

Package ‘NeuralEstimators’

September 11, 2024

Title Likelihood-Free Parameter Estimation using Neural Networks

Version 0.1.0

Description An 'R' interface to the 'Julia' package 'NeuralEstimators.jl'. The package facilitates the user-friendly development of neural point estimators, which are neural networks that map data to a point summary of the posterior distribution. These estimators are likelihood-free and amortised, in the sense that, after an initial setup cost, inference from observed data can be made in a fraction of the time required by conventional approaches; see Sainsbury-Dale, Zammit-Mangion, and Huser (2024) <[doi:10.1080/00031305.2023.2249522](https://doi.org/10.1080/00031305.2023.2249522)> for further details and an accessible introduction. The package also enables the construction of neural networks that approximate the likelihood-to-evidence ratio in an amortised manner, allowing one to perform inference based on the likelihood function or the entire posterior distribution; see Zammit-Mangion, Sainsbury-Dale, and Huser (2024, Sec. 5.2) <[doi:10.48550/arXiv.2404.12484](https://doi.org/10.48550/arXiv.2404.12484)>, and the references therein. The package accommodates any model for which simulation is feasible by allowing the user to implicitly define their model through simulated data.

Maintainer Matthew Sainsbury-Dale <msainsburydale@gmail.com>

License GPL (>= 2)

Encoding UTF-8

RoxygenNote 7.3.2

Imports JuliaConnectoR, magrittr

Suggests dplyr, ggplot2, ggplotify, ggpubr, gridExtra, knitr, rmarkdown, markdown, testthat (>= 3.0.0)

Config/testthat/edition 3

SystemRequirements Julia (>= 1.9)

NeedsCompilation no

Author Matthew Sainsbury-Dale [aut, cre]

Repository CRAN

Date/Publication 2024-09-11 17:20:02 UTC

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NeuralEstimators-package

NeuralEstimators: Likelihood-Free Parameter Estimation using Neural Networks

Description

An 'R' interface to the 'Julia' package 'NeuralEstimators.jl'. The package facilitates the user-friendly development of neural point estimators, which are neural networks that map data to a point summary of the posterior distribution. These estimators are likelihood-free and amortised, in the sense that, after an initial setup cost, inference from observed data can be made in a fraction of the time required by conventional approaches; see Sainsbury-Dale, Zammit-Mangion, and Huser (2024) [doi:10.1080/00031305.2023.2249522](https://doi.org/10.1080/00031305.2023.2249522) for further details and an accessible introduction. The package also enables the construction of neural networks that approximate the likelihood-to-evidence ratio in an amortised manner, allowing one to perform inference based on the likelihood function or the entire posterior distribution; see Zammit-Mangion, Sainsbury-Dale, and Huser (2024, Sec. 5.2) [doi:10.48550/arXiv.2404.12484](https://doi.org/10.48550/arXiv.2404.12484), and the references therein. The package accommodates any model for which simulation is feasible by allowing the user to implicitly define their model through simulated data.

Author(s)

Maintainer: Matthew Sainsbury-Dale <msainsburydale@gmail.com>

assess *assess a neural estimator*

Description

assess a neural estimator

Usage

```
assess(
  estimators,
  parameters,
  Z,
  estimator_names = NULL,
  parameter_names = NULL,
  use_gpu = TRUE,
  verbose = TRUE
)
```

Arguments

<code>estimators</code>	a list of (neural) estimators
<code>parameters</code>	true parameters, stored as a $p \times K$ matrix, where p is the number of parameters in the statistical model and K is the number of sampled parameter vectors
<code>Z</code>	data simulated conditionally on the parameters. If <code>Z</code> contains more data sets than parameter vectors, the parameter matrix will be recycled by horizontal concatenation.
<code>estimator_names</code>	list of names of the estimators (sensible defaults provided)
<code>parameter_names</code>	list of names of the parameters (sensible defaults provided)
<code>use_gpu</code>	a boolean indicating whether to use the GPU if it is available (default true)
<code>verbose</code>	a boolean indicating whether information should be printed to the console

Value

a list of two data frames: `run_times`, contains the total time taken for each estimator, while `estimates` is a long-form data frame with columns:

- "estimator"; the name of the estimator
- "parameter"; the name of the parameter
- "truth"; the true value of the parameter
- "estimate"; the estimated value of the parameter
- "m"; the sample size (number of iid replicates)
- "k"; the index of the parameter vector in the test set
- "j"; the index of the data set

See Also

[risk\(\)](#), [rmse\(\)](#), [bias\(\)](#), [plotestimates\(\)](#), and [plotdistribution\(\)](#) for computing various empirical diagnostics and visualisations based on an assessment object

bias	<i>computes a Monte Carlo approximation of an estimator's bias</i>
------	--

Description

computes a Monte Carlo approximation of an estimator's bias

Usage

```
bias(assessment, ...)
```

Arguments

assessment	an object returned by <code>assess()</code> (or the estimates data frame of this object)
...	optional arguments inherited from <code>risk</code> (excluding the argument <code>loss</code>)

Value

a dataframe giving the estimated bias

See Also

[assess\(\)](#), [risk\(\)](#), [rmse\(\)](#)

bootstrap	<i>bootstrap</i>
-----------	------------------

Description

Compute bootstrap estimates from a neural estimator

Usage

```
bootstrap(estimator, Z, B = 400, blocks = NULL, use_gpu = TRUE)
```

Arguments

estimator	a neural estimator
Z	either a list of data sets simulated conditionally on the fitted parameters (parametric bootstrap); or a single observed data set containing independent replicates, which will be sampled with replacement B (non-parametric bootstrap)
B	number of non-parametric bootstrap estimates (default 400)
blocks	integer vector specifying the blocks in non-parameteric bootstrap (default NULL). For example, with 5 replicates, the first two corresponding to block 1 and the remaining three corresponding to block 2, blocks should be <code>c(1,1,2,2,2)</code> . The bootstrap sampling algorithm aims to produce bootstrap data sets that are of a similar size to Z, but this can only be achieved exactly if all blocks are equal in length.
use_gpu	a boolean indicating whether to use the GPU if it is available (default TRUE)

Value

$p \times B$ matrix, where p is the number of parameters in the model and B is the number of bootstrap samples

encodedata	<i>encodedata</i>
------------	-------------------

Description

for data Z with missing (NA) entries, returns an augmented data set (U, W) where W encodes the missingness pattern as an indicator vector and U is the original data Z with missing entries replaced by a fixed constant c.

The indicator vector W is stored in the second-to-last dimension of Z, which should be singleton. If the second-to-last dimension is not singleton, then two singleton dimensions will be added to the array, and W will be stored in the new second-to-last dimension.

Usage

`encodedata(Z, c = 0)`

Arguments

Z	data containing NA entries
c	fixed constant with which to replace NA entries

Value

Augmented data set (U, W). If Z is provided as a list, the return type will be a JuliaProxy object; these objects can be indexed in the usual manner (e.g., using `[]`), or converted to an R object using `juliaGet()` (note however that `juliaGet()` can be slow for large data sets).

Examples

```
## Not run:
library("NeuralEstimators")
Z <- matrix(c(1, 2, NA, NA, 5, 6, 7, NA, 9), nrow = 3)
encodedata(Z)
encodedata(list(Z, Z))
## End(Not run)
```

estimate

estimate

Description

estimate parameters from observed data using a neural estimator

Usage

```
estimate(estimator, Z, theta = NULL, use_gpu = TRUE)
```

Arguments

estimator	a neural estimator
Z	data; format should be amenable to the architecture of estimator
theta	parameter vectors (only for neural estimators that take both the data and parameters as input, e.g., neural ratio estimators)
use_gpu	a boolean indicating whether to use the GPU if it is available (default true)

Value

a matrix of parameter estimates (i.e., estimator applied to Z)

Examples

```
## Not run:
library("NeuralEstimators")
library("JuliaConnectoR")

## Observed data: 100 replicates of a univariate random variable
Z = matrix(rnorm(100), nrow = 1)

## Construct an (un-trained) point estimator
estimator <- initialise_estimator(1, architecture = "MLP")

## Apply the estimator
estimate(estimator, Z)
## End(Not run)
```

initialise_estimator *Initialise a neural estimator*

Description

Helper function for initialising a neural estimator.

The estimator is couched in the DeepSets framework so that it can be applied to data with an arbitrary number of independent replicates (including the special case of a single replicate).

Usage

```
initialise_estimator(
    p,
    architecture,
    d = 1,
    estimator_type = "point",
    depth = 3,
    width = 32,
    activation = "relu",
    activation_output = "identity",
    variance_stabiliser = NULL,
    kernel_size = NULL,
    weight_by_distance = TRUE,
    probs = c(0.025, 0.975)
)
```

Arguments

p	number of unknown parameters in the statistical model
architecture	a string: for unstructured data, one may use a fully-connected MLP ("MLP"); for data collected over a grid, a convolutional neural network ("CNN"); and for graphical or irregular spatial data, a graphical neural network ("GNN").
d	for unstructured multivariate data (i.e., when architecture = "MLP"), the dimension of the data (e.g., d = 3 for trivariate data); otherwise, if architecture is "CNN" or "GNN", the argument d controls the number of input channels (e.g., d = 1 for univariate spatial processes).
estimator_type	the type of estimator; either "point" or "interval".
depth	the number of hidden layers. Either a single integer or an integer vector of length two specifying the depth of inner (summary) and outer (inference) network of the DeepSets framework. Since there is an input and an output layer, the total number of layers is $\text{sum}(\text{depth}) + 2$.
width	a single integer or an integer vector of length $\text{sum}(\text{depth})$ specifying the width (or number of convolutional filters/channels) in each layer.
activation	the (non-linear) activation function of each hidden layer. Accepts a string of Julia code (default "relu").

activation_output	the activation function of the output layer layer. Accepts a string of Julia code (default "identity").
variance_stabiliser	a function that will be applied directly to the input, usually to stabilise the variance.: a string ('log' for the natural logarithm, or 'cbrt' for the cube-root function), or a string of Julia code that will be converted to a Julia function using juliaEval().
kernel_size	(applicable only to CNNs) a list of length depth[1] containing lists of integers of length D, where D is the dimension of the convolution (e.g., D = 2 for two-dimensional convolution).
weight_by_distance	(applicable only to GNNs) flag indicating whether the estimator will weight by spatial distance; if true (default), a WeightedGraphConv layer is used in the propagation module; otherwise, a regular GraphConv layer is used.
probs	(applicable only if estimator_type = "interval") probability levels defining the lower and upper endpoints of the posterior credible interval.

Value

the initialised neural estimator, a JuliaProxy object

Examples

```
## Not run:
library("NeuralEstimators")
p = 2
initialise_estimator(p, architecture = "MLP")
initialise_estimator(p, architecture = "GNN")

## 1D convolution
initialise_estimator(p, architecture = "CNN", kernel_size = list(10, 5, 3))

## 2D convolution
initialise_estimator(p, architecture = "CNN",
                    kernel_size = list(c(10, 10), c(5, 5), c(3, 3)))

## End(Not run)
```

loadstate	<i>load a saved state of a neural estimator</i>
-----------	---

Description

load a saved state of a neural estimator

Usage

```
loadstate(estimator, filename)
```


Arguments

estimator the neural estimator that we wish to load the state into
 filename file (including absolute path) of the neural-network state in a bson file

Value

estimator updated with the saved state

loadweights *load a collection of saved weights of a neural estimator*

Description

load a collection of saved weights of a neural estimator

Usage

loadweights(estimator, filename)

Arguments

estimator the neural estimator that we wish to load weights into
 filename file (including absolute path) of the neural-network weights saved as a bson file

Value

estimator updated with the saved weights

See Also

[loadstate\(\)](#)

mapestimate *Maximum a posteriori estimation*

Description

Given data Z , a neural likelihood-to-evidence-ratio estimator, and a prior, computes the implied approximate maximum a posteriori (MAP) estimate

If a vector θ_0 of initial parameter estimates is given, the approximate posterior density is maximised by gradient descent. Otherwise, if a matrix of parameters θ_{grid} is given, the approximate posterior density is maximised by grid search.

Usage

```
mapestimate(
  estimator,
  Z,
  prior = NULL,
  theta_grid = NULL,
  theta0 = NULL,
  use_gpu = TRUE
)
```

Arguments

estimator	a neural likelihood-to-evidence-ratio estimator
Z	data; it's format should be amenable to the architecture of estimator
prior	the prior (default uniform), specified as a Julia or R function
theta_grid	a (fine) gridding of the parameter space, given as a matrix with p rows, where p is the number of parameters in the model
theta0	a vector of initial parameter estimates
use_gpu	a boolean indicating whether to use the GPU if it is available (default true)

Value

a $p \times K$ matrix of MAP estimates, where p is the number of parameters in the statistical model and K is the number of data sets provided in Z

See Also

[sampleposterior\(\)](#), [mlestimate\(\)](#)

mlestimate

Maximum likelihood estimation

Description

Given data Z and a neural likelihood-to-evidence-ratio estimator, computes the implied approximate maximum-likelihood estimate

If a vector theta0 of initial parameter estimates is given, the approximate likelihood is maximised by gradient descent. Otherwise, if a matrix of parameters theta_grid is given, the approximate likelihood is maximised by grid search.

Usage

```
mlestimate(estimator, Z, theta_grid = NULL, theta0 = NULL, use_gpu = TRUE)
```

Arguments

estimator	a neural likelihood-to-evidence-ratio estimator
Z	data; it's format should be amenable to the architecture of estimator
theta_grid	a (fine) gridding of the parameter space, given as a matrix with p rows, where p is the number of parameters in the model
theta0	a vector of initial parameter estimates
use_gpu	a boolean indicating whether to use the GPU if it is available (default true)

Value

a $p \times K$ matrix of maximum-likelihood estimates, where p is the number of parameters in the statistical model and K is the number of data sets provided in Z

See Also

[sampleposterior\(\)](#), [mapeestimate\(\)](#)

plotdistribution *Plot the empirical sampling distribution of an estimator.*

Description

Plot the empirical sampling distribution of an estimator.

Usage

```
plotdistribution(  
  df,  
  type = c("box", "density", "scatter"),  
  parameter_labels = NULL,  
  estimator_labels = ggplot2::waiver(),  
  truth_colour = "black",  
  truth_size = 8,  
  truth_line_size = NULL,  
  pairs = FALSE,  
  upper_triangle_plots = NULL,  
  legend = TRUE,  
  return_list = FALSE,  
  flip = FALSE  
)
```

Arguments

<code>df</code>	a long form data frame containing fields <code>estimator</code> , <code>parameter</code> , <code>estimate</code> , <code>truth</code> , and a column (e.g., <code>replicate</code>) to uniquely identify each observation.
<code>type</code>	string indicating whether to plot kernel density estimates for each individual parameter (<code>type = "density"</code>) or scatter plots for all parameter pairs (<code>type = "scatter"</code>).
<code>parameter_labels</code>	a named vector containing parameter labels.
<code>estimator_labels</code>	a named vector containing estimator labels.
<code>truth_colour</code>	the colour used to denote the true parameter value.
<code>truth_size</code>	the size of the point used to denote the true parameter value (applicable only for <code>type = "scatter"</code>).
<code>truth_line_size</code>	the size of the cross-hairs used to denote the true parameter value. If <code>NULL</code> (default), the cross-hairs are not plotted. (applicable only for <code>type = "scatter"</code>).
<code>pairs</code>	logical; should we combine the scatter plots into a single pairs plot (applicable only for <code>type = "scatter"</code>)?
<code>upper_triangle_plots</code>	an optional list of plots to include in the uppertriangle of the pairs plot.
<code>legend</code>	Flag; should we include the legend (only applies when constructing a pairs plot)
<code>return_list</code>	Flag; should the parameters be split into a list?
<code>flip</code>	Flag; should the boxplots be "flipped" using <code>coord_flip()</code> (default <code>FALSE</code>)?

Value

a list of 'ggplot' objects or, if `pairs = TRUE`, a single 'ggplot'.

Examples

```
## Not run:
# In the following, we have two estimators and, for each parameter, 50 estimates
# from each estimator.

estimators <- c("Estimator 1", "Estimator 2")
estimator_labels <- c("Estimator 1" = expression(hat(theta)[1](".")),
                     "Estimator 2" = expression(hat(theta)[2](".")))

# Single parameter:
df <- data.frame(
  estimator = estimators, truth = 0, parameter = "mu",
  estimate = rnorm(2*50),
  replicate = rep(1:50, each = 2)
)
parameter_labels <- c("mu" = expression(mu))
plotdistribution(df)
plotdistribution(df, type = "density")
```

```

plotdistribution(df, parameter_labels = parameter_labels, estimator_labels = estimator_labels)

# Two parameters:
df <- rbind(df, data.frame(
  estimator = estimators, truth = 1, parameter = "sigma",
  estimate = rgamma(2*50, shape = 1, rate = 1),
  replicate = rep(1:50, each = 2)
))
parameter_labels <- c(parameter_labels, "sigma" = expression(sigma))
plotdistribution(df, parameter_labels = parameter_labels)
plotdistribution(df, parameter_labels = parameter_labels, type = "density")
plotdistribution(df, parameter_labels = parameter_labels, type = "scatter")

# Three parameters:
df <- rbind(df, data.frame(
  estimator = estimators, truth = 0.25, parameter = "alpha",
  estimate = 0.5 * runif(2*50),
  replicate = rep(1:50, each = 2)
))
parameter_labels <- c(parameter_labels, "alpha" = expression(alpha))
plotdistribution(df, parameter_labels = parameter_labels)
plotdistribution(df, parameter_labels = parameter_labels, type = "density")
plotdistribution(df, parameter_labels = parameter_labels, type = "scatter")
plotdistribution(df, parameter_labels = parameter_labels, type = "scatter", pairs = TRUE)

# Pairs plot with user-specified plots in the upper triangle:
upper_triangle_plots <- lapply(1:3, function(i) {
  x = rnorm(10)
  y = rnorm(10)
  shape = sample(c("Class 1", "Class 2"), 10, replace = TRUE)
  ggplot() +
    geom_point(aes(x = x, y = y, shape = shape)) +
    labs(shape = "") +
    theme_bw()
})
plotdistribution(
  df,
  parameter_labels = parameter_labels, estimator_labels = estimator_labels,
  type = "scatter", pairs = TRUE, upper_triangle_plots = upper_triangle_plots
)
## End(Not run)

```

plotestimates

Plot estimates vs. true values.

Description

Plot estimates vs. true values.

Usage

```
plotestimates(
  df,
  estimator_labels = ggplot2::waiver(),
  parameter_labels = NULL
)
```

Arguments

`df` a long form data frame containing fields `estimator`, `parameter`, `estimate`, and `truth`.

`estimator_labels` a named vector containing estimator labels.

`parameter_labels` a named vector containing parameter labels.

Value

a 'ggplot' of the estimates for each parameter against the true value.

Examples

```
## Not run:
K <- 50
df <- data.frame(
  estimator = c("Estimator 1", "Estimator 2"),
  parameter = rep(c("mu", "sigma"), each = K),
  truth = 1:(2*K),
  estimate = 1:(2*K) + rnorm(4*K)
)
estimator_labels <- c("Estimator 1" = expression(hat(theta)[1]("·")),
  "Estimator 2" = expression(hat(theta)[2]("·")))
parameter_labels <- c("mu" = expression(mu), "sigma" = expression(sigma))

plotestimates(df, parameter_labels = parameter_labels, estimator_labels)
## End(Not run)
```

 risk

computes a Monte Carlo approximation of an estimator's Bayes risk

Description

computes a Monte Carlo approximation of an estimator's Bayes risk

Usage

```

risk(
  assessment,
  loss = function(x, y) abs(x - y),
  average_over_parameters = FALSE,
  average_over_sample_sizes = TRUE
)

```

Arguments

assessment an object returned by `assess()` (or the estimates data frame of this object)

loss a binary operator defining the loss function (default absolute-error loss)

average_over_parameters
if TRUE, the loss is averaged over all parameters; otherwise (default), the loss is averaged over each parameter separately

average_over_sample_sizes
if TRUE (default), the loss is averaged over all sample sizes (the column `m` in `df`); otherwise, the loss is averaged over each sample size separately

Value

a dataframe giving an estimate of the Bayes risk

See Also

[assess\(\)](#), [bias\(\)](#), [rmse\(\)](#)

rmse	<i>computes a Monte Carlo approximation of an estimator's root-mean-square error (RMSE)</i>
------	---

Description

computes a Monte Carlo approximation of an estimator's root-mean-square error (RMSE)

Usage

```
rmse(assessment, ...)
```

Arguments

assessment an object returned by `assess()` (or the estimates data frame of this object)

... optional arguments inherited from `risk` (excluding the argument `loss`)

Value

a dataframe giving the estimated RMSE

See Also

[assess\(\)](#), [bias\(\)](#), [risk\(\)](#)

sampleposterior	<i>sampleposterior</i>
-----------------	------------------------

Description

Given data Z , a neural likelihood-to-evidence-ratio estimator, and a prior, draws samples from the implied approximate posterior distribution

Currently, the sampling algorithm is based on a fine-gridding `theta_grid` of the parameter space. The approximate posterior density is evaluated over this grid, which is then used to draw samples. This is very effective when making inference with a small number of parameters. For models with a large number of parameters, other sampling algorithms may be needed (please feel free to contact the package maintainer for discussion).

Usage

```
sampleposterior(
  estimator,
  Z,
  theta_grid,
  N = 1000,
  prior = NULL,
  use_gpu = TRUE
)
```

Arguments

<code>estimator</code>	a neural likelihood-to-evidence-ratio estimator
<code>Z</code>	data; it's format should be amenable to the architecture of estimator
<code>theta_grid</code>	a (fine) gridding of the parameter space, given as a matrix with p rows, where p is the number of parameters in the model
<code>N</code>	number of samples to draw (default 1000)
<code>prior</code>	the prior (default uniform), specified as a Julia or R function
<code>use_gpu</code>	a boolean indicating whether to use the GPU if it is available (default true)

Value

a $p \times N$ matrix of posterior samples, where p is the number of parameters in the model. If multiple data sets are given in Z , a list of posterior samples will be returned

See Also

[mleestimate\(\)](#), [mapeestimate\(\)](#)

savestate	<i>save the state of a neural estimator</i>
-----------	---

Description

save the state of a neural estimator

Usage

```
savestate(estimator, filename)
```

Arguments

estimator	the neural estimator that we wish to save
filename	file in which to save the neural-network state as a bson file

Value

No return value, called for side effects

tanhloss	<i>tanhloss</i>
----------	-----------------

Description

For $k > 0$, defines Julia code that defines the loss function,

$$L(\hat{\theta}, \theta) = \tanh\left(\frac{|\hat{\theta} - \theta|}{k}\right),$$

which approximates the 0-1 loss as k tends to zero.

The resulting string is intended to be used in the function `train`, but can also be converted to a callable function using `juliaEval`.

Usage

```
tanhloss(k)
```

Arguments

k	Positive numeric value that controls the smoothness of the approximation.
-----	---

Value

String defining the tanh loss function in Julia code.

train	<i>Train a neural estimator</i>
-------	---------------------------------

Description

The function caters for different variants of "on-the-fly" simulation. Specifically, a sampler can be provided to continuously sample new parameter vectors from the prior, and a simulator can be provided to continuously simulate new data conditional on the parameters. If provided with specific sets of parameters (`theta_train` and `theta_val`) and/or data (`Z_train` and `Z_val`), they will be held fixed during training.

Note that using R functions to perform "on-the-fly" simulation requires the user to have installed the Julia package `RCall`.

Usage

```
train(
  estimator,
  sampler = NULL,
  simulator = NULL,
  theta_train = NULL,
  theta_val = NULL,
  Z_train = NULL,
  Z_val = NULL,
  m = NULL,
  M = NULL,
  K = 10000,
  xi = NULL,
  loss = "absolute-error",
  learning_rate = 1e-04,
  epochs = 100,
  batchsize = 32,
  savepath = "",
  stopping_epochs = 5,
  epochs_per_Z_refresh = 1,
  epochs_per_theta_refresh = 1,
  simulate_just_in_time = FALSE,
  use_gpu = TRUE,
  verbose = TRUE
)
```

Arguments

<code>estimator</code>	a neural estimator
<code>sampler</code>	a function that takes an integer <code>K</code> , samples <code>K</code> parameter vectors from the prior, and returns them as a <code>pxK</code> matrix
<code>simulator</code>	a function that takes a <code>pxK</code> matrix of parameters and an integer <code>m</code> , and returns <code>K</code> simulated data sets each containing <code>m</code> independent replicates

<code>theta_train</code>	a set of parameters used for updating the estimator using stochastic gradient descent
<code>theta_val</code>	a set of parameters used for monitoring the performance of the estimator during training
<code>Z_train</code>	a simulated data set used for updating the estimator using stochastic gradient descent
<code>Z_val</code>	a simulated data set used for monitoring the performance of the estimator during training
<code>m</code>	vector of sample sizes. If NULL (default), a single neural estimator is trained, with the sample size inferred from <code>Z_val</code> . If <code>m</code> is a vector of integers, a sequence of neural estimators is constructed for each sample size; see the Julia documentation for <code>trainx()</code> for further details
<code>M</code>	deprecated; use <code>m</code>
<code>K</code>	the number of parameter vectors sampled in the training set at each epoch; the size of the validation set is set to $K/5$.
<code>xi</code>	a list of objects used for data simulation (e.g., distance matrices); if it is provided, the parameter sampler is called as <code>sampler(K, xi)</code> .
<code>loss</code>	the loss function: a string ('absolute-error' for mean-absolute-error loss or 'squared-error' for mean-squared-error loss), or a string of Julia code defining the loss function.
<code>learning_rate</code>	the learning rate for the optimiser ADAM (default $1e-3$)
<code>epochs</code>	the number of epochs
<code>batchsize</code>	the batchsize to use when performing stochastic gradient descent
<code>savepath</code>	path to save the trained estimator and other information; if null (default), nothing is saved. Otherwise, the neural-network parameters (i.e., the weights and biases) will be saved during training as bson files; the risk function evaluated over the training and validation sets will also be saved, in the first and second columns of <code>loss_per_epoch.csv</code> , respectively; the best parameters (as measured by validation risk) will be saved as <code>best_network.bson</code> .
<code>stopping_epochs</code>	cease training if the risk doesn't improve in this number of epochs (default 5)
<code>epochs_per_Z_refresh</code>	integer indicating how often to refresh the training data
<code>epochs_per_theta_refresh</code>	integer indicating how often to refresh the training parameters; must be a multiple of <code>epochs_per_Z_refresh</code>
<code>simulate_just_in_time</code>	flag indicating whether we should simulate "just-in-time", in the sense that only a batchsize number of parameter vectors and corresponding data are in memory at a given time
<code>use_gpu</code>	a boolean indicating whether to use the GPU if it is available (default true)
<code>verbose</code>	a boolean indicating whether information should be printed to the console during training

Value

a trained neural estimator or, if `m` is a vector, a list of trained neural estimators

See Also

[assess\(\)](#) for assessing an estimator post training, and [estimate\(\)](#) for applying an estimator to observed data

Examples

```
## Not run:
# Construct a neural Bayes estimator for replicated univariate Gaussian
# data with unknown mean and standard deviation.

# Load R and Julia packages
library("NeuralEstimators")
library("JuliaConnector")
juliaEval("using NeuralEstimators, Flux, Distributions")

# Define the neural-network architecture
estimator <- juliaEval('
d = 1 # dimension of each replicate
p = 2 # number of parameters in the model
w = 32 # width of each layer
psi = Chain(Dense(d, w, relu), Dense(w, w, relu))
phi = Chain(Dense(w, w, relu), Dense(w, p))
deepset = DeepSet(psi, phi)
estimator = PointEstimator(deepset)
')

# Sampler from the prior
sampler <- function(K) {
  mu <- rnorm(K) # Gaussian prior for the mean
  sigma <- rgamma(K, 1) # Gamma prior for the standard deviation
  theta <- matrix(c(mu, sigma), byrow = TRUE, ncol = K)
  return(theta)
}

# Data simulator
simulator <- function(theta_set, m) {
  apply(theta_set, 2, function(theta) {
    t(rnorm(m, theta[1], theta[2]))
  }, simplify = FALSE)
}

# Train using fixed parameter and data sets
theta_train <- sampler(10000)
theta_val <- sampler(2000)
m <- 30 # number of iid replicates
Z_train <- simulator(theta_train, m)
Z_val <- simulator(theta_val, m)
estimator <- train(estimator,
```

```
        theta_train = theta_train,
        theta_val = theta_val,
        Z_train = Z_train,
        Z_val = Z_val)

# Train using simulation on-the-fly (requires Julia package RCall)
estimator <- train(estimator, sampler = sampler, simulator = simulator, m = m)

##### Simulation on-the-fly using Julia functions #####

# Defining the sampler and simulator in Julia can improve computational
# efficiency by avoiding the overhead of communicating between R and Julia.
# Julia is also fast (comparable to C) and so it can be useful to define
# these functions in Julia when they involve for-loops.

# Parameter sampler
sampler <- juliaEval("
function sampler(K)
  mu = rand(Normal(0, 1), K)
  sigma = rand(Gamma(1), K)
  theta = hcat(mu, sigma)'
  return theta
end")

# Data simulator
simulator <- juliaEval("
function simulator(theta_matrix, m)
  Z = [rand(Normal(theta[1], theta[2]), 1, m) for theta in eachcol(theta_matrix)]
  return Z
end")

# Train the estimator
estimator <- train(estimator, sampler = sampler, simulator = simulator, m = m)
## End(Not run)
```

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