# Petri Net System Modeling and Analysis

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# Abstract

- Petri nets are a promising tool for describing and studying information processing systems that are characterized as being concurrent, asynchronous, distributed, parallel, nondeterministic, and/or stochastic. This talk starts with a brief review of the history and the application areas. It then proceeds with introductory modeling examples, behavioral and structural properties, three methods of analysis. Also, it presents introductory discussions on high-level Petri nets with applications to logic programming and fuzzy logic systems.

# Outlines

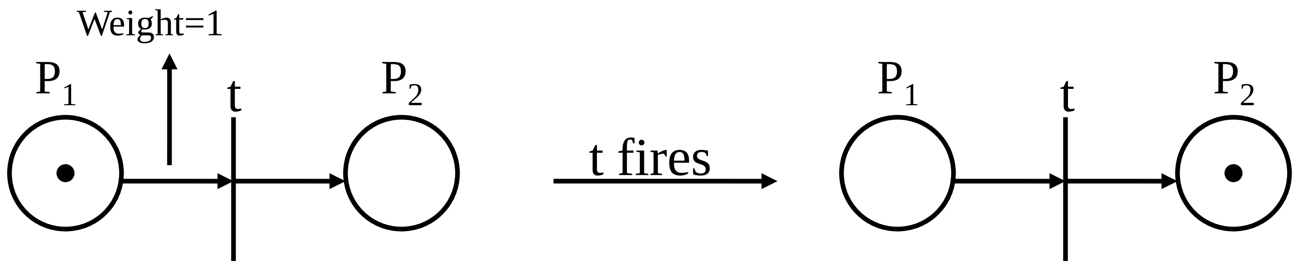
- Introduction
- Properties
- Methods of Analysis
- Predicate/ Transition Net- Logic Programs
- High-Level Fuzzy Petri Net- Fuzzy Logic
- Applications
- Conclusion

# 1. *Introduction*

- Brief History – 1962, Dr. Carl Adam Petri, Univ. of Bonn.
- *Definition 1.1:* Let $P$, $T$, $F$ be finite sets. The triple $PN = (P, T, F)$ is called a *Petri net structure* if and only if the following conditions hold: (a *bipartite* graph)
- (1) $P \cap T = \varnothing$,
- (2) $P \cup T \neq \varnothing$,
- (3) $F \subseteq (P \times T) \cup (T \times P)$,
- (4) $\text{domain}(F) \cup \text{codomain}(F) = P \cup T$.
- $P$ and $T$ are called the sets of *places* and *transitions* of $N$, respectively. $F$ is called the *flow relation* and the elements of $F$ are called the *arcs* of $PN$.

- A graphical and mathematical model, or data structure

Exp. 1：




P1 P2

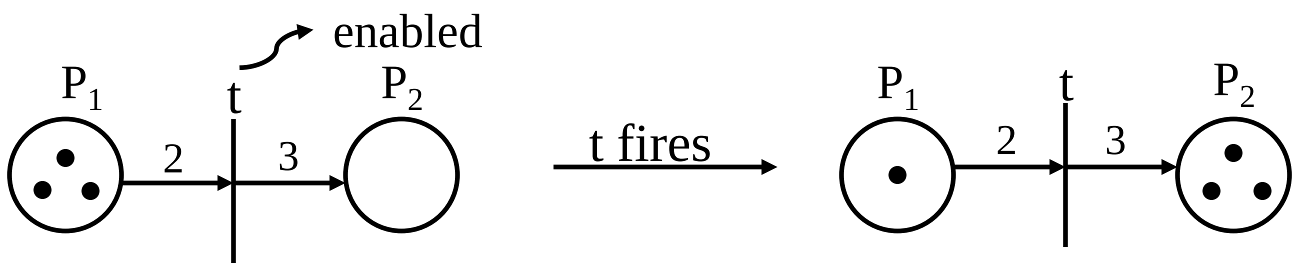
$M_0$=〔1 0〕= Initial Marking

P1 P2

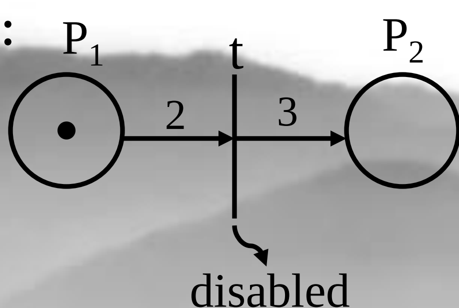
$M_f$=〔0 1〕= Final Marking

● Token (表fact or data)

Exp. 2：




Exp .3：




t cannot fire

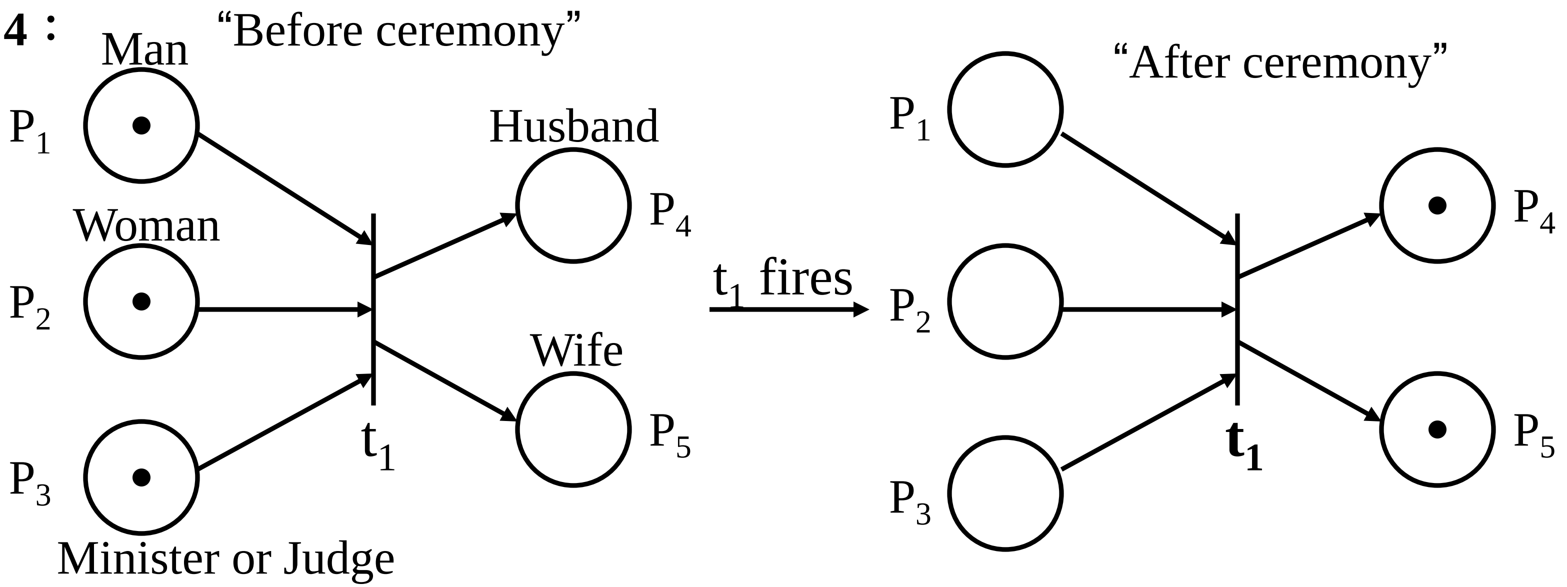
# 1. *Introduction (continued)*

- **Some Typical Interpretations of Transitions and Places**

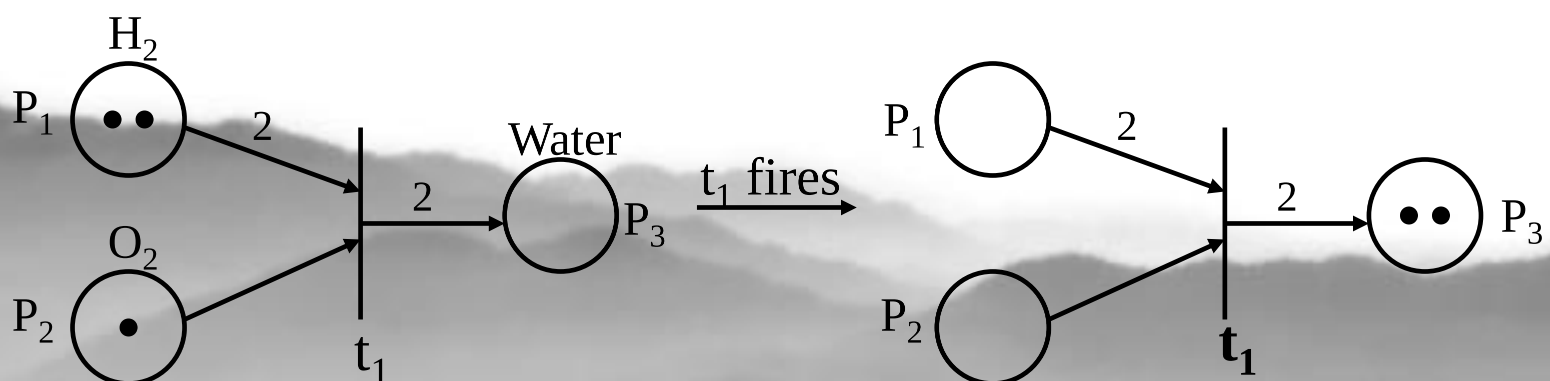
| Input Places | Transition | Output Places |
|---|---|---|
| Preconditions | Event | Postconditions |
| Input data | Computation step | Output data |
| Input signals | Signal processor | Output signals |
| Resources needed | Task or job | Resources released |
| Conditions | Clause in logic | Conclusion(s) |
| Buffers | Processor | Buffers |

- **Examples:**

**Exp. 4：**




**Exp. 5：** $2H_2 + O_2 \rightarrow 2H_2O$



# 2. Properties

- Behavioral Properties-
- 1) Reachability: $M \in R(M_0)$ ? $M = A^T x + M_0$
- 2) Boundedness: $M(p) < \infty$, $\forall p \in P$, $\forall M \in R(M_0)$ (or Safeness)
- 3) Liveness: different levels of liveness, $L$0, 1, 2, 3, 4
- 4) Reversibility and Home State: $\forall M \in R(M_0)$, $M_0 \in R(M)$
- 5) Coverability: $\forall M_1 \in R(M_0)$, $M_1(p) \geqq M(p)$, $\forall p \in P$
- 6) Persistence: any enabled transition can be disabled by its own firing.
- 7) Synchronic Distance: between two transitions $t_1$ and $t_2$.
- $d_{12} = \max \{\sigma(t_1) - \sigma(t_2)\}$

## "Reachability"

$$A = \text{Incidence Matrix} = \begin{array}{c} \\ t_1 \\ t_2 \\ t_3 \\ t_4 \end{array} \begin{array}{c} \begin{array}{cccc} P_1 & P_2 & P_3 & P_4 \end{array} \\ \begin{pmatrix} 1 & 0 & 0 & 0 \\ -1 & -1 & 1 & 0 \\ 0 & 1 & -1 & 1 \\ 0 & 0 & 0 & -1 \end{pmatrix} \end{array}$$

$\sigma_1$ = Firing Sequence : $t_1 t_2 t_3 t_4$

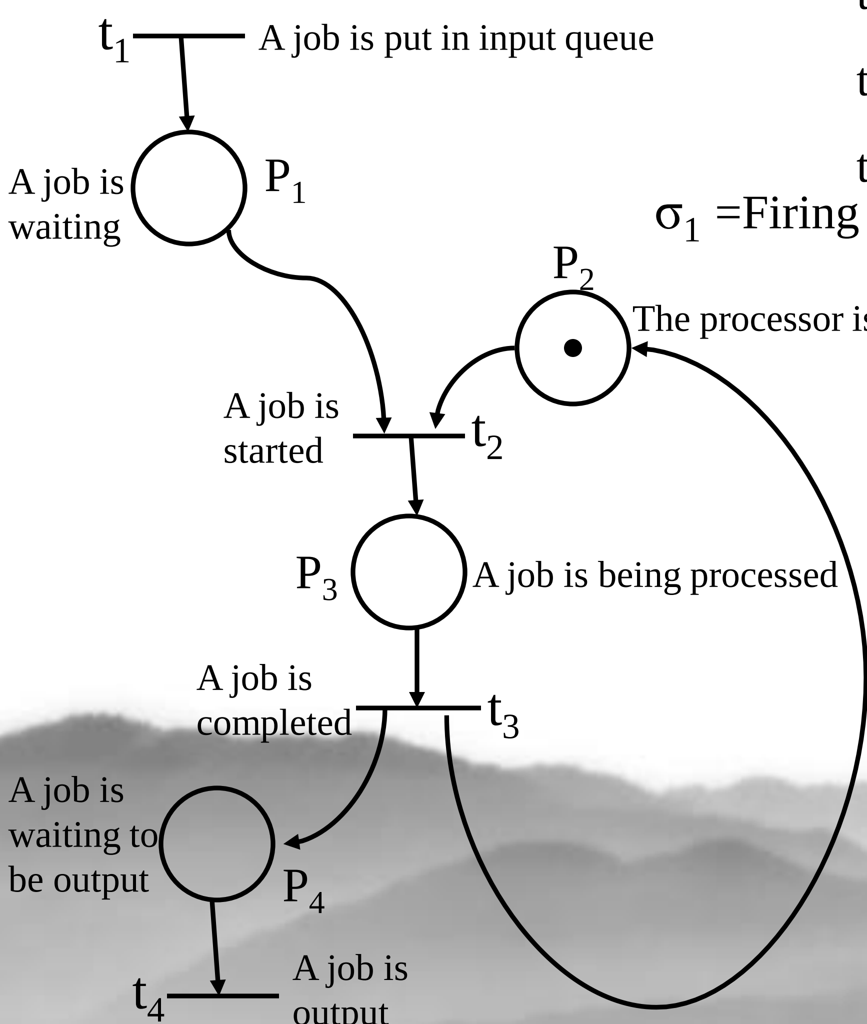



**Figure 3.3** Modeling of a simple computer system.

## "Reachability Graph"

| | $P_1$ | $P_2$ | $P_3$ | $P_4$ |
|---|---|---|---|---|
| $M_0=$ | [ 0 | 1 | 0 | 0 ] |
| $\downarrow t_1$ | | | | |
| $M_1=$ | [ 1 | 1 | 0 | 0 ] |
| $\downarrow t_2$ | | | | |
| $M_2=$ | [ 0 | 0 | 1 | 0 ] |
| $\downarrow t_3$ | | | | |
| $M_3=$ | [ 0 | 1 | 0 | 1 ] |

($t_4$: $M_3 \to M_0$)

Exp. $M_2 \overset{?}{=} A^T \cdot X + M_0$

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

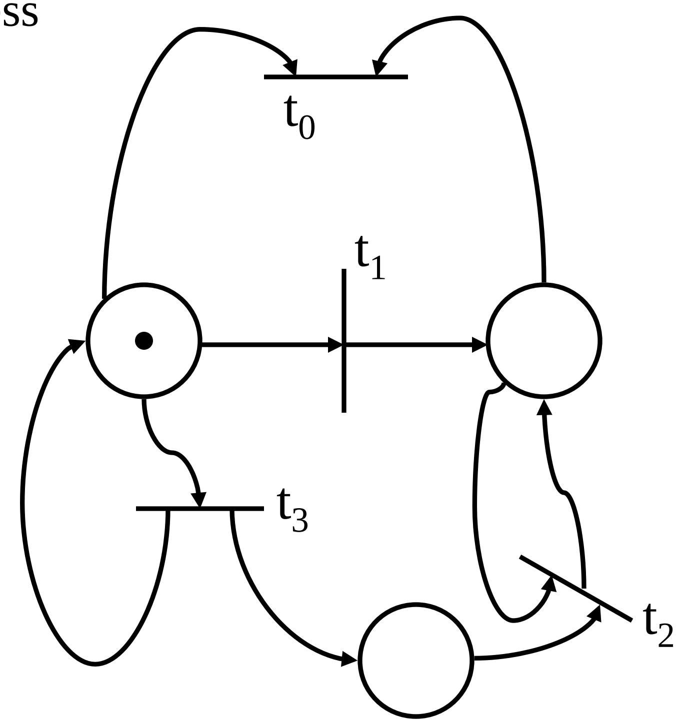
$$= \begin{bmatrix} 0 \\ -1 \\ 1 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \end{bmatrix}$$

$\therefore \sigma_2 = t_1 t_2$

$\therefore$ $M_2$ is reachable from $M_0$.

**"Liveness"** — different levels of liveness

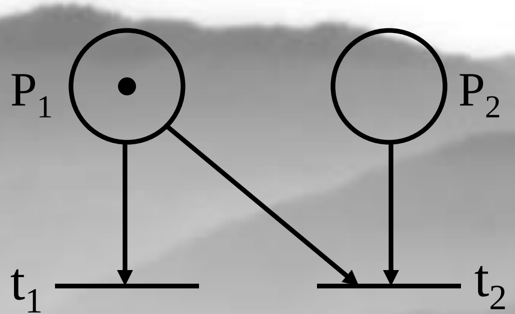
- L0 : dead
- L1 : at least once
- L2 : at least k times for a given $k \in N$
- L3 : $\infty$ - times
- L4 : L1 for all $M \in R(M_0)$




L4 ⟹ L3 ⟹ L2 ⟹ L1 ⟹ L0

| L4 | L3 | L2 | L1 | L0 |
|---|---|---|---|---|
| ($\forall M \in R(M_0)$, once) | ($\infty$ - times) | (k - times) | (once) | (dead) |
| | $t_3$ | $t_2$ | $t_1$ | $t_0$ |

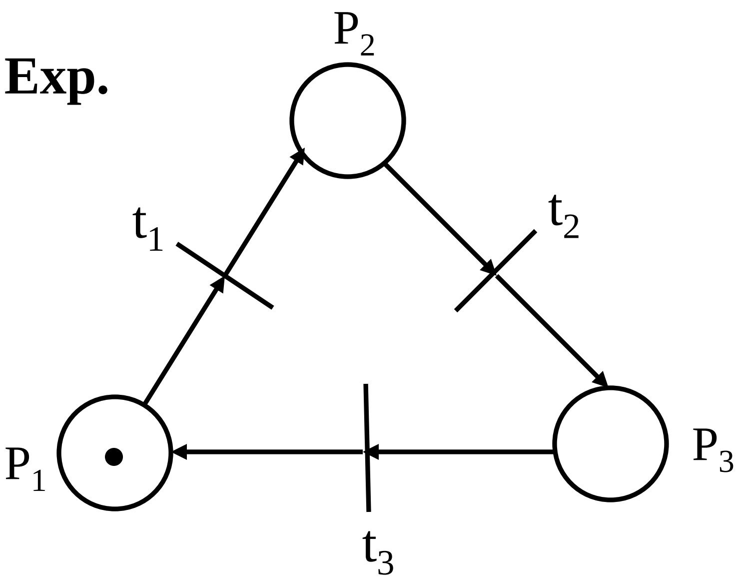
**"Persistence"**



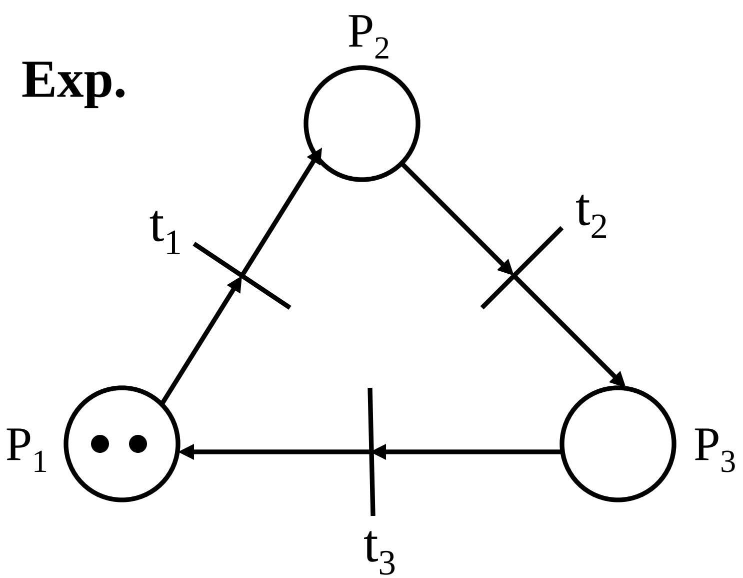

**a persistent PN.**

# "Synchronic Distance"

**Exp.**




**Exp.**




$\because \sigma = t_1 t_2 t_3 t_1 \ldots$

$\therefore d_{12} = \max| 2-1 | = 1$

$\because \sigma = t_1 t_1 t_2 t_2 t_3 t_3 t_1 t_1 \ldots$

$\therefore d_{12} = \max| 4-2 | = 2$

$$\mathbf{d_{12} = \max\{\sigma(t_1) - \sigma(t_2)\}}$$

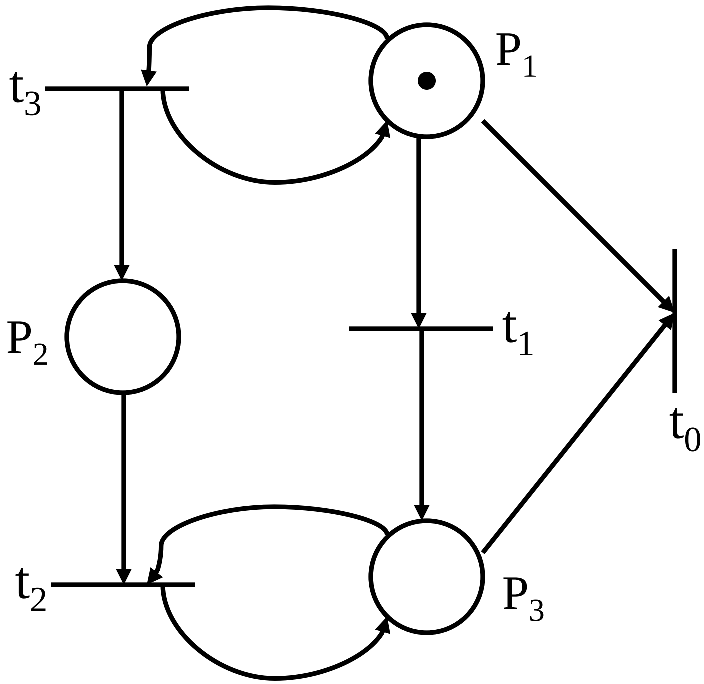
- **Structural Properties**
- **1) Structural Liveness: if there exists a live initial marking.**
- **2) Controllability: if any marking $M_n$ in PN is reachable from any initial marking $M_0$, Rank A=|p|**
- **3) Structural Bouundedness: if it exists > 0, Ay $\leqq$ 0**

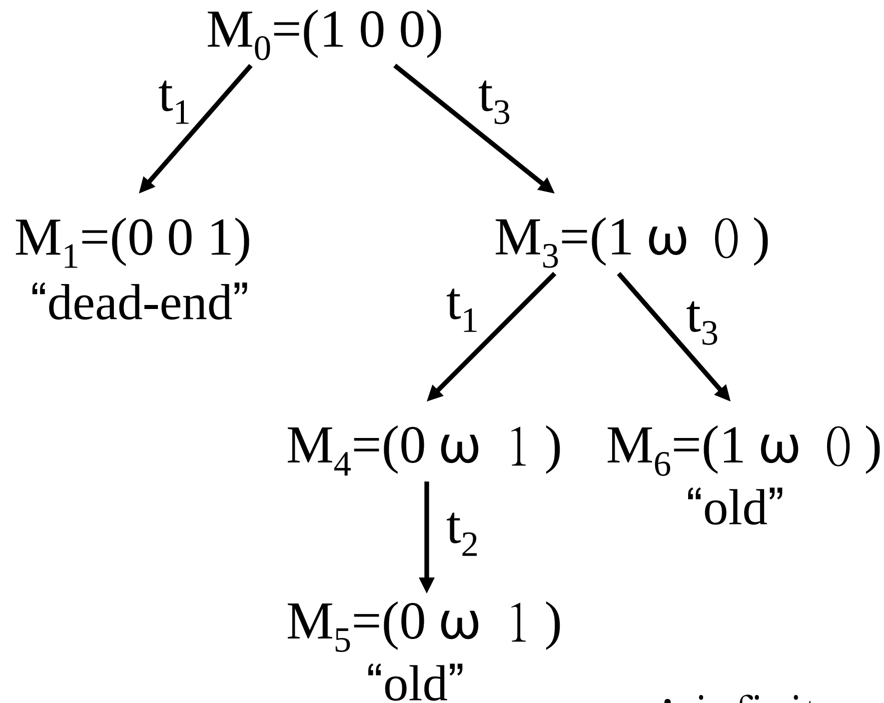
  **Y: place-vector**

# 3. Methods of Analysis

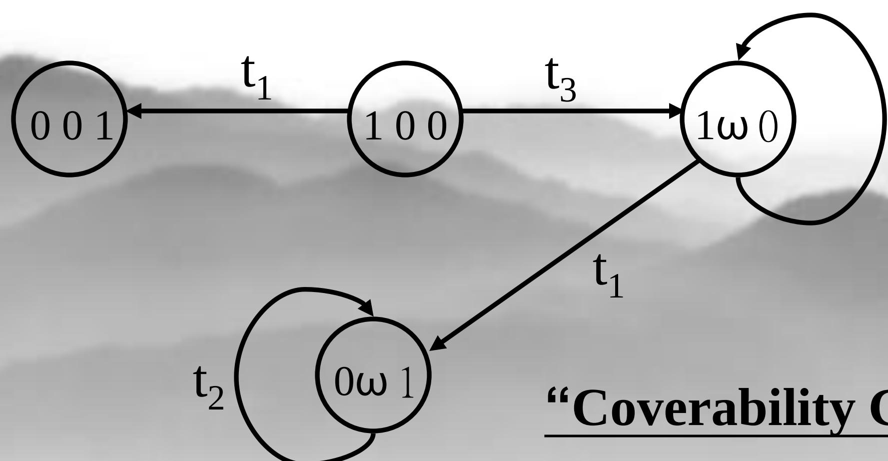
- Coverability Tree
- Incidence Matrix and State Equation
- Reduction Rules for Analysis

## “Coverability Tree”



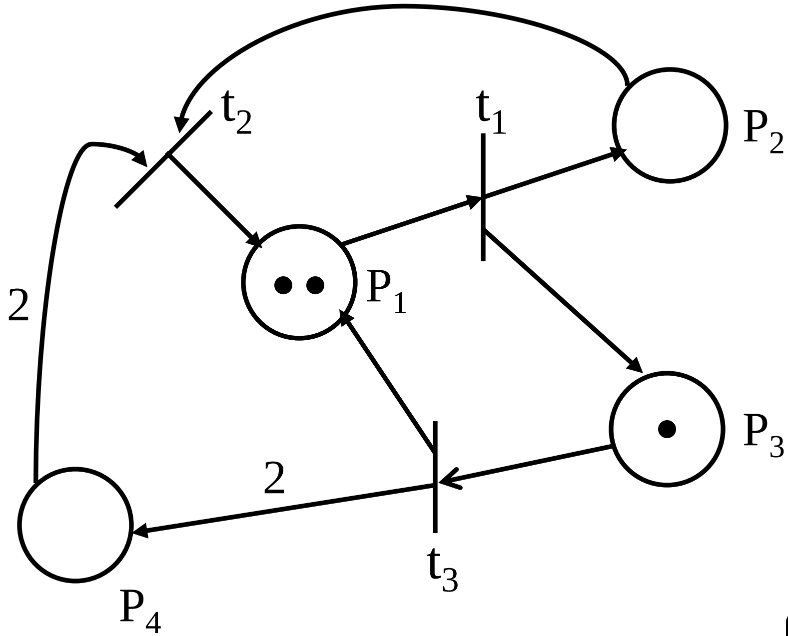




ω : infinity




## “Coverability Graph”

# "Incidence Matrix and State Equation"




$M_k = M_{k-1} + A^T \cdot X$ , k= 1,2,…

X : transition firing count vector

$A^T \cdot X = M_k - M_{k-1} = \triangle M$

$\triangle M = 0 \Rightarrow A^T \cdot X = 0$ …T-invariant

$A \cdot y = 0$ …S-invariant

$$
\begin{array}{c} \\ M_0 = \end{array}
\begin{array}{cccc} P_1 & P_2 & P_3 & P_4 \\ (\,2 & 0 & 1 & 0\,) \end{array}
$$

$$\downarrow t_3$$

$$M_1 = (\,3 \quad 0 \quad 0 \quad 2\,)$$

$$\downarrow$$

$$\vdots$$

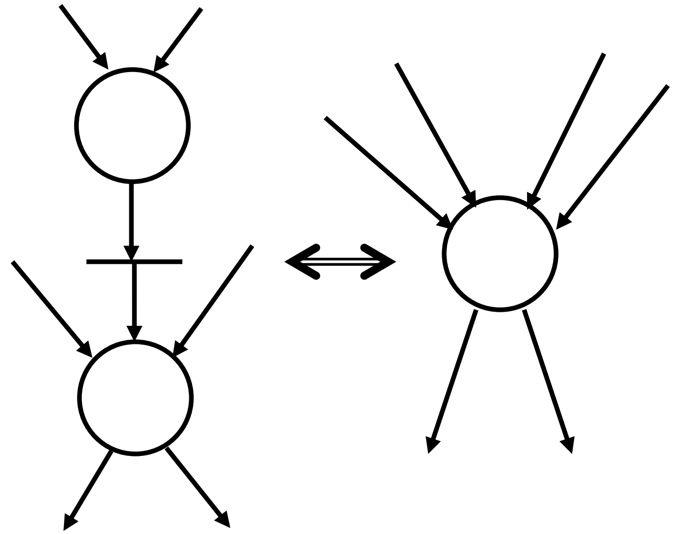
$M_1 = M_0 + A^T \cdot X$

$$
\begin{pmatrix} 3 \\ 0 \\ 0 \\ 2 \end{pmatrix} = \begin{pmatrix} 2 \\ 0 \\ 1 \\ 0 \end{pmatrix} + \begin{array}{c} \\ P_1 \\ P_2 \\ P_3 \\ P_4 \end{array} \begin{array}{c} \begin{array}{ccc} t_1 & t_2 & t_3 \end{array} \\ \begin{pmatrix} -1 & 1 & 1 \\ 1 & -1 & 0 \\ 1 & 0 & -1 \\ 0 & -2 & 2 \end{pmatrix} \end{array} \cdot \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \begin{array}{c} t_1 \\ t_2 \\ t_3 \end{array}
$$

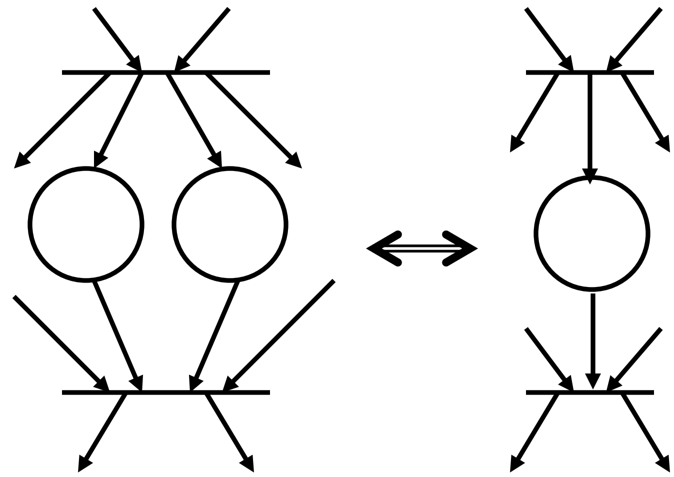
$\therefore M_1$ is reachable from $M_0$ .

## "Reduction Rules for Analysis"：preserving liveness, safeness, and boundedness

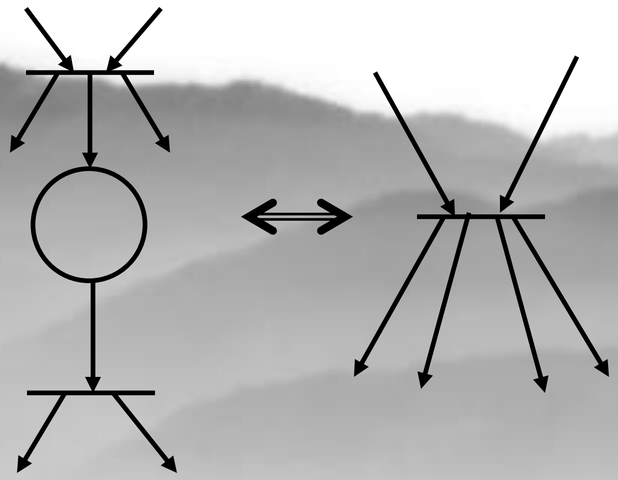
### 1)Fusion of Serial Places (FSP)



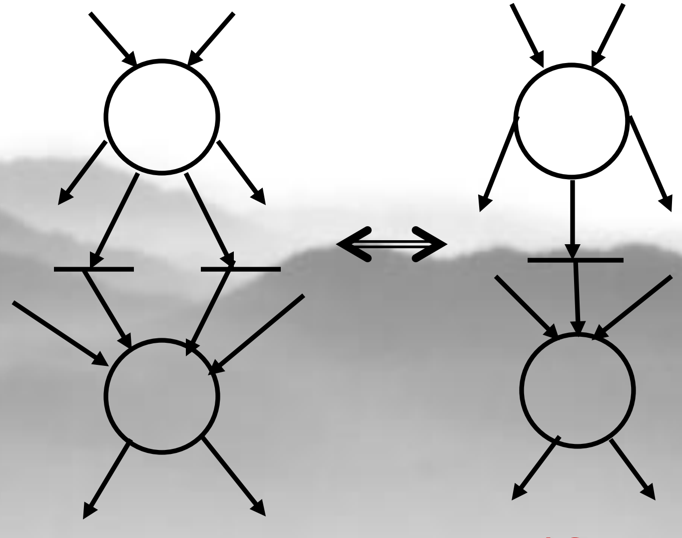
### 3)Fusion of Parallel Places (FPP)



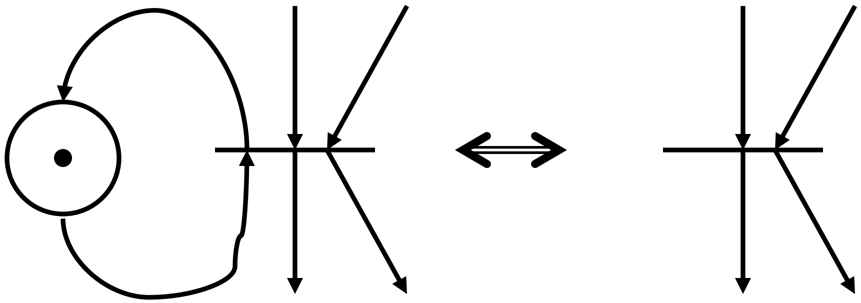
### 2)Fusion of SerialTransitions(FST)



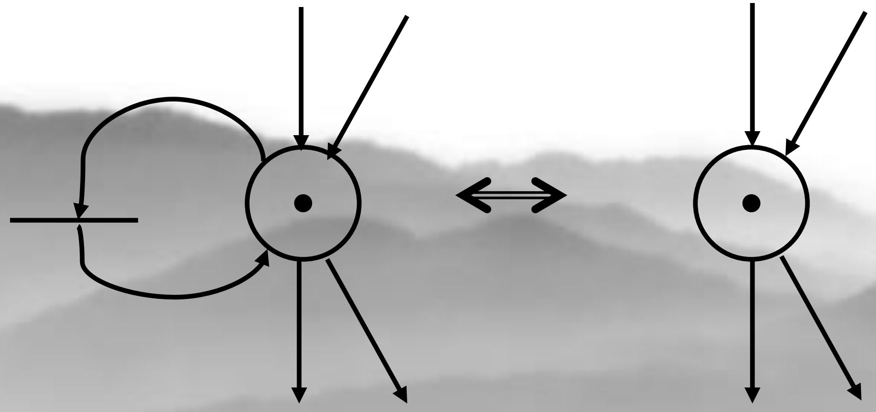
### 4)Fusion of Parallel Transitions(FPT)



## 5)Elimination of Self-loop Places(ESP)



## 6)Elimination of Self-loop Transitions(EST)



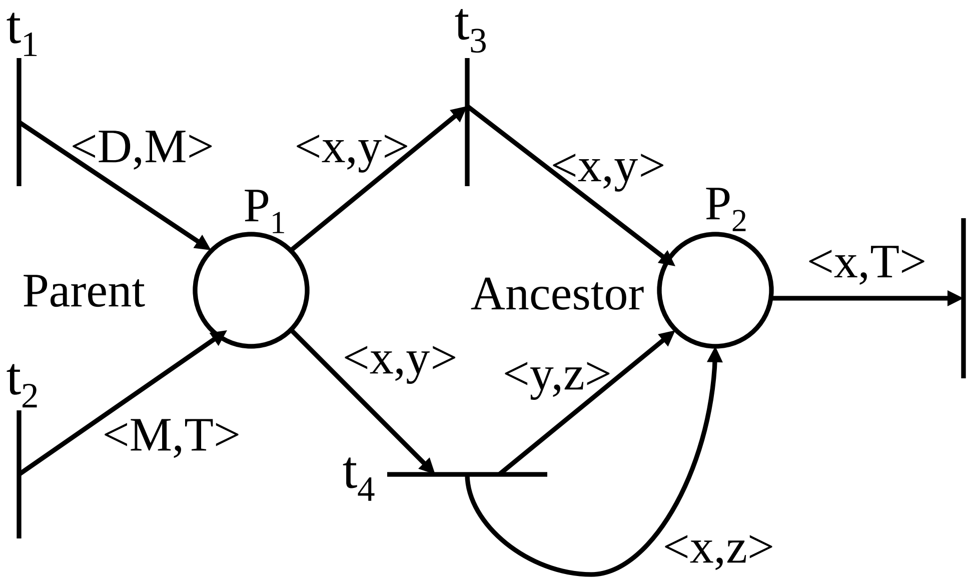
# 4. Predicate/Transition Net ( PrT Net )

- **Definition 4.1:* Let $\Omega = (P, T, F, L)$ be a 4-tuple such that
- (1) $(P, T, F)$ is a Petri net structure,
- (2) $L : F \rightarrow W \cup \ldots \cup W\ n$, where $W$ is a set of terms and $n$ is some integer value,
- (3) $\forall p \in P$ and $\forall x, y\ \ \{L((a,b)) \mid \{p\} \cap \{a, b\} \neq \varnothing\}$, we have $\propto(x) = \propto(y)$,
- then $\Omega$ is called a predicate/transition net (PrT net). The elements of $P$, $T$, $F$, and $L$ are called $\Omega$-predicates, $\Omega$-transitions, $\Omega$-arcs and $\Omega$-arc-labels, respectively. $\propto(x)$ in (3) defines the arity of the $\Omega$-predicate $p \in P$.
- In particular, a place can be viewed as a *precondition* or *postcondition*; a transition as an *event*; and an arc-label as a *data item*.

# Example 4.1 :

- Parent (David, Mary) ←
- Parent (Mary, Tom) ←
- Ancestor (x, y) ← Parent (x, y)
- Ancestor (x, z) ← Parent (x, y), Ancestor (y, z)
- ← Ancestor (x, Tom)

## Exp.4.1-PrT Net




$A^T \cdot X=0 \ldots$ T-invariant

$$X_1=\begin{array}{c} t_1 \\ t_2 \\ t_3 \\ t_4 \\ t_5 \end{array}\begin{pmatrix} \psi \\ \{\} \\ \{M|x,T|y\} \\ \psi \\ \{M|x\} \end{pmatrix} \quad \sigma_1=t_2t_3t_5$$

$$A=\begin{array}{c} \\ t_1 \\ t_2 \\ t_3 \\ t_4 \\ t_5 \end{array}\begin{array}{cc} \text{Parent}(P_1) & \text{Ancestor}(P_2) \\ \hline \langle D,M\rangle & 0 \\ \langle M,T\rangle & 0 \\ -\langle x,y\rangle & \langle x,y\rangle \\ -\langle x,y\rangle & -\langle y,z\rangle+\langle x,z\rangle \\ 0 & -\langle x,T\rangle \end{array}$$

$$X_2=\begin{array}{c} t_1 \\ t_2 \\ t_3 \\ t_4 \\ t_5 \end{array}\begin{pmatrix} \{\ \} \\ \{\ \} \\ \{M|x,T|y\} \\ \{D|x,M|y,T|z\} \\ \{D|x\} \end{pmatrix} \quad \sigma_2=t_1t_2t_3t_4t_5$$

∴Answer：x=Mary&David

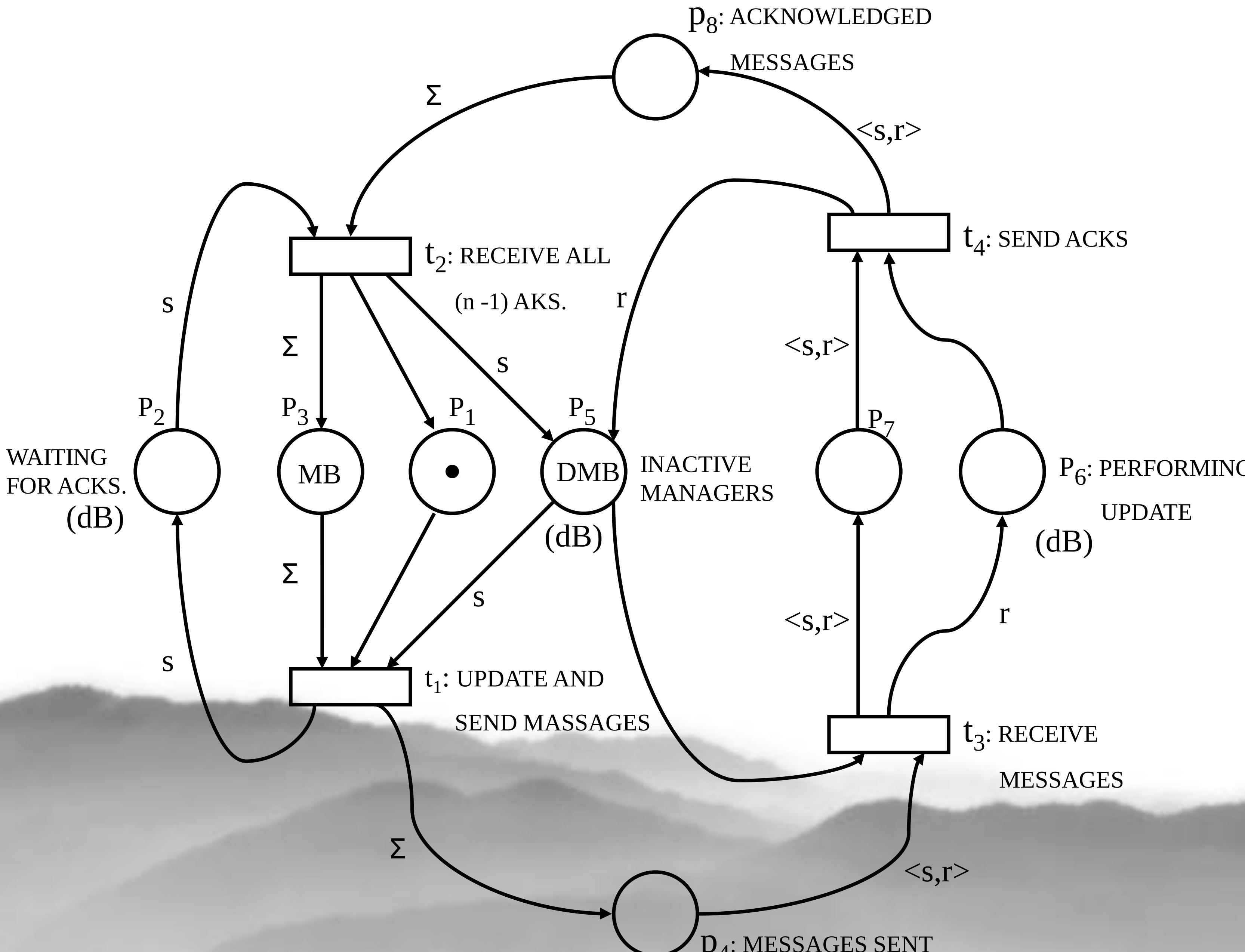



**Figure 3.21. A distributed database system model.**

# 5. High-Level Fuzzy Petri Net

- Definition 5.1: *HLFPN*
- The high-level fuzzy Petri net (HLFPN) is defined as an 8-tuple:
- $HLFPN = (P, T, F, C, V, \alpha, \beta, \delta)$,
- where
- $P = \{p_1, p_2, p_3, ..., p_k\}$ is a finite set of places;
- $T = \{t_1, t_2, t_3, ..., t_l\}$ is a finite set of transitions;
- $P \cup T \neq \emptyset$;
- $F \subseteq (P \times T) \cup (T \times P)$ is called the *flow relation* and is also a finite set of arcs, each representing the fuzzy set (i.e. fuzzy term) for an antecedent or a consequent; where the positive arcs (i.e. *THEN* parts) are denoted by $\rightarrow$;
- $C =$ a finite set of linguistic variables, e.g. $X$, $Y$, and $Z$;
- where $X = \{x_1, x_2, ..., x_n\}$, $Y = \{y_1, y_2, ..., y_m\}$, $Z = \{z_1, z_2, ..., z_q\}$;
- $V$ is known as the *fuzzy relational matrix* between the antecedent and the consequent of each rule;
- $\alpha : P \rightarrow C$ is an association function mapping from places to linguistic variables,

# 5. High-Level Fuzzy Petri Net (continued)

- $\alpha(p_i) = c_i$, $i = 1, ..., n$, where $C = \{ c_i \}$ is the set of linguistic variables in the knowledge base ( KB ) and $n$ denotes the number of linguistic variables in KB;
- $\beta : F \rightarrow [0, 1]$ is an association function mapping from the flow relation to the fuzzy truth values between zero and one (i.e. fuzzy sets);
- $\delta : T \rightarrow V$ is an association function mapping from the transition to the fuzzy relational matrix.

- * *R1*: IF it($X_1$) is hot($A_1$) AND the sky($X_2$) is cloudy($A_2$) THEN the humidity($Y$) is high($B$).
- $R_1$': IF $X_1(A_1)$ AND $X_2(A_2)$ Then $Y(B)$.

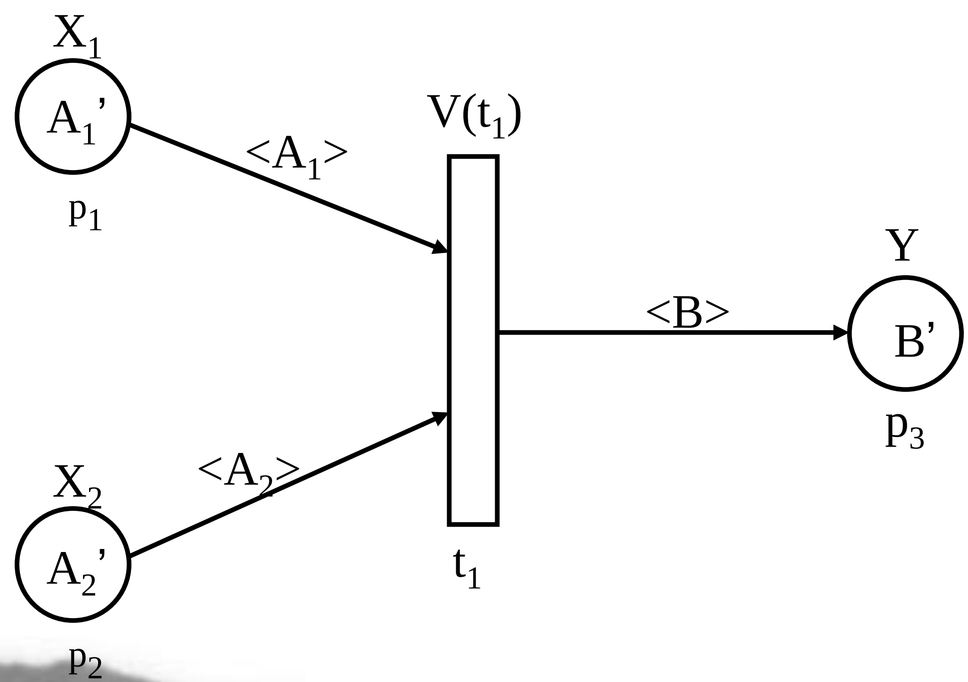



**Fig. 1.HLFPN for Example 2.2.**

# Example 5.1 :

- Consider that a set of three rules is shown as follows.
- $R_1$: IF $X_1$ is $A$ AND $X_2$ is $B$ THEN $Y_1$ is $C$.
- $R_2$: IF $X_2$ is $B$ AND $X_3$ is $D$ THEN $O$ is $E$.
- $R_3$: IF $Y_1$ is $C$ THEN $O$ is $F$.

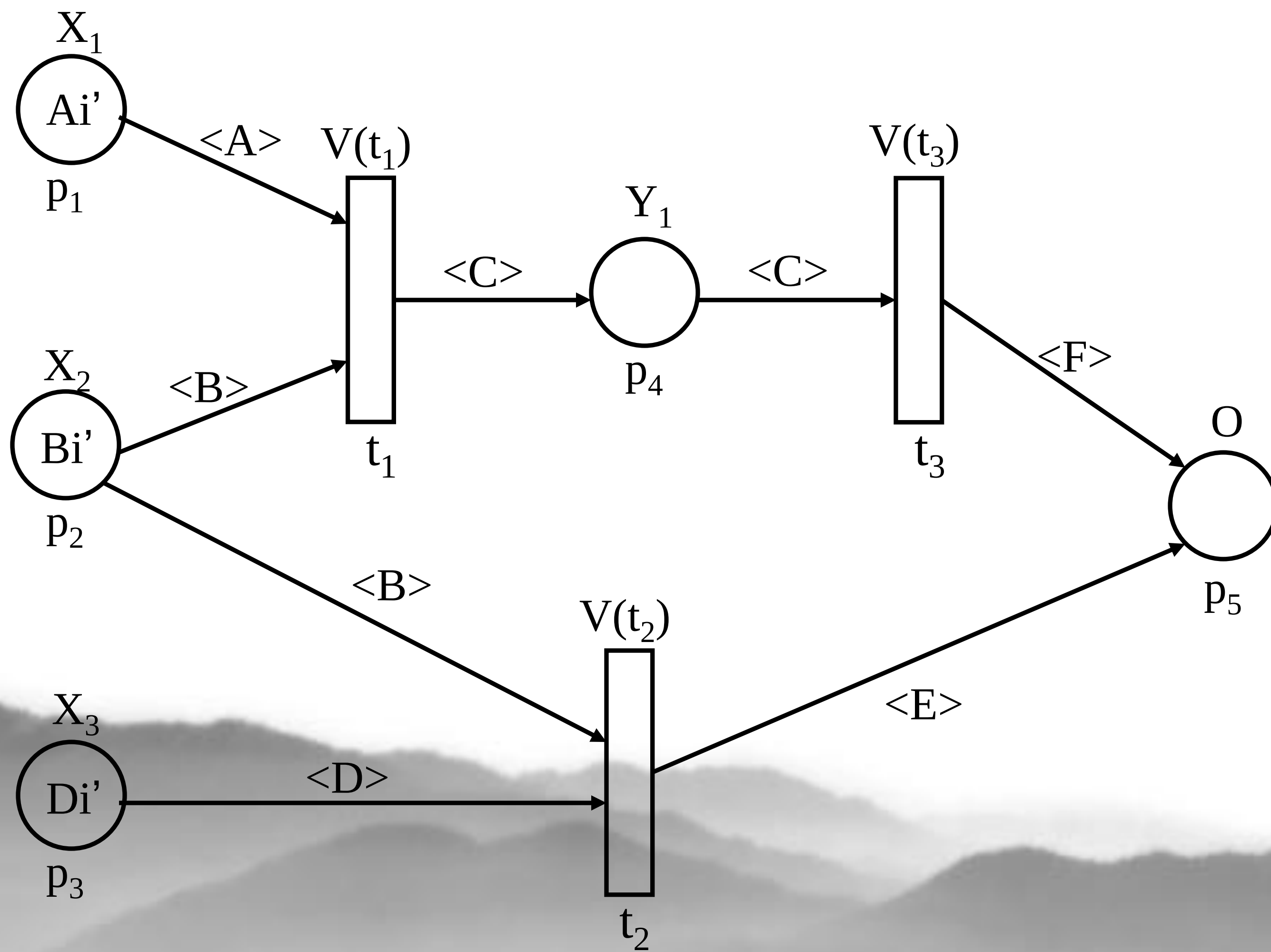



**Fig. 8. HLFPN for Example 5.1.**

# Example 5.2 : Temperature Control System

- In the temperature control system, a sensor is used to measure the current temperature in a room and obtain the temperature error by deducting the desired temperature from the real current temperature. Moreover, an electric heater is used to adjust the room temperature by tuning its electric power.
- Assume that the temperature error(E) is an input linguistic variable with fuzzy terms: high(H), zero(Z), and low(L);and the electric power(P) is an output linguistic variable with fuzzy terms: large(LA), medium(M), and small(S). Consider the following fuzzy production rules:
- $R_1$ : IF E is H THEN P is S.
- $R_2$ : IF E is L THEN P is LA.
- $R_3$ : IF E is Z THEN P is M.
- Fig. 13 illustrates an example of the HLFPN model representing the above three rules.

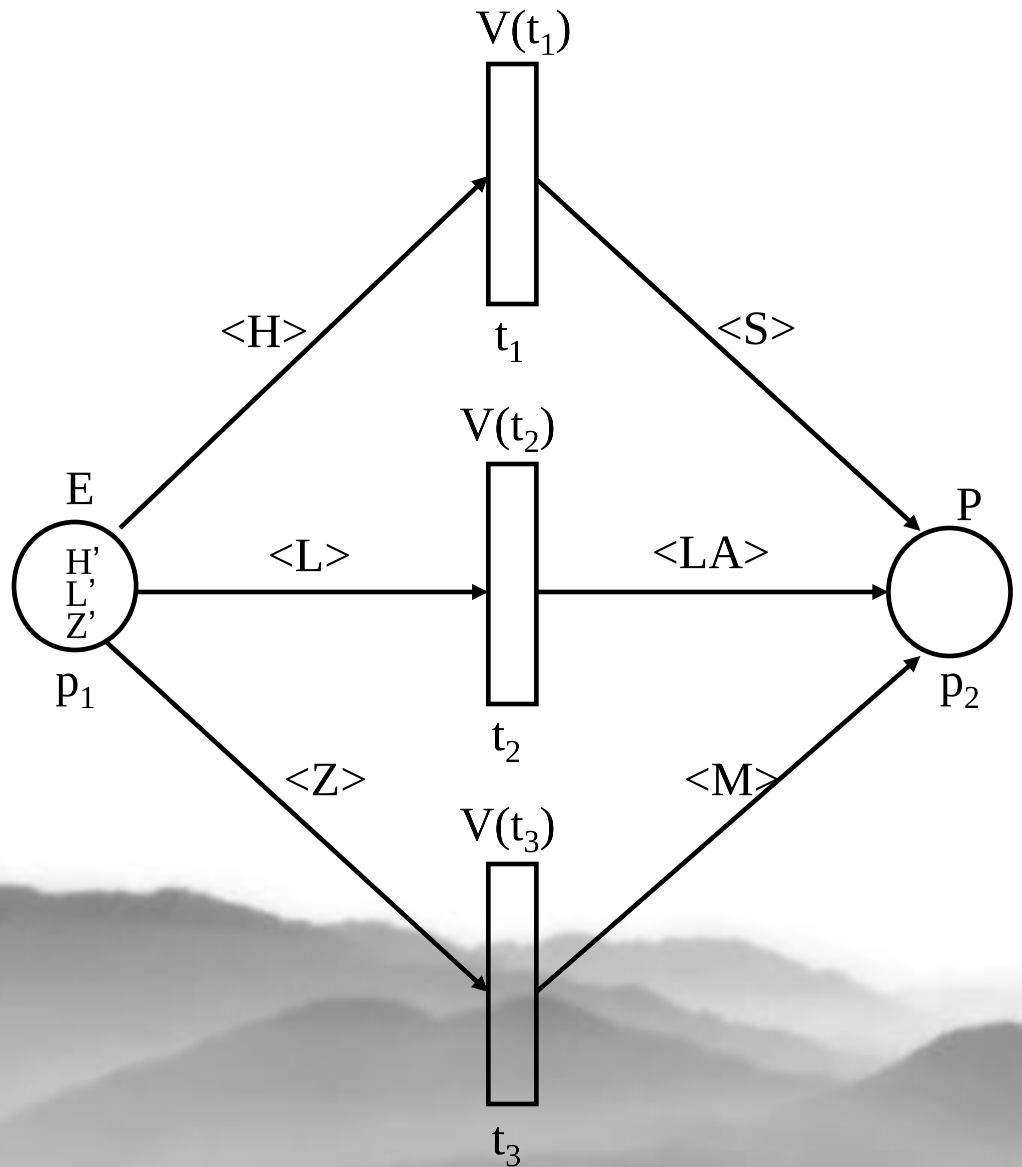



**Fig. 13.HLFPN for Example 5.2.**

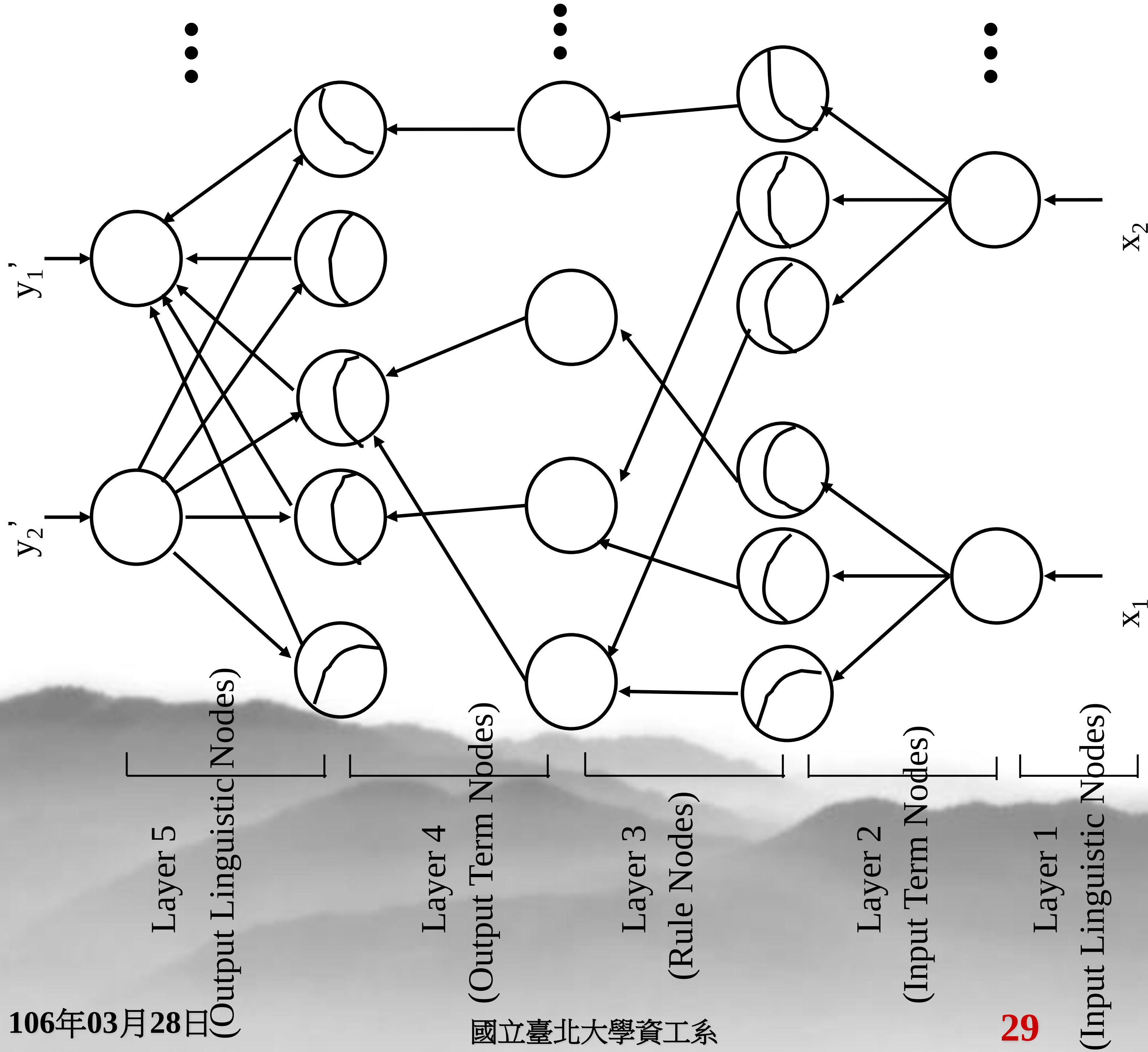



**Fig. 5. FALCON Structure.**

# Table 1: Functional Comparisons

| Items / Approaches | Data Structure | Information Storage | Type of Fuzzy Sets | Outputs Generation | Applicability | Learning Flexibility |
|---|---|---|---|---|---|---|
| HLFPN | Compact | Small | Discrete | Parallel | Broad | Yes |
| FALCON | Complex | Large | Continuous | Serial | Limited | No |

# Table 2: HLFPN *vs.* FALCON

| Average CPU Time (seconds) | HLFPN | | FALCON | |
|---|---|---|---|---|
| | Supervised | Unsupervised | Supervised | Unsupervised |
| *Fuzzy Car* | 3.6 | 4.7 | 5.9 | 6.3 |
| *Manufacturing Scheduling* | 2.3 | 3.8 | 4.8 | 6.1 |
| *Inverted Pendulum* | 3.7 | 4.9 | 6.2 | 7.9 |
| *Turning Force System* | 8.7 | 9.8 | 10.2 | 12.7 |

# 6. Applications

- Specifications and Verifications
- Computer Operating Systems
- Computer Software Systems
- Computer Hardware Systems
- Legal Systems
- Office Information System
- Formal Language Theory
- Communication Protocols
- Operational Research
- Chemical Systems
- Distributed Database Systems
- Factory Automation
- Performance Evaluation

# 7. Conclusions

* Verification, Simulation, and Performance Evaluation

* Natural Science and Social Science

* Broad Applications

* Thank you all for your attention!

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# 有關 Petri Nets 的影片

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# Petri Net Tools

- **HPSim (**Henryk Petri Simulator**)**
- **PIPE 2 (**Platform Independent Petri net Editor 2**)**
- **WoPeD (**Workflow Petri net Designer**)**


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