Lecture 1

Control System Design

Fuzzy Logic Control (FLC)
Artificial intelligence Systems
(Overview)

Presented by:
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Organization of the Course

- **Course SS 2021: Control System Design**
- **Introduction to Artificial Intelligence:** Fuzzy Logic Controller.
- **Type of work:** Lectures + exercises.
- **Requirements:** MATLAB, basic programming.
- **Score distribution: 100% >>>** 40% written exam, 40% quizzes and 20% report (Applications of Fuzzy Logic Controller using MATLAB).

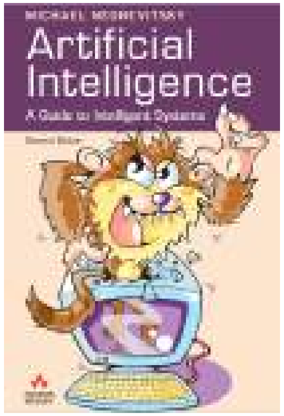
Objectives of this Course

By the end of this course you should be able to:

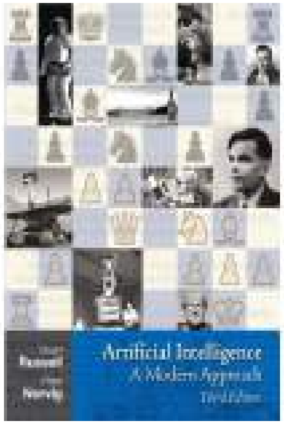
- Understand the concepts of AI.
- Understand fuzzy logic and fuzzy logic control structure.
- Build FLC based application and implement it.

Literature and References:

- **Artificial Intelligence, a Guide to Intelligent Systems.**
  - (second edition).
  - Mechael Negnevitsky.



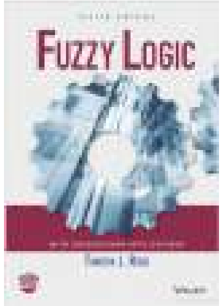
- **Artificial Intelligence, a Modern Approach**
  - (Third edition).
  - Stuart Russell & Peter Norvig.



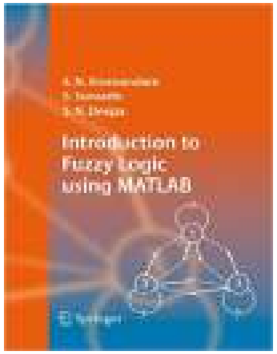
- **Introduction to Artificial Neural Systems**
  - Jacek M. Zurada, 1999.

Literature and References

- **Fuzzy Controllers**
  - http://research.iaun.ac.ir/pd/naghsh/pdfs/UploadFile_4810.pdf
  - Newne, 1997.
  - L. Reznik.



- **Fuzzy Logic with Engineering Applications**
  - fourth edithion, 2017.
  - T.J. Ross.
- **Fuzzy Control**
  - Kevin M. Passino and Stephen Yurkovich, 1998.
- **Introduction to Fuzzy Logic using MATLAB**
  - Springer, 2007
  - S. N. Sivanandam, S. Sumathi and S. N. Deepa



- **Fuzzy Logic Toolbox™ User's Guide, © COPYRIGHT 1995-2012 The MathWorks, Inc.**

Outlines:

- **Introduction to Artificial Intelligence (AI):**
  - History of AI
  - Applications of AI

- **Introduction to Fuzzy Logic Control (FLC):**
  - History of FLC
  - Fuzzy Logic Concepts, Fuzzy Sets, Fuzzy operations
  - FLC.

Artificial intelligence (AI)

Artificial Neural Networks (ANNs)

- McCullochi and Pits, 1943*

Fuzzy logic system (FLS)

- Zadeh, 1965*
- Mammdani, 1974*
- Sugeon, 1985*

Genetic algorithm (GA)

- Holland, 1975*

* Source: Zadeh. L., “*The Concept of a Linguistic Variable and its Application to Approximate Reasoning-I* “, 1975.
* Zurada J. M.,"*Introduction to Artificial Neural Systems*", Jaico publishing House, 1996.
* Pham D. T. and Xing L., “*Neural Networks for Identification, Prediction and Control*”, Spring-Verlag London Limited, 1997.

Artificial intelligence System

The discipline or simulation model which is developed by emulating certain characteristics of biological systems

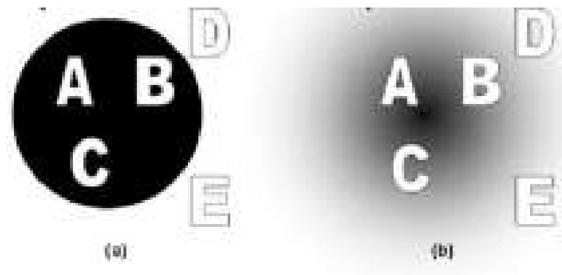
- **Artificial neural network:** An artificial neural network (ANN), usually called neural network (NN), is a mathematical model or computational model that is inspired by the structure and/or functional aspects of biological neural networks.

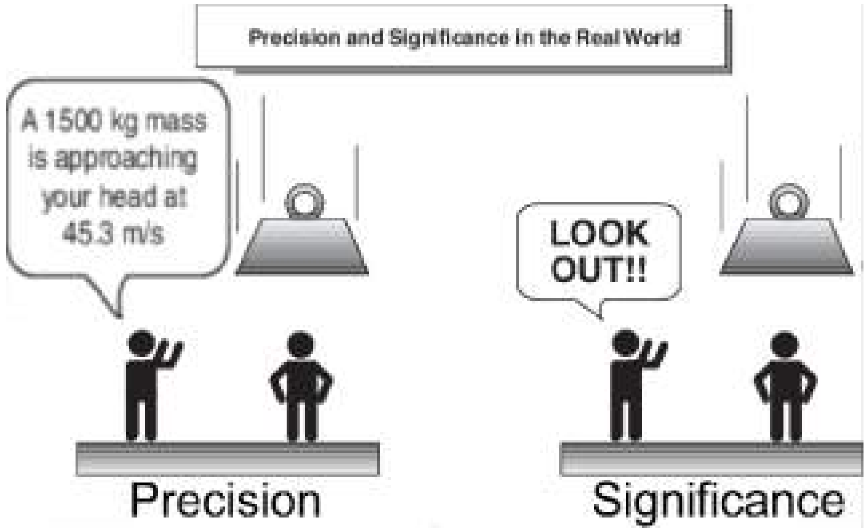
- **Fuzzy logic systems:** can be designed to emulate the human deductive process; that is, the process people use infers conclusions from what they know. They use collection of rules called knowledge bases or rule bases that hold a set of If- Then rules that quantify the expert's knowledge about solving a particular problem.

- **Genetic algorithms:** the goal is to embody the principles of evaluation, natural selection and genetics from natural biological systems in a computer algorithm.

Fuzzy Logic

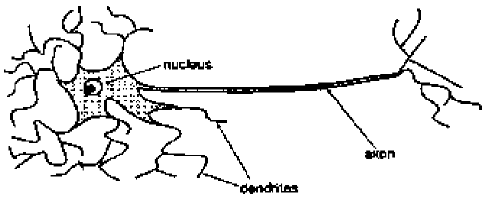
- Fuzzy logic is a form of many-valued logic in which the true values of variables may be any real number between 0 and 1.
- It has been employed to handle the concept of partial truth, where the truth value may range between completely true and completely false. Furthermore, when linguistic variables are used, these degrees may be managed by specific (membership) functions

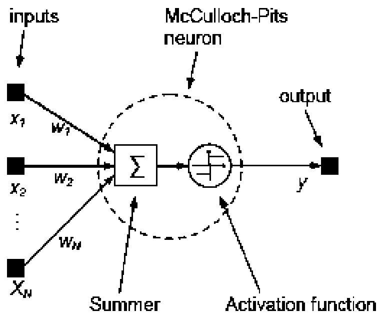


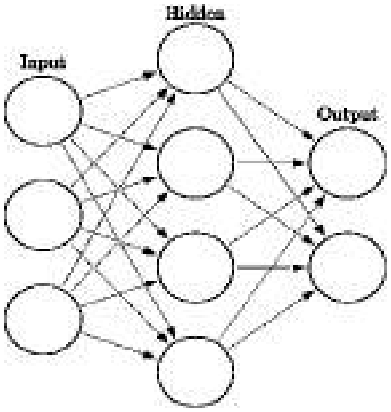


Artificial Neural Networks

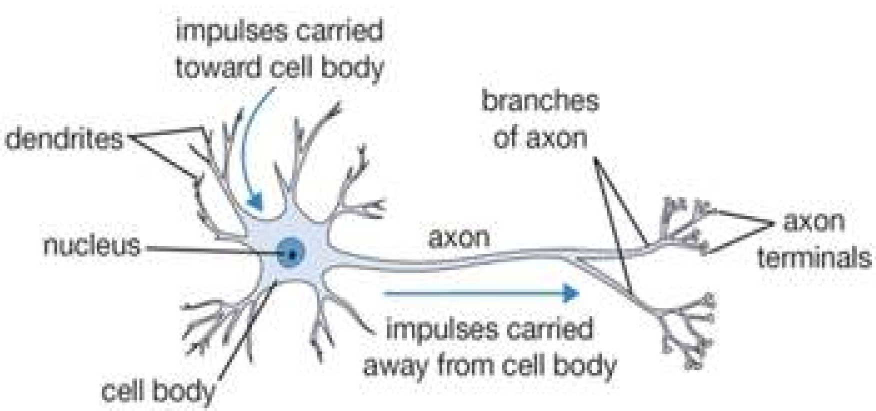
- Artificial neural networks (ANNs) -or connectionist systems- are computational models based on a large collection of simple neural units (artificial neurons).
- It is a try to mimic the observed behavior of a biological brain's cells.
- Its ability of **learning** is one main reason for its popularity, because of the wide range of applications it implements.

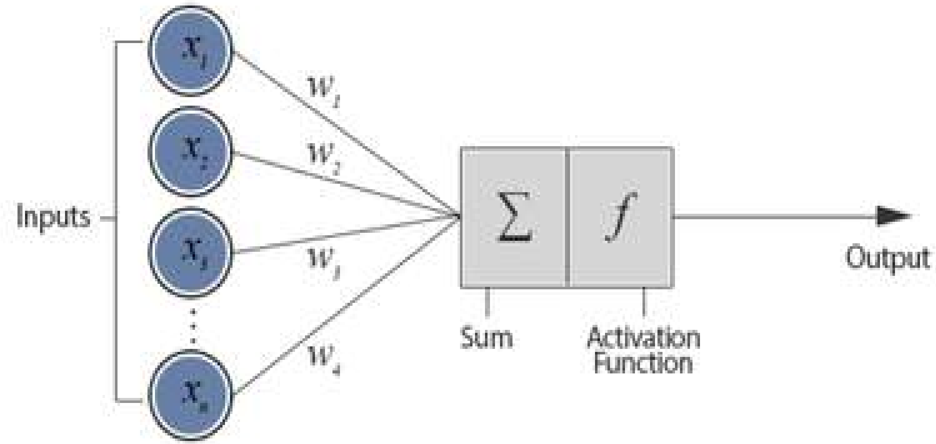






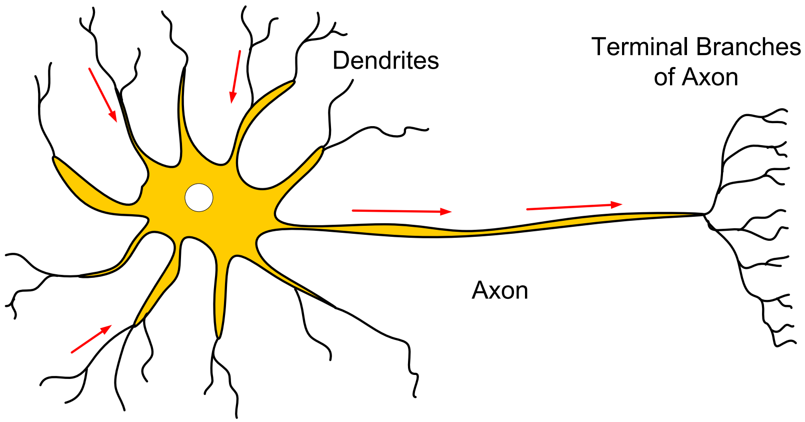
Biological and Artificial Neural Nets

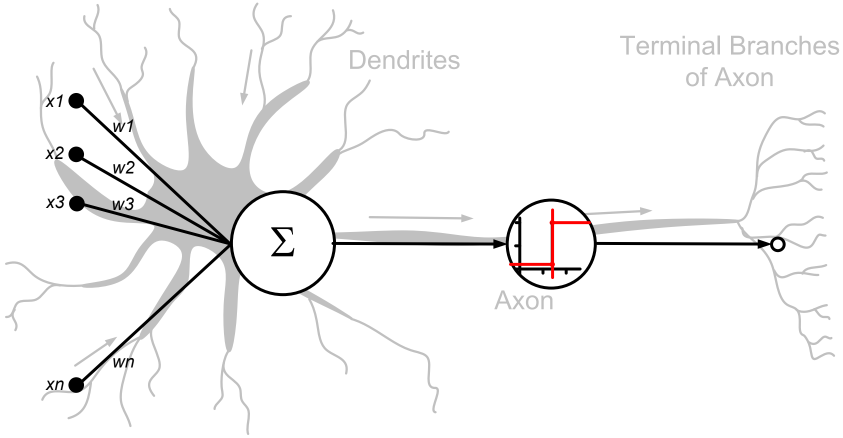




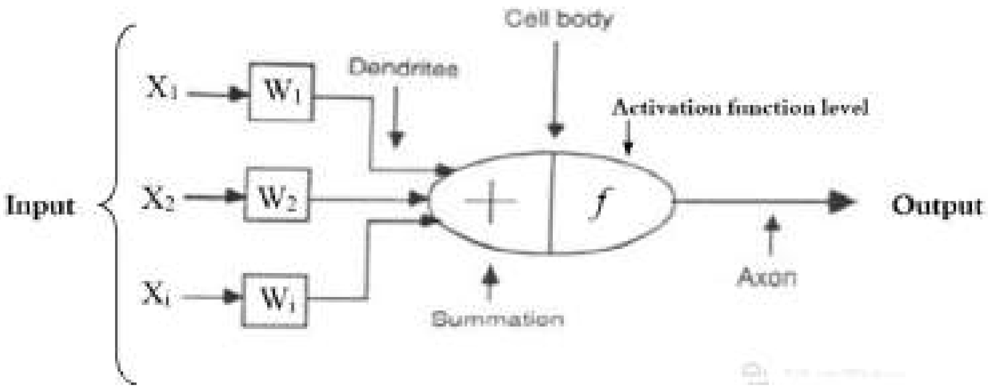
Biological neural network	Artificial neural network
Soma	Neuron
Dendrite	Input
Axon	Output
Synapse	Weight

➢ Analogy between biological and artificial neuron





➢ In 1943, McCulloch and Pits proposed a mathematical model of neurons

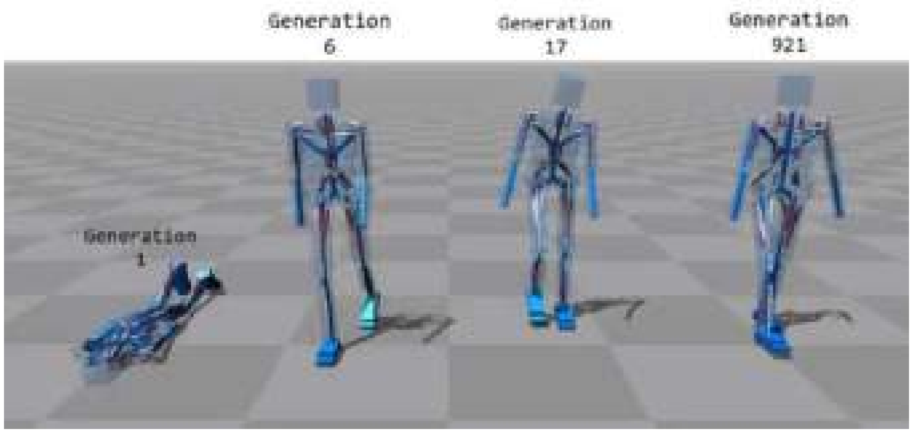


$$Output = f\left(\sum_{i=1}^{n} W_i X_i + b_i\right)$$

A Simple Neuron

Genetic Algorithm

- The genetic algorithm is a method for solving both constrained and unconstrained optimization problems. It is based on natural selection, the process that drives biological evolution. The genetic algorithm repeatedly modifies a population of individual solutions.

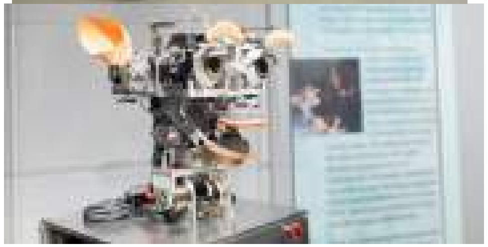


Applications of AI

❖Robotics

Wide variety of applications including –but not limited to- house holding, surgical robots, navigation (on earth and in space), office assistance,… etc.

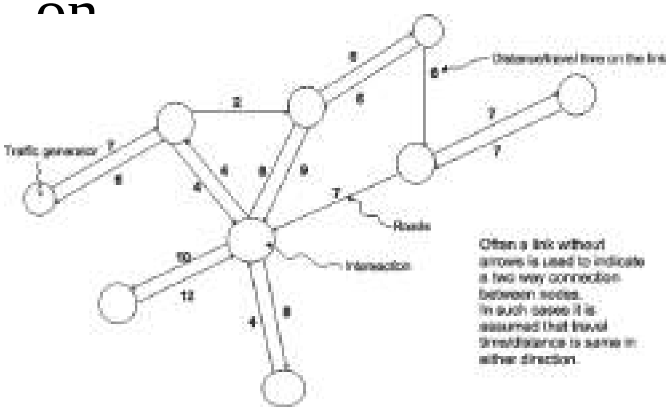




Applications of AI

❖Path finding

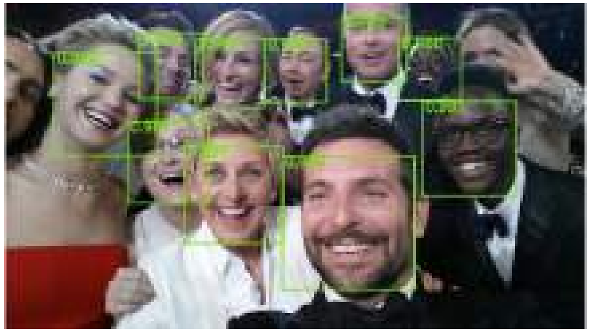
- Pathfinding is the plotting, by a computer application, of the shortest route between two points. It is a more practical variant on solving mazes.



Applications of AI

❖Face detection

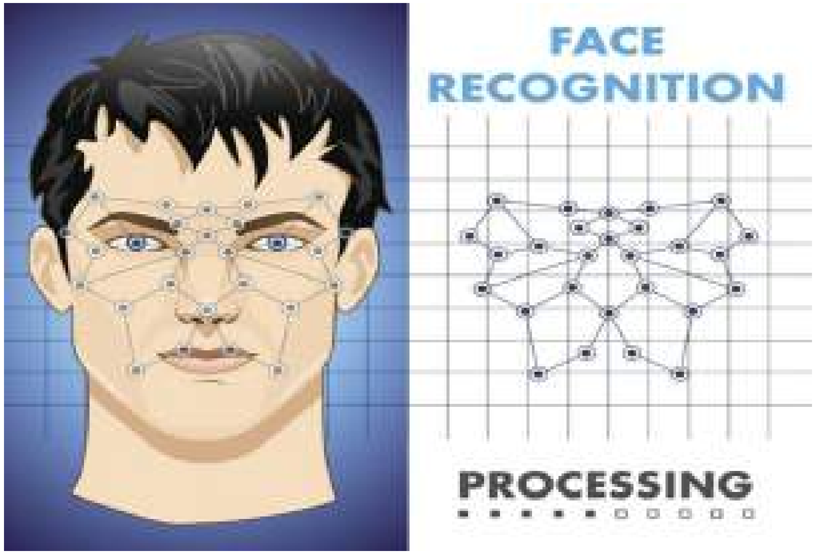
- A computer technology being used in a variety of applications that identifies human **faces** in digital images.



Applications of AI

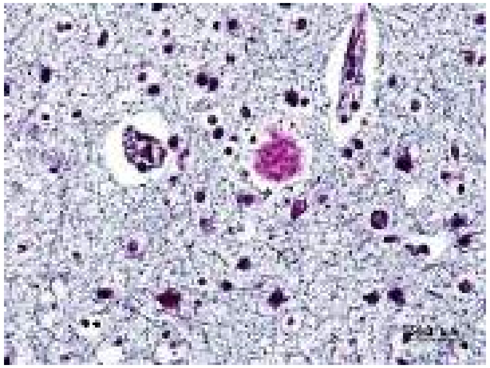
❖Face recognition

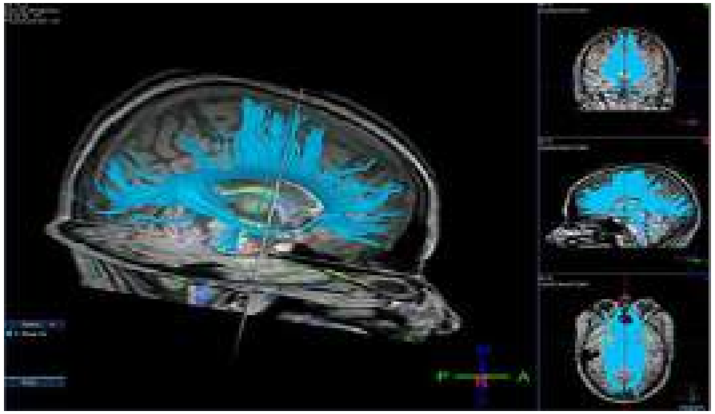
- A face recognition system is a computer application capable of **identifying** or **verifying a person** from a digital image or a video frame from a video source.
- Depends on discovering the features of the face.
- Mostly used in security applications.



Applications of AI

❖Medical diagnosis / Imaging





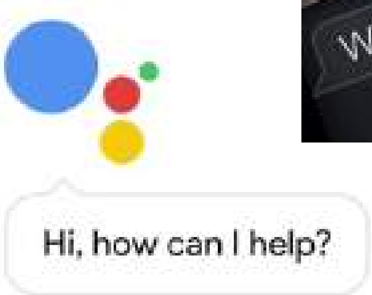
- Artificial intelligence in healthcare uses algorithms and software to approximate human cognition in the analysis of complex medical data.
- Artificial neural networks are used as clinical decision support systems for medical diagnosis, such as in Concept Processing technology in EMR software.

Applications of AI

❖Speech recognition

- Virtual Assistants:
  - Siri (Apple);
  - Cortana (Microsoft).
  - Google NOW.

- Deep neural networks handle the speech recognition and natural language understanding.



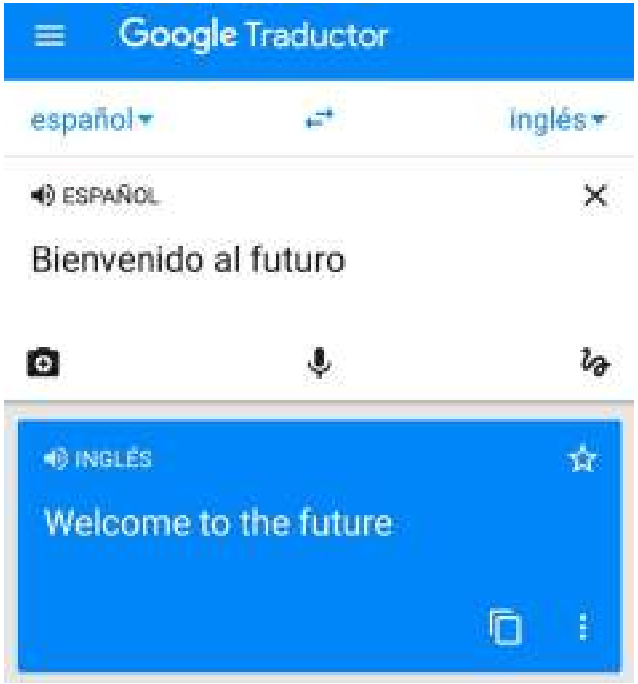
Applications of AI

❖Machine translation

- One-on-one translation was not working, an example of such translation:

  (out of sight, out of mind → Invisible, imbecile)

- Statistical Machine Translation: depends on analyzing large amounts of translated data, then **learning** the correct way of translation.



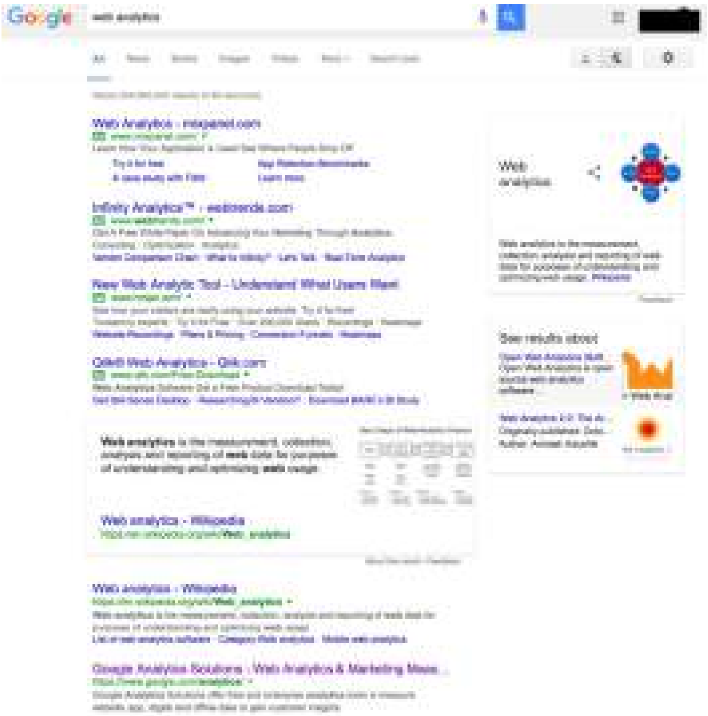
Applications of AI

❖Autonomous Driving

- An **autonomous** car (also known as a driverless car, auto, self-driving car, robotic car) is a vehicle that is capable of sensing its environment and navigating without human input.
- Many such vehicles are being developed, but as of February 2017 automated cars permitted on public roads are not yet fully autonomous.

Applications of AI

❖Web search engines



- A **web search engine** is a software system that is designed to search for information on the World Wide Web.
- An example is (RankBrain) from Google, that uses deep learning to help generate responses to search queries.

Applications of AI

❖Recommendation systems

- They are subclasses of information filtering systems that seek to predict the "rating" or "preference" that a user would give to an item.
- Used for efficient marketing.
- Suggests product that are related to the chosen product or those that other people usually research.

Applications of AI

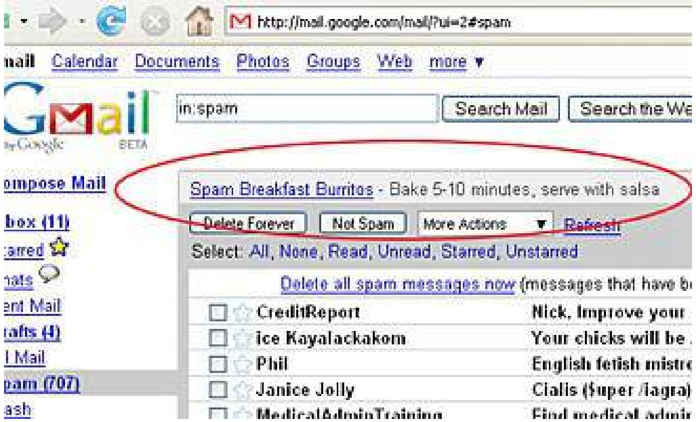
❖Question answering systems

- **Question answering** (QA) is a computer science discipline within the fields of information retrieval and natural language processing (NLP).
- It is concerned with building systems that automatically answer questions posed by humans in a natural language.

Applications of AI

❖Email spam filtering

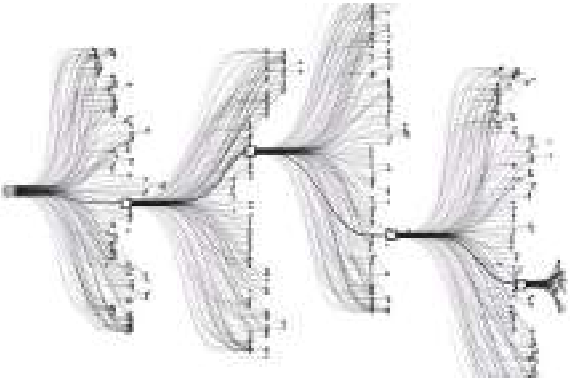
- Most often, this refers to the automatic processing of incoming messages, but the term also applies to the intervention of human intelligence in addition to **anti-spam** techniques, and to outgoing emails as well as those being received.



Applications of AI

❖ **Game playing**

- In video games, artificial intelligence is used to generate intelligent behaviors primarily in non-player characters (NPCs), often simulating human-like intelligence.
- **Chess**: Kasparov VS. IM Deep Blue (1997).
- **Jeopardy**: Humans VS. IBM Watson (2011).
- There are +10,921,506 total possible positions after 7 moves on a chess board.



Applications of AI

❖ Game playing

- **AlphaGo** is a narrow AI, computer program developed by Alphabet Inc.'s Google DeepMind in London to play the board game Go.
- In October 2015, it became the first Computer Go program to beat a human professional Go player without handicaps on a full-sized 19×19 board.
- Number of possible positions on a Go board exceeds the number of atoms in the universe.

Introduction to Fuzzy Logic Controller Structure and Design

Contents

Introduction to Fuzzy Logic systems

- Developement and History of Fuzzy Logic
- Fuzzy Logic Definition
- Fuzzy Sets
- Membership Functions
- Rule Bases
- Fuzzy Logic Controller
    - o Fuzzification
    - o Knowledge Base
    - o Inference Engine
    - o Defuzzification
- Fuzzy Inference Styles
    - o Mamdani-style inference
    - o Sugeno-style inference
- Applications of Fuzzy Logic Controller

History of Fuzzy Logic

In Zadeh's words:
Fuzzy logic is determined as a set of mathematical principles for knowledge representation based on degrees of membership rather than on crisp membership of classical binary logic.

- Lotfi Aliasker Zadeh, professor and head of the electrical engineering department at the University of California at Berkeley.
- Published his famous paper 'Fuzzy sets' in 1965.
- Zadeh extended the work on possibility theory into a formal system of mathematical logic, and even more importantly, he introduced a new concept for applying natural language terms.

http://www.computerworld.com/news/2004/story/0,11280,95282,00.html
http://www.cs.berkeley.edu/~zadeh/

Mamdani-style inference

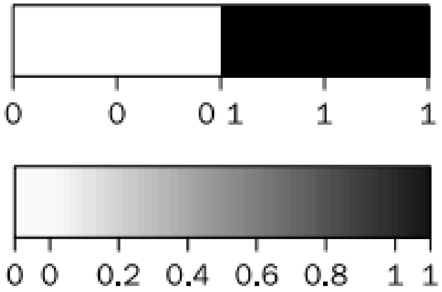
- Ebrahim Mamdani
- Professor of London University
- In 1975 built one of the first fuzzy systems to control a steam engine and boiler combination (Mamdani and Assilian, 1975).
- Mamdani's effort was based on Zadeh's (1973) paper on fuzzy algorithms for complex systems and decision processes.

Sugeno-Style Inference

- Michio Sugeno, Yokohama, Japan
- 'Zadeh of Japan'
- First introduced fuzzy measures and the Sugeno Integrals leading to the concept of the Choquet Integrals as an extension of the conventional Lebesgue Integrals.
- Introduced Sugeno-Style Inference in 1985
- Fuzzy logic was made practically useful in Japan in 1990s.

Fuzzy Definition

- Fuzzy logic is based on the probability of a state instead of a definite state
  - Boolean logic state is defined as either „zero“ or „one“.
  - A Fuzzy logic state is defined by it‘s probability of the state it occupies.



- The probability is referred to as the „degree of memberhsip“
- The Fuzzy Logic tool was introduced in 1965, by Lotfi Zadeh, as a mathematical tool for dealing with uncertainty.
- The Fuzzy theory provides a mechanism for representing linguistic constructs such as “many,” “low,” “medium,” “often,” “few.”
- In general, the Fuzzy logic provides an inference structure that enables appropriate human reasoning capabilities.

Development of Fuzzy Logic

Classical Logic

Proposition:

A fact is either **affirmed** or **denied (true** or **false)**

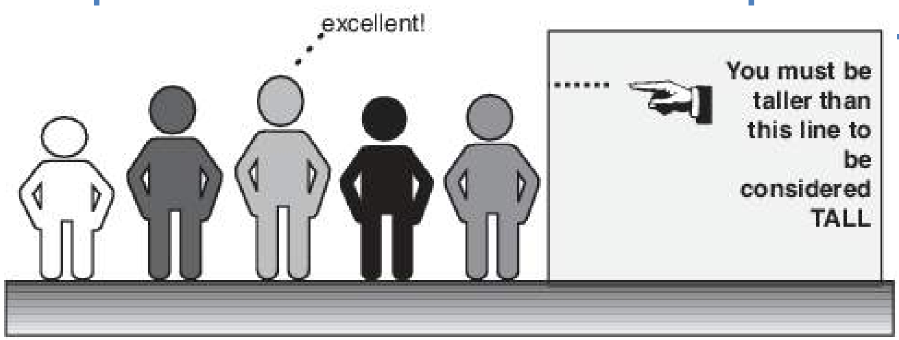
Tom is 167 cm tall

Fuzzy Logic

Fuzziness:

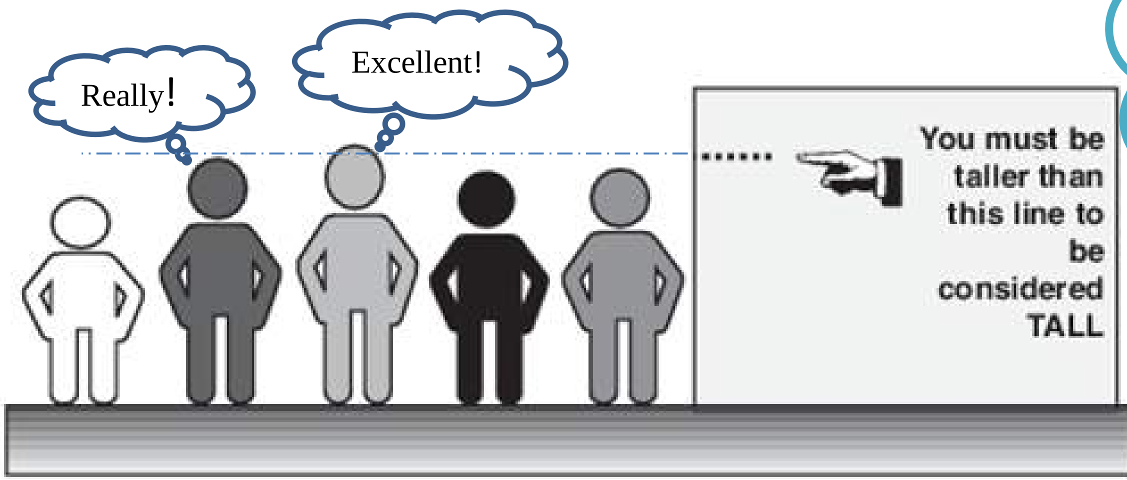
The **lack of well-defined boundaries** of the group, to which an object belongs.

Tom is not very tall



Introduction

- How tall are you? → Are you **TALL**?
  - Is 18 degrees Celsius **HOT**? Is it **HOT** in winter?
  - Is it **HOT** in summer?



Does it always make sense to give **EXACT** answers to any question?

Development of Fuzzy Logic

Classical Logic

<u>Proposition</u>:

A fact is either **affirmed** or **denied (true** or **false)**

<u>Tom is 167 cm tall</u>

Fuzzy Logic

<u>Fuzziness:</u>

The **lack of well-defined boundaries** of the group, to which an object belongs.

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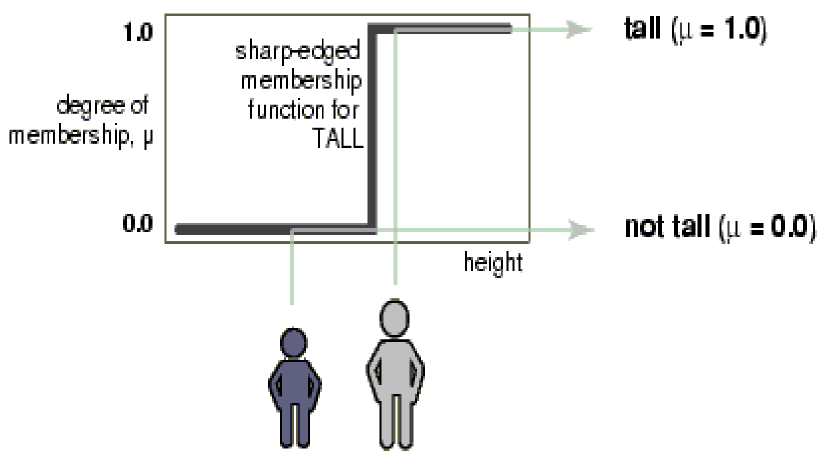
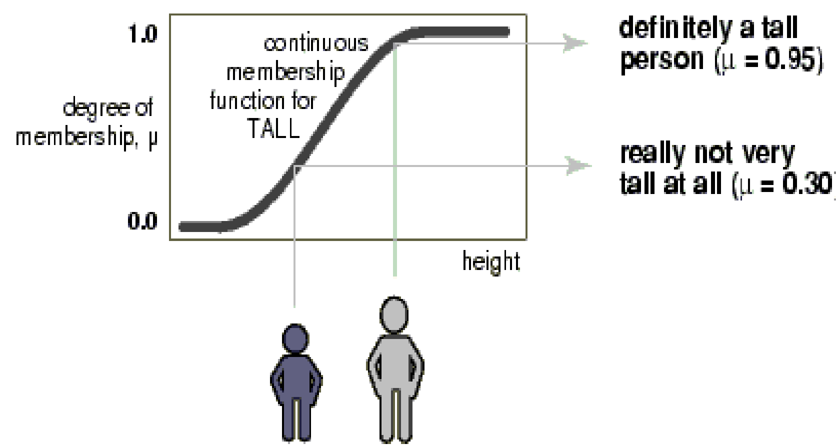




Fuzzy Logic Representation (Zadeh, 1965 & Mammdani, 1974)†

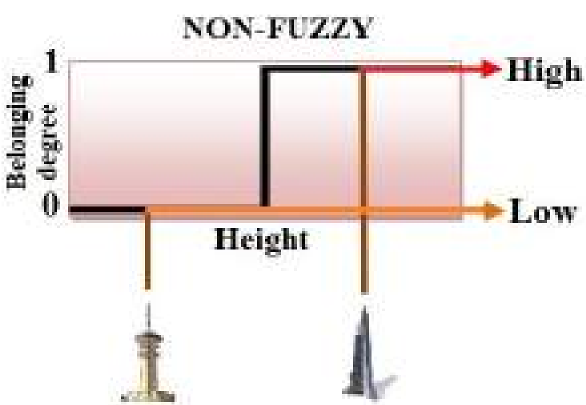
Khalifa Tower
Dubai, UAE,
2010
(828 m)

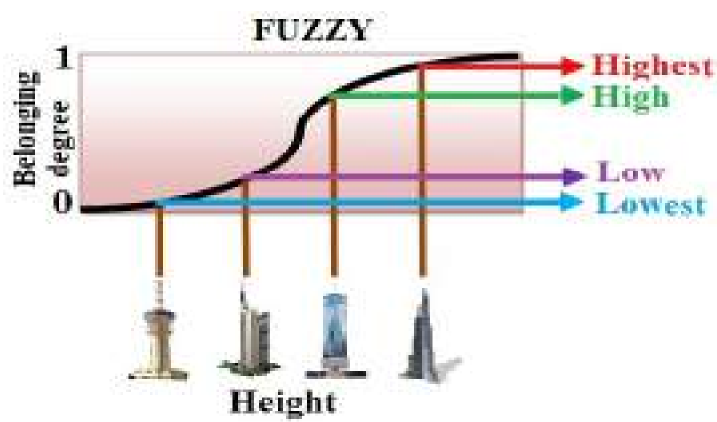
Freedom Tower
New Yourk, USA,
2013
(541 m)

Commerzbank Towe
Frankfurt, Germany,
1997
(259) m

Mamoon Tower ,
Baghdad, Iraq, 19
(205 m)

Highest	High	Low	Lowest
[0.75 – 1.00]	[0.50 – 0.75]	[0.25 – 0.50]	[0.0 – 0.25]



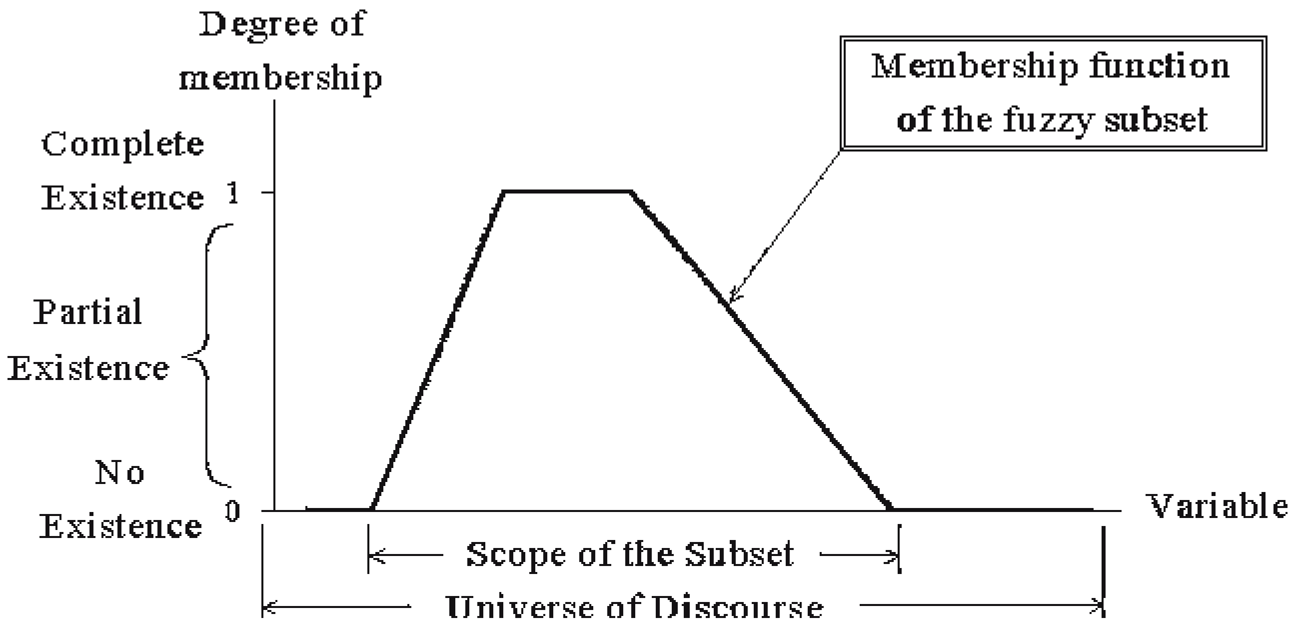


†Source: Zadeh. L., "The Concept of a Linguistic Variable and its Application to Approximate Reasoning-I ", 1975.

Membership Function

- Zadeh formed *fuzzy sets* as the sets on the universe X which can accommodate “degrees of membership.”
- Degrees of membership can be calculated by “Membership function”
- Membership value is between 0 and 1.
- The membership functions can be symmetrical or asymmetrical.

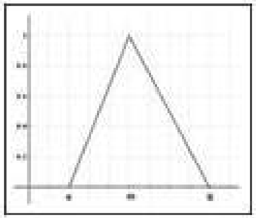
Fuzzy set and Membership function



Types of Membership functions

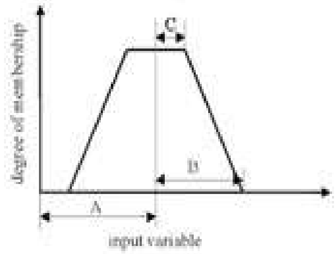
Triangular Membership Function

$$\text{Triangle}(x{:}\,a,b,c)=\begin{cases}0 & x<a\\ \dfrac{(x-a)}{(b-a)} & a\le x\le b\\ \dfrac{(c-x)}{(c-b)} & b\le x\le c\\ 0 & x>c\end{cases}$$



Trapezoidal membership function

$$\text{Trapezoidal}(x{:}\,a,b,c,d)=\begin{cases}0 & x<a\\ \dfrac{(x-a)}{(b-a)} & a\le x\le b\\ 1 & b\le x\le c\\ \dfrac{(d-x)}{(d-c)} & c\le x\le d\\ 0 & x\ge d\end{cases}$$



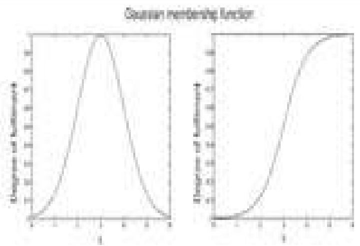
Types of Membership functions

Gaussian membership function

$$\text{Gaussian}(x; m, \sigma) = \exp\left\{-\frac{(x-m)^2}{\sigma^2}\right\}$$

Where m→center of the function

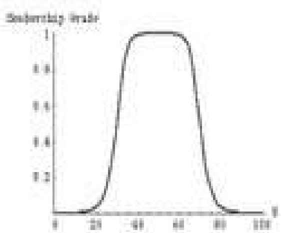
σ→ width of the function



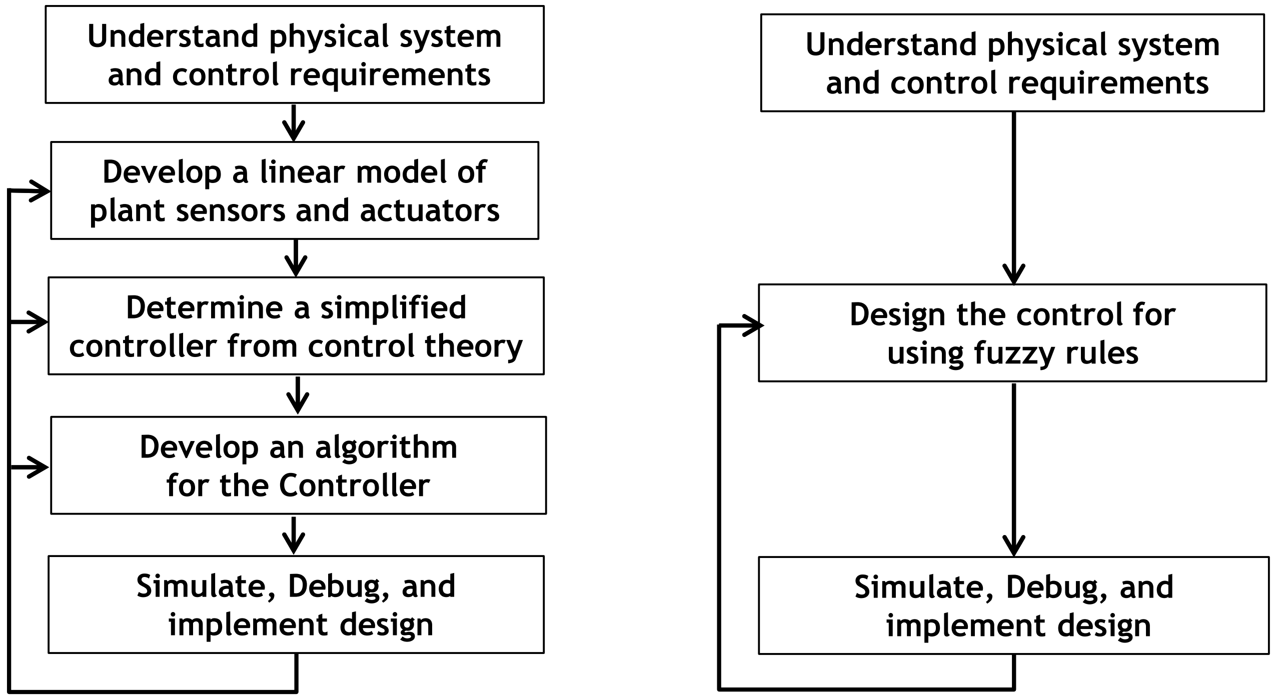
Bellshaped membership function

$$\text{Bell}(x; a, b, c) = \frac{1}{1 + \left|\frac{x-c}{a}\right|^{2b}}$$

Where the parameter b is usually positive and we can adjust c and a to vary the center and width of the function .



Why Fuzzy Logic over Traditional Logic?, Zadeh,1965, Mammdani, 1975*



* Source: Zadeh. L., *"The Concept of a Linguistic Variable and its Application to Approximate Reasoning-I "*, 1975

Expert Systems

- Appeared in the 1970s and had a great influence on the Fuzzy development.
- Based on the concept of representing the human knowledge in a way the machine can understand.
- Knowledge can be defined as: a theoretical or practical understanding of a subject or a domain.
- Those who own knowledge are called experts, and can be defined as: Anyone who has deep knowledge (of both facts and rules) and strong practical experience in a particular domain.
- To build an expert system, we need to make the machine think like a human expert.

→ How does an expert think?

Fuzzy IF-THEN rules

- One way to express human thinking is using **rules.**
- A simple example is:

IF *the weather is raining*

THEN *use an umbrella*

- These IF-THEN form of rules consists of two parts: the IF part, called the **antecedent** (**premise or condition**) and the THEN part called the **consequent** (**conclusion or action**).
- Rules can be joined by conjunctions or disjunctions

IF *<antecedent 1>*

AND *<antecedent 2>*

THEN *<consequent>*

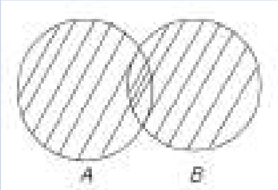
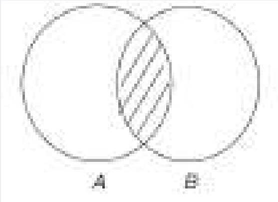
IF *<antecedent 1>*

OR *<antecedent 2>*

THEN *<consequent>*

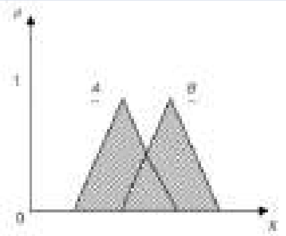
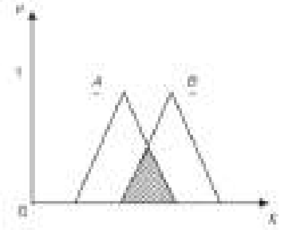
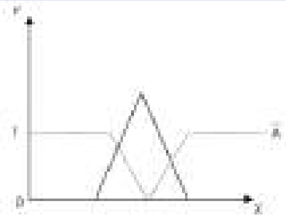
Operations on Classical Sets

Consider two sets A and B defined on the universe X.

Operation	Denote	Theoretic Form	
Union	$A \cup B$	$A \cup B = \{x/x \in A \text{ or } x \in B\}$	
Intersection	$A \cap B$	$A \cap B = \{x/x \in A \text{ and } x \in B\}$	
Complement	$\bar{A}$	$\bar{A}=\{x/x \notin A, x \in X\}$	

Fuzzy Set Operations

Considering three fuzzy sets A, B and C on the universe X. For a given element x of the universe is stated:

Operation	Theoretic Form	Illustration
Union	$\mu_{\underset{\sim}{A} \cup \underset{\sim}{B}}(x) = \mu_{\underset{\sim}{A}}(x) V \mu_{\underset{\sim}{B}}(x)$	
Intersection	$\mu_{\underset{\sim}{A} \cap \underset{\sim}{B}}(x) = \mu_{\underset{\sim}{A}}(x) \Lambda \mu_{\underset{\sim}{B}}(x)$	
Complement	$\mu_{\underset{\sim}{\bar{A}}}(x) = 1 - \mu_{\underset{\sim}{A}}(x)$	

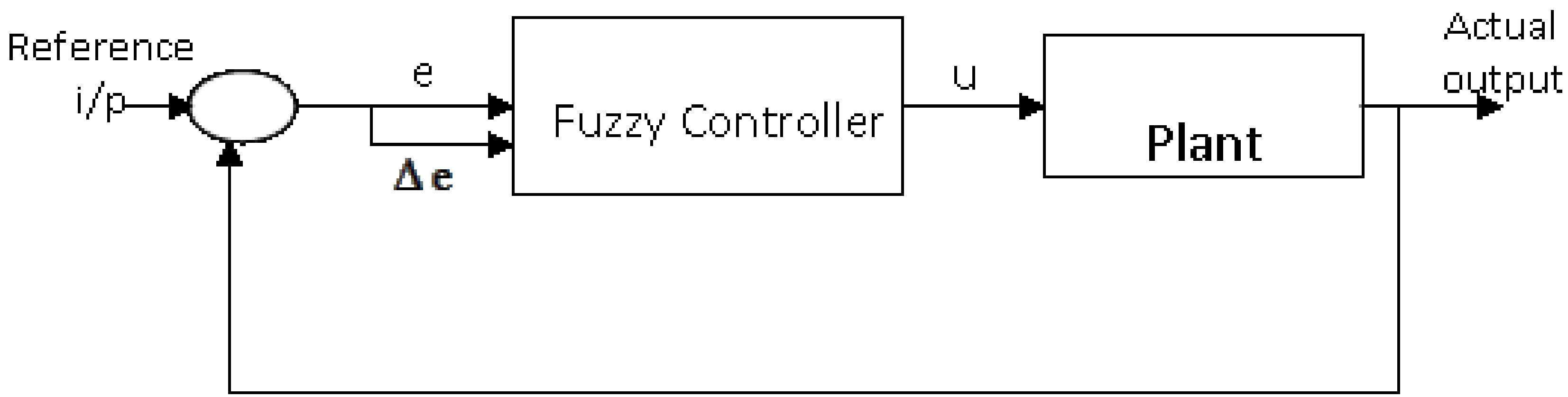
Rule Evaluation

To evaluate the disjunction of the rule antecedents, we use the **OR fuzzy operation**. Typically, fuzzy expert systems make use of the classical fuzzy operation **union**:

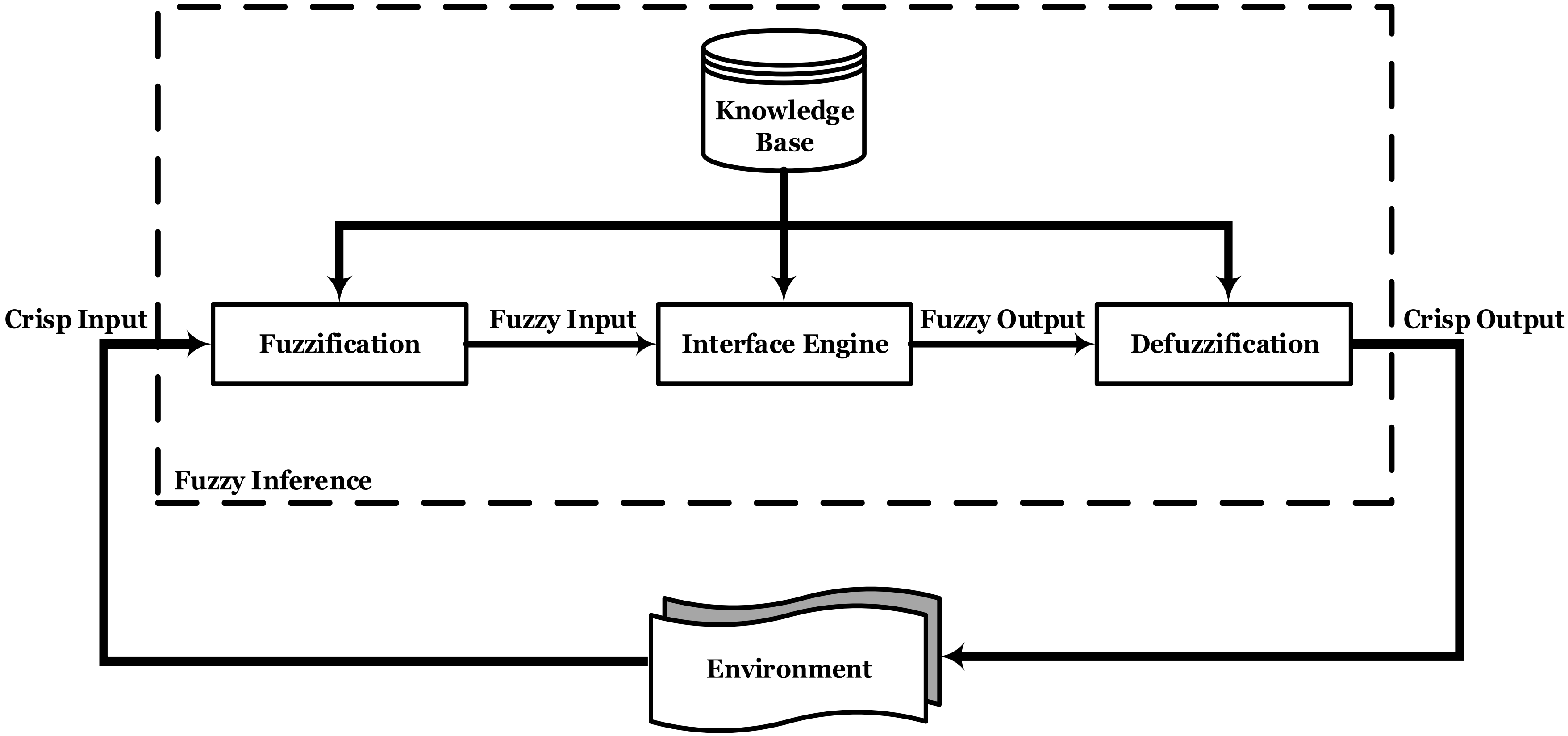
$$\mu_{A \cup B}(x) = \max [\mu_A(x), \mu_B(x)]$$

Similarly, in order to evaluate the conjunction of the rule antecedents, we apply the **AND fuzzy operation intersection**:

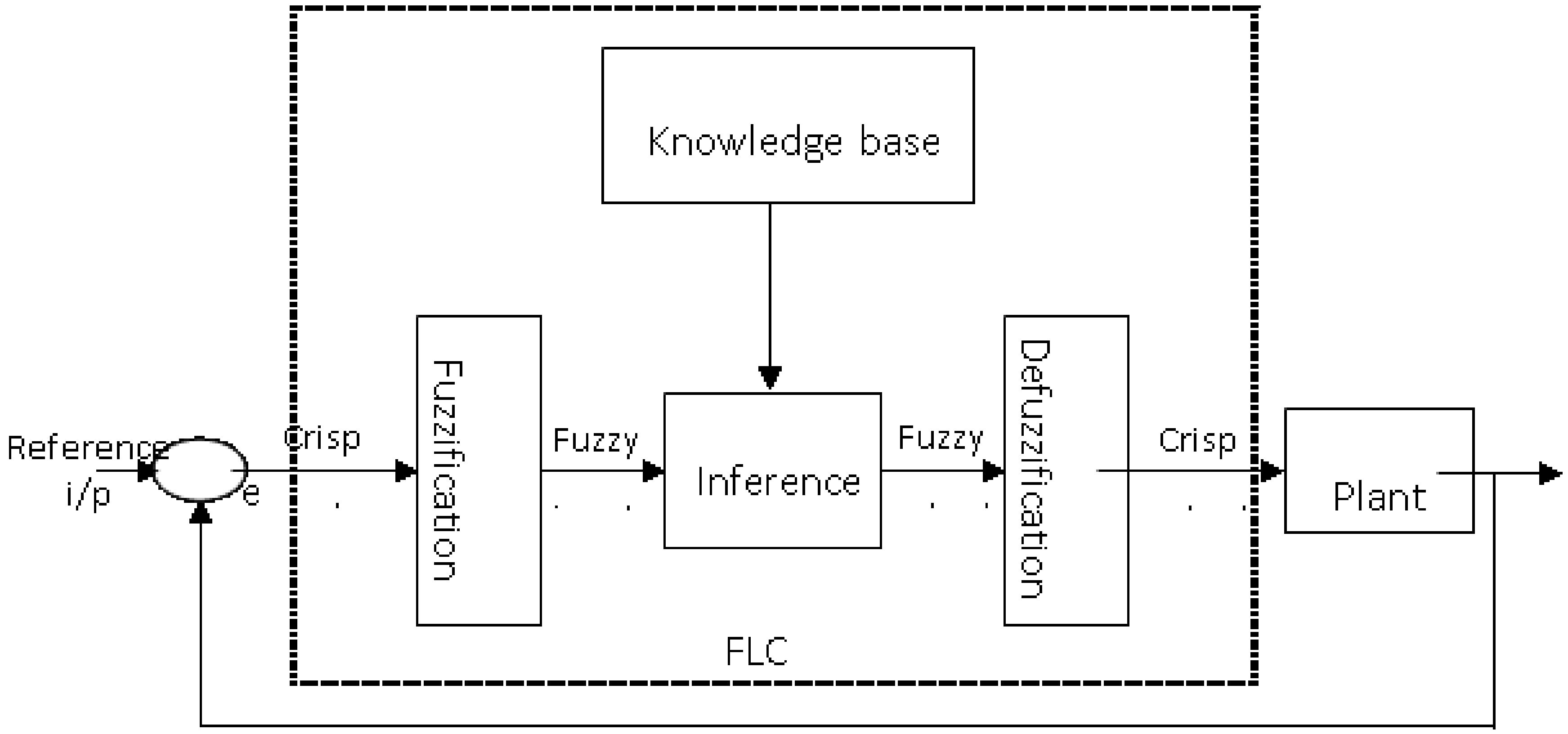
$$\mu_{A \cap B}(x) = \min [\mu_A(x), \mu_B(x)]$$


Reference
i/p
e
Δe
Fuzzy Controller
u
Plant
Actual
output

Fuzzy Logic Controller



Basic Structure of a Fuzzy Logic Controller



Basic elements of a Fuzzy Logic Controller

- **The fuzzification:** converts the measured "crisp" inputs to "fuzzy" values such as Positive Big (PB), Negative Small (NS).

- **The knowledge base:** contains a set of if-then rules or a relation matrix representing those rules

- **The decision-making unit (inference engine unit):** simulates the inference mechanism in human. It produces fuzzy control action using fuzzy implication.

- **The defuzzification:** is an interface unit between the process and the decision making unit which converts the fuzzy set output to crisp output.

Thank you!

Control System Design

Fuzzy Logic Control (FLC)
Artificial intelligence Systems
(Overview)

Lecture 2

Contents

Introduction to Fuzzy Logic systems

- Fuzzy Logic Controller
  - Fuzzification
  - Knowledge Base
  - Inference Engine
  - Defuzzification
- Fuzzy Inference Styles
  - Mamdani-style inference
  - Sugeno-style inference
- Applications of Fuzzy Logic Controller

Artificial intelligence (AI)

Artificial Neural Networks (ANNs)

- McCullochi and Pits, 1943*

Fuzzy logic system (FLS)

- Zadeh, 1965*
- Mammdani, 1974*
- Sugeon, 1985*

Genetic algorithm (GA)

- Holland, 1975*

* Source: Zadeh. L., "*The Concept of a Linguistic Variable and its Application to Approximate Reasoning-I*", 1975.
* Zurada J. M.,"*Introduction to Artificial Neural Systems*", Jaico publishing House, 1996.
* Pham D. T. and Xing L., "*Neural Networks for Identification, Prediction and Control*", Spring-Verlag London Limited, 1997.

Introduction to Fuzzy Logic Controller Structure and Design

Introduction: Conventional set vs. fuzzy set

X: universe of discourse. Set **A** is defined by **A={2,4,6,8}**

- where μ**(x)** is a **membership function**.
- For **conventional set**, the range of μ**(x) is {T, F}**
- **For fuzzy set**, the range of μ**(x) is [0,1].** So, the above definition cannot be used for fuzzy set. **We cannot say clearly if x is in A or not when 0<μ(x) < 1**.

- **Crisp logic** ⟹ **Boolean logic: True/False**

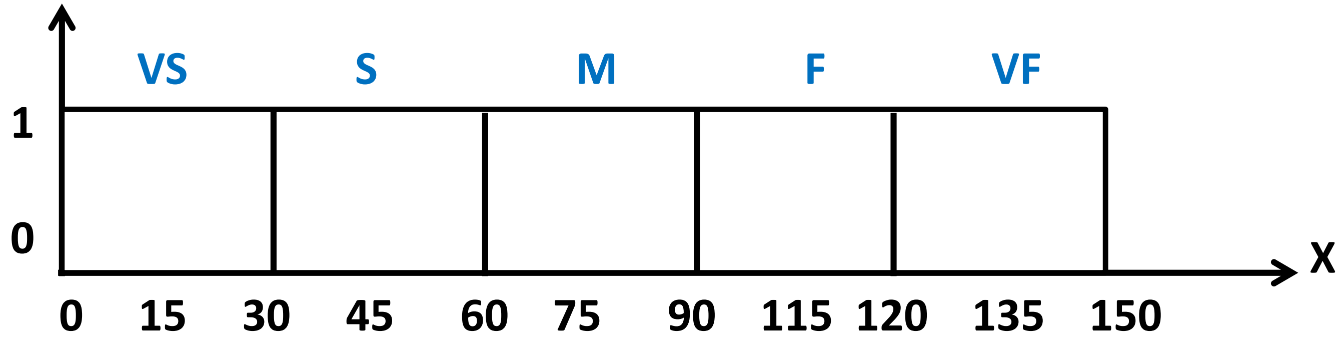
A={2,4,6,8}

X1=2 ⇨ **X1**$\in$ **A**

X2=3 **X2**$\notin$ **A**

Conventional set vs. fuzzy set

- Fuzzy logic and Fuzzy sets
- Linguistic variables and linguistic values
- For example: Speed ⟹ 150 Km/h
- **Very Slow (VS), Slow (S), Medium(M), Fast (F), Very Fast (VF)**



X: universe of discourse: range of the inputs: e.g. 0 to 150 km/h

Conventional set vs. fuzzy set

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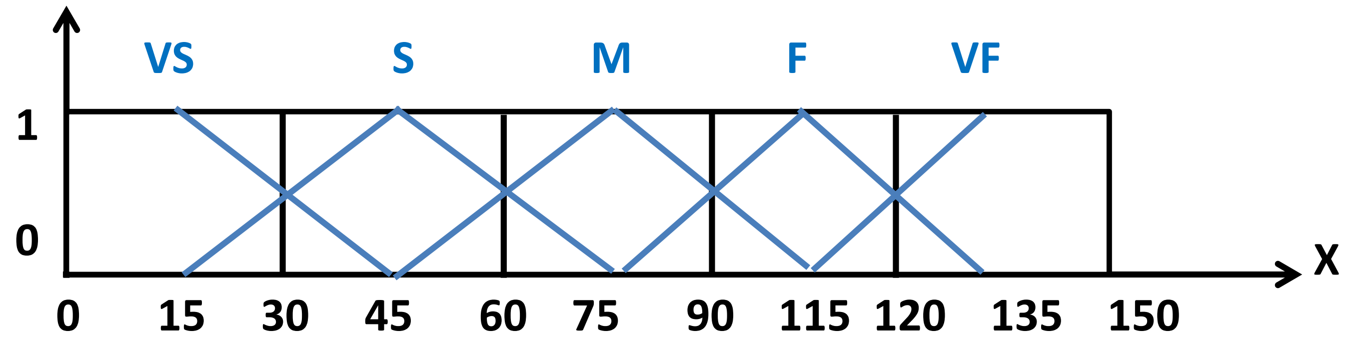

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Conventional set vs. fuzzy set

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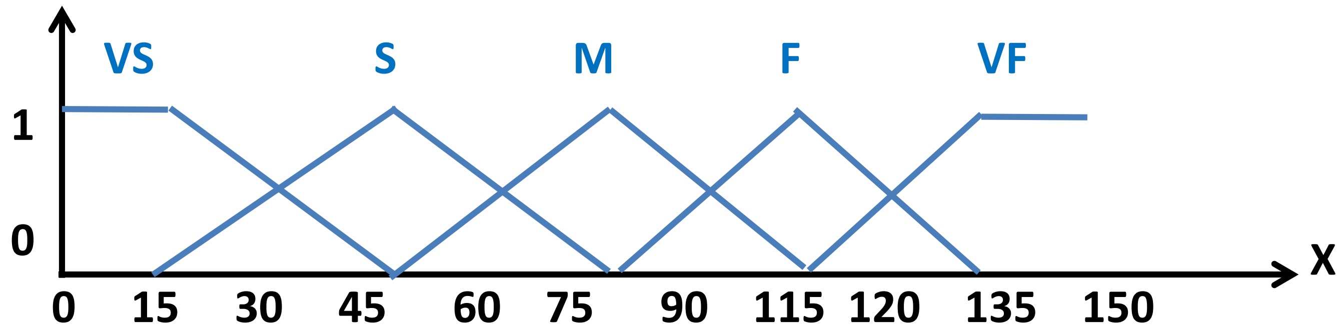
- **Very Slow (VS), Slow (S), Medium(M), Fast (F), Very Fast (VF)**



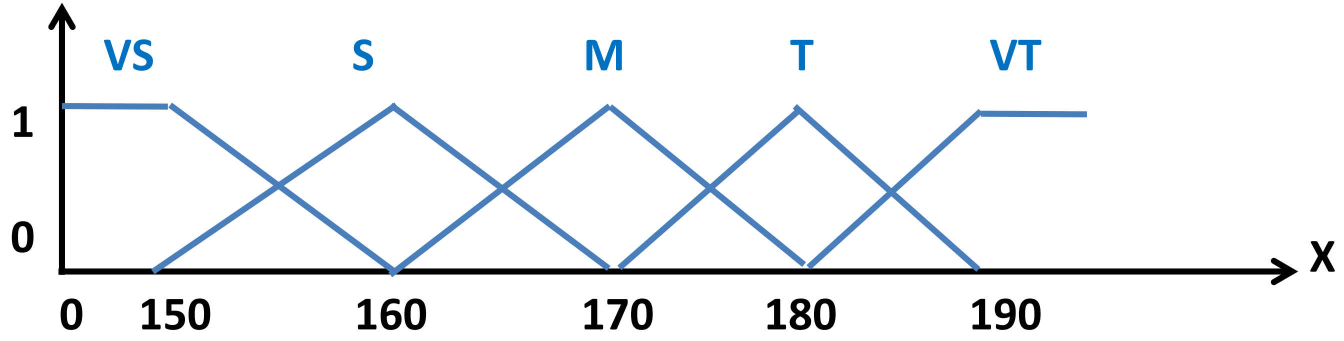
X: universe of discourse: range of the inputs: e.g. **0 to 150 km/h**

Conventional set vs. fuzzy set

- Fuzzy logic and Fuzzy sets
- **Tall person set**:

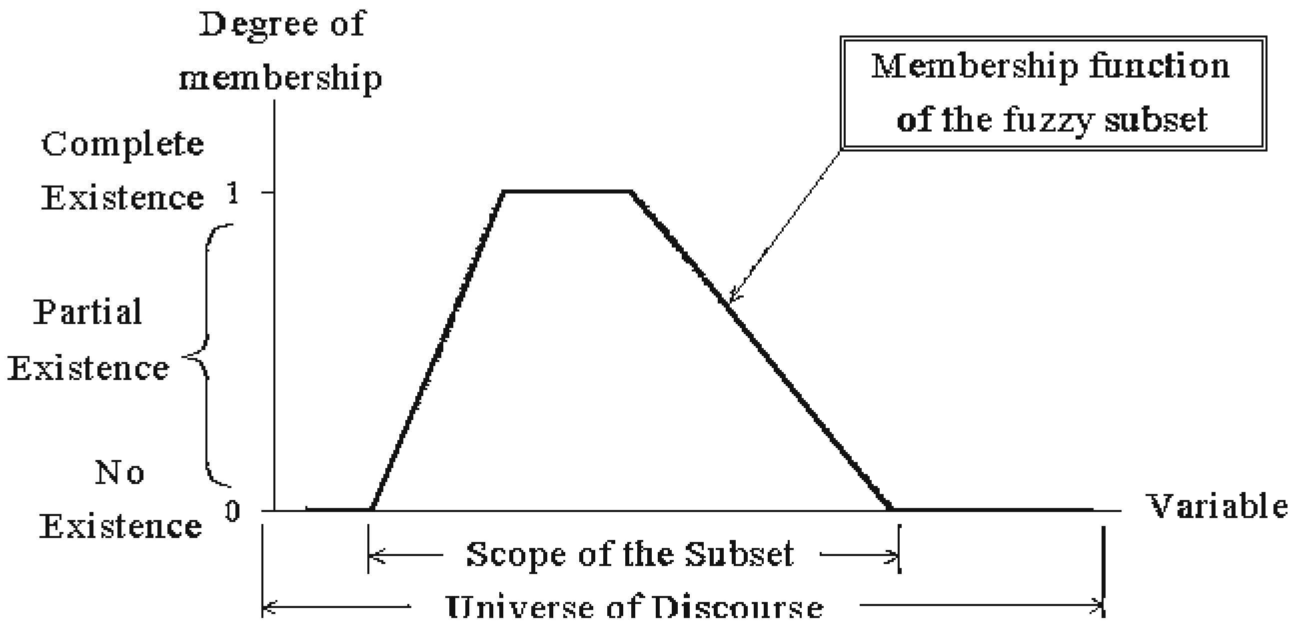
Very Short (VS), Short (S), Medium(M), Tall (T), Very Tall (VT)

- Linguistic variables and values



X: universe of discourse: range of the inputs

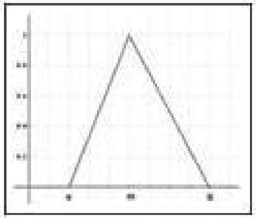
Fuzzy set and Membership function



Types of Membership functions

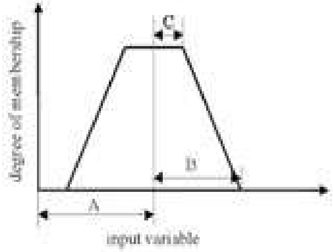
Triangular Membership Function

$$\text{Triangle}(x{:}\,a,b,c)=\begin{cases}0 & x<a\\ \dfrac{(x-a)}{(b-a)} & a\le x\le b\\ \dfrac{(c-x)}{(c-b)} & b\le x\le c\\ 0 & x>c\end{cases}$$



Trapezoidal membership function

$$\text{Trapezoidal}(x{:}\,a,b,c,d)=\begin{cases}0 & x<a\\ \dfrac{(x-a)}{(b-a)} & a\le x\le b\\ 1 & b\le x\le c\\ \dfrac{(d-x)}{(d-c)} & c\le x\le d\\ 0 & x\ge d\end{cases}$$



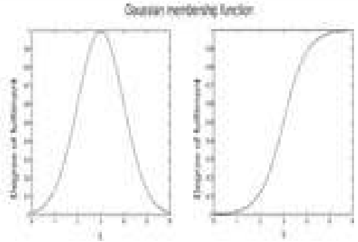
Types of Membership functions

Gaussian membership function

$$\text{Gaussian}(x: m, \square) = \exp\left\{-\frac{(x-m)^2}{\sigma^2}\right\}$$

Where m→center of the function

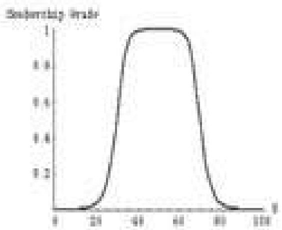
σ→ width of the function



Bellshaped membership function

$$\text{Bell}(x: a, b, c) = \frac{1}{1 + \left|\frac{x-c}{a}\right|^{2b}}$$

Where the parameter b is usually positive and we can adjust c and a to vary the center and width of the function .



Fuzzy IF-THEN rules

- One way to express human thinking is using **rules.**
- A simple example is:

IF temperature is hot THEN hot_water is reduced;

(or cold_water is increased)

- These IF-THEN form of rules consists of two parts: the IF part, called the **antecedent** (**premise or condition**) and the THEN part called the **consequent** (**conclusion or action**).
- Rules can be joined by conjunctions or disjunctions

IF *<antecedent 1>* **AND** *<antecedent 2>* **THEN** *<consequent>*

IF *<antecedent 1>* **OR** *<antecedent 2>* **THEN** *<consequent>*

Rules Bases

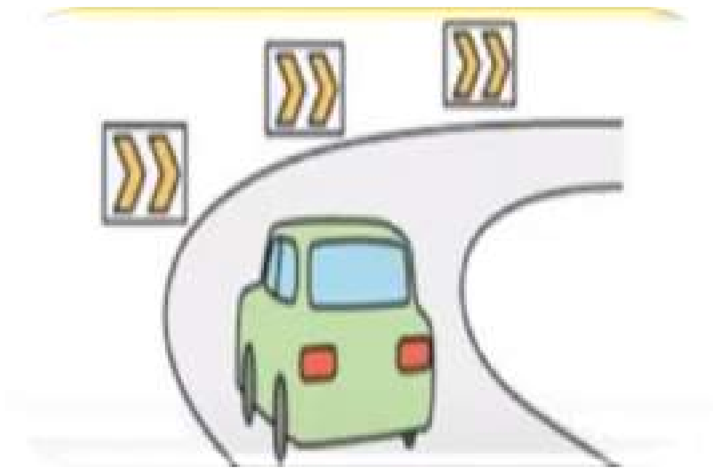
- **Single input single output**

Rule: IF x is A THEN z is C

- **Two inputs single output**

Rule: IF x is A AND y is B THEN z is C
Rule: IF x is A OR y is B THEN z is C

Fuzzy logic Rules for Speed control



The relation between the curvature and the speed limitation

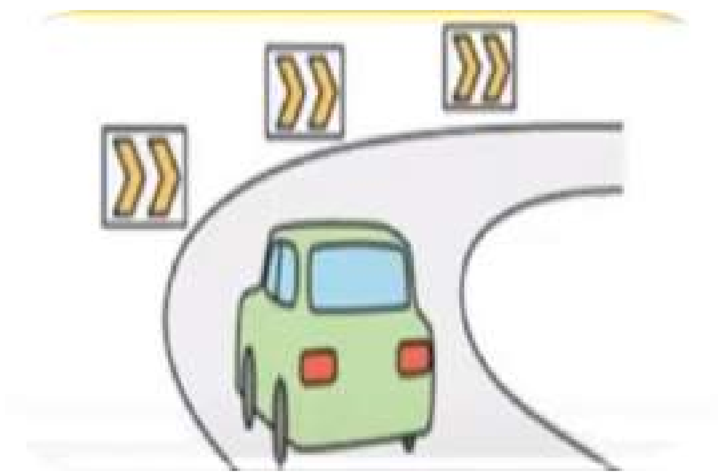
For example:

If the speed limit is 50 km/h, the radius of curve must be 100m or more

(see Table 5.4 in pp.94).

Reference: by Qlangfu Zhao, 2008, Example 5.3 pp. 93-96,

Fuzzy logic Rules for Speed control

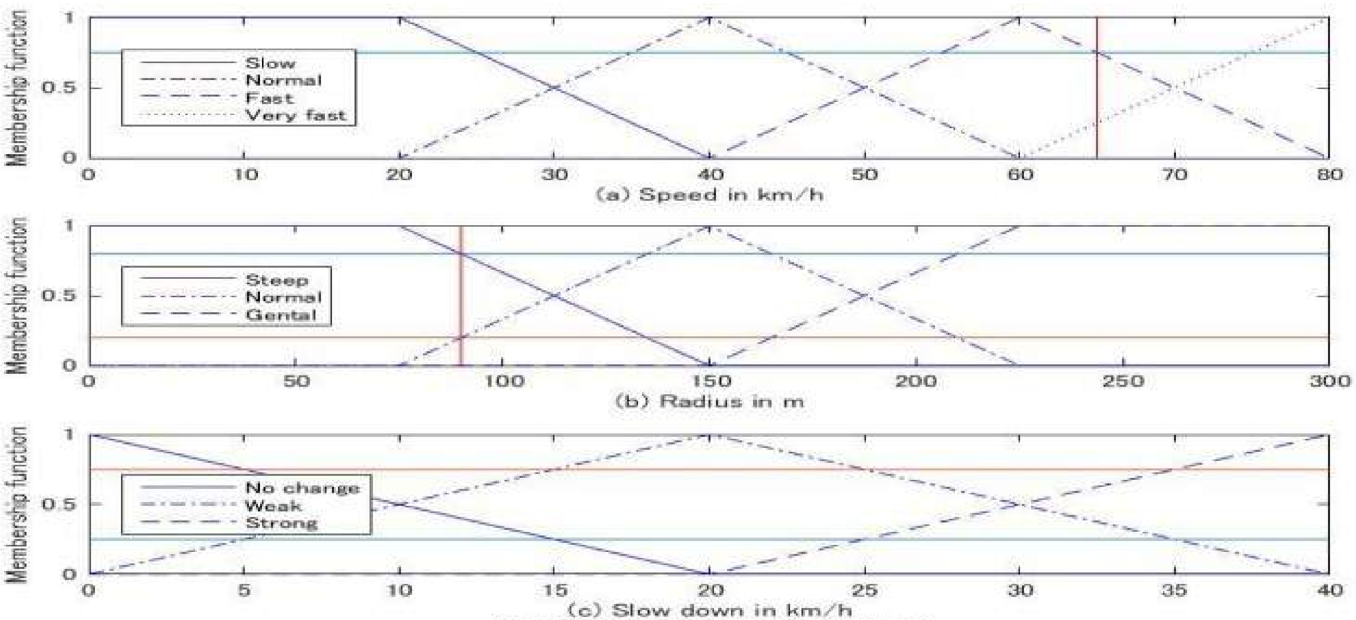


Speed (v)	Curvature (radius r)	Break (B)
Normal	large curve	As is
Normal	Normal	As is
Normal	**Sharp curve**	**Weak**
A little fast	Large curve	As is
A little fast	Normal	As is
A little fast	**Sharp curve**	**Weak**
Fast	Slow curve	As is
Fast	**Normal**	**Weak**
Fast	**Sharp curve**	**Strong**

- R1: If **v is Normal** AND **r is Sharp curve** Then **B is Weak**
- R2: If **v is A little fast** AND **r is Sharp curve** Then **B is Weak**
- R3: If **v is Fast** AND **r is Sharp curve** Then **B is Weak**
- R4: If **v is Fast** AND **r is Sharp curve** Then **B is Strong**

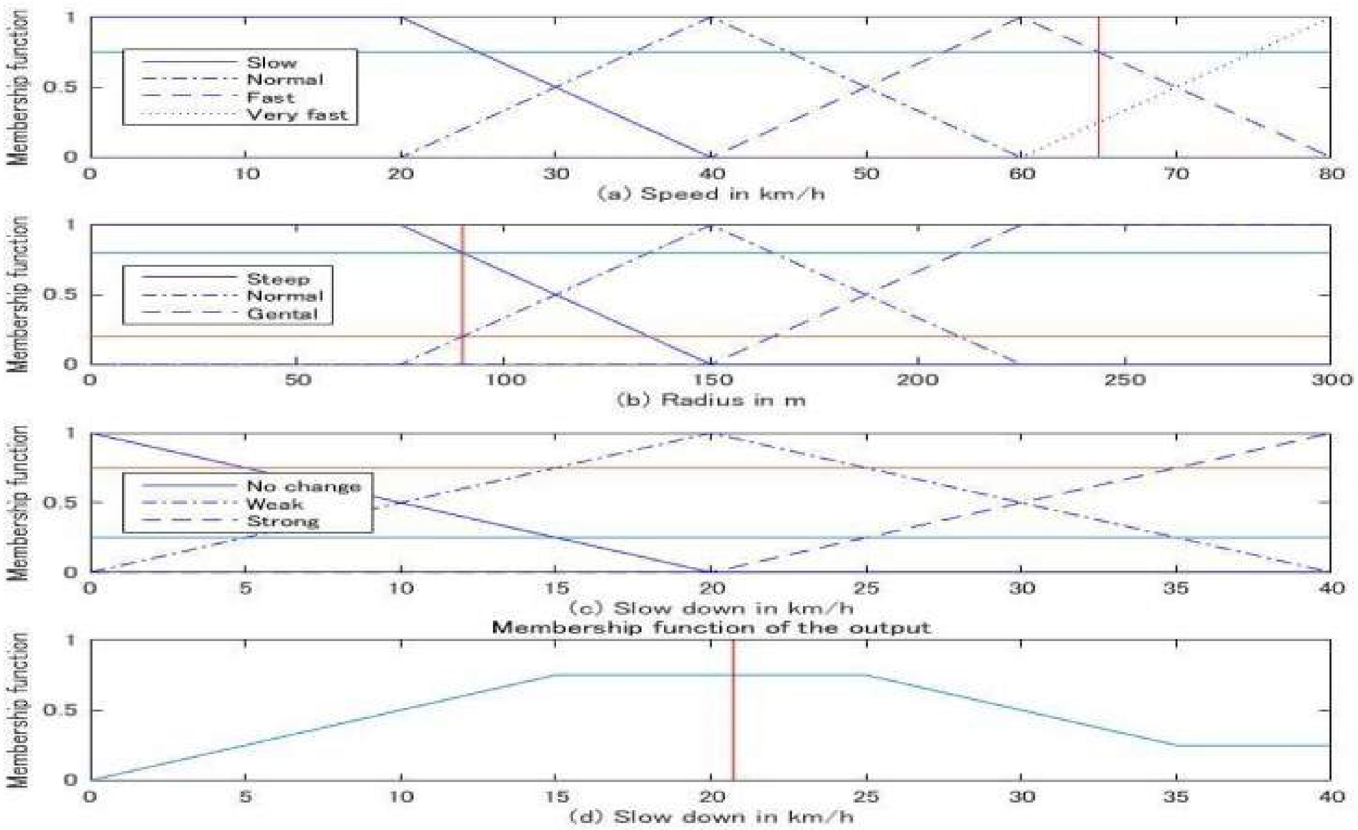
Reference: by Qlangfu Zhao, 2008, Example 5.3 pp. 93-96,

Fuzzy sets of inputs and outputs



Membership function of the output

Fuzzy sets of inputs and outputs

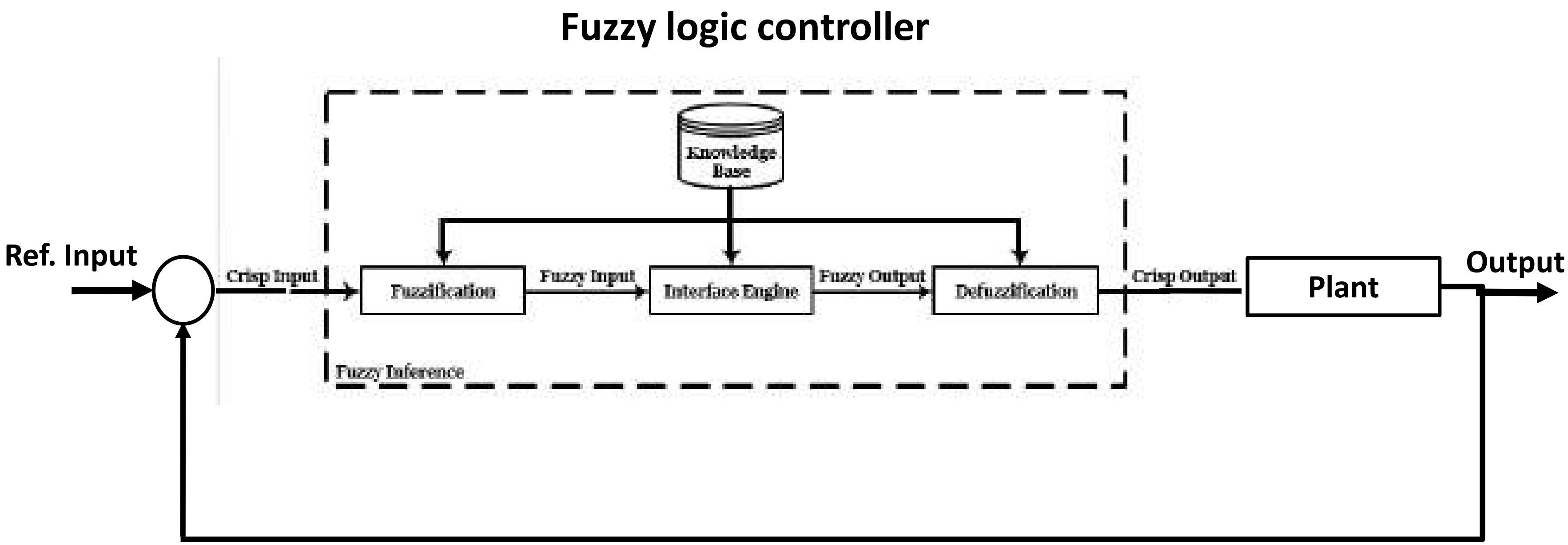


Reference: by Qlangfu Zhao, 2008, Example 5.3 pp. 93-96,

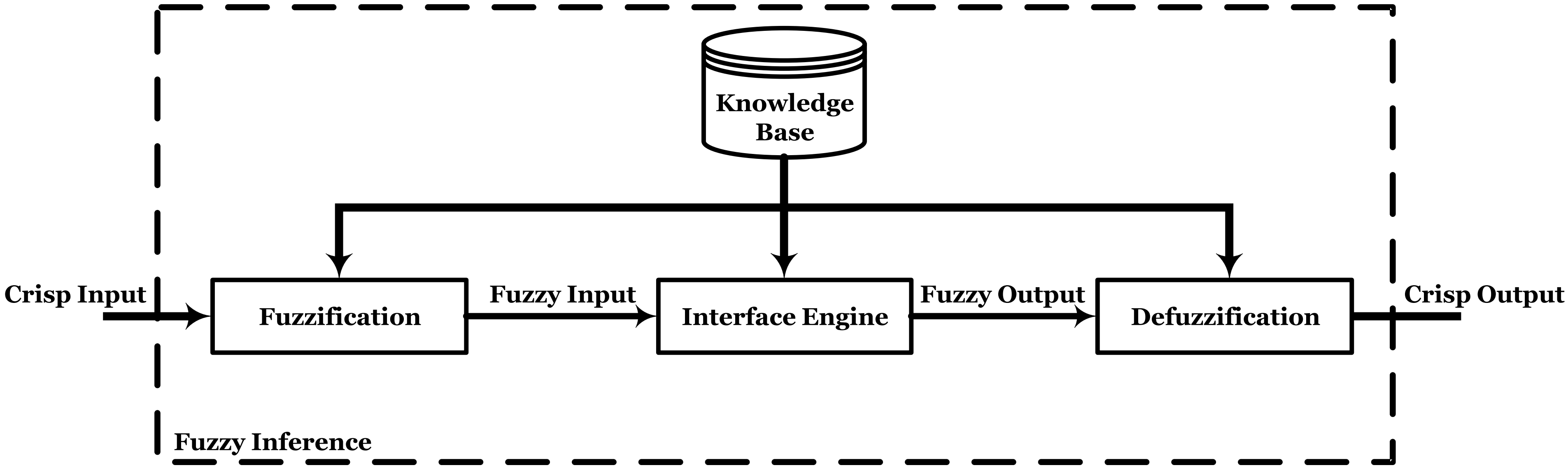
Lecture 3

Introduction to Fuzzy Logic Controller Structure and Design

Fuzzy logic System
(Fuzzy Logic Controller)



Fuzzy logic System
(Fuzzy Logic Controller)



Basic elements of a Fuzzy Logic Controller

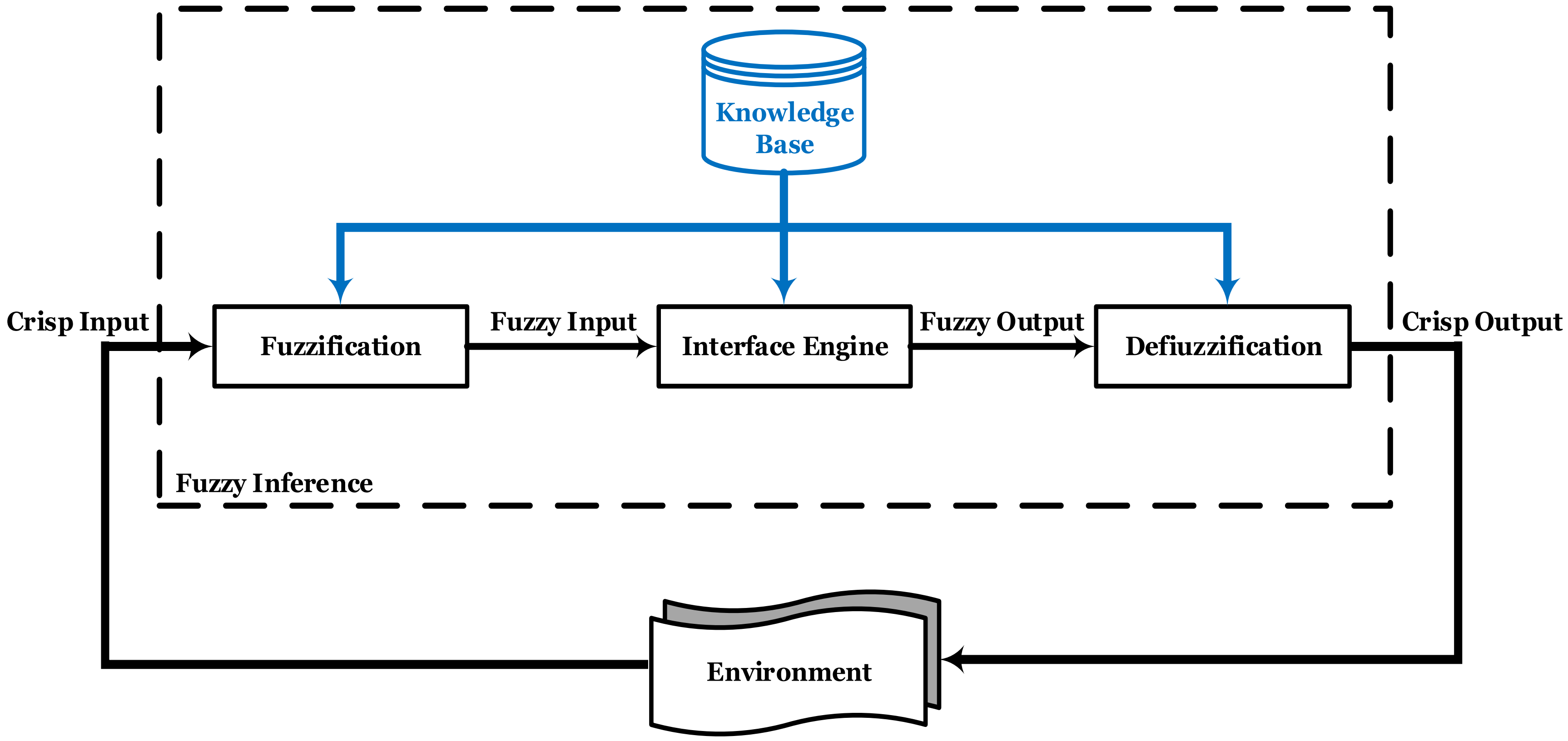
- **The fuzzification:** converts the measured "crisp" inputs to "fuzzy" values such as Positive Big (PB), Negative Small (NS).

- **The knowledge base:** contains a set of if-then rules or a relation matrix representing those rules

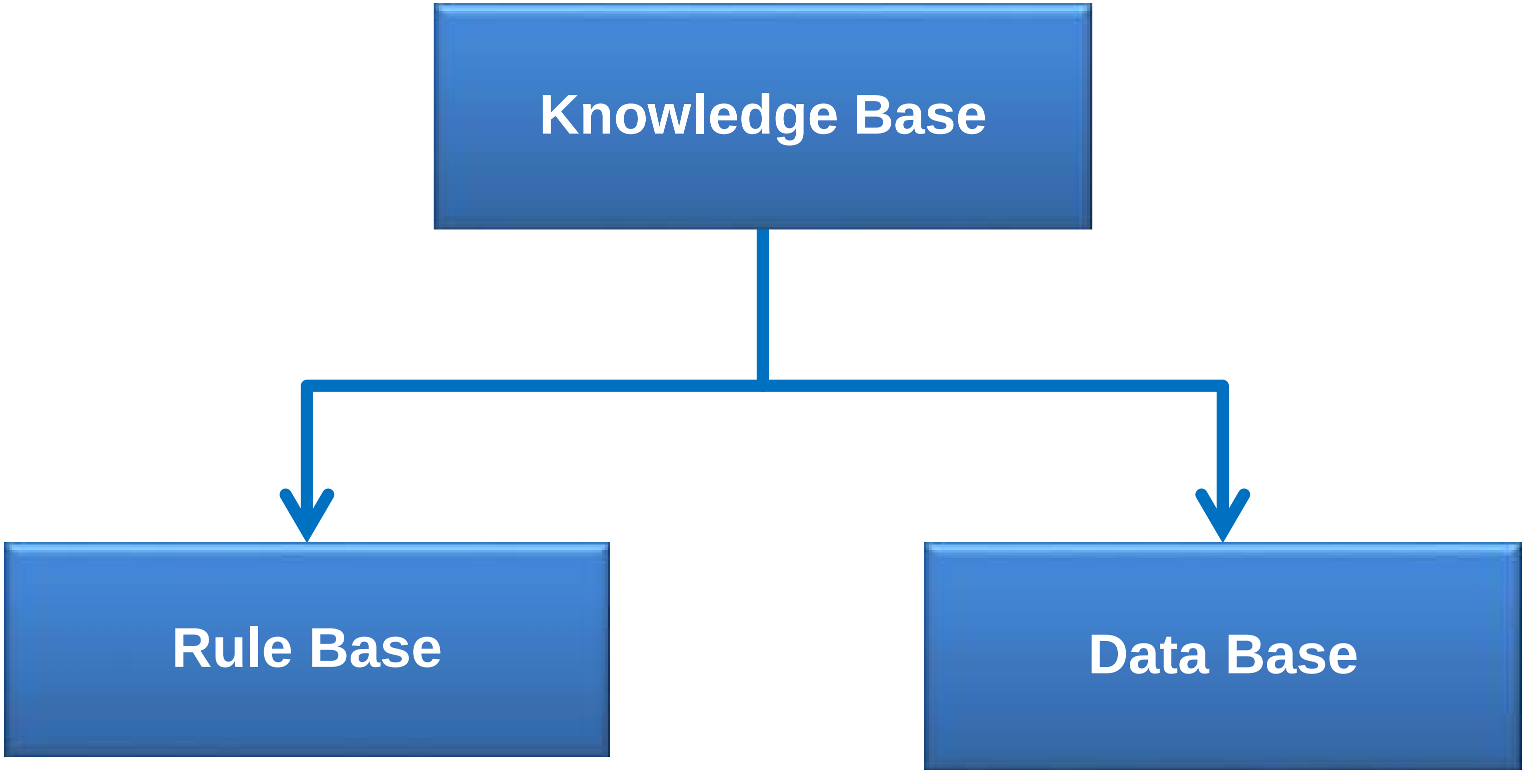
- **The decision-making unit (inference engine unit):** simulates the inference mechanism in human. It produces fuzzy control action using fuzzy implication.

- **The defuzzification:** is an interface unit between the process and the decision making unit which converts the fuzzy set output to crisp output.

Knowledge Base



Knowledge Base



Knowledge Base

• Rule-Base

• Data-Base

Containing a number of fuzzy IF–THEN rules.

Creating Fuzzy Rules:

if (input 1 is membership function 1)

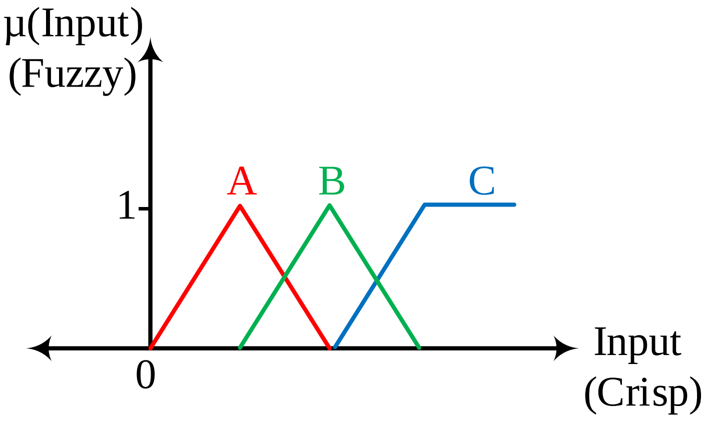
and/or (input 2 is membership function 2)

and/or

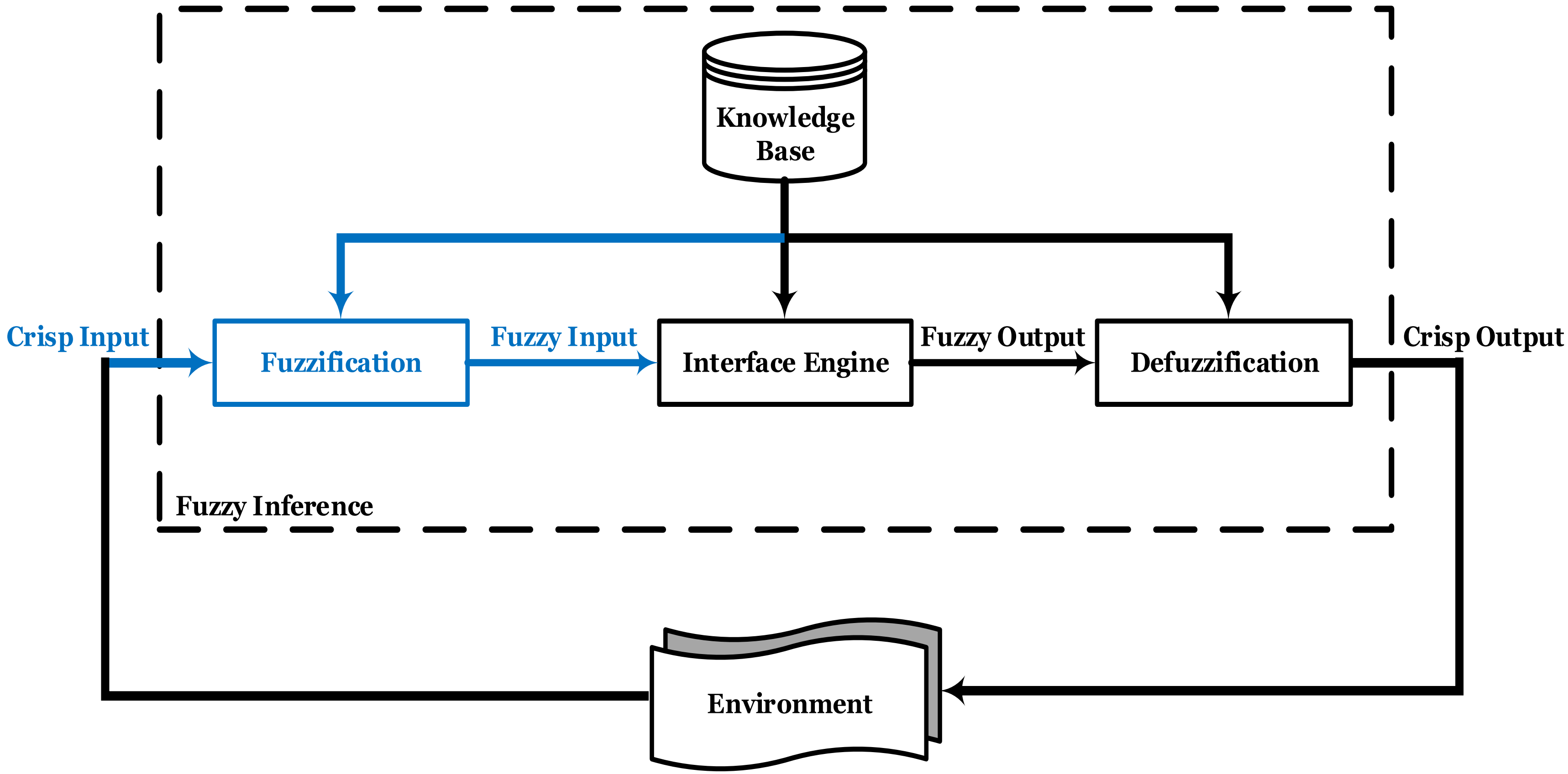
. . .

then (output **n** is output membership function).

Data-Base defines the membership functions of the fuzzy sets used in the fuzzy rules.

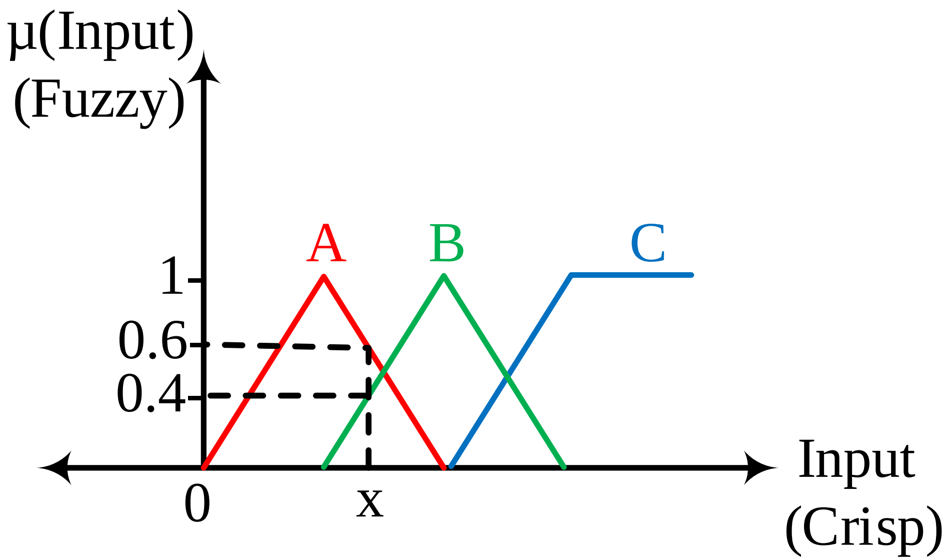


Fuzzification



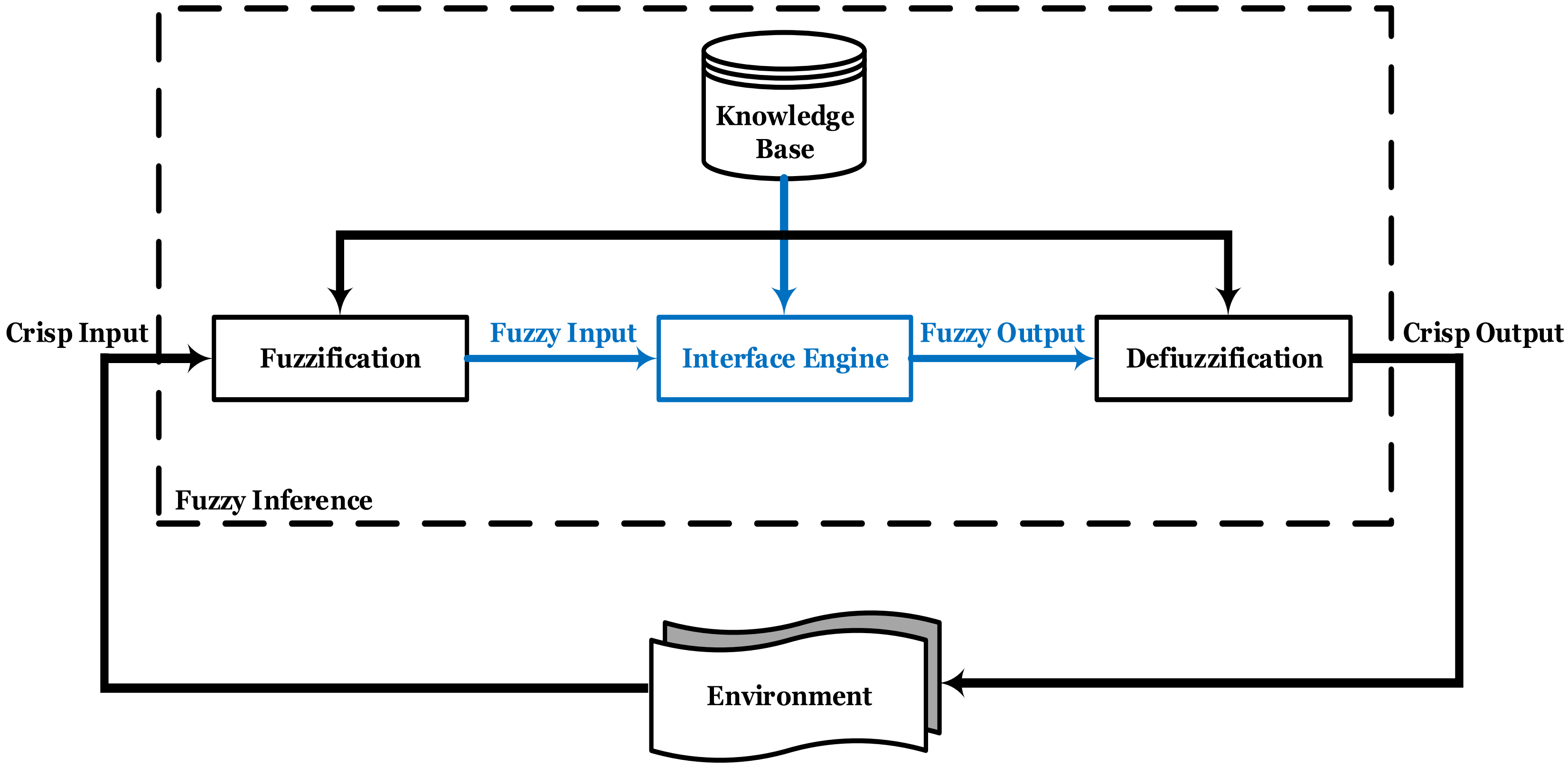
Fuzzification

- Fuzzification is the process where the crisp quantities are converted to fuzzy ones.
- The purpose of fuzzification is to map the inputs from a set of sensors to values from 0 to 1 using a set of input membership functions.



$$\mu(x) = 0.6(A)\ \&\ 0.4(B)$$

Inference Engine

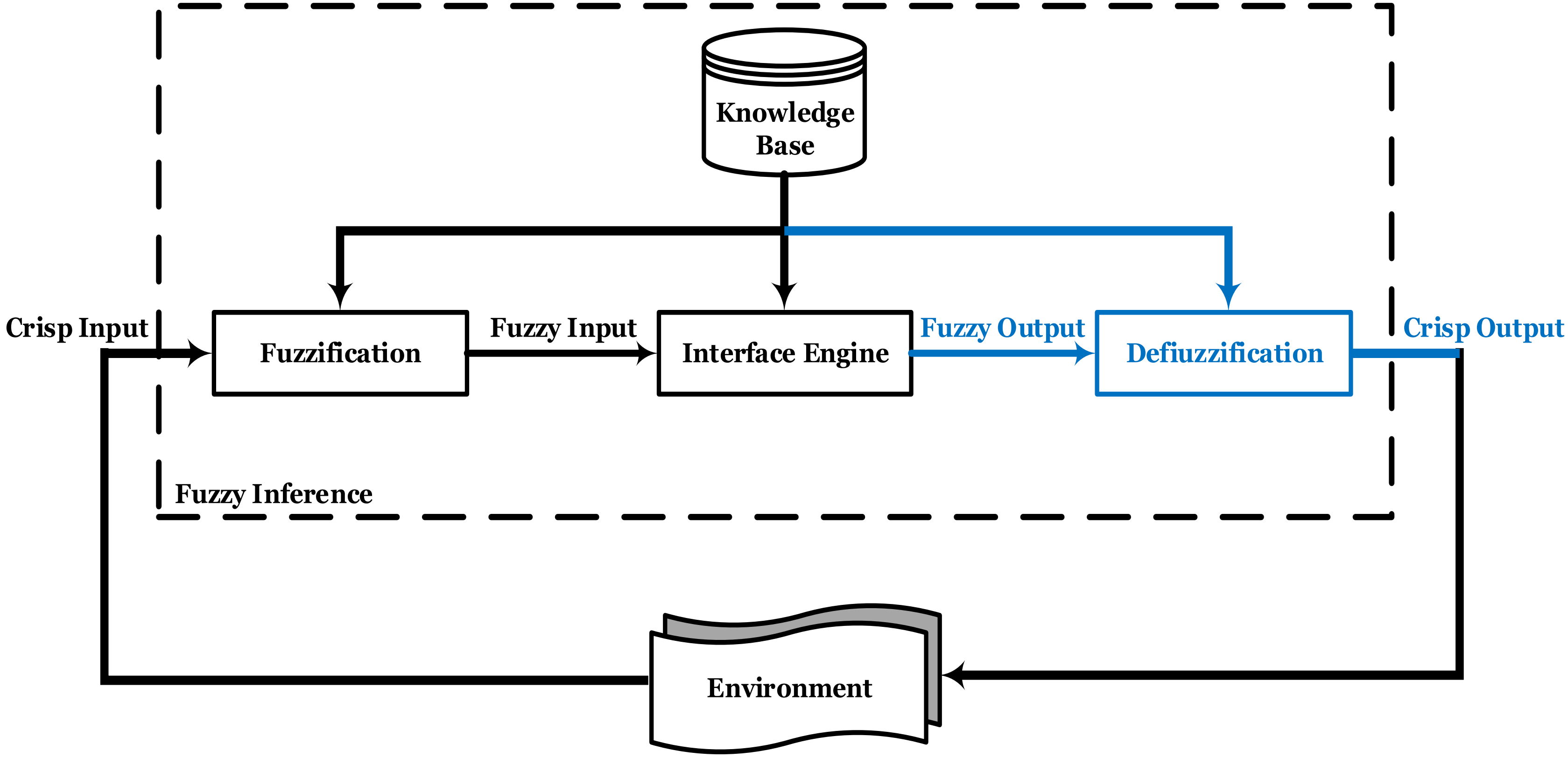


Inference Engine

- A program's protocol for navigating through the rules and data in a knowledge system in order to solve the problem.

- The major task of the **inference engine** is to select and then apply the most appropriate rule at each step as the expert system runs, which is called rule-based reasoning.

Defuzzification



Defuzzification

- **Defuzzification means the fuzzy to crisp conversions**
- **The defuzzification has the capability to produce a crisp single-valued quantity There are seven major defuzzification techniques:**
- 1- **The mean of maximum (MOM)**
- **2- Center- of-area/gravity**
- **3- Centre-of- largest-area**
- **4- First-of-maxima**
- **5- Middle-of-maxima**
- **6- Last-of-maxima**
- **7- Height**

Defuzzification

- Defuzzification means the fuzzy to crisp conversions.
- Defuzzification can also be called as "rounding off" method.
- Defuzzification has the capability to reduce a fuzzy quantity to a crisp single-valued quantity or as a set, or converting to the form in which fuzzy quantity is present.
- There are several methods used for defuzzifying the fuzzy output functions:
- **COA (center of Average)**
- **COG (center of Gravity/center of Area)**
- **MC (MAX criterion)**

Defuzzification Methods

Ther are several methods used for defuzzifying the fuzzy output functions:

Defuzzification Methods

A number of defuzzification strategies exist. Each provides a means to choose a single output (which we denote with u^{crisp}) based on either the implied fuzzy sets or the overall implied fuzzy set.

- **Center of Gravity (COG):** A crisp output u^{crisp} is chosen using the center of area and area of each implied fuzzy set, and is given by:

$$u^{crisp} = \frac{\sum_i b_i \int \mu_{(i)}}{\sum_i \int \mu_{(i)}}$$

Where:

b$_i$ is the center of area of the membership function of $\boldsymbol{\mu_{(i)}}$,

and $\int \mu_{(i)}$ denotes the area under $\boldsymbol{\mu_{(i)}}$ value

Defuzzification Methods

- **Center of Average (COA):** A crisp output u^{crisp} is chosen using the centers of the output membership functions and the maximum certainty of each of the conclusions represented with the implied fuzzy sets, and is given by:

$$\boldsymbol{u^{crisp}} = \frac{\sum_i \boldsymbol{b_i \mu_{(i)}}}{\sum_i \boldsymbol{\mu_{(i)}}}$$

where $\mathbf{b_i}$ is the center of area of the membership function of $\boldsymbol{\mu_{(i)}}$

Review Fuzzy Models

If <antecedence> then <consequence>.

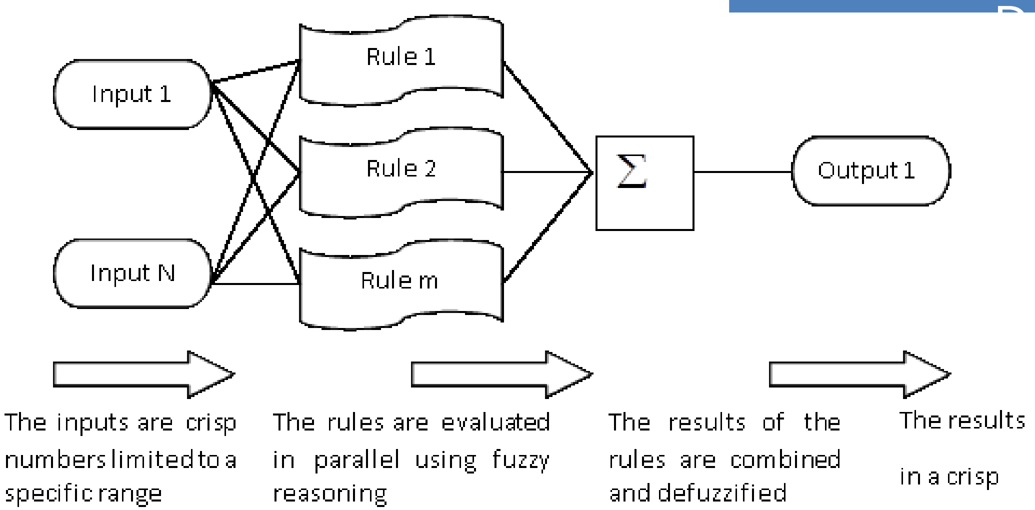
The same style for
- Mamdani Fuzzy models
- Sugeno Fuzzy Models
- Tsukamoto Fuzzy models

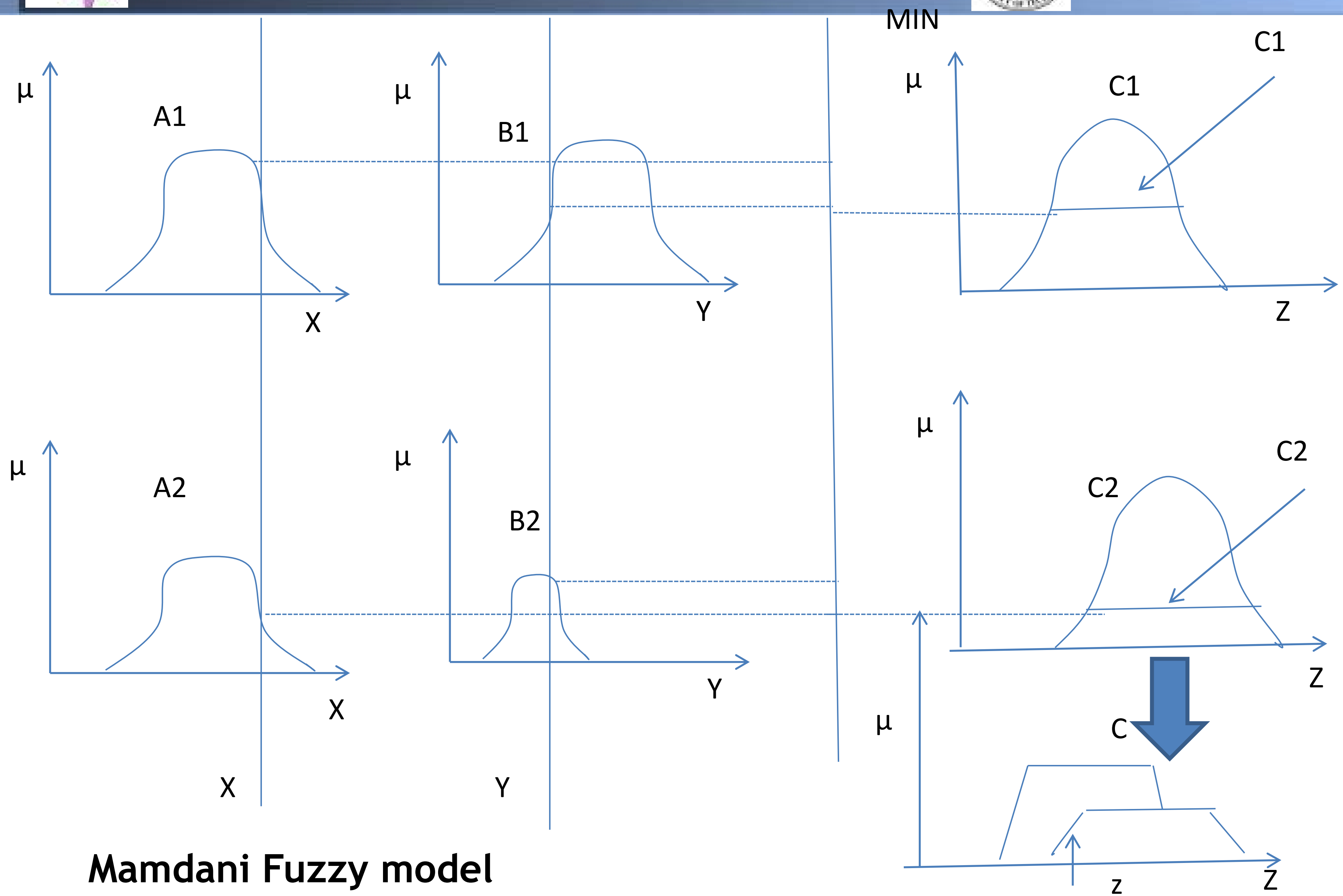
Different styles for
- Mamdani Fuzzy models
- Sugeno Fuzzy Models
- Tsukamoto Fuzzy models

Fuzzy inference system

Steps:

- Fuzzification of the Input Variables
- Rule Evaluation
- Aggregation of the Rule Outputs
- Defuzzification





Mamdani Fuzzy model

Sugeno-style inference

- Sugeno-style fuzzy inference is very similar to the Mamdani method.
- Sugeno changed only a rule consequent. Instead of a fuzzy set, it used a mathematical function of the input variable.
- A typical fuzzy rule in a Sugeno fuzzy model has the format

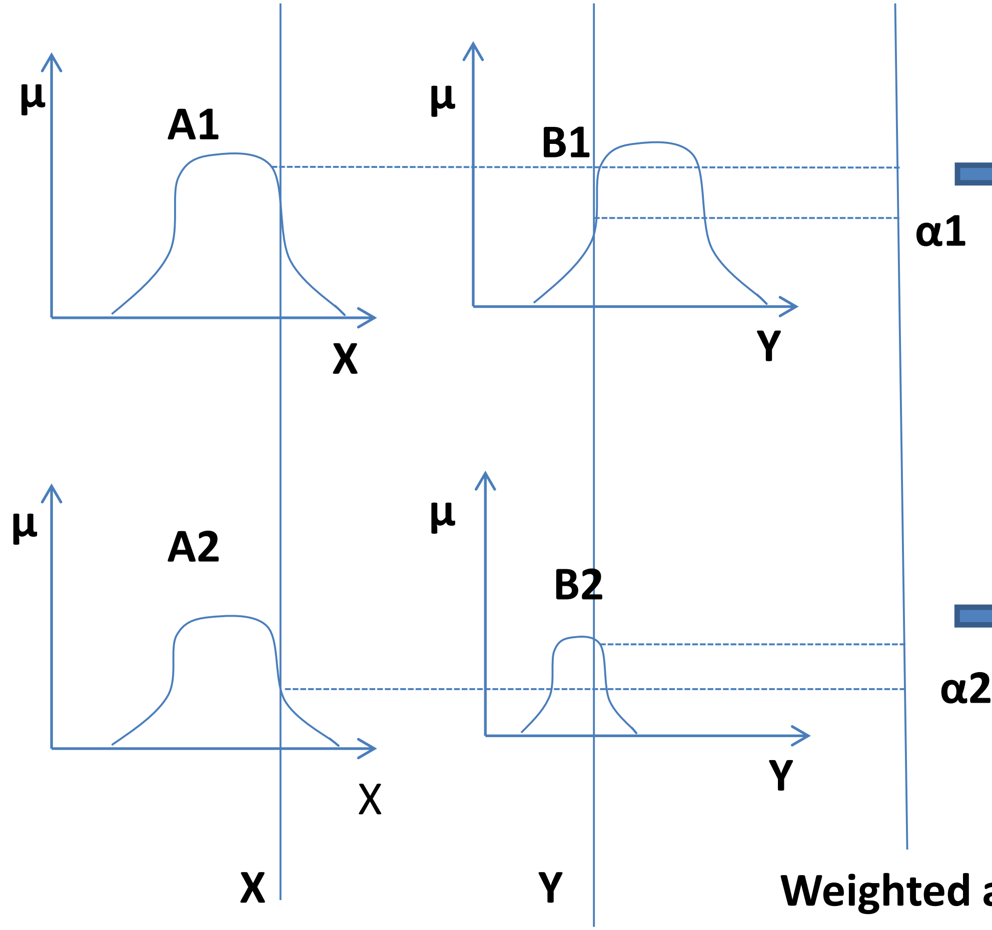
IF x is A and y is B THEN $z = f(x, y)$

Where:

A & B are fuzzy sets in the antecedent

Z = f(x, y) is a crisp function in the consequent.

Sugeno Fuzzy Model



$$z1 = p1x + q1y + r1$$

$$z2 = p2x + q2y + r2$$

Weighted average= $z = \dfrac{\alpha_1 z_1 + \alpha_2 z_2}{\alpha_1 + \alpha_2}$

Sugeno Fuzzy Model
Examples

R1: if *X* is small and *Y* is small then $z = -x + y + 1$

R2: if *X* is small and *Y* is large then $z = -y + 3$

R3: if *X* is large and *Y* is small then $z = -x + 3$

R4: if *X* is large and *Y* is large then $z = x + y + 2$

Tsukamoto Fuzzy model

In the Tsukamoto fuzzy model, the consequent of each fuzzy if-then rule is represented by a fuzzy set with a Monotonical MF

R1: If X is small then Y is C_1
R2: If X is medium then Y is C_2
R3: if X is large then Y is C_3

Fuzzy Control

1- Mamdani Style

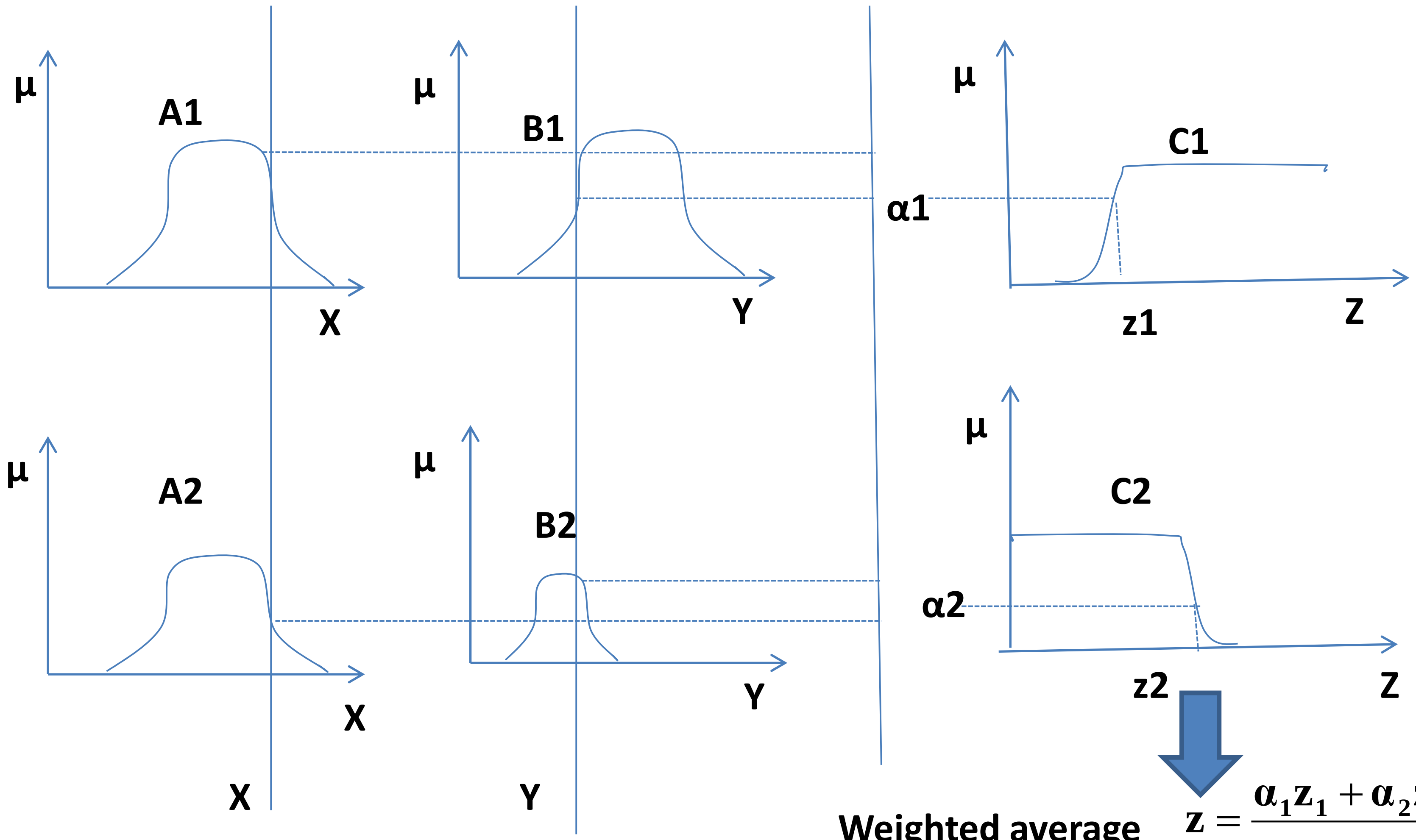
Rule: IF *x* is A and *y* is B THEN z is C: the output is single crisp value

2- Sugeno Style

Rule: IF *x* is A and *y* is B THEN z is a*A+b*B+c

The output is linear functions between input and output, a, b, c are Sugeno linear parameters. They can be found by expert, simulation studies or can be optimized and found by some computational methods such as neural networks, Adaptive Neural Fuzzy Inference System ANFIS.

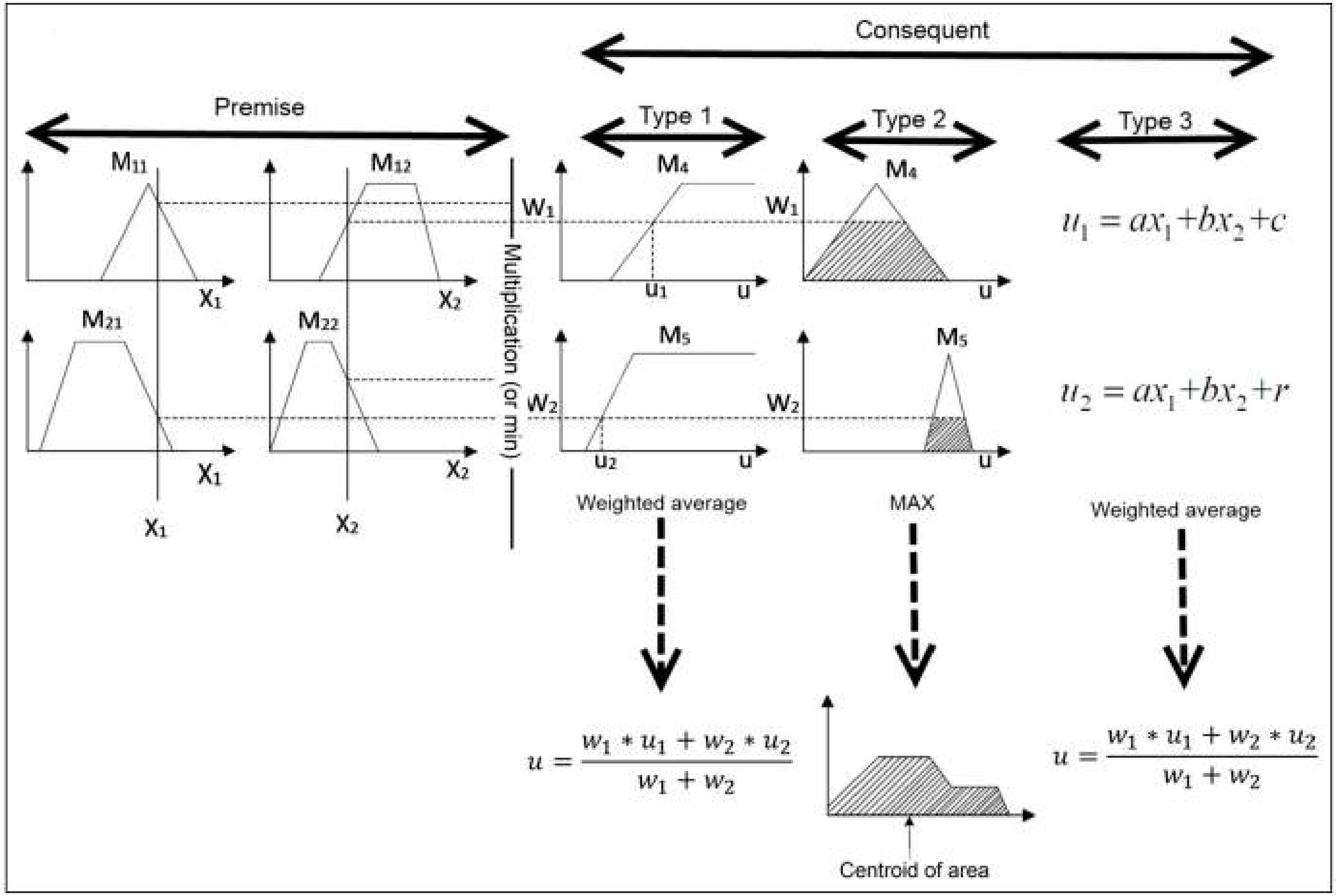
Tsukamoto Fuzzy model



Weighted average

$$z = \frac{\alpha_1 z_1 + \alpha_2 z_2}{\alpha_1 + \alpha_2}$$

Different types of Fuzzy inference systems

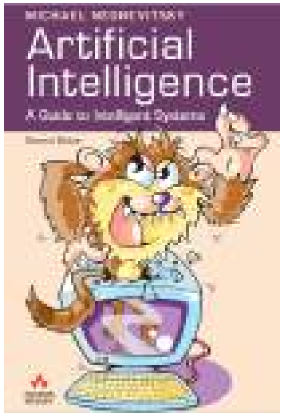


Some Applications of FLC

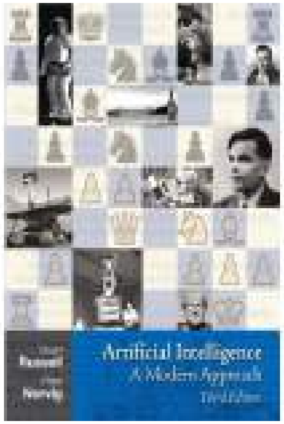
1. Telecommunications such as Channel equalization, call acceptance.
2. Signal processing such as fuzzy filters or fuzzy signal detection
3. Fuzzy system in Control engineering
4. Videography (Sanyo)
5. Air-conditioning (Mitsubishi)
6. Washing machines (combining smart sensors with fuzzy logic by Mitsubishi)
7. Cars (Nissan introduced fuzzy automatic transmission)
8. Fuzzy toasters
9. Fuzzy rice-cookers and so on.

Literature and References:

- **Artificial Intelligence, a Guide to Intelligent Systems.**
  - (second edition).
  - Mechael Negnevitsky.



- **Artificial Intelligence, a Modern Approach**
  - (Third edition).
  - Stuart Russell & Peter Norvig.



- **Introduction to Artificial Neural Systems**
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Literature and References

- **Fuzzy Controllers**
  - http://research.iaun.ac.ir/pd/naghsh/pdfs/UploadFile_4810.pdf
  - Newne, 1997.
  - L. Reznik.
- **Fuzzy Logic with Engineering Applications**
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  - T.J. Ross.
- **Fuzzy Control**
  - Kevin M. Passino and Stephen Yurkovich, 1998.
- **Introduction to Fuzzy Logic using MATLAB**
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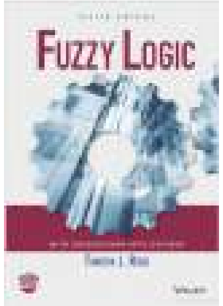
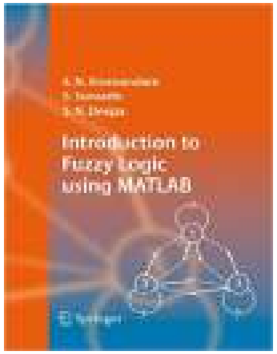
  - S. N. Sivanandam, S. Sumathi and S. N. Deepa
- **Fuzzy Logic Toolbox™ User's Guide, © COPYRIGHT 1995-2012 The MathWorks, Inc.**





Thank you!

Lecture 4

Control System Design

Fuzzy Logic Control (FLC)
Artificial intelligence Systems
(Overview)

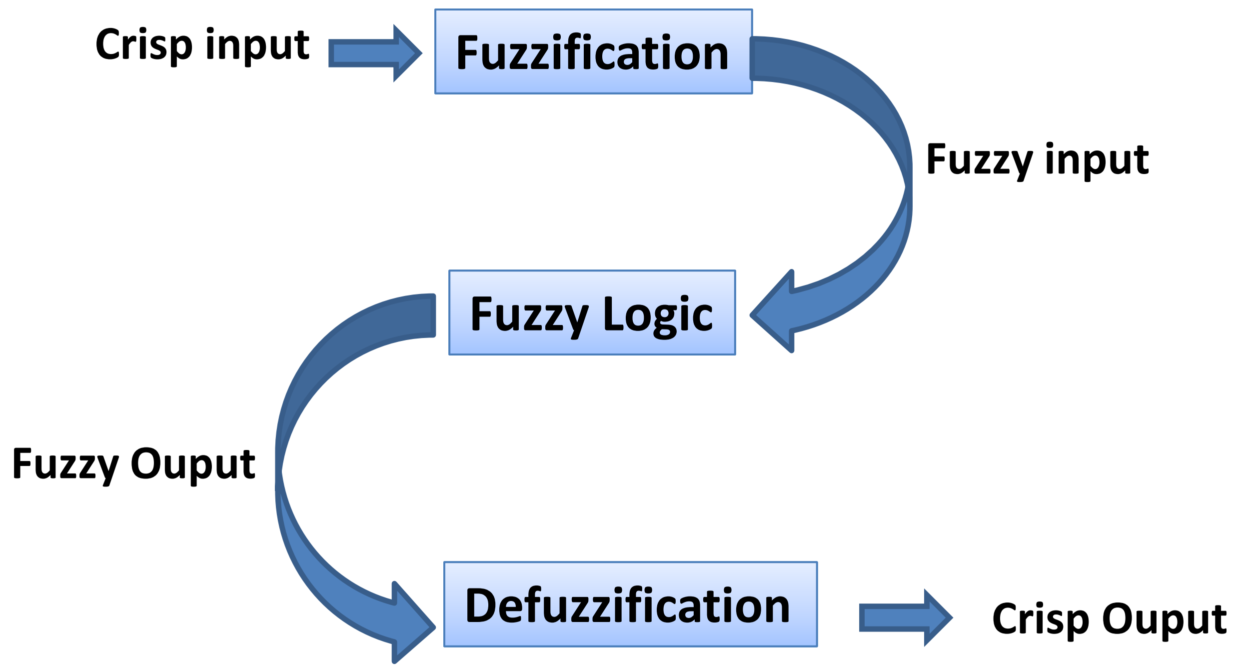
Introduction to Fuzzy Logic Controller Structure and Design

Contents

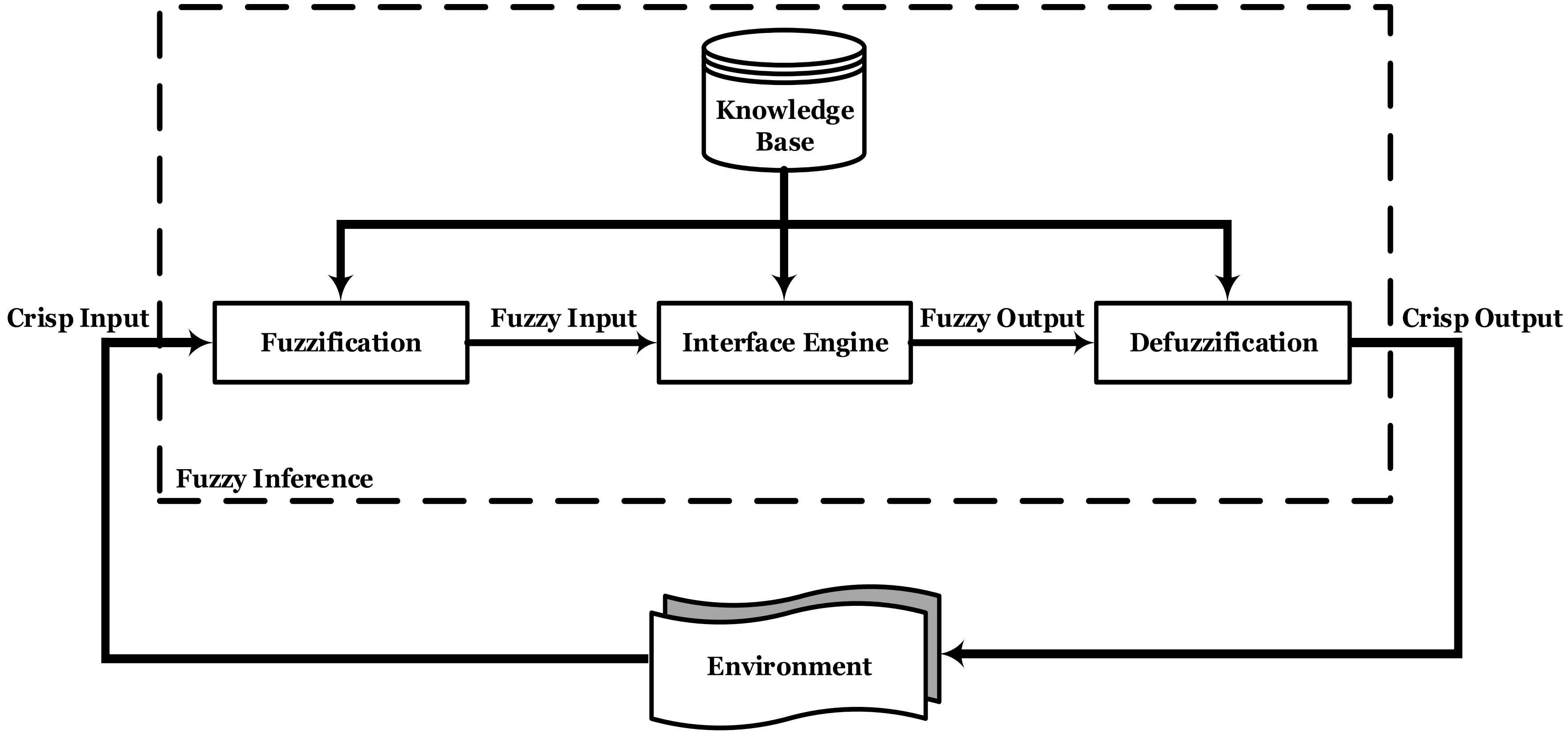
Introduction to:

- Fuzzy Logic Process
- Types of Fuzzy Inference systems (FIS)
  - o Mamdani-style fuzzy inference (Mamdani fuzzy model)
  - o Sugeno-style fuzzy inference (Sugeno fuzzy model)
  - o Tsukamoto-style fuzzy inference(Tsukamoto fuzzy model)
- Example using MATLAB

Process of Fuzzy Logic Controller



Fuzzy logic System
(Fuzzy Logic Controller)



Basic elements of a Fuzzy Logic Controller

- **The fuzzification:** converts the measured "crisp" inputs to "fuzzy" values such as Positive Big (PB), Negative Small (NS).
- **The knowledge base:** contains a set of if-then rules or a relation matrix representing those rules
- **The decision-making unit (inference engine unit):** simulates the inference mechanism in human. It produces fuzzy control action using fuzzy implication.
- **The defuzzification:** is an interface unit between the process and the decision making unit which converts the fuzzy set output to crisp output.

Fuzzy Logic Models

(Fuzzy Inference Styles)

If <antecedence> then <consequence>.

The same style for
- Mamdani Fuzzy models
- Sugeno Fuzzy Models
- Tsukamoto Fuzzy models

Different styles for
- Mamdani Fuzzy models
- Sugeno Fuzzy Models
- Tsukamoto Fuzzy models

Types od Fuzzy Logic Controllers

1- Mamdani Style

In the Mamdani fuzzy model, the consequent of each fuzzy if-then rule is represented by **a fuzzy set**.

Rule: IF *x* is A and *y* is B THEN z is C

2- Sugeno Style Sugeno changed only a rule consequent. Instead of a fuzzy set, it used a **mathematical function of the input variable**.

Rule: IF x is A and y is B THEN z = f(x, y)

Where:

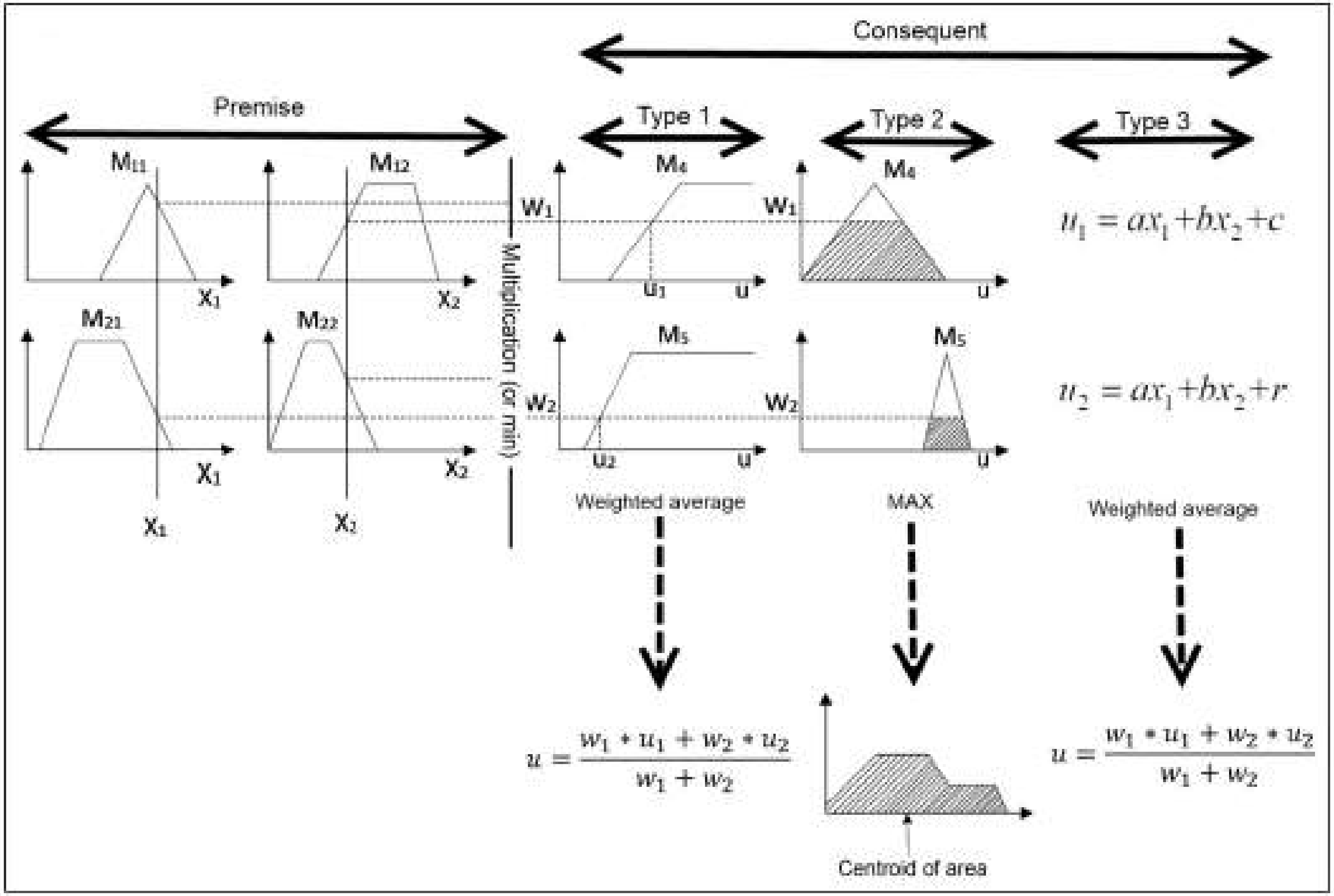
A & B are fuzzy sets in the antecedent

Z = f(x, y) is a crisp function in the consequent.

3- In the **Tsukamoto fuzzy model**, the consequent of each fuzzy if-then rule is represented by a fuzzy set with a **Monotonical MF**

Rule: IF x is A and y is B THEN z is C

Fuzzy Inference Systems



Mamdani-Style Inference

Mamdani-Style Inference

- To understand Mamdani-Style's steps, we will assume the following example:
- Assume that there is a system with
  - o Two inputs X and Y
  - o One output Z
- Each input has two membership functions A_1 and A_2 for the input X and B_1, B_2 for the input Y
- The output Z has three membership functions C_1, C_2 and C_3
- Includes four rules
  - Rule 1 If $X= A_1$ **OR** $Y= B_1$ Then $Z= C_1$
  - Rule 2 If $X= A_1$ **OR** $Y= B_2$ Then $Z= C_3$
  - Rule 3 If $X= A_2$ **OR** $Y= B_1$ Then $Z= C_2$
  - Rule 4 If $X= A_2$ **OR** $Y= B_2$ Then $Z= C_2$

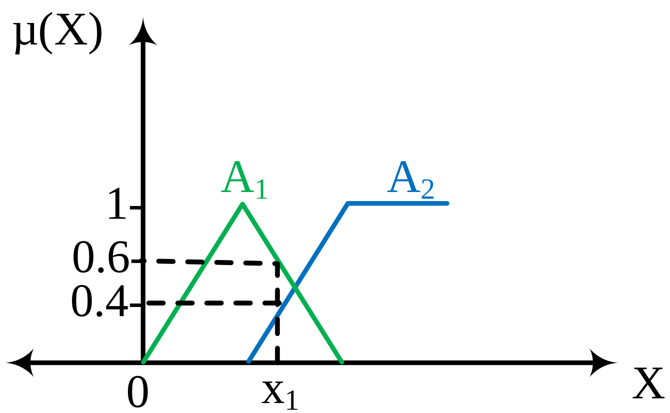
Mamdani-style inference

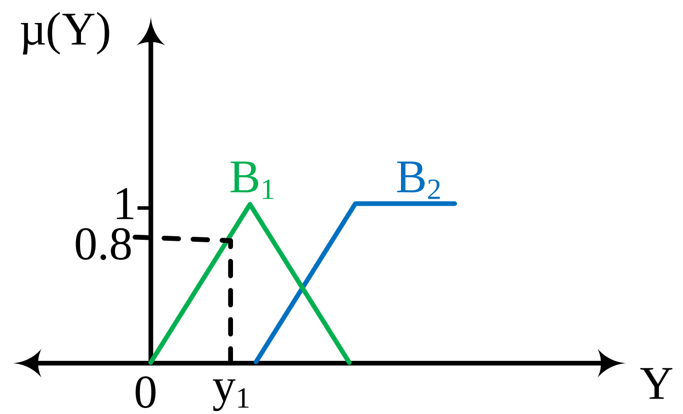
Step 1: Fuzzification

- These input membership functions, can represent fuzzy concepts such as “large” or “small,” “old” or “young,” “hot” or “cold,” etc.

the fuzzified inputs

$$\mu(x_1) = 0.6(A_1) \,\&\, 0.4(A_2) \qquad \mu(y_1) = 0.8(B_1) \,\&\, 0.0(B_2)$$





Mamdani-style inference

Step 2: Rule evaluation

The second step is to take the fuzzified inputs,

$$\mu(x_1) = 0.6(A_1), 0.4(A_2)$$

$$\mu(y_1) = 0.8(B_1), 0.0(B_2)$$

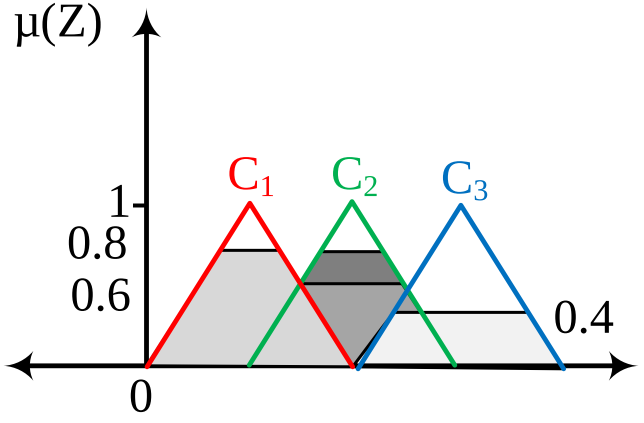
and apply them to the antecedents of the fuzzy rules.

If a given fuzzy rule has multiple antecedents, the fuzzy operator (AND or OR) is used to obtain a single number that represents the result of the antecedent evaluation. This number (the truth value) is then applied to the consequent membership function.

Mamdani-style inference

Step 2: Rule evaluation

- If x_1=0.6 A_1 OR y_1= 0.8 B_1 Then Z= 0.8 C_1
- If x_1=0.6 A_1 OR y_1= 0.0 B_2 Then Z= 0.6 C_3
- If x_1=0.4 A_2 OR y_1= 0.8 B_1 Then Z= 0.8 C_2
- If x_1=0.4 A_2 OR y_1= 0.0 B_2 Then Z= 0.4 C_2



Mamdani-style inference

Rule Evaluation

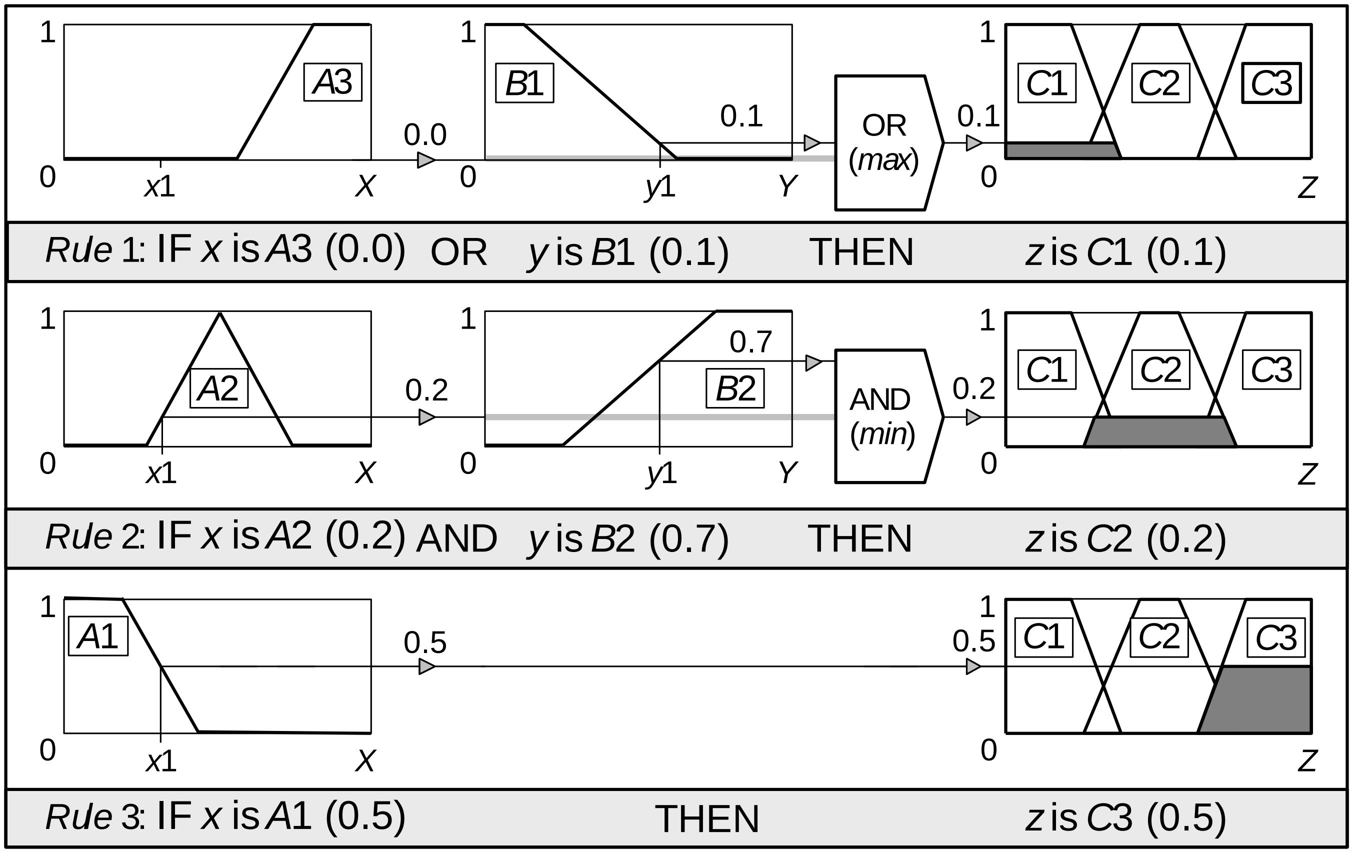
To evaluate the disjunction of the rule antecedents, we use the **OR fuzzy operation**. Typically, fuzzy expert systems make use of the classical fuzzy operation **union**:

$$\mu_{A \cup B}(x) = \max [\mu_A(x), \mu_B(x)]$$

Similarly, in order to evaluate the conjunction of the rule antecedents, we apply the **AND fuzzy operation intersection**:

$$\mu_{A \cap B}(x) = \min [\mu_A(x), \mu_B(x)]$$

Mamdani-style rule evaluation



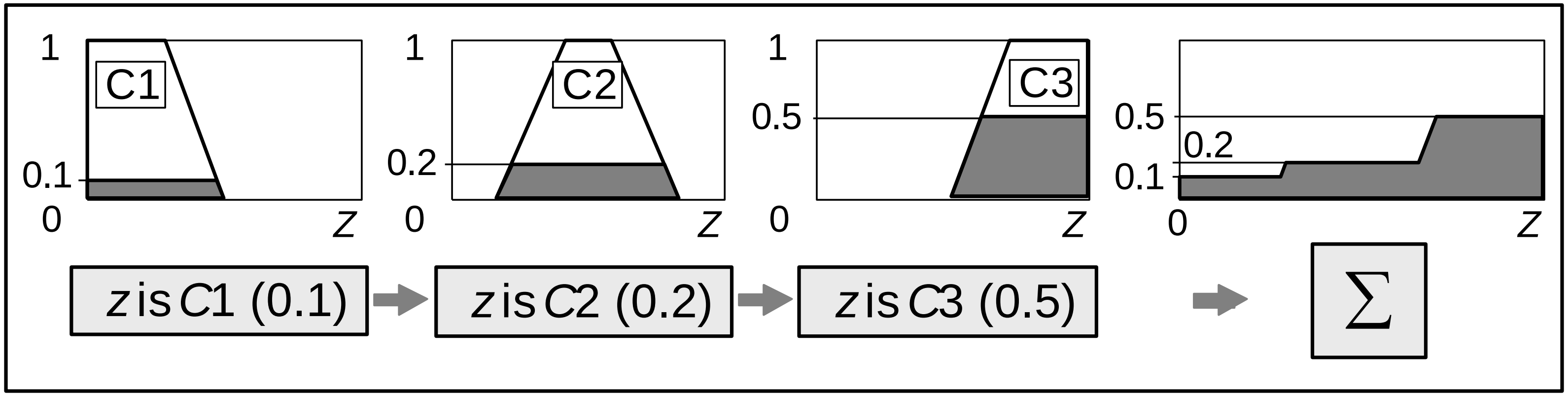
Mamdani-style inference

Step 3: Aggregation of the rule outputs

- The fuzzy rule-based system may involve more than one rule. The process of obtaining the overall conclusion from the individually mentioned consequents contributed by each rule in the fuzzy rule. This is known as aggregation of rule.

Mamdani-style inference

Step 3: Aggregation of the rule outputs



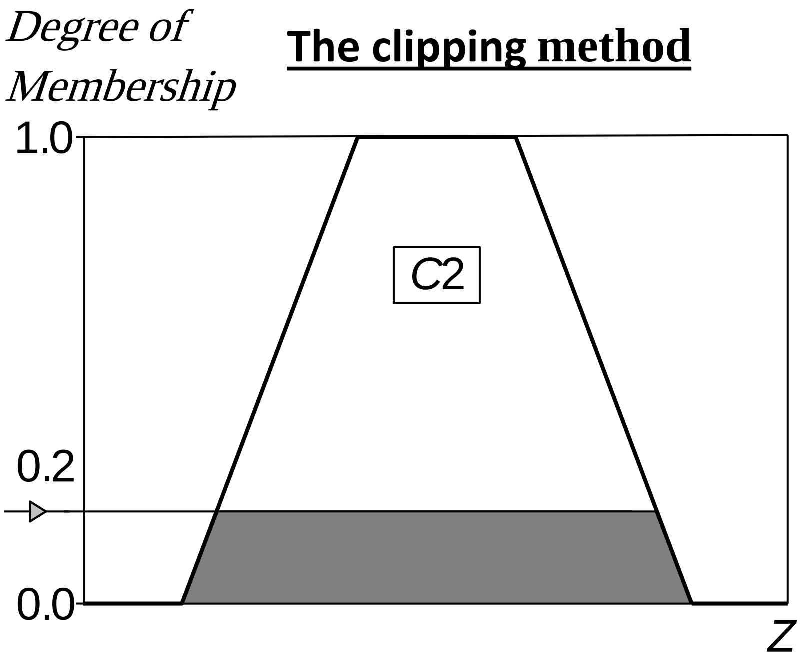
Mamdani-style inference

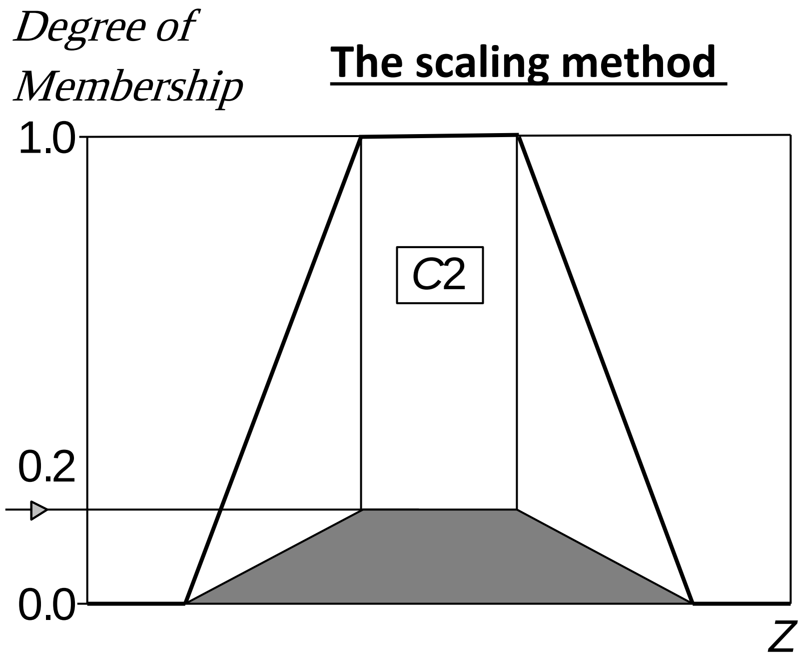
Step 3: Aggregation of the rule outputs

Aggregation is the process of unification of the outputs of all rules. We take the membership functions of all rule consequents previously clipped or scaled and combine them into a single fuzzy set.

The input of the aggregation process is the list of clipped or scaled consequent membership functions, and the output is one fuzzy set for each output variable.

Clipped and scaled membership functions





- **The clipping method** cuts off the **top of the membership function** whose value is higher than the degree of matching.
- **The scaling method (it also called *prod*)**, multiplies all the membership degrees by the value of the degree of matching, the scaled membership function will be produced.

Defuzzification

- Defuzzification means the fuzzy to crisp conversions
- The defuzzification has the capability to produce a crisp single-valued quantity There are seven major defuzzification techniques:

1- **The mean of maximum (MOM)**

2- Center- of-area/gravity

3- Centre-of- largest-area

4- First-of-maxima

5- Middle-of-maxima

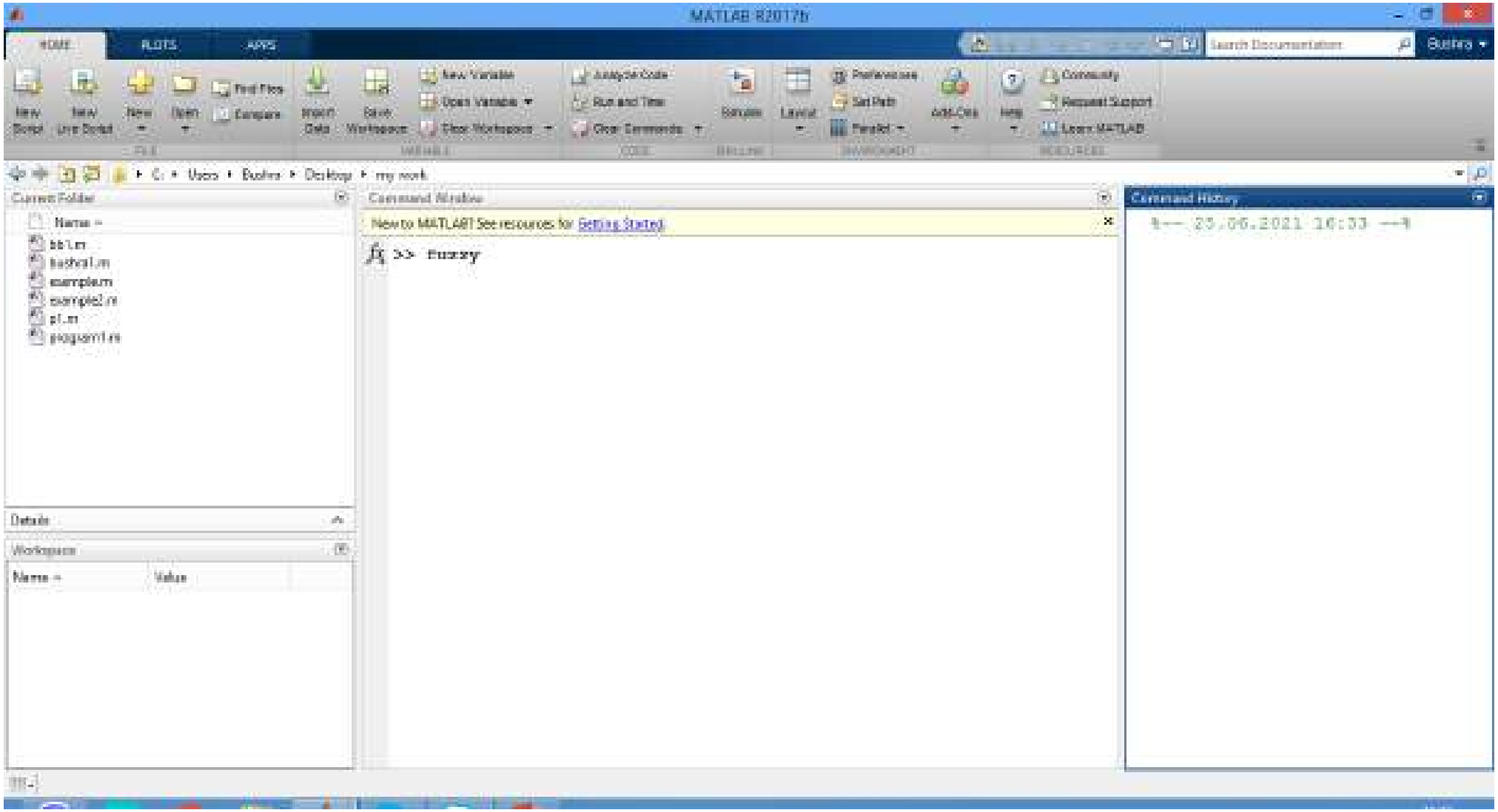
6- Last-of-maxima

7- Height

Lecture 5

Example using MATLAB

Example using MATLAB



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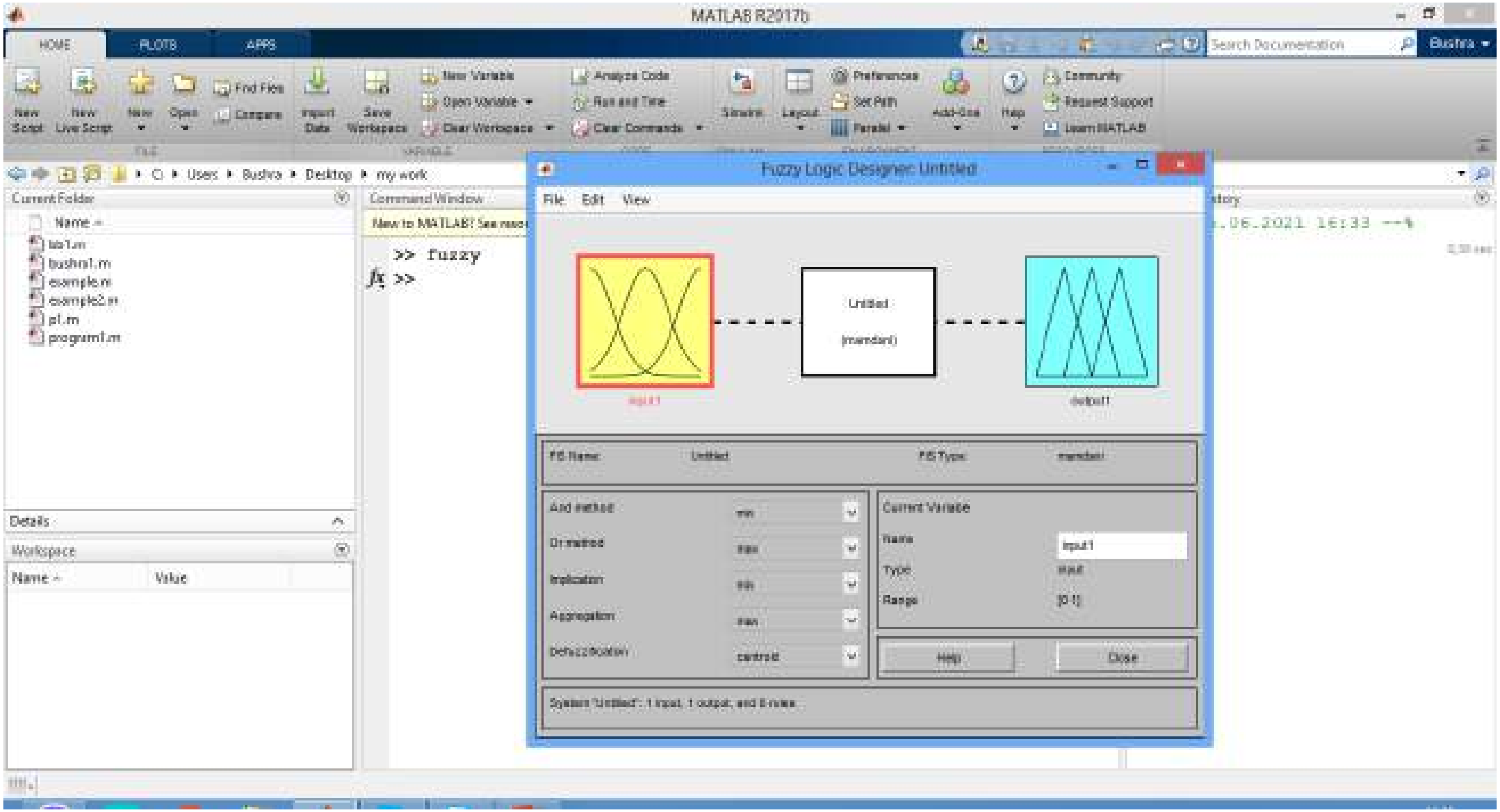

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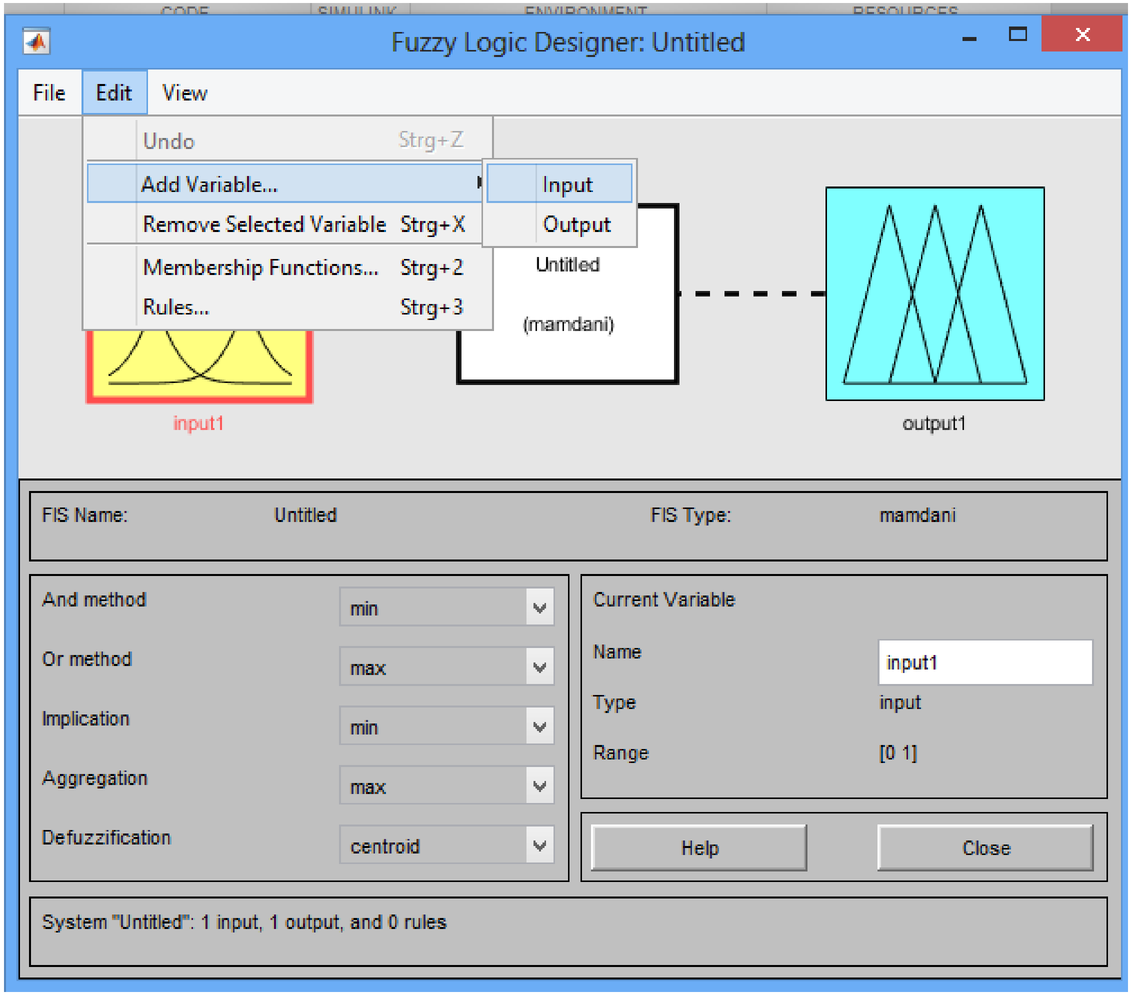

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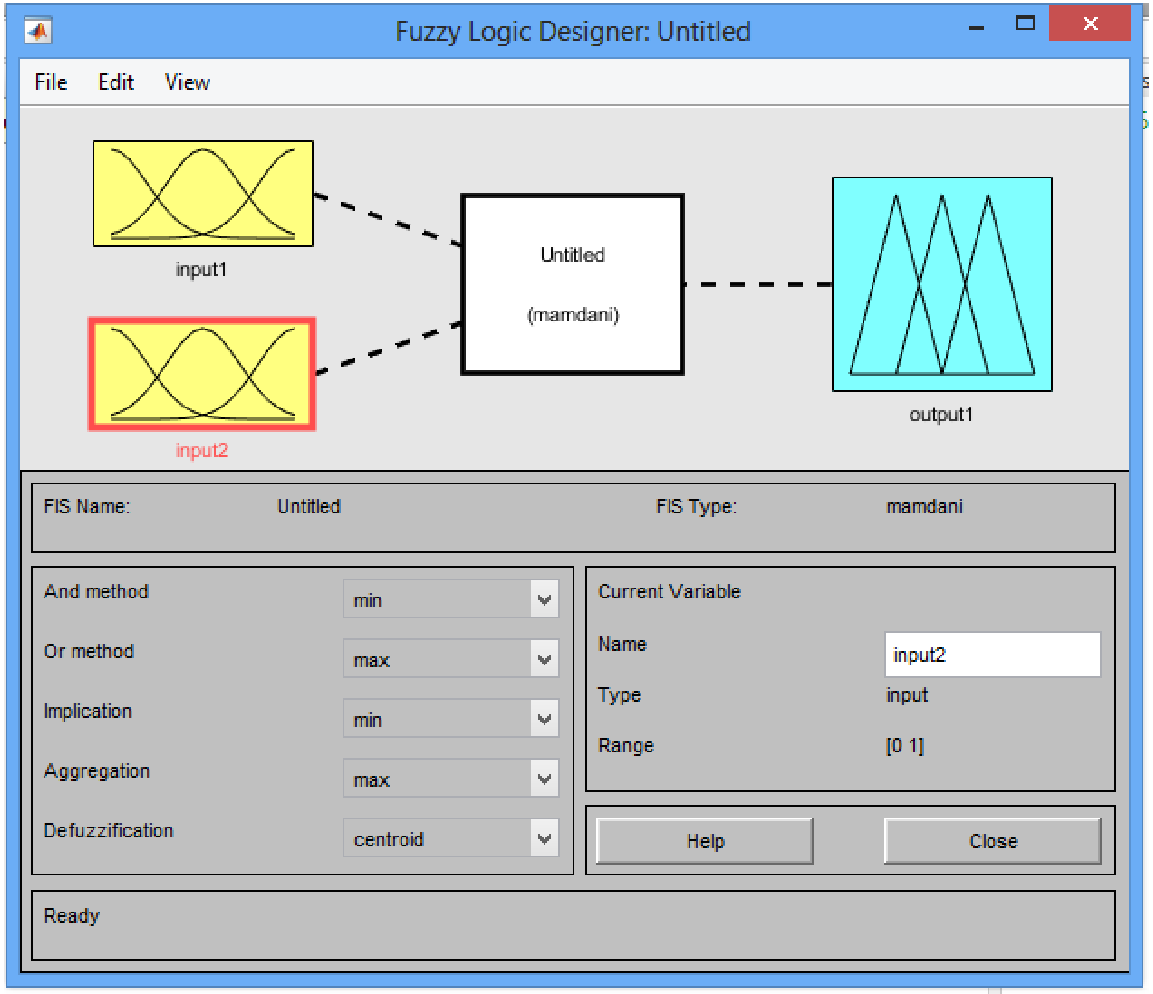

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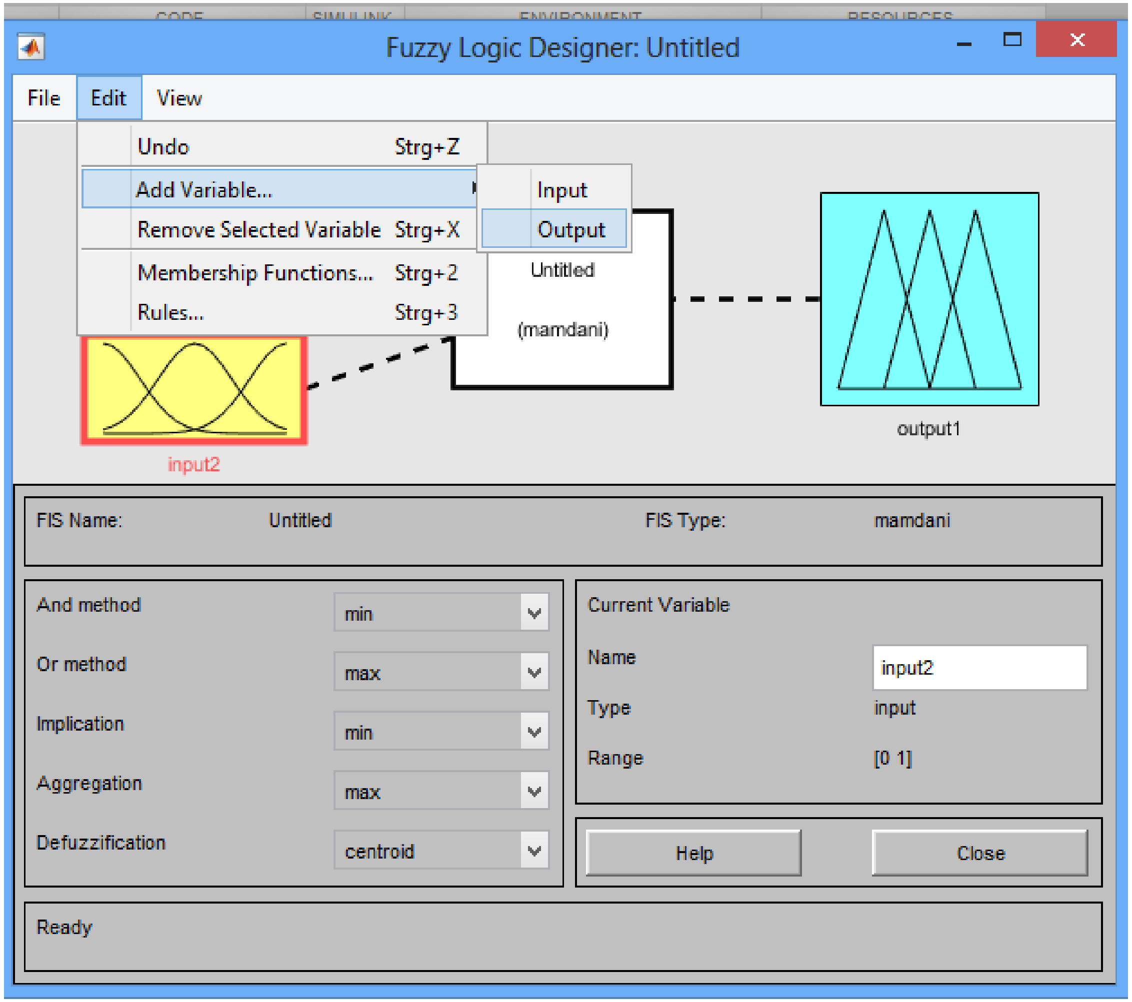

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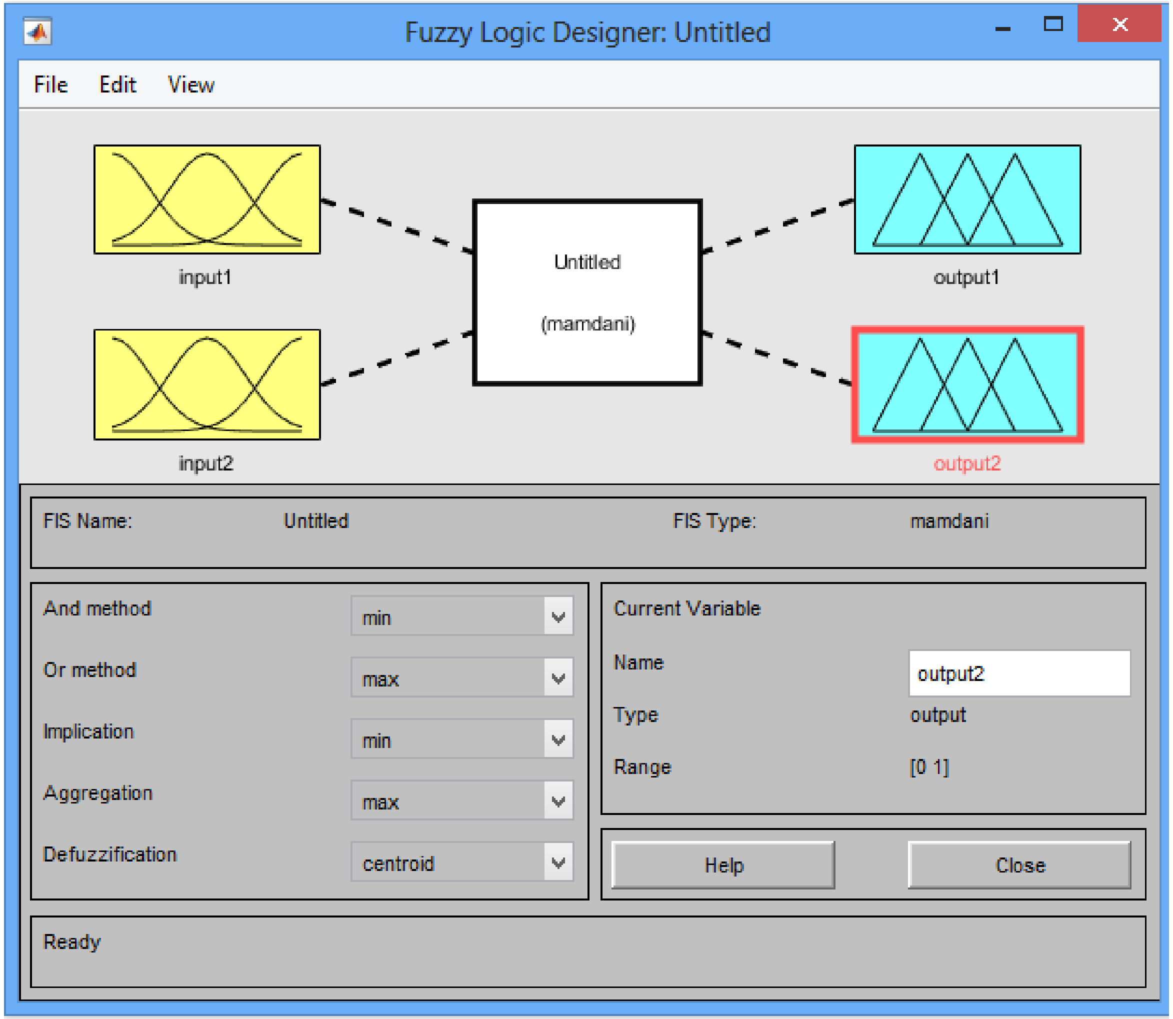

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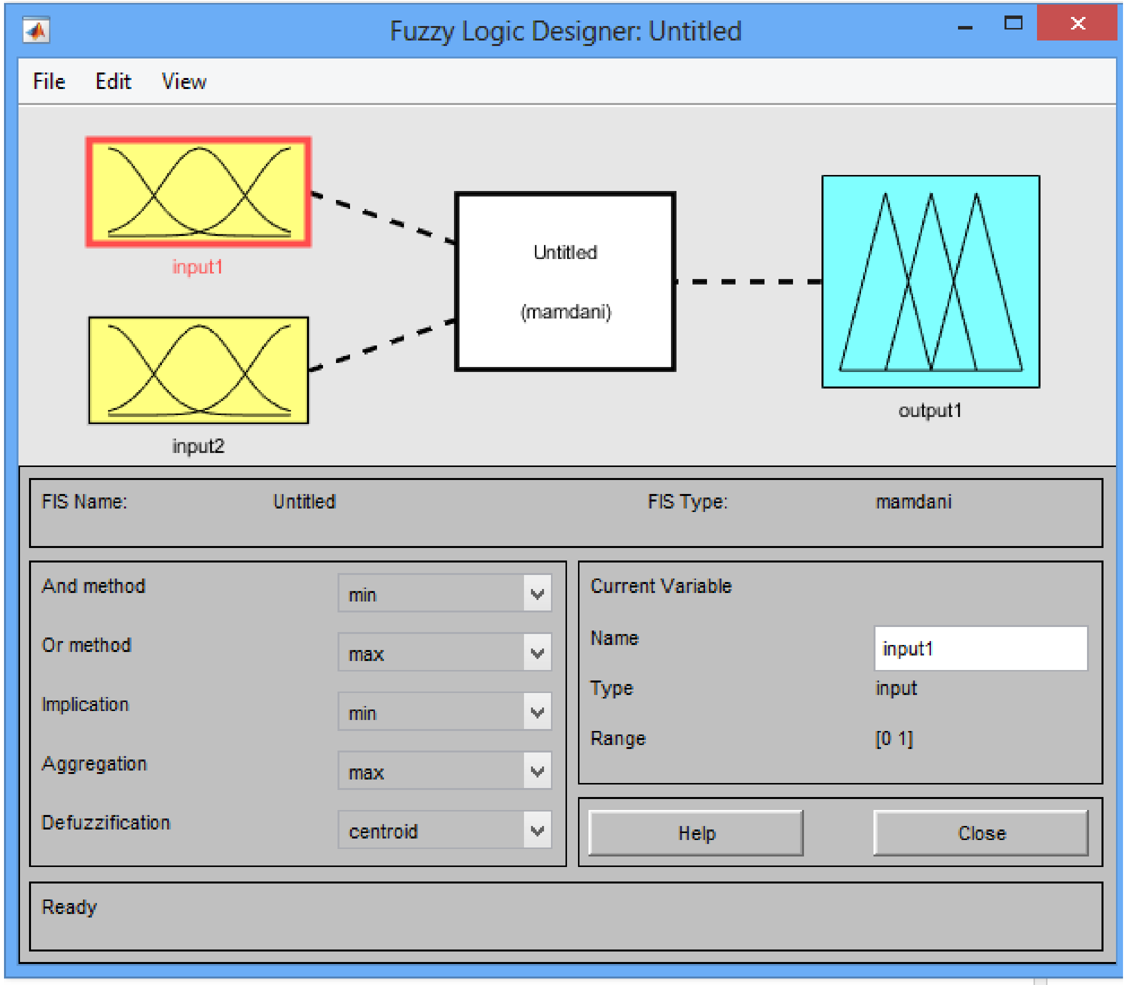

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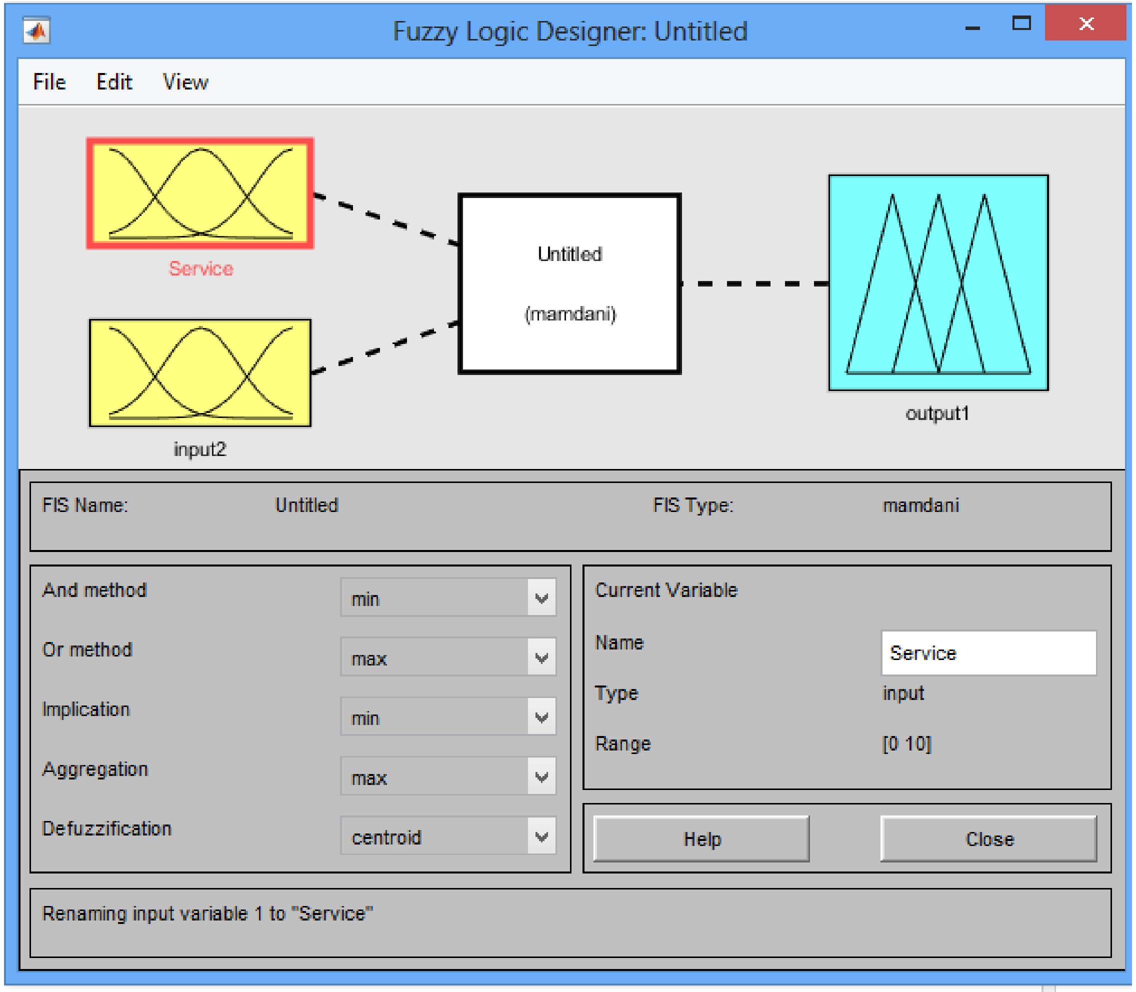

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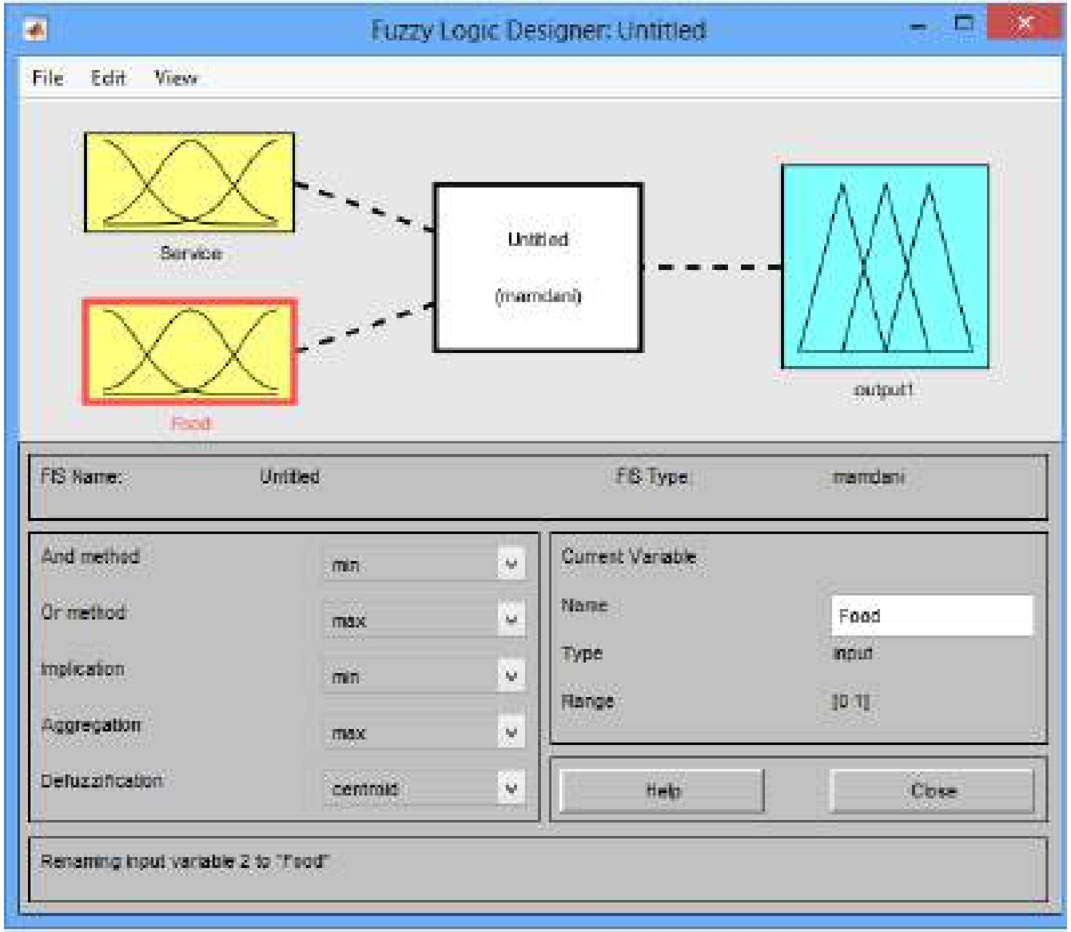

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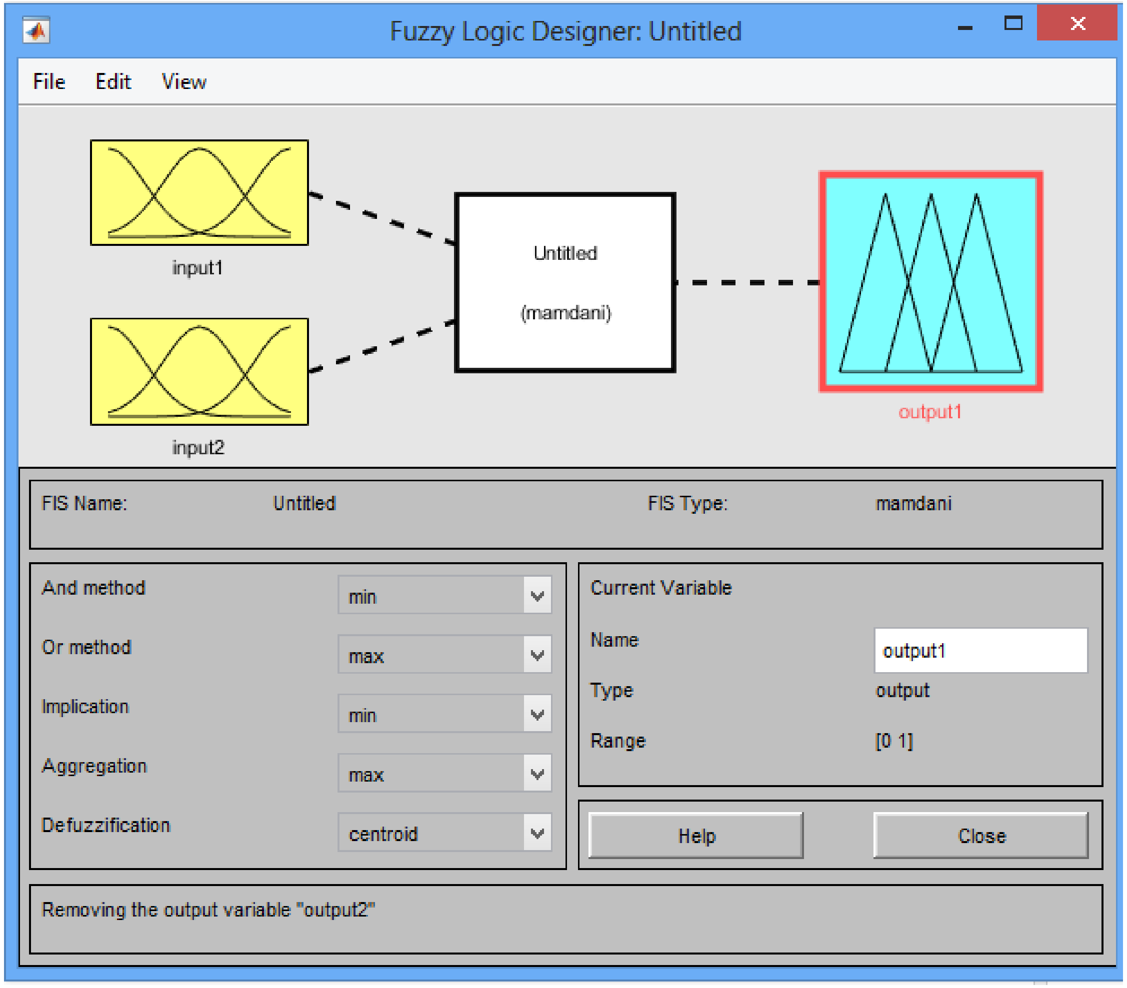

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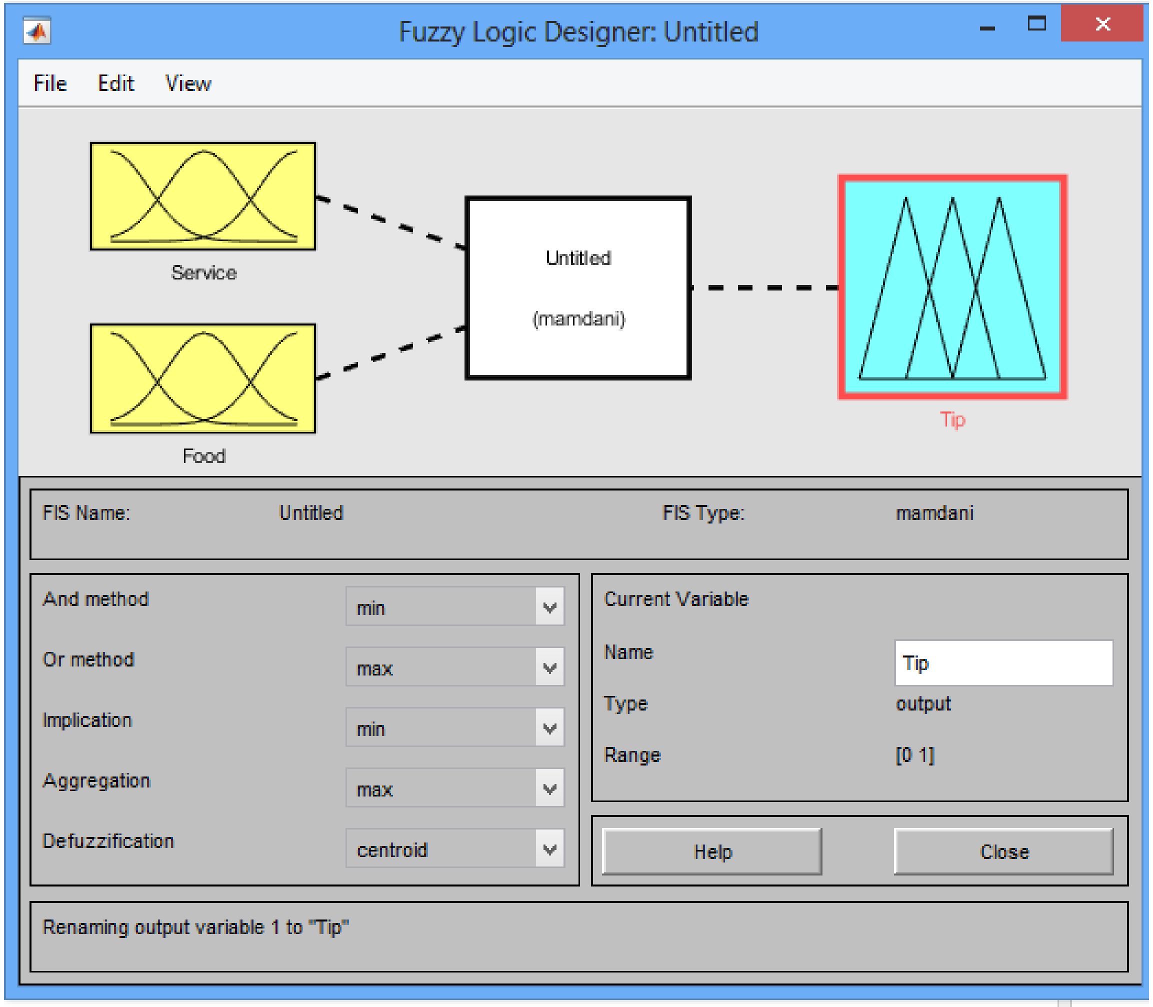

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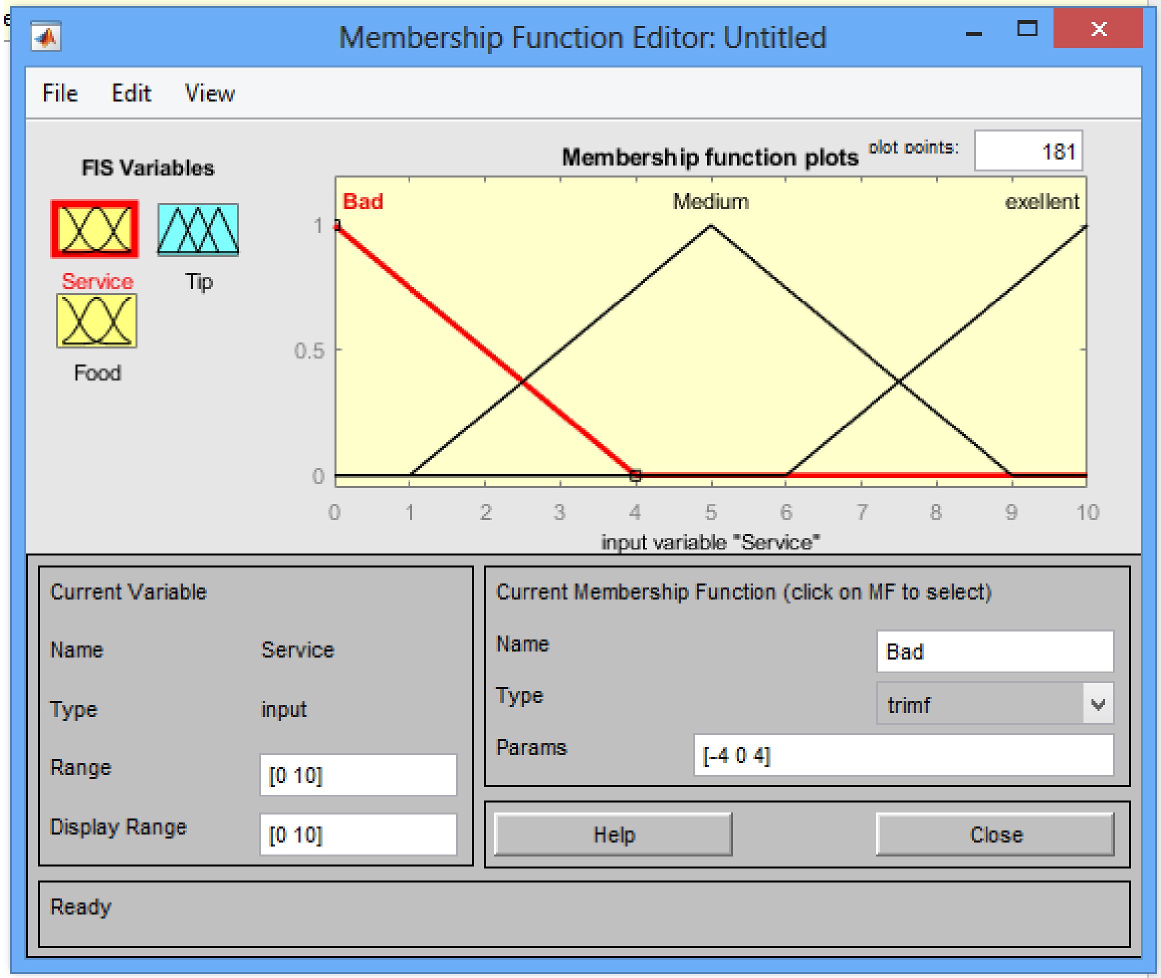

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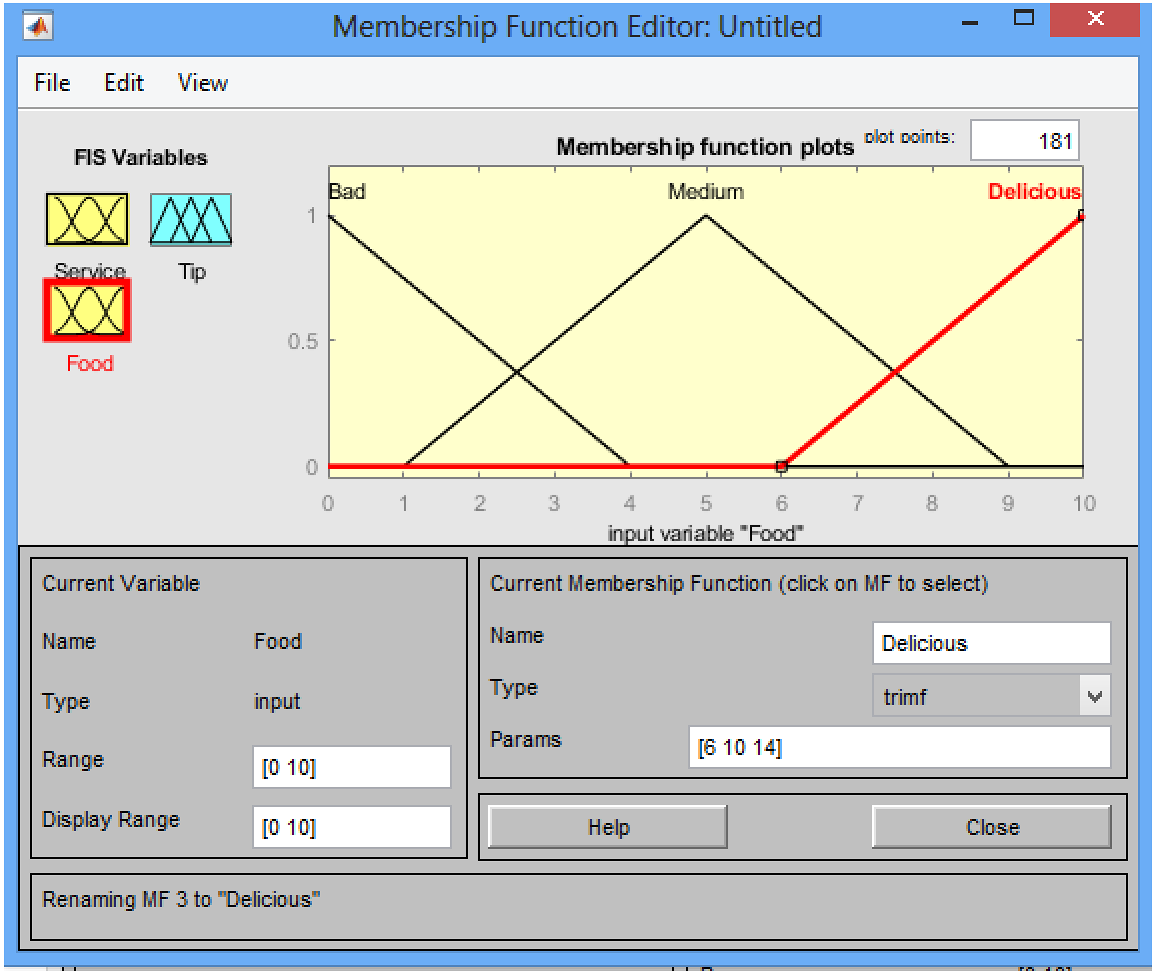

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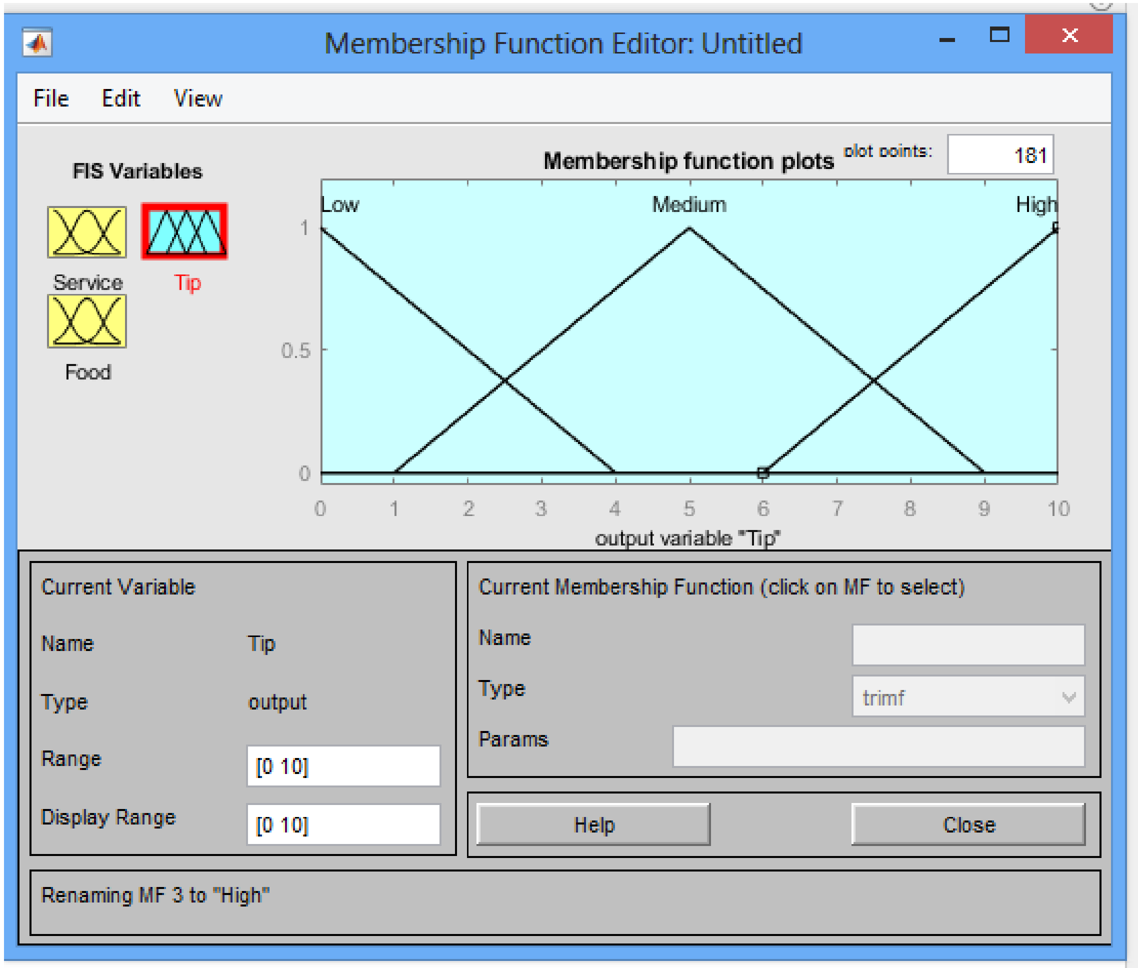

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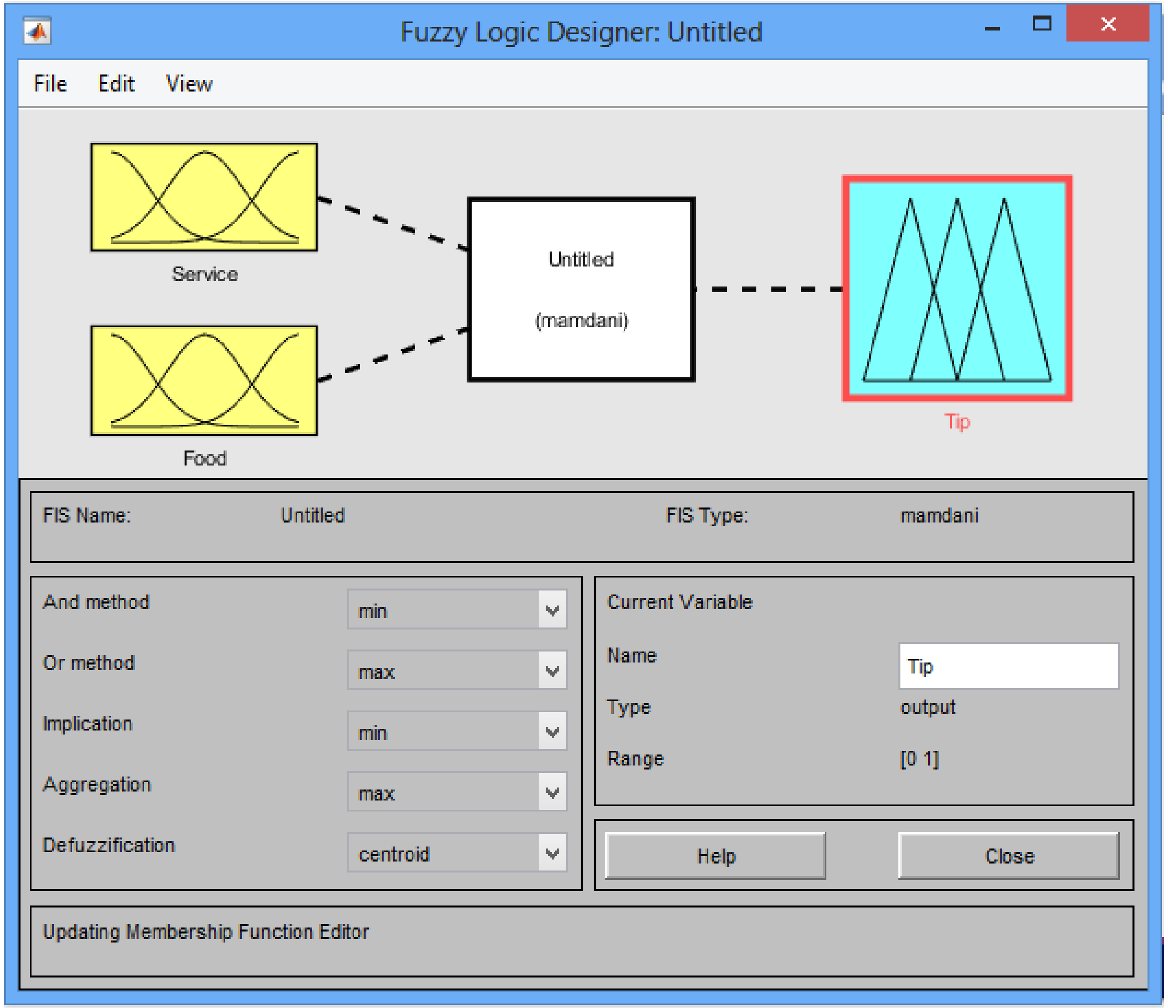

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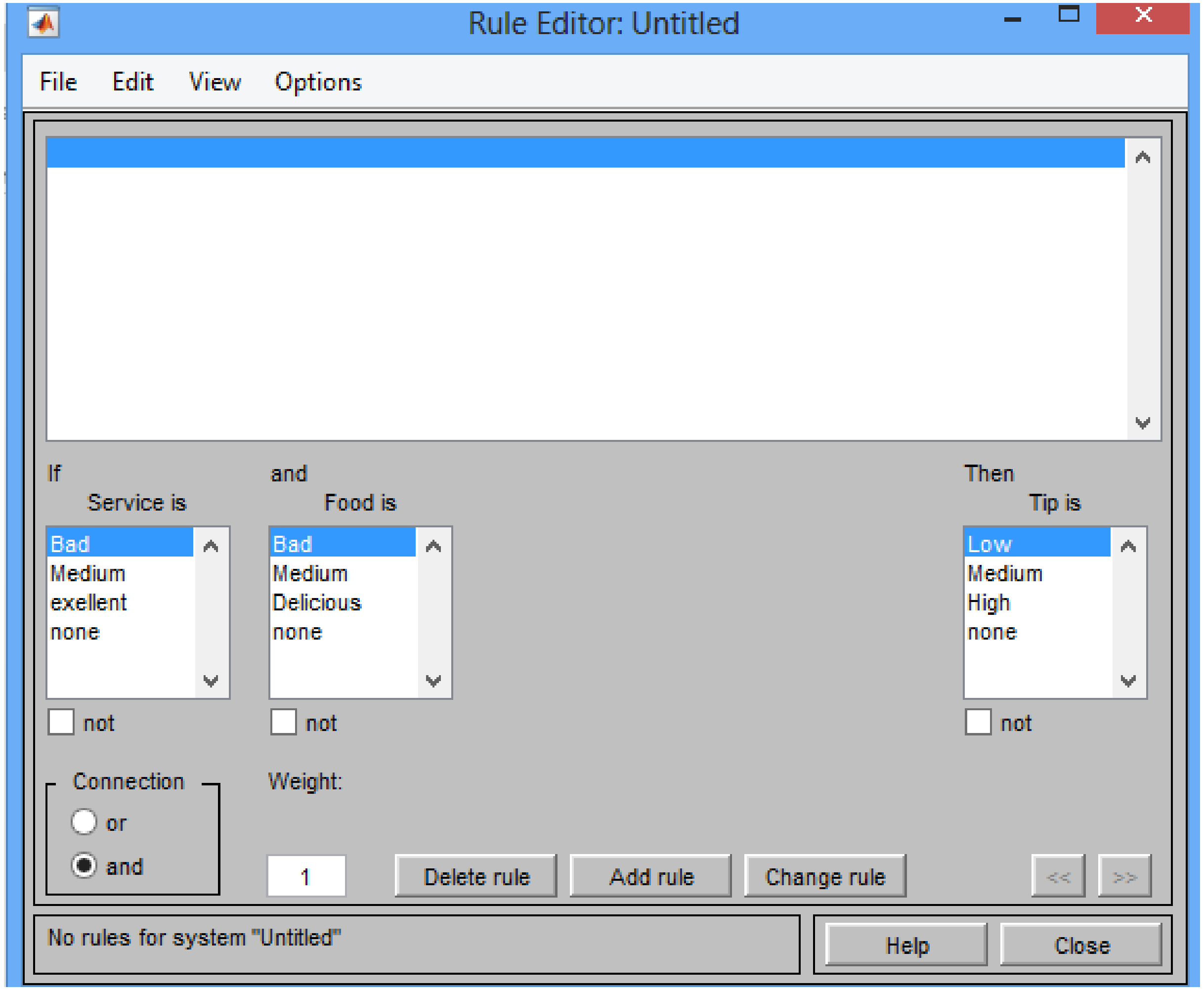

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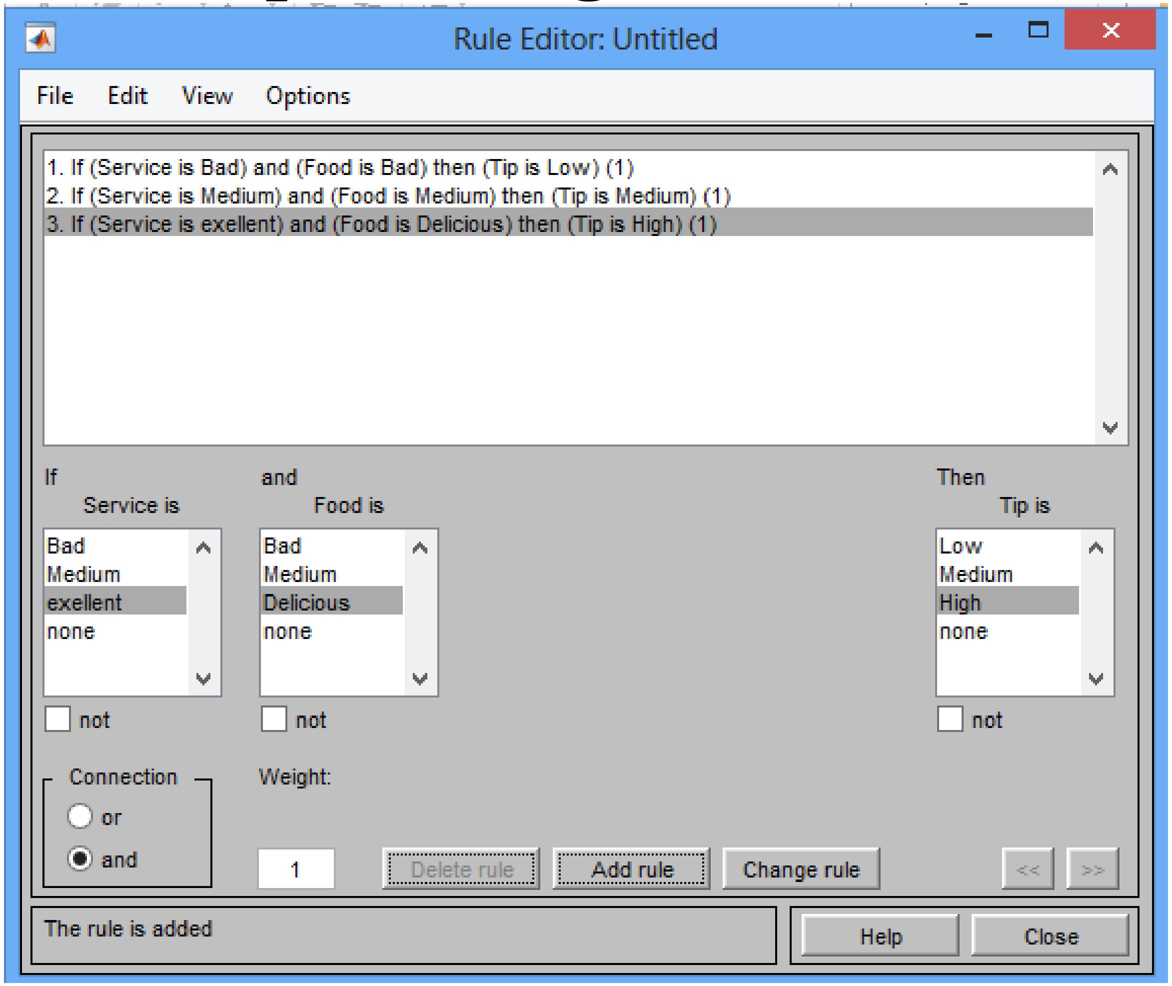

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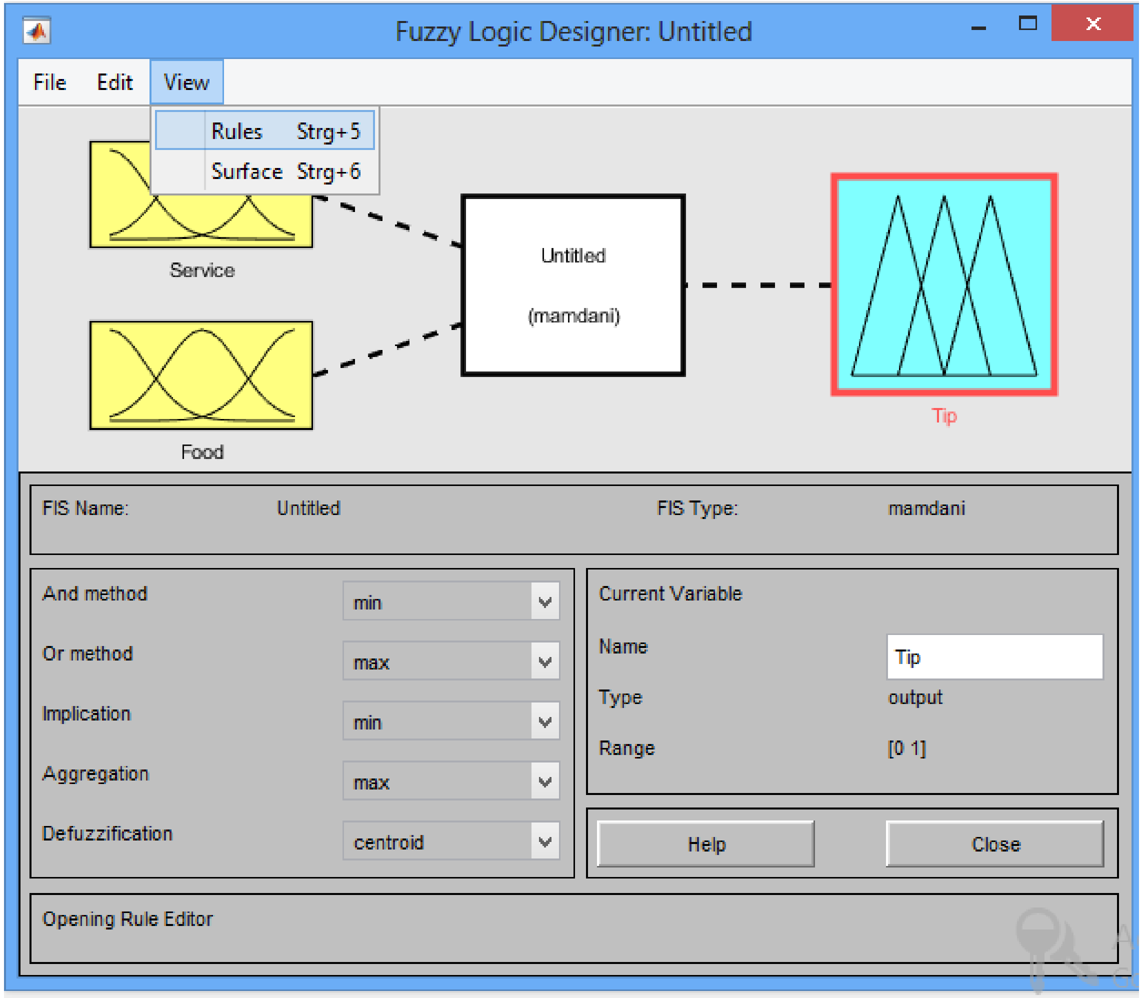

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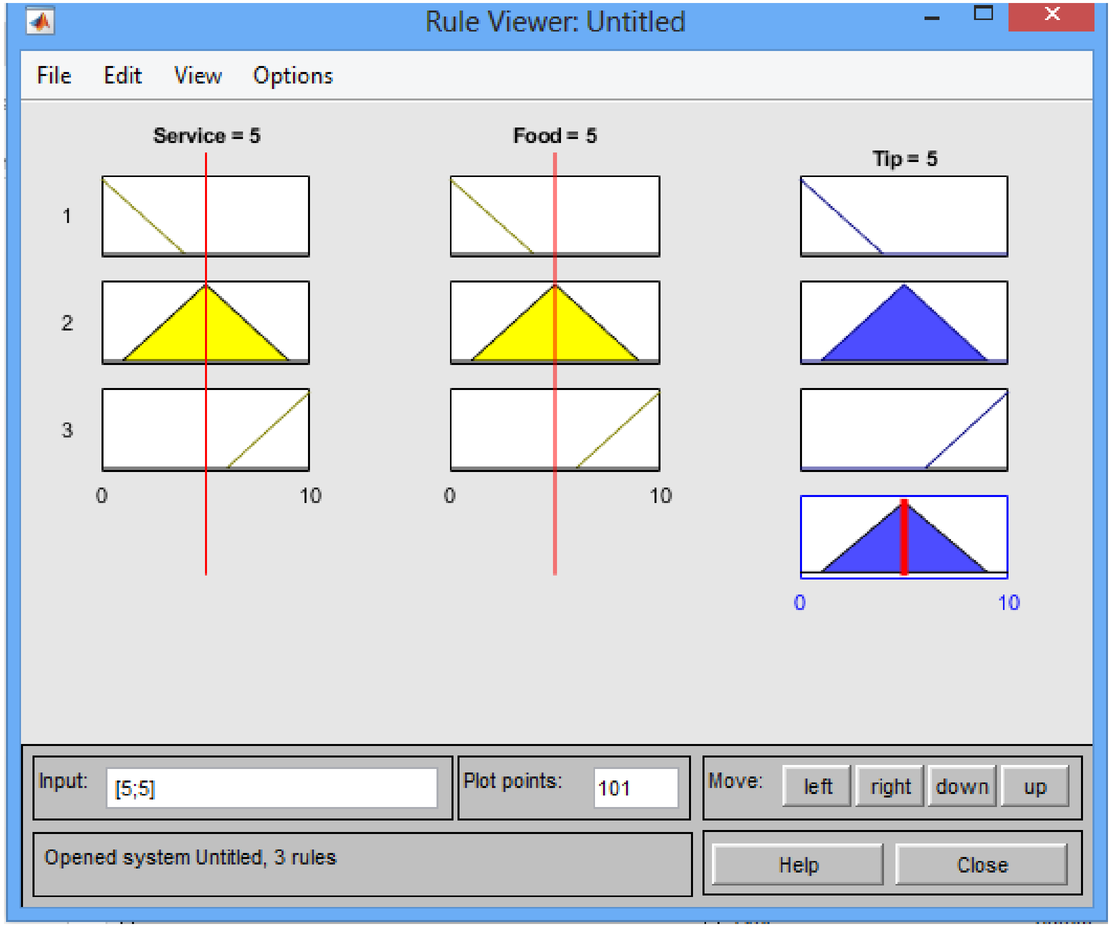

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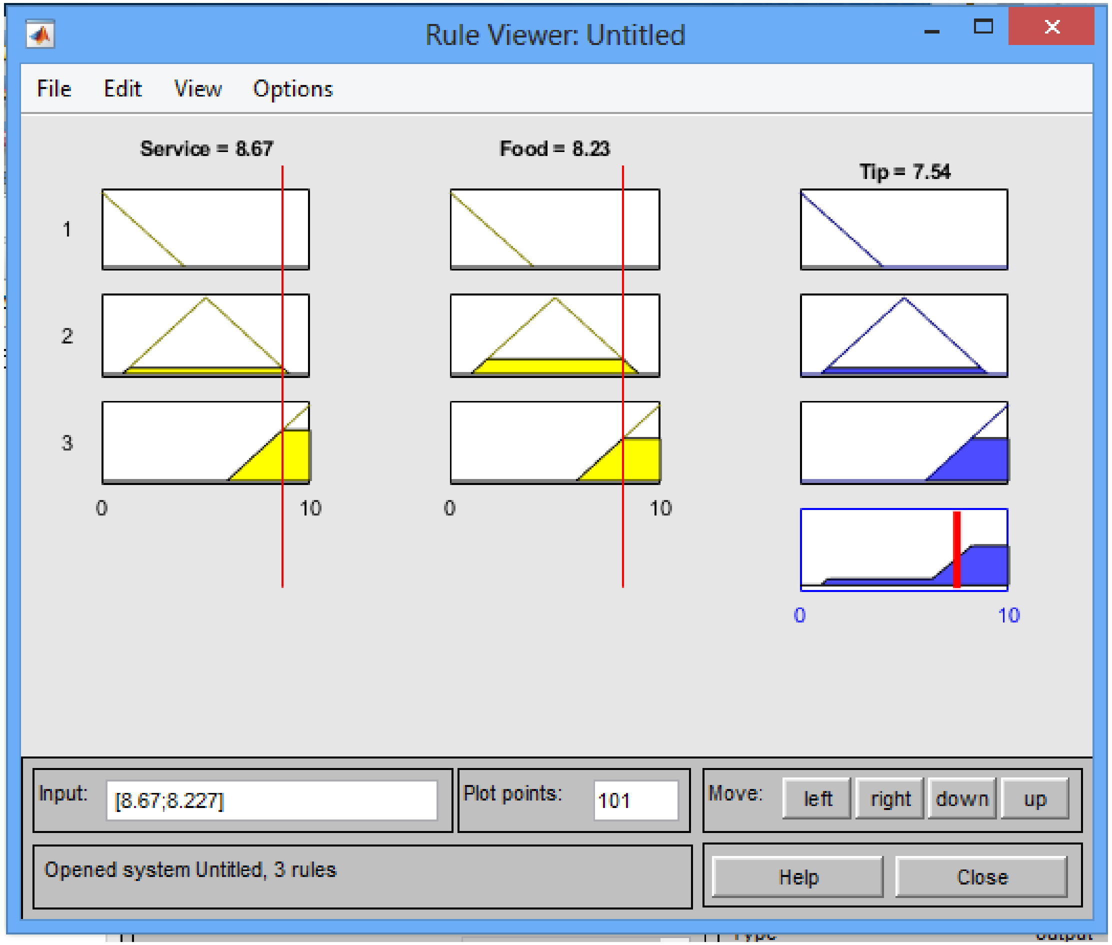

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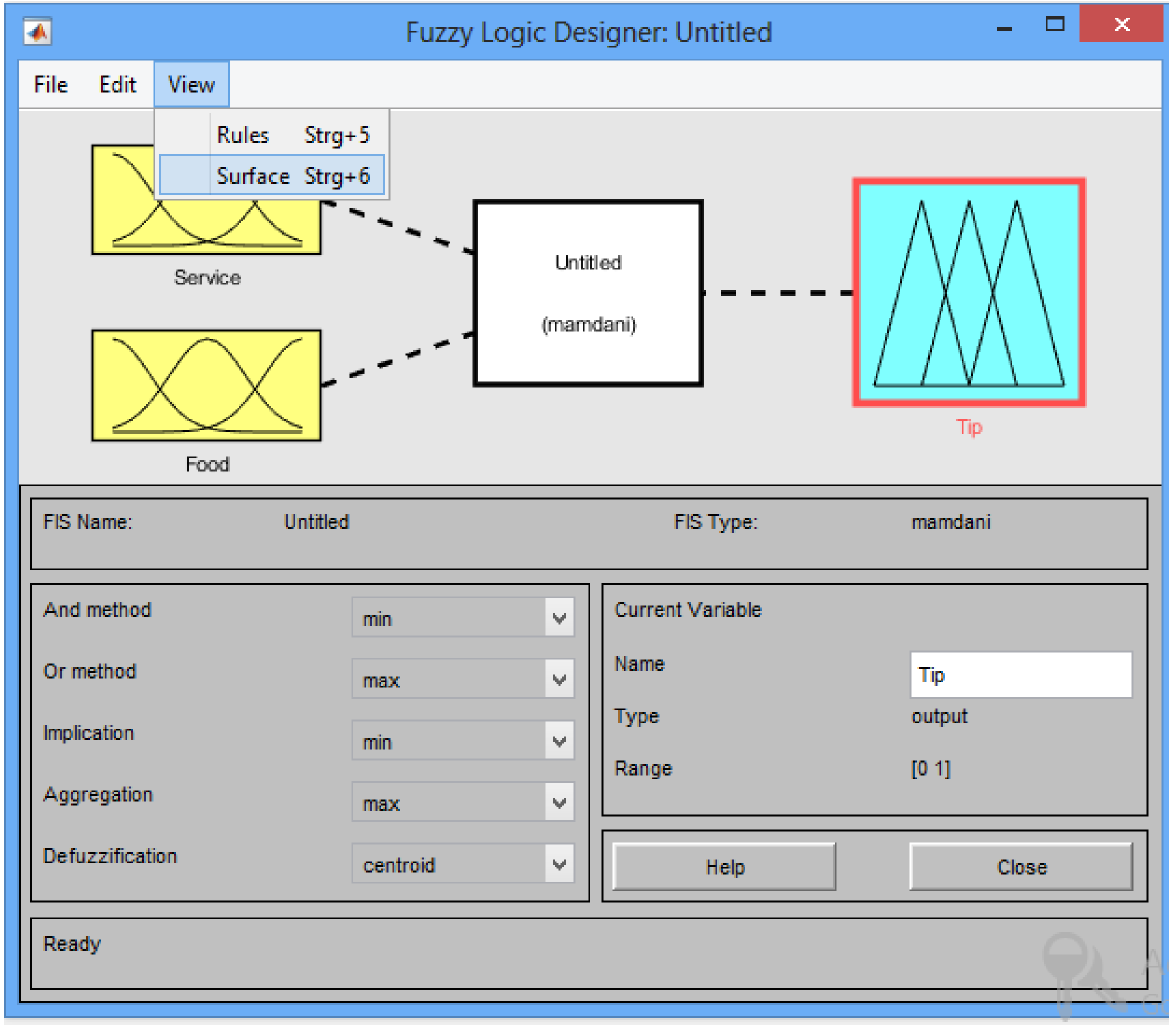

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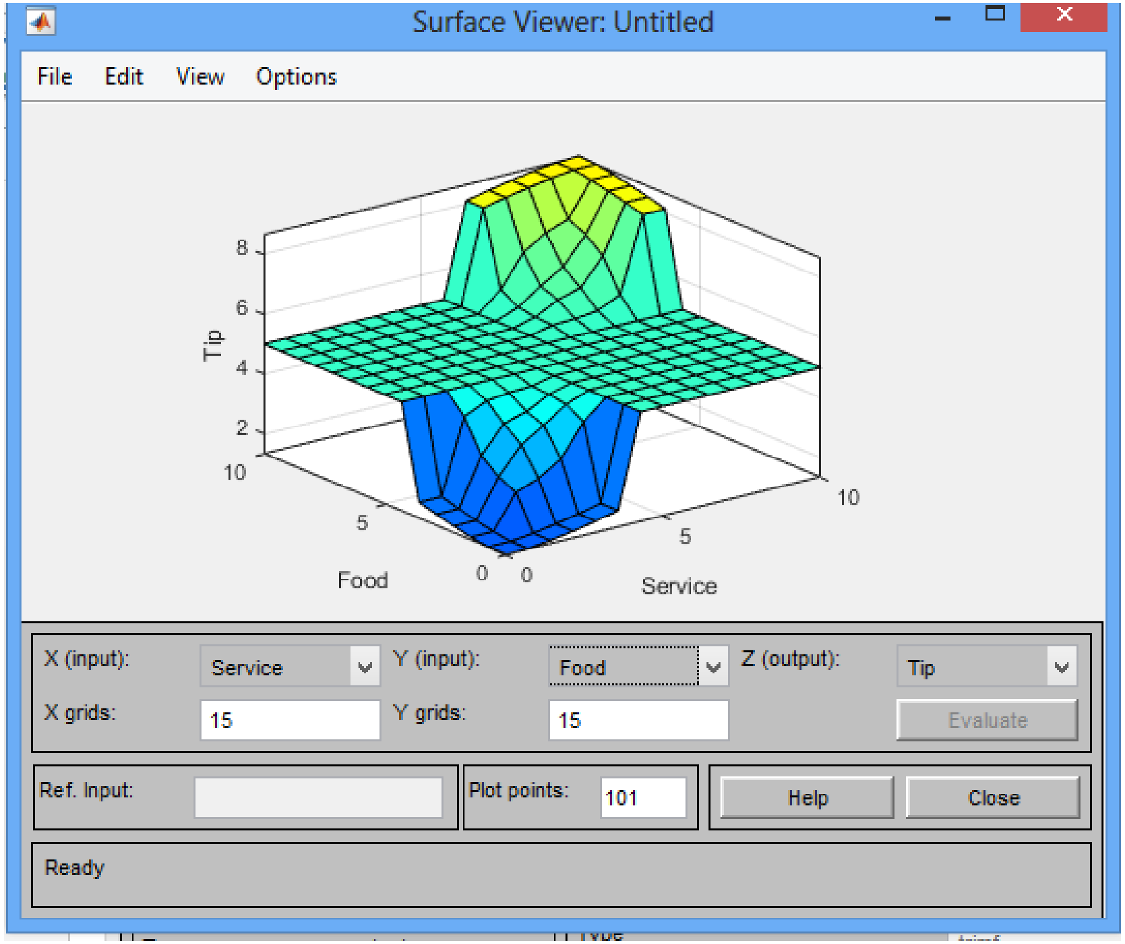

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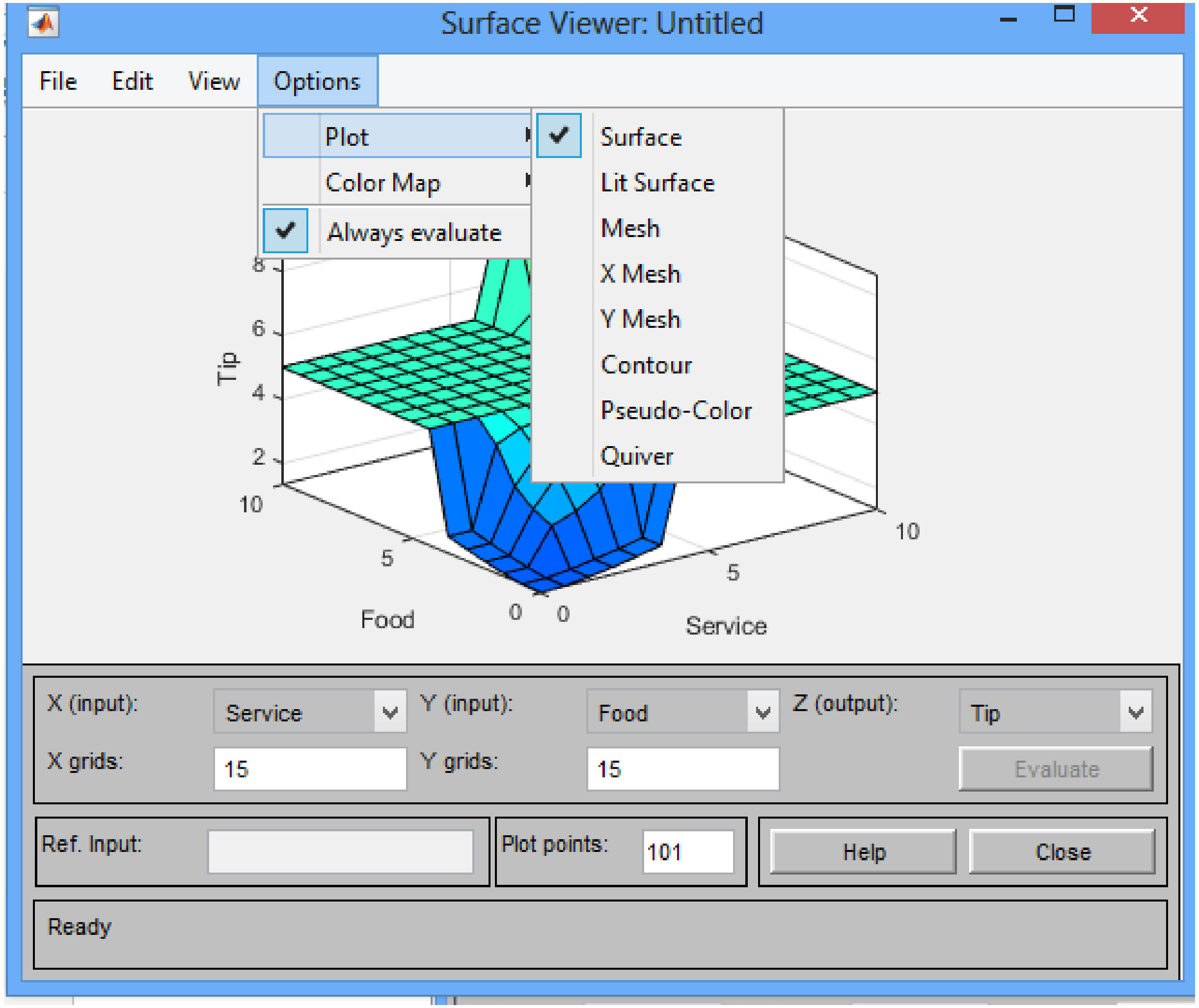

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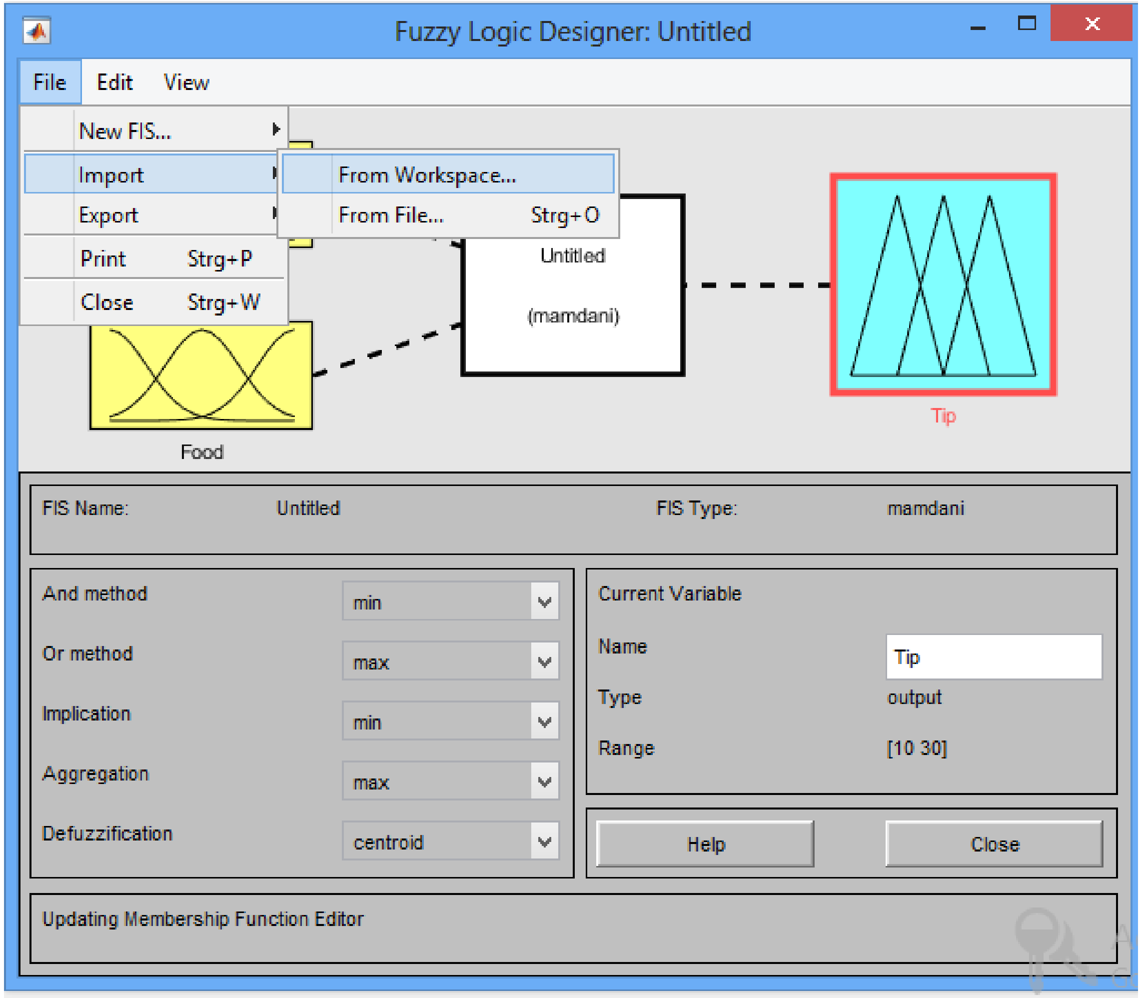

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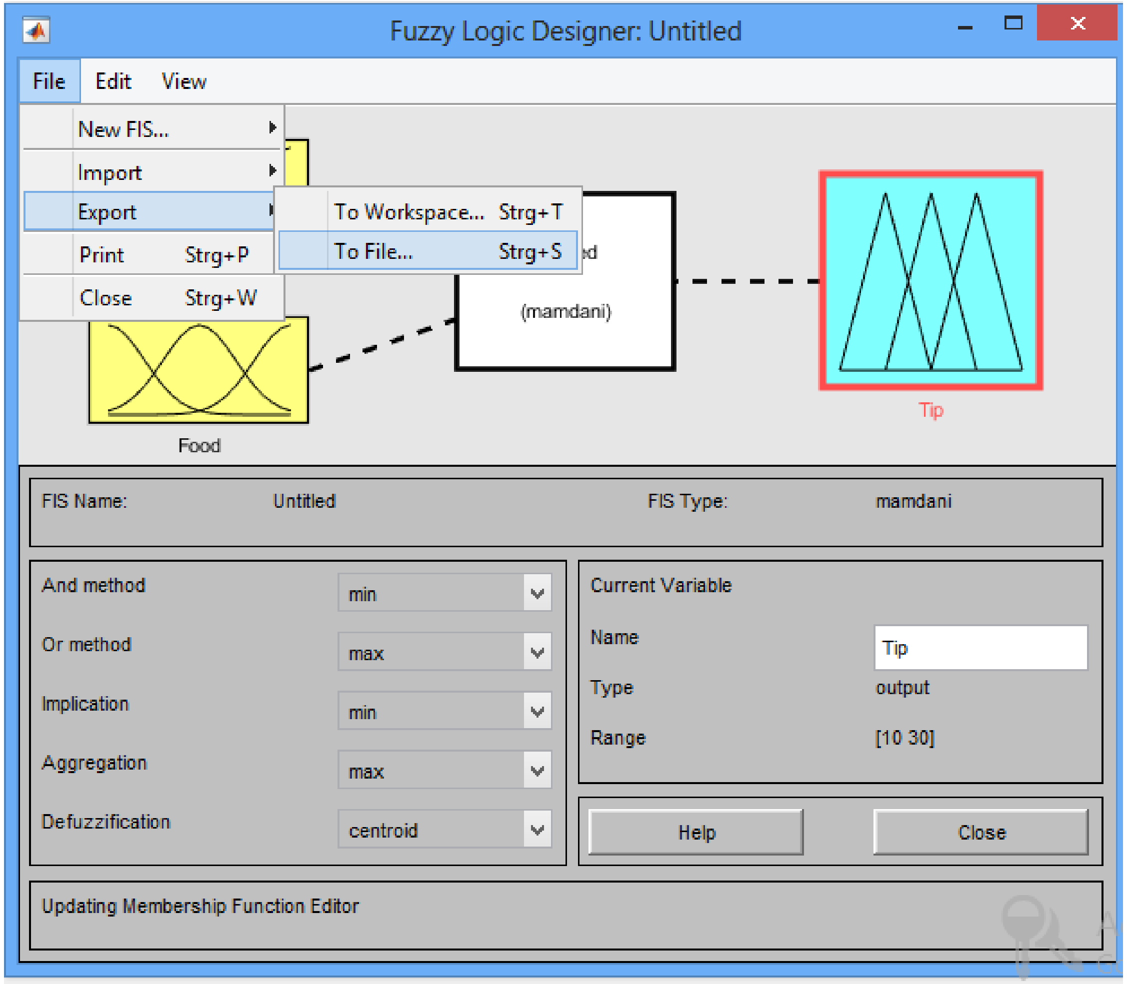

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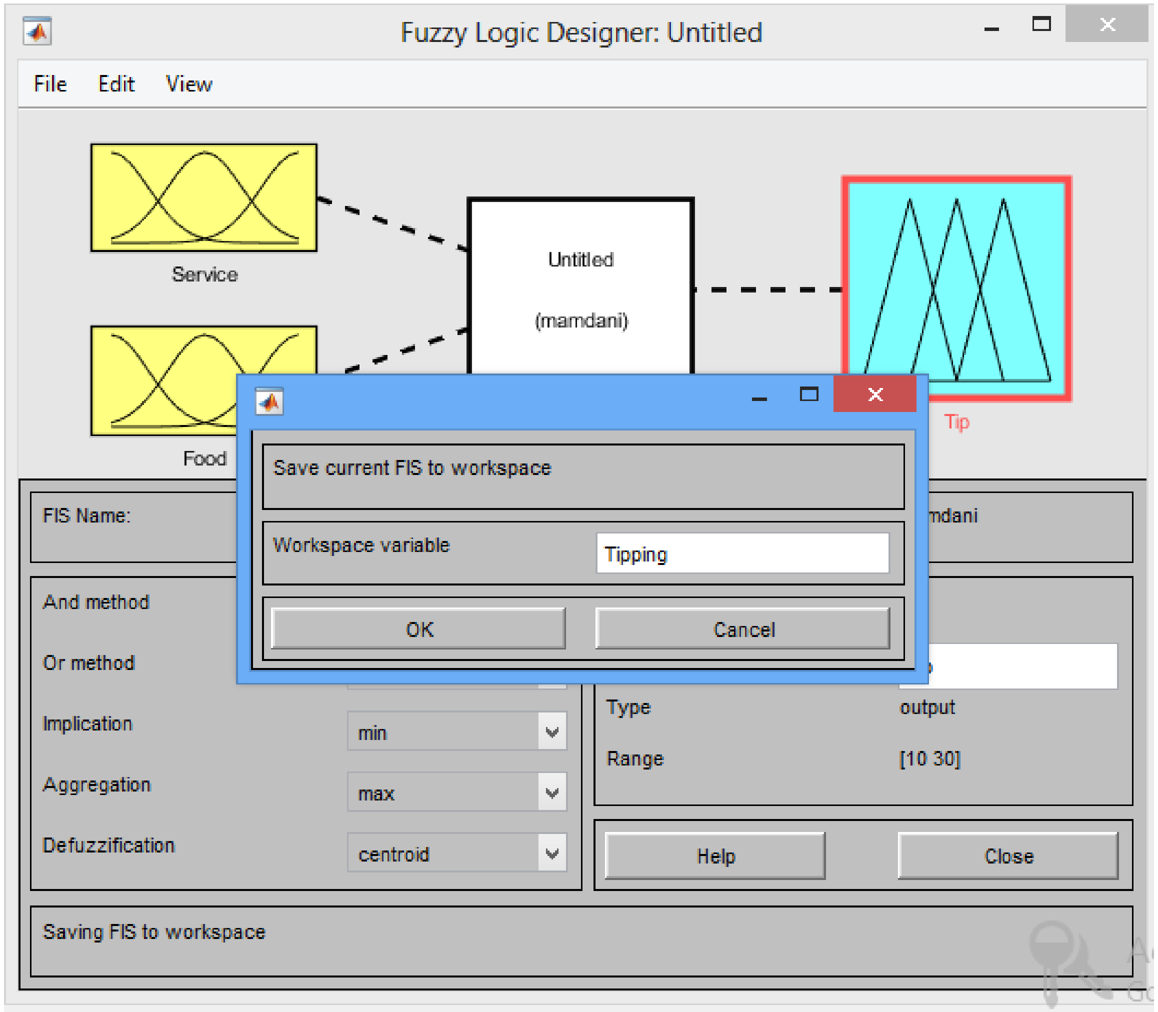

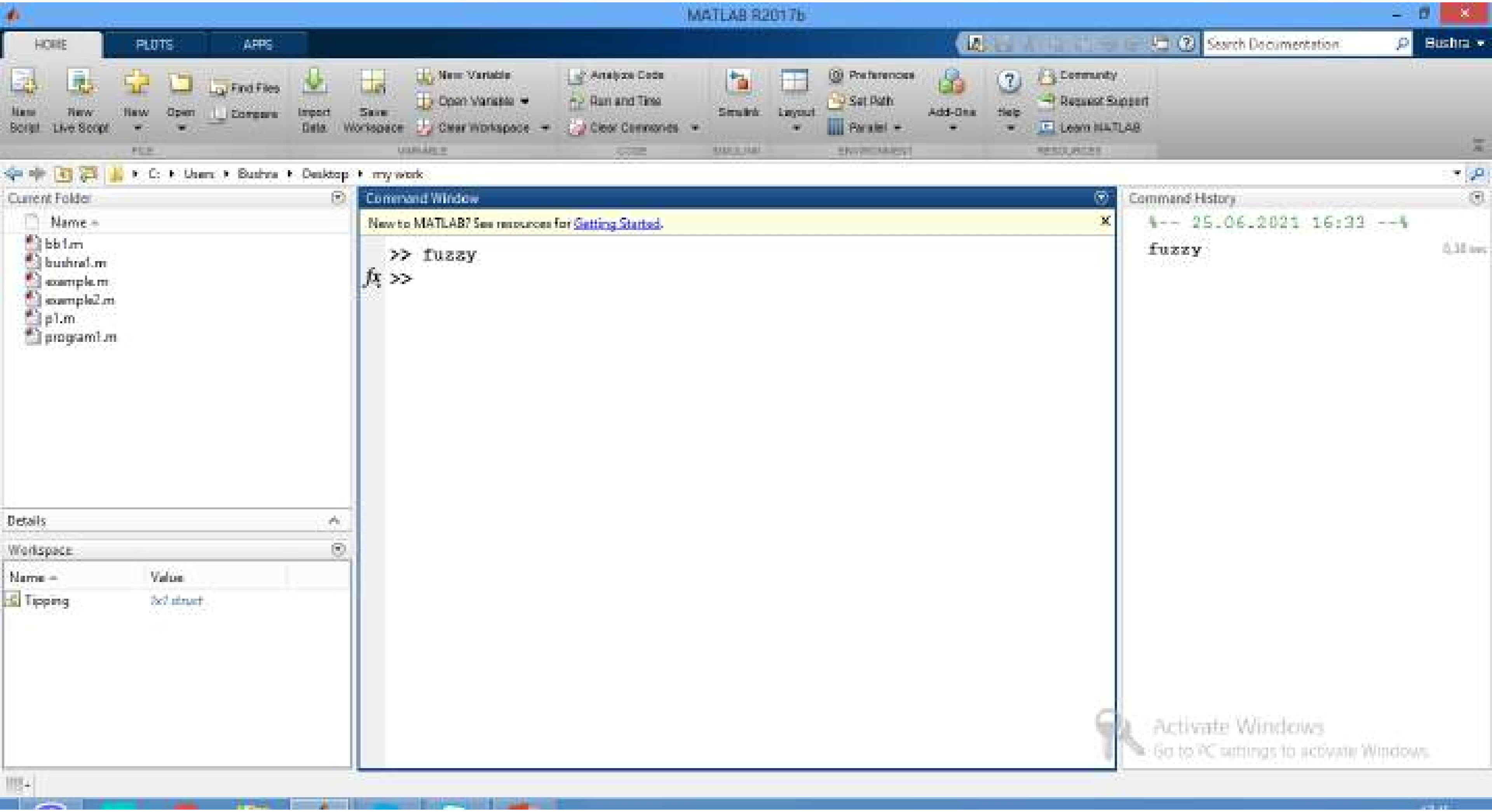
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HOME
PLOTS
APPS
Current Folder
Command Window
Command History
>> fuzzy
>>
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fuzzy
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bushra1.m
example.m
example2.m
p1.m
program1.m
Details
Workspace
Name
Value
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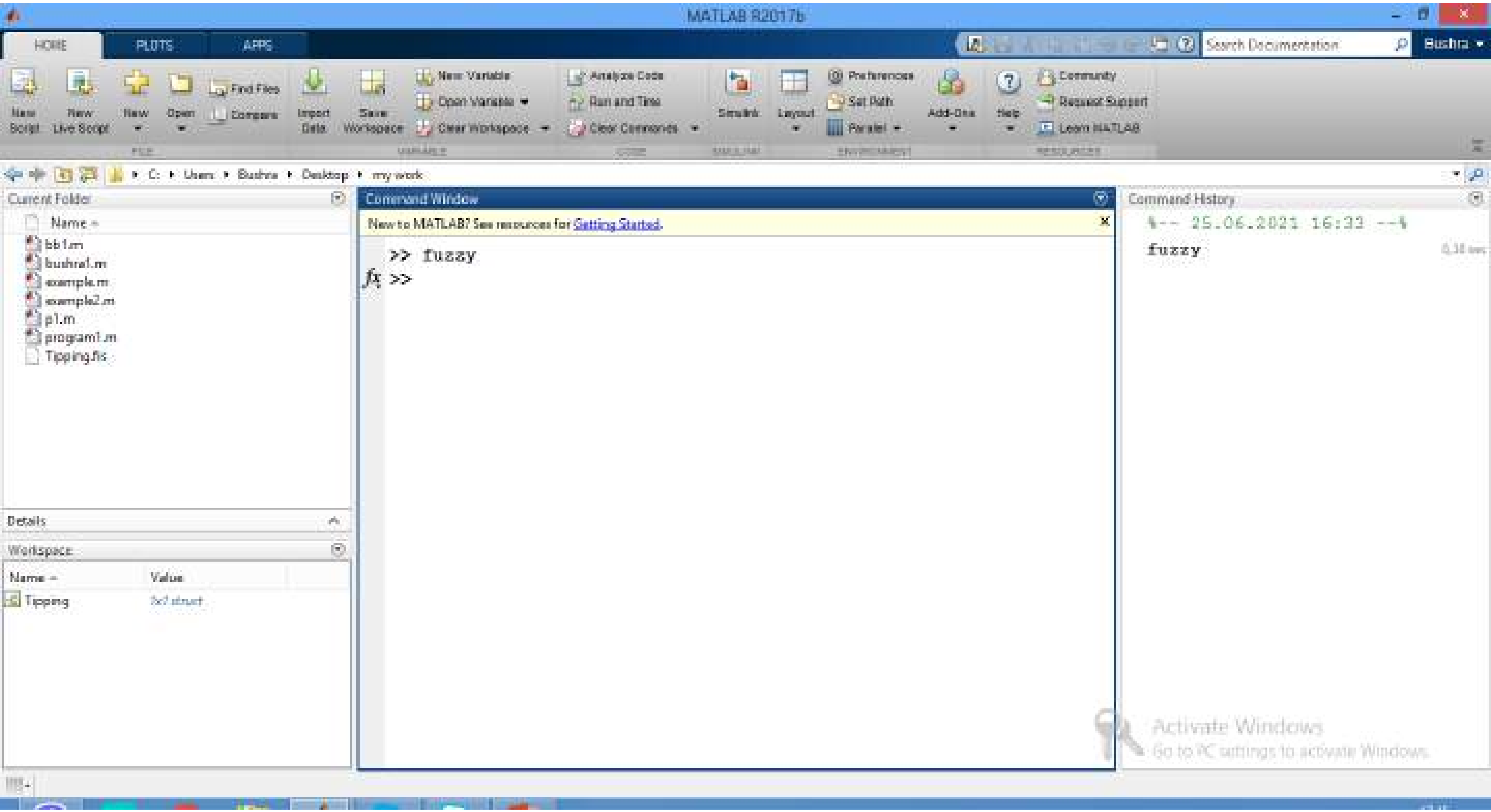
MATLAB R2017b
HOME
PLOTS
APPS
Search Documentation
New Script
New Live Script
New
Open
Find Files
Compare
Import Data
Save Workspace
New Variable
Open Variable
Clear Workspace
Analyze Code
Run and Time
Clear Commands
Simulink
Layout
Preferences
Set Path
Parallel
Add-Ons
Help
Community
Request Support
Learn MATLAB
C: ▸ Users ▸ Bushra ▸ Desktop ▸ my work
Current Folder
Name
bb1.m
bushra1.m
example.m
example2.m
p1.m
program1.m
Tipping.fis
Details
Workspace
Name
Value
Tipping
Command Window
New to MATLAB? See resources for Getting Started.
>> fuzzy
>>
Command History
%-- 25.06.2021 16:33 --%
fuzzy
Activate Windows
Go to PC settings to activate Windows.

There are several reasons why fuzzy logic is used

- The concept of fuzzy logic is easy to understand.
- The mathematical concept underlying fuzzy reasoning is very simple and easy to work out.
- It is very flexible. It means that fuzzy logic can adapt to variation and vagueness coming with problems.
- It can tolerate inaccurate data.
- It can model complex nonlinear functions.
- It can be directly constructed and applied in line with experts experiences without training.
- It can be used in conventional control systems.
- It is based on natural languages.

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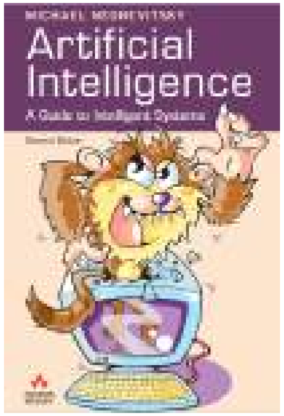
  - (second edition).
  - Mechael Negnevitsky.



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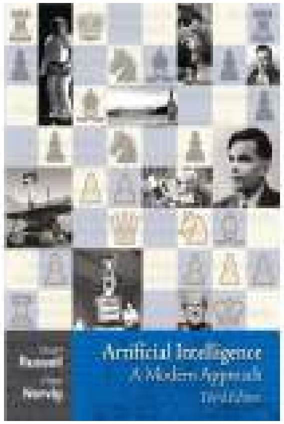

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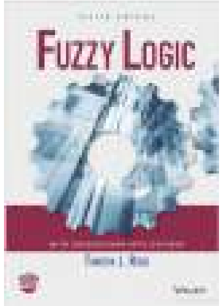

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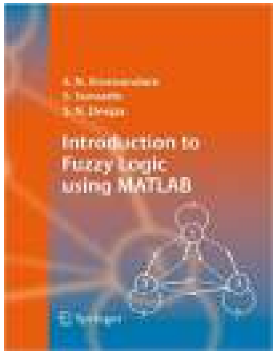

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