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
















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Efficient ancestry and mutation simulation with msprime 1.0

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Abstract

Stochastic simulation is a key tool in population genetics, since the models involved are often analytically intractable and simulation is usually the only way of obtaining ground-truth data to evaluate inferences. Because of this, a large number of specialized simulation programs have been developed, each filling a particular niche, but with largely overlapping functionality and a substantial duplication of effort. Here, we introduce *msprime* version 1.0, which efficiently implements ancestry and mutation simulations based on the succinct tree sequence data structure and the *tskit* library. We summarize *msprime*'s many features, and show that its performance is excellent, often many times faster and more memory efficient than specialized alternatives. These high-performance features have been thoroughly tested and validated, and built using a collaborative, open source development model, which reduces duplication of effort and promotes software quality via community engagement.

Keywords: simulation; coalescent; mutations; Ancestral Recombination Graphs

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Introduction

The coalescent process (Kingman 1982a, 1982b; Hudson 1983b; Tajima 1983) models the ancestry of a set of sampled genomes, providing a mathematical description of the genealogical tree that relates the samples to one another. It has proved to be a powerful model, and is now central to population genetics (Hudson 1990; Hein et al. 2004; Wakeley 2008). The coalescent is an efficient framework for population genetic simulation, because it allows us to simulate the genetic ancestry for a sample from an idealized population model, without explicitly representing the population in memory or stepping through the generations. Indeed, Hudson (1983b) independently derived the coalescent *in order* to efficiently simulate data, and used these simulations to characterize an analytically intractable distribution. This inherent efficiency, and the great utility of simulations for a wide range of purposes, has led to dozens of different tools being developed over the decades (Carvajal-Rodríguez 2008; Liu et al. 2008; Arenas 2012; Hoban et al. 2012; Yuan et al. 2012; Yang et al. 2014; Peng et al. 2015).

Two technological developments of recent years, however, pose major challenges to most existing simulation methods. First, fourth-generation sequencing technologies have made complete chromosome-level assemblies possible (Miga et al. 2020), and high quality assemblies are now available for many species. Thus, modeling genetic variation data as a series of unlinked non-recombining loci is no longer a reasonable approximation, and we must fully account for recombination. However, while a genealogical tree relating n samples in the single-locus coalescent can be simulated in $O(n)$ time (Hudson 1990), the coalescent with recombination is far more complex, and programs such as Hudson's classical `ms` (Hudson 2002) can only simulate short segments under the influence of recombination. The second challenge facing simulation methods is that sample sizes in genetic studies have grown very quickly in recent years, enabled by the precipitous fall in genome sequencing costs. Human datasets like the UK Biobank (Bycroft et al. 2018) and gnomAD (Karczewski et al. 2020) now consist of hundreds of thousands of genomes and many other datasets on a similar scale are becoming available (Tanjo et al. 2021). Classical simulators such as `ms` and even fast approximate methods such as `scrm` (Staab et al. 2015) simply cannot cope with such a large number of samples.

The `msprime` simulator (Kelleher et al. 2016; Kelleher and Lohse 2020) has greatly increased the scope of coalescent simulations, and it is now straightforward to simulate millions of whole chromosomes for a wide range of organisms. The “succinct tree sequence” data structure (Kelleher et al. 2016, 2018, 2019; Wohns et al. 2021), originally introduced as part of `msprime`, makes it possible to store such large simulations in a few gigabytes, several orders of magnitude smaller than commonly used formats. The succinct tree sequence has also led to major advances in forwards-time simulation (Haller et al. 2018; Kelleher et al. 2018), ancestry inference (Kelleher et al. 2019; Wohns et al. 2021), and calculation of population genetic statistics (Kelleher et al. 2016; Ralph et al. 2020). Through a rigorous open-source community development process, `msprime` has gained a large number of features since its introduction, making it a highly efficient and flexible platform for population genetic simulation. This paper marks the release of `msprime` 1.0. We provide an overview of its extensive features, demonstrate its performance advantages over alternative software, and discuss opportunities for ongoing open-source community-based development.

The efficiency of coalescent simulations depends crucially on the assumption of neutrality, and it is important to note that there are many situations in which this will be a poor approximation of biological reality (Johri et al. 2021). In particular, background selection has been shown to affect genome-wide sequence variation in a wide range of species (Charlesworth et al. 1993, 1995; Charlesworth and Jensen 2021). Thus care must be taken to ensure that the results of purely neutral simulations are appropriate for the question and genomic partition under study. A major strength of `msprime`, however, is that it can be used in conjunction with forwards-time simulators, enabling the simulation of more realistic models than otherwise possible (Haller et al. 2018; Kelleher et al. 2018).

Results

In the following sections, we describe the main features of `msprime` 1.0, focusing on the aspects that are either new for this version, or in which our approach differs significantly from classical methods (summarized in Table 1). Where appropriate, we benchmark `msprime` against other simulators, but the comparisons are illustrative and not intended to be systematic or exhaustive. Please see Kelleher et al. (2016) for a performance comparison of `msprime` against simulators such as `ms`, `msms`, and `scrm`.

User interface

The majority of simulation packages are controlled either through a command-line interface (e.g., Hudson 2002; Kern and Schrider 2016), a text-based input file format (e.g., Guillaume and Rougemont 2006; Excoffier and Foll 2011; Shlyakhter et al. 2014), or a mixture of both. Command-line interfaces make it easy to run simple simulations, but as model complexity and the number of parameters increase, they become difficult to understand and error-prone (Ragsdale et al. 2020; Gower et al. 2022). Specifying parameters through a text file alleviates this problem to a degree, but lacks flexibility, for example, when running simulations with parameters drawn from a distribution. In practice, for any reproducible simulation project, users will write a script to generate the required command lines or input parameter files, invoke the simulation engine, and process the results in some way. This process is cumbersome and labor intensive, and a number of packages have been developed to allow simulations to be run directly in a high-level scripting language (Staab and Metzler 2016; Parobek et al. 2017; Gladstein et al. 2018).

The more recent trend has been to move away from this file and command-line driven approach and to instead provide direct interfaces to the simulation engines via an Application Programming Interface (API) (e.g., Thornton 2014; Kelleher et al. 2016; Becheler et al. 2019; Haller and Messer 2019). The primary interface for `msprime` is through a thoroughly documented Python API, which has encouraged the development of an ecosystem of downstream tools (Terhorst et al. 2017; Chan et al. 2018; Spence and Song 2019; Adrion et al. 2020a, 2020b; Kamm et al. 2020; McKenzie and Eaton 2020; Montinaro et al. 2020; Rivera-Colón et al. 2021; Terasaki Hart et al. 2021). As well as providing a stable and efficient platform for building downstream applications, `msprime`'s Python API makes it much easier to build reproducible simulation pipelines, as the entire workflow can be encapsulated in a single script, and package and version dependencies explicitly stated using the `pip` or `conda` package managers. For example, the errors made in the influential simulation analysis of Martin et al. (2017) were only detected because the

Table 1 Major features of `msprime` 1.0 added since version 0.3.0 (Kelleher et al. 2016)

Interface	Separation of ancestry and mutation simulations. Ability to store arbitrary metadata along with simulation results, and automatic recording of provenance information for reproducibility. Jupyter Notebook (Kluyver et al. 2016) integration. Rich suite of analytical and visualization methods via the <code>tskit</code> library.
Ancestry	SMC, SMC', Beta- and Dirac-coalescent, discrete time Wright–Fisher, and selective sweep models. Instantaneous bottlenecks. Discrete or continuous genomic coordinates, arbitrary ploidy, gene conversion. Output full ARG with recombination nodes, ARG likelihood calculations. Record full migration history and census events. Improved performance for large numbers of populations. Integration with forward simulators such as SLiM and <code> fwdpy11 </code> (“recapitation”).
Demography	Improved interface with integrated metadata and referencing populations by name. Import from Newick species tree, *BEAST (Heled and Drummond 2010), and Demes (Gower et al. 2022). Numerical methods to compute coalescence rates.
Mutations	JC69, HKY, F84, GTR, BLOSUM62, PAM, infinite alleles, SLiM and general matrix mutation models. Varying rates along the genome, recurrent/back mutations, discrete or continuous genomic coordinates, overlaying multiple layers of mutations, exact times associated with mutations.

pipeline could be easily run and reanalyzed (Martin et al. 2020; Ragsdale et al. 2020).

A major change for the `msprime` 1.0 release is the introduction of a new set of APIs, designed in part to avoid sources of error (see *Demography*) but also to provide more appropriate defaults while keeping compatibility with existing code. In the new APIs, ancestry and mutation simulation are fully separated (see Figure 1), with the `sim_ancestry` and `sim_mutations` functions replacing the legacy `simulate` function. Among other changes, the new APIs default to discrete genome coordinates and finite sites mutations, making the default settings more realistic and resolving a major source of confusion and error. The previous APIs are fully supported and tested, and will be maintained for the foreseeable future. The `msp` program (a command-line interface to the library) has been extended to include new commands for simulating ancestry and mutations separately. A particularly useful feature is the ability to specify demographic models in Demes format (Gower et al. 2022) from the command line, making simulation of complex demographies straightforward. We also provide an `ms`-compatible command-line interface to support existing workflows.

Tree sequences

One of the key reasons for `msprime`'s substantial performance advantage over other simulators (Kelleher et al. 2016) is its use of the “succinct tree sequence” data structure to represent simulation results. The succinct tree sequence (usually abbreviated to “tree sequence”) was introduced by Kelleher et al. (2016) to concisely encode genetic ancestry and sequence variation and was originally implemented as part of `msprime`. We subsequently extracted the core tree sequence functionality from `msprime` to create the `tskit` library, which provides a large suite of tools for processing genetic ancestry and variation data via APIs in the Python and C languages (Tskit developers 2022). The availability of `tskit` as a liberally licensed (MIT) open source toolkit has enabled several other projects (e.g., Haller and Messer 2019; Kelleher et al. 2019; Terasaki Hart et al. 2021; Wohns et al. 2021) to take advantage of the same efficient data structures used in `msprime`, and we hope that many more will follow. While a full discussion of tree sequences and the capabilities of `tskit` is beyond the scope of this article, we summarize some aspects that are important for simulation.

Let us define a genome as the complete set of genetic material that a child inherits from one parent. Thus, a diploid individual has two (monoploid) genomes, one inherited from each parent. Since each diploid individual lies at the end of two distinct lineages of descent, they will be represented by two places (nodes) in

any genealogical tree. In the tree sequence encoding a *node* therefore corresponds to a single genome, which is associated with its creation time (and other optional information), and recorded in a simple tabular format (Figure 2). Genetic inheritance between genomes (nodes) is defined by edges. An *edge* consists of a parent node, a child node, and the left and right coordinates of the contiguous chromosomal segment over which the child genome inherited genetic material from the parent genome. Parent and child nodes may correspond to ancestor and descendant genomes separated by many generations. Critically, edges can span multiple trees along the genome (usually referred to as “marginal” trees), and identical node IDs across different trees corresponds to the same ancestral genome. For example, in Figure 2, the branch from node 0 to 4 is present in both marginal trees, and represented by a single edge (the first row in the edge table). This simple device, of explicitly associating tree nodes with specific ancestral genomes and recording the contiguous segments over which parent–child relationships exist, generalizes the original “coalescence records” concept (Kelleher et al. 2016), and is the key to the efficiency of tree sequences (Kelleher et al. 2018, 2019; Ralph et al. 2020). Note that this formulation is fully compatible with the concept of an Ancestral Recombination Graph (ARG) and any ARG topology can be fully and efficiently encoded in the node and edge tables illustrated in Figure 2; see the *Ancestral Recombination Graphs* section below for more details.

The final output of most population genetic simulations is some representation of sequence variation among the specified samples. For coalescent simulations, we usually have three steps: (1) simulate the genetic ancestry, and optionally output the resulting marginal trees; (2) simulate sequence evolution conditioned on this ancestry by generating mutations (see the *Simulating mutations* section); and (3) output the resulting nucleotide sequences by percolating the effects of the mutations through the trees. Information about the mutations themselves—e.g., where they have occurred on the trees—is usually not retained or made available for subsequent analysis. In `msprime`, however, we skip step (3), instead using `tskit`'s combined data model of ancestry and mutations to represent the simulated sequences. As illustrated in Figure 2, mutations are a fully integrated part of `tskit`'s tree sequence data model, and genetic variation is encoded by recording sites at which mutations have occurred, and where each mutation at those sites has occurred on the marginal tree. Crucially, the genome sequences themselves are never stored, or indeed directly represented in memory (although `tskit` can output the variant matrix in various formats, if required). It may at first seem inconvenient to

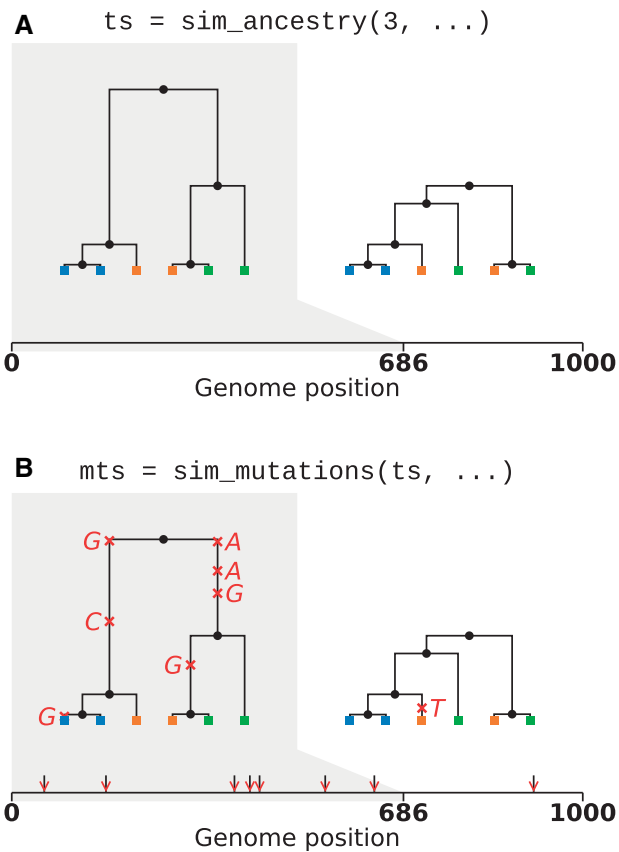


Figure 1 Visualization of the separation between ancestry and mutation simulation. (A) The result of an invocation of `sim_ancestry` is two trees along a 1 kb chunk of genome relating three diploid samples. Each diploid individual consists of two genomes (or nodes), indicated by color. (B) This ancestry is provided as the input to `sim_mutations`, which adds mutations. Graphics produced using `tskit`'s `draw_svg` method.

have only this indirect representation of the genome sequences, but it is extremely powerful. First, the storage space required for simulations is dramatically reduced. For a simulation of n samples with m variant sites, we would require $O(nm)$ space to store the sequence data as a variant matrix. However, if this simulation was of a recombining genome with t trees, then the `tskit` tree sequence encoding requires $O(n + t + m)$ space, assuming we have $O(1)$ mutations at each site (Kelleher et al. 2016). For large sample sizes, this difference is profound, making it conceivable, for example, to store the genetic ancestry and variation data for the entire human population on a laptop (Kelleher et al. 2019). As well as the huge difference in storage efficiency, it is often far more efficient to compute statistics of the sequence data from the trees and mutations than it is to work with the sequences themselves. For example, computing Tajima's D from simulated data stored in the `tskit` format is several orders of magnitude faster than efficient variant matrix libraries for large sample sizes (Ralph et al. 2020).

The vast genomic datasets produced during the SARS-CoV-2 pandemic have highlighted the advantages of storing genetic variation data using the underlying trees. Turakhia et al. (2021) propose the Mutation Annotated Tree (MAT) format (consisting of a Newick tree and associated mutations in a binary format) and the `matutils` program as an efficient way to store and process large viral datasets (McBroome et al. 2021), achieving excellent

compression and processing performance. Similarly, `phastsim` (De Maio et al. 2021) was developed to simulate sequence evolution on such large SARS-CoV-2 phylogenies, and also outputs a Newick tree annotated with mutations (not in MAT format) to avoid the bottleneck of generating and storing the simulated sequences. While these methods illustrate the advantages of the general approach of storing ancestry and mutations rather than sequences, they do not generalize beyond their immediate settings, and no software library support is available.

The software ecosystem built around `tskit` is stable, mature, and rapidly growing. Simulators such as `fwadpy11` (Thornton 2014), `SLiM` (Haller and Messer 2019), `stdpopsim` (Adrión et al. 2020a), `Geomics` (Terasaki Hart et al. 2021), and `GSpace` (Virgoulay et al. 2021), and inference methods such as `tsinfer` (Kelleher et al. 2019), `tsdate` (Wohns et al. 2021), and `Relate` (Speidel et al. 2019) use either the Python or C APIs to support outputting results in tree sequence format. Tree sequences are stored in an efficient binary file format, and are fully portable across operating systems and processor architectures. The `tskit` library ensures interoperability between programs by having strict definitions of how the information in each of the tables is interpreted, and stringent checks for the internal consistency of the data model.

Data analysis

The standard way of representing simulation data is to render the results in a text format, which must subsequently be parsed and processed as part of some analysis pipeline. For example, `ms` outputs a set of sequences and can also optionally output the marginal trees along the genome in Newick format, and variants of this approach are used by many simulators. Text files have many advantages, but are slow to process at scale. The ability to efficiently process simulation results is particularly important in simulation-based inference methods such as Approximate Bayesian Computation (ABC) (Beaumont et al. 2002; Csilléry et al. 2010; Wegmann et al. 2010) and machine learning-based approaches (Sheehan and Song 2016; Chan et al. 2018; Schrider and Kern 2018; Fligel et al. 2019; Sanchez et al. 2021). Clearly, simulation efficiency is crucial since the size and number of simulations that can be performed determines the depth to which one can sample from the model and parameter space. Equally important, however, is the efficiency with which the simulation results can be transformed into the specific input required by the inference method. In the case of ABC, this is usually a set of summary statistics of the sequence data, and methods avoid the bottleneck of parsing text-based file formats to compute these statistics by either developing their own simulators (e.g., Cornuet et al. 2008; Lopes et al. 2009) or creating forked versions (i.e., modified copies) of existing simulators (e.g., Thornton and Andolfatto 2006; Hickerson et al. 2007; Pavlidis et al. 2010; Huang et al. 2011; Quinto-Cortés et al. 2018), tightly integrated with the inference method. Modern approaches to ABC such as ABC-RF (Pudlo et al. 2016; Raynal et al. 2019) and ABC-NN (Blum and François 2010; Csilléry et al. 2012) use large numbers of weakly informative statistics, making the need to efficiently compute statistics from simulation results all the more acute. By using the stable APIs and efficient data interchange mechanisms provided by `tskit`, the results of an `msprime` simulation can be immediately processed, without format conversion overhead. The `tskit` library has a rich suite of population genetic statistics and other utilities, and is in many cases orders of magnitude faster than matrix-based methods for large sample sizes (Ralph et al. 2020). Thus,

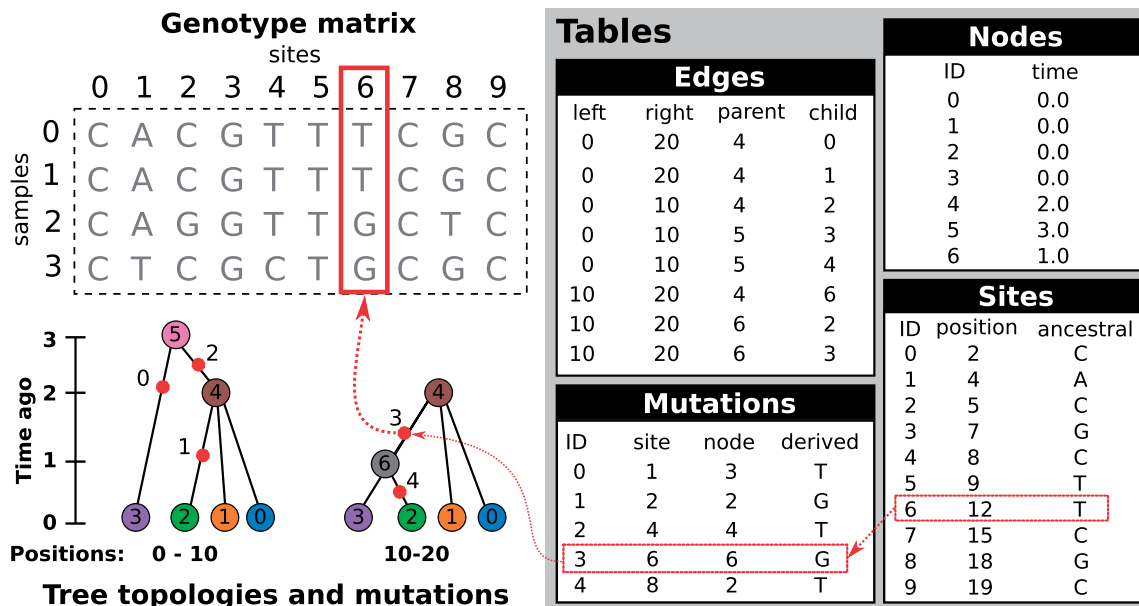


Figure 2 An example tree sequence describing genealogies and sequence variation for four samples at 10 sites on a chromosome of 20 bases long. Information is stored in a set of tables (the tables shown here include only essential columns, and much more information can be associated with the various entities). The node table stores information about sampled and ancestral genomes. The edge table describes how these genomes are related along a chromosome, and defines the genealogical tree at each position. The site and mutation tables together describe sequence variation among the samples. The genotype matrix and tree topologies shown on the left are derived from these tables.

the combination of `msprime` and `tskit` substantially increases the overall efficiency of many simulation analysis pipelines.

Classical text-based output formats like `ms` are inefficient to process, but also lack a great deal of important information about the simulated process. The tree-by-tree topology information output by simulators in Newick format lacks any concept of node identity, and means that we cannot reliably infer information about ancestors from the output. Because Newick stores branch lengths rather than node times, numerical precision issues also arise for large trees (McGill et al. 2013). Numerous forks of simulators have been created to access information not provided in the output. For example, `ms` has been forked to output information about migrating segments (Rosenzweig et al. 2016), ancestral lineages (Chen and Chen 2013), and `ms`'s fork `msHOT` (Hellenthal and Stephens 2007) has in turn been forked to output information on local ancestry (Racimo et al. 2017). All of this information is either directly available by default in `msprime`, or can be optionally stored via options such as `record_migrations` or `record_full_arg` (see *Ancestral Recombination Graphs*) and can be efficiently and conveniently processed via `tskit` APIs.

Simulating mutations

Because coalescent simulations are usually concerned with neutral evolution (see the *Selective sweeps* section, however), the problem of generating synthetic genetic variation can be decomposed into two independent steps: first, simulating genetic ancestry (the trees), then subsequently simulating variation by superimposing mutation processes on those trees (see Figure 1). A number of programs exist to place mutations on trees: for instance, the classical `Seq-Gen` program (Rambaut and Grassly 1997) supports a range of different models of sequence evolution, and various extensions to the basic models have been proposed (e.g., Cartwright 2005; Fletcher and Yang 2009). Partly for efficiency and partly in the interest of simplicity for users (i.e., to avoid intermediate text format conversions), population genetic simulators have tended to include their own implementations of

mutation simulation, with most supporting the infinite sites model (e.g., Hudson 2002) but with several supporting a wide range of different models of sequence evolution (e.g., Mailund et al. 2005; Excoffier and Foll 2011; Virgoulay et al. 2021). Thus, despite the logical separation between the tasks of simulating ancestry and neutral sequence evolution, the two have been conflated in practice.

Part of the reason for this poor record of software reuse and modularity is the lack of standardized file formats, and in particular, the absence of common library infrastructure to abstract the details of interchanging simulation data. Although `msprime` also supports simulating both ancestry and mutations, the two aspects are functionally independent within the software; both ancestry and mutation simulators are present in `msprime` for reasons of convenience and history, and could be split into separate packages. The efficient C and Python interfaces for `tskit` make it straightforward to add further information to an existing file, and because of its efficient data interchange mechanisms, there is no performance penalty for operations being performed in a different software package. Thanks to this interoperability, `msprime`'s mutation generator can work with any `tskit` tree sequence, be it simulated using `SLiM` (Haller and Messer 2019) or `fdpypy11` (Thornton 2014), or estimated from real data (Kelleher et al. 2019; Speidel et al. 2019; Wohns et al. 2021). It is a modular component intended to fit into a larger software ecosystem, and is in no way dependent on `msprime`'s ancestry simulator.

We have greatly extended the sophistication of `msprime`'s mutation generation engine for version 1.0, achieving near feature-parity with `Seq-Gen`. We support a large number of mutation models, including the JC69 (Jukes and Cantor 1969), F84 (Felsenstein and Churchill 1996), and GTR (Tavaré 1986) nucleotide models and the BLOSUM62 (Henikoff and Henikoff 1992) and PAM (Dayhoff et al. 1978) amino acid models. Other models, such as the Kimura two and three parameter models (Kimura 1980, 1981), can be defined easily and efficiently in user code by specifying a transition matrix between any number of alleles.

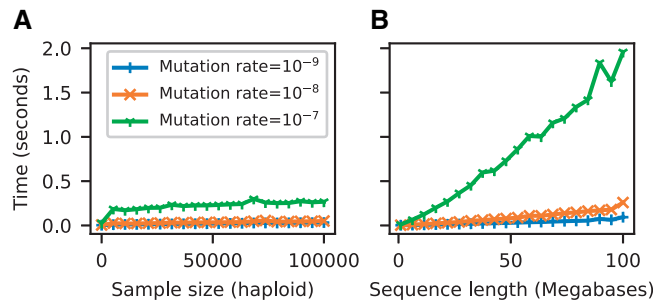


Figure 3 Time required to run `sim_mutations` on tree sequences generated by `sim_ancestry` (with a population size of 10^4 and recombination rate of 10^{-8}) for varying (haploid) sample size and sequence length. We ran 10 replicate mutation simulations each for three different mutation rates, and report the average CPU time required (Intel Core i7-9700). (A) Holding sequence length fixed at 10 megabases and varying the number of samples (tree tips) from 10 to 100,000. (B) Holding number of samples fixed at 1000, and varying the sequence length from 1 to 100 megabases.

Mutation rates can vary along the genome, and multiple mutation models can be imposed on a tree sequence by overlaying mutations in multiple passes. We have extensively validated the results of mutation simulations against both theoretical expectations and output from `Seq-Gen` (Rambaut and Grassly 1997) and `Pyvolve` (Spielman and Wilke 2015).

Simulating mutations in `msprime` is efficient. Figure 3 shows the time required to generate mutations (using the default JC69 model) on simulated tree sequences for a variety of mutation rates as we vary the number of samples (Figure 3A) and the sequence length (Figure 3B). For example, the longest running simulation in Figure 3B required less than 2 s to generate an average of 1.5 million mutations over 137,081 trees in a tree sequence with 508,125 edges. This efficiency for large numbers of trees is possible because the tree sequence encoding allows us to generate mutations on an edge-by-edge basis (see Figure 2 and the Mutation generation section in Appendix), rather than tree-by-tree and branch-by-branch as would otherwise be required. Simulating mutations on a single tree is also very efficient; for example, we simulated mutations under the BLOSUM62 amino acid model for a tree with 10^6 leaves over 10^4 sites (resulting in $\sim 260,000$ mutations) in about 0.8 s, including the time required for file input and output. We do not attempt a systematic benchmarking of `msprime`'s mutation generation code against other methods, because at this scale, it is difficult to disentangle the effects of inefficient input and output formats from the mutation generation algorithms. Given the above timings, it seems unlikely that generating mutations with `msprime` would be a bottleneck in any realistic analysis.

There are many ways in which the mutation generation code in `msprime` could be extended. For example, we intend to add support for microsatellites (Mailund et al. 2005), codon models (Arenas and Posada 2007), and indels (Cartwright 2005; Fletcher and Yang 2009), although changes may be required to `tskit`'s data model which is currently based on the assumption of independent sites.

Recombination

Crossover recombination is implemented in `msprime` using Hudson's algorithm, which works backwards in time, generating common ancestor and recombination events and tracking their effects on segments of ancestral material inherited from the sample (Hudson 1983a, 1990; Kelleher et al. 2016). Common ancestor events merge the ancestral material of two lineages, and

result in coalescences in the marginal trees when ancestral segments overlap. Recombination events split the ancestral material for some lineage at a breakpoint, creating two independent lineages. Using the appropriate data structures (Kelleher et al. 2016), this process is much more efficient to simulate than the equivalent left-to-right approach (Wiuf and Hein 1999a, 1999b). In `msprime` 1.0, recombination rates can vary along a chromosome, allowing us to simulate recombination hotspots and patterns of recombination from empirical maps. The implementation of recombination in `msprime` is extensively validated against analytical results (Hudson 1983a; Kaplan and Hudson 1985) and simulations by `ms`, `msHOT`, and `SLiM`.

The Sequentially Markovian Coalescent (SMC) is an approximation of the coalescent with recombination (McVean and Cardin 2005; Marjoram and Wall 2006), and was primarily motivated by the need to simulate longer genomes than was possible using tools like `ms`. The SMC is a good approximation to the coalescent with recombination when we have fewer than five sampled genomes (Hobolth and Jensen 2014; Wilton et al. 2015), but the effects of the approximation are less well understood for larger sample sizes, and several approaches have been proposed that allow simulations to more closely approximate the coalescent with recombination (Chen et al. 2009; Wang et al. 2014; Staab et al. 2015). The SMC and SMC' models are supported in `msprime` 1.0. However, they are currently implemented using a naive rejection sampling approach, and are somewhat slower to simulate than the exact coalescent with recombination. These models are therefore currently only appropriate for studying the SMC approximations themselves, although we intend to implement them more efficiently in future versions.

In human-like parameter regimes and for large sample sizes, `msprime`'s implementation of the exact coalescent with recombination comprehensively outperforms all other simulators, including those based on SMC approximations (Kelleher et al. 2016). However, it is important to note that although the implementation of Hudson's algorithm is very efficient, it is still quadratic in the population scaled recombination rate $\rho = 4N_eL$, where L is the length of the genome in units of recombination distance. This is because Hudson's algorithm tracks recombinations not only in segments ancestral to the sample, but also between ancestral segments. As mentioned above, common ancestor events in which the ancestral material of two lineages is merged only result in coalescences in the marginal trees if their ancestral segments overlap. If there is no overlap, the merged segments represent an ancestral chromosome that is a genetic ancestor of the two lineages, but not the most recent common genetic ancestor at any location along the genome. When this happens, the merged lineage carries "trapped" genetic material that is not ancestral to any samples, but where recombinations can still occur (Wiuf and Hein 1999b). For large ρ , recombination events in trapped ancestral material will dominate, and so we can use this as a proxy for the overall number of events in Hudson's algorithm. Hein et al. (2004, Equation 5.10) gave

$$\rho(\rho + 1) \left(\sum_{i=1}^{n-1} \frac{1}{i} \right)^2 \quad (1)$$

as an upper bound on the number of recombination events within trapped ancestral material for n samples. As discussed in the Time complexity of Hudson's algorithm Appendix, the quadratic dependence of simulation running time on ρ implied by Equation (1) is well supported by observations, and provides a

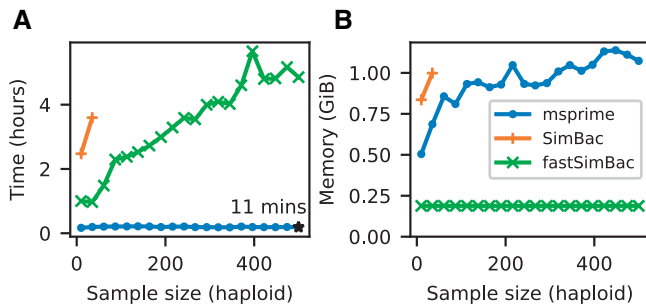


Figure 4 Comparison of simulation performance using `msprime` (`sim_ancestry`), `SimBac`, and `fastSimBac` for varying (haploid) sample sizes, and the current estimates for *E. coli* parameters (Lapierre et al. 2016): a 4.6 Mb genome, $N_e = 1.8 \times 10^8$, gene conversion rate of 8.9×10^{-11} per base and mean tract length of 542. We report (A) the total CPU time and (B) maximum memory usage averaged over five replicates (Intel Xeon E5-2680 CPU). We did not run `SimBac` beyond first two data points because of the very long running times.

useful means of predicting how long a particular simulation might require.

Gene conversion

Gene conversion is a form of recombination that results in the transfer of a short segment of genetic material, for example between homologous chromosomes (Chen et al. 2007). Since gene conversion impacts much shorter segments than crossover recombination (typically below 1 kb), it affects patterns of linkage disequilibrium differently (Korunes and Noor 2017). Wiuf and Hein (2000) modeled gene conversion in the coalescent via a rate at which gene conversion events are initiated along the genome and a geometrically distributed tract length. In terms of the ancestral process, gene conversion differs from crossover recombination (as described in the previous section) in that it extracts a short tract of ancestry into an independent lineage, rather than splitting ancestry to the left and right of a given breakpoint. We have implemented this model of gene conversion in `msprime` 1.0, and validated the output against `ms` and analytical results (Wiuf and Hein 2000).

Gene conversion is particularly useful to model homologous recombination in bacterial evolution, and so we compare the performance of `msprime` with gene conversion to two specialized bacterial simulators, `SimBac` (Brown et al. 2016) and `fastSimBac` (De Maio and Wilson 2017). Figure 4A shows that `msprime` is far more efficient than both `SimBac` and the SMC-based approximation `fastSimBac`. Figure 4B shows that `msprime` requires somewhat more memory than `fastSimBac` (as expected since `fastSimBac` uses a left-to-right SMC approximation), but is still reasonably modest at around 1 GiB for a simulation of 500 whole *Escherichia coli* genomes. However, `msprime` is currently lacking many of the specialized features required to model bacteria, and so an important avenue for future work is to add features such as circular genomes and bacterial gene transfer (Baumdicker and Pfaffelhuber 2014).

Demography

One of the key applications of population genetic simulations is to generate data for complex demographies. Beyond idealized cases such as stepping-stone or island models, or specialized cases such as isolation-with-migration models, analytical results are rarely possible. Simulation is therefore integral to the development and evaluation of methods for demographic inference. The demography model in `msprime` is directly derived from the

approach used in `ms`, and supports an arbitrary number of randomly mating populations exchanging migrants at specified rates. A range of demographic events are supported, which allow for varying population sizes and growth rates, changing migration rates over time, as well as population splits, admixtures, and pulse migrations.

A major change for `msprime` 1.0 is the introduction of the new Demography API, designed to address a design flaw in the `msprime` 0.x interface which led to avoidable errors in downstream simulations (Ragsdale et al. 2020). The new API is more user-friendly, providing the ability, for example, to refer to populations by name rather than their integer identifiers. We also provide numerical methods to compute the coalescence rates for two or more lineages which can be inverted to obtain the “inverse instantaneous coalescence rate” of Chikhi et al. (2018). Many popular approaches in population genetics use the distribution of coalescence rates between pairs of lineages to infer effective population sizes over time (Li and Durbin 2011; Sheehan et al. 2013; Schiffels and Durbin 2014) or split times and subsequent migration rates between populations (Wang et al. 2020). These numerical methods provide a valuable ground-truth when evaluating such inference methods, as illustrated by Adrion et al. (2020a).

Instantaneous bottlenecks

A common approach to modeling the effect of demographic history on genealogies is to assume that effective population size (N_e) changes in discrete steps which define a series of epochs (Griffiths et al. 1994; Marth et al. 2004; Keightley and Eyre-Walker 2007; Li and Durbin 2011). In this setting of piecewise constant N_e , capturing a population bottleneck requires three epochs: N_e is reduced by some fraction b at the start of the bottleneck, T_{start} , and recovers to its initial value at time T_{end} (Marth et al. 2004). If bottlenecks are short both on the timescale of coalescence and mutations, there may be little information about the duration of a bottleneck ($T_{end} - T_{start}$) in sequence data. Thus a simpler, alternative model is to assume that bottlenecks are instantaneous ($T_{end} - T_{start} \rightarrow 0$) and generate a sudden burst of coalescence events (a multiple merger event) in the genealogy. The strength of the bottleneck B can be thought of as an (imaginary) time period during which coalescence events are collapsed, i.e., there is no growth in genealogical branches during B and the probability that a single pair of lineages entering the bottleneck coalesce during the bottleneck is $1 - e^{-B}$. Although this simple two-parameter model of bottlenecks is attractive and both analytic results and empirical inference methods (Griffiths et al. 1994; Galtier et al. 2000; Birkner et al. 2009; Bunnefeld et al. 2015) have been developed under this model, there has been no software available to simulate data under instantaneous bottleneck histories.

We have implemented instantaneous bottlenecks in `msprime` 1.0 using a variant of Hudson’s linear time single-locus coalescent algorithm (Hudson 1990), and validated the results by comparing against analytical expectations (Bunnefeld et al. 2015).

Multiple merger coalescents

Kingman’s coalescent assumes that only two ancestral lineages can merge at each merger event. Although this is generally a reasonable approximation, there are certain situations in which the underlying mathematical assumptions are violated; for example, in certain highly fecund organisms (Beckenbach 1994; Hedgecock 1994; Árnason 2004; Hedgecock and Pudovkin 2011; Irwin et al. 2016; Vendrami et al. 2021), where individuals have the ability to produce numbers of offspring on the order of the population size and therefore a few individuals may produce the bulk of the

offspring in any given generation (Hedgecock 1994). These population dynamics violate basic assumptions of the Kingman coalescent, and are better modeled by “multiple-merger” coalescents (Donnelly and Kurtz 1999; Pitman 1999; Sagitov 1999; Schweinsberg 2000; Möhle and Sagitov 2001), in which more than two lineages can merge in a given event. Multiple-merger coalescent processes have also been shown to be relevant for modeling the effects of selection on gene genealogies (Gillespie 2000; Durrett and Schweinsberg 2004; Desai et al. 2013; Neher and Hallatschek 2013; Schweinsberg 2017).

Although multiple merger coalescents have been of significant theoretical interest for around two decades, there has been little practical software available to simulate these models. Kelleher et al. (2013, 2014) developed packages to simulate a related spatial continuum model (Barton et al. 2010), Zhu et al. (2015) simulate genealogies within a species tree based on a multiple-merger model, and Becheler and Knowles (2020) provide a general method for simulating multiple merger processes as part of the Quetzal framework (Becheler et al. 2019). The Beta-xi-sim simulator (Koskela 2018; Koskela and Berenguer 2019) also includes a number of extensions to the Beta-coalescent. None of these methods work with large genomes, and very little work has been performed on simulating multiple merger processes with recombination.

We have added two multiple merger coalescent models in *msprime* 1.0, the Beta-coalescent (Schweinsberg 2003), and “Dirac”-coalescent (Birkner et al. 2013a), allowing us to efficiently simulate such models with recombination for the first time. These simulation models have been extensively validated against analytical results from the site frequency spectrum (Birkner et al. 2013b; Blath et al. 2016; Hobolth et al. 2019) as well as more general properties of coalescent processes. See the Multiple merger coalescent model in Appendix for more details and model derivations.

Ancestral Recombination Graphs

The ARG was introduced by Griffiths (Griffiths 1991; Griffiths and Marjoram 1997) to represent the stochastic process of the coalescent with recombination as a graph. This formulation is complementary to Hudson’s earlier work (Hudson 1983a), and substantially increased our theoretical understanding of recombination. In Griffiths’ ARG formulation, a realization of the coalescent with recombination is a graph in which vertices represent common ancestor or recombination events, and edges represent lineages. There is the “big” ARG, in which we track lineages arising out of recombinations regardless of whether they carry ancestral material (Ethier and Griffiths 1990), and the “little” ARG in which we only track genetic ancestors. Over time, usage of the term has shifted away from its original definition as a stochastic process, to being interpreted as a representation of a particular genetic ancestry as a graph, without necessarily following the specific details of the Griffiths formulation (e.g., Minichiello and Durbin 2006; Mathieson and Scally 2020). Under the latter interpretation, the tree sequence encoding of genetic ancestry (described above) clearly is an ARG: the nodes and edges define a graph in which edges are annotated with the set of disjoint genomic intervals through which ancestry flows.

For our purposes, an ARG is a realization of the coalescent with recombination, in the Griffiths (little ARG) sense. As described in detail by Kelleher et al. (2016), Hudson’s algorithm works by dynamically traversing a little ARG. The graph is not explicitly represented in memory, but is partially present through the extant lineages and the ancestral material they carry over time. We do not output the graph directly, but rather store the information required to recover the genealogical history as nodes

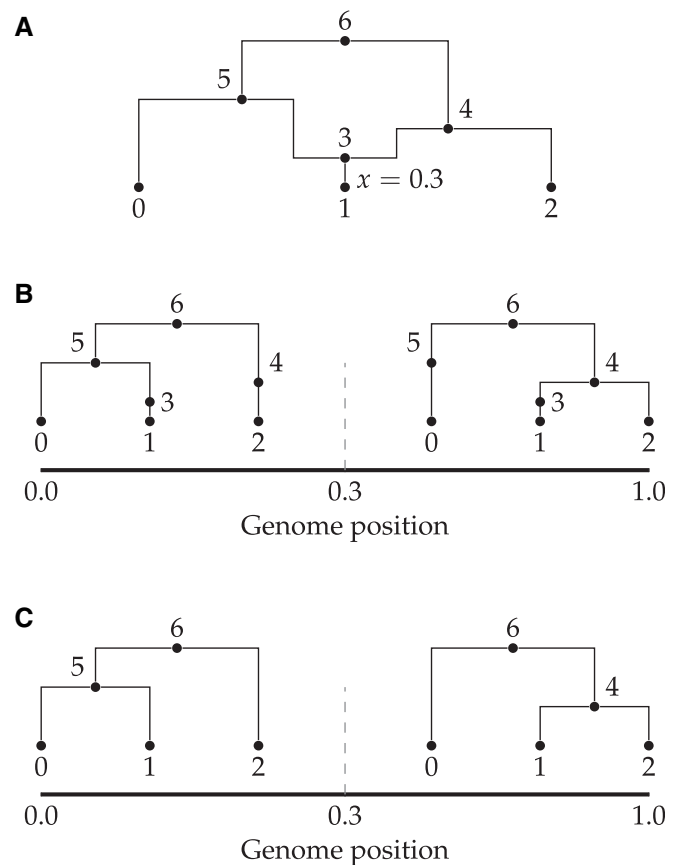


Figure 5 (A) A simple ARG in which a recombination occurs at position 0.3; (B) the equivalent topology depicted as a tree sequence, including the recombination node; (C) the same tree sequence topology “simplified” down to its minimal tree sequence representation. Note the original node IDs have been retained for clarity.

and edges in a tree sequence. This is far more efficient than outputting the simulated ARG in its entirety. For a given scaled recombination rate ρ (setting aside the dependency on the sample size n), we know from Equation (1) that the number of nodes in an ARG is $O(\rho^2)$, whereas the size of the tree sequence encoding is $O(\rho)$ (Kelleher et al. 2016). This difference between a quadratic and a linear dependency on ρ is profound, and shows why large simulations cannot output an ARG in practice.

Although by default *msprime* outputs tree sequences that contain full information about the genealogical trees, their correlation structure along the chromosome, and the ancestral genomes on which coalescences occurred, some information is lost in this mapping down from ARG space to the minimal tree sequence form. In particular, we lose information about ancestral genomes that were common ancestors but in which no coalescences occurred, and also information about the precise time and chromosomal location of recombination events. In most cases, such information is of little relevance as it is in principle unknowable, but there are occasions such as visualization or computing likelihoods in which it is useful. We therefore provide the `record_full_arg` option in *msprime* to store a representation of the complete ARG traversed during simulation. This is done by storing extra nodes (marked with specific flags, so they can be easily identified later) and edges in the tree sequence (Figure 5). One situation in which a record of the full ARG is necessary is when we wish to compute likelihoods during inference. The likelihood is a central quantity in evaluating the plausibility of a putative

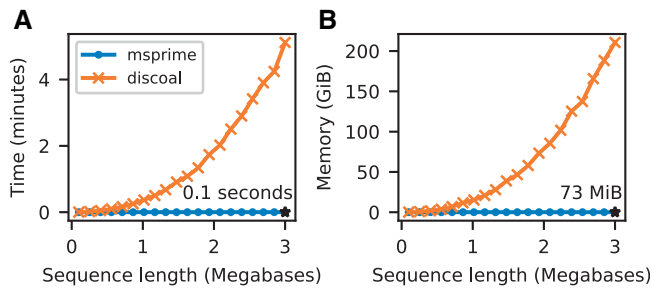


Figure 6 Comparison of selective sweep simulation performance in `msprime` (`sim_ancestry`) and `discoal` (Intel Xeon Gold 6148 CPU). We report the average CPU time and maximum memory usage when simulating three replicates for 100 diploid samples in a model with a single selective sweep in its history, where the beneficial allele had a selection coefficient of $s = 0.05$, a per-base recombination rate of 10^{-8} , population size of $N = 10^4$, and sequence length varying from 100 kb–3000 kb.

ancestry as an explanation of DNA sequence data, both directly through *e.g.*, approaches based on maximum likelihood, and as an ingredient of methods such as Metropolis–Hastings (Kuhner et al. 2000; Nielsen 2000; Wang and Rannala 2008). We provide functions to compute the likelihood of ARG realizations and mutational patterns under the standard coalescent and infinite sites mutation model. For details, see the Appendix: Likelihood calculations.

Selective sweeps

Another elaboration of the standard neutral coalescent with recombination is the addition of selective sweeps (Kaplan et al. 1989; Braverman et al. 1995; Kim and Stephan 2002). Sweeps are modeled by creating a structured population during the sojourn of the beneficial mutation through the population (*i.e.*, the sweep phase) in which lineages may transit between favored and unfavored backgrounds through recombination. This approach allows for many selective sweep scenarios to be simulated efficiently, including recurrent, partial, and soft selective sweeps. However, this efficiency comes at the cost of flexibility in comparison to forwards in time simulation. Several specialized simulators have been developed to simulate sweeps in the coalescent, including `SELsim` (Spencer and Coop 2004), `mbs` (Teshima and Innan 2009), `msms` (Ewing and Hermisson 2010), `cosi2` (Shlyakhter et al. 2014), and `discoal` (Kern and Schrider 2016).

Selective sweeps are implemented in the coalescent as a two-step process: first generating an allele frequency trajectory, and then simulating a structured coalescent process conditioned on that trajectory. Following `discoal`, we generate sweep trajectories in `msprime` using a jump process approximation to the conditional diffusion of an allele bound for fixation (Coop and Griffiths 2004), as detailed in the Selective sweeps model in Appendix. Given a randomly generated allele frequency trajectory, the simulation of a sweep works by assigning lineages to two different structured coalescent “labels,” based on whether they carry the beneficial allele. The allele frequency trajectory determines the relative sizes of the “populations” in these labels over time, and therefore the rates at which various events occur. Common ancestor events can then only merge lineages from *within* a label, but lineages can transfer from one label to the other (*i.e.*, from the advantageous to disadvantageous backgrounds, and vice versa) as a result of recombination events. Once we have reached the end of the simulated trajectory, the sweep is complete, and

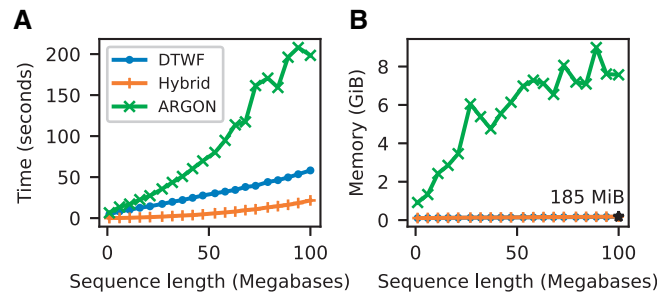


Figure 7 Comparison of DTWF simulation performance in `msprime` (`sim_ancestry`) and `ARGON` (Intel Xeon E5-2680 CPU). We ran simulations with a population size of 10^4 and recombination rate of 10^{-8} , with 500 diploid samples and varying sequence length. We report (A) total CPU time and (B) maximum memory usage; each point is the average over five replicate simulations. We show observations for `ARGON`, `msprime`’s DTWF implementation (“DTWF”) and a hybrid simulation of 100 generations of the DTWF followed by the standard coalescent with recombination (“Hybrid”). We ran `ARGON` with a mutation rate of 0 and with minimum output options, with a goal of measuring only ancestry simulation time. Memory usage for `msprime`’s DTWF and hybrid simulations are very similar.

we remove the structured coalescent labels. Simulation may then resume under any other ancestry model.

Figure 6 compares the performance of `msprime` and `discoal` under a simple sweep model, and shows that `msprime` has far better CPU time and memory performance. Since our implementation uses the abstract label system mentioned above, adding support for similar situations, such as inversions (Peischl et al. 2013), should be straightforward.

Discrete time Wright–Fisher

The coalescent is an idealized model and makes many simplifying assumptions, but it is often surprisingly robust to violations of these assumptions (Wakeley et al. 2012). One situation in which the model does break down is the combination of large sample size and long recombining genomes, where the large number of recombination events in the recent past results in more than the biologically possible 2^t ancestors in t diploid generations (Nelson et al. 2020). This pathological behavior results in identity-by-descent, long-range linkage disequilibrium, and ancestry patterns deviating from Wright–Fisher expectations, and the bias grows with larger sample sizes (Wakeley et al. 2012; Bhaskar et al. 2014; Nelson et al. 2020). Precisely this problem occurs when simulating modern human datasets, and we have implemented a Discrete Time Wright–Fisher (DTWF) model in `msprime` to address the issue. The DTWF simulates backwards in time generation-by-generation so that each gamete has a unique diploid parent, and multiple recombinations within a generation results in crossover events between the same two parental haploid copies. The method is described in detail by Nelson et al. (2020).

Figure 7 shows that `msprime` simulates the DTWF more quickly and requires substantially less memory than `ARGON` (Palamara 2016), a specialized DTWF simulator. However, the generation-by-generation approach of the DTWF is less efficient than the coalescent with recombination when the number of lineages is significantly less than the population size (the regime where the coalescent is an accurate approximation), which usually happens in the quite recent past (Bhaskar et al. 2014). We therefore support changing the simulation model during a simulation so that we can run hybrid simulations, as proposed by Bhaskar et al. (2014). Any number of different simulation models

can be combined, allowing for the flexible choice of simulation scenarios. As the DTWF improves accuracy of genealogical patterns in the recent past, we can simulate the recent history using this model and then switch to the standard coalescent to more efficiently simulate the more ancient history.

Integration with forward simulators

A unique feature of `msprime` is its ability to simulate genetic ancestries by extending an existing partial genetic ancestry. Given a tree sequence that is complete up until time t ago as input (where marginal trees may or may not have fully coalesced), `msprime` can efficiently obtain the segments of ancestral material present at this time, and then run the simulation backwards in time from there. This allows a simulated ancestry to be produced by any number of different processes across disjoint time slices. In practice, this feature is used to “complete” forwards-time ancestry simulations (Kelleher et al. 2018) that may have not fully coalesced. This process (“recapitation”) can be orders of magnitude faster than the standard approach of neutral burn-in; see Haller et al. (2018) for more details and examples. This interoperability between simulators, where a partial ancestry simulation produced by `SLiM` (Haller and Messer 2019) or `fwdpy11` (Thornton 2014) can be picked up and completed by another simulator, with complete information retained—at scale—is unprecedented. There may be an opportunity for other forward genetic simulators (e.g., Gaynor et al. 2021) to leverage the tree sequence data format and associated tools.

Development model

`Msprime` has a large number of features, encompassing the functionality of several more specialized simulators while maintaining excellent performance. It is developed by a geographically distributed team of volunteers under an open source community development model, with a strong emphasis on code quality, correctness, good documentation, and inclusive development. As in any large code base, unit tests play a key role in ensuring that new additions behave as expected and `msprime` has an extensive suite. These tests are run automatically on different operating systems on each pull request (where a contributor proposes a code change), using standard Continuous Integration (CI) methodology. Other CI services check for common errors, code formatting issues, and produce reports on the level of test coverage for the proposed change.

Unit tests are vital for ensuring software quality and correctness, but they are usually of little value in assessing the statistical properties of simulations. To validate the correctness of simulation output, we maintain a suite of statistical tests (as of 1.0.0, 217 validation tests). These consist of running many replicate simulations to check the properties of the output against other simulators, and where possible against analytical results. For example, simulations of complex demography are validated against `ms`, selective sweeps against `discoal`, and Wright–Fisher simulations against forwards in time simulations in `SLiM`. This suite of tests is run before every release, to ensure that statistical errors have not been introduced.

More visibly to the end user, we also have a high standard for documentation, with precise, comprehensive, and cross-linked documentation that is automatically built from the code base and served through the website <https://tskit.dev>. With the goal of lowering the entry barrier to new users, we have invested significant effort in writing examples and introductions, and making common tasks discoverable. We also view contributions to documentation as equally important to the project as writing

code or designing methods: what use would it be to write reliable, stable software if no-one used it?

An important goal of `msprime`’s development model is to maximize accessibility for prospective users and contributors, and to encourage diversity in our community. Gender and racial inequality caused by discrimination and marginalization is a major problem across the sciences (Wellenreuther and Otto 2016; Shannon et al. 2019) and in open source software development (Trinkenreich et al. 2021). Within our field, the contribution of women to early computational methods in population genetics was marginalized (Dung et al. 2019), and women continue to be under-represented in computational biology (Bonham and Stefan 2017). The authorship of our paper reflects these trends, with a skew toward men and affiliations in the United States and Europe. We know the importance of creating and strengthening networks to develop and maintain a diverse community of contributors, and we are committed to fostering a supportive and collaborative environment that helps to address these inequalities in our field.

Discussion

The 1.0 release of `msprime` marks a major increase in the breadth of available features and the potential biological realism of simulations. These abilities will allow researchers to perform more robust power analyses, more reliably test new methods, carry out more reliable inferences, and more thoroughly explore the properties of theoretical models. Despite this complexity and generality, `msprime`’s performance is state-of-the-art and all features are extensively tested and statistically validated. These advances have only been possible thanks to a distributed, collaborative model of software development, and the work of many people.

Even though simulation has long been a vital tool in population genetics, such collaborative software development has historically been uncommon. A huge proliferation of tools have been published (the references here are not exhaustive) and only a small minority of these are actively developed and maintained today. The ecosystem is highly fragmented, with numerous different ways of specifying parameters and representing results, and there are significant software quality issues at all stages. This is unsurprising, since the majority of simulation software development is performed by students, often without formal training in software development. The result resembles Haldane’s sieve for new mutations: many new pieces of software stay permanently on a dusty shelf of supplementary materials, while some of those that prove particularly useful when new (like dominant alleles) are quickly adopted. Although this has produced many good tools and enabled decades of research, it also represents a missed opportunity to invest as a community in shared infrastructure and mentorship in good software development practice.

Scientific software is vital apparatus, and must be engineered to a high quality if we are to trust its results. There is a growing realization across the sciences (e.g., Siepel 2019; Harris et al. 2020; Gardner et al. 2021) that investing in shared community infrastructure produces better results than a proliferation of individually maintained tools, allowing scientists to focus on their specific questions rather than software engineering. `Msprime` 1.0 is the result of such a community process, with features added by motivated users, taking advantage of the established development practices and infrastructure. Software development in a welcoming community, with mentorship by experienced developers, is a useful experience for many users. The skills that

contributors learn can lead to greatly increased productivity in subsequent work (e.g., through more reliable code and better debugging skills). We hope that users who find that features they require are missing will continue to contribute to `msprime`, leading to a community project that is both high quality and sustainable in the long term.

The succinct tree sequence data structure developed for `msprime` provides a view of not only genetic variation, but also the genetic ancestry that produced that variation. Recent breakthroughs in methods to infer genetic ancestry in recombining organisms (Rasmussen et al. 2014; Kelleher et al. 2019; Speidel et al. 2019, 2021; Schaefer et al. 2021; Wohns et al. 2021) have made it possible to estimate such ancestry from real data at scale for the first time (Harris 2019; Tang 2019). Given such inferred ancestry, many exciting applications become possible. For example, Osmond and Coop (2021) developed a method to estimate the location of genetic ancestors based on inferred trees, and other uses are sure to follow. Since the inferred genetic ancestry becomes the input for other downstream inferences, it is vitally important that these primary inferences are thoroughly validated, with the detailed properties of the inferred ancestries cataloged and understood. `msprime` will continue to be an important tool for these inferences and validations, and in this context the ability to interoperate with other methods—particularly forwards simulators—through the succinct tree sequence data structure and `tskit` library will be essential.

Data availability

`msprime` is freely available under the terms of the GNU General Public License v3.0, and can be installed from the Python Package Index or the `conda-forge` ([conda-forge community 2015](https://conda-forge.org/)) `conda` channel. Development is conducted openly on GitHub at <https://github.com/tskit-dev/msprime/>. The documentation for `msprime` is available at <https://tskit.dev/msprime/docs/>. The source code for all the evaluations and figures in this manuscript is available at <https://github.com/tskit-dev/msprime-1.0-paper/>.

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Conflicts of interest

The authors declare that there is no conflict of interest.

Literature cited

- Adrión JR, Cole CB, Dukler N, Galloway JG, Gladstein AL, et al. 2020a. A community-maintained standard library of population genetic models. *Elife*. 9:e54967.
- Adrión JR, Galloway JG, Kern AD. 2020b. Predicting the landscape of recombination using deep learning. *Mol Biol Evol*. 37:1790–1808.
- Arenas M. 2012. Simulation of molecular data under diverse evolutionary scenarios. *PLoS Comput Biol*. 8:e1002495.
- Arenas M, Posada D. 2007. Recodon: coalescent simulation of coding DNA sequences with recombination, migration and demography. *BMC Bioinformatics*. 8:458.
- Árnason E. 2004. Mitochondrial cytochrome *b* DNA variation in the high-fecundity Atlantic cod: trans-Atlantic clines and shallow gene genealogy. *Genetics*. 166:1871–1885.
- Barton NH, Kelleher J, Etheridge AM. 2010. A new model for extinction and recolonization in two dimensions: quantifying phylogeography. *Evolution*. 64:2701–2715.
- Baumdicker F, Pfaffelhuber P. 2014. The infinitely many genes model with horizontal gene transfer. *Electron J Probab*. 19:1–27.
- Beaumont MA, Zhang W, Balding DJ. 2002. Approximate Bayesian computation in population genetics. *Genetics*. 162:2025–2035.
- Becheler A, Coron C, Dupas S. 2019. The quetzal coalescence template library: a C++ programmers resource for integrating distributional, demographic and coalescent models. *Mol Ecol Resour*. 19:788–793.
- Becheler A, Knowles LL. 2020. Occupancy spectrum distribution: application for coalescence simulation with generic mergers. *Bioinformatics*. 36:3279–3280.
- Beckenbach AT. 1994. Mitochondrial haplotype frequencies in oysters: neutral alternatives to selection models. In: Golding B, editor. *Non-neutral Evolution*. Springer. p. 188–198.
- Bhaskar A, Clark AG, Song YS. 2014. Distortion of genealogical properties when the sample is very large. *Proc Natl Acad Sci U S A*. 111:2385–2390.
- Birkner M, Blath J, Eldon B. 2013a. An ancestral recombination graph for diploid populations with skewed offspring distribution. *Genetics*. 193:255–290.
- Birkner M, Blath J, Eldon B. 2013b. Statistical properties of the site-frequency spectrum associated with lambda-coalescents. *Genetics*. 195:1037–1053.
- Birkner M, Blath J, Möhle M, Steinrücken M, Tams J. 2009. A modified lookdown construction for the Xi-Fleming-Viot process with mutation and populations with recurrent bottlenecks. *Alea*. 6: 25–61.

- Birkner M, Liu H, Sturm A. 2018. Coalescent results for diploid exchangeable population models. *Electron J Probab.* 23:1–44.
- Blath J, Cronjäger MC, Eldon B, Hammer M. 2016. The site-frequency spectrum associated with Ξ -coalescents. *Theor Popul Biol.* 110:36–50.
- Blum MG, François O. 2010. Non-linear regression models for Approximate Bayesian Computation. *Stat Comput.* 20:63–73.
- Bonham KS, Stefan MI. 2017. Women are underrepresented in computational biology: an analysis of the scholarly literature in biology, computer science and computational biology. *PLoS Comput Biol.* 13:e1005134.
- Braverman JM, Hudson RR, Kaplan NL, Langley CH, Stephan W. 1995. The hitchhiking effect on the site frequency spectrum of DNA polymorphisms. *Genetics.* 140:783–796.
- Brown T, Didelot X, Wilson DJ, Maio ND. 2016. SimBac: simulation of whole bacterial genomes with homologous recombination. *Microb Genom.* 2:e000044.
- Bunnefeld L, Frantz LAF, Lohse K. 2015. Inferring bottlenecks from genome-wide samples of short sequence blocks. *Genetics.* 201:1157–1169.
- Bycroft C, Freeman C, Petkova D, Band G, Elliott LT, et al. 2018. The UK Biobank resource with deep phenotyping and genomic data. *Nature.* 562:203–209.
- Cartwright RA. 2005. DNA assembly with gaps (Dawg): simulating sequence evolution. *Bioinformatics.* 21:iii31–iii38.
- Carvajal-Rodríguez A. 2008. Simulation of genomes: a review. *Curr Genomics.* 9:155–159.
- Chan J, Perrone V, Spence JP, Jenkins PA, Mathieson S, et al. 2018. A likelihood-free inference framework for population genetic data using exchangeable neural networks. *Adv Neural Inf Process Syst.* 31:8594–8605.
- Charlesworth B, Jensen JD. 2021. Effects of selection at linked sites on patterns of genetic variability. *Annu Rev Ecol Evol Syst.* 52:177–197.
- Charlesworth B, Morgan M, Charlesworth D. 1993. The effect of deleterious mutations on neutral molecular variation. *Genetics.* 134:1289–1303.
- Charlesworth D, Charlesworth B, Morgan M. 1995. The pattern of neutral molecular variation under the background selection model. *Genetics.* 141:1619–1632.
- Chen GK, Marjoram P, Wall JD. 2009. Fast and flexible simulation of DNA sequence data. *Genome Res.* 19:136–142.
- Chen H, Chen K. 2013. Asymptotic distributions of coalescence times and ancestral lineage numbers for populations with temporally varying size. *Genetics.* 194:721–736.
- Chen J-M, Cooper DN, Chuzhanova N, Férec C, Patrinos GP. 2007. Gene conversion: mechanisms, evolution and human disease. *Nat Rev Genet.* 8:762–775.
- Chetwynd-Diggie JA, Eldon B, Etheridge AM. 2022. Beta-coalescents when sample size is large. (In preparation).
- Chikhi L, Rodríguez W, Grusea S, Santos P, Boitard S, et al. 2018. The IICR (inverse instantaneous coalescence rate) as a summary of genomic diversity: insights into demographic inference and model choice. *Heredity (Edinb).* 120:13–24.
- conda-forge community. 2015. The conda-forge Project: community-based Software Distribution Built on the conda Package Format and Ecosystem. Zenodo. <https://doi.org/10.5281/zenodo.4774217>
- Coop G, Griffiths RC. 2004. Ancestral inference on gene trees under selection. *Theor Popul Biol.* 66:219–232.
- Cornuet J-M, Santos F, Beaumont MA, Robert CP, Marin J-M, et al. 2008. Inferring population history with DIY ABC: a user-friendly approach to approximate Bayesian computation. *Bioinformatics.* 24:2713–2719.
- Csilléry K, Blum MG, Gaggiotti OE, François O. 2010. Approximate Bayesian Computation (ABC) in practice. *Trends Ecol Evol.* 25:410–418.
- Csilléry K, François O, Blum MGB. 2012. abc: an R package for approximate Bayesian computation (ABC). *Methods Ecol Evol.* 3:475–479.
- Dayhoff M, Schwartz R, Orcutt B. 1978. A model of evolutionary change in proteins. In: Dayhoff M, editor. *Atlas of Protein Sequence and Structure*, Nat. Biomed. Res. Found; Washington, DC, Vol. 5. p. 345–352.
- De Maio N, Weilguny L, Walker CR, Turakhia Y, Corbett-Detig R, et al. 2021. phastsim: efficient simulation of sequence evolution for pandemic-scale datasets. *bioRxiv.* <https://doi.org/10.1534/genetics.116.198796>
- De Maio N, Wilson DJ. 2017. The bacterial sequential markov coalescent. *Genetics.* 206:333–343.
- Der R, Epstein C, Plotkin JB. 2012. Dynamics of neutral and selected alleles when the offspring distribution is skewed. *Genetics.* 191:1331–1344.
- Desai MM, Walczak AM, Fisher DS. 2013. Genetic diversity and the structure of genealogies in rapidly adapting populations. *Genetics.* 193:565–585.
- Donnelly P, Kurtz TG. 1999. Particle representations for measure-valued population models. *Ann Probab.* 27:166–205.
- Dung SK, López A, Barragan EL, Reyes R-J, Thu R, et al. 2019. Illuminating women's hidden contribution to historical theoretical population genetics. *Genetics.* 211:363–366.
- Durrett R, Schweinsberg J. 2004. Approximating selective sweeps. *Theor Popul Biol.* 66:129–138.
- Eldon B, Freund F. 2018. Genealogical properties of subsamples in highly fecund populations. *J Stat Phys.* 172:175–207.
- Eldon B, Stephan W. 2018. Evolution of highly fecund haploid populations. *Theor Popul Biol.* 119:48–56.
- Eldon B, Wakeley J. 2006. Coalescent processes when the distribution of offspring number among individuals is highly skewed. *Genetics.* 172:2621–2633.
- Ethier S, Griffiths R. 1990. On the two-locus sampling distribution. *J Math Biol.* 29:131–159.
- Ewing G, Hermisson J. 2010. MSMS: a coalescent simulation program including recombination, demographic structure, and selection at a single locus. *Bioinformatics.* 26:2064–2065.
- Excoffier L, Foll M. 2011. Fastsimcoal: a continuous-time coalescent simulator of genomic diversity under arbitrarily complex evolutionary scenarios. *Bioinformatics.* 27:1332–1334.
- Felsenstein J, Churchill GA. 1996. A Hidden Markov Model approach to variation among sites in rate of evolution. *Mol Biol Evol.* 13:93–104.
- Flagel L, Brandvain Y, Schrider DR. 2019. The unreasonable effectiveness of convolutional neural networks in population genetic inference. *Mol Biol Evol.* 36:220–238.
- Fletcher W, Yang Z. 2009. INDELible: a flexible simulator of biological sequence evolution. *Mol Biol Evol.* 26:1879–1888.
- Freund F. 2020. Cannings models, population size changes and multiple-merger coalescents. *J Math Biol.* 80:1497–1521.
- Galtier N, Depaulis F, Barton NH. 2000. Detecting bottlenecks and selective sweeps from DNA sequence polymorphism. *Genetics.* 155:981–987.
- Gardner PP, Paterson JM, McGimpsey SR, Ghomi FA, Umu SU, et al. 2021. Sustained software development, not number of citations or journal choice, is indicative of accurate bioinformatic software. *bioRxiv.* <https://doi.org/10.1101/092205>.
- Gaynor RC, Gorjanc G, Hickey JM. 2021. AlphaSimR: an R-package for breeding program simulations. *G3 (Bethesda).* 11:jkaa017.

- Gillespie JH. 2000. Genetic drift in an infinite population: the pseudo-hitchhiking model. *Genetics*. 155:909–919.
- Gladstein AL, Quinto-Cortés CD, Pistorius JL, Christy D, Gantner L, et al. 2018. Simprily: a Python framework to simplify high-throughput genomic simulations. *SoftwareX*. 7:335–340.
- Gower G, Ragsdale AP, et al. 2022. Demes: a standard format for demographic models. (In preparation).
- Griffiths RC. 1991. The two-locus ancestral graph. *Lect Notes Monogr Ser*. 18:100–117.
- Griffiths RC, Marjoram P. 1997. An ancestral recombination graph. In: Donnelly P, Tavaré S, editors. *Progress in Population Genetics and Human Evolution, IMA Volumes in Mathematics and its Applications*, Vol. 87. Berlin: Springer-Verlag. p. 257–270.
- Griffiths RC, Tavaré S, Bodmer WF, Donnelly PJ. 1994. Sampling theory for neutral alleles in a varying environment. *Philos Trans R Soc Lond B Biol Sci*. 344:403–410.
- Guillaume F, Rougemont J. 2006. Nemo: an evolutionary and population genetics programming framework. *Bioinformatics*. 22:2556–2557.
- Haller BC, Galloway J, Kelleher J, Messer PW, Ralph PL. 2018. Tree-sequence recording in SLiM opens new horizons for forward-time simulation of whole genomes. *Mol Ecol Resour*. 19:552–566.
- Haller BC, Messer PW. 2019. SLiM 3: forward genetic simulations beyond the Wright–Fisher model. *Mol Biol Evol*. 36:632–637.
- Harris CR, Millman KJ, van der Walt SJ, Gommers R, Virtanen P, et al. 2020. Array programming with NumPy. *Nature*. 585:357–362.
- Harris K. 2019. From a database of genomes to a forest of evolutionary trees. *Nat Genet*. 51:1306–1307.
- Hedgecock D. 1994. Does variance in reproductive success limit effective population sizes of marine organisms? In: Beaumont A, editor. *Genetics and Evolution of Aquatic Organisms*, Chapman and Hall. p. 122–134.
- Hedgecock D, Pudovkin AI. 2011. Sweepstakes reproductive success in highly fecund marine fish and shellfish: a review and commentary. *Bull Mar Sci*. 87:971–1002.
- Hein J, Schierup M, Wiuf C. 2004. *Gene Genealogies, Variation and Evolution: A Primer in Coalescent Theory*. New York, NY: Oxford University Press.
- Heled J, Drummond AJ. 2010. Bayesian inference of species trees from multilocus data. *Mol Biol Evol*. 27:570–580.
- Hellenthal G, Stephens M. 2007. mshot: modifying Hudson’s ms simulator to incorporate crossover and gene conversion hotspots. *Bioinformatics*. 23:520–521.
- Henikoff S, Henikoff JG. 1992. Amino acid substitution matrices from protein blocks. *Proc Natl Acad Sci U S A*. 89:10915–10919.
- Hickerson MJ, Stahl E, Takebayashi N. 2007. msBayes: pipeline for testing comparative phylogeographic histories using hierarchical approximate Bayesian computation. *BMC Bioinformatics*. 8:268.
- Hoban S, Bertorelle G, Gaggiotti OE. 2012. Computer simulations: tools for population and evolutionary genetics. *Nat Rev Genet*. 13:110–122.
- Hobolth A, Jensen JL. 2014. Markovian approximation to the finite loci coalescent with recombination along multiple sequences. *Theor Popul Biol*. 98:48–58.
- Hobolth A, Siri-Jegousse A, Bladt M. 2019. Phase-type distributions in population genetics. *Theor Popul Biol*. 127:16–32.
- Huang W, Takebayashi N, Qi Y, Hickerson MJ. 2011. MTML-msBayes: approximate Bayesian comparative phylogeographic inference from multiple taxa and multiple loci with rate heterogeneity. *BMC Bioinformatics*. 12:1–14.
- Hudson RR. 1983a. Properties of a neutral allele model with intra-genic recombination. *Theor Popul Biol*. 23:183–201.
- Hudson RR. 1983b. Testing the constant-rate neutral allele model with protein sequence data. *Evolution*. 37:203–217.
- Hudson RR. 1990. Gene genealogies and the coalescent process. In: Futuyama D, Antonovics J, editors. *Oxford Surveys in Evolutionary Biology*, Oxford University Press, Oxford, Vol. 7. p. 1–44.
- Hudson RR. 2002. Generating samples under a Wright–Fisher neutral model of genetic variation. *Bioinformatics*. 18:337–338.
- Irwin KK, Laurent S, Matuszewski S, Vuilleumier S, Ormond L, et al. 2016. On the importance of skewed offspring distributions and background selection in virus population genetics. *Heredity (Edinb)*. 117:393–399.
- Johri P, Aquadro C, Beaumont M, Charlesworth B, Excoffier L, et al. 2021. Statistical inference in population genomics. *bioRxiv* 2021.10.27.466171
- Jukes TH, Cantor CR. 1969. Evolution of protein molecules. In: Munro HN, editor. *Mammalian Protein Metabolism*, Academic Press, New York, Vol. 3. p. 21–132.
- Kamm J, Terhorst J, Durbin R, Song YS. 2020. Efficiently inferring the demographic history of many populations with allele count data. *J Am Stat Assoc*. 115:1472–1487.
- Kaplan N, Hudson RR. 1985. The use of sample genealogies for studying a selectively neutral *m*-loci model with recombination. *Theor Popul Biol*. 28:382–396.
- Kaplan NL, Hudson RR, Langley CH. 1989. The “hitchhiking effect” revisited. *Genetics*. 123:887–899.
- Karczewski KJ, Francioli LC, Tiao G, Cummings BB, Alföldi J, et al.; Genome Aggregation Database Consortium. 2020. The mutational constraint spectrum quantified from variation in 141,456 humans. *Nature*. 581:434–443.
- Keightley PD, Eyre-Walker A. 2007. Joint inference of the distribution of fitness effects of deleterious mutations and population demography based on nucleotide polymorphism frequencies. *Genetics*. 177:2251–2261.
- Kelleher J, Barton NH, Etheridge AM. 2013. Coalescent simulation in continuous space. *Bioinformatics*. 29:955–956.
- Kelleher J, Etheridge AM, Barton NH. 2014. Coalescent simulation in continuous space: algorithms for large neighbourhood size. *Theor Popul Biol*. 95:13–23.
- Kelleher J, Etheridge AM, McVean G. 2016. Efficient coalescent simulation and genealogical analysis for large sample sizes. *PLoS Comput Biol*. 12:e1004842.
- Kelleher J, Lohse K. 2020. Coalescent simulation with msprime. In: JY Duthel, editor. *Statistical Population Genomics*. New York, NY: Springer US. p. 191–230.
- Kelleher J, Thornton KR, Ashander J, Ralph PL. 2018. Efficient pedigree recording for fast population genetics simulation. *PLoS Comput Biol*. 14:e1006581.
- Kelleher J, Wong Y, Wohns AW, Fadil C, Albers PK, et al. 2019. Inferring whole-genome histories in large population datasets. *Nat Genet*. 51:1330–1338.
- Kern AD, Schrider DR. 2016. Discoal: flexible coalescent simulations with selection. *Bioinformatics*. 32:3839–3841.
- Kim Y, Stephan W. 2002. Detecting a local signature of genetic hitchhiking along a recombining chromosome. *Genetics*. 160:765–777.
- Kimura M. 1980. A simple method for estimating evolutionary rates of base substitutions through comparative studies of nucleotide sequences. *J Mol Evol*. 16:111–120.
- Kimura M. 1981. Estimation of evolutionary distances between homologous nucleotide sequences. *Proc Natl Acad Sci U S A*. 78:454–458.
- Kingman JF. 1982a. On the genealogy of large populations. *J Appl Probab*. 19:27–43.

- Kingman JFC. 1982b. The coalescent. *Stoch Processes Their Appl.* 13: 235–248.
- Kluyver T, Ragan-Kelley B, Pérez F, Granger B, Bussonnier M, et al. 2016. Jupyter notebooks – a publishing format for reproducible computational workflows. In: F Loizides, Schmidt B, editors. *Positioning and Power in Academic Publishing: Players, Agents and Agendas*. IOS Press, Amsterdam. p. 87–90.
- Korunes KL, Noor MAF. 2017. Gene conversion and linkage: effects on genome evolution and speciation. *Mol Ecol.* 26:351–364.
- Koskela J. 2018. Multi-locus data distinguishes between population growth and multiple merger coalescents. *Stat Appl Genet Mol Biol.* 17:20170011.
- Koskela J, Berenguer MW. 2019. Robust model selection between population growth and multiple merger coalescents. *Math Biosci.* 311:1–12.
- Kuhner MK, Yamato J, Felsenstein J. 2000. Maximum likelihood estimation of recombination rates from population data. *Genetics.* 156:1393–1401.
- Lapierre M, Blin C, Lambert A, Achaz G, Rocha EPC. 2016. The impact of selection, gene conversion, and biased sampling on the assessment of microbial demography. *Mol Biol Evol.* 33:1711–1725.
- Li H, Durbin R. 2011. Inference of human population history from individual whole-genome sequences. *Nature.* 475:493–496.
- Li H, Stephan W. 2006. Inferring the demographic history and rate of adaptive substitution in *Drosophila*. *PLoS Genet.* 2:e166.
- Liu Y, Athanasiadis G, Weale ME. 2008. A survey of genetic simulation software for population and epidemiological studies. *Hum Genomics.* 3:79–86.
- Lopes JS, Balding D, Beaumont MA. 2009. PopABC: a program to infer historical demographic parameters. *Bioinformatics.* 25: 2747–2749.
- Mailund T, Schierup MH, Pedersen CN, Mechlenborg PJ, Madsen JN, et al. 2005. CoaSim: a flexible environment for simulating genetic data under coalescent models. *BMC Bioinformatics.* 6:252.
- Marjoram P, Wall JD. 2006. Fast “coalescent” simulation. *BMC Genet.* 7:16.
- Marth GT, Czabarka E, Murvai J, Sherry ST. 2004. The allele frequency spectrum in genome-wide human variation data reveals signals of differential demographic history in three large world populations. *Genetics.* 166:351–372.
- Martin AR, Gignoux CR, Walters RK, Wojcik GL, Neale BM, et al. 2017. Human demographic history impacts genetic risk prediction across diverse populations. *Am J Hum Genet.* 100:635–649.
- Martin AR, Gignoux CR, Walters RK, Wojcik GL, Neale BM, et al. 2020. Erratum: human demographic history impacts genetic risk prediction across diverse populations. *Am J Hum Genet.* 107: 788–789.
- Mathieson I, Scally A. 2020. What is ancestry? *PLoS Genet.* 16: e1008624.
- Matuszewski S, Hildebrandt ME, Achaz G, Jensen JD. 2018. Coalescent processes with skewed offspring distributions and nonequilibrium demography. *Genetics.* 208:323–338.
- McBroome J, Thornlow B, Hinrichs AS, De Maio N, Goldman N, et al. 2021. A daily-updated database and tools for comprehensive SARS-CoV-2 mutation-annotated trees. *MolBiolEvol.* 38: 5819–5824. <https://doi.org/10.1093/molbev/msab264>.
- McGill JR, Walkup EA, Kuhner MK. 2013. GraphML specializations to codify ancestral recombinant graphs. *Front Genet.* 4:146.
- McKenzie PF, Eaton DA. 2020. ipcoal: an interactive Python package for simulating and analyzing genealogies and sequences on a species tree or network. *Bioinformatics.* 36:4193–4196.
- McVean GAT, Cardin NJ. 2005. Approximating the coalescent with recombination. *Philos Trans R Soc Lond B Biol Sci.* 360:1387–1393.
- Miga KH, Koren S, Rhie A, Vollger MR, Gershman A, et al. 2020. Telomere-to-telomere assembly of a complete human X chromosome. *Nature.* 585:79–84.
- Minichiello MJ, Durbin R. 2006. Mapping trait loci by use of inferred ancestral recombination graphs. *Am J Hum Genet.* 79:910–922.
- Möhle M, Sagitov S. 2001. A classification of coalescent processes for haploid exchangeable population models. *Ann Probab.* 29: 1547–1562.
- Montinaro F, Pankratov V, Yelmen B, Pagani L, Mondal M. 2020. Revisiting the out of Africa event with a novel deep learning approach. *Am J Hum Genet.* 108:2037–2051.
- Neher RA, Hallatschek O. 2013. Genealogies of rapidly adapting populations. *Proc Natl Acad Sci U S A.* 110:437–442.
- Nelson D, Kelleher J, Ragsdale AP, Moreau C, McVean G, et al. 2020. Accounting for long-range correlations in genome-wide simulations of large cohorts. *PLoS Genet.* 16:e1008619.
- Nielsen R. 2000. Estimation of population parameters and recombination rates from single nucleotide polymorphism. *Genetics.* 154: 931–942.
- Osmond M, Coop G. 2021. Estimating dispersal rates and locating genetic ancestors with genome-wide genealogies. *bioRxiv.* <https://doi.org/10.1101/2021.07.13.452277>
- Palamara PF. 2016. ARGON: fast, whole-genome simulation of the discrete time Wright–Fisher process. *Bioinformatics.* 32: 3032–3034.
- Parobek CM, Archer FI, DePrenger-Levin ME, Hoban SM, Liggins L, et al. 2017. skeleSim: an extensible, general framework for population genetic simulation in R. *Mol Ecol Resour.* 17:101–109.
- Pavlidis P, Laurent S, Stephan W. 2010. msABC: a modification of Hudson’s ms to facilitate multi-locus ABC analysis. *Mol Ecol Resour.* 10:723–727.
- Peischl S, Koch E, Guerrero R, Kirkpatrick M. 2013. A sequential coalescent algorithm for chromosomal inversions. *Heredity (Edinb).* 111:200–209.
- Peng B, Chen H-S, Mechanic LE, Racine B, Clarke J, et al. 2015. Genetic data simulators and their applications: an overview. *Genet Epidemiol.* 39:2–10.
- Pitman J. 1999. Coalescents with multiple collisions. *Ann Probab.* 27: 1870–1902.
- Pudlo P, Marin JM, Estoup A, Cornuet JM, Gautier M, et al. 2016. Reliable ABC model choice via random forests. *Bioinformatics.* 32:859–866.
- Quinto-Cortés CD, Woerner AE, Watkins JC, Hammer MF. 2018. Modeling SNP array ascertainment with Approximate Bayesian Computation for demographic inference. *Sci Rep.* 8:10.
- Racimo F, Gokhman D, Fumagalli M, Ko A, Hansen T, et al. 2017. Archaic adaptive introgression in TBX15/WARS2. *Mol Biol Evol.* 34:509–524.
- Ragsdale AP, Nelson D, Gravel S, Kelleher J. 2020. Lessons learned from bugs in models of human history. *Am J Hum Genet.* 107: 583–588.
- Ralph P, Thornton K, Kelleher J. 2020. Efficiently summarizing relationships in large samples: a general duality between statistics of genealogies and genomes. *Genetics.* 215:779–797.
- Rambaut A, Grassly NC. 1997. Seq-Gen: an application for the Monte Carlo simulation of DNA sequence evolution along phylogenetic trees. *Comput Appl Biosci.* 13:235–238.
- Rasmussen MD, Hubisz MJ, Gronau I, Siepel A. 2014. Genome-wide inference of ancestral recombination graphs. *PLoS Genet.* 10: e1004342.
- Raynal L, Marin JM, Pudlo P, Ribatet M, Robert CP, et al. 2019. ABC random forests for Bayesian parameter inference. *Bioinformatics.* 35:1720–1728.

- Rivera-Colón AG, Rochette NC, Catchen JM. 2021. Simulation with RADinitio improves RADseq experimental design and sheds light on sources of missing data. *Mol Ecol Resour.* 21:363–378.
- Rosenzweig BK, Pease JB, Besansky NJ, Hahn MW. 2016. Powerful methods for detecting introgressed regions from population genomic data. *Mol Ecol.* 25:2387–2397.
- Sagitov S. 1999. The general coalescent with asynchronous mergers of ancestral lines. *J Appl Probab.* 36:1116–1125.
- Sanchez T, Cury J, Charpiat G, Jay F. 2021. Deep learning for population size history inference: design, comparison and combination with approximate Bayesian computation. *Mol Ecol Resour.* 21:2645–2660.
- Schaefer NK, Shapiro B, Green RE. 2021. An ancestral recombination graph of human, Neanderthal, and Denisovan genomes. *Sci Adv.* 7:eabc0776.
- Schiffels S, Durbin R. 2014. Inferring human population size and separation history from multiple genome sequences. *Nat Genet.* 46:919–925.
- Schrider DR, Kern AD. 2018. Supervised machine learning for population genetics: a new paradigm. *Trends Genet.* 34:301–312.
- Schweinsberg J. 2000. Coalescents with simultaneous multiple collisions. *Electron J Probab.* 5:1–50.
- Schweinsberg J. 2003. Coalescent processes obtained from supercritical Galton–Watson processes. *Stoch Processes Their Appl.* 106:107–139.
- Schweinsberg J. 2017. Rigorous results for a population model with selection II: genealogy of the population. *Electron J Probab.* 22:1–54.
- Shannon G, Jansen M, Williams K, Cáceres C, Motta A, et al. 2019. Gender equality in science, medicine, and global health: where are we at and why does it matter? *Lancet.* 393:560–569.
- Sheehan S, Harris K, Song YS. 2013. Estimating variable effective population sizes from multiple genomes: a sequentially Markov conditional sampling distribution approach. *Genetics.* 194:647–662.
- Sheehan S, Song YS. 2016. Deep learning for population genetic inference. *PLoS Comput Biol.* 12:e1004845.
- Shlyakhter I, Sabeti PC, Schaffner SF. 2014. C_{osi}2: an efficient simulator of exact and approximate coalescent with selection. *Bioinformatics.* 30:3427–3429.
- Siepel A. 2019. Challenges in funding and developing genomic software: roots and remedies. *Genome Biol.* 20:147.
- Speidel L, Cassidy L, Davies RW, Hellenthal G, Skoglund P, et al. 2021. Inferring population histories for ancient genomes using genome-wide genealogies. *Mol Biol Evol.* 38:3497–3511.
- Speidel L, Forest M, Shi S, Myers SR. 2019. A method for genome-wide genealogy estimation for thousands of samples. *Nat Genet.* 51:1321–1329.
- Spence JP, Song YS. 2019. Inference and analysis of population-specific fine-scale recombination maps across 26 diverse human populations. *Sci Adv.* 5:eaaw9206.
- Spencer CC, Coop G. 2004. Selsim: a program to simulate population genetic data with natural selection and recombination. *Bioinformatics.* 20:3673–3675.
- Spielman SJ, Wilke CO. 2015. Pyvolve: a flexible Python module for simulating sequences along phylogenies. *PLoS One.* 10:e0139047.
- Staab PR, Metzler D. 2016. Coala: an R framework for coalescent simulation. *Bioinformatics.* 32:1903–1904.
- Staab PR, Zhu S, Metzler D, Lunter G. 2015. scrm: efficiently simulating long sequences using the approximated coalescent with recombination. *Bioinformatics.* 31:1680–1682.
- Tajima F. 1983. Evolutionary relationship of DNA sequences in finite populations. *Genetics.* 105:437–460.
- Tang L. 2019. Genealogy at the genome scale. *Nat Methods.* 16:1077–1077.
- Tanjo T, Kawai Y, Tokunaga K, Ogasawara O, Nagasaki M. 2021. Practical guide for managing large-scale human genome data in research. *J Hum Genet.* 66:39–52.
- Tavaré S. 1986. Some probabilistic and statistical problems in the analysis of DNA sequences. In: Miura RM, editor. *Lectures on Mathematics in the Life Sciences*, American Mathematical Society, Providence, Rhode Island, Vol. 17. p. 57–86.
- Terasaki Hart DE, Bishop AP, Wang JI. 2021. Geonomics: forward-time, spatially explicit, and arbitrarily complex landscape genomic simulations. *Mol Biol Evol.* 38:4634–4646.
- Terhorst J, Kamm JA, Song YS. 2017. Robust and scalable inference of population history from hundreds of unphased whole genomes. *Nat Genet.* 49:303–309.
- Teshima KM, Innan H. 2009. mbs: modifying Hudson’s ms software to generate samples of DNA sequences with a biallelic site under selection. *BMC Bioinformatics.* 10:166.
- Thornton K, Andolfatto P. 2006. Approximate Bayesian inference reveals evidence for a recent, severe bottleneck in a Netherlands population of *Drosophila melanogaster*. *Genetics.* 172:1607–1619.
- Thornton KR. 2014. A C++ template library for efficient forward-time population genetic simulation of large populations. *Genetics.* 198:157–166.
- Trinkenreich B, Wiese I, Sarma A, Gerosa M, Steinmacher I. 2021. Women’s participation in open source software: a survey of the literature. *arXiv: https://arxiv.org/abs/2105.08777*.
- Tskit developers. 2022. Tskit: a portable library for population scale genealogical analysis. (In preparation).
- Turakhia Y, Thornlow B, Hinrichs AS, De Maio N, Gozashti L, et al. 2021. Ultrafast sample placement on existing trees (USHER) enables real-time phylogenetics for the SARS-CoV-2 pandemic. *Nat Genet.* 53:809–816.
- Vendrami DL, Peck LS, Clark MS, Eldon B, Meredith M, et al. 2021. Sweepstake reproductive success and collective dispersal produce chaotic genetic patchiness in a broadcast spawner. *Sci Adv.* 7:eabj4713.
- Virgoulay T, Rousset F, Noûs C, Leblois R. 2021. Gspace: an exact coalescence simulator of recombining genomes under isolation by distance. *Bioinformatics.* 37:3673–3675.
- Wakeley J. 2008. *Coalescent Theory: An Introduction*. Englewood, CO: Roberts and Company.
- Wakeley J, King L, Low BS, Ramachandran S. 2012. Gene genealogies within a fixed pedigree, and the robustness of Kingman’s coalescent. *Genetics.* 190:1433–1445.
- Wang K, Mathieson I, O’Connell J, Schiffels S. 2020. Tracking human population structure through time from whole genome sequences. *PLoS Genet.* 16:e1008552.
- Wang Y, Rannala B. 2008. Bayesian inference of fine-scale recombination rates using population genomic data. *Philos Trans R Soc Lond B Biol Sci.* 363:3921–3930.
- Wang Y, Zhou Y, Li L, Chen X, Liu Y, et al. 2014. A new method for modeling coalescent processes with recombination. *BMC Bioinformatics.* 15:273.
- Wegmann D, Leuenberger C, Neuenschwander S, Excoffier L. 2010. ABCtoolbox: a versatile toolkit for approximate Bayesian computations. *BMC Bioinformatics.* 11:116.
- Wellenreuther M, Otto S. 2016. Women in evolution—highlighting the changing face of evolutionary biology. *Evol Appl.* 9:3–16.
- Wilton PR, Carmi S, Hobolth A. 2015. The SMC’ is a highly accurate approximation to the ancestral recombination graph. *Genetics.* 200:343–355.

- Wiuf C, Hein J. 1999a. The ancestry of a sample of sequences subject to recombination. *Genetics*. 151:1217–1228.
- Wiuf C, Hein J. 1999b. Recombination as a point process along sequences. *Theor Popul Biol*. 55:248–259.
- Wiuf C, Hein J. 2000. The coalescent with gene conversion. *Genetics*. 155:451–462.
- Wohns AW, Wong Y, Jeffery B, Akbari A, Mallick S, et al. 2021. A unified genealogy of modern and ancient genomes. *bioRxiv*. <https://doi.org/10.1101/2021.02.16.431497>
- Yang T, Deng H-W, Niu T. 2014. Critical assessment of coalescent simulators in modeling recombination hotspots in genomic sequences. *BMC Bioinformatics*. 15:3.
- Yuan X, Miller DJ, Zhang J, Herrington D, Wang Y. 2012. An overview of population genetic data simulation. *J Comput Biol*. 19:42–54.
- Zhu S, Degnan JH, Goldstien SJ, Eldon B. 2015. Hybrid-Lambda: simulation of multiple merger and Kingman gene genealogies in species networks and species trees. *BMC Bioinformatics*. 16:292.

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Appendix

Mutation generation

The algorithm that `msprime` uses to simulate mutations on a tree sequence proceeds in two steps: first, mutations are “placed” on the tree sequence (i.e., sampling their locations in time, along the genome, and on the marginal tree), and then the ancestral and derived alleles of each mutation are generated. All mutation models share the code to place mutations, but choose alleles in different ways.

First, mutations are placed on the tree sequence under an inhomogeneous Poisson model by applying them independently to each edge. If an edge spans a region $[a, b]$ of the genome and connected parent and child nodes with times $s < t$, and the mutation rate locally is μ , then the number of mutations on the edge is Poisson with mean $\mu(t - s)(b - a)$, and each mutation is placed independently at a position chosen uniformly in $[a, b]$ and a time uniformly in $[s, t]$. In a discrete genome, all positions are integers and so more than one mutation may occur at the same position on the same edge. Otherwise (i.e., for an infinite-sites model), positions are rejection sampled to obtain a unique floating-point number. If an edge spans a region of the genome with more than one mutation rate, this is done separately for each sub-region on which the mutation rate is constant. Since each edge is processed independently, the algorithm scales linearly with the number of edges in the tree sequence.

Next, alleles are chosen for each mutation. If the site was not previously mutated, then a new ancestral allele is chosen for the site, according to an input distribution of ancestral state allele probabilities. Then, each mutation on the tree is considered in turn, and a derived allele is randomly chosen based on the parental allele (which may be the ancestral allele or the derived allele of a previous mutation). Finally, information about the mutations are recorded in the site and mutation tables of the tree sequence.

A mutation model must, therefore, provide two things: a way of choosing an ancestral allele for each new variant site, and a way of choosing a derived allele given the parental allele at each mutation. Perhaps the simplest mutation model implemented in `msprime` is the `InfiniteAlleles` mutation model, which keeps an internal counter so that the requested alleles are assigned subsequent (and therefore unique) integers.

The distribution of ancestral alleles is used to choose the allele present at the root of the tree at each mutated site, i.e., the `root_distribution`. Mutation models with a finite possible set of alleles have a natural choice for this distribution—the *stationary distribution* of the mutation process. (All mutation models are

Markovian, so this may be found as the top left eigenvector of the mutation matrix.) This is the default in most models, except, e.g., the `BinaryMutationModel`, whose alleles are 0 and 1 and always labels the ancestral allele “0.” However, mutational processes are not in general stationary, so we often allow a different root distribution to be specified.

Since the general algorithm above applies mutations at a single rate independent of ancestral state, a model in which different alleles mutate at different rates must necessarily produce some silent mutations, i.e., mutations in which the derived allele is equal to the parental allele. To illustrate this, consider a mutation model in which A or T mutates to a randomly chosen different nucleotide at rate α and C or G mutates at rate β , with $\beta < \alpha$. To implement this, first place mutations at the largest total rate, which is α . Then, at each site, choose an ancestral allele from the root distribution, and for each mutation, choose a derived allele as follows: if the parental allele is A or T, then choose a random derived allele different to the parental allele; if the parental allele is C or G, then choose the derived allele to be equal to the parent allele with probability $1 - \beta/\alpha$, and randomly choose a different nucleotide otherwise. This produces the correct distribution by Poisson thinning: a Poisson process with rate α in which each point is kept independently with probability β/α is equivalent to a Poisson process with rate β . All finite-state models (implemented under the generic `MatrixMutationModel` class) work in this way: mutations are placed at the maximum mutation rate, and then some silent mutations will result.

In previous versions of `msprime`, silent mutations were disallowed, and we could have removed them from the output entirely. However, we have chosen to leave them in, so that for instance simulating with the HKY mutation model will result in silent mutations if not all equilibrium frequencies are the same. The presence of silent mutations may at first be surprising but there is a good reason to leave them in: to allow layering of different mutation models. Suppose that we wanted to model the mutation process as a mixture of more than one model, e.g., Jukes–Cantor mutations at rate μ_1 , and HKY mutations occur at rate μ_2 . Layering multiple calls to `sim_mutations` is allowed, so we could first apply mutations with the JC69 model at rate μ_1 and then add more with the HKY model at rate μ_2 . However, there is a small statistical problem: suppose that after applying Jukes–Cantor mutations, we have an $A \rightarrow C$ mutation, but then the HKY mutations inserts another mutation in the middle, resulting in $A \rightarrow C \rightarrow C$. If neither mutation model allows silent transitions, then this is clearly not correct, i.e., it is not equivalent to a model that simultaneously applies the two models. (The impact is small, however, as it only affects sites with more than one mutation.) The solution is to make the Jukes–Cantor model *state-*

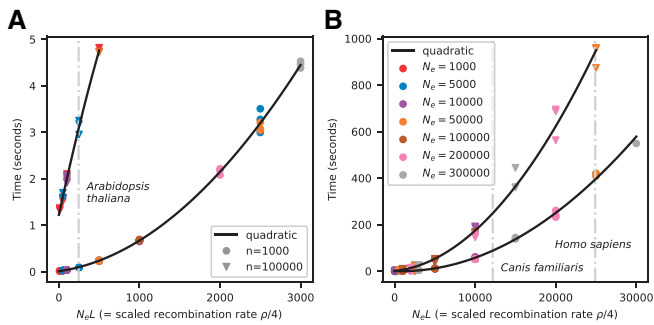


Figure 8 Running time of `sim_ancestry` for (A) small and (B) larger simulations on an Intel i7-6600U CPU. Each point is the run time of one simulation, for various values of effective population size (N_e), chromosome length in Morgans (L), and number of diploid samples (n). Run time scales quadratically with the product of N_e and L , shown on the horizontal axis. For example, (A) shows that 1000 samples of 1 Morgan-length chromosomes from a population of $N_e = 2,000$ diploids would take about 2 s, and (equivalently) that the same number of 0.01 Morgan segments with $N_e = 200,000$ would take the same time. Since recombination rate in these simulations was 10^{-8} , L is the number of base pairs divided by 10^8 . The black lines are quadratic fits separately in each panel and sample size. Vertical gray lines show the approximate values of $N_e L$ for chromosome 1 in three species, using values from the `stdpopsim` catalog (Adrión et al. 2020a).

independent (also called “parent-independent”), by placing mutations at rate $4/3\mu_1$ and then choosing the derived state for each mutation independently of the parent (so that one-fourth of mutations will be silent). If so—and, more generally, if the first mutational process put down is state-independent—then the result of sequentially applying the two mutation models is equivalent to the simultaneous model. To facilitate this, many mutation models have a `state_independent` option that increases the number of silent mutations and makes the model closer to state-independent.

Silent mutations are fully supported by `tskit`, which correctly accounts for their presence when computing statistics and performing other operations. For example, silent mutations have no effect on calculations of nucleotide site diversity.

Time complexity of Hudson’s algorithm

As discussed in the *Recombination* section, the time complexity of Hudson’s algorithm is predicted to be quadratic in the population scaled recombination rate $\rho = 4N_e L$ (where L is the length of the genome in units of recombination distance) by Equation (1). Figure 8 shows the running time for simulations with a variety of population sizes, chromosome length, and sample sizes, and shows this quadratic prediction is well supported by observations (see also Kelleher et al. 2016, Figure 2). We also see that the dependence on n is quite weak, since increasing sample size 100-fold only increases run time by a factor of 2 or so. However, the $\log^2 n$ factor implied by Equation (1) (the sum is a harmonic number and can be approximated by $\log n$) is not well supported by observed run times (or numbers of events) except possibly at very large values of ρ . It therefore appears that a different dependence on n is required to accurately predict simulation time for a given ρ and n .

Figure 8 is a useful yardstick, allowing us to predict how long simulations should take for a wide range of species. Taking a typical chromosome to be 1 Morgan in length, these plots show, roughly, that simulating chromosome-length samples from a population of thousands of individuals takes seconds, while samples from a population of tens of thousands take minutes. Simulating whole chromosomes for many species is very fast,

with 1000 samples of chromosome 1 for *Arabidopsis thaliana* taking less than a second, and a few minutes for dogs and humans. However, the dependence on ρ is quadratic, and if ρ is sufficiently large, simulations may not be feasible. For example, the *Drosophila melanogaster* chromosome 2L is about 23.5 Mb long with an average recombination rate of around 2.4×10^{-8} , so $L \approx 0.57$, and with $N_e = 1.7 \times 10^6$ (Li and Stephan 2006), $N_e L \approx 10^6$, so extrapolating the curve in Figure 8B predicts that simulation would require around 177 h for 1000 samples. For such large values of ρ , we recommend users consider approximate simulations. Since `msprime` does not currently have efficient implementations of approximate coalescent with recombination models, in these cases, we recommend using SMC-based methods such as `scrm`, particularly if sample sizes are small. In practice, to predict the running time of a given simulation in `msprime`, we recommend that users measure run time in a series of simulations with short genome lengths and the desired sample size, and then predict run time by fitting a quadratic curve to genome length as in Figure 8. It is important to note that the quadratic curves in the two panels of Figure 8 are different, and predicting the run times of days-long simulations using the timing of seconds-long runs is unlikely to be very accurate.

What about simulations with changing population size? To understand how run time depends on demography, it helps to consider why run time is quadratic in ρ . At any point in time, `msprime` must keep track of some number of lineages, each of which contains some number of chunks of genetic material. Common ancestor events reduce the number of lineages, and recombination events increase their number. However, with long genomes, only a small fraction of the common ancestor events will involve overlapping segments of ancestry and lead to coalescence in the marginal trees. Such disjoint segments are often far apart (on average, about distance $L/2$), and so recombine apart again immediately; it is these large numbers of rapid and inconsequential events that lead to the quadratic run time. The maximum number of lineages occurs when the increase and decrease in numbers of lineages due to common ancestor and recombination events balance out. To get an idea of run time we can estimate when this balance occurs. Suppose that the maximum number of lineages is M ; at this time, the rate of common ancestor events is $M(M-1)/(4N_e)$ and the total rate of recombination is $M\ell$, where ℓ is the mean length of genome carried by each lineage (including “trapped” non-ancestral material). At the maximum, coalescence and recombination rates are equal, so a typical segment of ancestry will spend roughly half its time in a lineage with at least one other such segment—and, since such lineages carry at least two segments, at most one-third of the lineages carry long trapped segments of ancestry. Since the maximum number of lineages is reached very quickly (Nelson et al. 2020), this implies that $\ell \approx L/6$. Setting the rates of recombination and common ancestor events to be equal and solving for M , we find that M is roughly equal to LN_e . The number of lineages then decreases gradually from this maximum on the coalescent time scale, and therefore over roughly $2N_e$ generations. Since the total rate of events when the maximum number of lineages is present is roughly $L^2 N_e / 6$, then the total number of events is proportional to $(LN_e)^2$ —i.e., proportional to ρ^2 .

What does this tell us about run time for simulating time-varying population sizes? Suppose that population size today is N_1 , while T generations ago it was N_2 . Does the run time depend more on $4N_1 L$ or $4N_2 L$? The answer depends on how T compares to N_1 : if $T/N_1 \ll 1$ then the number of extant lineages remaining after T generations is likely to be substantial, and the algorithm

runtime is primarily determined by N_2 . Conversely, if $T/N_1 \gg 1$, then few extant lineages are likely to remain by time T and runtime depends mainly on N_1 . For instance, in many agricultural species $N_1 \approx 100$, while $N_2 \approx 10^5$, and the run time will depend critically on T —in other words, simulation will be quick in a species with a strong domestication bottleneck, and slow otherwise.

Selective sweeps model

Sweep trajectories are generated in `msprime` using a jump process approximation to the conditional diffusion of an allele bound for fixation (Coop and Griffiths 2004). The jump process moves back in time following the beneficial allele frequency, P , from some initial frequency (e.g., $P=1$) back to the origination of the allele at $p = 1/(2N)$, tracking time in small increments δt . Then, given the frequency p at time t ago, the frequency p' at time $t + \delta t$ ago is given by

$$p' = \begin{cases} p + \mu(p)\delta t + \sqrt{p(1-p)\delta t} & \text{with probability } 1/2 \\ p + \mu(p)\delta t - \sqrt{p(1-p)\delta t} & \text{with probability } 1/2 \end{cases}$$

where

$$\mu(p) = \frac{\alpha p(1-p)}{\tanh(\alpha(1-p))}.$$

Here, $\alpha = 2Ns$ and s is the fitness advantage in homozygotes. This model assumes genic selection (i.e., that the dominance coefficient $h = 0.5$), but can be generalized straightforwardly to include arbitrary dominance. We can also define trajectories to model neutral alleles and soft selective sweeps, which we plan as future additions to `msprime`.

Likelihood calculations

We provide two functions to facilitate likelihood-based inference. Both are implemented only for the simplest case of the standard ARG with a constant population size, and require tree sequences compatible with the `record_full_arg` option as their arguments.

The `msprime.log_arg_likelihood(ts, r, N)` function returns the natural logarithm of the sampling probability of the tree sequence `ts` under the ARG with per-link, per-generation recombination probability r and population size N [e.g., Kuhner et al. 2000, Equation (1)]. Specifically, the function returns the logarithm of

$$\left(\frac{1}{2N}\right)^{q_c} \left(\prod_{i:\mathcal{R}} r g_i\right) \exp\left(-\sum_{i=1}^q \left[\frac{1}{2N} \binom{k_i}{2} + r l_i\right] t_i\right),$$

where t_i is the number of generations between the $(i-1)$ th and i th event, k_i is the number of extant ancestors in that interval, l_i is the number of links in that interval that would split ancestral material should they recombine, q is the total number of events in the tree sequence `ts`, q_c is the number of coalescences, \mathcal{R} is the set of indices of time intervals which end in a recombination, and g_i is the corresponding *gap*: the length of contiguous non-ancestral material around the link at which the recombination in question took place. The gap indicates the number of links (or length of genome in a continuous model) at which a recombination would result in exactly the observed pattern of ancestral material in the ARG. For a continuous model of the genome and a recombination in ancestral material, we set $g_i = 1$ and interpret the result as a density.

The `msprime.unnormalised_log_mutation_likelihood(ts, m)` function returns the natural logarithm of the probability of the

mutations recorded in the tree sequence `ts` given the corresponding ancestry, assuming the infinite sites model, up to a normalizing constant which depends on the pattern of mutations, but not on the tree sequence or the per-site, per-generation mutation probability m . Specifically, the function returns the logarithm of

$$e^{-Tm/2} \frac{(Tm/2)^M}{M!} \prod_{\gamma \in \mathcal{M}} \frac{h_\gamma}{T},$$

where T and \mathcal{M} are the total branch length and set of mutations in `ts`, respectively, M is the number of mutations, and for a mutation γ , h_γ is the total branch length on which γ could have arisen while appearing on all of the leaves of `ts` it does, and on no others. Unary nodes on marginal trees arising from the `record_full_arg` option mean that, in general h_γ corresponds to the length of one or more edges.

Multiple merger coalescent model

Multiple merger coalescents, in which no more than one group of a random number of ancestral lineages may merge into a common ancestor at a given time, are referred to as Λ -coalescents. The rate at which a given group of k out of a total of b lineages merges is

$$\lambda_{b,k} = \int_0^1 x^{k-2} (1-x)^{b-k} \Lambda(dx) + a \mathbf{1}_{\{k=2\}}, \quad 2 \leq k \leq b, \quad (2)$$

where $\mathbf{1}_{\{A\}} := 1$ if A holds, and zero otherwise, $a \geq 0$ is a constant, and Λ is a finite measure on the unit interval without an atom at zero (Donnelly and Kurtz 1999; Pitman 1999; Sagitov 1999). There is also a larger class of simultaneous multiple merger coalescents involving simultaneous mergers of distinct groups of lineages into several common ancestors (Schweinsberg 2000). These are commonly referred to as Ξ -coalescents, and often arise from population models incorporating diploidy or more general polyploidy (Birkner et al. 2013a; Blath et al. 2016). To describe a general Ξ -coalescent, let Δ denote the infinite simplex

$$\Delta := \left\{ (x_1, x_2, \dots) : x_1 \geq x_2 \geq \dots \geq 0, \sum_{j=1}^{\infty} x_j \leq 1 \right\}.$$

The rate of mergers is determined by $\Xi = \Xi_0 + a\delta_0$, where $a \geq 0$ is a constant, δ_0 is the Dirac delta measure, and Ξ_0 is a finite measure on Δ with no atom at $(0, 0, \dots)$. For an initial number of blocks $b \geq 2$ and $r \in \{1, 2, \dots, b-1\}$, let $k_1 \geq 2, \dots, k_r \geq 2$ be the sizes of r merger events and $s = b - k_1 - \dots - k_r$ be the number of blocks not participating in any merger. The rate of each possible set of mergers with sizes (k_1, \dots, k_r) is

$$\begin{aligned} \lambda_{n;k_1, \dots, k_r; s} &= \int_{\Delta} \sum_{\ell=0}^s \sum_{\substack{i_1, \dots, i_{r+\ell}=1 \\ \text{all distinct}}} \binom{s}{\ell} x_{i_1}^{k_1} \dots x_{i_r}^{k_r} x_{i_{r+1}} \dots x_{i_{r+\ell}} \\ &\times \left(1 - \sum_{j=1}^{\infty} x_j\right)^{s-\ell} \frac{1}{\sum_{j=1}^{\infty} x_j^2} \Xi_0(dx) \\ &+ a \mathbf{1}_{\{r=1, k_1=2\}}, \end{aligned}$$

and the number of such (k_1, \dots, k_r) mergers is

$$\mathcal{N}(b; k_1, \dots, k_r) = \binom{b}{k_1 \dots k_r s} \frac{1}{\prod_{j=2}^b \ell_j!},$$

where $\ell_j := \{i \in \{1, \dots, r\} : k_i = j\}$ is the number of mergers of size $j \geq 2$ (Schweinsberg 2000).

Viewing coalescent processes strictly as mathematical objects, it is clear that the class of Ξ -coalescents contains Λ -coalescents as a specific example in which at most one group of lineages can merge at each time, and the class of Λ -coalescents contain the Kingman-coalescent as a special case. However, viewed as limits of ancestral processes derived from specific population models, they are not nested. For example, one can obtain Λ -coalescents from haploid population models incorporating sweepstakes reproduction and high fecundity, and Ξ -coalescents for the same models for diploid populations (Birkner et al. 2013a). One should therefore apply the models as appropriate, i.e., Λ -coalescents to haploid (e.g., mtDNA) data, and Ξ -coalescents to diploid or polyloid (e.g., autosomal) data (Blath et al. 2016).

In `msprime`, we have incorporated two examples of multiple-merger coalescents. One is a diploid extension (Birkner et al. 2013a) of the haploid Moran model adapted to sweepstakes reproduction considered by Eldon and Wakeley (2006). Let N denote the population size, and take $\psi \in (0, 1]$ to be fixed. In every generation, with probability $1 - \varepsilon_N$, a single individual (picked uniformly at random) perishes. With probability ε_N , $\lfloor \psi N \rfloor$ individuals picked uniformly without replacement perish instead. In either case, a surviving individual picked uniformly at random produces enough offspring to restore the population size back to N . Taking $\varepsilon_N = 1/N^\gamma$ for some $\gamma > 0$, Eldon and Wakeley (2006) obtain Λ -coalescents for which the Λ measure in Equation (2) is a point mass at ψ . The simplicity of this model does allow one to obtain some explicit mathematical results (see e.g., Der et al. 2012; Eldon and Freund 2018; Freund 2020; Matuszewski et al. 2018), and the model has also been used to simulate gene genealogies within phylogenies (Zhu et al. 2015). As well as the haploid model of Eldon and Wakeley (2006), `msprime` provides the diploid version of Birkner et al. (2013a), in which individuals perish as above, but replacements are generated by sampling a single pair of diploid individuals as parents, with children sampling one chromosome from each parent. Hence, there are four parent chromosomes involved in each reproduction event, which can lead to up to four simultaneous mergers, giving rise to a Ξ -coalescent with merger rate

$$\lambda_{b;k_1,\dots,k_r;s}^{\text{Dirac}} = \frac{c\psi^2/4}{1+c\psi^2/4} \frac{4}{\psi^2} \sum_{\ell=0}^{s\wedge(4-r)} \binom{s}{\ell} (4)_{r+\ell} (1-\psi)^{s-\ell} \times \left(\frac{\psi}{4} \right)_{k_1+\dots+k_r+\ell} + \frac{\mathbb{1}_{\{r=1, k_1=2\}}}{1+c\psi^2/4}, \quad (3)$$

The interpretation of Equation (3) is that “small” reproduction events in which two lineages merge occur at rate $1/(1+c\psi^2/4)$, while large reproduction events with the potential to result in simultaneous multiple mergers occur at rate $(c\psi^2/4)/(1+c\psi^2/4)$.

The other multiple merger coalescent model incorporated in `msprime` is the haploid population model considered by Schweinsberg (2003), as well as its diploid extension (Birkner et al. 2018). In the haploid version, in each generation of fixed size N , individuals produce random numbers of juveniles (X_1, \dots, X_N) independently, each distributed according to a stable law satisfying

$$\lim_{k \rightarrow \infty} Ck^\alpha \mathbb{P}(X \geq k) = 1 \quad (4)$$

with index $\alpha > 0$, and where $C > 0$ is a normalizing constant. If the total number of juveniles $S_N := X_1 + \dots + X_N$ produced in this way is at least N , then N juveniles are sampled uniformly at

random without replacement to form the next generation. As long as $E[X_1] > 1$, one can show that $\{S_N < N\}$ has exponentially small probability in N , and does not affect the resulting coalescent as $N \rightarrow \infty$ (Schweinsberg 2003). If $\alpha \geq 2$, the ancestral process converges to the Kingman-coalescent; if $1 \leq \alpha < 2$, the ancestral process converges to a Λ -coalescent with Λ in Equation (2) given by the Beta($2 - \alpha, \alpha$) distribution, i.e.,

$$\Lambda(dx) = \mathbb{1}_{\{0 < x \leq 1\}} \frac{1}{B(2 - \alpha, \alpha)} x^{1-\alpha} (1-x)^{\alpha-1} dx, \quad (5)$$

where $B(a, b) = \Gamma(a)\Gamma(b)/\Gamma(a+b)$ for $a, b > 0$ is the beta function (Schweinsberg 2003). This model has been adapted to diploid populations by Birkner et al. (2018), and the resulting coalescent is Ξ -coalescent with merger rate

$$\lambda_{b;k_1,\dots,k_r;s}^{\text{Beta}} = \sum_{\ell=0}^{s\wedge(4-r)} \binom{s}{\ell} \frac{(4)_{r+\ell} B(k + \ell - \alpha, s - \ell + \alpha)}{4^{k+\ell} B(2 - \alpha, \alpha)}, \quad (6)$$

where $k := k_1 + \dots + k_r$ (Blath et al. 2016; Birkner et al. 2018). The interpretation of Equation (6) is that the random number of lineages participating in a potential merger is governed by the Λ -coalescent with rate Equation (5), and all participating lineages are randomly allocated into one of four groups corresponding to the four parental chromosomes, giving rise to up to four simultaneous mergers.

The stable law Equation (4) assumes that individuals can produce arbitrarily large numbers of juveniles. Since juveniles are at least fertilized eggs, it may be desirable to suppose that the number of juveniles surviving to reproductive maturity cannot be arbitrarily large. Hence we also consider an adaptation of the Schweinsberg (2003) model, where the random number of juveniles has a deterministic upper bound $\phi(N)$, and the distribution of the number of juveniles produced by a given parent (or pair of parents in the diploid case) is

$$P(X = k) = \mathbb{1}_{\{1 \leq k \leq \phi(N)\}} \frac{\phi(N+1)^z}{\phi(N+1)^z - 1} \left(\frac{1}{k^z} - \frac{1}{(k+1)^z} \right). \quad (7)$$

See Eldon and Stephan (2018) for a related model. One can follow the calculations of Schweinsberg (2003) or Birkner et al. (2018) to show that if $1 < \alpha < 2$ then, recalling that $k = k_1 + \dots + k_r$, the merger rate is

$$\lambda_{b;k_1,\dots,k_r;s}^{\text{Beta,M}} = \sum_{\ell=0}^{s\wedge(4-r)} \binom{s}{\ell} \frac{(4)_{r+\ell} B(M; k + \ell - \alpha, s - \ell + \alpha)}{4^{k+\ell} B(M; 2 - \alpha, \alpha)} \quad (8)$$

where $B(z; a, b) := \int_0^z t^{a-1} (1-t)^{b-1} dt$ for $a, b > 0$ and $0 < z \leq 1$ is the incomplete beta function, and

$$M := \lim_{N \rightarrow \infty} \frac{\phi(N)/N}{\phi(N)/N + E[X_1]} \in (0, 1]$$

(Chetwynd-Diggle et al. 2022). In other words, the measure Λ driving the multiple mergers is of the same form as in Equation (5) with $0 < x \leq M$ in the case $1 < \alpha < 2$ and $\lim_{N \rightarrow \infty} \phi(N)/N > 0$. If $\alpha \geq 2$ or $\phi(N)/N \rightarrow 0$, then the ancestral process converges to the Kingman-coalescent (Chetwynd-Diggle et al. 2022).