

# Package ‘beast’

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**Type** Package

**Title** Bayesian Estimation of Change-Points in the Slope of  
Multivariate Time-Series

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**Description** Assume that a temporal process is composed of contiguous segments with differing slopes and replicated noise-corrupted time series measurements are observed. The unknown mean of the data generating process is modelled as a piecewise linear function of time with an unknown number of change-points. The package infers the joint posterior distribution of the number and position of change-points as well as the unknown mean parameters per time-series by MCMC sampling. A-priori, the proposed model uses an overfitting number of mean parameters but, conditionally on a set of change-points, only a subset of them influences the likelihood. An exponentially decreasing prior distribution on the number of change-points gives rise to a posterior distribution concentrating on sparse representations of the underlying sequence, but also available is the Poisson distribution. See Papastamoulis et al (2019) <[doi:10.1515/ijb-2018-0052](https://doi.org/10.1515/ijb-2018-0052)> for a detailed presentation of the method.

**License** GPL-2

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**Depends** R (>= 2.10)

**NeedsCompilation** no

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beast-package	<i>Bayesian Estimation of Change-Points in the Slope of Multivariate Time-Series</i>
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## Description

Assume that a temporal process is composed of contiguous segments with differing slopes and replicated noise-corrupted time series measurements are observed. The unknown mean of the data generating process is modelled as a piecewise linear function of time with an unknown number of change-points. The package infers the joint posterior distribution of the number and position of change-points as well as the unknown mean parameters per time-series by MCMC sampling. A-priori, the proposed model uses an overfitting number of mean parameters but, conditionally on a set of change-points, only a subset of them influences the likelihood. An exponentially decreasing prior distribution on the number of change-points gives rise to a posterior distribution concentrating on sparse representations of the underlying sequence, but also available is the Poisson distribution. See Papastamoulis et al (2019) <doi:10.1515/ijb-2018-0052> for a detailed presentation of the method.

## Details

The beast package deals with **Bayesian** estimation of **change-points** in the **slope** of multivariate **time-series**, introduced by Papastamoulis et al (2017). For a given period  $t = 1, \dots, T$  we observe multiple time series which are assumed independent, each one consisting of multiple measurements (replicates). Each time series is assumed to have its own segmentation, which is common among its replicates. Thus, different time series have distinct mean parameters in the underlying normal distribution. The variance, which is assumed known, can be either shared between different time series or not and in practice it is estimated at a pre-processing stage.

Our model infers the joint posterior distribution of the number and location of change-points by MCMC sampling. For this purpose a Metropolis-Hastings MCMC sampler is used. The main function of the package is `beast`.

Assume that the observed data consists of  $N$  time-series, each one consisting of  $R$  variables (or replicates) measured at  $T$  consecutive time-points. The input of the main function `beast` should be given in the form of a list `myDataList` with the following attributes:

- `length(myDataList)` should be equal to  $R$ , that is, the number of variables (or replicates)
- `dim(myDataList)[[1]], \dots, dim(myDataList)[[R]]` should be all  $T \times N$ , that is, rows and columns should correspond to time-points and different series, respectively.

Then, a basic usage of the package consists of the following commands:

- `beastRun <- beast( myDataList = myDataList )`
- `print(beastRun)`
- `plot(beastRun)`

which correspond to running the MCMC sampler, printing and plotting output summaries, respectively.

### Author(s)

Panagiotis Papastamoulis [aut, cre] (<<https://orcid.org/0000-0001-9468-7613>>)

Maintainer: Panagiotis Papastamoulis <[papapast@yahoo.gr](mailto:papapast@yahoo.gr)>

### References

Papastamoulis P., Furukawa T., van Rhijn N., Bromley M., Bignell E. and Rattray M. (2019). Bayesian detection of piecewise linear trends in replicated time-series with application to growth data modelling. *International Journal of Biostatistics*. doi.org/10.1515/ijb-2018-0052.

### See Also

`beast`, `print.beast.object`, `plot.beast.object`

### Examples

```
# toy-example (MCMC iterations not enough)
library('beast') # load package
data("FungalGrowthDataset") # load dataset
myIndex <- c(392, 62, 3, 117) # run the sampler only for the
#                               specific subset of time-series
set.seed(1)
# Run MCMC sampler with very small number of iterations (nIter):
run_mcmc <- beast(myDataList = FungalGrowthDataset, subsetIndex = myIndex,
zeroNormalization = TRUE, nIter = 40, burn = 20)
# Print output:
print(run_mcmc)
# Plot output
plot(run_mcmc, timeScale=1/6, xlab = "hours", ylab = "growth")
```

```

# Run the following commands to obtain convergence:

## Not run:
# This example illustrates the package using a subset of four
#   time-series of the fungal dataset.
library('beast') # load package
data("FungalGrowthDataset") # load dataset
myIndex <- c(392, 62, 3, 117) # run the sampler only for the
#                               specific subset of time-series
set.seed(1) # optional
# Run MCMC sampler with the default number of iterations (nIter =70000):
run_mcmc <- beast(myDataList = FungalGrowthDataset, subsetIndex = myIndex,
zeroNormalization = TRUE)
# Print output:
print(run_mcmc)
# Plot output to file: "beast_plot.pdf"
plot(run_mcmc, fileName = "beast_plot.pdf", timeScale=1/6, xlab = "hours", ylab = "growth")
# NOTE 1: for a complete analysis remove the `subsetIndex = myIndex` argument.
# NOTE 2: `zeroNormalization = TRUE` is an optional argument that forces all
#   time-series to start from zero. It is not supposed to be used
#   for other applications.

## End(Not run)

```

---

beast

*Main function*


---

### Description

This is the main function of the package, implementing the MCMC sampler described in Papastamoulis et al (2017).

### Usage

```

beast(myDataList, burn, nIter, mhPropRange, mhSinglePropRange, startPoint,
      timeScale, savePlots, zeroNormalization, LRange, tau,
      gammaParameter, nu0, alpha0, beta0, subsetIndex, saveTheta, sameVariance,
      Prior
)

```

### Arguments

myDataList	Observed data in the form of a list with length $R$ , denoting the dimensionality of the multivariate time-series data. For each $r = 1, \dots, R$ , myDataList[[r]] should correspond to $T \times N$ array, with myDataList[[r]][t, n] corresponding to the observed data for time-series $n = 1, \dots, N$ and time-point $t = 1, \dots, T$ .
burn	Number of iterations that will be discarded as burn-in period. Default value: burn = 20000.

nIter	Number of MCMC iterations. Default value: nIter = 70000.
mhPropRange	Positive integer corresponding to the parameter $d_1$ of MCMC Move 3.a of Papastamoulis et al (2017). Default value: mhPropRange = 1.
mhSinglePropRange	Positive integer denoting the parameter $d_2$ of Papastamoulis et al (2017). Default value: mhPropRange = 40.
startPoint	An (optional) positive integer pointing at the minimum time-point where changes are allowed to occur. Default value: startPoint = 2 (all possible values are taken into account).
timeScale	Null.
savePlots	Character denoting the name of the folder where various plots will be saved to.
zeroNormalization	Logical value denoting whether to normalize to zero all time time-series for $t = 1$ . Default: zeroNormalization = FALSE.
LRange	Range of possible values for the number of change-points. Default value: LRange = 0:30.
tau	Positive real number corresponding to parameter $c$ in Move 2 of Papastamoulis et al (2017). Default value: tau = 0.05.
gammaParameter	Positive real number corresponding to parameter $\alpha$ of the exponential prior distribution. Default value: gammaParameter = 2.
nu0	Positive real number corresponding to prior parameter $\nu_0$ in Papastamoulis et al (2017). Default value: nu0 = 0.1.
alpha0	Positive real number corresponding to prior parameter $\alpha_0$ in Papastamoulis et al (2017). Default value: alpha0 = 1.
beta0	Positive real number corresponding to prior parameter $\beta_0$ in Papastamoulis et al (2017). Default value: beta0 = 1.
subsetIndex	Optional subset of integers corresponding to time-series indexes. If not null, the sampler will be applied only to the specified subset.
saveTheta	Logical value indicating whether to save the generated values of the mean per time-point across the MCMC trace. Default: FALSE.
sameVariance	Logical value indicating whether to assume the same variance per time-point across time-series. Default value: sameVariance = TRUE.
Prior	Character string specifying the prior distribution of the number of change-points. Allowed values: Prior = "complexity" (default) or Prior = "Poisson" (not suggested).

### Value

The output of the sampler is returned as a list, with the following features:

Cutpoint\_posterior\_median

The estimated medians per change-point, conditionally on the most probable number of change-points per time-series.

Cutpoint_posterior_variance	The estimated variances per change-points, conditionally on the most probable number of change-points per time-series.
NumberOfCutPoints_posterior_distribution	Posterior distributions of number of change-points per time-series.
NumberOfCutPoints_MAP	The most probable number of change-points per time-series.
Metropolis-Hastings_acceptance_rate	Acceptance of the MCMC move-types.
subject_ID	the identifier of individual time-series.
Cutpoint_mcmc_trace_map	The sampled values of each change-point per time series, conditionally on the MAP values.
theta	The sampled values of the means per time-series, conditionally on the MAP values.
nCutPointsTrace	The sampled values of the number of change-points, per time-series.

### Note

The complexity prior distribution with parameter `gammaParameter = 2` is the default prior assumption imposed on the number of change-points. Smaller (larger) values of `gammaParameter` will a-priori support larger (respectively: smaller) number of change-points.

For completeness purposes, the Poisson distribution is also allowed in the Prior. In this latter case, the `gammaParameter` denotes the rate parameter of the Poisson distribution. Note that in this case the interpretation of `gammaParameter` is reversed: Smaller (larger) values of `gammaParameter` will a-priori support smaller (respectively: larger) number of change-points.

### Author(s)

Panagiotis Papastamoulis

### References

Papastamoulis P., Furukawa T., van Rhijn N., Bromley M., Bignell E. and Rattray M. (2019). Bayesian detection of piecewise linear trends in replicated time-series with application to growth data modelling. *International Journal of Biostatistics*. doi.org/10.1515/ijb-2018-0052

### Examples

```
# toy-example (MCMC iterations not enough)
library('beast') # load package
data("FungalGrowthDataset") # load dataset
myIndex <- c(392, 62, 3, 117) # run the sampler only for the
#                               specific subset of time-series
set.seed(1)
# Run MCMC sampler with very small number of iterations (nIter):
run_mcmc <- beast(myDataList = FungalGrowthDataset, subsetIndex = myIndex,
```

```

zeroNormalization = TRUE, nIter = 40, burn = 20)
# Print output:
print(run_mcmc)
# Plot output to file: "beast_plot.pdf"
plot(run_mcmc, timeScale=1/6, xlab = "hours", ylab = "growth")
# Run the following commands to obtain convergence:

## Not run:
# This example illustrates the package using a subset of four
#   time-series of the fungal dataset.
library('beast') # load package
data("FungalGrowthDataset") # load dataset
myIndex <- c(392, 62, 3, 117) # run the sampler only for the
#                               specific subset of time-series
set.seed(1) # optional
# Run MCMC sampler with the default number of iterations (nIter =70000):
run_mcmc <- beast(myDataList = FungalGrowthDataset, subsetIndex = myIndex,
zeroNormalization = TRUE)
# Print output:
print(run_mcmc)
# Plot output to file: "beast_plot.pdf"
plot(run_mcmc, fileName = "beast_plot.pdf", timeScale=1/6, xlab = "hours", ylab = "growth")
# NOTE 1: for a complete analysis remove the `subsetIndex = myIndex` argument.
# NOTE 2: `zeroNormalization = TRUE` is an optional argument that forces all
#   time-series to start from zero. It is not supposed to be used
#   for other applications.

## End(Not run)

```

---

birthProbs

*Birth Probabilities*


---

## Description

This function defines the probability of proposing an addition of a change-point.

## Usage

```
birthProbs(LRange)
```

## Arguments

LRange            The range of possible values for the number of change-points.

## Value

probs            Vector of probabilities

## Author(s)

Panagiotis Papastamoulis

---

complexityPrior      *Complexity prior distribution*

---

### Description

This function computes the complexity prior distribution on the number of change-points, defined as  $f(\ell) = P(\ell_n = \ell) \propto e^{-\alpha \ell \log(bT/\ell)}$ ,  $a, b > 0$ ;  $\ell = 0, 1, 2, \dots$ . Note that this distribution has exponential decrease (Castillo and van der Vaart, 2012) when  $b > 1 + e$ , so we set  $b = 3.72$ .

### Usage

```
complexityPrior(Lmax = 20, gammaParameter, nTime)
```

### Arguments

Lmax                    maximum number of change-points (default = 20).  
gammaParameter       positive real number, corresponding to  $\alpha$ .  
nTime                    positive integer denoting the total number of time-points.

### Value

logPrior                Prior distribution values in the log-scale.

### Author(s)

Panagiotis Papastamoulis

### References

Castillo I. and van der Vaart A (2012). Needles and Straw in a Haystack: Posterior concentration for possibly sparse sequences. *The Annals of Statistics*, 40(4), 2069–2101.

---

computeEmpiricalPriorParameters  
*Compute the empirical mean.*

---

### Description

This function computes the empirical mean of the time-series.

### Usage

```
computeEmpiricalPriorParameters(myDataList, nu0 = 1, alpha0 = 1, beta0 = 1)
```

**Arguments**

<code>myDataList</code>	Observed multivariate time-series.
<code>nu0</code>	positive real number.
<code>alpha0</code>	positive real number.
<code>beta0</code>	positive real number.

**Value**

<code>mu0</code>	Empirical mean
------------------	----------------

**Author(s)**

Panagiotis Papastamoulis

---

`computePosteriorParameters`  
*Compute empirical posterior parameters*

---

**Description**

Compute empirical posterior parameters

**Usage**

```
computePosteriorParameters(myDataList, priorParameters)
```

**Arguments**

<code>myDataList</code>	Observed data.
<code>priorParameters</code>	Prior parameters.

**Value**

list of posterior parameters

**Author(s)**

Panagiotis Papastamoulis

computePosteriorParametersFree  
*Posterior parameters*

---

**Description**

Posterior parameters

**Usage**

```
computePosteriorParametersFree(myDataList, priorParameters)
```

**Arguments**

myDataList      observed data.  
priorParameters  
                 list of prior parameters.

**Value**

list of posterior parameters.

**Author(s)**

Panagiotis Papastamoulis

---

FungalGrowthDataset      *Fungal Growth Dataset*

---

**Description**

Time-series dataset with  $N \times R \times T$  growth levels for  $R = 3$  replicates of  $N = 411$  objects (mutants) measured every 10 minutes for  $T = 289$  time-points. See Papastamoulis et al (2017) for a detailed description.

**Usage**

```
data(FungalGrowthDataset)
```

**Format**

Time-series data.

**References**

Papastamoulis P., Furukawa T., van Rhijn N., Bromley M., Bignell E. and Rattray M. (2019). Bayesian detection of piecewise linear trends in replicated time-series with application to growth data modelling. International Journal of Biostatistics.]

---

localProposal	<i>Move 3.b</i>
---------------	-----------------

---

**Description**

Implements Move 3.b of the Metropolis-Hastings MCMC sampler.

**Usage**

```
localProposal(cutPoints, nTime, mhPropRange, startPoint)
```

**Arguments**

cutPoints	Current configuration of change-points.
nTime	Total number of time-points.
mhPropRange	Parameter $d_2$ .
startPoint	Integer, at least equal to 2.

**Value**

newState	Candidate state of the chain.
propRatio	Proposal ratio.

**Author(s)**

Panagiotis Papastamoulis

---

logLikelihoodFullModel	<i>Log-likelihood function.</i>
------------------------	---------------------------------

---

**Description**

Log-likelihood function.

**Usage**

```
logLikelihoodFullModel(myData, cutPoints, theta, startPoint)
```

**Arguments**

myData	data
cutPoints	change-points.
theta	means.
startPoint	optional integer at least equal to 2.

**Value**

log-likelihood value.

**Author(s)**

Panagiotis Papastamoulis

---

logPrior	<i>Log-prior.</i>
----------	-------------------

---

**Description**

Logarithm of the prior distribution on the number of change-points.

**Usage**

```
logPrior(cutPoints, nTime, startPoint)
```

**Arguments**

cutPoints	change-points.
nTime	number of time-points.
startPoint	optional integer, at least equal to 2.

**Value**

logarithm of the prior distribution.

**Author(s)**

Panagiotis Papastamoulis

---

mcmcSampler	<i>MCMC sampler</i>
-------------	---------------------

---

**Description**

This function implements the Metropolis-Hastings MCMC sampler for individual time-series.

**Usage**

```
mcmcSampler(myData, nIter, finalIterationPdf, modelVariance, mhPropRange,
mhSinglePropRange, movesRange, startPoint, postPar, dName, timeScale,
burn, iterPerPlotPrefix, priorParameters, L = 3, LRange, tau,
gammaParameter, saveTheta, Prior = "complexity")
```

**Arguments**

myData	observed data.
nIter	number of mcmc iterations
finalIterationPdf	output folder
modelVariance	null
mhPropRange	positive integer
mhSinglePropRange	positive integer
movesRange	null
startPoint	positive integer
postPar	list of empirically estimated parameters
dName	subject ID
timeScale	null
burn	burn-in period.
iterPerPlotPrefix	null
priorParameters	prior parameters.
L	null
LRange	range of possible values of the number of change-points.
tau	real.
gammaParameter	real.
saveTheta	TRUE.
Prior	character.

**Value**

MCMC output.

**Author(s)**

Panagiotis Papastamoulis

myUnicodeCharacters     *Printing*

---

**Description**

Printing various unicode symbols.

**Usage**

myUnicodeCharacters()

**Value**

printed symbol

---

normalizeTime0     *Zero normalization*

---

**Description**

Zero normalization at 1st time-point

**Usage**

normalizeTime0(myDataList)

**Arguments**

myDataList     data

**Value**

null

**Author(s)**

Panagiotis Papastamoulis

---

plot.beast.object      *Plot function*


---

**Description**

This function plots objects returned by the `beast` function.

**Usage**

```
## S3 method for class 'beast.object'
plot(x, fileName, width, height, pointsize, ylab, xlab, timeScale, myPal, boxwex, ...)
```

**Arguments**

<code>x</code>	An object of class <code>beast.object</code> , which is returned by the <code>beast</code> function.
<code>fileName</code>	If not <code>NULL</code> , the plot will be produced in the form of a pdf file. In this case, all output is diverted to a pdf file provided in the <code>fileName</code> argument. The default is <code>NULL</code> .
<code>width</code>	Width of pdf file. Default: 9
<code>height</code>	Height pdf file. Default: 6
<code>pointsize</code>	Pointsize. Default: 12
<code>ylab</code>	<i>y</i> -axis label. Default: <code>x</code> .
<code>xlab</code>	<i>x</i> -axis label. Default: <code>t</code> .
<code>timeScale</code>	A multiplicative-factor which will be used to scale the <i>x</i> -axis labels. For example, if time-points correspond to 10-minute periods, then setting <code>timeScale = 1/6</code> will make the <i>x</i> -axis labels correspond to hours. Default: <code>timeScale = 1</code> .
<code>myPal</code>	Vector of colors that will be used to produce the plot with all time-series overlaid. If the distinct values of the inferred numbers of change-points is less than 10, the <code>Set1</code> palette of the <code>RColorBrewer</code> library is used. Otherwise, the user has to manually define the colors.
<code>boxwex</code>	A scale factor to be applied to all boxes. The appearance of the plot can be improved by making the boxes narrower or wider. Default: 0.2.
<code>...</code>	ignored.

**Details**

The function will produce a plot with all time-series coloured according to the corresponding number of change-points. In addition, it will generate individual plots per time-series displaying the observed data with boxplots which summarize the posterior distribution of change-points locations, conditionally on the most probable number of change-points.

**Author(s)**

Panagiotis Papastamoulis

---

```
print.beast.object      Print function
```

---

**Description**

This function prints a summary of objects returned by the `beast` function.

**Usage**

```
## S3 method for class 'beast.object'
print(x, ...)
```

**Arguments**

<code>x</code>	An object of class <code>beast.object</code> , which is returned by the <code>beast</code> function.
<code>...</code>	ignored.

**Details**

The function prints a summary of the most probable number (MAP) of change-points per time-series in the form of a table, as well as a list containing the MAP number of change-points and the corresponding locations (posterior medians) per time-series.

**Author(s)**

Panagiotis Papastamoulis

---

```
proposeTheta           Move 2
```

---

**Description**

Proposes an update of  $\theta$  according to Metropolis-Hastings move 2.

**Usage**

```
proposeTheta(thetaOld, tau, alpha, beta)
```

**Arguments**

<code>thetaOld</code>	Current values
<code>tau</code>	Parameter $c$ .
<code>alpha</code>	null
<code>beta</code>	null

**Value**

mean            proposed values.

**Author(s)**

Panagiotis Papastamoulis

---

simMultiIndNormInvGamma  
*Prior random numbers*

---

**Description**

Generation of mean values according to the prior

**Usage**

simMultiIndNormInvGamma(mu, nu, alpha, beta)

**Arguments**

mu            means  
nu            precision parameter  
alpha        prior parameter  
beta         prior parameter

**Value**

null

**Author(s)**

Panagiotis Papastamoulis

---

simulateFromPrior	<i>Generate change-points according to the prior</i>
-------------------	--

---

**Description**

Generate change-points according to the prior distribution conditionally on a given number of change-points.

**Usage**

```
simulateFromPrior(nTime, startPoint, L = 3)
```

**Arguments**

nTime	Number of time-points
startPoint	At least equal to 2.
L	null

**Value**

cutPoints	Change-point locations
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**Author(s)**

Panagiotis Papastamoulis

---

singleLocalProposal	<i>Move 3.b</i>
---------------------	-----------------

---

**Description**

Implement Metropolis-Hastings Move 3.b.

**Usage**

```
singleLocalProposal(cutPoints, nTime, mhSinglePropRange, startPoint)
```

**Arguments**

cutPoints	Current state
nTime	Number of time-points
mhSinglePropRange	Prior parameter.
startPoint	Optional.

**Value**

newState	Candidate state
propRatio	Proposal ratio

**Author(s)**

Panagiotis Papastamoulis

---

truncatedPoisson	<i>Truncated Poisson pdf</i>
------------------	------------------------------

---

**Description**

Probability density function of the truncated Poisson distribution.

**Usage**

```
truncatedPoisson(Lmax = 20, gammaParameter = 1)
```

**Arguments**

Lmax	Max number
gammaParameter	Location parameter.

**Value**

logPrior	Log-pdf values
----------	----------------

**Author(s)**

Panagiotis Papastamoulis

---

updateNumberOfCutpoints	<i>Move 1</i>
-------------------------	---------------

---

**Description**

Update the number of change-points according to Metropolis-Hastings move 1.

**Usage**

```
updateNumberOfCutpoints(cutPoints, nTime, startPoint, LRange, birthProbs)
```

**Arguments**

cutPoints	Current configuration
nTime	Number of time-points
startPoint	Optional integer
LRange	Range of possible values
birthProbs	Birth probabilities

**Value**

newState	Candidate state
propRatio	Proposal ratio

**Author(s)**

Panagiotis Papastamoulis

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