A Tree Sampler for Bounded Context-Free Languages

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Abstract

The class of bounded context-free languages (BCFLs) consists of the subset of context-free languages which are finite. We provide a novel algorithm for sampling trees in BCFLs with and without replacement. Once the data structure is constructed, sampling trees is a straightforward matter of sampling integers uniformly without a replacement from a finite range. We demonstrate the utility of this technique on a dataset of Python statements.

1 Introduction

Recall that a CFG is a quadruple consisting of terminals (Σ), nonterminals (V), productions ($P\colon V \rightarrow (V \mid \Sigma)^*$), and a start symbol, ($S$). It is a well-known fact that every CFG is reducible to *Chomsky Normal Form*, $P'\colon V \rightarrow (V^2 \mid \Sigma)$, in which every production takes one of two forms, either $w \rightarrow xz$, or $w \rightarrow t$, where $w, x, z : V$ and $t : \Sigma$. For example, the CFG, $P := \{S \rightarrow SS \mid (S) \mid ()\}$, corresponds to the CNF:

$$P' = \left\{ S \rightarrow QR \mid SS \mid LR, \quad L \rightarrow (, \quad R \rightarrow), \quad Q \rightarrow LS \right\}$$

Given a CFG, $\mathcal{G}' : \langle \Sigma, V, P, S\rangle$ in CNF, we can construct a recognizer $R : \mathcal{G}' \rightarrow \Sigma^n \rightarrow \mathbb{B}$ for strings $\sigma : \Sigma^n$ as follows. Let 2^V be our domain, 0 be $\varnothing$, $\oplus$ be $\cup$, and $\otimes$ be defined as:

$$X \otimes Z := \left\{ w \mid \langle x, z\rangle \in X \times Z, (w \rightarrow xz) \in P \right\} \tag{1}$$

If we define $\sigma_r^{\Uparrow} := \{w \mid (w \rightarrow \sigma_r) \in P\}$, then initialize $M^0_{r+1=c}(\mathcal{G}', e) := \sigma_r^{\Uparrow}$ and solve for the fixpoint $M^* = M + M^2$,

$$M^0 := \begin{pmatrix} \varnothing & \sigma_1^{\rightarrow} & \varnothing & \cdots & \varnothing \\ \vdots & \ddots & \ddots & & \vdots \\ \vdots & & \ddots & & \varnothing \\ \vdots & & & \ddots & \sigma_n^{\uparrow} \\ \varnothing & \cdots & \cdots & \cdots & \varnothing \end{pmatrix} \Rightarrow M^* = \begin{pmatrix} \varnothing & \sigma_1^{\rightarrow} & \Lambda & \cdots & \Lambda_\sigma^* \\ \vdots & \ddots & \ddots & & \vdots \\ \vdots & & \ddots & & \Lambda \\ \vdots & & & \ddots & \sigma_n^{\uparrow} \\ \varnothing & \cdots & \cdots & \cdots & \varnothing \end{pmatrix}$$

we obtain the recognizer, $R(\mathcal{G}', \sigma) := S \in \Lambda_\sigma^*? \Leftrightarrow \sigma \in \mathcal{L}(\mathcal{G})$? Full details of the bisimilarity between parsing and matrix multiplication can be found in Valiant [4] and Lee [1], who shows its time complexity to be $\mathcal{O}(n^\omega)$ where ω is the least matrix multiplication upper bound (currently, $\omega < 2.77$).

2 Method

We define the porous completion problem as follows:

Definition 2.1 (Completion)**.** Let $\underline{\Sigma} := \Sigma \cup \{\_\}$, where $\_$ represents a hole. We denote $\sqsubseteq\colon \Sigma^n \times \underline{\Sigma}^n$ as the relation $\{\langle \sigma', \sigma\rangle \mid \sigma_i : \Sigma \implies \sigma_i' = \sigma_i\}$ and the set $\{\sigma' : \Sigma^+ \mid \sigma' \sqsubseteq \sigma\}$ as $\mathrm{H}(\sigma)$. Given $\sigma : \underline{\Sigma}^+$ we want to sample $\sigma' \sim \mathrm{H}(\sigma) \cap \ell$.

$\mathrm{H}(\sigma) \cap \ell$ is often a large-cardinality set, so we want a procedure which samples uniformly without replacement from the set, without enumerating the whole set and shuffling it.

We define an algebraic data type $\mathbb{T}_3 = (V \cup \Sigma) \rightharpoonup \mathbb{T}_2$ where $\mathbb{T}_2 = (V \cup \Sigma) \times (\mathbb{N} \rightharpoonup \mathbb{T}_2 \times \mathbb{T}_2)$[1]. Morally, we can think of $\mathbb{T}_2$ as an implicit set of possible trees sharing the same root, and $\mathbb{T}_3$ as a dictionary of possible $\mathbb{T}_2$ values indexed by possible roots, given by a specific CFG under a finite-length porous string. We construct $\hat{\sigma}_r = \dot{p}(\sigma_r)$ as follows:

$$\dot{p}(s : \Sigma) \mapsto \Big\{ \mathbb{T}_2\big(w, \big[\langle \mathbb{T}_2(s), \mathbb{T}_2(\varepsilon)\rangle\big]\big) \mid (w \rightarrow s) \in P \Big\}$$

$$\dot{p}(\_) \mapsto \bigoplus_{s \in \Sigma} p(s)$$

We then compute the fixpoint M_∞ by redefining $\oplus, \otimes : \mathbb{T}_3 \times \mathbb{T}_3 \rightarrow \mathbb{T}_3$ as follows:

$$X \oplus Z \mapsto \bigcup_{k \in \pi_1(X \cup Z)} \left\{ k \Rightarrow \mathbb{T}_2(k, Q_x \cup Q_z) \mid Q_x \in \pi_2(X \circ k), Q_z \in \pi_2(Z \circ k) \right\}$$

$$X \otimes Z \mapsto \bigoplus_{w,x,z} \Big\{ \mathbb{T}_2\big(w, \big[\langle X \circ x, Z \circ z\rangle\big]\big) \mid (w \rightarrow xz) \in P, x \in \pi_1(X), z \in \pi_1(Z) \Big\}$$

Decoding trees from $(\Lambda_\sigma^* \circ S) : \mathbb{T}_2$ becomes a straightforward matter of enumeration using a recursive choice function that emits a sequence of binary trees generated by the CFG. We define this construction more precisely in § 2.1.

In our experiments, we provide a comparison of the performance of the SAT algebra and these two semirings, evaluated on a dataset of Python statements.

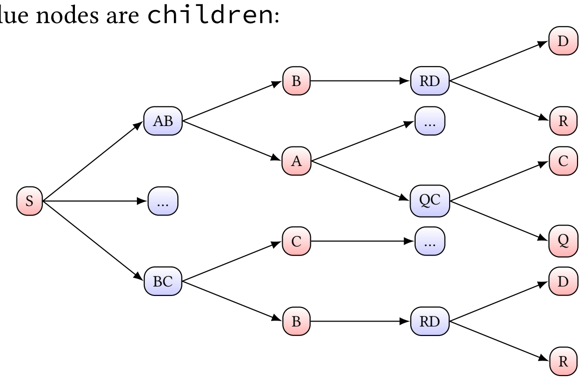
[1] Hereinafter, given a concrete $T : \mathbb{T}_2$, we shall refer to $\pi_1(T), \pi_2(T)$ as `root`(T) and `children`(T) respectively.

2.1 Pairing Breadth-Bounded Binary Trees

The type $\mathbb{T}_2$ of all possible trees that can be generated by a CFG in Chomksy Normal Form is identified by a recurrence relation:

$$L(p) = 1 + pL(p) \qquad\qquad P(a) = 1 + aL(P(a)^2)$$

We depict it as a tree, where red nodes are `roots` and blue nodes are `children`:



The number of binary trees inhabiting a single instance of $\mathbb{T}_2$ is sensitive to the number of nonterminals and rule expansions in the grammar. To obtain the total number of trees with breadth n, we can take the intersection between a CFG and the regular language, $\mathcal{L}(G^\cap) \coloneqq \mathcal{L}(\mathcal{G}) \cap \Sigma^n$, abstractly parse the string containing all holes, let $T = \Lambda^*_{\underline{\sigma}} \circ S$, and compute the total number of trees using the following recurrence:

$$|T : \mathbb{T}_2| \mapsto \begin{cases} 1 & \text{if } T \text{ is a leaf,} \\ \sum_{\langle T_1, T_2 \rangle \in \texttt{children}(T)} |T_1| \cdot |T_2| & \text{otherwise.} \end{cases}$$

To sample all trees in a given $T : \mathbb{T}_2$ uniformly without replacement, we first define a pairing function $\varphi : \mathbb{T}_2 \rightarrow \mathbb{Z}_{|T|} \rightarrow \texttt{BTree}$ as follows:

$$\varphi(T : \mathbb{T}_2, i : \mathbb{Z}_{|T|}) \mapsto \begin{cases} \Big\langle \texttt{BTree}\big(\texttt{root}(T)\big), i \Big\rangle & \text{if } T \text{ is a leaf,} \\ \text{Let } b = |\texttt{children}(T)|, & \\ \quad q_1, r = \big\langle \lfloor \frac{i}{b} \rfloor, i \pmod{b} \big\rangle, & \\ \quad lb, rb = \texttt{children}[r], & \\ \quad T_1, q_2 = \varphi(lb, q_1), & \\ \quad T_2, q_3 = \varphi(rb, q_2) \text{ in} & \\ \Big\langle \texttt{BTree}\big(\texttt{root}(T), T_1, T_2\big), q_3 \Big\rangle & \text{otherwise.} \end{cases}$$

Then, instead of sampling trees, we can simply sample integers uniformly without replacement from $\mathbb{Z}_{|T|}$ using the construction defined in § 2, and lazily decode them into trees.

3 Prior Work

Piantodosi define a similar construction, but it assumes the CFL is infinite and makes some additional assumptions about the CFG [3]. We provide a more general construction which works for any CFG. Sampling parse trees in CFGs can be viewed as sampling proofs in a limited kind of proof system [2].

4 Conclusion

We have presented a novel algorithm for sampling trees in bounded context-free languages with and without replacement. This technique has applications to code completion and program repair.

References

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[4] Leslie G Valiant. 1975. General context-free recognition in less than cubic time. Journal of computer and system sciences 10, 2 (1975), 308–315. http://people.csail.mit.edu/virgi/6.s078/papers/valiant.pdf