

# Package ‘rotations’

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**Type** Package

**Title** Tools for Working with Rotation Data

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**Description** This package implements tools for working with rotational data: it allows simulation from the most commonly used distributions on  $SO(3)$ , it includes methods for different Bayes, mean and median type estimators for the central orientation of a sample, it provides confidence and credible regions for the central orientation based on those estimators and it includes a novel visualization technique for rotation data.

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Angular-distributions *Angular distributions*

---

## Description

Density, distribution function and random variate generation for symmetric probability distributions in the rotations package.

## Details

The functions for the density function and random variate generation are named in the usual form `dxxxx`, `pxxxx` and `rxxxx`, respectively.

- See [Cayley](#) for the Cayley distribution.
- See [Fisher](#) for the matrix Fisher distribution.
- See [Haar](#) for the uniform distribution on the circle.
- See [Mises](#) for the von Mises-Fisher distribution.

---

Arithmetic *Arithmetic operators on SO(3)*

---

## Description

These binary operators perform arithmetic on rotations in quaternion or rotation matrix form (or objects which can be coerced into them).

## Usage

```
## S3 method for class 'S03'
x + y

## S3 method for class 'S03'
x - y = NULL

## S3 method for class 'Q4'
x + y

## S3 method for class 'Q4'
x - y = NULL
```

## Arguments

<code>x</code>	first argument
<code>y</code>	second argument (optional for subtraction)

**Details**

The rotation group  $SO(3)$  is a multiplicative group so “adding” rotations  $R_1$  and  $R_2$  results in  $R_1 + R_2 = R_2 R_1$ . Similarly, the difference between rotations  $R_1$  and  $R_2$  is  $R_1 - R_2 = R_2^\top R_1$ . With this definition it is clear that  $R_1 + R_2 - R_2 = R_2^\top R_2 R_1 = R_1$ . If only one rotation is provided to subtraction then the inverse (transpose) it returned, e.g.  $-R_2 = R_2^\top$ .

**Value**

+ the result of rotating the identity frame through x then y  
 - the difference of the rotations, or the inverse rotation of only one argument is provided

**Examples**

```

U <- c(1, 0, 0)          #Rotate about the x-axis
R1 <- as.S03(U, pi/8)   #Rotate pi/8 radians about the x-axis
R2 <- R1 + R1           #Rotate pi/8 radians about the x-axis twice
mis.axis(R2)            #x-axis: (1,0,0)
mis.angle(R2)           #pi/8 + pi/8 = pi/4

R3 <- R1 - R1           #Rotate pi/8 radians about x-axis then back again
R3                       #Identity matrix

R4 <- -R1               #Rotate in the opposite direction through pi/8
R5 <- as.S03(U, -pi/8) #Equivalent to R4

M1 <- matrix(R1, 3, 3) #If element-wise addition is required,
M2 <- matrix(R2, 3, 3) #translate them to matrices then treat as usual
M3 <- M1 + M2

M1 %% M1                #Equivalent to R2
t(M1) %% M1             #Equivalent to R3
t(M1)                   #Equivalent to R4 and R5

#The same can be done with quaternions: the identity rotation is (1, 0, 0, 0)
#and the inverse rotation of Q=(a, b, c, d) is -Q=(a, -b, -c, -d)

Q1 <- as.Q4(R1)
Q2 <- Q1 + Q1
mis.axis(Q2)
mis.angle(Q2)

Q1 - Q1                 #id.Q4 = (1, 0, 0, 0)

```

**Description**

Creates or tests for objects of class "Q4".

**Usage**

```
as.Q4(x, ...)

## Default S3 method:
as.Q4(x, theta = NULL, ...)

## S3 method for class 'S03'
as.Q4(x, ...)

## S3 method for class 'Q4'
as.Q4(x, ...)

## S3 method for class 'data.frame'
as.Q4(x, ...)

is.Q4(x)

id.Q4
```

**Arguments**

x	object to be coerced or tested
theta	vector or single rotation angle; if <code>length(theta)==1</code> , the same theta is used for all axes
...	additional arguments.

**Format**

`id.Q4` is the identity rotation given by the matrix  $[1, 0, 0, 0]^T$ .

**Details**

Construct a single or sample of rotations in 3-dimensions in quaternion form. Several possible inputs for `x` are possible and they are differentiated based on their class and dimension.

For `x` an `n`-by-3 matrix or a vector of length 3, the angle-axis representation of rotations is utilized. More specifically, each quaternion can be interpreted as a rotation of some reference frame about the axis  $U$  (of unit length) through the angle  $\theta$ . For each axis and angle the quaternion is formed through

$$q = [\cos(\theta/2), \sin(\theta/2)U]^T.$$

The object `x` is treated as if it has rows  $U$  and `theta` is a vector or angles. If no angle is supplied then the length of each axis is taken to be the angle of rotation `theta`.

For `x` an `n`-by-9 matrix of rotation matrices or an object of class "S03", this function will return the quaternion equivalent of `x`. See [S03](#) or the vignette "rotations-intro" for more details on rotation matrices.

For  $x$  an  $n$ -by-4 matrix, rows are treated as quaternions; rows that aren't of unit length are made unit length while the rest are returned untouched. A message is printed if any of the rows are not quaternions.

$x$  a "data.frame" it is translated into a matrix of the same dimension and the dimensionality of  $x$  is used to determine the data type: angle-axis, quaternion or rotation (see above). As demonstrated below, `is.Q4` may return TRUE for a data frame, but the functions defined for objects of class 'Q4' will not be called until `as.Q4` has been used.

### Value

`as.Q4` coerces its object into a Q4 type  
`is.Q4` returns TRUE or False depending on whether its argument satisfies the conditions to be an quaternion; namely it must be four-dimensional and of unit length

### Examples

```
data(drill)                #Pull off subject 1's wrist measurements
Subj1Wrist <- subset(drill, Subject == '1' & Joint == 'Wrist')

                                ## The measurements are in columns 5:8
all(is.Q4(Subj1Wrist[,5:8])) #TRUE, even though Qs is a data.frame, the rows satisfy the
                                #conditions necessary to be quaternions BUT,
                                #S3 methods (e.g. 'mean' or 'plot') for objects of class
                                #'Q4' will not work until 'as.Q4' is used

Qs <- as.Q4(Subj1Wrist[,5:8]) #Coerce measurements into 'Q4' type using as.Q4.data.frame
all(is.Q4(Qs))                #TRUE
mean(Qs)                      #Estimate central orientation for subject 1's wrist, see ?mean.Q4
Rs <- as.S03(Qs)              #Coerse a 'Q4' object into rotation matrix format, see ?as.S03

#Visualize the measuremenets, see ?plot.Q4 for more
## Not run:
plot(Qs, col = c(1, 2, 3))
## End(Not run)
```

---

as.S03

*Rotation matrices*

---

### Description

Creates or tests for objects of class "S03".

### Usage

```
as.S03(x, ...)
```

## Default S3 method:  
`as.S03(x, theta = NULL, ...)`

```

## S3 method for class 'Q4'
as.SO3(x, ...)

## S3 method for class 'S03'
as.SO3(x, ...)

## S3 method for class 'data.frame'
as.SO3(x, ...)

is.SO3(x)

id.SO3

```

### Arguments

x	object to be coerced or tested; see details for possible forms
theta	vector or single rotation angle; if length(theta)==1 the same theta is used for all axes
...	additional arguments.

### Format

id.SO3 is the identity rotation given by the the 3-by-3 identity matrix.

### Details

Construct a single or sample of rotations in 3-dimensions in 3-by-3 matrix form. Several possible inputs for x are possible and they are differentiated based on their class and dimension.

For x an n-by-3 matrix or a vector of length 3, the angle-axis representation of rotations is utilized. More specifically, each rotation matrix can be interpreted as a rotation of some reference frame about the axis  $U$  (of unit length) through the angle  $\theta$ . If a single axis (in matrix or vector format) or matrix of axes are provided for x, then for each axis and angle the matrix is formed through

$$R = \exp[\Phi(U\theta)]$$

where  $U$  is replace by x. If axes are provided but theta is not provided then the length of each axis is taken to be the angle of rotation, theta.

For x an n-by-4 matrix of quaternions or an object of class "Q4", this function will return the rotation matrix equivalent of x. See [Q4](#) or the vignette "rotations-intro" for more details on quaternions.

For x an n-by-9 matrix, rows are treated as 3-by-3 matrices; rows that don't form matrices in SO(3) are projected into SO(3) and those that are already in SO(3) are returned untouched. See [project.SO3](#) for more on projecting arbitrary matrices into SO(3). A message is printed if any of the rows are not proper rotations.

x a "data.frame" is translated into a matrix of the same dimension and the dimensionality of x is used to determine the data type: angle-axis, quaternion or rotation. As demonstrated below, is.SO3 may return TRUE for a data frame, but the functions defined for objects of class "S03" will not be called until as.SO3 has been used.

**Value**

as.S03                    coerces provided data into an S03 type.

is.S03                    returns TRUE or False depending on whether its argument satisfies the conditions to be an rotation matrix. Namely, has determinant one and its transpose is its inverse.

**Examples**

```
data(nickel)                    #Select one location to focus on
Loc698 <- subset(nickel, location == 698)

is.S03(Loc698[,5:13])            #Some of the rows are not rotations due to rounding or entry errors
                                  #as.S03 will project matrices not in S0(3) to S0(3)

Rs <- as.S03(Loc698[,5:13])    #Translate the Rs data.frame into an object of class 'S03'
                                  #Rows 4, 6 and 13 are not in S0(3) so they are projected to S0(3)

mean(Rs)                        #Estimate the central orientation with the average
median(Rs)                      #Re-estimate central orientation robustly
Qs <- as.Q4(Rs)                 #Coerse into "S03" format, see ?as.S03 for more

#Visualize the location, there appears to be two groups
## Not run:
plot(Rs, col = c(1, 2, 3))
## End(Not run)
```

---

bayes.mean

*Parameter estimates based on non-informative Bayes*

---

**Description**

Use non-informative Bayes to estimate the central orientation and concentration parameter of a sample of rotations.

**Usage**

```
bayes.mean(x, type, S0, kappa0, tuneS, tuneK, burn_in,
          m = 5000)

## S3 method for class 'S03'
bayes.mean(x, type, S0, kappa0, tuneS,
          tuneK, burn_in, m = 5000)

## S3 method for class 'Q4'
bayes.mean(x, type, S0, kappa0, tuneS,
          tuneK, burn_in, m = 5000)
```



**Arguments**

x	$n \times p$ matrix where each row corresponds to a random rotation in matrix ( $p = 9$ ) or quaternion ( $p = 4$ ) form.
type	Angular distribution assumed on R. Options are <a href="#">Cayley</a> , <a href="#">Fisher</a> or <a href="#">Mises</a>
S0	initial estimate of central orientation
kappa0	initial estimate of concentration parameter
tuneS	central orientation tuning parameter, concentration of proposal distribution
tuneK	concentration tuning parameter, standard deviation of proposal distribution
burn_in	number of draws to use as burn-in
m	number of draws to keep from posterior distribution

**Details**

The procedures detailed in *Bingham et al. (2009)* and *Bingham et al. (2010)* are implemented to obtain draws from the posterior distribution for the central orientation and concentration parameters for a sample of 3D rotations. A uniform prior on SO(3) is used for the central orientation and the Jeffreys prior determined by type is used for the concentration parameter.

**Value**

list of

- Shat Mode of the posterior distribution for the central orientation S
- kappa Mean of the posterior distribution for the concentration kappa

**References**

Bingham MA, Vardeman SB and Nordman DJ (2009). "Bayes one-sample and one-way random effects analyses for 3-D orientations with application to materials science." *Bayesian Analysis*, 4(3), pp. 607-629.

Bingham MA, Nordman DJ and Vardeman SB (2010). "Finite-sample investigation of likelihood and Bayes inference for the symmetric von Mises-Fisher distribution." *Computational Statistics & Data Analysis*, 54(5), pp. 1317-1327.

**See Also**

[mean.S03](#), [median.S03](#)

**Examples**

```
Rs <- ruars(20, rvmises, kappa = 10)

Shat <- mean(Rs)           #Estimate the central orientation using the projected mean
rotdist.sum(Rs, Shat, p = 2) #The projected mean minimizes the sum of squared Euclidean
rot.dist(Shat)           #distances, compute the minimized sum and estimator bias

#Estimate the central orientation using the posterior mode (not run due to time constraints)
```

```

#Compare it to the projected mean in terms of the squared Euclidean distance and bias
## Not run:
ests <- bayes.mean(Rs, type = "Mises", S0 = mean(Rs), kappa0 = 10, tuneS = 5000,
                  tuneK = 1, burn_in = 1000, m = 5000)

Shat2 <- ests$Shat          #The posterior mode is the 'Shat' object
rotdist.sum(Rs, Shat2, p = 2) #Compute sum of squared Euclidean distances
rot.dist(Shat2)            #Bayes estimator bias
## End(Not run)

```

---

 bayesCR

*Bayes credible regions*


---

### Description

Find the radius of a  $100(1 - \alpha)\%$  credible region for the central orientation and concentration parameter using non-informative Bayesian methods.

### Usage

```

bayesCR(x, type, S0, kappa0, tuneS, tuneK, burn_in,
        m = 5000, alp = 0.1)

## S3 method for class 'S03'
bayesCR(x, type, S0, kappa0, tuneS, tuneK,
        burn_in, m = 5000, alp = 0.1)

## S3 method for class 'Q4'
bayesCR(x, type, S0, kappa0, tuneS, tuneK,
        burn_in, m = 5000, alp = 0.1)

```

### Arguments

x	$n \times p$ matrix where each row corresponds to a random rotation in matrix ( $p = 9$ ) or quaternion ( $p = 4$ ) form.
type	Angular distribution assumed on R. Options are <a href="#">Cayley</a> , <a href="#">Fisher</a> or <a href="#">Mises</a>
S0	initial estimate of central orientation
kappa0	initial estimate of concentration parameter
tuneS	central orientation tuning parameter, concentration of proposal distribution
tuneK	concentration tuning parameter, standard deviation of proposal distribution
burn_in	number of draws to use as burn-in
m	number of draws to keep from posterior distribution
alp	alpha level desired, e.g. 0.05 or 0.10.

**Details**

Compute the radius of a  $100(1 - \alpha)\%$  credible region for the central orientation and concentration parameter as described in *Bingham et al. (2009)* and *Bingham et al. (2010)*. The posterior mode is returned along with the radius of the credible region centered at the posterior mode.

**Value**

list of

- Shat, Qhat Mode of the posterior distribution for the central orientation S
- Radius Radius of the credible region centered at the posterior mode

**References**

Bingham MA, Vardeman SB and Nordman DJ (2009). "Bayes one-sample and one-way random effects analyses for 3-D orientations with application to materials science." *Bayesian Analysis*, 4(3), pp. 607-629.

Bingham MA, Nordman DJ and Vardeman SB (2010). "Finite-sample investigation of likelihood and Bayes inference for the symmetric von Mises-Fisher distribution." *Computational Statistics & Data Analysis*, 54(5), pp. 1317-1327.

**See Also**

[fisheretal](#), [prentice](#), [chang](#), [zhang](#)

**Examples**

```
#Not run due to time constraints
## Not run:
Rs <- ruars(20, rvmises, kappa = 10)

#Compare the region size of the moment based theory mean estimator to the
#Bayes region.

region(Rs, method = "direct", type = "theory", estimator = "mean", alp=0.1, m = 100)
bayesCR <- region(Rs, type = "Mises", method = "Bayes", estimator = "mean", S0 = mean(Rs),
  kappa0 = 10, tuneS = 5000, tuneK = 1, burn_in = 1000, alp = .01, m = 5000)

bayesCR$Radius      #Region size is give by "Radius"
bayesCR$Shat        #The Bayes region is centered around the posterior mode: "Shat"
## End(Not run)
```

Cayley

*The symmetric Cayley distribution***Description**

Density, distribution function and random generation for the Cayley distribution with concentration kappa  $\kappa$ .

**Usage**

```
dcayley(r, kappa = 1, nu = NULL, Haar = TRUE)
```

```
pcayley(q, kappa = 1, nu = NULL, lower.tail = TRUE)
```

```
rcayley(n, kappa = 1, nu = NULL)
```

**Arguments**

r, q	vector of quantiles.
n	number of observations. If length(n)>1, the length is taken to be the number required.
kappa	concentration parameter.
nu	circular variance, can be used in place of kappa.
Haar	logical; if TRUE density is evaluated with respect to the Haar measure.
lower.tail	logical; if TRUE (default) probabilities are $P(X \leq x)$ otherwise, $P(X > x)$ .

**Details**

The symmetric Cayley distribution with concentration  $\kappa$  has density

$$C_C(r|\kappa) = \frac{1}{\sqrt{\pi}} \frac{\Gamma(\kappa + 2)}{\Gamma(\kappa + 1/2)} 2^{-(\kappa+1)} (1 + \cos r)^\kappa (1 - \cos r).$$

The Cayley distribution is equivalent to the de la Vallee Poussin distribution of *Schaeben (1997)*.

**Value**

dcayley	gives the density
pcayley	gives the distribution function
rcayley	generates a vector of random deviates

**References**

Schaeben H (1997). "A Simple Standard Orientation Density Function: The Hyperspherical de la Vallee Poussin Kernel." *Physica Status Solidi (B)*, 200, pp. 367-376.

Leon C, e JM and Rivest L (2006). "A statistical model for random rotations." *Journal of Multivariate Analysis*, 97(2), pp. 412-430.

**See Also**

[Angular-distributions](#) for other distributions in the rotations package.

**Examples**

```
r <- seq(-pi, pi, length = 500)

#Visualize the Cayley density fucntion with respect to the Haar measure
plot(r, dcayley(r, kappa = 10), type = "l", ylab = "f(r)")

#Visualize the Cayley density fucntion with respect to the Lebesgue measure
plot(r, dcayley(r, kappa = 10, Haar = FALSE), type = "l", ylab = "f(r)")

#Plot the Cayley CDF
plot(r, pcayley(r, kappa = 10), type = "l", ylab = "F(r)")

#Generate random observations from Cayley distribution
rs <- rcayley(20, kappa = 1)
hist(rs, breaks = 10)
```

---

cayley.kappa

*Circular variance and concentration parameter*


---

**Description**

Return the concentration parameter that corresponds to a given circular variance.

**Usage**

```
cayley.kappa(nu)
```

**Arguments**

nu                    circular variance

**Details**

The concentration parameter  $\kappa$  does not translate across circular distributions. A commonly used measure of spread in circular distributions that does translate is the circular variance defined as  $\nu = 1 - E[\cos(r)]$  where  $E[\cos(r)]$  is the mean resultant length. See *Mardia et al. (2000)* for more details. This function translates the circular variance  $\nu$  into the corresponding concentration parameter  $\kappa$  for the Cayley distribution.

**Value**

Concentration parameter corresponding to nu.

**References**

Mardia K and Jupp P (2000). Directional statistics. John Wiley & Sons, Chichester, England.

**See Also**

[Cayley](#)

**Examples**

```
#Find the concentration parameter for circular variances 0.25, 0.5, 0.75
cayley.kappa(0.25)
cayley.kappa(0.5)
cayley.kappa(0.75)
```

---

center

*Center rotation data*

---

**Description**

This function will take the sample Rs and return the sample Rs centered at S. That is, the  $i$ th observation of Rs denoted  $R_i$  is returned as  $S^\top R_i$ . If S is the true center then the projected mean should be close to the 3-by-3 identity matrix.

**Usage**

```
center(x, S)

## S3 method for class 'S03'
center(x, S)

## S3 method for class 'Q4'
center(x, S)
```

**Arguments**

x  $n \times p$  matrix where each row corresponds to a random rotation in matrix ( $p = 9$ ) or quaternion ( $p = 4$ ) form.

S the rotation or a matrix of  $n \times p$  rotations about which to center each row of x.

**Value**

The sample centered about S

**Examples**

```
Rs <- ruars(5, rcayley)
cRs <- center(Rs, mean(Rs))
mean(cRs) #Close to identity matrix

all.equal(cRs, Rs - mean(Rs)) #TRUE, center and '-' have the same effect
#See ?"-S03" for more details

center(Rs, Rs) #n-Identity matrices: If the second argument is of the same dimension
#as Rs then each row is centered around the corresponding
#row in the first argument
```

---

 chang

---

*M-estimator asymptotic confidence region*


---

**Description**

Compute the radius of a  $100(1 - \alpha)\%$  confidence region for the central orientation based on M-estimation theory.

**Usage**

```
chang(x, estimator, alp)

## S3 method for class 'S03'
chang(x, estimator, alp = NULL)

## S3 method for class 'Q4'
chang(x, estimator, alp = NULL)
```

**Arguments**

x	$n \times p$ matrix where each row corresponds to a random rotation in matrix ( $p = 9$ ) or quaternion ( $p = 4$ ) form.
estimator	character string either "mean" or "median."
alp	alpha level desired, e.g. 0.05 or 0.10.

**Details**

Compute the radius of a  $100(1 - \alpha)\%$  confidence region for the central orientation centered at the projected mean or median based on a result due to *Chang et al. (2001)* among others. By construction each axis will have the same radius so the radius reported is for all three axes. This method is called "direct" because it uses M-estimation theory for SO(3) directly instead of relying on the transformation of a result from directional statistics like [prentice](#) and [fisheretal](#) do.

**Value**

Radius of the confidence region centered at the specified estimator.

## References

Chang T and Rivest L (2001). "M-estimation for location and regression parameters in group models: A case study using Stiefel manifolds." *Annals of statistics*, 29(3), pp. 784-814.

## See Also

[bayesCR](#), [prentice](#), [fisheretal](#), [zhang](#)

## Examples

```
Rs <- ruars(20, rcayley, kappa = 100)

#The chang method can be accessed from the "region" function or the "chang" function
region(Rs, method = "direct", type = "asymptotic", alp = 0.1, estimator = "mean")
chang(Rs, estimator = "mean", alp = 0.1)
```

---

drill

*Drill data set*

---

## Description

The drill data set was collected to assess variation in human movement while performing a task (Rancourt 1995). Eight subjects drilled into a metal plate while being monitored by infrared cameras. Quaternions are used to represent the orientation of each subjects' wrist, elbow and shoulder in one of six positions. For some subjects several replicates are available. See Rancourt et al. (2000) for one approach to analyzing these data.

## Usage

```
data(drill)
```

## Format

A data frame with 720 observations on the following 8 variables.

Subject Subject number (1-8)  
 Joint Joint name (Wrist, elbow, shoulder)  
 Position Drilling position (1-6)  
 Replicate Replicate number (1-5)  
 Q1 First element of orientation (quaternion)  
 Q2 Second element of orientation (quaternion)  
 Q3 Third element of orientation (quaternion)  
 Q4 Fourth element of orientation (quaternion)



**Source**

<http://www.mat.ulaval.ca/departement-et-professeurs/direction-et-personnel/professeurs/louis-paul-rivest/publications/>

**References**

Rancourt D (1995). "Arm posture and hand mechanical impedance in the control of a hand-held power drill." Ph.D. Thesis, MIT.

Rancourt D, Rivest L and Asselin J (2000). "Using orientation statistics to investigate variations in human kinematics." *Journal of the Royal Statistical Society: Series C (Applied Statistics)*, 49(1), pp. 81-94.

**Examples**

```
#Load dataset into workspace
data(drill)

#Estimate central orientation of the first subject's wrist
Subject1Wrist <- subset(drill, Subject == 1 & Joint == "Wrist")
Qs <- as.Q4(Subject1Wrist[,5:8])
mean(Qs)

#Plot Subject 1's wrist measurements using the connection to rotation matrices
## Not run:
plot(Qs, col = c(1, 2, 3))
## End(Not run)

#Translate the quaternion measurements into rotations and estimate
#the central orientation in terms of rotations
Rs <- as.S03(Qs)
mean(Rs)
```

---

 Fisher

*The matrix-Fisher distribution*


---

**Description**

Density, distribution function and random generation for the matrix-Fisher distribution with concentration  $\kappa$ .

**Usage**

```
dfisher(r, kappa = 1, nu = NULL, Haar = TRUE)

pfisher(q, kappa = 1, nu = NULL, lower.tail = TRUE)

rfisher(n, kappa = 1, nu = NULL)
```

**Arguments**

<code>r, q</code>	vector of quantiles.
<code>n</code>	number of observations. If <code>length(n)&gt;1</code> , the length is taken to be the number required.
<code>kappa</code>	concentration parameter.
<code>nu</code>	circular variance, can be used in place of <code>kappa</code> .
<code>Haar</code>	logical; if TRUE density is evaluated with respect to the Haar measure.
<code>lower.tail</code>	logical; if TRUE (default), probabilities are $P(X \leq x)$ otherwise, $P(X > x)$ .

**Details**

The matrix-Fisher distribution with concentration  $\kappa$  has density

$$C_F(r|\kappa) = \frac{1}{2\pi[I_0(2\kappa) - I_1(2\kappa)]} e^{2\kappa \cos(r)} [1 - \cos(r)]$$

with respect to Lebesgue measure where  $I_p(\cdot)$  denotes the Bessel function of order  $p$  defined as  $I_p(\kappa) = \frac{1}{2\pi} \int_{-\pi}^{\pi} \cos(pr) e^{\kappa \cos r} dr$ . If `kappa>354` then random deviates are generated from the [Cayley](#) distribution because they agree closely for large `kappa` and generation is more stable from the Cayley distribution.

**Value**

<code>dfisher</code>	gives the density
<code>pfisher</code>	gives the distribution function
<code>rfisher</code>	generates random deviates

**See Also**

[Angular-distributions](#) for other distributions in the rotations package.

**Examples**

```
r <- seq(-pi, pi, length = 500)

#Visualize the matrix Fisher density function with respect to the Haar measure
plot(r, dfisher(r, kappa = 10), type = "l", ylab = "f(r)")

#Visualize the matrix Fisher density function with respect to the Lebesgue measure
plot(r, dfisher(r, kappa = 10, Haar = FALSE), type = "l", ylab = "f(r)")

#Plot the matrix Fisher CDF
plot(r, pfisher(r, kappa = 10), type = "l", ylab = "F(r)")

#Generate random observations from matrix Fisher distribution
rs <- rfisher(20, kappa = 1)
hist(rs, breaks = 10)
```

---

`fisher.kappa`*Circular variance and concentration parameter*

---

**Description**

Return the concentration parameter that corresponds to a given circular variance.

**Usage**

```
fisher.kappa(nu)
```

**Arguments**

nu                      circular variance

**Details**

The concentration parameter  $\kappa$  does not translate across circular distributions. A commonly used measure of spread in circular distributions that does translate is the circular variance defined as  $\nu = 1 - E[\cos(r)]$  where  $E[\cos(r)]$  is the mean resultant length. See *Mardia et al. (2000)* for more details. This function translates the circular variance  $\nu$  into the corresponding concentration parameter  $\kappa$  for the matrix-Fisher distribution.

**Value**

Concentration parameter corresponding to nu.

**References**

Mardia K and Jupp P (2000). *Directional statistics*. John Wiley & Sons, Chichester, England.

**See Also**

[Fisher](#)

**Examples**

```
#Find the concentration parameter for circular variances 0.25, 0.5, 0.75
fisher.kappa(0.25)
fisher.kappa(0.5)
fisher.kappa(0.75)
```

fisheretal

*Transformation based pivotal bootstrap confidence region***Description**

Find the radius of a  $100(1-\alpha)\%$  confidence region for the central orientation based on transforming a result from directional statistics.

**Usage**

```
fisheretal(x, alp, boot, m, symm)

## S3 method for class 'Q4'
fisheretal(x, alp = NULL, boot = T,
           m = 300, symm = TRUE)

## S3 method for class 'S03'
fisheretal(x, alp = NULL, boot = T,
           m = 300, symm = T)
```

**Arguments**

x	$n \times p$ matrix where each row corresponds to a random rotation in matrix ( $p = 9$ ) or quaternion ( $p = 4$ ) form.
alp	alpha level desired, e.g. 0.05 or 0.10.
boot	should the bootstrap or normal theory critical value be used.
m	number of bootstrap replicates to use to estimate critical value.
symm	logical; if TRUE (default), a symmetric region is constructed.

**Details**

Compute the radius of a  $100(1 - \alpha)\%$  confidence region for the central orientation based on the projected mean estimator using the method for the mean polar axis as proposed in *Fisher et al. (1996)*. To be able to reduce their method to a radius requires the additional assumption of rotational symmetry, equation (10) in *Fisher et al. (1996)*.

**Value**

Radius of the confidence region centered at the projected mean.

**References**

Fisher N, Hall P, Jing B and Wood A (1996). "Improved pivotal methods for constructing confidence regions with directional data." *Journal of the American Statistical Association*, 91(435), pp. 1062-1070.

**See Also**

[bayesCR](#), [prentice](#), [chang](#), [zhang](#)

**Examples**

```
Qs<-ruars(20, rcayley, kappa = 100, space = 'Q4')

#The Fisher et al. method can be accessed from the "region" function or the "fisheretal" function
region(Qs, method = "transformation", type = "bootstrap", alp = 0.1,
symm = TRUE, estimator = "mean")
fisheretal(Qs, alp = 0.1, boot = TRUE, symm = TRUE)
```

---

genR	<i>Generate rotations</i>
------	---------------------------

---

**Description**

Generate rotations in matrix format using Rodrigues' formula or quaternions.

**Usage**

```
genR(r, S = NULL, space = "SO3")
```

**Arguments**

<code>r</code>	vector of angles.
<code>S</code>	central orientation.
<code>space</code>	indicates the desired representation: rotation matrix "SO3" or quaternions "Q4."

**Details**

Given a vector  $U = (u_1, u_2, u_3)^\top \in R^3$  of length one and angle of rotation  $r$ , a  $3 \times 3$  rotation matrix is formed using Rodrigues' formula

$$\cos(r)I_{3 \times 3} + \sin(r)\Phi(U) + (1 - \cos(r))UU^\top$$

where  $I_{3 \times 3}$  is the  $3 \times 3$  identity matrix,  $\Phi(U)$  is a  $3 \times 3$  skew-symmetric matrix with upper triangular elements  $-u_3, u_2$  and  $-u_1$  in that order.

For the same vector and angle a quaternion is formed according to

$$q = [\cos(\theta/2), \sin(\theta/2)U]^\top.$$

**Value**

A  $n \times p$  matrix where each row is a random rotation matrix ( $p = 9$ ) or quaternion ( $p = 4$ ).

**Examples**

```
r <- rvmises(20, kappa = 0.01)
Rs <- genR(r, space = "S03")
Qs <- genR(r, space = "Q4")
```

---

 gradient.search

*Gradient optimization for rotation data*


---

**Description**

Gradient based optimization for user defined central orientation of a rotation sample.

**Usage**

```
gradient.search(sample, error, minerr = 1e-05,
  start = mean(sample), theta = NULL)
```

**Arguments**

sample	sample of rotations.
error	user defined function to observed distance between sample and estimate, has to have parameters for the sample and the estimate.
minerr	minimal distance to consider for convergence.
start	starting value for the estimation.
theta	size of the grid considered.

**Value**

list of

- Shat estimate of the main direction
- iter number of iterations necessary for convergence
- theta final size of the grid
- minerr error used for convergence
- error numeric value of total sample's distance from main direction

**Examples**

```
# minimize L1 norm:
L1.error <- function(sample, Shat) {
  sum(rot.dist(sample, Shat, method = "intrinsic", p = 1))
}

cayley.sample <- ruars(n = 10, rangle = rcayley, nu = 1, space = 'S03')
SL1 <- gradient.search(cayley.sample, L1.error, start = id.S03)
```

```
# visually no perceptible difference between median estimates from in-built function and
# gradient based search (for almost all starting values)

## Not run:
plot(cayley.sample, center=SL1$Shat, show_estimates="all")
## End(Not run)
```

---

Haar	<i>Uniform distribution</i>
------	-----------------------------

---

### Description

Density, distribution function and random generation for the uniform distribution.

### Usage

```
dhaar(r)

phaar(q, lower.tail = TRUE)

rhaar(n)
```

### Arguments

r, q	vector of quantiles.
n	number of observations. If length(n)>1, the length is taken to be the number required.
lower.tail	logical; if TRUE (default), probabilities are $P(X \leq x)$ otherwise, $P(X > x)$ .

### Details

The uniform distribution has density

$$C_U(r) = \frac{[1 - \cos(r)]}{2\pi}$$

with respect to the Lebesgue measure. The Haar measure is the volume invariant measure for SO(3) that plays the role of the uniform measure on SO(3) and  $C_U(r)$  is the angular distribution that corresponds to the uniform distribution on SO(3), see [UARS](#). The uniform distribution with respect to the Haar measure is given by

$$C_U(r) = \frac{1}{2\pi}.$$

Because the uniform distribution with respect to the Haar measure gives a horizontal line at 1 with respect to the Lebesgue measure, we called this distribution 'Haar.'

**Value**

dhaar	gives the density
phaar	gives the distribution function
rhaar	generates random deviates

**See Also**

[Angular-distributions](#) for other distributions in the rotations package.

**Examples**

```
r <- seq(-pi, pi, length = 1000)

#Visualize the uniform distribution with respect to Lebesgue measure
plot(r, dhaar(r), type = "l", ylab = "f(r)")

#Visualize the uniform distribution with respect to Haar measure, which is
#a horizontal line at 1
plot(r, 2*pi*dhaar(r)/(1-cos(r)), type = "l", ylab = "f(r)")

#Plot the uniform CDF
plot(r,phaar(r), type = "l", ylab = "F(r)")

#Generate random observations from uniform distribution
rs <- rhaar(50)

#Visualize on the real line
hist(rs, breaks = 10)
```

---

log.S03

*Rotation logarithm*


---

**Description**

Compute the logarithm of a rotation matrix, which results in a  $3 \times 3$  skew-symmetric matrix. This function maps the lie group  $SO(3)$  into its tangent space, which is the space of all  $3 \times 3$  skew symmetric matrices, the lie algebra  $so(3)$ . For details see e.g. *Moakher (2002)*.

**Usage**

```
## S3 method for class 'S03'
log(x, ...)
```

**Arguments**

x	$n \times 9$ matrix where each row corresponds to a random rotation matrix.
...	additional arguments.



**Value**

Skew symmetric matrix  $\log(R)$ .

**References**

Moakher M (2002). "Means and averaging in the group of rotations." *SIAM Journal on Matrix Analysis and Applications*, 24(1), pp. 1-16.

**Examples**

```
Rs <- ruars(20, rcayley)

#Here we demonstrate how the logarithm can be used to determine the angle and
#axis corresponding to the provided sample

lRs <- log(Rs)           #Take the logarithm of the sample
Ws <- lRs[,c(6, 7, 2)]   #The appropriate diagonal entries are the axis*angle
lens <- sqrt(rowSums(Ws^2))
axes <- mis.axis(Rs)
angs <- mis.angle(Rs)
all.equal(axes, Ws/lens)
all.equal(angs, lens)
```

---

MCMCSO3

*MCMC for rotation data*


---

**Description**

Use non-informative Bayesian methods to infer about the central orientation and concentration parameter for a sample of rotations.

**Usage**

```
MCMCSO3(x, type, S0, kappa0, tuneS, tuneK, burn_in,
        m = 5000)

## S3 method for class 'S03'
MCMCSO3(x, type, S0, kappa0, tuneS, tuneK,
        burn_in, m = 5000)

## S3 method for class 'Q4'
MCMCSO3(x, type, S0, kappa0, tuneS, tuneK,
        burn_in, m = 5000)
```

**Arguments**

x	$n \times p$ matrix where each row corresponds to a random rotation in matrix ( $p = 9$ ) or quaternion ( $p = 4$ ) form.
type	Angular distribution assumed on R. Options are <a href="#">Cayley</a> , <a href="#">Fisher</a> or <a href="#">Mises</a>
S0	initial estimate of central orientation
kappa0	initial estimate of concentration parameter
tuneS	central orientation tuning parameter, concentration of proposal distribution
tuneK	concentration tuning parameter, standard deviation of proposal distribution
burn_in	number of draws to use as burn-in
m	number of draws to keep from posterior distribution

**Details**

The procedures detailed in *Bingham et al. (2009)* and *Bingham et al. (2010)* are implemented to obtain draws from the posterior distribution for the central orientation and concentration parameters for a sample of 3D rotations. A uniform prior on SO(3) is used for the central orientation and the Jeffreys prior determined by type is used for the concentration parameter.

**Value**

list of

- S Draws from the posterior distribution for central orientation S
- kappa Draws from the posterior distribution for concentration parameter kappa
- Saccept Acceptance rate for central orientation draws
- Kaccept Acceptance rate for concentration draws

**References**

Bingham MA, Vardeman SB and Nordman DJ (2009). "Bayes one-sample and one-way random effects analyses for 3-D orientations with application to materials science." *Bayesian Analysis*, 4(3), pp. 607-629.

Bingham MA, Nordman DJ and Vardeman SB (2010). "Finite-sample investigation of likelihood and Bayes inference for the symmetric von Mises-Fisher distribution." *Computational Statistics & Data Analysis*, 54(5), pp. 1317-1327.

**Examples**

```
#Not run due to time constraints
## Not run:
Rs <- ruars(20, rvmises, kappa = 10)
draws <- MCMCSO3(Rs, type = "Mises", S0 = mean(Rs), kappa0 = 10, tuneS = 5000,
  tuneK = 1, burn_in = 1000, m = 5000)
## End(Not run)
```

---

 mean.SO3

*Mean rotation*


---

## Description

Compute the sample geometric or projected mean.

## Usage

```
## S3 method for class 'SO3'
mean(x, type = "projected",
     epsilon = 1e-05, maxIter = 2000, ...)

## S3 method for class 'Q4'
mean(x, type = "projected",
     epsilon = 1e-05, maxIter = 2000, ...)
```

## Arguments

x	$n \times p$ matrix where each row corresponds to a random rotation in matrix form ( $p = 9$ ) or quaternion ( $p = 4$ ) form.
type	string indicating "projected" or "geometric" type mean estimator.
epsilon	stopping rule for the geometric-mean.
maxIter	maximum number of iterations allowed for geometric-mean.
...	additional arguments.

## Details

This function takes a sample of 3D rotations (in matrix or quaternion form) and returns the projected arithmetic mean denoted  $\widehat{S}_P$  or geometric mean  $\widehat{S}_G$  according to the type option. For a sample of  $n$  rotations in matrix form  $\mathbf{R}_i \in SO(3), i = 1, 2, \dots, n$ , the mean-type estimator is defined as

$$\widehat{S} = \operatorname{argmin}_{S \in SO(3)} \sum_{i=1}^n d^2(\mathbf{R}_i, S)$$

where  $d$  is the Riemannian or Euclidean distance. For more on the projected mean see *Moakher (2002)* and for the geometric mean see *Manton (2004)*. For the projected mean from a quaternion point of view see *Tyler (1981)*.

## Value

Estimate of the projected or geometric mean of the sample in the same parameterization.

## References

Moakher M (2002). "Means and averaging in the group of rotations." *SIAM Journal on Matrix Analysis and Applications*, 24(1), pp. 1-16.

Manton JH (2004). "A globally convergent numerical algorithm for computing the centre of mass on compact Lie groups." In *Control, Automation, Robotics and Vision Conference, 2004. ICARCV 2004 8th*, volume 3, pp. 2211-2216. IEEE.

Tyler DE (1981). "Asymptotic inference for eigenvectors." *The Annals of Statistics*, 9(4), pp. 725-736.

## See Also

[median.S03](#), [bayes.mean](#), [weighted.mean.S03](#)

## Examples

```
Rs <- ruars(20, rvmises, kappa = 0.01)
mean(Rs)                                #Projected mean
project.S03(colMeans(Rs))                #Same as mean(Rs)

mean(Rs, type = "geometric")            #Geometric mean
rot.dist(mean(Rs))                       #Bias of the projected mean
rot.dist(mean(Rs, type = "geometric"))  #Bias of the geometric mean

Qs <- as.Q4(Rs)
mean(Qs)                                #Projected mean
mean(Qs, type = "geometric")            #Geometric mean
rot.dist(mean(Qs))                       #Bias of the projected mean
rot.dist(mean(Qs, type = "geometric"))  #Bias of the geometric mean
```

---

median.S03

*Median rotation*

---

## Description

Compute the sample projected or geometric median.

## Usage

```
median(x, ...)

## S3 method for class 'S03'
median(x, type = "projected",
       epsilon = 1e-05, maxIter = 2000, ...)

## S3 method for class 'Q4'
median(x, type = "projected",
       epsilon = 1e-05, maxIter = 2000, ...)
```

**Arguments**

x	$n \times p$ matrix where each row corresponds to a random rotation in matrix form ( $p = 9$ ) or quaternion ( $p = 4$ ) form.
type	string indicating "projected" or "geometric" type mean estimator.
epsilon	stopping rule.
maxIter	maximum number of iterations allowed before returning most recent estimate.
...	additional arguments.

**Details**

The median-type estimators are defined as

$$\tilde{\mathbf{S}} = \operatorname{argmin}_{\mathbf{S} \in SO(3)} \sum_{i=1}^n d(\mathbf{R}_i, \mathbf{S}).$$

If the choice of distance metric  $d$  is Riemannian then the estimator is called the geometric median, and if the distance metric is Euclidean then it is called the projected median. The algorithm used in the geometric case is discussed in *Hartley et al. (2011)* and the projected case is in *Stanfill et al. (2013)*.

**Value**

Estimate of the projected or geometric median in the same parameterization.

**References**

Hartley R, Aftab K and Trunpf J (2011). "L1 rotation averaging using the Weiszfeld algorithm." In 2011 IEEE Conference on Computer Vision and Pattern Recognition (CVPR), pp. 3041-3048. IEEE.

Stanfill B, Genschel U and Hofmann H (2013). "Point Estimation of the Central Orientation of Random Rotations." *Technometrics*, 55(4), pp. 524-535.

**See Also**

[mean.S03](#), [bayes.mean](#), [weighted.mean.S03](#)

**Examples**

```
Rs <- ruars(20, rvmises, kappa = 0.01)
median(Rs) #Projected median
median(Rs, type = "geometric") #Geometric median
rot.dist(median(Rs)) #Bias of the projected median
rot.dist(median(Rs, type = "geometric")) #Bias of the geometric median

Qs <- as.Q4(Rs)
median(Qs) #Projected median
median(Qs, type = "geometric") #Geometric median
rot.dist(median(Qs)) #Bias of the projected median
rot.dist(median(Qs, type = "geometric")) #Bias of the geometric median
```

---

mis.angle	<i>Misorientation angle</i>
-----------	-----------------------------

---

**Description**

Compute the misorientation angle of a rotation.

**Usage**

```
mis.angle(x)

## S3 method for class 'S03'
mis.angle(x)

## S3 method for class 'Q4'
mis.angle(x)
```

**Arguments**

`x`  $n \times p$  matrix where each row corresponds to a random rotation in matrix ( $p = 9$ ) or quaternion ( $p = 4$ ) form.

**Details**

Every rotation can be thought of as some reference coordinate system rotated about an axis through an angle. These quantities are referred to as the misorientation axis and misorientation angle, respectively, in the material sciences literature. This function returns the misorientation angle associated with a rotation assuming the reference coordinate system is the identity.

**Value**

Angle of rotation.

**See Also**

[mis.axis](#)

**Examples**

```
rs <- rcayley(20, kappa = 20)
Rs <- genR(rs, S = id.S03)
mis.angle(Rs)

#If the central orientation is id.S03 then mis.angle(Rs) and abs(rs) are equal
all.equal(mis.angle(Rs), abs(rs)) #TRUE

#For other reference frames, the data must be centered first
S <- genR(pi/2)
RsS <- genR(rs, S = S)
```

```

mis.axis(RsS-S)
all.equal(mis.angle(RsS-S),abs(rs)) #TRUE

#If the central orientation is NOT id.S03 then mis.angle(Rs) and abs(rs) are usual unequal
Rs <- genR(rs, S = genR(pi/8))
all.equal(mis.angle(Rs), abs(rs)) #Mean relative difference > 0

```

---

 mis.axis

*Misorientation axis*


---

### Description

Determine the misorientation axis of a rotation.

### Usage

```

mis.axis(x, ...)

## S3 method for class 'S03'
mis.axis(x, ...)

## S3 method for class 'Q4'
mis.axis(x, ...)

```

### Arguments

`x`  $n \times p$  matrix where each row corresponds to a random rotation in matrix ( $p = 9$ ) or quaternion ( $p = 4$ ) form.

`...` additional arguments.

### Details

Every rotation can be interpreted as some reference coordinate system rotated about an axis through an angle. These quantities are referred to as the misorientation axis and misorientation angle, respectively, in the material sciences literature. This function returns the misorientation axis associated with a rotation assuming the reference coordinate system is the identity. The data must be centered before calling `mis.axis` if a different coordinate system is required.

### Value

Axis in form of three dimensional vector of length one.

### See Also

[mis.angle](#)

**Examples**

```
rs <- rcayley(20, kappa = 20)

#If the reference frame is set to id.S03 then no centering is required
Rs <- genR(rs, S = id.S03)
mis.axis(Rs)
all.equal(Rs, as.S03(mis.axis(Rs), mis.angle(Rs)))

#For other reference frames, the data must be centered first
S <- genR(pi/2)
RsS <- genR(rs, S = S)
mis.axis(RsS-S)
all.equal(mis.angle(RsS-S), abs(rs)) #TRUE

Qs <- genR(rs, S = id.Q4, space = "Q4")
mis.axis(Qs)
all.equal(Qs, as.Q4(mis.axis(Qs), mis.angle(Qs)))
```

Mises

*The circular-von Mises distribution***Description**

Density, distribution function and random generation for the circular-von Mises distribution with concentration kappa  $\kappa$ .

**Usage**

```
dvmises(r, kappa = 1, nu = NULL, Haar = T)
pvmises(q, kappa = 1, nu = NULL, lower.tail = TRUE)
rvmises(n, kappa = 1, nu = NULL)
```

**Arguments**

r,q	vector of quantiles
n	number of observations. If length(n)>1, the length is taken to be the number required.
kappa	concentration parameter.
nu	circular variance, can be used in place of kappa.
Haar	logical; if TRUE density is evaluated with respect to the Haar measure.
lower.tail	logical; if TRUE (default), probabilities are $P(X \leq x)$ otherwise, $P(X > x)$ .



**Details**

The circular von Mises distribution with concentration  $\kappa$  has density

$$C_M(r|\kappa) = \frac{1}{2\pi I_0(\kappa)} e^{\kappa \cos(r)}.$$

where  $I_0(\kappa)$  is the modified Bessel function of order 0.

**Value**

dvmises	gives the density
pvmises	gives the distribution function
rvmises	generates random deviates

**See Also**

[Angular-distributions](#) for other distributions in the rotations package.

**Examples**

```
r <- seq(-pi, pi, length = 500)

#Visualize the von Mises density function with respect to the Haar measure
plot(r, dvmises(r, kappa = 10), type = "l", ylab = "f(r)", ylim = c(0, 100))

#Visualize the von Mises density function with respect to the Lebesgue measure
plot(r, dvmises(r, kappa = 10, Haar = FALSE), type = "l", ylab = "f(r)")

#Plot the von Mises CDF
plot(r, pvmises(r, kappa = 10), type = "l", ylab = "F(r)")

#Generate random observations from von Mises distribution
rs <- rvmises(20, kappa = 1)
hist(rs, breaks = 10)
```

---

nickel

*Nickel electron backscatter diffraction data set*


---

**Description**

Collection of EBSD data for a piece of nickel.

**Usage**

```
data(nickel)
```

**Format**

A data frame with 48,286 rows and the following 13 columns

xpos location x position

ypos location y position

location Location number for easy reference

rep Replicate scan identifier

V1 First element of x-axis describing crystal orientation at corresponding location

V2 Second element of x-axis describing crystal orientation at corresponding location

V3 Third element of x-axis describing crystal orientation at corresponding location

V4 First element of y-axis describing crystal orientation at corresponding location

V5 Second element of y-axis describing crystal orientation at corresponding location

V6 Third element of y-axis describing crystal orientation at corresponding location

V7 First element of z-axis describing crystal orientation at corresponding location

V8 Second element of z-axis describing crystal orientation at corresponding location

V9 Third element of z-axis describing crystal orientation at corresponding location

**Details**

This data set consists of electron backscatter diffraction (EBSD) data obtained by scanning a fixed 12.5  $\mu\text{m}$ -by-10  $\mu\text{m}$  nickel surface at individual locations spaced 0.2  $\mu\text{m}$  apart. This scan was repeated 14 times for each of the 3,449 locations yielding a total of 48,286 observations. Every observation corresponds to the orientation, expressed as a rotation matrix, of a cubic crystal on the metal surface at a particular location. Be aware that there are missing values and erroneous scans at some locations and scans. See Bingham et al. (2009) and Bingham et al. (2010) for more details and analysis.

**Source**

The data set was collected by The Ames Lab located in Ames, IA.

**References**

Bingham, M. A., Nordman, D., & Vardeman, S. (2009). "Modeling and inference for measured crystal orientations and a tractable class of symmetric distributions for rotations in three dimensions." *Journal of the American Statistical Association*, 104(488), pp. 1385-1397.

Bingham, M. A., Lograsso, B. K., & Laabs, F. C. (2010). "A statistical analysis of the variation in measured crystal orientations obtained through electron backscatter diffraction." *Ultramicroscopy*, 110(10), pp. 1312-1319.

Stanfill, B., Genschel, U., & Heike, H. (2013). "Point estimation of the central orientation of random rotations". *Technometrics*, 55(4), pp. 524-535.

**Examples**

```

data(nickel) #Load the dataset
Rep1 <- subset(nickel, rep == 1) #Subset the data to include only the first scan

#Get a rough idea of how the grain map looks by plotting the first
#element of the rotation matrix at each location
qplot(xpos, ypos, data = Rep1, colour = V1, size = I(2))

#Focus in on a particular location, for example location 698
Rs <- subset(nickel, location == 698)

Rs <- as.S03(Rs[,5:13])      #Translate the Rs data.frame into an object of class 'S03'
Rs <- Rs[is.S03(Rs),]      #Some observations are not rotations, remove them
mean(Rs)                   #Estimate the central orientation with the average
median(Rs)                 #Resetimate central orientation robustly
## Not run:
plot(Rs, col = c(1, 2, 3)) #Visualize the location, there appears to be two groups
## End(Not run)

```

---

plot.S03

*Visualizing random rotations*


---

**Description**

This function produces an interactive or static three-dimensional globe onto which one of the columns of the provided sample of rotations is projected. The data are centered around a user-specified rotation matrix. The interactive plot is based on the `sphereplot` package and the static plot uses `ggplot2`.

**Usage**

```

## S3 method for class 'S03'
plot(x, center = mean(x), col = 1,
     to_range = FALSE, show_estimates = NULL,
     label_points = NULL, mean_regions = NULL,
     median_regions = NULL, alp = NULL, m = 300,
     interactive = FALSE, ...)

## S3 method for class 'Q4'
plot(x, center = mean(x), col = 1,
     to_range = FALSE, show_estimates = NULL,
     label_points = NULL, mean_regions = NULL,
     median_regions = NULL, alp = NULL, m = 300,
     interactive = FALSE, ...)

```

**Arguments**

<code>x</code>	n rotations in SO3 or Q4 format.
<code>center</code>	rotation about which to center the observations.
<code>col</code>	integer or vector comprised of 1, 2, 3 indicating which column(s) to display. If <code>length(col)&gt;1</code> then each eyeball is labelled with the corresponding axis.
<code>to_range</code>	logical; if TRUE only part of the globe relevant to the data is displayed
<code>show_estimates</code>	character vector to specify which of the four estimates of the principal direction to show. Possibilities are "all", "proj.mean", "proj.median", "geom.mean", "geom.median".
<code>label_points</code>	vector of labels.
<code>mean_regions</code>	character vector to specify which of the three confidence regions to show for the projected mean. Possibilities are "all", "trans.theory", "trans.bootstrap", "direct.theory", "direct.bootstrap".
<code>median_regions</code>	character vector to specify which of the three confidence regions to show for the projected median. Possibilities are "all", "theory", "bootstrap."
<code>alp</code>	alpha level to be used for confidence regions. See <a href="#">region</a> for more details.
<code>m</code>	number of bootstrap replicates to use in bootstrap confidence regions.
<code>interactive</code>	logical; if TRUE <code>sphereplot</code> is used to create an interactive 3D plot, otherwise <code>ggplot2</code> is used
<code>...</code>	parameters passed onto the points layer.

**Value**

A visualization of rotation data.

**Note**

The option `interactive=TRUE` requires the `sphereplot` package. If `sphereplot` is not available then the static plot is created.

**Examples**

```
r <- rvmises(200, kappa = 1.0)
Rs <- genR(r)

plot(Rs, center = mean(Rs), show_estimates = "proj.mean", shape = 4)

## Not run:
# Z is computed internally and contains information on depth
plot(Rs, center = mean(Rs), show_estimates = c("proj.mean", "geom.mean"),
     label_points = sample(LETTERS, 200, replace = TRUE)) + aes(size = Z, alpha = Z) +
  scale_size(limits = c(-1, 1), range = c(0.5, 2.5))

plot(Rs, center = mean(Rs), interactive = TRUE)
## End(Not run)
```

---

pointsXYZ                      *Project rotation data onto sphere*

---

**Description**

Projection of rotation matrices onto sphere with given center.

**Usage**

```
pointsXYZ(data, center = id.S03, column = 1)
```

**Arguments**

data                      data frame of rotation matrices in  $3 \times 3$  matrix representation.  
center                    rotation matrix about which to center the observations.  
column                    integer 1 to 3 indicating which column to display.

**Value**

Data frame with columns X, Y, Z standing for the respective coordinates in 3D space.

**Examples**

```
Rs<-ruars(20, rcayley)

#Project the sample's 3 axes onto the 3-sphere centered at the identity rotation

pointsXYZ(Rs, center = id.S03, column = 1) #x-axis
pointsXYZ(Rs, center = id.S03, column = 2) #y-axis
pointsXYZ(Rs, center = id.S03, column = 3) #z-axis
```

---

prentice                      *Transformation based asymptotic confidence region*

---

**Description**

Find the radius of a  $100(1 - \alpha)\%$  confidence region for the projected mean based on a result from directional statistics.

**Usage**

```
prentice(x, alp)

## S3 method for class 'Q4'
prentice(x, alp = NULL)

## S3 method for class 'S03'
prentice(x, alp = NULL)
```

**Arguments**

x	$n \times p$ matrix where each row corresponds to a random rotation in matrix ( $p = 9$ ) or quaternion ( $p = 4$ ) form.
alp	alpha level desired, e.g. 0.05 or 0.10.

**Details**

Compute the radius of a  $100(1 - \alpha)\%$  confidence region for the central orientation based on the projected mean estimator using the method due to *Prentice (1986)*. For a rotation specific version see *Rancourt et al. (2000)*. The variability in each axis is different so each axis will have its own radius.

**Value**

Radius of the confidence region centered at the projected mean for each of the x-, y- and z-axes.

**References**

Prentice M (1986). "Orientation statistics without parametric assumptions." *Journal of the Royal Statistical Society. Series B (Methodological)*, 48(2), pp. 214-222.

Rancourt D, Rivest L and Asselin J (2000). "Using orientation statistics to investigate variations in human kinematics." *Journal of the Royal Statistical Society: Series C (Applied Statistics)*, 49(1), pp. 81-94.

**See Also**

[bayesCR](#), [fisheretal](#), [chang](#), [zhang](#)

**Examples**

```
Qs<-ruars(20, rcayley, kappa = 100, space = 'Q4')

#The prentice method can be accessed from the "region" function or the "prentice" function
region(Qs, method = "transformation", type = "asymptotic", alp = 0.1, estimator = "mean")
prentice(Qs, alp = 0.1)
```

---

project.SO3

*Projection into SO(3)*

---

**Description**

Project an arbitrary  $3 \times 3$  matrix into  $SO(3)$ .

**Usage**

```
project.SO3(M)
```

**Arguments**

$M$   $3 \times 3$  matrix to project into  $SO(3)$ .

**Details**

This function uses the process detailed in Section 3.1 of *Moakher (2002)* to project an arbitrary  $3 \times 3$  matrix into  $SO(3)$ . More specifically it finds the closest orthogonal 3-by-3 matrix with determinant one to the provided matrix.

**Value**

Projection of  $M$  into  $SO(3)$ .

**References**

Moakher M (2002). "Means and averaging in the group of rotations." *SIAM Journal on Matrix Analysis and Applications*, 24(1), pp. 1-16.

**See Also**

[mean.S03](#), [median.S03](#)

**Examples**

```
#Project an arbitrary 3x3 matrix into SO(3)
M<-matrix(rnorm(9), 3, 3)
project.S03(M)

#Project a sample arithmetic mean into SO(3), same as 'mean'
Rs <- ruars(20, rcayley)
Rbar <- colSums(Rs)/nrow(Rs)
project.S03(Rbar)          #The following is equivalent
mean(Rs)
```

---

Q4-class

*Q4 class.*

---

**Description**

Class for quaternion representation of rotations.

**See Also**

See the [Q4](#) functions.

---

 region

*Confidence and credible regions for the central orientation*


---

### Description

Find the radius of a  $100(1 - \alpha)\%$  confidence or credible region for the central orientation based on the projected mean or median. For more on the currently available methods see [prentice](#), [fisheretal](#), [chang](#), [zhang](#) and [bayesCR](#).

### Usage

```
region(x, method, type, estimator, alp, ...)
```

```
## S3 method for class 'Q4'
region(x, method, type, estimator,
      alp = NULL, ...)
```

```
## S3 method for class 'S03'
region(x, method, type, estimator,
      alp = NULL, ...)
```

### Arguments

x	$n \times p$ matrix where each row corresponds to a random rotation in matrix ( $p = 9$ ) or quaternion ( $p = 4$ ) form.
method	character string specifying which type of interval to report, "bayes", "transformation" or "direct" based theory.
type	character string, "bootstrap" or "asymptotic" are available. For Bayes regions, give the type of likelihood: "Cayley", "Mises" or "Fisher."
estimator	character string either "mean" or "median." Note that not all method/type combinations are available for both estimators.
alp	the alpha level desired, e.g. 0.05 or 0.10.
...	additional arguments that are method specific.

### Value

For frequentist regions only the radius of the confidence region centered at the specified estimator is returned. For Bayes regions the posterior mode and radius of the credible region centered at that mode is returned.

### See Also

[bayesCR](#), [prentice](#), [fisheretal](#), [chang](#), [zhang](#)



**Examples**

```
Rs <- ruars(20, rvmises, kappa = 10)

#Compare the region sizes that are currently available

region(Rs, method = "transformation", type = "asymptotic", estimator = "mean", alp = 0.1)
region(Rs, method = "transformation", type = "bootstrap", estimator = "mean",
alp = 0.1, symm = TRUE)
region(Rs, method = "direct", type = "bootstrap", estimator = "mean", alp = 0.1, m = 100)
region(Rs, method = "direct", type = "asymptotic", estimator = "mean", alp = 0.1)
## Not run:
region(Rs, method = "Bayes", type = "Mises", estimator = "mean",
      S0 = mean(Rs), kappa0 = 10, tuneS = 5000, tuneK = 1, burn_in = 1000, alp = .01, m = 5000)
## End(Not run)
```

---

rot.dist

*Rotational distance*


---

**Description**

Calculate the extrinsic or intrinsic distance between two rotations.

**Usage**

```
rot.dist(x, ...)

## S3 method for class 'S03'
rot.dist(x, R2 = id.S03,
  method = "extrinsic", p = 1, ...)

## S3 method for class 'Q4'
rot.dist(x, Q2 = id.Q4,
  method = "extrinsic", p = 1, ...)
```

**Arguments**

x	$n \times p$ matrix where each row corresponds to a random rotation in matrix ( $p = 9$ ) or quaternion ( $p = 4$ ) form.
R2, Q2	the second rotation in the same parameterization as x.
method	string indicating "extrinsic" or "intrinsic" method of distance.
p	the order of the distance.
...	additional arguments.

**Details**

This function will calculate the intrinsic (Riemannian) or extrinsic (Euclidean) distance between two rotations. R2 and Q2 are set to the identity rotations by default. For rotations  $R_1$  and  $R_2$  both in  $SO(3)$ , the Euclidean distance between them is

$$\|R_1 - R_2\|_F$$

where  $\|\cdot\|_F$  is the Frobenius norm. The Riemannian distance is defined as

$$\|Log(R_1^T R_2)\|_F$$

where  $Log$  is the matrix logarithm, and it corresponds to the misorientation angle of  $R_1^T R_2$ . See the vignette ‘rotations-intro’ for a comparison of these two distance measures.

**Value**

The rotational distance between each rotation in x and R2 or Q2.

**Examples**

```
rs <- rcayley(20, kappa = 10)
Rs <- genR(rs, S = id.S03)
dEs <- rot.dist(Rs, id.S03)
dRs <- rot.dist(Rs, id.S03 , method = "intrinsic")

#The intrinsic distance between the true central orientation and each observation
#is the same as the absolute value of observations' respective misorientation angles
all.equal(dRs, abs(rs))          #TRUE

#The extrinsic distance is related to the intrinsic distance
all.equal(dEs, 2*sqrt(2)*sin(dRs/2)) #TRUE
```

---

rotations

*A package for working with rotation data.*


---

**Description**

This package implements tools for working with rotational data: it allows simulation from the most commonly used distributions on  $SO(3)$ , it includes methods for different mean and median type estimators for the central orientation of a sample, it provides confidence regions for those estimates and it includes a novel visualization technique for rotation data.

---

rotdist.sum	<i>Sample distance</i>
-------------	------------------------

---

### Description

Compute the sum of the  $p^{\text{th}}$  order distances between each row of  $x$  and  $S$ .

### Usage

```
rotdist.sum(x, S = genR(0, space = class(x)),
  method = "extrinsic", p = 1)

## S3 method for class 'S03'
rotdist.sum(x, S = id.S03,
  method = "extrinsic", p = 1)

## S3 method for class 'Q4'
rotdist.sum(x, S = id.Q4,
  method = "extrinsic", p = 1)
```

### Arguments

$x$	$n \times p$ matrix where each row corresponds to a random rotation in matrix ( $p = 9$ ) or quaternion ( $p = 4$ ) form.
$S$	the individual matrix of interest, usually an estimate of the mean.
method	type of distance used method in "extrinsic" or "intrinsic"
$p$	the order of the distances to compute.

### Value

The sum of the  $p$ th order distance between each row of  $x$  and  $S$ .

### See Also

[rot.dist](#)

### Examples

```
Rs <- ruars(20, rvmises, kappa = 10)

SE1 <- median(Rs)           #Projected median
SE2 <- mean(Rs)            #Projected mean
SR2 <- mean(Rs, type = "geometric") #Geometric mean

#I will use "rotdist.sum" to verify these three estimators minimize the
#loss function they are designed to minimize relative to the other estimators.
#All of the following statements should evaluate to "TRUE"
```

```

#The projected mean minimizes the sum of squared Euclidean distances
rotdist.sum(Rs, S = SE2, p = 2) < rotdist.sum(Rs, S = SE1, p = 2)
rotdist.sum(Rs, S = SE2, p = 2) < rotdist.sum(Rs, S = SR2, p = 2)

#The projected median minimizes the sum of first order Euclidean distances
rotdist.sum(Rs, S = SE1, p = 1) < rotdist.sum(Rs, S = SE2, p = 1)
rotdist.sum(Rs, S = SE1, p = 1) < rotdist.sum(Rs, S = SR2, p = 1)

#The geometric mean minimizes the sum of squared Riemannian distances
rotdist.sum(Rs, S = SR2, p = 2, method = "intrinsic") <
  rotdist.sum(Rs, S = SE1, p = 2, method = "intrinsic")
rotdist.sum(Rs, S = SR2, p = 2, method = "intrinsic") <
  rotdist.sum(Rs, S = SE2, p = 2, method = "intrinsic")

```

---

skew.exp

*Matrix exponential*


---

## Description

Compute the matrix exponential for skew-symmetric matrices according to the usual Taylor expansion. The expansion is significantly simplified for skew-symmetric matrices, see *Moakher (2002)*. Maps a matrix belonging to the lie algebra  $so(3)$  into the lie group  $SO(3)$ .

## Usage

```
skew.exp(x)
```

## Arguments

`x` single  $3 \times 3$  skew-symmetric matrix or  $n \times 9$  sample of skew-symmetric matrices.

## Value

Matrix  $e^H$  in  $SO(3)$ .

## References

Moakher M (2002). "Means and averaging in the group of rotations." *SIAM Journal on Matrix Analysis and Applications*, 24(1), pp. 1-16.

## Examples

```

Rs <- ruars(20, rcayley)
lRs <- log(Rs)           #Take the matrix logarithm for rotation matrices
Rs2 <- skew.exp(lRs)    #Go back to rotation matrices
all.equal(Rs, Rs2)

```

---

SO3-class

*SO3 class.*


---

**Description**

Class for  $3 \times 3$  matrix representation of rotations.

**See Also**

See the [SO3](#) functions.

---

UARS

*Generic UARS Distribution*


---

**Description**

Density, distribution function and random generation for the the generic uniform axis-random spin (UARS) class of distributions.

**Usage**

```
duars(R, dangle, S = id.S03, kappa = 1, ...)
```

```
puars(R, pangle = NULL, S = id.S03, kappa = 1, ...)
```

```
ruars(n, rangle, S = NULL, kappa = 1, space = "SO3", ...)
```

**Arguments**

R	Value at which to evaluate the UARS density.
n	number of observations. If <code>length(n)&gt;1</code> , the length is taken to be the number required.
dangle	The function to evaluate the angles from, e.g. <code>dcayley</code> , <code>dvmises</code> , <code>dfisher</code> , <code>dhaar</code> .
pangle	The form of the angular density, e.g. <code>pcayley</code> , <code>pvmises</code> , <code>pfisher</code> , <code>phaar</code> .
rangle	The function from which to simulate angles, e.g. <code>rcayley</code> , <code>rvmises</code> , <code>rhaar</code> , <code>rfisher</code> .
S	central orientation of the distribution.
kappa	concentration parameter.
space	indicates the desired representation: matrix ("SO3") or quaternion ("Q4").
...	additional arguments.

## Details

For the rotation  $R$  with central orientation  $S$  and concentration  $\kappa$  the UARS density is given by

$$f(R|S, \kappa) = \frac{4\pi}{3 - \text{tr}(S^\top R)} C(\cos^{-1}[\text{tr}(S^\top R) - 1]/2|\kappa)$$

where  $C(r|\kappa)$  is one of the [Angular-distributions](#).

## Value

duars	gives the density
puars	gives the distribution function. If pangle is left empty, the empirical CDF is returned.
ruars	generates random deviates

## References

Bingham M, Nordman D and Vardeman S (2009). "Modeling and Inference for Measured Crystal Orientations and a Tractable Class of Symmetric Distributions for Rotations in three Dimensions." *Journal of the American Statistical Association*, 104(488), pp. 1385-1397.

## See Also

For more on the angular distribution options see [Angular-distributions](#).

## Examples

```
#Generate random rotations from the Cayley-UARS distribution with central orientation
#rotated about the y-axis through pi/2 radians
S <- as.S03(c(0, 1, 0), pi/2)
Rs <- ruars(20, rangle = rcayley, kappa = 1, S = S)

rs <- mis.angle(Rs-S)                                #Find the associated misorientation angles
frs <- duars(Rs, dcayley, kappa = 10, S = S)         #Compute UARS density evaluated at each rotations
plot(rs, frs)

cdf <- puars(Rs, pcayley, S = S)                     #By supplying 'pcayley', it is used to compute the
plot(rs, cdf)                                       #the CDF

ecdf <- puars(Rs, S = S)                             #No 'puars' argument is supplied so the empirical
plot(rs, ecdf)                                     #cdf is returned
```

---

`vmises.kappa`*Circular variance and concentration parameter*

---

**Description**

Return the concentration parameter that corresponds to a given circular variance.

**Usage**

```
vmises.kappa(nu)
```

**Arguments**

nu                      circular variance

**Details**

The concentration parameter  $\kappa$  does not translate across circular distributions. A commonly used measure of spread in circular distributions that does translate is the circular variance defined as  $\nu = 1 - E[\cos(r)]$  where  $E[\cos(r)]$  is the mean resultant length. See *Mardia et al. (2000)* for more details. This function translates the circular variance  $\nu$  into the corresponding concentration parameter  $\kappa$  for the circular-von Mises distribution.

**Value**

Concentration parameter corresponding to nu.

**References**

Mardia K and Jupp P (2000). *Directional statistics*. John Wiley & Sons, Chichester, England.

**See Also**

[Mises](#)

**Examples**

```
#Find the concentration parameter for circular variances 0.25, 0.5, 0.75
vmises.kappa(0.25)
vmises.kappa(0.5)
vmises.kappa(0.75)
```

---

weighted.mean.SO3	<i>Weighted mean rotation</i>
-------------------	-------------------------------

---

### Description

Compute the weighted geometric or projected mean of a sample of rotations.

### Usage

```
## S3 method for class 'SO3'
weighted.mean(x, w, type = "projected",
              epsilon = 1e-05, maxIter = 2000, ...)

## S3 method for class 'Q4'
weighted.mean(x, w, type = "projected",
              epsilon = 1e-05, maxIter = 2000, ...)
```

### Arguments

x	$n \times p$ matrix where each row corresponds to a random rotation in matrix form ( $p = 9$ ) or quaternion ( $p = 4$ ) form.
w	vector of weights the same length as the number of rows in x giving the weights to use for elements of x.
type	string indicating "projected" or "geometric" type mean estimator.
epsilon	stopping rule for the geometric method.
maxIter	maximum number of iterations allowed before returning most recent estimate.
...	only used for consistency with mean.default.

### Details

This function takes a sample of 3D rotations (in matrix or quaternion form) and returns the weighted projected arithmetic mean  $\hat{S}_P$  or geometric mean  $\hat{S}_G$  according to the type option. For a sample of  $n$  rotations in matrix form  $\mathbf{R}_i \in SO(3), i = 1, 2, \dots, n$ , the weighted mean is defined as

$$\hat{S} = \operatorname{argmin}_{\mathbf{S} \in SO(3)} \sum_{i=1}^n w_i d^2(\mathbf{R}_i, \mathbf{S})$$

where  $d$  is the Riemannian or Euclidean distance. For more on the projected mean see *Moakher (2002)* and for the geometric mean see *Manton (2004)*.

### Value

Weighted mean of the sample in the same parameterization.



## References

Moakher M (2002). "Means and averaging in the group of rotations." *SIAM Journal on Matrix Analysis and Applications*, 24(1), pp. 1-16.

Manton JH (2004). "A globally convergent numerical algorithm for computing the centre of mass on compact Lie groups." In *Control, Automation, Robotics and Vision Conference, 2004. ICARCV 2004 8th*, volume 3, pp. 2211-2216. IEEE.

## See Also

[median.S03](#), [mean.S03](#), [bayes.mean](#)

## Examples

```
Rs <- ruars(20, rvmises, kappa = 0.01)
mean(Rs)           #Find the equal-weight projected mean
wt <- abs(1/mis.angle(Rs)) #Use the rotation misorientation angle as weight
weighted.mean(Rs, wt) #as weight
rot.dist(mean(Rs))
rot.dist(weighted.mean(Rs, wt)) #usually much smaller than unweighted mean

#Can do the same thing with quaternions
Qs <- as.Q4(Rs)
mean(Qs)
wt <- abs(1/mis.angle(Qs))
weighted.mean(Qs, wt)
rot.dist(mean(Qs))
rot.dist(weighted.mean(Qs, wt))
```

---

zhang

*M-estimator theory pivotal bootstrap confidence region*

---

## Description

Compute the radius of a  $100(1 - \alpha)\%$  confidence region for the central orientation based on M-estimation theory.

## Usage

```
zhang(x, estimator, alp, m)

## S3 method for class 'S03'
zhang(x, estimator, alp = NULL, m = 300)

## S3 method for class 'Q4'
zhang(x, estimator, alp = NULL, m = 300)
```

**Arguments**

x	$n \times p$ matrix where each row corresponds to a random rotation in matrix ( $p = 9$ ) or quaternion ( $p = 4$ ) form.
estimator	character string either "mean" or "median."
alp	alpha level desired, e.g. 0.05 or 0.10.
m	number of replicates to use to estimate the critical value.

**Details**

Compute the radius of a  $100(1 - \alpha)\%$  confidence region for the central orientation based on the projected mean estimator using the method due to Zhang & Nordman (2009) (unpublished MS thesis). By construction each axis will have the same radius so the radius reported is for all three axis. A normal theory version of this procedure uses the theoretical chi-square limiting distribution and is given by the [chang](#) option. This method is called "direct" because it used M-estimation theory for SO(3) directly instead of relying on transforming a result from directional statistics as [prentice](#) and [fisheretal](#) do.

**Value**

Radius of the confidence region centered at the specified estimator.

**See Also**

[bayesCR](#), [prentice](#), [fisheretal](#), [chang](#)

**Examples**

```
Rs <- ruars(20, rcayley, kappa = 100)

#The zhang method can be accesed from the "region" function or the "zhang" function
#They will be different because it is a bootstrap.
region(Rs, method = "direct", type = "bootstrap", alp = 0.1, estimator = "mean")
zhang(Rs, estimator = "mean", alp = 0.1)
```

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