Smarter dating moves and faster proposals: revisiting the phylogenetic relaxed clock model

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Abstract

Author summary

Introduction

Models

Preliminaries

Let $\mathcal{T}$ be a binary rooted time tree with N taxa (and $2N-2$ branches). Let L be the number of sites within the multiple sequence alignment D, and let L_{eff} be the *effective* number of sites in the alignment (ie. the number of site patterns). The posterior density of a phylogenetic model is described by

$$p(\mathcal{T}, \vec{\mathcal{R}}, \sigma, \theta | D) \propto p(D|\mathcal{T}, r(\vec{\mathcal{R}}), \theta)\ p(\mathcal{T}|\theta)\ p(\vec{\mathcal{R}}|\sigma)\ p(\sigma)\ p(\theta), \tag{1}$$

for rate standard deviation σ and other model parameters θ. $\vec{\mathcal{R}}$ is a vector of abstracted substitution rates, which is transformed into real rates by $r(\vec{\mathcal{R}})$. Three methods of representing rates as $\vec{\mathcal{R}}$ are presented in **Rate parameterisations**.

Under the *relaxed clock model*, each internal and leaf node is assigned a substitution rate $r_i = r(\mathcal{R}_i)$, which corresponds to its parent branch. There are a total of $|\vec{\mathcal{R}}| = 2N-2$ rates, which are independently distributed under the relaxed clock model prior [1].

Rate parameterisations

In Bayesian inference, the way parameters are represented in the model can affect the mixing ability of the model and the meaning of the model itself. Three methods for parameterising substitution rates are described below, and are later evaluated in **Results and Discussion**. Each parameterisation technique is associated with i) an abstraction of the rates $\vec{\mathcal{R}}$, ii) some function for transforming this parameter into real rates $r(\vec{\mathcal{R}})$, and iii) a prior density function of the abstraction $p(\vec{\mathcal{R}}|\sigma)$. The three methods are summarised in **Fig 1**.

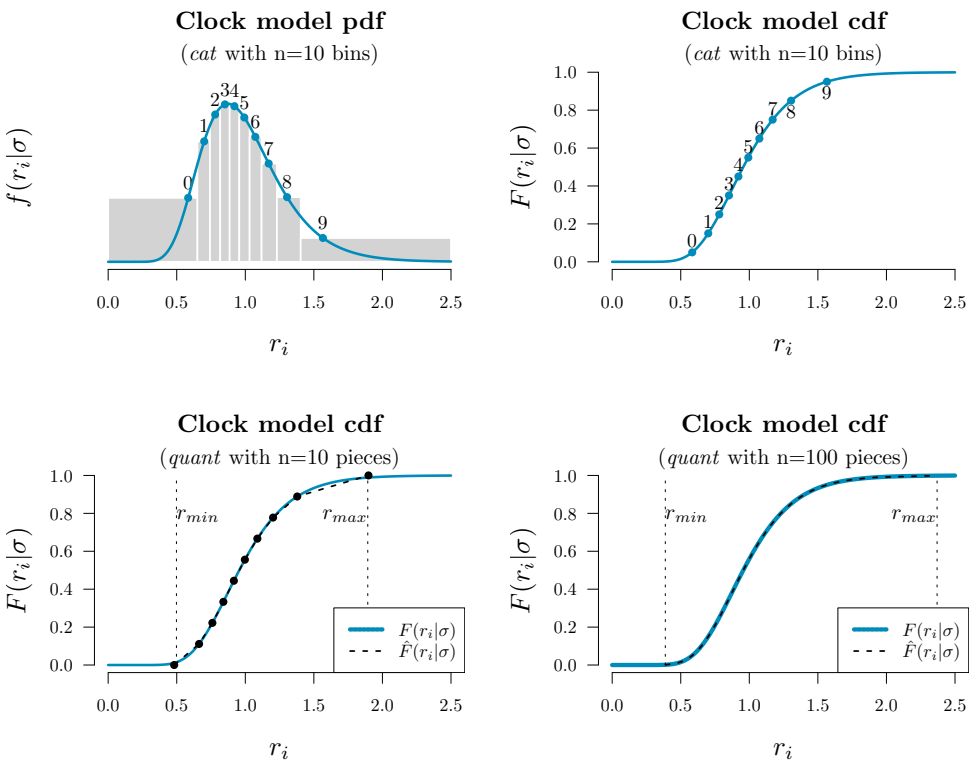

Fig 1. Methods of rate parameterisation. The *cat* and *quant* approximations are plotted on top of the true underlying rate prior distribution (*real*). In this example, rates are drawn from a LogNormal($\mu = -0.045, \sigma = 0.3$) distribution. The probability density function (pdf) and cumulative density function (cdf) of this distribution are shown.

1. Real rates

The natural (and unabstracted) parameterisation of a substitution rate is a real number $\mathcal{R}_i \in \mathbb{R}, \mathcal{R}_i > 0$ which is equal to the rate itself. Thus, under the *real* parameterisation:

$$r(\vec{\mathcal{R}}) = \vec{\mathcal{R}}\,. \tag{2}$$

Under the prior distribution $p(\vec{\mathcal{R}}\,|\sigma)$, rates are often log-normally or exponentially distributed with a mean of 1:

$$p(\mathcal{R}_i|\sigma) = \frac{1}{\mathcal{R}_i\sigma\sqrt{2\pi}} \exp\big(-\frac{(\ln \mathcal{R}_i - \mu)^2}{2\sigma^2}\big) \quad (\text{ LogNormal}(\mu, \sigma)\ ), \text{ or} \tag{3}$$

$$p(\mathcal{R}_i|\sigma) = p(\mathcal{R}_i) = e^{-\mathcal{R}_i} \quad (\text{ Exponential}(\lambda = 1)\ ) \tag{4}$$

where $\mu = -0.5\sigma^2$ is set such that the expected value of the log-normal distribution is 1.

Zhang and Drummond 2020 present a series of tree operators which propose internal/root node heights, and then recompute the rates of incident branches such that their genetic distances ($r_i \times \tau_i$) remain constant after the proposal. By maintaining genetic distances the likelihood can also be maintained. These operators account for the

correlation which exists between branch rates and branch times – a correlation which is induced by the likelihood function.

2. Categories

The category parameterisation (*cat*) is an abstraction of the *real* parameterisation. Each branch is assigned an integer from 0 to $n-1$:

$$\vec{\mathcal{R}} \in \{0, 1, \dots, n-1\}^{2N-2}. \tag{5}$$

The domain of $\vec{\mathcal{R}}$ is uniformly distributed:

$$p(\mathcal{R}_i|\sigma) = p(\mathcal{R}_i) = \frac{1}{n}. \tag{6}$$

Let $f(x|\sigma)$ be the probability density function (pdf) and let $F(x|\sigma) = \int_0^x f(t|\sigma)\, dt$ be the cumulative distribution function (cdf) of the prior distribution used by the underlying *real* clock model. Then, in the *cat* parameterisation, $f(x|\sigma)$ is discretised into n bins and the elements of $\vec{\mathcal{R}}$ each point to one of these bins. Each bin contains uniform probability density $1/n$. The rate of each bin is equal to the median value within the bin

$$r(\mathcal{R}_i) = F^{-1}\big(\frac{\mathcal{R}_i + 0.5}{n}\big), \tag{7}$$

where F^{-1} is the inverse cumulative distribution function (i-cdf).

The key advantage of the *cat* parameterisation is the removal of a term from the posterior density (Equation 1), or more accurately the replacement of a non-trivial $p(\vec{\mathcal{R}}\,|\sigma)$ term with that of a uniform prior. Thus, one fewer term needs to be estimated per rate.

This method was suggested in the original BEAST2 relaxed clock paper [1] and has been widely used. However, the constant distance operators since introduced by Zhang and Drummond 2020 – which are incompatible with the *cat* parameterisation – yield an increase in mixing rate under *real* by up to an order of magnitude over that of *cat*.

3. Quantiles

Finally, rates can be parameterised as real numbers $0 < \mathcal{R}_i < 1$ which describe the rate's quantile with respect to some underlying clock model distribution. Under the *quant* parameterisation, each element in $\vec{\mathcal{R}}$ is uniformly distributed.

$$\vec{\mathcal{R}} \in \mathbb{R}^{2N-2}, 0 < \mathcal{R}_i < 1 \tag{8}$$

$$p(\mathcal{R}_i|\sigma) = p(\mathcal{R}_i) = 1 \tag{9}$$

Transforming these quantiles into rates invokes the i-cdf of the underlying *real* clock model distribution. Thus, while this approach has clear similarities with *cat*, the domain of rates here is continuous (as opposed to being confined to a discrete number of bins) and is therefore compatible with the class of operators described by Zhang and Drummond 2020.

A potential disadvantage of the *quant* method would be the computational requirements of continuously evaluating the i-cdf, especially for trees with large N.

Hence, rather than evaluating the exact i-cdf F^{-1}, an approximation $\hat{F}^{-1}$ will be used instead:

$$r(\mathcal{R}_i) = \hat{F}^{-1}(\mathcal{R}_i). \tag{10}$$

In this article we have extended *quant* through a linear piecewise approximation of the i-cdf. As the piecewise approximation is linear, evaluating the derivatives $\frac{\partial}{\partial \mathcal{R}_i}\hat{F}^{-1}(\mathcal{R}_i) = D\hat{F}^{-1}(\mathcal{R}_i)$ and $\frac{\partial}{\partial r_i}\hat{F}(r_i) = D\hat{F}(r_i)$ – which are required for computing Hastings ratios – is trivial. The approximation is comprised of n pieces (where n is fixed) and upper and lower rate boundaries $r_{\min}$ and $r_{\max}$. The approximation is displayed in **Fig 1** and further detailed in **S1 Appendix**.

Zhang and Drummond 2020 introduced several tree operators for the *real* parameterisation – including **Constant Distance**, **Simple Distance**, and **Small Pulley**. In this project, we extended these three operators so that they are compatible with the *quant* parameterisation. These are presented in **S1 Appendix**.

Bactrian proposal kernel

The step size of a proposal kernal $q(x'|x)$ should be such that the proposed state x' is sufficiently far from the current state x to explore vast areas of parameter space, but not so large that the proposal is rejected too often [2]. Yang et al. have challenged the widely used uniform proposal kernel in place of the Bactrian kernel [3, 4]. The Bactrian(m) distribution is defined as the sum of two Normal distributions:

$$\Sigma \sim \text{Bactrian}(m) \equiv \frac{1}{2}\text{Normal}(-m, 1-m^2) + \frac{1}{2}\text{Normal}(m, 1-m^2) \tag{11}$$

where $0 \leq m < 1$ describes the modality of the Bactrian distribution. When $m = 0$, the Bactrian distribution is equivalent to a Normal$(0, 1)$ distribution. As $m \to 1$, the distribution becomes increasingly bimodal (**Fig. 2**). Yang et al. 2013 [3] suggest that Bactrian$(m = 0.95)$ yields a proposal kernel superior to the uniform kernel, by placing minimal probability on steps which are too small or too large.

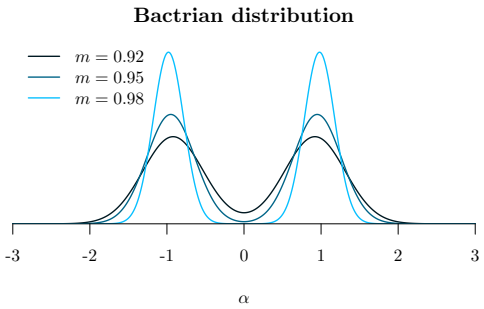

Fig 2. The Bactrian proposal kernel. Y-axis corresponds to probability density $f(\Sigma|m)$.

In this article we compare the performance of uniform and Bactrian proposal kernels in the clock model. Three Bactrian distributions are compared($m = 0.92$, $m = 0.95$, and $m = 0.98$). The clock model operators which these proposal kernels apply to are described in **Table 1**.

	Operator	Proposal	Parameters
1	**Random walk operator**	$x' \leftarrow x + s\Sigma$	t, σ, r, q
2	**Scale operator**	$x' \leftarrow x \times e^{s\Sigma}$	σ, r
3	**Constant distance operators**	$x' \leftarrow x + s\Sigma$	t

Table 1. Summary of proposal kernels $q(x'|x)$ of clock model operators. In each operator, Σ is drawn from either a Bactrian(m) or Uniform distribution (distributions are normalised so that they have a mean of 0 and a variance of 1). The scale size s is tunable. The proposal kernel may apply to node heights t, clock standard deviation σ, clock rates r (*real* only), and clock rate quantiles q (*quant* only). The Scale operator acts on parameters with non-negative domains.

Narrow Exchange Rate

The **Narrow Exchange** operator [5], widely used in BEAST [6] and BEAST2 [7], is similar to NNI, and works as follows (**Fig. 3**):

Step 1. Sample an internal/root node E from tree $\mathcal{T}$, where E has grandchildren.

Step 2. Identify the child of E with the greater height. Denote this child as D and its sibling as C (ie. $t_D > t_C$).

Step 3. Randomly identify the two children of D as A and B.

Step 4. Relocate the $B - D$ branch onto the $C - E$ branch, so that B and C become siblings and their parent is D. All node heights are unchanged.

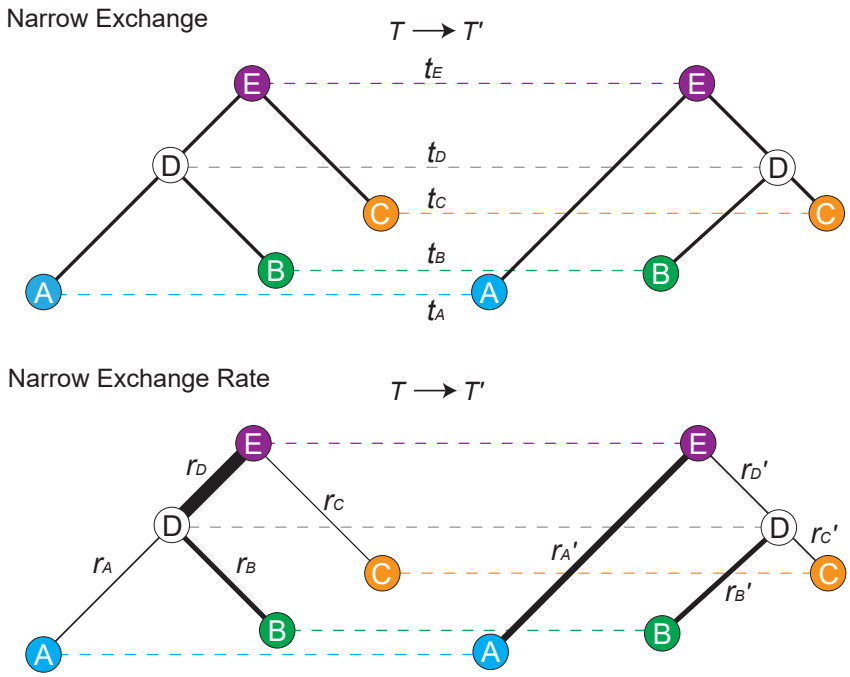

Fig 3. Depiction of Narrow Exchange and Narrow Exchange Rate operators. Proposals are denoted by $\mathcal{T} \rightarrow \mathcal{T}'$. The vertical axis corresponds to node height t. In the bottom figure, branch rates r are indicated by line thickness. In this example, the $\mathcal{D}_{AE}$ and $\mathcal{D}_{CE}$ constraints are satisfied.

Lakner et al. 2008 [8] found that tree operators which perterb topology (such as NNI and SPR) consistently perform better than those which also change branch lengths

(such as LOCAL [9] and Continuous Change [10]). If Narrow Exchange was adapted to the relaxed clock model by ensuring that genetic distances remain constant after the proposal, its performance may be improved even further. This may in turn permit proposing a new node height t_D and therefore changing branch (time) lengths.

Here, we present the **Narrow Exchange Rate** (NER) operator. Let r_A, r_B, r_C, and r_D be the clock rates of nodes A, B, C, and D, respectively. In addition to the modest topological change applied by Narrow Exchange, NER also proposes new clock rates $r_A{}'$, $r_B{}'$, $r_C{}'$, and $r_D{}'$. While NER does not alter t_D (ie. $t_D{}' \leftarrow t_D$), we also consider NERw - a special case of the NER operator which embarks t_D on a random walk:

$$t_D{}' \leftarrow t_D + s\Sigma \tag{12}$$

for random walk step size $s\Sigma$ where s is a tunable scalar parameter and Σ is drawn from a uniform or **Bactrian proposal kernel**. NER (and NERw) are compatible with both the *real* and *quant* parameterisations. Analagous to the Constant Distance operator, these rates are proposed such that genetic distances between nodes A, B, C, and E are maintained. Thus, there are $\binom{4}{2} = 6$ pairwise distance constraints.

$$\begin{aligned}
\mathcal{D}_{AB}: \quad & r_A(t_D - t_A) + r_B(t_D - t_B) = \\
& r_A{}'(t_E - t_A) + r_D{}'(t_E - t_D{}') + r_B{}'(t_D{}' - t_B) && (13)\\
\mathcal{D}_{AC}: \quad & r_A(t_D - t_A) + r_D(t_E - t_D) + r_C(t_E - t_C) = \\
& r_A{}'(t_E - t_A) + r_D{}'(t_E - t_D{}') + r_C{}'(t_D{}' - t_C) && (14)\\
\mathcal{D}_{AE}: \quad & r_A(t_D - t_A) + r_D(t_E - t_D) = \\
& r_A{}'(t_E - t_A) && (15)\\
\mathcal{D}_{BC}: \quad & r_B(t_D - t_B) + r_D(t_E - t_D) + r_C(t_E - t_D) = \\
& r_B{}'(t_D{}' - t_B) + r_C{}'(t_D{}' - t_C) && (16)\\
\mathcal{D}_{BE}: \quad & r_B(t_D - t_B) + r_D(t_E - t_D) = \\
& r_B{}'(t_D{}' - t_B) + r_D{}'(t_E - t_D{}') && (17)\\
\mathcal{D}_{CE}: \quad & r_C(t_E - t_C) = \\
& r_C{}'(t_D{}' - t_C) + r_D{}'(t_E - t_D{}') && (18)
\end{aligned}$$

Further constraints are imposed by the model itself:

$$r_i > 0 \text{ and } r_i{}' > 0 \text{ for } i \in \{A, B, C, D\} \tag{19}$$

$$\max\{t_B, t_C\} < t_D{}' < t_E. \tag{20}$$

Unfortunately, it is not possible to solve all six $\mathcal{D}_{ij}$ constraints without permitting non-positive rates or illegal trees. Therefore rather than conserving all six pairwise distances, NER conserves a *subset* of distances. It is not immediately clear which distances should be conserved.

Automated generation of operators and constraint satisfaction

The total space of NER operators is comprised of all possible subsets of distance constraints (ie. $\{\}, \{\mathcal{D}_{AB}\}, \{\mathcal{D}_{AC}\}, \ldots, \{\mathcal{D}_{AB}, \mathcal{D}_{AC}, \mathcal{D}_{AE}, \mathcal{D}_{BC}, \mathcal{D}_{BE}, \mathcal{D}_{CE}\}$) which are solvable. The simplest NER – the null operator denoted by NER$\{\}$ – does not satisfy any distance constraints. This is equivalent to Narrow Exchange.

As it is unclear which NER variants would perform the best, we developed an automated pipeline for generating and testing these operators.

1. Solution finding. Using standard analytical linear-system solving libraries in MATLAB, the $2^6 = 64$ subsets of distance constraints are solved. 54 out of the 64 subsets were found to be solvable, and the unsolvables were discarded.

2. Solving Jacobian determinants. The determinant of the Jacobian matrix J is required for computng the Hastings ratio of the proposal. J is defined as

$$J = \begin{bmatrix} \frac{\partial r_A{}'}{\partial r_A} & \frac{\partial r_A{}'}{\partial r_B} & \frac{\partial r_A{}'}{\partial r_C} & \frac{\partial r_A{}'}{\partial r_D} \\ \frac{\partial r_B{}'}{\partial r_A} & \frac{\partial r_B{}'}{\partial r_B} & \frac{\partial r_B{}'}{\partial r_C} & \frac{\partial r_B{}'}{\partial r_D} \\ \frac{\partial r_C{}'}{\partial r_A} & \frac{\partial r_C{}'}{\partial r_B} & \frac{\partial r_C{}'}{\partial r_C} & \frac{\partial r_C{}'}{\partial r_D} \\ \frac{\partial r_D{}'}{\partial r_A} & \frac{\partial r_D{}'}{\partial r_B} & \frac{\partial r_D{}'}{\partial r_C} & \frac{\partial r_D{}'}{\partial r_D} \end{bmatrix}. \tag{21}$$

Computing the determinant $|J|$ invokes standard analytical differentiation and linear algebra libraries of MATLAB. 6 of the 54 operators were found to have $|J| = 0$, corresponding to irreversible proposals, and were discarded.

3. Automated generation of BEAST2 operators. Java class files are generated using string processing. Each class corresponds to a single operator, extends the class of a meta-NER-operator, and is comprised of the solutions found in **1** and the Jacobian determinant found in **2**. $|J|$ is further augmented if the *quant* parameterisation is employed.

The 48 operators generated by this pipeline are evaluated and compared in **Results and Discussion**. Each operator is considered with and without a random walk on t_D and thus there are 96 total settings.

Clock model averaging

Results and Discussion

Assessment criteria and datasets

To avoid a cross-product explosion, the three targets for clock model improvement (**Rate parameterisations**, **Bactrian proposal kernel**, and **Narrow Exchange Rate**) are evaluated sequentially, in the order presented in this paper. The setting(s) which are considered to be the best in each step are then incorporated into the following step. This protocol and its outcomes are summarised in **Fig. 4**.

Methodologies are assessed according to the following criteria.

1. Validation. This is assessed by measuring the coverage of all estimated parameters in a well-calibrated simulation study, using 100 simulated datasets (with $N = 100$ taxa and $L = 5000$ nucleotide alignments). These are presented in **S2 Appendix**.

2. Time to convergence. Two independent MCMC chains are run and the time is measured until: a) the absolute difference in clade posterior probability between the two chains is less than 0.05 for all clades, b) the Rubin-Gelman statistic $\hat{R}$ [11] of every estimated parameter is less than 1.05, and c) the effective sample size [12] of every estimated parameter is greater than 100 in each chain.

3. Mixing of parameters. Key parameters are evaluated for the number of effective samples generated per hour (ESS/hr).

For the latter two criteria, methodologies are benchmarked using 30 empirical datasets compiled and partitioned [13] by Lanfear [14] In order to explore the effects of

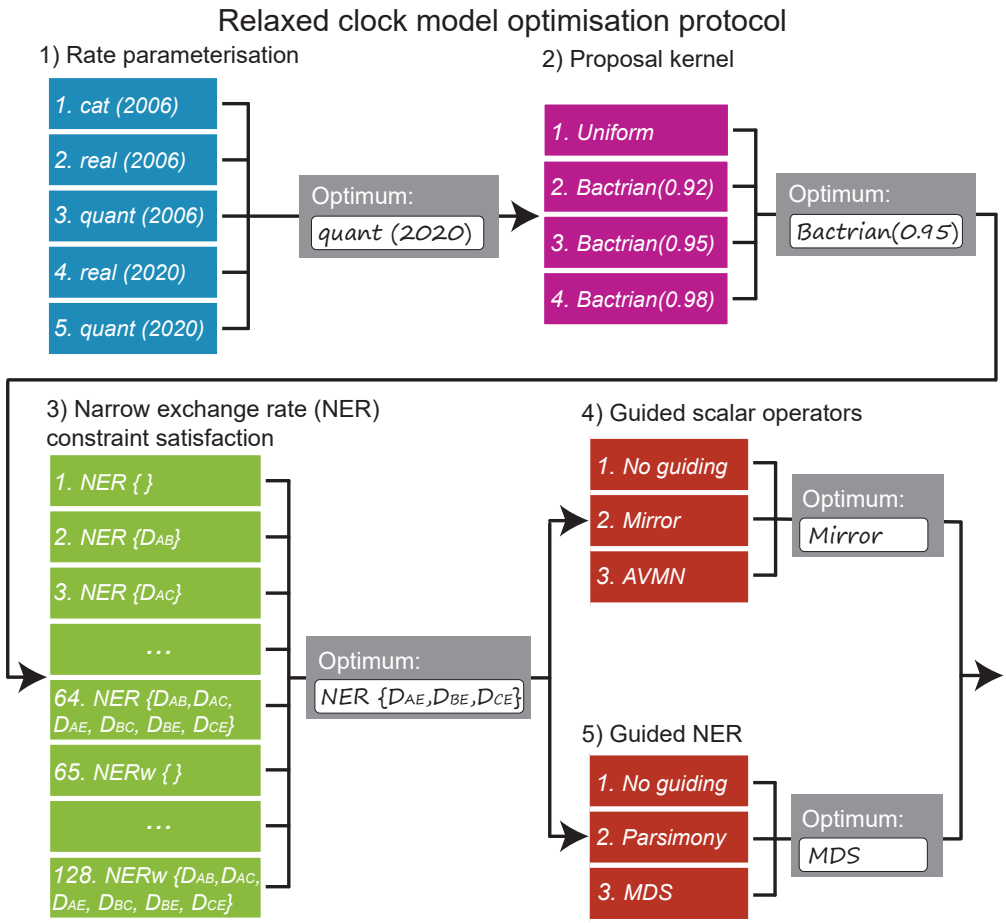

Fig 4. Protocol for optimising methodology settings. The three areas (detailed in **Models**) are optimised sequentially, where the best setting from each step is used when optimising the following step.

sequence length, the partitions of each empirical dataset are randomly subsampled at varying sample sizes (**Table 2**). Datasets and BEAST2 .xml templates are provided in the GitHub repository accompanying this article.

Methodologies are benchmarked using an Intel(R) Xeon(R) Gold 6138 CPU (2.00 GHz), with one two-threaded processing unit per pair of MCMC chains.

Comparison of rate parameterisations

We compared the three rate parameterisations described in **Rate parameterisations**. All three settings use the standard BEAST2 clock model operators from Drummond et al. 2006 [1]. *real* and *quant* additionally use the constant-distance tree operators described by Zhang and Drummond 2020. To determine whether the difference in performance between *real*/*quant* versus *cat* is because of the constant-distance tree operators or the parameterisation itself, we also included benchmarked two additional settings: *real 2006* and *quant 2006*, which do not used the constant-distance operators. These five settings are validated in **S2 Appendix**.

Fig. 5 shows that the *real 2006* performs considerably worse than any of the other settings. This is due to the poor sampling of the prior under this setting (ie. low ESS of

ID	N	P	L (kb)	L_{eff} (kb)	Reference
1	6	1/4/8/16	0.4/2.1/10.2/13.7	0.1/0.5/1/1.1	Richart 2015 [15]
2	10	1/4/8/16	0.4/1.5/3.1/6.7	0.1/0.3/0.5/0.9	Crawford 2012 [16]
3	11	1/4/8/16	0.5/2.2/4.9/10.1	0.1/0.4/0.7/1.3	Leache 2015 [17]
4	18	1/4/8/16	0.4/1.8/2.9/6.7	0.1/0.3/0.4/0.9	Meiklejohn 2016 [18]
5	27	1/4/8/16	0.8/1.4/2/4.3	0.3/0.6/1/1.7	Faircloth 2013 [19]
6	33	1/4/8/16	0.4/1.7/2.6/5.1	0.1/0.5/0.7/1.5	McCormack 2013 [20]
7	38	1/4	0.4/2.1	0.2/0.6	Bergsten 2013 [21]
8	38	1/4/8/16	1/2.4/8.1/14.9	0.7/1.8/5.6/10.1	Ran 2018 [22]
9	41	1/3	0.4/1.7	0.3/1.1	Brown 2012 [23]
10	44	1/3	0.6/1.9	0.2/0.8	Cognato 2001 [24]
11	44	1/4/7	0.8/2.9/5.9	0.3/0.8/1.8	Dornburg 2012 [25]
12	51	1/4/6	0.6/3.5/5.4	0.1/0.9/1.8	Sauquet 2011 [26]
13	61	1/4/8/16	0.9/4.2/7.5/15	0.7/2.8/4.6/9.6	Broughton 2013 [27]
14	69	1/2	0.7/0.8	0.1/0.1	Devitt 2013 [28]
15	70	1/3	0.7/2.2	0.3/0.9	Kawahara 2013 [29]
16	78	1/4/8/16	0.4/1.9/4.1/7.2	0.3/1.7/3.6/6.2	Cannon 2016 [30]
17	79	1/4/8/16	0.1/1.3/0.8/4.5	0/0.1/0.1/0.8	Oaks 2011 [31]
18	94	1/4/8/11	0.1/1.8/3/3.7	0.1/0.8/1.3/1.7	Rightmyer 2013 [32]
19	106	1/4/8/16	0.6/3.1/5.1/11.6	0.3/1.2/2/4.5	Moyle 2016 [33]
20	110	1/4/8/16	0.5/2.1/3.8/7.1	0.3/1.4/2.5/4.3	Fong 2012 [34]
21	152	1/4/5	1/3.5/3.6	0.6/1.6/1.6	Day 2013 [35]
22	187	1/4/8/16	0.3/0.9/1.4/3.5	0.2/0.7/1.1/2.9	Branstetter 2017 [36]
23	197	1/4/8/14	0.9/3.1/6.1/11.6	0.3/1.6/3.5/6.3	Horn 2014 [37]
24	235	1/4/8/16	2.3/6.4/8.5/25.7	0.9/2.3/3.2/12.2	Reddy 2017 [38]
25	237	1/4/5	0.8/2.4/3.1	0.2/1.2/1.5	Murray 2013 [39]
26	608	1/4/8/10	0.9/3.7/7.1/8.6	0.7/2.8/5.4/6.4	Near 2013 [40]

Table 2. Empirical datasets used during benchmarking. Number of taxa N, number of partitions P, total alignment length L, and number of patterns L_{eff} are specified. Where a dataset is sampled more than once, the dimensions of its multiple samples are separated by '/'.

$p(\theta)$). The failure of *real 2006* thus highlights the appeal of 1) the *cat* or *quant* parameterisations, both of which have trivial contributions to the prior density (ie. uniform priors), and 2) the smarter operators used by *real* (Zhang and Drummond 2020). Due to its computational burden, *real 2006* was not benchmarked for all of the datasets in **Table 2**.

Fig 5. Rate parameterisation evaluation.

Comparison of NER variants

Initial screening by acceptance rate

Advanced screening by congergence time

Comparison of random walk proposals

Conclusion

Supporting information

S1 Appendix. Rate quantiles. The linear piecewise approximation used in the *quant* parameterisation is described. Tree operators presented by Zhang and Drummond 2020 are extended to the *quant* parameterisation.

S2 Appendix. Well-calibated simulation studies. Methodologies are validated using well-calibated simulation studies.

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