

Simple Linear Interpolation Explains All Usual Choices in Fuzzy Techniques: Membership Functions, t-Norms, t-Conorms, and Defuzzification

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Abstract—Most applications of fuzzy techniques use piece-wise linear (triangular or trapezoid) membership functions, min or product t-norms, max or algebraic sum t-conorms, and centroid defuzzification. Similarly, most applications of interval-valued fuzzy techniques use piecewise-linear lower and upper membership functions. In this paper, we show that all these choices can be explained as applications of simple linear interpolation.

I. FORMULATION OF THE PROBLEM

Fuzzy techniques are needed. In many application areas, we have experts whose experience we would like to capture. Often, experts can express their experience in terms of rules, but the rules they describe use imprecise (“fuzzy”) words from natural language, like “small”, “large”, etc. To formalize these rules, L. Zadeh proposed special *fuzzy techniques* [1], [6], [7].

Fuzzy techniques: a brief reminder. A usual application of fuzzy techniques consists of the following three stages:

- first, we reformulate the imprecise (fuzzy) expert knowledge in computer-understandable terms – i.e., in terms of numbers;
- second, we process these numbers to come up with the degrees to which different possible actions are reasonable;
- finally, in situations when we need to come up with a unique recommendation, we “defuzzify” the above “fuzzy” recommendation into an exact strategy.

First stage of fuzzy techniques: eliciting a membership function. In the first stage, we formalize the original imprecise terms used by the experts, such as “small”, “hot”, and “fast”. Each such term is described by assigning, to different possible values x of the corresponding quantity, a degree $\mu(x)$ to which this value x can be described by this term (e.g., the degree to which x is small).

Some of these values $\mu(x)$ are obtained by asking the expert. However, there are infinitely many real numbers x , and we can only ask an expert a finite number of questions. Thus, after eliciting several values $\mu(x_i)$ from the expert we need to perform some *interpolation* to estimate the degrees $\mu(x)$ for intermediate values x . The resulting function μ is known as the *membership function*.

Interval-valued fuzzy degrees. Often, an expert is unable to describe his or her degree of confidence by an exact number; a more natural approach is to use *intervals* of possible values [2], [3], [5].

In this case, for each possible value of a quantity x , instead of a single value $\mu(x)$, we get an *interval* $[\underline{\mu}(x), \bar{\mu}(x)]$ of possible values. Determining such interval-valued membership function is equivalent to determining the functions $\underline{\mu}(x)$ and $\bar{\mu}(x)$. These functions are known as the *lower* and the *upper* membership functions.

Second stage of fuzzy techniques: “and”- and “or”-operations. Once we have elicited the membership functions, we know to what extent, e.g., the given value of the body temperature corresponds to high fever. However, many expert rules involve several conditions. For example, since some medicines increase blood pressure, a medical doctor will probably:

- prescribe the most efficient medicine if the fever is high *and* blood pressure is normal, and
- prescribe a different medicine – not so efficient but without the negative side effects – if the fever is high *and* blood pressure is high.

To handle such rules, we need to be able to transform the degrees $a = d(A)$ and $b = d(B)$ of individual conditions A and B into a degree of confidence in the composite statement $A \& B$. The corresponding estimate $f_{\&}(a, b)$ is known as an “*and*”-operation, or, alternatively, as a *t-norm*.

Similarly, we need an “*or*”-operation $f_{\vee}(a, b)$ (also known as *t-conorm*) to estimate the expert’s degree of confidence in

$A \vee B$ and the *negation operation* $f_-(a)$ to estimate the expert's degree of confidence in $\neg A$.

Third stage of fuzzy techniques: defuzzification. After performing the first two stages, for the given input x and for all possible control values u , we get a degree $\mu(u)$ to which this control value is reasonable to apply.

If we want to use this expert knowledge in an automated system, we need to transform this membership function $\mu(u)$ into a single value \bar{u} .

In principle, many versions of fuzzy techniques are possible. From the purely mathematical viewpoint, we can think of many different membership functions, many different “and”- and “or”-operations, many different defuzzification procedures.

How to select an appropriate technique? To select an appropriate combination of fuzzy techniques, a natural idea is to try different combinations and to see which combination leads to the best result.

Interesting empirical fact: in many cases, the same few combinations of fuzzy techniques lead to the best results. Interestingly, it turns out that in many practical applications, the same small number of combinations turn out to be most efficient. Specifically, in these applications, we use:

- *trapezoid* membership functions that start with 0, linearly go to 1, stay at 1, and then linearly decrease back to 0; in particular, when the stay-at-1 interval degenerates into a single point, we get *triangular* membership functions;
- “and”-operations $f_{\&}(a, b) = \min(a, b)$ (known as *min*) or $f_{\&}(a, b) = a \cdot b$ (known as *algebraic product*);
- “or”-operations $f_{\vee}(a, b) = \max(a, b)$ (known as *max*) or $f_{\vee}(a, b) = a + b - a \cdot b$ (known as *algebraic sum*);
- negation operation $f_-(a) = 1 - a$; and
- *centroid defuzzification*

$$\bar{u} = \frac{\int u \cdot \mu(u) du}{\int \mu(u) du}.$$

Similarly, in the applications of interval-valued techniques, both lower and upper membership functions are usually trapezoidal.

What we do in this paper. In this paper, we show that all these choices of fuzzy techniques can be explained in a very simple way – by the use of the simplest (linear) interpolation.

How this paper is structured. We start by explaining, in Section 2, why interpolation is needed, and why linear interpolation is the simplest. In the following sections, we explain how linear interpolation explains the usual choices of the membership functions (Section 3), t-norms and t-conorms (Sections 4 and 5), negation operations (Section 6), and defuzzification (Section 7).

Our result is also useful for teaching fuzzy techniques. Our explanation not only helps us understand why all these choices are made, but also makes it easier to *teach* the basic fuzzy techniques – since now all these techniques can be derived from the same linear interpolation idea.

II. INTERPOLATION: WHY WE NEED IT, AND WHY LINEAR INTERPOLATION IS THE SIMPLEST

Need for interpolation. In the above text, we have mentioned that we need interpolation to elicit a membership function from an expert.

Similarly, we can elicit the expert's degrees of confidence a_k , b_k , and c_k in different statements A_k , B_k , and $A_k \& B_k$. Then, we should get an “and”-operation $f_{\&}(a, b)$ for which $f_{\&}(a_k, b_k) = c_k$. This will enable us to find the values $f_{\&}(a, b)$ for a finite number of pairs (a_k, b_k) . To estimate the values $f_{\&}(a, b)$ for all other pairs, we need to use interpolation.

A similar interpolation is needed to determine the “or”-operation $f_{\vee}(a, b)$, the negation operation $f_-(a, b)$, and the appropriate defuzzification.

In the 1-D case, linear interpolation is the simplest. Interpolation means that we find a function that attains known values at given points.

The simplest possible functions are constants. The simplest possible non-constant functions are linear functions. When we use linear functions to interpolate, we get linear interpolation – which is, thus, the simplest possible interpolation.

To be more precise, if for two values $x_1 < x_2$, we know the values $y_1 = f(x_1)$ and $y_2 = f(x_2)$, then these two values uniquely determine a linear function:

$$f(x) = f(x_1) + \frac{y_2 - y_1}{x_2 - x_1} \cdot (x - x_1). \quad (1)$$

In this paper, as we have mentioned, we show that this simplest (linear) interpolation explains all usual choices of fuzzy techniques.

III. SIMPLE LINEAR INTERPOLATION EXPLAINS THE USUAL CHOICE OF MEMBERSHIP FUNCTIONS

Main idea. Usually, for each property like “small”,

- first, there are some values which are definitely not small (e.g., negative ones),
- then some values which are small to some extent;
- then, we have an interval of values which are definitely small;
- this is followed by values which are somewhat small; and
- finally, we get values which are absolutely not small.

Let us denote the values (“thresholds”) that separate these regions by t_1 , t_2 , t_3 , and t_4 . In terms of these thresholds, we have the following:

- for all the values $x \leq t_1$, the desired property is not satisfied, so we get $\mu(x) = 0$;

- for the values x between t_1 and t_2 , the property is satisfied to some degree, so we have $0 < \mu(x) < 1$;
- for the values x between t_2 and t_3 , the property is absolutely satisfied, so we have $\mu(x) = 1$;
- for the values x between t_3 and t_4 , the property is satisfied to some degree, so we have $0 < \mu(x) < 1$;
- finally, for $x \geq t_4$, the desired property is not satisfied, so we get $\mu(x) = 0$.

In this description, we know the values $\mu(x)$ for $x \leq t_1$, for $x \in [t_2, t_3]$, and for $x \geq t_4$. What we need is estimate the values $\mu(x)$ for $x \in [t_1, t_2]$ and $x \in [t_3, t_4]$.

Let us use linear interpolation. To find the values $\mu(x)$ for $x \in [t_1, t_2]$, we can apply linear interpolation to the known values $\mu(t_1) = 0$ and $\mu(t_2) = 1$. As a result, we get a linear increasing function on this interval.

Similarly, to find the values $\mu(x)$ for $x \in [t_3, t_4]$, we can apply linear interpolation to the known values $\mu(t_3) = 1$ and $\mu(t_4) = 0$. As a result, we get a linear decreasing function on this interval.

As a result of this interpolation, we get a trapezoid membership function; see, e.g., [4].

Conclusion. Simple linear interpolation explains the usual choice of a trapezoid membership function.

IV. SIMPLE LINEAR INTERPOLATION EXPLAINS THE USUAL CHOICE OF T-NORMS

Main idea. What do we know about “and”?

Intuitively, if one of the component statements A is false, then the composite statement $A \& B$ is also false. In other words, if $a = d(A) = 0$, then $f_{\&}(a, b) = f_{\&}(0, b) = 0$.

Also, if A is absolutely true, then our belief in $A \& B$ is equivalent to our degree of belief in B . In other words, if $a = d(A) = 1$, then $f_{\&}(a, b) = f_{\&}(1, b) = b$.

We thus know the values $f_{\&}(a, b)$ for the cases when a is equal to 0 or 1. We would like to use this information to estimate the value $f_{\&}(a, b)$ for all possible pairs (a, b) .

Let us use linear interpolation. Let us fix b and consider a function $F_b(a) \stackrel{\text{def}}{=} f_{\&}(a, b)$ that maps a into the value $f_{\&}(a, b)$. We know that:

- for $a = 0$, we have $F_b(0) = 0$, and that
- for $a = 1$, we have $F_b(1) = b$.

We can use linear interpolation to find the value $F_b(a)$ for all $a \in [0, 1]$. The general formula for linear interpolation leads to $F_b(a) = a \cdot b$, i.e., to the algebraic product $f_{\&}(a, b) = a \cdot b$.

Comment. Please note that while the resulting operation is commutative and associative, we did not require commutativity or associativity: all we required was linear interpolation.

What if we additionally require that $A \& A$ is equivalent to A . Another intuitive property of “and” is that for every statement A , “ A and A ” means the same as A . In terms of the “and”-operation, this means that for every $a = d(A)$, we have $f_{\&}(a, a) = a$.

Now, for each b , in addition to knowing the values $f_{\&}(a, b)$ for the values $a = 0$ and $a = 1$, we also know its value for $a = b$.

What if we also require that $A \& A$ is equivalent to A : let us use linear interpolation. Let us fix b and consider a function $F_b(a) = f_{\&}(a, b)$ that maps a into the value $f_{\&}(a, b)$.

We know that $F_b(0) = f_{\&}(0, b) = 0$ and that $F_b(b) = f_{\&}(b, b) = b$. Thus, on the interval $[0, b]$, linear interpolation leads to $F_b(a) = a$, i.e., to $f_{\&}(a, b) = a$.

Let us now apply linear interpolation to the interval $[b, 1]$. From $F_b(b) = b$ and $F_b(1) = f_{\&}(1, b) = b$, we conclude that for the values a from this interval, we have $F_b(a) = b$, i.e., we have $f_{\&}(a, b) = b$.

These two cases lead us to the following conclusion:

- when $a \leq b$, then $f_{\&}(a, b) = a$;
- when $b \leq a$, then $f_{\&}(a, b) = b$.

These two cases can be described by a single formula $f_{\&}(a, b) = \min(a, b)$. This is exactly the min-operation.

Conclusion. Simple linear interpolation explains the usual two choices of an “and”-operation: algebraic product and min.

V. SIMPLE LINEAR INTERPOLATION EXPLAINS THE USUAL CHOICE OF T-CONORMS

Main idea. What do we know about “or”?

Intuitively, if one of the component statements A is absolutely true, then the composite statement $A \vee B$ is also absolutely true. In other words, if $a = d(A) = 1$, then $f_{\vee}(a, b) = f_{\vee}(1, b) = 1$.

Also, if A is absolutely false, then our belief in $A \vee B$ is equivalent to our degree of belief in B . In other words, if $a = d(A) = 0$, then $f_{\vee}(a, b) = f_{\vee}(0, b) = b$.

We thus know the values $f_{\vee}(a, b)$ for the cases when a is equal to 0 or 1. We would like to use this information to estimate the value $f_{\vee}(a, b)$ for all possible pairs (a, b) .

Let us use linear interpolation. Let us fix b and consider a function $G_b(a) \stackrel{\text{def}}{=} f_{\vee}(a, b)$ that maps a into the value $f_{\vee}(a, b)$. We know that:

- for $a = 0$, we have $G_b(0) = b$, and that
- for $a = 1$, we have $G_b(1) = 1$.

We can use linear interpolation to find the value $G_b(a)$ for all $a \in [0, 1]$. The general formula for linear interpolation leads to $G_b(a) = b + a \cdot (1 - b)$, i.e., to the algebraic sum $f_{\vee}(a, b) = a + b - a \cdot b$.

Comment. Please note that, similarly to the case of “and”-operations, while the resulting operation is commutative and

associative, we did not require commutativity or associativity: all we required was linear interpolation.

What if we additionally require that $A \vee A$ is equivalent to A . Another intuitive property of “or” is that for every statement A , “ A or A ” means the same as A . In terms of the “and”-operation, this means that for every $a = d(A)$, we have $f_{\vee}(a, a) = a$.

Now, for each b , in addition to knowing the values $f_{\vee}(a, b)$ for the values $a = 0$ and $a = 1$, we also know its value for $a = b$.

What if we also require that $A \vee A$ is equivalent to A : let us use linear interpolation. Let us fix b and consider a function $G_b(a) = f_{\vee}(a, b)$ that maps a into the value $f_{\vee}(a, b)$.

We know that $G_b(0) = f_{\vee}(0, b) = b$ and that $G_b(b) = f_{\vee}(b, b) = b$. Thus, on the interval $[0, b]$, linear interpolation leads to $G_b(a) = b$, i.e., to $f_{\vee}(a, b) = b$.

Let us now apply linear interpolation to the interval $[b, 1]$. From $G_b(b) = b$ and $G_b(1) = f_{\vee}(1, b) = 1$, we conclude that for the values a from this interval, we have $G_b(a) = a$, i.e., we have $f_{\vee}(a, b) = a$.

These two cases lead us to the following conclusion:

- when $a \leq b$, then $f_{\vee}(a, b) = b$;
- when $b \leq a$, then $f_{\vee}(a, b) = a$.

These two cases can be described by a single formula $f_{\vee}(a, b) = \max(a, b)$. This is exactly the max-operation.

Conclusion. Simple linear interpolation explains the usual two choices of an “or”-operation: algebraic sum and max.

VI. SIMPLE LINEAR INTERPOLATION EXPLAINS THE USUAL CHOICE OF NEGATION OPERATIONS

Formulation of the problem. For the classical 2-valued logic, with two truth values 1 (“true”) and 0 (“false”), the negation operation is easy to define:

- the negation of “false” is “true”: $f_{-}(0) = 1$, and
- the negation of “true” is “false”: $f_{-}(1) = 0$.

We want to extend this operation from the 2-valued set $\{0, 1\}$ to the whole interval $[0, 1]$.

Let us use linear interpolation. In this case, in terms of the formula (1), we have $x_1 = 0$, $x_2 = 1$, $y_1 = 1$, and $y_2 = 0$. Thus, the formula for linear interpolation leads to

$$f_{-}(a) = 1 - a.$$

This is exactly the most frequently used negation operation in fuzzy logic.

Conclusion. Simple linear interpolation explains the usual choice of negation operation.

VII. SIMPLE LINEAR INTERPOLATION EXPLAINS THE USUAL CHOICE OF DEFUZZIFICATION

Main idea. The desired control \bar{u} should be close to reasonable control values u : $\bar{u} \approx u$. In principle, we have different possible control values u .

Let us start with a simplified situation in which we have finitely many reasonable values u_1, \dots, u_k , and all these values are equally reasonable. In this case, we want to find the values \bar{u} for which $\bar{u} \approx u_1, \bar{u} \approx u_2, \dots, \bar{u} \approx u_k$.

Since the values u_i are different, we cannot get the exact equality in all k cases, i.e., we cannot get all k approximation errors $e_k \stackrel{\text{def}}{=} \bar{u} - u_k$ to 0. What we want is to make the vector $e \stackrel{\text{def}}{=} (e_1, \dots, e_k)$ consisting of all these errors to be as close to the ideal point $(0, \dots, 0)$ as possible.

The distance between the vector e and the 0 point is equal to $\sqrt{e_1^2 + \dots + e_k^2}$. Minimizing this distance is equivalent to minimizing its square, i.e., the sum

$$e_1^2 + \dots + e_k^2 = (\bar{u} - u_1)^2 + \dots + (\bar{u} - u_k)^2.$$

This is the usual *Least Squares* method.

In the continuous case, when all the value u are possible, in the limit, we get an integral $\int (\bar{u} - u)^2 du$ instead of the sum described above.

This method works well if all the values u are equally possible. In reality, different values u have different degrees of possibility $\mu(u)$.

- If the value u is fully possible, i.e., if $\mu(u) = 1$, then we should keep the corresponding term $(\bar{u} - u)^2$ in the sum.
- If the value u is completely impossible, i.e., if $\mu(u) = 0$, then we should not consider this term at all.

In general, a natural idea is, instead of simply adding the squares, to first multiply each square by a weight $w(\mu(u))$ depending on the degree of possibility, so that:

- when $\mu(u) = 1$, we get full weight $w(\mu(u)) = w(1) = 1$;
- when $\mu(u) = 0$, we get zero weight $w(\mu(u)) = w(0) = 0$; and
- for values $\mu(u)$ intermediate between 0 and 1, we should use intermediate values of weight.

In the discrete case, we thus minimize the sum

$$\sum_i w(\mu(i)) \cdot (\bar{u} - u_i)^2;$$

in the continuous case, we minimize the corresponding integral

$$\int w(\mu(u)) \cdot (\bar{u} - u)^2 du. \quad (2)$$

Let us use linear interpolation. We know that $w(0) = 0$ and $w(1) = 1$. We want to estimate the values $w(\mu)$ for all $\mu \in [0, 1]$. Linear interpolation leads to $w(u) = u$.

Thus, we should select \bar{u} for which the integral

$$\int \mu(u) \cdot (\bar{u} - u)^2 du \quad (3)$$

attains the smallest possible value.

Differentiating the expression (3) with respect to \bar{u} and equating the derivative to 0, we conclude that

$$\int 2\mu(u) \cdot (\bar{u} - u) du = 0. \quad (4)$$

Dividing both sides of this equality by 2 and moving all the terms not depending on \bar{u} to the right-hand side, we conclude that

$$\bar{u} \cdot \int \mu(u) du = \int u \cdot \mu(u) du,$$

and thus, that

$$\bar{u} = \frac{\int u \cdot \mu(u) du}{\int \mu(u) du}.$$

This is exactly the centroid defuzzification which is efficiently and widely used in many practical applications of fuzzy logic.

Conclusion. Simple linear interpolation explains the usual choice of defuzzification.

VIII. CONCLUSION

In many real-life situations, we need to process expert knowledge, and experts often describe their knowledge by using imprecise (“fuzzy”) terms from natural language. For processing such knowledge, we can use different version of fuzzy techniques – techniques specifically designed for processing this knowledge. Most efficient practical applications of fuzzy techniques use a specific combination of fuzzy techniques: triangular or trapezoid membership functions, simple t-norms (min or product), simple t-conorms (max or algebraic sum), and centroid defuzzification.

For each of these choices, there exists an explanation of why this particular choice is efficient. The usual explanations, however, are different for different techniques: an explanation why selecting simple t-norms is efficient is different from an explanation of why centroid defuzzification is efficient. In this paper, we show that all these choices can be explained in the same way – by the use of the simplest (linear) interpolation. In our opinion, such a uniform explanation makes the resulting choices easier to accept (and easier to teach).

ACKNOWLEDGMENTS

This work was supported in part by the National Science Foundation grants HRD-0734825 and HRD-1242122 (Cyber-ShARE Center of Excellence) and DUE-0926721.

The authors are thankful to the anonymous referees for valuable suggestions.

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