

quollr: An R Package for Visualizing 2 – D Models from Non-linear Dimension Reduction in High Dimensional Space

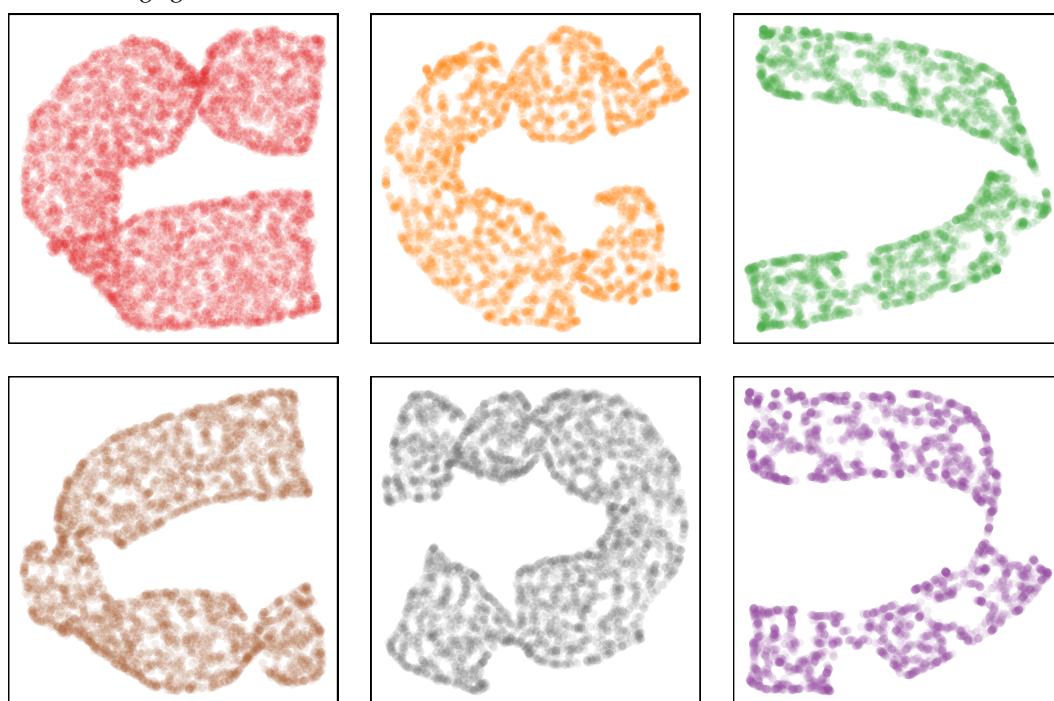
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Abstract Non-linear dimension reduction (NLDR) methods provide a low-dimensional representation of high-dimensional data (p -D) by applying a non-linear transformation. However, the complexity of the transformations and data structures can create wildly different representations depending on the method and (hyper)parameter choices. It is difficult to determine whether any of these representations are accurate, which one is the best, or whether they have missed important structures. The R package `quollr` has been developed as a new visual tool to determine which method and which (hyper)parameter choices provide the most accurate representation of high-dimensional data. The scurve data from the package is used to illustrate the algorithm. scRNA-seq data for Limb muscles of mice are used to discuss the usability of the package.

1 Introduction

This paper presents the R package, `quollr` which introduce a new visual tool in determining which Non-linear dimension reduction (NLDR) technique and which (hyper)parameter choice gives most accurate representation of high-dimensional data. The methodology of the algorithm is explained in *cite the methodology paper*. Furthermore, the `quollr` package enables users to perform hexagonal binning (Carr et al., 2023), resulting in the generation of regular hexagons. The software is available from the Comprehensive R Archive Network (CRAN) at <https://CRAN.R-project.org/package=quollr>.

Add the image generated with S-curve data



The paper is organized as follows. In next section, introduces the implementation of `quollr` package on CRAN, including demonstration of the package's key functions and visualization capabilities. We illustrate the algorithm's functionality to study about clustering data structure in **Application** section, and describe a visual heuristic to describe parameter selection. Finally, we give a brief conclusion of the paper and discuss potential opportunities for use of our algorithm.

2 Implementation

Installation

The package can be installed from CRAN:

```
install.packages("quollr")
```

and the development version can be installed from GitHub:

```
devtools::install_github("JayaniLakshika/quollr")
```

Web site

More documentation of the package can be found at the web site <https://jayanilakshika.github.io/quollr/>.

Package dependencies

Understanding the dependencies of the `quollr` package is essential for smooth operation and error prevention. The following dependencies refer to the other R packages that `quollr` relies on to execute its functions effectively.

```
#> $quollr
#> [1] "dplyr"      "ggplot2"     "grid"       "interp"     "langevitour"
#> [6] "proxy"      "rlang"       "rsample"    "stats"      "tibble"
#> [11] "tidyselect"
```

Data sets

Add a table of data sets that `quollr` have

The following demonstration of the package's functionality assumes `quollr` has been loaded. We also want to load the built-in data sets `scurve` and `scurve_umap`.

`scurve` is a 7-D simulated dataset. It is constructed by simulating 5000 observations from $\theta \sim U(-3\pi/2, 3\pi/2)$, $X_1 = \sin(\theta)$, $X_2 \sim U(0, 2)$ (adding thickness to the S), $X_3 = \text{sign}(\theta) \times (\cos(\theta) - 1)$. The remaining variables X_4, X_5, X_6, X_7 are all uniform error, with small variance. `scurve_umap` is the UMAP 2-D embedding for `scurve` data with `n_neighbors` is 46 and `min_dist` is 0.9. Each data set contains a unique ID column that maps `scurve` and `scurve_umap`.

Main function

The mains steps for the algorithm can be executed by the main function `fit_highd_model()`, or can be run separately for more flexibility.

This function requires several parameters: the high-dimensional data (`highd_data`), the emdedding data (`nldr_data`), the number of bins along the x-axis (`bin1`), the buffer amount as a proportion of data (`q`), and benchmark value to extract high density hexagons (`benchmark_highdens`). The function returns an object that includes the hexagonal object, the fitted model in both 2-D, and p -D, and triangular mesh.

```
fit_highd_model(
  highd_data = scurve,
  nldr_data = scurve_umap,
  bin1 = 15,
  q = 0.1,
  benchmark_highdens = 5)

#> $hb_obj
#> $a1
#> [1] 0.08326136
#>
```

```
#> $a2
#> [1] 0.07210645
#>
#> $bins
#> [1] 15 16
#>
#> $start_point
#> [1] -0.10000000 -0.08923607
#>
#> $centroids
#> # A tibble: 240 x 3
#>   hexID    c_x     c_y
#>   <int>  <dbl>   <dbl>
#> 1     1  -0.1  -0.0892
#> 2     2 -0.0167 -0.0892
#> 3     3  0.0665 -0.0892
#> 4     4  0.150  -0.0892
#> 5     5  0.233  -0.0892
#> 6     6  0.316  -0.0892
#> 7     7  0.400  -0.0892
#> 8     8  0.483  -0.0892
#> 9     9  0.566  -0.0892
#> 10    10 0.649  -0.0892
#> # i 230 more rows
#>
#> $hex_poly
#> # A tibble: 1,440 x 3
#>   hex_poly_id      x      y
#>   <int>  <dbl>   <dbl>
#> 1           1  -0.1  -0.0412
#> 2           1 -0.142 -0.0652
#> 3           1 -0.142 -0.113
#> 4           1  -0.1  -0.137
#> 5           1 -0.0584 -0.113
#> 6           1 -0.0584 -0.0652
#> 7           2 -0.0167 -0.0412
#> 8           2 -0.0584 -0.0652
#> 9           2 -0.0584 -0.113
#> 10          2 -0.0167 -0.137
#> # i 1,430 more rows
#>
#> $data_hb_id
#> # A tibble: 5,000 x 4
#>   emb1   emb2     ID hexID
#>   <dbl> <dbl> <int> <int>
#> 1 0.707 0.839     1   205
#> 2 0.231 0.401     2   109
#> 3 0.232 0.215     3    65
#> 4 0.790 0.564     4   146
#> 5 0.761 0.551     5   146
#> 6 0.445 0.721     6   172
#> 7 0.900 0.137     7    58
#> 8 0.247 0.392     8   110
#> 9 0.325 0.542     9   141
#> 10 0.278 0.231    10    80
#> # i 4,990 more rows
#>
#> $std_cts
#> # A tibble: 142 x 3
#>   hexID bin_counts std_counts
#>   <int>     <int>      <dbl>
#> 1     21        12     0.16
#> 2     22        17     0.227
#> 3     23        22     0.293
```

```

#> 4 24 10 0.133
#> 5 25 7 0.0933
#> 6 26 12 0.16
#> 7 27 1 0.0133
#> 8 36 42 0.56
#> 9 37 42 0.56
#> 10 38 44 0.587
#> # i 132 more rows
#>
#> $tot_bins
#> [1] 240
#>
#> $non_bins
#> [1] 142
#>
#> $pts_bins
#> # A tibble: 142 x 2
#>   hexID pts_list
#>   <int> <list>
#> 1 21 <int [12]>
#> 2 22 <int [17]>
#> 3 23 <int [22]>
#> 4 24 <int [10]>
#> 5 25 <int [7]>
#> 6 26 <int [12]>
#> 7 27 <int [1]>
#> 8 36 <int [42]>
#> 9 37 <int [42]>
#> 10 38 <int [44]>
#> # i 132 more rows
#>
#> attr(,"class")
#> [1] "hex_bin_obj"
#>
#> $model_highd
#> # A tibble: 130 x 8
#>   hexID x1 x2 x3 x4 x5 x6 x7
#>   <int> <dbl> <dbl> <dbl> <dbl> <dbl> <dbl>
#> 1 21 -0.992 1.91 1.11 -0.000427 0.000624 0.00749 0.00105
#> 2 22 -0.906 1.93 1.41 -0.0000183 0.00331 -0.0204 -0.000363
#> 3 23 -0.680 1.93 1.72 -0.000810 -0.00259 -0.00449 0.00153
#> 4 24 -0.272 1.93 1.96 0.00251 0.00668 -0.0460 0.00128
#> 5 25 0.0760 1.93 2.00 0.00876 0.00447 0.00851 -0.00195
#> 6 26 0.461 1.93 1.89 -0.00478 0.00492 0.00835 0.00172
#> 7 36 -0.985 1.75 0.853 -0.00202 0.000397 0.00331 0.000338
#> 8 37 -0.980 1.66 1.17 -0.000374 -0.00154 0.0165 0.000126
#> 9 38 -0.821 1.64 1.56 -0.000459 0.000538 -0.0123 0.000780
#> 10 39 -0.484 1.68 1.87 0.00313 0.00241 0.00823 -0.00117
#> # i 120 more rows
#>
#> $model_2d
#> # A tibble: 130 x 5
#>   hexID c_x c_y bin_counts std_counts
#>   <int> <dbl> <dbl> <dbl> <dbl>
#> 1 21 0.358 -0.0171 12 0.16
#> 2 22 0.441 -0.0171 17 0.227
#> 3 23 0.524 -0.0171 22 0.293
#> 4 24 0.608 -0.0171 10 0.133
#> 5 25 0.691 -0.0171 7 0.0933
#> 6 26 0.774 -0.0171 12 0.16
#> 7 36 0.316 0.0550 42 0.56
#> 8 37 0.400 0.0550 42 0.56
#> 9 38 0.483 0.0550 44 0.587
#> 10 39 0.566 0.0550 39 0.52

```

```
#> # i 120 more rows
#>
#> $trimesh_data
#> # A tibble: 324 x 6
#>   from    to x_from  y_from  x_to   y_to
#>   <int> <int> <dbl>  <dbl> <dbl>  <dbl>
#> 1    16    26 0.275  0.127  0.233  0.199
#> 2    25    26 0.150  0.199  0.233  0.199
#> 3    25    37 0.150  0.199  0.191  0.271
#> 4    36    49 0.108  0.271  0.150  0.343
#> 5    36    37 0.108  0.271  0.191  0.271
#> 6     1     7 0.358 -0.0171 0.316  0.0550
#> 7    48    49 0.0665 0.343  0.150  0.343
#> 8    37    38 0.191  0.271  0.275  0.271
#> 9    26    27 0.233  0.199  0.316  0.199
#> 10   27    38 0.316  0.199  0.275  0.271
#> # i 314 more rows
```

Constructing the 2-D Model

Constructing the 2-D model primarily involves (i) scaling the NLDR data, (ii) binning the data, (iii) obtaining bin centroids, (iv) connecting centroids with line segments to indicate neighbors, and (v) Remove low-density hexagons.

Scaling the Data

The algorithm starts by scaling the NLDR data to a standard range using the `gen_scaled_data()` function. This function standardizes the data so that the first embedding ranges from 0 to 1, while the second embedding scales from 0 to the maximum value of the second embedding. The output includes the scaled NLDR data along with the original limits of the embeddings.

```
scurve_nldr_obj <- gen_scaled_data(nldr_data = scurve_umap)

scurve_nldr_obj

#> $scaled_nldr
#> # A tibble: 5,000 x 3
#>   emb1   emb2   ID
#>   <dbl> <dbl> <int>
#> 1 0.707  0.839    1
#> 2 0.231  0.401    2
#> 3 0.232  0.215    3
#> 4 0.790  0.564    4
#> 5 0.761  0.551    5
#> 6 0.445  0.721    6
#> 7 0.900  0.137    7
#> 8 0.247  0.392    8
#> 9 0.325  0.542    9
#> 10 0.278 0.231   10
#> # i 4,990 more rows
#>
#> $lim1
#> [1] -14.42166 13.32655
#>
#> $lim2
#> [1] -12.43687 12.32455
```

Computing hexagon grid configurations

The configurations of the hexagonal grid is defined by the number of bins in each direction. To find the number of bins along the y-axis, `calc_bins_y()` is used. This function takes as input the number of bins along the x-axis, the ratio of the ranges of the original embedding components, and the buffer amount as a proportion of the data. Additionally, this function provides the bin width.

```

calc_bins_y(
  nldr_obj = scurve_nldr_obj,
  bin1 = 4,
  q = 0.1)

#> $bin2
#> [1] 5
#>
#> $a1
#> [1] 0.3122301
#>
#> $a2
#> [1] 0.2703992

```

Binning the data

Points are allocated to the bins they fall into based on the nearest centroid. The main steps of the hexagonal binning algorithm can be executed using the `hex_binning()` function, or they can be run separately for greater flexibility. The parameters used within `hex_binning()` include the scaled NLDR data, the number of bins along the x-axis, the ratio of the ranges of the original embedding components, and the buffer amount as a proportion of the data. The output is an object of the `hex_bin_obj` class, which contains the number of bins in each direction, the coordinates of the hexagonal grid starting point, the details of bin centroids, the coordinates of bins, embedding components with their corresponding hexagon IDs, hex bins with their corresponding standardized counts, the total number of bins, the number of non-empty bins, and the points within each hexagon.

```

hex_binning(
  nldr_obj = scurve_nldr_obj,
  bin1 = 4,
  q = 0.1)

#> $a1
#> [1] 0.3122301
#>
#> $a2
#> [1] 0.2703992
#>
#> $bins
#> [1] 4 5
#>
#> $start_point
#> [1] -0.10000000 -0.08923607
#>
#> $centroids
#> # A tibble: 20 x 3
#>   hexID    c_x     c_y
#>   <int>  <dbl>   <dbl>
#> 1     1  -0.1  -0.0892
#> 2     2   0.212 -0.0892
#> 3     3   0.524 -0.0892
#> 4     4   0.837 -0.0892
#> 5     5   0.0561  0.181
#> 6     6   0.368  0.181
#> 7     7   0.681  0.181
#> 8     8   0.993  0.181
#> 9     9  -0.1   0.452
#> 10   10   0.212  0.452
#> 11   11   0.524  0.452
#> 12   12   0.837  0.452
#> 13   13   0.0561  0.722
#> 14   14   0.368  0.722
#> 15   15   0.681  0.722
#> 16   16   0.993  0.722

```

```
#> 17    17 -0.1    0.992
#> 18    18  0.212   0.992
#> 19    19  0.524   0.992
#> 20    20  0.837   0.992
#>
#> $hex_poly
#> # A tibble: 120 x 3
#>   hex_poly_id      x      y
#>   <int>    <dbl>    <dbl>
#> 1       1 -0.1    0.0910
#> 2       1 -0.256   0.000897
#> 3       1 -0.256  -0.179
#> 4       1 -0.1    -0.270
#> 5       1  0.0561 -0.179
#> 6       1  0.0561  0.000897
#> 7       2  0.212   0.0910
#> 8       2  0.0561  0.000897
#> 9       2  0.0561 -0.179
#> 10      2  0.212  -0.270
#> # i 110 more rows
#>
#> $data_hex_id
#> # A tibble: 5,000 x 4
#>   emb1   emb2   ID hexID
#>   <dbl> <dbl> <int> <int>
#> 1 0.707  0.839     1    15
#> 2 0.231  0.401     2    10
#> 3 0.232  0.215     3     6
#> 4 0.790  0.564     4    12
#> 5 0.761  0.551     5    12
#> 6 0.445  0.721     6    14
#> 7 0.900  0.137     7     8
#> 8 0.247  0.392     8    10
#> 9 0.325  0.542     9    10
#> 10 0.278 0.231    10    6
#> # i 4,990 more rows
#>
#> $std_cts
#> # A tibble: 16 x 3
#>   hexID bin_counts std_counts
#>   <int>    <int>    <dbl>
#> 1     3      116    0.172
#> 2     4       82    0.122
#> 3     5      193    0.286
#> 4     6      674     1
#> 5     7      529    0.785
#> 6     8      243    0.361
#> 7     9       87    0.129
#> 8    10      601    0.892
#> 9    11      244    0.362
#> 10   12      355    0.527
#> 11   13      183    0.272
#> 12   14      627    0.930
#> 13   15      669    0.993
#> 14   16      318    0.472
#> 15   19        2    0.00297
#> 16   20       77    0.114
#>
#> $tot_bins
#> [1] 20
#>
#> $non_bins
#> [1] 16
#>
```

```
#> $pts_bins
#> # A tibble: 16 x 2
#>   hexID pts_list
#>   <int> <list>
#> 1     3 <int [116]>
#> 2     4 <int [82]>
#> 3     5 <int [193]>
#> 4     6 <int [674]>
#> 5     7 <int [529]>
#> 6     8 <int [243]>
#> 7     9 <int [87]>
#> 8    10 <int [601]>
#> 9    11 <int [244]>
#> 10   12 <int [355]>
#> 11   13 <int [183]>
#> 12   14 <int [627]>
#> 13   15 <int [669]>
#> 14   16 <int [318]>
#> 15   19 <int [2]>
#> 16   20 <int [77]>
#>
#> #> attr(,"class")
#> [1] "hex_bin_obj"
```

Indicating neighbors by line segments connecting centroids

To indicate neighbors, the `tri_bin_centroids()` function is used to triangulate bin centroids. Following this, `gen_edges()` function computes the line segments that connect neighboring bins by providing the triangulated data. This results the coordinates that generate the connecting lines.

```
tr1_object <- tri_bin_centroids(
  hex_df = df_bin_centroids,
  x = "c_x",
  y = "c_y"
)

tr_from_to_df <- gen_edges(
  tri_object = tr1_object
)
```

In some cases, distant centroids may be connected, resulting in long line segments that can affect the smoothness of the 2-D representation. To address this issue, the `find_lg_benchmark()` function is used. This function computes a threshold based on the distances of line segments, determining when long edges should be removed.

Remove low-density hexagons

In certain scenarios, hexagonal bins may contain a few number of points. To ensure comprehensive coverage of NLDR data, it is important to select hexagonal bins with a suitable number of data points. The `find_low_dens_hex()` function identifies hexagons with low point densities, considering the densities of their neighboring bins as well. Users can initially identify low-density hexagons and then use this function to evaluate how removing them might affect the model fit by examining their neighbors.

```
find_low_dens_hex(
  centroids_data,
  bin1 = 15,
  benchmark_mean_dens = 0.05
)
```

Lifting the model into high dimensions

The final step involves lifting the fitted 2-D model into p -D by computing the p -D mean of data points within each hexagonal bin to represent bin centroids. This transformation is performed using the `avg_highd_data()` function, which takes p -D data (`highd_data`) and embedding data with their corresponding hexagonal bin IDs as inputs (`scaled_nldr_hexid`).

```
df_bin <- avg_highd_data(
  highd_data = scurve,
  scaled_nldr_hexid
)
```

Prediction

The `predict_emb()` function is used to predict 2-D embedding for a new p -D data point using the fitted model. This function is useful to predict 2-D embedding irrespective of the NLDR technique.

In the prediction process, first, the nearest p -D model point is identified for a given new p -D data point by computing p -D Euclidean distance. Then, the corresponding 2-D bin centroid mapping for the identified p -D model point is determined. Finally, the coordinates of the identified 2-D bin centroid is used as the predicted NLDR embedding for the new p -D data point.

```
predict_emb(
  highd_data = scurve,
  model_2d = df_bin_centroids,
  model_highd = df_bin
)
```

Compute residuals and Mean Square Error (MSE)

As a Goodness of fit statistics for the model, `glance()` is used to compute residuals and MSE. These metrics are used to assess how well the fitted model will capture the underlying structure of the p -D data.

```
glance(
  highd_data = scurve,
  model_2d = df_bin_centroids,
  model_highd = df_bin
)
```

Furthermore, `augment()` accepts 2-D and p -D model points, and the p -D data and adds information about each observation in the data set. Most commonly, this includes predicted values, residuals, row wise total error, absolute error for the fitted values, and row wise total absolute error.

Users can pass data to `augment()` via either the `training_data` argument or the `newdata` argument. If data is passed to the `training_data` argument, it must be exactly the data that was used to fit the model. Alternatively, datasets can be passed to `newdata` to augment data that was not used during model fitting. This requires that at least all predictor variable columns used to fit the model are present. If the original outcome variable used to fit the model is not included in `newdata`, then no corresponding column will be included in the output.

The augmented dataset is always returned as a `tibble::tibble` with the same number of rows as the passed dataset.

```
augment(
  highd_data = scurve,
  model_2d = df_bin_centroids,
  model_highd = df_bin
)
```

Visualizations

The package provides five basic visualizations which includes one to visualize the full hexagonal grid in 2-D, three visualizations related to the 2-D model (static visualizations), and one related to the p -D model (dynamic visualization). Each visualization can be generated using its respective function, as described in this section.

2-D model visualization

The `geom_hexgrid()` function is used to plot the hexagonal grid from the provided centroid data set.

```
ggplot() +
  geom_hexgrid(
    data = all_centroids_df,
    aes(x = c_x, y = c_y)
  ) +
  coord_fixed()
```

To visualize the 2-D model, mainly three functions are used. As shown in Figure ??a, `geom_trimesh()` to visualize the triangular mesh by adding a new layer to `ggplot()`. After identifying benchmark value to remove long edge, `vis_lg_mesh()` is used to visualize the triangular mesh by coloring the small and long edges. As shown in Figure ??b, the small and long edges are colored by black and red respectively. Following this, `vis_rmlg_mesh()` is used to visualize smoothed 2-D model which is the 2-D model after removing the long edges (see Figure ??c). In `vis_lg_mesh()` and `vis_rmlg_mesh()`, `benchmark_value` argument controls the edge removal in 2-D. Using small value of `benchmark_value`, will produce a triangular mesh with missing data structure; for example `benchmark_value = 0.3` shows two clusters rather than continuous structure, while `benchmark_value = 0.8` creates long edges and mislead the data structure in p -D space.

```
ggplot() +
  geom_trimesh(
    data = df_bin_centroids,
    aes(x = c_x, y = c_y)
  ) +
  coord_fixed()

vis_mesh(
  distance_edges = distance_df,
  benchmark_value = 0.75,
  tr_coord_df = tr_from_to_df,
  distance_col = "distance"
)
```

p -D model visualization

Displaying the p -D model overlaid on the data is done using the function `show_langevitour()`. This visualization is helpful for visually evaluating how well the model fits the data. The function requires several arguments: data along with their corresponding hexagonal bin ID, 2-D and p -D model points, the threshold for removing long edges, and the distance data set.

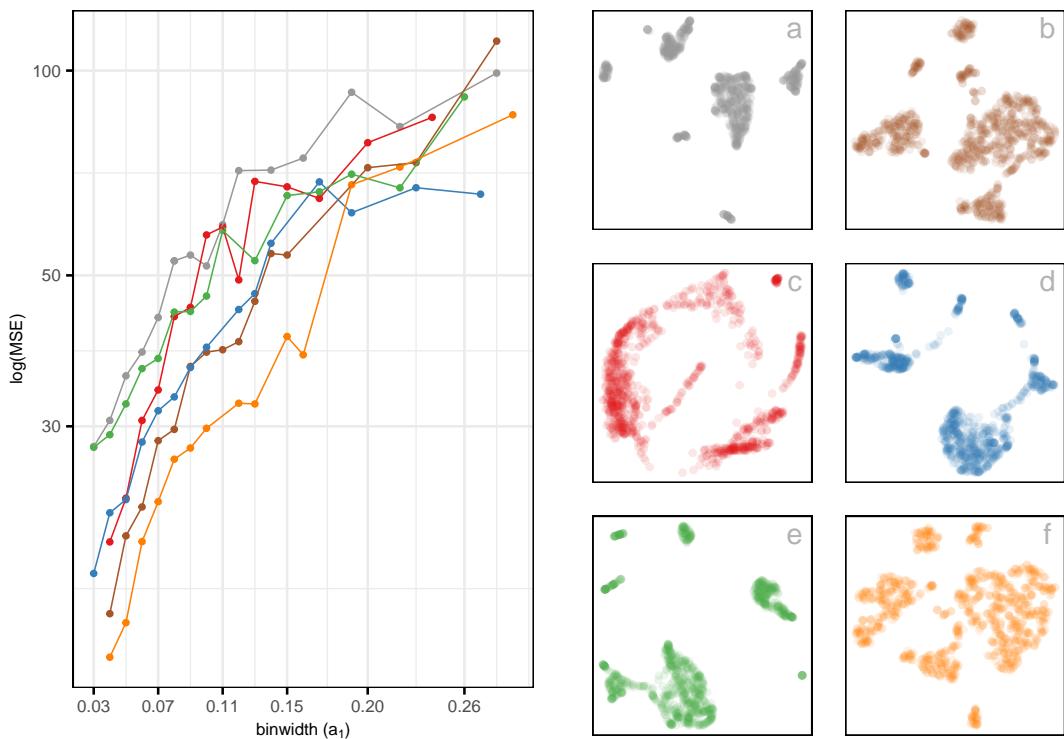
```
df_exe <- comb_data_mode(
  highd_data = scurve,
  model_highd = scurve_model_obj$model_highd,
  model_2d = scurve_model_obj$model_2d
)

show_langevitour(
  point_df,
  edge_df
)
```

Link plots

There are mainly two interactive link plots can be generated. `show_link_plots()` helps to examine the fit. The function requires several arguments: points data which contain Non-linear dimension reduction data, high-dimensional data, and high-dimensional model data, and edge data where the from and to links of the edges.

`show_error_link_plots()` helps to see investigate whether the model fits the points everywhere or fits better in some places, or simply mismatches the pattern. The function requires several arguments: points data which contain Non-linear dimension reduction data, high-dimensional data,



high-dimensional model data, and model error, and edge data where the from and to links of the edges.

```
show_link_plots(
  point_df = df_exe,
  edge_df = distance_small_df
)

show_error_link_plots(
  point_df = df_exe,
  edge_df = distance_small_df
)
```

3 Application

Need to find another application

<https://www.nature.com/articles/s41586-018-0590-4#data-availability> https://figshare.com/articles/dataset/Robjct_files_for_tissues_processed_by_Seurat/5821263/1

4 Discussion

This paper presents the R package `quollr` to develop a way to take the fitted model, as represented by the positions of points in 2-D, and turn it into a high-dimensional wireframe to overlay on the data, viewing it with a tour.

The paper includes a clustering example to illustrate how `quollr` is useful to assess which NLDR technique and which (hyper)parameter choice gives the most accurate representation. In addition, how to select parameters for hexagonal binning and fitting model are explained.

Possible future improvements would be...

This new tool provides an effective start point for automatically creating regular hexagons and help to evaluate which NLDR technique and which hyperparameter choice gives the most accurate representation of p -D data.

5 Acknowledgements

This article is created using `knitr` (Xie, 2015) and `rmarkdown` (Xie et al., 2018) in R with the `rjtools::rjournal_article` template. The source code for reproducing this paper can be found at: <https://github.com/JayaniLakshika/paper-quollr>.

Bibliography

- D. Carr, ported by Nicholas Lewin-Koh, M. Maechler, and contains copies of lattice functions written by Deepayan Sarkar. *hexbin: Hexagonal Binning Routines*, 2023. URL <https://CRAN.R-project.org/package=hexbin>. R package version 1.28.3. [p1]
- Y. Xie. *Dynamic Documents with R and knitr*. Chapman and Hall/CRC, Boca Raton, Florida, 2nd edition, 2015. URL <https://yihui.name/knitr/>. ISBN 978-1498716963. [p12]
- Y. Xie, J. Allaire, and G. Grolemund. *R Markdown: The Definitive Guide*. Chapman and Hall/CRC, Boca Raton, Florida, 2018. URL <https://bookdown.org/yihui/rmarkdown>. ISBN 978-1138359338. [p12]

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