

Package ‘mvMORPH’

June 12, 2020

Type Package

Title Multivariate Comparative Tools for Fitting Evolutionary Models to Morphometric Data

Version 1.1.3

Date 2020-06-08

Author Julien Clavel, with contributions from Aaron King, and Emmanuel Paradis

Maintainer Julien Clavel <julien.clavel@hotmail.fr>

Description Fits multivariate (Brownian Motion, Early Burst, ACDC, Ornstein-Uhlenbeck and Shifts) models of continuous traits evolution on trees and time series. 'mvMORPH' also proposes high-dimensional multivariate comparative tools (linear models using Generalized Least Squares and multivariate tests) based on penalized likelihood. See Clavel et al. (2015) <DOI:10.1111/2041-210X.12420>, Clavel et al. (2019) <DOI:10.1093/sysbio/syy045>, and Clavel & Morlon (2020) <DOI:10.1093/sysbio/syaa010>.

Depends R (>= 3.5.0), phytools, ape, corpcor, subplex

Imports stats, spam, graphics, glassoFast, parallel, pbmcapply

Suggests knitr, car

License GPL (>= 2.0)

URL <https://github.com/JClavel/mvMORPH>

VignetteBuilder knitr

NeedsCompilation yes

Repository CRAN

Date/Publication 2020-06-12 18:50:03 UTC

R topics documented:

mvMORPH-package	2
aicw	3
coef.mvgls	5
EIC	6

estim	8
fitted.mvglm	10
GIC	11
halflife	12
LRT	14
manova.glm	16
mv.Precalc	18
mvBM	20
mvEB	25
mvglm	28
mvglm.pca	32
mvLL	34
mvOU	37
mvOUTS	42
mvRWTS	46
mvSHIFT	50
mvSIM	53
phyllostomid	56
pruning	57
residuals.mvglm	59
stationary	60
vcov.mvglm	62

Index **63**

mvMORPH-package	<i>Multivariate Comparative Methods for Fitting Evolutionary Models to Morphometric Data</i>
-----------------	--

Description

Fits of multivariate evolutionary models on trees (with one or multiple selective regimes) and time-series dedicated to morphometrics or biometric continuous data with covariation. Testing for a phylogenetic signal in a multivariate dataset (including fossil and/or extant taxa), fitting linear models to high-dimensional multivariate comparative data, changes in rate or mode of evolution of continuous traits, simulating multivariate traits evolution, computing the likelihood of multivariate models, accounts for measurement errors and missing data, and other things...

Details

Package:	mvMORPH
Type:	Package
Version:	1.1.3
Date:	2013-07-22
License:	GPL (>=2.0)

Author(s)

Julien Clavel

Maintainer: Julien Clavel <julien.clavel@hotmail.fr>

References

Clavel et al. (2015). mvMORPH: an R package for fitting multivariate evolutionary models to morphometric data. *Methods in Ecology and Evolution*, 6(11):1311-1319. doi: 10.1111/2041-210X.12420.

Clavel et al. (2019). A Penalized Likelihood framework for high-dimensional phylogenetic comparative methods and an application to new-world monkeys brain evolution. *Systematic Biology* 68(1): 93-116. doi: 10.1093/sysbio/syy045.

Clavel & Morlon (2020). Reliable phylogenetic regressions for multivariate comparative data: illustration with the MANOVA and application to the effect of diet on mandible morphology in Phyllostomid bats. *Systematic Biology* doi: 10.1093/sysbio/syaa010.

See Also

[mvpls](#) [mvpls.pca](#) [manova.gls](#) [mvOU](#) [mvBM](#) [mvEB](#) [mvSHIFT](#) [mvOUTS](#) [mvRWTS](#) [mvSIM](#) [mvLL](#) [LRT](#) [half-life](#) [stationary](#) [estim](#) [aicw](#) [GIC](#) [EIC](#)

aicw

Akaike weights

Description

This function return the Akaike weights for a set of fitted models.

Usage

```
aicw(x, ...)
```

Arguments

x	A list with the fitted objects or a list/vector of AIC
...	Options to be passed through; e.g. <code>aicc=TRUE</code> when a list of fitted objects is provided.

Details

This function compute the Akaike weights for a set of model AIC or AICc. Akaike weights can be used for model comparison and model averaging.

Value

models	List of models
AIC	Akaike Information Criterion
diff	AIC difference with the best fit model
wi	Absolute weight
aicweights	Akaike weights (relative weights)

Author(s)

Julien Clavel

References

Burnham K.P., Anderson D.R. 2002. Model selection and multi-model inference: a practical information-theoretic approach. New York: Springer-Verlag.

See Also

[AIC mvMORPH](#)

Examples

```
set.seed(1)
# Generating a random tree
tree<-pbtree(n=50)

#simulate the traits
sigma <- matrix(c(0.01,0.005,0.003,0.005,0.01,0.003,0.003,0.003,0.01),3)
theta<-c(0,0,0)
data<-mvSIM(tree, model="BM1", nsim=1, param=list(sigma=sigma, theta=theta))

## Fitting the models
# BM1 - General structure
fit1 <- mvBM(tree, data, model="BM1", method="pic")

# BM1 - No covariations
fit2 <- mvBM(tree, data, model="BM1", method="pic", param=list(constraint="diagonal"))

# BM1 - Equal variances/rates
fit3 <- mvBM(tree, data, model="BM1", method="pic", param=list(constraint="equal"))

results <- list(fit1,fit2,fit3)

# or
# results <- c(AIC(fit1), AIC(fit2), AIC(fit3))

# Akaike weights
aicw(results)

# AICc weights
```

```
aicw(results, aicc=TRUE)

# we can compare the MSE...
# mean((fit1$sigma-sigma)^2)
# mean((fit3$sigma-sigma)^2)
```

`coef.mvglm`*Extract multivariate glm model coefficients*

Description

Returns the coefficients of a linear model fit of class 'mvglm'.

Usage

```
## S3 method for class 'mvglm'
coef(object, ...)
```

Arguments

`object` an object of class 'mvglm' obtained from a mvglm fit.
`...` other arguments (not used).

Value

The coefficients extracted from the model.

Note

For an intercept only model with phylogenetic structure this correspond to the ancestral states.

Author(s)

J. Clavel

See Also

[vcov.mvglm](#) [residuals.mvglm](#) [fitted.mvglm](#) [mvglm](#)

EIC	<i>Extended Information Criterion (EIC) to compare models fit with mvglS by Maximum Likelihood (ML) or Penalized Likelihood (PL).</i>
-----	---

Description

The EIC (Ishiguro et al. 1997, Kitagawa & Konishi 2010), uses bootstrap to estimate the bias term of the Extended Information Criterion. This criterion allows comparing models fit by Maximum Likelihood (ML) or Penalized Likelihood (PL).

Usage

```
EIC(object, nboot=100L, nbcores=1L, ...)
```

Arguments

object	An object of class 'mvglS'. See ?mvglS
nboot	The number of bootstrap replicates used for estimating the EIC.
nbcores	The number of cores used to speed-up the computations (uses the 'parallel' package)
...	Options to be passed through.

Details

The Extended Information Criterion (EIC) allows comparing the fit of various models estimated by Penalized Likelihood or Maximum Likelihood (see ?mvglS). Similar to the GIC or the more common AIC, the EIC has the form:

$$EIC = -2*(Likelihood) + 2*bias$$

Where *Likelihood* corresponds to either the full or the restricted likelihood (see the note below), and the bias term is estimated by (semi-parametric) bootstrap simulations rather than by using analytical or approximate solutions (see for instance ?GIC). The smaller the EIC, the better is the model. With small sample sizes, the variability around the bootstrap estimates is expected to be high, and one must increase the number of bootstrap replicates. Parallel computation (argument nbcores) allows to speed-up the computations.

Note: for models estimated by REML, it is generally not possible to compare the restricted likelihood when they have different fixed effects. However, it is possible to compare models with different fixed effects by using the full likelihood evaluated with the REML estimates (see e.g. Yafune et al. 2006, Verbyla 2019). Both options - evaluating the restricted likelihood or the full likelihood with parameters estimated by REML - are available through the REML argument in the EIC function. The default has been set to REML=FALSE to allow the comparison of models with different fixed effects using the full likelihood evaluated with the REML estimates (see Verbyla 2019).

Value

a list with the following components

LogLikelihood	the log-likelihood estimated for the model with estimated parameters
EIC	the EIC criterion
se	the standard error of the bias term estimated by bootstrap
bias	the values of the bias term estimated from the bootstrapped replicates to compute the EIC

Author(s)

J. Clavel

References

Clavel J., Aristide L., Morlon H., 2019. A Penalized Likelihood framework for high-dimensional phylogenetic comparative methods and an application to new-world monkeys brain evolution. *Syst. Biol.* 68:93-116.

Ishiguro M., Sakamoto Y., Kitagawa G., 1997. Bootstrapping log likelihood and EIC, an extension of AIC. *Ann. Inst. Statist. Math.* 49:411-434.

Kitagawa G., Konishi S., 2010. Bias and variance reduction techniques for bootstrap information criterion. *Ann. Inst. Stat. Math.* 62:209-234.

Konishi S., Kitagawa G., 1996. Generalised information criteria in model selection. *Biometrika.* 83:875-890.

Verbyla A. P., 2019. A note on model selection using information criteria for general linear models estimated using REML. *Aust. N. Z. J. Stat.* 61:39-50.

Yafune A., Funatogawa T., Ishiguro M., 2005. Extended information criterion (EIC) approach for linear mixed effects models under restricted maximum likelihood (REML) estimation. *Statist. Med.* 24:3417-3429.

See Also

[GIC mvglS mvglS.pca](#)

Examples

```
set.seed(1)
n <- 32 # number of species
p <- 50 # number of traits

tree <- pbtrees(n=n) # phylogenetic tree
R <- crossprod(matrix(runif(p*p), ncol=p)) # a random symmetric matrix (covariance)
# simulate a dataset
Y <- mvSIM(tree, model="BM1", nsim=1, param=list(sigma=R))
```

```
fit1 <- mvglms(Y~1, tree=tree, model="BM", method="H&L")
fit2 <- mvglms(Y~1, tree=tree, model="OU", method="H&L")
```

```
EIC(fit1); EIC(fit2)
```

estim	<i>Ancestral states reconstructions and missing value imputation with phylogenetic/time-series models</i>
-------	---

Description

This function imputes the missing cases (NA values) according to a given phylogenetic model (object of class "mvmorph"); it can also do ancestral state reconstruction.

Usage

```
estim(tree, data, object, error=NULL, asr=FALSE)
```

Arguments

tree	Phylogenetic tree (an object of class "phylo" or "simmap") or a time-series.
data	Matrix or data frame with species in rows and continuous traits with missing cases (NA values) in columns (preferentially with names and in the same order than in the tree).
object	A fitted object from an mvMORPH model (class "mvmorph").
error	Matrix or data frame with species in rows and continuous traits sampling variance (squared standard errors) in columns.
asr	If asr=TRUE, the ancestral states are estimated instead of the missing cases.

Details

Missing observations for species in a phylogenetic tree are estimated according to a given evolutionary model (and parameters). Multivariate models are useful to recover the variance and covariance structure of the dataset to be imputed.

When *asr=TRUE*, the estimates, their variances and standard errors are those of the ancestral states at each node of the tree (this option is not available for the time-series). Note that if there are missing cases, they are first imputed before estimating the ancestral states.

Value

estimates	The imputed dataset
var	Variance of the estimates
se	Standard error of the estimates
NA_index	Position of the missing cases in the dataset

Author(s)

Julien Clavel

References

- Clavel J., Merceron G., Escarguel G. 2014. Missing Data Estimation in Morphometrics: How Much is Too Much? Syst. Biol. 63:203-218.
- Cunningham C.W., Omland K.E., Oakley T.H. 1998. Reconstructing ancestral character states: a critical reappraisal. Trends Ecol. Evol. 13:361-366.

See Also

[mvMORPH](#) [mvOU](#) [mvEB](#) [mvBM](#) [mvSHIFT](#)

Examples

```
## Simulated dataset
set.seed(14)
# Generating a random tree
tree<-pbtree(n=50)

# Setting the regime states of tip species
sta<-as.vector(c(rep("Forest",20),rep("Savannah",30))); names(sta)<-tree$tip.label

# Making the simmap tree with mapped states
tree<-make.simmap(tree,sta , model="ER", nsim=1)
col<-c("blue", "orange"); names(col)<-c("Forest", "Savannah")

# Plot of the phylogeny for illustration
plotSimmap(tree,col, fsize=0.6, node.numbers=FALSE, lwd=3, pts=FALSE)

# Simulate two correlated traits evolving along the phylogeny
traits<-mvSIM(tree, nsim=1, model="BMM", param=list(sigma=list(matrix(c(2,1,1,1.5),2,2),
matrix(c(4,1,1,4),2,2)), names_traits=c("head.size", "mouth.size")))

# Introduce some missing cases (NA values)
data<-traits
data[8,2]<-NA
data[25,1]<-NA

# Fit of model 1
fit<-mvBM(tree,data,model="BMM")

# Estimate the missing cases
imp<-estim(tree, data, fit)

# Check the imputed data
imp$estim[1:10,]

## We want the ancestral states values at each nodes:
```

```
nodelabels() # To see where the nodes are situated

imp2<-estim(tree, data, fit, asr=TRUE)

# Check the 10 firsts ancestral states
imp2$estim[1:10,]
```

fitted.mvglm

Extract multivariate glm model fitted values

Description

Returns the fitted values of a linear model of class 'mvglm'.

Usage

```
## S3 method for class 'mvglm'
fitted(object, ...)
```

Arguments

object an object of class 'mvglm' obtained from a mvglm fit.
... other arguments (not used).

Value

The fitted values extracted from the model.

Author(s)

J. Clavel

See Also

[vcov.mvglm](#) [residuals.mvglm](#) [coef.mvglm](#) [mvglm](#)

GIC	<i>Generalized Information Criterion (GIC) to compare models fit with mvgl's by Maximum Likelihood (ML) or Penalized Likelihood (PL).</i>
-----	---

Description

The GIC (Konishi & Kitagawa 1996) allows comparing models fit by Maximum Likelihood (ML) or Penalized Likelihood (PL).

Usage

```
GIC(object, ...)
```

Arguments

object	An object of class 'mvgl's'. See ?mvgl's
...	Options to be passed through.

Details

The Generalized Information Criterion (GIC) allows comparing the fit of various models estimated by Penalized Likelihood (see ?mvgl's). See also the `gic_criterion` function in the RPANDA package. Note that the current implementation of the criterion has not been tested for multiple predictors comparison. Prefer simulation based comparisons instead.

Value

a list with the following components

LogLikelihood	the log-likelihood estimated for the model with estimated parameters
GIC	the GIC criterion
bias	the value of the bias term estimated to compute the GIC

Author(s)

J. Clavel

References

Clavel, J., Aristide, L., Morlon, H., 2019. A Penalized Likelihood framework for high-dimensional phylogenetic comparative methods and an application to new-world monkeys brain evolution. *Systematic Biology* 68(1): 93-116.

Konishi S., Kitagawa G. 1996. Generalised information criteria in model selection. *Biometrika*. 83:875-890.

See Also[mvglsl mvglsl.pca](#)**Examples**

```
set.seed(1)
n <- 32 # number of species
p <- 50 # number of traits

tree <- pbtree(n=n) # phylogenetic tree
R <- crossprod(matrix(runif(p*p), ncol=p)) # a random symmetric matrix (covariance)
# simulate a dataset
Y <- mvSIM(tree, model="BM1", nsim=1, param=list(sigma=R))

fit1 <- mvglsl(Y~1, tree=tree, model="BM", method="H&L")
fit2 <- mvglsl(Y~1, tree=tree, model="OU", method="H&L")

GIC(fit1); GIC(fit2)
```

halflife*The phylogenetic half-life for an Ornstein-Uhlenbeck process*

Description

This function returns the phylogenetic half-life for an Ornstein-Uhlenbeck process (object of class "ou").

Usage

```
halflife(object)
```

Arguments

object Object fitted with the "mvOU" function.

Details

The phylogenetic half-life describes the time to move halfway from the ancestral state to the primary optimum (Hansen, 1997). The multivariate counterpart is computed on the eigenvalues of the "selection" matrix (Bartoszek et al. 2012).

Value

The phylogenetic half-life computed from each eigenvalues (or alpha for the univariate case)

Author(s)

Julien Clavel

References

Bartoszek K., Pienaar J., Mostad P., Andersson S., Hansen T.F. 2012. A phylogenetic comparative method for studying multivariate adaptation. *J. Theor. Biol.* 314:204-215.

Hansen T.F. 1997. Stabilizing selection and the comparative analysis of adaptation. *Evolution.* 51:1341-1351.

See Also[mvMORPH mvOU stationary](#)**Examples**

```
# Simulated dataset
set.seed(14)
# Generating a random tree
tree<-pbtree(n=50)

# Setting the regime states of tip species
sta<-as.vector(c(rep("Forest",20),rep("Savannah",30))); names(sta)<-tree$tip.label

# Making the simmap tree with mapped states
tree<-make.simmap(tree,sta , model="ER", nsim=1)
col<-c("blue", "orange"); names(col)<-c("Forest", "Savannah")

# Plot of the phylogeny for illustration
plotSimmap(tree,col, fsize=0.6, node.numbers=FALSE, lwd=3, pts=FALSE)

# Simulate the traits
alpha<-matrix(c(2,0.5,0.5,1),2)
sigma<-matrix(c(0.1,0.05,0.05,0.1),2)
theta<-c(2,3,1,1.3)
data<-mvSIM(tree, param=list(sigma=sigma, alpha=alpha, ntraits=2, theta=theta,
names_traits=c("head.size", "mouth.size")), model="OUM", nsim=1)

## Fitting the models
# OUM - Analysis with multiple optima
result<-mvOU(tree, data)

halflife(result)
```

LRT

*Likelihood Ratio Test***Description**

This function compares the fit of two nested models of trait evolution with a loglikelihood-ratio statistic.

Usage

```
LRT(model1, model2, echo = TRUE, ...)
```

Arguments

model1	The most parameterized model. A fitted object from an mvMORPH model.
model2	The second model under comparison (fitted object).
echo	Whether to return the result or not.
...	Options to be passed through. (Not yet available)

Details

The LRT function extracts the log-likelihood of two nested models to compute the loglikelihood-ratio statistic which is compared to a Chi-square distribution. Note that if the models are not nested, the LRT is not an appropriate test and you should rely instead on Information criteria, evidence ratios, or simulated distributions (e.g., Lewis et al. 2011). This can be achieved using the `simulate` function (see examples below).

Value

pval	The p-value of the LRT test (comparison with Chi-square distribution).
ratio	The LRT (Loglikelihood-ratio test) statistic.
ddf	The number of degrees of freedom between the two models.
model1	Name of the first model.
model2	Name of the second model.

Note

When comparing BM models to OU models, the LRT test might not be at its nominal level. You should prefer a simulations based test.

Author(s)

Julien Clavel

References

- Neyman J., Pearson E.S. 1933. On the problem of the most efficient tests of statistical hypotheses. *Philos. Trans. R. Soc. A.* 231:289-337.
- Lewis F., Butler A., Gilbert L. 2011. A unified approach to model selection using the likelihood ratio test. *Meth. Ecol. Evol.* 2:155-162.

See Also

[mvMORPH](#) [mvOU](#) [mvEB](#) [mvBM](#) [mvSHIFT](#)

Examples

```
## Simulated dataset
set.seed(14)
# Generating a random tree
tree<-pbtree(n=50)

# Setting the regime states of tip species
sta<-as.vector(c(rep("Forest",20),rep("Savannah",30))); names(sta)<-tree$tip.label

# Making the simmap tree with mapped states
tree<-make.simmap(tree,sta , model="ER", nsim=1)
col<-c("blue","orange"); names(col)<-c("Forest","Savannah")

# Plot of the phylogeny for illustration
plotSimmap(tree,col, fsize=0.6,node.numbers=FALSE,lwd=3, pts=FALSE)

# Simulate two correlated traits evolving along the phylogeny
traits<-mvSIM(tree,nsim=1, model="BMM", param=list(sigma=list(matrix(c(2,1,1,1.5),2,2),
matrix(c(4,1,1,4),2,2)), ntraits=2, names_traits=c("head.size","mouth.size")))

# Fit of model 1
mod1<-mvBM(tree,traits,model="BMM")

# Fit of model 2
mod2<-mvBM(tree,traits,model="BM1")

# comparing the fit using LRT...
LRT(mod1,mod2)

# Simulation based test
nsim = 500
boot <- simulate(mod2, tree=tree, nsim=nsim)
simulations <- sapply(1:nsim, function(i){
  mod1boot<-mvBM(tree, boot[[i]], model="BMM", diagnostic=FALSE, echo=FALSE)
  mod2boot<-mvBM(tree, boot[[i]], model="BM1", diagnostic=FALSE, echo=FALSE, method="pic")
  2*(mod1boot$LogLik-mod2boot$LogLik)
```

```

}))

# Compute the p-value
LRT_stat<-(2*((mod1$LogLik-mod2$LogLik)))
mean(simulations>=LRT_stat)

plot(density(simulations), main="Non-parametric LRT");
abline(v=LRT_stat, col="red")

```

manova.gls

Multivariate Analysis of Variance

Description

Performs a Multivariate Analysis of Variance (MANOVA) on an object fitted by the `mvgl`s function. With the regularized methods by penalized likelihood implemented in `mvgl`s (ridgeArch penalty), this function can be used to compare model fit on high-dimensional datasets (where the number of variable is larger than the number of observations).

Usage

```

manova.gls(object, test=c("Pillai", "Wilks", "Hotelling-Lawley", "Roy"),
           type=c("I", "II", "III"), nperm=999L, L=NULL, ...)

```

Arguments

<code>object</code>	A model fit obtained by the <code>mvgl</code> s function.
<code>test</code>	The multivariate test statistic to compute - "Wilks", "Pillai", "Hotelling-Lawley", or "Roy"
<code>type</code>	The type of test (sums of squares and cross-products) - "I", "II", or "III"
<code>nperm</code>	The number of permutations used for building the null distribution of the chosen statistic. Permutation is the only available approach for high-dimensional PL models, but either permutations or parametric tests can be used with maximum likelihood (method "LL" in <code>mvgl</code> s)
<code>L</code>	A (contrasts) matrix or a vector giving linear combinations of the coefficients rows.
<code>...</code>	Further arguments to be passed through. (e.g., <code>nbcores=2L</code> to provide the number of cores used for parallel calculus; <code>parametric=FALSE</code> to obtain permutation instead of parametric tests for maximum likelihood fit; <code>verbose=TRUE</code> to display a progress bar during permutations; <code>rhs=0</code> the "right-hand-side" vector for general linear hypothesis testing. See details)

Details

`manova.gls` allows performing multivariate tests (e.g. Pillai's, Wilks, Hotelling-Lawley and Roy largest root) on generalized least squares (GLS) linear model (objects of class "mvgl") fit by either maximum likelihood (`method="LL"`) or penalized likelihood (`method="PL-L00"`) using the `mvgl` function.

General Linear Hypothesis of the form:

$$\mathbf{LB}=\mathbf{O}$$

an **L** matrix specifying linear combinations of the model coefficients (**B**) can be provided through the argument `L`. The right-hand-side matrix **O** is a constant matrix (of zeros by default) that can be provided through the argument `rhs`.

Permutations on high-dimensional datasets is time consuming. You can use the option `nbcores` to parallelize the calculus over several cores using forking in UNIX platforms (default is `nbcores=1L`). Estimated time to completion is displayed when `verbose=TRUE`.

Value

An object of class 'manova.mvgl' which is usually printed. It contains a list including the following components:

<code>test</code>	the multivariate test statistic used
<code>type</code>	the type of tests used to compute the SSCP matrices
<code>stat</code>	the statistic calculated for each terms in the model
<code>pvalue</code>	the pvalues calculated for each terms in the model

Note

For PL methods, only the "RidgeArch" penalty is allowed for now.

Author(s)

J. Clavel

References

Clavel, J., Aristide, L., Morlon, H., 2019. A Penalized Likelihood framework for high-dimensional phylogenetic comparative methods and an application to new-world monkeys brain evolution. *Systematic Biology* 68(1): 93-116.

Clavel, J., Morlon, H. 2020. Reliable phylogenetic regressions for multivariate comparative data: illustration with the MANOVA and application to the effect of diet on mandible morphology in phyllostomid bats. *Systematic Biology* (DOI:10.1093/sysbio/syaa010)

See Also

[mvgl](#), [GIC](#) [EIC](#)

Examples

```

set.seed(1)
n <- 32 # number of species
p <- 30 # number of traits

tree <- pbtree(n=n) # phylogenetic tree
R <- crossprod(matrix(runif(p*p),p)) # a random symmetric matrix (covariance)

# simulate a dataset
Y <- mvSIM(tree, model="BM1", nsim=1, param=list(sigma=R))
X <- rnorm(n) # continuous
grp <- rep(1:2, each=n/2)
dataset <- list(y=Y, x=X, grp=as.factor(grp))

# Model fit
model1 <- mvglms(y~x, data=dataset, tree=tree, model="BM", method="LOO")

# Multivariate test
(multivariate_test <- manova.gls(model1, nperm=999, test="Pillai"))

# MANOVA on a binary predictor
model2 <- mvglms(y~grp, data=dataset, tree=tree, model="lambda", method="LOO")

# Multivariate test
(multivariate_test <- manova.gls(model2, nperm=999, test="Pillai", verbose=TRUE))

```

mv.Precalc

Model parameterization for the various mvMORPH functions

Description

This function allows computing the fixed parameters or objects needed by the mvMORPH functions. This could be useful for bootstrap-like computations (see exemple)

Usage

```

mv.Precalc(tree, nb.traits = 1, scale.height = FALSE, param = list(pivot = "MMD",
  method = c("sparse"), smean = TRUE, model = "OUM"))

```

Arguments

tree	A "phylo" (or SIMMAP like) object representing the tree for which we want to precalculate parameters.
nb.traits	The number of traits involved in the subsequent analysis.
scale.height	Whether the tree should be scaled to unit length or not.
param	A list of parameters used in the computations (see details)

Details

The mv.Precalc function allows the pre-computation of the fixed parameters required by the different mvMORPH models (e.g., the design matrix, the vcv matrix, the sparsity structure...). In the "param" list you should provide the details about the model fit:

- model name (e.g., "OUM", "OU1")
- method (which kind of algorithm is used for computing the log-likelihood).
- smean (whether there is one ancestral state per trait or per selective regimes - for mvBM only).

Additional parameters can be fixed:

- root (estimation of the ancestral state for the Ornstein-Uhlenbeck model; see ?mvOU).
- pivot (pivot method used by the "sparse" matrix method for computing the log-likelihood; see ?spam).

Value

An object of class "mvmorph.precalc" which can be used in the "precalc" argument of the various mvMORPH functions.

Note

This function is mainly used internally; it is still in development. A misuse of this functions can result in a crash of the R session.

Author(s)

Julien Clavel

See Also

[mvMORPH](#) [mvOU](#) [mvEB](#) [mvBM](#) [mvSHIFT](#) [mvLL](#)

Examples

```
set.seed(14)
# Generating a random tree
tree<-pbtree(n=50)

# Simulate two correlated traits evolving along the phylogeny according to a
# Ornstein-Uhlenbeck process
alpha<-matrix(c(2,1,1,1.3),2,2)
sigma<-matrix(c(1,0.5,0.5,0.8),2,2)
theta<-c(3,1)
nsim<-50
simul<-mvSIM(tree,param=list(sigma=sigma, alpha=alpha, ntraits=2, theta=theta,
                             names_traits=c("head.size","mouth.size")), model="OU1", nsim=nsim)

# Do the pre-calculations
precal<-mv.Precalc(tree,nb.traits=2, param=list(method="sparse",model="OU1", root=FALSE))
```

```

mvOU(tree, simul[[1]], method="sparse", model="OU1", precalc=precal,
      param=list(decomp="cholesky"))

### Bootstrap

# Fit the model to the "nsim" simulated datasets
results<-lapply(1:nsim,function(x){
  mvOU(tree, simul[[x]], method="sparse", model="OU1", precalc=precal,
        param=list(decomp="cholesky"),
        echo=FALSE, diagnostic=FALSE)
})

### Use parallel package
library(parallel)
if(.Platform$OS.type == "unix"){
  number_of_cores<-2L # Only working on Unix systems
}else{
  number_of_cores<-1L
}

results<-mclapply(simul, function(x){
  mvOU(tree, x, method="sparse", model="OU1", precalc=precal,
        param=list(decomp="cholesky"), echo=FALSE, diagnostic=FALSE)
}, mc.cores = getOption("mc.cores", number_of_cores))

# Summarize (we use the generic S3 method "logLik" to extract the log-likelihood)
loglik<-sapply(results,logLik)
hist(loglik)

```

mvBM

Multivariate Brownian Motion models of continuous traits evolution

Description

This function allows the fitting of multivariate multiple rates of evolution under a Brownian Motion model. This function can also fit constrained models.

Usage

```

mvBM(tree, data, error = NULL, model = c("BMM", "BM1"),
      param = list(constraint = FALSE, smean = TRUE, trend=FALSE),
      method = c("rpf", "pic", "sparse", "inverse", "pseudoinverse"),
      scale.height = FALSE, optimization = c("L-BFGS-B", "Nelder-Mead", "subplex"),
      control = list(maxit = 20000), precalc = NULL, diagnostic = TRUE, echo = TRUE)

```

Arguments

tree	Phylogenetic tree in SIMMAP format by default. A "phylo" object can also be used with the "BM1" model.
data	Matrix or data frame with species in rows and continuous traits in columns (preferentially with names and in the same order than in the tree). NA values are allowed with the "rpf", "inverse", and "pseudoinverse" methods.
error	Matrix or data frame with species in rows and continuous trait sampling variance (squared standard errors) in columns.
model	"BMM" for multi-rate and multi-selective regimes, and "BM1" for a unique rate of evolution per trait.
param	List of arguments to be passed to the function. See details.
method	Choose between "rpf", "sparse", "inverse", "pseudoinverse", or "pic" for log-likelihood computation during the fitting process. See details.
scale.height	Whether the tree should be scaled to unit length or not.
optimization	Methods used by the optimization routines (see ?optim and ?subplex for details). The "fixed" method returns the log-likelihood function only.
control	Max. bound for the number of iteration of the optimizer; other options can be fixed in the list (see ?optim or ?subplex).
precalc	Optional. Precalculation of fixed parameters. See ?mvmorph.Precalc.
diagnostic	Whether the diagnostics of convergence should be returned or not.
echo	Whether the results must be returned or not.

Details

The mvBM function fits a multivariate Brownian Motion (BM) process, with unique or multiple BM rates (see O'Meara et al., 2006; Revell and Collar, 2009). Note that the function uses the non-censored approach of O'Meara et al. (2006) by default (i.e., a common ancestral state is assumed for the different regimes), but it is possible to specify multiple ancestral states (i.e., one for each regimes) through the "smean" parameter (smean=FALSE) in the "param" list.

The "method" argument allows the user to try different algorithms for computing the log-likelihood. The "rpf" and "sparse" methods use fast GLS algorithms based on factorization for avoiding the computation of the inverse of the variance-covariance matrix and its determinant involved in the log-likelihood estimation. The "inverse" approach uses the "stable" standard explicit computation of the inverse and determinant of the matrix and is therefore slower. The "pseudoinverse" method uses a generalized inverse that is safer for matrix near singularity but highly time consuming. The "pic" method uses a very fast algorithm based on independent contrasts. It should be used with strictly dichotomic trees (i.e., no polytomies) and is currently not available for the multivariate "BMM" model. See ?mvLL for more details on these computational methods.

The "**param**" list arguments:

"constraint" - The "constraint" argument in the "param" list allows the user to compute the joint likelihood for each trait by assuming they evolved independently (**constraint="diagonal"**, or **constraint="equaldiagonal"**). If **constraint="equal"**, the sigma values are constrained to be the same for each studied trait using the constrained Cholesky decomposition proposed by Adams

(2013) or a separation strategy based on spherical parameterization (when $p > 2$) because of an unstable behavior observed for the constrained Cholesky (Clavel et al. 2015).

This approach is extended here to the multi-rate case by specifying that the rates must be the same in different parts of the tree (common selective regime). It's also possible to constraint the rate matrices in the "BMM" model to share the same eigen-vectors (`constraint="shared"`); the same variance but different covariances (`constraint="variance"`); the same correlation but different variances (`constraint="correlation"`); or to fit a model with different but proportional rates matrices (`constraint="proportional"`).

Finally, user-defined constrained models can be specified through a numeric matrix (square and symmetric) with integer values taken as indices of the parameters. For instance, for three traits:

```
constraint=matrix(c(1,3,3,3,2,3,3,3,2),3).
```

Covariances constrained to be zero are introduced by NA values, e.g.,

```
constraint=matrix(c(1,4,4,4,2,NA,4,NA,3),3).
```

Difference between two nested fitted models can be assessed using the "LRT" function. See example below and ?LRT.

"decomp" - For the general case (unconstrained models), the sigma matrix is parameterized by various methods to ensure its positive definiteness (Pinheiro and Bates, 1996). These methods are the "cholesky", "eigen+", and "spherical" parameterizations.

"smean" - Default set to TRUE. If FALSE, the ancestral state for each selective regime is estimated (e.g., Thomas et al., 2006).

"trend" - Default set to FALSE. If TRUE, the ancestral state is allowed to drift linearly with time. This model is identifiable only with non-ultrametric trees. Note that it is possible to provide a vector of integer indices to constrain the estimated trends (see the vignettes).

"sigma" - Starting values for the likelihood estimation. By default the theoretical expected values are used as starting values for the likelihood optimization (for measurement errors, multiple rates...). The user can specify starting values with a list() object for the "BMM" model (e.g., two objects in the list for a two-regime analysis), or a simple vector of values for the "BM1" model. The parameterization is done using various factorizations for symmetric matrices (e.g., for the "decomp" argument; Pinheiro & Bates, 1996). Thus, you should provide $p*(p+1)/2$ values, with p the number of traits (e.g., random numbers or the values from the cholesky factor of a symmetric positive definite sigma matrix; see example below). If a constrained model is used, the number of starting values is $(p*(p-1)/2)+1$.

If no selective regime is specified the function works only with the model "BM1".

N.B.: Mapping of ancestral states can be done using the "make.simmap", "make.era.map" or "paintSub-Tree" functions from the "phytools" package.

Value

LogLik	The log-likelihood of the optimal model.
AIC	Akaike Information Criterion for the optimal model.
AICc	Sample size-corrected AIC.
theta	Estimated ancestral states.
sigma	Evolutionary rate matrix for each selective regime.

convergence	Convergence status of the optimizing function; "0" indicates convergence (See ?optim for details).
hess.values	Reliability of the likelihood estimates calculated through the eigen-decomposition of the hessian matrix. "0" means that a reliable estimate has been reached. (See ?mvOU).
param	List of model fit parameters (optimization, method, model, number of parameters...).
l1ik	The log-likelihood function evaluated in the model fit "\$l1ik(par, root.mle=TRUE)".

Note

The "pic" method is not yet implemented for the multivariate "BMM" model.

Author(s)

Julien Clavel

References

- Adams D.C. 2013. Comparing evolutionary rates for different phenotypic traits on a phylogeny using likelihood. *Syst. Biol.* 62:181-192.
- Clavel J., Escarguel G., Merceron G. 2015. mvMORPH: an R package for fitting multivariate evolutionary models to morphometric data. *Methods Ecol. Evol.* 6(11):1311-1319.
- O'Meara B.C., Ane C., Sanderson M.J., Wainwright P.C. 2006. Testing for different rates of continuous trait evolution. *Evolution.* 60:922-933.
- Revell L.J. 2012. phytools: An R package for phylogenetic comparative biology (and other things). *Methods Ecol. Evol.* 3:217-223.
- Revell L.J., Collar D.C. 2009. Phylogenetic analysis of the evolutionary correlation using likelihood. *Evolution.* 63:1090-1100.
- Thomas G.H., Freckleton R.P., Szekely T. 2006. Comparative analyses of the influence of developmental mode on phenotypic diversification rates in shorebirds. *Proc. R. Soc. B.* 273:1619-1624.

See Also

[mvMORPH](#) [mvgls](#) [mvOU](#) [mvEB](#) [mvSHIFT](#) [mvOUTS](#) [mvrWTS](#) [mvSIM](#) [LRT](#) [optim](#) [brownie.light](#) [evol.vcv](#) [make.simmap](#) [make.era.map](#) [paintSubTree](#)

Examples

```
# Simulated dataset
set.seed(14)
# Generating a random tree
tree<-pbtree(n=50)

# Setting the regime states of tip species
sta<-as.vector(c(rep("Forest",20),rep("Savannah",30))); names(sta)<-tree$tip.label

# Making the simmap tree with mapped states
```

```

tree<-make.simmap(tree,sta , model="ER", nsim=1)
col<-c("blue","orange"); names(col)<-c("Forest","Savannah")

# Plot of the phylogeny for illustration
plotSimmap(tree,col,fsize=0.6,node.numbers=FALSE,lwd=3, pts=FALSE)

# Simulate the traits
sigma<-matrix(c(0.1,0.05,0.05,0.1),2)
theta<-c(0,0)
data<-mvSIM(tree, param=list(sigma=sigma, ntraits=2, theta=theta,
                             names_traits=c("head.size","mouth.size")), model="BM1", nsim=1)

## Fitting the models
# BMM - Analysis with multiple rates
mvBM(tree, data)

# BM1 - Analysis with a unique rate matrix
fit1<-mvBM(tree, data, model="BM1", method="pic")

# BM1 constrained
fit2<-mvBM(tree, data, model="BM1", method="pic", param=list(constraint="equal"))

# Comparison with LRT test
LRT(fit1,fit2)

# Random starting values
mvBM(tree, data, model="BMM", method="sparse", param=list(sigma=list(runif(3), runif(3))))

# Specified starting values (from the Cholesky factor)
chol_factor<-chol(sigma)
starting_values<-chol_factor[upper.tri(chol_factor,TRUE)]
mvBM(tree, data, model="BMM", method="sparse",
      param=list( sigma=list(starting_values, starting_values)))

# Multiple mean
mvBM(tree, data, model="BMM", method="sparse", param=list(smean=FALSE))

# Introduce some missing cases (NA values)
data2<-data
data2[8,2]<-NA
data2[25,1]<-NA

mvBM(tree, data2, model="BM1")

## FAST FOR THE UNIVARIATE CASE!!

set.seed(14)
tree2<-pbtree(n=5416) # Number of Mammal species
# Setting the regime states of tip species
sta<-as.vector(c(rep("group_1",2000),rep("group_2",3416))); names(sta)<-tree2$tip.label

```



```
# Making the simmap tree with mapped states
tree2<-make.simmap(tree2,sta , model="ER", nsim=1)
col<-c("blue","orange"); names(col)<-c("Group_1","Group_2")
plotSimmap(tree2,col,fsiz=0.6,node.numbers=FALSE,lwd=3, pts=FALSE)

# Simulate a trait evolving by brownian motion on the tree
trait<-rTraitCont(tree2)

# Fitting the models
mvBM(tree2, trait, model="BMM", method="pic")
mvBM(tree2, trait, model="BM1", method="pic")
```

mvEB

*Multivariate Early Burst model of continuous traits evolution***Description**

This function fits to a multivariate dataset of continuous traits a multivariate Early Burst (EB) or ACDC models of evolution.

Usage

```
mvEB(tree, data, error = NULL, param = list(up = 0), method =
c("rpf", "sparse", "inverse", "pseudoinverse", "pic"), scale.height =
FALSE, optimization = c("Nelder-Mead", "L-BFGS-B", "subplex"),
control = list(maxit = 20000), precalc = NULL, diagnostic = TRUE,
echo = TRUE)
```

Arguments

tree	Phylogenetic tree (phylo object).
data	Matrix or data frame with species in rows and continuous traits in columns (preferentially with names and in the same order than in the tree). NA values are allowed with the "rpf", "inverse", and "pseudoinverse" methods.
error	Matrix or data frame with species in rows and continuous trait sampling variance (squared standard errors) in columns.
param	List of arguments to be passed to the function. See details.
method	Choose between "rpf", "sparse", "inverse", "pseudoinverse", or "pic" for computing the log-likelihood during the fitting process. See details.
scale.height	Whether the tree should be scaled to unit length or not.
optimization	Methods used by the optimization routines (see ?optim and ?subplex for details). The "fixed" method returns the log-likelihood function only.

control	Max. bound for the number of iteration of the optimizer; other options can be fixed in the list (see ?optim or ?subplex for details).
precalc	Optional. Precalculation of fixed parameters. See ?mvmorph.Precalc for details.
diagnostic	Whether the diagnostics of convergence should be returned or not.
echo	Whether the results must be returned or not.

Details

The Early Burst model (Harmon et al. 2010) is a special case of the ACDC model of Blomberg et al. (2003). Using an upper bound larger than zero transform the EB model to the accelerating rates of character evolution of Blomberg et al. (2003).

The "method" argument allows the user to try different algorithms for computing the log-likelihood. The "rpf" and "sparse" methods use fast GLS algorithms based on factorization for avoiding the computation of the inverse of the variance-covariance matrix and its determinant for the log-likelihood estimation. The "inverse" approach uses the "stable" standard explicit computation of the inverse and determinant of the matrix and is therefore slower. The "pseudoinverse" method uses a generalized inverse that is safer for matrix near singularity but highly time consuming. The "pic" method uses a very fast algorithm based on independent contrasts. See ?mvLL for more details on these computational methods.

The "param" list can be used to set the lower (low) and upper (up, default value is 0 - i.e., Early Burst model) bounds for the estimation of the exponential rate (beta). The default lower bound for decelerating rates (as assumed in Early Burst) is fixed as $\log(\text{min.rate}) / T$, where T is the depth of the tree and min.rate is the minimum rate that could be assumed for the model (following Slater and Pennell, 2014; $\log(10^{-5})/T$). Bounds may need to be adjusted by the user for specific cases.

Starting values for "sigma" and "beta" could also be provided through the "param" list.

Value

LogLik	The log-likelihood of the optimal model.
AIC	Akaike Information Criterion for the optimal model.
AICc	Sample size-corrected AIC.
theta	Estimated ancestral states.
beta	Exponent rate (of decay or increase).
sigma	Evolutionary rate matrix for each selective regimes.
convergence	Convergence status of the optimizing function; "0" indicates convergence (see ?optim for details).
hess.values	Reliability of the likelihood estimates calculated through the eigen-decomposition of the hessian matrix. "0" means that a reliable estimate has been reached. (see ?mvOU for details).
param	List of model fit parameters (optimization, method, model, number of parameters...).
llik	The log-likelihood function evaluated in the model fit "\$llik(par, root.mle=TRUE)".

Note

The derivative-free "Nelder-Mead" optimization method is used as default setting instead of "L-BFGS-B".

Author(s)

Julien Clavel

References

Blomberg S.P., Garland T.J., Ives A.R. 2003. Testing for phylogenetic signal in comparative data: behavioral traits are more labile. *Evolution*. 57:717-745.

Clavel J., Escarguel G., Merceron G. 2015. mvMORPH: an R package for fitting multivariate evolutionary models to morphometric data. *Methods Ecol. Evol.* 6(11):1311-1319.

Harmon L.J., Losos J.B., Davies J.T., Gillespie R.G., Gittleman J.L., Jennings B.W., Kozak K.H., McPeck M.A., Moreno-Roark F., Near T.J., Purvis A., Ricklefs R.E., Schluter D., Schulte II J.A., Seehausen O., Sidlauskas B.L., Torres-Carvajal O., Weir J.T., Mooers A.O. 2010. Early bursts of body size and shape evolution are rare in comparative data. *Evolution*. 64:2385-2396.

Slater G.J., Pennell M. 2014. Robust regression and posterior predictive simulation increase power to detect early bursts of trait evolution. *Syst. Biol.* 63: 293-308.

See Also

[mvMORPH](#) [mvg1s](#) [mvOU](#) [mvBM](#) [mvSHIFT](#) [mvOUTS](#) [mvRWTS](#) [mvSIM](#) [optim](#)

Examples

```
# Simulated dataset
set.seed(14)
# Generating a random tree
tree<-pbtree(n=50, scale=10)

# Simulate the traits
sigma<-matrix(c(0.1,0.05,0.05,0.1),2)
theta<-c(0,0)
beta<- -0.34 # 5 phylogenetic half-life ( log(2)/ (10/5) )
data<-mvSIM(tree, param=list(sigma=sigma, beta=beta, ntraits=2, theta=theta,
names_traits=c("head.size","mouth.size")), model="EB", nsim=1)

## Fitting the models
mvEB(tree, data)
mvEB(tree, data, method="pic")
mvEB(tree, data, method="pic", param=list(low=log(10^-5)/10)) # avoid internal estimation

# ACDC
# Note that the AC model is not differentiable from an OU model on ultrametric trees.
beta<- 0.34
data<-mvSIM(tree, param=list(sigma=sigma, beta=beta, ntraits=2, theta=theta,
names_traits=c("head.size","mouth.size")), model="EB", nsim=1)
```

```
fit<-mvEB(tree, data, method="pic", param=list(up=2, low=-2))

logLik(fit)
AIC(fit)
summary(fit)
```

mvglS	<i>Fit linear model using Generalized Least Squares to multivariate (high-dimensional) data sets.</i>
-------	---

Description

This function use maximum likelihood (or restricted likelihood) and penalized likelihood approaches to fit linear models where the errors are allowed to be correlated (i.e. a GLS model for serially correlated phylogenetic and time-series data). `mvglS` uses a penalized-likelihood (PL) approach (see descriptions in Clavel et al. 2019) to fit linear models to high-dimensional data sets (where the number of variables p is approaching or is larger than the number of observations n). The PL approach generally provides improved estimates compared to ML.

Usage

```
mvglS(formula, data, tree, model, method=c("PL-LOOCV", "LL"),
      REML=TRUE, ...)
```

Arguments

formula	An object of class "formula" (a two-sided linear formula describing the model to be fitted. See for instance <code>?lm</code>)
data	An optional list, data.frame or environment containing the variables in the model. If not found in <code>data</code> the variables are taken from the current environment. Prefer list for blocks of multivariate responses unless you're specifying the response variables by their names using <code>cbind</code> with data.frame.
tree	Phylogenetic tree (an object of class "phylo") or a time-series object (not yet available).
model	The evolutionary model: "BM" is Brownian Motion, "OU" is Ornstein-Uhlenbeck, "EB" is Early Burst, and "lambda" is Pagel's lambda transformation.
method	The method used to fit the model. "PL-LOOCV" (or equivalently just "LOOCV") is the nominal leave one out cross-validation of the penalized log-likelihood, "LL" is the log-likelihood (used in the conventional ML and REML estimation). Two approximated LOOCV methods are also available: "H&L" and "Mahalanobis". The method "H&L" is a fast LOOCV approach based on Hoffbeck and Landgrebe (1996) tricks, and "Mahalanobis" is an approximation of the LOOCV score proposed by Theiler (2012). Both "H&L" and "Mahalanobis" work only with the "RidgeArch" penalty and for intercept only models (see details).
REML	Use REML (default) or ML for estimating the parameters.

... Options to be passed through. For instance the type of penalization: `penalty="RidgeArch"` (default), `penalty="RidgeAlt"`, or `penalty="LASSO"`. The target matrices used by "RidgeArch" and "RidgeAlt" penalizations: `target="unitVariance"`, `target="Variance"` or `target="null"`... etc. (see details)

Details

`mvglS` allows fitting various multivariate linear models to high-dimensional datasets (i.e. where the number of variables p is larger than n) for which the residuals have a correlated structure (e.g. evolutionary models such as BM and OU). Models estimates are generally more accurate than maximum likelihood methods. Models fit can be compared using the GIC or EIC criterion (see ?GIC and ?EIC) and hypothesis testing can be performed using the `manova.gls` function.

The tree is assumed to be fully dichotomic and in "postorder", otherwise the functions `multi2di` and `reorder.phylo` are used internally.

The various *arguments* that can be passed through "...":

"penalty" - The "penalty" argument allow specifying the type of penalization used for regularization (described in Clavel et al. 2019). The various penalizations are: `penalty="RidgeArch"` (the default), `penalty="RidgeAlt"` and `penalty="LASSO"`. The "RidgeArch" penalization shrink linearly the covariance matrix toward a target structure (see below for `target`). This penalization is generally fast and the tuning parameter is bounded between 0 and 1 (see van Wieringen & Peeters 2016). The "RidgeAlt" penalization scheme uses a quadratic ridge penalty to shrink the covariance matrix toward a specified target matrix (see `target` below and also see van Wieringen & Peeters 2016). Finally, the "LASSO" regularize the covariance matrix by estimating a sparse estimate of its inverse (Friedman et al. 2008). The computation of the solution for this penalization is computationally intensive. Moreover, this penalization scheme is not invariant to arbitrary rotations of the data.

"target" - This argument allows specifying the target matrix toward which the covariance matrix is shrunk for "Ridge" penalties. `target="unitVariance"` (for a diagonal target proportional to the identity) and `target="Variance"` (for a diagonal unequal variance target) can be used with both "RidgeArch" and "RidgeAlt" penalties. `target="null"` (a null target matrix) is only available for "RidgeAlt". Penalization with the "Variance" target shrink the eigenvectors of the covariance matrix and is therefore not rotation invariant. See details on the various target properties in Clavel et al. (2019).

"error" - If TRUE the measurement error (or intra-specific variance) is estimated from the data as a nuisance parameter (like in mixed models). It should probably be systematically used with empirical data. See also Housworth et al. 2004 and Clavel et al. 2019 for details on the proposed implementation.

"scale.height" - Whether the tree should be scaled to unit length or not.

"echo" - Whether the results must be returned or not.

"grid_search" - A logical indicating whether or not a preliminary grid search must be performed to find the best starting values for optimizing the log-likelihood (or penalized log-likelihood). User-specified starting values can be provided through the **start** argument. Default is TRUE.

"upper" - The upper bound for the parameter search with the "L-BFGS-B" method. See `optim` for details.

"lower" - The lower bound for the parameter search with the "L-BFGS-B" method. See `optim` for details.

"tol" - Minimum value for the regularization parameter. Singularities can occur with a zero value in high-dimensional cases. (default is NULL)

Value

An object of class 'mvglS'. It contains a list including the following components:

coefficients	a named vector of coefficients
residuals	the residuals ("raw") of the model. That is response minus fitted values. Uses the <code>residuals(x, type="normalized")</code> function to obtain the normalized residuals.
fitted.values	the fitted mean values
variables	the variables used for model fit
sigma	the estimated covariance (Pi) and precision (P) matrix, as well as the sample estimate (S)
model	the evolutionary model. But more generally, the model used to specify the structure within the residuals
logLik	either the (negative) log-likelihood when <code>method="LL"</code> or the cross-validated penalized likelihood
param	the (evolutionary) model parameter estimates
tuning	the regularization/tuning parameter of the penalized likelihood
mserr	the estimated standard error when <code>error=TRUE</code>
start_values	the starting parameters used for the optimization of the LL or PL
corrSt	a list including the transformed tree, the determinant obtained from its covariance matrix and the normalized variables (by the inverse square root of the covariance matrix of the phylogenetic tree or the time-series)
penalty	the penalty used for the penalized likelihood approach
target	the target used with the "RidgeArch" or "RidgeAlt" penalized likelihood approaches
REML	logical indicating if the REML (TRUE) or ML (FALSE) method has been used
opt	optimizing function output. See <code>opt.im</code>

Author(s)

Julien Clavel

References

- Clavel, J., Aristide, L., Morlon, H., 2019. A Penalized Likelihood framework for high-dimensional phylogenetic comparative methods and an application to new-world monkeys brain evolution. *Systematic Biology* 68(1): 93-116.
- Friedman J., Hastie T., Tibshirani R. 2008. Sparse inverse covariance estimation with the graphical lasso. *Biostatistics*. 9:432-441.

Hoffbeck J.P., Landgrebe D.A. 1996. Covariance matrix estimation and classification with limited training data. *IEEE Trans. Pattern Anal. Mach. Intell.* 18:763-767.

Housworth E.A., Martins E.P., Lynch M. 2004. The phylogenetic mixed model. *Am. Nat.* 163:84-96.

Theiler J. 2012. The incredible shrinking covariance estimator. In: *Automatic Target Recognition XXII. Proc. SPIE 8391*, Baltimore, p. 83910P.

van Wieringen W.N., Peeters C.F.W. 2016. Ridge estimation of inverse covariance matrices from high-dimensional data. *Comput. Stat. Data Anal.* 103:284-303.

See Also

[manova.gls](#) [EIC](#) [GIC](#) [mvglS.pca](#) [fitted.mvglS](#) [residuals.mvglS](#) [coef.mvglS](#) [vcov.mvglS](#)

Examples

```
set.seed(1)
n <- 32 # number of species
p <- 50 # number of traits (p>n)

tree <- pbtree(n=n, scale=1) # phylogenetic tree
R <- crossprod(matrix(runif(p*p), ncol=p)) # a random covariance matrix
# simulate a BM dataset
Y <- mvSIM(tree, model="BM1", nsim=1, param=list(sigma=R, theta=rep(0,p)))
data=list(Y=Y)

fit1 <- mvglS(Y~1, data=data, tree, model="BM", penalty="RidgeArch")
fit2 <- mvglS(Y~1, data=data, tree, model="OU", penalty="RidgeArch")
fit3 <- mvglS(Y~1, data=data, tree, model="EB", penalty="RidgeArch")

GIC(fit1); GIC(fit2); GIC(fit3) # BM have the lowest GIC value

# Testing for phylogenetic signal with model fit
signal <- mvglS(Y~1, data=data, tree, model="lambda", penalty="RidgeArch")
summary(signal)

# A High-dimensional dataset
p <- 200 # number of traits (p>n)

R <- crossprod(matrix(runif(p*p), ncol=p)) # a random symmetric matrix (covariance)
# simulate a BM dataset
Y <- mvSIM(tree, model="BM1", nsim=1, param=list(sigma=R, theta=rep(0,p)))
data=list(Y=Y)

# Fast LOOCV using "H&L" with RidgeArch penalization
summary(mvglS(Y~1, data=data, tree, model="BM", penalty="RidgeArch", method="H&L"))
```

 mvgl.pca

Principal Component Analysis (PCA) based on GLS estimate of the traits variance-covariance matrix (possibly regularized).

Description

Performs a principal component analysis (PCA) on a regularized variance-covariance matrix obtained using the `mvgl` function. With "evolutionary" models, this performs the so-called phylogenetic PCA.

Usage

```
mvgl.pca(object, plot=TRUE, ...)
```

Arguments

<code>object</code>	A model fit obtained by the <code>mvgl</code> function.
<code>plot</code>	Plot of the PC's axes. Default is TRUE (see details).'
<code>...</code>	Options to be passed through. (e.g., <code>axes=c(1,2)</code> , <code>col</code> , <code>pch</code> , <code>cex</code> , <code>mode="cov"</code> or <code>"corr"</code> , etc.)

Details

`mvgl.pca` allows computing a principal component analysis based on a GLS estimate of the covariance matrix (see `mvgl`). The phylogenetic PCA (following Revell 2009) is a special case obtained from the (possibly regularized) evolutionary variance-covariance matrix (see also the `phyl.pca.pl` function in RPANDA). In the high-dimensional case the contribution of the firsts PC axes tend to be overestimated with traditional maximum likelihood approaches. Penalized/regularized model fits reduce this bias and allow the estimation of various error structure models (see Clavel et al. 2018). Plotting options, the number of axes to display (`axes=c(1,2)` is the default), and whether the covariance (`mode="cov"`) or correlation (`mode="corr"`) should be used can be specified through the ellipsis `"..."` argument.

Value

a list with the following components

<code>scores</code>	the PC scores
<code>values</code>	the eigenvalues of the variance-covariance matrix estimated by <code>mvgl</code>
<code>vectors</code>	the eigenvectors of the variance-covariance matrix estimated by <code>mvgl</code>
<code>rank</code>	the rank of the estimated variance-covariance matrix

Note

Contrary to conventional PCA, the principal axes of the gls PCA are not orthogonal, they represent the main axes of independent (according to a given phylogenetic or time-series model) changes.

Author(s)

J. Clavel

References

Clavel, J., Aristide, L., Morlon, H., 2019. A Penalized Likelihood framework for high-dimensional phylogenetic comparative methods and an application to new-world monkeys brain evolution. *Systematic Biology* 68(1): 93-116.

Revell, L.J., 2009. Size-correction and principal components for intraspecific comparative studies. *Evolution*, 63:3258-3268.

See Also

[mvgl](#), [GIC](#), [EIC](#)

Examples

```
set.seed(1)
n <- 32 # number of species
p <- 30 # number of traits

tree <- pbtree(n=n) # phylogenetic tree
R <- crossprod(matrix(runif(p*p),p)) # a random symmetric matrix (covariance)

# simulate a dataset
Y <- mvSIM(tree, model="BM1", nsim=1, param=list(sigma=R))

# The conventional phylogenetic PCA
phylo_pca <- mvgl(Y~1, tree=tree, model="BM", method="LL")
mvgl.pca(phylo_pca, plot=TRUE)

# fit a multivariate Pagel lambda model with Penalized likelihood
fit <- mvgl(Y~1, tree=tree, model="lambda", method="LOO", penalty="RidgeAlt")

# Perform a regularized phylogenetic PCA using the model fit (Pagel lambda model)
pca_results <- mvgl.pca(fit, plot=TRUE)

# retrieve the scores
head(pca_results$scores)
```

mvLL	<i>Multivariate (and univariate) algorithms for log-likelihood estimation of arbitrary covariance matrix/trees</i>
------	--

Description

This function allows computing the log-likelihood and estimating ancestral states of an arbitrary tree or variance-covariance matrix with different algorithms based on GLS (Generalized Least Squares) or Independent Contrasts. Works for univariate or multivariate models. Can be wrapped for maximizing the log-likelihood of user-defined models.

Usage

```
mvLL(tree, data, error = NULL, method = c("pic", "rpf", "sparse", "inverse",
    "pseudoinverse"), param = list(estim = TRUE, mu = 0, sigma = 0, D = NULL,
    check = TRUE), precalc = NULL)
```

Arguments

tree	A phylogenetic tree of class "phylo" or a variance-covariance matrix (vcv) of that tree (or time-series).
data	Matrix or data frame with species in rows and continuous traits in columns. NA values are allowed with the "rpf", "inverse" and "pseudoinverse" methods.
error	Matrix or data frame with species in rows and continuous trait sampling variance (squared standard errors) in columns.
method	Method used for computing the log-likelihood. Could be "pic", "sparse", "rpf", "inverse", or "pseudoinverse". See details below.
param	List of additional arguments to be passed through the function. The "estim", "mu" and "sigma" arguments are only used with the "pic" method. The "D" argument is used with the others to specify the design matrix. See details below.
precalc	Optional. Object of class "precalc.mvmorph". See ?mv.Precalc for details.

Details

The mvLL function computes the log-likelihood and the ancestral states (mean at the root- θ) for an arbitrary variance-covariance matrix (or trees for the pruning algorithm based on independent contrasts "pic") provided by the user. This function can be wrapped for optimizing various multivariate models of trait evolution (by transforming the branch lengths of a tree for the "pic" method, or feeding it with variance-covariance and design matrices for the other methods).

Five methods are proposed to compute the log-likelihood:

- "pic" is a very fast pruning algorithm based on independent contrasts which should be used with strictly dichotomic trees (i.e., no polytomies). This method can neither be used with measurement errors nor for multiple ancestral states estimation (θ values).

- "rpf" is a GLS algorithm using the rectangular packed format Cholesky factorization for solving the linear system without computing the inverse of the variance-covariance matrix and its determinant

(normally used in the loglikelihood estimation). This algorithm uses fast BLAS 3 routines with half storage in packed format for computing the Cholesky upper factor. This method is more efficient than the "inverse" method and can be used with dense matrices (no zero entries).

- "sparse" is a GLS algorithm using Cholesky factorization for sparse matrices (including zero entries). The matrices are stored in the "old Yale sparse format" internally. Depending on the sparsity structure of the variance-covariance matrix this algorithm can be more efficient than the "rpf" method.

- "inverse" is a GLS algorithm that uses explicit inversion of the variance-covariance matrix (through QR decomposition) as well as computation of its determinant in the log-likelihood estimation. This is the "textbook" method, that is computationally more intensive than the previous approaches.

- "pseudoinverse" is a GLS method that uses a generalized inverse (through SVD) for computing the log-likelihood. This method is safer when the matrix is near singularity, but it is the most time-consuming.

The user must provide a variance-covariance matrix (e.g., `vcv.phylo(tree)`) or a multivariate variance-covariance matrix (e.g., `kronecker(matrix(c(2,1,1,1.5),2),vcv.phylo(tree))`) as well as a design matrix (or multivariate design matrix) with the "rpf", "sparse", "inverse", and "pseudoinverse" methods.

Use the "param" list of arguments to define whether or not the brownian rate should be estimated and returned (`estim=TRUE`) with the "pic" method. Otherwise, the rate parameter (also called sigma) is fixed to 1. The arguments "mu" and "sigma" can be used to specify (e.g., in a MCMC setting) the mean at the root and the (squared) brownian rate, respectively.

You can choose to provide differently scaled trees for multivariate data with the "pic" method. In such a case, the trees (one per trait) should be embedded within a list() object. See example below.

Value

logl	Estimated log-likelihood for the data with the given matrix/tree.
theta	Estimated ancestral states at the root. They are defined by the design matrix (D) for all the methods but "pic".
sigma	Estimated (squared) rate parameters. Only when <code>param\$estim=TRUE</code> with the "pic" method.

Author(s)

Julien Clavel

References

- Andersen B. S., Wasniewski J., Gustavson F. G. 2001. A recursive formulation of Cholesky factorization of a matrix in packed storage. *ACM Trans. Math. Soft.* 27:214-244.
- Clavel J., Escarguel G., Merceron G. 2015. mvMORPH: an R package for fitting multivariate evolutionary models to morphometric data. *Methods Ecol. Evol.* 6(11):1311-1319.
- Freckleton R.P. 2012. Fast likelihood calculations for comparative analyses. *Methods Ecol. Evol.* 3:940-947.
- Golub G.H., Van Loan C.F. 2013. *Matrix computations*. Baltimore: The John Hopkins University Press.

Gustavson, F.G., Wasniewski, J., Dongarra, J.J., Langou, J. 2010. Rectangular full packed format for Cholesky's algorithm: factorization, solution and inversion. ACM Trans. Math. Soft., 37:1-33.

See Also

[mvMORPH](#) [mvgls](#) [mvOU](#) [mvEB](#) [mvBM](#) [mvSHIFT](#) [mvSIM](#)

Examples

```
## Simulated dataset
set.seed(14)
# Generating a random tree with 50 tips
n=50
tree<-pbtree(n=n)

# Simulated trait
data=rTraitCont(tree)

# Design matrix
D=matrix(rep(1,n),ncol=1)

## Compute the log-likelihood
# Inverse
mvLL(vcv.phylo(tree),data,method="inverse",param=list(D=D))

# Pseudoinverse
mvLL(vcv.phylo(tree),data,method="pseudoinverse",param=list(D=D))

# Sparse
mvLL(vcv.phylo(tree),data,method="sparse",param=list(D=D))

# RPF
mvLL(vcv.phylo(tree),data,method="rpf",param=list(D=D))

# Pic
mvLL(tree,data,method="pic",param=list(estim=TRUE))

# Pic with arbitrary values
mvLL(tree,data,method="pic",param=list(estim=FALSE, mu=0, sigma=1))
mvLL(tree,data,method="pic",param=list(estim=FALSE))
mvLL(tree,data,method="pic",param=list(estim=FALSE, sigma=1)) # similar to mu=NULL

# Arbitrary value for mu with other methods (similar to mu=0 and sigma=1 with "pic")
mvLL(vcv.phylo(tree),data,method="rpf",param=list(D=D, estim=FALSE, mu=0))

## Multivariate cases
# Simulate traits
data2<-mvSIM(tree,nsim=1,model="BM1",param=list(sigma=diag(2),theta=c(0,0),ntraits=2))
# Design matrix
D<-cbind(rep(c(1,0),each=50),rep(c(0,1),each=50))

# RPF
```

```

mvLL(kronecker(diag(2),vcv.phylo(tree)),data2,method="rpf", param=list(D=D))

# Inverse (with default design matrix if not provided)
mvLL(kronecker(diag(2),vcv.phylo(tree)),data2,method="inverse")

# Pic
mvLL(tree,data2,method="pic")
# NB: The trees in the list could be differently scaled for each traits...
mvLL(list(tree,tree),data2,method="pic")

## VERY FAST COMPUTATION FOR LARGE TREES (take few seconds)

# Big tree (1,000,000 species) - It's the time consuming part...
tree2<-rtree(1000000)
# Simulate trait with a Brownian motion process
trait<-rTraitCont(tree2)
system.time(mvLL(tree2,trait,method="pic",param=list(estim=FALSE, sigma=1)))

precalc<-mv.Precalc(tree2,nb.traits=1, param=list(method="pic"))
system.time(mvLL(tree2,trait,method="pic",param=list(estim=FALSE, sigma=1),
precalc=precalc))

# Check=FALSE !! Your tree should be in post-order !!
tr2<-reorder(tree2,"postorder")
system.time(mvLL(tr2,trait,method="pic",param=list(estim=FALSE, sigma=1, check=FALSE)))

```

mvOU

Multivariate Ornstein-Uhlenbeck model of continuous traits evolution

Description

This function allows the fitting of a multivariate Ornstein-Uhlenbeck (OU) model by allowing a given tree branch to be subdivided into multiple selective regimes using SIMMAP-like mapping of ancestral states. Species measurement errors or dispersions can also be included in the model.

Usage

```

mvOU(tree, data, error = NULL, model = c("OUM", "OU1"), param = list(sigma = NULL,
alpha = NULL, vcv = "fixedRoot", decomp = c("cholesky", "spherical", "eigen", "qr",
"diagonal", "upper", "lower")), method = c("rpf", "sparse", "inverse",
"pseudoinverse", "univarpf"), scale.height = FALSE, optimization = c("L-BFGS-B",
"Nelder-Mead", "subplex"), control = list(maxit = 20000), precalc = NULL,
diagnostic = TRUE, echo = TRUE)

```

Arguments

tree	Phylogenetic tree with mapped ancestral states in SIMMAP format. (See <code>make.simmap</code> function from <code>phytools</code> package). A "phylo" object can be used with model "OU1".
data	Matrix or data frame with species in rows and continuous traits in columns. NA values are allowed with the "rpf", "inverse", and "pseudoinverse" methods.
error	Matrix or data frame with species in rows and continuous trait sampling variance (squared standard errors) in columns.
model	Choose between "OUM" for a multiple selective regime model, or "OU1" for a unique selective regime for the whole tree.
param	List of arguments to be passed to the function. See details below.
method	Choose between "rpf", "sparse", "inverse", "pseudoinverse", or "univarpf" for computing the log-likelihood during the fitting process. See details below.
scale.height	Whether the tree should be scaled to unit length or not.
optimization	Methods used by the optimization routines (see <code>?optim</code> and <code>?subplex</code> for details). The "fixed" method returns the log-likelihood function only.
control	Max. bound for the number of iteration of the optimizer; other options can be fixed in the list. (See <code>?optim</code> or <code>?subplex</code> for details).
precalc	Optional. Precalculation of fixed parameters. See <code>?mvmorph.Precalc</code> for details.
diagnostic	Whether the convergence diagnostics should be returned or not.
echo	Whether the results must be returned or not.

Details

The `mvOU` function fits a multivariate model of evolution according to an Ornstein-Uhlenbeck process. The user can incorporate measurement errors and uses SIMMAP-like mapping of ancestral states (`phytools` objects of class "simmap"). SIMMAP mapping allows one to assign parts of branches to different selective regimes, and allows testing for change in trait variance that is not synchronous with the species divergence events. See the package vignette: `browseVignettes("mvMORPH")`.

Mapping of ancestral states can be done using the `"make.simmap"`, `"make.era.map"` or `"paintSubTree"` functions from the `"phytools"` package.

The `"method"` argument allows the user to try different algorithms for computing the log-likelihood. The `"rpf"`, `"univarpf"` (for univariate analysis) and `"sparse"` methods use fast GLS algorithms based on factorization for avoiding the computation of the inverse of the variance-covariance matrix and its determinant for the log-likelihood estimation. The `"inverse"` approach uses the "stable" standard explicit computation of the inverse and determinant of the matrix and is therefore slower. The `"pseudoinverse"` method uses a generalized inverse that is safer for matrix near singularity but highly time consuming. See `?mvLL` for details.

Arguments in the `"param"` list are:

"sigma" or **"alpha"** - Starting values for the likelihood search can be specified through the `"alpha"` and `"sigma"` arguments in the `param` list. It is also possible to test for the significance of the off-diagonal sigma (scatter) and alpha (drift) matrix in the full model by making comparison with a constrained model (using `sigma="constraint"`, or `alpha="constraint"`) in the `"param"` argument list.

You can also provide starting values for the constrained model. For instance, for two traits use `sigma=list("constraint", c(0.5,0.5))` (or `alpha=list("constraint", c(0.5,0.5))`).

"decomp" - You can further constrain the alpha matrix by specifying the decomposition of the matrix through the "decomp" argument in the "param" list. Indeed, the multivariate Ornstein-Uhlenbeck model is described by the spectral decomposition of the alpha matrix. Thus it is possible to parameterize the alpha matrix to be decomposable using various parameterizations (e.g., on its eigenvalues with different biological interpretations; Sy et al. 1997, Bartoszek et al. 2012). For a symmetric matrix parameterization the user can choose the "cholesky", "eigen", or "spherical" option.

For general square (non-symmetric) matrices the "svd", "qr" and "schur" parameterizations can be used. The "schur" parameterization constrains the eigenvalues of the alpha matrix to be real numbers. The "svd+", "qr+" or "eigen+" options forces the eigenvalues to be positives by taking their logarithm. It is also possible to specify "diagonal" which is similar to the use of the "constraint" argument for "alpha" argument, or to use "equal" and "equaldiagonal". Finally, one can specify that the alpha matrix is "upper" or "lower" triangular (i.e., one process affect the other unilaterally). Details can be found in the package vignette: `browseVignettes("mvMORPH")`.

"decompSigma" - The sigma matrix is parameterized by various methods to ensure its positive definiteness (Pinheiro and Bates, 1996). These methods can be accessed through the "decompSigma" argument and are the "cholesky", "eigen+", and "spherical" parameterization. The sigma matrix can also be forced to be diagonal using "diagonal" or "equaldiagonal" and forced to have the same variances using "equal". Details can be found in the package vignette: `browseVignettes("mvMORPH")`.

"vcv" - It is possible to specify in the "param" list what kind of variance-covariance matrix to use with the "vcv" argument, depending on how the root is treated. The `vcv="randomRoot"` option assumes that the value at the root is a random variable with the stationary distribution of the process. It cannot be used with the "sparse" method to speed up the computations. The `vcv="fixedRoot"` option assumes that the root is a fixed parameter. On ultrametric trees both approaches should converge on the same results when the OU process is stationary.

"root" - This argument allows the user to specify if the ancestral state at the root (θ_0) should be estimated (`root=TRUE`), or assumed to be at the oldest regime state stationary distribution (`root=FALSE`). An alternative is to follow Beaulieu et al. (2012) and explicitly drop the root state influence (`root="stationary"`). The first option should be used with non-ultrametric trees (i.e., with fossil species; e.g., Hansen 1997) where information on the ancestral state is directly available from the data. Indeed, estimating shifts in the ancestral state from extant species could be problematic and it seems preferable to assume each regime optimum to be at the stationary distribution.

For the **"decomp"** and **"decompSigma"** arguments, an user-defined matrix with integer values taken as indices of the parameters to be estimated can be provided. See `?mvBM` and `?mvRWTS`.

Note on the returned Hessian matrix in the result list (`paramopthessian`):

The hessian is the matrix of second order partial derivatives of the likelihood function with respect to the maximum likelihood parameter values. This matrix provides a measure of the steepness of the likelihood surface in the vicinity of the optimum. The eigen-decomposition of the hessian matrix returned by the optimizing function allows assessing the reliability of the fit of the model (even if the optimizer has converged). When the optimization function does not converge on a stable result, the user may consider increasing the "maxit" argument in the "control" option, or try a simpler model with fewer parameters to estimate. Changing the starting values ("alpha" and "sigma" options in the param list) as well as the optimizing method ("optimization" options) may help sometimes (e.g.,

alpha=runif(3) for a two-trait analysis with random starting values - i.e., the lower triangular alpha matrix). Note that the number of starting values to provide depends on the matrix decomposition chosen for the alpha parameter ($p*(p+1)/2$ values for symmetric alpha matrix, but $p*p$ values for non-symmetric ones - with p the number of traits).

Value

LogLik	The log-likelihood of the optimal model.
AIC	Akaike Information Criterion for the optimal model.
AICc	Sample size-corrected AIC.
theta	Estimated ancestral states.
alpha	Matrix of estimated alpha values (strength of selection).
sigma	Evolutionary rate matrix (drift).
convergence	Convergence status of the optimizing function; "0" indicates convergence. (see ?optim for details).
hess.values	Reliability of the likelihood estimates calculated through the eigen-decomposition of the hessian matrix. "0" means that a reliable estimate has been reached. See details above.
param	List of model fit parameters (optimization, method, model, number of parameters...).
llik	The log-likelihood function evaluated in the model fit "\$llik(par, root.mle=TRUE)".

Note

This function partly uses a modified version of the C code from the "OUCH" package built by Aaron King, as well as a C code which is part of the "ape" package by Emmanuel Paradis. I kindly thank those authors for sharing their sources. Note that Bartoszek et al. (2012) proposed the mvSLOUCH package also dedicated to multivariate Ornstein-Uhlenbeck processes, which allows fitting regression models with randomly evolving predictor variables.

The "symmetric", "nsymmetric", "symmetricPositive", and "nsymPositive" options for the "decomp" argument are deprecated.

Author(s)

Julien Clavel

References

- Bartoszek K., Pienaar J., Mostad P., Andersson S., Hansen T.F. 2012. A phylogenetic comparative method for studying multivariate adaptation. *J. Theor. Biol.* 314:204-215.
- Beaulieu J.M., Jhwueng D.-C., Boettiger C., O'Meara B.C. 2012. Modeling stabilizing selection: Expanding the Ornstein-Uhlenbeck model of adaptive evolution. *Evolution.* 66:2369-2389.
- Butler M.A., King A.A. 2004. Phylogenetic comparative analysis: a modeling approach for adaptive evolution. *Am. Nat.* 164:683-695.
- Clavel J., Escarguel G., Merceron G. 2015. mvMORPH: an R package for fitting multivariate evolutionary models to morphometric data. *Methods Ecol. Evol.* 6(11):1311-1319.

Hansen T.F. 1997. Stabilizing selection and the comparative analysis of adaptation. *Evolution*. 51:1341-1351.

Pinheiro J.C., Bates D.M. 1996. Unconstrained parameterizations for variance-covariance matrices. *Stat. Comput.* 6:289-296.

Sy J.P., Taylor J.M.G., Cumberland W.G. 1997. A stochastic model for the analysis of bivariate longitudinal AIDS data. *Biometrics*. 53:542-555.

See Also

[mvMORPH](#) [mvgl](#) [half](#) [life](#) [stationary](#) [mvBM](#) [mvEB](#) [mvSHIFT](#) [mvOUTS](#) [mvRWTS](#) [mvSIM](#) [LRT](#) [optim](#)
[make.simmap](#) [make.era.map](#) [paintSubTree](#)

Examples

```
# Simulated dataset
set.seed(14)
# Generating a random tree
tree<-pbtree(n=50)

# Setting the regime states of tip species
sta<-as.vector(c(rep("Forest",20),rep("Savannah",30))); names(sta)<-tree$tip.label

# Making the simmap tree with mapped states
tree<-make.simmap(tree,sta , model="ER", nsim=1)
col<-c("blue","orange"); names(col)<-c("Forest","Savannah")

# Plot of the phylogeny for illustration
plotSimmap(tree,col,fsize=0.6,node.numbers=FALSE,lwd=3, pts=FALSE)

# Simulate the traits
alpha<-matrix(c(2,0.5,0.5,1),2)
sigma<-matrix(c(0.1,0.05,0.05,0.1),2)
theta<-c(2,3,1,1.3)
data<-mvSIM(tree, param=list(sigma=sigma, alpha=alpha, ntraits=2, theta=theta,
names_traits=c("head.size","mouth.size")), model="OUM", nsim=1)

## Fitting the models

# OUM - Analysis with multiple optima
mvOU(tree, data)

# OU1 - Analysis with a unique optimum
mvOU(tree, data, model="OU1", method="sparse")

# various options
mvOU(tree, data, model="OUM", method="sparse", scale.height=FALSE,
param=list(decomp="svd", root="stationary"))# non-symmetric alpha
mvOU(tree, data, model="OUM", method="sparse", scale.height=FALSE,
param=list(decomp="qr", root=TRUE)) # non-symmetric alpha
mvOU(tree, data, model="OUM", method="sparse", scale.height=FALSE,
param=list(decomp="cholesky", root=TRUE)) # symmetric-positive
```

```

# OUCH setting
mvOU(tree, data, model="OUM", method="rpf", scale.height=FALSE,
      param=list(decomp="cholesky", root=FALSE, vcv="ouch"))

## Univariate case - FAST with RPF
set.seed(14)
tree<-pbtree(n=500)

# Setting the regime states of tip species
sta<-as.vector(c(rep("Forest",200),rep("Savannah",300))); names(sta)<-tree$tip.label

# Making the simmap tree with mapped states
tree<-make.simmap(tree,sta , model="ER", nsim=1)
col<-c("blue","orange"); names(col)<-c("Forest","Savannah")

# Plot of the phylogeny for illustration
plotSimmap(tree,col,fsize=0.6,node.numbers=FALSE,lwd=3, pts=FALSE)

# Parameters
alpha<-2.5
sigma<-0.1
theta<-c(0,2)
data<-mvSIM(tree, param=list(sigma=sigma, alpha=alpha, ntraits=1, theta=theta,
                             names_traits=c("body_size")), model="OUM", nsim=1)

# Fit the model
system.time(mvOU(tree, data, model="OUM", method="univarpf",
                 param=list(root="stationary")))
system.time(mvOU(tree, data, model="OU1", method="univarpf",
                 param=list(root="stationary")))

# Add measurement error
error=rnorm(500,sd=0.1)
mvOU(tree, data, error=error^2, model="OUM", method="univarpf",
      param=list(root="stationary"))

```

mvOUTS

*Multivariate continuous trait evolution for a stationary time series
(Ornstein-Uhlenbeck model)*

Description

This function allows the fitting of a multivariate Ornstein-Uhlenbeck (OU) model to a time series. Species measurement errors or dispersions can also be included in the model.

Usage

```
mvOUTS(times, data, error = NULL, param = list(sigma = NULL, alpha = NULL,
```

```
vcv = "randomRoot", decomp = c("cholesky", "spherical", "eigen", "qr",
"diagonal", "upper", "lower")), method = c("rpf", "inverse", "pseudoinverse",
"univarpf"), scale.height = FALSE, optimization = c("L-BFGS-B", "Nelder-Mead",
"subplex"), control = list(maxit = 20000), precalc = NULL, diagnostic = TRUE,
echo = TRUE)
```

Arguments

times	Time series - vector of sample ages.
data	Matrix or data frame with species in rows and continuous traits in columns. NA values are allowed.
error	Matrix or data frame with species in rows and continuous trait sampling variance (squared standard errors) in columns.
param	List of arguments to be passed to the function. See details below.
method	Choose between "rpf", "inverse", "pseudoinverse", or "univarpf" for computing the log-likelihood during the fitting process. See details below.
scale.height	Whether the time series should be scaled to unit length or not.
optimization	Methods used by the optimization routines (see ?optim and ?subplex for details). The "fixed" method returns the log-likelihood function only.
control	Max. bound for the number of iteration of the optimizer; other options can be fixed in the list (see ?optim or ?subplex).
precalc	Optional. Precalculation of fixed parameters. See ?mvmorph.Precalc for details.
diagnostic	Whether the convergence diagnostics should be returned or not.
echo	Whether the results must be returned or not.

Details

The mvOUTS function fits a multivariate model of trait evolution on a time series according to an Ornstein-Uhlenbeck process. The user can include measurement errors to the analyzed dataset.

The "method" argument allows the user to try different algorithms for computing the log-likelihood. The "rpf", "univarpf" (for univariate analysis) methods use fast GLS algorithms based on factorization for avoiding the computation of the inverse of the variance-covariance matrix and its determinant for the log-likelihood estimation. The "inverse" approach uses the "stable" standard explicit computation of the inverse and determinant of the matrix and is therefore slower. The "pseudoinverse" method uses a generalized inverse that is safer for matrix near singularity but highly time consuming. See ?mvLL for details.

Arguments in the "param" list are:

"sigma" or **"alpha"** - Starting values for the likelihood search can be specified through the "alpha" and "sigma" arguments in the param list. It is also possible to test for the significance of the off-diagonal sigma (scatter) and alpha (drift) matrix in the full model by making comparison with a constrained model (using sigma="constraint", or alpha="constraint") in the "param" argument list. You can also provide starting values for the constrained model. For instance, for two traits use sigma=list("constraint", c(0.5,0.5)) (or alpha=list("constraint", c(0.5,0.5))).

"decomp" - You can further constrain the alpha matrix by specifying the decomposition of the matrix through the "decomp" argument in the "param" list. Indeed, the multivariate Ornstein-Uhlenbeck model is described by the spectral decomposition of the alpha matrix. Thus it is possible to parameterize the alpha matrix to be decomposable using various parameterizations (e.g., on its eigenvalues with different biological interpretations; Sy et al. 1997, Bartoszek et al. 2012). For a symmetric matrix parameterization the user can choose the *"cholesky"*, *"eigen"*, or *"spherical"* option. For general square (non-symmetric) matrices the *"svd"*, *"qr"* and *"schur"* parameterizations can be used. The *"schur"* parameterization constrains the eigenvalues of the alpha matrix to be real numbers. The *"svd+"*, *"qr+"* or *"eigen+"* options forces the eigenvalues to be positives by taking their logarithm. It is also possible to specify *"diagonal"* which is similar to the use of the "constraint" argument for the "alpha" argument, or to use *"equal"* and *"equaldiagonal"*. Finally, one can specify that the alpha matrix is *"upper"* or *"lower"* triangular (i.e., one process affect the other unilaterally). Details can be found in the package vignette: `browseVignettes("mvMORPH")`.

"decompSigma" - The sigma matrix is parameterized by various methods to ensure its positive definiteness (Pinheiro and Bates, 1996). These methods can be accessed through the "decompSigma" argument and are the *"cholesky"*, *"eigen+"*, and *"spherical"* parameterization. The sigma matrix can also be forced to be diagonal using *"diagonal"* or *"equaldiagonal"* and forced to have the same variances using *"equal"*. Details can be found in the package vignette: `browseVignettes("mvMORPH")`.

"vcv" - It is possible to specify in the "param" list what kind of variance-covariance matrix to use with the "vcv" argument, depending on how the root is treated. The *vcv="randomRoot"* option assumes that the value at the root is a random variable with the stationary distribution of the process. The *vcv="fixedRoot"* option assumes that the root is a fixed parameter.

"root" - If `root=TRUE`, the ancestral state and the optimum (stationary mean) are estimated, otherwise (`root=FALSE`) the ancestral (initial) state and the optimum (long-term expectation) are assumed to be the same.

Note: for the **"decomp"** and **"decompSigma"** arguments, an user-defined matrix with integer values taken as indices of the parameters to be estimated can be provided. See `?mvBM` and `?mvRWTS`.

Value

LogLik	The log-likelihood of the optimal model.
AIC	Akaike Information Criterion for the optimal model.
AICc	Sample size-corrected AIC.
theta	Estimated ancestral states.
alpha	Matrix of estimated alpha values (strength of selection, drift matrix).
sigma	Evolutionary rate matrix (scatter).
convergence	Convergence status of the optimizing function; "0" indicates convergence. (See <code>?optim</code> for details).
hess.values	Reliability of the likelihood estimates calculated through the eigen-decomposition of the hessian matrix. "0" means that a reliable estimate has been reached. See details on <code>?mvOU</code> .
param	List of model fit parameters (optimization, method, model, number of parameters...).
llik	The log-likelihood function evaluated in the model fit <code>"\$llik(par, root.mle=TRUE)"</code> .

Author(s)

Julien Clavel

References

- Bartoszek K., Pienaar J., Mostad P., Andersson S., Hansen T.F. 2012. A phylogenetic comparative method for studying multivariate adaptation. *J. Theor. Biol.* 314:204-215.
- Clavel J., Escarguel G., Merceron G. 2015. mvMORPH: an R package for fitting multivariate evolutionary models to morphometric data. *Methods Ecol. Evol.* 6(11):1311-1319.
- Hunt G., Bell M.A., Travis M.P. 2008. Evolution toward a new adaptive optimum: phenotypic evolution in a fossil stickleback lineage. *Evolution* 62(3):700-710.
- Pinheiro J.C., Bates D.M. 1996. Unconstrained parameterizations for variance-covariance matrices. *Stat. Comput.* 6:289-296.
- Sy J.P., Taylor J.M.G., Cumberland W.G. 1997. A stochastic model for the analysis of bivariate longitudinal AIDS data. *Biometrics.* 53:542-555.

See Also

[mvMORPH](#) [halflife](#) [stationary](#) [mvOU](#) [mvRWTS](#) [mvBM](#) [mvEB](#) [mvSHIFT](#) [mvSIM](#) [LRT](#) [optim](#)

Examples

```
# Simulate the time series
set.seed(14)
timeseries <- 0:49
# Parameters with general alpha matrix on two competitive species (or two traits)
# asymmetric (drift) matrix with intervention from the lowest layer
alpha <- matrix(c(0.15,0,0.1,0.1),2,2)
# scatter matrix
sigma <- matrix(c(0.01,0.005,0.005,0.01),2)
# ancestral states and long term optimum expectation
theta <- matrix(c(0,1,0,.5),2) # columns=traits

# Simulate the data
traits <- mvSIM(timeseries, model="OUTS", param=list(theta=theta, alpha=alpha, sigma=sigma))

# Plot the time series
matplot(traits,type="o",pch=1, xlab="Time (relative)")

fit1 <- mvOUTS(timeseries, traits, param=list(decomp="qr"))
fit2 <- mvOUTS(timeseries, traits, param=list(decomp="eigen"))
fit3 <- mvOUTS(timeseries, traits, param=list(decomp="diagonal"))

results <- list(fit1,fit2,fit3)
aicw(results)

# Simulate under the MLE
```

```

traits2 <- simulate(fit1,tree=timeseries)
matplot(traits2, type="o", pch=1, xlab="Time (relative)")

mvOUTS(timeseries, traits2, param=list(decomp="eigen"))
mvOUTS(timeseries, traits2, param=list(decomp="diagonal"))
mvOUTS(timeseries, traits2, param=list(decomp="upper"))
mvOUTS(timeseries, traits2, param=list(decomp="lower"))

# try user defined constraints
set.seed(100)
ts <- 49
timeseries <- 1:ts

sigma <- matrix(c(0.01,0.005,0.003,0.005,0.01,0.003,0.003,0.003,0.01),3)
# upper triangular matrix with effect of trait 2 on trait 1.
alpha <- matrix(c(0.4,0,0,-0.5,0.3,0,0,0,0.2),3,3)
theta <- matrix(c(0,0,0,1,0.5,0.5),byrow=TRUE, ncol=3); root=TRUE

data <- mvSIM(timeseries, model="OUTS", param=list(alpha=alpha,
          sigma=sigma, theta=theta, root=root,
          names_traits=c("sp 1", "sp 2", "sp 3")))

# plot
matplot(data, type="o", pch=1, xlab="Time (relative)")
legend("bottomright", inset=.05, legend=colnames(data), pch=19, col=c(1,2,3), horiz=TRUE)

# define an user constrained drift matrix
indice <- matrix(NA,3,3)
diag(indice) <- c(1,2,3)
indice[1,2] <- 4

# fit the model
fit_1 <- mvOUTS(timeseries, data, param=list(vcv="fixedRoot", decomp=indice))
fit_2 <- mvOUTS(timeseries, data, param=list(vcv="fixedRoot", decomp="diagonal"))

LRT(fit_1, fit_2)

```

Description

This function allows the fitting of multivariate Brownian motion/Random walk model on time-series. This function can also fit constrained models.

Usage

```
mvRWTS(times, data, error = NULL, param =
  list(sigma=NULL, trend=FALSE, decomp="cholesky"), method = c("rpf",
  "inverse", "pseudoinverse"), scale.height = FALSE,
  optimization = c("L-BFGS-B", "Nelder-Mead", "subplex"),
  control = list(maxit = 20000), precalc = NULL, diagnostic = TRUE,
  echo = TRUE)
```

Arguments

times	Time series - vector of sample ages.
data	Matrix or data frame with species/sampled points in rows and continuous traits in columns
error	Matrix or data frame with species/sampled points in rows and continuous traits sampling variance (squared standard error) in columns.
param	List of arguments to be passed to the function. See details below.
method	Choose between "rpf", "inverse", or "pseudoinverse" for log-likelihood computation during the fitting process. See details below.
scale.height	Whether the time series should be scaled to unit length or not.
optimization	Methods used by the optimization routines (see ?optim and ?subplex for details). The "fixed" method returns the log-likelihood function only.
control	Max. bound for the number of iteration of the optimizer; other options can be fixed in the list (see ?optim or ?subplex).
precalc	Optional. Precalculation of fixed parameters. See ?mvmorph.Precalc.
diagnostic	Whether the diagnostics of convergence should be returned or not.
echo	Whether the results must be returned or not.

Details

The mvRWTS function fits a multivariate Random Walk (RW; i.e., the time series counterpart of the Brownian motion process).

The "method" argument allows the user to try different algorithms for computing the log-likelihood. The "rpf" and "sparse" methods use fast GLS algorithms based on factorization for avoiding the computation of the inverse of the variance-covariance matrix and its determinant involved in the log-likelihood estimation. The "inverse" approach uses the "stable" standard explicit computation of the inverse and determinant of the matrix and is therefore slower. The "pseudoinverse" method uses a generalized inverse that is safer for matrix near singularity but highly time consuming. See ?mvLL for more details on these computational methods.

Arguments in the "**param**" list are:

"constraint" - The "constraint" argument in the "param" list allows the user to compute the joint likelihood for each trait by assuming they evolved independently (constraint="diagonal", or constraint="eualdiagonal"). If constraint="equal", the sigma values are constrained to be the same for each trait using the constrained Cholesky decomposition proposed by Adams (2013) or a separation strategy based on spherical parameterization when $p > 2$ (Clavel et al. 2015).

User-defined constraints can be specified through a numeric matrix (square and symmetric) with integer values taken as indices of the parameters.

For instance, for three traits:

```
constraint=matrix(c(1,3,3,3,2,3,3,3,2),3).
```

Covariances constrained to be zero are introduced by NA values, e.g.,

```
constraint=matrix(c(1,4,4,4,2,NA,4,NA,3),3).
```

Difference between two nested fitted models can be assessed using the "LRT" function. See example below and ?LRT.

"decomp" - For the general case (unconstrained models), the sigma matrix is parameterized by various methods to ensure its positive definiteness (Pinheiro and Bates, 1996). These methods are the "cholesky", "eigen+", and "spherical" parameterizations.

"trend" - Default set to FALSE. If TRUE, the ancestral state is allowed to drift leading to a directional random walk. Note that it is possible to provide a vector of integer indices to constraint the estimated trends when $p > 1$ (see the vignettes).

"sigma" - Starting values for the likelihood estimation. By default the trait covariances are used as starting values for the likelihood optimization. The user can specify starting values as square symmetric matrices or a simple vector of values for the upper factor of the sigma matrix. The parameterization is done using the factorization determined through the "decomp" argument (Pinheiro and Bates, 1996). Thus, you should provide $p*(p+1)/2$ values, with p the number of traits (e.g., random numbers or the values from the cholesky factor of a symmetric positive definite sigma matrix; see example below). If a constrained model is used, the number of starting values is $(p*(p-1)/2)+1$.

Value

LogLik	The log-likelihood of the optimal model.
AIC	Akaike Information Criterion for the optimal model.
AICc	Sample size-corrected AIC.
theta	Estimated ancestral states.
sigma	Evolutionary rate matrix for each selective regime.
convergence	Convergence status of the optimizing function; "0" indicates convergence (see ?optim for details).
hess.values	Reliability of the likelihood estimates calculated through the eigen-decomposition of the hessian matrix. "0" means that a reliable estimate has been reached (see ?mvOU).
param	List of model fit parameters (optimization, method, model, number of parameters...).
llik	The log-likelihood function evaluated in the model fit "\$llik(par, root.mle=TRUE)".

Author(s)

Julien Clavel

References

- Adams D.C. 2013. Comparing evolutionary rates for different phenotypic traits on a phylogeny using likelihood. *Syst. Biol.* 62:181-192.
- Clavel J., Escarguel G., Merceron G. 2015. mvMORPH: an R package for fitting multivariate evolutionary models to morphometric data. *Methods Ecol. Evol.*, 6(11):1311-1319.
- Hunt G. (2012). Measuring rates of phenotypic evolution and the inseparability of tempo and mode. *Paleobiology*, 38(3):351-373.
- Revell L.J. 2012. phytools: An R package for phylogenetic comparative biology (and other things). *Methods Ecol. Evol.* 3:217-223.

See Also

[mvMORPH](#) [mvOU](#) [mvEB](#) [mvSHIFT](#) [mvSIM](#) [mvOUTS](#) [LRT](#) [optim](#)

Examples

```
set.seed(1)
# Simulate the time series
timeseries <- 0:49

# Simulate the traits
sigma <- matrix(c(0.01,0.005,0.005,0.01),2)
theta <- c(0,1)
error <- matrix(0,ncol=2,nrow=50);error[1,]=0.001
data<-mvSIM(timeseries, error=error,
            param=list(sigma=sigma, theta=theta), model="RWTS", nsim=1)

# plot the time series
matplot(data, type="o", pch=1, xlab="Time (relative)")

# model fit
mvRWTS(timeseries, data, error=error, param=list(decomp="diagonal"))
mvRWTS(timeseries, data, error=error, param=list(decomp="equal"))
mvRWTS(timeseries, data, error=error, param=list(decomp="cholesky"))

# Random walk with trend
set.seed(1)
trend <- c(0.02,0.02)
data<-mvSIM(timeseries, error=error,
            param=list(sigma=sigma, theta=theta, trend=trend), model="RWTS", nsim=1)

# plot the time serie
matplot(data, type="o", pch=1, xlab="Time (relative)")

# model fit
mvRWTS(timeseries, data, error=error, param=list(trend=TRUE))

# we can specify a vector of indices
mvRWTS(timeseries, data, error=error, param=list(trend=c(1,1)))
```

mvSHIFT

*Multivariate change in mode of continuous trait evolution***Description**

This function fits different models of evolution after a fixed point. This allows fitting models of change in mode of evolution following a given event.

Usage

```
mvSHIFT(tree, data, error = NULL, param = list(age = NULL, sigma = NULL,
  alpha = NULL, sig = NULL, beta = NULL), model = c("ER", "RR", "EC",
  "RC", "SR", "EBOU", "OUEB", "EBBM", "BMEB"), method = c("rpf",
  "sparse", "inverse", "pseudoinverse"), scale.height = FALSE,
  optimization = c("L-BFGS-B", "Nelder-Mead", "subplex"), control =
  list(maxit = 20000), precalc = NULL, diagnostic = TRUE, echo = TRUE)
```

Arguments

tree	Phylogenetic tree with a shift mapped (see "make.era.map" function from "phy-tools" package). A "phylo" object can be used if the "age" argument is provided in the "param" list.
data	Matrix or data frame with species in rows and continuous traits in columns. NA values are allowed with the "rpf", "inverse", and "pseudoinverse" methods.
error	Matrix or data frame with species in rows and continuous trait sampling variance (squared standard errors) in columns.
param	List of arguments to be passed to the function. See details.
model	Choose between the different models "OUBM", "BMOU", "EBOU", "OUEB", "BMEB", "EBBM"... See details below.
method	Choose between "rpf", "sparse", "inverse", or "pseudoinverse" for computing the log-likelihood during the fitting process. See details below.
scale.height	Whether the tree should be scaled to unit length or not.
optimization	Methods used by the optimization routines (see ?optim and ?subplex for details). The "fixed" method returns the log-likelihood function only.
control	Max. bound for the number of iteration of the optimizer; other options can be fixed in the list (see ?optim and ?subplex for details).
precalc	Optional. Precalculation of fixed parameters. See ?mvmorph.Precalc for details.
diagnostic	Whether the diagnostics of convergence should be returned or not.
echo	Whether the results must be returned or not.

Details

The mvSHIFT function fits a shift in mode or rate of evolution at a fixed point in time, as previously proposed by some authors (O'Meara et al. 2006; O'Meara, 2012; Slater, 2013). Shift in mode of evolution can be mapped on a modified "phylo" object using the "make.era.map" function from the "phytools" package. Note that only one shift is allowed by the current version of mvMORPH. The age of the shift can be otherwise directly provided (in unit of times of the tree) in the function by the "age" argument in the "param" list.

The function allows fitting model with shift from an Orstein-Uhlenbeck to a Brownian motion process and vice-versa ("OUBM" and "BMOU"), shifts from a Brownian motion to/from an Early Burst (ACDC) model ("BMEB" and "EBBM"), or shifts from an Orstein-Uhlenbeck to/from an Early Burst (ACDC) model ("OUEB" and "EBOU"). Note that the shift models with OU process are relevant only if you use fossil species.

In all these cases it is possible to allow the drift parameter to vary after the fixed point by specifying "i" (for independent) after the model name. For instance, to fit models of "ecological release" or "ecological release and radiate" following Slater (2013), one can use "OUBM" or "OUBMi", respectively.

Alternatively it is also possible to use the shortcuts "ER" or "RR" to fit models of "ecological release" and "ecological release and radiate" respectively, and "EC" for a model of "constrained ecology" (e.g., after invasion of a competitive species in a given ecosystem) where traits are constrained in an Ornstein-Uhlenbeck process after a fixed point in time ("RC" is the same model but assumes an independent rate during the early radiative phase). The "SR" model allows fitting different (Brownian) rates/drift before and after the shift point (note that this model could also be fitted using the mvBM function).

The "param" list can be used to provide lower and upper bounds for the exponential rate parameter of the Early-Burst/ACDC model. See ?mvEB for details.

The "method" argument allows the user to try different algorithms for computing the log-likelihood. The "rpf" and "sparse" methods use fast GLS algorithms based on factorization for avoiding the computation of the inverse of the variance-covariance matrix and its determinant involved in the log-likelihood estimation. The "inverse" approach uses the "stable" standard explicit computation of the inverse and determinant of the matrix and is therefore slower. The "pseudoinverse" method uses a generalized inverse that is safer for matrix near singularity but highly time consuming. See ?mvLL for details.

Value

LogLik	The log-likelihood of the optimal model.
AIC	Akaike Information Criterion for the optimal model.
AICc	Sample size-corrected AIC.
theta	Estimated ancestral states.
alpha	Matrix of estimated alpha values (strength of selection).
beta	Exponent rate (of decay or increase) for the ACDC/Early-Burst model.
sigma	Evolutionary rate matrix (drift) for the BM process before the shift.
sig	Evolutionary rate matrix (drift) for the BM process after the shift (only for "i" models).

convergence	Convergence status of the optimizing function; "0" indicates convergence (see ?optim for details).
hess.values	Reliability of the likelihood estimates calculated through the eigen-decomposition of the hessian matrix. "0" means that a reliable estimate has been reached (see ?mvOU for details).
param	List of model fit parameters (optimization, method, model, number of parameters...).
l1ik	The log-likelihood function evaluated in the model fit "\$l1ik(par, root.mle=TRUE)".

Note

Changes in rate of evolution and optima can also be fitted using the mvBM and mvOU functions using a 'make.era.map' transformed tree.

Author(s)

Julien Clavel

References

- Clavel J., Escarguel G., Merceron G. 2015. mvMORPH: an R package for fitting multivariate evolutionary models to morphometric data. *Methods in Ecology and Evolution*, 6(11):1311-1319.
- O'Meara B.C. 2012. Evolutionary inferences from phylogenies: a review of methods. *Annu. Rev. Ecol. Evol. Syst.* 43:267-285.
- O'Meara B.C., Ane C., Sanderson M.J., Wainwright P.C. 2006. Testing for different rates of continuous trait evolution. *Evolution*. 60:922-933.
- Slater G.J. 2013. Phylogenetic evidence for a shift in the mode of mammalian body size evolution at the Cretaceous-Palaeogene boundary. *Methods Ecol. Evol.* 4:734-744.

See Also

[mvMORPH](#) [mvOU](#) [mvBM](#) [mvEB](#) [mvOUTS](#) [mvRWTS](#) [mvSIM](#) [optim](#) [subplex](#) [paintSubTree](#) [make.era.map](#)

Examples

```
# Simulated dataset
set.seed(14)
# Generating a random tree
tree<-rtree(50)

# Providing a tree which the shift mapped on
tot<-max(nodeHeights(tree))
age=tot-3 # The shift occurred 3 Ma ago
tree<-make.era.map(tree,c(0,age))

# Plot of the phylogeny for illustration
plotSimmap(tree,fsize=0.6,node.numbers=FALSE,lwd=3, pts=FALSE)

# Simulate the traits
```

```

alpha<-matrix(c(2,0.5,0.5,1),2)
sigma<-matrix(c(0.1,0.05,0.05,0.1),2)
theta<-c(2,3)
data<-mvSIM(tree, param=list(sigma=sigma, alpha=alpha, ntraits=2, theta=theta,
names_traits=c("head.size","mouth.size")), model="ER", nsim=1)

## Fitting the models
# "Ecological release model"
mvSHIFT(tree, data, model="OUBM") # similar to mvSHIFT(tree, data, model="ER")

# "Release and radiate model"

mvSHIFT(tree, data, model="RR", method="sparse")
# similar to mvSHIFT(tree, data, model="OUBMi")

# More generally...

# OU to/from BM
mvSHIFT(tree, data, model="OUBM", method="sparse")
mvSHIFT(tree, data, model="BMOU", method="sparse")
mvSHIFT(tree, data, model="OUBMi", method="sparse")
mvSHIFT(tree, data, model="BMOUi", method="sparse")

# BM to/from EB
mvSHIFT(tree, data, model="BMEB", method="sparse")
mvSHIFT(tree, data, model="EBBM", method="sparse")
mvSHIFT(tree, data, model="BMEBi", method="sparse")
mvSHIFT(tree, data, model="EBBMi", method="sparse")

# OU to/from EB
mvSHIFT(tree, data, model="OUEB", method="sparse")
mvSHIFT(tree, data, model="OUEBi", method="sparse")
mvSHIFT(tree, data, model="EBOU", method="sparse")
mvSHIFT(tree, data, model="EBOUi", method="sparse")

## Without providing mapped tree
# The shift occurred 3Ma ago (param$age=3)
set.seed(14)
tree<-rtree(50)
data<-mvSIM(tree, param=list(sigma=sigma, alpha=alpha, ntraits=2, theta=theta,
names_traits=c("head.size","mouth.size"), age=3), model="ER", nsim=1)

## Fitting the models without mapped tree but by specifying the age in the param list.
mvSHIFT(tree, data, model="OUBM", param=list(age=3))

```

Description

This function allows simulating multivariate (as well as univariate) continuous traits evolving according to a BM (Brownian Motion), OU (Ornstein-Uhlenbeck), ACDC (Accelerating rates and Decelerating rates/Early bursts), or SHIFT models of phenotypic evolution.

Usage

```
mvSIM(tree, nsim = 1, error = NULL, model = c("BM1", "BMM", "OU1", "OUM", "EB"),
      param = list(theta = 0, sigma = 0.1, alpha = 1, beta = 0))
```

Arguments

tree	Phylogenetic tree with mapped ancestral states in SIMMAP format (see make.simmap function from phytools package) or a standard "phylo" object (ape). Or a time-series
nsim	The number of simulated traits (or datasets for multivariate analysis).
error	Matrix or data frame with species in rows and continuous trait sampling variance (squared standard errors) in columns.
model	The model of trait evolution for the simulations. Could be any of the models used by the mvBM, mvEB, mvOU and mvSHIFT functions.
param	List of parameter arguments used for the simulations. You should provide the sigma (values or matrix), alpha (for OU and SHIFT models), beta (EB and SHIFT), theta (ancestral states), ntraits (the number of traits) or others param arguments used in the models. Alternatively you can provide a fitted object of class "mvmorph". See details below.

Details

This function simulates multivariate (as well as univariate) continuous traits evolving along a given phylogenetic tree or time series according to a BM/RW (Brownian Motion/Random walk), OU (Ornstein-Uhlenbeck), ACDC (Accelerating rates and Decelerating rates/Early Bursts), and SHIFT models of phenotypic evolution. The traits are simulated by random sampling from a Multivariate Normal Distribution (Paradis, 2012).

The mvSIM function allows simulating continuous trait (univariate or multivariate) evolution along a phylogeny (or a time-series) with user specified parameters or parameters estimated from a previous fit.

The "simulate" wrapper can also be used with a fitted object of class "mvmorph": simulate(object, nsim=1, tree=tree). See example below.

If parameter values are not provided, the default values are fixed to 1 (sigma, sig, alpha, beta) or 0 for the mean at the root (ancestral state).

For the "BMM" model where different parts of the tree have their own rate, a list with one rate (or matrix of rates) per selective regime must be provided.

For the "OU1" and "OUM" models, the user can specify if the ancestral state (theta0) should be computed (param\$root=TRUE), assumed to be at the oldest regime state (param\$root=FALSE), or if there is no root and each regime is at the stationary point (param\$root="stationary"; see also ?mvOU).

For the "BM1", "BMM", and "RWTS" models, a trend can be simulated by providing values to the "trend" argument in the "param" list.

Traits names can be provided with the "names_traits" argument in the "param" list. For all the shift models, if the tree is not mapped the age of the shift should be directly provided (in unit of times of the tree) using the "age" argument in the "param" list.

Value

A matrix with simulated traits (columns) for the univariate case, or a list of matrix for the multivariate case (nsim>1).

Note

Ancestral states for Ornstein-Uhlenbeck processes (param\$root=TRUE) should be used with non-ultrametric trees. As this method uses Multivariate Normal distribution (MVN) for simulating the traits, it is advised to avoid its use with very large datasets/trees and rely instead on recursive algorithms (see, e.g., ?rTraitCont from "ape").

Author(s)

Julien Clavel

References

Paradis E. 2012. Analysis of Phylogenetics and Evolution with R. New York: Springer.

See Also

[mvMORPH](#) [mvg1s](#) [mvOU](#) [mvEB](#) [mvBM](#) [mvSHIFT](#) [mvRWTS](#) [mvOUTS](#) [mvLL](#)

Examples

```
## Simulated dataset
set.seed(14)
# Generating a random tree with 50 species
tree<-pbtree(n=50)

# Setting the regime states of tip species
sta<-as.vector(c(rep("Forest",20),rep("Savannah",30))); names(sta)<-tree$tip.label

# Making the simmap tree with mapped states
tree<-make.simmap(tree,sta , model="ER", nsim=1)
col<-c("blue","orange"); names(col)<-c("Forest","Savannah")

# Plot of the phylogeny for illustration
plotSimmap(tree,col,fsize=0.6,node.numbers=FALSE,lwd=3, pts=FALSE)

## Simulate trait evolution according to a bivariate "BMM" model
# Number of traits
ntraits<-2
```

```

# Number of simulated (pairs of) traits
nsim<-10
# Rates matrices for the "Forest" and the "Savannah" regimes
sigma<-list(Forest=matrix(c(2,0.5,0.5,1),2), Savannah=matrix(c(5,3,3,4),2))
# ancestral states for each traits
theta<-c(0,0)

# Simulate
simul<-mvSIM(tree,nsim=nsim, model="BMM",param=list(ntraits=ntraits,sigma=sigma,theta=theta))

# Try to fit a "BM1" model to the first simulated dataset
model_fit<-mvBM(tree,simul[[1]],model="BM1")

# Use the estimated parameters to simulate new traits!
simul2<-mvSIM(tree,nsim=nsim,param=model_fit)

# or try with generic "simulate" function
simul3<-simulate(model_fit,nsim=nsim,tree=tree)

## Just-for-fun :Comparing parameters

simul4<-simulate(model_fit,nsim=100,tree=tree)

results<-lapply(simul4,function(x){
  mvBM(tree,x,model="BM1",method="pic", echo=FALSE,diagnostic=FALSE)
})

sigma_simul<-sapply(results,function(x){x$sigma})

# comparison between the simulated (black) and the observed (red) multivariate rates
layout(matrix(1:4, ncol=2))
for(i in 1:4){
  hist(sigma_simul[i,], main=paste("Estimated sigma on simulated traits"),
  xlab="estimated sigma for 100 replicates");abline(v=mean(sigma_simul[i,]),lwd=2);
  abline(v=model_fit$sigma[i],col="red",lwd=2)
}

```

 phyllostomid

Phylogeny and trait data for a sample of Phyllostomid bats

Description

Phylogeny, diet, and morphological variables for 49 species of Phyllostomid bats.

Usage

```
data("phyllostomid")
```


Details

Illustrative phylogeny (*phyllostomid\$tree*) and morphological data (*phyllostomid\$mandible* - 73 variables composed of the superimposed procrustes 2D-coordinates for the mandible and the condylobasal length) of 49 species of Phyllostomid bats from Monteiro & Nogueira (2011). The firsts 22 coordinates represent anatomical landmarks and the last 50 coordinates are semilandmarks.

The four grouping factor variables (e.g., *phyllostomid\$grp1*, *phyllostomid\$grp2*, ...) are the adaptive regime models for association between mandible morphology and diet considered in Monteiro & Nogueira (2011).

References

Monteiro L.R., Nogueira M.R. 2011. Evolutionary patterns and processes in the radiation of phyllostomid bats. *BMC Evolutionary Biology*. 11:1-23.

Clavel, J., Morlon, H. 2020. Reliable phylogenetic regressions for multivariate comparative data: illustration with the MANOVA and application to the effect of diet on mandible morphology in phyllostomid bats. *Systematic Biology* (DOI:10.1093/sysbio/syaa010)

Examples

```
data(phyllostomid)
plot(phyllostomid$tree)
head(phyllostomid$mandible)

# Fit a linear model by PL
fit1 <- mvglms(mandible~grp1, data=phyllostomid, phyllostomid$tree, model="lambda", method="L00")

# regularized MANOVA test
(manova.gls(fit1, test="Wilks", verbose=TRUE))
```

pruning

Pruning algorithm to compute the square root of the phylogenetic covariance matrix and it's determinant.

Description

This function use the pruning algorithm (Felsenstein 1973) to efficiently compute the determinant of the phylogenetic covariance matrix as well as the square root of this matrix (or it's inverse; Stone 2011, Khabbazian et al. 2016). This algorithm is faster than using "eigen" or "cholesky" function to compute the determinant or the square root (see e.g., Clavel et al. 2015) and can be used to compute independent contrasts and the log-likelihood of a model in linear time.

Usage

```
pruning(tree, inv=TRUE, scaled=TRUE, trans=TRUE, check=TRUE)
```

Arguments

tree	Phylogenetic tree (an object of class "phylo" or "simmap").
inv	Return the matrix square root of either the covariance matrix (inv=FALSE) or it's inverse (inv=TRUE, the default). This matrix is a "contrasts" matrix.
scaled	Indicates whether the contrasts should be scaled with their expected variances (default to TRUE).
trans	Return the transpose (trans=TRUE) of the matrix square root/contrasts matrix. (i.e. by default it returns a matrix equivalent to the upper triangular Cholesky factor)
check	Check if the input tree is dichotomous and in "postorder" (see ?is.binary.tree and ?reorder.phylo).

Details

The tree is assumed to be fully dichotomic and in "postorder", otherwise the functions *multi2di* and *reorder.phylo* are used internally when *check=TRUE*.

Value

sqrtMat	The matrix square root (contrasts matrix)
varNode	Variance associated to each node values (similar to "contrasts" variance)
varRoot	Variance associated to the root value (similar to the ancestral state variance)
det	Log-determinant of the phylogenetic covariance of the tree

Author(s)

Julien Clavel

References

- Clavel J., Escarguel G., Merceron G. 2015. mvMORPH: an r package for fitting multivariate evolutionary models to morphometric data. *Methods Ecol. Evol.* 6:1311-1319.
- Felsenstein J. 1973. Maximum-likelihood estimation of evolutionary trees from continuous characters. *Am. J. Hum. Genet.* 25:471-492.
- Khabbazian M., Kriebel R., Rohe K., Ane C. 2016. Fast and accurate detection of evolutionary shifts in Ornstein-Uhlenbeck models. *Methods Ecol. Evol.* 7:811-824.
- Stone E.A. 2011. Why the phylogenetic regression appears robust to tree misspecification. *Syst. Biol.* 60:245-260

See Also

[mvLL mvglS](#)

Examples

```

## Simulated dataset
set.seed(14)
# Generating a random tree
tree<-pbtree(n=50)
Y <- mvSIM(tree, model="BM1", param=list(sigma=1, theta=0)) # trait
X <- matrix(1, nrow=Ntip(tree), ncol=1) # design matrix

## Use the GLS trick
# Compute the matrix square root
C <- vcv.phylo(tree)
D <- chol(C)
Cinv <- solve(C)
Di <- chol(Cinv)

# transform the traits
Xi <- Di%*%X
Yi <- Di%*%Y

# Compute the GLS estimate and determinant (see Clavel et al. 2015)
# GLS estimate for the root
print(pseudoinverse(Xi)%*%Yi)

# Determinant of the phylogenetic covariance matrix
print(sum(log(diag(D)^2)))

## Use the pruning algorithm (much faster)

M <- pruning(tree, inv=TRUE)

Xi <- M$sqrtMat%*%X
Yi <- M$sqrtMat%*%Y

# GLS estimate
print(pseudoinverse(Xi)%*%Yi)

# determinant
print(M$det)

## REML determinant (without variance of the root state; see Felsenstein 1973)
# full REML
log(det(C)) + log(det(t(X)%*%Cinv%*%X))

# pruning REML
sum(log(M$varNode))

```

Description

Returns the residuals of a linear model of class 'mvglS'.

Usage

```
## S3 method for class 'mvglS'
residuals(object, type, ...)
```

Arguments

object	an object of class 'mvglS' obtained from a mvglS fit.
type	an optional character string specifying the type of residuals to be used. To match conventions used in the <i>nlme</i> package: if "response", the "raw" residuals (observed-fitted) are used; else, if "normalized", the normalized residuals (the residuals pre-multiplied by the inverse square-root factor of the estimated (between observations) covariance matrix) are used. Note however that there is still between variables correlations with both types.
...	other arguments for this generic function (not used).

Value

A matrix with the residuals for the linear model fitted by mvglS.

Author(s)

J. Clavel

See Also

[vcov.mvglS](#) [residuals.mvglS](#) [coef.mvglS](#) [mvglS](#)

stationary

The stationary variance of an Ornstein-Uhlenbeck process

Description

This function returns the stationary variance for an Ornstein-Uhlenbeck process (object of class "ou").

Usage

```
stationary(object)
```

Arguments

object	Object fitted with the "mvOU" function.
--------	---

Details

This function computes the dispersion parameter of the Ornstein-Uhlenbeck process (i.e., the expected variance when the process is stationary). The multivariate normal stationary distribution of the Ornstein-Uhlenbeck process is computed following Bartoszek et al. (2012).

Value

The stationary variance-covariance matrix of the OU process

Author(s)

Julien Clavel

References

Bartoszek K., Pienaar J., Mostad P., Andersson S., Hansen T.F. 2012. A phylogenetic comparative method for studying multivariate adaptation. *J. Theor. Biol.* 314:204-215.

See Also

[mvMORPH](#) [mvOU](#) [halflife](#)

Examples

```
# Simulated dataset
set.seed(14)
# Generating a random tree
tree<-pbtree(n=50)

# Setting the regime states of tip species
sta<-as.vector(c(rep("Forest",20),rep("Savannah",30))); names(sta)<-tree$tip.label

# Making the simmap tree with mapped states
tree<-make.simmap(tree,sta , model="ER", nsim=1)
col<-c("blue","orange"); names(col)<-c("Forest","Savannah")

# Plot of the phylogeny for illustration
plotSimmap(tree,col, fsize=0.6, node.numbers=FALSE, lwd=3, pts=FALSE)

# Simulate the traits
alpha<-matrix(c(2,0.5,0.5,1),2)
sigma<-matrix(c(0.1,0.05,0.05,0.1),2)
theta<-c(2,3,1,1.3)
data<-mvSIM(tree, param=list(sigma=sigma, alpha=alpha, ntraits=2, theta=theta,
names_traits=c("head.size","mouth.size")), model="OUM", nsim=1)

## Fitting the models
# OUM - Analysis with multiple optima
result<-mvOU(tree, data)

stationary(result)
```

```
# Expected values when the process is stationary
expected<-list(alpha=alpha,sigma=sigma)
class(expected)<-c("mvmorph","mvmorph.ou")
stationary(expected)
```

vcov.mvglm	<i>Calculate variance-covariance matrix for a fitted object of class 'mvglm'</i>
------------	--

Description

Returns the variance-covariance matrix of the coefficients or the traits.

Usage

```
## S3 method for class 'mvglm'
vcov(object, ...)
```

Arguments

object	an object of class 'mvglm' obtained from a mvglm fit.
...	additional arguments for methods function. See <i>details</i> below.

Details

The vcov function returns by default the variance-covariance matrix of the main parameters of a fitted model object. The main parameters are the coefficients (this correspond to the argument type="coef"; see also coef.mvglm). With type="covariance", the vcov.mvglm function returns the estimated traits covariance matrix (possibly regularized for PL approaches) while type="precision" return the precision matrix (i.e. the inverse of the covariance).

Value

A matrix of the estimated covariances between the parameter estimates (of type "coef", "covariance", or "precision").

Author(s)

J. Clavel

See Also

[coef.mvglm](#) [residuals.mvglm](#) [fitted.mvglm](#) [mvglm](#)

Index

- *Topic **AIC**
 - aicw, 3
- *Topic **Accelerating rates**
 - mvEB, 25
- *Topic **Akaike weights**
 - aicw, 3
- *Topic **BM**
 - mvMORPH-package, 2
- *Topic **Brownian Motion**
 - mvBM, 20
 - mvRWTS, 46
 - mvSHIFT, 50
- *Topic **Cholesky constraint**
 - mvBM, 20
 - mvRWTS, 46
- *Topic **Decelerating rates**
 - mvEB, 25
- *Topic **Determinant**
 - pruning, 57
- *Topic **EB**
 - mvMORPH-package, 2
- *Topic **EC**
 - mvSHIFT, 50
- *Topic **ER**
 - mvSHIFT, 50
- *Topic **Early burst**
 - mvEB, 25
- *Topic **Early-Burst**
 - mvSHIFT, 50
- *Topic **Estim**
 - estim, 8
- *Topic **Evolutionary rates**
 - mvBM, 20
 - mvMORPH-package, 2
 - mvRWTS, 46
 - mvSHIFT, 50
- *Topic **GIC**
 - manova.gls, 16
 - mvglsl, 28
- mvglsl.pca, 32
- *Topic **GLS**
 - EIC, 6
 - GIC, 11
 - manova.gls, 16
 - mvglsl, 28
 - mvglsl.pca, 32
 - mvLL, 34
 - pruning, 57
- *Topic **General Linear Hypothesis**
 - manova.gls, 16
- *Topic **Hessian**
 - mvOU, 37
 - mvOUTS, 42
- *Topic **High dimensions**
 - EIC, 6
 - GIC, 11
 - manova.gls, 16
 - mvglsl, 28
 - mvglsl.pca, 32
- *Topic **Imputation**
 - estim, 8
- *Topic **Independent contrasts**
 - mvLL, 34
 - pruning, 57
- *Topic **LRT**
 - LRT, 14
- *Topic **Loglikelihood ratio test**
 - LRT, 14
- *Topic **Loglikelihood**
 - mvLL, 34
- *Topic **MANOVA**
 - manova.gls, 16
- *Topic **Matrix square root**
 - pruning, 57
- *Topic **Measurement error**
 - mvMORPH-package, 2
- *Topic **Methods**
 - mvLL, 34

- *Topic **Missing values**
 - estim, 8
 - *Topic **Model comparison**
 - EIC, 6
 - GIC, 11
 - *Topic **Models comparison**
 - LRT, 14
 - manova.gls, 16
 - *Topic **Multivariate Linear Models**
 - mvgl, 28
 - *Topic **Multivariate tests**
 - manova.gls, 16
 - *Topic **OU**
 - half-life, 12
 - mvMORPH-package, 2
 - mvOU, 37
 - mvOUTS, 42
 - stationary, 60
 - *Topic **Ornstein Uhlenbeck**
 - half-life, 12
 - mvOU, 37
 - mvOUTS, 42
 - mvSHIFT, 50
 - stationary, 60
 - *Topic **PCA**
 - mvgl.pca, 32
 - *Topic **Penalized likelihood**
 - manova.gls, 16
 - mvgl, 28
 - mvgl.pca, 32
 - *Topic **RR**
 - mvSHIFT, 50
 - *Topic **Random walk**
 - mvRWTS, 46
 - *Topic **Regularization**
 - manova.gls, 16
 - mvgl, 28
 - mvgl.pca, 32
 - *Topic **SIMMAP**
 - mvMORPH-package, 2
 - *Topic **SR**
 - mvSHIFT, 50
 - *Topic **Shifts**
 - mvMORPH-package, 2
 - mvSHIFT, 50
 - *Topic **Simulations**
 - mvMORPH-package, 2
 - *Topic **Time series**
 - mvOUTS, 42
 - mvRWTS, 46
 - *Topic **User defined constraints**
 - mvRWTS, 46
 - *Topic **bats**
 - phyllostomid, 56
 - *Topic **datasets**
 - phyllostomid, 56
 - *Topic **half-life**
 - half-life, 12
 - *Topic **manova.gls**
 - phyllostomid, 56
 - *Topic **mvgl**
 - mvMORPH-package, 2
 - phyllostomid, 56
 - *Topic **mvmorph object**
 - mvSIM, 53
 - *Topic **parameters**
 - mv.Precalc, 18
 - *Topic **precalculation**
 - mv.Precalc, 18
 - *Topic **simulate traits**
 - mvSIM, 53
 - *Topic **stationary**
 - stationary, 60
-
- AIC, 4
 - aicw, 3, 3

 - brownie.lite, 23

 - coef.mvgl, 5, 10, 31, 60, 62

 - EIC, 3, 6, 17, 31, 33
 - estim, 3, 8
 - evol.vcv, 23

 - fitted.mvgl, 5, 10, 31, 62

 - GIC, 3, 7, 11, 17, 31, 33

 - half-life, 3, 12, 41, 45, 61

 - LRT, 3, 14, 23, 41, 45, 49

 - make.era.map, 23, 41, 52
 - make.simmap, 23, 41
 - manova.gls, 3, 16, 31
 - mv.Precalc, 18
 - mvBM, 3, 9, 15, 19, 20, 27, 36, 41, 45, 52, 55

mvEB, 3, 9, 15, 19, 23, 25, 36, 41, 45, 49, 52, 55
mvglS, 3, 5, 7, 10, 12, 17, 23, 27, 28, 33, 36,
41, 55, 58, 60, 62
mvglS.pca, 3, 7, 12, 31, 32
mvLL, 3, 19, 34, 55, 58
mvMORPH, 4, 9, 13, 15, 19, 23, 27, 36, 41, 45,
49, 52, 55, 61
mvMORPH (mvMORPH-package), 2
mvMORPH-package, 2
mvOU, 3, 9, 13, 15, 19, 23, 27, 36, 37, 45, 49,
52, 55, 61
mvOUTS, 3, 23, 27, 41, 42, 49, 52, 55
mvRWTS, 3, 23, 27, 41, 45, 46, 52, 55
mvSHIFT, 3, 9, 15, 19, 23, 27, 36, 41, 45, 49,
50, 55
mvSIM, 3, 23, 27, 36, 41, 45, 49, 52, 53

optim, 23, 27, 41, 45, 49, 52

paintSubTree, 23, 41, 52
phyllostomid, 56
pruning, 57

residuals.mvglS, 5, 10, 31, 59, 60, 62

stationary, 3, 13, 41, 45, 60
subplex, 52

vcov.mvglS, 5, 10, 31, 60, 62