technische universität
dortmund

Computational Intelligence

Winter Term 2019/20

Prof. Dr. Günter Rudolph

Lehrstuhl für Algorithm Engineering (LS 11)

Fakultät für Informatik

TU Dortmund

Plan for Today

- Fuzzy relations
- Fuzzy logic
  - Linguistic variables and terms
  - Inference from fuzzy statements

relations with <u>conventional sets</u> $\mathcal{X}_1, \mathcal{X}_2, \ldots, \mathcal{X}_n$:

$$R(\mathcal{X}_1, \mathcal{X}_2, \ldots, \mathcal{X}_n) \subseteq \mathcal{X}_1 \times \mathcal{X}_2 \times \ldots \times \mathcal{X}_n$$

notice that cartesian product is a **set**!

$\Rightarrow$ all set operations remain valid!

crisp membership function (of x to relation R)

$$R(x_1, x_2, \ldots, x_n) = \begin{cases} 1 & \text{if } (x_1, x_2, \ldots, x_n) \in R \\ 0 & \text{otherwise} \end{cases}$$

Definition

Fuzzy relation = fuzzy set over crisp cartesian product $\mathcal{X}_1 \times \mathcal{X}_2 \times \ldots \times \mathcal{X}_n$ ■

→ each tuple $(x_1, ..., x_n)$ has a degree of membership to relation

→ degree of membership expresses
strength of relationship between elements of tuple

appropriate representation: n-dimensional membership matrix

example: Let X = { New York, Paris } and Y = { Bejing, New York, Dortmund }.

relation R = “very far away”

membership matrix →

relation R	New York	Paris
Bejing	1.0	0.9
New York	0.0	0.7
Dortmund	0.6	0.3

Definition

Let R(X, Y) be a fuzzy relation with membership matrix $\mathbf{R}$. The ***inverse fuzzy relation*** to R(X,Y), denoted R^{-1}(Y, X), is a relation on Y x X with membership matrix $\mathbf{R}^{-1} = \mathbf{R}'$. ■

Remark: $\mathbf{R}'$ is the transpose of membership matrix $\mathbf{R}$.

Evidently: $(\mathbf{R}^{-1})^{-1} = \mathbf{R}$ since $(\mathbf{R}')' = \mathbf{R}$

Definition

Let P(X, Y) and Q(Y, Z) be fuzzy relations. The operation ∘ on two relations, denoted P(X, Y) ∘ Q(Y, Z), is termed ***max-min-composition*** iff

$$R(x, z) = (P \circ Q)(x, z) = \max_{y \in Y} \min \{ P(x, y), Q(y, z) \}.$$

■

Theorem

a) max-min composition on relations is associative.

b) max-min composition on relations is not commutative.

c) $(P(X,Y) \circ Q(Y,Z))^{-1} = Q^{-1}(Z,Y) \circ P^{-1}(Y, X)$.

membership matrix of max-min composition
determinable via “fuzzy matrix multiplication”: $R = P \circ Q$

fuzzy matrix multiplication $$r_{ij} = \max_k \min\{p_{ik}, q_{kj}\}$$

crisp matrix multiplication $$r_{ij} = \sum_k p_{ik} \cdot q_{kj}$$

further methods for realizing compositions of relations:

max-prod composition

$$(P \odot Q)(x,z) = \max_{y \in \mathcal{Y}} \{ P(x,y) \cdot Q(y,z) \}$$

<u>generalization:</u> sup-t composition

$$(P \circ Q)(x,z) = \sup_{y \in \mathcal{Y}} \{ t(P(x,y), Q(y,z)) \},$$ where t(.,.) is a t-norm

e.g.: t(a,b) = min{a, b} ⇒ max-min-composition

t(a,b) = a · b ⇒ max-prod-composition

Binary fuzzy relations on X x X : properties

- **reflexive** $\Leftrightarrow \forall\ x \in X: R(x,x) = 1$
- **irreflexive** $\Leftrightarrow \exists\ x \in X : R(x,x) < 1$
- **antireflexive** $\Leftrightarrow \forall\ x \in X : R(x,x) < 1$

- **symmetric** $\Leftrightarrow \forall\ (x,y) \in X \times X : R(x,y) = R(y,x)$
- **asymmetric** $\Leftrightarrow \exists\ (x,y) \in X \times X : R(x,y) \neq R(y,x)$
- **antisymmetric** $\Leftrightarrow \forall\ (x,y) \in X \times X : R(x,y) \neq R(y,x)$

- **transitive** $\Leftrightarrow \forall\ (x,z) \in X \times X : R(x,z) \geq \max\limits_{y \in Y} \min \{ R(x,y), R(y,z) \}$
- **intransitive** $\Leftrightarrow \exists\ (x,z) \in X \times X : R(x,z) < \max\limits_{y \in Y} \min \{ R(x,y), R(y,z) \}$
- **antitransitive** $\Leftrightarrow \forall\ (x,z) \in X \times X : R(x,z) < \max\limits_{y \in Y} \min \{ R(x,y), R(y,z) \}$

actually, here: max-min-transitivity ($\rightarrow$ in general: sup-t-transitivity)

binary fuzzy relation on X x X: <u>example</u>

Let **X** be the set of all cities in Germany.

Fuzzy relation R is intended to represent the concept of „very close to“.

- R(x,x) = 1, since every city is certainly very close to itself.

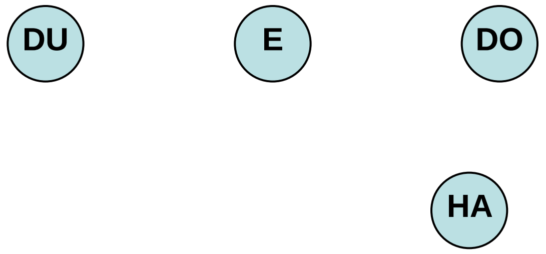
  ⇒ **reflexive**

- R(x,y) = R(y,x): if city x is very close to city y, then also vice versa.

  ⇒ **symmetric**

- R(Dortmund, Essen) = 0.8
  R(Essen, Duisburg) = 0.7
  R(Dortmund, Duisburg) = 0.5
  R(Dortmund, Hagen) = 0.9

  ⇒ **intransitive**



crisp:
relation R is equivalence relation $\Leftrightarrow$ R reflexive, symmetric, transitive

fuzzy:
relation R is similarity relation $\Leftrightarrow$ R reflexive, symmetric, (max-min-) transitive

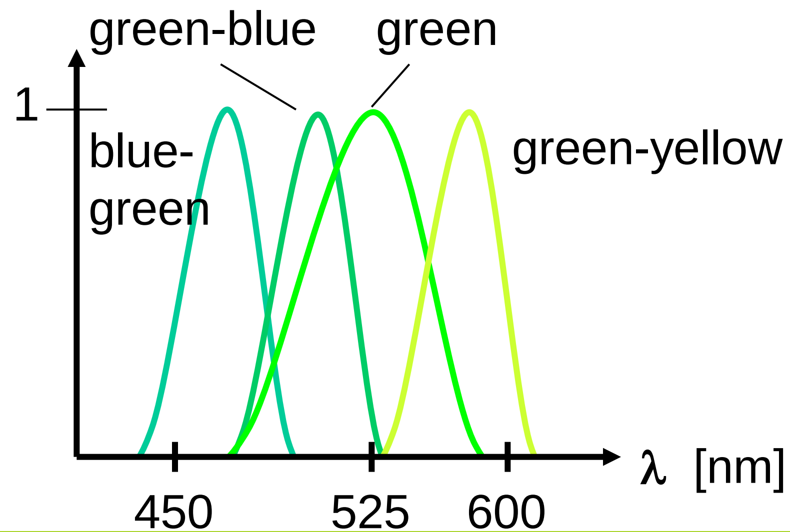
linguistic variable:

variable that can attain several values of lingustic / verbal nature

e.g.: **color** can attain values **red**, **green**, **blue**, **yellow**, …

values (red, green, …) of linguistic variable are called **linguistic terms**

linguistic terms are associated with fuzzy sets



fuzzy proposition

p: *temperature* is *high*

linguistic variable (LV) — linguistic term (LT)

- LV may be associated with several LT : *high, medium, low, …*
- *high, medium, low* temperature are fuzzy sets
  over numerical scale of crisp temperatures
- trueness of fuzzy proposition „temperature is high"
  for a given **concrete crisp** temperature value v
  is interpreted as equal to the degree of membership *high*(v)
  of the fuzzy set *high*

fuzzy proposition

p: V is F

linguistic variable (LV)

linguistic term (LT)

actually:

p: V is F(v)

and

T(p) = F(v) for a concrete crisp value v

trueness(p)

> establishes connection between *degree of membership* of a fuzzy set and the *degree of trueness* of a fuzzy proposition

fuzzy proposition

p: IF *heating* is *hot,* THEN *energy consumption* is *high*

LV LT LV LT

expresses <u>relation</u> between

a) temperature of heating and

b) quantity of energy consumption

relation

p: (*heating, energy consumption*) ∈ R

fuzzy proposition

p: IF *X* is A, THEN *Y* is B

$$\underbrace{X}_{\text{LV}} \text{ is } \underbrace{A}_{\text{LT}}, \quad \underbrace{Y}_{\text{LV}} \text{ is } \underbrace{B}_{\text{LT}}$$

How can we determine / express degree of trueness T(p) ?

- For crisp, given values x, y we know A(x) and B(y)
- A(x) and B(y) must be processed to single value via relation R
- R(x, y) = function(A(x), B(y)) is fuzzy set over X x Y
- as before: interprete T(p) as degree of membership R(x,y)

fuzzy proposition

p: IF *X* is A, THEN *Y* is B

A is fuzzy set over X

B is fuzzy set over Y

R is fuzzy set over X x Y

$\forall$ (x,y) $\in$ X x Y: R(x, y) = Imp(A(x), B(y))

What is Imp**(·,·)** ?

$\Rightarrow$ „appropriate“ fuzzy implication [0,1] x [0,1] $\rightarrow$ [0,1]

assumption: we know an „appropriate“ Imp(a,b).

How can we determine the degree of trueness T(p) ?

example:

let Imp(a, b) = min{ 1, 1 – a + b } and consider fuzzy sets

A:

x_1	x_2	x_3
0.1	0.8	1.0

B:

y_1	y_2
0.5	1.0

$\Rightarrow$

R	x_1	x_2	x_3
y_1	1.0	0.7	0.5
y_2	1.0	1.0	1.0

z.B.

$R(x_2, y_1) = Imp(A(x_2), B(y_1)) = Imp(0.8, 0.5) =$
$\min\{1.0, 0.7\} = 0.7$

and T(p) for (x_2,y_1) is $R(x_2, y_1) = 0.7$ ■

toward inference from fuzzy statements:

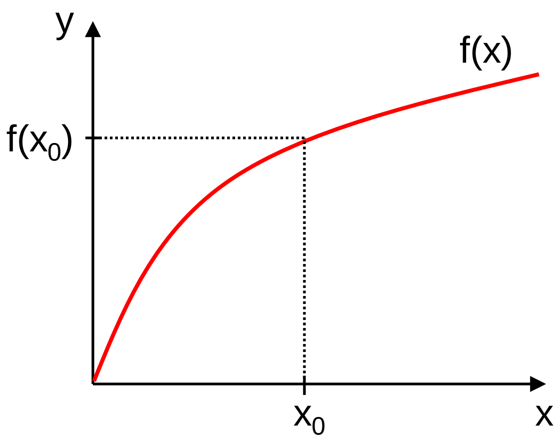
- let $\forall x, y: y = f(x)$.

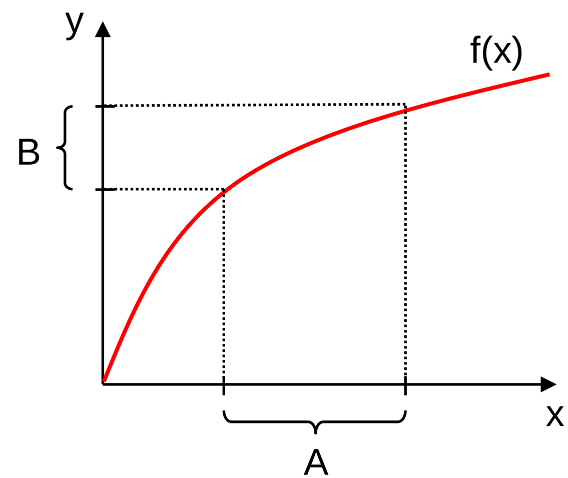
  IF $X = x_0$ THEN $Y = f(x_0)$

- IF $X \in A$ THEN $Y \in B = \{ y \in \mathcal{Y} : y = f(x), x \in A \}$

crisp case:

functional relationship





toward inference from fuzzy statements:

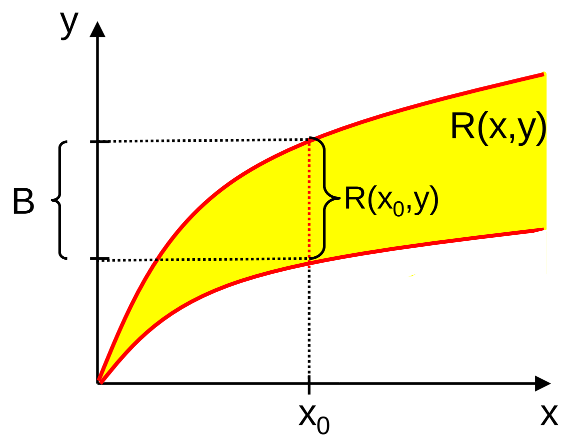
- let relationship between x and y be a relation R on $\mathcal{X} \times \mathcal{Y}$

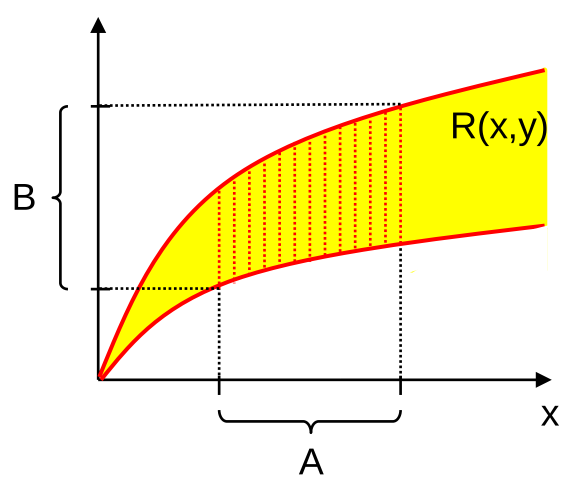
  IF $X = x_0$ THEN $Y \in B = \{ y \in \mathcal{Y} : (x_0, y) \in R \}$

- IF $X \in A$ THEN $Y \in B = \{ y \in \mathcal{Y} : (x, y) \in R,\ x \in A \}$

crisp case:

relational relationship





toward inference from fuzzy statements:

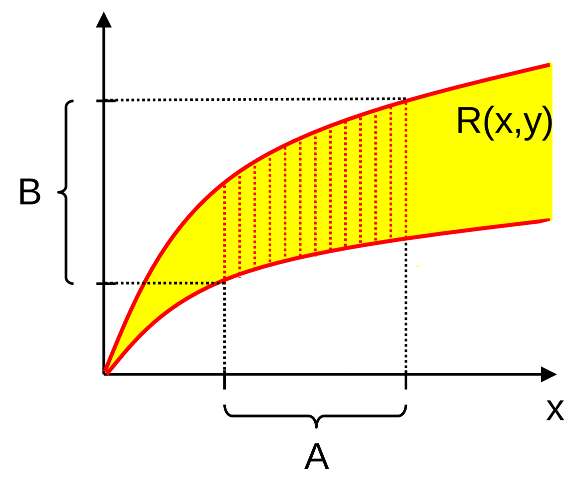
IF X $\in$ A THEN Y $\in$ B = $\{ y \in \mathcal{Y} : (x, y) \in R, \; x \in A \}$

also expressible via characteristic functions of sets A, B, R:

B(y) = 1 iff $\exists$ x: A(x) = 1 and R(x, y) = 1

$\Leftrightarrow \; \exists x: \min\{ A(x), R(x, y) \} = 1$

$\Leftrightarrow \; \max_{x \in \mathcal{X}} \min\{ A(x), R(x, y) \} = 1$



$$\forall y \in \mathcal{Y}: B(y) = \max_{x \in \mathcal{X}} \min \{ A(x), R(x, y) \}$$

inference from fuzzy statements

Now: A‘, B‘ fuzzy sets over $\mathcal{X}$ resp. $\mathcal{Y}$

Assume: R(x,y) and A‘(x) are given.

Idea: Generalize characteristic function of B(y) to membership function B‘(y)

$$\forall y \in \mathcal{Y}: B(y) = \max_{x \in \mathcal{X}} \min \{ A(x), R(x, y) \}$$

characteristic functions

$$\forall y \in \mathcal{Y}: B'(y) = \sup_{x \in \mathcal{X}} \min \{ A'(x), R(x, y) \}$$

membership functions

composition rule of inference (in matrix form): $\mathbf{B}^T = \mathbf{A} \circ \mathbf{R}$

inference from fuzzy statements

- conventional:
  modus ponens

$$\frac{\begin{array}{l} a \Rightarrow b \\ a \end{array}}{b}$$

- fuzzy:
  generalized modus ponens (GMP)

IF *X* is A, THEN *Y* is B
X is A‘

Y is B‘

e.g.: IF *heating* is hot, THEN *energy consumption* is high
heating is warm

---

energy consumption is normal

example: GMP

consider

A:

x_1	x_2	x_3
0.5	1.0	0.6

B:

y_1	y_2
1.0	0.4

with the rule: IF *X* is A THEN *Y* is B

given fact

A‘:

x_1	x_2	x_3
0.6	0.9	0.7

$\Rightarrow$

R	x_1	x_2	x_3
y_1	1.0	1.0	1.0
y_2	0.9	0.4	0.8

with Imp(a,b) = min{1, 1-a+b }

thus: A‘ ∘ R = B‘

with max-min-composition

$$\begin{pmatrix} 0.6 & 0.9 & 0.7 \end{pmatrix} \circ \begin{pmatrix} 1.0 & 0.9 \\ 1.0 & 0.4 \\ 1.0 & 0.8 \end{pmatrix} = \begin{pmatrix} 0.9 & 0.7 \end{pmatrix}$$

■

inference from fuzzy statements

- conventional:
  modus tollens

$$\begin{array}{l} a \Rightarrow b \\ \overline{b} \\ \hline \overline{a} \end{array}$$

- fuzzy:
  generalized modus tollens (GMT)

$$\begin{array}{l} \text{IF } X \text{ is A, THEN } Y \text{ is B} \\ Y \text{ is B'} \\ \hline X \text{ is A'} \end{array}$$

e.g.:

IF *heating* is hot, THEN *energy consumption* is high
energy consumption is normal

---

heating is warm

example: GMT

consider

A:

x_1	x_2	x_3
0.5	1.0	0.6

B:

y_1	y_2
1.0	0.4

with the rule: IF *X* is A THEN *Y* is B

given fact

B‘:

y_1	y_2
0.9	0.7

$\Rightarrow$

R	x_1	x_2	x_3
y_1	1.0	1.0	1.0
y_2	0.9	0.4	0.8

with Imp(a,b) = min{1, 1-a+b }

thus: $B' \circ R^{-1} = A'$

$$\begin{pmatrix} 0.9 & 0.7 \end{pmatrix} \circ \begin{pmatrix} 1.0 & 1.0 & 1.0 \\ 0.9 & 0.4 & 0.8 \end{pmatrix} = \begin{pmatrix} 0.9 & 0.9 & 0.9 \end{pmatrix}$$

with max-min-composition

■

inference from fuzzy statements

- conventional:
  hypothetic syllogism

$$\frac{\begin{array}{l} a \Rightarrow b \\ b \Rightarrow c \end{array}}{a \Rightarrow c}$$

- fuzzy:
  generalized HS

IF *X* is A, THEN *Y* is B
IF *Y* is B, THEN *Z* is C

IF X is A, THEN Z is C

e.g.:

IF *heating* is hot, THEN *energy consumption* is high
IF *energy consumption* is high, THEN *living* is expensive

IF *heating* is hot, THEN *living* is expensive

example: GHS

let fuzzy sets A(x), B(x), C(x) be given

$\Rightarrow$ determine the three relations

$R_1(x,y) = \mathrm{Imp}(A(x),B(y))$
$R_2(y,z) = \mathrm{Imp}(B(y),C(z))$
$R_3(x,z) = \mathrm{Imp}(A(x),C(z))$

and express them as matrices R_1, R_2, R_3

We say:

GHS is valid if $R_1 \circ R_2 = R_3$

So, ... what makes sense for Imp(·,·) ?

Imp(a,b) ought to express fuzzy version of implication ($a \Rightarrow b$)

conventional: $a \Rightarrow b$ identical to $\overline{a} \vee b$

But how can we calculate with fuzzy “boolean” expressions?

request: must be compatible to crisp version (and more) for $a,b \in \{ 0, 1 \}$

a	b	$a \wedge b$	t(a,b)
0	0	0	0
0	1	0	0
1	0	0	0
1	1	1	1

a	b	$a \vee b$	s(a,b)
0	0	0	0
0	1	1	1
1	0	1	1
1	1	1	1

a	$\overline{a}$	c(a)
0	1	1
1	0	0

So, ... what makes sense for Imp(·,·) ?

1st approach: S implications

conventional: $a \Rightarrow b$ identical to $\bar{a} \vee b$

fuzzy: $\text{Imp}(a, b) = s(\, c(a), b)$

2nd approach: R implications

conventional: $a \Rightarrow b$ identical to $\max\{\, x \in \{0,1\}:\ a \wedge x \leq b \,\}$

fuzzy: $\text{Imp}(a, b) = \max\{\, x \in [0,1] : t(a, x) \leq b \,\}$

3rd approach: QL implications

conventional: $a \Rightarrow b$ identical to $\bar{a} \vee b \equiv \bar{a} \vee (a \wedge b)$ law of absorption

fuzzy: $\text{Imp}(a, b) = s(\, c(a), t(a, b)\,)$ (dual tripel ?)

example: S implication $\mathrm{Imp}(a, b) = s(\, c_s(a), b)$ (c_s : std. complement)

1. Kleene-Dienes implication

   $s(a, b) = \max\{\, a, b \,\}$ (standard) $\mathrm{Imp}(a,b) = \max\{\, 1-a, b \,\}$

2. Reichenbach implication

   $s(a, b) = a + b - ab$ (algebraic sum) $\mathrm{Imp}(a, b) = 1 - a + ab$

3. Łukasiewicz implication

   $s(a, b) = \min\{\, 1, a + b \,\}$ (bounded sum) $\mathrm{Imp}(a, b) = \min\{\, 1, 1 - a + b \,\}$

example: R implicationen Imp(a, b) = max{ x ∈[0,1] : t(a, x) ≤ b }

1. Gödel implication

   t(a, b) = min{ a, b } (std.) $\text{Imp}(a, b) = \begin{cases} 1 & , \text{ if } a \le b \\ b & , \text{ else} \end{cases}$

2. Goguen implication

   t(a, b) = ab (algeb. product) $\text{Imp}(a, b) = \begin{cases} 1 & , \text{ if } a \le b \\ \frac{b}{a} & , \text{ else} \end{cases}$

3. Łukasiewicz implication

   t(a, b) = max{ 0, a + b – 1 } (bounded diff.) Imp(a, b) = min{ 1, 1 – a + b }

example: QL implication $\text{Imp}(a, b) = s(\, c(a), t(a, b) \,)$

1. Zadeh implication

   $t(a, b) = \min\{ a, b \}$ (std.) $\text{Imp}(a, b) = \max\{ 1 - a, \min\{a, b\} \}$
   $s(a,b) = \max\{ a, b \}$ (std.)

2. „NN“ implication ☺ (Klir/Yuan 1994)

   $t(a, b) = ab$ (algebr. prd.) $\text{Imp}(a, b) = 1 - a + a^2 b$
   $s(a,b) = a + b - ab$ (algebr. sum)

3. Kleene-Dienes implication

   $t(a, b) = \max\{ 0, a + b - 1 \}$ (bounded diff.) $\text{Imp}(a, b) = \max\{ 1-a, b \}$
   $s(a,b) = \min\{ 1, a + b)$ (bounded sum)

axioms for fuzzy implications

1.	$a \le b$ implies $Imp(a, x) \ge Imp(b, x)$	monotone in 1st argument
2.	$a \le b$ implies $Imp(x, a) \le Imp(x, b)$	monotone in 2nd argument
3.	$Imp(0, a) = 1$	dominance of falseness
4.	$Imp(1, b) = b$	neutrality of trueness
5.	$Imp(a, a) = 1$	identity
6.	$Imp(a, Imp(b, x)) = Imp(b, Imp(a, x))$	exchange property
7.	$Imp(a, b) = 1$ iff $a \le b$	boundary condition
8.	$Imp(a, b) = Imp(c(b), c(a))$	contraposition
9.	$Imp(\cdot,\cdot)$ is continuous	continuity

Caution!

Not all S-, R-, QL- implications obey all axioms for fuzzy implications!

Implication	Valid Axioms
Kleene-Dienes	1 2 3 4 – 6 – 8 9
Reichenbach	1 2 3 4 – 6 – 8 9
Łukasiewicz	1 2 3 4 5 6 7 8 9 ←
Gödel	1 2 3 4 5 6 7 – –
Goguen	1 2 3 4 5 6 7 – 9
Zadeh	1 2 3 4 – – – – 9
Klir-Yuan	– 2 3 4 – – – – 9

characterization of fuzzy implication

Theorem:
Imp: $[0,1] \times [0,1] \to [0,1]$ satisfies axioms 1 - 9 for fuzzy implications for a certain fuzzy complement $c(\cdot)$ $\Leftrightarrow$

$\exists$ strictly monotone increasing, continuous function $f: [0,1] \to [0, \infty)$ with

- $f(0) = 0$
- $\forall a, b \in [0,1]$: $\text{Imp}(a, b) = f^{-1}(\min\{ f(1) – f(a) + f(b), f(1)\})$
- $\forall a \in [0,1]$: $c(a) = f^{-1}(f(1) – f(a))$

Proof: Smets & Magrez (1987), p. 337f. ■

examples: (in tutorial)

choosing an „appropriate“ fuzzy implication ...

apt quotation: (Klir & Yuan 1995, p. 312)

„To select an appropriate fuzzy implication for approximate reasoning under each particular situation is a difficult problem.“

guideline:
GMP, GMT, GHS should be compatible with MP, MT, HS
for fuzzy implication in calculations with relations:
$B(y) = \sup \{ t(A(x), \mathrm{Imp}(A(x), B(y))) : x \in X \}$

example:
Gödel implication for t-norm = bounded difference