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Description Level-wise statistical methods for fuzzy random variables, implementing the Puri-Ralescu framework. Provides level-wise empirical distribution functions, moments, covariance and correlation, a level-wise Kolmogorov-Smirnov goodness-of-fit test, an approximate fuzzy normal distribution with simulation, and level-wise central limit theorem and law of large numbers inference. The package only depends on base R.

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alpha_levels	<i>Alpha grid of a fuzzy object</i>
--------------	-------------------------------------

Description

Alpha grid of a fuzzy object

Usage

alpha_levels(x)

Arguments

x A FuzzyNumber or FuzzySample.

Value

Numeric vector of alpha levels.

Examples

```
alpha_levels(triangular_fuzzy(1, 2, 4))[1:3]
```

as_fuzzy_sample	<i>Coerce to a FuzzySample</i>
-----------------	--------------------------------

Description

Coerces from a list of FuzzyNumber, an array, a data frame (with columns id, alpha, lower, upper) or a single FuzzyNumber (giving a sample of size 1).

Usage

```
as_fuzzy_sample(x, alpha = NULL, ...)

## Default S3 method:
as_fuzzy_sample(x, alpha = NULL, ...)

## S3 method for class 'FuzzyNumber'
as_fuzzy_sample(x, alpha = NULL, ...)

## S3 method for class 'data.frame'
as_fuzzy_sample(x, alpha = NULL, ...)
```

Arguments

x	Object to coerce.
alpha	Alpha grid (for array/data-frame input).
...	Unused.

Value

A FuzzySample.

Examples

```
fs <- as_fuzzy_sample(triangular_fuzzy(0, 1, 2))
n_obs(fs)
```

clt	<i>Central limit theorem for a fuzzy random sample</i>
-----	--

Description

Uses the level-wise central limit theorem (Puri & Ralescu, 1986): at each level α the sample-mean endpoints are approximately normal, so the fuzzy sample mean $\bar{X}$ is approximately a `fuzzy_normal` with mean `expectation(x)` and level-wise covariance `variance(x) / n`.

Usage

```
clt(x, alpha = NULL, ...)
```

Arguments

<code>x</code>	A <code>FuzzySample</code> .
<code>alpha</code>	Numeric levels (default: those of <code>x</code>).
<code>...</code>	Unused.

Value

An object of class `c("FuzzyCLT", "FuzzyNormal")`. Its `cov` is the covariance of $\bar{X}$ (i.e. Σ / n); `sigma` is the limiting covariance Σ .

Examples

```
set.seed(7)
s <- rnorm_fuzzy(500, triangular_fuzzy(0, 1, 2), diag(2) * 0.25)
cl <- clt(s); summary(cl)
simulate(cl, nsim = 4)
```

correlation	<i>Correlation of two fuzzy random variables (sample)</i>
-------------	---

Description

Level-wise Pearson correlation between the lower endpoints (`cor(X^-(alpha), Y^-(alpha))`) and between the upper endpoints (`cor(X^+(alpha), Y^+(alpha))`), plus the scalar reduction

$$\rho_{FHS}(X, Y) = \frac{1}{2} \int_0^1 [r_{--}(a) + r_{++}(a)] da.$$

Usage

```
correlation(x, y = NULL, alpha = NULL, ...)

## S3 method for class 'FuzzySample'
correlation(x, y = NULL, alpha = NULL, ...)
```

Arguments

x, y	Two FuzzySample objects.
alpha	Optional alpha grid.
...	Unused.

Value

An object of class "FuzzyCorrelation" (with a scalar slot).

Examples

```
set.seed(5)
x <- FuzzySample(replicate(50, triangular_fuzzy(0, 1, 2), simplify = FALSE))
y <- FuzzySample(replicate(50, triangular_fuzzy(0, 1, 2), simplify = FALSE))
correlation(x, y)
```

covariance

Covariance of two fuzzy random variables (sample)

Description

Level-wise covariance. At each level alpha the covariance of X and Y is the 2 x 2 matrix

$$\begin{array}{cc} \text{Cov}(X^{\wedge-}, Y^{\wedge-}) & \text{Cov}(X^{\wedge-}, Y^{\wedge+}) \\ \text{Cov}(X^{\wedge+}, Y^{\wedge-}) & \text{Cov}(X^{\wedge+}, Y^{\wedge+}). \end{array}$$

When y is omitted, x is paired with itself and the result is the variance. A scalar reduction through the Feng–Hu–Shu integral

$$\text{Cov}_{FHS}(X, Y) = \frac{1}{2} \int_0^1 [\text{Cov}(X^-(a), Y^-(a)) + \text{Cov}(X^+(a), Y^+(a))] da$$

is also returned.

Usage

```
covariance(x, y = NULL, alpha = NULL, ...)
```

```
## S3 method for class 'FuzzySample'
covariance(x, y = NULL, alpha = NULL, ...)
```

```
## S3 method for class 'FuzzySample'
cov(x, y = NULL, ...)
```

Arguments

x, y	Two FuzzySample objects (or x alone for the variance).
alpha	Optional alpha grid.
...	Unused.

Value

A FuzzyCovariance object.

Examples

```
set.seed(3)
x <- FuzzySample(replicate(30, triangular_fuzzy(0, 1, 2), simplify = FALSE))
y <- FuzzySample(replicate(30, triangular_fuzzy(1, 2, 3), simplify = FALSE))
covariance(x, y)
```

cut_at	<i>Cut of a fuzzy number at a single level</i>
--------	--

Description

Cut of a fuzzy number at a single level

Usage

```
cut_at(x, alpha, ...)

## S3 method for class 'FuzzyNumber'
cut_at(x, alpha = 0.5, ...)
```

Arguments

x	A FuzzyNumber.
alpha	A single level in $[0, 1]$.
...	Unused.

Value

A named numeric vector `c(lower = ..., upper = ...)`.

Examples

```
cut_at(triangular_fuzzy(1, 2, 4), 0.5)
```

cuts	<i>Alpha-level cuts of a fuzzy number</i>
------	---

Description

Alpha-level cuts of a fuzzy number

Usage

```
cuts(x, alpha = NULL, ...)

## S3 method for class 'FuzzyNumber'
cuts(x, alpha = NULL, ...)
```

Arguments

x	A FuzzyNumber (or other compatible object).
alpha	Optional alpha grid at which to evaluate the cuts.
...	Unused.

Value

A numeric matrix with columns lower and upper.

Examples

```
fn <- triangular_fuzzy(1, 2, 4)
cuts(fn, alpha = c(0, 0.5, 1))
```

expectation	<i>Expectation of a fuzzy random variable (sample)</i>
-------------	--

Description

Level-wise expectation. For a sample the estimator is the level-wise mean of the alpha-cuts:

$$[E[X]]_{\alpha} = \left[\frac{1}{n} \sum_i X_i^{-}(\alpha), \frac{1}{n} \sum_i X_i^{+}(\alpha) \right].$$

Usage

```
expectation(x, alpha = NULL, ...)

## S3 method for class 'FuzzySample'
expectation(x, alpha = NULL, ...)

## S3 method for class 'FuzzySample'
mean(x, ...)
```

Arguments

x	A FuzzySample.
alpha	Optional alpha grid on which to evaluate.
...	Unused.

Value

A FuzzyNumber, the sample expectation.

Examples

```
set.seed(2)
s <- FuzzySample(replicate(40, triangular_fuzzy(-1, 0, 1), simplify = FALSE))
ex <- expectation(s); plot(ex, main = "sample mean")
```

fuzzy_ecdf

*Empirical distribution function of a fuzzy random sample***Description**

Level-wise empirical cumulative distribution functions of the alpha-cut endpoints.

Usage

```
fuzzy_ecdf(x, alpha = NULL, at = NULL, ...)
```

```
## S3 method for class 'FuzzySample'
fuzzy_ecdf(x, alpha = NULL, at = NULL, ...)
```

Arguments

x	A FuzzySample.
alpha	Numeric vector of levels (default: the levels stored in x).
at	Numeric grid on which to evaluate the CDFs (default: 201 points over the data range).
...	Unused.

Value

An object of class "FuzzyECDF".

Examples

```
set.seed(8)
s <- FuzzySample(replicate(40, triangular_fuzzy(0, 1, 2), simplify = FALSE))
fe <- fuzzy_ecdf(s, alpha = c(0, 0.25, 0.5, 0.75, 1))
plot(fe)
```

fuzzy_from_membership *A fuzzy number from a membership function evaluated on a grid*

Description

Reconstructs the alpha-cuts of a (normal, quasi-concave) fuzzy number from a membership function evaluated on a grid. The level set $\{x : \mu(x) \geq \alpha\}$ is assumed to be a single interval.

Usage

```
fuzzy_from_membership(x, mu, alpha = NULL)
```

Arguments

x	Sorted numeric grid of the support (unsorted grids are sorted).
mu	Membership values in $[0, 1]$ evaluated at x.
alpha	Optional alpha grid.

Value

An object of class "FuzzyNumber".

Examples

```
x <- seq(-3, 3, length.out = 201)
mu <- pmax(1 - abs(x), 0)           # triangular membership
fn <- fuzzy_from_membership(x, mu)
plot(fn)
```

fuzzy_normal *Construct a fuzzy normal distribution*

Description

A fuzzy normal distribution is the family, over levels alpha, of bivariate-normal laws on the alpha-cut endpoints with fuzzy mean mean and level-wise covariance cov.

Usage

```
fuzzy_normal(mean, cov = NULL, n = NULL)
```

Arguments

mean	A FuzzyNumber (the fuzzy mean).
cov	A 2 x 2 covariance matrix, a length-4 vector, or a FuzzyCovariance whose levels match mean.
n	Optional sample size associated with the mean (used by clt).

Value

An object of class "FuzzyNormal".

Examples

```
fn <- fuzzy_normal(triangular_fuzzy(0, 1, 2), diag(2))
simulate(fn, nsim = 5)
```

FuzzyNumber

A fuzzy number given by its alpha-level cuts

Description

Build a [FuzzyNumber](#) object from its alpha-level envelopes. When alpha is not supplied it is taken as a regularly spaced grid on $[0, 1]$ with one node per supplied endpoint.

Usage

```
FuzzyNumber(alpha = NULL, lower, upper)
```

Arguments

alpha	Numeric vector in $[0, 1]$, strictly increasing.
lower	Numeric; lower envelope, non-decreasing in alpha.
upper	Numeric; upper envelope, non-increasing in alpha.

Value

An object of class "FuzzyNumber".

Examples

```
fn <- FuzzyNumber(alpha = c(0, 0.5, 1), lower = c(1, 2, 2), upper = c(4, 2, 2))
cuts(fn)
```

Description

FuzzyRandom is a computationally self-contained implementation of the level-wise ("Puri-Ralescu") theory of statistics for fuzzy random variables.

Details

Fuzzy numbers are represented through their alpha-level sets $[X^{-(\alpha)}, X^{+(\alpha)}]$, and every statistical operator is defined level-wise, so that the **expectation, variance, covariance, empirical distribution, law of large numbers** and **central limit theorem** are all handled in a single coherent framework.

The key design choices are:

- A *fuzzy number* is a list of alpha levels and the matching non-decreasing lower / non-increasing upper envelopes (class FuzzyNumber).
- A *sample of fuzzy random variables* is an $(n, m, 2)$ array of cuts (class FuzzySample), m being the number of levels.
- The covariance of two fuzzy random variables is returned as a level-wise 2×2 matrix of covariances between the lower and upper endpoints (class FuzzyCovariance); scalar reductions are provided through the Feng-Hu-Shu integral and scalar product.
- The central limit theorem yields the *fuzzy normal* distribution (class FuzzyNormal), whose level cuts are bivariate-normal intervals.

The package only depends on base R (stats, graphics).

References

- Puri, M. L. and Ralescu, D. A. (1986). Fuzzy random variables. *Journal of Mathematical Analysis and Applications*, **114**(2), 409-422.
- Klement, E. P., Puri, M. L. and Ralescu, D. A. (1986). Limit theorems for fuzzy random variables. *Proceedings of the Royal Society A*, **407**, 171-182.
- Feng, Y., Hu, L. and Shu, H. (2002). The variance and covariance of fuzzy random variables and their applications. *Fuzzy Sets and Systems*, **128**, 335-345.

FuzzySample

Build a sample of fuzzy random variables

Description

Build a sample of fuzzy random variables

Usage

```
FuzzySample(x, alpha = NULL)
```

Arguments

x	Either a list of FuzzyNumber objects, an (n, m, 2) numeric array of cuts (dimension 3 = c("lower", "upper")), or an existing FuzzySample.
alpha	Alpha grid shared by all observations. Required when x is an array with an unlabelled third dimension; otherwise inferred.

Value

An object of class "FuzzySample".

Examples

```
set.seed(1)
s <- FuzzySample(list(
  triangular_fuzzy(0, 1, 2),
  triangular_fuzzy(1, 2, 3),
  trapezoidal_fuzzy(0.5, 1, 3, 4)))
n_obs(s)
```

is_fuzzy_number

Whether an object is a (valid) fuzzy number

Description

Whether an object is a (valid) fuzzy number

Usage

```
is_fuzzy_number(x)
```

Arguments

x	Any R object.
---	---------------

Value

Logical; TRUE if x is a valid FuzzyNumber.

Examples

```
is_fuzzy_number(triangular_fuzzy(0, 1, 2))
is_fuzzy_number(1:3)
```

is_fuzzy_sample	<i>Whether an object is a FuzzySample</i>
-----------------	---

Description

Whether an object is a FuzzySample

Usage

```
is_fuzzy_sample(x)
```

Arguments

x Any R object.

Value

Logical.

Examples

```
is_fuzzy_sample(FuzzySample(list(triangular_fuzzy(0, 1, 2))))
```

ks_test	<i>One- and two-sample fuzzy Kolmogorov-Smirnov tests</i>
---------	---

Description

Performs, at each level alpha, a Kolmogorov-Smirnov test on the lower and upper endpoints of the alpha-cuts. With p0 a one-sample test against the CDF p0 is run; otherwise a two-sample test against the second sample y is run. The result is a family of level-wise tests consistent with the Puri-Ralescu level-wise approach.

Usage

```
ks_test(x, ...)
```

```
## S3 method for class 'FuzzySample'
```

```
ks_test(x, y = NULL, p0 = NULL, alpha = NULL, ...)
```

Arguments

<code>x</code>	A <code>FuzzySample</code> .
<code>...</code>	Additional arguments passed on to <code>ks.test</code> .
<code>y</code>	A second <code>FuzzySample</code> for a two-sample test (default <code>NULL</code>).
<code>p0</code>	Null CDF for the one-sample test: a character string naming a CDF in <code>stats</code> (e.g. <code>"pnorm"</code>) or a function <code>p0(q)</code> .
<code>alpha</code>	Numeric vector of levels (default: those of <code>x</code>).

Value

An object of class `"FuzzyKS"`.

Examples

```
set.seed(9)
s <- FuzzySample(replicate(50, triangular_fuzzy(-1, 0, 1), simplify = FALSE))
ks_test(s, p0 = "pnorm")
```

lln

Level-wise sample-mean convergence (LLN)

Description

Following Puri & Ralescu (1986), statistics on fuzzy random variables are evaluated level-wise on the alpha-cuts. This function computes the fuzzy sample mean for an increasing sequence of sample sizes and measures, at a fixed level, the sup-norm distance between the size-`s` mean and the full-sample mean. By the level-wise (fuzzy) law of large numbers this distance shrinks to zero with the sample size (at rate $1/\sqrt{s}$) under the level-wise CLT).

Usage

```
lln(x, sizes = NULL, alpha = NULL, levels = c(0.5, 1), ...)
```

Arguments

<code>x</code>	A <code>FuzzySample</code> .
<code>sizes</code>	Integer vector of sample sizes (default: a grid from 5 up to <code>x\$n</code>).
<code>alpha</code>	Optional alpha grid on which to evaluate the means.
<code>levels</code>	Numeric levels at which to measure convergence, used by the summary, <code>as.data.frame</code> and plot methods (default <code>c(0.5, 1)</code>).
<code>...</code>	Unused.

Value

An object of class `"FuzzyLLN"` with components `sizes`, `means`, `full` and `alpha`.

Examples

```
set.seed(23)
s <- rnorm_fuzzy(400, triangular_fuzzy(0, 1, 2), diag(2) * 0.25)
w <- llm(s)
plot(w)
summary(w)
```

n_cuts	<i>Number of alpha levels of a fuzzy object</i>
--------	---

Description

Number of alpha levels of a fuzzy object

Usage

```
n_cuts(x)
```

Arguments

x A FuzzyNumber or FuzzySample.

Value

Length-one integer.

Examples

```
n_cuts(triangular_fuzzy(1, 2, 4))
```

n_obs	<i>Number of observations in a sample</i>
-------	---

Description

Number of observations in a sample

Usage

```
n_obs(x)
```

Arguments

x A FuzzySample.

Value

Length-one integer.

Examples

```
s <- FuzzySample(list(triangular_fuzzy(0, 1, 2), triangular_fuzzy(1, 2, 3)))
n_obs(s)
```

rnorm_fuzzy

Sample fuzzy random variables from a fuzzy normal distribution

Description

Draws n fuzzy numbers whose alpha-cut endpoints have the bivariate-normal level-wise distribution $N_2(\mu_\alpha, \Sigma_\alpha)$.

Usage

```
rnorm_fuzzy(n, mean, cov = NULL, valid = TRUE, seed = NULL)
```

```
## S3 method for class 'FuzzyNormal'
simulate(object, nsim = 1, ...)
```

```
## S3 method for class 'FuzzyCLT'
simulate(object, nsim = 1, ...)
```

Arguments

n	Sample size.
mean	A FuzzyNumber (the fuzzy mean) or a FuzzyNormal.
cov	A 2 x 2 covariance matrix, a length-4 vector, or a FuzzyCovariance. Ignored if mean is a FuzzyNormal.
valid	Logical; whether to project draws to valid fuzzy numbers.
seed	Optional integer seed (NULL leaves the RNG alone).
object	A FuzzyNormal (or FuzzyCLT) object.
nsim	Number of simulations.
...	Unused.

Details

When `valid = TRUE` (the default) every draw is projected onto the cone of valid, nested alpha-cuts (lower $\leq$ upper; lower non-decreasing and upper non-increasing in α) so that it is a proper fuzzy number. When `valid = FALSE` the raw, unprojected level-wise bivariate-normal cuts are returned – useful for checking the level-wise central limit theorem, where projection would bias the marginals.

Value

A FuzzySample of n fuzzy random variables.

Examples

```
set.seed(123)
s <- rnorm_fuzzy(80, triangular_fuzzy(0, 1, 2), diag(2) * 0.25)
plot(s, main = "fuzzy normal sample")
```

spectral_covariance	<i>Scalar covariance (Feng–Hu–Shu integral)</i>
---------------------	---

Description

spectral_covariance returns the scalar covariance

$$\text{Cov}_{FHS}(X, Y) = \frac{1}{2} \int_0^1 [\text{Cov}(X^-(a), Y^-(a)) + \text{Cov}(X^+(a), Y^+(a))] da.$$

Usage

```
spectral_covariance(x, y = NULL, alpha = NULL, ...)

## S3 method for class 'FuzzySample'
spectral_covariance(x, y = NULL, alpha = NULL, ...)
```

Arguments

x, y	Two FuzzySample objects (or x alone).
alpha	Optional alpha grid.
...	Unused.

Value

A length-one numeric.

Examples

```
set.seed(6)
x <- FuzzySample(replicate(30, triangular_fuzzy(0, 1, 2), simplify = FALSE))
spectral_covariance(x)
```

spectral_variance	<i>Scalar variance (Feng–Hu–Shu integral)</i>
-------------------	---

Description

spectral_variance returns spectral_covariance(x, x).

Usage

```
spectral_variance(x, alpha = NULL, ...)
```

Arguments

x	A FuzzySample.
alpha	Optional alpha grid.
...	Unused.

Value

A length-one numeric.

Examples

```
set.seed(7)
x <- FuzzySample(replicate(30, triangular_fuzzy(0, 1, 2), simplify = FALSE))
spectral_variance(x)
```

trapezoidal_fuzzy	<i>Trapezoidal fuzzy number</i>
-------------------	---------------------------------

Description

The trapezoidal fuzzy number with support $[a, d]$ and core $[b, c]$ ($a \leq b \leq c \leq d$).

Usage

```
trapezoidal_fuzzy(a, b, c, d, alpha = NULL)
```

Arguments

a, b, c, d	Scalars with $a \leq b \leq c \leq d$.
alpha	Optional alpha grid.

Value

An object of class "FuzzyNumber".

Examples

```
plot(trapezoidal_fuzzy(1, 2, 3, 5))
```

triangular_fuzzy	<i>Triangular fuzzy number</i>
------------------	--------------------------------

Description

The triangular fuzzy number with support $[a, c]$ and core b ($a \leq b \leq c$). Its alpha-cuts are $[a + (b-a)*\alpha, c - (c-b)*\alpha]$.

Usage

```
triangular_fuzzy(a, b, c, alpha = NULL)
```

Arguments

<code>a, b, c</code>	Scalars with $a \leq b \leq c$.
<code>alpha</code>	Optional alpha grid (see FuzzyNumber).

Value

An object of class "FuzzyNumber".

Examples

```
plot(triangular_fuzzy(1, 2, 4))
```

variance	<i>Variance of a fuzzy random variable (sample)</i>
----------	---

Description

Level-wise variance, i.e. [covariance](#) of a sample with itself. Returns the level-wise 2×2 matrix $[[\text{Var}(X^-), \text{Cov}(X^-, X^+)], [\text{Cov}(X^+, X^-), \text{Var}(X^+)]]$ at each level, together with the scalar Feng–Hu–Shu variance

$$\text{Var}_{FHS}(X) = \frac{1}{2} \int_0^1 [\text{Var}(X^-(a)) + \text{Var}(X^+(a))] da.$$

Usage

```
variance(x, alpha = NULL, ...)  
  
## S3 method for class 'FuzzySample'  
variance(x, alpha = NULL, ...)  
  
## S3 method for class 'FuzzySample'  
var(x, ...)
```

Arguments

x	A FuzzySample.
alpha	Optional alpha grid.
...	Unused.

Value

A FuzzyCovariance object (with type = "variance").

Examples

```
set.seed(4)  
s <- FuzzySample(replicate(30, triangular_fuzzy(0, 1, 2), simplify = FALSE))  
variance(s)
```

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