Tidyparse: Real-Time Context Free Error Correction

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Abstract

Tidyparse is a program synthesizer that performs real-time error correction for context free languages. Given both an arbitrary context free grammar (CFG) and an invalid string, the tool lazily generates admissible repairs while the author is typing, ranked by Levenshtein edit distance. Repairs are guaranteed to be sound, complete, syntactically valid and minimal. Tidyparse is the first system of its kind offering these guarantees in a real-time editor. To accelerate code completion, we design and implement a novel incremental parser-synthesizer that transforms CFGs onto a dynamical system over finite field arithmetic, enabling us to suggest syntax repairs in-between keystrokes. We have released an IDE plugin demonsrating the system described.[1]

1 Introduction

Modern research on error correction can be traced back to the early days of coding theory, when researchers designed *error-correcting codes* (ECCs) to denoise transmission errors induced by external interference, whether due to collision with a high-energy proton, manipulation by an adversary or some typographical mistake. In this context, *code* can be any logical representation for communicating information between two parties (such as a human and a computer), and an ECC is a carefully-designed code which ensures that even if some portion of the message should be corrupted through accidental or intentional means, one can still recover the original message by solving a linear system of equations. In particular, we frame our work inside the context of errors arising from human factors in computer programming.

In programming, most such errors initially manifest as syntax errors, and though often cosmetic, manual repair can present a significant challenge for novice programmers. The ECC problem may be refined by introducing a language, $\mathcal{L} \subset \Sigma^*$ and considering admissible edits transforming an arbitrary string, $s \in \Sigma^*$ into a string, $s' \in \mathcal{L}$. Known as *error-correcting parsing* (ECP), this problem was well-studied in the early parsing literature, cf. Aho and Peterson [1], but fell out of favor for many years, perhaps due to its perceived complexity. By considering only minimal-length edits, ECP can be reduced to the so-called *language edit distance* (LED) problem, recently shown to be subcubic [2], suggesting its possible tractability. Previous results on ECP and LED were primarily of a theorietical nature, but now, thanks to our contributions, we have finally realized a practical prototype.

[1] https://plugins.jetbrains.com/plugin/19570-tidyparse

2 Toy Example

Suppose we are given the following context free grammar:

```
S -> S and S | S or S | ( S ) | true | false | ! S
```

For reasons that will become clear in the following section, this is automatically rewritten into the equivalent grammar:

```
 F.! → !   ε+ → ε       S → false    F.and → and
 F.( → (   ε+ → ε+ ε+   S → F.! S      S.) → S F.)
 F.) → )    S → <S>     S → S or.S    or.S → F.or S
 F.ε → ε    S → true    S → S and.S  and.S → F.and S
F.or → or   S → S ε+    S → F.( S.)
```

Given a string containing holes such as the one below, Tidyparse will return several completions in a few milliseconds:

```
true _ _ _ ( false _ ( _ _ _ _ ! _ _ ) _ _ _ _
```

```
true or ! ( false or ( <S> ) or ! <S> ) or <S>
true or ! ( false and ( <S> ) or ! <S> ) or <S>
true or ! ( false and ( <S> ) and ! <S> ) or <S>
true or ! ( false and ( <S> ) and ! <S> ) and <S>
true and ( false and ( <S> ) and ! ! <S> ) and <S>
...
```

Similarly, if provided with a string containing various errors, Tidyparse will return several suggestions how to fix it, where green is insertion, orange is substitution and red is deletion.

```
true and ( false or and true false
```

```
1.) true and ( false or ! true )
2.) true and ( false or <S> and true )
3.) true and ( false or ( true ) )
...
9.) true and ( false or ! <S> ) and true false
```

In the following paper, we will describe how we built it.

3 Matrix Theory

We recall that a CFG is a quadruple consisting of terminals, Σ, nonterminals, V, productions, $P : V \longrightarrow (V \mid \Sigma)^*$, and the start symbol, S. It is a well-known fact that every CFG can be reduced to *Chomsky Normal Form* (CNF), $P^* : V \longrightarrow (V^2 \mid \Sigma)$, in which every production takes one of two forms, either $v_0 \longrightarrow v_1 v_2$, or $v_0 \longrightarrow \sigma$, where $v_{0,1,2} : V$ and $\sigma : \Sigma$. For example, we can rewrite the CFG $\{S \rightarrow SS \mid (S) \mid ()\}$, into CNF as:

$$\{S \rightarrow XR \mid SS \mid LR,\ L \rightarrow (,\ R \rightarrow),\ X \rightarrow LS\}$$

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

$$a \otimes b := \{C \mid \langle A, B\rangle \in a \times b, (C \to AB) \in P\} \tag{1}$$

We initialize $\mathbf{M}^0_{r,c}(\mathcal{G}, \sigma) := \{V \mid c = r + 1, (V \to \sigma_r) \in P\}$ and search for a matrix $\mathbf{M}^*$ via fixpoint iteration,

$$\mathbf{M}^* = \begin{pmatrix} \varnothing & \{V\}_{\sigma_1} & \cdots & \mathcal{T} \\ \vdots & \ddots & \ddots & \vdots \\ & & & \{V\}_{\sigma_n} \\ \varnothing & \cdots & \cdots & \varnothing \end{pmatrix} \tag{2}$$

where $\mathbf{M}^*$ is the least solution to $\mathbf{M} = \mathbf{M} + \mathbf{M}^2$. We can then define the recognizer as: $S \in \mathcal{T}? \iff \sigma \in \mathcal{L}(\mathcal{G})?$

Note that $\bigoplus_{k=1}^{n} \mathbf{M}_{ik} \otimes \mathbf{M}_{kj}$ has cardinality bounded by $|V|$ and is thus representable as a fixed-length vector using the characteristic function, $\mathbb{1}$. In particular, $\oplus, \otimes$ are defined as $\boxplus, \boxtimes$, so that the following diagram commutes:

$$\begin{tikzcd} V \times V \arrow[r, "\oplus/\otimes"] \arrow[d, shift right, "\mathbb{1}^{-2}"'] & V \arrow[d, shift right, "\mathbb{1}^{-1}"'] \\ \mathbb{B}^{|V|} \times \mathbb{B}^{|V|} \arrow[r, "\boxplus/\boxtimes"'] \arrow[u, shift right, "\mathbb{1}^{2}"'] & \mathbb{B}^{|V|} \arrow[u, shift right, "\mathbb{1}"'] \end{tikzcd}$$

Full details of the bisimilarity between parsing and matrix multiplication can be found in Valiant [4], who shows its time complexity to be $\mathcal{O}(n^\omega)$ where ω is the matrix multiplication bound, and Lee [3], showing that speedups to Boolean matrix multiplication are realizable by CFL parsers.

3.1 Sampling k-combinations without replacement

Let $\mathbf{M} : \mathrm{GF}(2^{n\times n})$ be a matrix whose struture is depicted in Eq. 3, where P is a feedback polynomial over $GF(2^n)$ with coefficients $P_{1\ldots n}$ and semiring operators $\oplus := \veebar, \otimes := \wedge$. Selecting any $V \neq \mathbf{0}$ and coefficients $P_{1\ldots n}$ from a known *primitive polynomial* then powering the matrix $\mathbf{M}$ generates an ergodic sequence over $\mathrm{GF}(2^n)$, as shown in Eq. 4.

$$\mathbf{M}^t V = \begin{pmatrix} P_1 & \cdots & \cdots & \cdots & P_n \\ \top & \circ & \cdots & \cdots & \circ \\ \circ & \ddots & \ddots & & \vdots \\ \vdots & & \ddots & \ddots & \vdots \\ \circ & \cdots & \circ & \top & \circ \end{pmatrix}^t \begin{pmatrix} V_1 \\ \vdots \\ \vdots \\ \vdots \\ V_n \end{pmatrix} \tag{3}$$

$$\mathbf{S} = \begin{pmatrix} V & \mathbf{M}V & \mathbf{M}^2 V & \mathbf{M}^3 V & \cdots & \mathbf{M}^{2^n-1} V \end{pmatrix} \tag{4}$$

This sequence has *full periodicity*, in other words, for all $i, j \in [0, 2^n), \mathbf{S}_i = \mathbf{S}_j \Rightarrow i = j$. To uniformly sample $\boldsymbol{\sigma} \sim \Sigma^n$ without replacement, we form an injection $GF(2^n) \rightharpoonup \Sigma^d$, cycle through $\mathbf{S}$, then discard samples that do not identify an element in any indexed dimension. This procedure rejects $(1 - |\Sigma| 2^{-\lceil \log_2 |\Sigma| \rceil})^d$ samples on average and requires $\sim \mathcal{O}(1)$ per sample and $\mathcal{O}(2^n)$ to exhaustively search the space.

For example, in order to sample from $\Sigma^2 = \{A, B, C\}^2$, we could use the primitive polynomial $x^4 + x^3 + 1$ shown below:

S_0	S_1	S_2	S_3	S_4	S_5	S_6	S_7
1000	0100	0010	1001	1100	0110	1011	0101
C A	B A	A C	C B		B C		B B

We will use this technique to lazily sample from the space of hole configurations without replacement as described in §5.

3.2 SAT Encoding

By allowing the matrix $\mathbf{M}$ in Eq. 2 to contain bitvector variables representing holes in the string and nonterminal sets, we obtain a set of multilinear SAT equations whose solutions exactly correspond to the set of admissible repairs and their corresponding parse forests. Specifically, the repairs coincide with holes in the superdiagonal $\mathbf{M}^*_{r+1=c}$, whose parse forests occur along the upper-triangular entries $\mathbf{M}^*_{r+1<c}$.

$$\mathbf{M} = \begin{pmatrix} \varnothing & \{V\}_{\sigma_1} & \mathcal{L}_{1,3} & \mathcal{L}_{1,3} & \mathcal{V}_{1,4} & \cdots & \mathcal{V}_{1,n} \\ \vdots & \ddots & \{V\}_{\sigma_2} & \mathcal{L}_{2,3} & \vdots & & \vdots \\ & & \ddots & \{V\}_{\sigma_3} & \vdots & & \vdots \\ & & & \ddots & \mathcal{V}_{4,4} & & \vdots \\ & & & & \ddots & \ddots & \vdots \\ \vdots & & & & & \ddots & \mathcal{V}_{n,n} \\ \varnothing & \cdots & \cdots & \cdots & \cdots & \cdots & \varnothing \end{pmatrix}$$

Depicted above is a SAT tensor representing $\sigma_1\ \sigma_2\ \sigma_3\ \_\ \ldots\ \_$ where shaded regions demarcate known bitvector literals $\mathcal{L}_{r,c}$ (i.e., representing established nonterminal forests) and unshaded regions correspond to bitvector variables $\mathcal{V}_{r,c}$ (i.e., representing seeded nonterminal forests to be grown). Since $\mathcal{L}_{r,c}$ are fixed, we precompute them outside the SAT solver.

3.3 Deletion, Substitution, and Insertion

Deletion, substitution and insertion can be simulated by first adding a left- and right- ε-production to each unit production:

$$\frac{\Gamma \vdash \varepsilon \in \Sigma}{\Gamma \vdash (\varepsilon^+ \to \varepsilon \mid \varepsilon^+\ \varepsilon^+) \in P}\ \varepsilon\text{-DUP}$$

$$\frac{\Gamma \vdash (A \to B) \in P}{\Gamma \vdash (A \to B\ \varepsilon^+ \mid \varepsilon^+\ B \mid B) \in P}\ \varepsilon^+\text{-INT}$$

To generate the sketch templates, we substitute two holes at each index to be replaced, $H(\sigma, i) = \sigma_{1\ldots i-1}\ \_\ \_\ \sigma_{i+1\ldots n}$, and invoke the SAT solver. Five outcomes are then possible:

$$\sigma_1 \ldots \sigma_{i-1}\ \gamma_1 \gamma_2\ \sigma_{i+1} \ldots \sigma_n, \gamma_{1,2} = \varepsilon \tag{5}$$

$$\sigma_1 \ldots \sigma_{i-1}\ \gamma_1 \gamma_2\ \sigma_{i+1} \ldots \sigma_n, \gamma_1 \neq \sigma_i, \gamma_2 = \varepsilon \tag{6}$$

$$\sigma_1 \ldots \sigma_{i-1}\ \gamma_1 \gamma_2\ \sigma_{i+1} \ldots \sigma_n, \gamma_1 = \varepsilon, \gamma_2 \neq \sigma_i \tag{7}$$

$$\sigma_1 \ldots \sigma_{i-1}\ \gamma_1 \gamma_2\ \sigma_{i+1} \ldots \sigma_n, \gamma_1 = \sigma_i, \gamma_2 \neq \varepsilon \tag{8}$$

$$\sigma_1 \ldots \sigma_{i-1}\ \gamma_1 \gamma_2\ \sigma_{i+1} \ldots \sigma_n, \gamma_1 \notin \{\varepsilon, \sigma_i\}, \gamma_2 = \sigma_i \tag{9}$$

Eq. (5) corresponds to deletion, Eqs. (6, 7) correspond to substitution, and Eqs. (8, 9) correspond to insertion. This procedure is repeated for all indices in the replacement set. The solutions returned by the SAT solver will be strictly equivalent to handling each edit operation as separate cases.

4 Error Recovery

Unlike classical parsers which need special care to recover from errors, if the input string does not parse, Tidyparse can return partial subtrees. If no solution exists, the upper triangular entries will appear as a jagged-shaped ridge whose peaks represent the roots of parsable ASTs. These provide a natural debugging environment to aid the repair process.

```
true and true ! and false or true ! true and false
```

```
Parseable subtrees (3 leaves / 2 branches):
 🌿           🌿          🌿
 └── ! [3]    └── and [4]  └── or [6]
 🌿                   🌿
 └── S [0..2]         └── S [8..11]
     ├── true [0]         ├── S [8..9]
     ├── and [1]          │   ├── ! [8]
     └── true [2]         │   └── true [9]
                          ├── and [10]
                          └── false [11]
```

These branches correspond to peaks on the upper triangular (UT) matrix ridge. As depicted in Fig. 1, we traverse the peaks by decreasing elevation to collect partial AST branches.

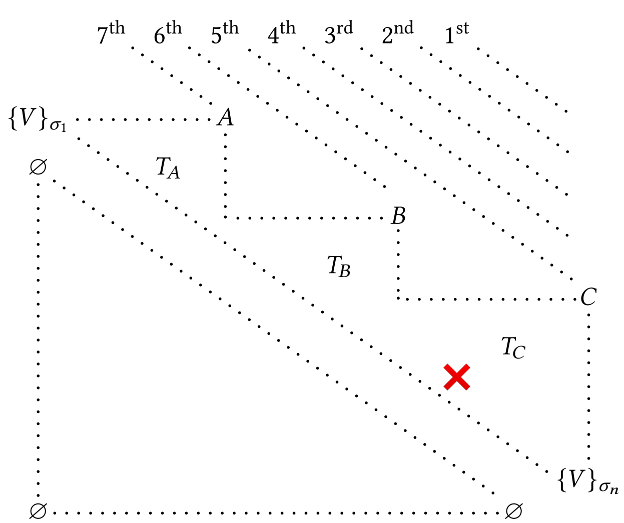


Figure 1. Peaks along the UT matrix ridge correspond to maximally parseable substrings. By recursing over upper diagonals of decreasing elevation and discarding all subtrees that fall under the shadow of another's canopy, we can recover the partial subtrees. The example depicted above contains three such branches, rooted at nonterminals C, B, A.

5 Realtime Error Correction

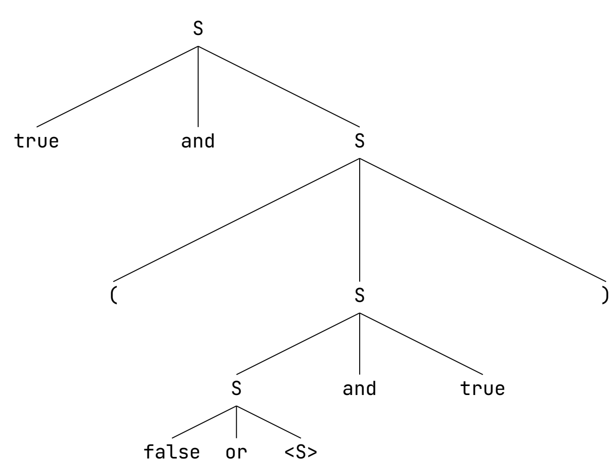
So we have a procedure $P : \mathcal{G} \times \Sigma^d \rightarrow \{\Sigma^d\}$. But where do we put the holes? For a given number of holes, k, there are roughly $\binom{n}{k}$ possible repairs. In practice the cardinality of this space can be very large. To provide real-time suggestions, we generate the repairs according to a nine-step procedure:

1. Fetch the most recent CFG and string from the editor.
2. Exclude parsable substrings from hollowing.
3. Enumerate hole configurations of increasing length.
4. Sample HCs without replacement using Eq. 4.
5. Prioritize HCs first by distance to caret location, then by Earthmover's distance to set of suspicious indices.
6. Translate HCs to sketch templates using §3.3.
7. Feed sketch templates to incremental SAT solver.
8. Decode and rerank models by Levenshtein distance.

The entire procedure is lazy and intermediate results are cached to avoid recomputation. As soon as a new repair is discovered, it is rendered to the screen. Incoming keystrokes interrupt the sequence and reset the process back to Step 1.

6 Tree Denormalization Procedure

The matrix parser produces a binary tree corresponding to the normalized grammar. To recover the original parse tree, we recursively remove synthetic nodes.



7 Example Workflow

Suppose we have the slightly more complicated grammar:

```
S -> X
X -> A | V | ( X , X ) | X X | ( X )
A -> FUN | F | L | L in X
FUN -> fun V `->` X
F -> if X then X else X
L -> let V = X | let rec V = X

V -> Vexp | ( Vexp ) | List | Vexp Vexp
Vexp -> VarName | FunName | Vexp VO Vexp | B
Vexp -> ( VarName , VarName ) | Vexp Vexp | I
List -> [] | V :: V
VarName -> a | b | c | d | e | ... | z
FunName -> foldright | map | filter
VO ->  + | - | * | / | >
VO -> = | < | `||` | &&
I -> 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9
B ->  true | false
```

7.1 Interactive Nonterminal Expansion

Tidyparse can be used to interactively build up an expression by targeting a nonterminal to expand and asking for a completion.

```
if <Vexp> X then <Vexp> else <Vexp>
```

Press Ctrl+Space and the tool will output the following suggestions, from which the users can expand:

```
if map X then <Vexp> else <Vexp>
if true X then <Vexp> else <Vexp>
if false X then <Vexp> else <Vexp>
if filter X then <Vexp> else <Vexp>
if uncurry X then <Vexp> else <Vexp>
if foldright X then <Vexp> else <Vexp>
if <Vexp> X then <Vexp> else <Vexp>
if <Vexp> <B> X then <Vexp> else <Vexp>
```

There are some more examples too.
The line between parsing and computation is blurry.

8 Shortcomings

The synthesis results are not very natural. This could be improved with a neural guided search procedure.

9 Conclusion

Tidyparse accepts a CFG and a string to parse and returns a set of candidate strings, ordered by their Levenshtein edit distance to the original string. Our method lowers the CFG and candidate string onto a matrix dynamical system using an extended version of Valiant's construction and solves for the fixpoint matrix using an incremental SAT solver. Our approach to parsing has many advantages.

- Error correction.
- Program repair.
- Program synthesis.
- Parsing with holes.
- Naturally integrates with masked language model (MLM)-based neural program repair.
- Parsing with natural error recovery.
- Helps to facilitate language learning.
- GPU acceleration.

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