Package 'slendr'

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Title A Simulation Framework for Spatiotemporal Population Genetics

Version 1.6.0

Description A framework for simulating spatially explicit genomic data which leverages real cartographic information for programmatic and visual encoding of spatiotemporal population dynamics on real geographic landscapes. Population genetic models are then automatically executed by the 'SLiM' software by Haller et al. (2019) <doi:10.1093/molbev/msy228> behind the scenes, using a custom built-in simulation 'SLiM' script. Additionally, fully abstract spatial models not tied to a specific geographic location are supported, and users can also simulate data from standard, non-spatial, random-mating models. These can be simulated either with the 'SLiM' built-in back-end script, or using an efficient coalescent population genetics simulator 'msprime' by Baumdicker et al. (2022) <doi:10.1093/genetics/iyab229> with a custom-built 'Python' script bundled with the R package. Simulated genomic data is saved in a tree-sequence format and can be loaded, manipulated, and summarised using tree-sequence functionality via an R interface to the 'Python' module 'tskit' by Kelleher et al. (2019) <doi:10.1038/s41588-019-0483-y>. Complete model configuration, simulation and analysis pipelines can be therefore constructed without a need to leave the R environment, eliminating friction between disparate tools for population genetic simulations and data analysis.

Depends R (>= 3.6.0)

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Encoding UTF-8

SystemRequirements 'SLiM' is a forward simulation software for population genetics and evolutionary biology. See <https://messerlab.org/slim/> for installation instructions and further information. The 'Python' coalescent framework 'msprime' and the 'tskit' module can by installed by following the instructions at <https://tskit.dev/>.

Imports ggplot2, dplyr, purrr, readr, magrittr, reticulate, tidyr, png, ijtiff, ape, scales, digest, ggrepel

Suggests testthat (>= 3.0.0), sf, stars, lwgeom, rnaturalearth, gganimate, knitr, rmarkdown, admixr, units, magick, cowplot, forcats, shinyWidgets, shiny, rsvg

VignetteBuilder knitr

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BugReports https://github.com/bodkan/slendr/issues

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animate_model *Animate the simulated population dynamics*

Description

Animate the simulated population dynamics

Usage

```
animate_model(model, file, steps, gif = NULL, width = 800, height = 560)
```

Arguments

model	Compiled slendr_model model object
file	Path to the table of saved individual locations
steps	How many frames should the animation have?
gif	Path to an output GIF file (animation object returned by default)
width, height	Dimensions of the animation in pixels

Value

If gif = NULL, return gganimate animation object. Otherwise a GIF file is saved and no value is returned.

area *Calculate the area covered by the given slendr object*

Description

Calculate the area covered by the given slendr object

Usage

```
area(x)
```

Arguments

x	Object of the class slendr

Value

Area covered by the input object. If a slendr_pop was given, a table with an population range area in each time point will be returned. If a slendr_region or slendr_world object was specified, the total area covered by this object's spatial boundary will be returned.

Examples

```
region_a <- region("A", center = c(20, 50), radius = 20)
region_b <- region("B", polygon = list(c(50, 40), c(70, 40), c(70, 60), c(50, 60)))
plot_map(region_a, region_b)

# note that area won't be *exactly* equal to pi*r^2:
#   https://stackoverflow.com/a/65280376
area(region_a)

area(region_b)
```

---

check_dependencies *Check that the required dependencies are available for slendr to work*

Description

Check that the required dependencies are available for slendr to work

Usage

```
check_dependencies(python = FALSE, slim = FALSE, quit = FALSE)
```

Arguments

python	Is the slendr Python environment required?
slim	Is SLiM required?
quit	Should the R interpreter quit if required slendr dependencies are missing? This option (which is not turned on by default, being set to FALSE) is used mainly in avoiding running slendr man page examples on machines which lack dependencies. If set to TRUE, a logical value is returned.

Value

If quit = TRUE, no values is returned, if quit = FALSE, a scalar logical value is returned indicating whether or not the dependencies are present.

check_env *Check that the active Python environment is setup for slendr*

Description

This function inspects the Python environment which has been activated by the reticulate package and prints the versions of all slendr Python dependencies to the console.

Usage

```
check_env(verbose = TRUE)
```

Arguments

verbose	Should a log message be printed? If FALSE, only a logical value is returned (invisibly).

Value

Either TRUE (slendr Python environment is present) or FALSE (slendr Python environment is not present).

Examples

```
init_env()
check_env()
```

clear_env *Remove the automatically created slendr Python environment*

Description

Remove the automatically created slendr Python environment

Usage

```
clear_env(force = FALSE, all = FALSE)
```

Arguments

force	Ask before deleting any environment?
all	Should all (present and past) slendr Python environments be removed (default is FALSE) or just the current environment?

Value

No return value, called for side effects

compile_model *Compile a slendr demographic model*

Description

First, compiles the vectorized population spatial maps into a series of binary raster PNG files, which is the format that SLiM understands and uses it to define population boundaries. Then extracts the demographic model defined by the user (i.e. population divergences and gene flow events) into a series of tables which are later used by the built-in SLiM script to program the timing of simulation events.

Usage

```
compile_model(
  populations,
  generation_time,
  gene_flow = list(),
  direction = NULL,
  simulation_length = NULL,
  serialize = TRUE,
  path = NULL,
  overwrite = FALSE,
  force = FALSE,
  description = "",
  time_units = NULL,
  resolution = NULL,
  competition = NULL,
  mating = NULL,
  dispersal = NULL,
  extension = NULL
)
```

Arguments

populations	Object(s) of the `slendr_pop` class (multiple objects need to be specified in a `list`)
generation_time	Generation time (in model time units)
gene_flow	Gene flow events generated by the `gene_flow` function (either a list of data.frame objects in the format defined by the `gene_flow` function, or a single data.frame)
direction	Intended direction of time. Under normal circumstances this parameter is inferred from the model and does not need to be set manually.
simulation_length	Total length of the simulation (required for forward time models, optional for models specified in backward time units which by default run to "the present time")

serialize	Should model files be serialized to disk? If not, only an R model object will be returned but no files will be created. This speeds up simulation with msprime but prevents using the SLiM back end.
path	Output directory for the model configuration files which will be loaded by the backend SLiM script. If NULL, model configuration files will be saved to a temporary directory.
overwrite	Completely delete the specified directory, in case it already exists, and create a new one?
force	Force a deletion of the model directory if it is already present? Useful for non-interactive uses. In an interactive mode, the user is asked to confirm the deletion manually.
description	Optional short description of the model
time_units	Units of time in which model event times are to be interpreted. If not specified and generation_time is set to 1, this will be set to "generations", otherwise the value is "model time units".
resolution	How many distance units per pixel?
competition, mating	Maximum spatial competition and mating choice distance
dispersal	Standard deviation of the normal distribution of the parent-offspring distance
extension	Path to a SLiM script to be used for extending slendr's built-in SLiM simulation engine. This can either be a file with the snippet of Eidos code, or a string containing the code directly. Regardless, the provided snippet will be appended after the contents of the bundled slendr SLiM script.

Value

Compiled slendr_model model object which encapsulates all information about the specified model (which populations are involved, when and how much gene flow should occur, what is the spatial resolution of a map, and what spatial dispersal and mating parameters should be used in a SLiM simulation, if applicable)

Examples

```
# spatial definitions ------------------------------------------------------

# create a blank abstract world 1000x1000 distance units in size
map <- world(xrange = c(0, 1000), yrange = c(0, 1000), landscape = "blank")

# create a circular population with the center of a population boundary at
# [200, 800] and a radius of 100 distance units, 1000 individuals at time 1
# occupying a map just specified
pop1 <- population("pop1", N = 1000, time = 1,
                   map = map, center = c(200, 800), radius = 100)

# printing a population object to a console shows a brief summary
pop1

# create another population occupying a polygon range, splitting from pop1
```

```
# at a given time point (note that specifying a map is not necessary because
# it is "inherited" from the parent)
pop2 <- population("pop2", N = 100, time = 50, parent = pop1,
                        polygon = list(c(100, 100), c(320, 30), c(500, 200),
                                  c(500, 400), c(300, 450), c(100, 400)))

pop3 <- population("pop3", N = 200, time = 80, parent = pop2,
                   center = c(800, 800), radius = 200)

# move "pop1" to another location along a specified trajectory and saved the
# resulting object to the same variable (the number of intermediate spatial
# snapshots can be also determined automatically by leaving out the
# `snapshots = ` argument)
pop1_moved <- move(pop1, start = 100, end = 200, snapshots = 6,
                   trajectory = list(c(600, 820), c(800, 400), c(800, 150)))
pop1_moved

# many slendr functions are pipe-friendly, making it possible to construct
# pipelines which construct entire history of a population
pop1 <- population("pop1", N = 1000, time = 1,
                   map = map, center = c(200, 800), radius = 100) %>%
  move(start = 100, end = 200, snapshots = 6,
       trajectory = list(c(400, 800), c(600, 700), c(800, 400), c(800, 150))) %>%
  set_range(time = 300, polygon = list(
    c(400, 0), c(1000, 0), c(1000, 600), c(900, 400), c(800, 250),
    c(600, 100), c(500, 50))
  )

# population ranges can expand by a given distance in all directions
pop2 <- expand_range(pop2, by = 200, start = 50, end = 150, snapshots = 3)

# we can check the positions of all populations interactively by plotting their
# ranges together on a single map
plot_map(pop1, pop2, pop3)

# gene flow events ------------------------------------------------------

# individual gene flow events can be saved to a list
gf <- list(
  gene_flow(from = pop1, to = pop3, start = 150, end = 200, proportion = 0.15),
  gene_flow(from = pop1, to = pop2, start = 300, end = 330, proportion = 0.25)
)

# compilation -----------------------------------------------------------

# compile model components in a serialized form to dist, returning a single
# slendr model object (in practice, the resolution should be smaller)
model <- compile_model(
  populations = list(pop1, pop2, pop3), generation_time = 1,
  resolution = 100, simulation_length = 500,
  competition = 5, mating = 5, dispersal = 1
)
```

distance *Calculate the distance between a pair of spatial boundaries*

Description

Calculate the distance between a pair of spatial boundaries

Usage

```
distance(x, y, measure, time = NULL)
```

Arguments

x, y	Objects of the class slendr
measure	How to measure distance? This can be either 'border' (distance between the borders of x and y) or 'center' (distance between their centroids).
time	Time closest to the spatial maps of x and y if they represent slendr_pop population boundaries (ignored for general slendr_region objects)

Value

If the coordinate reference system was specified, a distance in projected units (i.e. meters) is returned. Otherwise the function returns a normal Euclidean distance.

Examples

```
# create two regions on a blank abstract landscape
region_a <- region("A", center = c(20, 50), radius = 20)
region_b <- region("B", center = c(80, 50), radius = 20)
plot_map(region_a, region_b)

# compute the distance between the centers of both population ranges
distance(region_a, region_b, measure = "center")

# compute the distance between the borders of both population ranges
distance(region_a, region_b, measure = "border")
```

expand_range *Expand the population range*

Description

Expands the spatial population range by a specified distance in a given time-window

Usage

```
expand_range(
  pop,
  by,
  end,
  start,
  overlap = 0.8,
  snapshots = NULL,
  polygon = NULL,
  lock = FALSE,
  verbose = TRUE
)
```

Arguments

pop	Object of the class slendr_pop
by	How many units of distance to expand by?
start, end	When does the expansion start/end?
overlap	Minimum overlap between subsequent spatial boundaries
snapshots	The number of intermediate snapshots (overrides the overlap parameter)
polygon	Geographic region to restrict the expansion to
lock	Maintain the same density of individuals. If FALSE (the default), the number of individuals in the population will not change. If TRUE, the number of individuals simulated will be changed (increased or decreased) appropriately, to match the new population range area.
verbose	Report on the progress of generating intermediate spatial boundaries?

Details

Note that because slendr models have to accomodate both SLiM and msprime back ends, population sizes and times of events are rounded to the nearest integer value.

Value

Object of the class slendr_pop, which contains population parameters such as name, time of appearance in the simulation, parent population (if any), and its spatial parameters such as map and spatial boundary.

Examples

```
# spatial definitions ------------------------------------------------------

# create a blank abstract world 1000x1000 distance units in size
map <- world(xrange = c(0, 1000), yrange = c(0, 1000), landscape = "blank")

# create a circular population with the center of a population boundary at
# [200, 800] and a radius of 100 distance units, 1000 individuals at time 1
```

```
# occupying a map just specified
pop1 <- population("pop1", N = 1000, time = 1,
                   map = map, center = c(200, 800), radius = 100)

# printing a population object to a console shows a brief summary
pop1

# create another population occupying a polygon range, splitting from pop1
# at a given time point (note that specifying a map is not necessary because
# it is "inherited" from the parent)
pop2 <- population("pop2", N = 100, time = 50, parent = pop1,
                         polygon = list(c(100, 100), c(320, 30), c(500, 200),
                                   c(500, 400), c(300, 450), c(100, 400)))

pop3 <- population("pop3", N = 200, time = 80, parent = pop2,
                   center = c(800, 800), radius = 200)

# move "pop1" to another location along a specified trajectory and saved the
# resulting object to the same variable (the number of intermediate spatial
# snapshots can be also determined automatically by leaving out the
# `snapshots = ` argument)
pop1_moved <- move(pop1, start = 100, end = 200, snapshots = 6,
                   trajectory = list(c(600, 820), c(800, 400), c(800, 150)))
pop1_moved

# many slendr functions are pipe-friendly, making it possible to construct
# pipelines which construct entire history of a population
pop1 <- population("pop1", N = 1000, time = 1,
                   map = map, center = c(200, 800), radius = 100) %>%
  move(start = 100, end = 200, snapshots = 6,
       trajectory = list(c(400, 800), c(600, 700), c(800, 400), c(800, 150))) %>%
  set_range(time = 300, polygon = list(
    c(400, 0), c(1000, 0), c(1000, 600), c(900, 400), c(800, 250),
    c(600, 100), c(500, 50))
  )

# population ranges can expand by a given distance in all directions
pop2 <- expand_range(pop2, by = 200, start = 50, end = 150, snapshots = 3)

# we can check the positions of all populations interactively by plotting their
# ranges together on a single map
plot_map(pop1, pop2, pop3)

# gene flow events ----------------------------------------------------------

# individual gene flow events can be saved to a list
gf <- list(
  gene_flow(from = pop1, to = pop3, start = 150, end = 200, proportion = 0.15),
  gene_flow(from = pop1, to = pop2, start = 300, end = 330, proportion = 0.25)
)

# compilation ---------------------------------------------------------------
```

```
# compile model components in a serialized form to dist, returning a single
# slendr model object (in practice, the resolution should be smaller)
model <- compile_model(
  populations = list(pop1, pop2, pop3), generation_time = 1,
  resolution = 100, simulation_length = 500,
  competition = 5, mating = 5, dispersal = 1
)
```

`explore_model` *Open an interactive browser of the spatial model*

Description

Open an interactive browser of the spatial model

Usage

```
explore_model(model)
```

Arguments

`model`	Compiled `slendr_model` model object

Value

No return value, called in order to start an interactive browser-based interface to explore the dynamics of a slendr model

---

`extract_parameters` *Extract information from a compiled model or a simulated tree sequence*

Description

This function extract a slendr model parameters used to compile a given model object or simulate a tree sequence

Usage

```
extract_parameters(data)
```

Arguments

`data`	Either an object of the class `slendr_ts` or `slendr_model`

Value

A list of data frames containing parameters of the model used when compiling a model object

Examples

```
init_env()

# load an example model and simulate a tree sequence from it
model <- read_model(path = system.file("extdata/models/introgression", package = "slendr"))
ts <- msprime(model, sequence_length = 1e5, recombination_rate = 0)

# extract model parameters from a compiled model object as a list of data frames
extract_parameters(model)

# the function can also extract parameters of a model which simulated a
# tree sequence
extract_parameters(ts)
```

`gene_flow` *Define a gene-flow event between two populations*

Description

Define a gene-flow event between two populations

Usage

```
gene_flow(
  from,
  to,
  start,
  end,
  proportion = NULL,
  migration_rate = NULL,
  overlap = TRUE,
  rate = NULL
)
```

Arguments

`from`, `to`	Objects of the class `slendr_pop`
`start`, `end`	Start and end of the gene-flow event
`proportion`	Scalar value in the range (0, 1] specifying the total proportion of ancestry of the receiving population which will come from the source population over the entire gene-flow time window

migration_rate	Scalar value specifying the rate of gene flow per unit of time of the given gene-flow time window
overlap	Require spatial overlap between admixing populations? (default TRUE)
rate	DEPRECATED (Old name for what is now the proportion argument)

Value

Object of the class data.frame containing parameters of the specified gene-flow event.

Examples

```
# spatial definitions ------------------------------------------------------

# create a blank abstract world 1000x1000 distance units in size
map <- world(xrange = c(0, 1000), yrange = c(0, 1000), landscape = "blank")

# create a circular population with the center of a population boundary at
# [200, 800] and a radius of 100 distance units, 1000 individuals at time 1
# occupying a map just specified
pop1 <- population("pop1", N = 1000, time = 1,
                   map = map, center = c(200, 800), radius = 100)

# printing a population object to a console shows a brief summary
pop1

# create another population occupying a polygon range, splitting from pop1
# at a given time point (note that specifying a map is not necessary because
# it is "inherited" from the parent)
pop2 <- population("pop2", N = 100, time = 50, parent = pop1,
                         polygon = list(c(100, 100), c(320, 30), c(500, 200),
                                        c(500, 400), c(300, 450), c(100, 400)))

pop3 <- population("pop3", N = 200, time = 80, parent = pop2,
                   center = c(800, 800), radius = 200)

# move "pop1" to another location along a specified trajectory and saved the
# resulting object to the same variable (the number of intermediate spatial
# snapshots can be also determined automatically by leaving out the
# `snapshots = ` argument)
pop1_moved <- move(pop1, start = 100, end = 200, snapshots = 6,
                   trajectory = list(c(600, 820), c(800, 400), c(800, 150)))
pop1_moved

# many slendr functions are pipe-friendly, making it possible to construct
# pipelines which construct entire history of a population
pop1 <- population("pop1", N = 1000, time = 1,
                   map = map, center = c(200, 800), radius = 100) %>%
  move(start = 100, end = 200, snapshots = 6,
       trajectory = list(c(400, 800), c(600, 700), c(800, 400), c(800, 150))) %>%
  set_range(time = 300, polygon = list(
    c(400, 0), c(1000, 0), c(1000, 600), c(900, 400), c(800, 250),
    c(600, 100), c(500, 50))
```

```
  )

# population ranges can expand by a given distance in all directions
pop2 <- expand_range(pop2, by = 200, start = 50, end = 150, snapshots = 3)

# we can check the positions of all populations interactively by plotting their
# ranges together on a single map
plot_map(pop1, pop2, pop3)

# gene flow events ----------------------------------------------------

# individual gene flow events can be saved to a list
gf <- list(
  gene_flow(from = pop1, to = pop3, start = 150, end = 200, proportion = 0.15),
  gene_flow(from = pop1, to = pop2, start = 300, end = 330, proportion = 0.25)
)

# compilation ---------------------------------------------------------

# compile model components in a serialized form to dist, returning a single
# slendr model object (in practice, the resolution should be smaller)
model <- compile_model(
  populations = list(pop1, pop2, pop3), generation_time = 1,
  resolution = 100, simulation_length = 500,
  competition = 5, mating = 5, dispersal = 1
)
```

`get_python` *Get a path to internal Python interpreter of slendr*

Description

Get a path to internal Python interpreter of slendr

Usage

```
get_python()
```

Value

A character scalar path to slendr's Python binary

init_env *Activate the Python environment of slendr*

Description

This function activates a dedicated slendr Python environment set up via `setup_env`, or creates an ephemeral Python environment with uv.

Usage

```
init_env(uv = FALSE, quiet = NULL)
```

Arguments

`uv`	Should an ephemeral Python environment be created via uv (instead of activating a permanent virtual environment created via `setup_env`)?
`quiet`	Should informative messages be printed to the console? (DEPRECATED)

Value

No return value, called for side effects

join *Merge two spatial* `slendr` *objects into one*

Description

Merge two spatial `slendr` objects into one

Usage

```
join(x, y, name = NULL)
```

Arguments

`x`	Object of the class `slendr`
`y`	Object of the class `slendr`
`name`	Optional name of the resulting geographic region. If missing, name will be constructed from the function arguments.

Value

Object of the class `slendr_region` which encodes a standard spatial object of the class `sf` with several additional attributes (most importantly a corresponding `slendr_map` object, if applicable).

Examples

```
# create a blank abstract world 1000x1000 distance units in size
blank_map <- world(xrange = c(0, 1000), yrange = c(0, 1000), landscape = "blank")

# it is possible to construct custom landscapes (islands, corridors, etc.)
island1 <- region("island1", polygon = list(c(10, 30), c(50, 30), c(40, 50), c(0, 40)))
island2 <- region("island2", polygon = list(c(60, 60), c(80, 40), c(100, 60), c(80, 80)))
island3 <- region("island3", center = c(20, 80), radius = 10)
archipelago <- island1 %>% join(island2) %>% join(island3)

custom_map <- world(xrange = c(1, 100), c(1, 100), landscape = archipelago)

# real Earth landscapes can be defined using freely-available Natural Earth
# project data and with the possibility to specify an appropriate Coordinate
# Reference System, such as this example of a map of Europe

real_map <- world(xrange = c(-15, 40), yrange = c(30, 60), crs = "EPSG:3035")
```

`move` *Move the population to a new location in a given amount of time*

Description

This function defines a displacement of a population along a given trajectory in a given time frame

Usage

```
move(
  pop,
  trajectory,
  end,
  start,
  overlap = 0.8,
  snapshots = NULL,
  verbose = TRUE
)
```

Arguments

`pop`	Object of the class `slendr_pop`
`trajectory`	List of two-dimensional vectors (longitude, latitude) specifying the migration trajectory
`start, end`	Start/end points of the population migration
`overlap`	Minimum overlap between subsequent spatial boundaries
`snapshots`	The number of intermediate snapshots (overrides the `overlap` parameter)
`verbose`	Show the progress of searching through the number of sufficient snapshots?

Value

Object of the class `slendr_pop`, which contains population parameters such as name, time of appearance in the simulation, parent population (if any), and its spatial parameters such as map and spatial boundary.

Examples

```
# spatial definitions ------------------------------------------------

# create a blank abstract world 1000x1000 distance units in size
map <- world(xrange = c(0, 1000), yrange = c(0, 1000), landscape = "blank")

# create a circular population with the center of a population boundary at
# [200, 800] and a radius of 100 distance units, 1000 individuals at time 1
# occupying a map just specified
pop1 <- population("pop1", N = 1000, time = 1,
                   map = map, center = c(200, 800), radius = 100)

# printing a population object to a console shows a brief summary
pop1

# create another population occupying a polygon range, splitting from pop1
# at a given time point (note that specifying a map is not necessary because
# it is "inherited" from the parent)
pop2 <- population("pop2", N = 100, time = 50, parent = pop1,
                         polygon = list(c(100, 100), c(320, 30), c(500, 200),
                                   c(500, 400), c(300, 450), c(100, 400)))

pop3 <- population("pop3", N = 200, time = 80, parent = pop2,
                   center = c(800, 800), radius = 200)

# move "pop1" to another location along a specified trajectory and saved the
# resulting object to the same variable (the number of intermediate spatial
# snapshots can be also determined automatically by leaving out the
# `snapshots = ` argument)
pop1_moved <- move(pop1, start = 100, end = 200, snapshots = 6,
                   trajectory = list(c(600, 820), c(800, 400), c(800, 150)))
pop1_moved

# many slendr functions are pipe-friendly, making it possible to construct
# pipelines which construct entire history of a population
pop1 <- population("pop1", N = 1000, time = 1,
                   map = map, center = c(200, 800), radius = 100) %>%
  move(start = 100, end = 200, snapshots = 6,
       trajectory = list(c(400, 800), c(600, 700), c(800, 400), c(800, 150))) %>%
  set_range(time = 300, polygon = list(
    c(400, 0), c(1000, 0), c(1000, 600), c(900, 400), c(800, 250),
    c(600, 100), c(500, 50))
  )

# population ranges can expand by a given distance in all directions
pop2 <- expand_range(pop2, by = 200, start = 50, end = 150, snapshots = 3)
```

```
# we can check the positions of all populations interactively by plotting their
# ranges together on a single map
plot_map(pop1, pop2, pop3)

# gene flow events ----------------------------------------------------

# individual gene flow events can be saved to a list
gf <- list(
  gene_flow(from = pop1, to = pop3, start = 150, end = 200, proportion = 0.15),
  gene_flow(from = pop1, to = pop2, start = 300, end = 330, proportion = 0.25)
)

# compilation ---------------------------------------------------------

# compile model components in a serialized form to dist, returning a single
# slendr model object (in practice, the resolution should be smaller)
model <- compile_model(
  populations = list(pop1, pop2, pop3), generation_time = 1,
  resolution = 100, simulation_length = 500,
  competition = 5, mating = 5, dispersal = 1
)
```

`msprime` *Run a slendr model in msprime*

Description

This function will execute a built-in msprime script and run a compiled slendr demographic model.

Usage

```
msprime(
  model,
  sequence_length,
  recombination_rate,
  schedule = NULL,
  random_seed = NULL,
  verbose = FALSE,
  debug = FALSE,
  run = TRUE,
  path = NULL,
  coalescent_only = TRUE,
  samples = NULL
)
```

Arguments

model	Model object created by the compile function
sequence_length	Total length of the simulated sequence (in base-pairs)
recombination_rate	Recombination rate of the simulated sequence (in recombinations per basepair per generation)
schedule	A data frame of times at which a given number of individuals should be recorded in the tree-sequence (see schedule_recording for a function that can generate such recording schedule in the correct format). If missing, only individuals present at the end of the simulation will be recorded in the final tree-sequence file.
random_seed	Random seed (if NULL, a seed will be generated between 0 and the maximum integer number available)
verbose	Write the log information from the SLiM run to the console (default FALSE)?
debug	Write msprime's debug log to the console (default FALSE)?
run	Should the msprime engine be run? If FALSE, the command line msprime command will be printed (and returned invisibly as a character vector) but not executed.
path	Path to the directory where simulation result files will be saved. If NULL, this directory will be automatically created as a temporary directory. If TRUE, this path will be also returned by the function. If a string is given, it is assumed to be a path to a directory where simulation results will be saved. In this case, the function will return this path invisibly. Note that if a tree-sequence file should be simulated (along with other files, potentially), that tree-sequence file (named 'msprime.trees' by default) will have to be explicitly loaded using ts_read().
coalescent_only	Default is TRUE, which will only record the minimum amount of information necessary to represent the genealogical history of the simulated samples (i.e., only nodes which are MRCA of some pair of samples at some locus in the genome). Setting to FALSE will record much more information, resulting in unary nodes in the tree sequence. This parameter translates to the coalescing_segments_only argument of the underlying msprime method sim_ancestry. See Details for additional information.
samples	Deprecated, see schedule instead.

Details

For more information about the coalescent_only argument, please see msprime documentation, particularly the section on "Recording more information" and the coalescing_segments_only argument of the method sim_ancestry() here https://tskit.dev/msprime/docs/stable/ancestry.html#recording-more-information. and https://tskit.dev/msprime/docs/stable/api.html#msprime.sim_ancestry.

Value

A tree-sequence object loaded via Python-R reticulate interface function `ts_read` (internally represented by the Python object `tskit.trees.TreeSequence`). If the `path` argument was set, it will return the path as a single-element character vector.

Examples

```
init_env()

# load an example model
model <- read_model(path = system.file("extdata/models/introgression", package = "slendr"))

# afr and eur objects would normally be created before slendr model compilation,
# but here we take them out of the model object already compiled for this
# example (in a standard slendr simulation pipeline, this wouldn't be necessary)
afr <- model$populations[["AFR"]]
eur <- model$populations[["EUR"]]
chimp <- model$populations[["CH"]]

# schedule the recording of a couple of ancient and present-day individuals
# given model at 20 ky, 10 ky, 5ky ago and at present-day (time 0)
modern <- schedule_recording(model, times = 0, list(afr, 10), list(eur, 100), list(chimp, 1))
ancient <- schedule_recording(model, times = c(40000, 30000, 20000, 10000), list(eur, 1))

# recording schedules are just data frames and can be merged easily
schedule <- rbind(modern, ancient)

# run a simulation using the msprime back end from a compiled slendr model object
ts <- msprime(model, sequence_length = 1e5, recombination_rate = 0, schedule = schedule)

# simulated tree-sequence object can be saved to a file using ts_write()...
ts_file <- normalizePath(tempfile(fileext = ".trees"), winslash = "/", mustWork = FALSE)
ts_write(ts, ts_file)
# ... and, at a later point, loaded by ts_read()
ts <- ts_read(ts_file, model)

summary(ts)
```

`overlap` *Generate the overlap of two* `slendr` *objects*

Description

Generate the overlap of two `slendr` objects

Usage

```
overlap(x, y, name = NULL)
```

Arguments

x	Object of the class slendr
y	Object of the class slendr
name	Optional name of the resulting geographic region. If missing, name will be constructed from the function arguments.

Value

Object of the class slendr_region which encodes a standard spatial object of the class sf with several additional attributes (most importantly a corresponding slendr_map object, if applicable).

---

plot_map *Plot* slendr *geographic features on a map*

Description

Plots objects of the three slendr spatial classes (slendr_map, slendr_region, and slendr_pop).

Usage

```
plot_map(
  ...,
  time = NULL,
  gene_flow = FALSE,
  splits = FALSE,
  labels = FALSE,
  arrows = TRUE,
  graticules = "original",
  intersect = TRUE,
  show_map = TRUE,
  title = NULL,
  interpolated_maps = NULL
)
```

Arguments

...	Objects of classes slendr_map, slendr_region, or slendr_pop
time	Plot a concrete time point
gene_flow	Indicate gene-flow events by linking demes with a line
splits	Indicate split events with lines
labels	Should the (starting) polygons of each populations be labeled with a respective population label (default FALSE)?
arrows	Should gene-flow links be also indicated with an arrow?
graticules	Plot graticules in the original Coordinate Reference System (such as longitude-latitude), or in the internal CRS (such as meters)?

intersect	Intersect the population boundaries against landscape and other geographic boundaries (default TRUE)?
show_map	Show the underlying world map
title	Title of the plot
interpolated_maps	Interpolated spatial boundaries for all populations in all time points (this is only used for plotting using the explore shiny app)

Value

A ggplot2 object with the visualized slendr map

`plot_model` *Plot demographic history encoded in a slendr model*

Description

Plot demographic history encoded in a slendr model

Usage

```
plot_model(
  model,
  sizes = TRUE,
  proportions = FALSE,
  gene_flow = TRUE,
  log = FALSE,
  order = NULL,
  file = NULL,
  schedule = NULL,
  ...
)
```

Arguments

model	Compiled slendr_model model object
sizes	Should population size changes be visualized?
proportions	Should gene flow proportions be visualized (FALSE by default to prevent cluttering and overplotting)
gene_flow	Should gene-flow arrows be visualized (default TRUE).
log	Should the y-axis be plotted on a log scale? Useful for models over very long time-scales.
order	Order of the populations along the x-axis, given as a character vector of population names. If NULL (the default), the default plotting algorithm will be used, ordering populations from the most ancestral to the most recent using an in-order tree traversal.

file	Output file for a figure saved via ggsave
schedule	Recording schedule to be visualized over the model
...	Optional argument which will be passed to ggsave

Value

A ggplot2 object with the visualized slendr model

Examples

```
init_env()

# load an example model with an already simulated tree sequence
path <- system.file("extdata/models/introgression", package = "slendr")
model <- read_model(path)

plot_model(model, sizes = FALSE, log = TRUE)
```

---

population *Define a population*

Description

Defines the parameters of a population (non-spatial and spatial).

Usage

```
population(
  name,
  time,
  N,
  parent = NULL,
  map = FALSE,
  center = NULL,
  radius = NULL,
  polygon = NULL,
  remove = NULL,
  intersect = TRUE,
  competition = NA,
  mating = NA,
  dispersal = NA,
  dispersal_fun = NULL,
  aquatic = FALSE
)
```

Arguments

name	Name of the population
time	Time of the population's first appearance
N	Number of individuals at the time of first appearance
parent	Parent population object or NULL (which indicates that the population does not have an ancestor, as it is the first population in its "lineage")
map	Object of the type slendr_map which defines the world context (created using the world function). If the value FALSE is provided, a non-spatial model will be run.
center	Two-dimensional vector specifying the center of the circular range
radius	Radius of the circular range
polygon	List of vector pairs, defining corners of the polygon range or a geographic region of the class slendr_region from which the polygon coordinates will be extracted (see the region() function)
remove	Time at which the population should be removed
intersect	Intersect the population's boundaries with landscape features?
competition, mating	Maximum spatial competition and mating choice distance
dispersal	Standard deviation of the normal distribution of the distance that offspring disperses from its parent
dispersal_fun	Distribution function governing the dispersal of offspring. One of "normal", "uniform", "cauchy", "exponential", or "brownian" (in which vertical and horizontal displacements are drawn from a normal distribution independently).
aquatic	Is the species aquatic (FALSE by default, i.e. terrestrial species)?

Details

There are four ways to specify a spatial boundary: i) circular range specified using a center coordinate and a radius, ii) polygon specified as a list of two-dimensional vector coordinates, iii) polygon as in ii), but defined (and named) using the region function, iv) with just a world map specified (circular or polygon range parameters set to the default NULL value), the population will be allowed to occupy the entire landscape.

Note that because slendr models have to accomodate both SLiM and msprime back ends, population sizes and split times are rounded to the nearest integer value.

Value

Object of the class slendr_pop, which contains population parameters such as name, time of appearance in the simulation, parent population (if any), and its spatial parameters such as map and spatial boundary.

Examples

```
# spatial definitions ----------------------------------------------------

# create a blank abstract world 1000x1000 distance units in size
map <- world(xrange = c(0, 1000), yrange = c(0, 1000), landscape = "blank")

# create a circular population with the center of a population boundary at
# [200, 800] and a radius of 100 distance units, 1000 individuals at time 1
# occupying a map just specified
pop1 <- population("pop1", N = 1000, time = 1,
                   map = map, center = c(200, 800), radius = 100)

# printing a population object to a console shows a brief summary
pop1

# create another population occupying a polygon range, splitting from pop1
# at a given time point (note that specifying a map is not necessary because
# it is "inherited" from the parent)
pop2 <- population("pop2", N = 100, time = 50, parent = pop1,
                        polygon = list(c(100, 100), c(320, 30), c(500, 200),
                                  c(500, 400), c(300, 450), c(100, 400)))

pop3 <- population("pop3", N = 200, time = 80, parent = pop2,
                   center = c(800, 800), radius = 200)

# move "pop1" to another location along a specified trajectory and saved the
# resulting object to the same variable (the number of intermediate spatial
# snapshots can be also determined automatically by leaving out the
# `snapshots = ` argument)
pop1_moved <- move(pop1, start = 100, end = 200, snapshots = 6,
                   trajectory = list(c(600, 820), c(800, 400), c(800, 150)))
pop1_moved

# many slendr functions are pipe-friendly, making it possible to construct
# pipelines which construct entire history of a population
pop1 <- population("pop1", N = 1000, time = 1,
                   map = map, center = c(200, 800), radius = 100) %>%
  move(start = 100, end = 200, snapshots = 6,
       trajectory = list(c(400, 800), c(600, 700), c(800, 400), c(800, 150))) %>%
  set_range(time = 300, polygon = list(
    c(400, 0), c(1000, 0), c(1000, 600), c(900, 400), c(800, 250),
    c(600, 100), c(500, 50))
  )

# population ranges can expand by a given distance in all directions
pop2 <- expand_range(pop2, by = 200, start = 50, end = 150, snapshots = 3)

# we can check the positions of all populations interactively by plotting their
# ranges together on a single map
plot_map(pop1, pop2, pop3)

# gene flow events -------------------------------------------------------
```

```
# individual gene flow events can be saved to a list
gf <- list(
  gene_flow(from = pop1, to = pop3, start = 150, end = 200, proportion = 0.15),
  gene_flow(from = pop1, to = pop2, start = 300, end = 330, proportion = 0.25)
)

# compilation ------------------------------------------------------------

# compile model components in a serialized form to dist, returning a single
# slendr model object (in practice, the resolution should be smaller)
model <- compile_model(
  populations = list(pop1, pop2, pop3), generation_time = 1,
  resolution = 100, simulation_length = 500,
  competition = 5, mating = 5, dispersal = 1
)
```

`print.slendr_pop` *Print a short summary of a* `slendr` *object*

Description

All spatial objects in the slendr package are internally represented as Simple Features (`sf`) objects. This fact is hidden in most circumstances this, as the goal of the slendr package is to provide functionality at a much higher level (population boundaries, geographic regions, instead of individual polygons and other "low-level" geometric objects), without the users having to worry about low-level details involved in handling spatial geometries. However, the full `sf` object representation can be always printed by calling `x[]`.

Usage

```
## S3 method for class 'slendr_pop'
print(x, ...)

## S3 method for class 'slendr_region'
print(x, ...)

## S3 method for class 'slendr_map'
print(x, ...)

## S3 method for class 'slendr_model'
print(x, ...)
```

Arguments

`x`	Object of a class `slendr` (either `slendr_pop`, `slendr_map`, `slendr_region`, or `slendr_table`)
`...`	Additional arguments passed to `print`

Value

No return value, used only for printing

`print.slendr_ts` *Print tskit's summary table of the Python tree-sequence object*

Description

Print tskit's summary table of the Python tree-sequence object

Usage

```
## S3 method for class 'slendr_ts'
print(x, ...)
```

Arguments

`x`	Tree object of the class `slendr_phylo`
`...`	Additional arguments normally passed to `print` (not used in this case)

Value

No return value, simply prints the tskit summary table to the terminal

---

`read_model` *Read a previously serialized model configuration*

Description

Reads all configuration tables and other model data from a location where it was previously compiled to by the `compile` function.

Usage

```
read_model(path)
```

Arguments

`path`	Directory with all required configuration files

Value

Compiled `slendr_model` model object which encapsulates all information about the specified model (which populations are involved, when and how much gene flow should occur, what is the spatial resolution of a map, and what spatial dispersal and mating parameters should be used in a SLiM simulation, if applicable)

Examples

```
init_env()

# load an example model with an already simulated tree sequence
path <- system.file("extdata/models/introgression", package = "slendr")
model <- read_model(path)

plot_model(model, sizes = FALSE, log = TRUE)
```

---

region *Define a geographic region*

Description

Creates a geographic region (a polygon) on a given map and gives it a name. This can be used to define objects which can be reused in multiple places in a slendr script (such as `region` arguments of `population`) without having to repeatedly define polygon coordinates.

Usage

```
region(name = NULL, map = NULL, center = NULL, radius = NULL, polygon = NULL)
```

Arguments

`name`	Name of the geographic region
`map`	Object of the type `sf` which defines the map
`center`	Two-dimensional vector specifying the center of the circular range
`radius`	Radius of the circular range
`polygon`	List of vector pairs, defining corners of the polygon range or a geographic region of the class `slendr_region` from which the polygon coordinates will be extracted (see the `region()` function)

Value

Object of the class `slendr_region` which encodes a standard spatial object of the class `sf` with several additional attributes (most importantly a corresponding `slendr_map` object, if applicable).

Examples

```
# create a blank abstract world 1000x1000 distance units in size
blank_map <- world(xrange = c(0, 1000), yrange = c(0, 1000), landscape = "blank")

# it is possible to construct custom landscapes (islands, corridors, etc.)
island1 <- region("island1", polygon = list(c(10, 30), c(50, 30), c(40, 50), c(0, 40)))
island2 <- region("island2", polygon = list(c(60, 60), c(80, 40), c(100, 60), c(80, 80)))
island3 <- region("island3", center = c(20, 80), radius = 10)
archipelago <- island1 %>% join(island2) %>% join(island3)
```

```
custom_map <- world(xrange = c(1, 100), c(1, 100), landscape = archipelago)

# real Earth landscapes can be defined using freely-available Natural Earth
# project data and with the possibility to specify an appropriate Coordinate
# Reference System, such as this example of a map of Europe

real_map <- world(xrange = c(-15, 40), yrange = c(30, 60), crs = "EPSG:3035")
```

`reproject` *Reproject coordinates between coordinate systems*

Description

Converts between coordinates on a compiled raster map (i.e. pixel units) and different Geographic Coordinate Systems (CRS).

Usage

```
reproject(
  from,
  to,
  x = NULL,
  y = NULL,
  coords = NULL,
  model = NULL,
  add = FALSE,
  input_prefix = "",
  output_prefix = "new"
)
```

Arguments

`from`, `to`	Either a CRS code accepted by GDAL, a valid integer EPSG value, an object of class `crs`, the value "raster" (converting from/to pixel coordinates), or "world" (converting from/to whatever CRS is set for the underlying map)
`x`, `y`	Coordinates in two dimensions (if missing, coordinates are expected to be in the `data.frame` specified in the `coords` parameter as columns "x" and "y")
`coords`	data.frame-like object with coordinates in columns "x" and "y"
`model`	Object of the class `slendr_model`
`add`	Add column coordinates to the input data.frame `coords` (coordinates otherwise returned as a separate object)?
`input_prefix`, `output_prefix`	Input and output prefixes of data frame columns with spatial coordinates

Value

Data.frame with converted two-dimensional coordinates given as input

Examples

```
lon_lat_df <- data.frame(x = c(30, 0, 15), y = c(60, 40, 10))

reproject(
  from = "epsg:4326",
  to = "epsg:3035",
  coords = lon_lat_df,
  add = TRUE # add converted [lon,lat] coordinates as a new column
)
```

---

resize *Change the population size*

Description

Resizes the population starting from the current value of N individuals to the specified value

Usage

```
resize(pop, N, time, end = NULL, how = NULL)
```

Arguments

pop	Object of the class slendr_pop
N	Population size after the change
time	Time of the population size change
end	End of the population size change period (automatically implies an exponential change event)
how	Deprecated argument. Specifying the value of end now automatically implies an exponential resize, leaving it out implies an instantaneous size change.

Details

In the case of exponential size change, if the final N is larger than the current size, the population will be exponentially growing over the specified time period until it reaches N individuals. If N is smaller, the population will shrink exponentially.

Note that because slendr models have to accomodate both SLiM and msprime back ends, population sizes and split times are rounded to the nearest integer value.

Value

Object of the class slendr_pop, which contains population parameters such as name, time of appearance in the simulation, parent population (if any), and its spatial parameters such as map and spatial boundary.

Examples

```
# spatial definitions ------------------------------------------------------

# create a blank abstract world 1000x1000 distance units in size
map <- world(xrange = c(0, 1000), yrange = c(0, 1000), landscape = "blank")

# create a circular population with the center of a population boundary at
# [200, 800] and a radius of 100 distance units, 1000 individuals at time 1
# occupying a map just specified
pop1 <- population("pop1", N = 1000, time = 1,
                   map = map, center = c(200, 800), radius = 100)

# printing a population object to a console shows a brief summary
pop1

# create another population occupying a polygon range, splitting from pop1
# at a given time point (note that specifying a map is not necessary because
# it is "inherited" from the parent)
pop2 <- population("pop2", N = 100, time = 50, parent = pop1,
                         polygon = list(c(100, 100), c(320, 30), c(500, 200),
                                        c(500, 400), c(300, 450), c(100, 400)))

pop3 <- population("pop3", N = 200, time = 80, parent = pop2,
                   center = c(800, 800), radius = 200)

# move "pop1" to another location along a specified trajectory and saved the
# resulting object to the same variable (the number of intermediate spatial
# snapshots can be also determined automatically by leaving out the
# `snapshots = ` argument)
pop1_moved <- move(pop1, start = 100, end = 200, snapshots = 6,
                   trajectory = list(c(600, 820), c(800, 400), c(800, 150)))
pop1_moved

# many slendr functions are pipe-friendly, making it possible to construct
# pipelines which construct entire history of a population
pop1 <- population("pop1", N = 1000, time = 1,
                   map = map, center = c(200, 800), radius = 100) %>%
  move(start = 100, end = 200, snapshots = 6,
       trajectory = list(c(400, 800), c(600, 700), c(800, 400), c(800, 150))) %>%
  set_range(time = 300, polygon = list(
    c(400, 0), c(1000, 0), c(1000, 600), c(900, 400), c(800, 250),
    c(600, 100), c(500, 50))
  )

# population ranges can expand by a given distance in all directions
pop2 <- expand_range(pop2, by = 200, start = 50, end = 150, snapshots = 3)

# we can check the positions of all populations interactively by plotting their
# ranges together on a single map
plot_map(pop1, pop2, pop3)

# gene flow events ---------------------------------------------------------
```

```
# individual gene flow events can be saved to a list
gf <- list(
  gene_flow(from = pop1, to = pop3, start = 150, end = 200, proportion = 0.15),
  gene_flow(from = pop1, to = pop2, start = 300, end = 330, proportion = 0.25)
)

# compilation ------------------------------------------------------------

# compile model components in a serialized form to dist, returning a single
# slendr model object (in practice, the resolution should be smaller)
model <- compile_model(
  populations = list(pop1, pop2, pop3), generation_time = 1,
  resolution = 100, simulation_length = 500,
  competition = 5, mating = 5, dispersal = 1
)
```

`schedule_recording` *Define recording for a given populations at given times*

Description

Schedule recording events at specified times and, optionally, a given set of locations on a landscape

Usage

```
schedule_recording(model, times, ..., locations = NULL, strict = FALSE)
```

Arguments

`model`	Object of the class `slendr_model`
`times`	Integer vector of times (in model time units) at which to schedule remembering of individuals in the tree-sequence
`...`	Lists of two elements (`slendr_pop` population object-<number of individuals to sample), representing from which populations should how many individuals be remembered at times given by `times`. Alternatively, specifying `list("each", <number>)` will record the given number of samples from every population at the given time.
`locations`	List of vector pairs, defining two-dimensional coordinates of locations at which the closest number of individuals from given populations should be sampled. If `NULL` (the default), individuals will be sampled randomly throughout their spatial boundary.
`strict`	Should any occurence of a population not being present at a given time result in an error? Default is `FALSE`, meaning that invalid times of recording for any populations will be quietly ignored.

Details

If both times and locations are given, the recording will be scheduled on each specified location in each given time-point. Note that for the time-being, in the interest of simplicity, no sanity checks are performed on the locations given except the restriction that the points of recording must fall within the bounding box around the simulated world map. Other than that, slendr will simply instruct its SLiM backend script to sample individuals as close to the recording points given as possible, regardless of whether those points lie within a population spatial boundary at that particular moment of time.

Optionally, a name of a single sample from a population can be given, which will then replace the generic format of `"\{population\}_\{number\}"` name. See example for more detail.

Value

Data frame with three columns: time of sampling, population to sample from, how many individuals to sample

Examples

```
init_env()

# load an example model with an already simulated tree sequence
path <- system.file("extdata/models/introgression", package = "slendr")
model <- read_model(path)

# afr, eur, and nea objects would normally be created before slendr model
# compilation, but here we take them out of the model object already compiled for
# this example (in a standard slendr simulation pipeline, this wouldn't be necessary)
afr <- model$populations[["AFR"]]
eur <- model$populations[["EUR"]]
nea <- model$populations[["NEA"]]

# schedule the recording of 10 African and 100 European individuals from a
# given model at 20 ky, 10 ky, 5ky ago and at present-day (time 0)
schedule_amh <- schedule_recording(
  model, times = c(20000, 10000, 5000, 0),
  list(afr, 10), list(eur, 100)
)
# schedule the recording of the Vindija Neanderthal genome
schedule_nea <- schedule_recording(model, times = 40000, list(nea, 1, "Vindija"))

# the result of `schedule_recording` is a simple data frame (note that the locations
# of sampling locations have `NA` values because the model is non-spatial)
schedule <- rbind(schedule_amh, schedule_nea)
schedule

# simulate a tree sequence
ts <- msprime(model, sequence_length = 1e6, recombination_rate = 1e-8, schedule = schedule)

# inspect the recorded table of samples
ts_recorded(ts)
```

setup_env *Setup a dedicated Python virtual environment for slendr*

Description

This function will setup a dedicated Python virtual environment for slendr, either via a dedicated miniconda distribution or using a Python installation already available on the system.

Usage

```
setup_env(env = c("conda", "venv"), agree = FALSE, quiet = FALSE, pip = NULL)
```

Arguments

env	Should the Python virtual environment be created with conda (default) or using an already available Python interpreter and its built-in pip module?
agree	Automatically agree to all questions?
quiet	Should informative messages be printed to the console? Default is FALSE.
pip	Should pip be used instead of conda for installing slendr's Python dependencies? (DEPRECATED)

Value

No return value, called for side effects

set_dispersal *Change dispersal parameters*

Description

Changes either the competition interactive distance, mating choice distance, or the dispersal of offspring from its parent

Usage

```
set_dispersal(
  pop,
  time,
  competition = NA,
  mating = NA,
  dispersal = NA,
  dispersal_fun = NULL
)
```

Arguments

pop	Object of the class slendr_pop
time	Time of the population size change
competition, mating	Maximum spatial competition and mating choice distance
dispersal	Standard deviation of the normal distribution of the distance that offspring disperses from its parent
dispersal_fun	Distribution function governing the dispersal of offspring. One of "normal", "uniform", "cauchy", "exponential", or "brownian" (in which vertical and horizontal displacements are drawn from a normal distribution independently).

Value

Object of the class slendr_pop, which contains population parameters such as name, time of appearance in the simulation, parent population (if any), and its spatial parameters such as map and spatial boundary.

Examples

```
# spatial definitions ------------------------------------------------------

# create a blank abstract world 1000x1000 distance units in size
map <- world(xrange = c(0, 1000), yrange = c(0, 1000), landscape = "blank")

# create a circular population with the center of a population boundary at
# [200, 800] and a radius of 100 distance units, 1000 individuals at time 1
# occupying a map just specified
pop1 <- population("pop1", N = 1000, time = 1,
                   map = map, center = c(200, 800), radius = 100)

# printing a population object to a console shows a brief summary
pop1

# create another population occupying a polygon range, splitting from pop1
# at a given time point (note that specifying a map is not necessary because
# it is "inherited" from the parent)
pop2 <- population("pop2", N = 100, time = 50, parent = pop1,
                         polygon = list(c(100, 100), c(320, 30), c(500, 200),
                                   c(500, 400), c(300, 450), c(100, 400)))

pop3 <- population("pop3", N = 200, time = 80, parent = pop2,
                   center = c(800, 800), radius = 200)

# move "pop1" to another location along a specified trajectory and saved the
# resulting object to the same variable (the number of intermediate spatial
# snapshots can be also determined automatically by leaving out the
# `snapshots = ` argument)
pop1_moved <- move(pop1, start = 100, end = 200, snapshots = 6,
                   trajectory = list(c(600, 820), c(800, 400), c(800, 150)))
pop1_moved
```

```
# many slendr functions are pipe-friendly, making it possible to construct
# pipelines which construct entire history of a population
pop1 <- population("pop1", N = 1000, time = 1,
                   map = map, center = c(200, 800), radius = 100) %>%
  move(start = 100, end = 200, snapshots = 6,
       trajectory = list(c(400, 800), c(600, 700), c(800, 400), c(800, 150))) %>%
  set_range(time = 300, polygon = list(
    c(400, 0), c(1000, 0), c(1000, 600), c(900, 400), c(800, 250),
    c(600, 100), c(500, 50))
  )

# population ranges can expand by a given distance in all directions
pop2 <- expand_range(pop2, by = 200, start = 50, end = 150, snapshots = 3)

# we can check the positions of all populations interactively by plotting their
# ranges together on a single map
plot_map(pop1, pop2, pop3)

# gene flow events ----------------------------------------------------

# individual gene flow events can be saved to a list
gf <- list(
  gene_flow(from = pop1, to = pop3, start = 150, end = 200, proportion = 0.15),
  gene_flow(from = pop1, to = pop2, start = 300, end = 330, proportion = 0.25)
)

# compilation ---------------------------------------------------------

# compile model components in a serialized form to dist, returning a single
# slendr model object (in practice, the resolution should be smaller)
model <- compile_model(
  populations = list(pop1, pop2, pop3), generation_time = 1,
  resolution = 100, simulation_length = 500,
  competition = 5, mating = 5, dispersal = 1
)
```

`set_range` *Update the population range*

Description

This function allows a more manual control of spatial map changes in addition to the `expand` and `move` functions

Usage

```
set_range(
  pop,
  time,
```

```
  center = NULL,
  radius = NULL,
  polygon = NULL,
  lock = FALSE
)
```

Arguments

pop	Object of the class slendr_pop
time	Time of the change
center	Two-dimensional vector specifying the center of the circular range
radius	Radius of the circular range
polygon	List of vector pairs, defining corners of the polygon range (see also the region argument) or a geographic region of the class slendr_region from which the polygon coordinates will be extracted
lock	Maintain the same density of individuals. If FALSE (the default), the number of individuals in the population will not change. If TRUE, the number of individuals simulated will be changed (increased or decreased) appropriately, to match the new population range area.

Value

Object of the class slendr_pop, which contains population parameters such as name, time of appearance in the simulation, parent population (if any), and its spatial parameters such as map and spatial boundary.

Examples

```
# spatial definitions -----------------------------------------------------

# create a blank abstract world 1000x1000 distance units in size
map <- world(xrange = c(0, 1000), yrange = c(0, 1000), landscape = "blank")

# create a circular population with the center of a population boundary at
# [200, 800] and a radius of 100 distance units, 1000 individuals at time 1
# occupying a map just specified
pop1 <- population("pop1", N = 1000, time = 1,
                   map = map, center = c(200, 800), radius = 100)

# printing a population object to a console shows a brief summary
pop1

# create another population occupying a polygon range, splitting from pop1
# at a given time point (note that specifying a map is not necessary because
# it is "inherited" from the parent)
pop2 <- population("pop2", N = 100, time = 50, parent = pop1,
                         polygon = list(c(100, 100), c(320, 30), c(500, 200),
                                   c(500, 400), c(300, 450), c(100, 400)))
```

```
pop3 <- population("pop3", N = 200, time = 80, parent = pop2,
                   center = c(800, 800), radius = 200)

# move "pop1" to another location along a specified trajectory and saved the
# resulting object to the same variable (the number of intermediate spatial
# snapshots can be also determined automatically by leaving out the
# `snapshots = ` argument)
pop1_moved <- move(pop1, start = 100, end = 200, snapshots = 6,
                   trajectory = list(c(600, 820), c(800, 400), c(800, 150)))
pop1_moved

# many slendr functions are pipe-friendly, making it possible to construct
# pipelines which construct entire history of a population
pop1 <- population("pop1", N = 1000, time = 1,
                   map = map, center = c(200, 800), radius = 100) %>%
  move(start = 100, end = 200, snapshots = 6,
       trajectory = list(c(400, 800), c(600, 700), c(800, 400), c(800, 150))) %>%
  set_range(time = 300, polygon = list(
    c(400, 0), c(1000, 0), c(1000, 600), c(900, 400), c(800, 250),
    c(600, 100), c(500, 50))
  )

# population ranges can expand by a given distance in all directions
pop2 <- expand_range(pop2, by = 200, start = 50, end = 150, snapshots = 3)

# we can check the positions of all populations interactively by plotting their
# ranges together on a single map
plot_map(pop1, pop2, pop3)

# gene flow events ----------------------------------------------------

# individual gene flow events can be saved to a list
gf <- list(
  gene_flow(from = pop1, to = pop3, start = 150, end = 200, proportion = 0.15),
  gene_flow(from = pop1, to = pop2, start = 300, end = 330, proportion = 0.25)
)

# compilation ---------------------------------------------------------

# compile model components in a serialized form to dist, returning a single
# slendr model object (in practice, the resolution should be smaller)
model <- compile_model(
  populations = list(pop1, pop2, pop3), generation_time = 1,
  resolution = 100, simulation_length = 500,
  competition = 5, mating = 5, dispersal = 1
)
```

---

shrink_range *Shrink the population range*

Description

Shrinks the spatial population range by a specified distance in a given time-window

Usage

```
shrink_range(
  pop,
  by,
  end,
  start,
  overlap = 0.8,
  snapshots = NULL,
  lock = FALSE,
  verbose = TRUE
)
```

Arguments

pop	Object of the class slendr_pop
by	How many units of distance to shrink by?
start, end	When does the boundary shrinking start/end?
overlap	Minimum overlap between subsequent spatial boundaries
snapshots	The number of intermediate snapshots (overrides the overlap parameter)
lock	Maintain the same density of individuals. If FALSE (the default), the number of individuals in the population will not change. If TRUE, the number of individuals simulated will be changed (increased or decreased) appropriately, to match the new population range area.
verbose	Report on the progress of generating intermediate spatial boundaries?

Details

Note that because slendr models have to accomodate both SLiM and msprime back ends, population sizes and split times are rounded to the nearest integer value.

Value

Object of the class slendr_pop, which contains population parameters such as name, time of appearance in the simulation, parent population (if any), and its spatial parameters such as map and spatial boundary.

Examples

```
# spatial definitions ------------------------------------------------------

# create a blank abstract world 1000x1000 distance units in size
map <- world(xrange = c(0, 1000), yrange = c(0, 1000), landscape = "blank")

# create a circular population with the center of a population boundary at
```

```
# [200, 800] and a radius of 100 distance units, 1000 individuals at time 1
# occupying a map just specified
pop1 <- population("pop1", N = 1000, time = 1,
                   map = map, center = c(200, 800), radius = 100)

# printing a population object to a console shows a brief summary
pop1

# create another population occupying a polygon range, splitting from pop1
# at a given time point (note that specifying a map is not necessary because
# it is "inherited" from the parent)
pop2 <- population("pop2", N = 100, time = 50, parent = pop1,
                         polygon = list(c(100, 100), c(320, 30), c(500, 200),
                                   c(500, 400), c(300, 450), c(100, 400)))

pop3 <- population("pop3", N = 200, time = 80, parent = pop2,
                   center = c(800, 800), radius = 200)

# move "pop1" to another location along a specified trajectory and saved the
# resulting object to the same variable (the number of intermediate spatial
# snapshots can be also determined automatically by leaving out the
# `snapshots = ` argument)
pop1_moved <- move(pop1, start = 100, end = 200, snapshots = 6,
                   trajectory = list(c(600, 820), c(800, 400), c(800, 150)))
pop1_moved

# many slendr functions are pipe-friendly, making it possible to construct
# pipelines which construct entire history of a population
pop1 <- population("pop1", N = 1000, time = 1,
                   map = map, center = c(200, 800), radius = 100) %>%
  move(start = 100, end = 200, snapshots = 6,
       trajectory = list(c(400, 800), c(600, 700), c(800, 400), c(800, 150))) %>%
  set_range(time = 300, polygon = list(
    c(400, 0), c(1000, 0), c(1000, 600), c(900, 400), c(800, 250),
    c(600, 100), c(500, 50))
  )

# population ranges can expand by a given distance in all directions
pop2 <- expand_range(pop2, by = 200, start = 50, end = 150, snapshots = 3)

# we can check the positions of all populations interactively by plotting their
# ranges together on a single map
plot_map(pop1, pop2, pop3)

# gene flow events ----------------------------------------------------------

# individual gene flow events can be saved to a list
gf <- list(
  gene_flow(from = pop1, to = pop3, start = 150, end = 200, proportion = 0.15),
  gene_flow(from = pop1, to = pop2, start = 300, end = 330, proportion = 0.25)
)

# compilation ---------------------------------------------------------------
```

```
# compile model components in a serialized form to dist, returning a single
# slendr model object (in practice, the resolution should be smaller)
model <- compile_model(
  populations = list(pop1, pop2, pop3), generation_time = 1,
  resolution = 100, simulation_length = 500,
  competition = 5, mating = 5, dispersal = 1
)
```

`slim` *Run a slendr model in SLiM*

Description

This function will execute a SLiM script generated by the `compile` function during the compilation of a slendr demographic model.

Usage

```
slim(
  model,
  sequence_length,
  recombination_rate,
  schedule = NULL,
  ts = TRUE,
  path = NULL,
  random_seed = NULL,
  method = c("batch", "gui"),
  verbose = FALSE,
  run = TRUE,
  slim_path = NULL,
  burnin = 0,
  max_attempts = 1,
  spatial = !is.null(model$world),
  coalescent_only = TRUE,
  locations = NULL,
  samples = NULL
)
```

Arguments

`model`	Model object created by the `compile` function
`sequence_length`	Total length of the simulated sequence (in base-pairs)
`recombination_rate`	Recombination rate of the simulated sequence (in recombinations per basepair per generation)

schedule — A data frame of times at which a given number of individuals should be recorded in the tree-sequence (see schedule_recording for a function that can generate such recording schedule in the correct format). If missing, only individuals present at the end of the simulation will be recorded in the final tree-sequence file.

ts — Should a tree sequence be simulated from the model?

path — Path to the directory where simulation result files will be saved. If NULL, this directory will be automatically created as a temporary directory. If TRUE, this path will be also returned by the function. If a string is given, it is assumed to be a path to a directory where simulation results will be saved. In this case, the function will return this path invisibly. Note that if a tree-sequence file should be simulated (along with other files, potentially), that tree-sequence file (named 'slim.trees' by default) will have to be explicitly loaded using ts_read().

random_seed — Random seed (if NULL, a seed will be generated between 0 and the maximum integer number available)

method — How to run the script? ("gui" - open in SLiMgui, "batch" - run on the command line)

verbose — Write the log information from the SLiM run to the console (default FALSE)?

run — Should the SLiM engine be run? If FALSE, the command line SLiM command will be printed (and returned invisibly as a character vector) but not executed.

slim_path — Path to the appropriate SLiM binary (this is useful if the slim binary is not on the $PATH). Note that this argument must be specified if the function is being run on Windows.

burnin — Length of the burnin (in model's time units, i.e. years)

max_attempts — How many attempts should be made to place an offspring near one of its parents? Serves to prevent infinite loops on the SLiM backend. Default value is 1.

spatial — Should the model be executed in spatial mode? By default, if a world map was specified during model definition, simulation will proceed in a spatial mode.

coalescent_only — Should initializeTreeSeq(retainCoalescentOnly = <...>) be set to TRUE (the default) or FALSE? See "retainCoalescentOnly" in the SLiM manual for more detail.

locations — If NULL, locations are not saved. Otherwise, the path to the file where locations of each individual throughout the simulation will be saved (most likely for use with animate_model).

samples — Deprecated, see schedule instead.

Details

The arguments sequence_length and recombination_rate can be omitted for slendr models utilizing customized initialization of genomic architecture. In such cases, users may either provide hard-coded values directly through SLiM's initializeGenomicElement() and initializeRecombinationRate() functions or utilize slendr's templating functionality provided by its substitute() function. When ts = TRUE, the returning value of this function depends on whether or not the path argument was

set. If the user did provide the path where output files should be saved, the path is returned (invisibly). This is mostly intended to support simulations of customized user models. If path is not set by the user, it is assumed that a tree-sequence object is desired as a sole return value of the function (when ts = TRUE) and so it is automatically loaded when simulation finishes, or (when ts = FALSE) that only customized files are to be produced by the simulation, in which the user will be loading such files by themselves (and only the path is needed).

Value

A tree-sequence object loaded via Python-R reticulate interface function ts_read (internally represented by the Python object tskit.trees.TreeSequence). If the path argument was set, specifying the directory where results should be saved, the function will return this path as a single-element character vector.

Examples

```
init_env()

# load an example model
model <- read_model(path = system.file("extdata/models/introgression", package = "slendr"))

# afr and eur objects would normally be created before slendr model compilation,
# but here we take them out of the model object already compiled for this
# example (in a standard slendr simulation pipeline, this wouldn't be necessary)
afr <- model$populations[["AFR"]]
eur <- model$populations[["EUR"]]
chimp <- model$populations[["CH"]]

# schedule the recording of a couple of ancient and present-day individuals
# given model at 20 ky, 10 ky, 5ky ago and at present-day (time 0)
modern <- schedule_recording(model, times = 0, list(afr, 5), list(eur, 5), list(chimp, 1))
ancient <- schedule_recording(model, times = c(30000, 20000, 10000), list(eur, 1))

# recording schedules are just data frames and can be merged easily
schedule <- rbind(modern, ancient)

# run a simulation using the SLiM back end from a compiled slendr model object and return
# a tree-sequence object as a result
ts <- slim(model, sequence_length = 1e5, recombination_rate = 0, schedule = schedule)

# simulated tree-sequence object can be saved to a file using ts_write()...
ts_file <- normalizePath(tempfile(fileext = ".trees"), winslash = "/", mustWork = FALSE)
ts_write(ts, ts_file)
# ... and, at a later point, loaded by ts_read()
ts <- ts_read(ts_file, model)

ts
```

substitute_values *Substitute values of parameters in a SLiM extension template*

Description

Substitute values of templated {{parameters}} in a given SLiM extension template

Usage

```
substitute_values(template, ...)
```

Arguments

template	Either a path to an extension script file, or a string containing the entire SLiM extension code
...	Named function arguments interpreted as key=value pairs to be used in argument substitution

Details

If a file or a multi-line string given as `template` contains parameters specified as {{param}} where "param" can be arbitrary variable name, this function substitutes each templated {{parameter}} for a given values. Such modified template is then used to extend a built-in slendr SLiM script, allowing for a customization of its default behavior (most commonly replacing its assumption of neutrality for non-neutral scenarios, such as simulations of natural selection).

Value

Path to a file with a saved extension script containing all substituted values

subtract *Generate the difference between two* `slendr` *objects*

Description

Generate the difference between two `slendr` objects

Usage

```
subtract(x, y, name = NULL)
```

Arguments

x	Object of the class `slendr`
y	Object of the class `slendr`
name	Optional name of the resulting geographic region. If missing, name will be constructed from the function arguments.

Value

Object of the class `slendr_region` which encodes a standard spatial object of the class `sf` with several additional attributes (most importantly a corresponding `slendr_map` object, if applicable).

`summary.slendr_nodes` *Summarise the contents of a* `ts_nodes` *result*

Description

Summarise the contents of a `ts_nodes` result

Usage

```
## S3 method for class 'slendr_nodes'
summary(object, ...)
```

Arguments

`object`	Data frame produced by the function `ts_nodes`
`...`	Additional formal arguments to the `summary` method (unused here)

Value

Used for its output to the terminal

`ts_afs` *Compute the allele frequency spectrum (AFS)*

Description

This function computes the AFS with respect to the given set of individuals or nodes.

Usage

```
ts_afs(
  ts,
  sample_sets = NULL,
  mode = c("site", "branch", "node"),
  windows = NULL,
  span_normalise = FALSE,
  polarised = TRUE
)
```

Arguments

ts	Tree sequence object of the class slendr_ts
sample_sets	A list (optionally a named list) of character vectors with individual names (one vector per set). If NULL, allele frequency spectrum for all individuals in the tree sequence will be computed.
mode	The mode for the calculation ("sites" or "branch")
windows	Coordinates of breakpoints between windows. The first coordinate (0) and the last coordinate (equal to ts$sequence_length) are added automatically)
span_normalise	Argument passed to tskit's allele_frequency_spectrum method
polarised	When TRUE (the default) the allele frequency spectrum will not be folded (i.e. the counts will assume knowledge of which allele is ancestral, and which is derived, which is known in a simulation)

Details

For more information on the format of the result and dimensions, in particular the interpretation of the first and the last element of the AFS, please see the tskit manual at https://tskit.dev/tskit/docs/stable/python-api.html#tskit.TreeSequence.allele_frequency_spectrum and the example section dedicated to AFS at https://tskit.dev/tutorials/analysing_tree_sequences.html#zeroth-and-final-entries-in-the-afs.

Value

Allele frequency spectrum values for the given sample set. Note that the contents of the first and last elements of the AFS might surprise you. Read the links in the description for more detail on how tskit handles things.

Examples

```
init_env()

# load an example model with an already simulated tree sequence
slendr_ts <- system.file("extdata/models/introgression_slim.trees", package = "slendr")
model <- read_model(path = system.file("extdata/models/introgression", package = "slendr"))

# load the tree-sequence object from disk
ts <- ts_read(slendr_ts, model) %>% ts_mutate(mutation_rate = 1e-8, random_seed = 42)

samples <- ts_recorded(ts) %>% .[.$pop %in% c("AFR", "EUR"), ]

# compute AFS for the given set of individuals
ts_afs(ts, sample_sets = list(samples$name))
```

ts_ancestors *Extract (spatio-)temporal ancestral history for given nodes/individuals*

Description

Extract (spatio-)temporal ancestral history for given nodes/individuals

Usage

```
ts_ancestors(ts, x, verbose = FALSE, complete = TRUE)
```

Arguments

ts	Tree sequence object of the class slendr_ts
x	Either an individual name or an integer node ID
verbose	Report on the progress of ancestry path generation?
complete	Does every individual in the tree sequence need to have complete metadata recorded? If TRUE, only individuals/nodes with complete metadata will be included in the reconstruction of ancestral relationships. For instance, nodes added during the coalescent recapitation phase will not be included because they don't have spatial information associated with them.

Value

A table of ancestral nodes of a given tree-sequence node all the way up to the root of the tree sequence

Examples

```
init_env()

# load an example model with an already simulated tree sequence
slendr_ts <- system.file("extdata/models/introgression_slim.trees", package = "slendr")
model <- read_model(path = system.file("extdata/models/introgression", package = "slendr"))

# load the tree-sequence object from disk
ts <- ts_read(slendr_ts, model)

# find the complete ancestry information for a given individual
ts_ancestors(ts, "EUR_1", verbose = TRUE)
```

ts_coalesced *Check that all trees in the tree sequence are fully coalesced*

Description

Check that all trees in the tree sequence are fully coalesced

Usage

```
ts_coalesced(ts, return_failed = FALSE)
```

Arguments

ts	Tree sequence object of the class slendr_ts
return_failed	Report back which trees failed the coalescence check?

Value

TRUE or FALSE value if return_failed = FALSE, otherwise a vector of (tskit Python 0-based) indices of trees which failed the coalescence test

Examples

```
init_env()

# load an example model with an already simulated tree sequence
slendr_ts <- system.file("extdata/models/introgression_slim.trees", package = "slendr")
model <- read_model(path = system.file("extdata/models/introgression", package = "slendr"))

# load the tree-sequence object from disk
ts <- ts_read(slendr_ts, model)

ts_coalesced(ts) # is the tree sequence fully coalesced? (TRUE or FALSE)

# returns a vector of tree sequence segments which are not coalesced
not_coalesced <- ts_coalesced(ts, return_failed = TRUE)
```

ts_descendants *Extract all descendants of a given tree-sequence node*

Description

Extract all descendants of a given tree-sequence node

Usage

```
ts_descendants(ts, x, verbose = FALSE, complete = TRUE)
```

Arguments

ts	Tree sequence object of the class slendr_ts
x	An integer node ID of the ancestral node
verbose	Report on the progress of ancestry path generation?
complete	Does every individual in the tree sequence need to have complete metadata recorded? If TRUE, only individuals/nodes with complete metadata will be included in the reconstruction of ancestral relationships. For instance, nodes added during the coalescent recapitation phase will not be included because they don't have spatial information associated with them.

Value

A table of descendant nodes of a given tree-sequence node all the way down to the leaves of the tree sequence

Examples

```
init_env()

# load an example model with an already simulated tree sequence
slendr_ts <- system.file("extdata/models/introgression_slim.trees", package = "slendr")
model <- read_model(path = system.file("extdata/models/introgression", package = "slendr"))

# load the tree-sequence object from disk
ts <- ts_read(slendr_ts, model)

# find the complete descendancy information for a given individual
ts_descendants(ts, x = 62, verbose = TRUE)
```

---

ts_divergence *Calculate pairwise divergence between sets of individuals*

Description

Calculate pairwise divergence between sets of individuals

Usage

```
ts_divergence(
  ts,
  sample_sets,
  mode = c("site", "branch", "node"),
  windows = NULL,
  span_normalise = TRUE
)
```

Arguments

ts	Tree sequence object of the class slendr_ts
sample_sets	A list (optionally a named list) of character vectors with individual names (one vector per set)
mode	The mode for the calculation ("sites" or "branch")
windows	Coordinates of breakpoints between windows. The first coordinate (0) and the last coordinate (equal to ts$sequence_length) do not have to be specified as they are added automatically.
span_normalise	Divide the result by the span of the window? Default TRUE, see the tskit documentation for more detail.

Value

For each pairwise calculation, either a single divergence value or a vector of divergence values (one for each window)

Examples

```
init_env()

# load an example model with an already simulated tree sequence
slendr_ts <- system.file("extdata/models/introgression_slim.trees", package = "slendr")
model <- read_model(path = system.file("extdata/models/introgression", package = "slendr"))

# load the tree-sequence object from disk
ts <- ts_read(slendr_ts, model) %>% ts_mutate(mutation_rate = 1e-8, random_seed = 42)

# collect sampled individuals from all populations in a list
sample_sets <- ts_names(ts, split = TRUE)

# compute the divergence between individuals from each sample set (list of
# individual names generated in the previous step)
ts_divergence(ts, sample_sets)
```

---

ts_diversity *Calculate diversity in given sets of individuals*

Description

Calculate diversity in given sets of individuals

Usage

```
ts_diversity(
  ts,
  sample_sets,
  mode = c("site", "branch", "node"),
```

```
  windows = NULL,
  span_normalise = TRUE
)
```

Arguments

ts	Tree sequence object of the class slendr_ts
sample_sets	A list (optionally a named list) of character vectors with individual names (one vector per set). If a simple vector is provided, it will be interpreted as as.list(sample_sets), meaning that a given statistic will be calculated for each individual separately.
mode	The mode for the calculation ("sites" or "branch")
windows	Coordinates of breakpoints between windows. The first coordinate (0) and the last coordinate (equal to ts$sequence_length) are added automatically)
span_normalise	Divide the result by the span of the window? Default TRUE, see the tskit documentation for more detail.

Value

For each set of individuals either a single diversity value or a vector of diversity values (one for each window)

Examples

```
init_env()

# load an example model with an already simulated tree sequence
slendr_ts <- system.file("extdata/models/introgression_slim.trees", package = "slendr")
model <- read_model(path = system.file("extdata/models/introgression", package = "slendr"))

# load the tree-sequence object from disk
ts <- ts_read(slendr_ts, model) %>% ts_mutate(mutation_rate = 1e-8, random_seed = 42)

# collect sampled individuals from all populations in a list
sample_sets <- ts_recorded(ts) %>%
  split(., .$pop) %>%
  lapply(function(pop) pop$name)

# compute diversity in each population based on sample sets extracted
# in the previous step
ts_diversity(ts, sample_sets) %>% .[order(.$diversity), ]
```

---

ts_draw *Plot a graphical representation of a single tree*

Description

This function first obtains an SVG representation of the tree by calling the draw_svg method of tskit and renders it as a bitmap image in R. All of the many optional keyword arguments of the draw_svg method can be provided and will be automatically passed to the method behind the scenes.

Usage

```
ts_draw(
  x,
  width = 1000,
  height = 1000,
  labels = FALSE,
  sampled_only = TRUE,
  title = NULL,
  ...
)
```

Arguments

x	A single tree extracted by ts_tree
width, height	Pixel dimensions of the rendered bitmap
labels	Label each node with the individual name?
sampled_only	Should only individuals explicitly sampled through simplification be labeled? This is relevant in situations in which sampled individuals can themselves be among the ancestral nodes.
title	Optional title for the figure
...	Keyword arguments to the tskit draw_svg function.

Value

No return value, called for side effects

Examples

```
init_env()

# load an example model with an already simulated tree sequence
slendr_ts <- system.file("extdata/models/introgression_slim.trees", package = "slendr")
model <- read_model(path = system.file("extdata/models/introgression", package = "slendr"))

# load the tree-sequence object from disk
ts <- ts_read(slendr_ts, model)

# extract the first tree in the tree sequence and draw it
tree <- ts_tree(ts, i = 1)

# ts_draw accepts various optional arguments of tskit.Tree.draw_svg
ts_draw(tree, time_scale = "rank")
```

ts_edges — *Extract spatio-temporal edge annotation table from a given tree or tree sequence*

Description

Extract spatio-temporal edge annotation table from a given tree or tree sequence

Usage

```
ts_edges(x)
```

Arguments

x	Tree object generated by ts_phylo or a slendr tree sequence object produced by ts_read, ts_recapitate, ts_simplify, or ts_mutate

Value

Data frame of the sf type containing the times of nodes and start-end coordinates of edges across space

Examples

```
init_env()

# load an example model with an already simulated tree sequence
slendr_ts <- system.file("extdata/models/introgression_slim.trees", package = "slendr")
model <- read_model(path = system.file("extdata/models/introgression", package = "slendr"))

# load the tree-sequence object from disk
ts <- ts_read(slendr_ts, model)

# extract an annotated table with (spatio-)temporal edge information
ts_edges(ts)
```

ts_eigenstrat — *Convert genotypes to the EIGENSTRAT file format*

Description

EIGENSTRAT data produced by this function can be used by the admixr R package (https://bodkan.net/admixr/).

Usage

```
ts_eigenstrat(ts, prefix, chrom = "chr1", outgroup = NULL)
```

Arguments

ts	Tree sequence object of the class slendr_ts
prefix	EIGENSTRAT trio prefix
chrom	The name of the chromosome in the EIGENSTRAT snp file (default "chr1")
outgroup	Should a formal, artificial outgroup be added? If NULL (default), no outgroup is added. A non-NULL character name will serve as the name of the outgroup in an ind file.

Details

In case an outgroup was not formally specified in a slendr model which generated the tree sequence data, it is possible to artificially create an outgroup sample with the name specified by the outgroup argument, which will carry all ancestral alleles (i.e. value "2" in a geno file for each position in a snp file).

Value

Object of the class EIGENSTRAT created by the admixr package

---

ts_extend *Extend the span of sequences covered by ancestral nodes (EXPERIMENTAL)*

Description

Run the "extend haplotypes" algorithm to extend the span of sequence covered by ancestral nodes, as implemented by the tskit method TreeSequence.extend_haplotypes.

Usage

```
ts_extend(ts, iterations = 10)
```

Arguments

ts	Tree sequence object
iterations	Maximum number of iterations over the tree sequence (default is 10)

Details

For more details about this functionality, please read the following resources:

1. Paper by Fritze et al. 2025 (doi:10.1093/genetics/iyaf198)
2. Official tskit documentation at https://tskit.dev/tskit/docs/stable/python-api.html#tskit.TreeSequence.extend_haplotypes

Note that this function has been currently tested exclusively on tree sequences simulated by slendr's msprime() simulation engine.

Value

Tree-sequence object of the class `slendr_ts`

Examples

```
init_env()

# load an example model with an already simulated tree sequence
slendr_ts <- system.file("extdata/models/introgression_msprime.trees", package = "slendr")
model <- read_model(path = system.file("extdata/models/introgression", package = "slendr"))

ts <- ts_read(slendr_ts, model)
ts_ext <- ts_extend(ts, iterations = 10)

ts_ext
```

`ts_f2` *Calculate the f2, f3, f4, and f4-ratio statistics*

Description

These functions present an R interface to the corresponding f-statistics methods in tskit.

Usage

```
ts_f2(
  ts,
  A,
  B,
  mode = c("site", "branch", "node"),
  span_normalise = TRUE,
  windows = NULL
)

ts_f3(
  ts,
  A,
  B,
  C,
  mode = c("site", "branch", "node"),
  span_normalise = TRUE,
  windows = NULL
)

ts_f4(
  ts,
  W,
```

```
  X,
  Y,
  Z,
  mode = c("site", "branch", "node"),
  span_normalise = TRUE,
  windows = NULL
)

ts_f4ratio(
  ts,
  X,
  A,
  B,
  C,
  O,
  mode = c("site", "branch"),
  span_normalise = TRUE
)
```

Arguments

ts	Tree sequence object of the class slendr_ts
mode	The mode for the calculation ("sites" or "branch")
span_normalise	Divide the result by the span of the window? Default TRUE, see the tskit documentation for more detail.
windows	Coordinates of breakpoints between windows. The first coordinate (0) and the last coordinate (equal to ts$sequence_length) do not have to be specified as they are added automatically.
W, X, Y, Z, A, B, C, O	Character vectors of individual names (largely following the nomenclature of Patterson 2021, but see crucial differences between tskit and ADMIXTOOLS in Details)

Details

Note that the order of populations f3 statistic implemented in tskit (https://tskit.dev/tskit/docs/stable/python-api.html#tskit.TreeSequence.f3) is different from what you might expect from ADMIXTOOLS, as defined in Patterson 2012 (see doi:10.1534/genetics.112.145037 under heading "The three-population test and introduction of f-statistics", as well as ADMIXTOOLS documentation at https://github.com/DReichLab/AdmixTools/blob/master/README.3PopTest#L5). Specifically, the widely used notation introduced by Patterson assumes the population triplet as f3(C; A, B), with C being the "focal" sample (i.e., either the outgroup or a sample tested for admixture). In contrast, tskit implements f3(A; B, C), with the "focal sample" being A.

Although this is likely to confuse many ADMIXTOOLS users, slendr does not have much choice in this, because its ts_*() functions are designed to be broadly compatible with raw tskit methods.

Value

Data frame with statistics calculated for the given sets of individuals

Examples

```
init_env()

# load an example model with an already simulated tree sequence
slendr_ts <- system.file("extdata/models/introgression_slim.trees", package = "slendr")
model <- read_model(path = system.file("extdata/models/introgression", package = "slendr"))

# load the tree-sequence object from disk and add mutations to it
ts <- ts_read(slendr_ts, model) %>% ts_mutate(mutation_rate = 1e-8, random_seed = 42)

# calculate f2 for two individuals in a previously loaded tree sequence
ts_f2(ts, A = "AFR_1", B = "EUR_1")

# calculate f2 for two sets of individuals
ts_f2(ts, A = c("AFR_1", "AFR_2"), B = c("EUR_1", "EUR_3"))

# calculate f3 for two individuals in a previously loaded tree sequence
ts_f3(ts, A = "EUR_1", B = "AFR_1", C = "NEA_1")

# calculate f3 for two sets of individuals
ts_f3(ts, A = c("AFR_1", "AFR_2", "EUR_1", "EUR_2"),
          B = c("NEA_1", "NEA_2"),
          C = "CH_1")

# calculate f4 for single individuals
ts_f4(ts, W = "EUR_1", X = "AFR_1", Y = "NEA_1", Z = "CH_1")

# calculate f4 for sets of individuals
ts_f4(ts, W = c("EUR_1", "EUR_2"),
          X = c("AFR_1", "AFR_2"),
          Y = "NEA_1",
          Z = "CH_1")

# calculate f4-ratio for a given set of target individuals X
ts_f4ratio(ts, X = c("EUR_1", "EUR_2", "EUR_4", "EUR_5"),
               A = "NEA_1", B = "NEA_2", C = "AFR_1", O = "CH_1")
```

`ts_fst` *Calculate pairwise statistics between sets of individuals*

Description

For a discussion on the difference between "site", "branch", and "node" options of the `mode` argument, please see the tskit documentation at https://tskit.dev/tskit/docs/stable/stats.html#sec-stats-mode.

Usage

```
ts_fst(
  ts,
  sample_sets,
  mode = c("site", "branch", "node"),
  windows = NULL,
  span_normalise = TRUE
)
```

Arguments

ts	Tree sequence object of the class slendr_ts
sample_sets	A list (optionally a named list) of character vectors with individual names (one vector per set)
mode	The mode for the calculation ("sites" or "branch")
windows	Coordinates of breakpoints between windows. The first coordinate (0) and the last coordinate (equal to ts$sequence_length) do not have to be specified as they are added automatically.
span_normalise	Divide the result by the span of the window? Default TRUE, see the tskit documentation for more detail.

Value

For each pairwise calculation, either a single Fst value or a vector of Fst values (one for each window)

Examples

```
init_env()

# load an example model with an already simulated tree sequence
slendr_ts <- system.file("extdata/models/introgression_slim.trees", package = "slendr")
model <- read_model(path = system.file("extdata/models/introgression", package = "slendr"))

# load the tree-sequence object from disk
ts <- ts_read(slendr_ts, model) %>% ts_mutate(mutation_rate = 1e-8, random_seed = 42)

# compute F_st between two sets of individuals in a given tree sequence ts
ts_fst(ts, sample_sets = list(afr = c("AFR_1", "AFR_2", "AFR_3"),
                              eur = c("EUR_1", "EUR_2")))
```

---

ts_genotypes *Extract genotype table from the tree sequence*

Description

Extract genotype table from the tree sequence

Usage

```
ts_genotypes(ts, quiet = FALSE)
```

Arguments

ts	Tree sequence object of the class slendr_ts
quiet	Should messages about multiallelic sites be silenced? Default is FALSE.

Value

Data frame object of the class tibble containing genotypes of simulated individuals in columns

Examples

```
init_env()

# load an example model with an already simulated tree sequence
slendr_ts <- system.file("extdata/models/introgression_slim.trees", package = "slendr")
model <- read_model(path = system.file("extdata/models/introgression", package = "slendr"))

# load the tree-sequence object from disk, recapitate it, simplify it, and mutate it
ts <- ts_read(slendr_ts, model) %>%
  ts_recapitate(Ne = 10000, recombination_rate = 1e-8) %>%
  ts_simplify() %>%
  ts_mutate(mutation_rate = 1e-8)

# extract the genotype matrix (this could take  a long time consume lots
# of memory!)
gts <- ts_genotypes(ts)
```

---

ts_ibd *Extract Identity-by-Descent (IBD) segments (EXPERIMENTAL)*

Description

This function extracts IBD segments between pairs of individuals or nodes from a given tree sequence.

Usage

```
ts_ibd(
  ts,
  within = NULL,
  between = NULL,
  maximum_time = NULL,
  minimum_length = 0,
  sf = TRUE
)
```

Arguments

ts	Tree sequence object of the class slendr_ts
within	A character vector with individual names or an integer vector with node IDs indicating a set of nodes within which to look for IBD segments.
between	A list of lists of character vectors with individual names or integer vectors with node IDs, indicating a set of nodes between which to look for shared IBD segments.
maximum_time	Oldest MRCA of a node to be considered as an IBD ancestor to return that IBD segment in results. This is useful for reducing the total amount of IBD returned.
minimum_length	Minimum length of a ("squashed") IBD segment for it to be included in the results
sf	If IBD segments in a spatial tree sequence are being analyzed, should the returned table be a spatial sf object? Default is TRUE.

Details

The interface of this function is highly experimental. For full control over IBD segment detection in tree-sequence data, users can (and perhaps, for the time being, should) directly use the underlying tskit method ibd_segments (see https://tskit.dev/tskit/docs/stable/python-api.html#tskit.TreeSequence.ibd_segments).

Internally, this function leverages the tskit TreeSequence method ibd_segments. However, note that the ts_ibd function always returns a data frame of IBD tracts, it does not provide an option to iterate over individual IBD segments as shown in the official tskit documentation at https://tskit.dev/tskit/docs/stable/ibd.html. In general, R handles heavy iteration rather poorly and, as a result, this function does not attempt to serve as a full wrapper to ibd_segments.

Unfortunately, the distinction between "squashed IBD" (what many would consider to be the expected definition of IBD) and tskit's IBD which is defined via distinct genealogical paths (see https://github.com/tskit-dev/tskit/issues/2459 for a discussion of the topic), makes the meaning of the filtering parameter of the ibd_segments() method of tskit minimum_length somewhat unintuitive. As of this moment, the minimum length argument filters on IBD segments on the "squashed" level, not the level of smaller individual IBD segments which the tskit machinery operates with. Again, for more details, refer to the resources linked above.

Value

A data frame with IBD coordinates of each IBD segment shared by any pair of nodes in the tree sequence

See Also

ts_extend for information about the "extend haplotypes" procedure

Examples

```
init_env()

# load an example model with an already simulated tree sequence
```

```
slendr_ts <- system.file("extdata/models/introgression_slim.trees", package = "slendr")
model <- read_model(path = system.file("extdata/models/introgression", package = "slendr"))

# load the tree-sequence object from disk
ts <- ts_read(slendr_ts, model)

# find IBD segments between specified Neanderthals and Europeans
ts_ibd(
  ts,
  between = list(c("NEA_1", "NEA_2"), c("EUR_1", "EUR_2")),
  minimum_length = 40000
)
```

`ts_load` *Read a tree sequence from a file*

Description

Deprecated function. Please use `ts_read` instead.

Usage

```
ts_load(file, model = NULL)
```

Arguments

`file`	A path to the tree-sequence file (either originating from a slendr model or a standard non-slendr tree sequence).
`model`	Optional `slendr_model` object which produced the tree-sequence `file`. Used for adding various annotation data and metadata to the standard tskit tree-sequence object.

`ts_metadata` *Extract list with tree sequence metadata saved by SLiM*

Description

Extract list with tree sequence metadata saved by SLiM

Usage

```
ts_metadata(ts)
```

Arguments

`ts`	Tree sequence object of the class `slendr_ts`

Value

List of metadata fields extracted from the tree-sequence object

Examples

```
init_env()

# load an example model with an already simulated tree sequence
slendr_ts <- system.file("extdata/models/introgression_slim.trees", package = "slendr")
model <- read_model(path = system.file("extdata/models/introgression", package = "slendr"))

# load the tree-sequence object from disk
ts <- ts_read(slendr_ts, model)

# extract the list of metadata information from the tree sequence
ts_metadata(ts)
```

---

ts_mutate *Add mutations to the given tree sequence*

Description

Add mutations to the given tree sequence

Usage

```
ts_mutate(
  ts,
  mutation_rate,
  random_seed = NULL,
  keep_existing = TRUE,
  mutation_model = NULL
)
```

Arguments

ts	Tree sequence object of the class slendr_ts
mutation_rate	Mutation rate used by msprime to simulate mutations
random_seed	Random seed passed to msprime's mutate method (if NULL, a seed will be generated between 0 and the maximum integer number available)
keep_existing	Keep existing mutations?
mutation_model	Which mutation model to use? If NULL (default), no special mutation type will be used. Otherwise, a mutation model matching https://tskit.dev/msprime/docs/stable/mutations.html may be provided as a Python/reticulate object. For instance, msprime$SLiMMutationModel(type=42L) will add SLiM mutation with the mutation type 42.

Value

Tree-sequence object of the class `slendr_ts`, which serves as an interface point for the Python module tskit using slendr functions with the `ts_` prefix.

See Also

`ts_nodes` for extracting useful information about individuals, nodes, coalescent times and geospatial locations of nodes on a map

Examples

```
init_env()

# load an example model with an already simulated tree sequence
slendr_ts <- system.file("extdata/models/introgression_slim.trees", package = "slendr")
model <- read_model(path = system.file("extdata/models/introgression", package = "slendr"))

ts <- ts_read(slendr_ts, model)
ts_mutate <- ts_mutate(ts, mutation_rate = 1e-8, random_seed = 42)

ts_mutate
```

---

ts_names *Extract names of individuals of interest in a tree sequence produced by a slendr model*

Description

Extract names of individuals of interest in a tree sequence produced by a slendr model

Usage

```
ts_names(x, split = FALSE, schedule = NULL)
```

Arguments

`x`	Either a tree sequence object of the class `slendr_ts`, or a compiled slendr model of the class `slendr_model`
`split`	Should sample names in the tree sequence be split by population? If set to `TRUE`, a list of character vectors will be returned, one vector for each population.
`schedule`	If samples from a model (not yet a tree sequence) are to be obtained, this argument can be used to restrict the set of recorded individuals

Value

A vector of character sample names. If `split` is specified, a list of such vectors is returned, one element of the list per population or sampling time.

ts_nodes *Extract combined annotated table of individuals and nodes*

Description

This function combines information from the table of individuals and table of nodes into a single data frame which can be used in downstream analyses.

Usage

```
ts_nodes(x, sf = TRUE)
```

Arguments

x	Tree sequence object of the class slendr_ts or a phylo object extracted by ts_phylo
sf	Should spatial data be returned in an sf format? If FALSE, spatial geometries will be returned simply as x and y columns, instead of the standard POINT data type.

Details

The source of data (tables of individuals and nodes recorded in the tree sequence generated by SLiM) are combined into a single data frame. If the model which generated the data was spatial, coordinates of nodes (which are pixel-based by default because SLiM spatial simulations occur on a raster), the coordinates are automatically converted to an explicit spatial object of the sf class unless spatial = FALSE. See https://r-spatial.github.io/sf/ for an extensive introduction to the sf package and the ways in which spatial data can be processed, analysed, and visualised.

Value

Data frame with processed information from the tree sequence object. If the model which generated this data was spatial, result will be returned as a spatial object of the class sf.

See Also

ts_table for accessing raw tree sequence tables without added metadata annotation. See also ts_ancestors to learn how to extract information about relationship beteween nodes in the tree sequence, and how to analysed data about distances between nodes in the spatial context.

Examples

```
init_env()

# load an example model with an already simulated tree sequence
slendr_ts <- system.file("extdata/models/introgression_slim.trees", package = "slendr")
model <- read_model(path = system.file("extdata/models/introgression", package = "slendr"))
```

```
# load the tree-sequence object from disk
ts <- ts_read(slendr_ts, model)

# extract an annotated table with (spatio-)temporal node information
ts_nodes(ts)
```

`ts_phylo` *Convert a tree in the tree sequence to an object of the class* `phylo`

Description

Convert a tree in the tree sequence to an object of the class `phylo`

Usage

```
ts_phylo(
  ts,
  i,
  mode = c("index", "position"),
  labels = c("tskit", "pop"),
  quiet = FALSE
)
```

Arguments

`ts`	Tree sequence object of the class `slendr_ts`
`i`	Position of the tree in the tree sequence. If `mode = "index"`, an i-th tree will be returned (in zero-based indexing as in tskit), if `mode = "position"`, a tree covering the i-th base of the simulated genome will be returned (again, in tskit's indexing).
`mode`	How should the `i` argument be interpreted? Either "index" as an i-th tree in the sequence of genealogies, or "position" along the simulated genome.
`labels`	What should be stored as node labels in the final `phylo` object? Options are either a population name or a tskit integer node ID (which is a different thing from a `phylo` class node integer index).
`quiet`	Should ape's internal phylo validity test be printed out?

Value

Standard phylogenetic tree object implemented by the R package ape

Examples

```
init_env()

# load an example model with an already simulated tree sequence
slendr_ts <- system.file("extdata/models/introgression_slim.trees", package = "slendr")
model <- read_model(path = system.file("extdata/models/introgression", package = "slendr"))

# load the tree-sequence object from disk
ts <- ts_read(slendr_ts, model) %>%
  ts_recapitate(Ne = 10000, recombination_rate = 1e-8) %>%
  ts_simplify()

# extract the 1st tree from a given tree sequence, return ape object
tree <- ts_phylo(ts, i = 1, mode = "index", quiet = TRUE)
tree

# extract the tree at a 42th basepair in the given tree sequence
tree <- ts_phylo(ts, i = 42, mode = "position", quiet = TRUE)

# because the tree is a standard ape phylo object, we can plot it easily
plot(tree, use.edge.length = FALSE)
ape::nodelabels()
```

---

ts_read *Read a tree sequence from a file*

Description

This function loads a tree sequence file simulated from a given slendr model. Optionally, the tree sequence can be recapitated and simplified.

Usage

```
ts_read(file, model = NULL)
```

Arguments

`file`	A path to the tree-sequence file (either originating from a slendr model or a standard non-slendr tree sequence).
`model`	Optional `slendr_model` object which produced the tree-sequence `file`. Used for adding various annotation data and metadata to the standard tskit tree-sequence object.

Details

The loading, recapitation and simplification is performed using the Python module pyslim which serves as a link between tree sequences generated by SLiM and the tskit module for manipulation of tree sequence data. All of these steps have been modelled after the official pyslim tutorial and documentation available at: https://tskit.dev/pyslim/docs/latest/tutorial.html.

The recapitation and simplification steps can also be performed individually using the functions ts_recapitate and ts_simplify.

Value

Tree-sequence object of the class slendr_ts, which serves as an interface point for the Python module tskit using slendr functions with the ts_ prefix.

See Also

ts_nodes for extracting useful information about individuals, nodes, coalescent times and geospatial locations of nodes on a map

Examples

```
init_env()

# load an example model with an already simulated tree sequence
slendr_ts <- system.file("extdata/models/introgression_slim.trees", package = "slendr")
model <- read_model(path = system.file("extdata/models/introgression", package = "slendr"))

# load tree sequence generated by a given model
ts <- ts_read(slendr_ts, model)

# even tree sequences generated by non-slendr models can be
msprime_ts <- system.file("extdata/models/msprime.trees", package = "slendr")
ts <- ts_read(msprime_ts)

# load tree sequence and immediately simplify it only to sampled individuals
# (note that the example tree sequence is already simplified so this operation
# does not do anything in this case)
ts <- ts_read(slendr_ts, model = model) %>% ts_simplify(keep_input_roots = TRUE)

# load tree sequence and simplify it to a subset of sampled individuals
ts_small <- ts_simplify(ts, simplify_to = c("CH_1", "NEA_1", "NEA_2",
                                            "AFR_1", "AFR_2", "EUR_1", "EUR_2"))

# load tree sequence, recapitate it and simplify it
ts <- ts_read(slendr_ts, model) %>%
  ts_recapitate(recombination_rate = 1e-8, Ne = 10000, random_seed = 42) %>%
  ts_simplify()

# load tree sequence, recapitate it, simplify it and overlay neutral mutations
ts <- ts_read(slendr_ts, model) %>%
  ts_recapitate(recombination_rate = 1e-8, Ne = 10000, random_seed = 42) %>%
  ts_simplify() %>%
  ts_mutate(mutation_rate = 1e-8)

ts
```

`ts_recapitate` *Recapitate the tree sequence*

Description

Recapitate the tree sequence

Usage

```
ts_recapitate(
  ts,
  recombination_rate,
  Ne = NULL,
  demography = NULL,
  random_seed = NULL
)
```

Arguments

`ts`	Tree sequence object
`recombination_rate`	A constant value of the recombination rate
`Ne`	Effective population size during the recapitation process
`demography`	Ancestral demography to be passed internally to `msprime.sim_ancestry()` (see msprime's documentation for mode detail)
`random_seed`	Random seed passed to pyslim's `recapitate` method (if `NULL`, a seed will be generated between 0 and the maximum integer number available)

Value

Tree-sequence object of the class `slendr_ts`, which serves as an interface point for the Python module tskit using slendr functions with the `ts_` prefix.

See Also

`ts_nodes` for extracting useful information about individuals, nodes, coalescent times and geospatial locations of nodes on a map

Examples

```
init_env()

# load an example model with an already simulated tree sequence
slendr_ts <- system.file("extdata/models/introgression_slim.trees", package = "slendr")
model <- read_model(path = system.file("extdata/models/introgression", package = "slendr"))

ts <- ts_read(slendr_ts, model) %>%
```

```
  ts_recapitate(recombination_rate = 1e-8, Ne = 10000, random_seed = 42)

ts
```

`ts_recorded` *Extract names and times of individuals of interest recorded in a tree sequence produced from a slendr model*

Description

Extracts a table of metadata information about individuals recorded in a given simulated tree sequence or in a tree sequence which would be produced by a given model

Usage

```
ts_recorded(x, schedule = NULL)
```

Arguments

`x`	Either a tree sequence object of the class `slendr_ts`, or a compiled slendr model of the class `slendr_model`
`schedule`	If individuals from a model (not yet a tree sequence) are to be obtained, this argument can be used to only extract those individuals who would be simulated from the model

Details

If a model is provided as `x`, the function will first simulate a trivially small tree sequence using the built-in msprime engine.

Value

Table of individuals scheduled for recording across space and time

Examples

```
init_env()

# load an example model with an already simulated tree sequence
slendr_ts <- system.file("extdata/models/introgression_slim.trees", package = "slendr")
model <- read_model(path = system.file("extdata/models/introgression", package = "slendr"))

# load the tree-sequence object from disk
ts <- ts_read(slendr_ts, model)

# extract the table of individuals recorded in the tree sequence
ts_recorded(ts)
```

`ts_replicate` *Compute a tree-sequence expression across a given number of replicates*

Description

This function can be used to compute a given number of replicates of a specified tree-sequence statistical expression

Usage

```
ts_replicate(n, expr, parallel = NULL)
```

Arguments

`n`	Number of replicates to compute
`expr`	A tree-sequence expression to compute (see Details)
`parallel`	How many cores should be utilized for the computation?

Value

A data frame object

Examples

```
init_env()
p1 <- population("p1", time = 4000, N = 1000)
p2 <- population("p2", time = 3000, N = 1000, parent = p1)
p3 <- population("p3", time = 2000, N = 1000, parent = p2)

model <- compile_model(list(p1, p2, p3), generation_time = 1)
schedule <- schedule_recording(model, times = 0, list(p1, 10), list(p2, 10), list(p3, 10))
samples <- ts_names(model, split = TRUE, schedule = schedule)

# this is how we can compute a single tree-sequence statistic with slendr:
# 1. first we simulate a tree sequence from a model
ts <- msprime(model, sequence_length = 1e6, recombination_rate = 1e-8, schedule = schedule)
# 2. then we run a desired tskit-wrapper function
ts_f3(ts, A = samples["p1"], B = samples["p2"], C = samples["p3"], mode = "branch")

# this is how we can compute the same function across multiple replicates at once
ts_replicate(
  n = 10,
  {
   ts <- msprime(model, sequence_length = 1e6, recombination_rate = 1e-8, schedule = schedule)
    ts_f3(ts, A = samples["p1"], B = samples["p2"], C = samples["p3"], mode = "branch")
  }
)
```

ts_save *Write a tree sequence to a file*

Description

Deprecated function. Please use `ts_write` instead.

Usage

```
ts_save(ts, file)
```

Arguments

`ts`	Tree sequence object
`file`	File to which the tree sequence should be saved

ts_segregating *Calculate the density of segregating sites for the given sets of individuals*

Description

Calculate the density of segregating sites for the given sets of individuals

Usage

```
ts_segregating(
  ts,
  sample_sets,
  mode = c("site", "branch", "node"),
  windows = NULL,
  span_normalise = FALSE
)
```

Arguments

`ts`	Tree sequence object of the class `slendr_ts`
`sample_sets`	A list (optionally a named list) of character vectors with individual names (one vector per set). If a simple vector is provided, it will be interpreted as `as.list(sample_sets)`, meaning that a given statistic will be calculated for each individual separately.
`mode`	The mode for the calculation ("sites" or "branch")
`windows`	Coordinates of breakpoints between windows. The first coordinate (0) and the last coordinate (equal to `ts$sequence_length`) are added automatically)
`span_normalise`	Divide the result by the span of the window? Default TRUE, see the tskit documentation for more detail.

Value

For each set of individuals either a single diversity value or a vector of diversity values (one for each window)

Examples

```
init_env()

# load an example model with an already simulated tree sequence
slendr_ts <- system.file("extdata/models/introgression_slim.trees", package = "slendr")
model <- read_model(path = system.file("extdata/models/introgression", package = "slendr"))

# load the tree-sequence object from disk
ts <- ts_read(slendr_ts, model) %>% ts_mutate(mutation_rate = 1e-8, random_seed = 42)

# collect sampled individuals from all populations in a list
sample_sets <- ts_recorded(ts) %>%
  split(., .$pop) %>%
  lapply(function(pop) pop$name)

ts_segregating(ts, sample_sets)
```

---

ts_simplify *Simplify the tree sequence down to a given set of individuals*

Description

This function is a convenience wrapper around the `simplify` method implemented in tskit, designed to work on tree sequence data simulated by SLiM using the **slendr** R package.

Usage

```
ts_simplify(
  ts,
  simplify_to = NULL,
  keep_input_roots = FALSE,
  keep_unary = FALSE,
  keep_unary_in_individuals = FALSE,
  filter_nodes = TRUE
)
```

Arguments

`ts`	Tree sequence object of the class `slendr_ts`
`simplify_to`	A character vector of individual names. If NULL, all explicitly remembered individuals (i.e. those specified via the `schedule_recording` function will be left in the tree sequence after the simplification.

keep_input_roots
: Should the history ancestral to the MRCA of all samples be retained in the tree sequence? Default is FALSE.

keep_unary
: Should unary nodes be preserved through simplification? Default is FALSE.

keep_unary_in_individuals
: Should unary nodes be preserved through simplification if they are associated with an individual recorded in the table of individuals? Default is FALSE. Cannot be set to TRUE if keep_unary is also TRUE

filter_nodes
: Should nodes be reindexed after simplification? Default is TRUE. See tskit's documentation for the Python method simplify()

Details

The simplification process is used to remove redundant information from the tree sequence and retains only information necessary to describe the genealogical history of a set of samples.

For more information on how simplification works in pyslim and tskit, see the official documentation at https://tskit.dev/tskit/docs/stable/python-api.html#tskit.TreeSequence.simplify and https://tskit.dev/pyslim/docs/latest/tutorial.html#simplification.

A very clear description of the difference between remembering and retaining and how to use these techniques to implement historical individuals (i.e. ancient DNA samples) is in the pyslim documentation at https://tskit.dev/pyslim/docs/latest/tutorial.html#historical-individuals.

Value

Tree-sequence object of the class slendr_ts, which serves as an interface point for the Python module tskit using slendr functions with the ts_ prefix.

See Also

ts_nodes for extracting useful information about individuals, nodes, coalescent times and geospatial locations of nodes on a map

Examples

```
init_env()

# load an example model with an already simulated tree sequence
slendr_ts <- system.file("extdata/models/introgression_slim.trees", package = "slendr")
model <- read_model(path = system.file("extdata/models/introgression", package = "slendr"))

ts <- ts_read(slendr_ts, model)
ts

# simplify tree sequence to sampled individuals
ts_simplified <- ts_simplify(ts)

# simplify to a subset of sampled individuals
ts_small <- ts_simplify(ts, simplify_to = c("CH_1", "NEA_1", "NEA_2", "AFR_1",
                                            "AFR_2", "EUR_1", "EUR_2"))
```

```
ts_small
```

`ts_table` *Get the table of individuals/nodes/edges/mutations/sites from the tree sequence*

Description

This function extracts data from a given tree sequence table. All times are converted to model-specific time units from tskit's "generations backwards" time direction.

Usage

```
ts_table(ts, table = c("individuals", "edges", "nodes", "mutations", "sites"))
```

Arguments

`ts`	Tree sequence object of the class `slendr_ts`
`table`	Which tree sequence table to return

Details

For further processing and analyses, the output of the function `ts_nodes` might be more useful, as it merges the information in node and individual tables into one table and further annotates it with useful information from the model configuration data.

Value

Data frame with the information from the give tree-sequence table (can be either a table of individuals, edges, nodes, or mutations).

See Also

`ts_nodes` and `ts_edges` for accessing an annotated, more user-friendly and analysis-friendly tree-sequence table data

Examples

```
# load an example model with an already simulated tree sequence
slendr_ts <- system.file("extdata/models/introgression_slim.trees", package = "slendr")
model <- read_model(path = system.file("extdata/models/introgression", package = "slendr"))

# load the tree-sequence object from disk and add mutations to it
ts <- ts_read(slendr_ts, model) %>% ts_mutate(mutation_rate = 1e-8, random_seed = 42)

# get the 'raw' tskit table of individuals
ts_table(ts, "individuals")
```

```
# get the 'raw' tskit table of edges
ts_table(ts, "edges")

# get the 'raw' tskit table of nodes
ts_table(ts, "nodes")

# get the 'raw' tskit table of mutations
ts_table(ts, "mutations")

# get the 'raw' tskit table of sites
ts_table(ts, "sites")
```

`ts_tajima` *Calculate Tajima's D for given sets of individuals*

Description

For a discussion on the difference between "site" and "branch" options of the `mode` argument, please see the tskit documentation at https://tskit.dev/tskit/docs/stable/stats.html#sec-stats-mode

Usage

```
ts_tajima(ts, sample_sets, mode = c("site", "branch", "node"), windows = NULL)
```

Arguments

`ts`	Tree sequence object of the class `slendr_ts`
`sample_sets`	A list (optionally a named list) of character vectors with individual names (one vector per set). If a simple vector is provided, it will be interpreted as `as.list(sample_sets)`, meaning that a given statistic will be calculated for each individual separately.
`mode`	The mode for the calculation ("sites" or "branch")
`windows`	Coordinates of breakpoints between windows. The first coordinate (0) and the last coordinate (equal to `ts$sequence_length`) are added automatically)

Value

For each set of individuals either a single Tajima's D value or a vector of Tajima's D values (one for each window)

Examples

```
init_env()

# load an example model with an already simulated tree sequence
slendr_ts <- system.file("extdata/models/introgression_slim.trees", package = "slendr")
model <- read_model(path = system.file("extdata/models/introgression", package = "slendr"))
```

```
# load the tree-sequence object from disk
ts <- ts_read(slendr_ts, model) %>% ts_mutate(mutation_rate = 1e-8, random_seed = 42)

# calculate Tajima's D for given sets of individuals in a tree sequence ts
ts_tajima(ts, list(eur = c("EUR_1", "EUR_2", "EUR_3", "EUR_4", "EUR_5"),
                   nea = c("NEA_1", "NEA_2")))
```

`ts_tracts` *Extract ancestry tracts from a tree sequence (EXPERIMENTAL)*

Description

Extract a data frame with coordinates of ancestry tracts from a given tree sequence.

Usage

```
ts_tracts(
  ts,
  census,
  squashed = TRUE,
  source = NULL,
  target = NULL,
  quiet = FALSE
)
```

Arguments

`ts`	Tree sequence object of the class `slendr_ts`
`census`	Census time. See the documentation linked in the Details for more information. If a slendr-specific tree sequence was provided as `ts`, the census time is expected to be given in slendr model-specific time units, and must correspond to some gene-flow event encoded by the model.
`squashed`	Should ancestry tracts be squashed (i.e., should continuous tracts that can be traced to different ancestral nodes be merged)? Default is `TRUE`. If `FALSE`, these effectively continuous ancestry tracts will be split into individual segments, each assigned to a specific ancestral node ID (recorded in a column `ancestor_id`).
`source`	From which source population to extract tracts for? if `NULL` (the default), ancestry tracts for all populations contributing gene flow at the census time will be reported. Otherwise, ancestry tracts from only specified source populations will be extracted. Note that this option is ignored for non-slendr tree sequences!
`target`	Similar purpose as `source` above, except that it filters for tracts discovered in the target population(s)
`quiet`	Should the default summary output of the `tspop` Python package be silenced? Default is `FALSE`.

Details

This function implements an R-friendly interface to an algorithm for extracting ancestry tracts provided by the Python module tspop https://tspop.readthedocs.io/en/latest/ and developed by Georgia Tsambos. Please make sure to cite the paper which describes the algorithm in detail: doi:10.1093/bioadv/vbad163. For more technical details, see also the tutorial at: https://tspop.readthedocs.io/en/latest/basicusage.html.

In general, when using this function on a slendr-generated tree sequence, please be aware that the output changes slightly to what you would get by running the pure `tspop.get_pop_ancestry()` in Python. First, `ts_tracts()` populates the output data frame with additional metadata (such as names of individuals or populations). Additionally, for slendr models, it is specifically designed to only return ancestry tracts originating to a an ancestral population which contributed its ancestry during a gene-flow event which started at a specific time (i.e., scheduled in a model via the `gene_flow()`) function. It does not return every single ancestry tracts present in the tree sequence for every single sample node (and every single potential ancestry population) as does the `tspop.get_pop_ancestry()` Python method.

That said, when run on a tree sequence which does not originate from a slendr simulation, the behavior of `ts_tracts()` is identical to that of the underlying `tspop.get_pop_ancestry()`.

As of the current version of slendr, `ts_tracts()` only works for slendr/msprime sequences but not on slendr/SLiM tree sequences. Support for slendr-generated SLiM tree sequences is in development. Tracts from tree sequences originating from non-slendr msprime and SLiM simulations are not restricted in any way and, as mentioned in the previous paragraph, `ts_tracts()` in this situation effectively reduces to the standard `tspop.get_pop_ancestry()` call.

Value

A data frame containing coordinates of ancestry tracts

Examples

```
init_env()

# load an example model with an already simulated tree sequence
slendr_ts <- system.file("extdata/models/introgression_msprime.trees", package = "slendr")
model <- read_model(path = system.file("extdata/models/introgression", package = "slendr"))

# load the tree-sequence object from disk
ts <- ts_read(file = slendr_ts, model = model)

# extract Neanderthal ancestry tracts (i.e. those corresponding to the
# census event at the gene-flow time at 55000 kya as scheduled by
# the simulation which produced the tree sequence)
nea_tracts <- ts_tracts(ts, census = 55000, source = "NEA")
nea_tracts
```

ts_tree *Get a tree from a given tree sequence*

Description

For more information about optional keyword arguments see tskit documentation: https://tskit.dev/tskit/docs/stable/python-api.html#the-treesequence-class

Usage

```
ts_tree(ts, i, mode = c("index", "position"), ...)
```

Arguments

ts	Tree sequence object of the class slendr_ts
i	Position of the tree in the tree sequence. If mode = "index", an i-th tree will be returned (in zero-based indexing as in tskit), if mode = "position", a tree covering the i-th base of the simulated genome will be returned (again, in tskit's indexing).
mode	How should the i argument be interpreted? Either "index" as an i-th tree in the sequence of genealogies, or "position" along the simulated genome.
...	Additional keyword arguments accepted by tskit.TreeSequence.at and tskit.TreeSequence.at_in methods

Value

Python-reticulate-based object of the class tskit.trees.Tree

Examples

```
init_env()

# load an example model with an already simulated tree sequence
slendr_ts <- system.file("extdata/models/introgression_slim.trees", package = "slendr")
model <- read_model(path = system.file("extdata/models/introgression", package = "slendr"))

# load the tree-sequence object from disk
ts <- ts_read(slendr_ts, model)

# extract the zero-th tree in the tree sequence
tree <- ts_tree(ts, i = 0)

# extract the tree at a position in the tree sequence
tree <- ts_tree(ts, i = 100000, mode = "position")
```

ts_vcf *Save genotypes from the tree sequence as a VCF file*

Description

This function writes a VCF file with diploid genotypes from a given tree sequence.

Usage

```
ts_vcf(
  ts,
  path,
  chrom = "chr1",
  individuals = NULL,
  position_transform = "lambda x: np.fmax(1, x)"
)
```

Arguments

ts	Tree sequence object of the class slendr_ts
path	Path to a VCF file
chrom	Chromosome name to be written in the CHROM column of the VCF (default value will be "chr1").
individuals	A vector of individuals in the tree sequence to extract genotypes from. If missing, all individuals present in the tree sequence will be saved. For a slendr-based tree sequence a character vector of individual names is expected. For non-slendr tree sequences, a numeric vector of IDs of individuals is expected.
position_transform	How to transform coordinates in a tree sequence to coordinates in a VCF file? By default, any site with coordinate 0 is converted to a position 1 to ensure that the resulting VCF file adheres to the VCF specification. Setting this to NULL will disable this

Details

Users should note that, as with many other tskit-based slendr functions, ts_vcf is intended to provide some convenient defaults. For instance, even for non-slendr tree sequences, it will name each individual in the genotype columns after their integer IDs. In other words, if the individuals function argument is given as c(1, 42, 123), the individuals will be named as "ind_1", "ind_42", and "ind_123", instead of "tsk_0", "tsk_1", and "tsk_2". That said, the reticulate-based Python interface of slendr allows calling the write_vcf function of tskit directly!

By default, simulating a tree sequence with msprime and exporting the genotypes into VCF can cause issues with some downstream software because the VCF specification does not allow sites with the position 0. By default ts_vcf automatically transforms a site with a zero coordinate to a coordinate 1. Setting position_transform to NULL will disable this, and tsv_vcf will save coordinates in their original form. See this discussion for more detail: https://github.com/

tskit-dev/tskit/issues/2838#issuecomment-1931796988, as well as relevant topics in the tskit documentation on this issue, like here: https://tskit.dev/tskit/docs/latest/export.html#modifying-coordinates.

Value

No return value, called for side effects

`ts_write` *Save a tree sequence to a file*

Description

Save a tree sequence to a file

Usage

```
ts_write(ts, file)
```

Arguments

`ts`	Tree sequence object
`file`	File to which the tree sequence should be saved

Value

No return value, called for side effects

Examples

```
init_env()

# load an example model with an already simulated tree sequence
slendr_ts <- system.file("extdata/models/introgression_slim.trees", package = "slendr")
model <- read_model(path = system.file("extdata/models/introgression", package = "slendr"))

# load the tree sequence
ts <- ts_read(slendr_ts, model)

# save the tree-sequence object to a different location
another_file <- paste(tempfile(), ".trees")
ts_write(ts, another_file)
```

world *Define a world map for all spatial operations*

Description

Defines either an abstract geographic landscape (blank or containing user-defined landscape) or using a real Earth cartographic data from the Natural Earth project (https://www.naturalearthdata.com).

Usage

```
world(
  xrange,
  yrange,
  landscape = "naturalearth",
  crs = NULL,
  scale = c("small", "medium", "large")
)
```

Arguments

xrange	Two-dimensional vector specifying minimum and maximum horizontal range ("longitude" if using real Earth cartographic data)
yrange	Two-dimensional vector specifying minimum and maximum vertical range ("latitude" if using real Earth cartographic data)
landscape	Either "blank" (for blank abstract geography), "naturalearth" (for real Earth geography) or an object of the class sf defining abstract geographic features of the world
crs	EPSG code of a coordinate reference system to use for spatial operations. No CRS is assumed by default (NULL), implying an abstract landscape not tied to any real-world geographic region (when landscape = "blank" or when landscape is a custom-defined geographic landscape), or implying WGS-84 (EPSG 4326) coordinate system when a real Earth landscape was defined (landscape = "naturalearth").
scale	If Natural Earth geographic data is used (i.e. landscape = "naturalearth"), this parameter determines the resolution of the data used. The value "small" corresponds to 1:110m data and is provided with the package, values "medium" and "large" correspond to 1:50m and 1:10m respectively and will be downloaded from the internet. Default value is "small".

Value

Object of the class slendr_map, which encodes a standard spatial object of the class sf with additional slendr-specific attributes such as requested x-range and y-range.

Examples

```
# create a blank abstract world 1000x1000 distance units in size
blank_map <- world(xrange = c(0, 1000), yrange = c(0, 1000), landscape = "blank")

# it is possible to construct custom landscapes (islands, corridors, etc.)
island1 <- region("island1", polygon = list(c(10, 30), c(50, 30), c(40, 50), c(0, 40)))
island2 <- region("island2", polygon = list(c(60, 60), c(80, 40), c(100, 60), c(80, 80)))
island3 <- region("island3", center = c(20, 80), radius = 10)
archipelago <- island1 %>% join(island2) %>% join(island3)

custom_map <- world(xrange = c(1, 100), c(1, 100), landscape = archipelago)

# real Earth landscapes can be defined using freely-available Natural Earth
# project data and with the possibility to specify an appropriate Coordinate
# Reference System, such as this example of a map of Europe

real_map <- world(xrange = c(-15, 40), yrange = c(30, 60), crs = "EPSG:3035")
```

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