

# Package ‘imcRtools’

June 29, 2025

**Version** 1.14.0

**Title** Methods for imaging mass cytometry data analysis

**Description** This R package supports the handling and analysis of imaging mass cytometry and other highly multiplexed imaging data. The main functionality includes reading in single-cell data after image segmentation and measurement, data formatting to perform channel spillover correction and a number of spatial analysis approaches. First, cell-cell interactions are detected via spatial graph construction; these graphs can be visualized with cells representing nodes and interactions representing edges. Furthermore, per cell, its direct neighbours are summarized to allow spatial clustering. Per image/grouping level, interactions between types of cells are counted, averaged and compared against random permutations. In that way, types of cells that interact more (attraction) or less (avoidance) frequently than expected by chance are detected.

**License** GPL-3

**Depends** R (>= 4.1), SpatialExperiment

**Imports** S4Vectors, stats, utils, SummarizedExperiment, methods, pheatmap, scuttle, stringr, readr, EBImage, cytomapper, abind, BiocParallel, viridis, dplyr, magrittr, DT, igraph, SingleCellExperiment, vroom, BiocNeighbors, RTriangle, ggraph, tidygraph, ggplot2, data.table, sf, concaveman, tidyselect, distances, MatrixGenerics, rlang, grDevices

**Suggests** CATALYST, grid, tidyr, BiocStyle, knitr, rmarkdown, markdown, testthat

**biocViews** ImmunoOncology, SingleCell, Spatial, DataImport, Clustering

**VignetteBuilder** knitr

**URL** <https://github.com/BodenmillerGroup/imcRtools>

**BugReports** <https://github.com/BodenmillerGroup/imcRtools/issues>

**RoxygenNote** 7.2.3

**Encoding** UTF-8

**git\_url** <https://git.bioconductor.org/packages/imcRtools>

**git\_branch** RELEASE\_3\_21

**git\_last\_commit** baf3056

**git\_last\_commit\_date** 2025-04-15

**Repository** Bioconductor 3.21

**Date/Publication** 2025-06-29

**Author** Nils Eling [aut],  
 Tobias Hoch [ctb],  
 Vito Zanotelli [ctb],  
 Jana Fischer [ctb],  
 Daniel Schulz [ctb, cre] (ORCID:  
<https://orcid.org/0000-0002-0913-1678>),  
 Lasse Meyer [ctb]

**Maintainer** Daniel Schulz <daniel.schulz@uzh.ch>

## Contents

|                                |    |
|--------------------------------|----|
| aggregateNeighbors . . . . .   | 3  |
| binAcrossPixels . . . . .      | 4  |
| buildSpatialGraph . . . . .    | 6  |
| countInteractions . . . . .    | 8  |
| detectCommunity . . . . .      | 10 |
| detectSpatialContext . . . . . | 12 |
| filterPixels . . . . .         | 15 |
| filterSpatialContext . . . . . | 16 |
| findBorderCells . . . . .      | 18 |
| minDistToCells . . . . .       | 19 |
| patchDetection . . . . .       | 21 |
| patchSize . . . . .            | 23 |
| plotSpatial . . . . .          | 24 |
| plotSpatialContext . . . . .   | 28 |
| plotSpotHeatmap . . . . .      | 30 |
| readImagefromTXT . . . . .     | 32 |
| readSCEfromTXT . . . . .       | 34 |
| read_cpout . . . . .           | 35 |
| read_steinbock . . . . .       | 38 |
| show_cpout_features . . . . .  | 40 |
| testInteractions . . . . .     | 42 |

|              |           |
|--------------|-----------|
| <b>Index</b> | <b>46</b> |
|--------------|-----------|

---

|                    |  |
|--------------------|--|
| aggregateNeighbors | <i>Function to aggregate all neighbors of each cell.</i> |
|--------------------|--|

---

## Description

Function to summarize categorical or expression values of all neighbors of each cell.

## Usage

```
aggregateNeighbors(
  object,
  colPairName,
  aggregate_by = c("metadata", "expression"),
  count_by = NULL,
  proportions = TRUE,
  assay_type = NULL,
  subset_row = NULL,
  statistic = c("mean", "median", "sd", "var"),
  name = NULL
)
```

## Arguments

|              |   |
|--------------|---|
| object       | a SingleCellExperiment or SpatialExperiment object  |
| colPairName  | single character indicating the colPair(object) entry containing the neighbor information.  |
| aggregate_by | character specifying whether the neighborhood should be summarized by cellular features stored in colData(object) (aggregate_by = "metadata") or by marker expression of the neighboring cells (aggregate_by = "expression").                         |
| count_by     | for summarize_by = "metadata", a single character specifying the colData(object) entry containing the cellular metadata that should be summarized across each cell's neighborhood.  |
| proportions  | single logical indicating whether aggregated metadata should be returned in form of proportions instead of absolute counts.   |
| assay_type   | for summarize_by = "expression", single character indicating the assay slot to use.   |
| subset_row   | for summarize_by = "expression", an integer, logical or character vector specifying the features to use. If NULL, defaults to all features.   |
| statistic    | for summarize_by = "expression", a single character specifying the statistic to be used for summarizing the expression values across all neighboring cells. Supported entries are "mean", "median", "sd", "var". Defaults to "mean" if not specified. |
| name         | single character specifying the name of the data frame to be saved in the colData(object). Defaults to "aggregatedNeighbors" when summarize_by = "metadata" or "statis-tic_aggregatedExpression" when summarize_by = "expression".                    |

**Value**

returns an object of `class(object)` containing the aggregated values in form of a `DataFrame` object in `colData(object)[[name]]`.

**Author(s)**

Daniel Schulz (<daniel.schulz@uzh.ch>)

**Examples**

```
library(cytomapper)
data(pancreasSCE)

sce <- buildSpatialGraph(pancreasSCE, img_id = "ImageNb",
                        type = "knn", k = 3)

# Aggregating neighboring cell-types
sce <- aggregateNeighbors(sce, colPairName = "knn_interaction_graph",
                        aggregate_by = "metadata",
                        count_by = "CellType")
sce$aggregatedNeighbors

# Aggregating neighboring expression values
sce <- aggregateNeighbors(sce, colPairName = "knn_interaction_graph",
                        aggregate_by = "expression",
                        assay_type = "exprs",
                        statistic = "mean")
sce$mean_aggregatedExpression
```

---

binAcrossPixels

---

Aggregate consecutive pixels per single-metal spot

---

**Description**

Helper function for estimating the spillover matrix. Per metal spot, consecutive pixels are aggregated (default: summed).

**Usage**

```
binAcrossPixels(
  object,
  bin_size,
  spot_id = "sample_id",
  assay_type = "counts",
  statistic = "sum",
  ...
)
```

**Arguments**

|            |   |
|------------|---|
| object     | a SingleCellExperiment object containing pixel intensities for all channels. Individual pixels are stored as columns and channels are stored as rows. |
| bin_size   | single numeric indicating how many consecutive pixels per spot should be aggregated.  |
| spot_id    | character string indicating which colData(object) entry stores the isotope names of the spotted metal.  |
| assay_type | character string indicating which assay to use.   |
| statistic  | character string indicating the statistic to use for aggregating consecutive pixels.  |
| ...        | additional arguments passed to aggregateAcrossCells   |

**Value**

returns the binned pixel intensities in form of a SingleCellExperiment object

**Author(s)**

Nils Eling (<nils.eling@dqbm.uzh.ch>)

**See Also**

[aggregateAcrossCells](#) for the aggregation function

**Examples**

```
path <- system.file("extdata/spillover", package = "imcRtools")
# Read in .txt files
sce <- readSCEfromTXT(path)
dim(sce)

# Visualizes heatmap before aggregation
plotSpotHeatmap(sce)

# Sum consecutive pixels
sce <- binAcrossPixels(sce, bin_size = 10)
dim(sce)

# Visualizes heatmap after aggregation
plotSpotHeatmap(sce)
```

---

|                   |  |
|-------------------|--|
| buildSpatialGraph | <i>Builds an interaction graph based on the cells' locations</i> |
|-------------------|--|

---

## Description

Function to define cell-cell interactions via distance-based expansion, delaunay triangulation or k nearest neighbor detection.

## Usage

```
buildSpatialGraph(
  object,
  img_id,
  type = c("expansion", "knn", "delaunay"),
  k = NULL,
  directed = TRUE,
  max_dist = NULL,
  threshold = NULL,
  coords = c("Pos_X", "Pos_Y"),
  name = NULL,
  BNPARAM = KmknParam(),
  BPPARAM = SerialParam(),
  ...
)
```

## Arguments

|           |  |
|-----------|--|
| object    | a SingleCellExperiment or SpatialExperiment object   |
| img_id    | single character indicating the colData(object) entry containing the unique image identifiers.   |
| type      | single character specifying the type of graph to be build. Supported entries are "expansion" (default) to find interacting cells via distance thresholding; "delaunay" to find interactions via delaunay triangulation; "knn" to find the k nearest neighboring cells. |
| k         | (when type = "knn") single numeric integer defining the number of nearest neighbors to search for.   |
| directed  | (when type = "knn") should the returned graph be directed? (see details).  |
| max_dist  | (when type = "knn" or type = "delaunay") the maximum distance at which to consider neighboring cells. All neighbors within a distance larger than max_dist will be excluded from graph construction.   |
| threshold | (when type = "expansion") single numeric specifying the maximum distance for considering neighbors   |
| coords    | character vector of length 2 specifying the names of the colData (for a SingleCellExperiment object) or the spatialCoords entries of the cells' x and y locations.   |
| name      | single character specifying the name of the graph.   |

BNPARAM a [BiocNeighborParam](#) object defining the algorithm to use.  
 BPPARAM a [BiocParallelParam-class](#) object defining how to parallelize computations.  
 ... additional parameters passed to the [findNeighbors](#) function (type = "expansion"),  
 the [triangulate](#) function (type = "delaunay") or the [findKNN](#) function (type  
 = "knn").

### Value

returns a `SpatialExperiment` or `SingleCellExperiment` containing the graph in form of a `SelfHits` object in `colPair(object, name)`. The object is grouped by entries in the `img_id` slot.

### Building an interaction graph

This function defines interacting cells in different ways. They are based on the cells' centroids and do not incorporate cell shape or area.

1. When type = "expansion", all cells within the radius threshold are considered interacting cells.
2. When type = "delaunay", interacting cells are found via a delaunay triangulation of the cells' centroids.
3. When type = "knn", interacting cells are defined as the k nearest neighbors in the 2D spatial plane.

The directed parameter only affects graph construction via k nearest neighbor search. For directed = FALSE, each interaction will be stored as mutual edge (e.g. node 2 is connected to node 10 and vice versa). For type = "expansion" and type = "delaunay", each edge is stored as mutual edge by default.

The graph is stored in form of a `SelfHits` object in `colPair(object, name)`. This object can be regarded as an edgelist and coerced to an igraph object via `graph_from_edgelist(as.matrix(colPair(object, name)))`.

### Choosing the graph construction method

When finding interactions via expansion or knn, the [findNeighbors](#) or [findKNN](#) functions are used, respectively. Both functions accept the BNPARAM parameter via which the graph construction method can be defined (default [KmknnParam](#)). For an overview on the different algorithms, see [BiocNeighborParam](#). Within the `BiocNeighborParam` object, distance can be set to "Euclidean" (default), "Manhattan" or "Cosine".

### Ordering of the output object

The `buildSpatialGraph` function operates on individual images. Therefore the returned object is grouped by entries in `img_id`. This means all cells of a given image are grouped together in the object. The ordering of cells within each individual image is the same as the ordering of these cells in the input object.

### Author(s)

Nils Eling (<nils.eling@dqbm.uzh.ch>)

**See Also**

[findNeighbors](#) for the function finding interactions via expansion  
[findKNN](#) for the function finding interactions via nearest neighbor search  
[triangulate](#) for the function finding interactions via delaunay triangulation  
[plotSpatial](#) for visualizing spatial graphs

**Examples**

```
path <- system.file("extdata/mockData/steinbock", package = "imcRtools")
spe <- read_steinbock(path)

# Constructing a graph via expansion
spe <- buildSpatialGraph(spe, img_id = "sample_id",
                        type = "expansion", threshold = 10)
colPair(spe, "expansion_interaction_graph")

# Constructing a graph via delaunay triangulation
spe <- buildSpatialGraph(spe, img_id = "sample_id",
                        type = "delaunay")
colPair(spe, "delaunay_interaction_graph")

# Constructing a graph via k nearest neighbor search
spe <- buildSpatialGraph(spe, img_id = "sample_id",
                        type = "knn", k = 5)
colPair(spe, "knn_interaction_graph")
```

---

|                   |   |
|-------------------|---|
| countInteractions | <i>Summarizes cell-cell interactions within grouping levels (e.g. images)</i> |
|-------------------|---|

---

**Description**

Function to calculate the average number of neighbors B that a cell of type A has using different approaches.

**Usage**

```
countInteractions(
  object,
  group_by,
  label,
  colPairName,
  method = c("classic", "histocat", "patch"),
  patch_size = NULL
)
```



**Arguments**

|                          |  |
|--------------------------|--|
| <code>object</code>      | a <code>SingleCellExperiment</code> or <code>SpatialExperiment</code> object.  |
| <code>group_by</code>    | a single character indicating the <code>colData(object)</code> entry by which interactions are grouped. This is usually the image ID or patient ID.    |
| <code>label</code>       | single character specifying the <code>colData(object)</code> entry which stores the cell labels. These can be cell-types labels or other metadata.     |
| <code>colPairName</code> | single character indicating the <code>colPair(object)</code> entry containing cell-cell interactions in form of an edge list.                          |
| <code>method</code>      | which cell-cell interaction counting method to use (see details)   |
| <code>patch_size</code>  | if <code>method = "patch"</code> , a single numeric specifying the minimum number of neighbors of the same type to be considered a patch (see details) |

**Value**

a `DataFrame` containing one row per `group_by` entry and unique `label` entry combination (from `label`, to `label`). The `ct` entry stores the interaction count as described in the details. `NA` is returned if a certain label is not present in this grouping level.

**Counting and summarizing cell-cell interactions**

In principle, the `countInteractions` function counts the number of edges (interactions) between each set of unique entries in `colData(object)[[label]]`. Simplified, it counts for each cell of type A the number of neighbors of type B. This count is averaged within each unique entry `colData(object)[[group_by]]` in three different ways:

1. `method = "classic"`: The count is divided by the total number of cells of type A. The final count can be interpreted as "How many neighbors of type B does a cell of type A have on average?"
2. `method = "histocat"`: The count is divided by the number of cells of type A that have at least one neighbor of type B. The final count can be interpreted as "How many many neighbors of type B has a cell of type A on average, given it has at least one neighbor of type B?"
3. `method = "patch"`: For each cell, the count is binarized to 0 (less than `patch_size` neighbors of type B) or 1 (more or equal to `patch_size` neighbors of type B). The binarized counts are averaged across all cells of type A. The final count can be interpreted as "What fraction of cells of type A have at least a given number of neighbors of type B?"

**Author(s)**

Vito Zanutelli

Jana Fischer

adapted by Nils Eling (<nils.eling@dqbm.uzh.ch>)

**References**

Schulz, D. et al., Simultaneous Multiplexed Imaging of mRNA and Proteins with Subcellular Resolution in Breast Cancer Tissue Samples by Mass Cytometry., *Cell Systems* 2018 6(1):25-36.e5

Shapiro, D. et al., histoCAT: analysis of cell phenotypes and interactions in multiplex image cytometry data, *Nature Methods* 2017 14, p. 873–876

**See Also**

[testInteractions](#) for testing cell-cell interactions per grouping level.

**Examples**

```
library(cytomapper)
data(pancreasSCE)

pancreasSCE <- buildSpatialGraph(pancreasSCE, img_id = "ImageNb",
                                type = "knn", k = 3)

# Classic style calculation
(out <- countInteractions(pancreasSCE,
                          group_by = "ImageNb",
                          label = "CellType",
                          method = "classic",
                          colPairName = "knn_interaction_graph"))

# HistoCAT style calculation
(out <- countInteractions(pancreasSCE,
                          group_by = "ImageNb",
                          label = "CellType",
                          method = "histocat",
                          colPairName = "knn_interaction_graph"))

# Patch style calculation
(out <- countInteractions(pancreasSCE,
                          group_by = "ImageNb",
                          label = "CellType",
                          method = "patch",
                          patch_size = 3,
                          colPairName = "knn_interaction_graph"))
```

---

detectCommunity

*Detect the spatial community of each cell*

---

**Description**

Function to detect the spatial community of each cell as proposed by [Jackson et al., The single-cell pathology landscape of breast cancer, Nature, 2020](#). Each cell is clustered based on its interactions as defined by a spatial object graph.

**Usage**

```
detectCommunity(
  object,
  colPairName,
  size_threshold = 0,
```

```

    group_by = NULL,
    name = "spatial_community",
    cluster_fun = "louvain",
    BPPARAM = SerialParam()
  )

```

### Arguments

|                             |  |
|-----------------------------|--|
| <code>object</code>         | a <code>SingleCellExperiment</code> or <code>SpatialExperiment</code> object   |
| <code>colPairName</code>    | single character indicating the <code>colPair(object)</code> entry containing the neighbor information.  |
| <code>size_threshold</code> | single positive numeric that specifies the minimum number of cells per community. Defaults to 0.   |
| <code>group_by</code>       | single character indicating that spatial community detection will be performed separately for all unique entries to <code>colData(object)[,group_by]</code> .  |
| <code>name</code>           | single character specifying the name of the output saved in <code>colData(object)</code> . Defaults to "spatial_community".  |
| <code>cluster_fun</code>    | single character specifying the function to use for community detection. Options are all strings that contain the suffix of an <code>igraph</code> community detection algorithm (e.g. "walktrap"). Defaults to "louvain".   |
| <code>BPPARAM</code>        | a <a href="#">BiocParallelParam-class</a> object defining how to parallelize computations. Applicable when <code>group_by</code> is specified and defaults to <code>SerialParam()</code> . For reproducibility between runs, we recommend defining <code>RNGseed</code> in the <a href="#">BiocParallelParam-class</a> object. |

### Value

returns an object of `class(object)` containing a new column entry to `colData(object)[[name]]`.

### Spatial community detection procedure

1. Create an `igraph` object from the edge list stored in `colPair(object, colPairName)`.
2. Perform community detection using the specified `cluster_fun` algorithm.
3. Store the community IDs in a vector and replace all communities with a size smaller than `size_threshold` by `NA`.

Optional steps: Specify `group_by` to perform spatial community detection separately for all unique entries to `colData(object)[,group_by]` e.g. for tumor and non-tumor cells.

### Author(s)

Lasse Meyer (<lasse.meyer@uzh.ch>)

### References

Jackson et al., The single-cell pathology landscape of breast cancer, *Nature*, 2020

## Examples

```
library(cytomapper)
library(BiocParallel)
data(pancreasSCE)

sce <- buildSpatialGraph(pancreasSCE, img_id = "ImageNb",
                        type = "expansion",
                        name = "neighborhood",
                        threshold = 20)

## Detect spatial community
set.seed(22)
sce <- detectCommunity(sce,
                      colPairName = "neighborhood",
                      size_threshold = 10)

plotSpatial(sce,
            img_id = "ImageNb",
            node_color_by = "spatial_community",
            scales = "free")

## Detect spatial community - specify group_by
sce <- detectCommunity(sce,
                      colPairName = "neighborhood",
                      group_by = "CellType",
                      size_threshold = 10,
                      BPPARAM = SerialParam(RNGseed = 22))

plotSpatial(sce,
            img_id = "ImageNb",
            node_color_by = "spatial_community",
            scales = "free")
```

---

detectSpatialContext    *Detect the spatial context of each cell based on its neighborhood*

---

## Description

Function to detect the spatial context (SC) of each cell. Based on its sorted (high-to-low) cellular neighborhood (CN) fractions in a spatial interaction graph, the SC of each cell is assigned as the set of CNs that cumulatively exceed a user-defined fraction threshold.

The term was coined by [Bhate S. et al., Tissue schematics map the specialization of immune tissue motifs and their appropriation by tumors, Cell Systems, 2022](#) and describes tissue regions in which distinct CNs may be interacting.

**Usage**

```
detectSpatialContext(
  object,
  entry = "aggregatedNeighbors",
  threshold = 0.9,
  name = "spatial_context"
)
```

**Arguments**

|                        |   |
|------------------------|---|
| <code>object</code>    | a <code>SingleCellExperiment</code> or <code>SpatialExperiment</code> object  |
| <code>entry</code>     | single character specifying the <code>colData(object)</code> entry containing the <code>aggregateNeighbors</code> <code>DataFrame</code> output. Defaults to "aggregatedNeighbors". |
| <code>threshold</code> | single numeric between 0 and 1 that specifies the fraction threshold for SC assignment. Defaults to 0.9.  |
| <code>name</code>      | single character specifying the name of the output saved in <code>colData(object)</code> . Defaults to "spatial_context".   |

**Value**

returns an object of `class(object)` containing a new column entry to `colData(object)[[name]]`

**Spatial context background**

The function relies on CN fractions for each cell in a spatial interaction graph (originally a k-nearest neighbor (KNN) graph).

We can retrieve the CN fractions using the [buildSpatialGraph](#) and [aggregateNeighbors](#) functions.

The window size (k for KNN) for [buildSpatialGraph](#) should reflect a length scale on which biological signals can be exchanged and depends, among others, on cell density and tissue area. In view of their divergent functionality, we recommend to use a larger window size for SC (interaction between local processes) than for CN (local processes) detection.

Subsequently, the CN fractions are sorted from high-to-low and the SC of each cell is assigned the minimal combination of SCs that additively surpass a user-defined threshold. The default threshold of 0.9 aims to represent the dominant CNs, hence the most prevalent signals, in a given window.

For more details, please refer to: [Bhate S. et al., Tissue schematics map the specialization of immune tissue motifs and their appropriation by tumors, Cell Systems, 2022.](#)

**Author(s)**

Lasse Meyer (<lasse.meyer@uzh.ch>)

**References**

[Bhate S. et al., Tissue schematics map the specialization of immune tissue motifs and their appropriation by tumors, Cell Systems, 2022](#)

**See Also**

[filterSpatialContext](#) for the function to filter spatial contexts

[plotSpatialContext](#) for the function to plot spatial context graphs

**Examples**

```
set.seed(22)
library(cytomapper)
data(pancreasSCE)

## 1. Cellular neighborhood (CN)
sce <- buildSpatialGraph(pancreasSCE, img_id = "ImageNb",
                        type = "knn",
                        name = "knn_cn_graph",
                        k = 5)

sce <- aggregateNeighbors(sce, colPairName = "knn_cn_graph",
                        aggregate_by = "metadata",
                        count_by = "CellType",
                        name = "aggregatedCellTypes")

cur_cluster <- kmeans(sce$aggregatedCellTypes, centers = 3)
sce$cellular_neighborhood <- factor(cur_cluster$cluster)

plotSpatial(sce, img_id = "ImageNb",
            colPairName = "knn_cn_graph",
            node_color_by = "cellular_neighborhood",
            scales = "free")

## 2. Spatial context (SC)
sce <- buildSpatialGraph(sce, img_id = "ImageNb",
                        type = "knn",
                        name = "knn_sc_graph",
                        k = 15)

sce <- aggregateNeighbors(sce, colPairName = "knn_sc_graph",
                        aggregate_by = "metadata",
                        count_by = "cellular_neighborhood",
                        name = "aggregatedNeighborhood")

# Detect spatial context
sce <- detectSpatialContext(sce, entry = "aggregatedNeighborhood",
                        threshold = 0.9)

plotSpatial(sce, img_id = "ImageNb",
            colPairName = "knn_sc_graph",
            node_color_by = "spatial_context",
            scales = "free")
```

---

|              |   |
|--------------|---|
| filterPixels | <i>Filter pixels based on their assigned masses</i> |
|--------------|---|

---

### Description

Helper function for estimating the spillover matrix. After assigning each pixel to a spotted mass, this function will filter incorrectly assigned pixels and remove small pixel sets.

### Usage

```
filterPixels(
  object,
  bc_id = "bc_id",
  spot_mass = "sample_mass",
  minevents = 40,
  correct_pixels = TRUE
)
```

### Arguments

|                |  |
|----------------|--|
| object         | a SingleCellExperiment object containing pixel intensities per channel. Individual pixels are stored as columns and channels are stored as rows. |
| bc_id          | character string indicating which colData(object) entry stores the estimated mass  |
| spot_mass      | character string indicating which colData(object) entry stores the true isotope mass of the spotted metal.                                       |
| minevents      | single numeric indicating the threshold under which pixel sets are excluded from spillover estimation.   |
| correct_pixels | logical indicating if incorrectly assigned pixels should be excluded from spillover estimation.  |

### Value

returns a SingleCellExperiment object in which colData(object)\$bc\_id has been adjusted based on the filter criteria.

### Author(s)

Vito Zanutelli, adapted by Nils Eling (<nils.eling@dqbm.uzh.ch>)

### Examples

```
path <- system.file("extdata/spillover", package = "imcRtools")
sce <- readSCEfromTXT(path)
assay(sce, "exprs") <- asinh(counts(sce)/5)

# Pre-process via CATALYST
```

```

library(CATALYST)

bc_key <- as.numeric(unique(sce$sample_mass))
sce <- assignPrelim(sce, bc_key = bc_key)
sce <- estCutoffs(sce)
sce <- applyCutoffs(sce)

sce <- filterPixels(sce)

table(sce$sample_mass, sce$bc_id)

```

---

|                      |                                |
|----------------------|--------------------------------|
| filterSpatialContext | <i>Filter spatial contexts</i> |
|----------------------|--------------------------------|

---

### Description

Function to filter detected spatial contexts (SCs) based on a user-defined threshold for number of group entries and/or cells.

### Usage

```

filterSpatialContext(
  object,
  entry = "spatial_context",
  group_by = "sample_id",
  group_threshold = NULL,
  cells_threshold = NULL,
  name = "spatial_context_filtered"
)

```

### Arguments

|                 |   |
|-----------------|---|
| object          | a SingleCellExperiment or SpatialExperiment object  |
| entry           | a single character specifying the colData(object) entry containing the detectSpatialContext output. Defaults to "spatial_context".                  |
| group_by        | a single character indicating the colData(object) entry by which SCs are grouped. This is usually the image or patient ID. Defaults to "sample_id". |
| group_threshold | a single numeric specifying the minimum number of group entries in which a SC is detected.  |
| cells_threshold | a single numeric specifying the minimum total number of cells in a SC.  |
| name            | a single character specifying the name of the output saved in colData(object). Defaults to "spatial_context_filtered".                              |



**Value**

returns an object of class(object) containing a new column entry to colData(object)[[name]] and a new data.frame entry to metadata(object)[["filterSpatialContext"]] containing the group and cell counts per SC.

**Author(s)**

Lasse Meyer (<lasse.meyer@uzh.ch>)

**References**

Bhate S. et al., Tissue schematics map the specialization of immune tissue motifs and their appropriation by tumors, *Cell Systems*, 2022

**See Also**

[detectSpatialContext](#) for the function to detect spatial contexts

[plotSpatialContext](#) for the function to plot spatial context graphs

**Examples**

```
set.seed(22)
library(cytomapper)
data(pancreasSCE)

## 1. Cellular neighborhood (CN)
sce <- buildSpatialGraph(pancreasSCE, img_id = "ImageNb",
                        type = "knn",
                        name = "knn_cn_graph",
                        k = 5)

sce <- aggregateNeighbors(sce, colPairName = "knn_cn_graph",
                        aggregate_by = "metadata",
                        count_by = "CellType",
                        name = "aggregatedCellTypes")

cur_cluster <- kmeans(sce$aggregatedCellTypes, centers = 3)
sce$cellular_neighborhood <- factor(cur_cluster$cluster)

plotSpatial(sce, img_id = "ImageNb",
            colPairName = "knn_cn_graph",
            node_color_by = "cellular_neighborhood",
            scales = "free")

## 2. Spatial context (SC)
sce <- buildSpatialGraph(sce, img_id = "ImageNb",
                        type = "knn",
                        name = "knn_sc_graph",
                        k = 15)

sce <- aggregateNeighbors(sce, colPairName = "knn_sc_graph",
```

```

        aggregate_by = "metadata",
        count_by = "cellular_neighborhood",
        name = "aggregatedNeighborhood")

# Detect spatial context
sce <- detectSpatialContext(sce, entry = "aggregatedNeighborhood",
                           threshold = 0.9)

plotSpatial(sce, img_id = "ImageNb",
            colPairName = "knn_sc_graph",
            node_color_by = "spatial_context",
            scales = "free")

# Filter spatial context
# By group
sce <- filterSpatialContext(sce, group_by = "ImageNb",
                           group_threshold = 2)

plotSpatial(sce, img_id = "ImageNb",
            colPairName = "knn_sc_graph",
            node_color_by = "spatial_context_filtered",
            scales = "free")

# By cells
sce <- filterSpatialContext(sce, group_by = "ImageNb",
                           cells_threshold = 15)

plotSpatial(sce, img_id = "ImageNb",
            colPairName = "knn_sc_graph",
            node_color_by = "spatial_context_filtered",
            scales = "free")

```

---

|                 |                                       |
|-----------------|---------------------------------------|
| findBorderCells | <i>Find cells at the image border</i> |
|-----------------|---------------------------------------|

---

## Description

Detection of cells close to the image border for subsequent exclusion from downstream analyses.

## Usage

```
findBorderCells(object, img_id, border_dist, coords = c("Pos_X", "Pos_Y"))
```

## Arguments

|        |  |
|--------|--|
| object | a SingleCellExperiment or SpatialExperiment object.  |
| img_id | single character indicating the colData(object) entry containing the unique image identifiers. |

|             |  |
|-------------|--|
| border_dist | single numeric defining the distance to the image border. The image border here is defined as the minimum and maximum among the cells' x and y location.                   |
| coords      | character vector of length 2 specifying the names of the colData (for a SingleCellExperiment object) or the spatialCoords entries indicating the cells' x and y locations. |

**Value**

an object of class(object) containing the logical border\_cells entry in the colData slot.

**Examples**

```
library(cytomapper)
data("pancreasSCE")

sce <- findBorderCells(pancreasSCE, img_id = "ImageNb",
                      border_dist = 10)

plotSpatial(sce,
            img_id = "ImageNb",
            node_color_by = "border_cells",
            scales = "free")
```

---

minDistToCells

---

*Function to calculate minimal distance to cells of interest*


---

**Description**

Function to return the distance of the closest cell of interest for each cell in the data. In the case of patched/clustered cells negative distances are returned by default which indicate the distance of the cells of interest to the closest cell that is not of the type of cells of interest.

**Usage**

```
minDistToCells(
  object,
  x_cells,
  img_id,
  name = "distToCells",
  coords = c("Pos_X", "Pos_Y"),
  return_neg = TRUE,
  BPPARAM = SerialParam()
)
```

**Arguments**

|            |  |
|------------|--|
| object     | a SingleCellExperiment or SpatialExperiment object   |
| x_cells    | logical vector of length equal to the number of cells contained in object. TRUE entries define the cells to which distances will be calculated.                    |
| img_id     | single character indicating the colData(object) entry containing the unique image identifiers.   |
| name       | character specifying the name of the colData entry to save the distances in.   |
| coords     | character vector of length 2 specifying the names of the colData (for a SingleCellExperiment object) or the spatialCoords entries of the cells' x and y locations. |
| return_neg | logical indicating whether negative distances are to be returned for the distances of patched/spatially clustered cells.   |
| BPPARAM    | a <a href="#">BiocParallelParam-class</a> object defining how to parallelize computations.   |

**Value**

returns an object of class(object) containing a new column entry to colData(object)[[name]]. Cells in the object are grouped by entries in img\_id.

**Ordering of the output object**

The minDistToCells function operates on individual images. Therefore the returned object is grouped by entries in img\_id. This means all cells of a given image are grouped together in the object. The ordering of cells within each individual image is the same as the ordering of these cells in the input object.

**Author(s)**

Daniel Schulz (<daniel.schulz@uzh.ch>)

**Examples**

```
library(cytomapper)
data(pancreasSCE)

# Build interaction graph
pancreasSCE <- buildSpatialGraph(pancreasSCE, img_id = "ImageNb",
type = "expansion", threshold = 20)

# Detect patches of "celltype_B" cells
pancreasSCE <- patchDetection(pancreasSCE,
                             img_id = "ImageNb",
                             patch_cells = pancreasSCE$CellType == "celltype_B",
                             colPairName = "expansion_interaction_graph",
                             min_patch_size = 20,
                             expand_by = 1)

plotSpatial(pancreasSCE,
            img_id = "ImageNb",
```

```

        node_color_by = "patch_id",
        scales = "free")

# Distance to celltype_B patches
pancreasSCE <- minDistToCells(pancreasSCE,
                             x_cells = !is.na(pancreasSCE$patch_id),
                             coords = c("Pos_X", "Pos_Y"),
                             img_id = "ImageNb")

plotSpatial(pancreasSCE,
            img_id = "ImageNb",
            node_color_by = "distToCells",
            scales = "free")

```

---

|                |   |
|----------------|---|
| patchDetection | <i>Function to detect patches containing defined cell types</i> |
|----------------|---|

---

## Description

Function to detect spatial clusters of defined types of cells. By defining a certain distance threshold, all cells within the vicinity of these clusters are detected as well.

## Usage

```

patchDetection(
  object,
  patch_cells,
  colPairName,
  min_patch_size = 1,
  name = "patch_id",
  expand_by = 0,
  coords = c("Pos_X", "Pos_Y"),
  convex = FALSE,
  img_id = NULL,
  BPPARAM = SerialParam()
)

```

## Arguments

|                |   |
|----------------|---|
| object         | a SingleCellExperiment or SpatialExperiment object  |
| patch_cells    | logical vector of length equal to the number of cells contained in object. TRUE entries define the cells to consider for patch detection (see Details). |
| colPairName    | single character indicating the colPair(object) entry containing the neighbor information.  |
| min_patch_size | single integer indicating the minimum number of connected cells that make up a patch before expansion.  |

|           |  |
|-----------|--|
| name      | single character specifying the colData entry storing the patch IDs in the returned object.  |
| expand_by | single numeric indicating in which vicinity range cells should be considered as belonging to the patch (see Details).  |
| coords    | character vector of length 2 specifying the names of the colData (for a SingleCellExperiment object) or the spatialCoords entries of the cells' x and y locations. |
| convex    | should the convex hull be computed before expansion? Default: the concave hull is computed.  |
| img_id    | single character indicating the colData(object) entry containing the unique image identifiers.   |
| BPPARAM   | a <a href="#">BiocParallelParam-class</a> object defining how to parallelize computations.   |

### Value

An object of class(object) containing a patch ID for each cell in colData(object)[[name]]. If expand\_by > 0, cells in the output object are grouped by entries in img\_id.

### Detecting patches of defined cell types

This function works as follows:

1. Only cells defined by patch\_cells are considered for patch detection.
2. Patches of connected cells are detected. Here, cell-to-cell connections are defined by the interaction graph stored in colPair(object, colPairName). At this point, patches that contain fewer than min\_patch\_size cells are removed.
3. If expand\_by > 0, a concave (default) or convex hull is constructed around each patch. This is then expanded by expand\_by and cells within the expanded hull are detected and assigned to the patch. This expansion only works if a patch contains at least 3 cells.

The returned object contains an additional entry colData(object)[[name]], which stores the patch ID per cell. NA indicate cells that are not part of a patch.

### Ordering of the output object

If expand\_by > 0, the patchDetection function operates on individual images. Therefore the returned object is grouped by entries in img\_id. This means all cells of a given image are grouped together in the object. The ordering of cells within each individual image is the same as the ordering of these cells in the input object.

If expand\_by = 0, the ordering of cells in the output object is the same as in the input object.

### Author(s)

Tobias Hoch

adapted by Nils Eling (<nils.eling@dqbm.uzh.ch>)

### References

Hoch, T. et al., Multiplexed Imaging Mass Cytometry of Chemokine Milieus in Metastatic Melanoma Characterizes Features of Response to Immunotherapy., bioRxiv 2021

**Examples**

```

library(cytomapper)
data(pancreasSCE)

# Visualize cell types
plotSpatial(pancreasSCE,
             img_id = "ImageNb",
             node_color_by = "CellType",
             scales = "free")

# Build interaction graph
pancreasSCE <- buildSpatialGraph(pancreasSCE, img_id = "ImageNb",
                                type = "expansion", threshold = 20)

# Detect patches of "celltype_B" cells
pancreasSCE <- patchDetection(pancreasSCE,
                              patch_cells = pancreasSCE$CellType == "celltype_B",
                              colPairName = "expansion_interaction_graph")

plotSpatial(pancreasSCE,
             img_id = "ImageNb",
             node_color_by = "patch_id",
             scales = "free")

# Include cells in vicinity
pancreasSCE <- patchDetection(pancreasSCE,
                              patch_cells = pancreasSCE$CellType == "celltype_B",
                              colPairName = "expansion_interaction_graph",
                              expand_by = 20,
                              img_id = "ImageNb")

plotSpatial(pancreasSCE,
             img_id = "ImageNb",
             node_color_by = "patch_id",
             scales = "free")

```

---

patchSize

*Function to compute the area of c3ll patches*


---

**Description**

This function constructs polygons around patch cells and computes their area.

**Usage**

```

patchSize(
  object,
  patch_name = "patch_id",

```

```

    coords = c("Pos_X", "Pos_Y"),
    convex = FALSE
  )

```

### Arguments

|            |  |
|------------|--|
| object     | a SingleCellExperiment or SpatialExperiment object   |
| patch_name | single character indicating the colData(object) entry containing the patch cell identifiers.   |
| coords     | character vector of length 2 specifying the names of the colData (for a SingleCellExperiment object) or the spatialCoords entries of the cells' x and y locations. |
| convex     | should the convex hull be computed to construct the polygon? Default: the concave hull is computed.  |

### Value

A DataFrame object containing the patch identifier, the constructed polygon and the polygon size.

### Author(s)

Nils Eling (<nils.eling@dqbm.uzh.ch>)

### Examples

```

library(cytomapper)
data(pancreasSCE)

# Build interaction graph
pancreasSCE <- buildSpatialGraph(pancreasSCE, img_id = "ImageNb",
                                type = "expansion", threshold = 20)

# Detect patches of "celltype_B" cells
pancreasSCE <- patchDetection(pancreasSCE,
                              patch_cells = pancreasSCE$CellType == "celltype_B",
                              expand_by = 5, img_id = "ImageNb",
                              colPairName = "expansion_interaction_graph")

# Compute the patch area
patchSize(pancreasSCE)

```

---

plotSpatial

*Visualizes the spatial locations and interactions of cells*

---

### Description

A general function to plot spatial locations of cells while specifying color, shape, size. Cell-cell interactions can be visualized in form of edges between points.



**Usage**

```

plotSpatial(
  object,
  img_id,
  coords = c("Pos_X", "Pos_Y"),
  node_color_by = NULL,
  node_shape_by = NULL,
  node_size_by = NULL,
  node_color_fix = NULL,
  node_shape_fix = NULL,
  node_size_fix = NULL,
  assay_type = NULL,
  draw_edges = FALSE,
  directed = TRUE,
  edge_color_by = NULL,
  edge_width_by = NULL,
  edge_color_fix = NULL,
  edge_width_fix = NULL,
  arrow = NULL,
  end_cap = NULL,
  colPairName = NULL,
  nodes_first = TRUE,
  ncols = NULL,
  nrows = NULL,
  scales = "fixed",
  flip_x = FALSE,
  flip_y = TRUE,
  aspect_ratio = "auto"
)

```

**Arguments**

|                             |  |
|-----------------------------|--|
| <code>object</code>         | a SingleCellExperiment or SpatialExperiment object.  |
| <code>img_id</code>         | single character indicating the colData(object) entry containing the unique image identifiers.   |
| <code>coords</code>         | character vector of length 2 specifying the names of the colData (for a SingleCellExperiment object) or the spatialCoords entries indicating the the cells' x and y locations. |
| <code>node_color_by</code>  | single character indicating the colData(object) entry or marker name by which the nodes (cell locations) should be colored.  |
| <code>node_shape_by</code>  | single character indicating the colData(object) entry by which the shape of the nodes are defined.   |
| <code>node_size_by</code>   | single character indicating the colData(object) entry by which the size of the nodes are defined.  |
| <code>node_color_fix</code> | single character or numeric specifying the color of all nodes.   |
| <code>node_shape_fix</code> | single numeric or character specifying the shape of all nodes.   |
| <code>node_size_fix</code>  | single numeric specifying the size of all nodes  |

|                |   |
|----------------|---|
| assay_type     | single character indicating the assay slot from which to extract the expression data when node_color_by is set to one of rownames(object).  |
| draw_edges     | should cell-cell interactions be drawn as edges between nodes?  |
| directed       | should cell-cell interactions be handled as a directed graph?   |
| edge_color_by  | single character indicating by which to color the edges. See details for more information.  |
| edge_width_by  | single character determining the size of the edges. See details for more information.   |
| edge_color_fix | single character or numeric specifying the color of all edges.  |
| edge_width_fix | single numeric specifying the size of all edges.  |
| arrow          | an <a href="#">arrow</a> object specifying how to draw arrows between cells.  |
| end_cap        | a <a href="#">geometry</a> object specifying how long the edges are. This only takes effect when drawing arrows. Default: end_cap = circle(0.1, 'cm')   |
| colPairName    | single character specifying the colPair(object) slot to retrieve the cell-cell pairings.  |
| nodes_first    | should the nodes be plotted first and then the edges?   |
| ncols          | number of columns of the grid to arrange individual images.   |
| nrows          | number of rows of the grid to arrange individual images.  |
| scales         | one of "free", "fixed", "free_x" or "free_y" indicating if x- and y-axis ranges should be fixed across all images. Defaults to "fixed" to match physical units on the x- and y-axis.  |
| flip_x         | flip the x-axis?  |
| flip_y         | flip the y-axis?  |
| aspect_ratio   | single numeric, "auto" or NULL to define the relative ratio between the physical units of the x and y axis. If "auto" (default), the physical units match between the x and y axis if scales = "fixed". If scales = "free", the default aspect ratio is set to 1. Ignore setting the aspect ratio with aspect_ratio = NULL. |

### Value

returns a ggplot object.

### Visualizing cell locations and cell-cell interactions

By default, the cells' locations are visualized in form of points (here also referred to as "nodes") on a 2-dimensional plane. The cells' coordinates are extracted either from colData(object) slot (for a SingleCellExperiment input object) or from the spatialCoords(object) slot (for a SpatialExperiment input object). Node aesthetics are controlled by setting node\_color\_by, node\_shape\_by and node\_size\_by for associating the aesthetics with variables. If node aesthetics should be the same for all nodes, node\_color\_fix, node\_shape\_fix and node\_size\_fix can be set.

When draw\_edges = TRUE, cell-cell interactions are visualized in form of edges between nodes. For this, object needs to contain column pairings in colPair(object, colPairName). Edge color and size can be set by specifying either an entry in mcols(colPair(object, colPairName)) (edge

attributes) or in `colData(object)`. In the latter case, edges are colored by attributes associated to the "from" node. Variable aesthetics can be set using `edge_color_by` and `edge_width_by`. If all edges should have the same width or color, `edge_color_fix` and `edge_width_fix` can be set.

Arrows for displaying directed graphs can be drawn by supplying a [arrow](#) object. Arrow attributes can be set within this class. To cap the edge before it reaches the next node, the `end_cap` parameter can be used.

### Author(s)

Nils Eling (<nils.eling@dqbm.uzh.ch>)

### See Also

[buildSpatialGraph](#) for constructing interaction graphs

[ggraph](#) for handling graph aesthetics

### Examples

```
library(cytomapper)
data(pancreasSCE)

sce <- buildSpatialGraph(pancreasSCE, img_id = "ImageNb",
                        type = "knn", k = 3, directed = FALSE)

# Only nodes
plotSpatial(sce, img_id = "ImageNb",
            node_color_by = "CellType",
            node_shape_by = "ImageNb",
            node_size_by = "Area",
            scales = "free")

# With edges and nodes colored by expression
plotSpatial(sce, img_id = "ImageNb",
            node_color_by = "PIN",
            assay_type = "exprs",
            node_shape_by = "ImageNb",
            node_size_by = "Area",
            draw_edges = TRUE,
            colPairName = "knn_interaction_graph",
            edge_color_by = "Pattern",
            scales = "free")

# With arrows
plotSpatial(sce, img_id = "ImageNb",
            node_color_by = "CellType",
            node_shape_by = "ImageNb",
            node_size_by = "Area",
            draw_edges = TRUE,
            colPairName = "knn_interaction_graph",
            edge_color_fix = "green",
            arrow = grid::arrow(length = grid::unit(0.1, "inch")),
```

```
end_cap = ggraph::circle(0.2, "cm"),
scales = "free")
```

---

|                    |                                   |
|--------------------|-----------------------------------|
| plotSpatialContext | <i>Plot spatial context graph</i> |
|--------------------|-----------------------------------|

---

## Description

Function to plot directed spatial context graphs based on symbolic edge-lists and vertex metadata, which operates on the cohort-level. The user can specify node, node\_label and edge aesthetics.

## Usage

```
plotSpatialContext(
  object,
  entry = "spatial_context",
  group_by = "sample_id",
  node_color_by = NULL,
  node_size_by = NULL,
  node_color_fix = NULL,
  node_size_fix = NULL,
  node_label_repel = TRUE,
  node_label_color_by = NULL,
  node_label_color_fix = NULL,
  draw_edges = TRUE,
  edge_color_fix = NULL,
  return_data = FALSE
)
```

## Arguments

|                  |   |
|------------------|---|
| object           | a SingleCellExperiment or SpatialExperiment object.   |
| entry            | single character specifying the colData(object) entry containing the <a href="#">detectSpatialContext</a> output. Defaults to "spatial_context".    |
| group_by         | a single character indicating the colData(object) entry by which SCs are grouped. This is usually the image or patient ID. Defaults to "sample_id". |
| node_color_by    | single character either NULL, "name", "n_cells", "n_group" by which the nodes should be colored.  |
| node_size_by     | single character either NULL, "n_cells", "n_group" by which the size of the nodes are defined.  |
| node_color_fix   | single character specifying the color of all nodes.   |
| node_size_fix    | single numeric specifying the size of all nodes.  |
| node_label_repel | should nodes be labelled? Defaults to TRUE.   |

node\_label\_color\_by  
single character either NULL, "name", "n\_cells", "n\_group" by which the node labels should be colored.

node\_label\_color\_fix  
single character specifying the color of all node labels.

draw\_edges  
should edges be drawn between nodes? Defaults to TRUE.

edge\_color\_fix  
single character specifying the color of all edges.

return\_data  
should the edge list and vertex metadata for graph construction be returned as a list of two data.frames?

**Value**

returns a ggplot object or a list of two data.frames.

**Author(s)**

Lasse Meyer (<lasse.meyer@uzh.ch>)

**References**

Bhate S. et al., Tissue schematics map the specialization of immune tissue motifs and their appropriation by tumors, *Cell Systems*, 2022

**See Also**

[detectSpatialContext](#) for the function to detect spatial contexts

[filterSpatialContext](#) for the function to filter spatial contexts

**Examples**

```
set.seed(22)
library(cytomapper)
data(pancreasSCE)

## 1. Cellular neighborhood (CN)
sce <- buildSpatialGraph(pancreasSCE, img_id = "ImageNb",
                        type = "knn",
                        name = "knn_cn_graph",
                        k = 5)

sce <- aggregateNeighbors(sce, colPairName = "knn_cn_graph",
                        aggregate_by = "metadata",
                        count_by = "CellType",
                        name = "aggregatedCellTypes")

cur_cluster <- kmeans(sce$aggregatedCellTypes, centers = 3)
sce$cellular_neighborhood <- factor(cur_cluster$cluster)

plotSpatial(sce, img_id = "ImageNb",
            colPairName = "knn_cn_graph",
```

```

        node_color_by = "cellular_neighborhood",
        scales = "free")

## 2. Spatial context (SC)
sce <- buildSpatialGraph(sce, img_id = "ImageNb",
                        type = "knn",
                        name = "knn_sc_graph",
                        k = 15)

sce <- aggregateNeighbors(sce, colPairName = "knn_sc_graph",
                        aggregate_by = "metadata",
                        count_by = "cellular_neighborhood",
                        name = "aggregatedNeighborhood")

# Detect spatial context
sce <- detectSpatialContext(sce, entry = "aggregatedNeighborhood",
                        threshold = 0.9)

plotSpatial(sce, img_id = "ImageNb",
            colPairName = "knn_sc_graph",
            node_color_by = "spatial_context",
            scales = "free")

# Plot spatial context - default
plotSpatialContext(sce, group_by = "ImageNb")

# Plot spatial context - adjust aesthetics
plotSpatialContext(sce, group_by = "ImageNb",
                    node_color_by = "name",
                    node_size_by = "n_cells",
                    node_label_color_by = "name")

plotSpatialContext(sce, group_by = "ImageNb",
                    node_color_by = "n_cells",
                    node_size_by = "n_group")

# Plot spatial context - return data
plotSpatialContext(sce, group_by = "ImageNb",
                    return_data = TRUE)

```

---

plotSpotHeatmap

*Summarizes and visualizes the pixel intensities per spot and channel*


---

## Description

Helper function for estimating the spillover matrix. This function visualizes the median pixel intensities per spot (rows) and per channel (columns) in form of a heatmap.

**Usage**

```
plotSpotHeatmap(
  object,
  spot_id = "sample_id",
  channel_id = "channel_name",
  assay_type = "counts",
  statistic = "median",
  log = TRUE,
  threshold = NULL,
  order_metals = TRUE,
  color = viridis(100),
  breaks = NA,
  legend_breaks = NA,
  cluster_cols = FALSE,
  cluster_rows = FALSE,
  ...
)
```

**Arguments**

|                            |  |
|----------------------------|--|
| <code>object</code>        | a <code>SingleCellExperiment</code> object containing pixel intensities per channel. Individual pixels are stored as columns and channels are stored as rows.  |
| <code>spot_id</code>       | character string indicating which <code>colData(object)</code> entry stores the isotope names of the spotted metal. Entries should be of the form (mt)(mass) (e.g. Sm152 for Samarium isotope with the atomic mass 152). |
| <code>channel_id</code>    | character string indicating which <code>rowData(object)</code> entry contains the isotope names of the acquired channels.  |
| <code>assay_type</code>    | character string indicating which assay to use (default counts).   |
| <code>statistic</code>     | the statistic to use when aggregating channels per spot (default median)   |
| <code>log</code>           | should the aggregated pixel intensities be $\log_{10}(x + 1)$ transformed?   |
| <code>threshold</code>     | single numeric indicating a threshold after pixel aggregation. All aggregated values larger than threshold will be labeled as 1.   |
| <code>order_metals</code>  | should the metals be ordered based on spotted mass?  |
| <code>color</code>         | see parameter in <a href="#">pheatmap</a>  |
| <code>breaks</code>        | see parameter in <a href="#">pheatmap</a>  |
| <code>legend_breaks</code> | see parameter in <a href="#">pheatmap</a>  |
| <code>cluster_cols</code>  | see parameter in <a href="#">pheatmap</a>  |
| <code>cluster_rows</code>  | see parameter in <a href="#">pheatmap</a>  |
| <code>...</code>           | other arguments passed to <a href="#">pheatmap</a> .   |

**Value**

a [pheatmap](#) object

### Quality control for spillover estimation

Visualizing the aggregated pixel intensities serves two purposes:

1. Small median pixel intensities (< 200 counts) might hinder the robust estimation of the channel spillover. In that case, consecutive pixels can be summed (see [binAcrossPixels](#)).
2. Each spotted metal (row) should show the highest median pixel intensity in its corresponding channel (column). If this is not the case, either the naming of the .txt files was incorrect or the incorrect metal was spotted.

By setting the threshold parameter, the user can easily identify spots where pixel intensities are too low for robust spillover estimation.

### Author(s)

Nils Eling (<nils.eling@dqbm.uzh.ch>)

### See Also

[pheatmap](#) for visual modifications  
[aggregateAcrossCells](#) for the aggregation function

### Examples

```
path <- system.file("extdata/spillover", package = "imcRtools")
# Read in .txt files
sce <- readSCEfromTXT(path)

# Visualizes heatmap
plotSpotHeatmap(sce)

# Visualizes thresholding results
plotSpotHeatmap(sce, log = FALSE, threshold = 200)
```

---

|                               |  |
|-------------------------------|--|
| <code>readImagefromTXT</code> | <i>Reads one or multiple .txt files into a <code>CytoImageList</code> object</i> |
|-------------------------------|--|

---

### Description

Reader function to generate [Image](#) objects in form of a [CytoImageList](#) container from .txt files.

### Usage

```
readImagefromTXT(
  path,
  pattern = ".txt$",
  channel_pattern = "[A-Za-z]{1,2}[0-9]{2,3}Di",
  index_names = c("X", "Y"),
  BPPARAM = SerialParam()
)
```



**Arguments**

|                 |  |
|-----------------|--|
| path            | Full path to where the individual .txt files are located. This is usually the path where the .mcd file is located. |
| pattern         | pattern to select which files should be read in (default ".txt\$").  |
| channel_pattern | regular expression to select the channel names from the files.   |
| index_names     | exact names of the columns storing the x and y coordinates of the image  |
| BPPARAM         | parameters for parallelized reading in of images. This is only recommended for very large images.                  |

**Value**

returns a [CytoImageList](#) object containing one [Image](#) object per .txt file.

**Imaging mass cytometry .txt files**

As part of the raw data folder, the Hyperion imaging system writes out one .txt file per acquisition. These files store the ion counts per pixel and channel.

This function reads these .txt files into a single [CytoImageList](#) object for downstream analysis. The pattern argument allows selection of all .txt files or a specific subset of files. The [channelNames](#) of the CytoImageList object are determined by the channel\_pattern argument.

**Author(s)**

Nils Eling (<nils.eling@dqbm.uzh.ch>)

**See Also**

[CytoImageList](#) for the container

[MulticoreParam](#) for parallelized processing

[Image](#) for the multi-channel image object

`vignette("cytomapper")` for visualization of multi-channel images

**Examples**

```
path <- system.file("extdata/mockData/raw", package = "imcRtools")

# Read in all images
x <- readImagefromTXT(path)
x

# Read in specific files
y <- readImagefromTXT(path, pattern = "ROI_002")
y

# Read in other channelNames
z <- readImagefromTXT(path, channel_pattern = "[A-Za-z]{2}[0-9]{3}")
z
```

---

|                |   |
|----------------|---|
| readSCEfromTXT | <i>Generates a SingleCellExperiment from .txt files</i> |
|----------------|---|

---

## Description

Helper function to process raw .txt files acquired by the Hyperion imaging system into a [SingleCellExperiment](#) object. This function is mainly used to read-in data generated from a "spillover slide". Here, each .txt file contains the measurements of multiple pixels for a single stain across all open channels.

## Usage

```
readSCEfromTXT(
  x,
  pattern = ".txt$",
  metadata_cols = c("Start_push", "End_push", "Pushes_duration", "X", "Y", "Z"),
  verbose = TRUE,
  read_metal_from_filename = TRUE
)
```

## Arguments

|                          |  |
|--------------------------|--|
| x                        | input can be of different types:<br><b>A path</b> Full path to where the single stain .txt files are located.<br><b>A list object</b> A named list object where each entry is a data.frame or coercible to one. The names of each entry indicate the spotted metals (see details). |
| pattern                  | pattern to select which files should be read in (default ".txt\$"). Only used when x is a path.  |
| metadata_cols            | character vector indicating which column entries of the .txt files should be saved in the colData(sce) slot.   |
| verbose                  | logical indicating if additional information regarding the spotted and acquired masses should be shown.  |
| read_metal_from_filename | should the sample metal and mass be extracted from the file/object names?  |

## Value

returns a SCE object where pixels are stored as columns and acquired channels are stored as rows.

## Reading in .txt files for spillover correction

As described in the original publication, single metal spots are acquired using the Hyperion imaging system. Each acquisition corresponds to one spot. All acquisitions are stored in a single .mcd file and individual acquisitions are stored in single .txt files.

This function aggregates these measurements into a single SingleCellExperiment object. For this, two inputs are possible:

1. `x` is a path: By default all .txt files are read in from the specified path. Here, the path should indicate the location of the spillover slide measurement. The file names of the .txt file must contain the spotted metal isotope name in the format (mt)(mass) (e.g. Sm152 for Samarium isotope with the atomic mass 152). Internally, the last occurrence of such a pattern is read in as the metal isotope name and stored in the `colData(sce)$sample_id` slot.
2. `x` is a named list: If there are issues with reading in the metal isotope names from the .txt file names, the user can provide a list for which each entry contains the contents of a single .txt file. The names of the list must indicate the spotted metal in the format (mt)(mass). These names will be stored in the `colData(sce)$sample_id` slot.

When `read_metal_from_filename = FALSE`, the function will not attempt to read in the spotted metal isotopes from the file or list names. Therefore, only the `sample_id` will be set based on the file/list names.

### Author(s)

Nils Eling (<nils.eling@dqbm.uzh.ch>)

### References

Chevrier, S. et al. 2017. "Compensation of Signal Spillover in Suspension and Imaging Mass Cytometry." *Cell Systems* 6: 612–20.

### Examples

```
# Read files from path
path <- system.file("extdata/spillover", package = "imcRtools")

sce <- readSCEfromTXT(path)
sce

# Read files as list
cur_file_names <- list.files(path, pattern = ".txt", full.names = TRUE)
cur_files <- lapply(cur_file_names, read.delim)
names(cur_files) <- sub(".txt", "", basename(cur_file_names))

sce <- readSCEfromTXT(cur_files)
sce
```

---

read\_cpout

*Reads in single-cell data generated by the ImcSegmentationPipeline*

---

### Description

Reader function to generate a [SpatialExperiment](#) or [SingleCellExperiment](#) object from single-cell data obtained by the [ImcSegmentationPipeline](#) pipeline.

**Usage**

```

read_cpout(
  path,
  object_file = "cell.csv",
  image_file = "Image.csv",
  panel_file = "panel.csv",
  graph_file = "Object relationships.csv",
  object_feature_file = "var_cell.csv",
  intensities = "Intensity_MeanIntensity_FullStack",
  extract_imgid_from = "ImageNumber",
  extract_cellid_from = "ObjectNumber",
  extract_coords_from = c("Location_Center_X", "Location_Center_Y"),
  extract_cellmetadata_from = c("AreaShape_Area", "Neighbors_NumberOfNeighbors_8",
    "AreaShape_Eccentricity", "AreaShape_MajorAxisLength", "AreaShape_MinorAxisLength",
    "AreaShape_MeanRadius"),
  extract_imagemetadata_from = c("Metadata_acname", "Metadata_acid",
    "Metadata_description"),
  extract_graphimageid_from = "First Image Number",
  extract_graphcellids_from = c("First Object Number", "Second Object Number"),
  extract_metal_from = "Metal Tag",
  scale_intensities = TRUE,
  extract_scalingfactor_from = "Scaling_FullStack",
  return_as = c("spe", "sce")
)

```

**Arguments**

|                     |  |
|---------------------|--|
| path                | full path to the CellProfiler output folder.   |
| object_file         | single character indicating the file name storing the object/cell-specific intensities and metadata.                         |
| image_file          | single character indicating the file name storing meta data per image (can be NULL).   |
| panel_file          | single character indicating the file name storing the panel information (can be NULL).                                       |
| graph_file          | single character indicating the file name storing the object/cell interaction information (can be NULL).                     |
| object_feature_file | single character indicating the file name storing object/cell feature information.   |
| intensities         | single character indicating which column entries of the object_file contain the intensity features of interest. See details. |
| extract_imgid_from  | single character indicating which column entries of the object_file and image_file contain the image integer ID.             |
| extract_cellid_from | single character indicating which column entry of the object_file contains the object/cell integer ID.                       |

|                            |  |
|----------------------------|--|
| extract_coords_from        | character vector indicating which column entries of the object_file contain the x and y location of the objects/cells.   |
| extract_cellmetadata_from  | character vector indicating which additional object/cell specific metadata to extract from the object_file.  |
| extract_imagemetadata_from | character vector indicating which additional image specific metadata to extract from the image_file. These will be stored in the colData(x) slot as object/cell-specific entries.  |
| extract_graphimageid_from  | single character indicating which column entries of the graph_file contain the image integer ID.   |
| extract_graphcellids_from  | character vector indicating which column entries of the graph_file contain the first and second object/cell integer IDs. These will be stored as the from and to entry of the SelfHits object in colPair(x, "neighborhood"). |
| extract_metal_from         | single character indicating which column entry of the panel_file contains the metal isotopes of the used antibodies. This entry is used to match the panel information to the acquired channel information.                  |
| scale_intensities          | single logical. Should the measured intensity features be scaled by extract_scalingfactor_from.  |
| extract_scalingfactor_from | single character indicating which column entries of the image_file contain the image specific scaling factor.  |
| return_as                  | should the object be returned as <a href="#">SpatialExperiment</a> (return_as = "spe") or <a href="#">SingleCellExperiment</a> (return_as = "sce").  |

## Value

returns a [SpatialExperiment](#) or [SingleCellExperiment](#) object with markers in rows and cells in columns.

## The returned data container

In the case of both containers x, intensity features (as selected by the intensities parameter) are stored in the counts(x) slot. Cell metadata (e.g morphological features) are stored in the colData(x) slot. The interaction graphs are stored as [SelfHits](#) object in the colPair(x, "neighborhood") slot.

Intensity features are extracted via partial string matching. Internally, the read\_cpout function checks if per channel a single intensity feature is read in (by checking the \_cXY ending where XY is the channel number).

In the case of a returned [SpatialExperiment](#) object, the cell coordinates are stored in the spatialCoords(x) slot.

In the case of a returned [SingleCellExperiment](#) object, the cell coordinates are stored in the colData(x) slot named as Pos\_X and Pos\_Y.

**Author(s)**

Tobias Hoch

Nils Eling (&lt;nils.eling@dqbm.uzh.ch&gt;)

**See Also**<https://github.com/BodenmillerGroup/ImcSegmentationPipeline> for the pipeline[read\\_steinbock](#) for reading in single-cell data as produced by the steinbock pipeline[colPair](#) for information on how to work with the cell-cell interaction graphs**Examples**

```

path <- system.file("extdata/mockData/cpout", package = "imcRtools")

# Read in as SpatialExperiment object
x <- read_cpout(path, graph_file = "Object_relationships.csv")
x

# Read in as SingleCellExperiment object
x <- read_cpout(path, graph_file = "Object_relationships.csv",
                return_as = "sce")
x

```

read\_steinbock

*Reads in single-cell data generated by the steinbock pipeline***Description**

Reader function to generate a [SpatialExperiment](#) or [SingleCellExperiment](#) object from single-cell data obtained by the [steinbock](#) pipeline.

**Usage**

```

read_steinbock(
  path,
  intensities_folder = "intensities",
  regionprops_folder = "regionprops",
  graphs_folder = "neighbors",
  pattern = NULL,
  extract_cellid_from = "Object",
  extract_coords_from = c("centroid-1", "centroid-0"),
  image_file = "images.csv",
  extract_imagemetadata_from = c("width_px", "height_px"),
  panel_file = "panel.csv",
  extract_names_from = "name",
  return_as = c("spe", "sce"),

```

```
BPPARAM = SerialParam()
)
```

### Arguments

|                            |   |
|----------------------------|---|
| path                       | full path to the steinbock output folder  |
| intensities_folder         | name of the folder containing the intensity measurements per image  |
| regionprops_folder         | name of the folder containing the cell-specific morphology and spatial measurements per image. Can be set to NULL to exclude reading in morphology measures.                      |
| graphs_folder              | name of the folder containing the spatial connectivity graphs per image. Can be set to NULL to exclude reading in graphs.   |
| pattern                    | regular expression specifying a subset of files that should be read in.   |
| extract_cellid_from        | single character indicating which column entry in the intensity files contains the integer cell id.   |
| extract_coords_from        | character vector indicating which column entries in the regionprops files contain the x (first entry) and y (second entry) coordinates.   |
| image_file                 | single character indicating the file name storing meta data per image (can be NULL).  |
| extract_imagemetadata_from | character vector indicating which additional image specific metadata to extract from the image_file. These will be stored in the colData(x) slot as object/cell-specific entries. |
| panel_file                 | single character containing the name of the panel file. This can either be inside the steinbock path (recommended) or located somewhere else.                                     |
| extract_names_from         | single character indicating the column of the panel file containing the channel names.  |
| return_as                  | should the object be returned as <a href="#">SpatialExperiment</a> (return_as = "spe") or <a href="#">SingleCellExperiment</a> (return_as = "sce").                               |
| BPPARAM                    | parameters for parallelised processing.   |

### Value

returns a [SpatialExperiment](#) or [SingleCellExperiment](#) object markers in rows and cells in columns.

### The returned data container

In the case of both containers x, intensity features are stored in the counts(x) slot. Morphological features are stored in the colData(x) slot. The graphs are stored as [SelfHits](#) object in the colPair(x, "neighborhood") slot.

In the case of a returned `SpatialExperiment` object, the cell coordinates are stored in the `spatialCoords(x)` slot.

In the case of a returned `SingleCellExperiment` object, the cell coordinates are stored in the `colData(x)` slot named as `Pos_X` and `Pos_Y`.

### Author(s)

Nils Eling (<nils.eling@dqbm.uzh.ch>)

### See Also

<https://github.com/BodenmillerGroup/steinbock> for the pipeline  
[read\\_cpout](#) for reading in single-cell data as produced by the `ImcSegmentationPipeline`  
[SingleCellExperiment](#) and [SpatialExperiment](#) for the constructor functions.  
[colPair](#) for information on how to work with the cell-cell interaction graphs  
[bpparam](#) for the parallelised backend

### Examples

```
path <- system.file("extdata/mockData/steinbock", package = "imcRtools")

# Read in as SpatialExperiment object
x <- read_steinbock(path)
x

# Read in as SingleCellExperiment object
x <- read_steinbock(path, return_as = "sce")
x

# Read in a subset of files
x <- read_steinbock(path, pattern = "mockData1")
x

# Only read in intensities
x <- read_steinbock(path, graphs_folder = NULL, regionprops_folder = NULL)
x

# Parallelisation
x <- read_steinbock(path, BPPARAM = BiocParallel::bpparam())
```

---

|                     |   |
|---------------------|---|
| show_cpout_features | <i>Display all features measured by CellProfiler.</i> |
|---------------------|---|

---

### Description

Searchable datatable object of cell and image features as extracted by CellProfiler.



**Usage**

```
show_cpout_features(  
  path,  
  display = c("cell_features", "image_features"),  
  cell_features = "var_cell.csv",  
  image_features = "var_Image.csv"  
)
```

**Arguments**

|                |  |
|----------------|--|
| path           | full path to the CellProfiler output folder  |
| display        | single character indicating which features to display. Accepted entries are cell_features to display extracted single-cell features or image_features to display extracted image-level features. |
| cell_features  | single character indicating the name of the file storing the extracted cell features.  |
| image_features | single character indicating the name of the file storing the extracted image features.   |

**Value**

a [datatable](#) object

**Author(s)**

Nils Eling (<nils.eling@dqbm.uzh.ch>)

**See Also**

[read\\_cpout](#) for the CellProfiler reader function

**Examples**

```
path <- system.file("extdata/mockData/cpout", package = "imcRtools")  
  
# Display cell features  
show_cpout_features(path)  
  
# Display image features  
show_cpout_features(path, display = "image_features")
```

---

|                  |   |
|------------------|---|
| testInteractions | <i>Tests if cell types interact more or less frequently than random</i> |
|------------------|---|

---

## Description

Cell-cell interactions are summarized in different ways and the resulting count is compared to a distribution of counts arising from random permutations.

## Usage

```
testInteractions(
  object,
  group_by,
  label,
  colPairName,
  method = c("classic", "histocat", "patch"),
  patch_size = NULL,
  iter = 1000,
  p_threshold = 0.01,
  return_samples = FALSE,
  tolerance = sqrt(.Machine$double.eps),
  BPPARAM = SerialParam()
)
```

## Arguments

|                |   |
|----------------|---|
| object         | a SingleCellExperiment or SpatialExperiment object.   |
| group_by       | a single character indicating the colData(object) entry by which interactions are grouped. This is usually the image ID or patient ID.  |
| label          | single character specifying the colData(object) entry which stores the cell labels. These can be cell-types labels or other metadata entries.   |
| colPairName    | single character indicating the colPair(object) entry containing cell-cell interactions in form of an edge list.  |
| method         | which cell-cell interaction counting method to use (see details)  |
| patch_size     | if method = "patch", a single numeric specifying the minimum number of neighbors of the same type to be considered a patch (see details)  |
| iter           | single numeric specifying the number of permutations to perform   |
| p_threshold    | single numeric indicating the empirical p-value threshold at which interactions are considered to be significantly enriched or depleted per group.                                      |
| return_samples | single logical indicating if the permuted interaction counts of all iterations should be returned.  |
| tolerance      | single numeric larger than 0. This parameter defines the difference between the permuted count and the actual counts at which both are regarded as equal. Default taken from all.equal. |
| BPPARAM        | parameters for parallelized processing.   |

**Value**

a DataFrame containing one row per group\_by entry and unique label entry combination (from\_label, to\_label). The object contains following entries:

- ct: stores the interaction count as described in the details
- p\_gt: stores the fraction of perturbations equal or greater than ct
- p\_lt: stores the fraction of perturbations equal or less than ct
- interaction: is there the tendency for a positive interaction (attraction) between from\_label and to\_label? Is p\_lt greater than p\_gt?
- p: the smaller value of p\_gt and p\_lt.
- sig: is p smaller than p\_threshold?
- signal: Combination of interaction and sig.
  - -1: interaction == FALSE and sig == TRUE
  - 0: sig == FALSE
  - 1: interaction == TRUE and sig == TRUE

NA is returned if a certain label is not present in this grouping level.

**Counting and summarizing cell-cell interactions**

In principle, the `countInteractions` function counts the number of edges (interactions) between each set of unique entries in `colData(object)[[label]]`. Simplified, it counts for each cell of type A the number of neighbors of type B. This count is averaged within each unique entry `colData(object)[[group_by]]` in three different ways:

1. method = "classic": The count is divided by the total number of cells of type A. The final count can be interpreted as "How many neighbors of type B does a cell of type A have on average?"
2. method = "histocat": The count is divided by the number of cells of type A that have at least one neighbor of type B. The final count can be interpreted as "How many many neighbors of type B has a cell of type A on average, given it has at least one neighbor of type B?"
3. method = "patch": For each cell, the count is binarized to 0 (less than patch\_size neighbors of type B) or 1 (more or equal to patch\_size neighbors of type B). The binarized counts are averaged across all cells of type A. The final count can be interpreted as "What fraction of cells of type A have at least a given number of neighbors of type B?"

**Testing for significance**

Within each unique entry to `colData(object)[[group_by]]`, the entries of `colData(object)[[label]]` are randomized `iter` times. For each iteration, the interactions are counted as described above. The result is a distribution of the interaction count under spatial randomness. The observed interaction count is compared against this Null distribution to derive empirical p-values:

p\_gt: fraction of perturbations equal or greater than the observed count

p\_lt: fraction of perturbations equal or less than the observed count

Based on these empirical p-values, the interaction score (attraction or avoidance), overall p value and significance by comparison to p\_treshold (sig and signal) are derived.

**Author(s)**

Vito Zanutelli

Jana Fischer

adapted by Nils Eling (<nils.eling@dqbm.uzh.ch>)

**References**

Schulz, D. et al., Simultaneous Multiplexed Imaging of mRNA and Proteins with Subcellular Resolution in Breast Cancer Tissue Samples by Mass Cytometry., Cell Systems 2018 6(1):25-36.e5

Shapiro, D. et al., histoCAT: analysis of cell phenotypes and interactions in multiplex image cytometry data, Nature Methods 2017 14, p. 873–876

**See Also**

[countInteractions](#) for counting (but not testing) cell-cell interactions per grouping level.

[bpparam](#) for the parallelised backend

**Examples**

```
library(cytomapper)
library(BiocParallel)
data(pancreasSCE)

pancreasSCE <- buildSpatialGraph(pancreasSCE, img_id = "ImageNb",
                                type = "knn", k = 3)

# Classic style calculation - setting the seed inside SerialParam for reproducibility
(out <- testInteractions(pancreasSCE,
                        group_by = "ImageNb",
                        label = "CellType",
                        method = "classic",
                        colPairName = "knn_interaction_graph",
                        iter = 1000,
                        BPPARAM = SerialParam(RNGseed = 123)))

# HistoCAT style calculation
(out <- testInteractions(pancreasSCE,
                        group_by = "ImageNb",
                        label = "CellType",
                        method = "histocat",
                        colPairName = "knn_interaction_graph",
                        iter = 1000,
                        BPPARAM = SerialParam(RNGseed = 123)))

# Patch style calculation
(out <- testInteractions(pancreasSCE,
                        group_by = "ImageNb",
                        label = "CellType",
                        method = "patch",
                        patch_size = 3,
```

```
colPairName = "knn_interaction_graph",  
iter = 1000,  
BPPARAM = SerialParam(RNGseed = 123)))
```

# Index

aggregateAcrossCells, [5](#), [32](#)  
aggregateNeighbors, [3](#), [13](#)  
arrow, [26](#), [27](#)  
  
binAcrossPixels, [4](#), [32](#)  
BiocNeighborParam, [7](#)  
bpparam, [40](#), [44](#)  
buildSpatialGraph, [6](#), [13](#), [27](#)  
  
channelNames, [33](#)  
colPair, [38](#), [40](#)  
countInteractions, [8](#), [43](#), [44](#)  
CytoImageList, [32](#), [33](#)  
  
datatable, [41](#)  
detectCommunity, [10](#)  
detectSpatialContext, [12](#), [17](#), [28](#), [29](#)  
  
filterPixels, [15](#)  
filterSpatialContext, [14](#), [16](#), [29](#)  
findBorderCells, [18](#)  
findKNN, [7](#), [8](#)  
findNeighbors, [7](#), [8](#)  
  
geometry, [26](#)  
ggraph, [27](#)  
  
Image, [32](#), [33](#)  
  
KmknnParam, [7](#)  
  
minDistToCells, [19](#)  
MulticoreParam, [33](#)  
  
patchDetection, [21](#)  
patchSize, [23](#)  
pheatmap, [31](#), [32](#)  
plotSpatial, [8](#), [24](#)  
plotSpatialContext, [14](#), [17](#), [28](#)  
plotSpotHeatmap, [30](#)  
  
read\_cpout, [35](#), [40](#), [41](#)  
  
read\_steinbock, [38](#), [38](#)  
readImagefromTXT, [32](#)  
readSCEfromTXT, [34](#)  
  
SelfHits, [37](#), [39](#)  
show\_cpout\_features, [40](#)  
SingleCellExperiment, [34](#), [35](#), [37–40](#)  
SpatialExperiment, [35](#), [37–40](#)  
  
testInteractions, [10](#), [42](#)  
triangulate, [7](#), [8](#)