

Package ‘not’

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Title Narrowest-Over-Threshold Change-Point Detection

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Description Provides efficient implementation of the Narrowest-Over-Threshold methodology for detecting an unknown number of change-points occurring at unknown locations in one-dimensional data following 'deterministic signal + noise' model. Currently implemented scenarios are: piecewise-constant signal, piecewise-constant signal with a heavy-tailed noise, piecewise-linear signal, piecewise-quadratic signal, piecewise-constant signal and with piecewise-constant variance of the noise. For details, see Baranowski, Chen and Fryzlewicz (2019) <[doi:10.1111/rssb.12322](https://doi.org/10.1111/rssb.12322)>.

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Contents

not-package	2
aic.penalty	2
features	3
logLik.not	4
not	5
plot.not	8
predict.not	9
random.intervals	11
residuals.not	11
sic.penalty	12

not-package	<i>Narrowest-Over-Threshold Change-Point Detection</i>
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Description

Implements the Narrowest-Over-Threshold approach for general multiple change-point detection in one-dimensional data following 'deterministic signal + noise' model. Scenarios that are currently implemented are: piecewise-constant signal, piecewise-constant signal with a heavy tailed noise, piecewise-linear signal, piecewise-quadratic signal, piecewise-constant signal and with piecewise-constant standard deviation of the noise. The main routines of the package are `not` and `features`.

References

R. Baranowski, Y. Chen, and P. Fryzlewicz (2019). Narrowest-Over-Threshold Change-Point Detection. (<http://stats.lse.ac.uk/fryzlewicz/not/not.pdf>)

aic.penalty	<i>Akaike Information Criterion penalty</i>
-------------	---

Description

The function evaluates the penalty term for Akaike Information Criterion. This routine is typically not called directly by the user; its name can be passed as an argument to `features`.

Usage

```
aic.penalty(n, n.param, ...)
```

Arguments

n	The number of observations.
n.param	The number of parameters in the model for which the penalty is evaluated.
...	Not in use.

Value

The penalty term $2 \times n.param$.

References

R. Baranowski, Y. Chen, and P. Fryzlewicz (2019). Narrowest-Over-Threshold Change-Point Detection. (<http://stats.lse.ac.uk/fryzlewicz/not/not.pdf>)

Examples

```

**** a simple example how to use the AIC penalty
x <- rnorm(300) + c(rep(1,50),rep(0,250))
w <- not(x)
w.cpt <- features(w, penalty="aic")
w.cpt$cpt[[1]]

```

features	<i>Extract locations of features from a 'not' object</i>
----------	--

Description

The function applies user-specified stopping criteria to extract change-points from object generated by `not`.

Usage

```

features(object, ...)

## Default S3 method:
features(object, method = c("ic", "threshold"),
  penalty = c("sic", "aic", "user"), q.max = 25, penalty.fun, th, ...)

```

Arguments

object	An object of 'not' class returned by <code>not</code> .
...	Further arguments that can be passed to the penalty function.
method	A method of choosing the best solution in <code>object\$solution.path</code> . If <code>method="ic"</code> , model minimising a chosen information criterion is selected. If <code>method="threshold"</code> , model is selected based on thresholding (see references for more details).
penalty	Name of the penalty function to be used if <code>method="ic"</code> . If <code>penalty="user"</code> , a user-defined penalty function has to be passed via <code>penalty.fun</code> .
q.max	Maximum number of change-points allowed to be detected. Used only for <code>method="ic"</code> .
penalty.fun	Used only if <code>penalty="user"</code> . A function includes at least the following arguments: sample size <code>n</code> , number of parameters used in a model <code>n.param</code> , and For examples of such functions, see aic.penalty and sic.penalty .
th	Used only if <code>method="threshold"</code> . A positive real number.

Details

Denote by T_1, \dots, T_N the elements on the solution path `object$solution.path`, each representing a set of change-points. When (`method="ic"`), the returned set of change-points is the one that minimises

$$-2\log\text{-likelihood}(\text{object}, \text{cpt} = T_k) + \text{penalty}(\text{object}\$n, \text{n.param}, \dots),$$

over all k such that the number of change-points in T_k is smaller than or equal $q.\max$. The log-likelihood is computed using the `logLik` routine, while the penalty function is computed with `sic.penalty` (penalty="sic"), `aic.penalty` (penalty="aic") or a user-defined penalty function (penalty="user").

Value

th	Value of the threshold used (if method="threshold") or selected on the solution path (if method="ic").
cpt	Estimated locations of the change-points.
ic	Values of the information criterion minimised in order to find an optimal solution on the path (only if method="ic" was used).

References

R. Baranowski, Y. Chen, and P. Fryzlewicz (2019). Narrowest-Over-Threshold Change-Point Detection. (<http://stats.lse.ac.uk/fryzlewicz/not/not.pdf>)

Examples

```
# **** Piecewise-constant mean with Gaussian noise.
x <- c(rep(0, 100), rep(1,100)) + rnorm(100)
# *** identify potential locations of the change-points
w <- not(x, contrast = "pcwsConstMean")
# *** choose change-points using default settings
fo <- features(w)
# *** get the change-points
fo$cpt
# *** plot the SIC curve
plot(fo$ic)
```

logLik.not

Extract likelihood from a 'not' object

Description

Calculates the Gaussian log-likelihood for the signal estimated using `predict.not` with the change-points at `cpt`. The type of the signal depends on the value of `contrast` that has been passed to `not` (see `predict.not`).

Usage

```
## S3 method for class 'not'
logLik(object, cpt, ...)
```

Arguments

object	An object of class 'not', returned by not .
cpt	An integer vector with locations of the change-points. If missing, the features is called internally to extract the change-points from object.
...	Further parameters that can be passed to predict.not and features .

Examples

```
#' # **** Piecewise-constant mean with Gaussian noise.
x <- c(rep(0, 100), rep(1,100)) + rnorm(100)
# *** identify potential locations of the change-points
w <- not(x, contrast = "pcwsConstMean")
# *** log-likelihood for the model with the change-point estimated via 'not'
logLik(w)
# *** log-likelihood for the model with the change-point at 100
logLik(w, cpt=100)
```

not

*Narrowest-Over-Threshold Change-Point Detection***Description**

Identifies potential locations of the change-points in the data following 'deterministic signal + noise' model (see details below) in a number of different scenarios. The object returned by this routine can be further passed to the [features](#) function, which finds the final estimate of the change-points based on a chosen stopping criterion. It can be also passed to [plot](#), [predict](#) and [residuals](#) routines.

Usage

```
not(x, ...)
```

```
## Default S3 method:
```

```
not(x, M = 10000, method = c("not", "max"),
    contrast = c("pcwsConstMean", "pcwsConstMeanHT", "pcwsLinContMean",
                "pcwsLinMean", "pcwsQuadMean", "pcwsConstMeanVar"),
    rand.intervals = TRUE, parallel = FALSE, augmented = FALSE,
    intervals, ...)
```

Arguments

x	A numeric vector with data points.
...	Not in use.
M	A number of intervals drawn in the procedure.
method	Choice of "not" (recommended) and "max". If method="not", the Narrowest-Over-Threshold intervals are used in the algorithm. If method="max", the intervals corresponding to the largest contrast function are used. For an explanation, see the references.

contrast	A type of the contrast function used in the NOT algorithm. Choice of "pcwsConstMean", "pcwsConstMeanHT", "pcwsLinContMean", "pcwsLinMean", "pcwsQuadMean", "pcwsConstMeanVar". For the explanation, see details below.
rand.intervals	A logical variable. If rand.intervals=TRUE intervals used in the procedure are drawn uniformly using the random.intervals routine. If rand.intervals=FALSE, the intervals need to be passed using the intervals argument.
parallel	A logical variable. If TRUE some of computations are run in parallel using OpenMP framework. Currently this option is not supported on Windows.
augmented	A logical variable. if TRUE, the entire data are considered when the NOT segmentation tree is constructed (see the solution path algorithm in the references).
intervals	A 2-column matrix with the intervals considered in the algorithm, with start- and end- points of the intervals in, respectively, the first and the second column. The intervals are used only if rand.intervals=FALSE.

Details

The data points provided in x are assumed to follow

$$Y_t = f_t + \sigma_t \varepsilon_t,$$

for $t = 1, \dots, n$, where n is the number of observations in x , the signal f_t and the standard deviation σ_t are non-stochastic with structural breaks at unknown locations in time t . Currently, the following scenarios for f_t and σ_t are implemented:

- Piecewise-constant signal with a Gaussian noise and constant standard deviation.
Use contrast="pcwsConstMean" here.
- Piecewise-constant mean with a heavy-tailed noise and constant standard deviation.
Use contrast="pcwsConstMeanHT" here.
- Piecewise-linear continuous signal with Gaussian noise and constant standard deviation.
Use contrast="pcwsLinContMean" here.
- Piecewise-linear signal with Gaussian noise and constant standard deviation.
Use contrast="pcwsLinMean" here.
- Piecewise-quadratic signal with Gaussian noise and constant standard deviation.
Use contrast="pcwsQuadMean" here.
- Piecewise-constant signal and piecewise-constant standard deviation of the Gaussian noise.
Use contrast="pcwsConstMeanVar" here.

Value

An object of class "not", which contains the following fields:

x	The input vector.
n	The length of x.
contrast	A scenario for the change-points.

contrasts	A 5-column matrix with the values of the contrast function, where 's' and 'e' denote start- end points of the intervals in which change-points candidates 'arg.max' have been found; 'length' shows the length of the intervals drawn, column 'max.contrast' contains corresponding value of the contrast statistic.
solution.path	A list with the solution path of the NOT algorithm (see the references) containing three fields of the same length: cpt - a list with consecutive solutions, i.e. s the sets of change-point candidates, th - a vector of thresholds corresponding to the solutions, n.cpt - a vector with the number of change-points for each solution.

References

R. Baranowski, Y. Chen, and P. Fryzlewicz (2019). Narrowest-Over-Threshold Change-Point Detection. (<http://stats.lse.ac.uk/fryzlewicz/not/not.pdf>)

Examples

```
# **** Piecewise-constant mean with Gaussian noise.
# *** signal
pcws.const.sig <- c(rep(0, 100), rep(1,100))
# *** data vector
x <- pcws.const.sig + rnorm(100)
# *** identify potential locations of the change-points
w <- not(x, contrast = "pcwsConstMean")
# *** some examples of how the w object can be used
plot(w)
plot(residuals(w))
plot(predict(w))
# *** this is how to extract the change-points
fo <- features(w)
fo$cpt

# **** Piecewise-constant mean with a heavy-tailed noise.
# *** data vector, signal the same as in the previous example, but heavy tails
x <- pcws.const.sig + rt(100, 3)
# *** identify potential locations of the change-points,
# using a contrast tailored to heavy-tailed data
w <- not(x, contrast = "pcwsConstMeanHT")
plot(w)

# **** Piecewise-constant mean and piecewise-constant variance
# *** signal's standard deviation
pcws.const.sd <- c(rep(2, 50), rep(1,150))
# *** data vector with pcws-const mean and variance
x <- pcws.const.sig + pcws.const.sd * rnorm(100)
# *** identify potential locations of the change-points in this model
w <- not(x, contrast = "pcwsConstMeanVar")
# *** extracting locations of the change-points
fo <- features(w)
fo$cpt

# **** Piecewise-linear continuous mean
```

```

# *** signal with a change in slope
pcws.lin.cont.sig <- cumsum(c(rep(-1/50, 100), rep(1/50,100)))
# *** data vector
x <- pcws.lin.cont.sig + rnorm(100)
# *** identify potential locations of the change-points in the slope coefficient
w <- not(x, contrast = "pcwsLinContMean")
# *** plotting the results
plot(w)
# *** location(s) of the change-points
fo <- features(w)
fo$cpt

# **** Piecewise-linear mean with jumps
# *** signal with a change in slope and jumpe
pcws.lin.sig <- pcws.lin.cont.sig + pcws.const.sig
# *** data vector
x <- pcws.lin.sig + rnorm(100)
# *** identify potential locations of the change-points in the slope coefficient and the intercept
w <- not(x, contrast = "pcwsLinMean")
# *** plotting the results
plot(w)
# *** location(s) of the change-points
fo <- features(w)
fo$cpt

# **** Piecewise-quadratic mean with jumps
# *** Piecewise-quadratic signal
pcws.quad.sig <- 2*c((1:50)^2 /1000, rep(2, 100), 1:50 / 50 )
# *** data vector
x <- pcws.quad.sig + rnorm(100)
# *** identify potential locations of the change-points in the slope coefficient and the intercept
w <- not(x, contrast = "pcwsQuadMean")
# *** plotting the results
plot(w)
# *** location(s) of the change-points
fo <- features(w)
fo$cpt

```

plot.not

Plot a 'not' object

Description

Plots the input vector used to generate 'not' object x with the signal fitted with [predict.not](#).

Usage

```
## S3 method for class 'not'
plot(x, ...)
```

Arguments

`x` An object of class 'not', returned by `not`.
`...` Further parameters which may be passed to `predict.not` and `features`.

See Also

[predict.not not features](#)

Examples

```
# **** Piecewise-constant mean with Gaussian noise.
x <- c(rep(0, 100), rep(1,100)) + rnorm(100)
# *** identify potential locations of the change-points
w <- not(x, contrast = "pcwsConstMean")
# *** when 'cpt' is omitted, 'features' function is used internally
# to choose change-points locations
plot(w)
# *** estimate and plot the signal specifying the location of the change-point
plot(w, cpt=100)
```

predict.not	<i>Estimate signal for a 'not' object.</i>
-------------	--

Description

Estimates signal in `object$x` with change-points at `cpt`. The type of the signal depends on on the value of `contrast` that has been passed to `not` (see details below).

Usage

```
## S3 method for class 'not'
predict(object, cpt, ...)
```

Arguments

`object` An object of class 'not', returned by `not`.
`cpt` An integer vector with locations of the change-points. If missing, the `features` is called internally to extract the change-points from `object`.
`...` Further parameters that can be passed to `predict.not` and `features`.

Details

The data points provided in `object$x` are assumed to follow

$$Y_t = f_t + \sigma_t \varepsilon_t,$$

for $t = 1, \dots, n$, where n is the number of observations in `object$x`, the signal f_t and the standard deviation σ_t are non-stochastic with change-points at locations given in `cpt` and ε_t is a white-noise.

Denote by τ_1, \dots, τ_q the elements in `cpt` and set $\tau_0 = 0$ and $\tau_{q+1} = T$. Depending on the value of contrast that has been passed to `not` to construct object, the returned value is calculated as follows.

- For `contrast="pcwsConstantMean"` and `contrast="pcwsConstantMeanHT"`, in each segment $(\tau_j + 1, \tau_{j+1})$, f_t for $t \in (\tau_j + 1, \tau_{j+1})$ is approximated by the mean of Y_t calculated over $t \in (\tau_j + 1, \tau_{j+1})$.
- For `contrast="pcwsLinContMean"`, f_t is approximated by the linear spline fit with knots at τ_1, \dots, τ_q minimising the l2 distance between the fit and the data.
- For `contrast="pcwsLinMean"` in each segment $(\tau_j + 1, \tau_{j+1})$, the signal f_t for $t \in (\tau_j + 1, \tau_{j+1})$ is approximated by the line $\alpha_j + \beta_j t$, where the regression coefficients are found using the least squares method.
- For `contrast="pcwsQuad"`, the signal f_t for $t \in (\tau_j + 1, \tau_{j+1})$ is approximated by the curve $\alpha_j + \beta_j t + \gamma_j t^2$, where the regression coefficients are found using the least squares method.
- For `contrast="pcwsConstMeanVar"`, in each segment $(\tau_j + 1, \tau_{j+1})$, f_t and σ_t for $t \in (\tau_j + 1, \tau_{j+1})$ are approximated by, respectively, the mean and the standard deviation of Y_t , both calculated over $t \in (\tau_j + 1, \tau_{j+1})$.

Value

A vector with the estimated signal or a two-column matrix with the estimated signal and standard deviation if `contrast="pcwsConstMeanVar"` was used to construct object.

See Also

`not`

Examples

```
# **** Piecewise-constant mean with Gaussian noise.
x <- c(rep(0, 100), rep(1,100)) + rnorm(100)
# *** identify potential locations of the change-points
w <- not(x, contrast = "pcwsConstMean")
# *** when 'cpt' is omitted, 'features' function is used internally
# to choose change-points locations
signal.est <- predict(w)
# *** estimate the signal specifying the location of the change-point
signal.est.known.cpt <- predict(w, cpt=100)
# *** pass arguments of the 'features' function through 'predict'.
signal.est.aic <- predict(w, penalty.type="aic")

# **** Piecewise-constant mean and variance with Gaussian noise.
x <- c(rep(0, 100), rep(1,100)) + c(rep(2, 100), rep(1,100)) * rnorm(100)
# *** identify potential locations of the change-points
w <- not(x, contrast = "pcwsConstMeanVar")
# *** here signal is two-dimensional
signal.est <- predict(w)
```

random.intervals	<i>Generate random intervals</i>
------------------	----------------------------------

Description

The function generates M intervals of the length smaller or equal than `max.length`, whose endpoints are drawn uniformly without replacements from $1, 2, \dots, n$. This routine can be used inside `not` function and is typically not called directly by the user.

Usage

```
random.intervals(n, M, min.length = 1, max.length = n, ...)
```

Arguments

<code>n</code>	a number of endpoints to choose from
<code>M</code>	a number of intervals to generate
<code>min.length</code>	an integer specifying minimum interval length
<code>max.length</code>	an integer specifying maximum interval length
<code>...</code>	not in use

Value

a M by 2 matrix with start (first column) and end (second column) points of an interval in each row

See Also

`not`

Examples

```
#### draw 100 intervals with the endpoints in 1,...,100
intervals <- random.intervals(50, 100)
```

residuals.not	<i>Extract residuals from a 'not' object</i>
---------------	--

Description

Returns a difference between x in object and the estimated signal with change-points at `cpt`. Type of the signal depends on the value of `contrast` that has been passed to `not` in order to construct object (see details of `predict.not`).

Usage

```
## S3 method for class 'not'
residuals(object, cpt, type = c("raw", "standardised"),
  ...)
```

Arguments

object	An object of class 'not', returned by <code>not</code> .
cpt	An integer vector with locations of the change-points. If missing, the <code>features</code> is called internally to extract the change-points from object.
type	Choice of "raw" and "standardised".
...	Further parameters that can be passed to <code>predict.not</code> and <code>features</code> .

Value

If `type="raw"`, the difference between the data and the estimated signal. If `type="standardised"`, the difference between the data and the estimated signal, divided by the estimated standard deviation.

Examples

```
pcws.const.sig <- c(rep(0, 100), rep(1,100))
x <- pcws.const.sig + rnorm(100)
w <- not(x, contrast = "pcwsConstMean")
# *** plot residuals obtained via fitting piecewise-constant function with estimated change-points
plot(residuals(w))
# *** plot residuals with obtained via fitting piecewise-constant function with true change-point
plot(residuals(w, cpt=100))
# *** plot standardised residuals
plot(residuals(w, type="standardised"))
```

 sic.penalty

Schwarz Information Criterion penalty

Description

The function evaluates the penalty term for Schwarz Information Criterion. If `alpha` is greater than 1, the strengthened SIC proposed in Fryzlewicz (2014) is calculated. This routine is typically not called directly by the user; its name can be passed as an argument to `features`.

Usage

```
sic.penalty(n, n.param, alpha = 1, ...)
```

Arguments

n	The number of observations.
n.param	The number of parameters in the model for which the penalty is evaluated.
alpha	A scalar greater or equal than one.
...	Not in use.

Value

the penalty term $n.param \times (\log(n))^{\alpha}$.

References

R. Baranowski, Y. Chen, and P. Fryzlewicz (2019). Narrowest-Over-Threshold Change-Point Detection. (<http://stats.lse.ac.uk/fryzlewicz/not/not.pdf>)

P. Fryzlewicz (2014). Wild Binary Segmentation for multiple change-point detection. Annals of Statistics. (<http://stats.lse.ac.uk/fryzlewicz/wbs/wbs.pdf>)

Examples

```
#### a simple example how to use the AIC penalty
x <- rnorm(300) + c(rep(1,50),rep(0,250))
w <- not(x)
w.cpt <- features(w, penalty="sic")
w.cpt$cpt[[1]]
```

Index

aic.penalty, [2](#), [3](#), [4](#)

features, [2](#), [3](#), [5](#), [9](#), [12](#)

logLik, [4](#)

logLik.not, [4](#)

not, [2-5](#), [5](#), [9-12](#)

not-package, [2](#)

plot, [5](#)

plot.not, [8](#)

predict, [5](#)

predict.not, [4](#), [5](#), [8](#), [9](#), [9](#), [11](#), [12](#)

random.intervals, [6](#), [11](#)

residuals, [5](#)

residuals.not, [11](#)

sic.penalty, [3](#), [4](#), [12](#)