3 Characterization of Fuzzy Sets

Fuzzy Systems Engineering
Toward Human-Centric Computing

Contents

3.1 Generic characterization of fuzzy sets: Some fundamental descriptors

Fuzzy sets

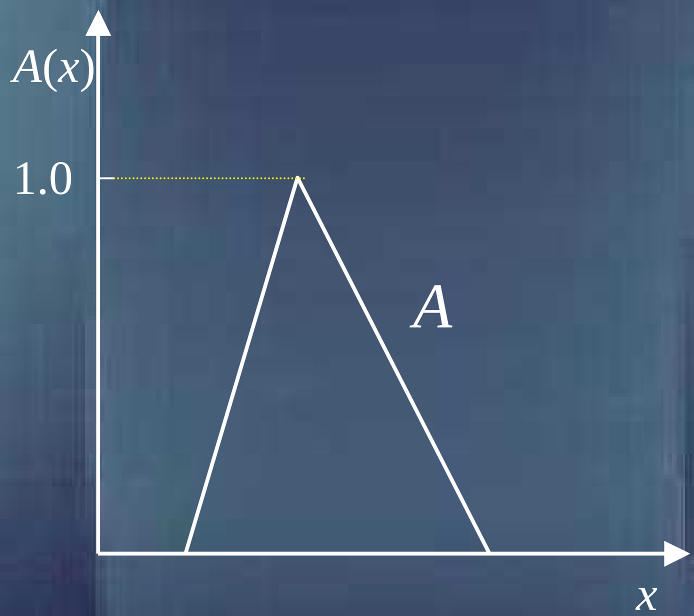
- Fuzzy sets are membership functions

$$A: \mathbf{X} \rightarrow [0, 1]$$

- In principle: any function is "eligible" to describe fuzzy sets

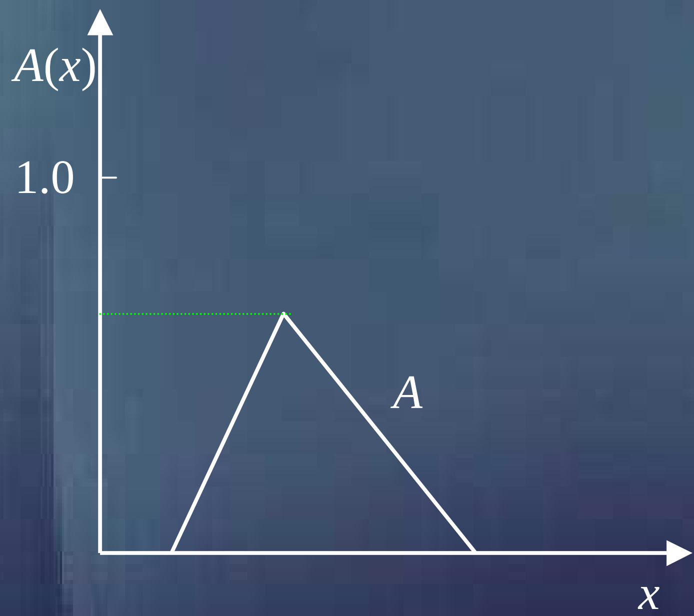
- In practice it is important to consider:
  – type, shape, and properties of the function
  – nature of the underlying phenomena
  – semantic soundness

Normality



Normal

$\mathrm{hgt}(A) = 1$

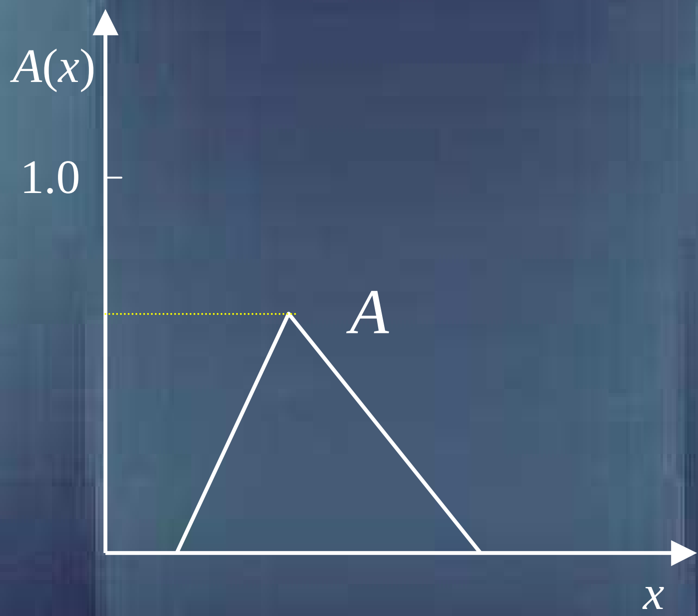


Subnormal

$\mathrm{hgt}(A) < 1$

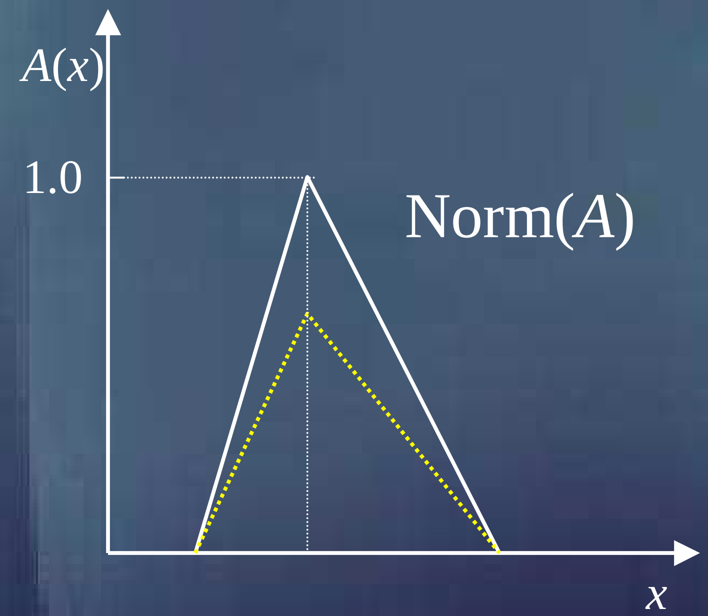
$$\mathrm{hgt}(A) = \sup_{x \in \mathbf{X}} A(x)$$

Normalization



Subnormal

$\mathrm{hgt}(A) < 1$

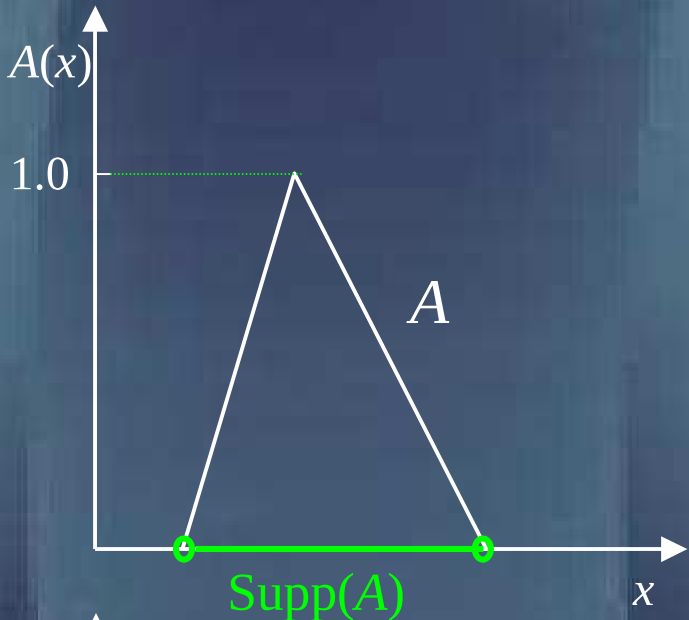


Normal

$\mathrm{hgt}(\mathrm{Norm}(A)) = 1$

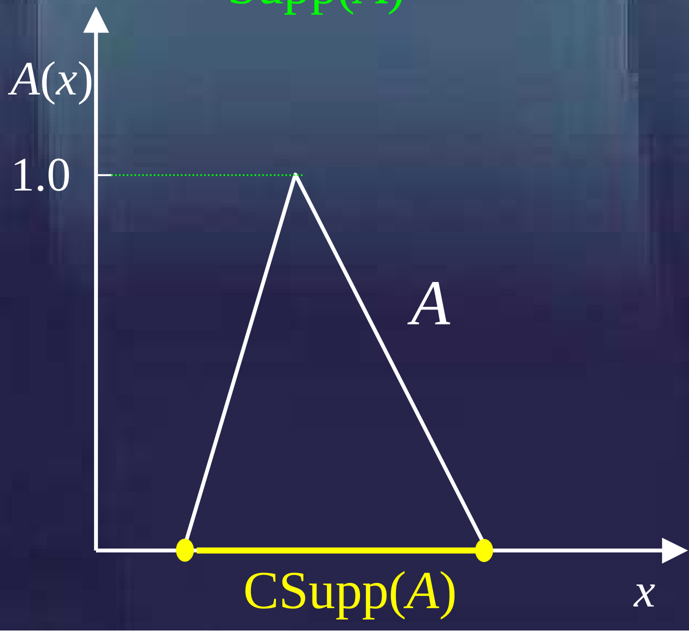
$$\mathrm{Norm}(A)(x) = \frac{A(x)}{\mathrm{hgt}(A)}$$

Support



$$\mathrm{Supp}(A) = \{x \in \mathbf{X} \mid A(x) > 0\}$$

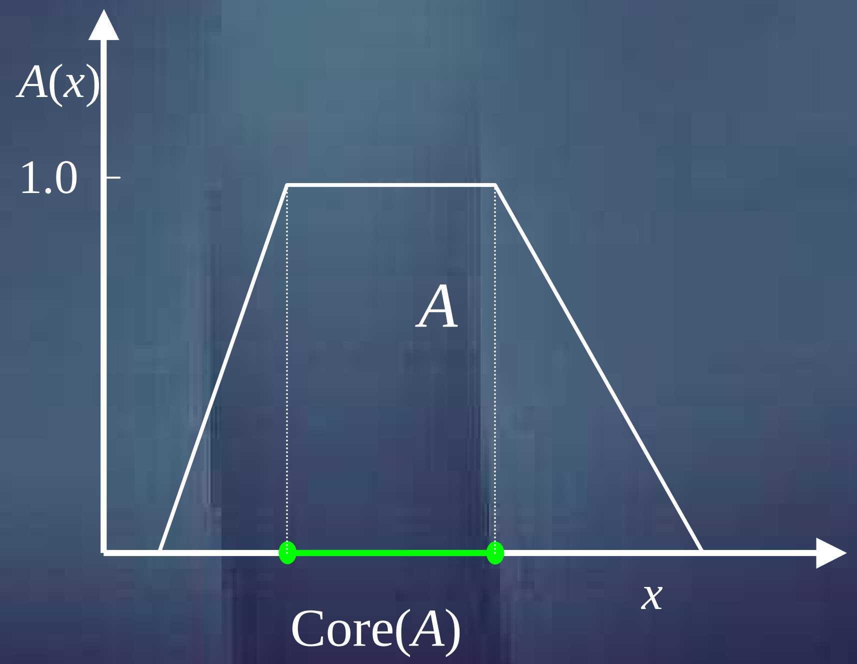
Open set



$$\mathrm{CSupp}(A) = closure\{x \in \mathbf{X} \mid A(x) > 0\}$$

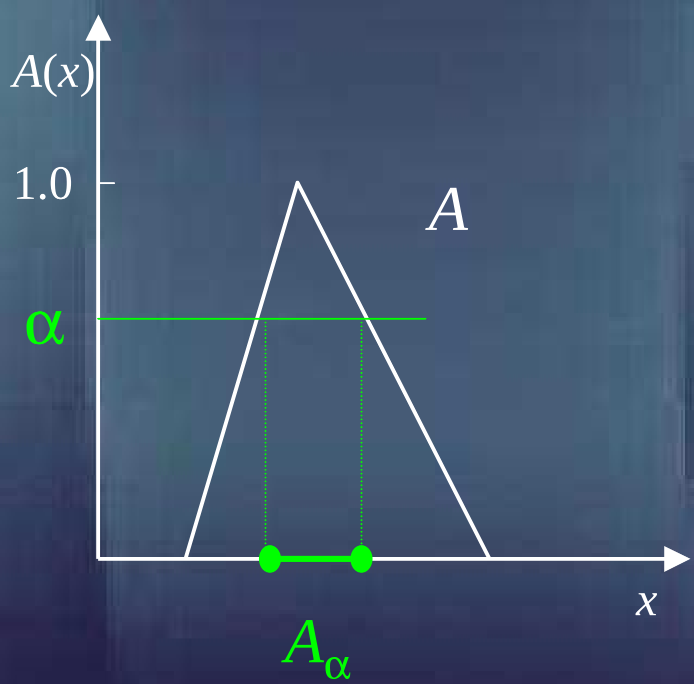
Closed set

Core

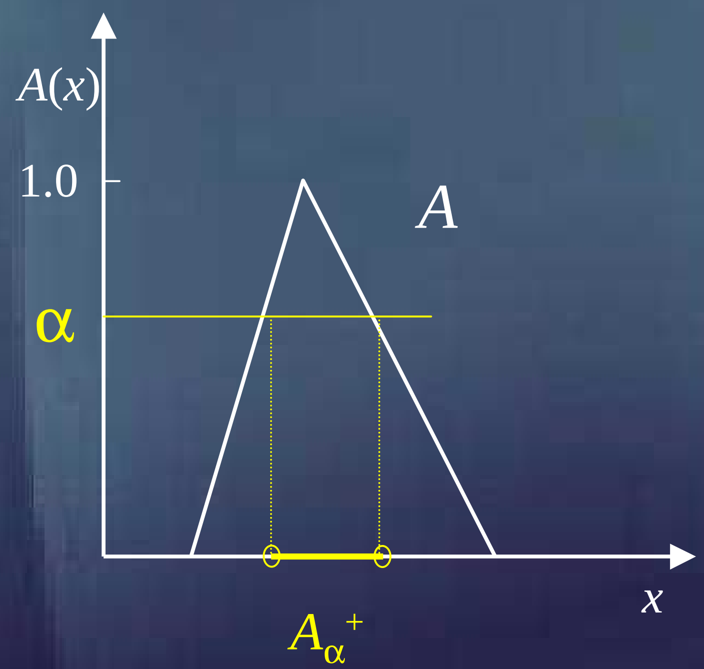


$$\mathrm{Core}(A) = \{x \in \mathbf{X} \mid A(x) = 1\}$$

α–cut



$$A_\alpha = \{x \in \mathbf{X} \mid A(x) \geq \alpha\}$$

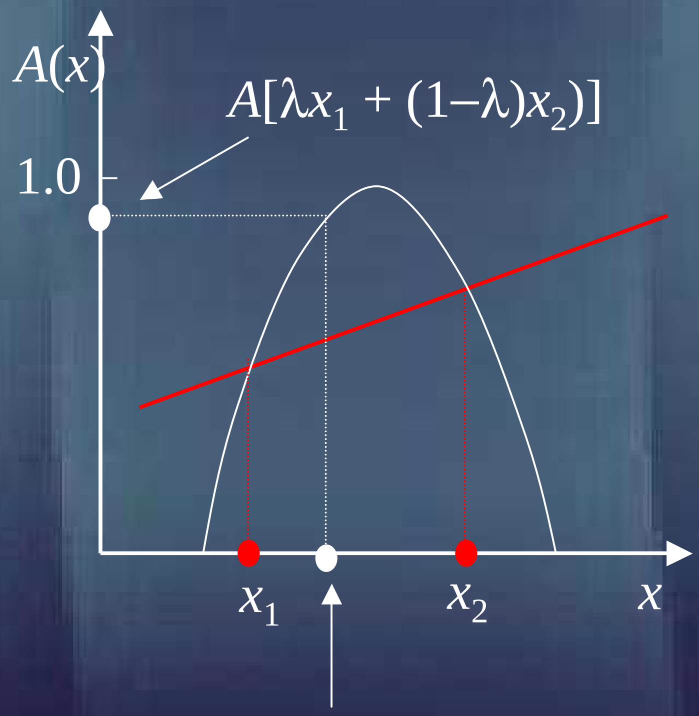


$$A_\alpha = \{x \in \mathbf{X} \mid A(x) > \alpha\}$$

Stronger condition

Convexity

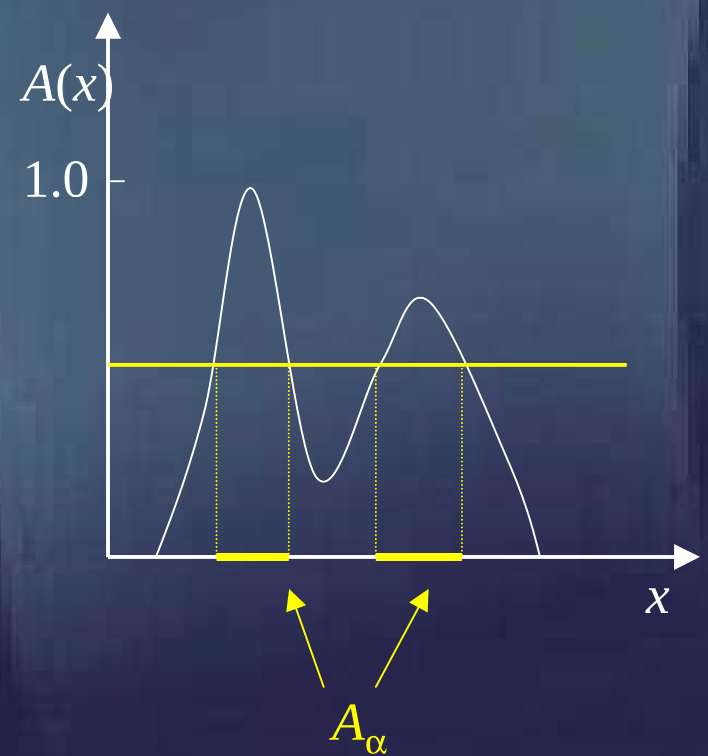
$$A[\lambda x_1 + (1-\lambda)x_2] \geq \min[A(x_1), A(x_2)]$$



$x = \lambda x_1 + (1-\lambda)x_2$

$0 \leq \lambda \leq 1$

Convex fuzzy set



$$A_\alpha = \{x \in \mathbf{X} \mid A(x) > \alpha\}$$

Nonconvex

Cardinality

$$\mathrm{Card}(A) = \sum_{x \in \mathbf{X}} A(x)$$

$\mathbf{X}$ finite or countable

$$\mathrm{Card}(A) = \int_{\mathbf{X}} A(x)\mathrm{d}x$$

$\mathrm{Card}(A) = |A|$ sigma count (σ–count)

3.2 Equality and inclusion relationships for fuzzy sets

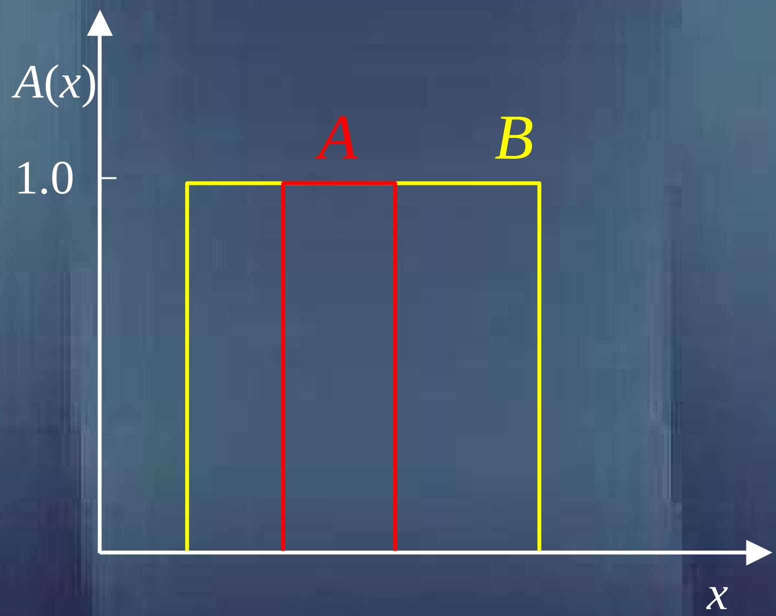
Equality

$$A = B \text{ iff } A(x) = B(x) \quad \forall x \in \mathbf{X}$$

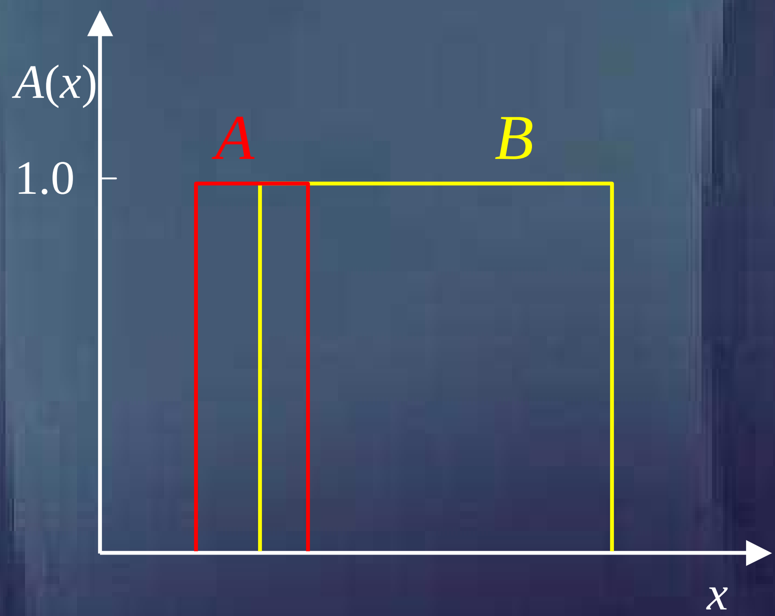
Inclusion

$$A \subseteq B \text{ iff } A(x) \leq B(x) \quad \forall x \in \mathbf{X}$$

Sets



$A \subseteq B$



$A \not\subset B$

Degree of inclusion

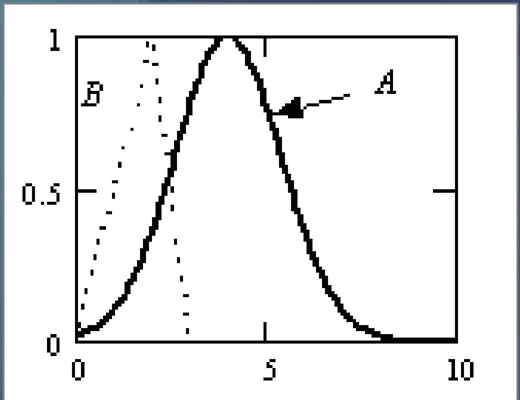
$$\|A(x) \subset B(x)\| = \frac{1}{\mathrm{Card}\,(\mathbf{X})} \int_X (A(x) \Rightarrow B(x))\mathrm{d}x$$

$$A(x) \Rightarrow B(x) = \begin{cases} 1 & \text{if } A(x) \le B(x) \\ 1\text{-}A(x) + B(x) & \text{otherwise} \end{cases}$$

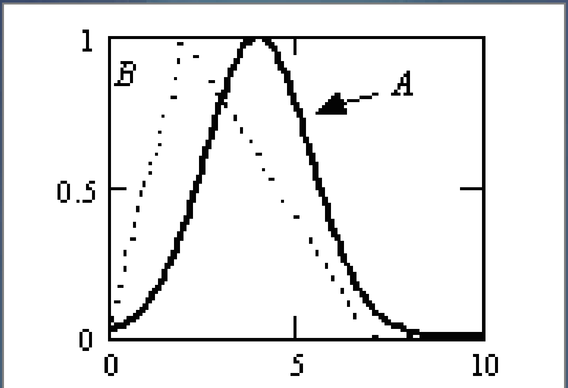
Degree of equality

$$\left\| A(x) = B(x) \right\| = \frac{1}{\mathrm{Card}(\mathbf{X})} \int_X [\min(A(x) \Rightarrow B(x), B(x) \Rightarrow A(x))] \mathrm{d}x$$

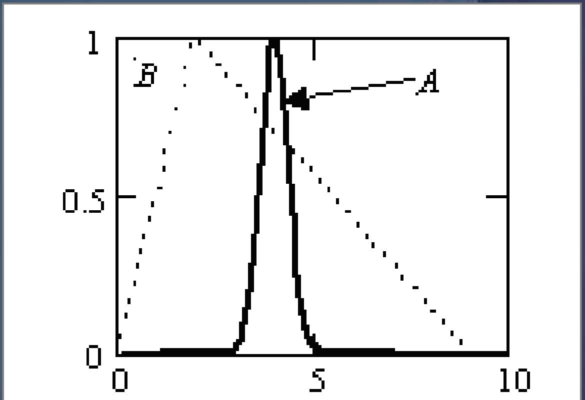
Example



(a)



(b)



(c)

Examples of fuzzy sets A and B along with their degrees of inclusion:

(a) $a = 0$, $n = 2$, $b = 3$; $m = 4$ $\sigma = 2$; $||A = B|| = 0.637$

(b) $b = 7$ $||A = B|| = 0.864$

(c) $a = 0$, $n = 2$, $b = 9$, $m = 4$, $\sigma = 0.5$ $|| A = B || = 0.987$

3.3 Energy and entropy measures of fuzziness

Energy measure of fuzziness

$$E(A) = \sum_{i=1}^{n} e[A(x_i)]$$

Card ($\mathbf{X}$) = n

$$E(A) = \int_{\mathbf{X}} e[A(x)]\mathrm{d}x$$

$e : [0, 1] \rightarrow [0, 1]$ such that

$e(0) = 0$

$e(1) = 1$

e: monotonically increasing

Example

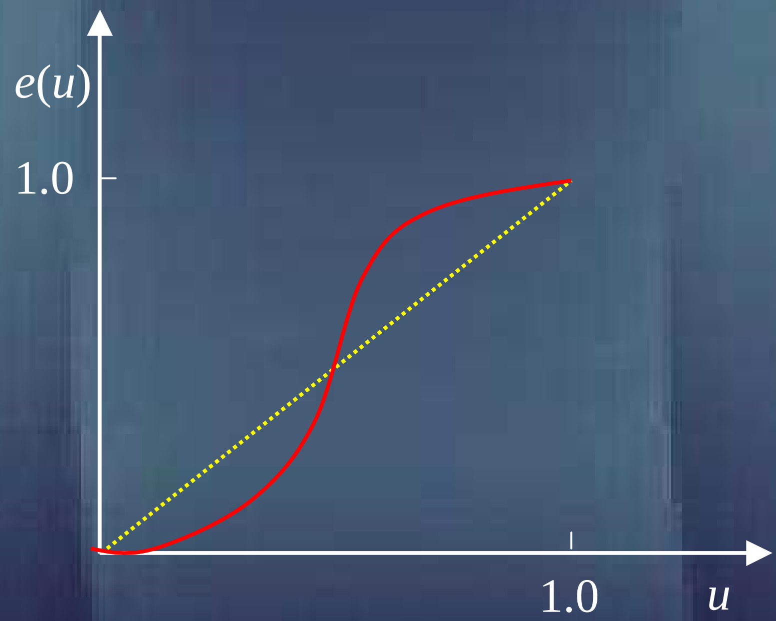
$e(u) = u \quad \forall u \in [0, 1]$ linear

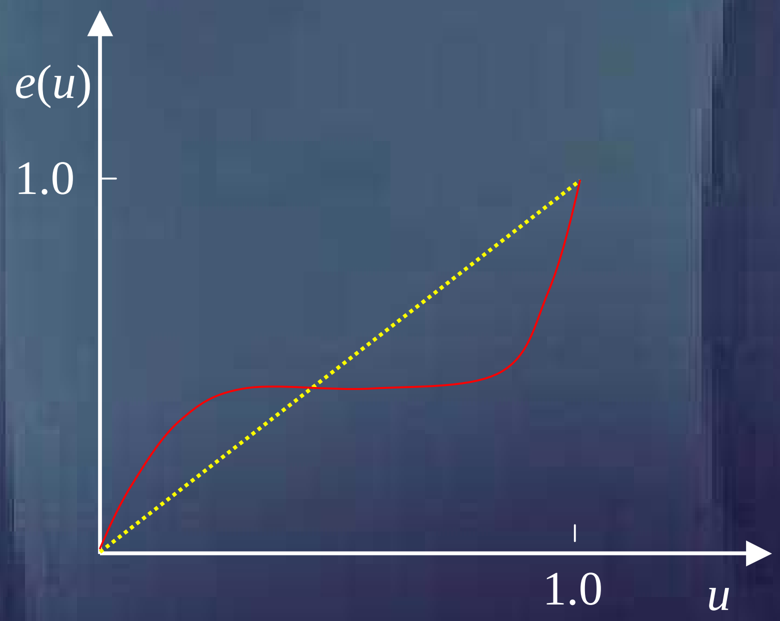
$$E(A) = \sum_{i=1}^{n} A(x_i) = \text{Card}(A)$$

$$E(A) = \sum_{i=1}^{n} A(x_i) = \sum_{i=1}^{n} | A(x_i) - \phi(x_i) | = d(A, \phi)$$

d = Hamming distance

$e(u)$ non-linear





Emphasis on high membership values

Emphasis on low membership values

Inclusion of probabilistic information

$$E(A) = \sum_{i=1}^{n} p_i e[A(x_i)]$$

p_i: probability of x_i

$$E(A) = \int_{\mathbf{X}} p(x) e[A(x)] \mathrm{d}x$$

$p(x)$: probability density function

Entropy measure of fuzziness

$$H(A) = \sum_{i=1}^{n} h[A(x_i)]$$

$$\mathrm{H}(A) = \int_X h(A(x))\mathrm{d}x$$

$h : [0,1] \rightarrow [0,1]$

1-monotonically increasing $[0, ½]$

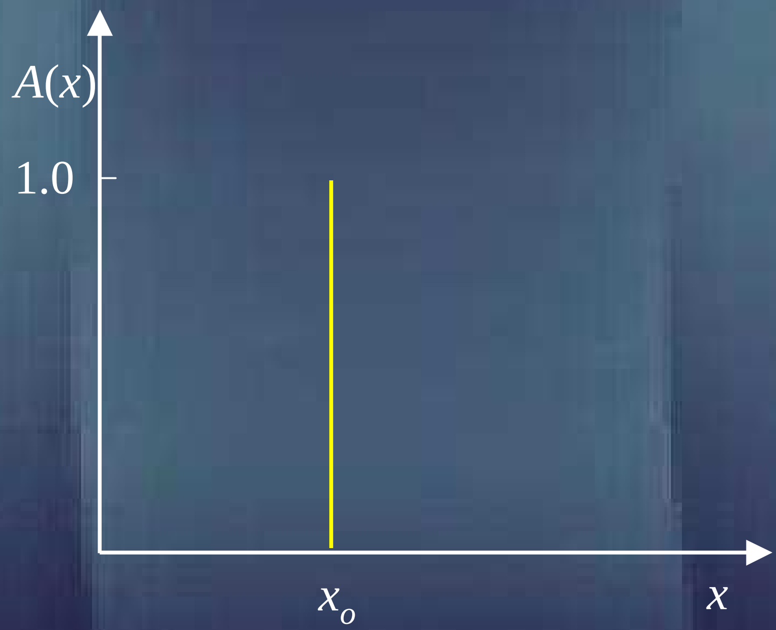
2-monotonically decreasing $(½, 1]$

3-boundary conditions:

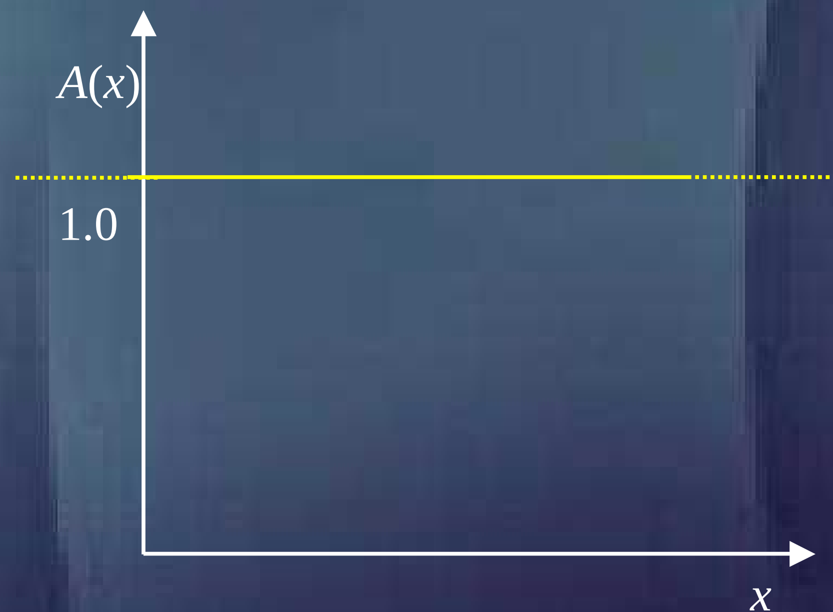
$h(0) = h(1) = 0$

$h(½) = 1$

Specificity of fuzzy sets



Specific fuzzy set



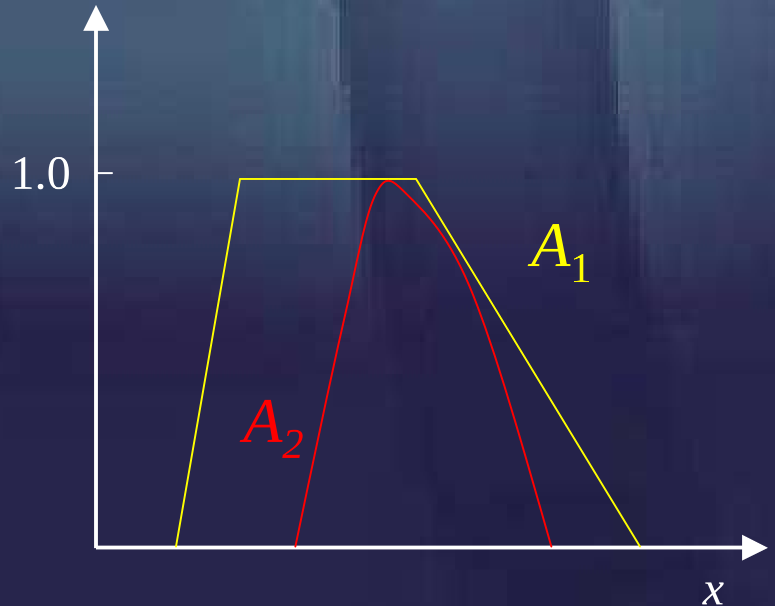
Lack of specificity

Specificity

1-Spec(A) = 1 if and only if $\exists x_0 \in A(x_0) = 1$, $A(x) = 0 \quad \forall x \neq x_0$

2-Spec(A) = 0 if and only if $A(x) = 0 \ \forall x \in \mathbf{X}$

3-Spec(A_1) $\leq$ Spec(A_2) if $A_1 \supset A_2$



Examples

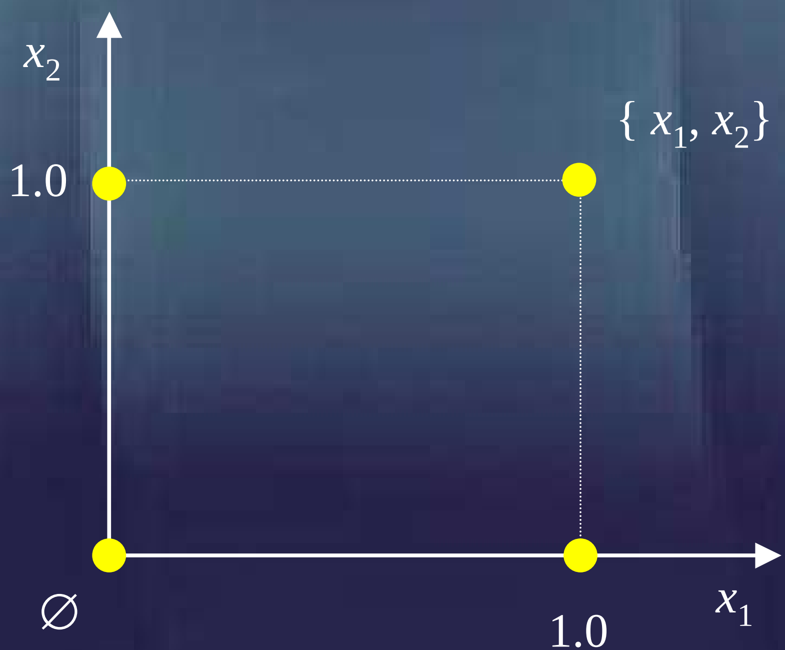
$$Spec(A) = \int_0^{\alpha_{\max}} \frac{1}{Card(A_\alpha)} d\alpha$$

$$Spec(A) = \sum_{i=1}^{m} \frac{1}{Card(A_{\alpha_i})} \Delta\alpha_i$$

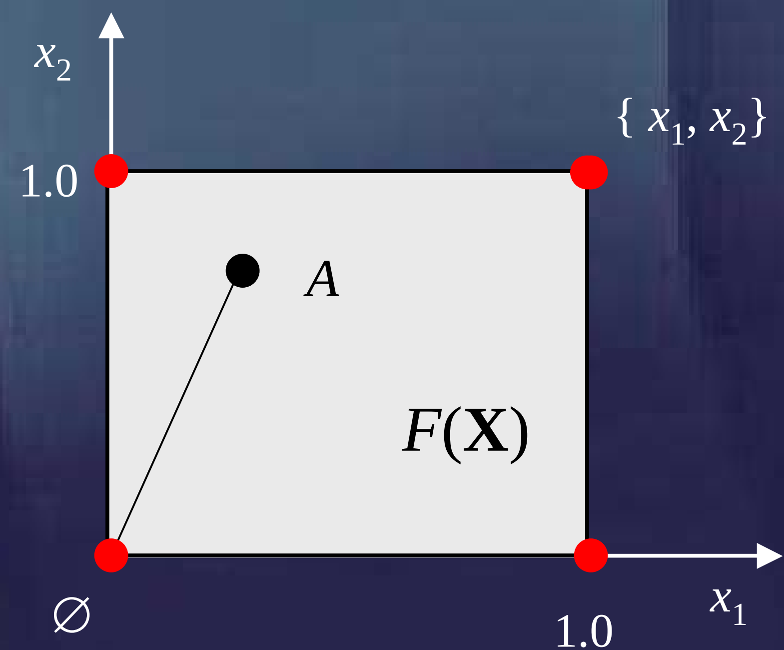
Yager (1993)

Geometric interpretation of sets and fuzzy sets

$\mathbf{X} = \{ x_1, x_2\} \quad P(\mathbf{X}) = \{\varnothing, \{x_1\}, \{x_2\}, \{ x_1, x_2\}\}$



Set



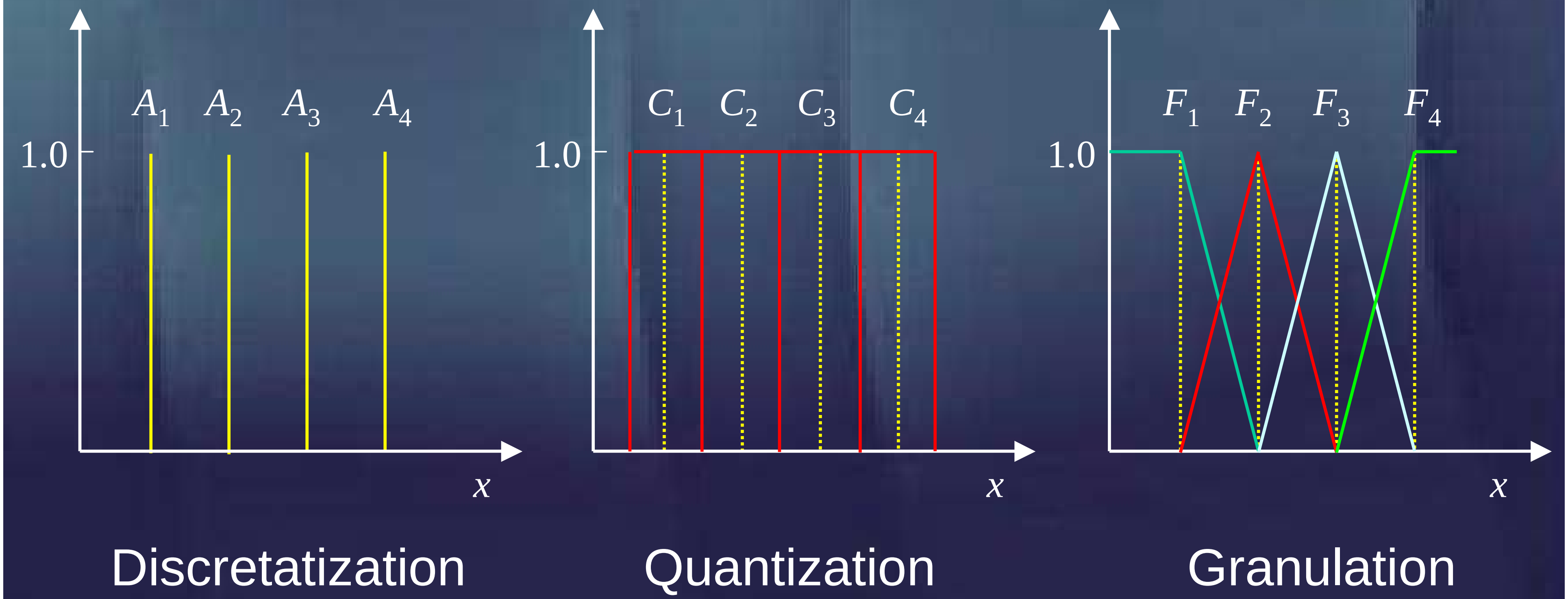
Fuzzy set

3.4 Granulation of information

Motivation

- **Need of granulation:**
  - – abstract information
  - – summarize information
- **Purpose:**
  - – comprehension
  - – decision making
  - – description

Discretization, quantization, granulation



Pedrycz and Gomide, FSE 2007

Formal mechanisms of granulation

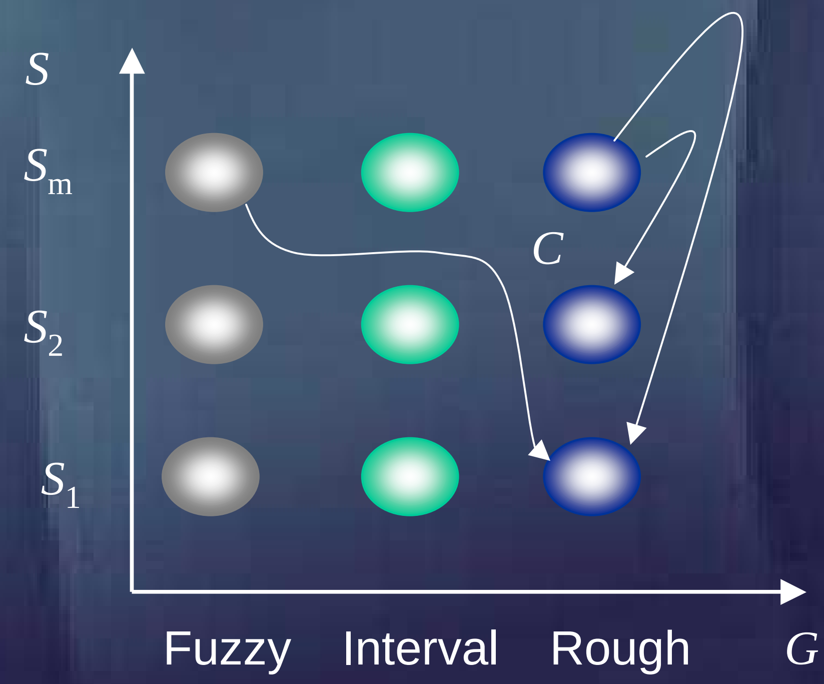
$\langle \mathbf{X}, G, S, C \rangle$

$\mathbf{X}$: universe

G: formal framework of granulation

S: collection of information granules

C: transformation



3.5 Characterization of families of fuzzy sets

Frame of cognition

- Codebook of conceptual entities
  - – family of linguistic landmarks

    $\Phi = \{A_1, A_2, \ldots., A_m\}$

    A_i is a fuzzy set on $\mathbf{X}$, $i = 1, \ldots, m$
- Granulation that satisfies semantic constraints
  - – coverage
  - – semantic soundness

Coverage

$\Phi = \{A_1, A_2, \ldots, A_m\}$ covers $\mathbf{X}$ if, for any $x \in \mathbf{X}$

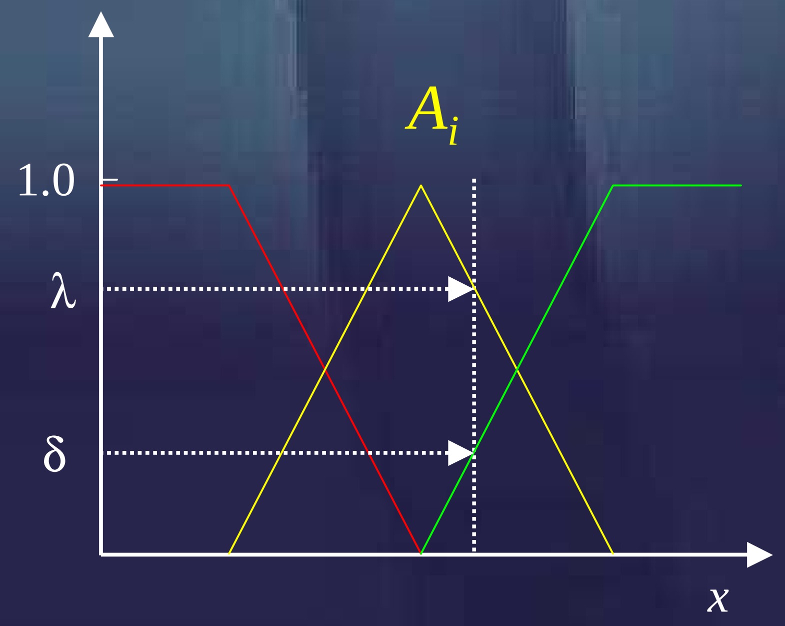
$\exists i \in \mathrm{I} \mid A_i(x) > 0$

$\exists i \in \mathrm{I} \mid A_i(x) > \delta$ (δ-level coverage) $\delta \in [0, 1]$

A_i´s are fuzzy set on $\mathbf{X}$, $i \in \mathrm{I} = \{1, \ldots, m\}$

Semantic soundness

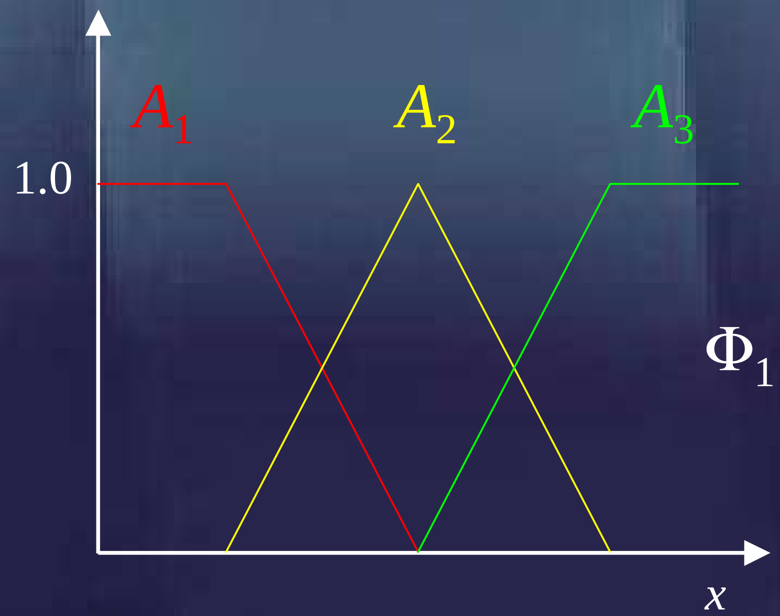
- Each A_i, $i \in \mathrm{I} = \{1, \ldots, m\}$ is unimodal and normal
- Fuzzy sets A_i are disjoint enough (λ-overlapping)
- Number of elements of Φ is low

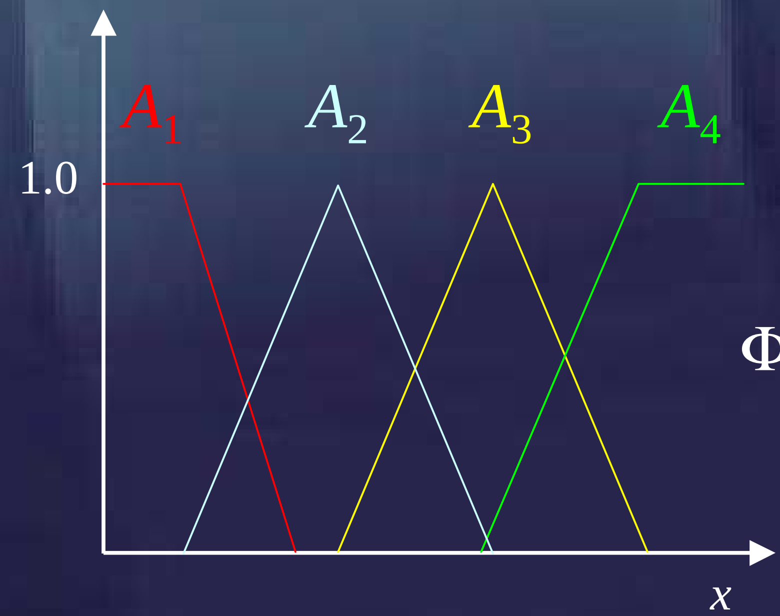


Pedrycz and Gomide, FSE 2007

Characteristics of frames of cognition

- Specificity: Φ_1 more specific than Φ_2 if $\mathrm{Spec}(A_{1i}) > \mathrm{Spec}(A_{2j})$
- Granularity: Φ_1 finer than Φ_2 if $|\Phi_1| > |\Phi_2|$





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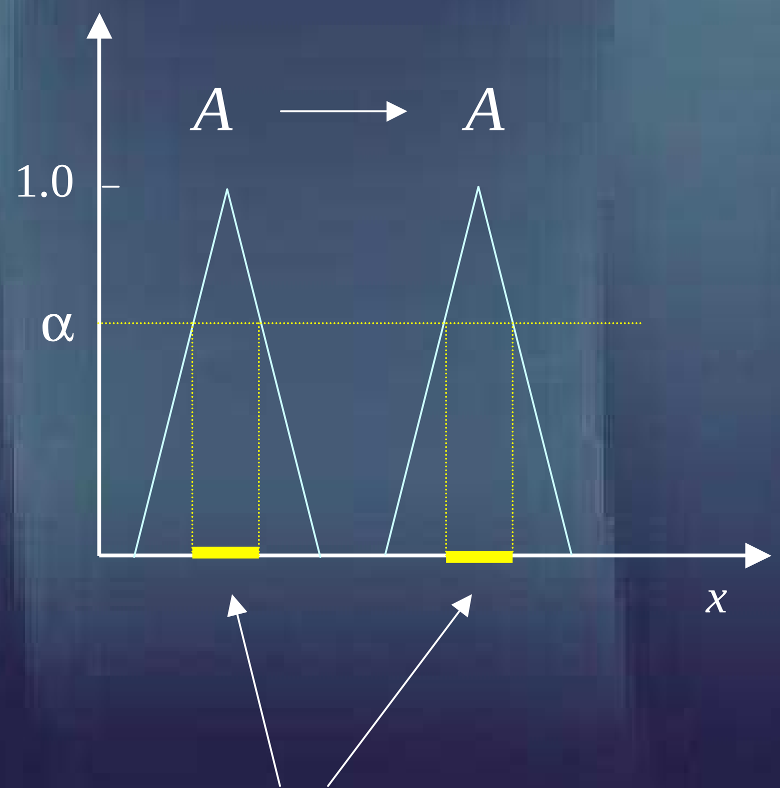
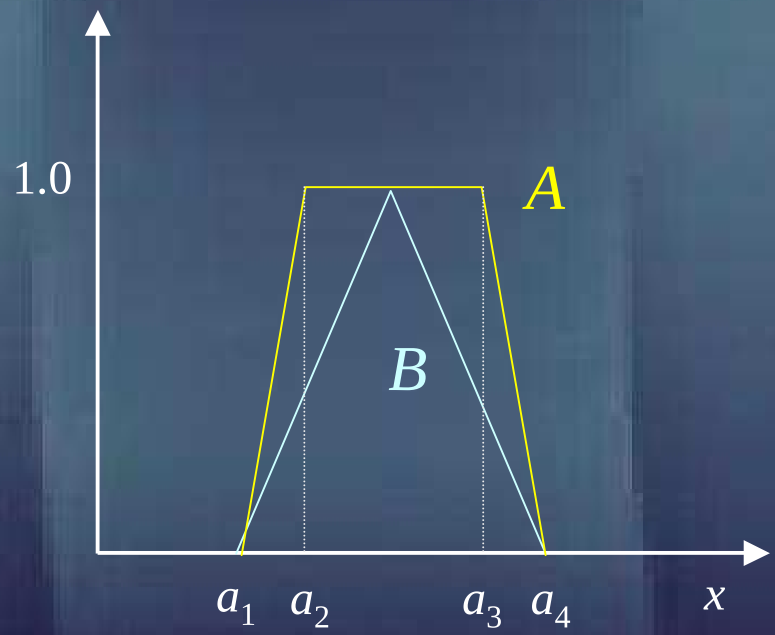
- Focus of attention



Regions of focus of attention implied by the corresponding fuzzy sets

- Information hiding



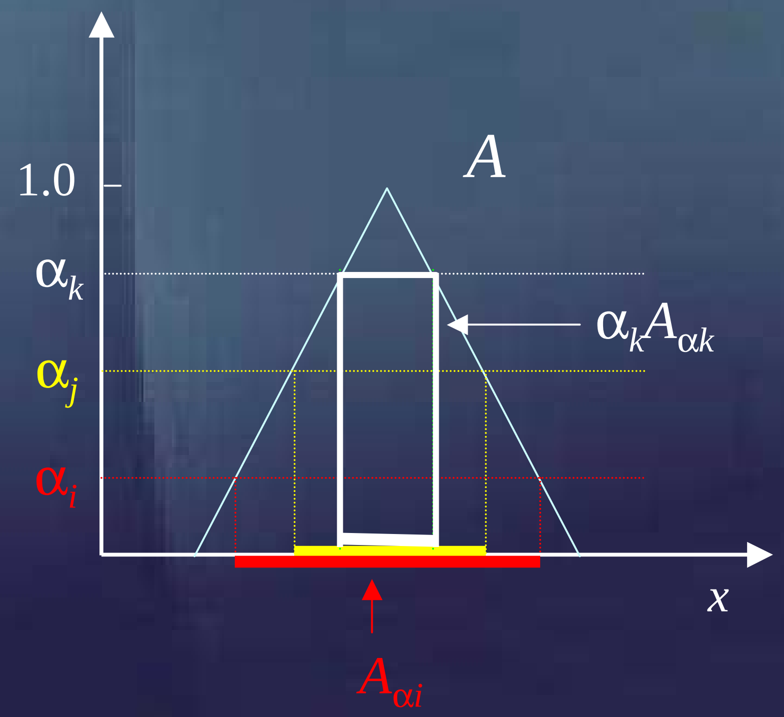
$x \in [a_2, a_3]$ indistinguishable for A, but not for B

3.6 Fuzzy sets, sets and the representation theorem

Any fuzzy set can be viewed as a family of sets:

$$A = \bigcup_{\alpha \in [0,1]} \alpha A_\alpha$$

$$A(x) = \sup_{\alpha \in [0,1]} \alpha A_\alpha(x)$$



Example

$\mathbf{X} = \{1, 2, 3, 4\}$

$A = \{0/1, 0.1/2, 0.3/3, 1/4, 0.3/5\} = [0, 0.1, 0.3, 1, 0.3]$

$A_{0.1} = \{0/1, 1/2, 1/3, 1/4, 1/5\} = [0, 1, 1, 1, 1] \rightarrow 0.1A_{0.1} = [0, 0.1, 0.1, 0.1, 0.1]$

$A_{0.3} = \{0/1, 0/2, 1/3, 1/4, 1/5\} = [0, 0, 1, 1, 1] \rightarrow 0.3A_{0.3} = [0, 0 , 0.3, 0.3, 0.3]$

$A_{1} = \{0/1, 0/2, 0/3, 1/4, 0/5\} = [0, 0, 0, 1, 0] \rightarrow 1.0A_{1} = [0, 0, 0, 1, 0]$

$A = \max (0.1A_{0.1} , 0.3A_{0.3} , 1A_{1})$

$A = [\max (0,0,0), \max(0.1,0,0), \max(0.1,0.3,0), \max(0.1,0.3,1), \max(0.1,0.3,0)]$

$A = [0, 0.1, 0.3, 1, 0.3]$