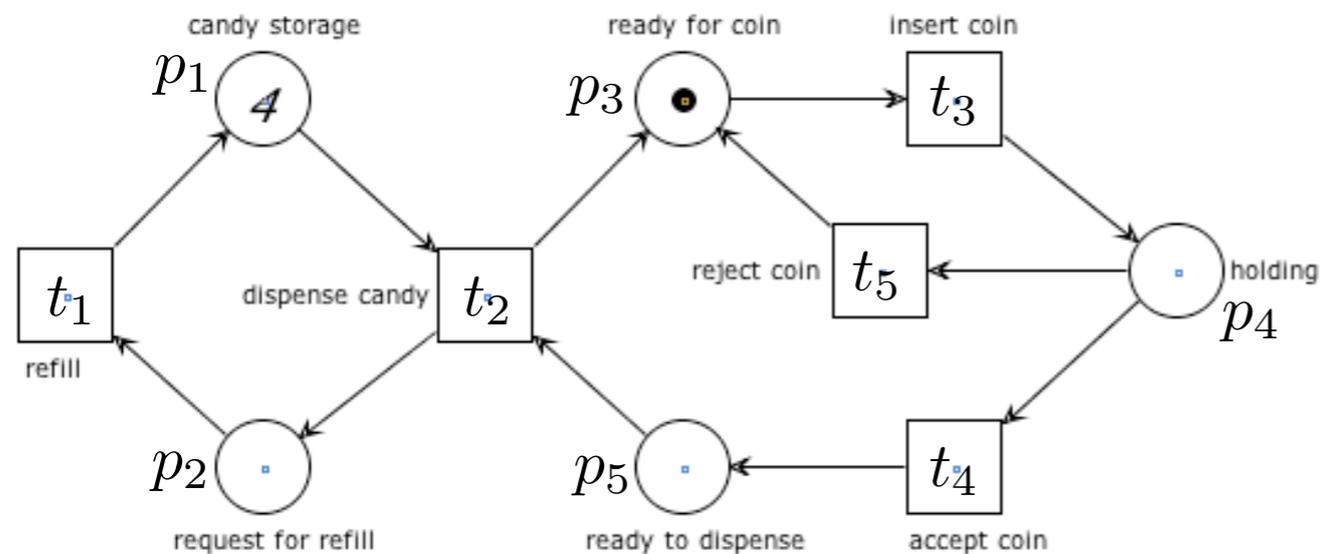
By hypothesis we have  $M \xrightarrow{\sigma'} M''$ ,

and by the Marking Equation Lemma  $M''(p) = M(p) - nk < 0$ , which is absurd.

# Repetition Lemma: consequences

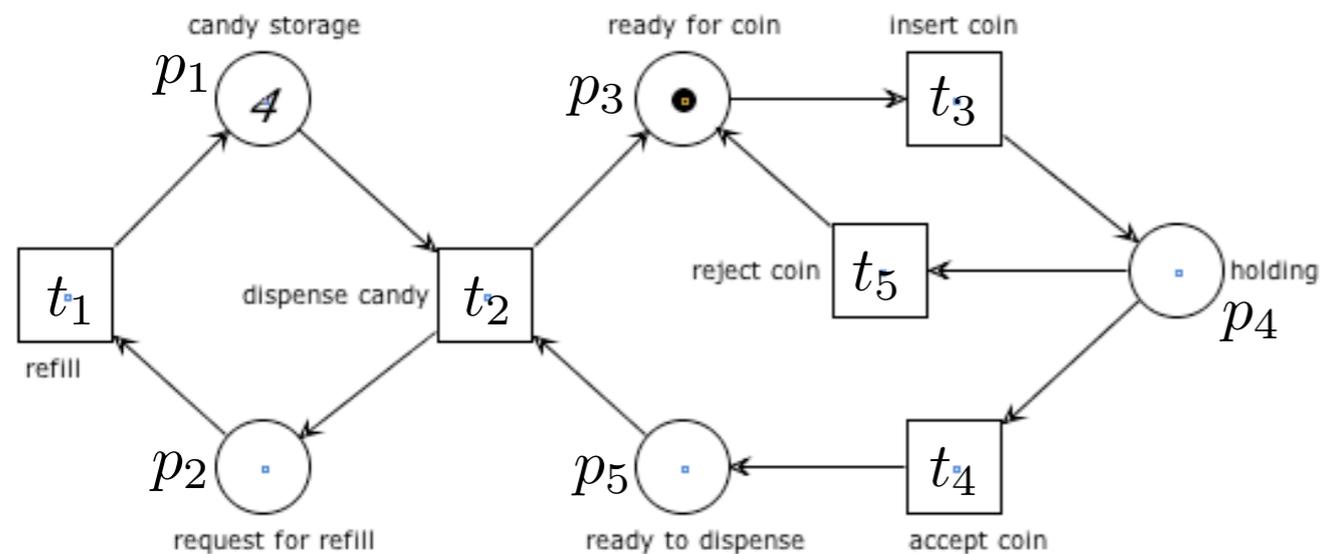
If  $\sigma$  can be fired any number of times  
it means that  $\sigma$  produces more resources than it consumes  
(or as many as it consumes)

# Exercises



- Compute the Parikh vector of  $\sigma = t_3 t_4 t_2 t_3 t_5 t_3 t_4 t_1 t_2 t_1 t_3 t_5 t_2$
- Show that  $\sigma$  is not enabled at  $M_0 = 4p_1 + p_3$   
(*Hint: Exploit the Marking Equation Lemma*)
- Let  $\sigma' = t_3 t_4 t_2 t_1$ . Prove that  $M_0 \xrightarrow{\sigma' \sigma' \dots}$   
(*Hint: Exploit the Corollary of Monotonicity Lemma*)

# Exercises

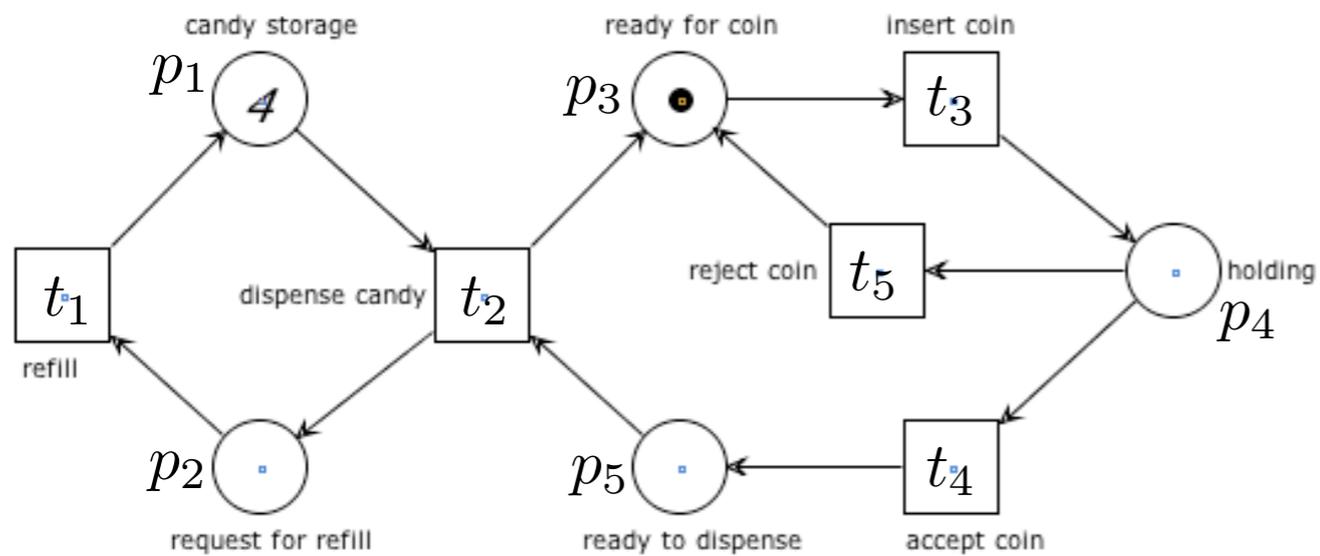


$$\vec{\sigma} = [ 2 \ 3 \ 4 \ 2 \ 2 ]$$

$$M_0 + \mathbf{N} \cdot \vec{\sigma} =$$

- Compute the Parikh vector of  $\sigma = t_3 t_4 t_2 t_3 t_5 t_3 t_4 t_1 t_2 t_1 t_3 t_5 t_2$
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# Exercises

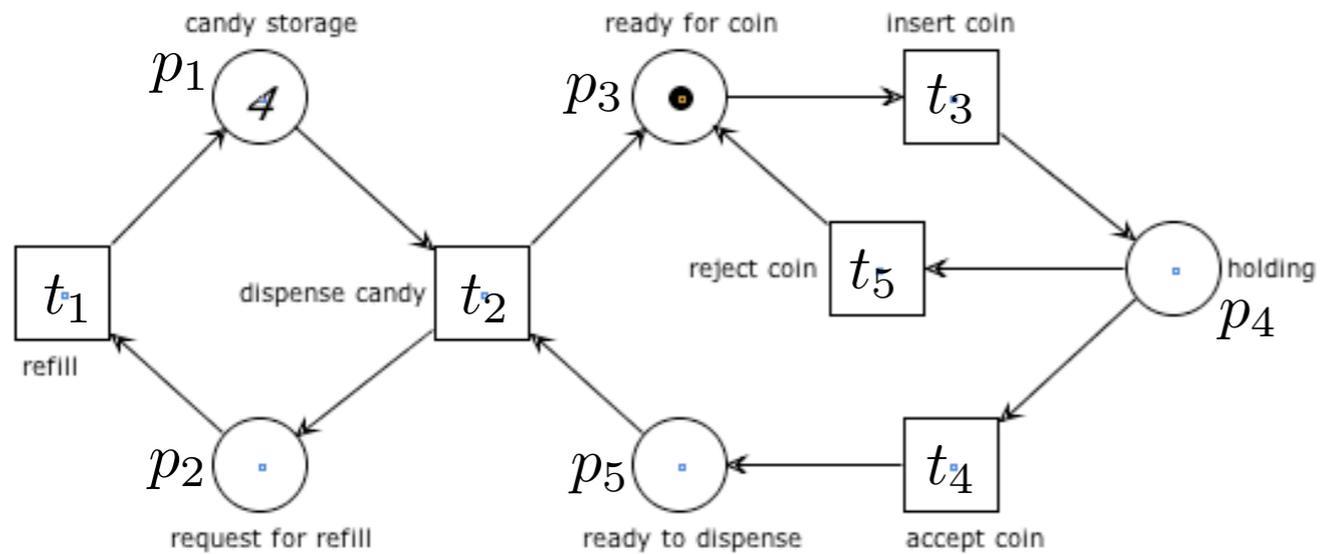


$$\vec{\sigma} = [ 2 \ 3 \ 4 \ 2 \ 2 ]$$

$$M_0 + \mathbf{N} \cdot \vec{\sigma} =$$

$$\begin{bmatrix} 4 \\ 0 \\ 1 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 1 & -1 & 0 & 0 & 0 \\ -1 & 1 & 0 & 0 & 0 \\ 0 & 1 & -1 & 0 & 1 \\ 0 & 0 & 1 & -1 & -1 \\ 0 & -1 & 0 & 1 & 0 \end{bmatrix} \cdot \begin{bmatrix} 2 \\ 3 \\ 4 \\ 2 \\ 2 \end{bmatrix}$$

# Exercises

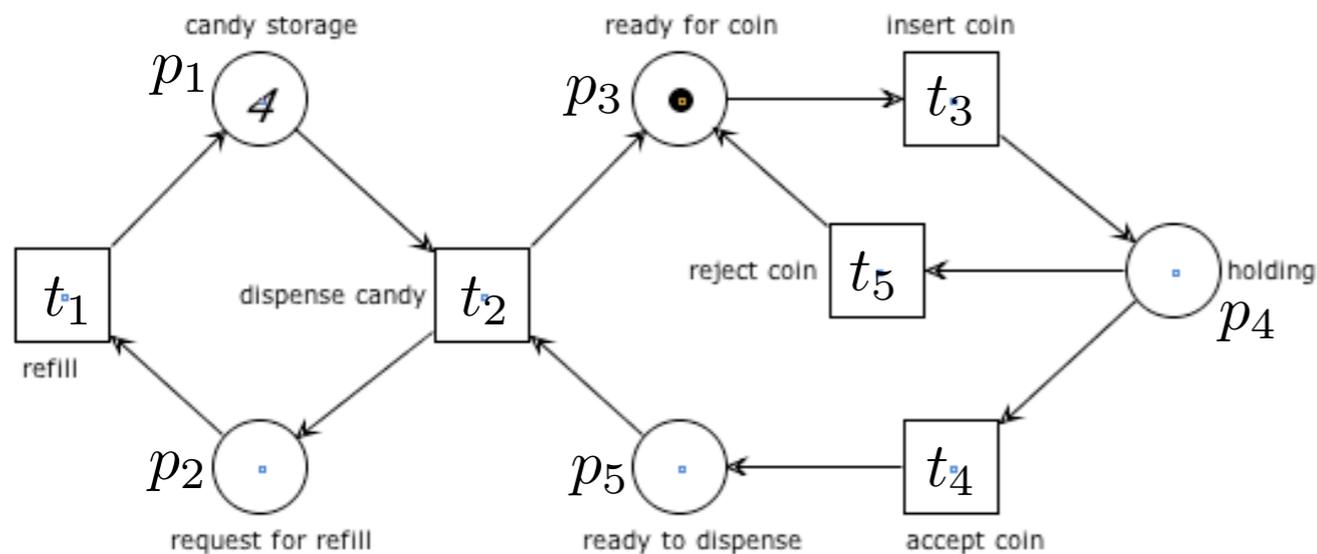


$$\vec{\sigma} = [ 2 \ 3 \ 4 \ 2 \ 2 ]$$

$$M_0 + \mathbf{N} \cdot \vec{\sigma} = [ 3 \ 1 \ 2 \ 0 \ -1 ]$$

$$\begin{bmatrix} 4 \\ 0 \\ 1 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 1 & -1 & 0 & 0 & 0 \\ -1 & 1 & 0 & 0 & 0 \\ 0 & 1 & -1 & 0 & 1 \\ 0 & 0 & 1 & -1 & -1 \\ 0 & -1 & 0 & 1 & 0 \end{bmatrix} \cdot \begin{bmatrix} 2 \\ 3 \\ 4 \\ 2 \\ 2 \end{bmatrix}$$

# Exercises



$$\vec{\sigma} = [ 2 \ 3 \ 4 \ 2 \ 2 ]$$

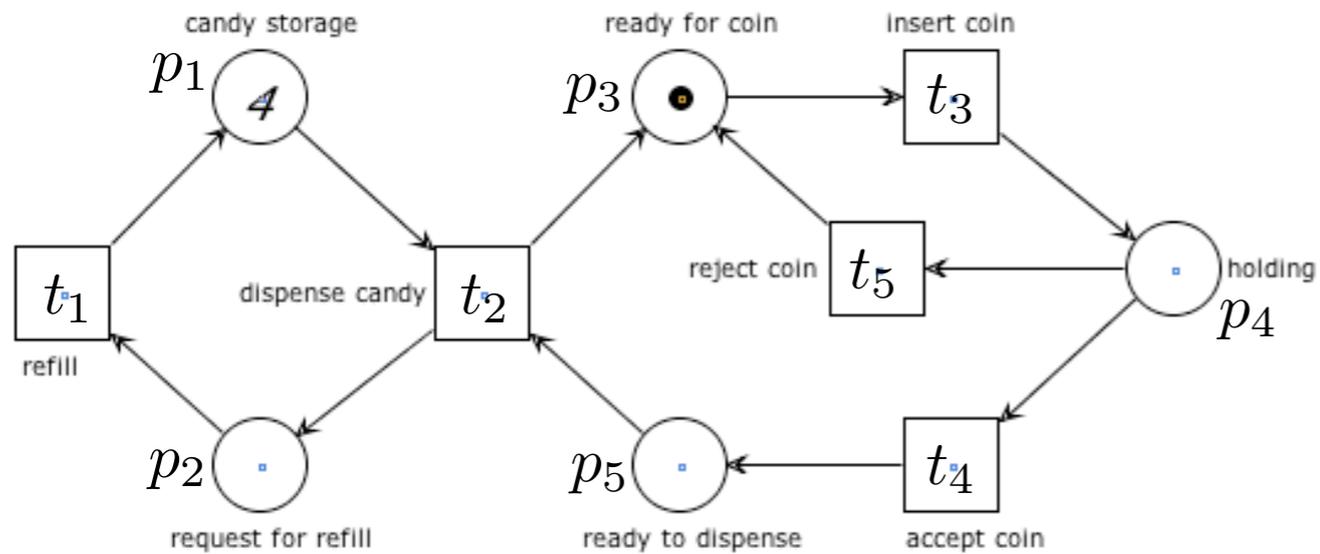
$$M_0 + \mathbf{N} \cdot \vec{\sigma} = [ 3 \ 1 \ 2 \ 0 \ \boxed{-1} ]$$

$$M_0 + \mathbf{N} \cdot \vec{\sigma}' =$$

$$\vec{\sigma}' = [ 1 \ 1 \ 1 \ 1 \ 0 ]$$

- Compute the Parikh vector of  $\sigma = t_3 t_4 t_2 t_3 t_5 t_3 t_4 t_1 t_2 t_1 t_3 t_5 t_2$
- Show that  $\sigma$  is not enabled at  $M_0 = 4p_1 + p_3$   
(*Hint:* Exploit the Marking Equation Lemma)
- Let  $\sigma' = t_3 t_4 t_2 t_1$ . Prove that  $M_0 \xrightarrow{\sigma' \sigma' \dots}$   
(*Hint:* Exploit the Corollary of Monotonicity Lemma)

# Exercises



$$\vec{\sigma} = [ 2 \ 3 \ 4 \ 2 \ 2 ]$$

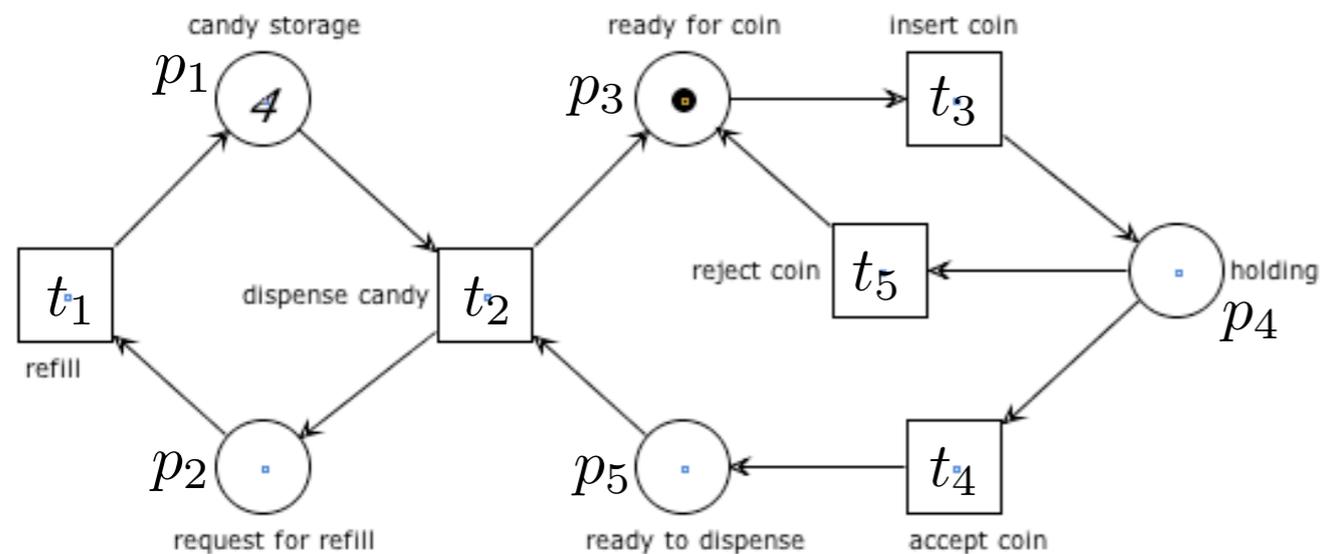
$$M_0 + \mathbf{N} \cdot \vec{\sigma} = [ 3 \ 1 \ 2 \ 0 \ \boxed{-1} ]$$

$$M_0 + \mathbf{N} \cdot \vec{\sigma}' =$$

$$\vec{\sigma}' = [ 1 \ 1 \ 1 \ 1 \ 0 ]$$

$$\begin{bmatrix} 4 \\ 0 \\ 1 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 1 & -1 & 0 & 0 & 0 \\ -1 & 1 & 0 & 0 & 0 \\ 0 & 1 & -1 & 0 & 1 \\ 0 & 0 & 1 & -1 & -1 \\ 0 & -1 & 0 & 1 & 0 \end{bmatrix} \cdot \begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 0 \end{bmatrix}$$

# Exercises



$$\vec{\sigma} = [ 2 \ 3 \ 4 \ 2 \ 2 ]$$

$$M_0 + \mathbf{N} \cdot \vec{\sigma} = [ 3 \ 1 \ 2 \ 0 \ -1 ]$$

$$M_0 + \mathbf{N} \cdot \vec{\sigma}' = M_0 \subseteq M_0$$

- Compute the Parikh vector of  $\sigma = t_3 t_4 t_2 t_3 t_5 t_3 t_4 t_1 t_2 t_1 t_3 t_5 t_2$
- Show that  $\sigma$  is not enabled at  $M_0 = 4p_1 + p_3$   
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