

# Defuzzification Techniques

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# What is defuzzification?

- Defuzzification means the fuzzy to crisp conversion.

- Example 1:**

Suppose,  $T_{HIGH}$  denotes a fuzzy set representing **temperature is High**.

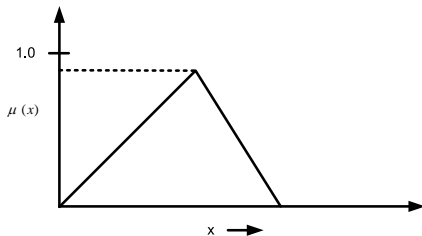
$T_{HIGH}$  is given as follows.

$T_{HIGH} = (15, 0.1), (20, 0.4), (25, 0.45), (30, 0.55), (35, 0.65), (40, 0.7), (45, 0.85), (50, 0.9)$

- What is the crisp value that implies for the high temperature?

## Example 2: Fuzzy to crisp

As an another example, let us consider a fuzzy set whose membership function is shown in the following figure.



What is the crisp value of the fuzzy set in this case?

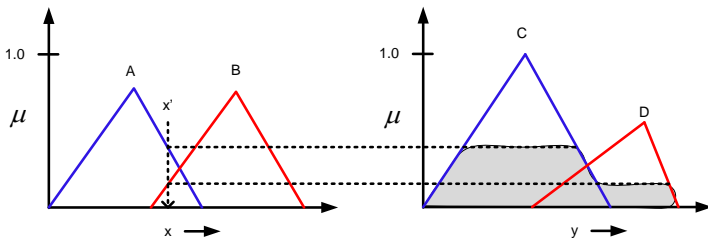
## Example 3: Fuzzy to crisp

Now, consider the following two rules in the fuzzy rule base.

R1: If  $x$  **is**  $A$  then  $y$  **is**  $C$

R2: If  $x$  **is**  $B$  then  $y$  **is**  $D$

A pictorial representation of the above rule base is shown in the following figures.



What is the crisp value that can be inferred from the above rules given an input say  $x'$ ?

# Why defuzzification?

The fuzzy results generated can not be used in an application, where decision has to be taken only on crisp values.

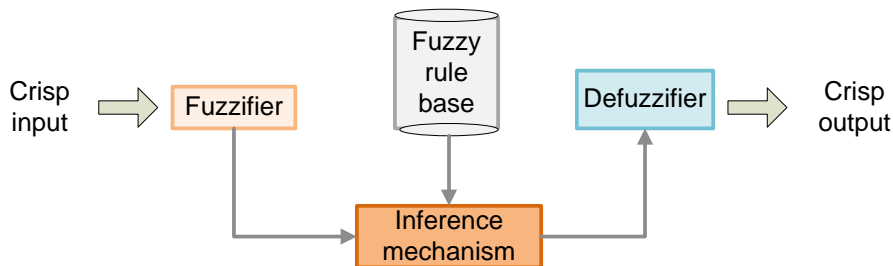
## Example:

If  $T_{HIGH}$  then rotate  $R_{FIRST}$ .

Here, may be input  $T_{HIGH}$  is fuzzy, but action **rotate** should be based on the crisp value of  $R_{FIRST}$ .

# Generic structure of a Fuzzy system

Following figures shows a general fraework of a fuzzy system.



# Defuzzification Techniques

# Defuzzification methods

A number of defuzzification methods are known. Such as

- 1 **Lambda-cut method**
- 2 **Weighted average method**
- 3 **Maxima methods**
- 4 **Centroid methods**



# Lambda-cut method

# Lambda-cut method

Lambda-cut method is applicable to derive crisp value of a fuzzy set or relation. Thus

- Lambda-cut method for fuzzy set
- Lambda-cut method for fuzzy relation

In many literature, Lambda-cut method is also alternatively termed as *Alpha-cut method*.

# Lamda-cut method for fuzzy set

- 1 In this method a fuzzy set  $A$  is transformed into a crisp set  $A_\lambda$  for a given value of  $\lambda$  ( $0 \leq \lambda \leq 1$ )
- 2 In other-words,  $A_\lambda = \{x | \mu_A(x) \geq \lambda\}$
- 3 That is, the value of Lambda-cut set  $A_\lambda$  is  $x$ , when the membership value corresponding to  $x$  is greater than or equal to the specified  $\lambda$ .
- 4 This Lambda-cut set  $A_\lambda$  is also called alpha-cut set.

# Lambda-cut for a fuzzy set : Example

$$A_1 = \{(x_1, 0.9), (x_2, 0.5), (x_3, 0.2), (x_4, 0.3)\}$$

$$\text{Then } A_{0.6} = \{(x_1, 1), (x_2, 0), (x_3, 0), (x_4, 0)\} = \{x_1\}$$

and

$$A_2 = \{(x_1, 0.1), (x_2, 0.5), (x_3, 0.8), (x_4, 0.7)\}$$

$$A_{0.2} = \{(x_1, 0), (x_2, 1), (x_3, 1), (x_4, 1)\} = \{x_2, x_3, x_4\}$$

# Lambda-cut sets : Example

Two fuzzy sets  $P$  and  $Q$  are defined on  $x$  as follows.

$\mu(x)$	$x_1$	$x_2$	$x_3$	$x_4$	$x_5$
P	0.1	0.2	0.7	0.5	0.4
Q	0.9	0.6	0.3	0.2	0.8

Find the following :

- (a)  $P_{0.2}, Q_{0.3}$
- (b)  $(P \cup Q)_{0.6}$
- (c)  $(P \cup \overline{P})_{0.8}$
- (d)  $(P \cap Q)_{0.4}$

# Lambda-cut for a fuzzy relation

The Lambda-cut method for a fuzzy set can also be extended to fuzzy relation also.

**Example:** For a fuzzy relation  $R$

$$R = \begin{bmatrix} 1 & 0.2 & 0.3 \\ 0.5 & 0.9 & 0.6 \\ 0.4 & 0.8 & 0.7 \end{bmatrix}$$

We are to find  $\lambda$ -cut relations for the following values of

$\lambda = 0, 0.2, 0.9, 0.5$

$$R_0 = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix} \text{ and } R_{0.2} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix} \text{ and}$$

$$R_{0.9} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix} \text{ and } R_{0.5} = \begin{bmatrix} 1 & 0 & 0 \\ 1 & 1 & 1 \\ 0 & 1 & 1 \end{bmatrix}$$

# Some properties of $\lambda$ -cut sets

If  $A$  and  $B$  are two fuzzy sets, defined with the same universe of discourse, then

- 1  $(A \cup B)_\lambda = A_\lambda \cup B_\lambda$
- 2  $(A \cap B)_\lambda = A_\lambda \cap B_\lambda$
- 3  $(\bar{A})_\lambda \neq \bar{A}_\lambda$  except for value of  $\lambda = 0.5$
- 4 For any  $\lambda \leq \alpha$ , where  $\alpha$  varies between 0 and 1, it is true that  $A_\alpha \subseteq A_\lambda$ , where the value of  $A_0$  will be the universe of discourse.

# Some properties of $\lambda$ -cut relations

If  $R$  and  $S$  are two fuzzy relations, defined with the same fuzzy sets over the same universe of discourses, then

$$5 \quad (R \cup S)_\lambda = R_\lambda \cup S_\lambda$$

$$6 \quad (R \cap S)_\lambda = R_\lambda \cap S_\lambda$$

$$7 \quad (\overline{R})_\lambda \neq \overline{R}_\lambda$$

$$8 \quad \text{For } \lambda \leq \alpha, \text{ where } \alpha \text{ between 0 and 1, then } R_\alpha \subseteq R_\lambda$$



# Summary: Lambda-cut methods

Lambda-cut method converts a fuzzy set (or a fuzzy relation) into crisp set (or relation).

# Output of a Fuzzy System

# Output of a fuzzy System

The output of a fuzzy system can be a single fuzzy set or union of two or more fuzzy sets.

To understand the second concept, let us consider a fuzzy system with  $n$ -rules.

$R_1$ : If  $x$  is  $A_1$  then  $y$  is  $B_1$

$R_2$ : If  $x$  is  $A_2$  then  $y$  is  $B_2$

.....

.....

$R_n$ : If  $x$  is  $A_n$  then  $y$  is  $B_n$

In this case, the output  $y$  for a given input  $x = x_1$  is possibly  $B = B_1 \cup B_2 \cup \dots B_n$

# Output fuzzy set : Illustration

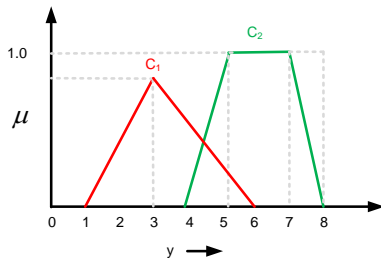
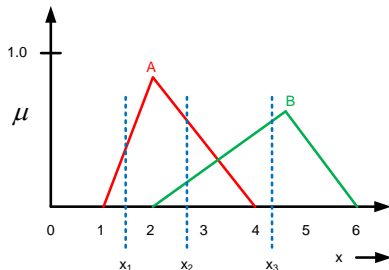
Suppose, two rules  $R_1$  and  $R_2$  are given as follows:

①  $R_1$ : If  $x$  is  $A_1$  then  $y$  is  $C_1$

②  $R_2$ : If  $x$  is  $A_2$  then  $y$  is  $C_2$

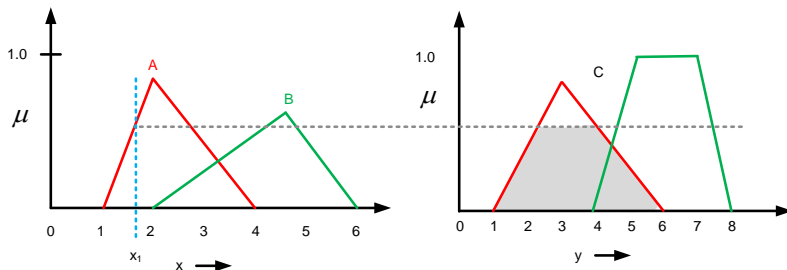
Here, the output fuzzy set  $C = C_1 \cup C_2$ .

For instance, let us consider the following:



# Output fuzzy set : Illustration

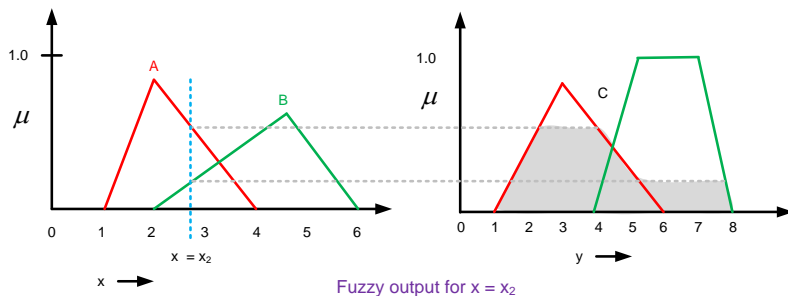
The fuzzy output for  $x = x_1$  is shown below.



Fuzzy output for  $x = x_1$

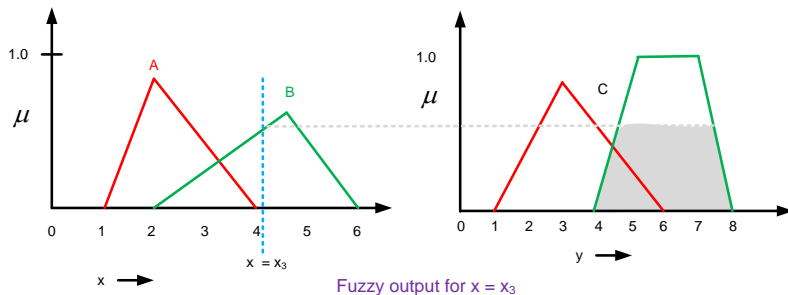
# Output fuzzy set : Illustration

The fuzzy output for  $x = x_2$  is shown below.



# Output fuzzy set : Illustration

The fuzzy output for  $x = x_3$  is shown below.



# Defuzzification Methods

Following defuzzification methods are known to calculate crisp output in the situations as discussed in the last few slides

- **Maxima Methods**

- 1 Height method
- 2 First of maxima (FoM)
- 3 Last of maxima (LoM)
- 4 Mean of maxima(MoM)

- **Centroid methods**

- 1 Center of gravity method (CoG)
- 2 Center of sum method (CoS)
- 3 Center of area method (CoA)

- **Weighted average method**



# Defuzzification Technique

## Maxima Methods

# Maxima methods

Following defuzzification methods are known to calculate crisp output.

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- **Centroid methods**

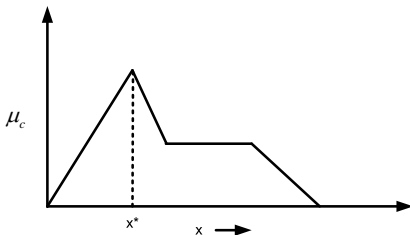
- 1 Center of gravity method (CoG)
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- **Weighted average method**

# Maxima method : Height method

This method is based on [Max-membership principle](#), and defined as follows.

$$\mu_C(x^*) \geq \mu_C(x) \text{ for all } x \in X$$

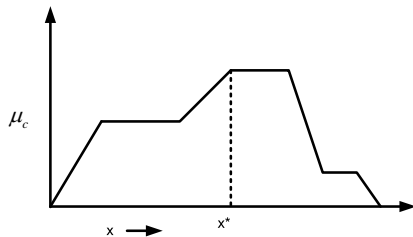


## Note:

1. Here,  $x^*$  is the height of the output fuzzy set  $C$ .
2. This method is applicable when height is unique.

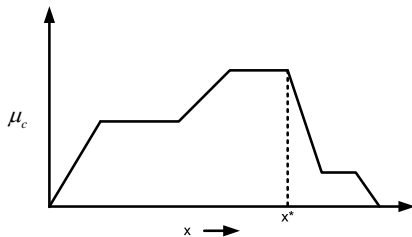
# Maxima method : FoM

FoM: First of Maxima :  $x^* = \min\{x | C(x) = \max_w C\{w\}\}$



# Maxima method : LoM

LoM : Last of Maxima :  $x^* = \max\{x | C(x) = \max_w C\{w\}\}$



# Maxima method : MoM

$$x^* = \frac{\sum_{x_i \in M} (x_i)}{|M|}$$

where,  $M = \{x_i | \mu(x_i) = h(C)\}$  where  $h(C)$  is the height of the fuzzy set  $C$

# MoM : Example 1

Suppose, a fuzzy set **Young** is defined as follows:

$$\text{Young} = \{(15,0.5), (20,0.8), (25,0.8), (30,0.5), (35,0.3)\}$$

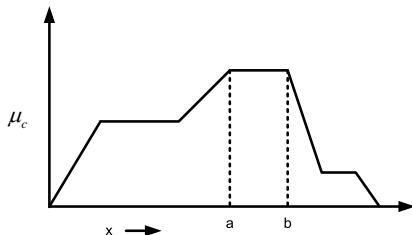
Then the crisp value of **Young** using MoM method is

$$x^* = \frac{20+25}{2} = 22.5$$

Thus, a person of 22.5 years old is treated as young!

# MoM : Example 2

What is the crisp value of the fuzzy set using MoM in the following case?



$$x^* = \frac{a+b}{2}$$

## Note:

- Thus, MoM is also synonymous to **middle of maxima**.
- MoM is also general method of **Height**.



# Defuzzification Technique

## Centroid Methods

# Cenroid methods

Following defuzzification methods are known to calculate crisp output.

- **Maxima Methods**

- 1 Height method
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- 4 Mean of maxima(MoM)

- **Centroid methods**

- 1 Center of gravity method (CoG)
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- 3 Center of area method (CoA)

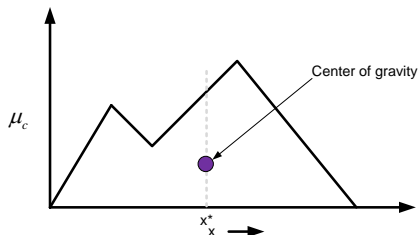
- **Weighted average method**

# Centroid method : CoG

- 1 The basic principle in CoG method is to find the point  $x^*$  where a vertical line would slice the aggregate into two equal masses.
- 2 Mathematically, the CoG can be expressed as follows :

$$x^* = \frac{\int x \cdot \mu_C(x) dx}{\int \mu_C(x) dx}$$

- 3 Graphically,



## Note:

- 1  $x^*$  is the x-coordinate of center of gravity.
- 2  $\int \mu_C(x)dx$  denotes the area of the region bounded by the curve  $\mu_C$ .
- 3 If  $\mu_C$  is defined with a discrete membership function, then CoG can be stated as :

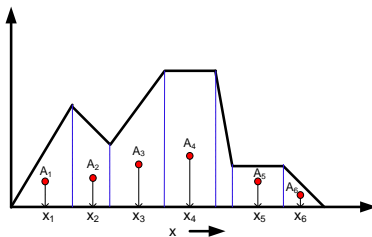
$$x^* = \frac{\sum_{i=1}^n x_i \cdot \mu_C(x_i)}{\sum_{i=1}^n \mu_C(x_i)} ;$$

- 4 Here,  $x_i$  is a sample element and  $n$  represents the number of samples in fuzzy set  $C$ .

# CoG : A geometrical method of calculation

## Steps:

- 1 Divide the entire region into a number of small **regular** regions (e.g. triangles, trapizoid etc.)

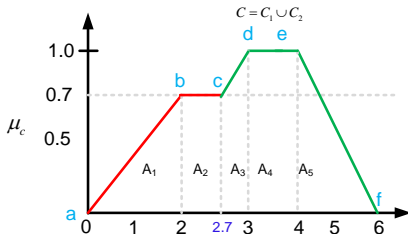
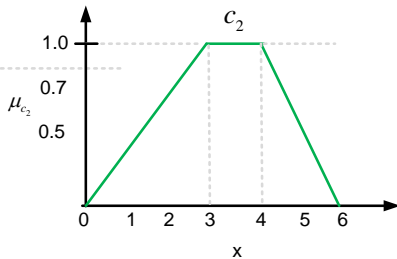
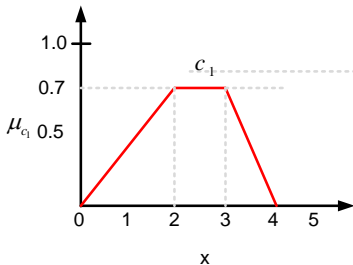


- 2 Let  $A_i$  and  $x_i$  denotes the area and c.g. of the  $i$ -th portion.
- 3 Then  $x^*$  according to CoG is

$$x^* = \frac{\sum_{i=1}^n x_i \cdot (A_i)}{\sum_{i=1}^n A_i}$$

where  $n$  is the number of smaller geometrical components.

# CoG: An example of integral method of calculation



# CoG: An example of integral method of calculation

$$\mu_C(x) = \begin{cases} 0.35x & 0 \leq x < 2 \\ 0.7 & 2 \leq x < 2.7 \\ x - 2 & 2.7 \leq x < 3 \\ 1 & 3 \leq x < 4 \\ (-0.5x + 3) & 4 \leq x \leq 6 \end{cases}$$

For  $A_1$  :  $y - 0 = \frac{0.7}{2}(x - 0)$ , or  $y = 0.35x$

For  $A_2$  :  $y = 0.7$

For  $A_3$  :  $y - 0 = \frac{1-0}{3-2}(x - 2)$ , or  $y = x - 2$

For,  $A_4$  :  $y = 1$

For,  $A_5$  :  $y - 1 = \frac{0-1}{6-4}(x - 4)$ , or  $y = -0.5x + 3$

# CoG: An example of integral method of calculation

$$\text{Thus, } x^* = \frac{\int x \cdot \mu_c(x) dx}{\int \mu_c(x) dx} = \frac{N}{D}$$

$$\begin{aligned} N &= \int_0^2 0.35x^2 dx + \int_2^{2.7} 0.7x dx + \int_{2.7}^3 (x^2 - 2x) dx + \int_3^4 x dx + \int_4^6 (-0.5x^2 + 3x) dx \\ &= 10.98 \end{aligned}$$

$$\begin{aligned} D &= \int_0^2 0.35x dx + \int_2^{2.7} 0.7x dx + \int_{2.7}^3 (x - 2) dx + \int_3^4 dx + \int_4^6 (-0.5x + 3) dx \\ &= 3.445 \end{aligned}$$

$$\text{Thus, } x^* = \frac{10.98}{3.445} = 3.187$$



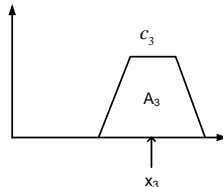
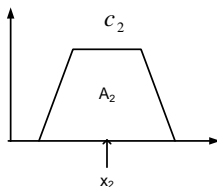
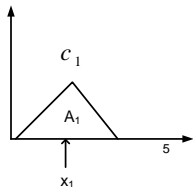
# Centroid method : CoS

If the output fuzzy set  $C = C_1 \cup C_2 \cup \dots C_n$ , then the crisp value according to CoS is defined as

$$x^* = \frac{\sum_{i=1}^n x_i \cdot A_{C_i}}{\sum_{i=1}^n A_{C_i}}$$

Here,  $A_{C_i}$  denotes the area of the region bounded by the fuzzy set  $C_i$  and  $x_i$  is the geometric center of the area  $A_{C_i}$ .

Graphically,

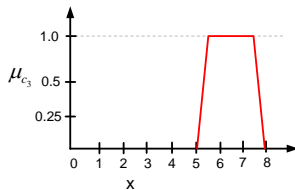
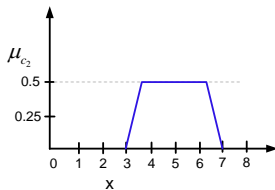
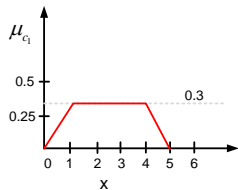


## Note:

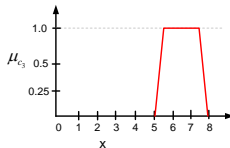
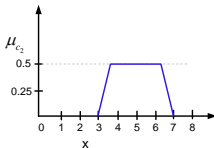
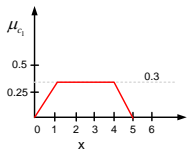
- 1 In CoG method, the overlapping area is counted once, whereas, in CoS , the overlapping is counted twice or so.
- 2 In CoS, we use the **center of area** and hence, its name instead of **center of gravity** as in CoG.

# CoS: Example

Consider the three output fuzzy sets as shown in the following plots:



# CoS: Example



In this case, we have

$$A_{c_1} = \frac{1}{2} \times 0.3 \times (3 + 5), x_1 = 2.5$$

$$A_{c_2} = \frac{1}{2} \times 0.5 \times (4 + 2), x_2 = 5$$

$$A_{c_3} = \frac{1}{2} \times 1 \times (3 + 1), x_3 = 6.5$$

$$\text{Thus, } x^* = \frac{\frac{1}{2} \times 0.3 \times (3+5) \times 2.5 + \frac{1}{2} \times 0.5 \times (4+2) \times 5 + \frac{1}{2} \times 1 \times (3+1) \times 6.5}{\frac{1}{2} \times 0.3 \times (3+5) + \frac{1}{2} \times 0.5 \times (4+2) + \frac{1}{2} \times 1 \times (3+1)} = 5.00$$

**Note:**

The crisp value of  $C = C_1 \cup C_2 \cup C_3$  using CoG method can be found to be calculated as  $x^* = 4.9$

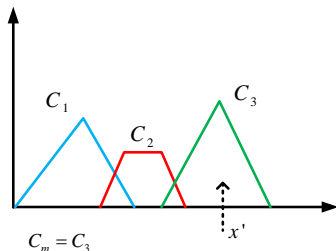
# Centroid method: Center of largest area

If the fuzzy set has two subregions, then the **center of gravity of the subregion with the largest area** can be used to calculate the defuzzified value.

**Mathematically,**  $x^* = \frac{\int \mu_{C_m}(x) \cdot x' dx}{\int \mu_{C_m}(x) dx}$ ;

Here,  $C_m$  is the region with largest area,  $x'$  is the center of gravity of  $C_m$ .

**Graphically,**



# Weighted Average Method

Following defuzzification methods are known to calculate crisp output.

- **Maxima Methods**

- 1 Height method
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- **Centroid methods**

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- **Weighted average method**

# Weighted average method

- 1 This method is also alternatively called "Sugeno defuzzification" method.
- 2 The method can be used only for symmetrical output membership functions.
- 3 The crisp value according to this method is

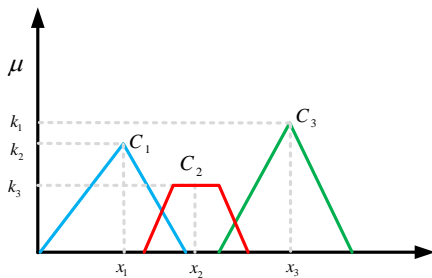
$$x^* = \frac{\sum_{i=1}^n \mu_{C_i}(x_i) \cdot (x_i)}{\sum_{i=1}^n \mu_{C_i}(x_i)}$$

where,  $C_1, C_2, \dots, C_n$  are the output fuzzy sets and  $(x_i)$  is the value where middle of the fuzzy set  $C_i$  is observed.



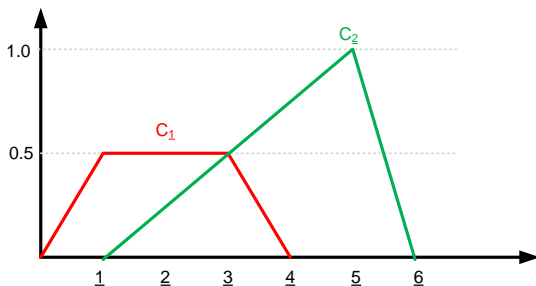
# Weighted average method

Graphically,



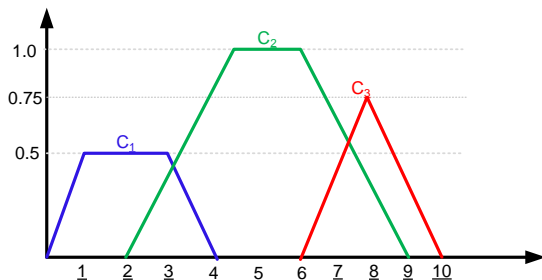
# Exercise 1

Find the crisp value of the following using all defuzzified methods.



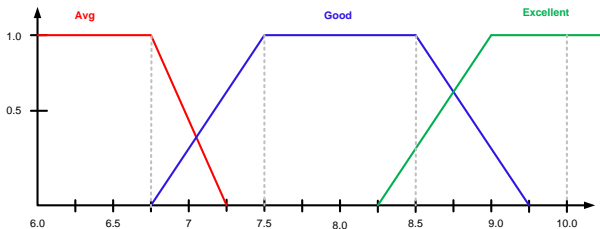
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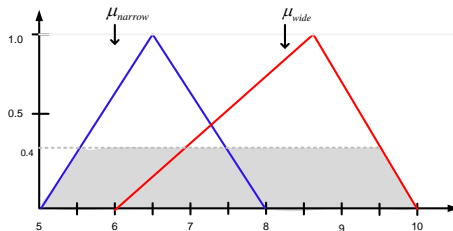
# Exercise 3

- The membership function defining a student as Average, Good, and Excellent denoted by respective membership functions are as shown below.



- Find the crisp value of "Good Student"
- Hint: Use CoG method to the portion "Good" to calculate it.

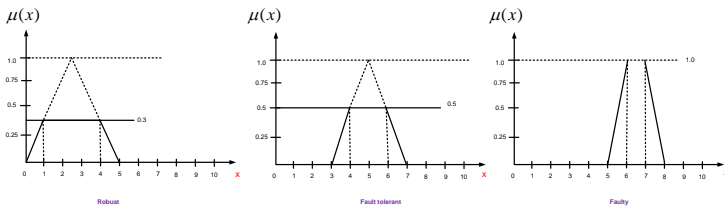
# Exercise 4



- The width of a road as narrow and wide is defined by two fuzzy sets, whose membership functions are plotted as shown above.
- If a road with its degree of membership value is 0.4 then what will be its width (in crisp) measure.
- Hint: Use CoG method for the shaded region.

# Exercise 5

- The faulty measure of a circuit is defined fuzzily by three fuzzy sets namely Faulty(F), Fault tolerant (FT) and Robust(R) defined by three membership functions with number of faults occur as universe of discourses and is shown below.



- Reliability is measured as  $R^* = F \cup FT \cup R$ .  
With a certain observation in testing  
 $(x, 0.3) \in R, (x, 0.5) \in FT, (x, 0.8) \in F$ .
- Calculate the reliability measure in crisp value.
- Calculate with 1) CoS 2) CoG .

# Any questions??