

NPTEL ONLINE CERTIFICATION COURSES

Course Name: Fuzzy logic and Neural Networks

Faculty Name: Prof. D. K. Pratihar

Department : Mechanical Engineering

Week 7

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Topic

Lecture 07: Optimal Design of Neural Networks

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CONCEPTS COVERED

Concepts Covered:

- Evolution of Neural Networks (NNs) using Nature-inspired Optimization Tool (say Genetic Algorithms)

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Combined Genetic Algorithms and Neural Network

Genetic-Neural System (GNS)

- To improve the performance of an NN using a GA.

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Approaches

Approach 1: - GA-based tuning of connecting weights, bias values and other parameters

- **Biological Adaptation: Evolution and Learning**
- **Concept of Evolutionary Robotics**
- **Comparisons with BPNN**

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Approaches (Contd.)

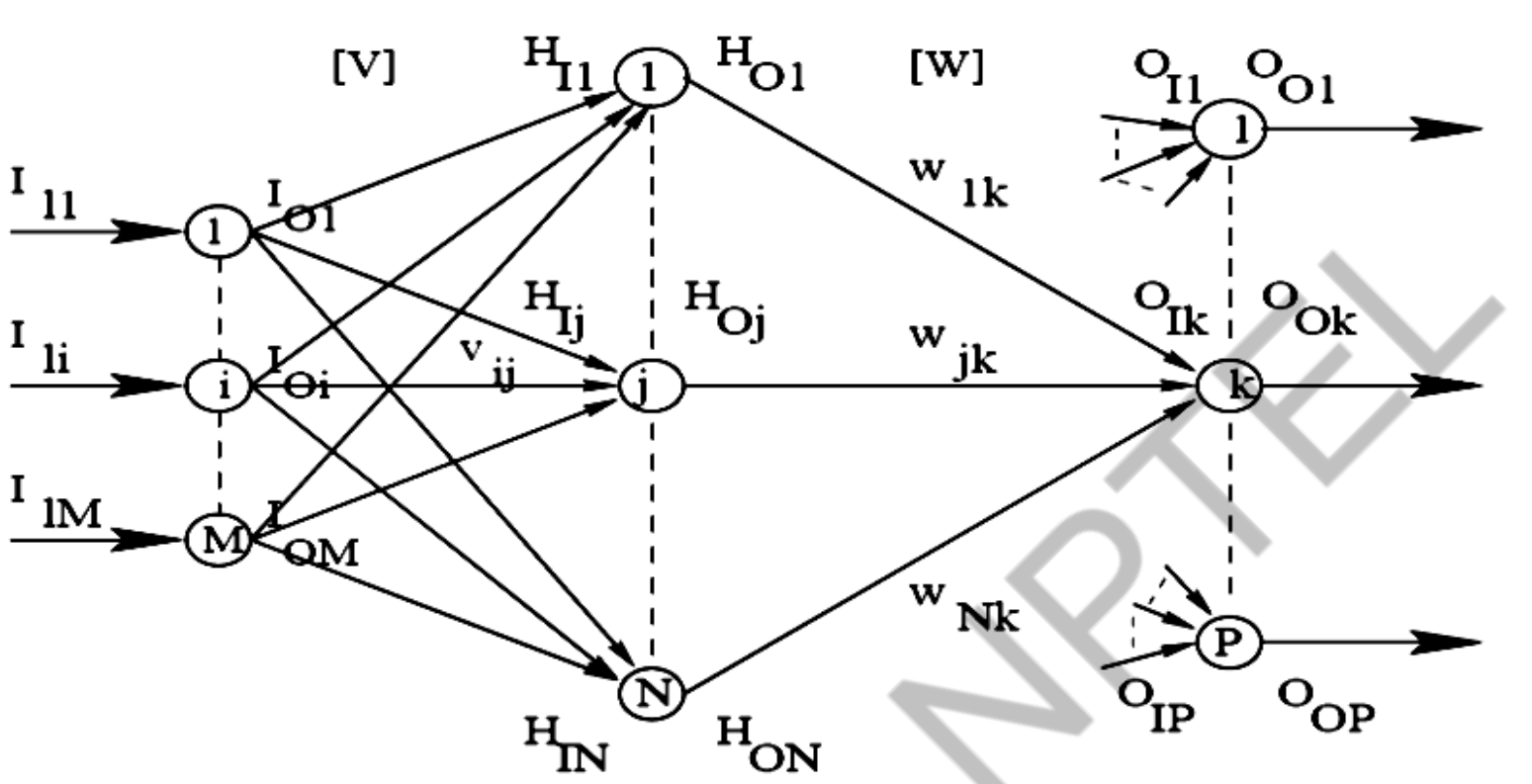
Approach 2:- GA-based tuning of neural network topologies

- **Topology is decided by the number of hidden layer(s) and no. of neurons present in the hidden layer(s)**

- **Variable string-length GA**

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Working Principle of GNS



Input Layer	Hidden Layer	Output Layer
M neurons	N neurons	P neurons
Linear T.F.	Log–sigmoid T.F.	Tan–sigmoid T.F.

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- **Error in prediction of k-th output neuron**

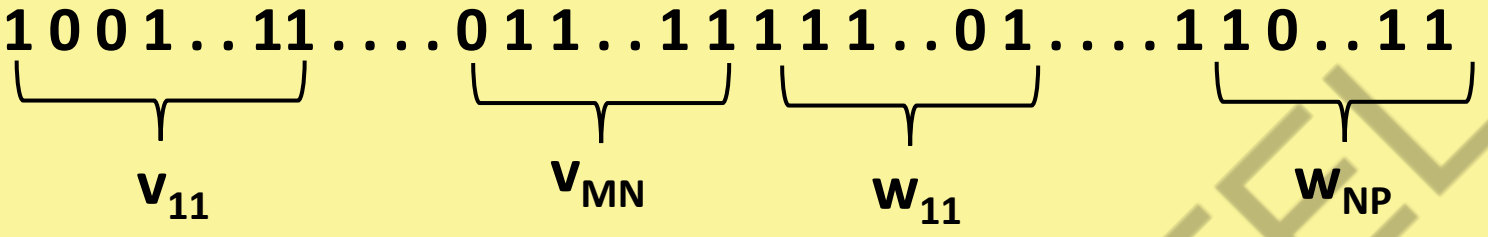
$$E_k = \frac{1}{2}(T_{Ok} - O_{Ok})^2$$

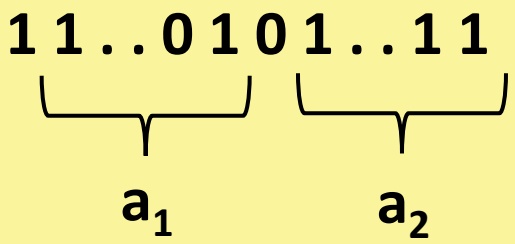
•Total error in prediction considering all the output neurons

$$E = \sum_{k=1}^{P} \frac{1}{2}(T_{Ok} - O_{Ok})^2$$

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A typical GA-string:





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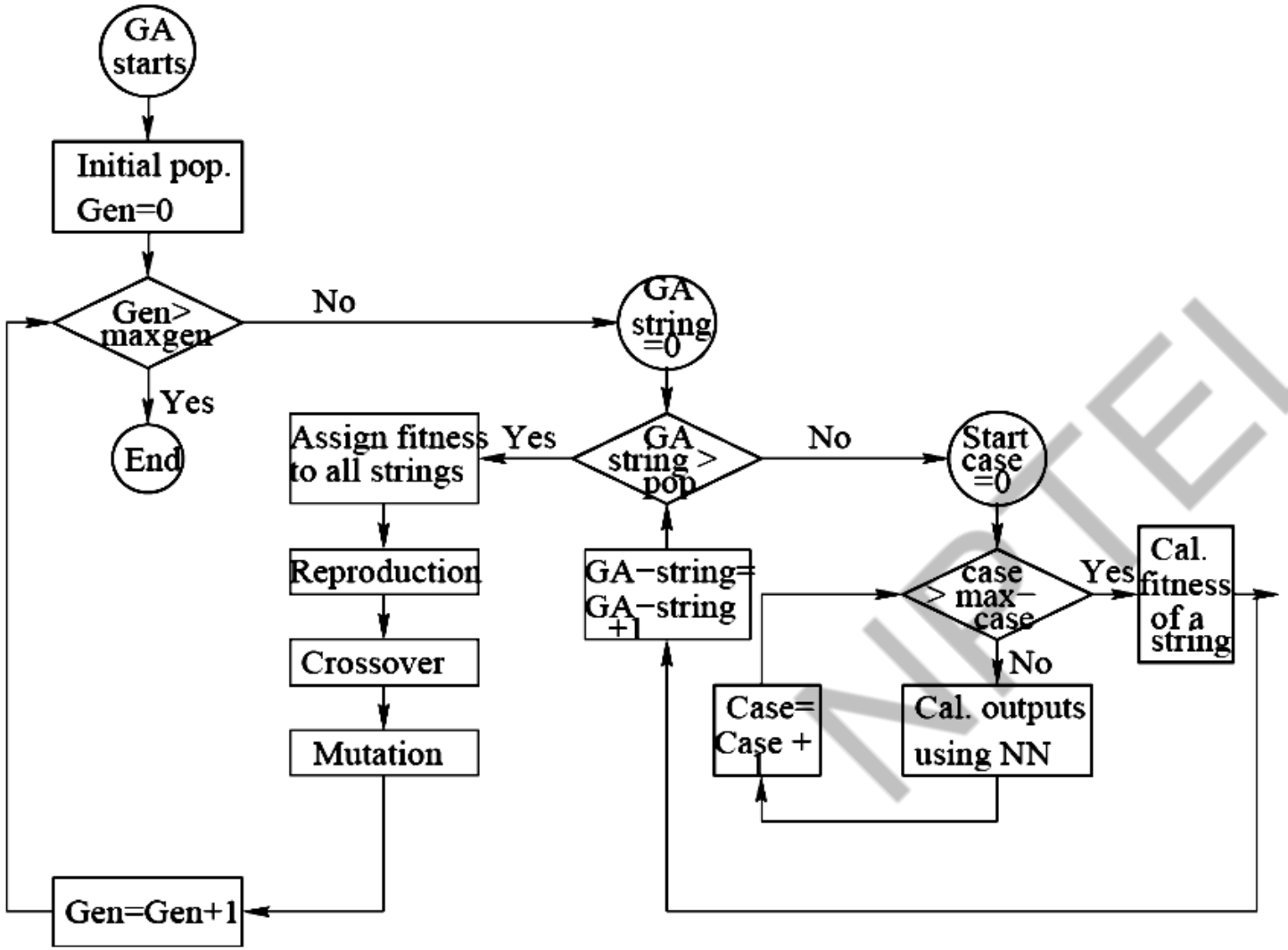
Batch Mode of Training

- **Fitness of the GA-string**

$$f = \frac{1}{L}\frac{1}{P}\sum_{l=1}^{L}\sum_{k=1}^{P}\frac{1}{2}\left(T_{Okl} - O_{Okl}\right)^2$$

where L: No. of training scenarios

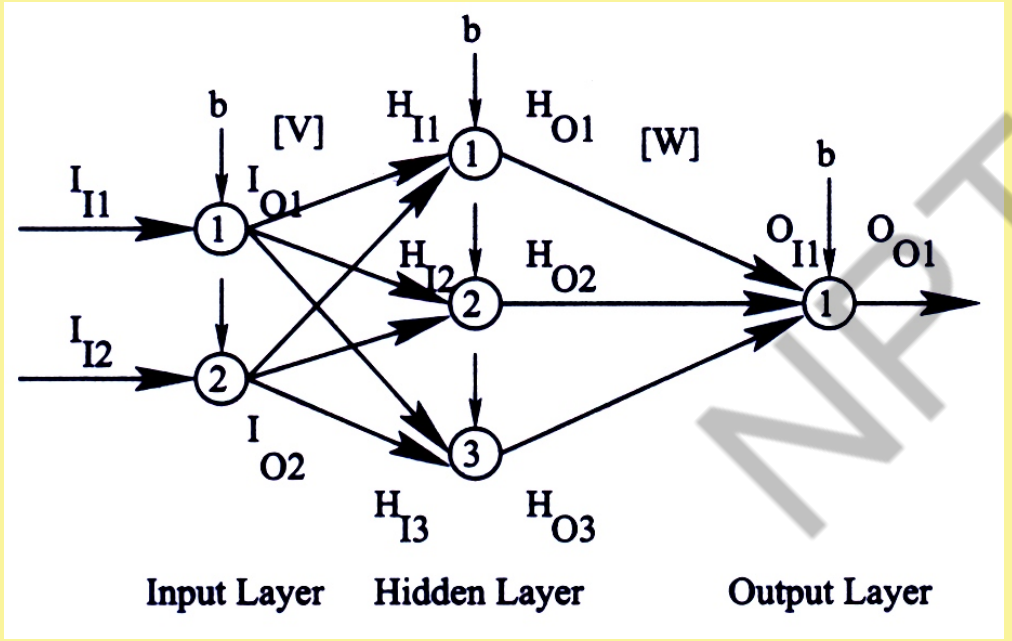
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GA starts
Initial pop. Gen=0
Gen> maxgen
No
Yes
End
GA string =0
GA string > pop
Yes
No
Assign fitness to all strings
Reproduction
Crossover
Mutation
Gen=Gen+1
GA−string= GA−string +1
Start case =0
case > max− case
Yes
No
Case= Case +
Cal. outputs using NN
Cal. fitness of a string

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Numerical Example

- A binary-coded GA is to be used to update the connecting weights, bias value and coefficients of transfer functions of an NN shown in the figure given below.



A 2-3-1 fully connected feed-forward NN

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- The neurons of input, hidden and output layers are assumed to have transfer functions of the form: $y = x, \quad y = \frac{1}{1+e^{-a_1 x}}, y = \frac{e^{a_2 x} - e^{-a_2 x}}{e^{a_2 x} + e^{-a_2 x}}$, respectively. The weights: *[V], [W]* vary in the range of 0.0 to 1.0. The bias value *b* varies in the range of 0.001 to 0.01. Both the coefficients of transfer functions: a_1, a_2 are assumed to vary in the range of (0.5, 2.0). The table shows one of the training cases. One of the GA-strings is given below, in which five bits are used to represent each real variable.

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Table: Training cases

Sl. No.	I_1	I_2	O
1	0.6	0.7	0.9
. . .	. . .	. . .	. . .
L	-	-	-

$$\underbrace{10110}_{v_{11}}\ \underbrace{01101}_{v_{12}}\ \underbrace{10001}_{v_{13}}\ \underbrace{01011}_{v_{21}}\ \underbrace{11011}_{v_{22}}\ \underbrace{00011}_{v_{23}}\ \underbrace{11001}_{w_{11}}\ \underbrace{11110}_{w_{21}}\ \underbrace{11101}_{w_{31}}\ \underbrace{10101}_{a_1}\ \underbrace{01110}_{a_2}\ \underbrace{11000}_{b}$$

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- **Determine the deviation in prediction for the training case shown in the above table, corresponding to the above GA-string.**

Solution:

- The variable v_{11} is represented by the binary sub-string 10110. Its decoded value is found to be equal to 22. It varies in the range of (0.0,1.0). Using the linear mapping rule, its real value can be determined as follows:

$$v_{11} = 0.0 + \frac{1.0 - 0.0}{2^5 - 1} \times 22 = 0.709677$$

- Similarly, the real values of all variables represented by the above GA-string can be calculated and those are shown in the following table.

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Table: Real values of the variables represented by a GA-string

Sl. No.	Variable	Binary String	Decoded value	Range	Real value
1	v_{11}	10110	22	0.0, 1.0	0.709677
2	v_{12}	01101	13	0.0, 1.0	0.419355
3	v_{13}	10001	17	0.0, 1.0	0.548387
4	v_{21}	01011	11	0.0, 1.0	0.354839
5	v_{22}	11011	27	0.0, 1.0	0.870968
6	v_{23}	00011	03	0.0, 1.0	0.096774
7	w_{11}	11001	25	0.0, 1.0	0.806452
8	w_{21}	11110	30	0.0, 1.0	0.967742
9	w_{31}	11101	29	0.0, 1.0	0.935484
10	a_1	10101	21	0.5, 2.0	1.516129
11	a_2	01110	14	0.5, 2.0	1.177419
12	b	11000	24	0.001, 0.01	0.007968

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- The outputs of the neurons of input layer are calculated as follows:

$$I_{O1} = I_{I1} + b = 0.6 + 0.007968 = 0.607968$$

$$I_{O2} = I_{I2} + b = 0.7 + 0.007968 = 0.707968$$

- The inputs of different neurons of hidden layer after adding the bias value is turning out to be like the following:

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$$H_{I1} + b = I_{O1} \times v_{11} + I_{O2} \times v_{21} + 0.007968 = 0.690644$$

$$H_{I2} + b = I_{O1} \times v_{12} + I_{O2} \times v_{22} + 0.007968 = 0.879539$$

$$H_{I3} + b = I_{O1} \times v_{13} + I_{O2} \times v_{23} + 0.007968 = 0.409883$$

- **The outputs of hidden neurons are found to be as follows:**

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$$H_{O1} = 0.740219$$

$$H_{O2} = 0.791418$$

$$H_{O3} = 0.650545$$

The input of the neuron lying on output layer after adding the bias value is turning out to be like the following:

$$O_{I1} + b = H_{O1} \times w_{11} + H_{O2} \times w_{21} + H_{O3} \times w_{31} + b$$

$$= 1.971413$$

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The output of the network is found to be as follows:

$$O_{O1} = \frac{e^{a_2(O_{I1}+b)} - e^{-a_2(O_{I1}+b)}}{e^{a_2(O_{I1}+b)} + e^{-a_2(O_{I1}+b)}} = 0.981265$$

Now, the target output for this training case, is equal to 0.9 (refer to the table). Thus, the deviation in prediction is found to be equal to $0.9 - 0.981265 = -0.081265$

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References

References:

D.K. Pratihar Soft Computing: Fundamentals and Applications. New Delhi, India: Narosa Publishing House, 2014.

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Conclusion

Conclusion:

Optimization/Evolution of NNs using a GA: Genetic-Neural System

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Lecture 08: Neuro-Fuzzy Systems

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CONCEPTS COVERED

Concepts Covered:

- Neuro-Fuzzy System (Mamdani Approach)
- Neuro-Fuzzy System (Takagi & Sugeno's Approach)

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Combined Neural Networks and Fuzzy Logic

Neural Networks have been combined with Fuzzy Logic technique in two different ways:

1. Neuro-Fuzzy System (NFS)

- A Fuzzy Logic Controller (FLC) is represented using the structure of an NN and trained using either a BP algorithm or a GA

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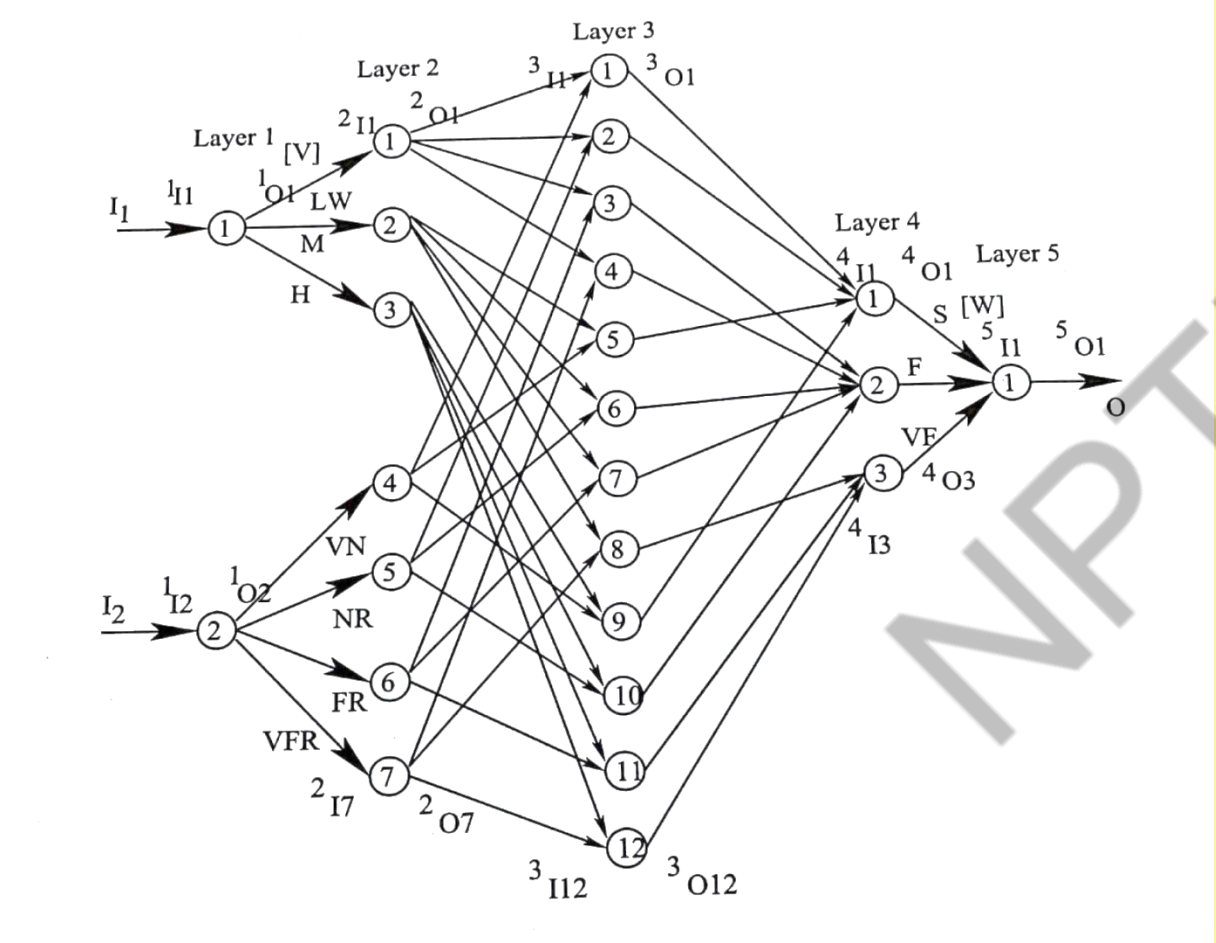
2. Fuzzy Neural Network (FNN)

- The Neurons of an NN has been designed using the concept of fuzzy set theory

- An FNN has been developed in the following ways:
  I. Real inputs but fuzzy weights
  II. Fuzzy inputs but real weights
  III. Fuzzy inputs and fuzzy weights

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Neuro-Fuzzy System (NFS) based on Mamdani Approach



Layer 1: Input Layer

Layer 2: Fuzzification

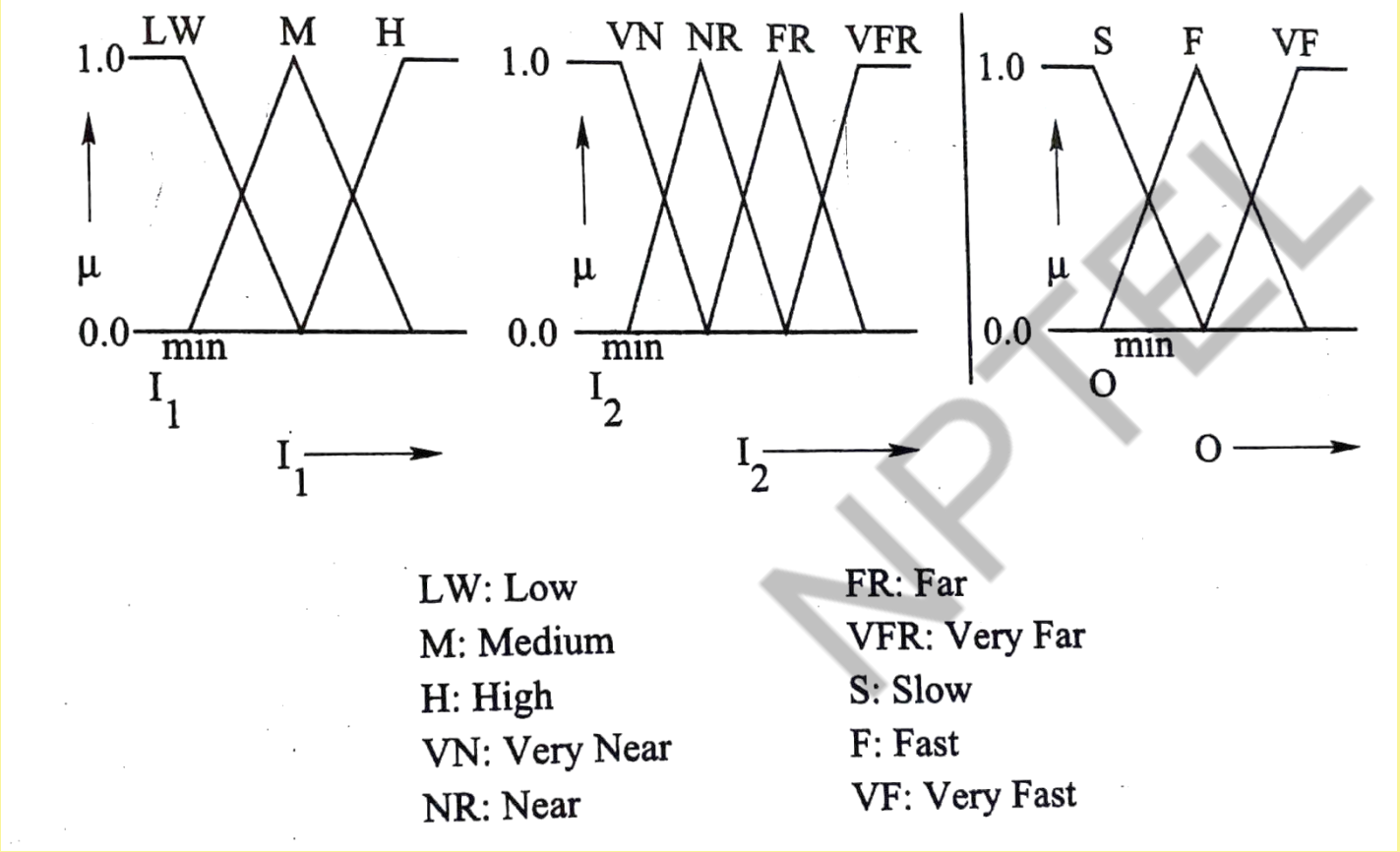
Layer 3: AND operation

Layer 4: Fuzzy Inference

Layer 5: Defuzzification

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Membership Function Distributions



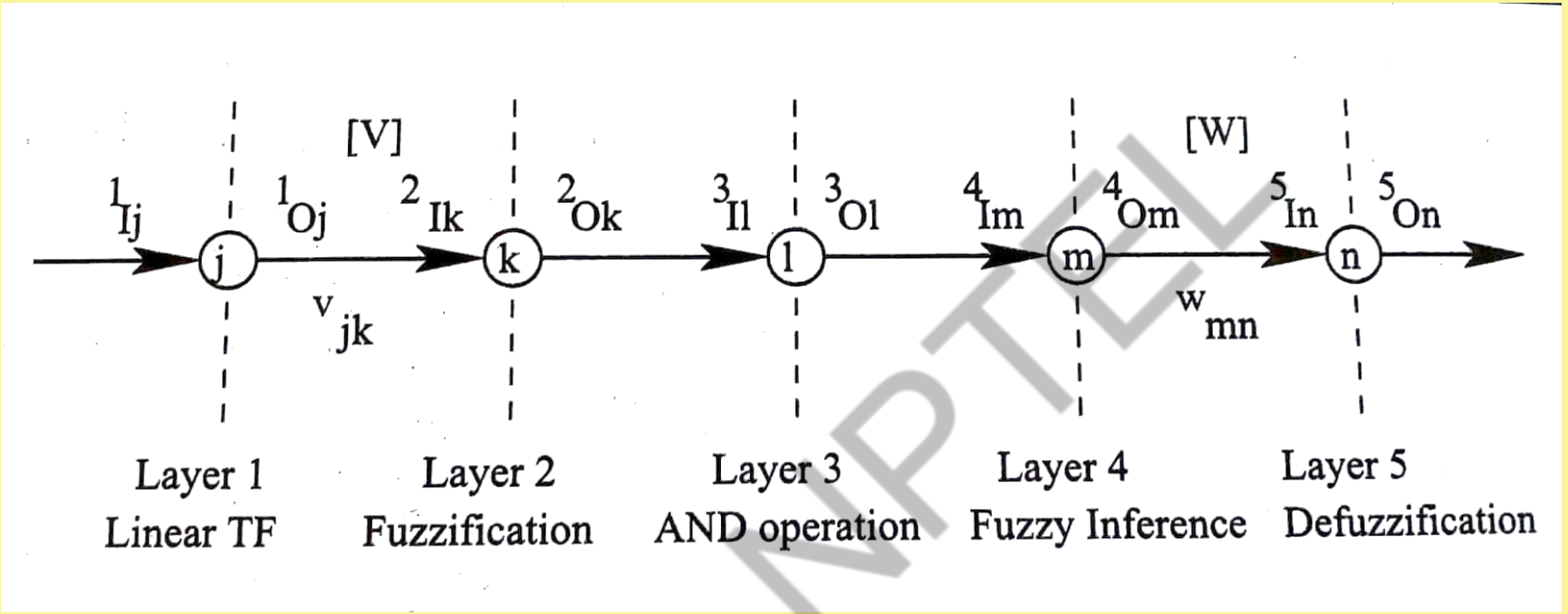
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Rule Base

I_1 \ I_2	VN	NR	FR	VFR
LW	S	S	F	F
M	S	F	F	VF
H	S	F	VF	VF

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A Specific Neuron at Each Layer of the NN



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Assumptions:

$$v_{1,av} = \frac{v_{11} + v_{12} + v_{13}}{3};\ Say, v_{11} = v_{12} = v_{13} = v_{1,av}$$

$$v_{2,av} = \frac{v_{24} + v_{25} + v_{26} + v_{27}}{4}; Say, v_{24} = v_{25} = v_{26} = v_{27} = v_{2,av}$$

$$w_{av} = \frac{w_{11} + w_{21} + w_{31}}{3}; Say, w_{11} = w_{21} = w_{31} = w_{av}$$

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Functions of Different Layers of the NN

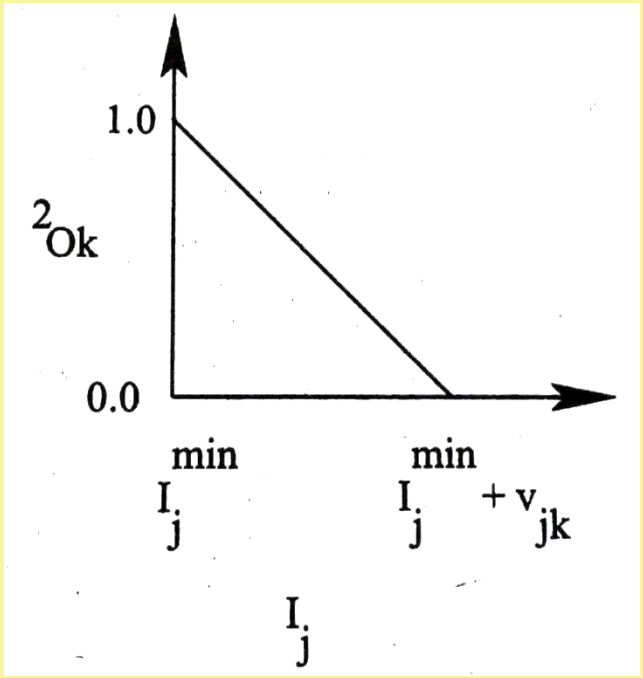
Layer 1: Linear TF ⟹ **outputs are the same with the corresponding inputs**

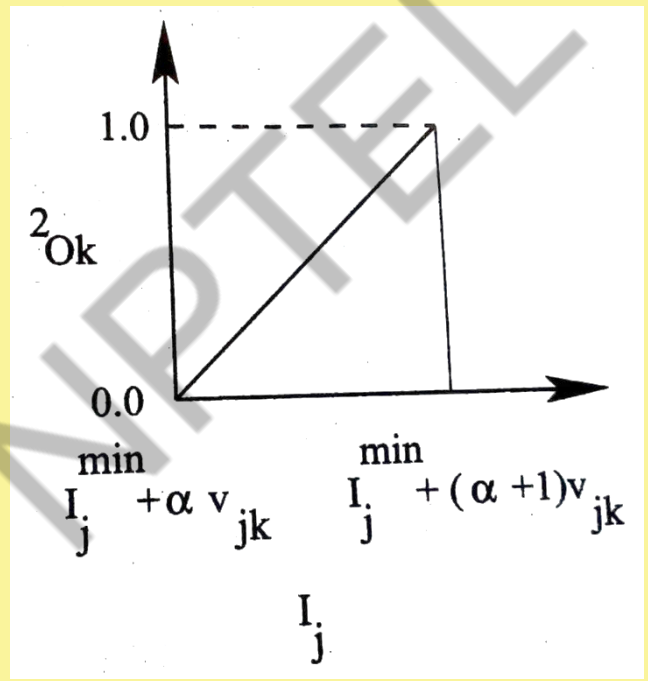
Layer 2: Fuzzification

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Possibilities

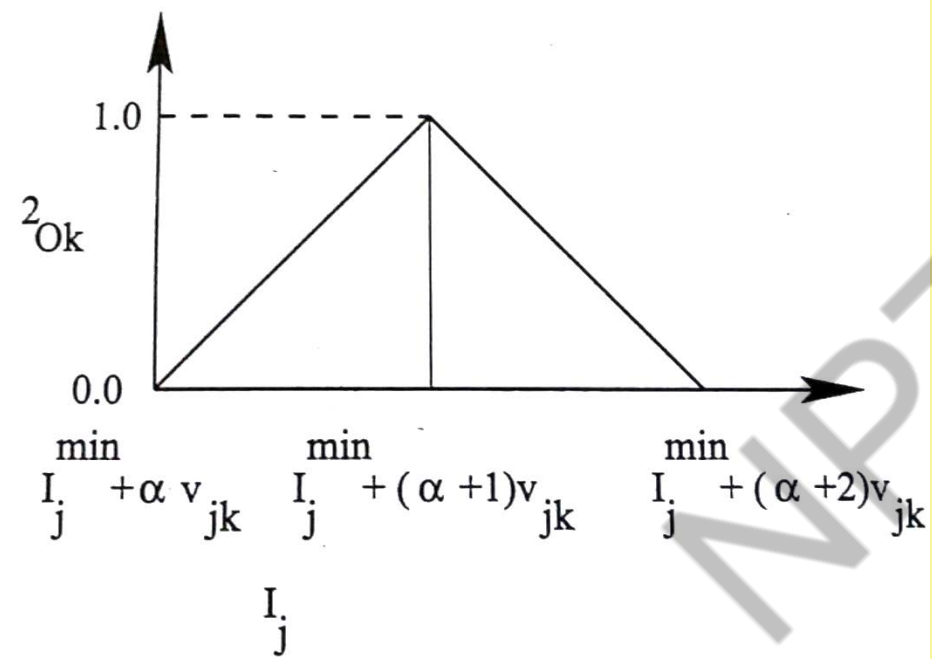
- **Right–angled triangles**





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- **Isosceles triangle**



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Layer 3: Performs logical AND operations

Layer 4: Carries out the task of fuzzy inference

Layer 5: Defuzzification

Center of Sums Method

$$\text{Crisp Output} = \frac{\sum_{i=1}^{r} A_i f_i}{\sum_{i=1}^{r} A_i}$$

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Tuning of NFS

- Batch mode of training
- BP algorithm
- Nature-inspired Optimization Tool say Genetic Algorithm (GA)

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Numerical Example:

• Figure shows the schematic view of a neuro-fuzzy system, in which an FLC (Mamdani Approach) has been represented using the structure of an NN. There are two inputs (such as $I_1 and\ I_2$) and one output (that is, O) of the controller. The NN consists of five layers and the function of each layer is indicated in this figure. The input I_1 has been expressed using three linguistic terms: Near (NR), Far (FR), Very Far (VFR). Similarly, three other linguistic terms, namely Small (SM), Medium (M) and Large (LR) have been utilized to represent the second input I_2. Moreover, the output O has been represented using three linguistic terms, such as Low (LW), High (H) and Very High(VH).

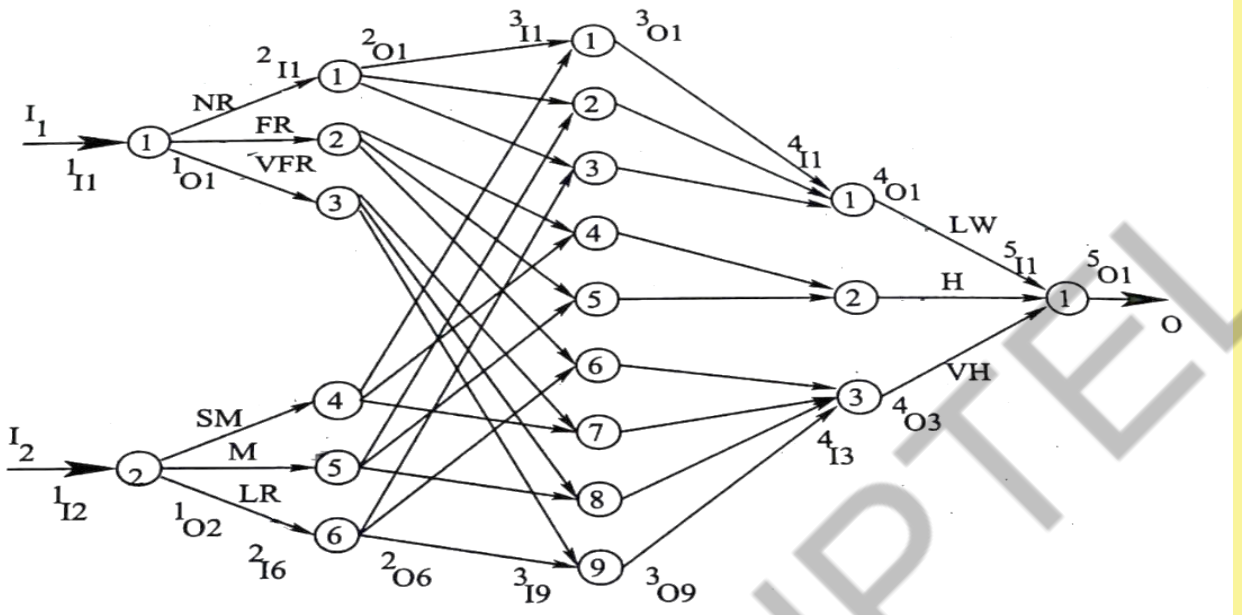
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The membership function distributions of the inputs and output are assumed to be triangular in nature (refer to Figure). For the first input I_1, the base-widths of NR, VFR and half base-width of FR triangles are kept equal to $v_{11}, v_{13}\ and\ v_{12}$, respectively. Similarly, $v_{24}, v_{26}\ and\ v_{25}$ represent the base-widths of SM, LR and half base-width of M triangles, respectively. Moreover, $w_{11}, w_{31}\ and\ w_{21}$ indicate the base-widths of the triangles representing LW, VH outputs and half base-width of H triangle, respectively. The starting values of I_1, I_2 and O are assumed to be equal to 1.0, 10.0 and 5.0, respectively. Determine the deviation in prediction for a case given below.

$$I_1 = 1.6, I_2 = 18.0, O = 9.0.$$

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•**Figure: A neuro-fuzzy system.**



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Let us assume that $v_{11} = v_{12} = v_{13}, v_{24} = v_{25} = v_{26}$ and $w_{11} = w_{21} = w_{31}$ for simplicity.

$$[v_{11} = v_{12} = v_{13} \quad v_{24} = v_{25} = v_{26} \quad w_{11} = w_{21} = w_{31}]^T = [0.3 \;\; 0.6 \;\; 0.4]^T.$$

Let us also suppose that $b_1, b_2 and\ b_3$ of Figure represent the real values, corresponding to the normalized weights $v_{11} = v_{12} = v_{13}, v_{24} = v_{25} = v_{26}$ and $w_{11} = w_{21} = w_{31}$, respectively. The b values are assumed to lie within the following ranges:

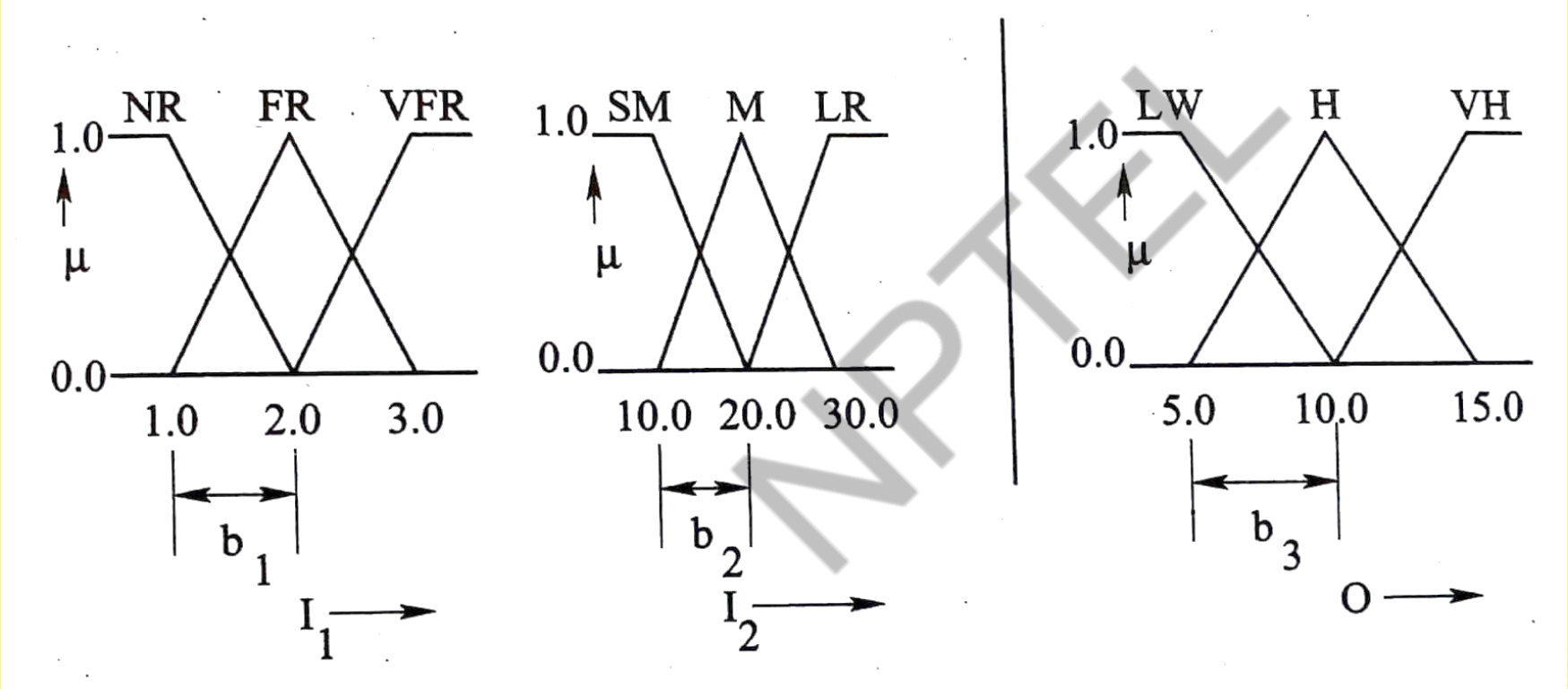
$$0.5 \leq b_1 \leq 1.5,$$
$$5.0 \leq b_2 \leq 15.0,$$
$$2.0 \leq b_3 \leq 8.0.$$

Use Center of Sums method for defuzzification.

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Solution:

- Figure: Manually constructed membership function distributions of the variables



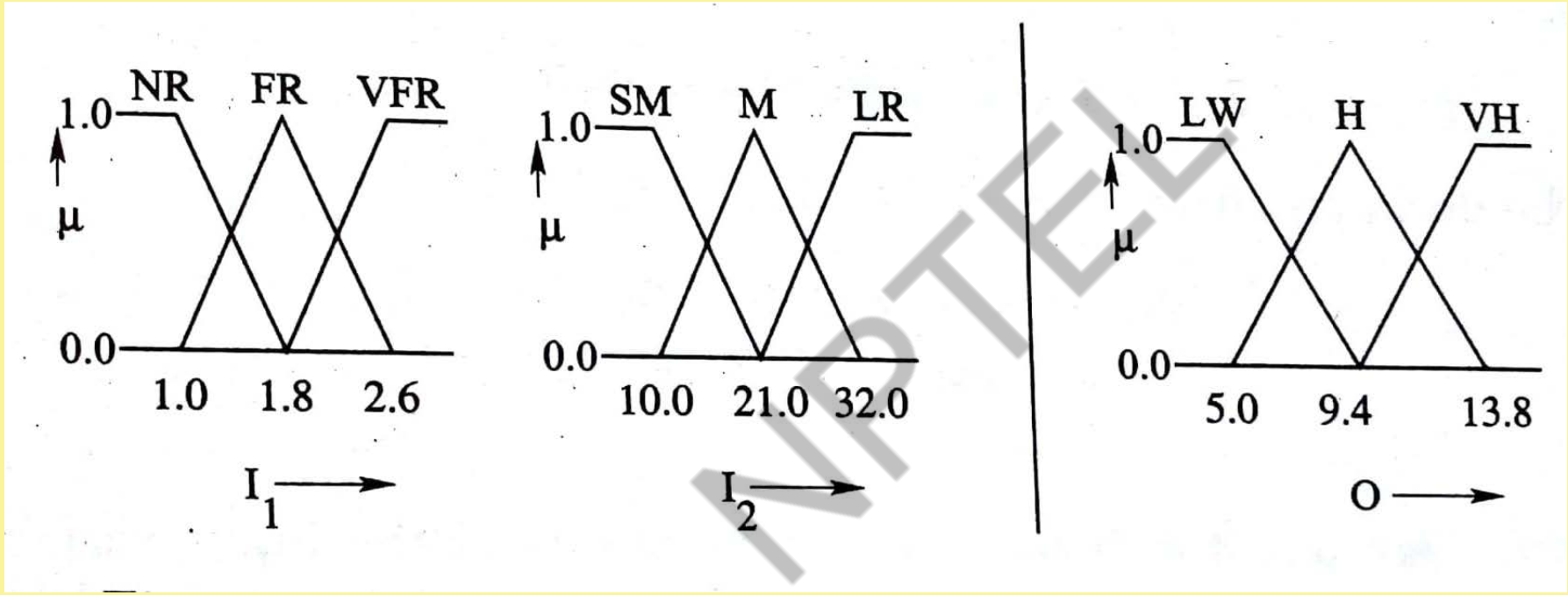
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$$x = n \times \left(x^{max} - x^{min}\right) + x^{min}$$

$$b_1 = 0.3(1.5 - 0.5) + 0.5 = 0.8$$
$$b_2 = 0.6(15 - 5.0) + 5.0 = 11.0$$
$$b_3 = 0.4(8.0 - 2.0) + 2.0 = 4.4$$

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•**Figure: Modified membership function distributions of the variables**



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- **Rule Base**

I_1 \ I_2	SM	M	LR
NR	LW	LW	LW
FR	H	H	VH
VFR	VH	VH	VH

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•To determine output of the controller, input-output relationships of different layers are calculated.

Layer 1:

$$1_{I1} = I_1 = 1.6$$
$$1_{I2} = I_2 = 18.0$$

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•As the neurons of first layer are assumed to have linear transfer function, the outputs are calculated like the following:

$$1_{O1} = 1_{I1} = 1.6$$
$$1_{O2} = 1_{I2} = 18.0$$

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Layer 2:

$$2_{I1} = 2_{I2} = 2_{I3} = 1_{O1} = 1.6$$

The input I_1 can be called either NR or FR. Therefore,

$$2_{O1} = \mu_{NR} = 0.25,$$
$$2_{O2} = \mu_{FR} = 0.75.$$

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Similarly, we get

$$2_{I4} = 2_{I5} = 2_{I6} = 1_{O2} = 18.0$$

The input I_2 can be declared either SM or M. Therefore,

$$2_{O4} = \mu_{SM} = 0.272727,$$
$$2_{O5} = \mu_{M} = 0.727272.$$

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Layer 3:

It indicates that there are 3X3 =9 possible combinations of the input variables. Only four input combinations will be activated corresponding to $I_1 = 1.6\ and I_2 = 18.0$, as given below.

$$If\ I_1\ is\ NR\ AND\ I_2\ is\ SM\ Then\ -$$
$$If\ I_1\ is\ NR\ AND\ I_2\ is\ M\ Then\ -$$
$$If\ I_1\ is\ FR\ AND\ I_2\ is\ SM\ Then\ -$$
$$If\ I_1\ is\ FR\ AND\ I_2\ is\ M\ Then\ -$$

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Thus, the first, second, fourth and fifth neurons of this layer Will be activated.

$$3_{I1} = (0.25, 0.272727)$$
$$3_{I2} = (0.25, 0.727272)$$
$$3_{I4} = (0.75, 0.272727)$$
$$3_{I5} = (0.75, 0.727272)$$

As this layer performs AND operation, the outputs of above neurons can be determined like the following:

$$3_{O1} = min(0.25, 0.272727) = 0.25$$
$$3_{O2} = min(0.25, 0.727272) = 0.25$$
$$3_{O4} = min(0.75, 0.272727) = 0.272727$$
$$3_{O5} = min(0.75, 0.727272) = 0.727272$$

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Layer 4:

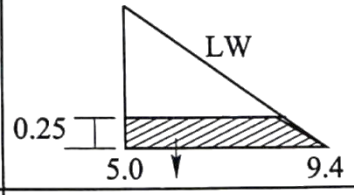
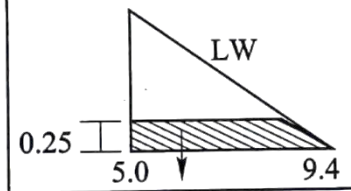
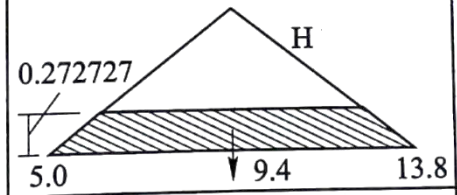
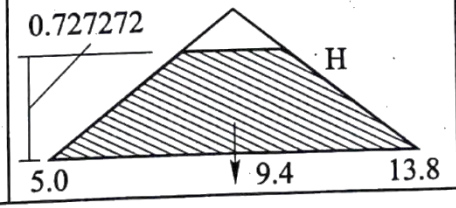
It indicates the outputs (consequent parts) of the activated input combinations. The output of this layer is nothing but the set of fired rules along with their strengths. The following four rules will be fired:

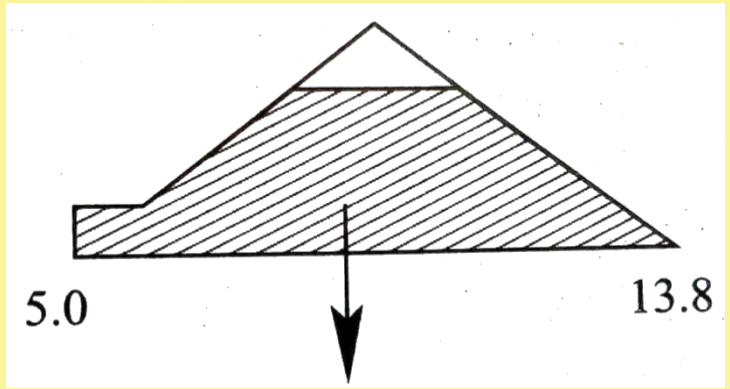
$$If\ I_1\ is\ NR\ AND\ I_2\ is\ SM\ Then\ O\ is\ LW$$
$$If\ I_1\ is\ NR\ AND\ I_2\ is\ M\ Then\ O\ is\ LW$$
$$If\ I_1\ is\ FR\ AND\ I_2\ is\ SM\ Then\ O\ is\ H$$
$$If\ I_1\ is\ FR\ AND\ I_2\ is\ M\ Then\ O\ is\ H$$

The strengths of above fired rules are found to be equal to 0.25, 0.25, 0.272727 and 0.727272, respectively.

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•**Figure: Fuzzified outputs of different fired rules**

Fired Rules	Fuzzified Outputs	Area and Center of Area
1. (NR–SM–LW)		A_1=0.9625 f_1=6.466667
2. (NR–M–LW)		A_2=0.9625 f_2=6.466667
3. (FR–SM–H)		A_3=2.072724 f_3=9.4
4. (FR–M–H)		A_4=4.072722 f_4=9.4



Combined Fuzzified Output

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Layer 5:

It determines the fuzzified output of different fired rules as shown in Figure.
The output 5_{O1} is then calculated using the Center of Sums Method as follows:

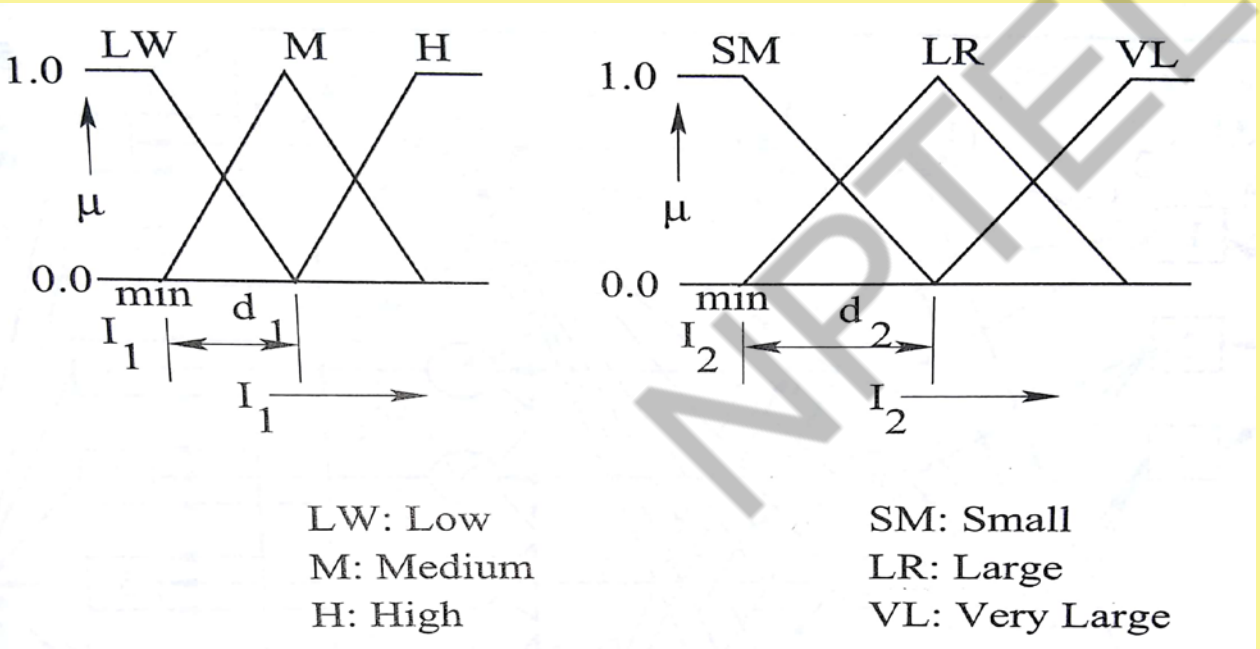
$$5_{O1} = \frac{A_1 f_1 + A_2 f_2 + A_3 f_3 + A_4 f_4}{A_1 + A_2 + A_3 + A_4} = 8.700328$$

Now, Target output $T_{O1} = 9.0$.
Therefore, the deviation in prediction d is found to be equal to
9.0 - 8.700328 = 0.299672.

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Neuro-Fuzzy System Based On Takagi and Sugeno's Approach

- It is also known as Adaptive Neuro-Fuzzy Inference System (ANFIS)
- Proposed by Jang, 1993
- Let us consider a process with two inputs: I_1 and I_2 and one output: O



Membership function distributions of input variables

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According to first-order Takagi and Sugeno's model of FLC

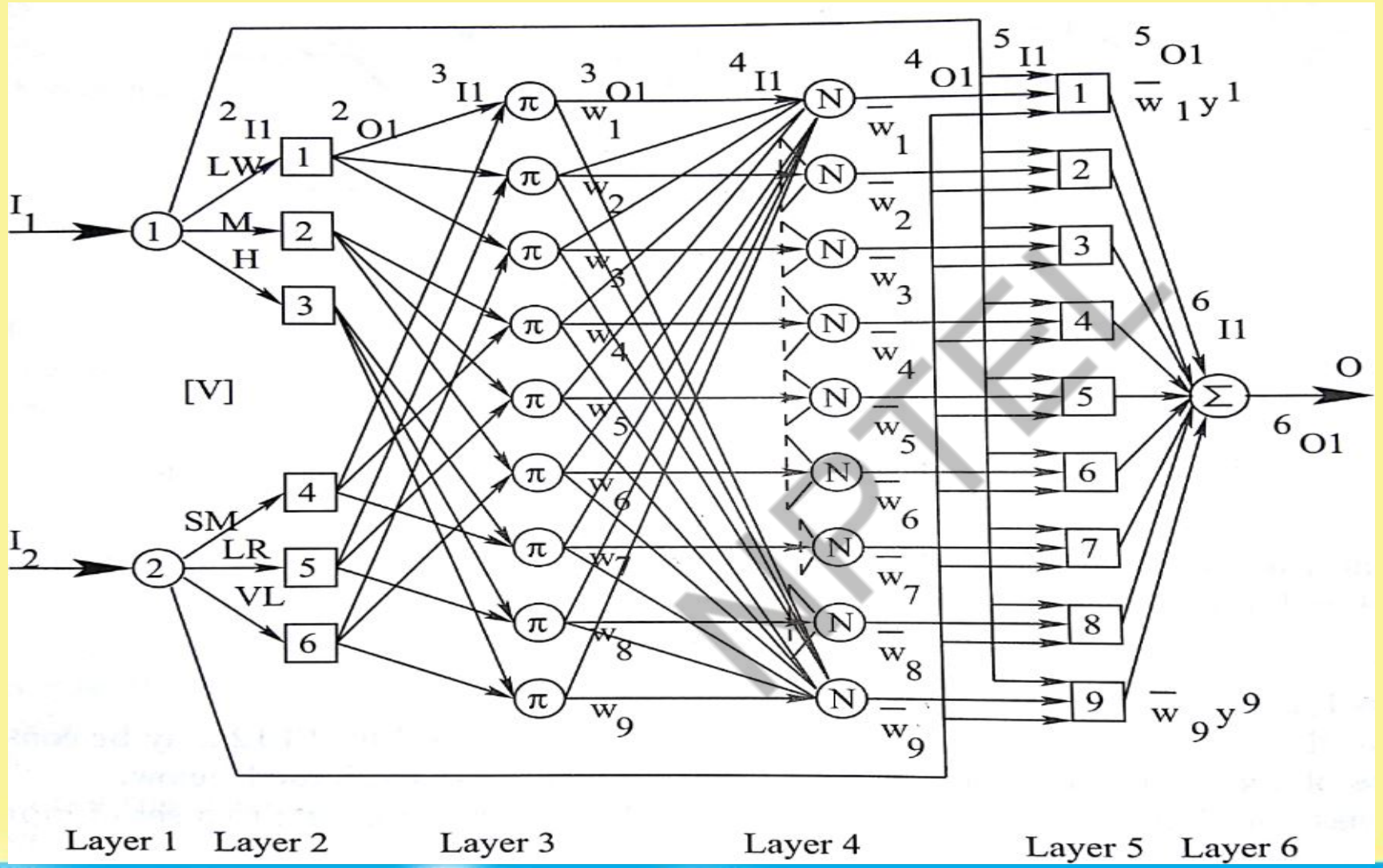
$$y^i = a_i I_1 + b_i I_2 + c_i ,$$

where i = 1, 2, ..., 9

a_i, b_i, c_i are coefficients

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ANFIS architecture



Let us assume that the following 4 rules are fired, corresponding to a set of inputs: I_1^* and I_2^*

If I_1 is LW and I_2 is SM the $y_1 = a_1 I_1 + b_1 I_2 + c_1$
If I_1 is LW and I_2 is LR then $y_2 = a_2 I_1 + b_2 I_2 + c_2$
If I_1 is M and I_2 is SM then $y_4 = a_4 I_1 + b_4 I_2 + c_4$
If I_1 is M and I_2 is LR then $y_5 = a_5 I_1 + b_5 I_2 + c_5$

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- **Layer 1:** Linear TF (output = input)

$$1_{O1} = 1_{I1} = I_1^*$$

$$1_{O2} = 1_{I2} = I_2^*$$

- **Layer 2:** Fuzzification
- **Layer 3:** Firing strengths of the rules are calculated considering the products of μ values

$$w_1 = \mu_{LW}(I_1^*) \; X \; \mu_{SM}(I_2^*)$$

Similarly, we get w_2, w_4 and w_5

- **Layer 4:** Calculate normalized firing strength of each rule

$$\overline{w_1} = \frac{w_1}{w_1 + w_2 + w_4 + w_5}$$

Similarly, we get $\overline{w_2}, \overline{w_4}, \overline{w_5}$

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- **Layer 5:** Output is calculated as the product of normalized firing strength and output of the corresponding fired rule y

$$5_{O1} = \bar{w}_1 \times y^1,$$
$$5_{O2} = \bar{w}_2 \times y^2,$$
$$5_{O4} = \bar{w}_4 \times y^4,$$
$$5_{O5} = \bar{w}_5 \times y^5$$

- **Layer 6:** Overall output $6_{O1} = \overline{w_1}\, y^1 + \overline{w_2}\, y^2 + \overline{w_4}\, y^4 + \overline{w_5}\, y^5$

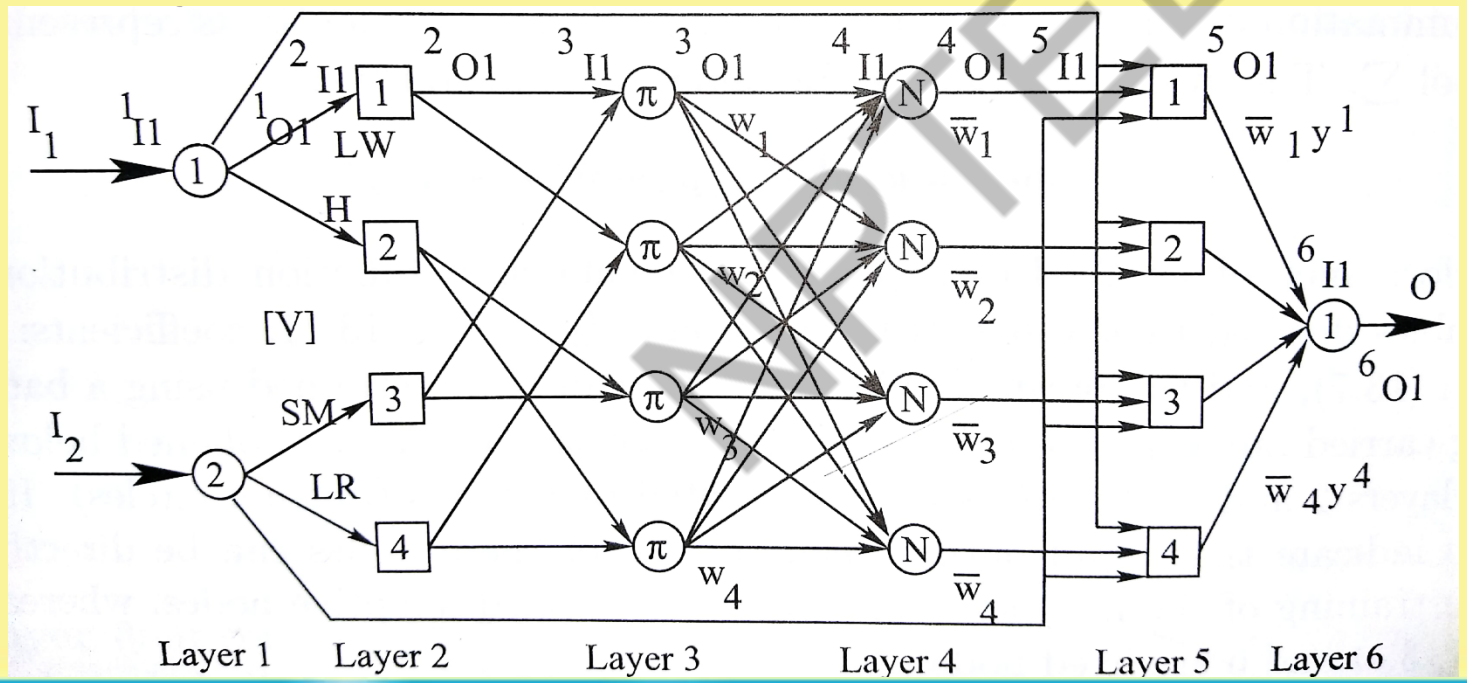
Note: Performance depends on membership function distributions of input variables: a_i, b_i, c_i

Tuning of ANFIS GA ⟹ **Genetic Neuro-Fuzzy System**

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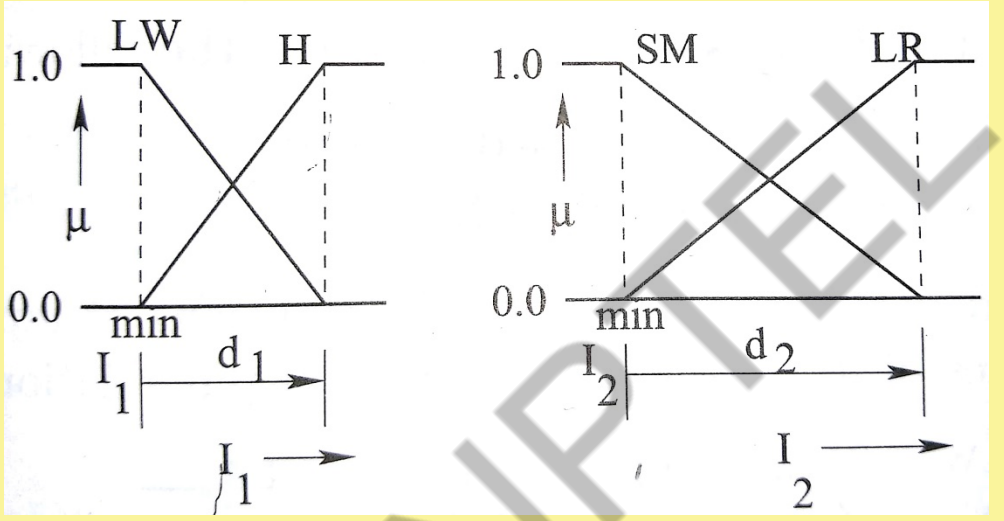
Numerical Example

Below figure shows the schematic view of an ANFIS used to model a process having two inputs: I_1 , I_2 and one output O. The network consists of six layers. Two linguistic terms, such as LW (Low) and H (High) have been utilized to represent first input I_1. Similarly, the second input I_2 has been expressed using two other linguistic terms, namely SM (Small) and LR (Large).



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The connecting weights (expressed in the normalized form from 0.0 to 1.0) between the nodes of first and second layers are denoted by [V] matrix. The membership function distributions of the input variables are assumed to be triangular in nature.



The starting values of I_1 (that is , I_1^{min}) and I_2 (that is, I_2^{min}) are assumed to be equal to 1.0 unit and 5.0 units, respectively. For the first input I_1 , the base width of LW and H right-angled triangles is kept equal to d_1 .

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Similarly, d_2 represents the base-width of SM and LR right-angled triangles. For simplicity, it has been assumed that $v_{11} = v_{12}$ and $v_{23} = v_{24}$.

Moreover, d_1 and d_2 indicate the real values corresponding to the normalized weights $v_{11} = v_{12}$ and $v_{23} = v_{24}$, respectively. As there are only two inputs and two linguistic terms have been utilized to represent each variable, there is a maximum of 2×2 = 4 possible rules.

According to the first-order Takagi and Sugeno's model of FLC ,
the rules can be expressed as follows:

$$y^i = a_i l_1 + b_i l_2 + c_i ,$$

where i = 1, 2, 3, 4 ; a_i, b_i, c_i are the coefficients of the rules.

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Rule Number	a_i	b_i	c_i
1	0.2	0.3	0.10
2	0.2	0.4	0.11
3	0.3	0.3	0.13
4	0.3	0.4	0.14

The values of d_1 and d_2 vary in the ranges as below.

$0.8 \leq d_1 \leq 1.5$; $4.0 \leq d_2 \leq 6.0$.

Assume the normalized weight values as follows:

$[\, v_{11} = v_{12} \quad v_{23} = v_{24} \,]^T = [0.3 \;\; 0.5]^T$

and determine the deviation in prediction for the training scenario .

$I_1 = 1.1$, $I_2 = 6.0$ and Output $O = 2.3$.

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Solution:

The normalized values of the variables are assumed to vary in the range of (0.0, 1.0). The relationship between the normalized value (n) and real value (x) of a variable can be represented as follows:

$$x = n \times \left(x^{max} - x^{min}\right) + x^{min}$$

Using the above relationship ,

$d_1 = 0.3(1.5 - 0.8) + 0.8 = 1.01$

$d_2 = 0.5(6.0 - 4.0) + 4.0 = 5.0$

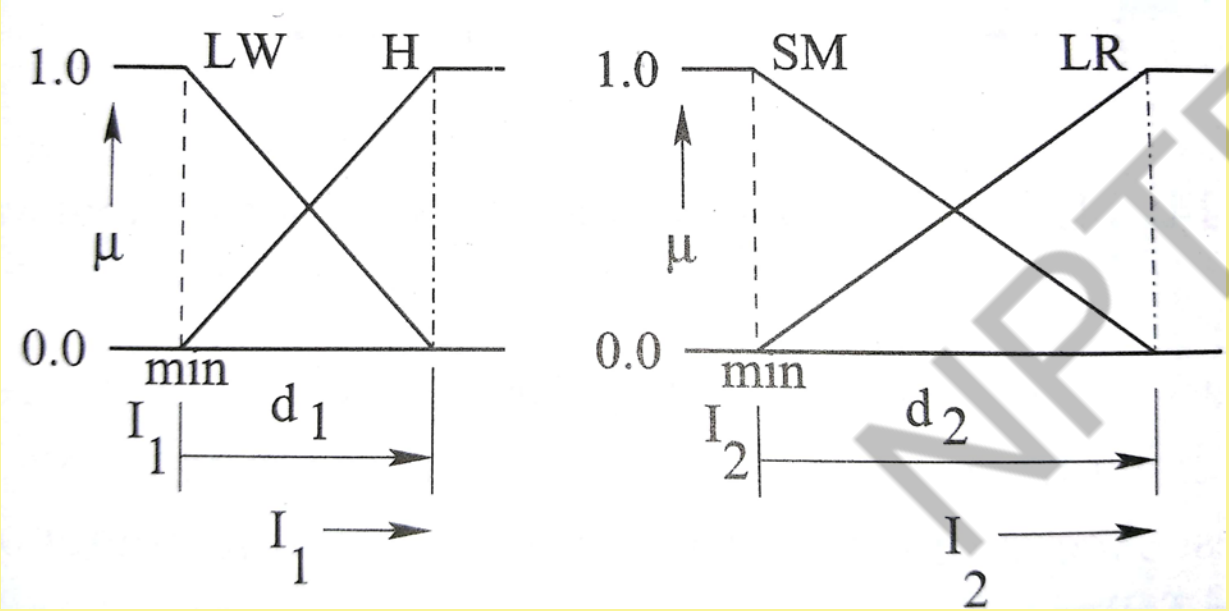
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Modified membership function distributions of input variables, corresponding to the above values of d_1 and d_2 are shown below:



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The input-output relationships of different layers are found to be as follows:

Layer 1:

$$1_{I1} = I_1^* = 1.1$$
$$1_{I2} = I_2^* = 6.0$$

As the neurons of first layer are assumed to have linear transfer function,

$$1_{O1} = 1_{I1} = 1.1$$
$$1_{O2} = 1_{I2} = 6.0$$

Layer 2:

The inputs of the first two neurons of second layer are coming out to be equal to 1_{O1} .

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$\therefore \quad 2_{I1} = 2_{I2} = 1_{O1} = 1.1$

The input I_1 can be called either LW or H.

$$\therefore \quad 2_{O1} = \mu_{LW}(I_1^*) = 0.900990$$
$$2_{O2} = \mu_{H}(I_1^*) = 0.099009$$

Similarly, $2_{I3} = 2_{I4} = 1_{O2} = 6.0$

The input I_2 can be declared either SM or LR.

$$\therefore \quad 2_{O3} = \mu_{SM}(I_2^*) = 0.8$$
$$2_{O4} = \mu_{LR}(I_2^*) = 0.2$$

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Layer 3:

Corresponding to the inputs $I_1 = 1.1$, $I_2 = 6.0$, all possible four rules will be fired and their inputs and outputs are given below.

$$3_{I1}=(0.900990,0.8)$$

$$3_{I2}=(0.900990,0.2)$$

$$3_{I3}=(0.099009,0.8)$$

$$3_{I4}=(0.099009,0.2)$$

As this layer performs multiplication operation, the outputs of the above neurons can be determined like the following:

$$3_{O1} = \mu_{LW}(I_1^*) \times \mu_{SM}(I_2^*) = 0.720792 = w_1$$

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Layer 3:

$$3_{O2} = \mu_{LW}(I_1^*) \times \mu_{LR}(I_2^*) = 0.180198 = w_2$$

$$3_{O3} = \mu_{H}(I_1^*) \times \mu_{SM}(I_2^*) = 0.079207 = w_3$$

$$3_{O4} = \mu_{H}(I_1^*) \times \mu_{LR}(I_2^*) = 0.019802 = w_4$$

Layer 4:

The normalized firing strengths $(\bar{w}s)$ can be calculated as follows:

$$4_{O1} = \frac{w_1}{w_1 + w_2 + w_3 + w_4} = 0.720792 = \bar{w}_1$$

$$4_{O2} = \frac{w_2}{w_1 + w_2 + w_3 + w_4} = 0.180198 = \bar{w}_2$$

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Layer 4:

$$4_{O3} = \frac{w_3}{w_1 + w_2 + w_3 + w_4} = 0.079207 = \bar{w}_3$$

$$4_{O4} = \frac{w_4}{w_1 + w_2 + w_3 + w_4} = 0.019802 = \bar{w}_4$$

Layer 5: The outputs of the rules can be obtained like the following:

$$y^1 = a_1 I_1^* + b_1 I_2^* + c_1 = 2.12$$

$$y^2 = a_2 I_1^* + b_2 I_2^* + c_2 = 2.73$$

$$y^3 = a_3 I_1^* + b_3 I_2^* + c_3 = 2.26$$

$$y^4 = a_4 I_1^* + b_4 I_2^* + c_4 = 2.87$$

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Layer 5: The outputs of different neurons of fifth layer can be obtained like the following:

$$5_{O1} = \bar{w}_1 y^1 = 1.528079$$
$$5_{O2} = \bar{w}_2 y^2 = 0.491941$$
$$5_{O3} = \bar{w}_3 y^3 = 0.179008$$
$$5_{O4} = \bar{w}_4 y^4 = 0.056832$$

Layer 6: The overall output 6_{O1} can be calculated as follows:

$$6_{O1} = \bar{w}_1 y^1 + \bar{w}_2 y^2 + \bar{w}_3 y^3 + \bar{w}_4 y^4 = 2.255860$$

Now, Target output $T_{O1} = 2.3$

$\therefore$ Deviation in prediction = 2.3 – 2.255860 = 0.044140

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References

References:

D.K. Pratihar Soft Computing: Fundamentals and Applications. New Delhi, India: Narosa Publishing House, 2014.

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Conclusion

Conclusion:

Principles of Neuro-Fuzzy Systems (both Mamdani Approach as well as Takagi and Sugeno's Approach) have been discussed with suitable numerical examples

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Thank you!

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