

Evolutionary triplet models of structured RNA

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Abstract

The existence of an all-RNA primordial ribosome was proposed by Francis Crick in 1968. Recently, a domain-level model for the original ribosome was proposed by Smith et al. Given the abundance of ribosomal RNA sequence data and the many successful reconstructions of ancestral proteins, the reconstruction and synthesis of ancestral ribosomes (and other RNAs) is a feasible goal for paleogenetics. This will require new bioinformatics tools and methods, in particular a robust theoretical framework for reconstructing histories of substitutions, indels and changes in RNA structure.

We describe a “transducer composition” algorithm for extending pairwise statistical models of RNA structural evolution to models of multiple sequences related by a phylogenetic tree. This algorithm draws on formal models of computational linguistics as well as the 1985 “protosequence” algorithm of David Sankoff. The output of the composition algorithm is a multiple-sequence stochastic context-free grammar. We describe dynamic programming algorithms, which are robust to null cycles and empty bifurcations, for parsing this grammar. Example applications include structural alignment of non-coding RNAs, propagation of structural information from an experimentally-characterized sequence to its homologs, and inference of the ancestral structure of a set of diverged RNAs.

We implemented these algorithms for a three-taxon phylogeny. Using our implementation on a simple model of pairwise RNA structural evolution, we simulated data under the model and tested the dependence of alignment inference and ancestral structure reconstruction accuracy on phylogenetic branch length. Our results suggest that we may be able to accurately reconstruct ancestral structures despite sequence and structural divergence if the evolutionary process is well-understood. We discuss the implications of our results for RNA algorithm design and phylogenetic reconstruction of RNA evolutionary history.

The programs described are available as part of the DART software package for sequence analysis, released under the GNU Public License at <http://biowiki.org/dart>.

Author Summary

Introduction

In 1968, Francis Crick hypothesized that the first ribosome consisted entirely of RNA, without any protein cofactors [1]. A domain structure for this primeval ribosome was recently proposed [2]. To synthesize such a reconstructed ribosome or reconstructions of other evolutionarily significant RNAs such as group II introns [3] or telomerase [4], it will be necessary to develop methods that can predict the sequences and structures of ancient RNAs based on the divergent sequences of their many descendants.

An inspection of RNA alignments, such as those in the RFAM database [5], suggests that an evolutionary model for RNA structure must eventually include multiple layers of detail: point substitutions, covariant substitutions of base-pairs [6, 7], indels [8], local changes in secondary structure such as helix slippage [9], and changes in domain structure [2]. Stochastic context-free grammars (SCFGs), which can efficiently model the long-range correlations generated by RNA secondary structures, are natural probabilistic models of such phenomena and have been used for ncRNA homology detection [10–13], gene prediction [14, 15], folding [16, 17] and alignment [18–20].

By analogy with substitution processes, which are well-understood [21], we may split the ancestral reconstruction problem into two halves. The first half is the development of a **pairwise model**, describing the probability distribution $P(Y|X)$ of a descendant (Y) conditional on its immediate ancestor (X). In substitution processes, the pairwise model is a conditional substitution matrix. Often (but not always) the pairwise model is derived from an instantaneous model of change, i.e., a continuous-time Markov chain (parametrized by a rate matrix); obtaining the transition probabilities of this chain (via exponentiation of the rate matrix) yields a pairwise model whose parameters are smoothly-varying functions of a finite time parameter T . A pairwise model represents an individual branch of a phylogenetic tree, with T representing the length of that branch.

The second half of the problem involves extending the model (and related inference algorithms) from a single branch to a complete phylogeny, i.e., from a pairwise model of two sequences to a **multiple-sequence model** of many sequences. In a typical situation, the sequences at the leaves of the tree are observed, but those at internal nodes are unobserved. Questions of interest then include:

- A. What is the likelihood for the observed sequence data?
- B. Can we sample (find the mode, take moments, etc.) from the posterior distribution of the unobserved sequence at the root node?

- C. Can we sample (etc.) from the posterior of the unobserved sequences at the other internal nodes?
- D. Can we estimate summaries of the evolutionary history, such as the number of substitution events on each branch (for a substitution model), the alignment (for a model which includes indels), or changes in the underlying structure (for a model of RNA structure)?

For substitution models, there has been extensive work focused on answering each of these questions. Given a pairwise substitution model, questions A and B can be answered exactly by Felsenstein’s pruning algorithm [22] and question C can be answered by the peeling algorithm (first presented for pedigree analysis by Elston and Stewart [23]). The estimation of evolutionary histories (question D) has been addressed by exact summarization [24] and sampling [25] approaches. Many of these questions and answers can be unified by an appropriate framework; for example, another representation of answers A-C is that the “pruning” and “peeling” algorithms (combined) are just the sum-product algorithm on a directed graphical model [26], yielding exact marginal distributions for unobserved variables. Graphical models also suggest general-purpose sampling approaches in addition to the exact sum-product algorithm.

The two halves of the reconstruction problem — developing a pairwise model and then extending it to multiple sequences — are largely independent. Felsenstein’s pruning algorithm, for example, is essentially blind to the parametric form of the pairwise substitution model; it just assumes that a substitution model is provided for every branch. Subsequent models developed by other researchers can be plugged into the pruning algorithm without modification [27, 28].

We therefore addressed the problem of modeling the indel-evolution of multiple structured RNAs in a similarly-modular fashion by separating the creation of pairwise and multiple-sequence models. In previous work, we addressed the first (pairwise) part of the RNA reconstruction problem by describing a simple continuous-time model of RNA structural evolution [29]. This model corresponded to a Pair SCFG with a time-dependent parametrization which we used to simultaneously align and predict the structure of pairs of related RNAs. The focus of the present work is to solve the second (multiple-sequence) part of the RNA reconstruction problem by giving a general procedure for extending a pairwise model to multiple sequences related by a phylogenetic tree. This process yields a multiple-sequence SCFG, a natural model of the evolutionary relationships between multiple structured RNAs.

The main contributions of this paper are (1) an algorithm that transforms a phylogenetic ensemble of pair grammars, representing models on branches of a phylogenetic tree, into a coherent, multiple-sequence

SCFG, (2) dynamic programming (DP) algorithms for performing inference under this multiple-sequence SCFG, and (3) freely-available software implementing algorithms (1) and (2) for the simplified case of a three-branch star-topology tree. While the idea of composing conditionally-normalized models on trees is intuitive, the resulting models can be very complex, even for simple models of RNA evolution, making (1) necessary. Studies of related indel models have suggested that an implementation of dynamic programming (DP) algorithms on the three-branch tree topology is sufficient to draw samples from the posterior distribution of ancestral sequences on more complex tree topologies, using Markov Chain Monte Carlo or MCMC [30–32], suggesting that (2) and (3) are, in principle, sufficient for analyzing trees relating many sequences.

We show that our algorithm produces a multiple-sequence grammar which is much more compact than suggested by naive approaches to model construction. We provide analyses of the asymptotic complexities of models constructed using our procedure and provide estimates of the time and memory required to reconstruct the structures of several RNA families for the case of a 3-taxon phylogeny, which we have implemented in the program INDIEGRAM. While by these estimates only the smallest sequences currently fit into affordable memory, thereby preventing us from applying our method to many problems of interest, a simulation study suggests that we can hope to accurately reconstruct ancestral structures over long evolutionary time, even in the presence of structural divergence.

In the Discussion, we speculate on algorithmic extensions that may reduce memory requirements, inspired by related work in reconstructing DNA and protein sequences.

Methods

We describe below a general method for constructing a multiple-sequence stochastic grammar for alignment, folding and ancestral reconstruction of RNA, given a phylogenetic tree and a description of the evolutionary process acting along each branch.

Overview

Our problem statement is this: **Given a phylogenetic tree relating several structured RNAs and a description of the evolution of a structured RNA along a single branch of the tree (in the form of a Pair SCFG), (1) find the corresponding phylogenetic multiple-sequence grammar and (2) use that grammar to reconstruct, *a posteriori*, the evolutionary histories of the RNAs.** We assume that the phylogeny, including both the tree topology and branch lengths, is known.

This paper focuses on model construction and inference algorithms rather than the heuristics and constraints which will be necessary to make these algorithms fast enough for analysis of many biological datasets. As discussed below, the complexity of general inference algorithms is prohibitively high for many problems of interest. However, this complexity can be significantly reduced by incorporating outside knowledge. For example, if we know the consensus structure of several sequences or their individual structures, then we can constrain our algorithms accordingly. Similarly, we might consider only ancestral structures which are compatible with a given multiple sequence alignment, or a relatively small set of candidate alignments (as in the ORTHEUS program [33]). Such constraints are commonly used by programs for SCFG-based RNA sequence analysis such as QRNA [34], Stemloc [18] and CONSAN [19]. Alignment and structural constraints can be combined [18].

In the following sections we introduce more precise definitions for two-sequence models of RNA structure and outline our algorithms for (1) combining these two-sequence models on a phylogenetic tree and (2) using the composite phylogenetic grammars for inference.

Two-sequence models

We discuss the general problem of creating state-space models of the evolution of related sequences, beginning with models of substitution processes acting at independent sites (as studied in likelihood phylogenetics) and generalizing to models of indels, first in primary sequences and then in sequences with

conserved secondary structure.

A stochastic model for the evolution of one sequence (the ancestor, X) into another (the descendant, Y) over an interval of time (T) can be described by a joint distribution, $P(X, Y|T)$. This joint distribution can be factored as $P(X) \cdot P(Y|X, T)$, where $P(X)$ is the marginal distribution over ancestral sequences and $P(Y|X, T)$ is the conditional distribution over descendant sequences given an ancestral sequence. In terms of phylogenetics, the conditional distribution $P(Y|X, T)$ describes the evolution $X \xrightarrow{T} Y$ along a branch of length T .

It is possible to “multiply” two such models together. More precisely, one multiplies two conditional distributions and sums out the intermediate sequence. Thus, successive evolution along two branches $X \xrightarrow{T_1} Y \xrightarrow{T_2} Z$ is modeled by the distribution

$$P(Y, Z|X, T_1, T_2) = P(Y|X, T_1)P(Z|Y, T_2)$$

and we can sum sequence Y out of this, obtaining the distribution

$$P(Z|X, T_1 + T_2) = \sum_Y P(Y|X, T_1)P(Z|Y, T_2)$$

for the composite branch $X \xrightarrow{T_1+T_2} Z$.

This formalism underlies likelihood phylogenetics. Working under the independent-sites assumption, $P(X, Y|T)$ is the (X, Y) ’th element of the joint substitution matrix for a single site and $P(Y|X, T)$ is the corresponding element of the conditional matrix. The conditional matrix is in fact the matrix exponential $\exp(\mathbf{R}T)$, where \mathbf{R} is the substitution rate matrix [24]. Composition of two branches just amounts to a matrix multiplication.

A similar formalism can be used to describe the evolution of whole sequences with indels. Suppose that the joint distribution $P(X, Y|T)$ is the distribution modeled by a pair hidden Markov model (Pair HMM) [11], a probabilistic model of the evolution of two sequences under the approximation that only adjacent characters are directly correlated, and the marginal $P(X)$ is the distribution of a single-sequence HMM, a probabilistic model of single sequences under the same approximation. The conditional distribution $P(Y|X, T)$ then corresponds to a conditional Pair HMM, a finite-state machine which transforms one sequence (the input, X) into another (the output, Y). Following computational linguists, we call this

conditionally-normalized state machine a **string transducer** or simply a **transducer** [35]. Because of its conditional normalization, this state machine is distinct from a standard Pair HMM. A Pair HMM has two outputs X and Y and emits symbols to both of those outputs, while a transducer absorbs symbols from the input X and emits symbols to the output Y . Despite this distinction, Pair HMMs and transducers share very similar inference algorithms; for example, $P(Y|X, T)$ is computed using a direct analogue of the Forward algorithm [11].

We extend this formalism to the case of structured RNA as follows. Let X and Y now represent structured RNA sequences or, more precisely, parse trees. A single-sequence SCFG models the marginal $P(X)$; a jointly-normalized Pair SCFG [11] models the joint distribution $P(X, Y|T)$. The conditional distribution $P(Y|X, T)$ is modeled by a conditionally-normalized Pair SCFG. Following terminology from computational linguistics [36], we call this conditionally-normalized grammar a **parse-tree transducer**.

String transducers are special cases of parse-tree transducers, just as HMMs are special cases of SCFGs. Henceforth, we will drop the distinction between strings and parse trees. We will also refer interchangeably to “states” (in the state-machine representation) and “nonterminals” (in the grammar representation). Likewise, we will refer interchangeably to “state paths” (machines) and “parse trees” (grammars).

Terminology and normalization. Consider the stochastic grammar which generates parse trees from the marginal distribution $P(X)$. It is occasionally convenient to represent this grammar as a transducer whose input is constrained to be null, i.e. a machine that accepts a dummy (empty) input sequence, and outputs sequence X . We refer to this as the **singlet transducer**. In contrast, the more general type of transducer that absorbs parse trees X and generates modified parse trees Y from the conditional distribution $P(Y|X, T)$ is a **branch transducer**. By definition, singlet transducers only emit symbols to their output sequence, and use a restricted set of state types. Branch transducers, in contrast, can both emit symbols to their outputs and absorb symbols from their inputs, and so use the full range of state types.

Transducers can have states of type **Start**, **End**, **Wait**, **Insert** and **Match**. The first three state types, **Start**, **End** and **Wait**, are null: they do not emit or absorb any symbols and are required solely for “organizational” purposes (see following section). Two types of states can emit and/or absorb symbols, **Insert** and **Match**. An **Insert** state emits a symbol to the output without absorbing anything. A

Match state absorbs a symbol on the input and either emits the same symbol to the output, substitutes a different output symbol, or emits no output symbol at all, the last corresponding to a deletion.

As stated above, the Pair SCFG must be “conditionally normalized” so that models can be chained together, extending the pairwise model to multiple sequences. The transformation rules are partitioned into co-normalized groups; within each group, the rule probabilities must sum to one. In a jointly-normalized Pair SCFG, each group corresponds to the set of all rules that can be applied to a given nonterminal (i.e., all outgoing transitions from a particular state). In a conditionally-normalized Pair SCFG, in contrast, each co-normalized group includes all rules that can be applied to a given nonterminal *for a given set of absorbed symbols*.

Multiple-sequence models

We can use the concepts of factoring probability distributions introduced in the two-sequence framework to model the common descent of many homologous sequences. Given a phylogenetic tree and a two-sequence model, we wish to obtain a multiple-sequence SCFG describing the common descent of the observed sequences.

A singlet transducer (which emits, but does not absorb, symbols) lies at the root of the phylogeny and serves as a generative model of the ancestral sequence. To represent the evolution of an ancestral sequence into many descendant sequences, we place a branch transducer on each branch of the phylogeny. Figures 1 and 2 show simple examples of building a model to represent such an evolution.

Throughout this paper we frequently refer to two and three-taxon (star) phylogenies. In all cases, the sequence W is assumed to be the (unobserved) ancestral sequence and the sequences X , Y , and Z the (observed) extant sequences (as in Figures 1 and 2).

The composition algorithm

While this composition of conditionally-normalized models on a phylogenetic tree is intuitive, in practice building such an ensemble model is challenging due to the sheer number of possible states and transitions of the ensemble model. The maximum possible state space of the ensemble is the Cartesian product of the individual transducer state spaces. If the singlet transducer has a states, each branch transducer has b states, and the phylogeny has N branches, then an upper bound on the number of ensemble states is $O(a \cdot b^N)$. However, in practice there are many fewer states than suggested by this bound; many state

configurations are not reachable. For example, for the tree with two extant sequences and a single parent, the branch transducers above leaves X and Y cannot simultaneously be in **Insert** states, as this would correspond to aligning non-homologous (inserted) characters. Similarly, while an upper bound on the number of possible transitions in the transition matrix of the ensemble model is $O((a \cdot b^N)^2)$, in practice models never reach this bound, due both to inaccessible configurations, such as the one described above, and the sparseness of transitions between the remaining, accessible configurations.

While the accessible state space of the ensemble is smaller than that given by the exponential upper bound, it is generally nonetheless too complex to deal with by hand. For example, the simple model of RNA structural evolution described in Results yields an ensemble model of three sequences with 230 states and 1,789 transitions. More realistic models of RNA give rise to even larger ensemble models.

We therefore need an algorithm to efficiently construct the “state graph” of the ensemble model, consisting of a list of accessible states and the possible transitions between them. By analogy with algorithms for uninformed graph search in artificial intelligence, the transition graph of the ensemble can be constructed by an uninformed depth-first search, where at each step of the search we obtain the next possible ensemble states by changing the state of one or more of the singlet or branch transducers. Beginning with the entire ensemble in state **Start**, the depth-first search of states continues until all nodes are in state **End**.

The allowed transitions of the ensemble can be categorized as follows:

1. **Null Transition:** A branch transducer makes a transition into a **Wait** state, with no terminal emission or bifurcation.
2. **Terminal Emission:** A singlet or branch transducer makes a transition into a state of type **Insert**, emitting left and/or right terminal symbols (e.g., a single base or base-pair). These symbols are absorbed by the immediately-descended transducers, which are pushed into states of type **Match** and may themselves emit terminal symbols that will be absorbed by *their* descendant transducers. This continues down the tree: The terminal symbols are passed from parents to children to grandchildren (albeit possibly being replaced by other terminal symbols as they are propagated down) and they propel branch transducers into **Match** states as they go. Eventually, the cascade of emitted terminal symbols stops when all the symbols have been deleted or when the cascade reaches the leaves of the tree.

3. **Bifurcation:** A singlet or branch transducer makes a transition into a state of type **Insert** that spawns left and/or right nonterminal states. These nonterminals are processed recursively down the tree, just as in a terminal emission (conceptually, a bifurcation is a “nonterminal emission”). As with terminal emissions, absorption of nonterminal emissions propels descendant transducers into **Match** states, making transitions which may themselves propagate nonterminals further down the tree. A biologically-relevant example of a bifurcation is the insertion of a stem into an ancestral RNA structure, which may then be conserved or deleted in the descendant structures.
4. **End Transition:** The singlet transducer at the root makes a transition to the **End** state, pushing all the descendant branch transducers into **End** states and terminating the current branch of the parse tree.

Co-ordination between the various branch machines is achieved by specifying an ordering on the nodes and by having branch transducers “pause” in **Wait** states while waiting to absorb a symbol from the node above. Only one transducer is allowed to make a spontaneous transition at a time. If this transition corresponds to a terminal emission or a bifurcation, then this may force descendant transducers into making reactive transitions.

The four types of allowed transitions listed above can be formalized as follows. Let the total order on the nodes correspond to a preorder traversal of the tree, from which it follows that $m \prec n$ if m is ancestral to n . Let \mathcal{T}_m denote the singlet or branch transducer which emits symbols to node m . Transducer \mathcal{T}_m changes state if and only if one of the following three mutually-exclusive conditions holds:

Type 1: Transducer \mathcal{T}_m is not in a **Wait** state, while all its successor transducers \mathcal{T}_n are in **Wait** states (where $m \prec n$). \mathcal{T}_m is free to make any transition.

Type 2: Transducer \mathcal{T}_m is in a **Wait** state. Its parent transducer emits a symbol, forcing \mathcal{T}_m into a **Match** state so it can absorb that symbol.

Type 3: Transducer \mathcal{T}_m is in a **Wait** state. Its parent transducer enters the **End** state, forcing \mathcal{T}_m into the **End** state as well.

These possible transitions of the ensemble generate multiple alignments as follows:

1. The singlet transducer and all branch transducers begin in their respective **Start** states.

2. Before any residues can appear at the root, the branch transducers all “wind back” into **Wait** states, via type-1 transitions. This occurs in reverse order (i.e., a postorder traversal of the tree).
3. During this initial windback, clade-specific insertions can occur. This process is described in detail at step 9.
4. With all the branch transducers wound back into **Wait** states, the singlet transducer makes a (type-1) transition into an **Insert** state, emitting a symbol to the sequence at the root node.
5. The transducers on outgoing branches from the root then make (type-2) transitions into **Match** states, either copying the root symbol to their own outputs, substituting it for a different symbol or staying silent (this silence corresponds to a clade-specific deletion; in our formalism, both substitutions and deletions are handled by **Match** states.)
6. The transducers on branches one step away from the root then process the symbols which reached them (if any did), followed by transducers on branches two steps away from the root, then three steps, and so on (these can all be regarded as occurring simultaneously, in a single “wave” or “cascade” of emissions).
7. Eventually the emitted symbols are propagated, via type-2 transitions, all the way to the tips of the tree (if they survived) or to the nodes where they were deleted (if they did not survive). The wave of type-2 transitions has left a lot of branch transducers in **Insert** and **Match** states.
8. The branch transducers then, in postorder, each wind back into **Wait** states, just as at step 2. (These windback transitions can be collapsed into a single ensemble transition, as with the emission cascade; however, the windback may be interrupted by clade-specific insertions; see below.)
9. During the postorder windback, each branch transducer gets an opportunity to generate a new symbol (via type-1 transitions to **Insert** states). (If such a transition to **Insert** occurs, it corresponds to a clade-specific insertion. This insertion is propagated down the tree via a wave of type-2 transitions, as above, then we go back to step 7.)
10. Eventually, the entire ensemble has wound back, so that every transducer is in a **Wait** state except the singlet transducer at the root, which is still in an **Insert** state. At this point, all clade-specific insertions have been processed.

11. The singlet transducer now makes another type-1 transition. If this transition is to an **Insert** state, the entire cycle begins again: the singlet transducer emits the next symbol at the root, and we go back to step 4.
12. If, on the other hand, the singlet transducer enters its **End** state, then a wave of type-3 transitions drives all the branch transducers into their respective **End** states too, bringing the entire ensemble to a halt.

The total sizes of both the state space and the transition matrix are, in general, dramatically smaller than implied by the exponential upper bounds of $O(a \cdot b^N)$ and $O((a \cdot b^N)^2)$. While we do not have provable bounds on the size of the state space, we have observed that the size of the state space is roughly linear in the number of branches, $O(a \cdot b \cdot N)$, and the number of transitions is approximately linear in the number of states for several pairwise models, including the pairwise model which we use here. However, these empirical observations are based on a limited class of pairwise models and we do not have theoretical results for how they will generalize to other pairwise models. We do believe, however, that the worst-case exponential bound will be avoided by (1) omitting inaccessible state configurations and (2) eliminating “windback” states as described in the following section (which we believe will prevent affine gap penalties from generating exponential growth in the number of states).

Therefore, for the models which we have characterized, the search algorithm given above for enumerating all allowed transitions of the ensemble model typically generates $O(b)$ transitions from any given state, thereby creating a very sparse transition matrix of size $O(a \cdot b^2 \cdot N)$.

Inference algorithms for multiple-sequence models

In this section, we describe dynamic programming (DP) algorithms for inferring the alignment, structure and evolutionary history of multiple related RNAs, using the multiple-sequence SCFG we have derived.

The model construction algorithm described above creates a phylogenetic SCFG which generates a joint distribution over both ancestral and extant sequences. A parse tree for this SCFG represents a structural and evolutionary explanation of the extant sequences, including a complete ancestral reconstruction. Therefore, given a set of extant sequences, many of the questions of interest to us can be reduced to searches over, or summarizations of, the set of possible parse trees.

Well-known algorithms exist for searching or summing over SCFG parse trees. The Cocke-Younger-

Kasami (CYK) algorithm performs maximum-likelihood (ML) inference; the Inside algorithm can be used to sum over parse trees or sample them *a posteriori*; and the Inside-Outside algorithm yields posterior probabilities for individual parse tree nodes.

All of these algorithms are, however, complicated for phylogenetic SCFGs by the possibility of fragments of ancestral sequence that were universally deleted and therefore are unobserved in any of the extant sequences. These unobserved fragments can be unbounded in length. In the parse tree, these fragments correspond to cyclic detours through `Null` states, along with bifurcations where one or both sides terminate without observable emissions (e.g. $B \rightarrow X Y$ followed by $X \rightarrow \epsilon$). In the CYK, Inside and Outside recursions, this causes cyclic dependencies which cannot be resolved.

Therefore, before presenting equivalents of the CYK, Inside and Outside algorithms, we first give a method to eliminate “null cycles” from the ensemble model, by transforming any SCFG to an equivalent acyclic SCFG. Some such step is required, in order to deal with cyclic dependencies, but alternative approaches to ours are clearly possible. A CYK-only approach appears in the computational linguistics literature [37]. We have also developed an independent heuristic that iteratively re-fills entries of the DP matrix until the approximation is sufficiently good.

Eliminating null cycles in SCFGs

As noted above, the ensemble grammar contains many rules that can be applied redundantly, together or in isolation, to generate subtrees of the parse tree that do not generate any terminals. This generates cyclic dependencies in the standard DP recursions for inference. In this subsection, we describe how to transform the SCFG so as to eliminate such redundant rules, yielding strictly acyclic DP recursions. This transformation can be applied to any SCFG so as to remove null states and/or bifurcations: the procedure is not restricted to grammars that were generated using our transducer composition algorithm.

We begin by identifying two distinct classes of redundant parse-subtree: **empty bifurcations** and **empty paths**. We will eliminate each of these in turn.

An **empty bifurcation** occurs when a child branch of a bifurcation state transitions to the `End` state without emitting any symbols and can be removed from the model by creating an effective direct transition encapsulating the empty bifurcation. For example, we can create an effective direct transition $N_1 \rightarrow N_3$ between null states N_1 and N_3 in place of the empty parse-subtree $N_1 \rightarrow B \rightarrow (N_2 N_3) \rightarrow (End N_3)$, where B is a bifurcation state with children $(N_2 N_3)$. Bifurcation states are the most computationally-

costly part of our models, so it is important to eliminate as many as possible without reducing model expressiveness.

In contrast, an **empty path** is defined as any parse-subtree *without* bifurcations that does not emit terminal symbols. Most common are paths of “windback” null transitions via non-emitting placeholder states. If **Emit** states E_1 and E_2 are connected in the state graph via **Null** states N_1 and N_2 , then the path $E_1 \rightarrow N_1 \rightarrow N_2 \rightarrow E_2$ with probability $P(E_1 \rightarrow N_1) \cdot P(N_1 \rightarrow N_2) \cdot P(N_2 \rightarrow E_2)$ can be replaced by a single direct transition $E_1 \rightarrow E_2$ with an identical probability.

Empty paths occur in Hidden Markov Models (which are special cases of SCFGs) and independent-sites models (which can be viewed as special cases of HMMs). Conceptually, empty paths can represent histories that are valid according to the model but cannot be resolved by direct observation. Such null events can be real (e.g., ancestral residues that have been deleted in all extant lineages) or they can be artefactual (e.g., transitions between placeholder null states of an HMM).

Empty paths and empty bifurcations can be combined to give finite-probability sequences of rules that transform a nonterminal back into itself, with no observable emissions. We refer to such sequences of rules as **null cycles**. Our goal is an algorithmic procedure to account for the likelihood of such cycles by exact marginalization. For simpler models, solutions to this problem are published. Eliminating missing (empty) columns from an independent-sites model of sequence involves a straightforward application of a correction factor to account for the proportion of columns that are unobserved [38]. The slightly more complicated situation of missing emissions in a HMM can be dealt with by summing over all empty paths, yielding a geometric series that is solvable by matrix inversion [39–41].

Algorithms for exact elimination of empty paths from HMMs by matrix inversion are implemented by programs such as PhyloComposer [39, 40] and HMMoC [41]. These algorithms effectively replace the HMM with an equivalent HMM that contains no null cycles but generates the same probability distribution over sequences. The “wing retraction” algorithms used in the repetitively structured profile HMMs of HMMER [42] appear similar in operation. However, these solutions do not easily generalize to SCFGs, which contain bifurcations (and, therefore, may generate empty bifurcations as well as empty paths).

Null cycles can be removed systematically from SCFGs by two steps:

- (i) separating bifurcations into those which have one or more empty children (and can therefore be represented using transition or termination rules) and those that have two nonempty children;

- (ii) replacing all empty paths through null states with effective direct transitions between non-null states, obtaining sum-over-paths probabilities by inverting the grammar's transition matrix.

We give a formal description of the null-cycle elimination procedure, along with procedures for probabilistically “restoring” null cycles to sampled parse trees and Inside-Outside expectation counts, below.

Definitions. Let $G = (\Omega, \mathcal{N}, \mathbf{R}, P)$ be a stochastic context-free grammar (SCFG) consisting of a set of terminal symbols Ω , a set of nonterminal symbols (a.k.a. “states”) \mathcal{N} , a set \mathbf{R} of *production rules* $L \rightarrow R$ (where $L \in \mathcal{N}$ and $R \in (\mathcal{N} \cup \Omega)^*$) and a probability function on the rules, $P : (\mathcal{N} \times (\mathcal{N} \cup \Omega)^*) \rightarrow [0, \infty)$.

Let $\mathcal{L}(A)$ be the set of rules that can be applied to nonterminal $A \in \mathcal{N}$ (i.e., rules in which A appears on the left), and let $\mathcal{R}(A)$ be the set of rules that can generate nonterminal A (i.e., rules in which A appears on the right, including bifurcations which also generate another nonterminal as well as A). Let $\mathcal{A}(A) = \mathcal{L}(A) \cup \mathcal{R}(A)$ be the set of all rules involving A . Define these also on sets of nonterminals, e.g., $\mathcal{L}(\mathbf{N}) = \bigcup_{A \in \mathbf{N}} \mathcal{L}(A)$ for $\mathbf{N} \subseteq \mathcal{N}$.

Let \mathcal{T} be the set of all parse trees for G . Suppose that parse tree $T \in \mathcal{T}$ makes $n_T(\rho)$ uses of rule ρ ; then define the parse tree likelihood $P(T) = \prod_{\rho \in \mathbf{R}} [P(\rho)]^{n_T(\rho)}$.

If $\sum_{T \in \mathcal{T}} P(T) = 1$, we say that G is *probabilistically normalized by parse tree*. If $\sum_{\rho \in \mathcal{L}(A)} P(\rho) = 1$ for all $A \in \mathcal{N}$, we say that G is *probabilistically normalized by production rule*. Note that normalization by production rule \Rightarrow normalization by parse tree.

Let $S \in \Omega^*$ denote a terminal sequence. Let $\text{seq} : \mathcal{T} \rightarrow \Omega^*$ be the function mapping a parse tree to its terminal sequence. and let $\text{root} : \mathcal{T} \rightarrow \mathcal{N}$ be the function returning the root nonterminal of a parse tree. The *inside probability of S rooted at A* is $P(S|A) = \sum_{T: \text{seq}(T)=S, \text{root}(T)=A} P(T)$. Of particular relevance to null state elimination is the probability $P(\epsilon|A)$, where ϵ is the empty sequence. This is the probability that a nonterminal A will expire without generating any sequence.

Following earlier formalisms [11, 18, 43], we say that the grammar G has *RNA normal-form rules* if each rule in \mathbf{R} takes one of the following four forms:

Termination rules with one nonterminal on the left and the empty string on the right

$$A \rightarrow \epsilon$$

Transition rules with one nonterminal on the left and the right

$$A \rightarrow B$$

Bifurcation rules with one nonterminal on the left and two on the right

$$A \rightarrow B C$$

Emission rules with one nonterminal on the left and right and at least one terminal on the right

$$A \rightarrow x B$$

$$A \rightarrow B y$$

$$A \rightarrow x B y$$

Here $A, B, C \in \mathcal{N}$ and $x, y \in \Omega$.

Suppose that grammar G has RNA normal-form rules. We further say that G has *RNA normal-form states* if each nonterminal (state) $A \in \mathcal{N}$ takes one of the following forms:

Null states : $\mathcal{L}(A)$ contains only transition and termination rules.

Bifurcation states : $\mathcal{L}(A)$ contains exactly one bifurcation rule, $A \rightarrow X Y$, where $X \neq Y$ and X, Y are both null states.

Emit states : $\mathcal{L}(A)$ contains only emission rules. Further, $\mathcal{L}(A) = \mathcal{R}(B)$ for some null state B . This null state B is called A 's *post-emit* state.

Define a *null cycle* to be a nonterminal A and a sequence of rules $\rho_1, \rho_2 \dots \rho_k$ that, when applied consecutively to A , leave A unchanged; that is, $\rho_k(\rho_{k-1} \dots \rho_2(\rho_1(A))) = A$. Define a *null subtree* to be a null cycle using at least one bifurcation rule.

Suppose that $G = (\Omega, \mathcal{N}, \mathbf{R}, P)$ and $G' = (\Omega, \mathcal{N}', \mathbf{R}', P')$ are two grammars. We say that G and G' are *equivalent in sequence* if there is a mapping between nonterminals, $f : \mathcal{N} \rightarrow \mathcal{N}'$, such that $P(S|A) = P(S|f(A))$. We say that G and G' are *equivalent in parse* if there is a mapping between parse trees, $g : \mathcal{T} \rightarrow \mathcal{T}'$, such that $P'(T') = \sum_{T: T'=g(T)} P(T)$ and we can define

$$P(T|T') = P(T|g(T) = T') = \frac{P(T)}{P'(T')}$$

Note that equivalence in parse \Rightarrow equivalence in sequence.

Suppose that a grammar G contains null cycles. We seek to transform G into a grammar G'' that is equivalent in parse and sequence, but has no null cycles. If G is normalized by parse tree, then G'' will be too; but G'' is not (necessarily) normalized by production rule.

We do the transformation in two steps, $G \rightarrow G' \rightarrow G''$. We also provide a stochastic “null cycle restoration” algorithm for sampling from $P(T|T'')$.

Eliminating null bifurcations. Note first that any SCFG can be transformed into an equivalent one with RNA normal-form states by adding null states. Without loss of generality, we therefore consider SCFGs with RNA normal-form states.

Let $G = (\Omega, \mathcal{N}, \mathbf{R}, P)$ be such an SCFG. Let $\mathbf{N} \subseteq \mathcal{N}$ be the set of null states in \mathcal{N} , **excluding** post-emit states. Let $\mathbf{E} \subset \mathcal{N}$ be the set of post-emit states. Let $\mathbf{B} \subseteq \mathcal{N}$ be the set of bifurcation states.

We here define the grammar G' ,

$$G' = (\Omega, \mathcal{N}', \mathbf{R}', P')$$

which is equivalent to G in sequence but has no null subtrees.

The new states \mathcal{N}' are defined as follows. Start with \mathcal{N} ; remove bifurcation states; then introduce a new state N' for every null $N \in \mathbf{N}$ and three new states B^0, B', B^2 for every bifurcation $B \in \mathbf{B}$.

$$\mathcal{N}' = \left(\bigcup_{N \in \mathbf{N}} \{N'\} \right) \cup \left(\bigcup_{B \in \mathbf{B}} \{B^0, B', B^2\} \right) \cup \mathcal{N} \setminus \mathbf{B}$$

The idea is that N' (in G') is a null state that is equivalent to null state N (in G) for non-empty sequence only. That is, for any terminal sequence S ,

$$P'(S|N') = \begin{cases} P(S|N) & \text{if } S \neq \epsilon \\ 0 & \text{if } S = \epsilon \end{cases}$$

Similarly, B' is a null state that is equivalent to bifurcation state B for non-empty sequence, while B^2 is a null state that is equivalent to B for parse trees where both children of B are non-empty.

In contrast, B^0 is **exactly** equivalent to B in sequence. However, null subtrees in B^0 are explicitly accounted for, their probabilities factored into the transitions $B' \rightarrow L'$ and $B' \rightarrow R'$ and the termination $B^0 \rightarrow \epsilon$, using the inside probabilities for empty sequences, $P(\epsilon|L)$ and $P(\epsilon|R)$.

The probabilities $P(\epsilon|X)$ are related by the following system of equations

$$P(\epsilon|X) = P(X \rightarrow \epsilon) + \sum_Y P(X \rightarrow Y)P(\epsilon|Y) + \sum_{L,R} P(X \rightarrow LR)P(\epsilon|L)P(\epsilon|R)$$

which are nonlinearly coupled but may be solved numerically, e.g., by the Newton-Raphson method, or by iterated approximation starting from a lower bound $P(\epsilon|X) \geq 0$.

The new rules and their probabilities are

$$\begin{aligned} \forall \rho \in (\mathbf{R} \setminus \mathcal{A}(\mathbf{B})) : \quad & P'(\rho) = P(\rho) \\ \forall N \in \mathbf{N} : \quad & P'(N' \rightarrow \epsilon) = 0 \\ \dots \forall B \in \mathbf{B} : \quad & P'(N' \rightarrow B') = P(N \rightarrow B) \\ \dots \forall M \in \mathbf{N} : \quad & P'(N' \rightarrow M') = P(N \rightarrow M) \\ \dots \forall E \in \mathbf{E} : \quad & P'(N' \rightarrow E) = P(N \rightarrow E) \\ \forall (A \rightarrow B) \in \mathcal{R}(\mathbf{B}) : \quad & P'(A \rightarrow B^0) = P(A \rightarrow B) \\ \forall (B \rightarrow LR) \in \mathcal{L}(\mathbf{B}) : \quad & P'(B^0 \rightarrow \epsilon) = P(B \rightarrow LR) P(\epsilon|L) P(\epsilon|R) \\ & P'(B^0 \rightarrow B') = 1 \\ & P'(B' \rightarrow \epsilon) = 0 \\ & P'(B' \rightarrow L') = P(B \rightarrow LR) P(\epsilon|R) \\ & P'(B' \rightarrow R') = P(B \rightarrow LR) P(\epsilon|L) \\ & P'(B' \rightarrow B^2) = 1 \\ & P'(B^2 \rightarrow L' R') = P(B \rightarrow LR) \end{aligned}$$

Note that grammar G' , like G , has RNA normal-form states. Note also that G' is not, in general,

normalized by production rule; however, G' is equivalent to G in parse and is therefore normalized by parse tree (if G is).

Eliminating null states. We now proceed to eliminate null cycles from G' . Since null subtrees have been eliminated, the remaining null cycles use only transition rules.

We create the grammar

$$G'' = (\Omega, \mathcal{N}', \mathbf{R}'', P'')$$

which has the same nonterminals as G' , but different rules and rule probabilities.

Let $\mathbf{N}' \subseteq \mathcal{N}'$ be the set of null states in \mathcal{N}' , **including** post-emit states.

Define \mathbf{t} , the *transition matrix* of G' , as $t_{XY} = P'(X \rightarrow Y)$ for all $X, Y \in \mathcal{N}'$. The effective transition probability q_{XY} between two states X, Y sums over all paths through null states (in the summand, n is the length of the null path):

$$\mathbf{q} = \sum_{n=0}^{\infty} \mathbf{t}^n = (\mathbf{1} - \mathbf{t})^{-1}$$

Here $\mathbf{1}$ is the identity matrix. The matrix inverse may be computed in the usual ways (Gauss-Jordan elimination, LU decomposition, etc.)

Since the bifurcation states of G' explicitly generate non-empty sequence, the system of equations relating the probabilities $P'(\epsilon|X)$ is completely linear and may be solved in the same way. Let $u_X = P'(\epsilon|X)$ and $v_X = P'(X \rightarrow \epsilon)$. Then

$$\mathbf{u} = \mathbf{v} + \mathbf{t}\mathbf{u}$$

whose solution is $\mathbf{u} = \mathbf{q}\mathbf{v}$. Thus $P'(\epsilon|X) = \sum_Y q_{XY} P'(Y \rightarrow \epsilon)$.

We now define P'' as follows.

- For all rules $\rho \in \mathbf{R}'$ that are **not** transitions or terminations, set $P''(\rho) = P'(\rho)$.
- For terminations from null states $X \in \mathbf{N}'$, set $P''(X \rightarrow \epsilon) = u_X$. (NB this may create some terminations $X \rightarrow \epsilon$ that were not present in G' .)
- For transitions from null states $X \in \mathbf{N}'$ to non-null states $Y \notin \mathbf{N}'$, set $P''(X \rightarrow Y) = q_{XY}$. (NB this may create some transitions $X \rightarrow Y$ that were not present in G' .)

- For transitions **to** null states $X \in \mathbf{N}'$, set $P''(A \rightarrow X) = 0$.

Although we have left null states in G'' , they now have no incoming transitions and are inaccessible unless they are post-bifurcation states (i.e., states which appear on the right-hand side of bifurcation rules), post-emit states, or the start (root) state. All other null states can therefore be dropped from \mathcal{N}'' .

Restoring null states. Suppose that ρ'' is a rule in G'' . Algorithm 1 samples from the distribution of equivalent parse subtrees in G' (possibly containing null cycles). In order to sample from $P(T'|T'')$ we need simply map Algorithm 1 to each rule in T'' .

For parameter estimation by Expectation Maximization and some other applications, it is useful to know the expected number of times that a transition was used, summed over the posterior distribution of parse trees (including those with null cycles). If $n''(\rho'')$ is the expected number of times that transition ρ'' was used according to an Inside-Outside computation on G'' , then the corresponding expectations $n'(\rho')$ are given by

$$\begin{aligned} n'(X \rightarrow Y) &= n''(X \rightarrow Y) \frac{P''(X \rightarrow Y)}{q_{XY}} + \sum_Z n''(X \rightarrow Z) \frac{P''(X \rightarrow Y) q_{YZ}}{q_{XZ}} \\ n'(X \rightarrow \epsilon) &= n''(X \rightarrow \epsilon) \frac{P''(X \rightarrow \epsilon)}{P''(\epsilon|X)} + \sum_W n''(W \rightarrow \epsilon) \frac{q_{WX} P''(X \rightarrow \epsilon)}{P''(\epsilon|W)} \end{aligned}$$

Expectations for other rules (bifurcations and emissions) are the same for G' as G'' .

Restoring null bifurcations. Suppose that ρ' is a rule in G' . Algorithm 2 samples from the distribution of equivalent parse subtrees in G (possibly containing null subtrees). This algorithm also calls Algorithm 3, which samples from the distribution of empty subtrees rooted at a particular nonterminal. In order to sample from $P(T|T')$ we need simply map Algorithm 2 to each rule in T' .

If $n'(\rho')$ is the expected number of times that rule ρ' was used by G' , then the corresponding expectations $n(\rho)$ are given by

$$\begin{aligned}
n(B \rightarrow L R) &= n'(B' \rightarrow L') + n'(B' \rightarrow R') + n'(B^0 \rightarrow L' R') + d(B \rightarrow L R) \\
n(X \rightarrow Y) &= n'(X \rightarrow Y) + d(X \rightarrow Y) \\
n(X \rightarrow \epsilon) &= n'(X \rightarrow \epsilon) + d(X \rightarrow \epsilon)
\end{aligned}$$

Expectations for emissions are the same for G as G' . In the above expressions $d(\rho)$ is the expected usage of rule ρ by null subtrees:

$$d(\rho) = \sum_{(B \rightarrow LR) \in \mathbf{R}} [n'(B' \rightarrow L')c_R(\rho) + n'(B' \rightarrow R')c_L(\rho) + n'(B^0 \rightarrow \epsilon)(c_L(\rho) + c_R(\rho))]$$

where $c_W(\rho)$ is the expected usage of rule ρ by an empty parse tree rooted at W , given by

$$\begin{aligned}
c_X(\rho)P(\epsilon|X) &= P(X \rightarrow \epsilon)\delta_{\rho=(X \rightarrow \epsilon)} + \sum_Y P(X \rightarrow Y)P(\epsilon|Y) (c_Y(\rho) + \delta_{\rho=(X \rightarrow Y)}) \\
&\quad + \sum_{L,R} P(X \rightarrow LR)P(\epsilon|L)P(\epsilon|R) (c_L(\rho) + c_R(\rho) + \delta_{\rho=(X \rightarrow LR)})
\end{aligned}$$

where δ_U is the Kronecker delta (1 if condition U is true, 0 if it is false). Note that in contrast to the system of equations for $P(\epsilon|X)$, this is a linear system of equations of the form $\mathbf{c} = \mathbf{M}\mathbf{c} + \mathbf{k}$, which may be solved by matrix inversion: $\mathbf{c} = (\mathbf{I} - \mathbf{M})^{-1}\mathbf{k}$.

Dynamic programming algorithms for inference

Once we have performed the transformations described above to remove null cycles from the multiple-sequence SCFGs generated by our model-construction algorithm, we can compute likelihoods and sample parse trees using the “standard” CYK, Inside and Outside algorithms for multiple-sequence SCFGs [11, 44].

The asymptotic time and memory complexities of our inference algorithms are essentially the same as for Sankoff’s algorithm [44]: the DP algorithms take memory $O(A \cdot L^{2N})$ and time $O(B \cdot L^{3N})$ for N sequences of length L , where A is the number of (accessible) states in the multiple-SCFG and B is the number of bifurcations. Note that A and B are also dependent on N (see “The TKFST model on a

three-taxon phylogeny”).

Exact inference on a star phylogeny with N extant sequences therefore has complexities $O(A \cdot L^{2N})$ and $O(B \cdot L^{3N})$ in space and time for a multiple-SCFG with A states and B bifurcations. As described earlier, in practice we frequently have expert knowledge (such as a curated multiple alignment) about the structures and/or evolutionary histories of the sequences of interest. We can use this knowledge as a constraint to reduce the accessible volume of the DP matrix [18]. Algorithms 4–10, described below, give the Inside, CYK, Outside and CYK traceback algorithms for a three-taxon star phylogeny, constrained using the “fold envelope” concept.

Fold Envelopes. We use the fold envelope concept [29, 43] to constrain the set of structures which our algorithms consider. A fold envelope $\mathcal{F}^{(X)}$ for a sequence X is a set of coordinate pairs satisfying

$$\mathcal{F}^{(X)} \subset \left\{ (i, j) : 0 \leq i \leq j \leq L^{(X)} \right\} ; \quad L^{(X)} = |X|. \quad (1)$$

We consider a subsequence $x_{i+1} \dots x_j$ only if the corresponding coordinate pair $(i, j) \in \mathcal{F}^{(X)}$. The unconstrained fold envelope has set equality in Equation 1.

We use two orderings for sequences in the fold envelopes. An inside-outside ordering is used for the iteration in the Inside algorithm: Subsequences are ordered such that each successive subsequence contains all previous subsequences in the fold envelope. More precisely, subsequences in $\mathcal{F}^{(X)}$ are sorted in the same order as coordinate pairs (i, j) are generated by the iteration $\{ \text{for } i = L^{(X)} \text{ to } 0 \} \{ \text{for } j = i \text{ to } L^{(X)} \}$.

The Outside algorithm uses an outside-inside ordering, where subsequences starting at a fixed i are reverse-sorted with respect to the inside-outside ordering described above. Subsequences in $\mathcal{F}^{(X)}$ are then sorted in the same order as coordinate pairs (i, j) are generated by the iteration $\{ \text{for } i = 0 \text{ to } L^{(X)} \} \{ \text{for } j = L^{(X)} \text{ to } i \}$. We frequently refer to subsequences by their index in the fold envelope. The m^{th} subsequence in $\mathcal{F}^{(X)}$ is labeled $m^{(X)}$ and corresponds to the coordinate pair (i_m, j_m) . The index of a pair $(i, j) \in \mathcal{F}^{(X)}$ is $n^{(X)}[i, j]$.

In order to take full advantage of the reduction in computational complexity offered by restricting our inference algorithms to subsequences contained in the fold envelopes, we must avoid iterating over unreachable combinations of subsequences (unreachable because they are not permitted by the fold envelope constraints). An efficient implementation relies on iterators over subsequences in the fold envelope which are connected by production rules of the ensemble grammar. Inward and outward emission connections

for a sequence X , specifying which subsequence is reachable from a given subsequence $m^{(X)}$ and ensemble state \mathbf{b} , are defined as

$$\begin{aligned} c_{in}(\mathbf{b}; m^{(X)}) &= n^{(X)} \left[i_m + \Delta_L^{(X)}(\mathbf{b}), j_m - \Delta_R^{(X)}(\mathbf{b}) \right] \\ c_{out}(\mathbf{b}; m^{(X)}) &= n^{(X)} \left[i_m - \Delta_L^{(X)}(\mathbf{b}), j_m + \Delta_R^{(X)}(\mathbf{b}) \right], \end{aligned}$$

where the quantities $\Delta_L^{(X)}(\mathbf{b})$ and $\Delta_R^{(X)}(\mathbf{b})$ are the lengths of the left and right emissions of the ensemble state \mathbf{b} to the sequence X . (Recall that the m^{th} subsequence in $\mathcal{F}^{(X)}$ is labeled $m^{(X)}$ and corresponds to the coordinate pair (i_m, j_m) .) The emission connection is undefined if the corresponding subsequence is not in the fold envelope. Inward, outward-left and outward-right bifurcation connections, specifying which subsequences are connected by bifurcation production rules of the ensemble SCFG, are defined for a subsequence $n^{(X)}$ as

$$b_{in}(n^{(X)}) = \left\{ \left(n_L^{(X)}, n_R^{(X)} \right) : i_{n_L^{(X)}} = i_{n^{(X)}}, j_{n_L^{(X)}} = i_{n^{(X)}}, j_{n_R^{(X)}} = j_{n^{(X)}} \right\} \quad (2)$$

$$b_{out,L}(n^{(X)}) = \left\{ \left(n_O^{(X)}, n_L^{(X)} \right) : i_{n_L^{(X)}} = i_{n_O^{(X)}}, j_{n_L^{(X)}} = i_{n^{(X)}}, j_{n^{(X)}} = j_{n_O^{(X)}} \right\} \quad (3)$$

$$b_{out,R}(n^{(X)}) = \left\{ \left(n_O^{(X)}, n_R^{(X)} \right) : i_{n^{(X)}} = i_{n_O^{(X)}}, j_{n^{(X)}} = i_{n_R^{(X)}}, j_{n_R^{(X)}} = j_{n_O^{(X)}} \right\} \quad (4)$$

We generally write out explicit subsequence coordinate pairs (i, j) when their usage will make mathematical formulas clearer and fold-envelope labels $n^{(X)}$ when writing pseudocode.

The Inside algorithm. The Inside algorithm is used to calculate the likelihood of sequences under an ensemble model. It is analogous to the Forward algorithm for HMMs.

The inside probability $\alpha_{\mathbf{a}}(n^{(X)}, n^{(Y)}, n^{(Z)})$ is the summed probability of the triplet of subsequences $(n^{(X)}, n^{(Y)}, n^{(Z)})$ for sequences X, Y, Z under all paths through the model which are rooted in state \mathbf{a} . Algorithm 4 gives pseudocode for the fold-envelope version of the Inside algorithm. The subroutines `calcTransEmitProb`, `calcLBifurcProb` and `calcRBifurcProb` used in the Inside algorithm are defined below.

The transition and emission probability `calcTransEmitProb($\mathbf{a}; \cdot$)` can be calculated by iterating over ensemble states \mathbf{b} which connect the subsequence triplet $(n^{(X)}, n^{(Y)}, n^{(Z)})$ to others in the fold envelopes. Pseudocode for the constrained calculation is given in Algorithm 5.

The left-bifurcation probability for an ensemble state \mathbf{a} bifurcating to two ensemble states,

$\text{calcLBifurcProb} \left(\mathbf{a}; n_L^{(X)}, n_R^{(X)}, n_L^{(Y)}, n_R^{(Y)}, n_L^{(Z)}, n_R^{(Z)} \right)$, is

$$\sum_{\mathbf{b} \mid \exists \mathbf{a} \rightarrow \mathbf{cb}} P(\mathbf{a} \rightarrow \mathbf{cb}) \alpha_{\mathbf{c}} \left(n_L^{(X)}, n_L^{(Y)}, n_L^{(Z)} \right) \alpha_{\mathbf{b}} \left(n_R^{(X)}, n_R^{(Y)}, n_R^{(Z)} \right)$$

and the right-bifurcation probability for an ensemble state \mathbf{a} bifurcating to two ensemble states,

$\text{calcRBifurcProb} \left(\mathbf{a}; n_L^{(X)}, n_R^{(X)}, n_L^{(Y)}, n_R^{(Y)}, n_L^{(Z)}, n_R^{(Z)} \right)$, is

$$\sum_{\mathbf{b} \mid \exists \mathbf{a} \rightarrow \mathbf{bd}} P(\mathbf{a} \rightarrow \mathbf{bd}) \alpha_{\mathbf{b}} \left(n_L^{(X)}, n_L^{(Y)}, n_L^{(Z)} \right) \alpha_{\mathbf{d}} \left(n_R^{(X)}, n_R^{(Y)}, n_R^{(Z)} \right).$$

The boundary condition of the probability of 0-length subsequences is determined by the probability of transitions to **End**. The termination condition is

$$P(X, Y, Z) = \alpha_{\text{Start}} \left(N^{(X)}, N^{(Y)}, N^{(Z)} \right),$$

where **Start** is the unique start state of the ensemble grammar and $N^{(X)}$ is the outermost subsequence for sequence X , etc.

Note that we are assuming that the transformations described in “Eliminating null states” have been performed, such that there are no cycles of **Null** states as well as no empty bifurcations.

The CYK algorithm. The CYK algorithm is used to calculate the probability of the most-likely state path (or parse) capable of generating the input sequences. It is analogous to the Viterbi algorithm for HMMs.

The CYK algorithm can be obtained from the Inside algorithm by replacing sums over paths through the ensemble model with the max operation. The CYK probability for indices $\gamma_{\mathbf{a}} \left(n^{(X)}, n^{(Y)}, n^{(Z)} \right)$ then represents the probability of the most likely path through the model generating the triplet of subsequences $(n^{(X)}, n^{(Y)}, n^{(Z)})$.

The resulting CYK algorithm is shown in Algorithm 6. The subroutine calcTransEmitProb is defined in Algorithm 7. The subroutines calcLBifurcProb and calcRBifurcProb used in the CYK algorithm are defined as

$$\max_{\mathbf{b} \mid \exists \mathbf{a} \rightarrow \mathbf{cb}} P(\mathbf{a} \rightarrow \mathbf{cb}) \gamma_{\mathbf{c}} \left(n_L^{(X)}, n_L^{(Y)}, n_L^{(Z)} \right) \gamma_{\mathbf{b}} \left(n_R^{(X)}, n_R^{(Y)}, n_R^{(Z)} \right)$$

and

$$\max_{\mathbf{b} | \exists \mathbf{a} \rightarrow \mathbf{b}\mathbf{d}} P(\mathbf{a} \rightarrow \mathbf{b}\mathbf{d}) \gamma_{\mathbf{b}}(n_L^{(X)}, n_L^{(Y)}, n_L^{(Z)}) \alpha_{\mathbf{d}}(n_R^{(X)}, n_R^{(Y)}, n_R^{(Z)}).$$

The Outside algorithm. The Outside algorithm is primarily used as an intermediary for posterior decoding on the model. It is analogous to the Backward algorithm for HMMs.

The outside probability $\beta_{\mathbf{b}}(n^{(X)}, n^{(Y)}, n^{(Z)})$ for an ensemble state \mathbf{b} is the summed probability of the sequences X, Y, Z under all paths through the ensemble model which are rooted in the start state of the model, excluding all paths for the triplet of subsequences $(n^{(X)}, n^{(Y)}, n^{(Z)})$ which are rooted in the ensemble state \mathbf{b} . Algorithm 8 gives pseudocode for the fold-envelope version of the Outside algorithm. The subroutines `calcTransEmitProb`, `calcLBifurcProb` and `calcRBifurcProb` used in the Outside algorithm are defined below.

As with the Inside and CYK algorithms, the transition and emission probability `calcTransEmitProb` can be calculated efficiently using the subsequence connections defined earlier (Algorithm 9). The left-bifurcation probability `calcLBifurcProb` $(\mathbf{b}; n_O^{(X)}, n_L^{(X)}, n_O^{(Y)}, n_L^{(Y)}, n_O^{(Z)}, n_L^{(Z)})$ is

$$\sum_{\mathbf{a} | \exists \mathbf{a} \rightarrow \mathbf{c}\mathbf{b}} P(\mathbf{a} \rightarrow \mathbf{c}\mathbf{b}) \beta_{\mathbf{a}}(n_O^{(X)}, n_O^{(Y)}, n_O^{(Z)}) \alpha_{\mathbf{c}}(n_L^{(X)}, n_L^{(Y)}, n_L^{(Z)})$$

and the right-bifurcation probability `calcRBifurcProb` $(\mathbf{b}; n_O^{(X)}, n_R^{(X)}, n_O^{(Y)}, n_R^{(Y)}, n_O^{(Z)}, n_R^{(Z)})$ is

$$\sum_{\mathbf{a} | \exists \mathbf{a} \rightarrow \mathbf{b}\mathbf{d}} P(\mathbf{a} \rightarrow \mathbf{b}\mathbf{d}) \beta_{\mathbf{a}}(n_O^{(X)}, n_O^{(Y)}, n_O^{(Z)}) \alpha_{\mathbf{d}}(n_R^{(X)}, n_R^{(Y)}, n_R^{(Z)})$$

The boundary condition is just

$$\beta_{\text{Start}}(N^{(X)}, N^{(Y)}, N^{(Z)}) = 1,$$

where $N^{(X)}$ is the outermost subsequence for sequence X , etc.

The CYK traceback algorithm. The CYK traceback algorithm, in combination with the CYK algorithm, is used to find the most-likely state path generating the extant sequences (in other words, the maximum-likelihood parse generating the observed data). It is analogous to the Viterbi traceback algorithm for HMMs. Algorithm 10 gives the constrained CYK traceback algorithm.

Results

Automated grammar construction

We implemented our model construction algorithm on the three-taxon star phylogeny. Given a singlet transducer modeling ancestral structures and a branch transducer modeling structural evolution, our Perl modules generate C++ code for the corresponding jointly-normalized three-sequence (Triplet) SCFG. Any model of structural evolution which can be represented as a Pair SCFG and factored into singlet and branch transducers is permitted as input to the packages, allowing for flexible, automated model design.

A simple model of RNA structural evolution

We illustrated our method for building models of structured sequences using a simplified model which was introduced in previous work, the TKF Structure Tree model [29], a simple probabilistic model of the evolution of RNA structure.

The TKF Structure Tree (TKFST) model is based on the Thorne-Kishino-Felsenstein (TKF) model of the stochastic evolution of primary sequences via indel events [45]. In the original TKF model, sequence evolves under a time-homogeneous linear birth-death-immigration process [46]. Single characters are inserted with rate λ and deleted with rate μ . At equilibrium, sequences obey a geometric length distribution with parameter κ . Although this model has flaws (e.g., it lacks affine gap penalties, rate heterogeneity and context-dependent mutation rates), it illustrates many of the key ideas used by more sophisticated indel models, notably the possibility for systematic derivation of pairwise alignment automata from first principles via analysis of birth-death processes [45, 47].

The TKF Structure Tree model is an extension of the TKF model to RNA structure. In this model, loop and stem regions are mutually nested (Figure 3). Both loops and stems have geometric length distributions with parameters κ_l and κ_s . Single bases are inserted and deleted in loops with rates λ_l and μ_l ; similarly, base-pairs are inserted and deleted in stems with rates λ_s and μ_s . Insertions of a new stem into an existing loop sequence (or deletions of an existing stem) occur at the same rate as single-base insertions (or deletions) and can model large-scale structural changes (Figure 4).

We parametrized the singlet and branch transducers of the TKFST model using estimates reported by a phylo-grammar for RNA secondary structure prediction, PFOLD [16] and an implementation of pairwise alignment for the TKF Structure Tree model, EVOLDOER [29]. The equilibrium distributions

of unpaired and paired nucleotides of the singlet and branch transducers, as well as the substitution models of unpaired and paired nucleotides of the branch transducers, were derived from the substitution rate matrices of the PFOLD program. These rate matrices, which have proven useful for RNA structure prediction [16,17,48], were derived from the Bayreuth tRNA database [49] and the European large subunit rRNA database [50].

This continuous-time model corresponds to a Pair SCFG and as such fits neatly into our modeling framework once the probability distribution is appropriately factored into marginal and conditional distributions (generated by singlet and branch transducers). Tables 1 and 2 show the states and transitions of the singlet transducer (single-sequence SCFG) which generates ancestral sequence under the Structure Tree model. Tables 3 and 4 show the states and transitions of the branch transducer (conditionally-normalized Pair SCFG) which evolves a sequence and structure along a branch of the phylogenetic tree.

The equilibrium distribution and transition probabilities between states of the TKFST model can be expressed in terms of functions of the evolutionary time along a branch and the insertion and deletion rates λ_l and μ_l of the model. The length of ancestral sequences is geometric in κ_l (Table 2), defined as $\kappa_l = \lambda_l / \mu_l$. The three functions $\alpha(t)$, $\beta(t)$ and $\gamma(t)$ which govern the transition probabilities in Table 4 are defined for loop sequences as

$$\begin{aligned}\alpha_l(t) &= \exp(-\mu_l t) \\ \beta_l(t) &= \frac{\lambda_l (1 - \exp((\lambda_l - \mu_l)t))}{\mu_l - \lambda_l \exp((\lambda_l - \mu_l)t)} \\ \gamma_l(t) &= 1 - \frac{\mu_l (1 - \exp((\lambda_l - \mu_l)t))}{(1 - \exp(-\mu_l t)) (\mu_l - \lambda_l \exp((\lambda_l - \mu_l)t))}\end{aligned}$$

and similarly for stem sequences [29].

Assessing TKFST as a model of RNA structure

The TKFST model, like the original TKF model, probably needs refinements in order to accurately model many structural RNAs. For example, it fails to model certain phenomena observed in natural RNA structures (such as base-stacking or tetraloops) and in alignments of those structures (such as helix slippage). We assessed its appropriateness as a model of RNA structural evolution by conducting benchmarks of its capabilities for (1) multiple sequence alignment of structured RNAs, summing over

all possible structures, and (2) structure prediction of homologous structured RNAs and comparing its performance to one of the best-performing pairwise SCFGs for RNA multiple alignment [20]. The results of these benchmarks, reported in Table 5 and Table 6, suggest that TKFST is a useful guide for deriving more complicated models of RNA evolution: while it has relatively poor sensitivity (but high positive predictive value) as a base-pairing predictor, it is competitive with one of the most accurate RNA multiple sequence alignment programs [20].

TKFST’s poorer performance at base-pairing prediction is likely due to its much-simpler model of RNA structure. The richer grammar, as described in [18], is much more complex than TKFST: excluding the substitution model, it has 14 free parameters (compared to TKFST’s 4), uses an affine gap penalty (compared to TKFST’s linear gap penalty), and explicitly models structural features such as multiple-branched loops, symmetric/asymmetric bulges, and minimum loop lengths. Unlike TKFST, the richer grammar is structurally unambiguous: a one-to-one mapping exists from structures to parse trees. Although we use the TKFST model as an illustrative example of a Pair SCFG that can be extended with our method, the model is not fundamental to our approach and can be replaced by a different and more realistic pairwise model, such as the pairwise SCFG used in these comparisons [20]. We anticipate that further improvements should be possible by reviewing other comparisons of SCFGs at structure prediction, such as the study by [17].

The TKFST model on a three-taxon phylogeny

We used our model-construction algorithm to build the grammar corresponding to the TKFST model acting on a star phylogeny with three (extant) leaf sequences and a single (unobserved) ancestral sequence. We chose this phylogeny for two reasons: (1) it is the simplest extension of the well-studied, standard two-sequence (Pair SCFG) model and (2) algorithms on a phylogeny with three leaves should be sufficient for ergodic sampling of reconstructions on any larger phylogeny, using e.g. a Gibbs-sampling MCMC kernel [31] or a progressive suboptimal-alignment sampling heuristic [33].

The statistics of the TKFST model on the three-taxon phylogeny illustrate the advantages of our procedure for model construction. While the singlet and branch transducers are relatively simple—the singlet transducer, shown in Table 2, has 7 total states and 2 bifurcation states and the branch transducer, shown in Table 4, has 21 total states and 6 bifurcation states—the ensemble model of three extant sequences is very complex. The naive exponential upper-bound gives a maximal state space of

size $O(7 \cdot 21^3) \Rightarrow 6 \cdot 10^4$ states. Using our uninformed search algorithm, we determined that there are 287 accessible states and 686 possible transitions between these states (compare with the $287^2 \simeq 8 \cdot 10^4$ transitions estimated with the exponential calculation). After performing the transformations described in “Eliminating null cycles in SCFGs” to eliminate useless windback states, the ensemble model has a reduced state space with 230 states, albeit at the cost of extra transitions, bring the total to 1,789 transitions (here we are trading reduced memory complexity, which is linear in the number of states, for increased time complexity, which is linear in the number of transitions). Note that both before and after the reduction in complexity, the total number of states and transitions are less than the approximate bounds of $O(a \cdot b \cdot N) = O(7 \cdot 21 \cdot 3) \Rightarrow 441$ states and $O(a \cdot b^2 \cdot N) = O(7 \cdot 21^2 \cdot 3) \Rightarrow 9,261$ transitions suggested in “The composition algorithm.” Nonetheless, the extreme complexity of the ensemble model, despite the simplicity of the underlying model of RNA structure, makes clear the necessity for automated procedures for model construction. Dataset S1 gives the state space of the composed model constructed by the search algorithm and Dataset S2 the reduced model after eliminating “windback” states; both are in Graphviz format for visualization and show the state of the singlet transducer generating ancestral sequence as well as the states of the branch transducers generating observed sequences.

We implemented constrained maximum-likelihood inference of the structural alignment and ancestral structure of three extant sequences in a C++ program (INDIEGRAM). For tractability, INDIEGRAM uses the concept of fold envelopes described earlier to limit the fold space considered by the CYK algorithm, permitting structural information for the three extant sequences to be (optionally) supplied as input. If no structural information is supplied, then INDIEGRAM uses a single-sequence SCFG to estimate a set of plausible folds [18], which are used to constrain the CYK algorithm.

The inference algorithms in INDIEGRAM could be further constrained to enforce, for example, a fixed multiple alignment or consensus structure of extant sequences. While experimentally-determined structures of individual RNAs are relatively rare, curated deep sequence alignments, such as those constructed for ribosomal RNAs [51], are frequently available for characterized RNA families. By constraining the inference algorithms with such sequence alignments, the memory and time complexity of the algorithms could be dramatically reduced. Such constraints can be naturally expressed with “alignment envelopes,” the sequence-level counterpart of fold envelopes [18]. However, in this paper we focus on model construction and inference algorithms and postpone exploration of heuristics and constraints of these algorithms for future work.

Reconstructing small RNAs with the TKFST model

While reconstructing large RNAs such as ribosomal subunits is currently computationally-inaccessible without further heuristics to constrain our algorithms, reconstructing small RNAs of biological interest will soon be feasible. Table 7 shows estimates of the memory and time required to reconstruct biologically-interesting subunits of the *nanos* 3' translational control element and tRNAs, as well as two small RNAs which show significant structural divergence, the Y RNAs and Group II introns, and therefore promise to be interesting candidates for ancestral reconstruction. The reconstructed structures for three *nanos* 3' translational control elements (TCEs) and three tRNAs, which could be analyzed given current computational limitations, can be found at <http://biowiki.org/IndieGram>; however, the phylogenetic trees relating the tested sequences have short branch lengths, making the reconstruction problem easy by forcing the reconstructed structures to be essentially-identical to those of one of the extant RNAs.

The dependence of reconstruction accuracy on outgroup branch length

Guided by our experience with the *nanos* 3' TCE and tRNA, where the reconstruction problem was made easy by the presence of a close outgroup, we conducted a simulation study to investigate the dependence of reconstruction accuracy on outgroup branch length. (We here use the term “outgroup” loosely, to denote the variable-length branch in a three-branch study, where the other two branches are held at unit length. Technically, the term “outgroup” is only correct if the outgroup’s branch is longer than the other two branches.)

We simulated the evolution of RNAs under the TKFST model along 3-taxon phylogenies (with one internal node), where we kept the branch lengths of two sibling species constant and varied the branch length of the outgroup. We chose the parameters of the TKFST model to generate “interesting” alignments (~ 0.3 substructure indels per alignment) and considered only alignments with at least two ancestral stems, sequences of length $\in [30, 70]$ bp, loops of length $\in [3, 10]$ bp and stems of lengths $\in [1, 20]$ bp. We then used INDIEGRAM to reconstruct maximum likelihood reconstructions of the ancestral structure and the four-way multiple alignment (ancestor + three descendants).

The results of our simulations, illustrated in Figure 5, demonstrate that the accuracy of both structural reconstruction and alignment accuracy depend on the outgroup branch length. However, while the difficulty of alignment inference increases in proportion to the outgroup branch length, becoming near-

impossible for very long outgroup branch lengths, the same need not be true for structural reconstruction accuracy. As the branch length of the outgroup increases, the outgroup’s structure becomes increasingly decoupled from that of its ancestor, allowing the algorithm to “ignore” the information which it contains. In the trivial case where the outgroup branch length is zero (so the ancestor is identical to the outgroup), we can perfectly reconstruct the ancestral structure (as expected), but we cannot perfectly reconstruct the three-way multiple alignment (since there are still two finite-length branches, on which some unreconstructable mutations inevitably occur).

These results correspond to a best-case scenario in which we have a perfectly-parametrized evolutionary model and exactly-known descendant structures. Recent results demonstrating that inference of sequence alignment is robust to mis-parametrized probabilistic models [41] suggest that the same may be true for probabilistic inference of ancestral structures. The effect of imperfect knowledge of the ancestral structures has not been explored.

The program that we wrote to simulate RNA structural alignments from the TKFST model, EVOL-SAYER, is available as part of the same software distribution as INDIEGRAM (the DART package).

Discussion

Following the conception of paleogenetics [52], a large number of synthetic reconstructions of ancient proteins have been reported in the literature [53–60]. There are also the beginnings of a movement to reconstruct ancient DNA [33, 61–66]. Given the importance of the RNA world hypothesis to current discussions of the origin of life [67–73], the many modern-day relics of this world [74–77] and the recent proposal of a structural model for the primordial ribosome [2], we believe that phylogenetic reconstruction of ancient RNA is a significant problem, deserving of strong bioinformatics support.

The work reported in this paper builds on substantial prior art in the areas of evolutionary modeling and ancestral reconstruction. The reconstruction of ancient sequences was first proposed in 1963 by Pauling and Zuckerkandl [52]; current applications of this idea, mostly using substitution models, are surveyed in the book edited by Liberles [78]. Many algorithms in phylogenetics implicitly reconstruct substitution histories, whether by parsimony [79, 80] or likelihood [22]. There has been much effort to model the evolution of sequences related by a tree with models permitting indels [30, 35, 39, 45, 81–88]. Recent work has extended these ideas to the reconstruction of indel histories [89, 90], particularly at the genomic scale [33, 91]. There is substantial prior work in computational linguistics on the theory of transducers for sequences [92] and parse trees [36, 37, 93, 94] (from which we take the terms “string transducer” and “parse-tree transducer”). We draw on the bioinformatics literature for SCFGs [10, 11, 95], especially Pair SCFGs [14, 18, 19] and phylogenetic SCFGs [16]. In particular, an early example of a pairwise conditional model $P(Y|X)$ for structure-dependent RNA evolution may be found in [12]. A conditional framework similar to ours in some respects is described by Sakakibara et al [96]. The dynamic programming inference algorithms for multiple-sequence SCFGs are closely related to the “protosequence algorithm” of Sankoff [44].

While we have focused on the TKF Structure Tree model in our Results, our model-construction algorithm is applicable to any model of the evolution of secondary structure which can be expressed as a Pair SCFG. Realistic structural and thermodynamic effects—such as base-stacking or loop length distributions—can, in principle, be incorporated.

An implementation of inference algorithms for models on the three-taxon phylogeny is sufficient to construct a MCMC sampling algorithm over many sequences on an arbitrary phylogeny. A sketch of such a sampling algorithm is as follows: at each step of the sampling algorithm, we re-sample the sequence

and structure of the ancestral node W , conditioned on the sequences and structures of X , Y and Z . The structural alignment of all four sequences can change at each step, providing for fast mixing and guaranteeing ergodicity. This move is similar to the sampler proposed by [31] for models with a HMM structure. Note that this, in principle, permits construction of a crude sampler to simultaneously infer phylogeny as well, by proposing and accepting or rejecting changes to the underlying tree as well as the implied structural alignment.

Reconstructing structural changes of large RNAs using the three-way sampling kernel which we have described would require resources far in excess of those currently available; barring the availability of supercomputers with terabytes of memory, such algorithms will only be feasible for short RNAs (Table 7). Thus, alternate strategies will have to be explored, such as the progressive reconstruction used by the Ortheus program for reconstructing ancestral genomes [33]. Another promising direction is to consider variations on the three-way sampling kernel, such as the importance-sampling approach described for the TKF model by [32]. This approach first proposes an ancestor W by aligning extant sequence X to Y (ignoring Z); then, in a second step, the proposed W is independently aligned to Z . The proposed three-way alignment and reconstruction is then randomly accepted (or rejected) using a Hastings ratio based on the three-way transducer composition. The complexity of this kernel is the same as the pairwise case; with suitable constraints, this is feasible for RNA grammars on present hardware, at least for ribosomal domains (if not yet whole subunits—although pairwise alignment of those should also be possible soon). The approach of Redelings and Suchard therefore merits future consideration in the context of modeling the evolution of RNAs on a tree.

An alternative MCMC scheme for sampling RNA phylogeny, structure and alignment was developed for the SimulFold program [97]. SimulFold does not use a strictly normalized probabilistic model, resulting in some oddities in the ways that structure and indels interact (for example, it does not penalize deletion of one half of a basepair). Currently, it is not clear how appropriate SimulFold would be for ancestral reconstruction, although it has several advantages (e.g. explicit treatment of pseudoknots). Of course, MCMC kernels can often be adapted for use with different models, and the MCMC moves used by SimulFold may be useful for inference under our model as well.

In summary, the evolutionary models we have described form a theoretical foundation for studying the structural evolution of RNA gene families in detail. By opening the door to ancestral sequence reconstruction and paleogenomics, these algorithms will allow us to test our knowledge of RNA evolution

by direct experimental investigation of early ribonucleic machines.

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Figure Legends

Figure 1. A simple example of transducer composition to build an evolutionary model of two extant sequences. An ancestral sequence W evolves into two descendant sequences X and Y . A singlet transducer (the horizontal gray box) emits an ancestral sequence and structure and two branch transducers (the gray boxes labeled T_X and T_Y) mutate it according to the specified evolutionary model. Gray nodes correspond to observed data and white nodes unobserved data.

Figure 2. Transducer composition on a star phylogeny with three (extant) leaf sequences. An ancestral sequence W evolves into three descendant sequences X , Y and Z . A singlet transducer (the horizontal gray box) emits an ancestral sequence and structure and three branch transducers (the gray boxes labeled T_X , T_Y and T_Z) mutate it according to the specified evolutionary model. Gray nodes correspond to observed data and white nodes unobserved data. If the branch transducers are time-reversible, then this star phylogeny with three leaves is the neighborhood of any interior node in a (binary) phylogenetic tree, from which it follows that evaluating the likelihood function on this star phylogeny is sufficient, in principle, for a sampling algorithm on an arbitrary phylogeny.

Figure 3. The TKF Structure Tree model represents the evolution of RNA structure as nested stem and loop sequences. The model consists of recursively nested loop sequences (gray, horizontal) and stem sequences (black, vertical). The loops are sequences of unpaired bases and the stems are sequences of covarying base-pairs. Both loop and stem sequences evolve according to the Thorne-Kishino-Felsenstein (TKF) model [45] of molecular evolution. Figure is extended from a similar version in [29].

Figure 4. Evolution of a RNA structure under the TKF Structure Tree model. The TKF Structure Tree model includes phenomena such as point mutations in loop sequences ($1 \rightarrow 2$ and $4 \rightarrow 5$), covariant mutations in stem sequences ($2 \rightarrow 3$), insertions in loop sequences ($3 \rightarrow 4$), insertions in stem sequences ($5 \rightarrow 6$), structural insertions ($6 \rightarrow 7$), and structural deletions ($7 \rightarrow 8$). Figure is extended from a similar version in [29].

Figure 5. Dependence of reconstruction accuracy on outgroup branch length. We investigated the dependence of structural reconstruction and alignment accuracy on outgroup branch length by simulating the evolution of three structural RNAs under our model. The two sister species were equidistant from the ancestral sequence, with a branch length of 1, corresponding to one expected substitution per site in loop sequence. We allowed the outgroup branch length to vary between $[0, 2.5]$. We divided this interval into 25 bins and simulated 25 alignments for each bin. Parameters used were $\lambda_l = 0.025$ and $\mu_l = 0.03$ for loop sequence and $\lambda_l = 0.007$ and $\mu_l = 0.01$ for stem sequence; the probability of a stem insertion was 0.1. These yielded a mean loop length of 5 bp and a mean stem length of 2.33 bp, with ~ 0.3 substructure indels per alignment. We selected challenging alignments to reconstruct by requiring that there be at least two ancestral stems, loops of length $\in [3, 10]$ bp and stems of length $\in [1, 20]$ bp; to reduce the complexity of our algorithms we additionally required that the sequences have lengths $\in [30, 70]$ bp. “Structural reconstruction accuracy” is the fraction of base-pairs in the ancestral structure present in the maximum-likelihood reconstruction thereof; “Alignment accuracy” is a measure of sequence alignment accuracy which takes both aligned and unaligned (indels) nucleotides into account, qualitatively corresponding to giving equal weight to sensitivity and specificity (see [98] for a precise definition).

Tables

Table 1. State types of the singlet transducer (single-sequence SCFG) of the TKF Structure Tree model.

State	type	absorb	emit	description
L	Start			Start of a loop
I_L	Insert		(x, null)	Single-base emission
S	Start			Start of a stem
I_S	Insert		(x, y)	Base-pair emission
B	Insert		$(L S)$	Bifurcation

Singlet transducers can only have states of type **Start** or **Insert**.

Table 2. Singlet transducer (single-sequence SCFG) of the TKF Structure Tree model.

Source	→	Destination	probability	Source	→	Destination	probability
L	→	$u I_L$	$\kappa_l \cdot \pi_l(u)$	S	→	$u I_S v$	$\kappa_s \cdot \pi_s(uv)$
		B	$\kappa_l \cdot \pi_l(S)$			B_e	$1 - \kappa_s$
		End	$1 - \kappa_l$				
I_L	→	$u I_L$	$\kappa_l \cdot \pi_l(u)$	I_S	→	$u I_S v$	$\kappa_s \cdot \pi_s(uv)$
		B	$\kappa_l \cdot \pi_l(S)$			B_e	$1 - \kappa_s$
		End	$1 - \kappa_l$				
B	→	$(L S)$	1				
B_e	→	$(L \text{ End})$	1				

The state types for this model are shown in Table 1. The singlet transducer generates ancestral RNA sequences and structures. We use the notation of formal grammars to represent state transformation rules; for example, the rule $I_L \rightarrow u I_L$ corresponds to (in a Pair HMM) an **Insert** state I_L emitting a nucleotide u and then making a self-transition. Both loop (L and I_L) and stem (S and I_S) sequence evolve as TKF sequences with length parameters κ_l and κ_s (defined in “A simple model of RNA structural evolution”). $\pi_l(u)$ and $\pi_s(uv)$ are the equilibrium distributions of unpaired nucleotides u and paired nucleotides (u, v) and are normalized such that $\pi_l(S) + \sum_u \pi_l(u) = 1$ and $\sum_{u,v} \pi_s(uv) = 1$. The bifurcation state B_e is used to end stem sequences (only loop sequences are allowed to transition to the empty string).

Table 3. State types of the branch transducer (conditionally-normalized Pair SCFG) of the TKF Structure Tree model.

State	type	absorb	emit	description
L	Start			Start of a loop
I_L	Insert		(u, null)	Single-base insertion
M_L	Match	(x, null)	(u, null)	Single-base substitution
D_L	Match	(x, null)		Single-base deletion
W_L	Wait			Wait for next base
S	Start			Start of a stem
I_S	Insert		(u, v)	Base-pair insertion
M_S	Match	(x, y)	(u, v)	Base-pair substitution
D_S	Match	(x, y)		Base-pair deletion
W_S	Wait			Wait for next base-pair
B_i	Insert		$(L_i S_i)$	Stem insertion
B	Match	$(L S)$	$(L S)$	Stem conservation
B_p	Match	$(L S)$	$(L \text{End})$	Stem deletion
B_e	Match	$(L \text{End})$	$(L \text{End})$	Stem extinction

States which have the same names as states of the singlet transducer in Table 1 are the branch-transducer equivalents of the corresponding singlet-transducer states (e.g., a **Match** state might be the branch equivalent of an **Insert** state). States L_i and S_i are the **Start** states of a sub-model (not shown) identical in structure to the singlet transducer. They are used to insert a new stem-loop structure.

Table 4. Branch transducer (conditionally-normalized Pair SCFG) of the TKF Structure Tree model.

Source	→	Destination	probability	Source	→	Destination	probability
L	→	$w I_L$	$\beta_l(t) \cdot \pi_l(w)$	S	→	$w I_S x$	$\beta_s(t) \cdot \pi_s(wx)$
		B_i	$\beta_l(t) \cdot \pi_l(S)$			W_S	$1 - \beta_s(t)$
		W_L	$1 - \beta_l(t)$				
I_L	→	$w I_L$	$\beta_l(t) \cdot \pi_l(w)$	I_S	→	$w I_S x$	$\beta_s(t) \cdot \pi_s(wx)$
		B_i	$\beta_l(t) \cdot \pi_l(S)$			W_S	$1 - \beta_s(t)$
		W_L	$1 - \beta_l(t)$				
M_L	→	$w I_L$	$\beta_l(t) \cdot \pi_l(w)$	M_S	→	$w I_S x$	$\beta_s(t) \cdot \pi_s(wx)$
		B_i	$\beta_l(t) \cdot \pi_l(S)$			W_S	$1 - \beta_s(t)$
		W_L	$1 - \beta_l(t)$				
D_L	→	$w I_L$	$\gamma_l(t) \cdot \pi_l(w)$	D_S	→	$w I_S x$	$\gamma_s(t) \cdot \pi_s(wx)$
		B_i	$\gamma_l(t) \cdot \pi_l(S)$			W_S	$1 - \gamma_s(t)$
		W_L	$1 - \gamma_l(t)$				
W_L	→	$w M_L$	$\alpha_l(t) \cdot M_l(u \rightarrow w)$	W_S	→	$w M_S x$	$\alpha_s(t) \cdot M_s(uv \rightarrow wx)$
		D_L	$1 - \alpha_l(t)$			D_S	$1 - \alpha_s(t)$
		B	$\alpha_l(t)$			B_e	1
		B_p	$1 - \alpha_l(t)$				
		End	1				
B	→	$L S$	1	B_p	→	$L \text{ End}$	1
B_i	→	$L_i S_i$	1	B_e	→	$L \text{ End}$	1

The state types for this model are shown in Table 3. The branch transducer evolves a sequence and structure along a branch of the phylogenetic tree. States L_i and S_i are the **Start** states for a sub-model corresponding to an insertion of a new stem in the descendant sequences; the sub-model (not shown) is identical in structure to the singlet transducer shown in Table 2. $\pi_l(w)$ and $\pi_s(wx)$ are the equilibrium distributions of, respectively, descendant unpaired nucleotide w and descendant paired nucleotides (w, x) ; $M_l(u \rightarrow w)$ and $M_l(uv \rightarrow wx)$ are the conditional distributions (i.e., match probabilities) of a descendant unpaired nucleotide w given an ancestral unpaired nucleotide u and descendant paired nucleotides (w, x) given ancestral nucleotides (u, v) . The functions $\alpha_{l,s}(t)$, $\beta_{l,s}(t)$ and $\gamma_{l,s}(t)$ are parametrized by the insertion and deletion rates of the TKFST model and are defined in “A simple model of RNA structural evolution.”

Table 5. Percentage sensitivity and positive predictive value (Sensitivity / PPV) for pairwise nucleotide-level alignments in the BRalibaseII benchmark.

	U5	g2intron	rRNA	tRNA
TKFST grammar	81.6 / 81.7	75.4 / 75.0	91.4 / 92.6	94.6 / 94.4
STEMLOC grammar	82.6 / 83.7	74.2 / 74.8	92.6 / 92.8	93.2 / 93.9

We compared the performance of the TKFST model for progressive multiple alignment of RNAs against the performance of a grammar with a richer model of RNA structure (“STEMLOC”; [18]). Sensitivity is defined as $TP/(TP + FN)$ and PPV is defined as $TP/(TP + FP)$, where TP is the number of true positives (correctly aligned residue pairs), FN is the number of false negatives (residue pairs that should have been aligned but were not) and FP is the number of false positives (residue pairs that were incorrectly aligned). These statistics are summed over all pairs of sequences in the multiple alignment; therefore, “Sensitivity” for pairwise residue alignments is equivalent to the Sum of Pairs Score or SPS [99]. “g2intron” is the RFAM entry *Intron_gpII*, containing domains V and VI of the Group II intron.

Table 6. Percentage sensitivity and positive predictive value (Sensitivity / PPV) for predicted base-pairs in the BRalibaseII benchmark.

	U5	g2intron	rRNA	tRNA
TKFST grammar	37.9 / 68.0	42.1 / 63.8	37.4 / 66.5	70.9 / 88.3
STEMLOC grammar	74.9 / 73.9	64.3 / 56.7	51.0 / 59.0	74.0 / 76.4

We compared the performance of the TKFST model for structure-prediction accuracy during progressive multiple alignment of RNAs against the performance of a grammar with a richer model of RNA structure (“STEMLOC”; [18]). “g2intron” is the RFAM entry *Intron_gpII*, containing domains V and VI of the Group II intron.

Table 7. Estimates of the memory and time required to reconstruct ancestral structures of three RNAs from several families of biological interest (as reported by INDIEGRAM).

Family	Sequence lengths	Memory	Time
<i>nanos</i> 3' TCE	61-64 nt	3 Gb	3 min
tRNA	69-73 nt	11 Gb	19 min
Y RNA	47-81 nt	33 Gb	70 min
Group II intron (domains V and VI)	76-91 nt	122 Gb	90 min

The *nanos* 3' translational control element (TCE) sequences are the seed sequences of the corresponding RFAM family [5] and the three tRNA sequences are from the BRalibaseII database [100] (identifiers AB042432.1-14140_14072, Z82044.1-16031_16103 and AC008670.6-83725_83795). The group II intron sequences (identifiers Z00044.1-87253_87177, X57546.1-2817_2907 and X04465.1-2700_2775) are from BRalibaseII [100]. The Y RNAs are hY1, hY4, and hY5 from [101]; sequence lengths exclude the conserved stem S1. The time estimates are for a 2.2GHz AMD Opteron 848 CPU.

Algorithms

```

Input: Rule  $\rho'' \in \mathbf{R}''$ 
Output: Parse (sub)tree  $T' \in \mathcal{T}'$ 
switch  $\rho''$  do
  case  $X \rightarrow Y$ 
    if  $\text{Random}[0,1] < P(X \rightarrow Y)/q_{XY}$  then
      return  $(X \rightarrow Y)$  ;
    else
      Let  $z = \sum_W q_{XW} P'(W \rightarrow Y)$  ;
      Sample state  $V$  from probability distribution  $P(V) = q_{XV} P'(V \rightarrow Y)/z$  ;
      return  $(\text{restoreTransitions}(X \rightarrow V) \rightarrow Y)$  ;
    end
  end
  case  $X \rightarrow \epsilon$ 
    if  $\text{Random}[0,1] < P'(X \rightarrow \epsilon)/P'(\epsilon|X)$  then
      return  $(X \rightarrow \epsilon)$  ;
    else
      Let  $z = \sum_W q_{XW} P'(W \rightarrow \epsilon)$  ;
      Sample state  $V$  from probability distribution  $P(V) = q_{XV} P'(V \rightarrow \epsilon)/z$  ;
      return  $(\text{restoreTransitions}(X \rightarrow V) \rightarrow \epsilon)$  ;
    end
  end
  otherwise
    return  $(\rho'')$  ;
  end
end

```

Algorithm 1: Subroutine $\text{restoreTransitions}(\rho'')$ for the null cycle elimination procedure.

```

Input: Rule  $\rho' \in \mathbf{R}'$ 
Output: Parse (sub)tree  $T \in \mathcal{T}$ 
switch  $\rho'$  do
  case  $B^0 \rightarrow \epsilon$ 
    Let  $B \rightarrow L R$  be the original bifurcation in  $\mathbf{R}$  ;
     $T_L \leftarrow \text{sampleNullSubtree}(L)$  ;
     $T_R \leftarrow \text{sampleNullSubtree}(R)$  ;
    return  $(B \rightarrow T_L T_R)$  ;
  end
  case  $B' \rightarrow L'$ 
    Let  $B \rightarrow L R$  be the original bifurcation in  $\mathbf{R}$  ;
     $T_R \leftarrow \text{sampleNullSubtree}(R)$  ;
    return  $(B \rightarrow L T_R)$  ;
  end
  case  $B' \rightarrow R'$ 
    Let  $B \rightarrow L R$  be the original bifurcation in  $\mathbf{R}$  ;
     $T_L \leftarrow \text{sampleNullSubtree}(L)$  ;
    return  $(B \rightarrow T_L R)$  ;
  end
  case  $B^2 \rightarrow L' R'$ 
    Let  $B \rightarrow L R$  be the original bifurcation in  $\mathbf{R}$  ;
    return  $(B \rightarrow L R)$  ;
  end
  case  $B^0 \rightarrow B'$  return  $()$  ;
  case  $B' \rightarrow B^2$  return  $()$  ;
  otherwise
    Let  $\rho$  be the original rule in  $\mathbf{R}$  ;
    return  $(\rho)$  ;
  end
end

```

Algorithm 2: Subroutine $\text{restoreBifurcations}(\rho')$ for the null cycle elimination procedure.

```

Input: Nonterminal  $A \in \mathcal{N}$ 
Output: Parse tree  $T \in \mathcal{T} : \text{seq}(T) = \epsilon, \text{root}(T) = A$ 
if  $A$  is a bifurcation state,  $A \rightarrow X Y$ , then
   $T_X \leftarrow \text{sampleNullSubtree}(X)$  ;
   $T_Y \leftarrow \text{sampleNullSubtree}(Y)$  ;
  return  $(A \rightarrow T_X T_Y)$  ;
else
  if  $\text{Random}[0,1] < P(A \rightarrow \epsilon)/P(\epsilon|A)$  then
    return  $(A \rightarrow \epsilon)$  ;
  else
    Let  $z = \sum_Y P(A \rightarrow Y)P(\epsilon|Y)$  ;
    Sample state  $X$  from probability distribution  $P(X) = P(A \rightarrow X)P(\epsilon|X)/z$  ;
     $T_X \leftarrow \text{sampleNullSubtree}(X)$  ;
    return  $(A \rightarrow T_X)$  ;
  end
end

```

Algorithm 3: Subroutine $\text{sampleNullSubtree}(A)$ for the null cycle elimination procedure.

```

Input: sequences  $X, Y, Z$ 
foreach  $n^{(X)} \in \mathcal{F}^{(X)}$  do                                     /* inside-outside sorted */
  foreach  $n^{(Y)} \in \mathcal{F}^{(Y)}$  do                                     /* inside-outside sorted */
    foreach  $n^{(Z)} \in \mathcal{F}^{(Z)}$  do                                     /* inside-outside sorted */
      foreach state  $a$  do
        bifurcProb  $\leftarrow 0$ ;
        foreach  $(n_L^{(X)}, n_R^{(X)}) \in b_{in}(n^{(X)})$  do
          foreach  $(n_L^{(Y)}, n_R^{(Y)}) \in b_{in}(n^{(Y)})$  do
            foreach  $(n_L^{(Z)}, n_R^{(Z)}) \in b_{in}(n^{(Z)})$  do
              bifurcProb  $+= \text{calcLBifurcProb}(a; \cdot)$ ;
              bifurcProb  $+= \text{calcRBifurcProb}(a; \cdot)$ ;
            end
          end
        end
         $\alpha_a(n^{(X)}, n^{(Y)}, n^{(Z)}) \leftarrow \text{calcTransEmitProb}(a; n^{(X)}, n^{(Y)}, n^{(Z)})$ ;
         $\alpha_a(n^{(X)}, n^{(Y)}, n^{(Z)}) += \text{bifurcProb}$ ;
        store  $\alpha_a(n^{(X)}, n^{(Y)}, n^{(Z)})$ ;
      end
    end
  end
end
return  $\alpha_a(n^{(X)}[0, L^{(X)}], n^{(Y)}[0, L^{(Y)}], n^{(Z)}[0, L^{(Z)}])$ ;

```

Algorithm 4: The constrained Inside algorithm for three sequences X, Y, Z . Ensemble states a in the iteration over states are sorted in Inside fill order with **Emit** states first, then **Null** states in reverse topological order.

```

Input: state  $a, n^{(X)}, n^{(Y)}, n^{(Z)}$ , intermediate Inside matrix  $\alpha$ 
emitProb  $\leftarrow 0$ ;
foreach  $b : \exists a \rightarrow b$  do
  emitProb  $+= P(a \rightarrow b) \alpha_b(n^{(X)}, n^{(Y)}, n^{(Z)})$ ;
end
foreach  $b : \exists a \rightarrow l b r$  do
  if  $c_{in}(b; n^{(X)}) \notin \mathcal{F}^{(X)}$  or  $c_{in}(b; n^{(Y)}) \notin \mathcal{F}^{(Y)}$  or  $c_{in}(b; n^{(Z)}) \notin \mathcal{F}^{(Z)}$  then next;
  emitProb  $+= P(a \rightarrow l b r) \alpha_b(c_{in}(b; n^{(X)}), c_{in}(b; n^{(Y)}), c_{in}(b; n^{(Z)}))$ ;
end
return emitProb;

```

Algorithm 5: Subroutine calcTransEmitProb() for the Inside algorithm. a and b are ensemble states; l and r are left and right terminal emissions.

```

Input: sequences  $X, Y, Z$ 
foreach  $n^{(X)} \in \mathcal{F}^{(X)}$  do                                     /* inside-outside sorted */
  foreach  $n^{(Y)} \in \mathcal{F}^{(Y)}$  do                                     /* inside-outside sorted */
    foreach  $n^{(Z)} \in \mathcal{F}^{(Z)}$  do                                     /* inside-outside sorted */
      foreach state  $a$  do
        bifurcProb  $\leftarrow 0$ ;
        foreach  $(n_L^{(X)}, n_R^{(X)}) \in b_{in}(n^{(X)})$  do
          foreach  $(n_L^{(Y)}, n_R^{(Y)}) \in b_{in}(n^{(Y)})$  do
            foreach  $(n_L^{(Z)}, n_R^{(Z)}) \in b_{in}(n^{(Z)})$  do
              bifurcProb  $+= \text{calcLBifurcProb}(a; \cdot)$ ;
              bifurcProb  $+= \text{calcRBifurcProb}(a; \cdot)$ ;
            end
          end
        end
         $\gamma_a(n^{(X)}, n^{(Y)}, n^{(Z)})$ 
         $\leftarrow \max(\text{calcTransEmitProb}(a; n^{(X)}, n^{(Y)}, n^{(Z)}), \text{bifurcProb})$ ;
        store  $\gamma_a(n^{(X)}, n^{(Y)}, n^{(Z)})$ ;
      end
    end
  end
end
return  $\gamma_a(n^{(X)}[0, L^{(X)}], n^{(Y)}[0, L^{(Y)}], n^{(Z)}[0, L^{(Z)}])$ ;

```

Algorithm 6: The constrained CYK algorithm for three sequences X, Y, Z . Ensemble states a in the iteration over states are sorted in Inside fill order with **Emit** states first, then **Null** states in reverse topological order.

```

Input: state  $a, n^{(X)}, n^{(Y)}, n^{(Z)}$ , intermediate CYK matrix  $\gamma$ 
emitProb  $\leftarrow 0$ ;
foreach  $b : \exists a \rightarrow b$  do
  emitProb = max(emitProb,  $P(a \rightarrow b) \gamma_b(n^{(X)}, n^{(Y)}, n^{(Z)})$ );
end
foreach  $b : \exists a \rightarrow l b r$  do
  if  $c_{in}(b; n^{(X)}) \notin \mathcal{F}^{(X)}$  or  $c_{in}(b; n^{(Y)}) \notin \mathcal{F}^{(Y)}$  or  $c_{in}(b; n^{(Z)}) \notin \mathcal{F}^{(Z)}$  then next;
  emitProb = max(emitProb,  $P(a \rightarrow l b r) \gamma_b(c_{in}(b; n^{(X)}), c_{in}(b; n^{(Y)}), c_{in}(b; n^{(Z)}))$ );
end
return emitProb;

```

Algorithm 7: Subroutine calcTransEmitProb() for the CYK algorithm. a and b are ensemble states; l and r are left and right terminal emissions.

```

Input: sequences  $X, Y, Z$ , Inside matrix  $\alpha$ 
foreach  $n^{(X)} \in \mathcal{F}^{(X)}$  do                                     /* outside-inside sorted */
  foreach  $n^{(Y)} \in \mathcal{F}^{(Y)}$  do                                     /* outside-inside sorted */
    foreach  $n^{(Z)} \in \mathcal{F}^{(Z)}$  do                                     /* outside-inside sorted */
      foreach state  $b$  do
        bifurcProb  $\leftarrow 0$ ;
        foreach  $(n_O^{(X)}, n_L^{(X)}) \in b_{out,L}(n^{(X)})$  do
          foreach  $(n_O^{(Y)}, n_L^{(Y)}) \in b_{out,L}(n^{(Y)})$  do
            foreach  $(n_O^{(Z)}, n_L^{(Z)}) \in b_{out,L}(n^{(Z)})$  do
              | bifurcProb  $+= \text{calcLBifurcProb}(b; \cdot)$ ;
            end
          end
        end
        foreach  $(n_O^{(X)}, n_R^{(X)}) \in b_{out,R}(n^{(X)})$  do
          foreach  $(n_O^{(Y)}, n_R^{(Y)}) \in b_{out,R}(n^{(Y)})$  do
            foreach  $(n_O^{(Z)}, n_R^{(Z)}) \in b_{out,R}(n^{(Z)})$  do
              | bifurcProb  $+= \text{calcRBifurcProb}(b; \cdot)$ ;
            end
          end
        end
         $\beta_b(n^{(X)}, n^{(Y)}, n^{(Z)}) \leftarrow \text{calcTransEmitProb}(b; n^{(X)}, n^{(Y)}, n^{(Z)})$ ;
         $\beta_b(n^{(X)}, n^{(Y)}, n^{(Z)}) += \text{bifurcProb}$ ;
        store  $\beta_b(n^{(X)}, n^{(Y)}, n^{(Z)})$ ;
      end
    end
  end
end

```

Algorithm 8: The constrained Outside algorithm for three sequences X, Y, Z . Ensemble states \mathbf{a} in the iteration over states are sorted in Outside fill order with **Emit** states first, then **Null** states in topological order.


```

Input: state  $\mathbf{b}, n^{(X)}, n^{(Y)}, n^{(Z)}$ , intermediate Outside matrix  $\beta$ 
emitProb  $\leftarrow 0$ ;
foreach  $\mathbf{a} : \exists \mathbf{a} \rightarrow \mathbf{b}$  do
  | emitProb  $+= P(\mathbf{a} \rightarrow \mathbf{b}) \beta_{\mathbf{a}}(n^{(X)}, n^{(Y)}, n^{(Z)})$ ;
end
foreach  $\mathbf{a} : \exists \mathbf{a} \rightarrow \mathbf{l} \mathbf{b} \mathbf{r}$  do
  | if  $c_{out}(\mathbf{b}; n^{(X)}) \notin \mathcal{F}^{(X)}$  or  $c_{out}(\mathbf{b}; n^{(Y)}) \notin \mathcal{F}^{(Y)}$  or  $c_{out}(\mathbf{b}; n^{(Z)}) \notin \mathcal{F}^{(Z)}$  then next;
  | emitProb  $+= P(\mathbf{a} \rightarrow \mathbf{l} \mathbf{b} \mathbf{r}) \beta_{\mathbf{a}}(c_{out}(\mathbf{b}; n^{(X)}), c_{out}(\mathbf{b}; n^{(Y)}), c_{out}(\mathbf{b}; n^{(Z)}))$ ;
end
return emitProb;

```

Algorithm 9: Subroutine calcTransEmitProb() for the Outside algorithm. \mathbf{a} and \mathbf{b} are ensemble states; \mathbf{l} and \mathbf{r} are left and right terminal emissions.

```

Input: sequences  $X, Y, Z$ 
pushdown stack coordinateStack;          /* hold (state, subsequence triplet) pairs */
 $a \leftarrow \text{Start}$ ;                      /* current ensemble state */
 $n^{(X)} \leftarrow N^{(X)}$ ;                /* current  $X$  subsequence;  $N^{(X)}$  is the outermost subsequence */
 $n^{(Y)} \leftarrow N^{(Y)}$ ;                /* current  $Y$  subsequence;  $N^{(Y)}$  is the outermost subsequence */
 $n^{(Z)} \leftarrow N^{(Z)}$ ;                /* current  $Z$  subsequence;  $N^{(Z)}$  is the outermost subsequence */
clear coordinateStack;
begin main loop:
  output current state  $a$  and subsequence triplet  $(n^{(X)}, n^{(Y)}, n^{(Z)})$ ;
  if  $a$  is the End state then                      /* end of a parse subtree */
    if coordinateStack is empty then return ;      /* end of the parse tree */
    pop  $(a, n^{(X)}, n^{(Y)}, n^{(Z)})$  from coordinateStack ;
    goto main loop ;
  else if  $a$  is a bifurcation state then              /* bifurcation  $a \rightarrow cb$  */
    select  $(n_L^{(X)}, n_R^{(X)}) \in b_{in}(n^{(X)}), (n_L^{(Y)}, n_R^{(Y)}) \in b_{in}(n^{(Y)}), (n_L^{(Z)}, n_R^{(Z)}) \in b_{in}(n^{(Z)})$ 
    such that
     $\gamma_a(n^{(X)}, n^{(Y)}, n^{(Z)}) = \gamma_a(n_L^{(X)}, n_L^{(Y)}, n_L^{(Z)}) \gamma_a(n_R^{(X)}, n_R^{(Y)}, n_R^{(Z)})$  ;
    push  $(c, n_R^{(X)}, n_R^{(Y)}, n_R^{(Z)})$  onto coordinateStack ;
     $a \leftarrow b$ ;
     $n^{(X)} \leftarrow n_L^{(X)}$ ;
     $n^{(Y)} \leftarrow n_L^{(Y)}$ ;
     $n^{(Z)} \leftarrow n_L^{(Z)}$ ;
    goto main loop ;
  else                      /* Emit or Null state */
     $m^{(X)} \leftarrow c_{in}(b; n^{(X)})$  ;
     $m^{(Y)} \leftarrow c_{in}(b; n^{(Y)})$  ;
     $m^{(Z)} \leftarrow c_{in}(b; n^{(Z)})$  ;
    select  $b \in \{b : \exists a \rightarrow lbr\}$ 
    such that
     $\gamma_a(n^{(X)}, n^{(Y)}, n^{(Z)}) = P(a \rightarrow lbr) \gamma_b(m^{(X)}, m^{(Y)}, m^{(Z)})$ ;
     $a \leftarrow b$ ;
     $n^{(X)} \leftarrow m^{(X)}$ ;
     $n^{(Y)} \leftarrow m^{(Y)}$ ;
     $n^{(Z)} \leftarrow m^{(Z)}$ ;
    goto main loop ;
end

```

Algorithm 10: The constrained CYK traceback algorithm for three sequences X, Y, Z .