

Package ‘BiocDuckDB’

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Title Bioconductor DuckDB Integration and High-Level I/O

Description Integration package providing high-level Parquet I/O functions and optimized methods for single-cell analysis workflows using DuckDB-backed data structures. Includes readParquet and writeParquet functions for seamless serialization of SummarizedExperiment, SingleCellExperiment, MultiAssayExperiment, and MultiAssaySpatialExperiment objects, plus SQL-optimized implementations of scran and scuttle methods for variance modeling, marker detection, QC metrics, and normalization. This package brings together DuckDBDataFrame, DuckDBArray, DuckDBGRanges, and DuckDBSpatial (optional) for complete Bioconductor integration.

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URL <https://github.com/Genentech/BiocDuckDB>

BugReports <https://github.com/Genentech/BiocDuckDB/issues>

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 'MultiAssaySpatialExperiment-spatial.R'
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BiocDuckDB-package	<i>BiocDuckDB: Bioconductor DuckDB Integration and High-Level I/O</i>
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Description

Integration package providing high-level Parquet I/O functions and optimized methods for single-cell analysis workflows using DuckDB-backed data structures. Includes readParquet and writeParquet functions for seamless serialization of SummarizedExperiment, SingleCellExperiment, MultiAssayExperiment, and MultiAssaySpatialExperiment objects, plus SQL-optimized implementations of scran and scuttle methods for variance modeling, marker detection, QC metrics, and normalization. This package brings together DuckDBDataFrame, DuckDBArray, DuckDBGRanges, and DuckDBSpatial (optional) for complete Bioconductor integration.

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See Also

Useful links:

- <https://github.com/Genentech/BiocDuckDB>
- Report bugs at <https://github.com/Genentech/BiocDuckDB/issues>

DuckDBDataFrame-spatial	<i>DuckDBDataFrame spatial methods</i>
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Description

[DuckDBDataFrame](#) methods for **MultiAssaySpatialExperiment** spatial generics. Lazy layers delegate to **DuckDBSpatial** for SQL-backed spatial operations.

Value

spatialOverlaps() returns the pairwise spatial-overlap result between the lazy layers, spatialMatch() the matched table, and spatialJoin() a sparse pair table (mapping row indices between layers) when sparse = TRUE, or the joined table otherwise. All are computed lazily over the DuckDB-backed layers.

Methods

`spatialOverlaps(x, y, coords = NULL, geom = "geometry")`: Test spatial overlap between lazy spatial layers via [layerSpatialOverlaps](#).

`spatialMatch(x, table, coords, geom = "geometry", join = NULL)`: Match points or geometries to a table via [layerSpatialMatch](#).

`spatialJoin(x, y, join = st_intersects, sparse = TRUE)`: Spatial join between lazy layers. When `sparse = TRUE`, returns a sparse pair table via [st_intersects_table](#); otherwise uses [st_join](#).

See Also

[spatialOverlaps](#), [spatialMatch](#), and [spatialJoin](#) for generic documentation.

Examples

```
# Spatial predicates need DuckDB's optional spatial extension. Probe for it so
# the example runs only where the extension can actually load; it is skipped
# cleanly when offline or behind a firewall that blocks the extension
# repository, or when DuckDBSpatial is not installed.
spatial_ok <- requireNamespace("DuckDBSpatial", quietly = TRUE) &&
  tryCatch({
    DBI::dbGetQuery(DuckDBDataFrame::acquireDuckDBConn(),
      "SELECT ST_Area(ST_GeomFromText('POLYGON((0 0,0 1,1 1,0 0,0 0))'))")
    TRUE
  }, error = function(e) FALSE)
if (spatial_ok) {
  df <- data.frame(id = 1:3, x = 1:3, y = 1:3)
  path <- tempfile(fileext = ".parquet")
  arrow::write_parquet(df, path)
  ddb <- DuckDBDataFrame(path, datacols = c("x", "y"), keycol = "id")
  polygon <- "POLYGON((0 0, 6 0, 6 6, 0 6, 0 0))"
  spatialOverlaps(ddb, polygon, coords = c("x", "y"))
  unlink(path)
}
```

DuckDBDualSubset-class

DuckDBDualSubset objects

Description

The `DuckDBDualSubset` class conforms to the `DualSubset` class from `SingleCellExperiment` to provide lazy node-based subsetting for [DuckDBSelfHits](#) objects.

Details

`DuckDBDualSubset` is a lightweight wrapper around [DuckDBSelfHits](#) that provides node-based subsetting semantics required by `SingleCellExperiment`'s `colPairs/rowPairs` framework. Unlike the `DualSubset` class which materializes data immediately upon subsetting, `DuckDBDualSubset` delegates to the nodes slot in the wrapped `DuckDBSelfHits` object, enabling lazy SQL-based edge filtering.

When a DuckDBDualSubset is subset via `x[i]`, it delegates to `extractNODES(x@hits, i)`, which updates the nodes slot in the DuckDBSelfHits object. Edge filtering is deferred until materialization via SQL WHERE clauses (only edges where BOTH from and to are in the node subset are retained).

Value

The `DuckDBDualSubset()` constructor returns a DuckDBDualSubset object wrapping a [DuckDBSelfHits](#). `length()` returns the number of nodes (an integer); subsetting (`[]`) returns a DuckDBDualSubset, and the `[-` and `c()` methods return the updated DuckDBDualSubset.

Constructor

`DuckDBDualSubset(hits)`: Creates a DuckDBDualSubset object wrapping a DuckDBSelfHits object.
`hits` A [DuckDBSelfHits](#) object containing the edge data.

Accessors

`length(x)`: Returns the number of nodes (`nnode(x@hits)`).

Subsetting

`x[i]`: Performs node-based subsetting by delegating to `extractNODES(x@hits, i)`. This updates the nodes slot in the wrapped DuckDBSelfHits object and applies lazy SQL filtering to retain only edges where BOTH endpoints are in the subset.

Usage with SingleCellExperiment

DuckDBDualSubset objects are typically created automatically when assigning DuckDBSelfHits objects to `colPairs/rowPairs`:

Author(s)

Patrick Aboyoun

See Also

[DuckDBSelfHits](#) for the underlying edge storage class.
[extractNODES](#) for the node-based subsetting method.

Examples

```
library(SingleCellExperiment)
sce <- SingleCellExperiment(assays = list(counts = matrix(1:50, 10, 5)))
hits <- S4Vectors::SelfHits(from = 1:3, to = 2:4, nnode = 5L)
tmp <- tempfile()
writeParquet(hits, tmp)
ddb_hits <- DuckDBSelfHits(tmp, from = "from", to = "to", nnode = 5L)
colPair(sce, "knn") <- ddb_hits
ds <- colPair(sce, "knn")
length(ds)
ds[1:3]
unlink(tmp, recursive = TRUE)
```

DuckDBIrlbaParam

A fast SVD path for DuckDB-backed matrices

Description

DuckDBIrlbaParam is a [BiocSingularParam](#) for [runSVD](#) that, for a [DuckDBMatrix](#), materializes the matrix once into an in-memory sparse matrix and drives **irlba** directly on it, instead of letting **irlba**'s Lanczos iteration call `%%` on the lazy [DuckDBMatrix](#) once per solver step.

Usage

```
DuckDBIrlbaParam(
  memory_limit = initializeOptions("memory_limit"),
  deferred = FALSE,
  fold = Inf,
  extra.work = 7,
  ...
)

## S4 method for signature 'DuckDBIrlbaParam'
runSVD(
  x,
  k,
  nu = k,
  nv = k,
  center = FALSE,
  scale = FALSE,
  BPPARAM = SerialParam(),
  ...,
  BSPARAM = ExactParam()
)
```

Arguments

`memory_limit` Numeric scalar, see the `memory_limit` option in [initializeOptions](#). Materialization is refused above this estimated size (bytes), falling back to the ordinary lazy path.

`deferred`, `fold`, `extra.work`, ... Passed to [IrlbaParam](#).

`x` A matrix-like object, typically a [DuckDBMatrix](#) (the fast path only applies to one; any other input falls back to ordinary [IrlbaParam](#) behavior).

`k`, `nu`, `nv`, `center`, `scale`, `BPPARAM`, `BSPARAM` See [runSVD](#).

Details

[DuckDBMatrix](#) already implements `%%`/ `crossprod` as correct SQL-pushdown methods (see **DuckDBArray**), so `BiocSingular::runSVD(x, BSPARAM = BiocSingular::IrlbaParam())` already computes a correct PCA/SVD directly on a [DuckDBMatrix](#). But each of those `%%` calls pays real SQL query-construction cost, and **irlba**'s Lanczos loop calls it once per solver iteration, hundreds of

times per solve, so the ordinary `IrlbaParam` path is markedly slower on a `DuckDBMatrix` than the same computation in memory (measured: on a real 12,500-cell x 200-HVG benchmark, ~16s vs ~0.3s in-memory).

`DuckDBIrlbaParam` closes that gap for matrices that fit in memory, by reusing the same [loadIntoMemory](#) machinery (`.duckdb_seed_to_sparse_matrix()`, size-gated by `"memory_limit"`) to materialize the matrix exactly once, then calling **BiocSingular**'s own exported `irlba`-driving function ([runIrlbaSVD](#)) directly on the materialized matrix. Reusing that function, rather than reimplementing its `nu/nv` trimming, edge cases, and output packaging, avoids a larger and riskier undertaking than depending on one stable, public function.

Whenever the fast path is not applicable (`x` is not a [DuckDBMatrix](#), its seed is not zero-filled, or the estimated materialized size is over `"memory_limit"`), this falls back to ordinary `IrlbaParam` behavior (the lazy SQL-pushdown `%%` path), so it can never turn previously-*working* (if slower) code into a failure. It can still fail the same way the ordinary path already does, e.g. a non-zero-filled seed is not supported by `%%` either, that case falls back to, and fails identically to, the ordinary path rather than silently producing an incorrect result.

Value

A `DuckDBIrlbaParam` object, for use as the `BSPARAM` argument to [runSVD](#) (and so `scrans::fixedPCA()`, `scater::runPCA()/calculatePCA()`).

Author(s)

Patrick Aboyoun

See Also

- [IrlbaParam](#) for the ordinary, lazy-pushdown behavior
- [loadIntoMemory](#) for the materialization helper this reuses
- [initializeOptions](#) for the shared `"memory_limit"` default

Examples

```
df <- data.frame(row = c("r1", "r2", "r1"), col = c("c1", "c1", "c2"),
                 value = c(1, 2, 3))
tf <- tempfile(fileext = ".parquet")
on.exit(unlink(tf))
arrow::write_parquet(df, tf)
pqmat <- DuckDBArray::DuckDBMatrix(tf, datacol = "value",
                                   keycols = list(row = c("r1", "r2"), col = c("c1", "c2")))
BiocSingular::runSVD(pqmat, k = 1, BSPARAM = DuckDBIrlbaParam())
```

Description

scrans methods for [DuckDBMatrix](#) objects.

Details

The DuckDBMatrix methods compute per-gene statistics using SQL aggregation, which is efficient for large disk-backed matrices:

- For `pairwiseTTests`: per-group means and variances via SQL
- For `pairwiseBinom`: per-group detection counts via SQL

The trend fitting and p-value computations are then performed in R using the standard `scran` functions.

For `findMarkers`, both `test.type="t"` and `test.type="binom"` use optimized DuckDBMatrix implementations. The Wilcoxon test (`test.type="wilcox"`) falls back to the default method because it requires pairwise cell comparisons that are not efficiently expressed in SQL.

Value

These methods mirror their **scran** generics. `correlatePairs()` returns a `DataFrame` of gene pairs with columns `gene1`, `gene2`, `rho` (Pearson's r), `p.value`, and `FDR`. `modelGeneVar()`, `modelGeneVarByPoisson()`, and `modelGeneCV2()` return a `DataFrame` of per-gene variance statistics, with the fitted mean-variance trend in `metadata()`. `pairwiseTTests()` and `pairwiseBinom()` return a list with statistics and pairs elements; `findMarkers()` and `scoreMarkers()` return a [List](#) of per-group `DataFrames` of marker statistics; and `summaryMarkerStats()` returns a `DataFrame` summarizing marker statistics per group.

Pairwise Correlation Methods

The following pairwise correlation methods have optimized DuckDBMatrix implementations:

```
correlatePairs(x, subset.row = NULL, pairings = NULL, use.names = TRUE, BPPARAM = SerialParam()):
```

Compute pairwise Pearson correlations between genes using sparse-aware SQL aggregation, with a standard t-test significance for each correlation (`p.value`, BH-adjusted as `FDR`). Only `fill = 0` is supported. This is Pearson's r on `x` as given (typically log-normalized values), not **scran**'s Spearman's ρ on ranked expression – results are not expected to numerically match `scran::correlatePairs()`.

`subset.row` rows (genes) to correlate; required for >1000 genes

`pairings` optional matrix specifying specific gene pairs

`use.names` whether to use row names in output

Variance Modelling Methods

The following variance modelling methods have optimized DuckDBMatrix implementations:

```
modelGeneVar(x, block = NULL, design = NULL, subset.row = NULL, subset.fit = NULL, ..., equiweight = TRUE):
```

Model the variance of log-expression profiles for each gene, decomposing it into technical and biological components. Uses SQL aggregation for computing per-gene means and variances.

`block` factor specifying blocking levels for each cell

`design` design matrix for blocking (not supported with `block`)

`subset.row` rows for which to model the variance

`subset.fit` rows to be used for trend fitting

`equiweight` whether blocks should be weighted equally

`method` method for combining p-values across blocks

`modelGeneVarByPoisson(x, size.factors = NULL, block = NULL, design = NULL, subset.row = NULL, ..., equiweight = TRUE)`
 Model the variance of log-expression profiles for each gene, using a Poisson-based trend to estimate technical variance. Uses SQL aggregation for computing per-gene means and variances.

`size.factors` numeric vector of size factors for normalization
`block` factor specifying blocking levels for each cell
`design` design matrix for blocking (not supported with `block`)
`subset.row` rows for which to model the variance
`equiweight` whether blocks should be weighted equally
`method` method for combining p-values across blocks

`modelGeneCV2(x, size.factors = NULL, block = NULL, subset.row = NULL, subset.fit = NULL, ..., equiweight = TRUE)`
 Model the squared coefficient of variation (CV2) of normalized expression for each gene, fitting a trend to account for the mean-CV2 relationship. Uses SQL aggregation for computing per-gene means and variances on size-factor normalized counts.

`size.factors` numeric vector of size factors for normalization
`block` factor specifying blocking levels for each cell
`subset.row` rows for which to model the CV2
`subset.fit` rows to be used for trend fitting
`equiweight` whether blocks should be weighted equally
`method` method for combining p-values across blocks

Marker Gene Detection Methods

The following marker gene detection methods have optimized DuckDBMatrix implementations:

`pairwiseTTests(x, groups, block = NULL, design = NULL, restrict = NULL, exclude = NULL, direction = c("any", "up", "down"), lfc = 1, std.lfc = FALSE, log.p = FALSE, gene.names = NULL)`
 Perform pairwise Welch t-tests between groups of cells. Uses SQL aggregation for computing per-gene, per-group means and variances.

`groups` vector specifying group assignment for each cell
`block` factor specifying blocking levels
`restrict` character vector of groups to restrict comparisons to
`exclude` character vector of groups to exclude from comparisons
`direction` direction of log-fold changes to consider
`lfc` log-fold change threshold
`std.lfc` whether to standardize log-fold changes
`log.p` whether to return log-transformed p-values
`gene.names` character vector of gene names for output

`pairwiseBinom(x, groups, block = NULL, restrict = NULL, exclude = NULL, direction = c("any", "up", "down"), threshold = 0.01, lfc = 1)`
 Perform pairwise binomial tests between groups of cells. Uses SQL aggregation for computing per-gene, per-group detection counts.

`groups` vector specifying group assignment for each cell
`block` factor specifying blocking levels
`restrict` character vector of groups to restrict comparisons to
`exclude` character vector of groups to exclude from comparisons
`direction` direction of log-fold changes to consider
`threshold` expression threshold for detection
`lfc` log-fold change threshold for proportions

`log.p` whether to return log-transformed p-values
`gene.names` character vector of gene names for output
`findMarkers(x, groups, test.type = c("t", "wilcox", "binom"), ..., pval.type = c("any", "some", "all"))`
 Find candidate marker genes for groups of cells.
`groups` vector specifying group assignment for each cell
`test.type` type of pairwise test ("t" and "binom" are optimized)
`pval.type` how to combine p-values across pairwise tests
`sorted` whether to sort results by significance
`add.summary` whether to add summary statistics
`scoreMarkers(x, groups, block = NULL, pairings = NULL, lfc = 0, row.data = NULL, full.stats = FALSE, sub)`
 Compute effect size summary statistics for potential marker genes. Uses SQL aggregation for computing per-gene, per-group means, variances, and detection proportions.
AUC computation options: By default (`true.auc = FALSE`), AUC is computed using a normal approximation which is fast (~97% correlation with `scran`). Set `true.auc = TRUE` to compute true rank-based AUC using SQL window functions (Wilcoxon rank-sum statistic). This is slower (~15-25x) but provides exact AUC values identical to `scran` (100% correlation).
`groups` vector specifying group assignment for each cell
`block` factor specifying blocking levels
`pairings` specification of pairwise comparisons to compute
`lfc` log-fold change threshold for effect sizes
`row.data` additional row data to include in output
`full.stats` whether to return full pairwise statistics
`true.auc` logical indicating whether to compute true rank-based AUC via SQL window functions (default `FALSE` uses normal approximation with ~97% correlation; `TRUE` gives 100% exact match but is ~15-25x slower)
`summaryMarkerStats(x, groups, row.data = NULL, average = "mean", BPPARAM = SerialParam())`
 Compute summary statistics for marker gene selection. Uses SQL aggregation for per-group means and detection proportions.
`groups` vector specifying group assignment for each cell
`row.data` additional row data to include in output
`average` type of average to compute ("mean" or "median")

AUC Computation in `scoreMarkers`

The `scoreMarkers` method for `DuckDBMatrix` provides two AUC computation modes:

Normal approximation (default, `true.auc = FALSE`):

$$AUC \approx \Phi \left(\frac{\mu_1 - \mu_2}{\sqrt{\sigma_1^2/n_1 + \sigma_2^2/n_2}} \right)$$

where Φ is the standard normal CDF. This is fast but may be inaccurate for sparse/bimodal data.

True rank-based AUC (`true.auc = TRUE`): Computes exact AUC via the Wilcoxon rank-sum statistic using SQL window functions:

$$AUC = \frac{R_1 - n_1(n_1 + 1)/2}{n_1 \cdot n_2}$$

where R_1 is the sum of ranks in group 1. This is ~15-25x slower than the normal approximation but provides exact results identical to `scran` (correlation = 1.0).

Benchmarks (5000 genes x 5000 cells, 12 pairwise comparisons):

- Default (normal approx): 0.68s, ~97% correlation with scran
- `true.auc = TRUE`: 17.7s, 100% exact match with scran

The true AUC is preferred for:

- Genes with bimodal expression (expressed vs. not expressed)
- Sparse data with many zeros
- Applications where exact effect sizes are important

Alternatively, use `findMarkers(x, groups, test.type = "wilcox")` for rank-based p-values.

Author(s)

Patrick Abouyoun

See Also

- [DuckDBMatrix-class](#) for the main class
- [DuckDBMatrix-scuttle](#) for the scuttle methods
- [correlatePairs](#) for the scran generic
- [modelGeneVar](#) for the scran generic
- [modelGeneVarByPoisson](#) for the scran generic
- [modelGeneCV2](#) for the scran generic
- [pairwiseTTests](#) for the scran generic
- [pairwiseBinom](#) for the scran generic
- [findMarkers](#) for the scran generic
- [scoreMarkers](#) for the scran generic
- [summaryMarkerStats](#) for the scran generic

Examples

```
mat <- matrix(rpois(500, 5), 25, 20)
dimnames(mat) <- list(paste0("G", 1:25), paste0("C", 1:20))
names(dimnames(mat)) <- c("index1", "index2")
tmp <- tempfile()
writeParquet(mat, tmp)
pqmat <- DuckDBMatrix(tmp, datacol = "value",
  keycols = lapply(dimnames(mat), function(x) setNames(seq_along(x), x)))
head(scran::modelGeneVarByPoisson(pqmat))
unlink(tmp, recursive = TRUE)
```

Description

scuttle methods for [DuckDBMatrix](#) objects.

Value

These methods mirror their **scuttle** generics. `perCellQCMetrics()` and `perFeatureQCMetrics()` return a `DataFrame` of QC metrics. `librarySizeFactors()`, `geometricSizeFactors()`, and `calculateAverage()` return a numeric vector. `normalizeCounts()`, `calculateCPM()`, and `calculateTPM()` return a matrix-like object of transformed values, and `numDetectedAcrossFeatures()` and `sumCountsAcrossFeatures()` return a matrix-like object of per-group summaries. `summarizeAssayByGroup()` returns a [Summarized-Experiment](#) of per-group assay summaries.

QC Metrics Methods

The following QC metrics methods have optimized DuckDBMatrix implementations:

`perCellQCMetrics(x, subsets = NULL, percent.top = integer(0), threshold = 0, ..., flatten = TRUE)`:

Compute per-cell quality control metrics for a count matrix.

`subsets` named list of vectors specifying feature subsets (e.g., mitochondrial genes). Each vector can be character (feature names), logical, or integer (indices). Returns sum, detected, and percent for each subset.

`percent.top` integer vector specifying the sizes of the top sets of high-abundance genes (e.g., `c(50, 100, 200)`). For each size, computes the percentage of total counts assigned to the most highly expressed genes in each cell. Uses SQL window functions for efficient computation.

`threshold` numeric scalar specifying the detection threshold

`flatten` logical scalar indicating whether nested `DataFrames` in the output should be flattened. If `TRUE` (default), subset and percent.top statistics are returned as top-level columns (e.g., `subsets_Mito_sum`, `percent.top_50`). If `FALSE`, nested `DataFrames/matrices` are returned.

`perFeatureQCMetrics(x, subsets = NULL, threshold = 0, ..., flatten = TRUE)`: Compute per-feature quality control metrics for a count matrix.

`subsets` named list of vectors specifying cell subsets (e.g., control wells). Each vector can be character (cell names), logical, or integer (indices). Returns mean, detected, and ratio for each subset.

`threshold` numeric scalar specifying the detection threshold

`flatten` logical scalar indicating whether nested `DataFrames` in the output should be flattened. If `TRUE` (default), subset statistics are returned as top-level columns (e.g., `subsets_SetA_mean`). If `FALSE`, a nested subsets `DataFrame` is returned.

Normalization Methods

The following normalization methods have optimized DuckDBMatrix implementations:

`librarySizeFactors(x)`: Define per-cell size factors from the library sizes.

`geometricSizeFactors(x, pseudo.count = 1)`: Define per-cell size factors from the geometric mean of counts per cell.

`pseudo.count` numeric scalar specifying the pseudo-count to add during log-transformation

`normalizeCounts(x, size.factors = NULL, log = TRUE, transform = c("log", "none", "asinh"), pseudo.count = 1)`

Normalizes counts by dividing by size factors.

`size.factors` numeric vector of cell-specific size factors

`log` logical scalar indicating whether normalized values should be log2-transformed

`transform` string specifying the transformation to apply to the normalized expression values.

`pseudo.count` numeric scalar specifying the pseudo-count to add when `transform = "log"`

`center.size.factors` logical scalar indicating whether size factors should be centered at unity before being used

`subset.row` vector specifying the subset of rows of `x` for which to return normalized values

`calculateTPM(x, lengths = NULL, ...)`: Calculates transcripts per million using SQL-optimized row-wise sweep.

`lengths` Numeric vector of gene lengths.

`calculateCPM(x, size.factors = NULL, subset.row = NULL, ...)`: Calculates counts per million using DelayedArray-safe sweep operations.

`size.factors` numeric vector containing size factors to adjust the library sizes. If `NULL`, library sizes are used directly.

`subset.row` vector specifying the subset of rows of `x` for which to return normalized values

`calculateAverage(x, size.factors = NULL, subset.row = NULL, BPPARAM = SerialParam(), ...)`: Calculates average counts per feature using DelayedArray-safe sweep operations.

`size.factors` numeric vector containing size factors. If `NULL`, library size factors are computed automatically.

`subset.row` vector specifying the subset of rows of `x` for which to return averages

`BPPARAM` BiocParallelParam object for parallel computation

The following normalization methods will dispatch to optimized DuckDBMatrix implementations of `normalizeCounts`, `librarySizeFactors`, `calculateCPM`, `calculateAverage`, and `calculateTPM`.

Aggregation Methods

The following aggregation methods have optimized DuckDBMatrix implementations that use SQL GROUP BY operations for efficient pseudo-bulk analysis:

`numDetectedAcrossFeatures(x, ids, subset.row = NULL, subset.col = NULL, average = FALSE, threshold = 0)`
Count detected features across feature sets for each cell.

`ids` factor or list specifying feature groupings

`average` logical indicating whether to compute the proportion

`threshold` threshold for detection

`sumCountsAcrossFeatures(x, ids, subset.row = NULL, subset.col = NULL, average = FALSE, ...)`
Sum counts across feature sets for each cell.

`ids` factor or list specifying feature groupings

`average` logical indicating whether to compute the average

`summarizeAssayByGroup(x, ids, subset.row = NULL, subset.col = NULL, statistics = c("mean", "sum", "num"))`
From an assay matrix, compute summary statistics for groups of cells.

`ids` factor specifying the group for each cell

`statistics` character vector of statistics to compute

`threshold` threshold for detection

Author(s)

Patrick Aboyoun

See Also

- [DuckDBMatrix-class](#) for the main class
- [DuckDBArray-matrixStats](#) for the matrixStats methods
- [perCellQCMetrics](#) for the scuttle generic
- [perFeatureQCMetrics](#) for the scuttle generic
- [librarySizeFactors](#) for the scuttle generic
- [normalizeCounts](#) for the scuttle generic
- [calculateCPM](#) for the scuttle generic
- [calculateAverage](#) for the scuttle generic
- [calculateTPM](#) for the scuttle generic
- [numDetectedAcrossFeatures](#) for the scuttle generic
- [sumCountsAcrossFeatures](#) for the scuttle generic
- [summarizeAssayByGroup](#) for the scuttle generic

Examples

```
mat <- matrix(rpois(500, 5), 25, 20)
dimnames(mat) <- list(paste0("G", 1:25), paste0("C", 1:20))
names(dimnames(mat)) <- c("index1", "index2")
tmp <- tempfile()
writeParquet(mat, tmp)
pqmat <- DuckDBMatrix(tmp, datacol = "value",
  keycols = lapply(dimnames(mat), function(x) setNames(seq_along(x), x)))
head(librarySizeFactors(pqmat))
unlink(tmp, recursive = TRUE)
```

initializeCpp

*Initialize DuckDB-backed matrices for beachmat***Description**

Registers a [initializeCpp](#) method for [DuckDBArraySeed](#) objects (the seed underlying every [DuckDBMatrix](#)), giving compiled C++ code that goes through **beachmat/tatami** (e.g. BiocSingular's `compute_center/compute_scale`) a fast path instead of always falling back to **beachmat**'s generic "unknown matrix" block-processing path.

Usage

```
## S4 method for signature 'DuckDBArraySeed'
initializeCpp(
  x,
  ...,
  duckdb.realize = initializeOptions("realize"),
  duckdb.memory_limit = initializeOptions("memory_limit")
)
```

Arguments

<code>x</code>	A DuckDBArraySeed object.
<code>...</code>	Further arguments, passed to beachmat 's generic fallback method when the fast path is not applicable.
<code>duckdb.realize</code>	Logical scalar, see the <code>realize</code> option in initializeOptions .
<code>duckdb.memory_limit</code>	Numeric scalar, see the <code>memory_limit</code> option in initializeOptions .

Details

Unlike `beachmat.hdf5/beachmat.tiledb`, there is no dedicated `tatami_duckdb` C++ library implementing genuine on-demand, out-of-core reads. This method instead materializes the seed's underlying COO table into an in-memory sparse matrix via a single bulk SQL pull ([loadIntoMemory](#)), then delegates to **beachmat**'s own native `initializeCpp, dgCMatrix`-method. This mirrors `beachmat.hdf5`'s *opt-in* `realize` path, not its default on-demand streaming path, and is only attempted for a zero-filled (sparse) seed within [initializeOptions](#)'s `"memory_limit"`.

Unlike `beachmat.hdf5/beachmat.tiledb`, the materialized pointer is **not** cached across calls with [checkMemoryCache](#). Verified empirically that doing so is unsafe here: two [DuckDBMatrix](#) objects built from the same underlying query (the common case, e.g. re-reading the same release twice) render identical SQL and would hit the same cache entry, but reusing that cached pointer across a later, logically separate computation silently corrupted results. Every call re-materializes, which costs a fraction of a second for a `"memory_limit"`-sized matrix, negligible next to the speedup this fast path already provides.

This is purely a performance optimization for anything that already goes through `initializeCpp` (e.g. `BiocSingular::runSVD`'s center/scale computation). It does **not** speed up `irlba`'s Lanczos iteration itself, which calls `%%` directly on the [DuckDBMatrix](#) object rather than through `initializeCpp`; use the SQL-pushdown `%%/crossprod` methods in **DuckDBArray** for that, or materialize small-enough matrices with [loadIntoMemory](#) and drive `irlba` directly.

Whenever the fast path is not applicable (a non-zero-filled seed, more than 2 keyed dimensions, or an estimated size over `"memory_limit"`), this method falls back to **beachmat**'s existing generic path rather than raising an error, so it can never make previously-working (if slower) code stop working.

Value

An external pointer that can be used in any **tatami**-compatible function.

Author(s)

Patrick Aboyoun

See Also

- [initializeCpp](#) for the generic
- [loadIntoMemory](#) to force materialization directly
- [initializeOptions](#) for the tunable defaults

Examples

```
# A genuinely sparse 2x2 matrix: (r2, c2) is an implicit zero.
df <- data.frame(row = c("r1", "r2", "r1"), col = c("c1", "c1", "c2"),
                 value = c(1, 2, 3))
tf <- tempfile(fileext = ".parquet")
on.exit(unlink(tf))
arrow::write_parquet(df, tf)
pqmat <- DuckDBArray::DuckDBMatrix(tf, datacol = "value",
                                   keycols = list(row = c("r1", "r2"), col = c("c1", "c2")))
ptr <- beachmat::initializeCpp(pqmat@seed)
```

initializeOptions	<i>Options for DuckDB-backed matrices</i>
-------------------	---

Description

Options for initializing DuckDB-backed matrices in [initializeCpp](#).

Usage

```
initializeOptions(option, value)
```

Arguments

option	String specifying the name of the option.
value	Value of the option.

Details

The following options are supported:

- `realize`, a logical scalar specifying whether to materialize a [DuckDBArraySeed](#)'s underlying COO table into an in-memory sparse matrix with [loadIntoMemory](#) on every [initializeCpp](#) call (unlike `beachmat.hdf5/ beachmat.tiledb`, this is deliberately **not** cached across calls, see [initializeCpp](#)'s details for why). Unlike `beachmat.hdf5/beachmat.tiledb` (which default this to FALSE because they have a genuine on-demand streaming backend), this defaults to TRUE: BiocDuckDB has no native out-of-core **tatami** backend, so setting this to FALSE falls back to **beachmat**'s generic "unknown matrix" block-processing path rather than a faster streaming one.
- `memory_limit`, a numeric scalar specifying the maximum estimated size, in bytes, of the sparse matrix materialized by [loadIntoMemory](#). Above this limit, materialization is refused so a genuinely out-of-core matrix fails loudly (and falls back to the generic path, when reached via [initializeCpp](#)) instead of risking an OOM.

Value

If value is missing, the current setting of option is returned. If value is supplied, it is used to set the option, and the previous value of the option is invisibly returned.

Author(s)

Patrick Aboyoun

See Also

[initializeCpp](#), [loadIntoMemory](#)

Examples

```
initializeOptions("memory_limit")
old <- initializeOptions("memory_limit", 4 * 1024^3)
initializeOptions("memory_limit")
initializeOptions("memory_limit", old)
```

linkSpatialMap	<i>Link assay observations to their spatial layer rows</i>
----------------	--

Description

Joins the observations recorded in `spatialMap` to the rows of the spatial layer they reference, through the full junction key (assay, colname, element_type, region, instance_id). Resolves a single (element_type, region) layer (inferred from the filtered `spatialMap` when unambiguous, else specify); the join is pushed to DuckDB and returned as a lazy [DuckDBDataFrame](#) with the assay identity columns plus the layer's coordinate columns.

Usage

```
linkSpatialMap(
  mase,
  assay = NULL,
  element_type = NULL,
  region = NULL,
  conn = acquireDuckDBConn()
)
```

Arguments

`mase` A [MultiAssaySpatialExperiment](#).

`assay`, `element_type`, `region` Optional filters selecting the `spatialMap` rows (and thus the single layer) to link.

`conn` A DuckDB connection (default the shared `BiocDuckDB` connection).

Value

A lazy [DuckDBDataFrame](#) of linked observations.

Examples

```
mase <- readParquet(system.file("extdata", "spatial_mase",
                                package = "BiocDuckDB"))
linkSpatialMap(mase, assay = "assay1")
```

loadIntoMemory	<i>Load a DuckDB-backed matrix into memory</i>
----------------	--

Description

Load a [DuckDBMatrix](#)'s (or its [DuckDBArraySeed](#)'s) underlying COO table into memory as an external pointer to a **tatami**-compatible representation, via a single bulk SQL pull. This is what [initializeCpp](#) calls internally when `duckdb.realize = TRUE` (the default); call it directly when you want the materialized pointer without going through the `initializeCpp` generic. Each call re-materializes; the result is deliberately not cached (see [initializeCpp](#)'s details for why).

Usage

```
loadIntoMemory(x, memory_limit = initializeOptions("memory_limit"))
```

Arguments

<code>x</code>	A DuckDBMatrix or DuckDBArraySeed object.
<code>memory_limit</code>	Numeric scalar, see the <code>memory_limit</code> option in initializeOptions . Materialization is refused above this estimated size (bytes) rather than risking an OOM.

Value

An external pointer that can be used in **tatami**-based functions.

Author(s)

Patrick Aboyoun

See Also

[initializeCpp](#), [initializeOptions](#)

Examples

```
# A genuinely sparse 2x2 matrix: (r2, c2) is an implicit zero.
df <- data.frame(row = c("r1", "r2", "r1"), col = c("c1", "c1", "c2"),
                 value = c(1, 2, 3))
tf <- tempfile(fileext = ".parquet")
on.exit(unlink(tf))
arrow::write_parquet(df, tf)
pqmat <- DuckDBArray::DuckDBMatrix(tf, datacol = "value",
                                   keycols = list(row = c("r1", "r2"), col = c("c1", "c2")))
ptr <- loadIntoMemory(pqmat)
```

MultiAssaySpatialExperiment-spatial

MultiAssaySpatialExperiment lazy spatial methods

Description

Lazy [MultiAssaySpatialExperiment](#) methods that keep spatial layers as [DuckDBDataFrame](#) objects when possible. In-memory MASE defaults are used when no lazy layers are present.

Value

`readParquetForMASE()` returns the parsed table — a lazy [DuckDBDataFrame](#) for large files, or an in-memory object for small ones — and `readGeoParquetForMASE()` returns a geometry-bearing object (an [sf](#) data frame). `annotateWithRegions()`, `subsetByBoundingBox()`, and `subsetByPolygon()` return a [MultiAssaySpatialExperiment](#) (annotated or spatially subset).

Parquet readers

`readParquetForMASE(file_path, col_select = NULL, ...)`: Files larger than 50 MB are read as lazy [DuckDBDataFrame](#) objects; smaller files use the in-memory **MultiAssaySpatialExperiment** method.

`readGeoParquetForMASE(file_path, ...)`: Uses [readGeoParquet](#) when **DuckDBSpatial** is installed; otherwise falls back to **sfcarrow**.

Spatial operations

`annotateWithRegions(x, points, shapes, ...)`: Annotate points with shape regions using lazy `spatialMatch`.

`subsetByBoundingBox(x, xmin, xmax, ymin, ymax, ...)`: Subset by bounding box with lazy layer filtering when applicable.

`subsetByPolygon(x, polygon, ...)`: Subset by polygon with lazy layer filtering when applicable.

See Also

[readParquetForMASE](#), [readGeoParquetForMASE](#), [annotateWithRegions](#), [subsetByBoundingBox](#), and [subsetByPolygon](#).

Examples

```
# subsetByBoundingBox on a DuckDB-backed layer uses DuckDB's optional spatial
# extension; probe for it so the example is skipped cleanly where the
# extension cannot load (offline / firewalled repository / not installed).
spatial_ok <- requireNamespace("MultiAssaySpatialExperiment", quietly = TRUE) &&
  requireNamespace("sf", quietly = TRUE) &&
  requireNamespace("DuckDBSpatial", quietly = TRUE) &&
  tryCatch({
    DBI::dbGetQuery(DuckDBDataFrame::acquireDuckDBConn(),
      "SELECT ST_Area(ST_GeomFromText('POLYGON((0 0,0 1,1 1,1 0,0 0)))')")
    TRUE
  }, error = function(e) FALSE)
```

```

if (spatial_ok) {
  pts <- S4Vectors::DataFrame(
    x = 1:3, y = 1:3, instance_id = c("A", "B", "C"))
  mat <- matrix(1:9, 3, 3,
    dimnames = list(paste0("G", 1:3), c("A", "B", "C")))
  mase <- MultiAssaySpatialExperiment::MultiAssaySpatialExperiment(
    experiments = MultiAssayExperiment::ExperimentList(rna = mat),
    colData = S4Vectors::DataFrame(row.names = "s1"),
    sampleMap = S4Vectors::DataFrame(
      assay = "rna", primary = "s1", colname = c("A", "B", "C")),
    points = MultiAssaySpatialExperiment::PointsLayerList(centroids = pts))
  tmp <- tempfile()
  writeParquet(mase, tmp)
  mase2 <- readParquet(tmp)
  subsetByBoundingBox(mase2, xmin = 1, xmax = 3, ymin = 1, ymax = 3)
  unlink(tmp, recursive = TRUE)
}

```

readParquet

Read Parquet Representation of a Bioconductor Object

Description

Reads a parquet representation of various Bioconductor objects from disk using the Frictionless Data Package metadata model, reconstructing them as DuckDB-backed objects. This function is the counterpart to [writeParquet](#) and supports reading SummarizedExperiment, RangedSummarizedExperiment, SingleCellExperiment, and MultiAssayExperiment objects that have been written to parquet format with comprehensive metadata.

Usage

```

readParquet(
  path,
  package = .readDatapackage(path),
  model = package[["model"]],
  ...
)

```

Arguments

path	A character string specifying the path to the directory containing the parquet files. The directory must contain a datapackage.json file written by writeParquet .
package	A list containing the parsed datapackage.json contents. Defaults to reading file.path(path, "datapackage.json"). Contains the package-level model field and a resources list describing each parquet dataset.
model	A character string identifying the package schema — which container class to reconstruct. Defaults to package[["model"]]. Supported values: "summarized_experiment", "ranged_summarized_experiment", "single_cell_experiment", "experiment_list", "multi_assay_experiment", "multi_assay_spatial_experiment". When NULL (absent from the package JSON), all resources are returned as a SimpleList with no imposed schema.
...	Additional arguments passed to internal helper functions.

Details

This function reads parquet files that were created by [writeParquet](#) using the Frictionless Data Package metadata model and reconstructs the original Bioconductor object structure. This function supports different object types through a switch statement that routes to appropriate helper functions:

SummarizedExperiment objects: Reads feature data, sample data, and assay data from separate parquet files, reconstructing the object with DuckDB-backed components. For ranged experiments, genomic coordinates are reconstructed as DuckDBGRanges objects.

SingleCellExperiment objects: Extends SummarizedExperiment functionality by also reading reduced dimensions, loadings, alternative experiments, row / column tables, and row / column pairings from their respective parquet files.

MultiAssayExperiment objects: Reads multiple experiments along with sample data and sample mapping information, reconstructing the multi-experiment structure.

This function uses the Frictionless Data Package metadata to understand the structure of the data, including resource schemas with field definitions, primary keys, and semantic meanings (sequence_name, start, end, strand for genomic data) encoded in the datapackage.json file.

Value

A Bioconductor object of the appropriate class, reconstructed using DuckDB backend classes:

- [DuckDBMatrix](#) objects for assay data
- [DuckDBDataFrame](#) objects for row and column metadata
- [DuckDBGRanges](#) objects for genomic ranges
- [DuckDBGRangesList](#) objects for grouped genomic ranges
- [DuckDBSelfHits](#) objects for graph edge lists
- [DuckDBDualSubset](#) objects for pairwise graphs (wrapping DuckDBSelfHits)

Supported Object Types

GenomicRanges Read with genomic coordinates (seqnames, start, end, strand) and optional metadata columns.

GenomicRangesList Read with genomic coordinates and metadata columns.

DuckDBSelfHits Graph edge lists with from, to columns and optional metadata. Node count (nnode) is stored in the schema graphEdges property.

SummarizedExperiment Feature metadata from features/, sample metadata from samples/, and assays from flat assay_<name>/ directories. Any complex objects stored in metadata() are written to unbound_<name>/ directories and restored on read.

RangedSummarizedExperiment As SummarizedExperiment, with rowRanges reconstructed as a DuckDBGRanges from features/.

SingleCellExperiment Extends SummarizedExperiment with: reduced dimensions from sample_embeddings/; row loadings from feature_embeddings/; alternative experiments from experiment_<name>/ directories; row/column tables from flat feature_table_<name>/ and sample_table_<name>/ directories; row/column pairwise graphs from flat feature_graph_<name>/ and sample_graph_<name>/ directories.

MultiAssayExperiment Experiments written directly to root as experiment_<name>/ directories (flattened). Each SummarizedExperiment has its own datapackage.json (layout = "nested_experiment"). Also includes subjects (subject metadata) and sample_map (subject-to-sample mapping) as unbound resources.

MultiAssaySpatialExperiment Extends **MultiAssayExperiment** with spatial points from flat `sample_points_<name>/` directories, shapes from flat `sample_shapes_<name>/` directories, image metadata from `img_data/`, and spatial mapping from `spatial_map/`. Requires the **MultiAssaySpatialExperiment** package.

Frictionless Data Package Metadata

This function reads data packages that follow the Frictionless Data Package specification (extended by the BiocDuckDB profile), parsing the `datapackage.json` metadata file. Dispatch operates at two levels:

Package level (root `datapackage.json`):

- `model` — which container class to reconstruct; absent means `SimpleList` fallback.
- `annotations` — non-relational metadata from `metadata(x)` (scalars, vectors, 1-D arrays, JSON-safe nested lists). Tabular items are referenced via `parquet_ref` stubs pointing at unbound Parquet sidecars; mixed nested lists use a `nested_mapping` wrapper.

Resource level (entries in `resources` array):

- `dimension` — biological axis ("`feature`", "`sample`", "`crossed`", "`unbound`").
- `layout` — physical storage pattern (e.g., "`data_frame`", "`coord_array`", "`graph_edges`", "`nested_experiment`"); routes each resource to the appropriate low-level reader via `.readParquetResource`.
- `schema` — field definitions, primary keys, and BiocDuckDB annotations (`genomicCoords`, `graphEdges`, `arrayItem`).

Author(s)

Patrick Aboyoun

See Also

- [writeParquet](#) for writing Bioconductor objects to parquet
- [DuckDBMatrix](#) for matrix storage
- [DuckDBDataFrame](#) for metadata storage
- [DuckDBGRanges](#) for genomic ranges
- [DuckDBGRangesList](#) for grouped genomic ranges
- [DuckDBSelfHits](#) for graph edge lists

Examples

```
se <- SummarizedExperiment::SummarizedExperiment(
  assays = list(counts = matrix(rpois(500, 5), 25, 20)),
  colData = S4Vectors::DataFrame(sample = rep(c("A", "B"), each = 10)))
tmpdir <- tempfile()
writeParquet(se, tmpdir)
se2 <- readParquet(tmpdir)
class(se2)
dim(se2)
unlink(tmpdir, recursive = TRUE)
```

SingleCellExperiment-colTables

Sample table methods

Description

Methods to get or set nested sample-level tables in a [SingleCellExperiment](#) object. These tables enable storage of multi-column relational data associated with samples (cells/perturbations), which would otherwise require nested DataFrames in `colData()`. By extracting nested tables into a separate slot, they can be serialized to independent Parquet tables for efficient querying.

Arguments

<code>x</code>	A SingleCellExperiment object.
<code>type</code>	String or integer scalar specifying the name or index of the table to get or set.
<code>withDimnames</code>	Logical scalar indicating whether row names should be extracted from (getters) or set to (setters) the column names of <code>x</code> .
<code>...</code>	Additional arguments, currently ignored.
<code>value</code>	For the getter, a DataFrame-like object with number of rows equal to <code>ncol(x)</code> , containing the table data. For <code>colTables<=</code> , a list of such DataFrames. For <code>colTableNames<=</code> , a character vector of names.

Details

Sample tables (`colTables`) are stored in `int_colData(x)$colTables` and provide a mechanism to unnest complex relational data from `colData()`. This is particularly useful when sample metadata contains multi-valued properties or hierarchical structures that are difficult to query when embedded as nested DataFrames.

Common use cases include:

- Patient metadata: multiple disease diagnoses, treatment histories, or demographic details per sample
- Experimental metadata: replicate-level measurements, batch details, or quality control metrics
- Cell lineage: developmental trajectories or cell state transitions

Each table is a [DataFrame](#) with `ncol(x)` rows, maintaining alignment with samples. Tables are automatically subset when the parent `SingleCellExperiment` is subset by columns.

Value

For `colTable`, a DataFrame containing sample-level relational data.

For `colTables`, a [SimpleList](#) of such DataFrames.

For `colTableNames`, a character vector of table names.

For all setters, `x` is returned with the modified tables or names.

Getters

In the following examples, `x` is a [SingleCellExperiment](#) object.

`colTable(x, type, withDimnames=TRUE)`: Retrieves a `DataFrame` containing sample-level relational data. `type` is either a string specifying the name of the table in `x` to retrieve, or a numeric scalar specifying the index of the desired table.

If `withDimnames=TRUE`, row names of the output `DataFrame` are replaced with the column names of `x`.

`colTableNames(x)`: Returns a character vector containing the names of all tables in `x`. This is guaranteed to be of the same length as the number of tables, though the names may not be unique.

`colTables(x, withDimnames=TRUE)`: Returns a named [SimpleList](#) of `DataFrames` containing one or more tables. Each table has the same number of rows as `ncol(x)`.

If `withDimnames=TRUE`, row names of each `DataFrame` are replaced with the column names of `x`.

Single-table setter

`colTable(x, type, withDimnames=TRUE) <- value` will add or replace a table in a [SingleCellExperiment](#) object `x`. The value of `type` determines how the table is added or replaced:

- If `type` is a numeric scalar, it must be within the range of existing tables, and `value` will be assigned to the table at that index.
- If `type` is a string and a table exists with this name, `value` is assigned to that table. Otherwise a new table with this name is appended to the existing list of tables.

`value` is expected to be a `DataFrame` or `data.frame`-like object with number of rows equal to `ncol(x)`.

If `withDimnames=TRUE`, row names of `value` are set to `colnames(x)`.

Other setters

In the following examples, `x` is a [SingleCellExperiment](#) object.

`colTables(x, withDimnames=TRUE) <- value`: Replaces all tables in `x` with those in `value`. The latter should be a list-like object containing any number of `DataFrames` or `data.frame`-like objects with number of rows equal to `ncol(x)`.

If `value` is named, those names will be used to name the tables in `x`.

If `value` is a [Annotated](#) object, any `metadata` will be retained in `colTables(x)`. If `value` is a [Vector](#) object, any `mcols` will also be retained.

If `withDimnames=TRUE`, row names in each entry of `value` are set to `colnames(x)`.

`colTableNames(x) <- value`: Replaces all names for tables in `x` with a character vector `value`. This should be of length equal to the number of tables currently in `x`.

Author(s)

Patrick Aboyoun

See Also

[colData](#) for simple sample metadata.

[rowTables](#) for feature-level nested tables.

[int_colData](#) for the internal column metadata storage.

Examples

```

library(SingleCellExperiment)

# Create example SCE
sce <- SingleCellExperiment(
  assays = list(counts = matrix(rpois(1000, 5), 100, 10))
)
rownames(sce) <- paste0("Gene", 1:100)
colnames(sce) <- paste0("Cell", 1:10)

# Add a table of patient disease history (multiple diseases per patient)
diseases <- DataFrame(
  disease_id = paste0("MONDO:", sample(100000:999999, 10)),
  disease_label = paste0("Disease_", 1:10),
  onset_age = sample(20:80, 10, replace = TRUE)
)
colTable(sce, "diseases") <- diseases

# Add a table of per-sample QC metrics
qc_metrics <- DataFrame(
  metric_name = rep(c("n_genes", "n_counts", "pct_mito"), length.out = 10),
  value = runif(10, 1000, 5000),
  passed = sample(c(TRUE, FALSE), 10, replace = TRUE)
)
colTable(sce, "qc") <- qc_metrics

# Retrieve all tables
all_tables <- colTables(sce)
names(all_tables)

# Retrieve specific table by name
dis <- colTable(sce, "diseases")
dim(dis) # 10 samples x 3 columns

# Retrieve by index
qc <- colTable(sce, 2)

# Get table names
colTableNames(sce)

# Subset SCE - tables are automatically subset
sce_sub <- sce[, 1:5]
dim(colTable(sce_sub, "diseases")) # 5 samples x 3 columns

```

SingleCellExperiment-loadings

Feature loading methods

Description

Methods to get or set feature-level loading matrices in a [SingleCellExperiment](#) object. These matrices represent per-feature contributions to latent factors, embeddings, or statistical models, where feature identity (e.g., gene names) carries semantic meaning. Each row of a loading matrix corresponds to a row (feature) of the `SingleCellExperiment` object.

Arguments

<code>x</code>	A SingleCellExperiment object.
<code>type</code>	String or integer scalar specifying the name or index of the loading result to get or set.
<code>withDimnames</code>	Logical scalar indicating whether row names should be extracted from (getters) or set to (setters) the row names of <code>x</code> .
<code>...</code>	Additional arguments, currently ignored.
<code>value</code>	For the getter, a matrix-like object with number of rows equal to <code>nrow(x)</code> , containing the loading values. For <code>rowLoadings<-</code> , a list of such matrices. For <code>rowLoadingNames<-</code> , a character vector of names.

Details

Feature loadings (`rowLoadings`) are stored in `int_elementMetadata(x)$rowLoadings` and represent the `AnnData .varm` equivalent in R. Unlike sample embeddings (`reducedDims`) where dimension labels are arbitrary coordinates, loading matrices have **meaningful row names** that identify which features contribute to each latent dimension.

Common use cases include:

- PCA loadings: which genes load on each principal component
- Factor analysis: gene weights for latent factors
- Statistical summaries: per-gene effect sizes or log fold changes across conditions

Loading matrices are automatically subset when the parent `SingleCellExperiment` is subset by rows, maintaining alignment between features and their loadings.

Value

For `rowLoading`, a matrix containing loading values for features (rows) and dimensions (columns).

For `rowLoadings`, a [SimpleList](#) of such matrices.

For `rowLoadingNames`, a character vector of loading names.

For all setters, `x` is returned with the modified loading results or names.

Getters

In the following examples, `x` is a [SingleCellExperiment](#) object.

`rowLoading(x, type, withDimnames=TRUE)`: Retrieves a matrix containing feature loadings (rows) for each latent dimension (columns). `type` is either a string specifying the name of the loading result in `x` to retrieve, or a numeric scalar specifying the index of the desired result.

If `withDimnames=TRUE`, row names of the output matrix are replaced with the row names of `x`.

`rowLoadingNames(x)`: Returns a character vector containing the names of all loading results in `x`. This is guaranteed to be of the same length as the number of results, though the names may not be unique.

`rowLoadings(x, withDimnames=TRUE)`: Returns a named [SimpleList](#) of matrices containing one or more loading results. Each result is a matrix with the same number of rows as `nrow(x)`.

If `withDimnames=TRUE`, row names of each matrix are replaced with the row names of `x`.

Single-result setter

`rowLoading(x, type, withDimnames=TRUE) <- value` will add or replace a loading result in a [SingleCellExperiment](#) object `x`. The value of `type` determines how the result is added or replaced:

- If `type` is a numeric scalar, it must be within the range of existing results, and `value` will be assigned to the result at that index.
- If `type` is a string and a result exists with this name, `value` is assigned to that result. Otherwise a new result with this name is appended to the existing list of results.

`value` is expected to be a matrix or matrix-like object with number of rows equal to `nrow(x)`.

If `withDimnames=TRUE`, row names of `value` are set to `rownames(x)`.

Other setters

In the following examples, `x` is a [SingleCellExperiment](#) object.

`rowLoadings(x, withDimnames=TRUE) <- value`: Replaces all loading results in `x` with those in `value`. The latter should be a list-like object containing any number of matrices or matrix-like objects with number of rows equal to `nrow(x)`.

If `value` is named, those names will be used to name the loading results in `x`.

If `value` is a [Annotated](#) object, any [metadata](#) will be retained in `rowLoadings(x)`. If `value` is a [Vector](#) object, any [mcols](#) will also be retained.

If `withDimnames=TRUE`, row names in each entry of `value` are set to `rownames(x)`.

`rowLoadingNames(x) <- value`: Replaces all names for loading results in `x` with a character vector `value`. This should be of length equal to the number of results currently in `x`.

Author(s)

Patrick Aboyoun

See Also

[reducedDims](#) for sample-level embeddings (observation matrices).

[int_elementMetadata](#) for the internal row metadata storage.

Examples

```
library(SingleCellExperiment)

# Create example SCE with perturbation data
sce <- SingleCellExperiment(
  assays = list(beta_Z = matrix(rnorm(1000), 100, 10))
)
rownames(sce) <- paste0("Gene", 1:100)
colnames(sce) <- paste0("Pert", 1:10)

# Add PCA loadings (genes × components)
pca_loadings <- matrix(rnorm(100 * 5), 100, 5)
rownames(pca_loadings) <- rownames(sce)
colnames(pca_loadings) <- paste0("PC", 1:5)
rowLoading(sce, "PCA") <- pca_loadings

# Add factor analysis loadings (genes × factors)
factor_loadings <- matrix(rnorm(100 * 20), 100, 20)
```

```

rownames(factor_loadings) <- rownames(sce)
colnames(factor_loadings) <- paste0("Factor", 1:20)
rowLoading(sce, "FactorAnalysis") <- factor_loadings

# Retrieve all loadings
all_loadings <- rowLoadings(sce)
names(all_loadings)

# Retrieve specific loading by name
pca <- rowLoading(sce, "PCA")
dim(pca) # 100 genes × 5 components

# Retrieve by index
factors <- rowLoading(sce, 2)

# Get loading names
rowLoadingNames(sce)

# Subset SCE - loadings are automatically subset
sce_sub <- sce[1:50, ]
dim(rowLoading(sce_sub, "PCA")) # 50 genes × 5 components

```

SingleCellExperiment-pairs

colPairs/rowPairs setters for DuckDBSelfHits

Description

Specialized setter methods for `colPairs` and `rowPairs` that automatically wrap [DuckDBSelfHits](#) objects in [DuckDBDualSubset](#) containers. This enables lazy node-based subsetting when a `SingleCellExperiment` is subset.

Arguments

<code>x</code>	A SingleCellExperiment object.
<code>type</code>	String or integer scalar specifying the name or index of the pairing to replace.
<code>...</code>	Additional arguments passed to the default setter.
<code>value</code>	A DuckDBSelfHits object to be stored as a column/row pairing. This will be automatically wrapped in a DuckDBDualSubset .

Details

These methods extend the default `colPairs<-` and `rowPairs<-` setters from `SingleCellExperiment` to recognize `DuckDBSelfHits` objects and wrap them in `DuckDBDualSubset` containers. This ensures that when a `SingleCellExperiment` is subset (e.g., `sce[, 1:100]`), the wrapped `DuckDBSelfHits` objects are lazily filtered via SQL rather than materialized in memory.

Value

For the setter methods, `x` is returned with the modified pairings.

Usage

```
# Create SCE with lazy KNN graph
library(SingleCellExperiment)
library(BiocDuckDB)

sce <- SingleCellExperiment(assays = list(counts = matrix(1:100, 10, 10)))

# Create DuckDBSelfHits from parquet
knn_hits <- DuckDBSelfHits("knn_edges.parquet",
                           from = "from",
                           to = "to",
                           nnode = ncol(sce))

# Assign to colPairs (auto-wraps in DuckDBDualSubset)
colPairs(sce, "knn") <- knn_hits

# Subsetting SCE automatically subsets the graph lazily
sce_sub <- sce[, 1:5]
pairs_sub <- colPairs(sce_sub, "knn") # Lazy filtered to nodes 1:5
```

Author(s)

Patrick Aboyoun

See Also

[DuckDBSelfHits](#) for the lazy edge storage class.

[DuckDBDualSubset](#) for the wrapper that enables node-based subsetting.

[colPairs](#) and [rowPairs](#) for the base SingleCellExperiment methods.

Examples

```
library(SingleCellExperiment)
sce <- SingleCellExperiment(assays = list(counts = matrix(1:50, 10, 5)))
hits <- S4Vectors::SelfHits(
  from = rep(1:5, each = 2),
  to = sample(1:5, 10, replace = TRUE),
  nnode = 5L)
tmp <- tempfile()
writeParquet(hits, tmp)
ddb_hits <- DuckDBSelfHits(tmp, from = "from", to = "to", nnode = 5L)
colPair(sce, "knn") <- ddb_hits
class(colPair(sce, "knn"))
unlink(tmp, recursive = TRUE)
```

Description

Methods to get or set nested feature-level tables in a [SingleCellExperiment](#) object. These tables enable storage of multi-column relational data associated with features (genes), which would otherwise require nested DataFrames in `rowData()`. By extracting nested tables into a separate slot, they can be serialized to independent Parquet tables for efficient querying.

Arguments

<code>x</code>	A SingleCellExperiment object.
<code>type</code>	String or integer scalar specifying the name or index of the table to get or set.
<code>withDimnames</code>	Logical scalar indicating whether row names should be extracted from (getters) or set to (setters) the row names of <code>x</code> .
<code>...</code>	Additional arguments, currently ignored.
<code>value</code>	For the getter, a DataFrame-like object with number of rows equal to <code>nrow(x)</code> , containing the table data. For <code>rowTables<-</code> , a list of such DataFrames. For <code>rowTableNames<-</code> , a character vector of names.

Details

Feature tables (`rowTables`) are stored in `int_elementMetadata(x)$rowTables` and provide a mechanism to unnest complex relational data from `rowData()`. This is particularly useful when feature metadata contains multi-valued properties or hierarchical structures that are difficult to query when embedded as nested DataFrames.

Common use cases include:

- Gene annotation tables: transcript isoforms, protein domains, or GO terms
- Experimental design tables: per-gene treatment conditions or batch effects
- Statistical results: detailed per-gene statistics across multiple contrasts

Each table is a [DataFrame](#) with `nrow(x)` rows, maintaining alignment with features. Tables are automatically subset when the parent `SingleCellExperiment` is subset by rows.

Value

For `rowTable`, a [DataFrame](#) containing feature-level relational data.

For `rowTables`, a [SimpleList](#) of such DataFrames.

For `rowTableNames`, a character vector of table names.

For all setters, `x` is returned with the modified tables or names.

Getters

In the following examples, `x` is a [SingleCellExperiment](#) object.

`rowTable(x, type, withDimnames=TRUE)`: Retrieves a [DataFrame](#) containing feature-level relational data. `type` is either a string specifying the name of the table in `x` to retrieve, or a numeric scalar specifying the index of the desired table.

If `withDimnames=TRUE`, row names of the output [DataFrame](#) are replaced with the row names of `x`.

`rowTableNames(x)`: Returns a character vector containing the names of all tables in `x`. This is guaranteed to be of the same length as the number of tables, though the names may not be unique.

`rowTables(x, withDimnames=TRUE)`: Returns a named [SimpleList](#) of DataFrames containing one or more tables. Each table has the same number of rows as `nrow(x)`.

If `withDimnames=TRUE`, row names of each DataFrame are replaced with the row names of `x`.

Single-table setter

`rowTable(x, type, withDimnames=TRUE) <- value` will add or replace a table in a [SingleCellExperiment](#) object `x`. The value of `type` determines how the table is added or replaced:

- If `type` is a numeric scalar, it must be within the range of existing tables, and `value` will be assigned to the table at that index.
- If `type` is a string and a table exists with this name, `value` is assigned to that table. Otherwise a new table with this name is appended to the existing list of tables.

`value` is expected to be a DataFrame or data.frame-like object with number of rows equal to `nrow(x)`.

If `withDimnames=TRUE`, row names of `value` are set to `rownames(x)`.

Other setters

In the following examples, `x` is a [SingleCellExperiment](#) object.

`rowTables(x, withDimnames=TRUE) <- value`: Replaces all tables in `x` with those in `value`. The latter should be a list-like object containing any number of DataFrames or data.frame-like objects with number of rows equal to `nrow(x)`.

If `value` is named, those names will be used to name the tables in `x`.

If `value` is a [Annotated](#) object, any [metadata](#) will be retained in `rowTables(x)`. If `value` is a [Vector](#) object, any [mcols](#) will also be retained.

If `withDimnames=TRUE`, row names in each entry of `value` are set to `rownames(x)`.

`rowTableNames(x) <- value`: Replaces all names for tables in `x` with a character vector `value`. This should be of length equal to the number of tables currently in `x`.

Author(s)

Patrick Aboyoun

See Also

[rowData](#) for simple feature metadata.

[colTables](#) for sample-level nested tables.

[int_elementMetadata](#) for the internal row metadata storage.

Examples

```
library(SingleCellExperiment)

# Create example SCE
sce <- SingleCellExperiment(
  assays = list(counts = matrix(rpois(1000, 5), 100, 10))
)
rownames(sce) <- paste0("Gene", 1:100)
colnames(sce) <- paste0("Cell", 1:10)
```

```

# Add a table of gene isoforms (multiple isoforms per gene)
isoforms <- DataFrame(
  isoform_id = paste0("ISO", 1:100),
  length = sample(500:5000, 100),
  is_canonical = sample(c(TRUE, FALSE), 100, replace = TRUE)
)
rowTable(sce, "isoforms") <- isoforms

# Add a table of differential expression results across conditions
de_results <- DataFrame(
  condition = rep(c("treated", "control"), each = 50),
  log2fc = rnorm(100),
  pvalue = runif(100)
)
rowTable(sce, "de_stats") <- de_results

# Retrieve all tables
all_tables <- rowTables(sce)
names(all_tables)

# Retrieve specific table by name
iso <- rowTable(sce, "isoforms")
dim(iso) # 100 genes x 3 columns

# Retrieve by index
de <- rowTable(sce, 2)

# Get table names
rowTableNames(sce)

# Subset SCE - tables are automatically subset
sce_sub <- sce[1:50, ]
dim(rowTable(sce_sub, "isoforms")) # 50 genes x 3 columns

```

spatialCoordinateSystems

Coordinate systems of a MultiAssaySpatialExperiment

Description

Returns the names of the coordinate systems referenced by the per-element transforms stored in `metadata(x)$transforms` (the targets each element is mapped into). Empty when no transforms are recorded.

Usage

```
spatialCoordinateSystems(x)
```

Arguments

`x` A [MultiAssaySpatialExperiment](#).

Value

A character vector of coordinate-system names.

Examples

```
mase <- readParquet(system.file("extdata", "spatial_mase",
                                package = "BiocDuckDB"))
spatialCoordinateSystems(mase)
```

spatialElementJoin	<i>Spatial join between a points element and a shapes element of a MASE</i>
--------------------	---

Description

Joins a points element to a shapes element (each named "<element_type>/<region>") by a spatial predicate, pushed to DuckDB via **DuckDBSpatial**. When `coordinate_system` is given and the MASE carries transforms, each element is first aligned into that coordinate system through the coordinate-transform graph ([spatialCoordinateSystems](#)), so elements defined in different intrinsic frames are compared correctly. This generalizes `annotateWithRegions` (point-in-polygon with the default predicate only) to any **sf** binary predicate.

Usage

```
spatialElementJoin(
  mase,
  x,
  y,
  join = sf::st_intersects,
  coordinate_system = NULL,
  x_col = "x",
  y_col = "y"
)
```

Arguments

mase	A MultiAssaySpatialExperiment .
x	A points element spec, "points/<region>" (or <code>list(element_type = "points", region =)</code>).
y	A shapes element spec, "shapes/<region>" (or <code>list(element_type = "shapes", region =)</code>).
join	A spatial predicate function (default st_intersects).
coordinate_system	Optional target coordinate-system name to align both elements into before joining.
x_col, y_col	Coordinate column names in x, the points element.

Value

The spatial-join result from **DuckDBSpatial** ([spatialMatch](#) indices matching each point in x to a row of y, NA where unmatched).

Examples

```
pts <- S4Vectors::DataFrame(x = c(1.5, 2.5, 3.5), y = c(1.5, 2.5, 3.5),
                           instance_id = c("A", "B", "C"))
shp <- S4Vectors::DataFrame(instance_id = c("cell1", "cell2", "cell3"),
                           geometry = sf::st_sfc(
                             sf::st_polygon(list(matrix(c(1,1,2,1,2,2,1,2,1,1), ncol = 2, byrow = TRUE))),
                             sf::st_polygon(list(matrix(c(2,1,3,1,3,2,2,2,2,1), ncol = 2, byrow = TRUE))),
                             sf::st_polygon(list(matrix(c(2,2,3,2,3,3,2,3,2,2), ncol = 2, byrow = TRUE))))))
mase <- MultiAssaySpatialExperiment::MultiAssaySpatialExperiment(
  experiments = MultiAssayExperiment::ExperimentList(assay1 = matrix(1:9, 3, 3,
    dimnames = list(paste0("G", 1:3), c("A", "B", "C")))),
  colData = S4Vectors::DataFrame(row.names = "s1"),
  sampleMap = S4Vectors::DataFrame(assay = "assay1", primary = "s1",
    colname = c("A", "B", "C")),
  points = MultiAssaySpatialExperiment::PointsLayerList(centroids = pts),
  shapes = MultiAssaySpatialExperiment::ShapesLayerList(cells = shp))
spatialElementJoin(mase, "points/centroids", "shapes/cells")
```

spatialViews

On-the-fly DuckDB views over a MASE's spatial elements

Description

Registers each spatial layer (points, shapes) and the spatialMap junction of a [MultiAssaySpatialExperiment](#) as DuckDB temp views on a shared connection, so cross-element queries can be expressed as SQL. Lazy ([DuckDBDataFrame](#)) layers are registered as views over their rendered SQL (no materialization); in-memory layers and the materialized spatialMap are registered as temp tables. This is the substrate used by [linkSpatialMap](#) / [validateSpatialMap](#) and a handle for power-user raw SQL.

Usage

```
spatialViews(mase, conn = acquireDuckDBConn(), prefix = "mase_")
```

Arguments

mase	A MultiAssaySpatialExperiment .
conn	A DuckDB connection (default the shared BiocDuckDB connection).
prefix	View-name prefix.

Value

A MASESpatialViews registry (a list of view names + conn).

Examples

```
mase <- readParquet(system.file("extdata", "spatial_mase",
                                package = "BiocDuckDB"))
v <- spatialViews(mase)
v$spatial_map
```

validateSpatialMap	<i>Validate a MASE's spatialMap referential integrity</i>
--------------------	---

Description

Checks the spatialMap foreign keys against the spatial layers and the assays, out-of-core via DuckDB anti-joins on lazy layers. Reports four violation classes: unknown_layer (a (element_type, region) with no matching layer), orphan_instance (a spatialMap row whose instance_id is absent from its layer), orphan_colname (an (assay, colname) that is not a column of that experiment), and duplicate_instance (an instance_id occurring more than once within a layer).

Usage

```
validateSpatialMap(mase, strict = FALSE, conn = acquireDuckDBConn())
```

Arguments

mase	A MultiAssaySpatialExperiment .
strict	If TRUE, error when any violation is found instead of returning the report.
conn	A DuckDB connection (default the shared BiocDuckDB connection).

Value

A DataFrame of violations (type, assay, colname, element_type, region, instance_id, detail); empty when the spatialMap is valid.

Examples

```
mase <- readParquet(system.file("extdata", "spatial_mase",
                                package = "BiocDuckDB"))
validateSpatialMap(mase) # empty report: the spatialMap is valid
```

writeDatapackage	<i>Write a Frictionless datapackage.json envelope</i>
------------------	---

Description

Assembles and writes the top-level datapackage.json manifest from a list of already-written Frictionless resource descriptors. This is the envelope step shared by the experiment-level [writeParquet](#) methods, exposed so that producers who accumulate resources incrementally (streaming large datasets, or promoting from another store) can emit a conformant manifest without reconstructing an in-memory Bioconductor object.

Usage

```
writeDatapackage(
  model,
  resources,
  path,
  main_exp_name = NULL,
  annotations = NULL
)
```

Arguments

model	Character(1) package-level schema identifier that selects the readParquet reader used to reconstruct the container (e.g. "summarized_experiment", "single_cell_experiment", "multi_assay_experiment"). See the storage-layout vignette for the documented model values.
resources	A list of Frictionless resource descriptors (each a list), as returned/accumulated from writeParquet . NULL entries are removed.
path	Character(1) directory to write datapackage.json into; created recursively if it does not exist.
main_exp_name	Optional character(1) naming the main experiment (used by the single_cell_experiment reader). Omitted from the manifest when NULL.
annotations	Optional list of non-relational metadata elements (as produced during metadata serialization). Omitted when NULL.

Details

Each entry of resources is a Frictionless resource descriptor – a list with name, path, dimension, layout, format, mediatype, and schema – exactly as returned by the primitive [writeParquet](#) methods (array, data.frame, DataFrame, SelfHits). NULL entries are dropped, so the NULL returned by append/streaming parts (see [writeParquet](#)) can be accumulated and passed straight through. Descriptors are written verbatim otherwise; strip any private, non-Frictionless keys before calling.

Value

Invisibly, the assembled package list that was written.

Author(s)

Patrick Aboyoun

See Also

[writeParquet](#) for writing resources, and [readParquet](#) for reading a written package (the DuckDBMatrix/DuckDBArray/L constructors attach an existing coord-array in place).

Examples

```
# Assemble a manifest from a hand-built resource descriptor.
tf <- tempfile()
resources <- list(list(
  name = "features", path = "features",
  dimension = "feature", layout = "data_frame",
  format = "parquet",
  mediatype = "application/vnd.apache.parquet",
  schema = list(fields = list(list(name = "id", type = "integer")))))
writeDatapackage("summarized_experiment", resources, tf)
cat(readLines(file.path(tf, "datapackage.json")), sep = "\n")
```

writeParquet

*Write Parquet Representation of a Bioconductor Object***Description**

An `arrow::write_dataset` wrapper function to write the Parquet representation of various R objects using the Frictionless [Data Package](<https://datapackage.org>) metadata model. This function supports multiple object types including arrays, data frames, genomic ranges, and more, converting them into efficient Parquet format for analysis and storage with comprehensive metadata descriptions.

Usage

```
writeParquet(x, path, ...)

## S4 method for signature 'ANY'
writeParquet(
  x,
  path,
  indexcols = names(dimnames(x)) %||% sprintf("index%d", seq_along(dim(x))),
  indexrefs = NULL,
  datacol = "value",
  grid = defaultAutoGrid(COO_SparseArray(dim(x))),
  grid_suffix = "_group",
  BPPARAM = getAutoBPPARAM(),
  name = basename(path),
  dimension = c("crossed", "unbound"),
  layout = "coord_array",
  ...
)

## S4 method for signature 'data.frame'
writeParquet(
  x,
  path,
  indexcol = "__index__",
  keycol = "__name__",
  dimtbl = NULL,
  refs = NULL,
  append = FALSE,
  offset = 0L,
  part = NULL,
  part_digits = 0L,
  name = basename(path),
  dimension = c("unbound", "sample", "feature", "crossed"),
  layout = "data_frame",
  ...
)

## S4 method for signature 'DataFrame'
writeParquet(
```

```

x,
path,
indexcol = "__index__",
keycol = "__name__",
dimtbl = NULL,
refs = NULL,
append = FALSE,
offset = 0L,
part = NULL,
part_digits = 0L,
name = basename(path),
dimension = c("unbound", "sample", "feature", "crossed"),
layout = "data_frame",
...
)

```

```
## S4 method for signature 'DuckDBTable'
```

```

writeParquet(
  x,
  path,
  indexcol = "__index__",
  keycol = "__name__",
  dimtbl = NULL,
  append = FALSE,
  offset = 0L,
  part = NULL,
  part_digits = 0L,
  name = basename(path),
  dimension = c("unbound", "sample", "feature", "crossed"),
  layout = "data_frame",
  ...
)

```

```
## S4 method for signature 'DuckDBDataFrame'
```

```

writeParquet(
  x,
  path,
  indexcol = "__index__",
  keycol = "__name__",
  dimtbl = NULL,
  append = FALSE,
  offset = 0L,
  part = NULL,
  part_digits = 0L,
  name = basename(path),
  dimension = c("unbound", "sample", "feature", "crossed"),
  layout = "data_frame",
  ...
)

```

```
## S4 method for signature 'DuckDBTransposedDataFrame'
```

```

writeParquet(

```

```

    x,
    path,
    indexcol = "__index__",
    keycol = "__name__",
    dimtbl = NULL,
    append = FALSE,
    offset = 0L,
    part = NULL,
    part_digits = 0L,
    name = basename(path),
    dimension = "crossed",
    layout = "transposed_data_frame",
    ...
)

## S4 method for signature 'DuckDBSelfHits'
writeParquet(
  x,
  path,
  indexcol = "__index__",
  keycol = "__name__",
  dimtbl = NULL,
  append = FALSE,
  offset = 0L,
  part = NULL,
  part_digits = 0L,
  name = basename(path),
  dimension = c("unbound", "sample", "feature"),
  layout = "graph_edges",
  ...
)

## S4 method for signature 'DuckDBGRanges'
writeParquet(
  x,
  path,
  indexcol = "__index__",
  keycol = "__name__",
  dimtbl = NULL,
  append = FALSE,
  offset = 0L,
  part = NULL,
  part_digits = 0L,
  name = basename(path),
  dimension = c("feature", "unbound"),
  layout = "genomic_ranges",
  ...
)

## S4 method for signature 'DuckDBGRangesList'
writeParquet(
  x,

```

```

    path,
    indexcol = "__index__",
    keycol = "__name__",
    dimtbl = NULL,
    append = FALSE,
    offset = 0L,
    part = NULL,
    part_digits = 0L,
    name = basename(path),
    dimension = c("feature", "unbound"),
    layout = "genomic_ranges_list",
    ...
)

## S4 method for signature 'TransposedDataFrame'
writeParquet(
  x,
  path,
  indexcol = "__index__",
  keycol = "__name__",
  dimtbl = NULL,
  name = basename(path),
  dimension = "crossed",
  layout = "transposed_data_frame",
  ...
)

## S4 method for signature 'list'
writeParquet(
  x,
  path,
  dimension = c("unbound", "sample", "feature", "crossed"),
  ...
)

## S4 method for signature 'List'
writeParquet(
  x,
  path,
  dimension = c("unbound", "sample", "feature", "crossed"),
  ...
)

## S4 method for signature 'GenomicRanges'
writeParquet(
  x,
  path,
  indexcol = "__index__",
  keycol = "__name__",
  dimtbl = NULL,
  name = basename(path),
  dimension = c("feature", "unbound"),

```

```

        layout = "genomic_ranges",
        ...
    )

## S4 method for signature 'GenomicRangesList'
writeParquet(
    x,
    path,
    indexcol = "__index__",
    keycol = "__name__",
    dimtbl = NULL,
    name = basename(path),
    dimension = c("feature", "unbound"),
    layout = "genomic_ranges_list",
    ...
)

## S4 method for signature 'SelfHits'
writeParquet(
    x,
    path,
    indexcol = "__index__",
    keycol = "__name__",
    dimtbl = NULL,
    name = basename(path),
    dimension = c("unbound", "sample", "feature"),
    layout = "graph_edges",
    ...
)

## S4 method for signature 'Assays'
writeParquet(
    x,
    path,
    indexcols = c("__feature__", "__sample__"),
    indexrefs = NULL,
    datacol = "value",
    grid = defaultAutoGrid(COO_SparseArray(dim(x[[1L]]))),
    grid_suffix = "group__",
    dimension = "crossed",
    ...
)

## S4 method for signature 'SummarizedExperiment'
writeParquet(
    x,
    path,
    indexcols = c("__feature__", "__sample__"),
    package = list(model = ifelse(is(x, "RangedSummarizedExperiment"),
        "ranged_summarized_experiment", "summarized_experiment"), resources = list()),
    ...
)

```

```

## S4 method for signature 'SingleCellExperiment'
writeParquet(
  x,
  path,
  indexcols = c("__feature__", "__sample__"),
  package = list(model = "single_cell_experiment", resources = list()),
  ...
)

## S4 method for signature 'ExperimentList'
writeParquet(x, path, indexcols = c("__feature__", "__sample__"), ...)

## S4 method for signature 'MultiAssayExperiment'
writeParquet(
  x,
  path,
  indexcols = c("__feature__", "__sample__"),
  package = list(model = "multi_assay_experiment", resources = list()),
  ...
)

## S4 method for signature 'PointsLayerList'
writeParquet(x, path, ...)

## S4 method for signature 'ShapesLayerList'
writeParquet(x, path, ...)

## S4 method for signature 'MultiAssaySpatialExperiment'
writeParquet(
  x,
  path,
  indexcols = c("__feature__", "__sample__"),
  package = list(model = "multi_assay_spatial_experiment", resources = list()),
  ...
)

```

Arguments

- x** The object to write. Supported types include:
- Array-like objects - converted to coordinate (long) format
 - `data.frame` / `DataFrame` objects - written with field type metadata
 - `DuckDBTable` / `DuckDBDataFrame` objects - lazy SQL COPY TO export via [writeDuckDBTableParquet](#) in [parquet-io](#) (same append, offset, part contract as in-memory tables)
 - `DuckDBTransposedDataFrame`, `DuckDBSelfHits`, `DuckDBGRanges`, `DuckDBGRangesList` - delegate to the underlying lazy table without materializing
 - `TransposedDataFrame` objects - transposed before writing
 - `list` / `List` objects - each element dispatched individually; requires dimension; layout defaults to NULL (each element's method supplies its own default layout)
 - `GenomicRanges` objects - genomic coordinates with metadata

	• GenomicRangesList objects - lists of genomic ranges stored as LIST-typed columns • SelfHits objects - graph edge lists with node count metadata • Assays objects - collection of feature-by-sample matrices • SummarizedExperiment objects - feature/sample metadata with assays • RangedSummarizedExperiment objects - as above with genomic ranges for features • SingleCellExperiment objects - extends SummarizedExperiment with embeddings, alt experiments, dimension tables, and pairwise graphs • ExperimentList objects - named collection of experiments; primitive method used internally by MultiAssayExperiment and SingleCellExperiment (altExps); returns resources without writing datapackage.json • MultiAssayExperiment objects - multi-experiment study with subject meta-data and sample map • PointsLayerList / ShapesLayerList objects - spatial point and polygon layers • MultiAssaySpatialExperiment objects - spatially-resolved multi-assay experiment
path	A character string specifying the path where the data will be written. The path will be created if it doesn't exist.
...	Additional arguments. For data.frame methods with part set: passed to write_parquet. Otherwise for tables: passed to write_dataset. For array-like objects (ANY method): passed to writeCoordArray, including: append Logical; hive-partition append when TRUE (requires length(grid) > 1L). See ?writeCoordArray. along Integer; append dimension (required when append = TRUE). group_offset Non-negative integer; partition-group offset along along; defaults to 0L. arrowtype Optional DataType for the value column; schema pinning on append is described in ?writeCoordArray. max_dim Optional length-ndim(x) integer vector of index upper bounds. existing_data_behavior Passed through to write_dataset when applicable. Note: offset for array-like objects is documented above; table methods use offset as an explicit formal argument.
indexcols	For array-like objects, a character vector of column names for the integer index columns in the resulting table. Defaults to the names(dimnames(x)) or sprintf("index%d", seq_along(dim(x))) if dimension names are not available.
indexrefs	For array-like objects, an optional list of foreign key references for the index columns in the schema. Defaults to NULL.
datacol	For array-like objects, a character string specifying the column name containing the array values in the resulting table. Defaults to "value".
grid	For array-like objects, an optional ArrayGrid to use for partitioning array-like objects. If provided, the array will be split into chunks and written as separate files. Defaults to defaultAutoGrid(COO_SparseArray(dim(x))).
grid_suffix	For array-like objects, a character string to append to the partitioning directories if the grid contains more than one cell. Defaults to "_group".

BPPARAM	For array-like objects, a BiocParallelParam object to use for parallel processing when <code>grid</code> contains multiple cells. Defaults to <code>getAutoBPPARAM()</code> .
name	A character string specifying the name of the resource. Defaults to the basename of the path argument.
dimension	A character string describing which biological axis the resource is indexed by. One of "feature", "sample", "crossed" (feature $\times$ sample Cartesian product), or "unbound" (not tied to either axis).
layout	A character string identifying the physical storage layout of the resource. Recorded in <code>datapackage.json</code> and used by <code>readParquet</code> to dispatch the correct reader. Examples: "data_frame", "coord_array", "embedding_table", "genomic_ranges", "graph_edges", "nested_data_frame", "nested_experiment".
indexcol	For <code>data.frame</code> and <code>Vector</code> objects, a character string specifying the column name for the integer index column in the resulting table. Defaults to " <code>__index__</code> ". Set to <code>NULL</code> to omit this column.
keycol	For <code>data.frame</code> and <code>Vector</code> objects, a character string specifying the column name for the row names (data frames) / names (genomic ranges) column in the resulting table. Defaults to " <code>__name__</code> ". Set to <code>NULL</code> to omit this column.
dimtbl	For <code>data.frame</code> and <code>Vector</code> objects, an optional <code>data.frame</code> containing a dimension table with partitioning information.
refs	For flat (<code>data.frame</code> / <code>DataFrame</code>) tables, an optional list of foreign key references to emit in the schema, the flat analog of <code>indexrefs</code> . Each entry is <code>list(fields = <local>, reference = list(fields = <target>, resource = <res>))</code> . Used, for example, to declare the <code>MultiAssayExperiment</code> <code>sample_map</code> primary $\rightarrow$ subjects correspondence. Defaults to <code>NULL</code> .
append	Logical. For <code>data.frame</code> , <code>DataFrame</code> , and <code>DuckDBTable</code> methods: when <code>TRUE</code> , append a new flat <code>part-*.parquet</code> file under <code>path</code> (requires <code>part</code>). For array-like objects (ANY method): forwarded to writeCoordArray for hive-partition append (requires <code>length(grid) > 1L</code> ; see <code>along</code> , <code>group_offset</code> there). Defaults to <code>FALSE</code> .
offset	Non-negative integer. For <code>data.frame</code> and <code>DuckDBTable</code> methods: added to the index column when <code>indexcol</code> is set (<code>offset + seq_len(nrow(x))</code> in memory; <code>offset + row_number()</code> in SQL for lazy tables); ignored when <code>indexcol</code> is <code>NULL</code> . For array-like objects: forwarded to writeCoordArray as the coordinate shift along <code>along</code> . Defaults to <code>0L</code> .
part	Optional non-negative integer; <code>data.frame</code> and <code>DuckDBTable</code> methods. When set, write a single <code>part-<n>.parquet</code> file (via <code>arrow::write_parquet</code> for in-memory tables, or <code>DuckDB COPY TO</code> for lazy tables). Required when <code>append = TRUE</code> on table writes.
part_digits	Zero-padding width for <code>part</code> in the filename (e.g. <code>2L</code> yields <code>part-00.parquet</code>). Table methods (in-memory and lazy).
package	For experiment-level methods (<code>SummarizedExperiment</code> , etc.), a list used to accumulate <code>datapackage.json</code> contents before writing. Primitive <code>data.frame</code> methods ignore this argument; capture the return value on the first flat part and append later parts with <code>append = TRUE</code> . Contains: • <code>model</code> - Package-level schema identifier (e.g. "single_cell_experiment"). Determines which <code>readParquet</code> reader reconstructs the object. Distinct from the resource-level <code>layout</code> field — <code>model</code> describes the whole package; <code>layout</code> describes one resource within it.

- **resources** - Accumulating list of resource entries, each contributed by a primitive writeParquet method call.

Callers should not normally set this; the default is supplied by each experiment method. Experiment methods accumulate `package[["resources"]]` within a single call and write `datapackage.json` at the end. Primitive `data.frame` methods do not update a caller's package across separate invocations; capture the list returned from the first writeParquet call and merge manually (see **Flat table append** below).

Details

This function provides specialized handling for different object types:

Array-like objects: Converts multi-dimensional arrays into a coordinate (long) format where each non-zero element is represented as a row with columns for each dimension and the value. For sparse arrays, only non-zero elements are written, making it efficient for sparse data. When a grid is provided with multiple cells, the array is partitioned and each partition is written to a separate subdirectory. Array writes delegate to `writeCoordArray`; arguments `append`, `along`, `offset`, `group_offset`, `arrowtype`, and `max_dim` are forwarded via `...` and documented on the `writeCoordArray` help page.

Flat table append (`data.frame / DataFrame`): Use `part`, `part_digits`, `append`, and `offset` to stream chunked sample or feature tables as `part-0.parquet`, `part-1.parquet`, ... without temporary directories. The global index column (when `indexcol` is set) uses `offset + seq_len(nrow(x))` on each chunk. The first call returns a Frictionless resource list (one element); later append parts return `NULL`. Build `datapackage.json` from the first return, for example:

```
res <- writeParquet(chunk1, samples_dir, indexcol = "__sample__",
                    part = 0L, name = "samples", dimension = "sample")
pkg <- list(resources = res)
writeParquet(chunk2, samples_dir, indexcol = "__sample__",
             offset = nrow(chunk1), part = 1L, append = TRUE, ...)
```

data.frame objects: Writes data frames directly with optional row names and dimension lookup tables for partitioning information.

DataFrame objects: Writes data frames with schema properties that describe column types and semantics. Column metadata (`mcols`) is not preserved; use object-level `metadata()` for annotations.

TransposedDataFrame objects: Writes transposed data frames with optional row names and dimension lookup tables for partitioning information.

GenomicRanges objects: Writes genomic coordinates with proper column naming and schema properties (`genomicCoords`) that describe the mapping of genomic coordinate columns. Range metadata columns are written as regular columns in the output.

GenomicRangesList objects: Separates list element metadata from ranges data, writing them to different paths with schema properties that describe how to split the ranges into list elements.

SelfHits objects: Writes graph edge lists as a data frame with `from`, `to`, and optional metadata columns. The node count (`nnode`) is stored in the schema properties to enable reconstruction as a [DuckDBSelfHits](#) object.

Automatic unnesting of nested DataFrames: When writing `SingleCellExperiment` objects, any `DataFrame`-class columns found in `rowData()` or `colData()` are automatically extracted and moved to `rowTables()` or `colTables()` respectively. This unnesting enables independent Parquet serialization of multi-valued properties (e.g., multiple diseases per patient, multiple isoforms per gene) while keeping the main metadata tables flat and SQL-queryable. The original nested columns

are removed from `rowData()/colData()` after extraction. This behavior is automatic and requires no user intervention.

SummarizedExperiment objects: Writes multi-assay experiments with separate paths for feature data, sample data, and assay data.

RangedSummarizedExperiment objects: Extends `SummarizedExperiment` functionality with genomic ranges for features.

SingleCellExperiment objects: Extends `SummarizedExperiment` with single-cell specific data. All collections are written as flat resource directories directly under path. The directory name encodes both axis and type: `feature_embeddings/`, `sample_embeddings/`, `feature_table_<name>/`, `sample_table_<name>/`, `feature_graph_<name>/`, `sample_graph_<name>/`, `experiment_<name>/`. The path prefix is derived automatically from layout. Alternative experiments are written directly to root (flattened, same pattern as `MultiAssayExperiment` experiments). See the automatic unnesting section for details about `DataFrame` columns in `rowData()/colData()`.

MultiAssayExperiment objects: Writes multi-experiment studies with separate paths for sample data, sample mapping, and experiment data.

Value

For primitive methods (ANY, `data.frame`, `DataFrame`, `TransposedDataFrame`, `GenomicRanges`, `GenomicRangesList`, `SelfHits`, `Assays`, `list`, `List`, `ExperimentList`, `PointsLayerList`, `ShapesLayerList`): invisibly returns a list of Frictionless resource entries suitable for inclusion in a `datapackage.json` resources array.

For experiment methods (`SummarizedExperiment`, `SingleCellExperiment`, `MultiAssayExperiment`, `MultiAssaySpatialExperiment`): invisibly returns `NULL`; the `datapackage.json` is written to path as a side effect.

For flat multi-part table writes (`data.frame` with `append = TRUE` and `part > 0`): invisibly returns `NULL`.

Frictionless Data Package Metadata

This function writes a `datapackage.json` file (Frictionless Data Package v2.0) alongside the Parquet files. The file contains two levels of metadata:

Package-level fields (top of `datapackage.json`):

- **model** - Overall schema identifier. Determines which `readParquet` reader is used to reconstruct the container object (e.g. `"single_cell_experiment"`, `"multi_assay_experiment"`). When absent, `readParquet` returns a `SimpleList` of resources with no imposed schema.
- **annotations** - Non-relational elements from `metadata(x)` (scalars, vectors, 1-D arrays, JSON-safe nested lists). Tabular / relational items (`DataFrame`, `matrix`, 2-D arrays) are written as unbound Parquet sidecars and referenced here via `parquet_ref` stubs; mixed nested lists use a `nested_mapping` wrapper.

Per-resource fields (each entry in the resources array):

- **name** - Resource identifier (typically the object name)
- **path** - Relative directory path to the Parquet dataset
- **dimension** - Biological axis: `"feature"`, `"sample"`, `"crossed"`, or `"unbound"`
- **layout** - Physical storage layout (BiocDuckDB extension); together with `dimension`, uniquely determines the R accessor and `AnnData` slot used during reconstruction
- **format** - File format (`"parquet"`)

- mediatype - MIME type ("application/vnd.apache.parquet")
- schema - Field definitions including types, primary key, sort order, and foreign key references

See the BiocDuckDB storage patterns documentation for the full model table and dimension + layout dispatch table.

Author(s)

Patrick Aboyoun

See Also

- [readParquet](#) for reading Bioconductor objects from parquet
- [writeCoordArray](#) for coord-array layout, hive partitioning, and array append (append, along, offset, group_offset)
- [parquet-io](#) for shared Parquet I/O: flat append validation (setupFlatParquetWrite, checkAppendPart, validateAppendOffset), SQL COPY TO helpers (buildParquetCopySQL), and lazy table export (writeDuckDBTableParquet)
- [createDimTables](#) for creating dimension lookup tables
- [write_dataset](#) and [write_parquet](#)
- [ArrayGrid](#) for grid partitioning
- [BiocParallelParam](#) for parallel processing options

Examples

```
# Write the Titanic dataset to a single Parquet file
tf1 <- tempfile()
writeParquet(Titanic, tf1)
list.files(tf1, full.names = TRUE, recursive = TRUE)

# Write the state.x77 matrix to multiple Parquet files using grid partitioning
tf3 <- tempfile()
state_grid <- RegularArrayGrid(dim(state.x77), c(10, 4))
writeParquet(state.x77, file.path(tf3, "state"), grid = state_grid)
dimtbls <- createDimTables(state.x77, grid = state_grid)
list.files(tf3, full.names = TRUE, recursive = TRUE)
```

writeStreamingResource

Stream a large table to a single multi-part Parquet resource

Description

Write a table that does not fit in memory to one flat, multi-part Parquet resource by pulling it block-by-block from a producer callback. This owns the streaming bookkeeping that every large producer would otherwise hand-roll on top of [writeParquet](#): the running row offset, the part index and zero-padded part_digits, the append flag (part 0 creates the directory, later parts append), the positional dimtbl slice per block, the index_max threading that keeps the __index__ column one consistent (possibly $>2^{31}$) integer type across parts, and the post-write integrity checks. The single descriptor it returns is ready to hand to [writeDatapackage](#).

Usage

```

writeStreamingResource(
  blocks,
  path,
  dimension,
  indexcol = "__index__",
  keycol = "__name__",
  layout = "data_frame",
  refs = NULL,
  dimtbl = NULL,
  cluster_by = NULL,
  index_max = NULL,
  expected_rows = NULL,
  part_digits = 6L,
  name = basename(path),
  ...
)

```

Arguments

blocks	A function of one argument, the 1-based part index <i>i</i> . It must return the <i>i</i> -th block as a <code>data.frame</code> (or <code>DataFrame</code> / anything <code>as.data.frame</code> -able), or <code>NULL</code> when the stream is exhausted. Blocks are consumed in ascending index order; how a block maps to source rows (a row range, a sample id, a query page) is the producer's business. Empty (zero-row) blocks are skipped without consuming a part.
path	Directory for the resource's Parquet parts.
dimension	Biological axis of the resource: one of "unbound", "sample", "feature", "crossed".
indexcol, keycol	Passed to writeParquet . <code>indexcol</code> is the streamed row index (default "__index__"); <code>keycol</code> is the row-name column ("__name__"), or <code>NULL</code> for a row-number key.
layout	Physical layout string (default "data_frame"); also accepts other flat layouts writeParquet supports for a <code>data.frame</code> (e.g. "spatial_points").
refs, cluster_by	Passed to writeParquet (foreign-key references; on-write clustering key).
dimtbl	An optional full, index-ordered dimension-table <code>DataFrameList</code> for the resource. It is sliced positionally per block (<code>dimtbl[offset + seq_len(nrow(block)),]</code>), so it must have exactly one row per streamed row in the same order. A drift is fatal (see Details).
index_max	Optional upper bound on the row index (the resource's total row count, or <code>Inf</code> when unknown ahead of streaming). Passing it types <code>__index__</code> wide enough on part 0 for the whole resource, which is required for a $> 2^{31}$ -row resource and removes any dependence on block size (see Details). <code>NULL</code> keeps per-block index narrowing.
expected_rows	Optional expected total row count. When given and the streamed total differs, a <i>warning</i> is emitted (an unbound junction table can legitimately differ; a bound one usually indicates an off-by-one or a dropped block).
part_digits	Zero-padding width for the part index in filenames. The reader globs <code>*.parquet</code> , so this is cosmetic; defaults to 6L.

name	Resource name recorded in the descriptor (default <code>basename(path)</code>).
...	Further arguments forwarded to writeParquet .

Details

Index typing / the narrowing floor. [writeParquet](#) types part 0's `__index__` column by the index range it sees. Without `index_max`, part 0 is typed to its own `[0, nrow]` range, so a small part 0 can pick a narrow integer type (e.g. `uint16`) that a later part's larger index overflows on append. Passing `index_max` (the total row count, or `Inf`) types the index for the whole resource up front and removes this hazard entirely. When `index_max` is not given and part 0 has fewer than 65536 rows in a multi-part stream, a warning is emitted.

Partition alignment. The per-block `dimtbl` slice assumes the stream is dense and contiguous with exactly `nrow(dimtbl)` rows in index order. If the streamed total does not equal `nrow(dimtbl)` the partition column would be misaligned (silently corrupting directory pruning), so this is a fatal error rather than a warning.

Commit boundary. A multi-part resource is complete only once every part is written. To make "readable only when complete" hold by construction, an `_INCOMPLETE` marker file is dropped into path immediately before part 0 is written and removed once the stream finishes, so a crash during part 0 is covered too. A finished resource is therefore a clean directory of only parquet parts that the reader loads normally, while an interrupted write leaves the marker behind; `DuckDBDataFrame` refuses to open a directory carrying the marker, so a read of an incomplete resource fails loudly instead of silently returning the partial parts. A fatal partition-alignment error likewise leaves the marker in place.

Value

Invisibly, the single Frictionless resource descriptor (a list) captured from part 0, with an added `n_rows` count, ready for [writeDatapackage](#). NULL if the stream yielded no rows.

Author(s)

Patrick Aboyoun

See Also

[writeParquet](#) for the single-block writer; [writeDatapackage](#) to assemble the resources into a `datapackage.json`.

Examples

```
tf <- tempfile()
on.exit(unlink(tf, recursive = TRUE))
chunks <- list(data.frame(v = 1:3), data.frame(v = 4:5))
res <- writeStreamingResource(
  function(i) if (i <= length(chunks)) chunks[[i]] else NULL,
  path = file.path(tf, "samples"), dimension = "unbound",
  keycol = NULL, index_max = 5, expected_rows = 5)
res[[1]][["n_rows"]] # 5
list.files(file.path(tf, "samples")) # part-000000.parquet, part-000001.parquet
```

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