

# Syntax Repair as Language Intersection

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We introduce a new technique for correcting syntax errors in arbitrary context-free languages. Our work addresses the problem of syntax error correction, which we solve by defining a finite language that provably generates every repair within a certain edit distance. To do this, we adapt the Bar-Hillel construction from formal languages, guaranteeing the language is sound and complete with respect to the programming language grammar. This technique also admits a polylogarithmic time algorithm for deciding intersection nonemptiness between CFLs and acyclic NFAs, the first of its kind in the parsing literature.

## 1 INTRODUCTION

During programming, one invariably encounters a recurring scenario in which the editor occupies an unparseable state, either due to an unfinished or malformed piece of code. Faced with this predicament, programmers must spend time to locate and repair the error before proceeding. We attempt to solve this problem automatically by generating a list of candidate repairs which contains with high probability the true repair, assuming this repair differs by no more than a few edits.

## 2 BACKGROUND

We will first give some background on Brzozowski differentiation. Let us consider the generalized regular expression (GRE) fragment containing concatenation, conjunction and disjunction:

*Definition 2.1 (Generalized Regex).* Let  $e$  be an expression defined by the grammar:

$$e ::= \emptyset \mid \varepsilon \mid \Sigma \mid e \cdot e \mid e \vee e \mid e \wedge e$$

Semantically, we can interpret these expressions as denoting regular languages:

$$\begin{array}{ll} \mathcal{L}(\emptyset) = \emptyset & \mathcal{L}(x \cdot z) = \mathcal{L}(x) \times \mathcal{L}(z)^1 \\ \mathcal{L}(\varepsilon) = \{\varepsilon\} & \mathcal{L}(x \vee z) = \mathcal{L}(x) \cup \mathcal{L}(z) \\ \mathcal{L}(a) = \{a\} & \mathcal{L}(x \wedge z) = \mathcal{L}(x) \cap \mathcal{L}(z) \end{array}$$

Brzozowski introduces the concept of differentiation, which allows us to quotient a regular language by some given prefix.

*Definition 2.2 (Brzozowski, 1964).* To compute the quotient  $\partial_a(L) = \{b \mid ab \in L\}$ , we:

$$\begin{array}{ll} \partial_a(\emptyset) = \emptyset & \delta(\emptyset) = \emptyset \\ \partial_a(\varepsilon) = \emptyset & \delta(\varepsilon) = \varepsilon \\ \partial_a(b) = \begin{cases} \varepsilon & \text{if } a = b \\ \emptyset & \text{if } a \neq b \end{cases} & \delta(a) = \emptyset \\ \partial_a(x \cdot z) = (\partial_a x) \cdot z \vee \delta(x) \cdot \partial_a z & \delta(x \cdot z) = \delta(x) \wedge \delta(z) \\ \partial_a(x \vee z) = \partial_a x \vee \partial_a z & \delta(x \vee z) = \delta(x) \vee \delta(z) \\ \partial_a(x \wedge z) = \partial_a x \wedge \partial_a z & \delta(x \wedge z) = \delta(x) \wedge \delta(z) \end{array}$$

Primarily, this gadget was designed to handle membership queries, for which purpose it has received considerable attention in recent years:

<sup>1</sup>Or  $\{a \cdot b \mid a \in \mathcal{L}(x) \wedge b \in \mathcal{L}(z)\}$  to be more precise, however we make no distinction.

THEOREM 2.3 (RECOGNITION). For any regex  $e$  and  $\sigma : \Sigma^*$ ,  $\sigma \in \mathcal{L}(e) \iff \varepsilon \in \mathcal{L}(\partial_\sigma e)$ , where:

$$\partial_\sigma(e) : E \rightarrow E = \begin{cases} e & \text{if } \sigma = \varepsilon \\ \partial_b(\partial_a e) & \text{if } \sigma = a \cdot b, a \in \Sigma, b \in \Sigma^* \end{cases}$$

It can also be used, however, to decode witnesses. We will first focus on the nonempty disjunctive fragment, and define this process in two steps:

THEOREM 2.4 (GENERATION). For any nonempty  $(\varepsilon, \wedge)$ -free regex,  $e$ , to witness  $\sigma \in \mathcal{L}(e)$ :

$$\text{follow}(e) : E \rightarrow 2^\Sigma = \begin{cases} \{e\} & \text{if } e \in \Sigma \\ \text{follow}(x) & \text{if } e = x \cdot z \\ \text{follow}(x) \cup \text{follow}(z) & \text{if } e = x \vee z \end{cases}$$

$$\text{choose}(e) : E \rightarrow \Sigma^+ = \begin{cases} e & \text{if } e \in \Sigma \\ (s \overset{\$}{\leftarrow} \text{follow}(e)) \cdot \text{choose}(\partial_s e) & \text{if } e = x \cdot z \\ \text{choose}(e' \overset{\$}{\leftarrow} \{x, z\}) & \text{if } e = x \vee z \end{cases}$$

Here, we use the  $\overset{\$}{\leftarrow}$  operator to denote probabilistic choice, however any deterministic choice function will also suffice to generate a witness. Now we are equipped to handle conjunction.

## 2.1 Language intersection

THEOREM 2.5 (BAR-HILLEL, 1961). For any context-free grammar (CFG),  $G = \langle V, \Sigma, P, S \rangle$ , and nondeterministic finite automata,  $A = \langle Q, \Sigma, \delta, I, F \rangle$ , there exists a CFG  $G_\cap = \langle V_\cap, \Sigma_\cap, P_\cap, S_\cap \rangle$  such that  $\mathcal{L}(G_\cap) = \mathcal{L}(G) \cap \mathcal{L}(A)$ .

Definition 2.6 (Salomaa, 1973). One could construct  $G_\cap$  like so,

$$\frac{q \in I \quad r \in F}{(S \rightarrow qSr) \in P_\cap} \sqrt{\quad} \frac{(w \rightarrow a) \in P \quad (q \overset{a}{\rightarrow} r) \in \delta}{(qwr \rightarrow a) \in P_\cap} \uparrow \frac{(w \rightarrow xz) \in P \quad p, q, r \in Q}{(pwr \rightarrow (pxq)(qzr)) \in P_\cap} \bowtie$$

However most synthetic productions in  $P_\cap$  will be non-generating or unreachable. This naïve method will construct a synthetic production for state pairs which are not even connected by any path, which is clearly excessive. We will instead proceed considering a simpler problem, then constructing a parse chart which efficiently computes the intersection.

## 3 METHOD

Our method is to treat finite language intersections as matrix exponentiation.

THEOREM 3.1. For every CFG,  $G$ , and every acyclic NFA (ANFA),  $A$ , there exists a decision procedure  $\varphi : \text{CFG} \rightarrow \text{ANFA} \rightarrow \mathbb{B}$  such that  $\varphi(G, A) \models [\mathcal{L}(G) \cap \mathcal{L}(A) \neq \emptyset]$  which requires  $\mathcal{O}((\log |Q|)^c)$  time using  $\mathcal{O}((|V||Q|)^k)$  parallel processors for some  $c, k < \infty$ .

PROOF. WTS there exists a path  $p \rightsquigarrow r$  in  $A$  such that  $p \in I, r \in F$  where  $p \rightsquigarrow r \vdash S$ .

There are two cases, at least one of which must hold for  $w \in V$  to parse a given  $p \rightsquigarrow r$  pair:

- (1)  $p$  steps directly to  $r$  in which case it suffices to check  $\exists a. ((p \overset{a}{\rightarrow} r) \in \delta \wedge (w \rightarrow a) \in P)$ , or,
- (2) there is some midpoint  $q \in Q$ ,  $p \rightsquigarrow q \rightsquigarrow r$  such that  $\exists x, z. ((w \rightarrow xz) \in P \wedge \overbrace{p \rightsquigarrow q}^w, \overbrace{q \rightsquigarrow r}^z)$ .

This decomposition immediately suggests a dynamic programming solution. Let  $M$  be a matrix of type  $E^{|Q| \times |Q| \times |V|}$  indexed by  $Q$ . Since we assumed  $\delta$  is acyclic, there exists a topological sort of  $\delta$  imposing a total order on  $Q$  such that  $M$  is strictly upper triangular (SUT). Initiate it thusly:

$$M_0[r, c, w] = \bigvee_{a \in \Sigma} \{a \mid (w \rightarrow a) \in P \wedge (q_r \xrightarrow{a} q_c) \in \delta\} \quad (1)$$

The algebraic operations  $\oplus, \otimes : E^{2|V|} \rightarrow E^{|V|}$  will be defined elementwise:

$$[\ell \oplus r]_w = [\ell_w \vee r_w] \quad (2)$$

$$[\ell \otimes r]_w = \bigvee_{x, z \in V} \{\ell_x \cdot r_z \mid (w \rightarrow xz) \in P\} \quad (3)$$

By slight abuse of notation<sup>2</sup>, we will redefine the matrix exponential over this domain as:

$$\exp(M) = \sum_{i=0}^{\infty} M_0^i = \sum_{i=0}^{|Q|} M_0^i \text{ (since } M \text{ is SUT.)} \quad (4)$$

To solve for the fixpoint, we can instead use exponentiation by squaring:

$$S(2n) = \begin{cases} M_0, & \text{if } n = 1, \\ S(n) + S(n)^2 & \text{otherwise.} \end{cases} \quad (5)$$

Therefor, we only need a maximum of  $\lceil \log_2 |Q| \rceil$  sequential steps to reach the fixpoint. Finally,

$$S_\cap = \bigvee_{q \in I, q' \in F} \exp(M)[q, q', S] \text{ and } \varphi = [S_\cap \neq \emptyset] \quad (6)$$

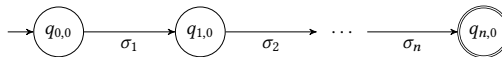
To decode a witness in case of non-emptiness, we simply choose  $(S_\cap)$ .  $\square$

## 4 EXAMPLES

In this section, we will consider three examples of intersections with finite languages. First, parsing can be viewed as a special case of language intersection with an automaton accepting a single word. Second, completion can be seen as a case of intersection with terminal wildcards in known locations. Finally, we will consider syntax repair, in which case we will intersect a language representing all possible edits to determine the location(s) and fill them with appropriate terminals.

### 4.1 Recognition as intersection

In the case of ordinary parsing, the automaton accepts a single word, the word to be parsed:



Given a CFG,  $G' : \mathcal{G}$  in Chomsky Normal Form (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  $\emptyset$ ,  $\oplus$  be  $\cup$ , and  $\otimes$  be defined as:

$$X \otimes Z = \{ w \mid \langle x, z \rangle \in X \times Z, (w \rightarrow xz) \in P \} \quad (7)$$

<sup>2</sup>Traditionally, there is a  $\frac{1}{k!}$  factor to suppress exploding entries.

If we define  $\hat{\sigma}_r = \{w \mid (w \rightarrow \sigma_r) \in P\}$ , then construct a matrix with nonterminals on the superdiagonal representing each token,  $M_0[r+1=c](G', \sigma) = \hat{\sigma}_r$ , the fixpoint  $M_{i+1} = M_i + M_i^2$  is uniquely determined by the superdiagonal entries. The fixedpoint iteration proceeds as follows:

$$M_0 = \begin{pmatrix} \emptyset & \hat{\sigma}_1 & \emptyset & \dots & \emptyset \\ & \ddots & \ddots & \ddots & \ddots \\ & & \emptyset & \ddots & \hat{\sigma}_n \\ \emptyset & \dots & \dots & \dots & \emptyset \end{pmatrix} \Rightarrow \begin{pmatrix} \emptyset & \hat{\sigma}_1 & \Lambda & \dots & \emptyset \\ & \ddots & \ddots & \ddots & \ddots \\ & & \Lambda & \ddots & \hat{\sigma}_n \\ \emptyset & \dots & \dots & \dots & \emptyset \end{pmatrix} \Rightarrow \dots \Rightarrow M_\infty = \begin{pmatrix} \emptyset & \hat{\sigma}_1 & \Lambda & \dots & \Lambda_\sigma^* \\ & \ddots & \ddots & \ddots & \ddots \\ & & \Lambda & \ddots & \hat{\sigma}_n \\ \emptyset & \dots & \dots & \dots & \emptyset \end{pmatrix}$$

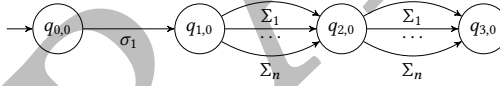
Once obtained, the proposition  $[S \in \Lambda_\sigma^*]$  decides language membership, i.e.,  $[\sigma \in \mathcal{L}(G)]$ <sup>3</sup>. So far, this procedure is essentially the textbook CYK algorithm in a linear algebraic notation [26].

## 4.2 Completion as intersection

We can also consider a more general automaton for completing a string with holes, representing missing terminals in known locations. The same procedure can be lifted to the domain of strings containing free variables, which we call the *porous completion problem*. In this case, the fixpoint is characterized by a system of language equations, whose solutions are the set of all sentences consistent with the template.

**Definition 4.1 (Porous completion).** Let  $\underline{\Sigma} = \Sigma \cup \{\_ \}$ , where  $\_$  denotes a hole. We denote  $\sqsubseteq: \Sigma^n \times \underline{\Sigma}^n$  as the relation  $\{\langle \sigma', \sigma \rangle \mid \sigma_i \in \Sigma \implies \sigma'_i = \sigma_i\}$  and the set of all inhabitants  $\{\sigma' : \Sigma^+ \mid \sigma' \sqsubseteq \sigma\}$  as  $H(\sigma)$ . Given a *porous string*,  $\sigma : \underline{\Sigma}^*$  we seek all syntactically valid inhabitants, i.e.,  $A(\sigma) = H(\sigma) \cap \ell$ .

Here the automaton takes a similar shape, but can have multiple arcs between subsequent states:



Let us consider an example with two holes,  $\sigma = 1 \_ \_$ , and the context-free grammar being  $G = \{S \rightarrow NON, O \rightarrow + \mid \times, N \rightarrow 0 \mid 1\}$ . This grammar will first be rewritten into CNF as  $G' = \{S \rightarrow NL, N \rightarrow 0 \mid 1, O \rightarrow \times \mid +, L \rightarrow ON\}$ . Using the powerset algebra we just defined, the matrix fixpoint  $M' = M + M^2$  can be computed as follows, shown in the leftmost column below:

	$2^V$	$\mathbb{Z}_2^{ V }$	$\mathbb{Z}_2^{ V } \rightarrow \mathbb{Z}_2^{ V }$
$M_0$	$\begin{pmatrix} \{N\} \\ \{N, O\} \\ \{N, O\} \end{pmatrix}$	$\begin{pmatrix} \blacksquare \blacksquare \blacksquare \\ & \blacksquare \blacksquare \blacksquare \\ & & \blacksquare \blacksquare \blacksquare \end{pmatrix}$	$\begin{pmatrix} V_{0,1} \\ V_{1,2} \\ V_{2,3} \end{pmatrix}$
$M_1$	$\begin{pmatrix} \{N\} & \emptyset \\ \{N, O\} & \{L\} \\ & \{N, O\} \end{pmatrix}$	$\begin{pmatrix} \blacksquare \blacksquare \blacksquare & \square \square \square \square \\ & \square \blacksquare \blacksquare & \blacksquare \square \square \square \\ & & \square \blacksquare \blacksquare \end{pmatrix}$	$\begin{pmatrix} V_{0,1} & V_{0,2} \\ V_{1,2} & V_{1,3} \\ & V_{2,3} \end{pmatrix}$
$M_2 = M_\infty$	$\begin{pmatrix} \{N\} & \emptyset & \{S\} \\ & \{N, O\} & \{L\} \\ & & \{N, O\} \end{pmatrix}$	$\begin{pmatrix} \blacksquare \blacksquare \blacksquare & \square \square \square \square & \square \square \blacksquare \\ & \square \blacksquare \blacksquare & \blacksquare \square \square \square \\ & & \square \blacksquare \blacksquare \end{pmatrix}$	$\begin{pmatrix} V_{0,1} & V_{0,2} & V_{0,3} \\ & V_{1,2} & V_{1,3} \\ & & V_{2,3} \end{pmatrix}$

<sup>3</sup>Hereinafter, we use Iverson brackets to denote the indicator function of a predicate with free variables, i.e.,  $[P] \Leftrightarrow \mathbb{1}(P)$ .

The same procedure can be translated, without loss of generality, into the bit domain ( $\mathbb{Z}_2^{|V|}$ ) using a lexicographic nonterminal ordering, however  $M_\infty$  in both  $2^V$  and  $\mathbb{Z}_2^{|V|}$  represents a decision procedure, i.e.,  $[S \in V_{0,3}] \Leftrightarrow [V_{0,3,3} = \blacksquare] \Leftrightarrow [A(\sigma) \neq \emptyset]$ . Since  $V_{0,3} = \{S\}$ , we know there exists at least one solution  $\sigma' \in A(\sigma)$ , but  $M_\infty$  does not explicitly reveal its identity.

To extract the inhabitants, we can translate the bitwise procedure into an equation with free variables. Here, we can encode the idempotency constraint directly as  $M = M^2$ . We first define  $X \boxtimes Z = [X_2 \wedge Z_1, \perp, \perp, X_1 \wedge Z_0]$  and  $X \boxplus Z = [X_i \vee Z_i]_{i \in [0, |V|]}$ , mirroring  $\oplus, \otimes$  from the powerset domain, now over bitvectors. Since the unit nonterminals  $O, N$  can only occur on the superdiagonal, they may be safely ignored by  $\boxtimes$ . To solve for  $M_\infty$ , we proceed by first computing  $V_{0,2}, V_{1,3}$ :

$$\begin{aligned} V_{0,2} &= V_{0,j} \cdot V_{j,2} = V_{0,1} \boxtimes V_{1,2} & V_{1,3} &= V_{1,j} \cdot V_{j,3} = V_{1,2} \boxtimes V_{2,3} \\ &= [L \in V_{0,2}, \perp, \perp, S \in V_{0,2}] & &= [L \in V_{1,3}, \perp, \perp, S \in V_{1,3}] \\ &= [O \in V_{0,1} \wedge N \in V_{1,2}, \perp, \perp, N \in V_{0,1} \wedge L \in V_{1,2}] & &= [O \in V_{1,2} \wedge N \in V_{2,3}, \perp, \perp, N \in V_{1,2} \wedge L \in V_{2,3}] \\ &= [V_{0,1,2} \wedge V_{1,2,1}, \perp, \perp, V_{0,1,1} \wedge V_{1,2,0}] & &= [V_{1,2,2} \wedge V_{2,3,1}, \perp, \perp, V_{1,2,1} \wedge V_{2,3,0}] \end{aligned}$$

Now we solve for the corner entry  $V_{0,3}$  by dotting the first row and last column, which yields:

$$\begin{aligned} V_{0,3} &= V_{0,j} \cdot V_{j,3} = (V_{0,1} \boxtimes V_{1,3}) \boxplus (V_{0,2} \boxtimes V_{2,3}) \\ &= [V_{0,1,2} \wedge V_{1,3,1} \vee V_{0,2,2} \wedge V_{2,3,1}, \perp, \perp, V_{0,1,1} \wedge V_{1,3,0} \vee V_{0,2,1} \wedge V_{2,3,0}] \end{aligned}$$

Since we only care about  $V_{0,3,3} \Leftrightarrow [S \in V_{0,3}]$ , we can ignore the first three entries and solve for:

$$\begin{aligned} V_{0,3,3} &= V_{0,1,1} \wedge V_{1,3,0} \vee V_{0,2,1} \wedge V_{2,3,0} \\ &= V_{0,1,1} \wedge (V_{1,2,2} \wedge V_{2,3,1}) \vee V_{0,2,1} \wedge \perp \\ &= V_{0,1,1} \wedge V_{1,2,2} \wedge V_{2,3,1} \\ &= [N \in V_{0,1}] \wedge [O \in V_{1,2}] \wedge [N \in V_{2,3}] \end{aligned}$$

Now we know that  $\sigma = 1 \underline{O} \underline{N}$  is a valid solution, and we can take the product  $\{1\} \times \hat{\sigma}_2^{-1}(O) \times \hat{\sigma}_3^{-1}(N)$  to recover the inhabitants, yielding  $A = \{1 + 0, 1 + 1, 1 \times 0, 1 \times 1\}$ . In this case, since  $G$  is unambiguous, there is only one parse tree satisfying  $V_{0,|\sigma|,3}$ , but in general, there can be multiple valid parse trees.

### 4.3 Repair as intersection

Finally, we are ready to consider the general case of syntax repair, in which case the edit locations are not localized but can occur anywhere in the string. In this case, we construct a lattice of all possible edit paths up to a fixed distance. This structure is called a Levenshtein automaton.

As the original construction defined by Schultz and Mihov [45] contains cycles and  $\varepsilon$ -transitions, we propose a variant which is  $\varepsilon$ -free and acyclic. Furthermore, we adopt a nominal form which supports infinite alphabets and considerably simplifies the language intersection to follow. Illustrated in Fig. 1 is an example of a small Levenshtein automaton recognizing  $L(\sigma : \Sigma^5, 3)$ . Unlabeled arcs accept any terminal from the alphabet,  $\Sigma$ . Equivalently, this transition system can be viewed as a kind of proof system within an unlabeled lattice. The following construction is equivalent to Schultz and Mihov's

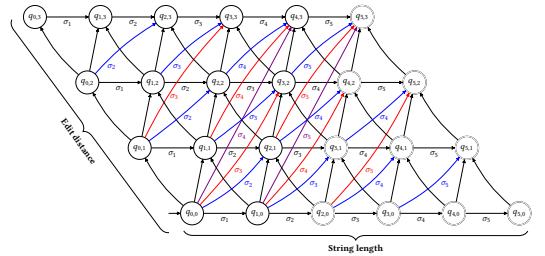


Fig. 1. NFA recognizing Levenshtein  $L(\sigma : \Sigma^5, 3)$ .



THEOREM 5.2 (ENUMERATION). To enumerate, invoke  $\bigcup_{i=0}^{|R|} \{enum(R, i)\}$ :

$$enum(e, n) : E \times \mathbb{N} \rightarrow \Sigma^* = \begin{cases} e & \text{if } R \in \Sigma \\ enum(x, \lfloor \frac{n}{|z|} \rfloor) \cdot enum(z, n \bmod |z|) & \text{if } e = x \cdot z \\ enum((x, z)_{\min(1, \lfloor \frac{n}{|x|} \rfloor)}, n - |x| \min(1, \lfloor \frac{n}{|x|} \rfloor)) & \text{if } e = x \vee z \end{cases}$$

## 5.2 Mode collapse

Ordinarily, we would use top-down PCFG sampling, however in the case of non-recursive CFGs, this method is highly degenerate, exhibiting poor sample diversity. Consider an illustrative pathological case for top-down ancestral (TDA) sampling:

$$\begin{aligned} S &\rightarrow AB \ (0.9999) & S &\rightarrow CC \ (0.0001) \\ A &\rightarrow a \ (1) & B &\rightarrow b \ (1) & C &\rightarrow a \left(\frac{1}{26}\right) \mid \dots \mid z \left(\frac{1}{26}\right) \end{aligned}$$

TDA sampling will almost always generate the string  $ab$ , but most of the language is concealed in the hidden branch,  $S \rightarrow CC$ . Although contrived example, it illustrates precisely why TDA sampling is unviable: we want a sampler that matches the true distribution over the finite CFL, not the PCFG's local approximation thereof.

## 5.3 Ambiguity

Another approach would be to sample trees and rerank them by their PCFG score. More pernicious is the issue of ambiguity. Since the CFG can be ambiguous, this causes certain repairs to be overrepresented, resulting in a subtle bias. Consider for example,

LEMMA 5.3. If the FSA,  $\alpha$ , is ambiguous, then the intersection grammar,  $G_{\cap}$ , can be ambiguous.

PROOF. Let  $\ell$  be the language defined by  $G = \{S \rightarrow LR, L \rightarrow (, R \rightarrow )\}$ , where  $\alpha = L(\sigma, 2)$ , the broken string  $\sigma$  is  $) ($ , and  $\mathcal{L}(G_{\cap}) = \ell \cap \mathcal{L}(\alpha)$ . Then,  $\mathcal{L}(G_{\cap})$  contains the following two identical repairs:  $) ($  with the parse  $S \rightarrow q_{00}Lq_{21} \ q_{21}Rq_{22}$ , and  $) ($  with the parse  $S \rightarrow q_{00}Lq_{11} \ q_{11}Rq_{22}$ .  $\square$

We would like the underlying sample space to be a proper set, *not* a multiset.



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