Methods of Soft Control
(Methoden der Soft-Control)

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Organisational issues

- **Lecture:** Prof. Dr. Ping Zhang
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- **Exercise:** Dipl.-Ing. Anna Nehring
  Email: nehring@eit.uni-kl.de
- **Language of the course:** English
- **Scope:** 2 SWS
- **Script:** available on OLAT (password: artiint17)
- **Examination:** written examination, 90 min.

Review of control courses

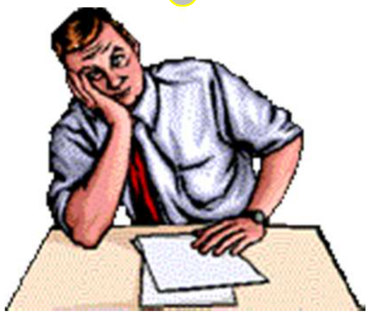
Typical control courses

- **Basics:**
  - Grundlagen der Automatisierungstechnik
  - Lineare Regelungen
- **Advanced:**
  - Logic control
  - Processautomatisierung
  - Optimal control
  - Nichtlineare und adaptive Regelungen
  - Robust control
  - Model predictive control
- **Modelling:**
  - Modelling and identification
- **Implementation**:
  - CAE in der Regelungstechnik
  - Lab courses

Review of control courses

What happens

- **if it is very difficult to get a model of the system to be controlled, or**
- **if the system is too complex, or**
- **If the optimization problem is too complex?**



„Soft control“

What is Soft Control?

- **Soft control:** application of **soft computing** in control
- **Soft computing**:
  - deal with **imprecision** and **uncertainty**
  - make use of **human expertise**
- **Main content of this course:**
  - Fuzzy control: **fuzzy inference / experience based control**
  - Neural network: **brain (network of neurons, learning ability)**
  - Evolutionary algorithms: **evolution theory**

Three different design philosophies…

Key idea: learn from NATURE!

Learning goals

- **What** are the soft control methods (basic ideas, basic principles, advantages and disadvantages)?
- **How** to apply them (basic procedures, choice of parameters)?
- **When** to apply them (application examples)?

Literature

- Adamy, J.: *Fuzzy Logic, Neuronale Netze und Evolutionäre Algorithmen*. Shaker Verlag, 2011.
- Lippe, W.M.: *Soft-Computing*. Springer, 2006.
- Haykin S.: *Neural networks and learning machines*. Pearson, 2009.

Organisation of this course

Chapter 1: Introduction

Chapter 2: Fuzzy control

Chapter 3: Neural networks

Chapter 4: Evolutionary algorithms

Chapter 2

Fuzzy control

Introduction

- The basic idea of fuzzy sets and fuzzy logic was introduced by Zadeh (1965).
- The first fuzzy control scheme was presented by Mamdani (1975).
- A number of applications appeared in Japan in the 80‘s.
- Fuzzy control has been widely used in various consumer electronic devices, for instance, washing machines, video cameras, TV and sound systems.

Introduction

- An example of fuzzy controller used to control the amount of cooling medium in a drilling machine:

Rule 1: IF $Speed = very\ low$,
THEN $Amount\ of\ Cooling\ medium\ = very\ little$.

Rule 2: IF $Speed = low$,
THEN $Amount\ of\ Cooling\ medium\ = little$.

Rule 3: IF $Speed = middle$,
THEN $Amount\ of\ Cooling\ medium\ = normal$.

Rule 4: IF $Speed = high$,
THEN $Amount\ of\ Cooling\ medium\ = much$.

Rule 5: IF $Speed = very\ high$,
THEN $Amount\ of\ Cooling\ medium\ = very\ much$.

Introduction

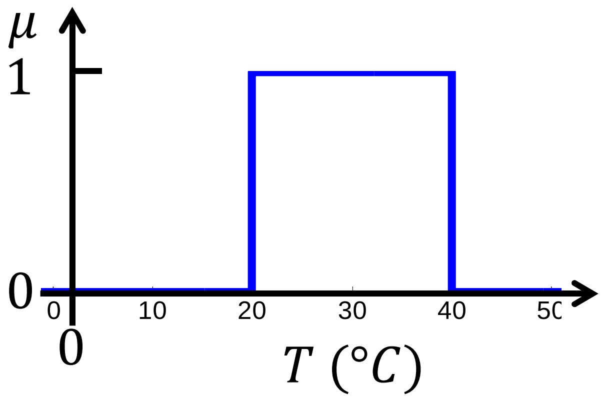
- Fuzzy Takagi-Sugeno (T-S) models have been much investigated around year 2000.
- Journals on this topic:
  - Fuzzy Sets and Systems (since 1978)
  - IEEE Transactions on Fuzzy Systems (since 1993)
- Key of fuzzy control:
  - Introduction of **fuzzy sets** and membership functions
  - Based on that, **fuzzy logic** (especially fuzzy inference mechanism) was developed.

Classical crisp set:

- Examples: $\{1,2,3\}$, $\{\, T \mid 20°C \le T \le 40°C \,\}$, **R, RH**$_\infty$
- An element either belongs to or doesn‘t belong to a crisp set.
  For instance,

$$3 \in \{1,2,3\}, \qquad 5 \notin \{1,2,3\}$$

$$39.9°C \in \{\, T \mid 20°C \le T \le 40°C \,\}, \quad 40.1°C \notin \{\, T \mid 20°C \le T \le 40°C \,\}$$



$$\mu(T) = \begin{cases} 1, & \text{if } T \text{ belongs to the set} \\ 0, & \text{if } T \text{ belongs to the set} \end{cases}$$

How much is the difference between 39.9°C and 40.1°C?

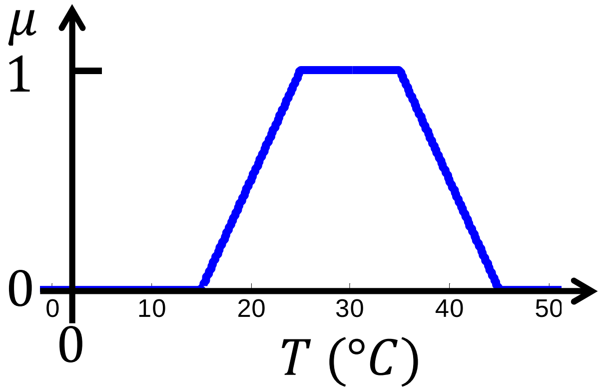
Fuzzy sets

Fuzzy set:

- An element may **partly** belong to a set.
- A fuzzy set is described by

$$M = \{(x, \mu(x)) \mid x \in G\}$$

where G is a set, $\mu(x)$ is the **membership function**, $0 \le \mu(x) \le 1$.

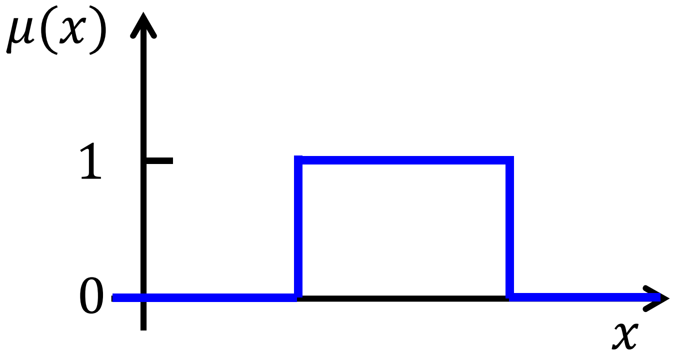


$$\mu(39.9) = 0.51$$
$$\mu(40.1) = 0.49$$

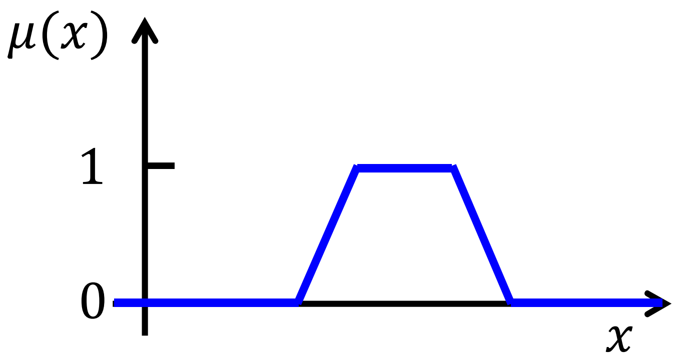
Membership function

Membership function $\mu(x)$ denotes the **grade of membership** of an element x in the set.

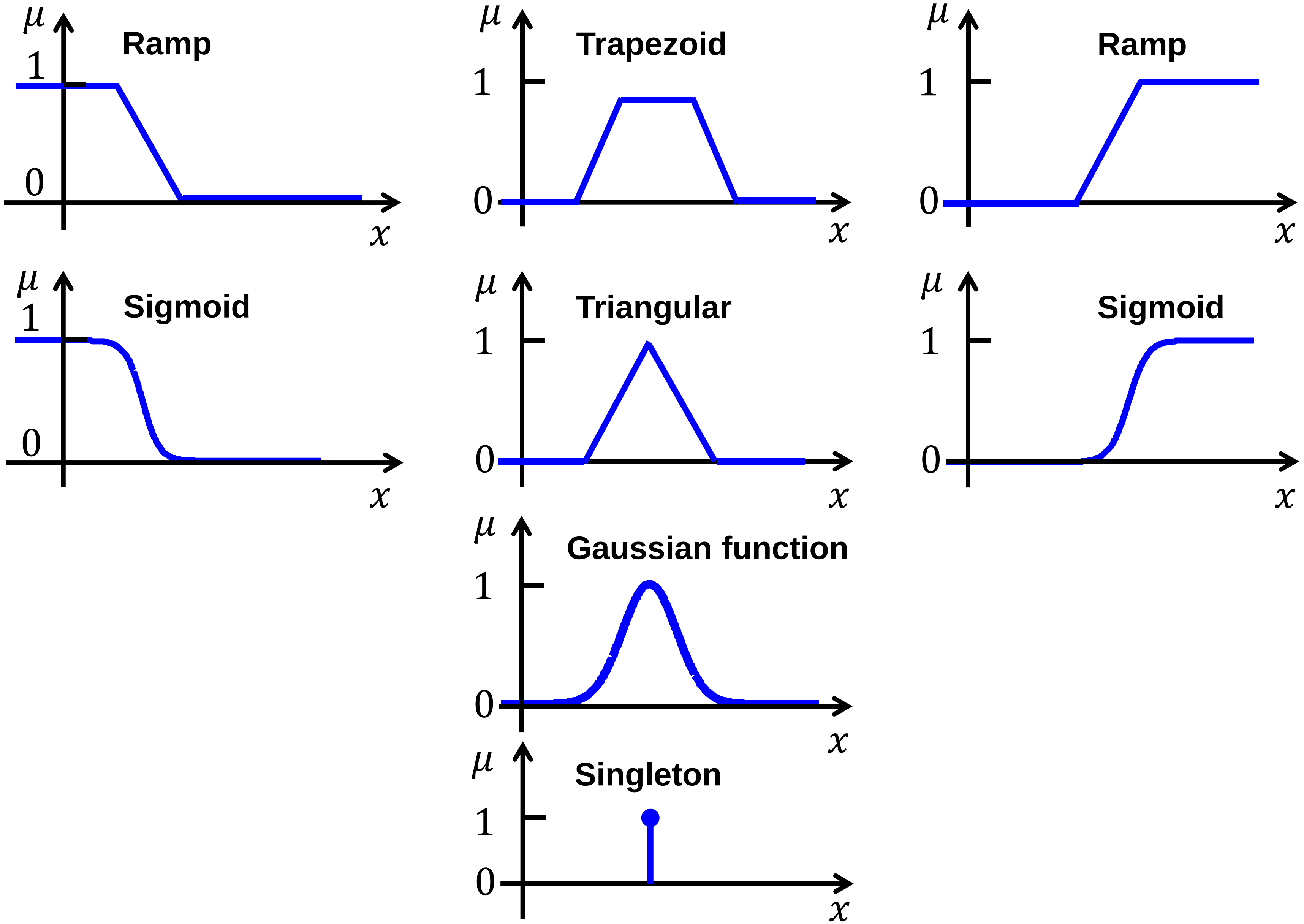
crisp set



fuzzy set



Typical membership functions



Membership function

- **Support** of the fuzzy set M:

$$supp(M) = \{x \mid \mu(x) > 0\}$$

- **Core** of the fuzzy set M:

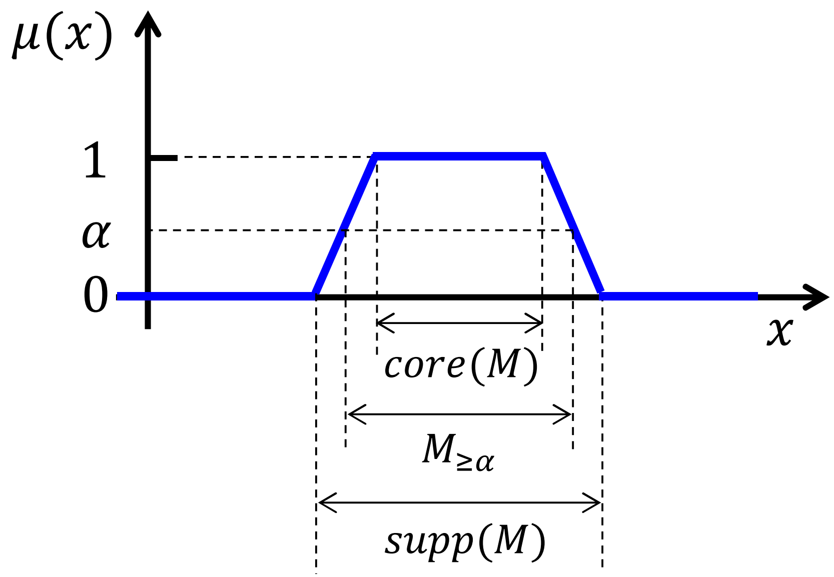
$$core(M) = \{x \mid \mu(x) = 1\}$$

- $\boldsymbol{\alpha}$ **level set** of the fuzzy set M:

$$M_{\geq\alpha} = \{x \mid \mu(x) \geq \alpha\}$$

- $\mu(x)$ is said to be **normalized**, if

$$\max \mu(x) = 1$$



Operations on fuzzy sets

Given two fuzzy sets

$$M_1 = \{(x, \mu_1(x)) \mid x \in G\}$$
$$M_2 = \{(x, \mu_2(x)) \mid x \in G\}$$

- M_1 is said to be a **subset** of M_2, if $\mu_1(x) \le \mu_2(x), \ \forall x \in G$.
- **Union**

$$M_1 \cup M_2 = \{(x, \mu(x)) \mid x \in G\}$$
$$\mu(x) = \mu_1(x) \cup \mu_2(x)$$

- **Intersection**

$$M_1 \cap M_2 = \{(x, \mu(x)) \mid x \in G\}$$
$$\mu(x) = \mu_1(x) \cap \mu_2(x)$$

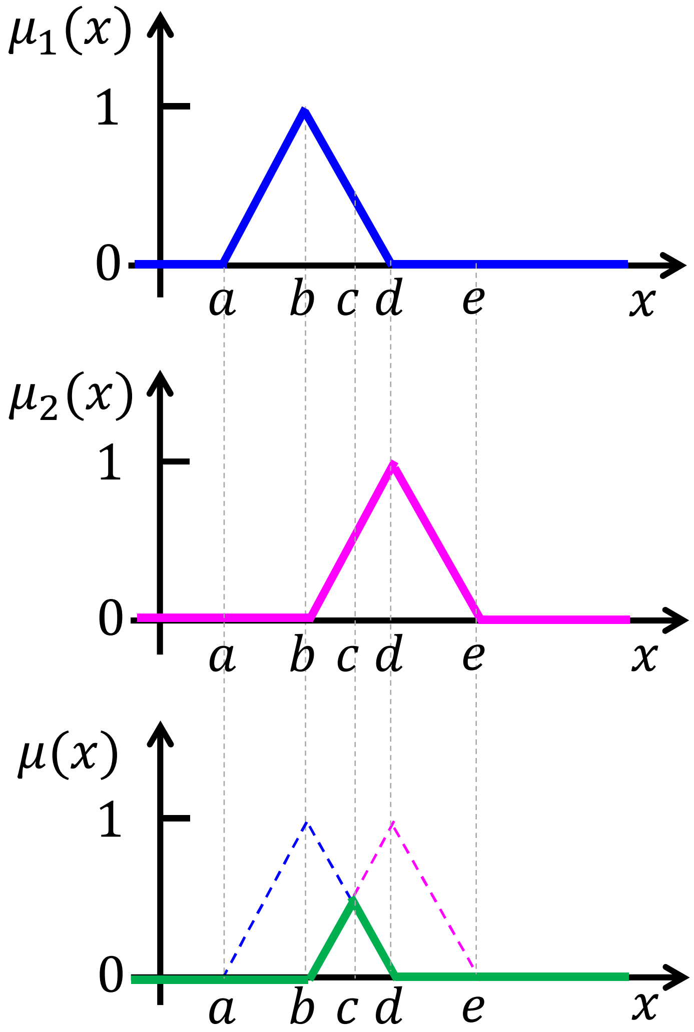
- **Complement**

$$\bar{M}_1 = \{(x, \overline{\mu_1}(x)) \mid x \in G\}$$
$$\overline{\mu_1}(x) = 1 - \mu_1(x)$$

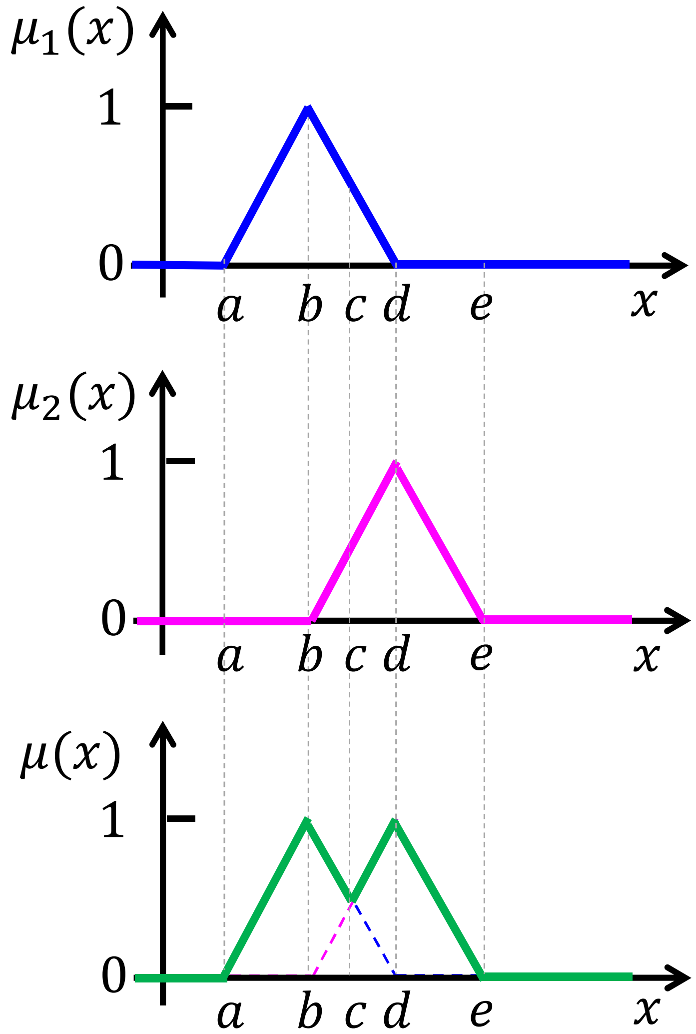
How to get $\mu_1(x) \cup \mu_2(x)$ or $\mu_1(x) \cap \mu_2(x)$?

Min/Max operators

$$\mu(x) = \mu_1(x) \cap \mu_2(x)$$
$$= \textcolor{red}{\min}\ \{\mu_1(x), \mu_2(x)\}$$



$$\mu(x) = \mu_1(x) \cup \mu_2(x)$$
$$= \textcolor{red}{\max}\ \{\mu_1(x), \mu_2(x)\}$$



Some often used operators

Operators	$\mu_1(x) \cap \mu_2(x)$	$\mu_1(x) \cup \mu_2(x)$
Min/Max	$\min\{\mu_1(x), \mu_2(x)\}$	$\max\{\mu_1(x), \mu_2(x)\}$
Algebraic product / sum	$\mu_1(x)\mu_2(x)$	$\mu_1(x) + \mu_2(x) - \mu_1(x)\mu_2(x)$
Einstein product / sum	$\frac{\mu_1(x)\mu_2(x)}{1+(1-\mu_1(x))(1-\mu_2(x))}$	$\frac{\mu_1(x)+\mu_2(x)}{1+\mu_1(x)\mu_2(x)}$
Bounded difference / sum	$\max\{0, \mu_1(x) + \mu_2(x) - 1\}$	$\min\{1, \mu_1(x) + \mu_2(x)\}$

Properties of operations on fuzzy sets

Most of the properties of classical crisp sets hold also for fuzzy sets.

Identity: $\mu_1 \cap 1 = \mu_1, \qquad \mu_1 \cup 0 = \mu_1$

Commutativity: $\mu_1 \cap \mu_2 = \mu_2 \cap \mu_1, \qquad \mu_1 \cup \mu_2 = \mu_2 \cup \mu_1$

Associativity: $\mu_1 \cap \mu_2 \cap \mu_3 = (\mu_1 \cap \mu_2) \cap \mu_3 = \mu_1 \cap (\mu_2 \cap \mu_3)$

$\mu_1 \cup \mu_2 \cup \mu_3 = (\mu_1 \cup \mu_2) \cup \mu_3 = \mu_1 \cup (\mu_2 \cup \mu_3)$

Distributivity: $\mu_1 \cap (\mu_2 \cup \mu_3) = (\mu_1 \cap \mu_2) \cup (\mu_1 \cap \mu_3)$

$\mu_1 \cup (\mu_2 \cap \mu_3) = (\mu_1 \cup \mu_2) \cap (\mu_1 \cup \mu_3)$

Absorption: $\mu_1 \cup (\mu_1 \cap \mu_2) = \mu_1, \qquad \mu_1 \cap (\mu_1 \cup \mu_2) = \mu_1$

De Morgan‘s Law: $\overline{\mu_1 \cap \mu_2} = \overline{\mu_1} \cup \overline{\mu_2}, \qquad \overline{\mu_1 \cup \mu_2} = \overline{\mu_1} \cap \overline{\mu_2}$

Exercise:

1. Prove Absorption Law.
2. Prove De Morgan‘s Law

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Properties of operations on fuzzy sets

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Commutativity: $\mu_1 \cap \mu_2 = \mu_2 \cap \mu_1,\qquad \mu_1 \cup \mu_2 = \mu_2 \cup \mu_1$

Associativity:

$$\mu_1 \cap \mu_2 \cap \mu_3 = (\mu_1 \cap \mu_2) \cap \mu_3 = \mu_1 \cap (\mu_2 \cap \mu_3)$$

$$\mu_1 \cup \mu_2 \cup \mu_3 = (\mu_1 \cup \mu_2) \cup \mu_3 = \mu_1 \cup (\mu_2 \cup \mu_3)$$

Distributivity:

$$\mu_1 \cap (\mu_2 \cup \mu_3) = (\mu_1 \cap \mu_2) \cup (\mu_1 \cap \mu_3)$$

$$\mu_1 \cup (\mu_2 \cap \mu_3) = (\mu_1 \cup \mu_2) \cap (\mu_1 \cup \mu_3)$$

Absorption: $\mu_1 \cup (\mu_1 \cap \mu_2) = \mu_1,\qquad \mu_1 \cap (\mu_1 \cup \mu_2) = \mu_1$

De Morgan's Law: $\overline{\mu_1 \cap \mu_2} = \overline{\mu_1} \cup \overline{\mu_2},\qquad \overline{\mu_1 \cup \mu_2} = \overline{\mu_1} \cap \overline{\mu_2}$

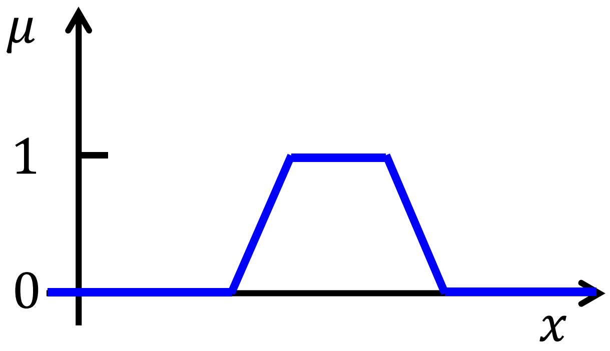
How about the law of complements?

$$\mu_1 \cap \overline{\mu_1} = 0\,?$$
$$\mu_1 \cup \overline{\mu_1} = 1\,?$$

Properties of operations on fuzzy sets

Exercise: Given a membership function $\mu(x)$. Calculate

(1) $\bar{\mu}(x)$, (2) $\mu(x) \cap \bar{\mu}(x)$, (3) $\mu(x) \cup \bar{\mu}(x)$



Properties of operations on fuzzy sets

The laws of complement don‘t hold for min/max operators!