

# Package ‘peco’

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**Type** Package

**Version** 1.23.0

**Title** A Supervised Approach for **Predicting Cell Cycle Progression** using scRNA-seq data

**Description** Our approach provides a way to assign continuous cell cycle phase using scRNA-seq data, and consequently, allows to identify cyclic trend of gene expression levels along the cell cycle. This package provides method and training data, which includes scRNA-seq data collected from 6 individual cell lines of induced pluripotent stem cells (iPSCs), and also continuous cell cycle phase derived from FUCCI fluorescence imaging data.

**URL** <https://github.com/jhsiao999/peco>

**BugReports** <https://github.com/jhsiao999/peco/issues>

**License** GPL (>= 3)

**Depends** R (>= 2.10)

**Imports** assertthat, circular, conicfit, doParallel, foreach, genlasso  
(>= 1.4), graphics, methods, parallel, scater,  
SingleCellExperiment, SummarizedExperiment, stats, utils

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cellcyclegenes\_whitfield2002  
*list of cell cycle genes identified in Whitfield et al. 2002.*

---

Description

List of cell cycle genes and their associated cell cycle state as reported in Whitfield et al. 2002.

Usage

data(cellcyclegenes\_whitfield2002)

**Format**

A list with the following elements

**hgnc** Gene symbol

**ensembl** ENSEMBL gene ID

**phase** Marker phase identified in Whitfield et al. 2002

---

|           |                                                         |
|-----------|---------------------------------------------------------|
| circ_dist | <i>Pairwise distance between two circular variables</i> |
|-----------|---------------------------------------------------------|

---

**Description**

We define distance between two angles: the minimum of the differences in both clockwise and counterclockwise directions.

**Usage**

```
circ_dist(y1, y2)
```

**Arguments**

y1                    A vector of angles.

y2                    A vector of angles.

**Value**

A vector of distances between angles.

**Author(s)**

Joyce Hsiao, Matthew Stephens

**Examples**

```
# a vector of angles
theta_ref <- seq(0, 2*pi, length.out=100)

# shift the origin of theta_ref to pi
theta_compare <- shift_origin(theta_ref, origin = pi)
mean(circ_dist(theta_ref, theta_compare))

# after rotation of angles, difference is 0 between the original
# and the shifted angles
theta_compare_rotated <- rotation(ref_var=theta_ref,
  shift_var=theta_compare)
mean(circ_dist(theta_ref, theta_compare_rotated))
```

---

cycle\_npreg\_insample    *Obtain cyclic trend estimates from the training data*

---

### Description

Estimates cyclic trends of gene expression levels using training data.

### Usage

```
cycle_npreg_insample(Y, theta, ncores = 2, polyorder = 2,
  method.trend = c("trendfilter", "loess", "bspline"))
```

### Arguments

|              |                                                                                                                                     |
|--------------|-------------------------------------------------------------------------------------------------------------------------------------|
| Y            | A matrix of normalized and transformed gene expression values. Gene by sample.                                                      |
| theta        | A vector of angles.                                                                                                                 |
| ncores       | We use doParallel package for parallel computing.                                                                                   |
| polyorder    | We estimate cyclic trends of gene expression levels using nonparamtric trend filtering. The default fits second degree polynomials. |
| method.trend | Varous methods that can be applied to estimate cyclic trend of gene expression levels.                                              |

### Value

A list with four elements:

|           |                                                                                               |
|-----------|-----------------------------------------------------------------------------------------------|
| Y         | Gene expression marix.                                                                        |
| theta     | Vector of angles or cell cycle phases.                                                        |
| sigma_est | Estimated standard error of the cyclic trend for each gene.                                   |
| funs_est  | A list of functions for approximating the cyclic trends of gene express levels for each gene. |

### Author(s)

Joyce Hsiao

### See Also

[cycle\\_npreg\\_mstep](#) for estimating cyclic functions given inferred phases from [cycle\\_npreg\\_loglik](#), [cycle\\_npreg\\_outsample](#) for predicting cell cycle phase using parameters learned from [cycle\\_npreg\\_insample](#)

Other peco classifier functions: [cycle\\_npreg\\_loglik](#), [cycle\\_npreg\\_mstep](#), [cycle\\_npreg\\_outsample](#), [initialize\\_grids](#)

**Examples**

```
# see \link{cycle_npreg_insample}
```

---

|                    |                                                                       |
|--------------------|-----------------------------------------------------------------------|
| cycle_npreg_loglik | <i>Infer angles or cell cycle phase based on gene expression data</i> |
|--------------------|-----------------------------------------------------------------------|

---

**Description**

Infer angles or cell cycle phase based on gene expression data

**Usage**

```
cycle_npreg_loglik(Y, sigma_est, funs_est, grids = 100,
  method.grid = c("pca", "uniform"))
```

**Arguments**

|             |                                                                                                                                                                                                                                                                                                               |
|-------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Y           | Gene by sample expression matrix.                                                                                                                                                                                                                                                                             |
| sigma_est   | A vector of standard errors for each gene from the training data.                                                                                                                                                                                                                                             |
| funs_est    | A vector of cyclic functions estimated for each gene from the training data.                                                                                                                                                                                                                                  |
| grids       | number of bins to be selected along 0 to 2pi.                                                                                                                                                                                                                                                                 |
| method.grid | The approach to initialize angles in the computation. <code>uniform</code> creates k equally-spaced bins (grids). <code>pca</code> uses gene expression values to infer angles, and then use these <code>pca</code> -based angles to move the cells to the closest bin (as defined by <code>uniform</code> ). |

**Value**

A list with the following three elements:

|                            |                                                    |
|----------------------------|----------------------------------------------------|
| cell_times_est             | Inferred angles or cell cycle phases, NOT ordered. |
| loglik_est                 | Log-likelihood estimates for each gene.            |
| prob_per_cell_by_celltimes | Probabilities of each cell belong to each bin.     |

**Author(s)**

Joyce Hsiao

**See Also**

[initialize\\_grids](#) for selecting angles in [cycle\\_npreg\\_loglik](#), [cycle\\_npreg\\_mstep](#) for estimating cyclic functions given inferred phases from [cycle\\_npreg\\_loglik](#), [cycle\\_npreg\\_outsample](#) for predicting cell cycle phase using parameters learned from [cycle\\_npreg\\_insample](#)

Other peco classifier functions: [cycle\\_npreg\\_insample](#), [cycle\\_npreg\\_mstep](#), [cycle\\_npreg\\_outsample](#), [initialize\\_grids](#)

---

|                   |                                                 |
|-------------------|-------------------------------------------------|
| cycle_npreg_mstep | <i>Estimate parameters of the cyclic trends</i> |
|-------------------|-------------------------------------------------|

---

### Description

This is used in both `cycle_npreg_insample` (training data fitting) and `cycle_npreg_outsample` (testing data prediction) to estimate cyclic trends of gene expression values. The function outputs for each gene standard error of the cyclic trend, cyclic function, and the estimated expression levels given the cyclic function.

### Usage

```
cycle_npreg_mstep(Y, theta, method.trend = c("trendfilter", "loess",
      "bspline"), polyorder = 2, ncores = 2)
```

### Arguments

|                           |                                                                                                                                                                                                                                                                                                                                                                                               |
|---------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <code>Y</code>            | Gene by sample expression matrix (log2CPM).                                                                                                                                                                                                                                                                                                                                                   |
| <code>theta</code>        | Observed cell times.                                                                                                                                                                                                                                                                                                                                                                          |
| <code>method.trend</code> | How to estimate cyclic trend of gene expression values? We offer three options: 'trendfilter' ( <code>fit_trendfilter()</code> ), 'loess' ( <code>fit_loess()</code> ) and 'bsplines' ( <code>fit_bspline()</code> ). 'trendfilter' provided the best fit in our study. But 'trendfilter' uses cross-validation and takes some time. Therefore, we recommend using bspline for quick results. |
| <code>polyorder</code>    | We estimate cyclic trends of gene expression levels using nonparamtric trend filtering. The default fits second degree polynomials.                                                                                                                                                                                                                                                           |
| <code>ncores</code>       | How many computing cores to use? We use doParallel package for parallel computing.                                                                                                                                                                                                                                                                                                            |

### Value

A list with the following elements:

|                        |                                                                      |
|------------------------|----------------------------------------------------------------------|
| <code>Y</code>         | Input gene expression data.                                          |
| <code>theta</code>     | Input angles.                                                        |
| <code>mu_est</code>    | Estimated expression levels given the cyclic function for each gene. |
| <code>sigma_est</code> | Estimated standard error of the cyclic trends for each gene          |
| <code>funs</code>      | Estimated cyclic functions                                           |

### Author(s)

Joyce Hsiao

**See Also**

[cycle\\_npreg\\_insample](#) for estimating cyclic functions given known phases from training data,  
[cycle\\_npreg\\_outsample](#) for predicting cell cycle phase using parameters learned from [cycle\\_npreg\\_insample](#)

Other peco classifier functions: [cycle\\_npreg\\_insample](#), [cycle\\_npreg\\_loglik](#), [cycle\\_npreg\\_outsample](#),  
[initialize\\_grids](#)

---

cycle\_npreg\_outsample *Predict test-sample ordering using training labels (no update)*

---

**Description**

Apply the estimates of `cycle_npreg_insample` to another gene expression dataset to infer an angle or cell cycle phase for each cell.

**Usage**

```
cycle_npreg_outsample(Y_test, sigma_est, funs_est,
  method.trend = c("trendfilter", "loess", "bspline"), normed = TRUE,
  polyorder = 2, method.grid = "uniform", ncores = 2, grids = 100,
  get_trend_estimates = FALSE)
```

**Arguments**

|                                  |                                                                                                                                                                                    |
|----------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <code>Y_test</code>              | A <code>SingleCellExperiment</code> object.                                                                                                                                        |
| <code>sigma_est</code>           | Input from training data. A vector of gene-specific standard error of the cyclic trends.                                                                                           |
| <code>funs_est</code>            | Input from training data. A vector of cyclic functions estimating cyclic trends.                                                                                                   |
| <code>method.trend</code>        | Various methods that can be applied to estimate cyclic trend of gene expression levels.                                                                                            |
| <code>normed</code>              | Is the data already normalized? TRUE or FALSE.                                                                                                                                     |
| <code>polyorder</code>           | We estimate cyclic trends of gene expression levels using nonparametric trend filtering. The default fits second degree polynomials.                                               |
| <code>method.grid</code>         | Method for defining bins along the circle.                                                                                                                                         |
| <code>ncores</code>              | We use <code>doParallel</code> package for parallel computing.                                                                                                                     |
| <code>grids</code>               | number of bins to be selected along 0 to 2pi.                                                                                                                                      |
| <code>get_trend_estimates</code> | To re-estimate the cyclic trend based on the predicted cell cycle phase or not (T or F). Default FALSE. This step calls <code>trendfilter</code> and is computationally intensive. |

**Value**

A list with the following elements:

|                                         |                                                                                                                                                |
|-----------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------|
| <code>Y</code>                          | The input gene expression matrix.                                                                                                              |
| <code>cell_times_est</code>             | Inferred angles or cell cycle phases, NOT ordered.                                                                                             |
| <code>loglik_est</code>                 | Log-likelihood estimates for each gene.                                                                                                        |
| <code>cell_times_reordered</code>       | The inferred angles reordered (in ascending order).                                                                                            |
| <code>Y_reordered</code>                | The input gene expression matrix reordered by <code>cell_times_reordered</code> .                                                              |
| <code>sigma_reordered</code>            | Estimated standard error of the cyclic trend for each gene, reordered by <code>cell_times_reordered</code> .                                   |
| <code>funs_reordered</code>             | A list of functions for approximating the cyclic trends of gene express levels for each gene, reordered by <code>cell_times_reordered</code> . |
| <code>mu_reordered</code>               | Estimated cyclic trend of gene expression values for each gene, reordered by <code>cell_times_reordered</code> .                               |
| <code>prob_per_cell_by_celltimes</code> | Probabilities of each cell belong to each bin.                                                                                                 |

**See Also**

[cycle\\_npreg\\_insample](#) for obtaining parameters for cyclic functions from training data, [cycle\\_npreg\\_loglik](#) for log-likelihood at angles between 0 to 2pi, [initialize\\_grids](#) for selecting angles in [cycle\\_npreg\\_loglik](#), [cycle\\_npreg\\_mstep](#) for estimating cyclic functions given inferred phases from [cycle\\_npreg\\_loglik](#)  
Other pecco classifier functions: [cycle\\_npreg\\_insample](#), [cycle\\_npreg\\_loglik](#), [cycle\\_npreg\\_mstep](#), [initialize\\_grids](#)

**Examples**

```
# import data
library(SingleCellExperiment)
data(sce_top101genes)

# select top 5 cyclic genes
sce_top5 <- sce_top101genes[order(rowData(sce_top101genes)$pve_fucci,
                                     decreasing=TRUE)[1:5],]

# Select samples from NA18511 for our prediction example
coldata <- colData(sce_top5)
which_samples_train <- rownames(coldata)[coldata$chip_id != "NA18511"]
which_samples_predict <- rownames(coldata)[coldata$chip_id == "NA18511"]

# learning cyclic functions of the genes using our training data
sce_top5 <- data_transform_quantile(sce_top5)
expr_quant <- assay(sce_top5, "cpm_quantNormed")
Y_train <- expr_quant[, colnames(expr_quant) %in% which_samples_train]
theta_train <-
  coldata$theta_shifted[rownames(coldata) %in% which_samples_train]
names(theta_train) <-
```

```

    rownames(coldata)[rownames(coldata) %in% which_samples_train]

# obtain cyclic function estimates
model_5genes_train <- cycle_npreg_insample(Y = Y_train,
                                           theta = theta_train,
                                           polyorder=2,
                                           ncores=2,
                                           method.trend="trendfilter")

# predict cell cycle
model_5genes_predict <- cycle_npreg_outsample(
  Y_test=sce_top5[,colnames(sce_top5) %in% which_samples_predict],
  sigma_est=model_5genes_train$sigma_est,
  funs_est=model_5genes_train$funs_est,
  method.trend="trendfilter",
  ncores=2,
  get_trend_estimates=FALSE)

# estimate cyclic gene expression levels given cell cycle for each gene
predict_cyclic <-
  fit_cyclical_many(Y=assay(model_5genes_predict$Y,"cpm_quantNormed"),
                    theta=colData(model_5genes_predict$Y)$cellcycle_peco)
all.equal(names(predict_cyclic[[2]]), colnames(predict_cyclic[[1]]))

par(mfrow=c(2,3), mar=c(4,4,3,1))
for (g in seq_along(rownames(model_5genes_predict$Y))) {
  plot(assay(model_5genes_predict$Y,"cpm_quantNormed")[
    rownames(model_5genes_predict$Y)[g],],
    x=colData(model_5genes_predict$Y)$cellcycle_peco, axes=FALSE,
    xlab="FUCCI phase",
    ylab="Predicted phase")
  points(y=predict_cyclic$cellcycle_function[[
    rownames(model_5genes_predict$Y)[g]]](
    seq(0, 2*pi, length.out = 100)),
    x=seq(0, 2*pi, length.out = 100),
    pch=16, col="royalblue")
  axis(2); axis(1,at=c(0,pi/2, pi, 3*pi/2, 2*pi),
    labels=c(0,expression(pi/2), expression(pi),
    expression(3*pi/2), expression(2*pi)))
  abline(h=0, lty=1, col="black", lwd=.7)
  title(rownames(model_5genes_predict$Y_reordered)[g])
}
title("Predicting cell cycle phase for NA18511", outer=TRUE)

```

---

data\_transform\_quantile

*Transform counts by first computing counts-per-million (CPM), then quantile-normalize CPM for each gene*

---

**Description**

For each gene, transform counts to CPM and then to a normal distribution.

**Usage**

```
data_transform_quantile(sce, ncores = 2)
```

**Arguments**

sce                    SingleCellExperiment Object.  
ncores                We use doParallel package for parallel computing.

**Value**

SingleCellExperiment Object with an added slot of cpm\_quant, cpm slot is added if it doesn't exist.

**Author(s)**

Joyce Hsiao

**Examples**

```
# use our data
library(SingleCellExperiment)
data(sce_top101genes)

# perform CPM normalization using scater, and
# quantile-normalize the CPM values of each gene to normal distribution
sce_top101genes <- data_transform_quantile(sce_top101genes, ncores=2)

plot(y=assay(sce_top101genes, "cpm_quantNormed")[1,],
     x=assay(sce_top101genes, "cpm")[1,],
     xlab = "CPM bbefore quantile-normalization",
     ylab = "CPM after quantile-normalization")
```

---

fit\_bspline

---

*Use bsplines to cyclic trend of gene expression levels*


---

**Description**

Use bsplines to cyclic trend of gene expression levels

**Usage**

```
fit_bspline(yy, time)
```

**Arguments**

|      |                                                                                                                                                             |
|------|-------------------------------------------------------------------------------------------------------------------------------------------------------------|
| yy   | A vector of gene expression values for one gene. The expression values are assumed to have been normalized and transformed to standard normal distribution. |
| time | A vector of angles (cell cycle phase).                                                                                                                      |

**Value**

A list with one element, `pred.yy`, giving the estimated cyclic trend.

**Author(s)**

Joyce Hsiao

**Examples**

```
library(SingleCellExperiment)
data(sce_top101genes)

# select top 10 cyclic genes
sce_top10 <- sce_top101genes[order(rowData(sce_top101genes)$pve_fucci,
                                     decreasing=TRUE)[1:10],]

coldata <- colData(sce_top10)

# cell cycle phase based on FUCCI scores
theta <- coldata$theta
names(theta) <- rownames(coldata)

# normalize expression counts
sce_top10 <- data_transform_quantile(sce_top10, ncores=2)
exprs_quant <- assay(sce_top10, "cpm_quantNormed")

# order FUCCI phase and expression
theta_ordered <- theta[order(theta)]
yy_ordered <- exprs_quant[1, names(theta_ordered)]

fit <- fit_bspline(yy_ordered, time=theta_ordered)

plot(x=theta_ordered, y=yy_ordered, pch=16, cex=.7, axes=FALSE,
     ylab="quantile-normalized expression values", xlab="FUCCI phase",
     main = "bspline fit")
points(x=theta_ordered, y=fit$pred.yy, col="blue", pch=16, cex=.7)
axis(2)
axis(1, at=c(0, pi/2, pi, 3*pi/2, 2*pi),
     labels=c(0, expression(pi/2), expression(pi), expression(3*pi/2),
              expression(2*pi)))
abline(h=0, lty=1, col="black", lwd=.7)
```

---

|                   |                                                                                                               |
|-------------------|---------------------------------------------------------------------------------------------------------------|
| fit_cyclical_many | <i>Compute proportion of variance explained by cyclic trends in the gene expression levels for each gene.</i> |
|-------------------|---------------------------------------------------------------------------------------------------------------|

---

## Description

We applied quadratic (second order) trend filtering using the `trendfilter` function in the `genlasso` package (Tibshirani, 2014). The `trendfilter` function implements a nonparametric smoothing method which chooses the smoothing parameter by cross-validation and fits a piecewise polynomial regression. In more specifics: The `trendfilter` method determines the folds in cross-validation in a non-random manner. Every  $k$ -th data point in the ordered sample is placed in the  $k$ -th fold, so the folds contain ordered subsamples. We applied five-fold cross-validation and chose the smoothing penalty using the option `lambda.1se`: among all possible values of the penalty term, the largest value such that the cross-validation standard error is within one standard error of the minimum. Furthermore, we desired that the estimated expression trend be cyclical. To encourage this, we concatenated the ordered gene expression data three times, with one added after another. The quadratic trend filtering was applied to the concatenated data series of each gene.

## Usage

```
fit_cyclical_many(Y, theta, polyorder = 2, ncores = 2)
```

## Arguments

|                        |                                                                                                                                                                 |
|------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <code>Y</code>         | A matrix (gene by sample) of gene expression values. The expression values are assumed to have been normalized and transformed to standard normal distribution. |
| <code>theta</code>     | A vector of cell cycle phase (angles) for single-cell samples.                                                                                                  |
| <code>polyorder</code> | We estimate cyclic trends of gene expression levels using nonparametric trend filtering. The default fits second degree polynomials.                            |
| <code>ncores</code>    | <code>doParallel</code> package is used to perform parallel computing to reduce computational time.                                                             |

## Value

A list containing the following objects

|                                     |                                                                                        |
|-------------------------------------|----------------------------------------------------------------------------------------|
| <code>predict.yy</code>             | A matrix of predicted expression values at observed cell cycle.                        |
| <code>cellcycle_peco_ordered</code> | A vector of predicted cell cycle. The values range between 0 to $2\pi$                 |
| <code>cellcycle_function</code>     | A list of predicted cell cycle functions.                                              |
| <code>pve</code>                    | A vector of proportion of variance explained in each gene by the predicted cell cycle. |

**Author(s)**

Joyce Hsiao

**See Also**[fit\\_trendfilter](#) for fitting one gene using trendfilter**Examples**

```

library(SingleCellExperiment)
data(sce_top101genes)

# select top 10 cyclic genes
sce_top10 <- sce_top101genes[order(rowData(sce_top101genes)$pve_fucci,
                                     decreasing=TRUE)[1:10],]

coldata <- colData(sce_top10)

# cell cycle phase based on FUCCI scores
theta <- coldata$theta
names(theta) <- rownames(coldata)

# normalize expression counts
sce_top10 <- data_transform_quantile(sce_top10, ncores=2)
exprs_quant <- assay(sce_top10, "cpm_quantNormed")

# order FUCCI phase and expression
theta_ordered <- theta[order(theta)]
yy_ordered <- exprs_quant[, names(theta_ordered)]

fit <- fit_cyclical_many(Y=yy_ordered, theta=theta_ordered)

```

---

fit\_loess*Use loess to estimate cyclic trends of expression values*

---

**Description**

Use loess to estimate cyclic trends of expression values

**Usage**

fit\_loess(yy, time)

**Arguments**

|      |                                                                                                                                                             |
|------|-------------------------------------------------------------------------------------------------------------------------------------------------------------|
| yy   | A vector of gene expression values for one gene. The expression values are assumed to have been normalized and transformed to standard normal distribution. |
| time | A vector of angles (cell cycle phase).                                                                                                                      |

**Value**

A list with one element, `pred.yy`, giving the estimated cyclic trend.

**Author(s)**

Joyce Hsiao

**Examples**

```
library(SingleCellExperiment)
data(sce_top101genes)

# select top 10 cyclic genes
sce_top10 <- sce_top101genes[order(rowData(sce_top101genes)$pve_fucci,
                                     decreasing=TRUE)[1:10],]

coldata <- colData(sce_top10)

# cell cycle phase based on FUCCI scores
theta <- coldata$theta
names(theta) <- rownames(coldata)

# normalize expression counts
sce_top10 <- data_transform_quantile(sce_top10, ncores=2)
exprs_quant <- assay(sce_top10, "cpm_quantNormed")

# order FUCCI phase and expression
theta_ordered <- theta[order(theta)]
yy_ordered <- exprs_quant[1, names(theta_ordered)]

fit <- fit_loess(yy_ordered, time=theta_ordered)

plot(x=theta_ordered, y=yy_ordered, pch=16, cex=.7, axes=FALSE,
     ylab="quantile-normalized expression values", xlab="FUCCI phase",
     main = "loess fit")
points(x=theta_ordered, y=fit$pred.yy, col="blue", pch=16, cex=.7)
axis(2)
axis(1, at=c(0, pi/2, pi, 3*pi/2, 2*pi),
     labels=c(0, expression(pi/2), expression(pi), expression(3*pi/2),
              expression(2*pi)))
abline(h=0, lty=1, col="black", lwd=.7)
```

---

fit\_trendfilter

---

*Using trendfiltering to estimate cyclic trend of gene expression*


---

**Description**

We applied quadratic (second order) trend filtering using the `trendfilter` function in the `genlasso` package (Tibshirani, 2014). The `trendfilter` function implements a nonparametric smoothing method

which chooses the smoothing parameter by cross-validation and fits a piecewise polynomial regression. In more specifics: The trendfilter method determines the folds in cross-validation in a non-random manner. Every k-th data point in the ordered sample is placed in the k-th fold, so the folds contain ordered subsamples. We applied five-fold cross-validation and chose the smoothing penalty using the option `lambda.1se`: among all possible values of the penalty term, the largest value such that the cross-validation standard error is within one standard error of the minimum. Furthermore, we desired that the estimated expression trend be cyclical. To encourage this, we concatenated the ordered gene expression data three times, with one added after another. The quadratic trend filtering was applied to the concatenated data series of each gene.

### Usage

```
fit_trendfilter(yy, polyorder = 2)
```

### Arguments

|                        |                                                                                                                                                                                   |
|------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <code>yy</code>        | A vector of gene expression values for one gene that are ordered by cell cycle phase. Also, the expression values are normalized and transformed to standard normal distribution. |
| <code>polyorder</code> | We estimate cyclic trends of gene expression levels using nonparametric trend filtering. The default fits second degree polynomials.                                              |

### Value

A list with two elements:

|                       |                                                                                     |
|-----------------------|-------------------------------------------------------------------------------------|
| <code>trend.yy</code> | The estimated cyclic trend.                                                         |
| <code>pve</code>      | Proportion of variance explained by the cyclic trend in the gene expression levels. |

### Author(s)

Joyce Hsiao

### Examples

```
library(SingleCellExperiment)
data(sce_top101genes)

# select top 10 cyclic genes
sce_top10 <- sce_top101genes[order(rowData(sce_top101genes)$pve_fucci,
                                     decreasing=TRUE)[1:10],]

coldata <- colData(sce_top10)

# cell cycle phase based on FUCCI scores
theta <- coldata$theta
names(theta) <- rownames(coldata)

# normalize expression counts
sce_top10 <- data_transform_quantile(sce_top10, ncores=2)
exprs_quant <- assay(sce_top10, "cpm_quantNormed")
```

```

# order FUCCI phase and expression
theta_ordered <- theta[order(theta)]
yy_ordered <- exprs_quant[1, names(theta_ordered)]

fit <- fit_trendfilter(yy_ordered)

plot(x=theta_ordered, y=yy_ordered, pch=16, cex=.7, axes=FALSE,
     ylab="quantile-normalized expression values", xlab="FUCCI phase",
     main = "trendfilter fit")
points(x=theta_ordered, y=fit$trend.yy, col="blue", pch=16, cex=.7)
axis(2)
axis(1, at=c(0, pi/2, pi, 3*pi/2, 2*pi),
     labels=c(0, expression(pi/2), expression(pi), expression(3*pi/2),
     expression(2*pi)))
abline(h=0, lty=1, col="black", lwd=.7)

```

---

|                  |                                                                                 |
|------------------|---------------------------------------------------------------------------------|
| initialize_grids | <i>For prediction, initialize grid points for cell cycle phase on a circle.</i> |
|------------------|---------------------------------------------------------------------------------|

---

### Description

For prediction, initialize grid points for cell cycle phase on a circle.

### Usage

```
initialize_grids(Y, grids = 100, method.grid = c("pca", "uniform"))
```

### Arguments

|             |                                                                                                                                                                                                                                                                                                               |
|-------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Y           | Gene expression matrix. Gene by sample.                                                                                                                                                                                                                                                                       |
| grids       | number of bins to be selected along 0 to 2pi.                                                                                                                                                                                                                                                                 |
| method.grid | The approach to initialize angles in the computation. <code>uniform</code> creates k equally-spaced bins (grids). <code>pca</code> uses gene expression values to infer angles, and then use these <code>pca</code> -based angles to move the cells to the closest bin (as defined by <code>uniform</code> ). |

### Value

A vector of initialized angles to be used in `cycle_npreg_loglik` to infer angles.

### Author(s)

Joyce Hsiao

**See Also**

[cycle\\_npreg\\_loglik](#) for log-likelihood at angles between 0 to 2pi, [cycle\\_npreg\\_mstep](#) for estimating cyclic functions given inferred phases from [cycle\\_npreg\\_loglik](#), [cycle\\_npreg\\_outsample](#) for predicting cell cycle phase using parameters learned from [cycle\\_npreg\\_insample](#)

Other peco classifier functions: [cycle\\_npreg\\_insample](#), [cycle\\_npreg\\_loglik](#), [cycle\\_npreg\\_mstep](#), [cycle\\_npreg\\_outsample](#)

---

|                  |                                                                                 |
|------------------|---------------------------------------------------------------------------------|
| intensity2circle | <i>Infer angles for each single-cell samples using fluorescence intensities</i> |
|------------------|---------------------------------------------------------------------------------|

---

**Description**

We use FUCCI intensities to infer the position of the cells in cell cycle progression. The result is a vector of angles on a unit circle corresponding to the positions of the cells in cell cycle progression.

**Usage**

```
intensity2circle(mat, plot.it = FALSE, method = c("trig", "algebraic"))
```

**Arguments**

|         |                                                                                                                                                                                                                                                                            |
|---------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| mat     | A matrix of two columns of summarized fluorescence intensity. Rows correspond to samples.                                                                                                                                                                                  |
| plot.it | TRUE or FALSE. Plot the fitted results.                                                                                                                                                                                                                                    |
| method  | The method used to fit the circle. <code>trig</code> uses trigonometry to transform intensity measurements from cartesian coordinates to polar coordinates. <code>algebraic</code> uses an algebraic approach for circle fitting, using the <code>conicfit</code> package. |

**Value**

The inferred angles on unit circle based on the input intensity measurements.

**Author(s)**

Joyce Hsiao

**Examples**

```
# use our data
library(SingleCellExperiment)
data(sce_top101genes)

# FUCCI scores - log10 transformed sum of intensities that were
# corrected for background noise
ints <- colData(sce_top101genes)[,c("rfp.median.log10sum.adjust",
                                   "gfp.median.log10sum.adjust")]
intensity2circle(ints, plot.it=TRUE, method = "trig")
```

---

model\_5genes\_predict    *A SingleCellExperiment object*

---

### Description

Pre-computed results. Applied *cycle\_npreg\_outsample* and results stored in *model\_5genes\_train* to predict cell cycle phase for single-cell samples of NA19098. The predicted cell cycle is stored as variable *celcycle\_peco*.

### Usage

```
data(model_5genes_predict)
```

### Format

A list with the following elements

**celcycle\_peco** Predict cell cycle, the values ranged between 0 to 2pi

---

model\_5genes\_train    *Training model results among samples from 5 individuals.*

---

### Description

Pre-computed results. Applied *cycle\_npreg\_insample* to obtain gene-specific cyclic trend parameters using samples from 5 individuals

### Usage

```
data(model_5genes_train)
```

### Format

A list with the following elements

**Y** a data.frame (gene by sample) of quantile-normalized gene expression values

**theta** a vector of cell cycle phase values (range between 0 to 2pi)

**sigma\_est** a vector of estimated standard errors

**funs\_est** a list of estimated cyclic functions

---

|          |                                                                                              |
|----------|----------------------------------------------------------------------------------------------|
| rotation | <i>Rotate circular variable shift_var to minimize distance between ref_var and shift_var</i> |
|----------|----------------------------------------------------------------------------------------------|

---

### Description

Because the origin of the cell cycle phases is arbitrary, we transform the angles prior to computing the distance (rotation and shifting) to minimize the distance between two vectors. After this, one can apply `circ_dist` to compute the distance between the output value and `ref_var`.

### Usage

```
rotation(ref_var, shift_var)
```

### Arguments

|                        |                                                             |
|------------------------|-------------------------------------------------------------|
| <code>ref_var</code>   | A vector of reference angles.                               |
| <code>shift_var</code> | A vector of angles to be compared to <code>ref_var</code> . |

### Value

The transformed values of `shift_var` after rotation and shifting.

### Author(s)

Matthew Stephens

### Examples

```
# a vector of angles
theta_ref <- seq(0,2*pi, length.out=100)

# shift the origin of theta_ref to pi
theta_compare <- shift_origin(theta_ref, origin = pi)

# rotate theta_compare in a such a way that the distance
# between theta_ref and thet_compare is minimized
theta_compare_rotated <- rotation(ref_var=theta_ref, shift_var=theta_compare)

par(mfrow=c(1,2))
plot(x=theta_ref, y = theta_compare)
plot(x=theta_ref, y = theta_compare_rotated)
```

---

|                 |                                                                                                        |
|-----------------|--------------------------------------------------------------------------------------------------------|
| sce_top101genes | <i>Molecule counts of the 101 significant cyclical genes in the 888 samples analyzed in the study.</i> |
|-----------------|--------------------------------------------------------------------------------------------------------|

---

### Description

A SingleCellExperiment object (require SingleCellExperiment package) including molecule count data after gene and sample filtering. The 'colData()' slot contains sample phenotype information and the 'rowData()' slot contains gene feature information.

### Usage

```
data(sce_top101genes)
```

### Format

A SingleCellExperiment object with 888 samples and the 101 significant cyclic genes,

**theta** Inferred angles of each cell along a circle, also known as FUCCI phase.

---

|              |                                   |
|--------------|-----------------------------------|
| shift_origin | <i>Shift origin of the angles</i> |
|--------------|-----------------------------------|

---

### Description

Shift origin of the angles for visualization

### Usage

```
shift_origin(phase, origin)
```

### Arguments

|        |                                  |
|--------|----------------------------------|
| phase  | A vector of angles (in radians). |
| origin | the new origin of the angles.    |

### Value

A vector of angles shifted to the new origin.

### Author(s)

Joyce Hsiao

**Examples**

```
# make a vector of angles
theta <- seq(0,2*pi, length.out=100)

# shift the origin of theta to pi
theta_shifted <- shift_origin(theta, origin = pi)

plot(x=theta, y = theta_shifted)
```

---

|                |                                                                            |
|----------------|----------------------------------------------------------------------------|
| training_human | <i>Training data from 888 single-cell samples and 101 top cyclic genes</i> |
|----------------|----------------------------------------------------------------------------|

---

**Description**

Pre-computed results. Applied *fit\_cyclic\_many* to 888 single-cell samples that have both normalized gene expression values and cell cycle labels to obtain training results that can be used as input for predicting cell cycle phase in other data.

**Usage**

```
data(training_human)
```

**Format**

A list with the following elements

**predict.yy** Estimated cyclic expression values in the training data

**cellcycle\_peco\_ordered** Training labels ordered from 0 to  $2\pi$

**cell\_cycle function** Nonparametric function of cyclic gene expression trend obtained by trendfilter function in genlasso

**pve** Proportion of variance explained in each gene by the cell cycle phase label

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