IQ-TREE version 2.1.2: Tutorials and Manual
Phylogenomic software by maximum likelihood

http://www.iqtree.org

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## Contents

1 **Introduction** .................................................. 9
   1.1 Why IQ-TREE? ................................................. 9
   1.2 Key features .................................................. 10
   1.3 Free web server ............................................. 10
   1.4 User support .................................................. 11
   1.5 Documentation ................................................ 11
   1.6 How to cite IQ-TREE? ....................................... 12
   1.7 Development team ........................................... 13
   1.8 Credits and acknowledgements ............................. 14

2 **Getting started** ........................................... 15
   2.1 IQ-TREE web server .......................................... 15
   2.2 Installation .................................................. 15
      2.2.1 Packages and bundles .................................. 15
      2.2.2 Manual download ........................................ 16
   2.3 For Windows users ............................................ 16
   2.4 For Mac OS X users .......................................... 16
   2.5 Minimal command-line examples ........................... 17
   2.6 Where to go from here? ...................................... 20

3 **Web server tutorial** ................................... 21
   3.1 Tree Inference ................................................. 21
   3.2 Model Selection .............................................. 23
   3.3 Analysis Results ............................................. 23

4 **Beginner’s tutorial** ................................... 27
   4.1 Input data ..................................................... 27
   4.2 First running example ....................................... 28
   4.3 Choosing the right substitution model ........................ 30
   4.4 Using codon models .......................................... 32
## CONTENTS

4.5 Binary, morphological and SNP data ........................................... 33
4.6 Assessing branch supports with ultrafast bootstrap approximation .... 34
4.7 Reducing impact of severe model violations with UFBt... ... 35
4.8 Assessing branch supports with standard nonparametric bootstrap ... 35
4.9 Assessing branch supports with single branch tests ................. 35
4.10 Utilizing multi-core CPUs .................................................. 37
4.11 Where to go from here? ................................................... 38

5 Advanced tutorial ................................................................. 39
5.1 Partitioned analysis for multi-gene alignments ......................... 39
5.2 Partitioned analysis with mixed data .................................... 41
5.3 Choosing the right partitioning scheme ................................. 42
5.4 Ultrafast bootstrapping with partition model ......................... 43
5.5 Constrained tree search ..................................................... 43
5.6 Tree topology tests .......................................................... 45
5.7 Testing constrained tree ..................................................... 46
5.8 Consensus construction and bootstrap value assignment .......... 48
5.9 User-defined substitution models ....................................... 49
5.10 Inferring site-specific rates .............................................. 50
5.11 Where to go from here? ................................................... 52

6 Assessing phylogenetic assumptions ......................................... 53
6.1 Tests of symmetry ............................................................ 53
6.2 Likelihood mapping ........................................................... 55

7 Concordance Factor .............................................................. 59
7.1 Inferring species tree ........................................................ 60
7.2 Inferring gene/locus trees .................................................. 60
7.3 Gene concordance factor (gCF) .......................................... 61
7.4 Site concordance factor (sCF) ............................................ 61
7.5 Putting it all together ....................................................... 62

8 Phylogenetic Dating .............................................................. 63
8.1 Inferring time tree with tip dates ..................................... 64
8.2 Calibrating tree using ancestral dates ................................ 66
8.3 Dating an existing tree ...................................................... 67
8.4 Obtaining confidence intervals ........................................ 67
8.5 Excluding outlier taxa/nodes ............................................. 67
8.6 Full list of LSD2 options .................................................. 68

9 Rooting phylogenetic trees .................................................... 75
CONTENTS

9.1 Inferring unrooted tree with outgroup ........................................... 75
9.2 Inferring rooted trees without outgroup ...................................... 77
9.3 Testing root positions ................................................................. 80

10 Command reference ........................................................................ 83
  10.1 General options ................................................................. 83
    10.1.1 Example usages: ......................................................... 85
  10.2 Checkpointing to resume stopped run .................................. 85
  10.3 Likelihood mapping analysis .................................................. 86
    10.3.1 Example usages: ......................................................... 87
  10.4 Automatic model selection ..................................................... 89
    10.4.1 Example usages: ......................................................... 92
  10.5 Specifying substitution models .............................................. 93
    10.5.1 Example usages: ......................................................... 94
  10.6 Rate heterogeneity ............................................................ 94
  10.7 Partition model options ....................................................... 95
  10.8 Site-specific frequency model options ................................... 96
  10.9 Tree search parameters ....................................................... 96
    10.9.1 Example usages: ......................................................... 98
  10.10Ultrafast bootstrap parameters ............................................ 98
    10.10.1 Example usages: ....................................................... 99
  10.11Nonparametric bootstrap ................................................... 99
  10.12Single branch tests .......................................................... 99
    10.12.1 Example usages: ...................................................... 100
  10.13Ancestral sequence reconstruction ..................................... 100
    10.13.1 Example usages: ...................................................... 100
  10.14Tree topology tests .......................................................... 101
    10.14.1 Example usages: ...................................................... 102
  10.15Constructing consensus tree .............................................. 102
  10.16Computing Robinson-Foulds distance ................................ 103
    10.16.1 Example usages: ...................................................... 103
  10.17Generating random trees .................................................... 104
    10.17.1 Example usages: ...................................................... 104
  10.18Miscellaneous options ....................................................... 104
    10.18.1 Example usages: ...................................................... 105

11 Substitution models .................................................................. 109
  11.1 DNA models ................................................................. 109
    11.1.1 Base substitution rates ............................................ 109
    11.1.2 Base frequencies ..................................................... 111
    11.1.3 Lie Markov models ................................................... 111
## CONTENTS

11.2 Protein models ........................................... 113
   11.2.1 Amino-acid exchange rate matrices .................. 113
   11.2.2 Protein mixture models ................................. 114
   11.2.3 User-defined empirical protein models ............... 115
   11.2.4 Amino-acid frequencies ............................... 116
11.3 Codon models ............................................. 117
   11.3.1 Codon substitution rates ............................... 117
   11.3.2 Codon frequencies ..................................... 119
11.4 Binary and morphological models .......................... 120
11.5 Ascertainment bias correction ............................. 120
11.6 Rate heterogeneity across sites ......................... 120

12 Complex models ............................................. 123
   12.1 Partition models ......................................... 123
      12.1.1 Partition file format ................................. 124
      12.1.2 Partitioned analysis ................................. 126
   12.2 Mixture models ........................................... 126
      12.2.1 What is the difference between partition and mixture models? 126
      12.2.2 Defining mixture models .............................. 126
      12.2.3 Profile mixture models ............................... 127
      12.2.4 NEXUS model file ...................................... 128
   12.3 Site-specific frequency models .......................... 129
      12.3.1 Example usages ...................................... 130
   12.4 Heterotachy models ....................................... 131
      12.4.1 Quick usages ........................................ 131

13 Polymorphism-aware models ................................. 133
   13.1 Counts files .............................................. 134
      13.1.1 Conversion scripts .................................. 134
   13.2 First running example ................................... 135
   13.3 Substitution models ...................................... 135
   13.4 Virtual population size ................................. 136
   13.5 Level of polymorphism ................................... 136
   13.6 Sampling method .......................................... 137
   13.7 State frequency type .................................... 137
   13.8 Rate heterogeneity ....................................... 138
   13.9 Bootstrap branch support ................................. 138
   13.10 Interpretation of branch lengths ....................... 138

14 Compilation guide ........................................... 141
   14.1 General requirements .................................... 141
14.2 Downloading source code ........................................... 142
14.3 Compiling under Linux ............................................. 142
14.4 Compiling under Mac OS X ........................................ 143
14.5 Compiling under Windows .......................................... 144
14.6 Compiling 32-bit version ......................................... 145
14.7 Compiling MPI version ............................................. 146
14.8 Compiling Xeon Phi Knights Landing version ................... 147
14.9 About precompiled binaries ...................................... 147
14.10 Setup an Xcode project in MacOS ............................... 148
14.11 This will generate a subfolder build-xcode/iqtree.xcodeproj,
      which you can open in Xcode now. .............................. 149

15 Frequently asked questions ........................................ 151
15.1 How do I get help? .................................................. 151
15.2 How do I report bug? .............................................. 151
15.3 How do I interpret ultrafast bootstrap (UFBoot) support values? .... 152
15.4 How does IQ-TREE treat gap/missing/ambiguous characters? ........ 152
15.5 Can I mix DNA and protein data in a partitioned analysis? ............ 153
15.6 What is the interpretation of branch lengths when mixing codon and
      DNA data? .................................................................. 154
15.7 What is the purpose of composition test? ......................... 154
15.8 What is the good number of CPU cores to use? .................... 155
15.9 How do I save time for standard bootstrap? ....................... 156
15.10 Why does IQ-TREE complain about the use of +ASC model? ...... 157
15.11 How does IQ-TREE treat identical sequences? .................... 158
15.12 What are the differences between alignment columns/sites and patterns? 158
Chapter 1

Introduction

1.1 Why IQ-TREE?

Thanks to the recent advent of next-generation sequencing techniques, the amount of phylogenomic/transcriptomic data have been rapidly accumulated. This extremely facilitates resolving many “deep phylogenetic” questions in the tree of life. At the same time it poses major computational challenges to analyze such big data, where most phylogenetic software cannot handle. Moreover, there is a need to develop more complex probabilistic models to adequately capture realistic aspects of genomic sequence evolution.

This trends motivated us to develop the IQ-TREE software with a strong emphasis on phylogenomic inference. Our goals are:

- **Accuracy**: Proposing novel computational methods that perform better than existing approaches.
- **Speed**: Allowing fast analysis on big data sets and utilizing high performance computing platforms.
- **Flexibility**: Facilitating the inclusion of new (phylogenomic) models and sequence data types.
- **Versatility**: Implementing a broad range of commonly-used maximum likelihood analyses.

IQ-TREE has been developed since 2011 and freely available at http://www.iqtree.org/ as open-source software under the GNU-GPL license version 2. It is actively maintained by the core development team (see below) and a number of collaborators.

The name IQ-TREE comes from the fact that it is the successor of IQPNNI and TREE-PUZZLE software.
1.2 Key features

- **Efficient search algorithm**: Fast and effective stochastic algorithm to reconstruct phylogenetic trees by maximum likelihood. IQ-TREE compares favorably to RAxML and PhyML in terms of likelihood while requiring similar amount of computing time (Nguyen et al., 2015).

- **Ultrafast bootstrap**: An ultrafast bootstrap approximation (UFBoot) to assess branch supports. UFBoot is 10 to 40 times faster than RAxML rapid bootstrap and obtains less biased support values (Minh et al., 2013; Hoang et al., 2018).

- **Ultrafast model selection**: An ultrafast and automatic model selection (ModelFinder) which is 10 to 100 times faster than jModelTest and ProtTest. ModelFinder also finds best-fit partitioning scheme like PartitionFinder.

- **Big Data Analysis**: Supporting huge datasets with thousands of sequences or millions of alignment sites via checkpointing, safe numerical and low memory mode. Multicore CPUs and parallel MPI system are utilized to speedup analysis.

- **Phylogenetic testing**: Several fast branch tests like SH-aLRT and aBayes test (Anisimova et al., 2011) and tree topology tests like the approximately unbiased (AU) test (Shimodaira, 2002).

The strength of IQ-TREE is the availability of a wide variety of phylogenetic models:

- **Common models**: All common substitution models for DNA, protein, codon, binary and morphological data with rate heterogeneity among sites and ascertainment bias correction for e.g. SNP data.

- **Partition models**: Allowing individual models for different genomic loci (e.g. genes or codon positions), mixed data types, mixed rate heterogeneity types, linked or unlinked branch lengths between partitions.

- **Mixture models**: Fully customizable mixture models and empirical protein mixture models and.

- **Polymorphism-aware models**: Accounting for incomplete lineage sorting to infer species tree from genome-wide population data (Schrempf et al., 2016).

1.3 Free web server

For a quick start you can also try the IQ-TREE web server, which performs online computation using a dedicated computing cluster. It is very easy to use with as few as just 3 clicks! Try it out at

http://iqtree.cibiv.univie.ac.at
1.4 User support

Please refer to the user documentation and frequently asked questions. If you have further questions, feedback, feature requests, and bug reports, please sign up the following Google group (if not done yet) and post a topic to the

https://groups.google.com/d/forum/iqtree

The average response time is two working days.

1.5 Documentation

IQ-TREE has an extensive documentation with several tutorials and manual:

- **Getting started guide**: recommended for users who just downloaded IQ-TREE.
- **Web Server Tutorial**: A quick starting guide for the IQ-TREE Web Server.
- **Beginner’s tutorial**: recommended for users starting to use IQ-TREE.
- **Advanced tutorial**: recommended for more experienced users who want to explore more features of IQ-TREE.
- **Command Reference**: Comprehensive documentation of command-line options available in IQ-TREE.
- **Substitution Models**: All common substitution models and usages.
- **Complex Models**: Complex models such as partition and mixture models.
- **Polymorphism Aware Models**: Polymorphism-aware phylogenetic Models (PoMo) related documentation.
- **Compilation guide**: for advanced users who wants to compile IQ-TREE from source code.
- **Frequently asked questions (FAQ)**: recommended to have a look before you post a question in the IQ-TREE group.
1.6 How to cite IQ-TREE?

To maintain IQ-TREE, support users and secure fundings, it is important for us that you cite the following papers, whenever the corresponding features were applied for your analysis.

- **Example 1:** We obtained branch supports with the ultrafast bootstrap (Hoang et al., 2018) implemented in the IQ-TREE software (Nguyen et al., 2015).

- **Example 2:** We inferred the maximum-likelihood tree using the edge-linked partition model in IQ-TREE (Chernomor et al., 2016; Nguyen et al., 2015).

If you performed the tests of symmetry, please cite:


If you used the polymorphism-aware models please cite:


If you used the heterotachy model (GHOST) please cite:


If you performed the ultrafast bootstrap (UFBoot) please cite:


If you used posterior mean site frequency model please cite:

1.7. DEVELOPMENT TEAM

If you used ModelFinder please cite:


If you performed tree reconstruction please cite:


If you used partition models e.g., for phylogenomic analysis please cite:


If you used the IQ-TREE web server please cite:


1.7 Development team

IQ-TREE is actively developed by:

**Bui Quang Minh**, Team leader, Designs and implements software core, tree search, ultrafast bootstrap, model selection.


**Olga Chernomor**, Developer, Implements partition models.

**Heiko A. Schmidt**, Developer, Integrates TREE-PUZZLE features.

**Dominik Schrempf**, Developer, Implements polymorphism-aware models (PoMo).

**Michael Woodhams**, Developer, Implements Lie Markov models.

**Diep Thi Hoang**, Developer, Improves ultrafast bootstrap.

**Arndt von Haeseler**, Advisor.

Past members:
Lam Tung Nguyen, Developer, Implemented tree search algorithm.
Jana Trifinopoulos, Developer, Implemented web service.

1.8 Credits and acknowledgements

Some parts of the code were taken from the following packages/libraries: Phylogenetic likelihood library, TREE-PUZZLE, BIONJ, Nexus Class Library, Eigen library, SPRNG library, Zlib library, gzstream library, vectorclass library, GNU scientific library.

IQ-TREE was funded by the Austrian Science Fund (grant no. I760-B17 from 2012-2015 and I 2508-B29 from 2016-2017), the University of Vienna (Initiativkolleg I059-N from 2012-2015), the Australian National University (2018-onwards), Chan-Zuckerberg Initiative (2020).
Chapter 2

Getting started

Recommended for users who just downloaded IQ-TREE the first time.

2.1 IQ-TREE web server

The quickest is to try out the IQ-TREE web server, where you only need to upload an alignment, choose the options and start the analysis. There is a web server tutorial here.

If you want to use the command-line version, follow the instructions below.

2.2 Installation

For reasons of performance, IQ-TREE is a command-line program, i.e., IQ-TREE needs to be run from a terminal/console (command prompt under Windows).

2.2.1 Packages and bundles

Ready made IQ-TREE packages are available for the following distributions/repositories (command to install iqtree):

- **Debian Linux**: sudo apt-get install iqtree
- **Arch Linux (AUR)**
- **Anaconda**: conda install -c bioconda iqtree
- **Homebrew**: brew install brewsci/bio/iqtree2
- **FreeBSD**: pkg install iqtree
2.2.2 Manual download

IQ-TREE for Windows, MacOSX and Linux can be downloaded here.

- Extract the .zip (Windows, MacOSX) or .tar.gz (Linux) file to create a directory `iqtree-X.Y.Z-OS`, where `X.Y.Z` is the version number and `OS` is the operating system (Windows, MacOSX or Linux).
- You will find the executable in the `bin` sub-folder. Copy all files in `bin` folder to your system search path such that you can run IQ-TREE by entering `iqtree` from the Terminal.

Now you need to open a Terminal (or Console) to run IQ-TREE. See below the guide for Windows users and Mac OS X users.

2.3 For Windows users

Since IQ-TREE is a command-line program, clicking on `iqtree.exe` will not work. You have to open a Command Prompt for all analyses:

1. Click on “Start” menu (below left corner of Windows screen).
2. Type in “cmd” and press “Enter”. It will open the Command Prompt window (see Figure below).
3. Go into IQ-TREE folder you just extracted by entering e.g. (assuming you downloaded version 1.5.0):
   
   ```
   cd Downloads\iqtree-1.5.0-Windows
   ```
   
   (assuming that IQ-TREE was downloaded into `Downloads` folder).
4. Now you can try an example run by entering:
   
   ```
   bin\iqtree -s example.phy
   ```
   
   (example.phy is the example PHYLIP alignment file also extracted in that folder).
5. After a few seconds, IQ-TREE finishes and you may see something like this:

Congratulations ;-) You have finished the first IQ-TREE analysis.

2.4 For Mac OS X users

1. Open the “Terminal”, e.g., by clicking on the Spotlight icon (top-right corner), typing “terminal” and press “Enter”.
2. Go into IQ-TREE folder by entering (assuming you downloaded version 1.5.0):

```
cd Downloads/iqtree-1.5.0-MacOSX
```

(assuming that IQ-TREE was downloaded into Downloads folder).

3. Now you can try an example run by entering

```
bin/iqtree -s example.phy
```

(example.phy is the example PHYLIP alignment file also extracted in that folder).

4. After a few seconds, IQ-TREE finishes and you may see something like this:

Congratulations ;-) You have finished the first IQ-TREE analysis.

### 2.5 Minimal command-line examples

A few typically analyses are listed in the following. Note that it is assumed that `iqtree` executable was already copied into system search path. If not, please replace `iqtree` with actual path to executable.

- Infer maximum-likelihood tree from a sequence alignment (`example.phy`) with the best-fit model automatically selected by ModelFinder:
Figure 2.2: Mac terminal
2.5. **MINIMAL COMMAND-LINE EXAMPLES**

- Infer maximum-likelihood tree using GTR+I+G model:
  ```
  iqtree -s example.phy -m GTR+I+G
  ```

- Perform ModelFinder without subsequent tree inference:
  ```
  iqtree -s example.phy -m MF
  ```

- Combine ModelFinder, tree search, SH-aLRT test and ultrafast bootstrap with 1000 replicates:
  ```
  iqtree -s example.phy -B 1000 -alrt 1000
  # for version 1.x, change -B to -bb
  ```

- Perform edge-linked proportional partition model (example.nex):
  ```
  iqtree -s example.phy -p example.nex
  # for version 1.x change -p to -spp
  ```

- Find best partition scheme by possibly merging partitions:
  ```
  iqtree -s example.phy -p example.nex -m MF+MERGE
  ```

- Find best partition scheme followed by tree inference and ultrafast bootstrap:
  ```
  iqtree -s example.phy -p example.nex -m MFP+MERGE -B 1000
  # for version 1.x change -B to -bb
  ```

- Use 4 CPU cores to speed up computation:
  ```
  iqtree -s example.phy -T 4
  # for version 1.x change -T to -nt
  ```

- Determine the best number of cores to use under GTR+R4 model:
  ```
  iqtree -s example.phy -m GTR+R4 -T AUTO
  # for version 1.x change -T to -nt
  ```

- Show all available options:
  ```
  iqtree -h
  ```
2.6 Where to go from here?

Please continue with the Beginner’s tutorial for further usages.
Chapter 3

Web server tutorial

A quick starting guide for the IQ-TREE Web Server.

This tutorial explains briefly how to use the IQ-TREE web server for fast online phylogenetic inference, accessible at iqtree.cibiv.univie.ac.at.

There are three tabs: Tree Inference, Model Selection and Analysis Results.

3.1 Tree Inference

Tree Inference provides the most frequently used features of IQ-TREE and allows users to carry out phylogenetic analysis on a multiple sequence alignment (MSA). In the most basic case, no more than an MSA file is required to submit the job. Without further input, IQ-TREE will run with the default parameters and auto-detect the sequence type as well as the best-fitting substitution model. Additionally, Ultrafast Bootstrap (Hoang et al., 2018) and the SH-aLRT branch test (Guindon et al., 2010) will be performed.

You can either try out the web server with an example alignment by ticking the corresponding box or upload your own alignment file. By clicking on ‘Browse’ a dialog will open where you can select your MSA; the file formats Phylip, Fasta, Nexus, Clustal and MSF are supported.

After that you can submit the job. If you provide an email address, a notification will be sent to you once the job is finished. In case you don’t specify an email address, you will receive a link in the next step; you can bookmark this link to retrieve your results after the job is finished.
Figure 3.1: Tree Inference Tab
3.2 Model Selection

IQ-TREE supports a wide range of substitution models for DNA, protein, codon, binary and morphological alignments. In case you do not know which model is appropriate for your data, IQ-TREE can automatically determine the best-fit model for your alignment. Use the Model Selection tab if you only want to find the best-fit model without doing tree reconstruction.

![Figure 3.2: Model Selection Tab](image)

Like with Tree Inference, the only obligatory input is a multiple sequence alignment. You can either upload your own alignment file or use the example alignment to try out the web server and then submit the job.

3.3 Analysis Results

In the tab Analysis Results you can monitor your jobs. With our example file, a run will only take a few seconds, depending on the server load. For your own alignments
the CPU time limit is 24 hours. If you provided an email address when submitting the job, you will get an email once it is finished.

Once a job is finished, you can select it by checking the corresponding box and then **download the selected jobs** as a zip file. This zip file will contain the results of your run, including the **Run Log** and the **Full Result** which are also accessible in the webserver.

<table>
<thead>
<tr>
<th>Suffix</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>.iqtree</td>
<td>Full result of the run, this is the main report file</td>
</tr>
</tbody>
</table>
### 3.3. ANALYSIS RESULTS

<table>
<thead>
<tr>
<th>Suffix</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>.log</td>
<td>Run log</td>
</tr>
<tr>
<td>.treefile</td>
<td>Maximum likelihood tree in NEWICK format, can be visualized with treeviewer programs</td>
</tr>
<tr>
<td>.svg</td>
<td>Graphical tree representation in SVG format, done with ete view</td>
</tr>
<tr>
<td>.pdf</td>
<td>Graphical tree representation in PDF format, done with ete view</td>
</tr>
<tr>
<td>.contree</td>
<td>Consensus tree with assigned branch supports where branch lengths are optimized on the original alignment; printed if Ultrafast Bootstrap is selected</td>
</tr>
<tr>
<td>.ckp.gz</td>
<td>Checkpoint file; included if a job was stopped because of RAM/CPU limits</td>
</tr>
</tbody>
</table>

**NOTE**: Jobs which require more than 24 hours or 1GB RAM will be stopped. In such a case, you can download the stopped job and resume the run from the last checkpoint on your local PC as described here.
Chapter 4

Beginner’s tutorial

This tutorial gives a beginner’s guide.

Please first download and install the binary for your platform. For the next steps, the folder containing your iqtree executable should be added to your PATH environment variable so that IQ-TREE can be invoked by simply entering iqtree at the command-line. Alternatively, you can also copy iqtree binary into your system search.

**TIP**: For quick overview of all supported options in IQ-TREE, run the command iqtree -h.

4.1 Input data

IQ-TREE takes as input a multiple sequence alignment and will reconstruct an evolutionary tree that is best explained by the input data. If you have raw (unaligned) sequences, you need to first run an alignment program like MAFFT or ClustalW to align the sequences, before feeding them into IQ-TREE.

The input alignment can be in various common formats. For example the PHYLIP format which may look like:

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>28</td>
</tr>
<tr>
<td>Frog</td>
<td>AAATTTGCTCTGATTCAGCAGTGAT</td>
</tr>
<tr>
<td>Turtle</td>
<td>CTTCACACCCCCAGGACTCAGCAGTGAT</td>
</tr>
<tr>
<td>Bird</td>
<td>CTACCAACCCAGGACTCAGCAGTAAT</td>
</tr>
<tr>
<td>Human</td>
<td>CTACCACACCCCCAGGAAACAGCAGTGAT</td>
</tr>
<tr>
<td>Cow</td>
<td>CTACCACACCCCCAGGAAACAGCAGTGAC</td>
</tr>
<tr>
<td>Whale</td>
<td>CTACCACGCCCCAGGACACAGCAGTGAT</td>
</tr>
</tbody>
</table>
CHAPTER 4. BEGINNER’S TUTORIAL

This tiny alignment contains 7 DNA sequences from several animals with the sequence length of 28 nucleotides. IQ-TREE also supports other file formats such as FASTA, NEXUS, CLUSTALW. The FASTA file for the above example may look like this:

```
>Mouse
CTACCACACCCCCAGGACTCAGCAGTGAT
```

**TIP**: From version 2 you can input a directory of alignment files. IQ-TREE 2 will load and concatenate all alignments within the directory, eliminating the need for users to manually perform this step.

4.2 First running example

From the download there is an example alignment called `example.phy` in PHYLIP format. This example contains parts of the mitochondrial DNA sequences of several animals (Source: Phylogenetic Handbook).

You can now start to reconstruct a maximum-likelihood tree from this alignment by entering (assuming that you are now in the same folder with `example.phy`):

```
iqtree -s example.phy
```

`-s` is the option to specify the name of the alignment file that is always required by IQ-TREE to work. At the end of the run IQ-TREE will write several output files including:
• **example.phy.iqtree**: the main report file that is self-readable. You should look at this file to see the computational results. It also contains a textual representation of the final tree (see below).

• **example.phy.treefile**: the ML tree in NEWICK format, which can be visualized by any supported tree viewer programs like FigTree or iTOL.

• **example.phy.log**: log file of the entire run (also printed on the screen). To report bugs, please send this log file and the original alignment file to the authors.

For this example data the resulting maximum-likelihood tree may look like this (extracted from `.iqtree` file):

```
NOTE: Tree is UNROOTED although outgroup taxon 'LngfishAu' is drawn at root

+--------------LngfishAu
|              +--------------LngfishSA
|              +--LngfishAf
|                +--------------Frog
|                           +--------------Turtle
|                                       +--------------Sphenodon
|                                       +--------------Lizard
|                                       +--------------Crocodile
|                                       +--------------Bird
+--------------Human
|              +--------------Seal
|              +--------------Cow
|              +--------------Whale
|              +--------------Mouse
|              +--------------Rat
+--------------
```
This makes sense as the mammals (Human to Opossum) form a clade, whereas the reptiles (Turtle to Crocodile) and Bird form a separate sister clade. Here the tree is drawn at the outgroup Lungfish which is more ancient than other species in this example. However, please note that IQ-TREE always produces an unrooted tree as it knows nothing about this biological background; IQ-TREE simply draws the tree this way as LungfishAu is the first sequence occurring in the alignment.

During the example run above, IQ-TREE periodically wrote to disk a checkpoint file example.phy.ckp.gz (gzip-compressed to save space). This checkpoint file is used to resume an interrupted run, which is handy if you have a very large data sets or time limit on a cluster system. If the run did not finish, invoking IQ-TREE again with the very same command line will recover the analysis from the last stopped point, thus saving all computation time done before.

If the run successfully completed, running again will issue an error message:

```
ERROR: Checkpoint (example.phy.ckp.gz) indicates that a previous run successfully finished
Use `--redo` option if you really want to redo the analysis and overwrite all output files.
```

This prevents lost of data if you accidentally re-run IQ-TREE. However, if you really want to re-run the analysis and overwrite all previous output files, use `--redo` option:

```
iqtree -s example.phy --redo
```

Finally, the default prefix of all output files is the alignment file name. You can change the prefix with:

```
iqtree -s example.phy --prefix myprefix
# for version 1.x change --prefix to -pre
```

This prevents output files being overwritten when you perform multiple analyses on the same alignment within the same folder.

### 4.3 Choosing the right substitution model

NOTE: If you use model selection please cite the following paper:
IQ-TREE supports a wide range of substitution models for DNA, protein, codon, binary and morphological alignments. If you do not know which model is appropriate for your data, you can use ModelFinder to determine the best-fit model:

```
 iqtree -s example.phy -m MFP
 # change -m MFP to -m TEST to resemble jModelTest/ProtTest
```

-`m` is the option to specify the model name to use during the analysis. The special `MFP` keyword stands for ModelFinder Plus, which tells IQ-TREE to perform ModelFinder and the remaining analysis using the selected model. ModelFinder computes the log-likelihoods of an initial parsimony tree for many different models and the Akaike information criterion (AIC), corrected Akaike information criterion (AICc), and the Bayesian information criterion (BIC). Then ModelFinder chooses the model that minimizes the BIC score (you can also change to AIC or AICc by adding the option `-AIC` or `-AICc`, respectively).

**TIP:** Starting with version 1.5.4, `-m MFP` is the default behavior. Thus, this run is equivalent to `iqtree -s example.phy`.

Here, IQ-TREE will write an additional file:

- `example.phy.model`: log-likelihoods for all models tested. It serves as a checkpoint file to recover an interrupted model selection.

If you now look at `example.phy.iqtree` you will see that IQ-TREE selected `TIM2+I+G4` as the best-fit model for this example data. Thus, for additional analyses you do not have to perform the model test again and can use the selected model:

```
 iqtree -s example.phy -m TIM2+I+G
```

Sometimes you only want to find the best-fit model without doing tree reconstruction, then run:

```
 iqtree -s example.phy -m MF
 # change -m MF to -m TESTONLY to resemble jModelTest/ProtTest
```
By default, the maximum number of categories is limited to 10 due to computational reasons. If your sequence alignment is long enough, then you can increase this upper limit with the \texttt{cmax} option:

\begin{verbatim}
iqtree -s example.phy -m MF -cmax 15
\end{verbatim}

will test \texttt{+R2} to \texttt{+R15} instead of at most \texttt{+R10}.

To reduce computational burden, one can use the option \texttt{-mset} to restrict the testing procedure to a subset of base models instead of testing the entire set of all available models. For example, \texttt{-mset WAG, LG} will test only models like \texttt{WAG+...} or \texttt{LG+...}. Another useful option in this respect is \texttt{-msub} for AA data sets. With \texttt{-msub nuclear} only general AA models are included, whereas with \texttt{-msub viral} only AA models for viruses are included.

If you have enough computational resource, you can perform a thorough and more accurate analysis that invokes a full tree search for each model considered via the \texttt{-mtree} option:

\begin{verbatim}
iqtree -s example.phy -m MF -mtree
\end{verbatim}

### 4.4 Using codon models

IQ-TREE supports a number of codon models. You need to input a protein-coding DNA alignment and specify codon data by option \texttt{-st CODON} (Otherwise, IQ-TREE applies DNA model because it detects that your alignment has DNA sequences):

\begin{verbatim}
iqtree -s coding_gene.phy -st CODON
\end{verbatim}

If your alignment length is not divisible by 3, IQ-TREE will stop with an error message. IQ-TREE will group sites 1,2,3 into codon site 1; sites 4,5,6 to codon site 2; etc. Moreover, any codon, which has at least one gap/unknown/ambiguous nucleotide, will be treated as unknown codon character.

Note that the above command assumes the standard genetic code. If your sequences follow ‘The Invertebrate Mitochondrial Code’ (see the full list of supported genetic code here), then run:

\begin{verbatim}
iqtree -s coding_gene.phy -st CODON5
\end{verbatim}
4.5 Binary, morphological and SNP data

Binary alignments contain sequences with characters 0 and 1, which can be in any common formats supported by IQ-TREE, for example, in PHYLIP format:

```
4 6
S1 010101
S2 110011
S3 0--100
S4 10--10
```

Morphological alignments have an extended character alphabet of 0-9 and A-Z (for states 10-31). For example (PHYLIP format):

```
4 10
S1 0123401234
S2 03---20432
S3 3202-04--0
S4 4230120340
```

IQ-TREE will automatically determine the sequence type and the alphabet size. To run IQ-TREE on such alignments:

```
iqtree -s morphology.phy
```

or

```
iqtree -s morphology.phy -st MORPH
```

IQ-TREE implements two morphological ML models: MK and ORDERED. Morphological data typically do not have constant (uninformative) sites. In such cases, you should apply ascertainment bias correction model by e.g.:

```
iqtree -s morphology.phy -st MORPH -m MK+ASC
```

You can again select the best-fit binary/morphological model:

```
iqtree -s morphology.phy -st MORPH
```

For SNP data (DNA) that typically do not contain constant sites, you can explicitly tell the model to include ascertainment bias correction:

```
iqtree -s SNP_data.phy -m GTR+ASC
```
You can explicitly tell model testing to only include +ASC model with:

```
iqtree -s SNP_data.phy -m MFP+ASC
```

### 4.6 Assessing branch supports with ultrafast bootstrap approximation

To overcome the computational burden required by the nonparametric bootstrap, IQ-TREE introduces an ultrafast bootstrap approximation (UFBoot) (Minh et al., 2013; Hoang et al., 2018) that is orders of magnitude faster than the standard procedure and provides relatively unbiased branch support values. Citation for UFBoot:


To run UFBoot:

```
iqtree -s example.phy -m TIM2+I+G -B 1000
# for version 1.x change -B to -bb
```

-B specifies the number of bootstrap replicates where 1000 is the minimum number recommended. The section **MAXIMUM LIKELIHOOD TREE** in `example.phy.iqtree` shows a textual representation of the maximum likelihood tree with branch support values in percentage. The NEWICK format of the tree is printed to the file `example.phy.treefile`. In addition, IQ-TREE writes the following files:

- **example.phy.contree**: the consensus tree with assigned branch supports where branch lengths are optimized on the original alignment.
- **example.phy.splits.nex**: support values in percentage for all splits (bipartitions), computed as the occurrence frequencies in the bootstrap trees. This file can be viewed with the program **SplitsTree** to explore the conflicting signals in the data. So it is more informative than consensus tree, e.g. you can see how highly supported the second best conflicting split is, which had no chance to enter the consensus tree.
- **example.phy.splits** (if using -wsplits option): This file contains the same information as `example.phy.splits.nex` but in star-dot format.
4.7 Reducing impact of severe model violations with UFBoot

Starting with IQ-TREE version 1.6 we provide a new option `-bnni` to reduce the risk of overestimating branch supports with UFBoot due to severe model violations. With this option UFBoot will further optimize each bootstrap tree using a hill-climbing nearest neighbor interchange (NNI) search based directly on the corresponding bootstrap alignment.

Thus, if severe model violations are present in the data set at hand, users are advised to append `-bnni` to the regular UFBoot command:

```
iqtree -s example.phy -m TIM2+I+G -B 1000 -bnni
# for version 1.x change -B to -bb
```

4.8 Assessing branch supports with standard non-parametric bootstrap

The standard nonparametric bootstrap is invoked by the `-b` option:

```
iqtree -s example.phy -m TIM2+I+G -b 100
```

`-b` specifies the number of bootstrap replicates where 100 is the minimum recommended number. The output files are similar to those produced by the UFBoot procedure.

4.9 Assessing branch supports with single branch tests

IQ-TREE provides an implementation of the SH-like approximate likelihood ratio test (Guindon et al., 2010). To perform this test, run:

```
iqtree -s example.phy -m TIM2+I+G -alrt 1000
```
-alrt specifies the number of bootstrap replicates for SH-aLRT where 1000 is the minimum number recommended.

IQ-TREE also supports other tests such as the aBayes test (Anisimova et al., 2011) and the local bootstrap test (Adachi and Hasegawa, 1996b). See single branch tests for more details.

You can also perform both SH-aLRT and the ultrafast bootstrap within one single run:

```bash
tc -s example.phy -m TIM2+I+G -alrt 1000 -B 1000
# for version 1.x change -B to -bb
```

The branches of the resulting .treefile will be assigned with both SH-aLRT and UFBoot support values, which are readable by any tree viewer program like FigTree, Dendroscope or ETE. You can also look at the textual tree figure in .iqtree file:

```
NOTE: Tree is UNROOTED although outgroup taxon 'LngfishAu' is drawn at root
Numbers in parentheses are SH-aLRT support (%) / ultrafast bootstrap support (%)

+---------------------LngfishAu
|                     |
|                     |
| +--------------------LngfishSA
+-------------| (100/100)
|                     |
| +-------------------LngfishAf
|                     |
|                     |
| +-------------------Frog
+-------------| (99.8/100)
|                     |
| +--------------------Turtle
+-------------| (85/72)
|                     |
| +--------------------Bird
|                     |
| +--------------------Sphenodon
|                     |
| +-------------------Crocodile
|                     |
| +-------------------Human
+-------------| (100/100)
|                     |
| +-------------------Seal
```

|                     |
| +-------------------Bird
|                     |
| +--------------------Sphenodon
|                     |
| +-------------------Crocodile
|                     |
| +-------------------Human
+-------------| (100/100)
|                     |
| +-------------------Seal
```
From this figure, the branching patterns within reptiles are poorly supported (e.g. *Sphenodon* with SH-aLRT: 39%, UFBoot: 51% and *Turtle* with SH-aLRT: 85%, UFBoot: 72%) as well as the phylogenetic position of *Seal* within mammals (SH-aLRT: 68.3%, UFBoot: 75%). Other branches appear to be well supported.

### 4.10 Utilizing multi-core CPUs

IQ-TREE can utilize multiple CPU cores to speed up the analysis. A complement option `-T` (or `-nt` for version 1.x) allows specifying the number of CPU cores to use.

For example:

```bash
iqtree -s example.phy -m TIM2+I+G -T 2
# for version 1.x change -T to -nt
```

Here, IQ-TREE will use 2 CPU cores to perform the analysis.

Note that the parallel efficiency is only good for long alignments. A good practice is to use `-T AUTO` to determine the best number of cores:

```bash
iqtree -s example.phy -m TIM2+I+G -T AUTO
# for version 1.x change -T to -nt
```

Then while running IQ-TREE may print something like this on to the screen:

```plaintext
Measuring multi-threading efficiency up to 8 CPU cores
Threads: 1 / Time: 8.001 sec / Speedup: 1.000 / Efficiency: 100% / LogL: -22217
Threads: 2 / Time: 4.346 sec / Speedup: 1.841 / Efficiency: 92% / LogL: -22217
```
Therefore, I would only use 3 cores for this example data. For later analysis with your same data set, you can stick to the determined number.

Depending on the compute system it might be required to set an upper limit of CPU cores that can automatically be assigned. Use the -ntmax option to do so. For instance

\[
\text{iqtree} -s \text{example.phy} -m \text{TIM2+I+G} -T \text{AUTO} -ntmax 8 \\
\# \text{for version 1.x change } -T \text{ to } -nt
\]

does the same as above, but only allows to use up to 8 CPU cores. By default all cores of the current machine would be used as maximum.

4.11 Where to go from here?

Once confident enough you can go on with a more advanced tutorial, which covers topics like phylogenomic (multi-gene) analyses using partition models or mixture models.
Chapter 5

Advanced tutorial

Recommended for experienced users to explore more features.

To get started, please read the Beginner’s Tutorial first if not done so yet.

5.1 Partitioned analysis for multi-gene alignments

If you used partition model in a publication please cite:


In the partition model, you can specify a substitution model for each gene/character set. IQ-TREE will then estimate the model parameters separately for every partition. Moreover, IQ-TREE provides edge-linked or edge-unlinked branch lengths between partitions:

- `-q partition_file`: all partitions share the same set of branch lengths (like `-q` option of RAxML).
- `-p partition_file (-spp in version 1.x)`: like above but allowing each partition to have its own evolution rate.
- `-Q partition_file (-sp in version 1.x)`: each partition has its own set of branch lengths (like combination of `-q` and `-m` options in RAxML) to account for, e.g. heterotachy (Lopez et al., 2002).
NOTE: \(-p\) is recommended for typical analysis. \(-q\) is unrealistic and \(-Q\) is very parameter-rich. One can also perform all three analyses and compare e.g. the BIC scores to determine the best-fit partition model.

IQ-TREE supports RAxML-style and NEXUS partition input file. The RAxML-style partition file may look like:

\[
\begin{align*}
\text{DNA, part1} &= 1-100 \\
\text{DNA, part2} &= 101-384
\end{align*}
\]

If your partition file is called \texttt{example.partitions}, the partition analysis can be run with:

\[
\texttt{iqtree -s example.phy -p example.partitions -m GTR+I+G} \\
\quad \texttt{# for version 1.x change -p to -spp}
\]

Note that using RAxML-style partition file, all partitions will use the same rate heterogeneity model given in \(-m\) option (\(+I+G\) in this example). If you want to specify, say, \(+G\) for the first partition and \(+I+G\) for the second partition, then you need to create the more flexible NEXUS partition file. This file contains a \texttt{SETS} block with \texttt{CharSet} and \texttt{CharPartition} commands to specify individual genes and the partition, respectively. For example:

\[
\begin{verbatim}
# nexus
begin sets;
  charset part1 = 1-100;
  charset part2 = 101-384;
  charpartition mine = HKY+G:part1, GTR+I+G:part2;
end;
\end{verbatim}
\]

If your NEXUS file is called \texttt{example.nex}, then you can use the option \(-p\) to input the file as following:

\[
\texttt{iqtree -s example.phy -p example.nex} \\
\quad \texttt{# for version 1.x change -p to -spp}
\]

Here, IQ-TREE partitions the alignment \texttt{example.phy} into 2 sub-alignments named \texttt{part1} and \texttt{part2} containing sites (columns) 1-100 and 101-384, respectively. Moreover, IQ-TREE applies the subtitution models \texttt{HKY+G} and \texttt{GTR+I+G} to \texttt{part1} and \texttt{part2}, respectively. Substitution model parameters and trees with branch lengths can be found in the result file \texttt{example.nex.iqtree}.

Moreover, the \texttt{CharSet} command allows to specify non-consecutive sites with e.g.:
5.2 PARTITIONED ANALYSIS WITH MIXED DATA

That means, \texttt{part1} contains sites 1-100 and 200-384 of the alignment. Another example is:

\begin{verbatim}
charset part1 = 1-100\3;
\end{verbatim}

for extracting sites 1,4,7,...,100 from the alignment. This is useful for getting codon positions from the protein-coding alignment.

5.2 Partitioned analysis with mixed data

IQ-TREE also allows combining sub-alignments from different alignment files, which is helpful if you want to combine mixed data (e.g. DNA and protein) in a single analysis. Here is an example for mixing DNA, protein and codon models:

\begin{verbatim}
#nexus
begin sets;
  charset part1 = dna.phy: 1-100 201-300;
  charset part2 = dna.phy: 101-200;
  charset part3 = prot.phy: 1-400;
  charset part4 = prot.phy: 401-600;
  charset part5 = codon.phy:CODON, *;
  charpartition mine = HKY:part1, GTR+G:part2, LG+G:part3, WAG+
                    I+G:part4, GY:part5;
end;
\end{verbatim}

Here, \texttt{part1} and \texttt{part2} contain sub-alignments from alignment file \texttt{dna.phy}, whereas \texttt{part3} and \texttt{part4} are loaded from alignment file \texttt{prot.phy} and \texttt{part5} from \texttt{codon.phy}. The : is needed to separate the alignment file name and site specification. Note that, for convenience * in \texttt{part5} specification means that \texttt{part5} corresponds to the entire alignment \texttt{codon.phy}.

\textbf{TIP}: For \texttt{part5} the \texttt{CODON} keyword is specified so that IQ-TREE will apply a codon model. Moreover, this implicitly assumes the standard genetic code. If you want to use another genetic code, append \texttt{CODON} with the code ID described here.

Because the alignment file names are now specified in this NEXUS file, you can omit the \texttt{-s} option:
Note that `aln.phy` and `prot.phy` does not need to contain the same set of sequences. For instance, if some sequence occurs in `aln.phy` but not in `prot.phy`, IQ-TREE will treat the corresponding parts of sequence in `prot.phy` as missing data. For your convenience IQ-TREE writes the concatenated alignment into the file `example.nex`. conaln.

5.3 Choosing the right partitioning scheme

ModelFinder implements a greedy strategy (Lanfear et al., 2012) that starts with the full partition model and subsequentially merges two genes until the model fit does not increase any further:

```
 iqtree -s example.phy -p example.nex -m MFP+MERGE
 # for version 1.x change -p to -spp
```

Note that this command considers the FreeRate heterogeneity model (see model selection tutorial). If you want to resemble PartitionFinder by just considering the invariable site and Gamma rate heterogeneity (thus saving computation times), then run:

```
 iqtree -s example.phy -p example.nex -m TESTMERGE
 # for version 1.x change -p to -spp
```

After ModelFinder found the best partition, IQ-TREE will immediately start the tree reconstruction under the best-fit partition model. Sometimes you only want to find the best-fit partition model without doing tree reconstruction, then run:

```
 iqtree -s example.phy -p example.nex -m MF+MERGE
 # for version 1.x change -p to -spp
```

To resemble PartitionFinder and save time:

```
 iqtree -s example.phy -p example.nex -m TESTMERGEONLY
 # for version 1.x change -p to -spp
```

To reduce the computational burden IQ-TREE implements the relaxed hierarchical clustering algorithm (Lanfear et al., 2014), which is invoked via `-rcluster` option:
5.4 Ultrafast bootstrapping with partition model

IQ-TREE can perform the ultrafast bootstrap with partition models by e.g.,

```
iqtree -s example.phy -p example.nex -B 1000
# for version 1.x change -p to -spp and -B to -bb
```

Here, IQ-TREE will resample the sites within partitions (i.e., the bootstrap replicates are generated per partition separately and then concatenated together). The same holds true if you do the standard nonparametric bootstrap.

IQ-TREE supports the partition-resampling strategy as suggested by (Nei et al., 2001):

```
iqtree -s example.phy -p example.nex -B 1000 --sampling GENE
# for version 1.x change -p to -spp and -B to -bb and --sampling to -bsam
```

to resample partitions instead of sites. Moreover, IQ-TREE allows an even more complicated strategy: resampling partitions and then sites within resampled partitions (Gadagkar et al., 2005; Seo et al., 2005). This may help to reduce false positives (i.e. wrong branch receiving 100% support):

```
iqtree -s example.phy -p example.nex -B 1000 --sampling GENESITE
# for version 1.x change -p to -spp and -B to -bb and --sampling to -bsam
```

5.5 Constrained tree search

IQ-TREE supports constrained tree search via -g option, so that the resulting tree must obey a constraint tree topology. The constraint tree can be multifurcating and need not to contain all species. To illustrate, let’s return to the first running example, where we want to force Human grouping with Seal whereas Cow with Whale. If you use the following constraint tree (NEWICK format):

```
((Human,Seal),(Cow,Whale));
```
Save this to a file example.constr0 and run:

```bash
iqtree -s example.phy -m TIM2+I+G -g example.constr0 --prefix example.constr0
# for version 1.x change --prefix to -pre
```

(We use a prefix in order not to overwrite output files of the previous run). The resulting part of the tree extracted from example.constr0.iqtree looks exactly like a normal unconstrained tree search:

```
+----------------+Human
  +--|
  | +----+Seal
  |     +--|
  |       | +----+Cow
  |       |     +----+Whale
  | +-----|
  | +------+Mouse
  | +-------|
  | +-------+Rat
```

This is the correct behavior: although Human and Seal are not monophyletic, this tree indeed satisfies the constraint, because the induced subtree separates (Human,Seal) from (Cow,Whale). This comes from the fact that the tree is unrooted. If you want them to be sister groups, then you need to include outgroup taxa into the constraint tree. For example:

```
((Human,Seal),(Cow,Whale),Mouse);
```

Save this to example.constr1 and run:

```bash
iqtree -s example.phy -m TIM2+I+G -g example.constr1 --prefix example.constr1
# for version 1.x change --prefix to -pre
```

The resulting part of the tree is then:

```
+----------------+Human
  +--|
  | +----+Seal
  |     +--|
  |       | +----+Cow
  |       |     +----|
  | +-----|
  | +------+Rat
```

which shows the desired effect.

NOTE: While this option helps to enforce the tree based on prior knowledge, it is advised to always perform tree topology tests to make sure that the resulting constrained tree is NOT significantly worse than an unconstrained tree! See tree topology tests and testing constrained tree below for a guide how to check this.

5.6 Tree topology tests

IQ-TREE can compute log-likelihoods of a set of trees passed via the \(-z\) option:

```
iqtree -s example.phy -z example.treels -m GTR+G
```

assuming that `example.treels` is an existing file containing a set of trees in NEWICK format. IQ-TREE first reconstructs an ML tree. Then, it will compute the log-likelihood of the trees in `example.treels` based on the estimated parameters done for the ML tree. `example.phy.iqtree` will have a section called USER TREES that lists the tree IDs and the corresponding log-likelihoods. The trees with optimized branch lengths can be found in `example.phy.treels.trees`. If you only want to evaluate the trees without reconstructing the ML tree, you can run:

```
iqtree -s example.phy -z example.treels -n 0
```

Here, the number of search iterations is set to 0 \((-n 0\)), such that model parameters are quickly estimated from an initial parsimony tree, which is normally accurate enough for our purpose. If you, however, prefer to estimate model parameters based on a tree (e.g. reconstructed previously), use `-te <treefile>` option.

IQ-TREE also supports several tree topology tests using the RELL approximation (Kishino et al., 1990). This includes bootstrap proportion (BP), Kishino-Hasegawa test (Kishino and Hasegawa, 1989), Shimodaira-Hasegawa test (Shimodaira and Hasegawa, 1999), expected likelihood weights (Strimmer and Rambaut, 2002):

```
iqtree -s example.phy -z example.treels -n 0 -zb 1000
```
Here, `-zb` specifies the number of RELL replicates, where 1000 is the recommended minimum number. The USER TREES section of `example.phy.iqtree` will list the results of BP, KH, SH, and ELW methods.

If you also want to perform the weighted KH and weighted SH tests, simply add `-zw` option:

```
iqtree -s example.phy -z example.treels -n 0 -zb 1000 -zw
```

Starting with version 1.4.0 IQ-TREE supports approximately unbiased (AU) test (Shimodaira, 2002) via `-au` option:

```
iqtree -s example.phy -z example.treels -n 0 -zb 1000 -zw -au
```

This will perform all above tests plus the AU test.

Finally, note that IQ-TREE will automatically detect duplicated tree topologies and omit them during the evaluation.

**HINTS:**

- The KH, SH and AU tests return p-values, thus a tree is rejected if its p-value < 0.05 (marked with a `-` sign).
- bp-RELL and c-ELW return posterior weights which are not p-value. The weights sum up to 1 across the trees tested.
- The KH test (Kishino and Hasegawa, 1989) was designed to test 2 trees and thus has no correction for multiple testing. The SH test (Shimodaira and Hasegawa, 1999) fixes this problem.
- However, the SH test becomes too conservative (i.e., rejecting fewer trees than expected) when testing many trees. The AU test (Shimodaira, 2002) fixes this problem and is thus recommended as replacement for both KH and SH tests.

### 5.7 Testing constrained tree

We now illustrate an example to use the AU test (see above) to test trees from unconstrained versus constrained search, which is helpful to know if a constrained search is sensible or not. Thus:

1. Perform an unconstrained search:

```
iqtree -s example.phy -m TIM2+I+G --prefix example.unconstr
# for version 1.x change --prefix to -pre
```
5.7. TESTING CONSTRAINED TREE

2. Perform a constrained search, where `example.constr1` file contains: 
   ```
   ((Human, Seal), (Cow, Whale), Mouse);
   ```
   
   ```
   iqtree -s example.phy -m TIM2+I+G -g example.constr1 --prefix example.constr1
   # for version 1.x change --prefix to -pre
   ```

3. Perform another constrained search, where `example.constr2` file contains 
   ```
   ((Human, Cow, Whale), Seal, Mouse);
   ```
   
   ```
   iqtree -s example.phy -m TIM2+I+G -g example.constr2 --prefix example.constr2
   # for version 1.x change --prefix to -pre
   ```

4. Perform the last constrained search, where `example.constr3` file contains 
   ```
   ((Human, Mouse), (Cow, Rat), Opossum);
   ```
   
   ```
   iqtree -s example.phy -m TIM2+I+G -g example.constr3 --prefix example.constr3
   # for version 1.x change --prefix to -pre
   ```

5. Concatenate all trees into a file:

   ```
   # for Linux or macOS
   cat example.unconstr.treefile example.constr1.treefile
   example.constr2.treefile example.constr3.treefile > example.treels
   # for Windows
   type example.unconstr.treefile example.constr1.treefile
   example.constr2.treefile example.constr3.treefile > example.treels
   ```

6. Test the set of trees:

   ```
   iqtree -s example.phy -m TIM2+I+G -z example.treels -n 0 -zb 1000 -au
   ```

Now look at the resulting `.iqtree` file:

```
USER TREES
---------
See example.phy.trees for trees with branch lengths.
```
### 5.8 Consensus construction and bootstrap value assignment

IQ-TREE can construct an extended majority-rule consensus tree from a set of trees written in NEWICK or NEXUS format (e.g., produced by MrBayes):

```
  iqtree -con mytrees
```
To build a majority-rule consensus tree, simply set the minimum support threshold to 0.5:

```
iqtree -con mytrees -minsup 0.5
```

If you want to specify a burn-in (the number of beginning trees to ignore from the trees file), use `-bi` option:

```
iqtree -con mytrees -minsup 0.5 -bi 100
```

to skip the first 100 trees in the file.

IQ-TREE can also compute a consensus network and print it into a NEXUS file by:

```
iqtree -net mytrees
```

Finally, a useful feature is to read in an input tree and a set of trees, then IQ-TREE can assign the support value onto the input tree (number of times each branch in the input tree occurs in the set of trees). This option is useful if you want to compute the support values for an ML tree based on alternative topologies.

```
iqtree -sup input_tree set_of_trees
```

## 5.9 User-defined substitution models

Users can specify any DNA model using a 6-letter code that defines which rates should be equal. For example, 010010 corresponds to the HKY model and 012345 to the GTR model. In fact, IQ-TREE uses this specification internally to simplify the coding. The 6-letter code is specified via the `-m` option, e.g.:

```
iqtree -s example.phy -m 010010+G
```

Moreover, with the `-m` option one can input a file which contains the 6 rates (A-C, A-G, A-T, C-G, C-T, G-T) and 4 base frequencies (A, C, G, T). For example:

```
iqtree -s example.phy -m mymodel+G
```

where `mymodel` is a file containing the 10 entries described above, in the correct order. The entries can be separated by either empty space(s) or newline character. One can even specify the rates within `-m` option by e.g.:

```
iqtree -s example.phy -m 'TN{2.0,3.0}+G8{0.5}+I{0.15}"
```
That means, we use Tamura-Nei model with fixed transition-transversion rate ratio of 2.0 and purine/pyrimidine rate ratio of 3.0. Moreover, we use 8-category Gamma-distributed site rates with the shape parameter (alpha) equal to 0.5 and a proportion of invariable sites p-inv=0.15.

By default IQ-TREE computes empirical state frequencies from the alignment by counting, but one can also estimate the frequencies by maximum-likelihood with \(+\) Fo in the model name:

```
iqtree -s example.phy -m GTR+G+Fo
```

For amino-acid alignments, IQ-TREE use the empirical frequencies specified in the model. If you want frequencies as counted from the alignment, use \(+\)F, for example:

```
iqtree -s myprotein_alignment -m WAG+G+F
```

Note that all model specifications above can be used in the partition model NEXUS file.

### 5.10 Inferring site-specific rates

IQ-TREE allows to infer site-specific evolutionary rates if a site-rate heterogeneity model such as Gamma or FreeRate is the best model. Here, IQ-TREE will estimate model parameters and then apply an empirical Bayesian approach to assign site-rates as the mean over rate categories, weighted by the posterior probability of the site falling into each category. This approach is provided in IQ-TREE because such empirical Bayesian approach was shown to be most accurate (Mayrose et al., 2004). An example run:

```
iqtree -s example.phy --rate
# for version 1.x change --rate to -wsr
```

IQ-TREE will write an output file `example.phy.rate` that looks like:

<table>
<thead>
<tr>
<th>Site</th>
<th>Rate</th>
<th>Category</th>
<th>Categorized_rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.26625</td>
<td>2</td>
<td>0.24393</td>
</tr>
<tr>
<td>2</td>
<td>0.99345</td>
<td>3</td>
<td>0.81124</td>
</tr>
<tr>
<td>3</td>
<td>2.69275</td>
<td>4</td>
<td>2.91367</td>
</tr>
<tr>
<td>4</td>
<td>0.25822</td>
<td>2</td>
<td>0.24393</td>
</tr>
<tr>
<td>5</td>
<td>0.25822</td>
<td>2</td>
<td>0.24393</td>
</tr>
<tr>
<td>6</td>
<td>0.42589</td>
<td>2</td>
<td>0.24393</td>
</tr>
<tr>
<td>7</td>
<td>0.30194</td>
<td>2</td>
<td>0.24393</td>
</tr>
<tr>
<td>8</td>
<td>0.72790</td>
<td>3</td>
<td>0.81124</td>
</tr>
</tbody>
</table>
5.10. INFERRING SITE-SPECIFIC RATES

The 1st column is site index of the alignment (starting from 1), the 2nd column Rate shows the mean site-specific rate as explained above, and the 3rd and 4th columns show the category index and rate of the Gamma rate category with the highest probability for this site (1 for slow and 4 for fast rate).

The above run will perform a full tree search. To speed up you can use -n 0 to only use a parsimony tree for site rate estimates. Or if you have already inferred an ML tree, you can specify it to improve the rate estimate:

```
iqtree -s example.phy -t ml.treefile -n 0 --rate
# for version 1.x change --rate to -wsr
```

where -t is the option to input a fixed tree topology and ml.treefile is the ML tree reconstructed previously.

If you already know the best-fit model for the alignment, you can use specify it via -m option to omit model selection and hence speed it up:

```
iqtree -s example.phy -m GTR+R10 -n 0 --rate
# for version 1.x change --rate to -wsr
```

Finally, IQ-TREE 2 allows to estimate rates by maximum likelihood via --mlrate option:

```
iqtree -s example.phy -n 0 --mlrate
```

This will print an output file example.phy.mlrate that looks like:

```
# Site-specific substitution rates determined by maximum likelihood
# This file can be read in MS Excel or in R with command:
# tab=read.table('example.phy.mlrate',header=TRUE)
# Columns are tab-separated with following meaning:
# Site: Alignment site ID
# Rate: Site rate estimated by maximum likelihood

<table>
<thead>
<tr>
<th>Site</th>
<th>Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.51550</td>
</tr>
<tr>
<td>2</td>
<td>12.89129</td>
</tr>
<tr>
<td>3</td>
<td>34.31350</td>
</tr>
<tr>
<td>4</td>
<td>2.44313</td>
</tr>
</tbody>
</table>
| 5    | 2.44313 |```
### 5.11 Where to go from here?

See Command Reference for a complete list of all options available in IQ-TREE.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>4.41889</td>
</tr>
<tr>
<td>7</td>
<td>2.69577</td>
</tr>
<tr>
<td>8</td>
<td>9.27503</td>
</tr>
<tr>
<td>9</td>
<td>2.44313</td>
</tr>
<tr>
<td>10</td>
<td>0.00001</td>
</tr>
</tbody>
</table>
Assessing phylogenetic assumptions

It is important to know that phylogenetic models rely on various simplifying assumptions to ease computations. If your data severely violate these assumptions, it might cause bias in phylogenetic estimates of tree topologies and other model parameters. Some common assumptions include treelikeness (all sites in the alignment have evolved under the same tree), stationarity (nucleotide/amino-acid frequencies remain constant over time), reversibility (substitutions are equally likely in both directions), and homogeneity (substitution rates remain constant over time).

This document shows several ways to check some of these assumptions that you should perform before doing phylogenetic analysis.

6.1 Tests of symmetry

IQ-TREE provides three matched-pairs tests of symmetry (Naser-Khdour et al., 2019) to test the two assumptions of stationarity and homogeneity. A simple analysis:

```
iqtree2 -s example.phy -p example.nex --symtest-only
```

will perform the three tests of symmetry on every partition of the alignment and print the result into a .symtest.csv file. --symtest-only option tells IQ-TREE to only perform the tests of symmetry and then exit. In this example the content of example.nex.symtest.csv looks like this:

```
# Matched-pair tests of symmetry
# This file can be read in MS Excel or in R with command:
#    dat=read.csv('example.nex.symtest.csv',comment.char='#')
# Columns are comma-separated with following meanings:
```
### CHAPTER 6. ASSESSING PHYLOGENETIC ASSUMPTIONS

<table>
<thead>
<tr>
<th>Name</th>
<th>SymSig</th>
<th>SymNon</th>
<th>SymPval</th>
<th>MarSig</th>
<th>MarNon</th>
<th>MarPval</th>
<th>IntSig</th>
<th>IntNon</th>
<th>IntPval</th>
</tr>
</thead>
<tbody>
<tr>
<td>part1</td>
<td>44</td>
<td>92</td>
<td>0.475639</td>
<td>50</td>
<td>86</td>
<td>0.722371</td>
<td>4</td>
<td>132</td>
<td>0.23869</td>
</tr>
<tr>
<td>part2</td>
<td>43</td>
<td>93</td>
<td>0.142052</td>
<td>49</td>
<td>87</td>
<td>0.205232</td>
<td>5</td>
<td>131</td>
<td>0.169618</td>
</tr>
<tr>
<td>part3</td>
<td>53</td>
<td>83</td>
<td>0.004998</td>
<td>58</td>
<td>78</td>
<td>0.001641</td>
<td>6</td>
<td>130</td>
<td>0.343127</td>
</tr>
</tbody>
</table>

The three important columns are:

- **SymPval**: a small p-value (say < 0.05) indicates that the assumptions of stationarity or homogeneity or both is rejected. In this case, partition `part3` does not comply with these two assumptions (p-value = 0.00499855), whereas the other two partitions are “good”.

- **MarPval**: a small p-value means that the assumption of stationarity is rejected. In this case, only partition `part3` does not comply with the stationary condition (p-value = 0.00164132).

- **IntPval**: a small p-value means that the homogeneity assumption is reject. In this case, no partitions are “bad” according to this test, i.e., they all comply with the homogeneity assumption.

This little example shows that only `part3` is problematic by not complying with the stationary assumption.

Now you may want to perform the phylogenetic analysis excluding all “bad” partitions by:

```bash
iqtree2 -s example.phy -p example.nex --symtest-remove-bad
```
6.2. **LIKELIHOOD MAPPING**

that will remove all “bad” partitions where SymPval < 0.05 and continue the analysis with the remaining “good” partitions. You may then compare the trees from “all” partitions and from “good” only partitions to see if there is significant difference between them with tree topology tests.

Other options can be seen when running `iqtree2 -h`:

<table>
<thead>
<tr>
<th>TEST OF SYMMETRY:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>--symtest</td>
<td>Perform three tests of symmetry</td>
</tr>
<tr>
<td>--symtest-only</td>
<td>Do --symtest then exist</td>
</tr>
<tr>
<td>--symtest-remove-bad</td>
<td>Do --symtest and remove bad partitions</td>
</tr>
<tr>
<td>--symtest-remove-good</td>
<td>Do --symtest and remove good partitions</td>
</tr>
<tr>
<td>--symtest-type MAR</td>
<td>INT removing partitions</td>
</tr>
<tr>
<td>--symtest-pval NUMER</td>
<td>P-value cutoff (default: 0.05)</td>
</tr>
<tr>
<td>--symtest-keep-zero</td>
<td>Keep NAs in the tests</td>
</tr>
</tbody>
</table>

**6.2 Likelihood mapping**

Likelihood mapping ([Strimmer and von Haeseler, 1997](#)) is a visualisation method to display the phylogenetic information of an alignment. It visualises the treelikeness of all quartets in a single triangular graph and therefore renders a quick interpretation of the phylogenetic content.

A simple likelihood mapping analysis can be conducted with:

```
  iqtree -s example.phy -lmap 2000 -n 0
```

where `-lmap` option specify the number of quartets of taxa that will be drawn randomly from the alignment. `-n 0` tells IQ-TREE to stop the analysis right after running the likelihood mapping. IQ-TREE will print the result in the `.iqtree` report file as well as the likelihood mapping plot `.lmap.svg` (in SVG format) and `.lmap.eps` file (in EPS figure format).

You can now view the likelihood mapping plot file `example.phy.lmap.svg`, which looks like this:

It shows phylogenetic information of the alignment `example.phy`.

- Top sub-figure: distribution of quartets depicted by dots on the likelihood mapping plot.
- Left sub-figure: percentages of quartets falling in each of the three areas. The three areas show support for one of the different groupings like (a,b)-(c,d).
Figure 6.1: Likelihood mapping plot.
6.2. LIKELIHOOD MAPPING

- Right sub-figure: percentages of quartets falling in each of the seven areas. Quartets falling into the three corners are informative and called fully-resolved quartets. Those in three rectangles are partly informative (partly resolved quartets) and those in the center are uninformative (unresolved quartets). A good data set should have high number of fully resolved quartets and low number of unresolved quartets.

The meanings can also be found in the LIKELIHOOD MAPPING STATISTICS section of the report file example.phy.iqtree:

```
LIKELIHOOD MAPPING STATISTICS
-------------------------------
(a,b)-(c,d)  (a,b)-(c,d)
/ \        / \  
/  \       /  \  
/    a1    /    1  
/ \         / \  
/  \        /  \  
/    6      /    4  
/ \         / \  
/  \        /  \  
/    7      /    7  
/ \         / \  
/    \      /  \  
\  a3      | a2 \  / 3 | 5 | 2
\_________|__________\ /_____|________|
\_____
(a,d)-(b,c)  (a,c)-(b,d)  (a,d)-(b,c)  (a ,c)-(b,d)
Division of the likelihood mapping plots into 3 or 7 areas. On the left the areas show support for one of the different groupings like (a,b|c,d). On the right the right quartets falling into the areas 1, 2 and 3 are informative. Those in the rectangles 4, 5 and 6 are partly informative and those in the center (7) are not informative. 
```

The command reference will provide more options and how to perform 2-, 3-, or 4-
cluster likelihood mapping analysis.
Chapter 7

Concordance Factor

Since IQ-TREE 2, we provide two measures for quantifying genealogical concordance in phylogenomic datasets: the gene concordance factor (gCF) and the site concordance factor (sCF). For every branch of a reference tree, gCF is defined as the percentage of “decisive” gene trees containing that branch. gCF is already in wide usage, but here we allow to calculate gCF while correctly accounting for variable taxon coverage among the gene trees. sCF is defined as the percentage of decisive alignment sites supporting a branch in the reference tree. sCF is a novel measure that is particularly useful when individual gene alignments are relatively uninformative, such that gene trees are uncertain. gCF and sCF complement classical measures of branch support (e.g. bootstrap) in phylogenetics by providing a full description of underlying disagreement among loci and sites.

If you use this feature please cite:


NOTE: For this feature please use IQ-TREE version 2!

See very nice tips on how to use and interpret concordance factors by Rob Lanfear.
7.1 Inferring species tree

First, you need to infer a reference tree (e.g. a species tree), on which the concordance factors will be annotated. The species tree can be reconstructed by a concatenation/supermatrix approach or a coalescent/reconciliation/supertree approach. Here, we will use the concatenation approach in IQ-TREE.

As an example, you can apply an edge-linked proportional partition model with ultra-fast bootstrap (1000 replicates; for comparison with concordance factors):

```
iqtree -s ALN_FILE -p PARTITION_FILE --prefix concat -B 1000 -T AUTO
```

where \texttt{ALN\_FILE} and \texttt{PARTITION\_FILE} are your input files. \texttt{-T AUTO} is to detect the best number of CPU cores. Here we use a prefix \texttt{concat}, so that all output files (\texttt{concat.\*}) do not interfere with analyses below. If \texttt{--prefix} is omitted, all output files will be \texttt{PARTITION\_FILE.\*}.

Moreover, IQ-TREE 2 provides a new convenient feature: if you have a directory with many (locus) alignments, you can specify this directory directly with \texttt{-p} option:

```
iqtree -p ALN\_DIR --prefix concat -B 1000 -T AUTO
```

IQ-TREE detects if \texttt{-p} argument is a directory and automatically load all alignment files and concatenate them into a supermatrix for the partition analysis.

7.2 Inferring gene/locus trees

We now construct a set of gene/locus trees. One can manually do a for-loop, but IQ-TREE 2 provides a new convenient option \texttt{-S} to compute individual locus trees given a partition file or a directory:

```
iqtree -s ALN\_FILE -S PARTITION\_FILE --prefix loci -T AUTO
# or
iqtree -S ALN\_DIR --prefix loci -T AUTO
```

In the second case, IQ-TREE automatically detects that \texttt{ALN\_DIR} is a directory and will load all alignment files within the directory. So \texttt{-S} takes the same argument as \texttt{-p} except that it performs model selection (ModelFinder) and tree inference separately for each partition/alignment. The output files are similar to those from a partitioned analysis, except that \texttt{loci.treefile} now contains a set of trees.
7.3 Gene concordance factor (gCF)

Given the species tree `concat.treefile` and the set of locus trees `loci.treefile` computed above, you can calculate gCF for each branch of the species tree as the fraction of decisive gene trees concordant with this branch:

```
iqtree -t concat.treefile --gcf loci.treefile --prefix concord
```

Note that `-t` accepts any reference tree (e.g., by coalescent/reconciliation approach) and `--gcf` accepts any set of trees (e.g., locus trees and bootstrap trees), which may contain a subset of taxa from the reference tree. IQ-Tree will write three files:

- `concord.cf.tree`: Newick tree with gCF assigned for each internal branch of the reference tree. If the reference tree already has some branch label (such as bootstrap support in this case), gCF will be appended to the existing label separated by a `/`.
- `concord.cf.branch`: Newick tree with internal branch IDs.
- `concord.cf.stat`: A tab-separated table with gCF and gDF (gene discordance factor) for every internal branch (rows of the table). The ID column can be linked with `concord.cf.branch` file. This file can be read in R to do some plot (see below).

If you omit `--prefix`, all output files will be written to `concat.treefile.*`.

7.4 Site concordance factor (sCF)

Given the species tree `concat.treefile` and the alignment, you can calculate sCF for each branch of the species tree as the fraction of decisive alignment sites supporting that branch:

```
iqtree -t concat.treefile -s ALN_FILE --scf 100 --prefix concord
-T 10
```

`--scf` specifies the number of quartets (randomly sampled around each internal branch) for computing sCF. We recommend at least 100 quartets for stable sCF values. Note that running this command several times may lead to slightly different sCF due to randomness. To make it reproducible, you need to use `--seed` option to provide a random number generator seed.

Instead of `-s`, you can alternatively provide a directory or a partition file. IQ-Tree then computes sCF for the concatenated alignment:
Finally, you can combine gCF and sCF within a single run:

```
  iqtree -t concat.treefile --gcf loci.treefile -p ALN_DIR --scf 100 --prefix concord -T 10
```

Here, each branch of `concord.cf.tree` will be assigned (or appended) with gCF/sCF values and `concord.cf.stat` will be written with both gCF and sCF values.

### 7.5 Putting it all together

If you have separate alignments for each locus in a folder, then perform the following commands:

```
# infer a concatenation-based species tree with 1000 ultrafast bootstrap and an edge-linked partition model
  iqtree -p ALN_DIR --prefix concat -B 1000 -T AUTO

# infer the locus trees
  iqtree -S ALN_DIR --prefix loci -T AUTO

# compute concordance factors
  iqtree -t concat.treefile --gcf loci.treefile -p ALN_DIR --scf 100 --prefix concord -T 10
```

If you have a single concatenated alignment with a partition file that defines loci:

```
# infer a concatenation-based species tree with 1000 ultrafast bootstrap and an edge-linked partition model
  iqtree -s ALN_FILE -p PARTITION_FILE --prefix concat -B 1000 -T AUTO

# infer the locus trees
  iqtree -s ALN_FILE -S PARTITION_FILE --prefix loci -T AUTO

# compute concordance factors
  iqtree -t concat.treefile --gcf loci.treefile -s ALN_FILE --scf 100 --prefix concord -T 10
```

Note that you can adjust `-T 10` if you have fewer/larger CPU cores.
Chapter 8

Phylogenetic Dating

Since IQ-TREE 2.0.3, we integrate the least square dating (LSD2) method to build a
time tree when you have date information for tips or ancestral nodes. So if you use
this feature please cite:

Thu-Hien To, Matthieu Jung, Samantha Lycett, Olivier Gascuel (2016) Fast

We will now walk through examples but the full options are:

**TIME TREE RECONSTRUCTION:**

```
--date FILE  Dates of tips or ancestral nodes
--date TAXNAME ' ' Extract dates from taxon names after last
                 '|'                
--date-tip STRING Tip dates as a real number or YYYY-MM-DD
--date-root STRING Root date as a real number or YYYY-MM-DD
--date-ci NUM Number of replicates to compute confidence
                interval
--clock-sd NUM Std-dev for lognormal relaxed clock (default: 0.2)
--date-outlier NUM Z-score cutoff to exclude outlier nodes (e
           .g. 3)
--date-options ".." Extra options passing directly to LSD2
```
8.1 Inferring time tree with tip dates

This is a common scenario e.g. in virus datasets where you have sampling time for many sequences. You need first to prepare a *date file*, which comprises several lines, each with a taxon name (from your sequence alignment) and its date separated by spaces, tabs or blanks. Note that it is not required to have dates for all tips. For example, this date file is part of the new corona virus dataset:

<table>
<thead>
<tr>
<th>Taxon</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>hCoV-19/Wuhan-Hu-1</td>
<td>2019-12-31</td>
</tr>
<tr>
<td>hCoV-19/China/WF0028</td>
<td>2020-02</td>
</tr>
<tr>
<td>hCoV-19/USA/WA-S88</td>
<td>2020-03-01</td>
</tr>
<tr>
<td>hCoV-19/USA/CA-CDPH-UC1</td>
<td>2020</td>
</tr>
<tr>
<td>hCoV-19/Italy/SPL1</td>
<td>2020-01-29</td>
</tr>
<tr>
<td>hCoV-19/Spain/Valencia5</td>
<td>2020-02-27</td>
</tr>
<tr>
<td>hCoV-19/Australia/QLD01</td>
<td>2020-01-28</td>
</tr>
<tr>
<td>hCoV-19/Vietnam/CM295</td>
<td>2020-03-06</td>
</tr>
<tr>
<td>hCoV-19/bat/Yunnan</td>
<td>2013-07-24</td>
</tr>
<tr>
<td>hCoV-19/pangolin/Guangdong</td>
<td>2019-02-01:2019-12-31</td>
</tr>
</tbody>
</table>

The date information here can be uncertain. For example, hCoV-19/China/WF0028 was sampled in Feb 2020, hCoV-19/USA/CA-CDPH-UC1 was sampled in 2020, and hCoV-19/pangolin/Guangdong was sample between 1st Feb 2019 and 31st Dec 2019. For such data range you can use “NA” to mean that the lower or upper bound is missing, e.g.:

<table>
<thead>
<tr>
<th>Taxon</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>TaxonA</td>
<td>2018-02-01:NA</td>
</tr>
<tr>
<td>TaxonB</td>
<td>NA:2018-03-31</td>
</tr>
</tbody>
</table>

which means that TaxonA was sampled after 1st Feb 2018 and TaxonB was sampled before 31st Mar 2018.

Now run IQ-TREE with:

```
  iqtree -s ALN_FILE --date DATE_FILE
```

where *ALN_FILE* is the sequence alignment and *DATE_FILE* is the date file. This single command line will perform three steps: (1) find the best-fit model using ModelFinder,
8.1. INFERRING TIME TREE WITH TIP DATES

(2) find the maximum likelihood (ML) tree with branch lengths in number of substitutions per site, and (3) rescale the branch lengths of the ML tree to build a time tree with dated ancestral node. As output IQ-TREE will additional print three files:

- **ALN_FILE.timetree.lsd**: The report of LSD.
- **ALN_FILE.timetree.nex**: Time tree file in NEXUS format, that can be viewed nicely in FigTree (Click on “Node Labels” on the left tab and choose “Display” as “date” in FigTree, see figure below).
- **ALN_FILE.timetree.nwk**: Time tree file in NEWICK format.

```
Figure 8.1: Node dates in FigTree
```

This command will automatically detect the best root position (according to LSD criterion). However, if the root is incorrectly inferred, it may produce wrong dates. Therefore, it is advisable to provide outgroup taxa if possible. In this example, we have this information, so you can use `-o` option:

```
iqtree -s ALN_FILE --date DATE_FILE -o "hCoV-19/bat/Yunnan,hCoV-19/pangolin/Guangdong"
```

to instruct IQ-TREE that the root is on the branch separating bat and pangolin sequences from the rest.

Alternatively you can also append the dates into the sequence names of the alignment file using the | separator, such as (assuming a FASTA file here):

```
>hCoV-19/Wuhan-Hu-1|2019-12-31
```

........
>hCoV-19/China/WF0028|2020-02
......
>hCoV-19/USA/WA-S88|2020-03-01
......
>hCoV-19/USA/CA-CDPH-UC1|2020
......
>hCoV-19/Italy/SPL1|2020-01-29
......
>hCoV-19/Spain/Valencia5|2020-02-27
......
>hCoV-19/Australia/QLD01|2020-01-28
......
>hCoV-19/Vietnam/CM295|2020-03-06
......
>hCoV-19/bat/Yunnan|2013-07-24
......
>hCoV-19/pangolin/Guangdong|2019
......

Then run IQ-TREE:

```
iqtree -s ALN_FILE --date TAXNAME -o "hCoV-19/bat/Yunnan,hCoV-19/pangolin/Guangdong"
```

The special keyword `TAXNAME` for the `--date` option instructs IQ-TREE to automatically extract the dates from the taxon names.

### 8.2 Calibrating tree using ancestral dates

Another scenario is that we have sequences from present day and want to calibrate the dates of the ancestral nodes. This will only work if you have fossil date record of at least one ancestral node in the tree. Then you again need to prepare a date file which looks like:

```
taxon1,taxon2  -50
taxon3,taxon4,taxon5 -100
taxon6         -10
```

which, for example, mean that the most recent common ancestor (MRCA) of `taxon1` and `taxon2` was 50 mya (million year ago) and the MRCA of `taxon3`, `taxon4`, `taxon5` was 100 mya. Note that no empty space should be added to the comma-separated list of taxa, as empty space is used as a separator between taxon list and dates.
Now run IQ-TREE:

```bash
iqtree -s ALN_FILE --date DATE_FILE --date-tip 0
```

This means that except for taxon6, all other taxa have the date of 0 for presence.

If you know the root date, then you can set it via `--date-root` option.

### 8.3 Dating an existing tree

If you already have a tree, you can use option `-te TREE_FILE` to ask IQ-TREE to load and fix this tree topology:

```bash
iqtree -s ALN_FILE --date DATE_FILE -te TREE_FILE
```

This will work with the scenarios above, i.e., IQ-TREE will date the user-defined tree instead of the ML tree. To further speed up the process: If you know the model already, you set can it via `-m` option; or in a partitioned analysis, you can provide a partition file with specified models.

### 8.4 Obtaining confidence intervals

To infer the confidence interval of the estimated dates, use `--date-ci` option:

```bash
iqtree -s ALN_FILE --date DATE_FILE --date-ci 100
```

which will resample branch lengths 100 times to infer the confidence intervals. Note that this is not bootstrap and the method is much faster but unpublished. Roughly speaking, it is based on a mixture of Poisson and lognormal distributions for a relaxed clock model. You can control the standard deviation of the lognormal distribution via `--clock-sd` option. The default is 0.2. If you set a higher value, the confidence interval will become wider.

### 8.5 Excluding outlier taxa/nodes

Long branches may cause biased date estimates. To detect and exclude outlier taxa or nodes prior to dating, use `--date-outlier` option:

```bash
iqtree -s ALN_FILE --date DATE_FILE --date-outlier 3
```

that specifies a z-score threshold to detect outliers. The higher this value is, the more outliers will be removed from the resulting time tree.
8.6 Full list of LSD2 options

The main options in IQ-TREE provide easy access to the key LSD2 functions. If you would like more control of what LSD2 is doing, you can use the --date-options "..." command to pass any valid options to LSD2. For example, to control the way that LSD2 treats outliers, you can do this:

```
iqtree -s ALN_FILE --date DATE_FILE --date-options "-e 2"
```

A full list of the options for LSD2 can be obtained by downloading LSD2 and running lsd2 -h, the output of that command is reproduced here for convenience:

```
LSD: LEAST-SQUARES METHODS TO ESTIMATE RATES AND DATES - v.1.8

DESCRIPTION
This program estimates the rate and the dates of the input phylogenies given some temporal constraints.
It minimizes the square errors of the branch lengths under normal distribution model.

SYNOPSIS
./lsd [-i inputFile] [-d inputDateFile] [-o outputFile] [-s sequenceLength] [-g outgroupFile] [-f nbSamplings]

OPTIONS
-a rootDate
   To specify the root date if there's any. If the root date is not a number, but a string (ex: 2020-01-10, or b (2019,2020)) then it should be put between the quotes.
-b varianceParameter
   The parameter (between 0 and 1) to compute the variances in option -v. It is the pseudo positive constant to add to the branch lengths when calculating variances, to adjust the dependency of variances to branch lengths. By default b is the maximum between median branch length and 10/seqLength; but it should be adjusted based on how/whether the input tree is relaxed or strict. The smaller it is the more variances would be linear to branch lengths, which is relevant for strict clock. The bigger it is the less effect of branch lengths on variances, which might be better for relaxed clock.
-d inputDateFile
```
This option is used to read the name of the input date file which contains temporal constraints of internal nodes or tips. An internal node can be defined either by its label (given in the input tree) or by a subset of tips that have it as the most recent common ancestor (mrca). A date could be a real or a string or format year-month-day.

The first line of this file is the number of temporal constraints. A temporal constraint can be fixed date, or a lower bound l(value), or an upper bound u(value), or an interval b(v1, v2).

For example, if the input tree has 4 taxa a, b, c, d, and an internal node named n, then following is a possible date file:

```
6
a l(2003.12)
b u(2007.07)
c 2005
Mrca(a, b, c, d) b(2000, 2001)
n l(2004.3)
```

If this option is omitted, and option -a, -z are also omitted, the program will estimate relative dates by giving T[root]=0 and T[tips]=1.

-D outDateFormat

Specify output date format: 1 for real, 2 for year-month-day. By default the program will guess the format of input dates and uses it for output dates.

-e ZscoreOutlier

This option is used to estimate and exclude outlier nodes before dating process.

LSD2 normalize the branch residus and decide a node is outlier if its related residus is great than the ZscoreOutlier.

A normal value of ZscoreOutliercould be 3, but you can adjust it bigger/smaller depending if you want to have less/more outliers. Note that for now, some functionalities could not be combined with outliers estimation, for example estimating multiple rates, imprecise date constraints.
This option calculates the confidence intervals of the estimated rate and dates. The branch lengths of the estimated tree are sampled samplingNumberCI times to generate a set of simulated trees. To generate simulated lengths for each branch, we use a Poisson distribution whose mean equals to the estimated one multiplied by the sequence length, which is 1000 by default if nothing was specified via option -s. Long sequence length tends to give small confidence intervals. To avoid over-estimate the confidence intervals in the case of very long sequence length but not necessarily strict molecular clock, you could use a smaller sequence length than the actual ones. Confidence intervals are written in the nexus tree with label CI_height, and can be visualized with Figtree under Node bar feature.

If your data contain outgroups, then specify the name of the outgroup file here. The program will use the outgroups to root the trees. If you use this combined with options -G, then the outgroups will be removed. The format of this file should be:

n
OUTGROUP1
OUTGROUP2
...
OUTGROUPn

By default without this option, we impose the constraints that the date of every node is equal or smaller then the dates of its descendants, so the running time is quasi-linear. Using this option we ignore this temporal constraints, and the running time becomes linear, much faster.

Print this message.

The name of the input trees file. It contains tree(s) in
newick format, each tree on one line. Note that the
taxa sets of all
trees must be the same.

-j
Verbose mode for output messages.

-G
Use this option to remove the outgroups (given in option -g) in the estimated tree. If this option is not used, the outgroups will be kept and the root position in estimated on the branch defined by the outgroups.

-l nullBlen
A branch in the input tree is considered informative if its length is greater this value. By default it is 0.5/seq_length. Only informative branches are forced to be bigger than a minimum branch length (see option -u for more information about this).

-m samplingNumberOutlier
The number of dated nodes to be sampled when detecting outlier nodes. This should be smaller than the number of dated nodes, and is 10 by default.

-n datasetNumber
The number of trees that you want to read and analyse.

-o outputFile
The base name of the output files to write the results and the time-scale trees.

-p partitionFile
The file that defines the partition of branches into multiple subsets in the case that you know each subset has a different rate.
In the partition file, each line contains the name of the group, the prior proportion of the group rate compared to the main rate (selecting an appropriate value for this helps to converge faster), and a list of subtrees whose branches are supposed to have the same substitution rate. All branches that are not assigned to any subtree form a group having another rate. A subtree is defined between {}: its first node corresponds to the root of the subtree, and the following nodes (if there any)
correspond to the tips of the subtree. If the first node is a tip label then it takes the mrca of all tips as the root of the subtree.

If the tips of the subtree are not defined (so there's only the defined root), then by default this subtree is extended down to the tips of the full tree. For example the input tree is

\(((A:0.12,D:0.12)n1:0.3,((B:0.3,C:0.5)n2:0.4,(E:0.5,(F:0.2,G:0.3)n3:0.33)n4:0.22)n5:0.2)root;\)

and you have the following partition file:

```
group1 1 {n1} {n5 n4}
group2 1 {n3}
```

then there are 3 rates: the first one includes the branches (n1,A), (n1,D), (n5,n4), (n5,n2), (n2,B), (n2,C); the second one includes the branches (n3,F), (n3,G), and the last one includes all the remaining branches. If the internal nodes don't have labels, then they can be defined by mrca of at least two tips, for example n1 is mrca(A,D)

-q standardDeviationRelaxedClock

This value is involved in calculating confidence intervals to simulate a lognormal relaxed clock. We multiply the simulated branch lengths with a lognormal distribution with mean 1, and standard deviation q. By default q is 0.2. The bigger q is, the more your tree is relaxed and give you bigger confidence intervals.

-r rootingMethod

This option is used to specify the rooting method to estimate the position of the root for unrooted trees, or re-estimate the root for rooted trees. The principle is to search for the position of the root that minimizes the objective function.

Use -r l if your tree is rooted, and you want to re-estimate the root locally around the given root.

Use -r a if you want to estimate the root on all branches (ignoring the given root if the tree is rooted).

In this case, if the constrained mode is chosen (option -c), method "a" first estimates the root without using the constraints.

After that, it uses the constrained mode to improve
locally the position of the root around this pre-
estimated root.

Use \(-r\) as if you want to estimate to root using
constrained mode on all branches.

Use \(-r\ k\) if you want to re-estimate the root position on
the same branch of the given root.

If combined with option \(-g\), the root will be estimated
on the branch defined by the outgroups.

\textbf{-R round\_time}

This value is used to round the minimum branch length of
the time scaled tree. The purpose of this is to make
the minimum branch length
a meaningful time unit, such as day, week, year ... By
default this value is 365, so if the input dates are
year, the minimum branch
length is rounded to day. The rounding formula is \(\text{round}(R\times
\text{minblen})/R\).

\textbf{-s sequenceLength}

This option is used to specify the sequence length when
estimating confidence intervals (option \(-f\)). It is used
to generate
integer branch lengths (number of substitutions) by
multiplying this with the estimated branch lengths. By
default it is 1000.

\textbf{-S minSupport}

Together with collapsing internal short branches (see
option \(-l\)), users can also collapse internal branches
having weak support values (if
provided in the input tree) by using this option. The
program will collapse all internal branches having
support \(<=\) the specified value.

\textbf{-t rateLowerBound}

This option corresponds to the lower bound for the
estimating rate. It is \(1e^{-10}\) by default.

\textbf{-u minBlen}

By default without this option, lsd2 forces every branch
of the time scaled tree to be greater than \(1/(\\text{seq\_length}\times\text{rate})\) where rate is
an pre-estimated median rate. This value is rounded to the
number of days or weeks or years, depending on the
rounding parameter \(-R\).

By using option \(-u\), the program will not estimate the
minimum branch length but use the specified value
-U minExBlen
   Similar to option -u but applies for external branches if specified. If it's not specified then the minimum branch length of external branches is set the same as the one of internal branch.

-v variance
   Use this option to specify the way you want to apply variances for the branch lengths. Variances are used to recompense big errors on long estimated branch lengths. The variance of the branch Bi is Vi = (Bi+b) where b is specified by option -b.
   If variance=0, then we don't use variance. If variance=1, then LSD uses the input branch lengths to calculate variances.
   If variance=2, then LSD runs twice where the second time it calculates the variances based on the estimated branch lengths of the first run. By default variance=1.

-V
   Get the actual version.

-w givenRte
   This option is used to specify the name of the file containing the substitution rates. In this case, the program will use the given rates to estimate the dates of the nodes.
   This file should have the following format
   RATE1
   RATE2
   ...
   where RATEi is the rate of the tree i in the inputTreesFile.

-z tipsDate
   To specify the tips date if they are all equal. If the tips date is not a number, but a string (ex: 2020-01-10, or b(2019,2020)) then it should be put between the quotes.
Chapter 9

Rooting phylogenetic trees

Using time-reversible Markov models is a very common practice in phylogenetic analysis, because they provide high computational efficiency. However, these models infer unrooted trees hence lack the ability to infer the root placement of the estimated phylogeny. In order to compensate for the inability of these models to root the tree, many researchers use external information such as using outgroup taxa or additional assumptions such as molecular-clocks.

This guide provides the outgroup approach and another rooting approach using non-reversible models (Naser-Khdour et al., 2021), which will be useful when an outgroup is lacking. Please make sure that you use IQ-TREE version 2.1.3 or later for full features below and cite this manuscript:


9.1 Inferring unrooted tree with outgroup

We first demonstrate the outgroup approach to root the Bovidae family of five sampled species (Yak, Cow, Goat, Sheep and Tibetan antelope) using two outgroup species (Pig and Whale). Please download:

- An input DNA alignment file for these 7 species.
- An input partition file that defines 52 genes in this alignment. This is a subset of the mammal dataset (Wu et al., 2018).
Choosing a “good” outgroup is an entire topic on its own. In generally, the outgroup must contain taxa that do not belong to the ingroup but are evolutionarily close enough to the ingroup taxa.

To infer an unrooted tree, run:

```bash
docker run --rm -it -v $(pwd):/mnt/ --entrypoint iqtree2 ./docker/iqtree2 --prefix rev_dna_outg -s bovidae_outgroup.phy -p bovidae.nex -B 1000 -T AUTO -st NT2AA
```

that will invoke the ultrafast bootstrap with 1000 replicates (-B 1000), detect the optimal number of threads (-T AUTO) and write all output files with the prefix `rev_dna_outg`.

The input alignment contains protein-coding genes. We can ask IQ-TREE to translate the alignment into protein sequences using the standard genetic code (-st NT2AA) and perform an amino-acid analysis on the translated alignment with:

```bash
docker run --rm -it -v $(pwd):/mnt/ --entrypoint iqtree2 ./docker/iqtree2 --prefix rev_aa_outg -s bovidae_outgroup.phy -p bovidae.nex -B 1000 -T AUTO -st NT2AA
```

where setting the prefix to `rev_aa_outg` avoids file overwriting with the previous run. The resulting tree may now look like (extracted from `rev_aa_outg.iqtree`):

```
+--Yak
 |  +--Cow
 |     |  +--Goat
 |     |      +--Sheep
 |     +--Tibetan_antelope
 +--Sheep +--(100)
     +--Minke_whale
```

NOTE: Tree is UNROOTED although outgroup taxon 'Yak' is drawn at root
Numbers in parentheses are ultrafast bootstrap support (%)
9.2. INFERRING ROOTED TREES WITHOUT OUTGROUP

You can open `rev_aa_outg.treefile` in a tree viewer software (e.g. FigTree) and re-root the tree on the branch separating the outgroup (Wild_pig and Minke_whale) from the remaining ingroup to obtain an outgroup-rooted tree.

Finally, if you want you can also perform a non-partition analysis by removing the option `-p`.

9.2 Inferring rooted trees without outgroup

We will now infer a rooted tree using non-reversible models. Please download:

- An input DNA alignment file for 5 ingroup species (Yak, Cow, Goat, Sheep and Tibetan antelope). This is a sub-alignment of the alignment above. We can re-use the same partition file.

To speed up the analysis, we will perform two steps. The first step is the same as the run above to infer an unrooted tree using reversible models:

```
iqtree2 -s bovidae.phy -p bovidae.nex -B 1000 -T AUTO --prefix rev_dna
```

This run will also write the best partitioning scheme to `rev_dna.best_scheme.nex` file. In the second step, we will re-use this best scheme but replace the substitution model with the most general non-reversible DNA model, 12.12 or UNREST (see this doc) to obtain a rooted tree:

```
iqtree2 -s bovidae.phy -p rev_dna.best_scheme.nex --model-joint 12.12 -B 1000 -T AUTO --prefix nonrev_dna
```

The option `--model-joint 12.12` tells IQ-TREE use a linked substitution model 12.12 across all partitions. This is to avoid potential over-parameterization as this is very parameter-rich model with 12 parameters.

The resulting tree extracted from .iqtree file might look like this:

```
NOTE: Tree is ROOTED at virtual root '__root__'
Numbers in parentheses are ultrafast bootstrap support (%)

+----|---Yak
 |   ---|---Goat
 |     |   +----|---Sheep
 |     |       |    | (100)
 |     +------------------Sheep
 |                         | (95)
```

```
```

```
```
CHAPTER 9. ROOTING PHYLOGENETIC TREES

---

(You can better visualize the .treefile in a tree viewer software).

This run will write an additional tree file `nonrev_dna.rootstrap.nex` with \textit{rootstrap} support values (see box below for definition) annotated on every branch of the tree. If you open this file in FigTree it may look like this (click on “Branch Labels” and choose \textit{rootstrap} for “Display” as shown in the figure):

![FigTree screenshot](image)

**Figure 9.1:** Rooted tree with rootstrap supports for DNA

It shows that the tree might be rooted in the branch leading to \textit{Cow} with a rootstrap support of 72\%, which is rather low. The 2nd best branch separating \textit{Cow} and \textit{Yak} from the rest has a rootstrap support of 17.9\%. So with this dataset the DNA model cannot reliably tell where the root position is, but at least provides some candidates.
9.2. INFERRING ROOTED TREES WITHOUT OUTGROUP

**Rootstrap**: To compute rootstrap supports, we conduct a bootstrap analysis to obtain a number of rooted bootstrap trees using non-reversible models. We define the rootstrap support for each branch in the maximum likelihood (ML) tree, as the proportion of rooted bootstrap trees that have the root on that branch. The rootstrap support values are computed for all the branches including external branches. The sum of the rootstrap support values along the tree are always smaller than or equal to one. A sum that is smaller than one can occur when one or more bootstrap replicates are rooted on a branch that does not occur in the ML tree.

We will now try the amino-acid model to see if that helps. We again use `-st NT2AA` option to conveniently perform this analysis:

```bash
# step 1: infer unrooted tree with reversible models
iqtree2 -s bovidae.phy -p bovidae.nex -B 1000 -T AUTO -st NT2AA --prefix rev_aa

# step 2: infer rooted tree with linked non-reversible models
iqtree2 -s bovidae.phy -p rev_aa.best_scheme.nex --model-joint NONREV -B 1000 -T AUTO -st NT2AA --prefix nonrev_aa
```

The option `--model-joint NONREV` tells IQ-TREE to use the most general amino-acid model NONREV and to link the NONREV model parameters across all partitions: NONREV has 379 parameters and linking them across partitions will avoid over-parameterization. The tree extracted from `nonrev_aa.iqtree` file now may look like:

```
NOTE: Tree is ROOTED at virtual root '__root__'
Numbers in parentheses are ultrafast bootstrap support (%)

            +------------Yak
            |           | (100)
            |           +------------Cow
            |             | (100)
            |             +------------Goat
            |                   | (100)
            +---------------------Sheep
            |                                                 +------------Tibetan_antelope
            |                                                 | (100)
            |                                                 +------------
            |                                                 ***__root__
```
Interestingly, the amino-acid model suggests a different root position compared with the DNA model. But this position agrees with the outgroup rooting approach. And the tree `nonrev_aa.rootstrap.nex` with rootstrap supports look like:

![FigTree](image)

**Figure 9.2:** Rooted tree with rootstrap supports using amino-acid nonreversible model

That means, the branch separating Yak and Cow from the rest receives a very high rootstrap support of 99.9%. Therefore, the amino-acid model seems to have a much higher power to detect the root, compared with the DNA model.

### 9.3 Testing root positions

The rootstrap introduced above is one way to measure our confidence in the root placement, but it is not a statistical test. Alternatively, we can apply the **tree topology tests** to compare the log-likelihoods of the trees being rooted on every branch of the ML tree. IQ-TREE v2.1.3 provides a convenient option `--root-test` that will re-root the tree on every branch and perform the test for you. So you can run:

```
iqtree2 -s bovidae.phy -p rev_aa.best_scheme.nex --model-joint NONREV -st NT2AA --root-test -zb 1000 -au -te nonrev_aa.treefile --prefix nonrev_aa_test
```
9.3. TESTING ROOT POSITIONS

-zb 1000 -au is to perform several tree topology tests including the approximately-unbiased (AU) test for the tree found above (-te nonrev_aa.treefile). This run will write a file nonrev_aa_test.roottest.csv which might look like:

<table>
<thead>
<tr>
<th>ID, logL, deltaL, bp-RELL, p-KH, p-SH, c-ELW, p-AU</th>
</tr>
</thead>
<tbody>
<tr>
<td>1, -90388.66044, 0.983, 0.96, 1.0, 0.975595105</td>
</tr>
<tr>
<td>8, -90401.6833, 13.02286164, 0.005, 0.01, 0.01262108065, 0.00558089101</td>
</tr>
<tr>
<td>5, -90401.68371, 13.0232665, 0.01, 0.019, 0.01262245766, 0.006374445939</td>
</tr>
<tr>
<td>3, -90410.10499, 21.44455589, 0.002, 0.016, 0.104, 0.002397842346, 0.001014359781</td>
</tr>
<tr>
<td>2, -90410.1084, 21.44796542, 0.016, 0.104, 0.002389013519, 0.0008999725939</td>
</tr>
<tr>
<td>6, -90413.04441, 24.38397245, 0.005, 0.059, 0.002047272296, 0.0004975092439</td>
</tr>
<tr>
<td>7, -90413.04797, 24.38753181, 0.005, 0.059, 0.002046654974, 0.0005061888325</td>
</tr>
</tbody>
</table>

The branches are sorted by log-likelihoods in descending order. The last column (p-AU) shows the p-values of the AU test. The branch ID 1 has an AU p-value of 0.9975595105, whereas all other branches has p-values < 0.01. To associate branch ID you can return to the FigTree window for nonrev_aa.rootstrap.nex file and select “Display” to “id” in the “Branch Labels” tab.

The conclusion from this analysis: we can reject all rooting positions on branches other than branch ID 1, which agrees with the rootstrap measure.

TIP: These options --root-test -zb 1000 -au can be combined with the rootstrap
run in the previous section to calculate the rootstrap support values and the rooting test p-values in one single analysis.
Chapter 10

Command reference

Comprehensive documentation of command-line options.

IQ-TREE is invoked from the command-line with e.g.:

```
iqtree -s <alignment> [OPTIONS]
```

assuming that IQ-TREE can be run by simply entering `iqtree`. If not, please change `iqtree` to the actual path of the executable or read the Quick start guide.

10.1 General options

General options are mainly intended for specifying input and output files:

<table>
<thead>
<tr>
<th>Option</th>
<th>Usage and meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>-h or -?</td>
<td>Print help usage.</td>
</tr>
<tr>
<td>-s</td>
<td>Specify input alignment file in PHYLIP, FASTA, NEXUS, CLUSTAL or MSF format.</td>
</tr>
</tbody>
</table>
CHAPTER 10. COMMAND REFERENCE

<table>
<thead>
<tr>
<th>Option</th>
<th>Usage and meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>-st</code></td>
<td>Specify sequence type as either of DNA, AA, BIN, MORPH, CODON or NT2AA for DNA, amino-acid, binary, morphological, codon or DNA-to-AA-translated sequences. This is only necessary if IQ-TREE did not detect the sequence type correctly. Note that <code>-st CODON</code> is always necessary when using codon models (otherwise, IQ-TREE applies DNA models) and you also need to specify a genetic code like this if differed from the standard genetic code. <code>-st NT2AA</code> tells IQ-TREE to translate protein-coding DNA into AA sequences and then subsequent analysis will work on the AA sequences. You can also use a genetic code like <code>-st NT2AA5</code> for the Invertebrate Mitochondrial Code (see genetic code table).</td>
</tr>
<tr>
<td><code>-t</code></td>
<td>Specify a file containing starting tree for tree search. The special option <code>-t BIONJ</code> starts tree search from BIONJ tree and <code>-t RANDOM</code> starts tree search from completely random tree. DEFAULT: 100 parsimony trees + BIONJ tree</td>
</tr>
<tr>
<td><code>-te</code></td>
<td>Like <code>-t</code> but fixing user tree. That means, no tree search is performed and IQ-TREE computes the log-likelihood of the fixed user tree.</td>
</tr>
<tr>
<td><code>-o</code></td>
<td>Specify an outgroup taxon name to root the tree. The output tree in <code>.treefile</code> will be rooted accordingly. DEFAULT: first taxon in alignment</td>
</tr>
<tr>
<td><code>-pre</code></td>
<td>Specify a prefix for all output files. DEFAULT: either alignment file name (<code>-s</code>) or partition file name (<code>-q</code>, <code>-spp</code> or <code>-sp</code>)</td>
</tr>
<tr>
<td><code>-nt</code></td>
<td>Specify the number of CPU cores for the multicore version. A special option <code>-nt AUTO</code> will tell IQ-TREE to automatically determine the best number of cores given the current data and computer.</td>
</tr>
<tr>
<td><code>-ntmax</code></td>
<td>Specify the maximal number of CPU cores <code>-nt AUTO</code> is allowed to allocate DEFAULT: #CPU cores on the current machine</td>
</tr>
<tr>
<td><code>-seed</code></td>
<td>Specify a random number seed to reproduce a previous run. This is normally used for debugging purposes. DEFAULT: based on current machine clock</td>
</tr>
<tr>
<td><code>-v</code></td>
<td>Turn on verbose mode for printing more messages to screen. This is normally used for debugging purposes. DEFAULT: OFF</td>
</tr>
<tr>
<td><code>-quiet</code></td>
<td>Silent mode, suppress printing to the screen. Note that <code>.log</code> file is still written.</td>
</tr>
<tr>
<td><code>-keep-ident</code></td>
<td>Keep identical sequences in the alignment. By default: IQ-TREE will remove them during the analysis and add them in the end.</td>
</tr>
</tbody>
</table>
10.2. CHECKPOINTING TO RESUME STOPPED RUN

<table>
<thead>
<tr>
<th>Option</th>
<th>Usage and meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>-safe</code></td>
<td>Turn on safe numerical mode to avoid numerical underflow for large data sets with many sequences (typically in the order of thousands). This mode is automatically turned on when having more than 2000 sequences.</td>
</tr>
<tr>
<td><code>-mem</code></td>
<td>Specify maximal RAM usage, for example, <code>-mem 64G</code> to use at most 64 GB of RAM. By default, IQ-TREE will try to not to exceed the computer RAM size.</td>
</tr>
</tbody>
</table>

10.1.1 Example usages:

- Reconstruct a maximum-likelihood tree given a sequence alignment file `example.phy`:

  ```
  iqtree -s example.phy
  ```

- Reconstruct a maximum-likelihood tree using at most 8 GB RAM and automatically detect the number of cores to use:

  ```
  # For version <= 1.5.X
  iqtree-omp -s example.phy -nt AUTO -mem 8G
  # For version >= 1.6.0, change iqtree-omp to just iqtree
  iqtree -s example.phy -nt AUTO -mem 8G
  ```

- Like above but write all output to `myrun.*` files:

  ```
  # For version <= 1.5.X
  iqtree-omp -s example.phy -nt AUTO -mem 8G -pre myrun
  # For version <= 1.6.0
  iqtree -s example.phy -nt AUTO -mem 8G -pre myrun
  ```

10.2 Checkpointing to resume stopped run

Starting with version 1.4.0 IQ-TREE supports checkpointing: If an IQ-TREE run was interrupted for some reason, rerunning it with the same command line and input data will automatically resume the analysis from the last stopped point. The previous log file will then be appended. If a run successfully finished, IQ-TREE will deny to rerun and issue an error message. A few options that control checkpointing behavior:
86  

CHAPTER 10. COMMAND REFERENCE

<table>
<thead>
<tr>
<th>Option</th>
<th>Usage and meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>-redo</td>
<td>Redo the entire analysis no matter if it was stopped or successful.</td>
</tr>
<tr>
<td></td>
<td>WARNING: This option will overwrite all existing output files.</td>
</tr>
<tr>
<td>-cptime</td>
<td>Specify the minimum checkpoint time interval in seconds (default: 20s)</td>
</tr>
</tbody>
</table>

**NOTE:** IQ-TREE writes a checkpoint file with name suffix `.ckp.gz` in gzip format. Do not modify this file. If you delete this file, all checkpointing information will be lost!

10.3 Likelihood mapping analysis

Starting with version 1.4.0, IQ-TREE implements the likelihood mapping approach (Strimmer and von Haeseler, 1997) to assess the phylogenetic information of an input alignment. The detailed results will be printed to `.iqtree` report file. The likelihood mapping plots will be printed to `.lmap.svg` and `.lmap.eps` files.

Compared with the original implementation in TREE-PUZZLE, IQ-TREE is much faster and supports many more substitution models (including partition and mixture models).

<table>
<thead>
<tr>
<th>Option</th>
<th>Usage and meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>-lmap</td>
<td>Specify the number of quartets to be randomly drawn. If you specify -lmap ALL, all</td>
</tr>
<tr>
<td></td>
<td>unique quartets will be drawn, instead.</td>
</tr>
<tr>
<td>-lmclust</td>
<td>Specify a NEXUS file containing taxon clusters (see below for example) for quartet</td>
</tr>
<tr>
<td></td>
<td>mapping analysis.</td>
</tr>
<tr>
<td>-n 0</td>
<td>Skip subsequent tree search, useful when you only want to assess the phylogenetic</td>
</tr>
<tr>
<td></td>
<td>information of the alignment.</td>
</tr>
<tr>
<td>-wql</td>
<td>Write quartet log-likelihoods into <code>.lmap.quartetlh</code> file (typically not needed).</td>
</tr>
</tbody>
</table>

**TIP:** The number of quartets specified via -lmap is recommended to be at least 25 times the number of sequences in the alignment, such that each sequence is covered ~100 times in the set of quartets drawn.

An example NEXUS cluster file (where A, B, C, etc. are sequence names):
# NEXUS

begin sets;
    taxset Cluster1 = A B C;
    taxset Cluster2 = D E;
    taxset Cluster3 = F G H I;
    taxset Cluster4 = J;
    taxset IGNORED = X;
end;

Here, Cluster1 to Cluster4 are four user-defined clusters of sequences. Note that users can give any names to the clusters instead of Cluster1, etc. If a cluster is named ignored or IGNORED the sequences included will be ignored in the likelihood mapping analysis.

If you provide a cluster file it has to contain between 1 and 4 clusters (plus an optional IGNORED or ignored cluster), which will tell IQ-TREE to perform an unclustered (default without a cluster file) or a clustered analysis with 2, 3 or 4 groups, respectively.

The names given to the clusters in the cluster file will be used to label the corners of the triangle diagrams.

### 10.3.1 Example usages:

- Perform solely likelihood mapping analysis (ignoring tree search) with 2000 quartets for an alignment example.phy with model being automatically selected:

  ```
  iqtree -s example.phy -lmap 2000 -n 0 -m TEST
  ```

You can now view the likelihood mapping plot file example.phy.lmap.svg, which looks like this:

It shows phylogenetic information of the alignment example.phy. On the top: distribution of quartets depicted by dots on the likelihood mapping plot. On the left: the three areas show support for one of the different groupings like (a,b)-(c,d). On the right: quartets falling into the three corners are informative. Those in three rectangles are partly informative and those in the center are uninformative. A good data set should have high number of informative quartets and low number of uninformative quartets. The meanings can also be found in the LIKELIHOOD MAPPING STATISTICS section of the report file example.phy.iqtree:

| LIKELIHOOD MAPPING STATISTICS | ----------------------------- |
Figure 10.1: Likelihood mapping plot.
10.4 Automatic model selection

The default model (e.g., HKY+F for DNA, LG for protein data) may not fit well to the data. Therefore, IQ-TREE allows to automatically determine the best-fit model via a series of `-m TEST...` option:

<table>
<thead>
<tr>
<th>Option</th>
<th>Usage and meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>-m TESTONLY</code></td>
<td>Perform standard model selection like jModelTest (for DNA) and ProtTest (for protein). Moreover, IQ-TREE also works for codon, binary and morphological data. If a partition file is specified, IQ-TREE will find the best-fit model for each partition.</td>
</tr>
</tbody>
</table>

Division of the likelihood mapping plots into 3 or 7 areas. On the left the areas show support for one of the different groupings like (a,b|c,d). On the right the right quartets falling into the areas 1, 2 and 3 are informative. Those in the rectangles 4, 5 and 6 are partly informative and those in the center (7) are not informative.

.....
CHAPTER 10. COMMAND REFERENCE

Option Usage and meaning

- \texttt{m TEST} Like \texttt{-m TESTONLY} but immediately followed by tree reconstruction using the best-fit model found. So this performs both model selection and tree inference within a single run.

- \texttt{m TESTNEWONLY} or \texttt{m MF} Perform an extended model selection that additionally includes FreeRate model compared with \texttt{-m TESTONLY}. \textit{Recommended as replacement for \texttt{-m TESTONLY}.} Note that LG4X is a FreeRate model, but by default is not included because it is also a protein mixture model. To include it, use \texttt{-madd} option (see table below).

- \texttt{m TESTNEW or MFP} Like \texttt{-m MF} but immediately followed by tree reconstruction using the best-fit model found.

---

\textbf{TIP}: During model section, IQ-TREE will write a model checkpoint file (suffix .\texttt{model} in version <= 1.5.X or .\texttt{model.gz} in version >= 1.6.X) that stores information of all models tested so far. Thus, if IQ-TREE is interrupted for whatever reason, restarting the run will load this file to reuse the computation.

IQ-TREE version 1.6 or later allows to additionally test \textbf{Lie Markov DNA models} by adding the following keyword to \texttt{-m} option:

<table>
<thead>
<tr>
<th>Option</th>
<th>Usage and meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>\texttt{+LM}</td>
<td>Additionally consider all Lie Markov models</td>
</tr>
<tr>
<td>\texttt{+LMRY}</td>
<td>Additionally consider all Lie Markov models with RY symmetry</td>
</tr>
<tr>
<td>\texttt{+LMWS}</td>
<td>Additionally consider all Lie Markov models with WS symmetry</td>
</tr>
<tr>
<td>\texttt{+LMMK}</td>
<td>Additionally consider all Lie Markov models with MK symmetry</td>
</tr>
<tr>
<td>\texttt{+LMSS}</td>
<td>Additionally consider all strand-symmetric Lie Markov models</td>
</tr>
</tbody>
</table>

When a partition file is specified then you can append \texttt{MERGE} keyword into \texttt{-m} option to find the best-fit partitioning scheme like PartitionFinder (Lanfear et al., 2012). More specifically,

<table>
<thead>
<tr>
<th>Option</th>
<th>Usage and meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>\texttt{-m TESTMERGEONLY}</td>
<td>Select best-fit partitioning scheme by possibly merging partitions to reduce over-parameterization and increase model fit. It implements the greedy algorithm of PartitionFinder.</td>
</tr>
</tbody>
</table>
10.4. **AUTOMATIC MODEL SELECTION**

<table>
<thead>
<tr>
<th>Option</th>
<th>Usage and meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>-m TESTMERGE</td>
<td>Like <code>-m TESTMERGEONLY</code> but immediately followed by tree reconstruction using the best partitioning scheme found.</td>
</tr>
<tr>
<td>-m TESTNEWMERGEONLY</td>
<td>Like <code>-m TESTMERGEONLY</code> but additionally includes FreeRate model.</td>
</tr>
<tr>
<td>or <code>-m MF+MERGE</code></td>
<td></td>
</tr>
<tr>
<td>-m TESTNEWMERGE</td>
<td>Like <code>-m MF+MERGE</code> but immediately followed by tree reconstruction using the best partitioning scheme found.</td>
</tr>
<tr>
<td>or <code>-m MFP+MERGE</code></td>
<td></td>
</tr>
<tr>
<td>-rcluster</td>
<td>Specify the percentage for the relaxed clustering algorithm (<a href="#">Lanfear et al., 2014</a>) to speed up the computation instead of the default slow greedy algorithm. This is similar to <code>--rcluster-percent</code> option of PartitionFinder. For example, with <code>-rcluster 10</code> only the top 10% partition schemes are considered to save computations.</td>
</tr>
<tr>
<td>-rclusterf</td>
<td>Similar to <code>-rcluster</code> but using the fast relaxed clustering algorithm (<a href="#">Lanfear et al., 2017</a>) of PartitionFinder2. Introduced in version 1.6.</td>
</tr>
<tr>
<td>-rcluster-max</td>
<td>Specify the absolute maximum number of partition pairs in the partition merging phase. Default: the larger of 1000 and 10 times the number of partitions. This option is similar to <code>--rcluster-max</code> option of PartitionFinder2.</td>
</tr>
</tbody>
</table>

**WARNING:** For versions <= 1.5.X, all commands with `-m ...MERGE...` will always perform an edge-unlinked partition scheme finding even if `-spp` option is used. Only in the next phase of tree reconstruction, then an edge-linked partition model is used. However, for versions 1.6.X onwards, the edge-linked partition finding is performed by `-spp` option.

Several parameters can be set to e.g. reduce computations:

<table>
<thead>
<tr>
<th>Option</th>
<th>Usage and meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>-mset</td>
<td>Specify the name of a program (<code>raxml</code>, <code>phyml</code> or <code>mrbayes</code>) to restrict to only those models supported by the specified program. Alternatively, one can specify a comma-separated list of base models. For example, <code>-mset WAG,LG,JTT</code> will restrict model selection to WAG, LG, and JTT instead of all 18 AA models to save computations.</td>
</tr>
<tr>
<td>-msub</td>
<td>Specify either <code>nuclear</code>, <code>mitochondrial</code>, <code>chloroplast</code> or <code>viral</code> to restrict to those AA models designed for specified source.</td>
</tr>
</tbody>
</table>
CHAPTER 10. COMMAND REFERENCE

<table>
<thead>
<tr>
<th>Option</th>
<th>Usage and meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>-mfreq</td>
<td>Specify a comma-separated list of frequency types for model selection. DEFAULT: -mfreq FU,F for protein models (FU = AA frequencies given by the protein matrix, F = empirical AA frequencies from the data), -mfreq ,F1x4,F3x4,F for codon models</td>
</tr>
<tr>
<td>-cmin</td>
<td>Specify minimum number of categories for FreeRate model. DEFAULT: 2</td>
</tr>
<tr>
<td>-cmax</td>
<td>Specify maximum number of categories for FreeRate model. It is recommended to increase if alignment is long enough. DEFAULT: 10</td>
</tr>
<tr>
<td>-merit</td>
<td>Specify either AIC, AICc or BIC for the optimality criterion to apply for new procedure. DEFAULT: all three criteria are considered</td>
</tr>
<tr>
<td>-mtree</td>
<td>Turn on full tree search for each model considered, to obtain more accurate result. Only recommended if enough computational resources are available. DEFAULT: fixed starting tree</td>
</tr>
<tr>
<td>-mredo</td>
<td>Ignore model checkpoint file computed earlier. DEFAULT: model checkpoint file (if exists) is loaded to reuse previous computations</td>
</tr>
<tr>
<td>-madd</td>
<td>Specify a comma-separated list of mixture models to additionally consider for model selection. For example, -madd LG4M,LG4X to additionally include these two protein mixture models.</td>
</tr>
<tr>
<td>-mdef</td>
<td>Specify a NEXUS model file to define new models.</td>
</tr>
</tbody>
</table>

NOTE: Some of the above options require a comma-separated list, which should not contain any empty space!

10.4.1 Example usages:

- Select best-fit model for alignment data.phy based on Bayesian information criterion (BIC):
  ```
iqtree -s data.phy -m TESTONLY
  ```

- Select best-fit model for a protein alignment prot.phy using the new testing procedure and only consider WAG, LG and JTT matrix to save time:
  ```
iqtree -s prot.phy -m MF -mset WAG, LG, JTT
  ```
10.5 SPECIFYING SUBSTITUTION MODELS

- m is a powerful option to specify substitution models, state frequency and rate heterogeneity type. The general syntax is:

- m MODEL+FreqType+RateType

where MODEL is a model name, +FreqType (optional) is the frequency type and +RateType (optional) is the rate heterogeneity type.

The following MODELS are available:

<table>
<thead>
<tr>
<th>DataType</th>
<th>Model names</th>
</tr>
</thead>
<tbody>
<tr>
<td>DNA</td>
<td>JC/JC69, F81, K2P/K80, HKY/HKY85, TN/TrN/TN93, TNe, K3P/K81, K81u, TPM2, TPM2u, TPM3, TPM3u, TIM, TIMe, TIM2, TIM2e, TIM3, TIM3e, TVM, TVMe, SYM, GTR and 6-digit specification. See DNA models for more details.</td>
</tr>
<tr>
<td>Protein</td>
<td>BLOSUM62, cpREV, Dayhoff, DCMut, FLU, HIVb, HIVw, JTT, JTTDCMut, LG, mtART, mtMAM, mtREV, mtZOA, mtMet, mtVer, mtInv, Poisson, PMB, rtREV, VT, WAG.</td>
</tr>
<tr>
<td>Protein</td>
<td>Mixture models: C10, ... , C60 (CAT model) (Lartillot and Philippe, 2004), EX2, EX3, EHO, UL2, UL3, EX_EHO, LG4M, LG4X, CF4. See Protein models for more details.</td>
</tr>
<tr>
<td>Codon</td>
<td>MG, MGK, MG1KTS, MG1KTV, MG2K, GY, GY1KTS, GY1KTV, GY2K, ECMK07/KOSI07, ECMrest, ECMS05/SCHN05 and combined empirical-mechanistic models. See Codon models for more details.</td>
</tr>
<tr>
<td>Binary</td>
<td>JC2, GTR2. See Binary and morphological models for more details.</td>
</tr>
<tr>
<td>Morphology</td>
<td>MK, ORDERED. See Binary and morphological models for more details.</td>
</tr>
</tbody>
</table>

The following FreqTypes are supported:
<table>
<thead>
<tr>
<th>FreqType</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>+F</td>
<td>Empirical state frequency observed from the data.</td>
</tr>
<tr>
<td>+FO</td>
<td>State frequency optimized by maximum-likelihood from the data. Note that this is with letter-O and not digit-0.</td>
</tr>
<tr>
<td>+FQ</td>
<td>Equal state frequency.</td>
</tr>
<tr>
<td>+F1x4</td>
<td>See Codon frequencies.</td>
</tr>
<tr>
<td>+F3x4</td>
<td>See Codon frequencies.</td>
</tr>
</tbody>
</table>

Further options:

<table>
<thead>
<tr>
<th>Option</th>
<th>Usage and meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>-mwopt</td>
<td>Turn on optimizing weights of mixture models. Note that for models like LG+C20+F+G this mode is automatically turned on, but not for LG+C20+G.</td>
</tr>
</tbody>
</table>

### 10.5.1 Example usages:

- Infer an ML tree for a DNA alignment dna.phy under GTR+I+G model:
  
  ```
  iqtree -s dna.phy -m GTR+I+G
  ```

- Infer an ML tree for a protein alignment prot.phy under LG+F+G model:
  
  ```
  iqtree -s prot.phy -m LG+F+G
  ```

- Infer an ML tree for a protein alignment prot.phy under profile mixture model LG+C10+F+G:
  
  ```
  iqtree -s prot.phy -m LG+C10+F+G
  ```

### 10.6 Rate heterogeneity

The following RateTypes are supported:

<table>
<thead>
<tr>
<th>RateType</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>+I</td>
<td>Allowing for a proportion of invariable sites.</td>
</tr>
<tr>
<td>+G</td>
<td>Discrete Gamma model (Yang, 1994) with default 4 rate categories. The number of categories can be changed with e.g. +G8.</td>
</tr>
</tbody>
</table>
### Rate Type Options

<table>
<thead>
<tr>
<th>RateType</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>+I+G</td>
<td>Invariable site plus discrete Gamma model (Gu et al., 1995).</td>
</tr>
<tr>
<td>+R</td>
<td>FreeRate model (Yang, 1995; Soubrier et al., 2012) that generalizes +G by relaxing the assumption of Gamma-distributed rates. The number of categories can be specified with e.g. +R6. <strong>DEFAULT</strong>: 4 categories.</td>
</tr>
<tr>
<td>+I+R</td>
<td>Invariable site plus FreeRate model.</td>
</tr>
</tbody>
</table>

See [Rate heterogeneity across sites](#) for more details.

### Further Options:

<table>
<thead>
<tr>
<th>Option</th>
<th>Usage and meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>-a</td>
<td>Specify the Gamma shape parameter (default: estimate)</td>
</tr>
<tr>
<td>-gmedian</td>
<td>Perform the <em>median</em> approximation for Gamma rate heterogeneity instead of the default <em>mean</em> approximation (Yang, 1994)</td>
</tr>
<tr>
<td>-i</td>
<td>Specify the proportion of invariable sites (default: estimate)</td>
</tr>
<tr>
<td>--opt-gamma-inv</td>
<td>Perform more thorough estimation for +I+G model parameters</td>
</tr>
<tr>
<td>-wsr</td>
<td>Write per-site rates to <code>.rate</code> file</td>
</tr>
</tbody>
</table>

Optionally, one can specify [Ascertainment bias correction](#) by appending `+ASC` to the model string. [Advanced mixture models](#) can also be specified via `MIX{...}` and `FMIX {...}` syntax. Option `-mwopt` can be used to turn on optimizing weights of mixture models.

## 10.7 Partition model options

Partition models are used for phylogenomic data with multiple genes. You first have to prepare a partition file in NEXUS or RAxML-style format. Then use the following options to input the partition file:

<table>
<thead>
<tr>
<th>Option</th>
<th>Usage and meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>-q</td>
<td>Specify partition file for edge-equal partition model. That means, all partitions share the same set of branch lengths (like <code>-q</code> option of RAxML).</td>
</tr>
<tr>
<td>-spp</td>
<td>Like <code>-q</code> but allowing partitions to have different evolutionary speeds (edge-proportional partition model).</td>
</tr>
</tbody>
</table>
CHAPTER 10. COMMAND REFERENCE

10.8 Site-specific frequency model options

The site-specific frequency model is used to substantially reduce the time and memory requirement compared with full profile mixture models C10 to C60. For full details see site-specific frequency model. To use this model you have to specify a profile mixture model with e.g. `-m LG+C20+F+G` together with a guide tree or a site frequency file:

<table>
<thead>
<tr>
<th>Option</th>
<th>Usage and meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>-sp</code></td>
<td>Specify partition file for edge-unlinked partition model. That means, each partition has its own set of branch lengths (like <code>-M</code> option of RAxML). This is the most parameter-rich partition model to accommodate heterotachy.</td>
</tr>
</tbody>
</table>

10.9 Tree search parameters

The new IQ-TREE search algorithm (Nguyen et al., 2015) has several parameters that can be changed with:

<table>
<thead>
<tr>
<th>Option</th>
<th>Usage and meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>-allnni</code></td>
<td>Turn on more thorough and slower NNI search. It means that IQ-TREE will consider all possible NNIs instead of only those in the vicinity of previously applied NNIs. DEFAULT: OFF</td>
</tr>
<tr>
<td>Option</td>
<td>Usage and meaning</td>
</tr>
<tr>
<td>--------</td>
<td>-------------------</td>
</tr>
<tr>
<td>-djc</td>
<td>Avoid computing ML pairwise distances and BIONJ tree.</td>
</tr>
<tr>
<td>-fast</td>
<td>Turn on the fast tree search mode, where IQ-TREE will just construct two starting trees: maximum parsimony and BIONJ, which are then optimized by nearest neighbor interchange (NNI). Introduced in version 1.6.</td>
</tr>
<tr>
<td>-g</td>
<td>Specify a topological constraint tree file in NEWICK format. The constraint tree can be a multifurcating tree and need not to include all taxa.</td>
</tr>
<tr>
<td>-ninit</td>
<td>Specify number of initial parsimony trees. <strong>DEFAULT:</strong> 100. Here the PLL library (Flouri et al., 2015) is used, which implements the randomized stepwise addition and parsimony subtree pruning and regrafting (SPR).</td>
</tr>
<tr>
<td>-n</td>
<td>Specify number of iterations to stop. This option overrides <code>-nstopt</code> criterion.</td>
</tr>
<tr>
<td>-ntop</td>
<td>Specify number of top initial parsimony trees to optimize with ML nearest neighbor interchange (NNI) search to initialize the candidate set. <strong>DEFAULT:</strong> 20</td>
</tr>
<tr>
<td>-nbest</td>
<td>Specify number of trees in the candidate set to maintain during ML tree search. <strong>DEFAULT:</strong> 5</td>
</tr>
<tr>
<td>-nstop</td>
<td>Specify number of unsuccessful iterations to stop. <strong>DEFAULT:</strong> 100</td>
</tr>
<tr>
<td>-pers</td>
<td>Specify perturbation strength (between 0 and 1) for randomized NNI. <strong>DEFAULT:</strong> 0.5</td>
</tr>
<tr>
<td>-sprrad</td>
<td>Specify SPR radius for the initial parsimony tree search. <strong>DEFAULT:</strong> 6</td>
</tr>
</tbody>
</table>

**NOTE:** While the default parameters were empirically determined to work well under our extensive benchmark (Nguyen et al., 2015), it might not hold true for all data sets. If in doubt that tree search is still stuck in local optima, one should repeat analysis with at least 10 IQ-TREE runs. Moreover, our experience showed that `-pers` and `-nstop` are the most relevant options to change in such case. For example, data sets with many short sequences should be analyzed with smaller perturbation strength (e.g. `-pers 0.2`) and larger number of stop iterations (e.g. `-nstop 500`).
10.9.1 Example usages:

- Infer an ML tree for an alignment `data.phy` with increased stopping iteration of 500 and reduced perturbation strength of 0.2:
  
  ```
  iqtree -s data.phy -m TEST -nstop 500 -pers 0.2
  ```

- Infer an ML tree for an alignment `data.phy` obeying a topological constraint tree `constraint.tree`:
  
  ```
  iqtree -s data.phy -m TEST -g constraint.tree
  ```

10.10 Ultrafast bootstrap parameters

The ultrafast bootstrap (UFBoot) approximation (Minh et al., 2013; Hoang et al., in press) has several parameters that can be changed with:

<table>
<thead>
<tr>
<th>Option</th>
<th>Usage and meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>-bb</code></td>
<td>Specify number of bootstrap replicates (&gt;=1000).</td>
</tr>
<tr>
<td><code>-bcor</code></td>
<td>Specify minimum correlation coefficient for UFBoot convergence criterion. <em>DEFAULT: 0.99</em></td>
</tr>
<tr>
<td><code>-beps</code></td>
<td>Specify a small epsilon to break tie in RELL evaluation for bootstrap trees. <em>DEFAULT: 0.5</em></td>
</tr>
<tr>
<td><code>-bni</code></td>
<td>Perform an additional step to further optimize UFBoot trees by nearest neighbor interchange (NNI) based directly on bootstrap alignments. This option is recommended in the presence of <strong>severe model violations</strong>. It increases computing time by 2-fold but reduces the risk of overestimating branch supports due to severe model violations. Introduced in IQ-TREE 1.6.</td>
</tr>
<tr>
<td><code>-bsam</code></td>
<td>Specify the resampling strategies for partitioned analysis. By default, IQ-TREE resamples alignment sites within partitions. With <code>-bsam GENE</code> IQ-TREE will resample partitions. With <code>-bsam GENESITE</code> IQ-TREE will resample partitions and then resample sites within resampled partitions (Gadagkar et al., 2005; Seo et al., 2005).</td>
</tr>
<tr>
<td><code>-nm</code></td>
<td>Specify maximum number of iterations to stop. <em>DEFAULT: 1000</em></td>
</tr>
<tr>
<td><code>-nstep</code></td>
<td>Specify iteration interval checking for UFBoot convergence. <em>DEFAULT: every 100 iterations</em></td>
</tr>
<tr>
<td><code>-wbt</code></td>
<td>Turn on writing bootstrap trees to <code>.ufboot</code> file. <em>DEFAULT: OFF</em></td>
</tr>
<tr>
<td><code>-wblt</code></td>
<td>Like <code>-wbt</code> but bootstrap trees written with branch lengths. <em>DEFAULT: OFF</em></td>
</tr>
</tbody>
</table>
10.10.1 Example usages:

- Select best-fit model, infer an ML tree and perform ultrafast bootstrap with 1000 replicates:
  
  \texttt{iqtree -s data.phy -m TEST -bb 1000}

- Reconstruct ML and perform ultrafast bootstrap (5000 replicates) under a partition model file \texttt{partition.nex}:
  
  \texttt{iqtree -s data.phy -spp partition.nex -m TEST -bb 5000}

10.11 Nonparametric bootstrap

The slow standard nonparametric bootstrap (Felsenstein, 1985) can be run with:

<table>
<thead>
<tr>
<th>Option</th>
<th>Usage and meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>(-b)</td>
<td>Specify number of bootstrap replicates (recommended (\geq 100)). This will perform both bootstrap and analysis on original alignment and provide a consensus tree.</td>
</tr>
<tr>
<td>(-bc)</td>
<td>Like (-b) but omit analysis on original alignment.</td>
</tr>
<tr>
<td>(-bo)</td>
<td>Like (-b) but only perform bootstrap analysis (no analysis on original alignment and no consensus tree).</td>
</tr>
</tbody>
</table>

10.12 Single branch tests

The following single branch tests are faster than all bootstrap analysis and recommended for extremely large data sets (e.g., \(>10,000\) taxa):

<table>
<thead>
<tr>
<th>Option</th>
<th>Usage and meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>(-alrt)</td>
<td>Specify number of replicates ((\geq 1000)) to perform SH-like approximate likelihood ratio test (SH-aLRT) (Guindon et al., 2010). If number of replicates is set to 0 ((-alrt\ 0)), then the parametric aLRT test (Anisimova and Gascuel 2006) is performed, instead of SH-aLRT.</td>
</tr>
<tr>
<td>(-abayes)</td>
<td>Perform approximate Bayes test (Anisimova et al., 2011).</td>
</tr>
<tr>
<td>(-lbp)</td>
<td>Specify number of replicates ((\geq 1000)) to perform fast local bootstrap probability method (Adachi and Hasegawa, 1996b).</td>
</tr>
</tbody>
</table>
TIP: One can combine all these tests (also including UFBoot -bb option) within a single IQ-TREE run. Each branch in the resulting tree will be assigned several support values separated by slash (/), where the order of support values is stated in the .iqtree report file.

10.12.1 Example usages:

- Infer an ML tree and perform SH-aLRT test as well as ultrafast bootstrap with 1000 replicates:

```
  iqtree -s data.phy -m TEST -alrt 1000 -bb 1000
```

10.13 Ancestral sequence reconstruction

This feature is newly introduced in version 1.6. You can combine this feature with -te option to determine ancestral sequences along a user-defined tree (Otherwise, IQ-TREE computes ancestral sequences of the ML tree).

<table>
<thead>
<tr>
<th>Option</th>
<th>Usage and meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>-asr</td>
<td>Write ancestral sequences (by empirical Bayesian method) for all nodes of the tree to .state file.</td>
</tr>
<tr>
<td>-asr-min</td>
<td>Specify the minimum threshold of posterior probability to determine the best ancestral state. Default: observed state frequency from the alignment.</td>
</tr>
<tr>
<td>-te</td>
<td>Specify a user-defined tree to determine ancestral sequences along this tree. You can assign each node of this tree with a node name, and IQ-TREE will report the ancestral sequences of the corresponding nodes. If nodes do not have names, IQ-TREE will automatically assign node names as Node1, Node2, etc.</td>
</tr>
</tbody>
</table>

10.13.1 Example usages:

```
  iqtree -s example.phy -m JC+G -asr
```

The first few lines of the output file example.phy.state may look like this:

```
# Ancestral state reconstruction for all nodes in example.phy.
treefile
```
10.14. TREE TOPOLOGY TESTS

IQ-TREE provides a number of tests for significant topological differences between trees. The AU test implementation in IQ-TREE is much more efficient than the original CONSEL by supporting SSE, AVX and multicore parallelization. Moreover, it is more appropriate than CONSEL for partition analysis by bootstrap resampling sites within partitions, whereas CONSEL is not partition-aware.

NOTE: There is a discrepancy between IQ-TREE and CONSEL for the AU test: IQ-TREE implements the least-square estimate for \( p \)-values whereas CONSEL provides the maximum-likelihood estimate (MLE) for \( p \)-values. Hence, the AU \( p \)-values might be slightly different. We plan to implement MLE for AU \( p \)-values in IQ-TREE soon.

### Option Usage and meaning

<table>
<thead>
<tr>
<th>Option</th>
<th>Usage and meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>-z</td>
<td>Specify a file containing a set of trees. IQ-TREE will compute the log-likelihoods of all trees.</td>
</tr>
<tr>
<td>-zb</td>
<td>Specify the number of RELL (Kishino et al., 1990) replicates (( \geq 1000 )) to perform several tree topology tests for all trees passed via -z. The tests include bootstrap proportion (BP), KH test (Kishino and Hasegawa, 1989), SH test (Shimodaira and Hasegawa, 1999) and expected likelihood weights (ELW) (Strimmer and Rambaut, 2002).</td>
</tr>
<tr>
<td>-zw</td>
<td>Used together with -zb to additionally perform the weighted-KH and weighted-SH tests.</td>
</tr>
</tbody>
</table>
Option | Usage and meaning
--- | ---
-\texttt{au} & Used together with -\texttt{zb} to additionally perform the approximately unbiased (AU) test (Shimodaira, 2002). Note that you have to specify the number of replicates for the AU test via -\texttt{zb}.
-\texttt{n 0} & Only estimate model parameters on an initial parsimony tree and ignore a full tree search to save time.
-\texttt{te} & Specify a fixed user tree to estimate model parameters. Thus it behaves like -\texttt{n 0} but uses a user-defined tree instead of parsimony tree.

10.14.1 Example usages:

- Given alignment \texttt{data.phy}, test a set of trees in \texttt{data.trees} using AU test with 10,000 replicates:

\begin{verbatim}
iqtree -s data.phy -m GTR+G -n 0 -z data.trees -zb 10000 -au
\end{verbatim}

- Same above but for a partitioned data \texttt{partition.nex} and additionally performing weighted test:

\begin{verbatim}
iqtree -s data.phy -spp partition.nex -n 0 -z data.trees -zb 10000 -au -zw
\end{verbatim}

10.15 Constructing consensus tree

IQ-TREE provides a fast implementation of consensus tree construction for post analysis:

Option | Usage and meaning
--- | ---
\texttt{t} & Specify a file containing a set of trees.
\texttt{con} & Compute consensus tree of the trees passed via -\texttt{t}. Resulting consensus tree is written to \texttt{.contree} file.
\texttt{net} & Compute consensus network of the trees passed via -\texttt{t}. Resulting consensus network is written to \texttt{.nex} file.
\texttt{minsup} & Specify a minimum threshold (between 0 and 1) to keep branches in the consensus tree. -\texttt{minsup 0.5} means to compute majority-rule consensus tree. \texttt{DEFAULT: 0 to compute extended majority-rule consensus.}
10.16 Computing Robinson-Foulds distance

IQ-TREE provides a fast implementation of Robinson-Foulds (RF) distance computation between trees:

<table>
<thead>
<tr>
<th>Option</th>
<th>Usage and meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>-t</code></td>
<td>Specify a file containing a set of trees.</td>
</tr>
<tr>
<td><code>-rf</code></td>
<td>Specify a second set of trees. IQ-TREE computes all pairwise RF distances between</td>
</tr>
<tr>
<td></td>
<td>two tree sets passed via <code>-t</code> and <code>-rf</code></td>
</tr>
<tr>
<td><code>-rf_all</code></td>
<td>Compute all-to-all RF distances between all trees passed via <code>-t</code></td>
</tr>
<tr>
<td><code>-rf_adj</code></td>
<td>Compute RF distances between adjacent trees passed via <code>-t</code></td>
</tr>
</tbody>
</table>

10.16.1 Example usages:

- Compute the pairwise RF distances between 2 sets of trees:
  
  ```
  iqtreen -rf tree_set1 tree_set2
  ```

- Compute the all-to-all RF distances within a set of trees:
  
  ```
  iqtreen -rf_all tree_set
  ```
10.17 Generating random trees

IQ-TREE provides several random tree generation models:

<table>
<thead>
<tr>
<th>Option</th>
<th>Usage and meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>-r</td>
<td>Specify number of taxa. IQ-TREE will create a random tree under Yule-Harding model with specified number of taxa.</td>
</tr>
<tr>
<td>-ru</td>
<td>Like -r, but a random tree is created under uniform model.</td>
</tr>
<tr>
<td>-rcat</td>
<td>Like -r, but a random caterpillar tree is created.</td>
</tr>
<tr>
<td>-rbal</td>
<td>Like -r, but a random balanced tree is created.</td>
</tr>
<tr>
<td>-rcsg</td>
<td>Like -r, but a random circular split network is created.</td>
</tr>
<tr>
<td>-rlen</td>
<td>Specify three numbers: minimum, mean and maximum branch lengths of the random tree. DEFAULT: -rlen 0.001 0.1 0.999</td>
</tr>
</tbody>
</table>

10.17.1 Example usages:

- Generate a 100-taxon random tree into the file 100.tree under the Yule Harding model:
  
  ```
  iqtree -r 100 100.tree
  ```

- Generate 100-taxon random tree with mean branch lengths of 0.2 and branch lengths are between 0.05 and 0.3:
  
  ```
  iqtree -r 100 -rlen 0.05 0.2 0.3 100.tree
  ```

- Generate a random tree under uniform model:
  
  ```
  iqtree -ru 100 100.tree
  ```

- Generate a random tree where taxon labels follow an alignment:
  
  ```
  iqtree -s example.phy -r 17 example.random.tree
  ```

Note that, you still need to specify the -r option being equal to the number of taxa in the alignment.

10.18 Miscellaneous options
10.18. MISCELLANEOUS OPTIONS

<table>
<thead>
<tr>
<th>Option</th>
<th>Usage and meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>-alninfo</td>
<td>Print alignment site statistics to .alninfo file.</td>
</tr>
<tr>
<td>-blfix</td>
<td>Fix branch lengths of tree passed via -t or -te. This is useful to evaluate the log-likelihood of an input tree with fixed topology and branch lengths. DEFAULT: OFF</td>
</tr>
<tr>
<td>-blmin</td>
<td>Specify minimum branch length. Default: the smaller of 0.000001 and 0.1/alignment_length.</td>
</tr>
<tr>
<td>-blmax</td>
<td>Specify the maximum branch length. Default: 10</td>
</tr>
<tr>
<td>-czb</td>
<td>Collapse near zero branches, so that the final tree may be multifurcating. This is useful for bootstrapping in the presence of polytomy to reduce bootstrap supports of short branches.</td>
</tr>
<tr>
<td>-me</td>
<td>Specify the log-likelihood epsilon for final model parameter estimation (Default: 0.01). With -fast option, the epsilon is raised to 0.05.</td>
</tr>
<tr>
<td>-wpl</td>
<td>Write partition log-likelihoods to .partlh file. Only effective with partition model.</td>
</tr>
<tr>
<td>-wspr</td>
<td>Write site posterior probabilities per rate category to .siteprob file.</td>
</tr>
<tr>
<td>-wspm</td>
<td>Write site posterior probabilities per mixture class to .siteprob file.</td>
</tr>
<tr>
<td>-wspmr</td>
<td>Write site posterior probabilities per mixture class and rate category to .siteprob file.</td>
</tr>
<tr>
<td>-wsl</td>
<td>Write site log-likelihoods to .sitelh file in TREE-PUZZLE format. Such file can then be passed on to CONSEL for further tree tests.</td>
</tr>
<tr>
<td>-wslr</td>
<td>Write site log-likelihoods per rate category to .sitelh file.</td>
</tr>
<tr>
<td>-wslm</td>
<td>Write site log-likelihoods per mixture class to .sitelh file.</td>
</tr>
<tr>
<td>-wslmr</td>
<td>Write site log-likelihoods per mixture class and rate category to .sitelh file.</td>
</tr>
<tr>
<td>-wt</td>
<td>Turn on writing all locally optimal trees into .treels file.</td>
</tr>
<tr>
<td>-fconst</td>
<td>Specify a list of comma-separated integer numbers. The number of entries should be equal to the number of states in the model (e.g. 4 for DNA and 20 for protein). IQ-TREE will then add a number of constant sites accordingly. For example, -fconst 10,20,15,40 will add 10 constant sites of all A, 20 constant sites of all C, 15 constant sites of all G and 40 constant sites of all T into the alignment.</td>
</tr>
</tbody>
</table>

10.18.1 Example usages:

- Print alignment information about parsimony informative sites:

  ```
  iqtree -s example.phy -m JC -n 0 -alninfo
  ```

  The first few lines of the output file `example.phy.alninfo` may look like this:
# Alignment site statistics
# This file can be read in MS Excel or in R with command:
# tab=read.table('example.phy.alninfo',header=TRUE)
# Columns are tab-separated with following meaning:
# Site: Site ID
# Stat: Statistic, I=informative, C=constant, c=constant+
# ambiguous, 
# U=Uninformative but not constant, -=all-gaps

<table>
<thead>
<tr>
<th>Site</th>
<th>Stat</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>U</td>
</tr>
<tr>
<td>2</td>
<td>I</td>
</tr>
<tr>
<td>3</td>
<td>I</td>
</tr>
<tr>
<td>4</td>
<td>U</td>
</tr>
<tr>
<td>5</td>
<td>U</td>
</tr>
</tbody>
</table>

- Print site log-likelihood and posterior probability for each Gamma rate category:

```
iqtree -s example.phy -m JC+G -wspr -wslr -n 0
```

The first few lines of the output file example.phy.siteprob (printed by -wspr option) may look like this:

<table>
<thead>
<tr>
<th>Site</th>
<th>p1</th>
<th>p2</th>
<th>p3</th>
<th>p4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.180497</td>
<td>0.534405</td>
<td>0.281</td>
<td>0.00409816</td>
</tr>
<tr>
<td>2</td>
<td>4.73239e-05</td>
<td>0.0373409</td>
<td>0.557705</td>
<td>0.404907</td>
</tr>
<tr>
<td>3</td>
<td>1.23186e-08</td>
<td>0.000426294</td>
<td>0.0672021</td>
<td>0.932372</td>
</tr>
<tr>
<td>4</td>
<td>0.180497</td>
<td>0.534405</td>
<td>0.281</td>
<td>0.00409816</td>
</tr>
<tr>
<td>5</td>
<td>0.180497</td>
<td>0.534405</td>
<td>0.281</td>
<td>0.00409816</td>
</tr>
</tbody>
</table>

where px is the probability of the site falling into rate category x.

The first few lines of the output file example.phy.sitelh (printed by -wslr option) may look like this:

```
# Site likelihood per rate/mixture category
# This file can be read in MS Excel or in R with command:
# tab=read.table('example.phy.sitelh',header=TRUE,fill=TRUE)
# Columns are tab-separated with following meaning:
# Site: Alignment site ID
# LnL: Logarithm of site likelihood
# Thus, sum of LnL is equal to tree log-likelihood
# LnLW_k: Logarithm of (category-k site likelihood times category-k weight)
```

# Site likelihood per rate/mixture category
# This file can be read in MS Excel or in R with command:
# tab=read.table('example.phy.sitelh',header=TRUE,fill=TRUE)
# Columns are tab-separated with following meaning:
# Site: Alignment site ID
# LnL: Logarithm of site likelihood
# Thus, sum of LnL is equal to tree log-likelihood
# LnLW_k: Logarithm of (category-k site likelihood times category-k weight)
Thus, sum of $\exp(LnLW_k)$ is equal to $\exp(LnL)$

<table>
<thead>
<tr>
<th>Site</th>
<th>LnL</th>
<th>LnLW_1</th>
<th>LnLW_2</th>
<th>LnLW_3</th>
<th>LnLW_4</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>-17.5900</td>
<td>-27.5485</td>
<td>-20.8776</td>
<td>-18.4941</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>-7.0432</td>
<td>-8.7552</td>
<td>-7.6698</td>
<td>-8.3126</td>
<td>-12.5404</td>
</tr>
<tr>
<td>5</td>
<td>-7.0432</td>
<td>-8.7552</td>
<td>-7.6698</td>
<td>-8.3126</td>
<td>-12.5404</td>
</tr>
</tbody>
</table>
Chapter 11

Substitution models

All common substitution models and usages.

IQ-TREE supports a wide range of substitution models, including advanced partition and mixture models. This guide gives a detailed information of all available models.

**TIP:** If you do not know which model to use, simply run IQ-TREE with the standard model selection (-m TEST option) or the new ModelFinder (-m MFP). It automatically determines best-fit model for your data.

11.1 DNA models

11.1.1 Base substitution rates

IQ-TREE includes all common DNA models (ordered by complexity):

<table>
<thead>
<tr>
<th>Model</th>
<th>df</th>
<th>Explanation</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>JC or JC69</td>
<td>0</td>
<td>Equal substitution rates and equal base frequencies (Jukes and Cantor, 1969).</td>
<td>000000</td>
</tr>
<tr>
<td>F81</td>
<td>3</td>
<td>Equal rates but unequal base freq. (Felsenstein, 1981).</td>
<td>000000</td>
</tr>
<tr>
<td>K80 or K2P</td>
<td>1</td>
<td>Unequal transition/transversion rates and equal base freq. (Kimura, 1980).</td>
<td>010010</td>
</tr>
<tr>
<td>HKY or</td>
<td>4</td>
<td>Unequal transition/transversion rates and unequal base freq. (Hasegawa, Kishino and Yano, 1985).</td>
<td>010010</td>
</tr>
<tr>
<td>HKY85</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TN or</td>
<td>5</td>
<td>Like HKY but unequal purine/pyrimidine rates (Tamura and Nei, 1993).</td>
<td>010020</td>
</tr>
<tr>
<td>TN93</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### CHAPTER 11. SUBSTITUTION MODELS

<table>
<thead>
<tr>
<th>Model</th>
<th>df</th>
<th>Explanation</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>TNe</td>
<td>2</td>
<td>Like TN but equal base freq.</td>
<td>010020</td>
</tr>
<tr>
<td>K81 or K3P</td>
<td>2</td>
<td>Three substitution types model and equal base freq. (Kimura, 1981).</td>
<td>012210</td>
</tr>
<tr>
<td>K81u</td>
<td>5</td>
<td>Like K81 but unequal base freq.</td>
<td>012210</td>
</tr>
<tr>
<td>TPM2</td>
<td>2</td>
<td>AC=AT, AG=CT, CG=GT and equal base freq.</td>
<td>010212</td>
</tr>
<tr>
<td>TPM2u</td>
<td>5</td>
<td>Like TPM2 but unequal base freq.</td>
<td>012012</td>
</tr>
<tr>
<td>TPM3</td>
<td>2</td>
<td>AC=CG, AG=GT, AT=GT and equal base freq.</td>
<td>012012</td>
</tr>
<tr>
<td>TPM3u</td>
<td>5</td>
<td>Like TPM3 but unequal base freq.</td>
<td>012012</td>
</tr>
<tr>
<td>TIM</td>
<td>6</td>
<td>Transition model, AC=GT, AT=CG and unequal base freq.</td>
<td>012230</td>
</tr>
<tr>
<td>TIMe</td>
<td>3</td>
<td>Like TIM but equal base freq.</td>
<td>012230</td>
</tr>
<tr>
<td>TIM2</td>
<td>6</td>
<td>AC=AT, CG=GT and unequal base freq.</td>
<td>010232</td>
</tr>
<tr>
<td>TIM2e</td>
<td>3</td>
<td>Like TIM2 but equal base freq.</td>
<td>010232</td>
</tr>
<tr>
<td>TIM3</td>
<td>6</td>
<td>AC=CG, AT=GT and unequal base freq.</td>
<td>010232</td>
</tr>
<tr>
<td>TIM3e</td>
<td>3</td>
<td>Like TIM3 but equal base freq.</td>
<td>010232</td>
</tr>
<tr>
<td>TVM</td>
<td>7</td>
<td>Transversion model, AG=CT and unequal base freq.</td>
<td>012314</td>
</tr>
<tr>
<td>TVMe</td>
<td>4</td>
<td>Like TVM but equal base freq.</td>
<td>012314</td>
</tr>
<tr>
<td>SYM</td>
<td>5</td>
<td>Symmetric model with unequal rates but equal base freq. (Zharkikh, 1994).</td>
<td>012345</td>
</tr>
<tr>
<td>GTR</td>
<td>8</td>
<td>General time reversible model with unequal rates and unequal base freq. (Tavare, 1986).</td>
<td>012345</td>
</tr>
</tbody>
</table>

The last column Code is a 6-digit code defining the equality constraints for 6 relative substitution rates: A-C, A-G, A-T, C-G, C-T and G-T. 010010 means that A-G rate is equal to C-T rate (corresponding to 1 in the code) and the remaining four substitution rates are equal (corresponding to 0 in the code). Thus, 010010 is equivalent to K80 or HKY model (depending on whether base frequencies are equal or not). 012345 is equivalent to GTR or SYM model as there is no restriction defined by such 6-digit code.

Moreover, IQ-TREE supports arbitrarily restricted DNA model via a 6-digit code, e.g. with option -m 012012+G.

**NOTE:** The digits in the codes do not necessarily have to have the same order as above. That means ‘101101’ describes the same matrix as ‘010010’. The last rate, which corresponds to G-T, (and all rates with the same digit) is always set equal to 1.0 for convenience because the rates are relative.
If users want to fix model parameters, append the model name with a curly bracket {, followed by the comma-separated rate parameters, and a closing curly bracket }. For example, GTR\{1.0,2.0,1.5,3.7,2.8\} specifies 6 substitution rates A-C=1.0, A-G=2.0, A-T=1.5, C-G=3.7, C-T=2.8 and G-T=1.0.

Another example is for model TIM2 that has the 6-digit code 010232. Thus, TIM2 \{4.39,5.30,12.1\} means that A-C=A-T=4.39 (coded 0), A-G=5.30 (coded 1), C-T=12.1 (coded 3) and C-G=G-T=1.0 (coded 2). This is, in turn, equivalent to specifying GTR\{4.39,5.30,4.39,1.0,12.1\}.

### 11.1.2 Base frequencies

Users can specify three different kinds of base frequencies:

<table>
<thead>
<tr>
<th>FreqType</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>+F</td>
<td>Empirical base frequencies. This is the default if the model has unequal base freq. In AliSim, if users neither specify base frequencies nor supply an input alignment, AliSim will generate base frequencies from empirical distributions.</td>
</tr>
<tr>
<td>+FQ</td>
<td>Equal base frequencies.</td>
</tr>
<tr>
<td>+FO</td>
<td>Optimized base frequencies by maximum-likelihood.</td>
</tr>
</tbody>
</table>

For example, GTR+FQ optimizes base frequencies by ML whereas GTR+F (default) counts base frequencies directly from the alignment.

Finally, users can fix base frequencies with e.g. GTR+F\{0.1,0.2,0.3,0.4\} to fix the corresponding frequencies of A, C, G and T (must sum up to 1.0).

### 11.1.3 Lie Markov models

Starting with version 1.6, IQ-TREE supports a series of Lie Markov models (Woodhams et al., 2015), many of which are non-reversible models. Lie Markov models have a consistent property, which is lacking in other common models such as GTR. The following table shows the list of all Lie Markov models (the number before . in the name shows the number of parameters of the model):

<table>
<thead>
<tr>
<th>Model</th>
<th>Rev?</th>
<th>Freq</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Yes</td>
<td>0</td>
<td>equiv. to JC</td>
</tr>
<tr>
<td>2.2b</td>
<td>Yes</td>
<td>0</td>
<td>equiv. to K2P</td>
</tr>
<tr>
<td>3.3a</td>
<td>Yes</td>
<td>0</td>
<td>equiv. to K3P</td>
</tr>
<tr>
<td>Model</td>
<td>Rev?</td>
<td>Freq</td>
<td>Note</td>
</tr>
<tr>
<td>-------</td>
<td>------</td>
<td>------</td>
<td>-----------------------</td>
</tr>
<tr>
<td>3.3b</td>
<td>No</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>3.3c</td>
<td>Yes</td>
<td>0</td>
<td>equiv. to TNe</td>
</tr>
<tr>
<td>3.4</td>
<td>Yes</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>4.4a</td>
<td>Yes</td>
<td>3</td>
<td>equiv. to F81</td>
</tr>
<tr>
<td>4.4b</td>
<td>Yes</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>4.5a</td>
<td>No</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>4.5b</td>
<td>No</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>5.6a</td>
<td>No</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>5.6b</td>
<td>No</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>5.7a</td>
<td>No</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>5.7b</td>
<td>No</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>5.7c</td>
<td>No</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>5.11a</td>
<td>No</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>5.11b</td>
<td>No</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>5.11c</td>
<td>No</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>5.16</td>
<td>No</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>6.6</td>
<td>No</td>
<td>1</td>
<td>equiv. to STRSYM (strand symmetric model)</td>
</tr>
<tr>
<td>6.7a</td>
<td>No</td>
<td>3</td>
<td>F81+K3P</td>
</tr>
<tr>
<td>6.7b</td>
<td>No</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>6.8a</td>
<td>No</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>6.8b</td>
<td>No</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>6.17a</td>
<td>No</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>6.17b</td>
<td>No</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>8.8</td>
<td>No</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>8.10a</td>
<td>No</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>8.10b</td>
<td>No</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>8.16</td>
<td>No</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>8.17</td>
<td>No</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>8.18</td>
<td>No</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>9.20a</td>
<td>No</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>9.20b</td>
<td>No</td>
<td>0</td>
<td>Doubly stochastic</td>
</tr>
<tr>
<td>10.12</td>
<td>No</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>10.34</td>
<td>No</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>12.12</td>
<td>No</td>
<td>3</td>
<td>equiv. to UNREST (unrestricted model)</td>
</tr>
</tbody>
</table>

Column **Rev?** shows whether the model is reversible or not. Column **Freq** shows the number of free base frequencies. 0 means equal base frequency; 1 means \( f(A) = f(G) \) and \( f(C) = f(T) \); 2 means \( f(A) + f(G) = 0.5 = f(C) + f(T) \); 3 means unconstrained frequencies.
11.2. PROTEIN MODELS

All Lie Markov models can have one of the following prefixes:

<table>
<thead>
<tr>
<th>Prefix</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>RY</td>
<td>purine-pyrimidine pairing (default)</td>
</tr>
<tr>
<td>WS</td>
<td>weak-strong pairing</td>
</tr>
<tr>
<td>MK</td>
<td>aMino-Keto pairing</td>
</tr>
</tbody>
</table>

### 11.2 Protein models

#### 11.2.1 Amino-acid exchange rate matrices

IQ-TREE supports all common empirical amino-acid exchange rate matrices (alphabetical order):

<table>
<thead>
<tr>
<th>Model</th>
<th>Region</th>
<th>Explanation</th>
</tr>
</thead>
</table>
| Blosum62         | nuclear| BLOcks SUBstitution Matrix (Henikoff and Henikoff, 1992).
|                  |        | Note that BLOSUM62 is not recommended for phylogenetic analysis as it was designed mainly for sequence alignments. |
| cpREV            | chloroplast | chloroplast matrix (Adachi et al., 2000). |
| Dayhoff          | nuclear | General matrix (Dayhoff et al., 1978). |
| DCMut            | nuclear | Revised Dayhoff matrix (Kosiol and Goldman, 2005). |
| FLAVI            | viral  | Flavivirus (Le and Vinh, 2020). |
| FLU              | viral  | Influenza virus (Dang et al., 2010). |
| GTR20            | general| General time reversible models with 190 rate parameters. WARNING: Be careful when using this parameter-rich model as parameter estimates might not be stable, especially when not having enough phylogenetic information (e.g. not long enough alignments). |
| HIVb             | viral  | HIV between-patient matrix HIV-Bm (Nickle et al., 2007). |
| HIVw             | viral  | HIV within-patient matrix HIV-Wm (Nickle et al., 2007). |
| JTT              | nuclear| General matrix (Jones et al., 1992). |
| JTTDCMut         | nuclear| Revised JTT matrix (Kosiol and Goldman, 2005). |
| LG               | nuclear| General matrix (Le and Gascuel, 2008). |
| mtART            | mitochondrial Arthropoda (Abascal et al., 2007). |
| mtMAM            | mitochondrial Mammalia (Yang et al., 1998). |
| mtREV            | mitochondrial Vertebrate (Adachi and Hasegawa, 1996). |
| mtZOA            | mitochondrial Metazoa (Animals) (Rota-Stabelli et al., 2009). |
| mtMet            | mitochondrial Metazoa (Vinh et al., 2017). |
| mtVer            | mitochondrial Vertebrate (Vinh et al., 2017). |
### 11.2.2 Protein mixture models

IQ-TREE also supports a series of protein mixture models:

<table>
<thead>
<tr>
<th>Model</th>
<th>Region</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>C10 to C60</td>
<td>10, 20, 30, 40, 50, 60-profile mixture models (Le et al., 2008a) as variants of the CAT model (Lartillot and Philippe, 2004) for ML. Note that these models assume Poisson AA replacement and implicitly include a Gamma rate heterogeneity among sites.</td>
<td></td>
</tr>
<tr>
<td>EX2</td>
<td>Two-matrix model for exposed/buried AA sites (Le et al., 2008b).</td>
<td></td>
</tr>
<tr>
<td>EX3</td>
<td>Three-matrix model for highly exposed/intermediate/buried AA sites (Le et al., 2008b).</td>
<td></td>
</tr>
<tr>
<td>EHO</td>
<td>Three-matrix model for extended/helix/other sites (Le et al., 2008b).</td>
<td></td>
</tr>
<tr>
<td>UL2, UL3</td>
<td>Unsupervised-learning variants of EX2 and EX3, respectively.</td>
<td></td>
</tr>
<tr>
<td>EX_EHO</td>
<td>Six-matrix model combining EX2 and EHO (Le and Gascuel, 2010).</td>
<td></td>
</tr>
<tr>
<td>LG4M</td>
<td>Four-matrix model fused with Gamma rate heterogeneity (Le et al., 2012).</td>
<td></td>
</tr>
<tr>
<td>LG4X</td>
<td>Four-matrix model fused with FreeRate heterogeneity (Le et al., 2012).</td>
<td></td>
</tr>
<tr>
<td>CF4</td>
<td>Five-profile mixture model (Wang et al., 2008).</td>
<td></td>
</tr>
</tbody>
</table>
11.2. PROTEIN MODELS

- **LG+C20**: Applying LG matrix instead of Poisson for all 20 classes of AA profiles and a Gamma rate heterogeneity.
- **LG+C20+F**: Applying LG matrix for 20 classes plus the 21th class of empirical AA profile (counted from the current data) and Gamma rate heterogeneity.
- **JTT+CF4+G**: Applying JTT matrix for all 5 classes of AA profiles and Gamma rate heterogeneity.

Moreover, one can override the Gamma rate by FreeRate heterogeneity:

- **LG+C20+R4**: Like LG+C20 but replace Gamma by FreeRate heterogeneity.

11.2.3 User-defined empirical protein models

If the matrix name does not match any of the above listed models, IQ-TREE assumes that it is a file containing AA exchange rates and frequencies in PAML format. It contains the lower diagonal part of the matrix and 20 AA frequencies, e.g.:

```
 0.425093 0.276818 0.751878 0.395144 0.123954 5.076149
 2.489084 0.534551 0.528768 0.062556
 0.969894 2.807908 1.695752 0.523386 0.084808
 1.038545 0.363970 0.541712 5.243870 0.003499 4.128591
 2.066040 0.390192 1.437645 0.844926 0.569265 0.267959 0.348847
 0.358858 2.426601 4.509238 0.927114 0.640543 4.813505 0.423881
 0.311484
 0.149830 0.126991 0.191503 0.010690 0.320627 0.072854 0.044265
 0.008705 0.108882
 0.395337 0.301848 0.068427 0.015076 0.594007 0.582457 0.069673
 0.044261 0.366317 4.145067
 0.536518 6.326067 2.145078 0.282959 0.013266 3.234294 1.807177
 0.296636 0.697264 0.159069 0.137500
 1.124035 0.484133 0.371004 0.025548 0.893680 1.672569 0.173735
 0.139538 0.442472 4.273607 6.312358 0.656604
 0.253701 0.052722 0.089525 0.017416 1.105251 0.035855 0.018811
 0.089586 0.682139 1.112727 2.592692 0.023918 1.798853
 1.177651 0.332533 0.161787 0.394456 0.075382 0.624294 0.419409
 0.196961 0.508851 0.078281 0.249060 0.390322 0.099849 0.094464
 4.727182 0.858151 4.008358 1.240275 2.784478 1.223828 0.611973
 1.739990 0.990012 0.064105 0.182287 0.748683 0.346960 0.361819
 1.338132
 2.139501 0.578987 2.000679 0.425860 1.143480 1.080136 0.604545
 0.129836 0.584262 1.033739 0.302936 1.136863 2.020366 0.165001
 0.571468 6.472279
```
CHAPTER 11. SUBSTITUTION MODELS

This is an example of an LG matrix taken from PAML package. Note that the amino-acid order in this file is:

<table>
<thead>
<tr>
<th>A</th>
<th>R</th>
<th>N</th>
<th>D</th>
<th>C</th>
<th>Q</th>
<th>E</th>
<th>G</th>
<th>H</th>
<th>I</th>
<th>L</th>
<th>K</th>
<th>M</th>
<th>F</th>
<th>P</th>
<th>S</th>
<th>T</th>
<th>W</th>
<th>Y</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ala</td>
<td>Arg</td>
<td>Asn</td>
<td>Asp</td>
<td>Cys</td>
<td>Gln</td>
<td>Glu</td>
<td>Gly</td>
<td>His</td>
<td>Ile</td>
<td>Leu</td>
<td>Lys</td>
<td>Met</td>
<td>Phe</td>
<td>Pro</td>
<td>Ser</td>
<td>Thr</td>
<td>Trp</td>
<td>Tyr</td>
<td>Val</td>
</tr>
</tbody>
</table>

11.2.4 Amino-acid frequencies

By default, AA frequencies are given by the model. Users can change this with:

<table>
<thead>
<tr>
<th>FreqType</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>+F</td>
<td>empirical AA frequencies from the data. In AliSim, if users neither specify the base frequencies nor supply an input alignment, AliSim will randomly generate the base frequencies from Uniform distribution.</td>
</tr>
<tr>
<td>+FO</td>
<td>ML optimized AA frequencies from the data.</td>
</tr>
<tr>
<td>+FQ</td>
<td>Equal AA frequencies.</td>
</tr>
</tbody>
</table>

Users can also specify AA frequencies with, e.g.:

+F

\{0.079066, 0.055941, 0.041977, 0.053052, 0.012937, 0.040767, 0.071586, 0.057337, 0.022355, 0.062157, 0.099081, 0.064600, 0.022951, 0.042302, 0.044040, 0.061197, 0.053287, 0.012066, 0.034155, 0.069147\}
11.3. Codon models

To apply a codon model one should use the option \texttt{-st CODON} to tell IQ-TREE that the alignment contains protein coding sequences (otherwise, IQ-TREE thinks that it contains DNA sequences and will apply DNA models). This implicitly applies the standard genetic code. You can change to another genetic code by appending the appropriate ID to the \texttt{CODON} keyword:

<table>
<thead>
<tr>
<th>Code</th>
<th>Genetic code meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>CODON1</td>
<td>The Standard Code (same as \texttt{-st CODON})</td>
</tr>
<tr>
<td>CODON2</td>
<td>The Vertebrate Mitochondrial Code</td>
</tr>
<tr>
<td>CODON3</td>
<td>The Yeast Mitochondrial Code</td>
</tr>
<tr>
<td>CODON4</td>
<td>The Mold, Protozoan, and Coelenterate Mitochondrial Code and the Mycoplasma/Spiroplasma Code</td>
</tr>
<tr>
<td>CODON5</td>
<td>The Invertebrate Mitochondrial Code</td>
</tr>
<tr>
<td>CODON6</td>
<td>The Ciliate, Dasycladacean and Hexamita Nuclear Code</td>
</tr>
<tr>
<td>CODON7</td>
<td>The Echinoderm and Flatworm Mitochondrial Code</td>
</tr>
<tr>
<td>CODON8</td>
<td>The Euplotid Nuclear Code</td>
</tr>
<tr>
<td>CODON9</td>
<td>The Bacterial, Archaeal and Plant Plastid Code</td>
</tr>
<tr>
<td>CODON10</td>
<td>The Alternative Yeast Nuclear Code</td>
</tr>
<tr>
<td>CODON11</td>
<td>The Ascidian Mitochondrial Code</td>
</tr>
<tr>
<td>CODON12</td>
<td>The Alternative Flatworm Mitochondrial Code</td>
</tr>
<tr>
<td>CODON13</td>
<td>Chlorophyceae Mitochondrial Code</td>
</tr>
<tr>
<td>CODON14</td>
<td>Trematode Mitochondrial Code</td>
</tr>
<tr>
<td>CODON15</td>
<td>Scenedesmus obliquus Mitochondrial Code</td>
</tr>
<tr>
<td>CODON16</td>
<td>Thraustochytrium Mitochondrial Code</td>
</tr>
<tr>
<td>CODON17</td>
<td>Pterobranchia Mitochondrial Code</td>
</tr>
<tr>
<td>CODON18</td>
<td>Candidate Division SR1 and Gracilibacteria Code</td>
</tr>
</tbody>
</table>

(The IDs follow the specification at \url{http://www.ncbi.nlm.nih.gov/Taxonomy/Utils/wprintgc.cgi}).

11.3.1 Codon substitution rates

IQ-TREE supports several codon models:
<table>
<thead>
<tr>
<th>Model</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>MG</td>
<td>Nonsynonymous/synonymous (dn/ds) rate ratio (Muse and Gaut, 1994).</td>
</tr>
<tr>
<td>MGK</td>
<td>Like MG with additional transition/transversion (ts/tv) rate ratio.</td>
</tr>
<tr>
<td>MG1KTS or</td>
<td>Like MG with a transition rate (Kosiol et al., 2007).</td>
</tr>
<tr>
<td>MGKAP2</td>
<td></td>
</tr>
<tr>
<td>MG1KTV or</td>
<td>Like MG with a transition rate and a transversion rate (Kosiol et al., 2007).</td>
</tr>
<tr>
<td>MGKAP3</td>
<td></td>
</tr>
<tr>
<td>MG2K or</td>
<td>Like MG with a transition rate and a transversion rate (Kosiol et al., 2007).</td>
</tr>
<tr>
<td>MGKAP4</td>
<td></td>
</tr>
<tr>
<td>GY</td>
<td>Nonsynonymous/synonymous and transition/transversion rate ratios (Goldman and Yang, 1994).</td>
</tr>
<tr>
<td>GY1KTS or</td>
<td>Like GY with a transition rate (Kosiol et al., 2007).</td>
</tr>
<tr>
<td>GYKAP2</td>
<td></td>
</tr>
<tr>
<td>GY1KTV or</td>
<td>Like GY with a transition rate (Kosiol et al., 2007).</td>
</tr>
<tr>
<td>GYKAP3</td>
<td></td>
</tr>
<tr>
<td>GY2K or</td>
<td>Like GY with a transition rate and a transversion rate (Kosiol et al., 2007).</td>
</tr>
<tr>
<td>GYKAP4</td>
<td></td>
</tr>
<tr>
<td>ECMK07 or</td>
<td>Empirical codon model (Kosiol et al., 2007).</td>
</tr>
<tr>
<td>KOSI07</td>
<td></td>
</tr>
<tr>
<td>ECMrest</td>
<td>Restricted version of ECMK07 that allows only one nucleotide exchange.</td>
</tr>
<tr>
<td>ECMS05 or</td>
<td>Empirical codon model (Schneider et al., 2005).</td>
</tr>
<tr>
<td>SCHN05</td>
<td></td>
</tr>
</tbody>
</table>

Users could specify the model parameters (e.g., Nonsynonymous/synonymous (dn/ds) rate ratio, and/or transition/transversion (ts/tv) rate ratio, and/or transition rate, and/or a transversion rate) by `<Model_Name>{<omega>,[<kappa>],[<kappa2>]}`. For example, `MG2K{1.0,0.3,0.5}` specifies the nonsynonymous/synonymous (dn/ds) rate ratio, the transition rate, and the transversion rate are 1.0, 0.3, 0.5, respectively. The number of input parameters depends on the definition of each model.

The last three models (ECMK07, ECMrest or ECMS05) are called *empirical* codon models, whereas the others are called *mechanistic* codon models.

Moreover, IQ-TREE supports combined empirical-mechanistic codon models using an underscore separator (_). For example:

- **ECMK07_GY2K**: The combined ECMK07 and GY2K model, with the rate entries being multiplication of the two corresponding rate matrices.
11.3. CODON MODELS

Thus, there can be many such combinations.

**Starting with version 1.5.6:** If the model name does not match any of the above listed models, IQ-TREE assumes that it is a file containing lower diagonal part of non-stop codon exchange rate matrix, non-stop codon frequencies and a list of non-stop codons. The rest of the file will be ignored. Example files (ECMrest.dat and ECMunrest.dat) can be downloaded from the supplementary material (Kosiol et al., 2007).

**NOTE:** Branch lengths under codon models are interpreted as number of nucleotide substitutions per codon site. Thus, they are typically 3 times longer than under DNA models.

### 11.3.2 Codon frequencies

IQ-TREE supports the following codon frequencies:

<table>
<thead>
<tr>
<th>FreqType</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>+F</td>
<td>Empirical codon frequencies counted from the data. In AliSim, if users neither specify base frequencies nor supply an input alignment, AliSim will generate base frequencies from empirical distributions.</td>
</tr>
<tr>
<td>+FQ</td>
<td>Equal codon frequencies.</td>
</tr>
<tr>
<td>+F1X4</td>
<td>Unequal nucleotide frequencies but equal nt frequencies over three codon positions. In AliSim, if users don’t supply an input alignment, the base frequencies are randomly generated based on empirical distributions, or users could specify the frequencies via +F1X4{&lt;freq_0&gt;,...,&lt;freq_4&gt;}.</td>
</tr>
<tr>
<td>+F3X4</td>
<td>Unequal nucleotide frequencies and unequal nt frequencies over three codon positions. In AliSim, if users don’t supply an input alignment, the base frequencies are randomly generated based on empirical distributions, or users could specify the frequencies via +F3X4{&lt;freq_0&gt;,...,&lt;freq_11&gt;}</td>
</tr>
</tbody>
</table>

If not specified, the default codon frequency will be +F3X4 for MG-type models, +F for GY-type models and given by the model for empirical codon models.
CHAPTER 11. SUBSTITUTION MODELS

11.4 Binary and morphological models

The binary alignments should contain state 0 and 1, whereas for morphological data, the valid states are 0 to 9 and A to Z.

<table>
<thead>
<tr>
<th>Model</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>JC2</td>
<td>Jukes-Cantor type model for binary data.</td>
</tr>
<tr>
<td>GTR2</td>
<td>General time reversible model for binary data.</td>
</tr>
<tr>
<td>MK</td>
<td>Jukes-Cantor type model for morphological data.</td>
</tr>
<tr>
<td>ORDERED</td>
<td>Allowing exchange of neighboring states only.</td>
</tr>
</tbody>
</table>

Except for GTR2 that has unequal state frequencies, all other models have equal state frequencies.

**TIP:** If morphological alignments do not contain constant sites (typically the case), then an ascertainment bias correction model (+ASC) should be applied to correct the branch lengths for the absence of constant sites.

11.5 Ascertainment bias correction

An ascertainment bias correction (+ASC) model (Lewis, 2001) should be applied if the alignment does not contain constant sites (such as morphological or SNPs data). For example:

- MK+ASC: For morphological data.
- GTR+ASC: For SNPs data.

+ASC will correct the likelihood conditioned on variable sites. Without +ASC, the branch lengths might be overestimated.

11.6 Rate heterogeneity across sites

IQ-TREE supports all common rate heterogeneity across sites models:

<table>
<thead>
<tr>
<th>RateType</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>+I</td>
<td>allowing for a proportion of invariable sites.</td>
</tr>
<tr>
<td>+G</td>
<td>discrete Gamma model (Yang, 1994) with default 4 rate categories. The number of categories can be changed with e.g. +G8.</td>
</tr>
</tbody>
</table>
### Rate Heterogeneity Across Sites

<table>
<thead>
<tr>
<th>RateType</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>+GC</td>
<td>continuous Gamma model (<a href="#">Yang, 1994</a>) (for AliSim only).</td>
</tr>
<tr>
<td>+I+G</td>
<td>invariable site plus discrete Gamma model (<a href="#">Gu et al., 1995</a>).</td>
</tr>
<tr>
<td>+R</td>
<td>FreeRate model (<a href="#">Yang, 1995</a>; <a href="#">Soubrier et al., 2012</a>) that generalizes the +G model by relaxing the assumption of Gamma-distributed rates. The number of categories can be specified with e.g. +R6 (default 4 categories if not specified). The FreeRate model typically fits data better than the +G model and is recommended for analysis of large data sets.</td>
</tr>
<tr>
<td>+I+R</td>
<td>invariable site plus FreeRate model.</td>
</tr>
</tbody>
</table>

**TIP:** The new ModelFinder (`-m MFP` option) tests the FreeRate model, whereas the standard procedure (`-m TEST`) does not.

Users can fix the parameters of the model. For example, +I{0.2} will fix the proportion of invariable sites (pinvar) to 0.2; +G{0.9} will fix the Gamma shape parameter (alpha) to 0.9; +I{0.2}+G{0.9} will fix both pinvar and alpha. To fix the FreeRate model parameters, use the syntax +Rk{w1,r1,...,wk,rk} (replacing k with the number of categories). Here, w1, ..., wk are the weights and r1, ..., rk the rates for each category.

**NOTE:** For the +G model IQ-TREE implements the mean approximation approach ([Yang, 1994](#)). The same is done in RAxML and PhyML. However, some programs like TREE-PUZZLE implement the median approximation approach, which makes the resulting log-likelihood not comparable. IQ-TREE can change to this approach via the `-gmedian` option.
Chapter 12

Complex models

Complex models such as partition and mixture models.

This document gives detailed descriptions of complex maximum-likelihood models available in IQ-TREE. It is assumed that you know the basic substitution models already.

12.1 Partition models

Partition models are intended for phylogenomic (e.g., multi-gene) alignments, which allow each partition to have its own substitution models and evolutionary rates. IQ-TREE supports three types of partition models:

1. *Edge-equal* partition model with equal branch lengths: All partitions share the same set of branch lengths.
2. *Edge-proportional* partition model with proportional branch lengths: Like above but each partition has its own partition specific rate, that rescales all its branch lengths. This model accommodates different evolutionary rates between partitions (e.g. between 1st, 2nd, and 3rd codon positions).
3. *Edge-unlinked* partition model: Each partition has its own set of branch lengths. This is the most parameter-rich partition model, that accounts for e.g., heterotachy (Lopez et al., 2002).
**TIP**: The edge-equal partition model is typically unrealistic as it does not account for different evolutionary speeds between partitions, whereas the edge-unlinked partition model can be overfitting if there are many short partitions. Therefore, the edge-proportional partition model is recommended for a typical analysis.

### 12.1.1 Partition file format

To apply partition models users must first prepare a partition file in RAxML-style or NEXUS format. The RAxML-style is defined by the RAxML software and may look like:

```
DNA, part1 = 1-100
DNA, part2 = 101-384
```

This means two DNA partitions of an alignment, where one groups alignment sites 1-100 into `part1` and 101-384 into `part2`.

The NEXUS format is more complex but more powerful. For example, the above partition scheme may look like:

```
#nexus
begin sets;
  charset part1 = 1-100;
  charset part2 = 101-384;
  charpartition mine = HKY+G:part1, GTR+I+G:part2;
end;
```

The first line contains the keyword `#nexus` to indicate a NEXUS file. It has a `sets` block, which contains two character sets (`charset` command) named `part1` and `part2`. Furthermore, with the `charpartition` command we set the model HKY+G for `part1` and GTR+I+G for `part2`. This is not possible with the RAxML-style format (i.e., one cannot specify +G rate model for one partition and +I+G rate model for the other partition).

**TIP**: IQ-TREE fully supports mixed rate heterogeneity types between partitions (see above example).

One can also specify non-consecutive sites of a partition, e.g. under RAxML-style format:

```
DNA, part1 = 1-100, 250-384
```
12.1. PARTITION MODELS

DNA, part2 = 101-249\3, 102-249\3
DNA, part3 = 103-249\3

or under NEXUS format:

```nexus
begin sets;
  charset part1 = 1-100 250-384;
  charset part2 = 101-249\3 102-249\3;
  charset part3 = 103-249\3;
end;
```

This means, part2 contains sites 101, 102, 104, 105, 107, …, 246, 248, 249; whereas part3 contains sites 103, 106, …, 247. This is useful to specify partitions corresponding to 1st, 2nd and 3rd codon positions.

Moreover, the NEXUS file allows each partition to come from a separate alignment file (not possible under RAxML-style format) with e.g.:

```nexus
begin sets;
  charset part1 = aln1.phy: 1-100\3 201-300;
  charset part2 = aln1.phy: 101-200;
  charset part3 = aln2.phy: *;
  charpartition mine = HKY:part1, GTR+G:part2, WAG+I+G:part3;
end;
```

Here, part1 and part2 correspond to sub-alignments of aln1.phy file and part3 is the entire alignment file aln2.phy. Note that aln2.phy is a protein alignment in this example.

**TIP:** IQ-TREE fully supports mixed data types between partitions.

If you want to specify codon model for a partition, use the **CODON** keyword (otherwise, the partition may be detected as DNA):

```nexus
begin sets;
  charset part1 = aln1.phy:CODON, 1-300;
  charset part2 = aln1.phy: 301-400;
  charset part3 = aln2.phy: *;
  charpartition mine = GY:part1, GTR+G:part2, WAG+I+G:part3;
end;
```
Note that this assumes part1 has standard genetic code. If not, append CODON with the right genetic code ID.

12.1.2 Partitioned analysis

Having prepared a partition file, one is ready to start a partitioned analysis with -q (edge-equal), -spp (edge-proportional) or -sp (edge-unlinked) option. See this tutorial for more details.

12.2 Mixture models

12.2.1 What is the difference between partition and mixture models?

Mixture models, like partition models, allow more than one substitution model along the sequences. However, while a partition model assigns each alignment site a given specific model, mixture models do not need this information. A mixture model will compute for each site its probability (or weight) of belonging to each of the mixture classes (also called categories or components). Since the site-to-class assignment is unknown, the site likelihood under mixture models is the weighted sum of site likelihoods per mixture class.

For example, the discrete Gamma rate heterogeneity is a simple mixture model type. It has several rate categories with equal weight. IQ-TREE also supports a number of predefined protein mixture models such as the profile mixture models C10 to C60 (The ML variants of Bayesian CAT models).

Here, we discuss several possibilities to define new mixture models in IQ-TREE.

12.2.2 Defining mixture models

To start with, the following command:

\[ \texttt{iqtree -s example.phy -m "MIX\{JC,HKY\}"} \]

specifies a mixture model (via the \texttt{MIX} keyword in the model string) with two components. The components (1) JC model, and (2) HKY model, are given in curly brackets and separated with a comma. IQ-TREE will then estimate the parameters of both mixture components as well as their weights: the proportion of sites belonging to each component.
12.2. MIXTURE MODELS

NOTE: Do not forget the double-quotes around model string! They prevent interpretation of the curly brackets by the command line shell, i.e., MIX\{JC, HKY\} would otherwise be interpreted as MIXJC MIXHKY.

Mixture models can be combined with rate heterogeneity, e.g.:

```
iqtree -s example.phy -m "MIX\{JC, HKY\}+G4"
```

Here, we specify two mixture components and four Gamma rate categories. Effectively, this means that there are eight mixture components. Each site has a probability belonging to either JC or HKY and to one of the four rate categories.

12.2.3 Profile mixture models

Sometimes one only wants to model the changes in nucleotide or amino-acid frequencies along the sequences while keeping the substitution rate matrix the same. This can be specified in IQ-TREE via FMIX(...) model syntax. For convenience the mixture components can be defined in a NEXUS file like this (example corresponds to the CF4 model of (Wang et al., 2008)):

```
#nexus
begin models;
  frequency Fclass1 = 0.02549352 0.01296012 0.005545202
                     0.006005566 0.01002193 0.01112289 0.008811948
                     0.001796161 0.003512188 0.2108274 0.2730413
                     0.005545202 0.006005566 0.01002193 0.008811948
                     0.001796161 0.003512188 0.2108274 0.2730413
                     0.01379098 0.2376598;
  frequency Fclass2 = 0.09596966 0.008786096 0.02805857
                     0.01880183 0.005026264 0.006454635 0.01582725
                     0.7215719 0.003379354 0.002257725 0.003013483
                     0.001511657 0.002107865 0.006751404 0.04798539
                     0.01141559 0.000523736 0.004934972;
  frequency Fclass3 = 0.01726065 0.005467988 0.01092937
                     0.3627871 0.001046402 0.01984758 0.5149206
                     0.004145081 0.002563289 0.002955213 0.005286931
                     0.01558693 0.002693098 0.002075771 0.003006167
                     0.01263069 0.01082144 0.002693098 0.002075771
                     0.01144787 0.004573568;
  frequency Fclass4 = 0.1263139 0.09564027 0.07050061
                     0.03316681 0.02095119 0.05473468 0.02790523
                     0.009007538 0.03441334 0.008565319 0.008061884
                     0.1070804 0.009019514 0.05018693 0.07948
                     0.09447839 0.09258897 0.01390669 0.05367769
                     0.01230413;
```
frequency CF4model = FMIX{empirical,Fclass1,Fclass2,Fclass3, Fclass4};
end;

NOTE: The amino-acid order in this file is: A R N D C Q E G H I L K M F P S T W Y V.

Here, the NEXUS file contains a models block to define new models. More explicitly, we define four AA profiles Fclass1 to Fclass4, each containing 20 AA frequencies. Then, the frequency mixture is defined with

```
FMIX{empirical,Fclass1,Fclass2,Fclass3,Fclass4}
```

This means, we have five components: the first corresponds to empirical AA frequencies to be inferred from the data and the remaining four components are specified in this NEXUS file. Please save this to a file, say, mymodels.nex. One can now start the analysis with:

```
iqtree -s some_protein.aln -mdef mymodels.nex -m JTT+CF4model+G
```

The -mdef option specifies the NEXUS file containing user-defined models. Here, the JTT matrix is applied for all alignment sites and one varies the AA profiles along the alignment. One can use the NEXUS syntax to define all other profile mixture models such as C10 to C60.

### 12.2.4 NEXUS model file

In fact, IQ-TREE uses this NEXUS model file internally to define all protein mixture models. In addition to defining state frequencies, one can specify the entire model with rate matrix and state frequencies together. For example, the LG4M model (Le et al., 2012) can be defined by:

```
#nexus
begin models;
  model LG4M1 =
    0.269343
    0.254612 0.150988
    0.236821 0.659648
    ....;
  ....;
  model LG4M4 = ....;
```
Here, we first define the four matrices $\text{LG4M}_1$, $\text{LG4M}_2$, $\text{LG4M}_3$ and $\text{LG4M}_4$ in PAML format (see protein models). Then $\text{LG4M}$ is defined as a mixture model with these four components fused with Gamma rate heterogeneity (via $\ast\text{G}_4$ syntax instead of $+\text{G}_4$). This means that, in total, we have 4 mixture components instead of 16. The first component $\text{LG4M}_1$ is rescaled by the rate of the lowest Gamma rate category. The fourth component $\text{LG4M}_4$ corresponds to the highest rate.

Note that both frequency and model commands can be embedded into a single model file.

### 12.3 Site-specific frequency models

Starting with version 1.5.0, IQ-TREE provides a new posterior mean site frequency (PMSF) model as a rapid approximation to the time and memory consuming profile mixture models C10 to C60 (Le et al., 2008a; a variant of PhyloBayes' CAT model). The PMSF are the amino-acid profiles for each alignment site computed from an input mixture model and a guide tree. The PMSF model is much faster and requires much less RAM than C10 to C60 (see table below), regardless of the number of mixture classes. Our extensive simulations and empirical phylogenomic data analyses demonstrate that the PMSF models can effectively ameliorate long branch attraction artefacts.

If you use this model in a publication please cite:


Here is an example of computation time and RAM usage for an Obazoa data set (68 sequences, 43615 amino-acid sites) from Brown et al. (2013) using 16 CPU cores:

<table>
<thead>
<tr>
<th>Models</th>
<th>CPU time</th>
<th>Wall-clock time</th>
<th>RAM usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>LG+F+G</td>
<td>43h:38m:23s</td>
<td>3h:37m:23s</td>
<td>1.8 GB</td>
</tr>
<tr>
<td>LG+C20+F+G</td>
<td>584h:25m:29s</td>
<td>46h:39m:06s</td>
<td>38.8 GB</td>
</tr>
<tr>
<td>LG+C60+F+G</td>
<td>1502h:25m:31s</td>
<td>125h:15m:29s</td>
<td>112.8 GB</td>
</tr>
<tr>
<td>LG+PMSF+G</td>
<td>73h:30m:37s</td>
<td>5h:7m:27s</td>
<td>2.2 GB</td>
</tr>
</tbody>
</table>
12.3.1 Example usages

To use the PMSF model you have to provide a guide tree, which, for example, can be obtained by a quicker analysis under the simpler LG+F+G model. The guide tree can then be specified via -ft option, for example:

```bash
iqtree -s <alignment> -m LG+C20+F+G -ft <guide_tree>
```

Here, IQ-TREE will perform two phases. In the first phase, IQ-TREE estimates mixture model parameters given the guide tree and then infers the site-specific frequency profile (printed to .sitefreq file). In the second phase, IQ-TREE will conduct typical analysis using the inferred frequency model instead of the mixture model to save RAM and running time. Note that without -ft option, IQ-TREE will conduct the analysis under the specified mixture model.

The PMSF model allows one, for the first time, to conduct nonparametric bootstrap under such complex models, for example (with 100 bootstrap replicates):

```bash
iqtree -s <alignment> -m LG+C20+F+G -ft <guide_tree> -b 100
```

Please note that the first phase still consumes as much RAM as the mixture model. To overcome this, you can perform the first phase in a high-memory server and the second phase in a normal PC as follows:

```bash
iqtree -s <alignment> -m LG+C20+F+G -ft <guide_tree> -n 0
```

This will stop the analysis after the first phase and also write a .sitefreq file. You can now copy this .sitefreq file to another low-memory machine and run with the same alignment:

```bash
iqtree -s <alignment> -m LG+C20+F+G -fs <file.sitefreq> -b 100
```

This will omit the first phase and thus need much less RAM.

Finally, note that for long (phylogenomic) alignments you can utilize the multicore IQ-TREE version to further save the computing times with, say, 24 cores by:

```bash
# For IQ-TREE version <= 1.5.X
iqtree-omp -nt 24 -s <alignment> -m LG+C20+F+G -fs <file.sitefreq
```

```bash
# For IQ-TREE version >= 1.6.0
iqtree -nt 24 -s <alignment> -m LG+C20+F+G -fs <file.sitefreq>
```

See also the list of relevant command line options.
12.4 Heterotachy models

Sequence data that have evolved under heterotachy, i.e., rate variation across sites and lineages (Lopez, Casane, and Philippe, 2002), are known to mislead phylogenetic inference (Kolaczkowski and Thornton, 2004). To address this issue we introduce the General Heterogeneous evolution On a Single Topology (GHOST) model. More specifically, GHOST is an edge-unlinked mixture model consisting of several site classes, each having a separate set of model parameters and edge lengths on the same tree topology. Thus, GHOST naturally accounts for heterotachous evolution. In contrast to an edge-unlinked partition model, the GHOST model does not require the a priori data partitioning, a possible source of model misspecification.

Extensive simulations show that the GHOST model can accurately recover the tree topology, branch lengths, substitution rate and base frequency parameters from heterotachously-evolved sequences. Moreover, we compare the GHOST model to the partition model and show that, owing to the minimization of model constraints, the GHOST model is able to offer unique biological insights when applied to empirical data.

If you use this model in a publication please cite:


12.4.1 Quick usages

Make sure that you have IQ-TREE version 1.6.0 or later. The GHOST model with k mixture classes is executed by adding +Hk to the model option (-m). For example if one wants to fit a GHOST model with 4 classes in conjunction with the GTR model of DNA evolution to sequences contained in data.fst, one would use the following command:

```
iqtree -s data.fst -m GTR+H4
```

By default the above command will link GTR parameters across all classes. If you want tounlink GTR parameters, so that IQ-TREE estimates them separately for each class, replace +H4 by *H4:

```
iqtree -s data.fst -m GTR*H4
```
Note that this infers one set of empirical base frequencies and apply those to all classes. If one wishes to infer separate base frequencies for each class then the +FO option is required:

```
iqtree -s data.fst -m GTR+FO*H4
```

The -wspm option will generate a .siteprob output file. This contains the probability of each site belonging to each class:

```
iqtree -s data.fst -m GTR+FO*H4 -wspm
```
Chapter 13

Polymorphism-aware models

Use population data to improve inferences.

Polymorphism-aware phylogenetic Models (PoMo) improve phylogenetic inference using population data (site frequency data). Thereby they builds on top of DNA substitution models and naturally account for incomplete lineage sorting. In order to run PoMo, you need more sequences per species/population (ideally five or more chromosomes per species/population) so that information about the site frequency spectrum is available.

Currently this model is only available in the beta version 1.6. Please download it from here:

http://www.iqtree.org/#variant

TIP: For a quick overview of all PoMo related options in IQ-TREE, run the command `iqtree -h` and scroll to the heading POLYMORPHISM AWARE MODELS (PoMo).

If you use PoMo, please cite Schrempf et al., 2016:

13.1 Counts files

The input of PoMo is allele frequency data. Especially, when populations have many individuals it is preferable to count the number of bases at each position compared to providing data for each chromosome in a FASTA file. Thereby file size is decreased and parsed faster.

Counts files contain:

- One headerline that specifies the file as counts file and states the number of populations (leaves on the tree) as well as the number of sites (separated by white space).
- A second headerline with white space separated headings: CRHOM (chromosome), POS (position) and sequence names.
- Many lines with counts of A, C, G and T bases and their respective positions.

Comments:
- Lines before the first headerline starting with # are treated as comments.

Example:

<table>
<thead>
<tr>
<th>CHROM</th>
<th>POS</th>
<th>Sheep</th>
<th>BlackSheep</th>
<th>RedSheep</th>
<th>Wolf</th>
<th>RedWolf</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>0,0,1,0</td>
<td>0,0,1,0</td>
<td>0,0,1,0</td>
<td>0,0,5,0</td>
<td>0,0,0,1</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>0,0,0,1</td>
<td>0,0,0,1</td>
<td>0,0,0,1</td>
<td>0,0,0,5</td>
<td>0,0,0,1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>9</td>
<td>8373</td>
<td>0,0,0,1</td>
<td>1,0,0,0</td>
<td>0,1,0,0</td>
<td>0,1,4,0</td>
<td>0,0,1,0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Y</td>
<td>9999</td>
<td>0,0,0,1</td>
<td>0,1,0,0</td>
<td>0,1,0,0</td>
<td>0,5,0,0</td>
<td>0,0,1,0</td>
</tr>
</tbody>
</table>

The download also includes an example counts file called example.cf. This file is a subset of the great ape data that has been analyzed in one of our publications. It includes twelve great ape population with one to 23 individuals each (two to 56 chromosomes).

13.1.1 Conversion scripts

If you do not want to create counts files with your own scripts, you can use the python script that we provide. For detailed instructions, please refer to the GitHub repository
of the counts file library \texttt{cflib}.

### 13.2 First running example

You can now start to reconstruct a maximum-likelihood tree from this alignment by entering (assuming that \texttt{example.cf} is in the same folder):

```
iqtree -s example.cf -m HKY+P
```

or, e.g.,

```
iqtree -nt 4 -s example.cf -m HKY+P
```

if you use the multicore (OMP) version.\texttt{-s} specifies of the alignment file and \texttt{-m} the model (HKY substitution model with polymorphisms; PoMo), similar to the standard IQ-TREE usage. At the end of the run IQ-TREE writes the same output files as in the standard version (see tutorial).

- \texttt{example.cf.iqtree}: the main report file that is self-readable. You should look at this file to see the computational results. It also contains a textual representation of the final tree.
- \texttt{example.cf.treefile}: the ML tree in NEWICK format, which can be visualized by any supported tree viewer programs like FigTree or iTOL.
- \texttt{example.cf.log}: log file of the entire run (also printed on the screen). To report bugs, please send this log file and the original alignment file to the authors.

The default prefix of all output files is the alignment file name. However, you can always change the prefix using the \texttt{-pre} option, e.g.:

```
iqtree -s example.cf -pre myprefix
```

This prevents output files to be overwritten when you perform multiple analyses on the same alignment within the same folder.

### 13.3 Substitution models

Different DNA substitution models can be selected with the \texttt{-m} option. E.g., to select the GTR model, run IQ-TREE with:

```
iqtree -s example.cf -m GTR+P
```
13.4 Virtual population size

PoMo describes the evolution of populations along a phylogeny by means of a virtual population of constant size $N$, which defaults to nine (for details, see Schrempf et al., 2016). This is a good and stable default value. If only very few chromosomes have been sequenced per population (e.g., two to four), $N$ should be lowered to the average number of chromosomes per population. If enough data is available and calculations are not too time consuming, we advise to increase $N$ up to a maximum of 19. You can choose odd values from three to 19 as well as 2 and 10. E.g., to set $N$ to 19:

```
iqtree -s example.cf -m HKY+P+N19
```

13.5 Level of polymorphism

As of version 1.6, IQ-TREE with PoMo also allows fixation of the level of heterozygosity, which is also called Watterson’s theta or $4Nu$. When analyzing population data, the amount of polymorphism is inferred during maximization of the likelihood. However, in some situations it may be useful to set the level of polymorphism to the observed value in the data (empirical value):

```
iqtree -s example.cf -m HKY+P{EMP}
```

or to set the level of polymorphism by hand, e.g.,:

```
iqtree -s example.cf -m HKY+P{0.0025}
```

Together with the ability to set model parameters, the model can be fully specified, e.g.:

```
iqtree -s example.cf -m HKY{6.0}+P{0.0025}
```

This sets the transition to transversion ratio to a value of 6.0 and the level of polymorphism to a value of 0.0025. In this case, IQ-TREE only performs a tree search because the model is fully specified.
13.6  Sampling method

For advanced users, PoMo offers different methods to read in the data (Schrempf et al., 2016). Briefly, each population and site are treated as follows:

1. **Weighted binomial** (default, +WB): assign the likelihood of each PoMo state to its probability of leading to the observed data, assuming it is binomially sampled. Example:
   ```
   iqtree -s example.cf -m HKY+P+WB
   ```

2. **Weighted hypergeometric** (+WH): assign the likelihood of each PoMo state to its probability of leading to the observed data, assuming it is hypergeometrically sampled. Example:
   ```
   iqtree -s example.cf -m HKY+P+WH
   ```

3. **Sampled**: randomly draw N samples with replacement from the given data. The N picked samples constitute a PoMo state which will be assigned a likelihood of 1. All other PoMo states have likelihood 0. Example:
   ```
   iqtree -s example.cf -m HKY+P+S
   ```

We expect a slight overestimation of the heterozygosity for weighted binomial sampling. This is because monomorphic (fixed) states can be reached from polymorphic states during the sampling step, while polymorphic states cannot be reached from monomorphic states (sampling does not involve mutation). I.e., only when the level of heterozygosity at the leaves is overestimated, the sampling step leads to the correct amount of heterozygosity observed in the data.

If you wish to avoid this effect, use weighted hypergeometric sampling. However, we have observed that weighted binomial sampling is more stable.

13.7  State frequency type

Similar to standard models, the state frequency type can be selected with +F model string modifiers. The default is to set the state frequencies (i.e., the frequencies of the nucleotides A, C, G and T) to the observed values in the data (empirical value). To estimate the allele frequencies together with the rate parameters during maximization of the likelihood, use:

   ```
   iqtree -s example.cf -m GTR+P+FO
   ```
13.8 Rate heterogeneity

Recently, PoMo allows inference with different rate categories. As of version 1.6, only discrete Gamma rate heterogeneity is supported. Please be aware, that for biological and mathematical reasons (we cannot simply scale the full transition matrix but have to separate the mutational component from genetic drift), the run time scales linearly with the number of rate categories. In the future, we plan to work on decreasing run time as well as implement more rate heterogeneity types. To use a discrete Gamma model with 4 rate categories, use:

```
iqtree -s example.cf -m HKY+P+G4
```

13.9 Bootstrap branch support

Bootstrapping works as expected with PoMo. The standard non-parametric bootstrap is invoked by the `-b` option, e.g., for 100 replicates:

```
iqtree -s example.cf -m HKY+P -b 100
```

To overcome the computational burden required by the non-parametric bootstrap, IQ-TREE introduces an ultra fast bootstrap approximation (UFBoot) that is orders of magnitude faster than the standard procedure and provides relatively unbiased branch support values. To run UFBoot, use the option `-bb`, e.g., for 1000 replicates:

```
iqtree -s example.cf -m HKY+P -bb 1000
```

For a detailed description, please refer to the bootstrap tutorial.

13.10 Interpretation of branch lengths

PoMo estimates the branch length in number of mutations and frequency shifts (drift) per site. The number of drift events compared to the number of mutations becomes higher if the virtual population size is increased. To get the branch length measured in number of substitutions per site which enables a comparison to the branch length estimated by standard DNA substitution models, it has to be divided by $N^2$. PoMo also outputs the total tree length measured in number of substitutions per site in `example.cf.iqtree`. An example of the relevant section:

```
NOTE: The branch lengths of PoMo measure mutations and frequency shifts.
```
To compare PoMo branch lengths to DNA substitution models use the tree length measured in substitutions per site.

Total tree length (sum of branch lengths)
- measured in number of mutations and frequency shifts per site: 0.71200751
- measured in number of substitutions per site (divided by $N^2$): 0.00879022

Sum of internal branch lengths
- measured in mutations and frequency shifts per site: 0.01767814 (2.48285810% of tree length)
- measured in substitutions per site: 0.01767814 (2.48285810% of tree length)
Chapter 14

Compilation guide

For advanced users to compile IQ-TREE source code.

14.1 General requirements

- A C++ compiler such as GCC (version >= 4.8), Clang, MS Visual Studio and Intel C++ compiler.
- CMake version >= 2.8.10.
- Boost library for IQ-TREE version 2. Boost library is typically available under Linux. Under MacOS you use Homebrew and run `brew install boost` to install the Boost library. By default IQ-TREE will detect the path to the installed Boost library.
- Eigen3 library (for IQ-TREE version >= 1.6). Under MacOS you use Homebrew and run `brew install eigen` to install the Boost library. By default IQ-TREE will detect the path to the installed Eigen3 library. If this failed, you have to manually specify `-DEIGEN3_INCLUDE_DIR=<installed_eigen3_dir>` to the `cmake` command (see below).
- OpenMP library, which is used to compile the multicore version. This should typically be the case with gcc under Linux. Under MacOS you use Homebrew and run `brew install libomp` to install the OpenMP library.
- *(Optional)* Install git if you want to clone source code from IQ-TREE GitHub repository.
14.2 Downloading source code

Choose the source code (zip or tar.gz) of the IQ-TREE release you want to use from:
https://github.com/iqtree/iqtree2/releases

For IQ-TREE version 1 please use:
https://github.com/Cibiv/IQ-TREE/releases/

Alternatively, if you have git installed, you can also clone the source code from GitHub with:

```bash
git clone https://github.com/iqtree/iqtree2.git
```

For IQ-TREE version 1 please clone:

```bash
git clone https://github.com/Cibiv/IQ-TREE.git
```

Please find below separate compilation guide for Linux, Mac OS X, and Windows as well as for 32-bit version or for MPI version.

14.3 Compiling under Linux

**TIP:** Ready made IQ-TREE packages are provided for Debian and Arch Linux (AUR).

1. Open a Terminal.
2. Change to the source code folder:

```bash
cd PATH_TO_EXTRACTED_SOURCE_CODE
```

3. Create a subfolder, say, build and go into this subfolder:

```bash
mkdir build
cd build
```

4. Configure source code with CMake:

```bash
cmake ..
```
If `cmake` failed with message about `Eigen3 not found`, then install Eigen3 library and run `cmake` again. If this still failed, you have to manually specify the downloaded directory of Eigen3 with:

```
cmake -DEIGEN3_INCLUDE_DIR=<eigen3_dir> ..
```

5. Compile source code with `make`:

```
make -j
```

`j` option tells it to use all CPU cores to speed up the compilation. Without this option, `make` uses only one core, which might be slow.

This creates an executable `iqtree2` (`iqtree` for version 1). It can be copied to your system search path so that IQ-TREE can be called from the Terminal simply with the command line `iqtree2`.

**TIP:** The above guide typically compiles IQ-TREE with `gcc`. If you have Clang installed and want to compile with Clang, the compilation will be similar to Mac OS X like below.

### 14.4 Compiling under Mac OS X

**TIP:** A ready made IQ-TREE package is provided by *Homebrew* by simply running `brew install homebrew/science/iqtree2`.

- Make sure that Clang compiler is installed, which is typically the case if you installed Xcode and the associated command line tools.
- If you installed `cmake` with Homebrew
- Find the path to the CMake executable, which is typically `/Applications/CMake.app/Contents/bin/cmake`. For later convenience, please create a symbolic link `cmake` to this cmake executable, so that cmake can be invoked from the Terminal by simply entering `cmake`.

The steps to compile IQ-TREE are similar to Linux (see above), except that you need to specify `clang` as compiler when configuring source code with CMake (step 4):

```
cmake -DCMAKE_C_COMPILER=clang -DCMAKE_CXX_COMPILER=clang++ ..
```
14.5 Compiling under Windows

- Please first install TDM-GCC (a GCC version for Windows) from http://tdm-gcc.tdragon.net.

**WARNING**: Although IQ-TREE can also be built with TDM-GCC, the executable does not run properly due to stack alignment issue and the libgomp library causes downgraded performance for the OpenMP version. Thus, it is recommended to compile IQ-TREE with Clang.

1. Open Command Prompt.
2. Change to the source code folder:

```bash
cd PATH_TO_EXTRACTED_SOURCE_CODE
```

Please note that Windows uses back-slash (\) instead of slash (/) as path name separator.
3. Create a subfolder, say, `build` and go into this subfolder:

```bash
mkdir build
cd build
```
4. Configure source code with CMake:
14.6. COMPILING 32-BIT VERSION

```plaintext
cmake -G "MinGW Makefiles" -DCMAKE_C_COMPILER=clang -DCMAKE_CXX_COMPILER=clang++ -DCMAKE_C_FLAGS=--target=x86_64-pc-windows-gnu -DCMAKE_CXX_FLAGS=--target=x86_64-pc-windows-gnu -DCMAKE_MAKE_PROGRAM=mingw32-make ..
```

To build the multicore version please add `-DIQTREE_FLAGS=omp` to the cmake command. Note that the make program shipped with TDM-GCC is called `mingw32-make`, thus needed to specify like above. You can also copy `mingw32-make` to `make` to simplify this step.

5. Compile source code with:

```plaintext
mingw32-make
```

or

```plaintext
mingw32-make -j4
```

to use 4 cores for compilation instead of only 1.

14.6 Compiling 32-bit version

**NOTE:** Typically a 64-bit IQ-TREE version is built and recommended! The 32-bit version has several restriction like maximal RAM usage of 2GB and no AVX support, thus not suitable to analyze large data sets.

To compile the 32-bit version instead, simply add `m32` into `IQTREE_FLAGS` of the cmake command:

```plaintext
cmake -DIQTREE_FLAGS=m32 ..
```

To build the 32-bit multicore version, run:

```plaintext
cmake -DIQTREE_FLAGS=omp-m32 ..
```

For Windows you need to change Clang target with:

```plaintext
cmake -G "MinGW Makefiles" -DCMAKE_C_FLAGS=--target=i686-pc-windows-gnu -DCMAKE_CXX_FLAGS=--target=i686-pc-windows-gnu -DCMAKE_MAKE_PROGRAM=mingw32-make ..
```
14.7 Compiling MPI version

Requirements:

- Download source code of IQ-TREE version 1.5.1 or later.
- Install an MPI library (e.g., OpenMPI) if not available in your system. For Mac OS X, the easiest is to install Homebrew package manager, and then install OpenMPI library from the command line with:

```
brew install openmpi
```

Then simply run CMake and make by:

```
cmake -DIQTREE_FLAGS=mpi ..
make -j4
```

IQ-TREE will automatically detect and setup the MPI paths and library. Alternatively, you can also use the MPI C/C++ compiler wrappers (typically named mpicc and mpicxx), for example:

```
cmake -DCMAKE_C_COMPILER=mpicc -DCMAKE_CXX_COMPILER=mpicxx ..
make -j4
```

The executable is named iqtree-mpi. One can then run mpirun to start the MPI version with e.g. 2 processes:

```
mpirun -np 2 iqtree-mpi -s alignment ...
```

If you want to compile the hybrid MPI/OpenMP version, simply run:

```
cmake -DIQTREE_FLAGS=omp-mpi ..
make -j4
```

The resulting executable is then named iqtree-mpi (iqtree-omp-mpi for IQ-TREE versions <= 1.5.X). This can be used to start an MPI run with e.g. 4 processes and 2 cores each (i.e., a total of 8 cores will be used):

```
# For IQ-TREE version <= 1.5.X
mpirun -np 4 iqtree-omp-mpi -nt 2 -s alignment ...

# For IQ-TREE version >= 1.6.0
mpirun -np 4 iqtree-mpi -nt 2 -s alignment ...
```
NOTE: Please be aware that OpenMP and OpenMPI are different! OpenMP is the standard to implement shared-memory multithreading program, that we use to provide the multicore IQ-TREE version. Whereas OpenMPI is a message passing interface (MPI) library for distributed memory parallel system, that is used to compile iqtree-mpi. Thus, one cannot run iqtree with mpirun!

14.8 Compiling Xeon Phi Knights Landing version

Starting with version 1.6, IQ-TREE supports Xeon Phi Knights Landing (AVX-512 instruction set). To build this version the following requirements must be met:

- A C++ compiler, which supports AVX-512 instruction set: GCC 5.1, Clang 3.7, or Intel compiler 14.0.

The compilation steps are the same except that you need to add `-DIQTREE_FLAGS=KNL` to the cmake command:

```
cmake -DIQTREE_FLAGS=KNL ..
make -j4
```

The compiled iqtree binary will automatically choose the proper computational kernel for the running computer. Thus, it works as normal and will speed up on Knights Landing CPUs. Run `./iqtree` to make sure that the binary was compiled correctly:

```
IQ-TREE multicore Xeon Phi KNL version 1.6.beta for Linux 64-bit built May 7 2017
```

14.9 About precompiled binaries

To provide the pre-compiled IQ-TREE binaries at http://www.iqtree.org, we used Clang 3.9.0 for Windows and Clang 4.0 for Linux and macOS. We recommend to use Clang instead of GCC as Clang-compiled binaries run about 5-10% faster than GCC-compiled ones.

Linux binaries were statically compiled with Ubuntu 16.4 using libc++ library. The static-linked binaries will thus run on most Linux distributions. The CMake command is (assuming that clang-4 and clang++-4 point to the installed Clang):

```
# 64-bit version
cmake -DIQTREE_FLAGS=static-libcxx -DCMAKE_C_COMPILER=clang-4 -DCMAKE_CXX_COMPILER=clang++-4 <source_dir>
```
macOS binaries were compiled under macOS Sierra, but the binaries are backward compatible with Mac OS X 10.7 Lion:

```
cmake -DCMAKE_C_COMPILER=clang-4 -DCMAKE_CXX_COMPILER=clang++-4 <source_dir>
```

Windows binaries were statically compiled under Windows 7 using Clang 3.9.0 in combination with TDM-GCC 5.1.0, which provides the necessary libraries for Clang.

```
# 64-bit version
make -G "MinGW Makefiles" -DIQTREE_FLAGS=static -
    DCMAKE_C_COMPILER=clang -DCMAKE_CXX_COMPILER=clang++ -
    DCMAKE_C_FLAGS=--target=x86_64-pc-windows-gnu -
    DCMAKE_CXX_FLAGS=--target=x86_64-pc-windows-gnu -
    DCMAKE_MAKE_PROGRAM=mingw32-make ..

# 32-bit version
make -G "MinGW Makefiles" -DIQTREE_FLAGS=static -
    DCMAKE_C_COMPILER=clang -DCMAKE_CXX_COMPILER=clang++ -
    DCMAKE_C_FLAGS=--target=i686-pc-windows-gnu -DCMAKE_CXX_FLAGS
    =--target=i686-pc-windows-gnu -DCMAKE_MAKE_PROGRAM=mingw32-make ..
```

14.10 Setup an Xcode project in MacOS

Many developers in MacOS use Xcode to develop the code. To generate an XCode project for IQ-TREE, you need to run:

```
mkdir build-xcode
cd build-xcode
cmake -G Xcode <IQTREE_SOURCE_DIR>
```
14.11 This will generate a subfolder `build-xcode/iqtree.xcodeproj`, which you can open in Xcode now.
Chapter 15

Frequently asked questions

For common questions and answers.

15.1 How do I get help?

If you have questions please follow the steps below:

1. Continue to read the FAQ below, which may answer your questions already.
2. If not, read the documentation http://www.iqtree.org/doc.
3. If you still could not find the answer, search the IQ-TREE Google group. There is a “Search for topics” box at the top of the Google group web page.
4. Finally, if no answer is found, post a question to the IQ-TREE group. The average response time is one to two working days.

For other feedback and feature request, please post a topic to the IQ-TREE Google group. We welcome all suggestions to further improve IQ-TREE! For feature request, please also explain why you think such a new feature would be useful or how can it help for your work.

15.2 How do I report bug?

For bug report, please send the following information to the IQ-TREE Google group:

1. A description of the behaviour, which you think might be unexpected or caused by a bug.
2. The first 10 lines and last 10 lines of the .log file.
3. (If possible) the assertion message printed on the screen, which may look like this:

```
```

The development team will get back to you and may ask for the full .log file and input data files for debugging purpose, if necessary. In such case please **only send your data files directly to the developers for confidential reason!** Keep in mind that everyone can see all emails sent to the group!

### 15.3 How do I interpret ultrafast bootstrap (UF-Boot) support values?

The ultrafast bootstrap (UFBoot) feature (-bb option) was published in (Minh et al., 2013). One of the main conclusions is, that UFBoot support values are more unbiased: 95% support correspond roughly to a probability of 95% that a clade is true. So this has a different meaning than the normal bootstrap supports (where you start to believe in the clade if it has >80% BS support). For UFBoot, you should only start to believe in a clade if its support is >= 95%. Thus, the interpretations are different and you should not compare BS% with UFBoot% directly.

Moreover, it is recommended to also perform the SH-aLRT test (Guindon et al., 2010) by adding `-alrt 1000` into the IQ-TREE command line. Each branch will then be assigned with SH-aLRT and UFBoot supports. One would typically start to rely on the clade if its SH-aLRT >= 80% and UFBoot >= 95%.

### 15.4 How does IQ-TREE treat gap/missing/ambiguous characters?

Gaps (-) and missing characters (?) or N for DNA alignments) are treated in the same way as unknown characters, which represent no information. The same treatment holds for many other ML software (e.g., RAxML, PhyML). More explicitly, for a site (column) of an alignment containing AC-AG-A (i.e. A for sequence 1, C for sequence 2, - for sequence 3, and so on), the site-likelihood of a tree T is equal to the site-likelihood of the subtree of T restricted to those sequences containing non-gap characters (ACAGA).

Ambiguous characters that represent more than one character are also supported: each represented character will have equal likelihood. For DNA the following ambiguous nucleotides are supported according to **IUPAC nomenclature**:
15.5. **CAN I MIX DNA AND PROTEIN DATA IN A PARTITIONED ANALYSIS?**

<table>
<thead>
<tr>
<th>Nucleotide</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>A or G (purine)</td>
</tr>
<tr>
<td>Y</td>
<td>C or T (pyrimidine)</td>
</tr>
<tr>
<td>W</td>
<td>A or T (weak)</td>
</tr>
<tr>
<td>S</td>
<td>G or C (strong)</td>
</tr>
<tr>
<td>M</td>
<td>A or C (amino)</td>
</tr>
<tr>
<td>K</td>
<td>G or T (keto)</td>
</tr>
<tr>
<td>B</td>
<td>C, G or T (next letter after A)</td>
</tr>
<tr>
<td>H</td>
<td>A, C or T (next letter after G)</td>
</tr>
<tr>
<td>D</td>
<td>A, G or T (next letter after C)</td>
</tr>
<tr>
<td>V</td>
<td>A, G or C (next letter after T)</td>
</tr>
<tr>
<td>?, - , . , ~ , O</td>
<td>A, G, C or T (unknown; all 4 nucleotides are equally likely)</td>
</tr>
<tr>
<td>N, X</td>
<td></td>
</tr>
</tbody>
</table>

For protein the following ambiguous amino-acids are supported:

<table>
<thead>
<tr>
<th>Amino-acid</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>N or D</td>
</tr>
<tr>
<td>Z</td>
<td>Q or E</td>
</tr>
<tr>
<td>J</td>
<td>I or L</td>
</tr>
<tr>
<td>U</td>
<td>unknown AA (although it is the 21st AA)</td>
</tr>
<tr>
<td>?, - , . , ~ , *</td>
<td>unknown AA (all 20 AAs are equally likely)</td>
</tr>
</tbody>
</table>

15.5 **Can I mix DNA and protein data in a partitioned analysis?**

Yes! You can specify this via a NEXUS partition file. In fact, you can mix any data types supported in IQ-TREE, including also codon, binary and morphological data. To do so, each data type should be stored in a separate alignment file (see also [Partitioned analysis with mixed data](#)). As an example, assuming `dna.phy` is a DNA alignment and and `prot.phy` is a protein alignment. Then a partition file mixing two types of data can be specified as follows:

```nexml
begin sets;
  charset part1 = dna.phy: 1-100 201-300;
  charset part2 = dna.phy: 101-200;
  charset part3 = prot.phy: 1-150;
```
CHAPTER 15. FREQUENTLY ASKED QUESTIONS

```
charset part4 = prot.phy: 151-400;
charpartition mine = HKY:part1, GTR+G:part2, WAG+I+G:part3,
    LG+G:part4;
end;
```

**NOTE:** The site count for each alignment should start from 1, and **not** continue from the last position of a previous alignment (e.g., see part3 and part4 declared above).

### 15.6 What is the interpretation of branch lengths when mixing codon and DNA data?

When mixing codon and DNA data in a partitioned analysis, the branch lengths are interpreted as the number of nucleotide substitutions per nucleotide site! This is different from having only codon data, where branch lengths are the number of nucleotide substitutions per codon site (thus typically 3 times longer than under DNA models).

Note that if you mix codon, DNA and protein data, the branch lengths are then the number of character substitutions per site, where character is either nucleotide or amino-acid.

### 15.7 What is the purpose of composition test?

At the beginning of each run, IQ-TREE performs a composition chi-square test for every sequence in the alignment. The purpose is to test for homogeneity of character composition (e.g., nucleotide for DNA, amino-acid for protein sequences). A sequence is denoted **failed** if its character composition significantly deviates from the average composition of the alignment.

More specifically, for each sequence, compute:

\[
\text{chi2} = \sum_{i=1}^{k} \frac{(O_i - E_i)^2}{E_i}
\]

where \( k \) is the size of the alphabet (e.g. 4 for DNA, 20 for amino acids) and the values 1 to \( k \) correspond uniquely to one of the characters. \( O_i \) is the character frequency in the sequence tested. \( E_i \) is the overall character frequency from the entire alignment.

Whether the character composition deviates significantly from the overall composition is done by testing the \( \text{chi2} \) value using the chi2-distribution with \( k-1 \) degrees of freedom (\( df=3 \) for DNA or \( df=19 \) for amino acids). By and large it is a normal Chi^2 test.
This test should be regarded as an explorative tool which might help to nail down problems in a dataset. One would typically not remove failing sequences by default. But if the tree shows unexpected topology the test might point in direction of the origin of the problem.

Furthermore, please keep in mind, this test is performed at the very beginning, where IQ-TREE does not know anything about the models yet. That means:

- If you have partitioned (multi-gene) data, it might be more reasonable to test this separately for each partition in a partition analysis. Here, one might want to be able to decide whether some partitions should better be discarded if it is hard to find a composition representing the sequences in the partition. Or on the other hand if a sequence fails for many partitions and show very unexpected phylogenetic topologies, try without it.
- If you have (phylogenomic) protein data, you can also try several protein mixture models, which account for different amino-acid compositions along the sequences, for example, the C10 to C60 profile mixture models.
- Finally, it is recommended to always check the alignment (something one should always do anyway), especially if they have been collected and produced automatically.

15.8 What is the good number of CPU cores to use?

Starting with version 1.5.1, you can use option \(-\texttt{nt\ AUTO}\) to automatically determine the best number of threads for your current data and computer.

If you want to know more details: IQ-TREE can utilize multicore machines to speed up the analysis via \(-\texttt{nt}\) option. However, it does not mean that using more cores will always result in less running time: if your alignment is short, using too many cores may even slow down the analysis. This is because IQ-TREE parallelizes the likelihood computation along the alignment. Thus, the parallel efficiency is only increased with longer alignments.

If you want to restrict the number of CPU cores allocated by \(-\texttt{nt\ AUTO}\) use \(-\texttt{ntmax}\) to specify the maximal number of CPU cores allowed (DEFAULT: \#CPU cores on the current machine).
15.9 How do I save time for standard bootstrap?

The standard bootstrap is rather slow and may take weeks/months for large data sets. One way to speed up is to use the multicore version. However, this only works well for long alignments (see What is the good number of CPU cores to use?). Another way is to use many machines or a computing cluster and split the computation among the machines. To illustrate, you want to perform 100 bootstrap replicates and have 5 PCs, each has 4 CPU cores. Then you can:

1. Perform 5 independent bootstrap runs (each with 20 replicates) on the 5 machines with 5 prefix outputs (such that output files are not overwritten). For example:

```
# For old IQ-TREE versions <= 1.5.X, change iqtree to iqtree-omp
iqtree -nt 4 -s input_alignment -bo 20 ... -pre boot1
iqtree -nt 4 -s input_alignment -bo 20 ... -pre boot2
iqtree -nt 4 -s input_alignment -bo 20 ... -pre boot3
iqtree -nt 4 -s input_alignment -bo 20 ... -pre boot4
iqtree -nt 4 -s input_alignment -bo 20 ... -pre boot5
```

Note that if you have access to a computing cluster, you may want to submit these jobs onto the cluster queue in parallel and with even more fine-grained parallelization (e.g. one replicate per job).

2. Once all 5 runs finished, combine the 5 .boottrees file into one file (e.g. by `cat` command under Linux):

```
cat boot*.boottrees > alltrees
```

3. Construct a consensus tree from the combined bootstrap trees:

```
iqtree -con -t alltrees
```

The consensus tree is then written to .contree file.

4. Estimate branch lengths of the consensus tree using the original alignment:

```
iqtree -s input_alignment -te alltrees.contree -pre alltrees.contree
```

5. You can also perform the analysis on the original alignment:

```
# For old IQ-TREE versions <= 1.5.X, change iqtree to iqtree-omp
```
15.10 Why does IQ-TREE complain about the use of +ASC model?

When using ascertainment bias correction (ASC) model, sometimes you may get an error message:

```
ERROR: Invalid use of +ASC because of ... invariant sites in the alignment
```

or when performing model testing:

```
Skipped since +ASC is not applicable
```

This is because your alignment contains invariant sites (columns), which violate the mathematical condition of the model. The invariant sites can be:

- **Constant sites**: containing a single character state over all sequences. For example, all sequences show an A (Adenine) at a particular site in a DNA alignment.
- **Partially constant sites**: containing a single character, gap or unknown character. For example, at a particular site some sequences show a G (Guanine), some sequences have - (gap) and the other have N.
- **Ambiguously constant sites**: For example, some sequences show a C (Cytosine), some show a Y (meaning C or T) and some show a - (gap).

All these sites must be removed from the alignment before a +ASC model can be applied.

**TIP**: Starting with IQ-TREE version 1.5.0, an output alignment file with suffix `.varsites` is written in such cases, which contain only variable sites from the input alignment. The `.varsites` alignment can then be used with the +ASC model.
15.11 How does IQ-TREE treat identical sequences?

Among a group of identical sequences, IQ-TREE will keep the first two and ignore the rest. If the sequence is the 2nd one, it will be “kept for subsequent analysis”. If it is the 3rd or more, it will be “ignored but added at the end”. The rationale for this is to still be able to calculate the bootstrap support for this group of identical sequences: it is not always 100%. Because by bootstrap resampling, on average only two third of the sites will be present in a bootstrap alignment (due to sampling with replacement), and suddenly another sequence not in this group may actually become identical to this group of sequences. In that case, the bootstrap value will be < 100%.

Therefore, the .uniqueseq.phy printed by IQ-TREE may still contain the identical sequences, but no more than two of each identical group.

15.12 What are the differences between alignment columns/sites and patterns?

Columns are the columns/sites in the alignment and the number of columns is the length of the alignment. In the alignment there might be the same columns. Different columns are called patterns. While (parsimony) informative sites are patterns that have at least two different characters (nucleotides or amino acids) and each character should occur in at least two species. Essentially, informative sites have information for the grouping of species. These patterns are mainly important in the context of parsimony, where no evolutionary model is used. In maximum likelihood inference all patterns containing different characters are important for the estimation of tree topology and branch lengths, while constant/invariant sites (containing only the same character: only A’s or only G’s etc) are important for the correct estimation of the branch lengths. Therefore, should not be excluded from the alignment.

Example:

<table>
<thead>
<tr>
<th>species_1</th>
<th>123456789</th>
</tr>
</thead>
<tbody>
<tr>
<td>species_2</td>
<td>AACGTACGT</td>
</tr>
<tr>
<td>species_3</td>
<td>AACGATCGT</td>
</tr>
<tr>
<td>species_4</td>
<td>AACGTCCT</td>
</tr>
<tr>
<td>species_5</td>
<td>AACCTACCT</td>
</tr>
</tbody>
</table>

- sites/columns 1 and 2 are identical and contain only A’s - invariant site pattern, uninformative
15.12. WHAT ARE THE DIFFERENCES BETWEEN ALIGNMENT COLUMNS/SITES AND PATTERNS?

- sites/columns 3 and 7 are identical and contain only C’s - invariant site pattern, uninformative
- sites/columns 4 and 8 are identical and contain 2 G’s and 2 C’s - informative site pattern
- sites/columns 5, 6 and 9 occur only once, each site is a different pattern. 5th is uninformative, 6th is informative, 9th is invariant and uninformative

Summing up, the alignment has 9 columns,

6 patterns

```
A C G T A T
A C G A T T
A C C G T T
A C C T A T
```

(2 informative)

```
G A
G T
C T
C A
```