Package 'not'

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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>.

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`not-package` *Narrowest-Over-Threshold Change-Point Detection*

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` *Akaike Information Criterion penalty*

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` *Extract locations of features from a 'not' object*

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

Details

Denote by $T_1, \ldots, T_N$ 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

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

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

```
# **** Piecewisce-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 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

```
#' # **** Piecewisce-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 $t = 1, \ldots, n$, 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, thefollowing 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

```
# **** Piecewisce-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

# **** Piecewisce-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 taylored to heavy-tailed data
w <- not(x, contrast = "pcwsConstMeanHT")
plot(w)

# **** Piecewisce-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

# **** Piecewisce-linear coninuous 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")
# *** ploting the results
plot(w)
# *** location(s) of the change-points
fo <- features(w)
fo$cpt

# **** Piecewisce-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")
# *** ploting the results
plot(w)
# *** location(s) of the change-points
fo <- features(w)
fo$cpt

# **** Piecewisce-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")
# *** ploting 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

```
# **** Piecewisce-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 *Estimate signal for a 'not' object.*

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 $t = 1, \ldots, n$, 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 $\tau_1, \ldots, \tau_q$ 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 $\tau_1, \ldots, \tau_q$ 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 wit the estimated signal or a two-column matrix with the estimated estimated signal and standard deviation if `contrast="pcwsConstMeanVar"` was used to construct `object`.

See Also

`not`

Examples

```
# **** Piecewisce-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")

# **** Piecewisce-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 *Generate random intervals*

Description

The function generates M intervals of the length smaller or equal than max.length, whose endpoints are are drawn uniformly without replacements from 1,2,..., 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

n	a number of endpoints to choose from
M	a number of intervals to generate
min.length	an integer specifying minimum interval length
max.length	an integer specifying maximum interval length
...	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 *Extract residuals from a 'not' object*

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 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.
type	Choice of "raw" and "standardised".
...	Further parameters that can be passed to predict.not and features.

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 strengthen SIC proposed 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` $\times$ $(\log(n))^{\texttt{alpha}}$.

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]]
```

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