babette: BEAUti 2, BEAST2 and Tracer for R

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Summary

1. In the field of phylogenetics, BEAST2 is one of the most widely used software tools. It comes with the graphical user interfaces BEAUti 2, DensiTree and Tracer, to create BEAST2 configuration files and to interpret BEAST2's output files. However, when many different alignments or model setups are required, a workflow of graphical user interfaces is cumbersome.

2. Here, we present a free, libre and open-source package, `babette`: 'BEAUti 2, BEAST2 and Tracer for R', for the R programming language. `babette` creates BEAST2 input files, runs BEAST2 and parses its results, all from an R function call.

3. We describe `babette`'s usage and the novel functionality it provides compared to the original tools and we give some examples.

4. As `babette` is designed to be of high quality and extendable, we conclude by describing the further development of the package.

Keywords: computational biology, evolution, phylogenetics, BEAST2, R

1

1 Introduction

Phylogenies are commonly used to explore evolutionary hypotheses. Not only can phylogenies show us how species (or other evolutionary units) are related to each other, but we also estimate relevant parameters such as extinction and speciation rates. There are many phylogenetics tools available to obtain an estimate of the phylogenetic tree of a given set of species. BEAST2 (Bouckaert *et al.* 2014) is one of the most widely used ones. It creates a posterior of jointly estimated phylogenies and model parameters, from one or more DNA, RNA or amino acid alignments (see figure 1 for an overview of the workflow). It has a graphical and a command-line interface, that both need a configuration file containing alignments and model parameters. BEAST2 is bundled with BEAUti 2 (Drummond *et al.* 2012) ('BEAUti' from now on), a desktop application to create a BEAST2 configuration file. BEAUti has a user-friendly graphical user interface, with helpful default settings. As such, BEAUti is an attractive alternative to manual and error-prone editing of BEAST2 configuration files.

However, BEAUti cannot be called from a command-line script. This implies that when the user wants to explore the consequences of various settings, this must be done manually. This is the managable workflow when using a few alignments and doing a superficial analysis of sensitivity of the reconstructed tree to model settings. For exploring many trees (for instance from simulations) and for more thorough sensitivity analysis, one would like to loop through multiple (simulated) alignments, nucleotide substitution models, clock models and tree priors. One such tool to replace BEAUti is `BEASTmasteR` (Matzke 2015), which focuses on morphological traits and tip-dating, but also supports DNA data. `BEASTmasteR`, however, requires hundreds of lines of R code to setup the BEAST2 model configuration and a Microsoft Excel file to specify alignment files.

BEAST2 is also associated with Tracer (Rambaut & Drummond 2007) and DensiTree (Bouckaert & Heled 2014). Both are desktop applications to analyze the output of BEAST2, each with a user-friendly graphical user interface. Tracer's purpose is to analyze the parameter estimates generated from a BEAST2 run. It shows, among others, the effective sample size (ESS) and time series ('the trace', hence the name) of each variable in the MCMC run. Both ESS and trace are needed to assess the strength of the inference. DensiTree visualizes the phylogenies of a BEAST2 posterior, with many options to improve the simultaneous display of many phylogenies.

However, for exploring the output of many BEAST2 runs, one would like a script to collect all parameters' ESSes, parameter traces and posterior phylogenies. There is no single package that offers a complete solution, but examples of R packages that offer a partial solution are `BEASTmasteR`, `rBEAST` (Ratmann 2015) and `RBeast` (Faria & Suchard 2015). `BEASTmasteR` is a partial BEAUti alternative, does not offer a way to call BEAST2, nor allows for the same data analysis as done by Tracer. `RBeast` provides some plotting options and parsing of BEAST2 output files. `rBEAST` is a package developed around testing a biological hypothesis, that does not aim to be a generally used package.

Here, we present `babette`: BEAUti 2, BEAST2 and Tracer for R, which creates BEAST2 (v.2.4.7) configuration files, runs BEAST2, and analyzes its results, all from an R function call. This will save time, tedious mouse clicking and reduces the chances of errors in such repetitive actions. The interface of `babette` mimics the tools it is based on. This familiarity helps both beginner and experienced BEAST2 users to make the step from those tools to `babette`. `babette` enables the creation of a single-script pipeline from sequence alignments to posterior analysis in R.

3

2   Description

babette is written in the R programming language (R Core Team 2013) and enables the full BEAST2 workflow from an R function call, in a similar way to what BEAUti, DensiTree and Tracer do. babette's main function is `run_beast2`, which configures BEAST2, runs it and parses its output. `run_beast2` needs at least the name of a FASTA file containing a DNA alignment. The default settings for the other arguments of `run_beast2` are identical to BEAUti's and BEAST2's default settings. Per alignment, a site model, clock model and tree prior can be chosen. Multiple alignments can be used, each with its own (unlinked) site model, clock model and tree prior.

babette currently has 100 exported functions to set up a BEAST2 configuration file. babette can currently handle a majority of BEAUti use cases. Because of BEAUti's high number of plugins, babette uses a software architecture that is designed to be extended. Furthermore, babette has 12 exported functions to run and help run BEAST2. One function is used to run BEAST2, others allow the user to check if a BEAST2 configuration file is indeed valid. Finally, babette has 21 exported function to parse the BEAST2 output files and analyze the created posterior. babette gives the same ESSes and summary statistics as Tracer. The data is formatted such that it can easily be visualized using `ggplot2` (for a trace, similar to Tracer) or `phangorn` (Schliep 2011) (for the phylogenies in a posterior, similar to DensiTree).

Currently, babette does not replace all functionality in BEAUti, as it does not provide 3 out of 7 tree priors, nor does it support RNA alignments or use of morphological data. The many plug-ins of BEAUti are not yet supported by babette. babette does not support all command-line arguments of BEAST2, does not provide the more specialized Tracer analysis options, nor is it as feature-rich in plotting options as DensiTree. Up until now, the babette fea-

tures implemented are those requested by users. Further extension of `babette` will be based on future user requests.

3   Usage

In R, the functions of a package need to be loaded in the global namespace first:

```
library(babette)
```

BEAUti, and likewise `babette`, needs at least a FASTA filename to produce a BEAST2 configuration file. In BEAUti, this is achieved by loading a FASTA file, then saving an output file using a common save file dialog. After this, BEAST2 needs to be applied to the created configuration file. It creates multiple files storing the posterior. These output files must be parsed by either Tracer of DensiTree. In `babette`, all this is achieved by:

```
out <- run_beast2("anthus_aco.fas")
```

This code will create a (temporary) BEAST2 configuration file, from the FASTA file with name `anthus_aco.fas` (which is supplied with the package, from (Van Els & Norambuena 2018)), using the same default settings as BEAUti, which are, among others, a Jukes-Cantor site model, a strict clock, and a Yule birth tree prior. `babette` will then execute BEAST2 using that file, and parses the output. The returned data structure, named `out`, is a list of parameter estimates (called `estimates`), posterior phylogenies (called `anthus_aco_trees`, named after the alignment's name) and MCMC operator performance (`operators`). An example of using a different site model, clock model and tree prior is:

```
out <- run_beast2(
  "anthus_aco.fas",
  site_models = create_hky_site_model(),
  clock_models = create_rln_clock_model(),
```

5

```
128    tree_priors = create_bd_tree_prior()
129  )
```

This code uses an HKY site model, a relaxed log-normal clock model and a birth-death tree prior, each with their default settings in BEAUti. Table 1 shows an overview of all functions to create site models, clock models and tree priors. Note that the arguments' names `site_models`, `clock_models` and `tree_priors` are plural, as each of these can be (a list of) one or more elements. Each of these arguments must have the same number of elements, so that each alignment has its own site model, clock model and tree prior. An example of two alignments, each with its own site model, is:

```
138  out <- run_beast2(
139    c("anthus_aco.fas", "anthus_nd2.fas"),
140    site_models = list(
141      create_tn93_site_model(),
142      create_gtr_site_model()
143    )
144  )
```

`babette` also uses the same default prior distributions as BEAUti for each of the site models, clock models and tree priors. For example, by default, a Yule tree prior assumes that the birth rate follows a uniform distribution, from minus infinity to plus infinity. This assumption implies that negative and positive birth rates are just as likely, where a negative birth rate is biologically impossible (note that in practice, this usually works out just fine). One may prefer an exponential distribution instead, as this would assume only positive birth rates, and makes high birth rates unlikely. To do this in `babette`:

```
153  out <- run_beast2(
154    "anthus_aco.fas",
```

```
155    tree_priors = create_yule_tree_prior(
156      birth_rate_distr = create_exp_distr()
157    )
158  )
```

In this same example, one may specify the initial shape parameters of the exponential distribution. In BEAST2's implementation, an exponential distribution has one shape parameter: its mean, which can be set to any value with `BEAUti`. Within `babette`, to set the mean value of the exponential distribution to a fixed (non-estimated) value, do:

```
164  out <- run_beast2(
165    "anthus_aco.fas",
166    tree_priors = create_yule_tree_prior(
167      birth_rate_distr = create_exp_distr(
168        mean = create_mean_param(
169          value = 1.0,
170          estimate = FALSE
171        )
172      )
173    )
174  )
```

Our initial motivation to create `babette` was that we wanted to fix the crown age of a phylogeny. BEAUti assumes that a phylogeny has a crown age that needs to be jointly estimated with the phylogeny and other parameters. It does not allow for fixing the crown age. Without `babette`, one needs to manually edit the BEAST2 configuration file (Bouckaert & Vaughan 2017), which is tedious and prone to errors. Fixing the crown ages is especially useful for theoretical experiments, as this allows for one less source of variation. This is how to specify a fixed crown age with `babette`:

```
183  out <- run_beast2(
184    "anthus_aco.fas",
185    posterior_crown_age = 15
186  )
```

187 `babette` allows for the same functionality as Tracer. Tracer works on the values
188 of the parameter estimates sampled in the BEAST2 run. This is called the
189 "trace" (hence the name). The start of the trace is usually discarded, as an
190 MCMC algorithm (such as used by BEAST2) first has to converge to its equi-
191 librium. The start of the trace, called the "burn-in", will be removed, because
192 its parameter estimates are not representative. By default, Tracer discards the
193 first 10% of all the parameter estimates. To remove a 20% burn-in from all
194 parameter estimates in `babette`, the following code can be used:

```
195  traces <- remove_burn_ins(
196    out$estimates,
197    burn_in_fraction = 0.2
198  )
```

199 Tracer shows the ESSes of each posterior's variables. These ESSes are important
200 to determine the strength of the inference. As a rule of thumb, an ESS of 200 is
201 acceptable for any parameter estimate. To calculate the effective sample sizes
202 (of all estimated variables) in `babette`:

```
203  esses <- calc_esses(
204    traces,
205    sample_interval = 1000
206  )
```

207 Tracer displays multiple summary statistics for each estimated variable: the
208 mean and its standard error, standard deviation, variance, median, mode, geo-
209 metric mean, 95% highest posterior density interval, auto-correlation time and

effective sample size. It displays these statistics per variable. In `babette`, these summary statistics are collected for all estimated parameters at once:

```
sum_stats <- calc_summary_stats(
    traces,
    sample_interval = 1000
)
```

`babette` allows for the same functionality as DensiTree. DensiTree displays the phylogenies in a posterior at the same time scale, drawn one over one another, allowing to see the uncertainty in topology and branch lengths. Within the object `out`, the posterior phylogenies are stored as `anthus_aco_trees`, and can be plotted as such:

```
plot_densitree(out$anthus_aco_trees)
```

4 babette resources

`babette` is free, libre and open source software available from the official R package archive at `http://cran.r-project.org/src/contrib/PACKAGES.html#babette` and is licensed under the GNU General Public License v3.0. `babette` uses the Travis CI (`https://travis-ci.org`) continuous integration service, which is known to significantly increase the number of bugs exposed (Vasilescu *et al.* 2015) and increases the speed at which new features are added (Vasilescu *et al.* 2015). `babette` has a 100% code coverage, which correlates with code quality (Horgan *et al.* 1994; Del Frate *et al.* 1995). `babette` follows Hadley Wickham's style guide (Wickham 2015), which improves software quality (Fang 2001). `babette` dependends on multiple packages, which are `ape` (Paradis *et al.* 2004), `beautier` (Bilderbeek 2018b), `beastier` (Bilderbeek 2018a), `devtools` (Wickham & Chang 2016), `geiger` (Harmon *et al.* 2008), `ggplot2` (Wickham 2009),

9

knitr (Xie 2017), phangorn (Schliep 2011), rmarkdown (Allaire *et al.* 2017), seqinr (Charif & Lobry 2007), stringr (Wickham 2017), testit (Xie 2014) and tracerer (Bilderbeek 2018c). babette is tested to give a clean error message for incorrect input, by calling babette one million times with random or random sensible inputs, using the Peregrine high performance computer cluster. The scripts to do so, are supplied with babette.

babette's development takes place on GitHub, https://github.com/richelbilderbeek/babette, which accommodates collaboration (Perez-Riverol *et al.* 2016) and improves transparency (Gorgolewski & Poldrack 2016). babette's GitHub facilitates feature requests and has guidelines how to do so.

babette's documentation is extensive. All functions are documented in the package's internal documentation. For quick use, each exported function shows a minimal example. For easy exploration, each exported function's documentation links to related functions. Additionally, babette has a vignette that demonstrates extensively how to use it. There is documentation on the GitHub to get started, with a dozen examples of BEAUti screenshots with equivalent babette code. Finally, babette has some tutorial video's that can be downloaded or viewed on YouTube, https://goo.gl/weKaaU.

5 Citation of babette

Scientists using babette in a published paper can cite this article, and/or cite the babette package directly. To obtain this citation from within an R script, use:

```
> citation("babette")
```

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6   Acknowledgements

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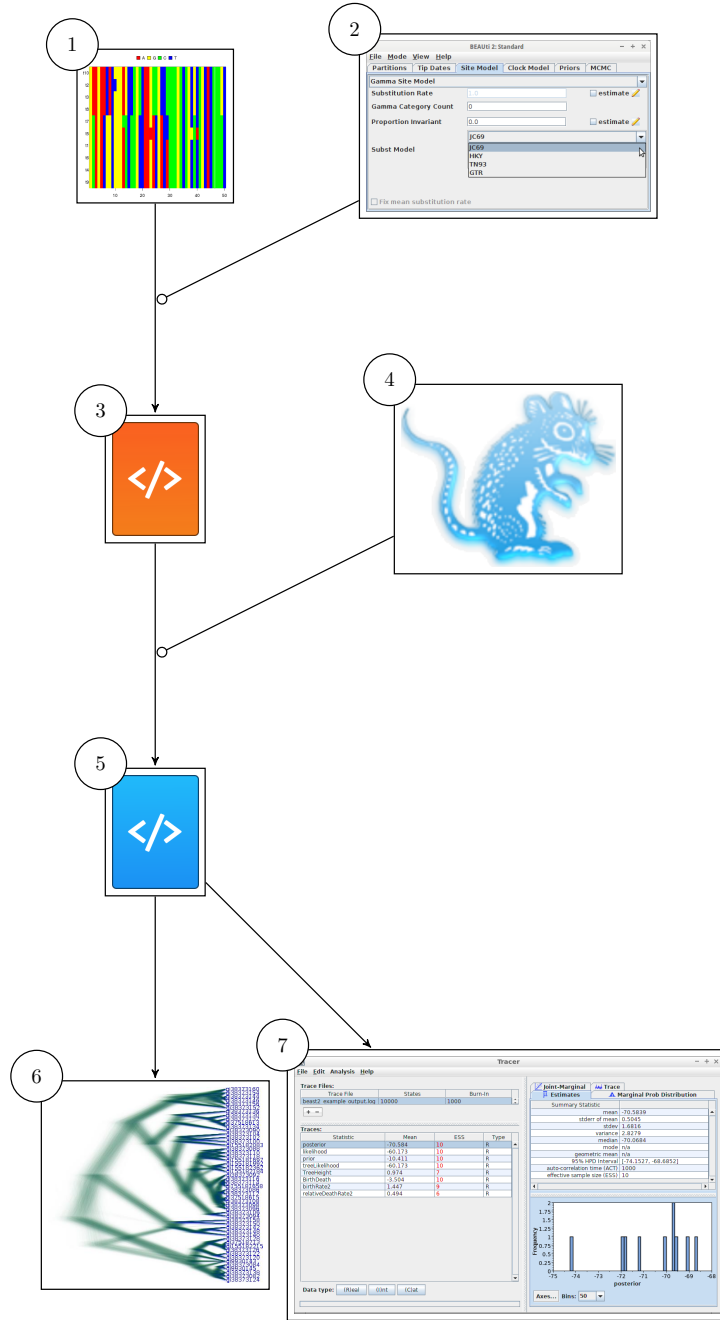
Figure 1: Workflow using GUI tools. From an alignment (1) and BEAUti (2), a BEAST2 configuration file (3) is created. BEAST2 (4) uses that file to infer a posterior, storing it in multiple files (5). These results are visualized using DensiTree (6) and Tracer (7). babette allows for the same workflow, all from an R function call.

Name	Description
run_beast2	Run BEAST2
create_gtr_site_model	Create a GTR site model
create_hky_site_model	Create an HKY site model
create_jc69_site_model	Create a Jukes-Cantor site model
create_tn93_site_model	Create a TN93 site model
create_rln_clock_model	Create a relaxed log-normal clock model
create_strict_clock_model	Create a strict clock model
create_bd_tree_prior	Create a birth-death tree prior
create_cbs_tree_prior	Create a coalescent Bayesian skyline tree prior
create_ccp_tree_prior	Create a coalescent constant-population tree prior
create_cep_tree_prior	Create a coalescent exponential-population tree prior
create_yule_tree_prior	Create a Yule tree prior
create_beta_distr	Create a beta distribution
create_exp_distr	Create an exponential distribution
create_gamma_distr	Create a gamma distribution
create_inv_gamma_distr	Create an inverse gamma distribution
create_laplace_distr	Create a Laplace distribution
create_log_normal_distr	Create a log-normal distribution
create_normal_distr	Create a normal distribution
create_one_div_x_distr	Create a 1/X distribution
create_poisson_distr	Create a Poisson distribution
create_uniform_distr	Create a uniform distribution

Table 1: babette's main functions