Package 'spaths'

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Type Package

Title Shortest Paths Between Points in Grids

Version 1.2.0

Description Shortest paths between points in grids. Optional barriers and custom transition functions. Applications regarding planet Earth, as well as generally spheres and planes. Optimized for computational performance, customizability, and user friendliness. Graph-theoretical implementation tailored to gridded data. Currently focused on Dijkstra's (1959) <doi:10.1007/BF01386390> algorithm. Future updates broaden the scope to other least cost path algorithms and to centrality measures.

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Encoding UTF-8

URL https://github.com/cdueben/spaths

BugReports https://github.com/cdueben/spaths/issues

Imports base (>= 4.0.0), Rcpp (>= 1.0.9), data.table, parallel, stats, utils

LinkingTo Rcpp

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Author Christian Düben [aut, cre]

Maintainer Christian Düben <cdueben.ml+cran@proton.me>

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Contents

`max_edges` *Maximum number of edges in your grid*

Description

The maximum number of edges in your grid, determining what type of transition function you can use in shortest_paths.

Usage

```
max_edges(
  rst,
  contiguity = c("queen", "rook"),
  spherical = TRUE,
  extent = NULL
)
```

Arguments

`rst`	SpatRaster (terra), RasterLayer (raster), matrix, or list of matrices object. RasterLayers are converted to SpatRasters.
`contiguity`	`"queen"` (default) for queen's case contiguity or `"rook"` for rook's case contiguity. In the latter case, the algorithm only moves between horizontally or vertically adjacent cells. In the former case, it is also travels between diagonally adjacent cells.
`spherical`	Logical specifying whether coordinates are unprojected, i.e. lonlat, and refer to a sphere, e.g., a planet, if `rst` is a matrix or a list of matrices. It defaults to `TRUE`. If `FALSE`, the function assumes the coordinates to originate from a planar projection. This argument has no effect when `rst` is a SpatRaster or RasterLayer.
`extent`	Vector of length 4, specifying the extent of `rst`, if `rst` is a matrix or a list of matrices. It must contain xmin, xmax, ymin, and ymax, in that order. The argument has no effect when `rst` is a SpatRaster or RasterLayer.

Details

An edge is a connection between adjacent grid cells. With queen's case contiguity, each cell has up to 8 edges. With rook's case contiguity, they have up 4 edges. It is up to 8 and 4, and not exactly 8 or 4, because `rst`'s outer pixels do not have neighbors in all directions.

If the data is unprojected and spans from 180 degrees West to 180 degrees East, the easternmost cells are connected to the westernmost cells. Like in any other geo-spatial software, this is the

only scenario in which the algorithm connects cells across the grid boundary, i.e. in which, e.g., a shortest path leaves the grid on one side and enters it on the opposite side. In all other cases, cells are only connected to their direct neighbors within the grid.

Another source of edge removal are NA cells. There are no edges to or from NA cells in `rst`.

Value

Returns a numeric value denoting the maximum number of edges in `rst` that `shortest_paths` may store in an adjacency list in R at some point. If there are any NA cells, the returned number is greater than the final graph's number of edges for two reasons. First, shortest_paths assembles the adjacency list in multiple steps. Second, for efficiency reasons, `max_edges` does not evaluate where in the grid the NA cells are and assumes the most conservative impact.

The returned value is the same number upon which shortest_paths decides to either construct the adjacency list in R or in C++. If the result is larger than 2,147,483,647 (the maximum number of elements native R objects can store), it chooses C++. Otherwise, it selects R. In the C++ case, any `tr_fun` transition function must be an Rcpp C++ function with various restrictions (see the transition functions vignette).

See Also

shortest_paths.

Examples

```
# Generate example data
set.seed(2L)
input_grid <- terra::rast(crs = "epsg:4326", resolution = 2, vals = sample(c(1L, NA_integer_),
  16200L, TRUE, c(0.8, 0.2)))

# Obtain maximum number of edges
max_edges(input_grid)
```

`rnd_locations` *Random location drawing*

Description

This function draws random unprojected (lonlat) locations.

Usage

```
rnd_locations(
  nobs,
  xmin = -180,
  xmax = 180,
  ymin = -90,
  ymax = 90,
```

```
  output_type = c("data.table", "data.frame", "SpatVector")
)
```

Arguments

nobs	Number of observations
xmin	Minimum longitude
xmax	Maximum longitude
ymin	Minimum latitude
ymax	Maximum latitude
output_type	type of output object. Either "data.table" (default), "data.frame", or "SpatVector".

Details

By default, the function draws a global sample of random locations. You can restrict it to a certain region via specifying xmin, xmax, ymin, and ymax. The function draws from a uniform spatial distribution that assumes the planet to be a perfect sphere. The spherical assumption is common in GIS functions, but deviates from Earth's exact shape.

Value

Returns a data.table, data.frame, or SpatVector object of unprojected (lonlat) points.

See Also

shortest_paths.

Examples

```
rnd_locations(1000)
```

---

shortest_paths *Shortest paths and/ or distances between locations*

Description

The shortest paths and/ or distance between locations in a grid according to Dijkstra's (1959) algorithm.

Usage

```
shortest_paths(
  rst,
  origins,
  destinations = NULL,
  output = c("distances", "lines", "both"),
  output_class = NULL,
  origin_names = NULL,
  destination_names = NULL,
  pairwise = FALSE,
  contiguity = c("queen", "rook"),
  spherical = TRUE,
  radius = 6371010,
  extent = NULL,
  dist_comp = c("spaths", "terra"),
  tr_fun = NULL,
  v_matrix = FALSE,
  tr_directed = TRUE,
  pre = TRUE,
  early_stopping = TRUE,
  bidirectional = FALSE,
  update_rst = NULL,
  touches = TRUE,
  ncores = NULL,
  par_lvl = c("update_rst", "points"),
  show_progress = FALSE,
  bar_limit = 150L,
  path_type = c("int", "unsigned short int"),
  distance_type = c("double", "float", "int", "unsigned short int")
)
```

Arguments

`rst`	SpatRaster (terra), RasterLayer (raster), matrix, or list of matrices object. RasterLayers are converted to SpatRasters. Pixels with non-NA values in all layers mark the cells through which the algorithm may pass. The values of `rst` can be accessed in `tr_fun`.
`origins`	Origin points at which the shortest paths start. If `rst` is a SpatRaster or RasterLayer object, these points can be passed as a single SpatVector (terra), sf (sf), or Spatial* (sp) object. sf and sp objects are converted to SpatVectors. Polygons and lines are converted to points using their centroid. If `rst` is a matrix or list of matrices, `origins` must be a single matrix, data.frame, or data.table of coordinates with columns named `"x"` and `"y"`. The coordinates must refer to points in the reference system that `rst` utilizes. Lines and polygons are thus not accepted in this case. Details on which points the function connects are outlined below.
`destinations`	Destination points to which the shortest paths are derived. It defaults to `NULL`, resulting in the function to compute shortest paths between the `origins` points.

Otherwise, the same input rules as for origins apply. Details on which points the function connects are outlined below.

output "distances" (default), "lines", or "both". "distances" lists the total transition costs along the shortest paths. By default, it is the distance between origin and destination in meters, if rst is an unprojected SpatRaster or RasterLayer or if dist_comp = "terra". Otherwise, it is denoted in the projection's units. If you pass another function to tr_fun, the total transition cost is measured in the units of tr_fun's results. "lines" returns the shortest paths as spatial lines. "both" returns both distances and lines. "distances" is faster and requires less RAM than "lines" or "both".

output_class Class of the returned object. With output = "distances", the options are "data.table" (default) and "data.frame". With output = "lines" or output = "both", the options are "SpatVector" (default when rst is a SpatRaster or RasterLayer) and "list" (default when rst is a matrix or a list of matrices). In the case of "list", the attributes, the line coordinates, and the CRS are returned as individual list elements. The first element in the list of line coordinates refers to the first row in the attributes table etc. "SpatVector" is only available with a SpatRaster or RasterLayer rst. output_class changes the format of the returned object, not the information it contains.

origin_names Character specifying the name of the column in the origins object used to label the origins in the output object. It defaults to row numbers.

destination_names
Character specifying the name of the column in the destinations object used to label the destinations in the output object. It defaults to row numbers.

pairwise Logical specifying whether to compute pairwise paths, if origins and destinations have equally many rows. If TRUE, the function computes the shortest path between the first origin and the first destination, the second origin and the second destination, etc. Otherwise, it derives the shortest paths from all origins to all destinations. pairwise = TRUE can alter the order in which results are returned. Check the output's origins and destinations columns for the respective order.

contiguity "queen" (default) for queen's case contiguity or "rook" for rook's case contiguity. In the latter case, the algorithm only moves between horizontally or vertically adjacent cells. In the former case, it is also travels between diagonally adjacent cells. "rook" is more efficient than "queen" as it implies fewer edges.

spherical Logical specifying whether coordinates are unprojected, i.e. lonlat, and refer to a sphere, e.g., a planet, if rst is a matrix or a list of matrices. It defaults to TRUE. If FALSE, the function assumes the coordinates to originate from a planar projection. This argument has no effect when rst is a SpatRaster or RasterLayer.

radius Radius of the object, e.g. planet, if spherical = TRUE. This argument has no effect when rst is a SpatRaster or RasterLayer.

extent Vector of length 4, specifying the extent of rst, if rst is a matrix or a list of matrices. It must contain xmin, xmax, ymin, and ymax, in that order. The argument has no effect when rst is a SpatRaster or RasterLayer.

dist_comp Method to compute distances between adjacent cells. "spaths" (default) or "terra". The default "spaths" uses spherical (Haversine) distances in case of lonlat data and planar (Euclidean) distances in case of projected (non-lonlat)

data. The functions are optimized based on the fact that many inter-pixel distances are identical. Modelling the planet as a perfect sphere is in line with e.g. the s2 package, but is of course an oversimplification. With "terra", the function derives distances via terra::distance. Because this computes all inter-pixel distances separately, it is slower than the "spaths" approach. It does take the non-spherical nature of the planet into account though. With tr_fun, you can specify a custom distance function that uses neither "spaths" nor "terra" distances.

tr_fun The transition function based on which to compute edge weights, i.e. the travel cost between adjacent grid cells. Defaults to the geographic distance between pixel centroids. Permitted function parameter names are d (distance between the pixel centroids), x1 (x coordinate or longitude of the first cell), x2 (x coordinate or longitude of the second cell), y1 (y coordinate or latitude of the first cell), y2 (y coordinate or latitude of the second cell), v1 (rst layers' values from the first cell), v2 (rst layers' values from the second cell), and nc (number of CPU cores according to the ncores argument). If the data is unprojected, i.e. lonlat, or if dist_comp = "terra", d is measured in meters. Otherwise, it uses the units of the CRS. If rst has one layer, the values are passed to v1 and v2 as vectors, otherwise they are passed as a data table where the first column refers to the first layer, the second column to the second layer etc. Note that data tables are data frames. If rst produces a graph with more than 2,147,483,647 edges, the adjacency list cannot be stored in R and any tr_fun needs to be written in C++ with a few additional requirements. See the details below.

v_matrix Logical specifying whether to pass values to v1 and v2 in tr_fun as matrices (TRUE) instead of data tables in the multi-layer case and vectors in the single-layer case (FALSE). It defaults to FALSE. Setting it to TRUE might, e.g., be useful when defining tr_fun as a C++ Armadillo function.

tr_directed Logical specifying whether tr_fun creates a directed graph. In a directed graph, transition costs can be asymmetric. Traveling from cells A to B may imply a different cost than traveling from B to A. It defaults to TRUE and only has an effect when tr_fun is not NULL. The default without tr_fun constructs an undirected graph.

pre Logical specifying whether to compute the distances between neighboring cells before executing the shortest paths algorithm in C++. pre only has an effect, when no tr_fun is specified and dist_comp = "spaths", as the distances are otherwise imported from R. TRUE (default) is in the vast majority of cases faster than FALSE. FALSE computes distances between neighboring cells while the shortest paths algorithm traverses the graph. This requires less RAM, but is slower than TRUE, unless early_stopping = TRUE and all points are close to each other. TRUE's speed advantage is even larger, when update_rst is not NULL.

early_stopping Logical specifying whether to stop the shortest path algorithm once the target cells are reached. It defaults to TRUE, which can be faster than FALSE, if the points are close to each other compared to the full set of rst cells. If at least one points pair is far from each other, FALSE is the faster setting. FALSE computes the distance to all cells and then extracts the distance to the target cells. It, therefore, does not check for each visited cell, whether it is in the set of targets. TRUE

and FALSE produce the same result and only differ in terms of computational performance.

bidirectional — Logical specifying whether to produce paths or distances in both directions, if destinations are not specified and no directed transition function is given. In that case, the distance and the path from point A to point B is the same as the distance and path from point B to point A. FALSE (default) only returns distances or paths in one direction. Declaring TRUE returns distances or paths in both directions. This parameter's objective is to control the return object's RAM requirement. It only has an effect, if destinations are not specified and no directed transition function is given.

update_rst — Object updating rst with moving barriers. It defaults to NULL, corresponding to rst not being updated. If rst is a SpatRaster or RasterLayer, update_rst can be a SpatVector (terra), sf (sf), or Spatial* (sp) object, or a list of them. sf and sp objects are converted to SpatVectors. The function updates rst by setting any cell intersecting with update_rst to NA, thereby not allowing the shortest paths algorithm to pass through that cell. update_rst only sets non-NA cells to NA, not vice versa. The elements of update_rst always update the unmodified rst. I.e. if update_rst is a list of two polygons, the shortest paths are derived three times: once based on the not updated rst, denoted layer 0 in the output, once based on rst updated with the first polygon, referred to as layer 1, and once based on rst updated with the second polygon, termed layer 2. The second polygon updates the unmodified rst, not the rst updated by the first polygon. If rst is a matrix or a list of matrices, update_rst can be a vector of cell numbers, a matrix, or a list of either. Analogously to the SpatRaster case, these objects mark which cells to set to NA. As in terra, cell numbers start with 1 in the top left corner and then increase first from left to right and then from top to bottom. The cell numbers in the vector and the NA cells in the matrix identify the pixels to set to NA. Accordingly, the matrix is of equal dimensions as rst.

touches — Logical specifying the touches argument of terra::extract used when update_rst is a SpatVector, sf, or Spatial* object. It defaults to TRUE. If FALSE, the function only removes cells on the line render path or with the center point inside a polygon.

ncores — An integer specifying the number of CPU cores to use. It defaults to the number of cores installed on the machine. A value of 1 induces a single-threaded process.

par_lvl — "points" or "update_rst", indicating the level at which to parallelize when using multiple cores and update_rst is a list. "points" parallelizes over the origin (and destination) point combinations in both the base grid not updated by update_rst and the grids updated with update_rst. The default "update_rst" is equivalent to "points" in the base grid, but parallelizes at the update_rst list level in the updated grid stage.

show_progress — Logical specifying whether the function prints messages on progress. It defaults to FALSE.

bar_limit — Integer specifying until up to how many paths or list elements of update_rst to display a progress bar, if show_progress = TRUE. It defaults to 150, in which case the function prints one = per computed path, if there are no more than 150 paths requested. In the grids updated with update_rst, the function displays

one = per processed update_rst list element, not per path. In parallel applications, the progress bar can notably slow the execution as the functions only permit one thread to write to output at a time. Do not set the argument too high to avoid R crashes from text buffer overflows.

path_type Data type with which C++ stores cell numbers. "int" (default) is the 4 byte signed integers that R also uses and is the fastest option. "unsigned short int" is a 2 byte unsigned integer which requires less RAM than "int", but only works if there are less than 65,535 non-NA cells and is comparatively slower because it requires type conversions.

distance_type Data type with which C++ stores distances. "double" (default) is a double precision 8 byte floating point number. It is the fastest and most precise option and also used by R as its numeric data type. "float" is a single precision 4 byte floating point number, which stores decimal values less precisely than "double" does and is comparatively slower because it requires type conversions. "int" and "unsigned short int" are the integer types described in the path_type documentation above. With "int" and "unsigned short int", distances are rounded to integers. When employing these integers types, the distance between any cells in rst, not just the cells of interest, must not exceed 2,147,483,647 and 65,535 respectively. The distance difference caused by rounding double values to another type can accumulate along the shortest paths and can result in notable distance deviation in the output. The recommendations is to stick with the default "double" unless the machine does not have enough RAM to run the function otherwise.

Details

This function computes shortest paths and/ or distance between locations in a grid using Dijkstra's algorithm. Examples are a ship navigating around land masses or a hiker traversing mountains.

Let us explore the ship example to illustrate how shortest_paths works. To compute shortest paths between ports around the world, you start with a global SpatRaster, in which all land pixels are set to NA and all ocean pixels are set a non-NA value, e.g. 1. A SpatVector marks port locations as points on water pixels. Passing these two objects to the parameters rst and origins respectively derives the shortest paths from each port to all other ports conditional on ships solely traversing water pixels and returns the distances, i.e. lengths of these paths. If you are not interested in the distances, but in the spatial lines themselves, set output to "lines". If you want to obtain both, set it to "both".

In a different application, you do not want to compute the paths between all ports, but only the paths between the ports on the northern hemisphere and the ports on the southern hemisphere, but not the paths between ports within the same hemisphere. To assess this, you split the ports into two SpatVectors and pass them to origins and destinations respectively. What if you do not want to connect all orgins to all destinations? Set pairwise to TRUE to connect the first origin just to the first destination, the second origin to the second destination, etc.

By default, the distance or transition cost between adjacent cells of the input grid is the geographic distance between the cells' centroids. What if the boat is a sailing vessel that minimizes travel time conditional on wind speed, wind direction, and ocean currents? Construct a SpatRaster with three layers containing information on the three variables respectively. Define a transition function that combines the three layers into a travel time measure and pass the SpatRaster to rst and this function

to tr_fun. tr_fun makes this package very versatile. With custom transition functions, you can take this software out of the geo-spatial context and, e.g., apply it to biomedical research.

If rst produces a graph with no more than 2,147,483,647 edges, tr_fun can either be an R or an Rcpp C++ function returning a numeric R vector. Beyond that limit, the number of edges exceed the maximum of elements that R's native data structures can store. The data then has to be kept in C++, and most function inputs and output are Rcpp::XPtr types. max_edges tells you how many edges your rst could produce and, hence, what type of tr_fun you may use. Check the transition functions vignette for details.

Further boosting efficiency, shortest_paths allows you to handle multiple tasks in one function call. In the ship routing example, consider that there are hurricanes in the Caribbean. Ships traveling from India to Australia do not care, but ships traveling from Mexico to the Netherlands have to go around the storm and must not take the shortest path through the hurricane. You have ten SpatVector polygons delineating the extent of the hurricane on ten different days. You want to know what the shortest paths are given that ships must go around the polygon on that day. Calling shortest_paths ten times with ten different SpatRasters would be very inefficient. This would assemble the graph ten times and recompute also paths unaffected by the hurricanes, such as the path between India and Australia, in each iteration. Instead, pass the SpatVector polygons to update_rst. shortest_paths then produces the shortest paths for a hurricane-free route and all ten hurricane days, only reestimating the paths that are affected by the hurricane polygon on a specific day.

Applications to Earth should always pass a SpatRaster or RasterLayer to rst. The option to use a matrix or a list of matrices is meant for applications to other planets, non-geo-spatial settings, and users who cannot install the terra package on their system.

The largest source of runtime inefficiency is the quantity of non-NA pixels in the rst grid. Limit the rst argument to the relevant area. E.g., crop the grid to the North Atlantic when computing shipping routes between Canada and France. And set regions through which the shortest path does certainly not pass to NA.

shortest_paths is optimized for computational performance. Most of its functions are written in C++ and it does not use a general purpose graph library, but comes with its custom graph-theoritical implementation tailored to gridded inputs.

The introduction vignette provides further details on the package.

Value

If output = "distances", the output is by default returned as a data table. If you want the result to be a data frame only, not a data table, set output_class to "data.frame". If output is "lines" or "both", the the function returns a SpatVector, if rst is a SpatRaster or a RasterLayer, and a list, if rst is a matrix or a list of matrices. Explicitly setting output_class to "list" returns a list in any case. output_class = "SpatVector", however, returns a SpatVector only if rst is a SpatRaster or a RasterLayer.

If output = "distances" or output = "both", the distances variable marks which points are connected. Unconnected point pairs have an Inf distance, if distance_type = "double" or distance_type = "float", and an NA distance, if distance_type = "int" or distance_type = "unsigned short int". If output = "lines", the connected variable marks which points are connected. Points are connected, when it is possible to travel between them via non-NA cells in rst.

References

Dijkstra, E. W. 1959. "A note on two problems in connexion with graphs." *Numerische Mathematik* 1 (1): 269–71.

See Also

max_edges, rnd_locations.

Examples

```
# Generate example data
set.seed(2L)
input_grid <- terra::rast(crs = "epsg:4326", resolution = 2, vals = sample(c(1L, NA_integer_),
  16200L, TRUE, c(0.8, 0.2)))
origin_pts <- rnd_locations(5L, output_type = "SpatVector")
origin_pts$name <- sample(letters, 5)
destination_pts <- rnd_locations(5L, output_type = "SpatVector")

# Compute distances
shortest_paths(input_grid, origin_pts)
shortest_paths(input_grid, origin_pts, bidirectional = TRUE)
shortest_paths(input_grid, origin_pts, destination_pts)
shortest_paths(input_grid, origin_pts, origin_names = "name")
shortest_paths(input_grid, origin_pts, destination_pts, pairwise = TRUE)

# Compute lines
shortest_paths(input_grid, origin_pts, output = "lines")

# Compute distances and lines
shortest_paths(input_grid, origin_pts, output = "both")

# Use custom transition function
input_grid[input_grid == 1L] <- stats::runif(terra::freq(input_grid, value = 1L)$count,
  max = 1000)
shortest_paths(input_grid, origin_pts, tr_fun = function(d, v1, v2) sqrt(d^2 + abs(v2 - v1)^2),
  tr_directed = FALSE)

# Compute distances with grid updating
barrier <- terra::vect("POLYGON ((-179 1, 30 1, 30 0, -179 0, -179 1))", crs = "epsg:4326")
shortest_paths(input_grid, origin_pts, update_rst = barrier)
barriers <- list(barrier, terra::vect("POLYGON ((0 0, 0 89, 1 89, 1 0, 0 0))",
  crs = "epsg:4326"))
shortest_paths(input_grid, origin_pts, update_rst = barriers)
```

Index