

Parse this!

Summoning Context-Sensitive Inputs with GOBLIN

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Problem Introduction

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- Complex input formats are difficult for testing, especially **automated testing**
- We will discuss techniques for **automated input generation** of software with complex input formats
- Given an input specification, how to generate inputs?

Roadmap

1. Existing approaches to input generation
2. Syntax and language features
3. Semantics
4. GOBLIN workflow
 - Well-formedness checks
 - Derived fields
 - Main search algorithm
5. Formal guarantees
6. Evaluation
7. Discussion and future work

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Wishlist

An input generation approach that gives...

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**Refine CFG-based approaches to be more expressive,
while maintaining their generality**

Context-free input generation

First, a CFG-based input generation example: XML!

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```
1 <xml-tree> ::= <openclose-tag> |  
2           <open-tag> <inner-tree> <close-tag>  
3  
4 <inner-tree> ::= <TEXT> | <xml-tree>  
5               | <inner-tree> <inner-tree>  
6  
7 <open-tag>   ::= '<' <id> '>' | '<' <id> ' ' <attribute> '>'  
8 <close-tag>  ::= '</' <id> '>'  
9  
10 <openclose-tag> := '<' <id> '/>'  
11                | '<' <id> ' ' <attribute> '/>'  
12  
13 <attribute> ::= <id> '=' <TEXT> > '"'  
14              | <attribute> ' ' <attribute>  
15  
16 <id> ::= <ID-START-CHAR> <ID-CHAR>*
```


Context-free input generation

Termination? (Mostly) well-formed inputs?

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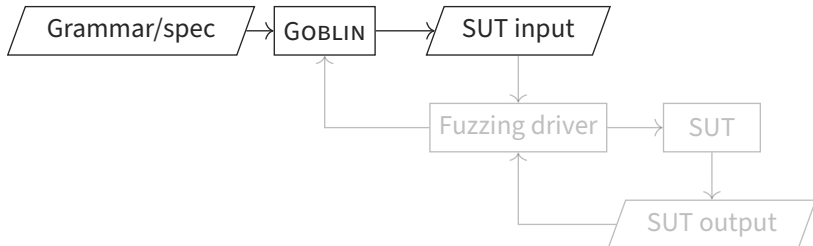
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```

Input generation vs fuzzing

GOBLIN is an **input generator**, but not a (complete) **fuzzer**

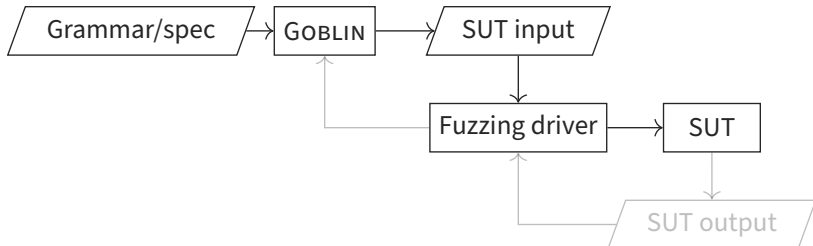
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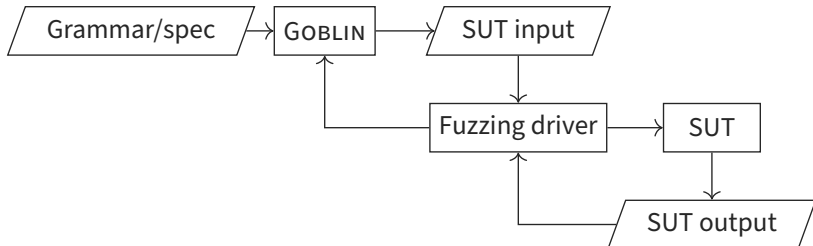
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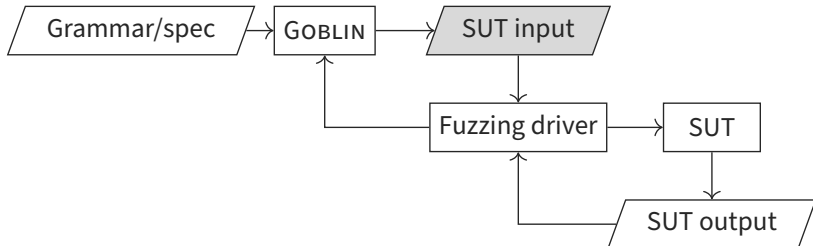
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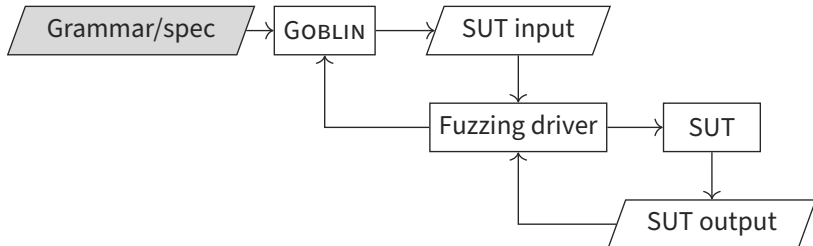
Input generation vs fuzzing

Most tools perform mutations at the **byte level**



Input generation vs fuzzing

Some tools perform **structure-aware mutations** (ATFuzz, SAECCRED)



Structure-aware mutations

How to perform context-sensitive, structure-aware mutations?

Structure-aware mutations

How to perform **context-sensitive, structure-aware** mutations?

Crossover mutation swapping `GROUP_ID` and `RG_LIST`

```
1 COMMIT ::= SEQ GROUP_ID SCALAR
2   { GROUP_ID is equal to 13 and SEQ is greater than 4 }
3 RG_CONT ::= RG_LENGTH RG_TY RG_LIST
4   { RG_LENGTH is the length of RG_LIST }
5 ...
6 ~
7 COMMIT ::= SEQ RG_LIST SCALAR
8   { SEQ is greater than 4 }
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Structure-aware mutations

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```

Prior work cannot tie **global constraints to mutations**

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ISLa

- Global constraints make structure-aware mutations less precise
- Only natively supports string constraints
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Fandango

- Uses **genetic algorithms** with built-in fitness functions
- Constraints may be **non-monotonic** (no monotonically decreasing notion of distance for constraint satisfaction)
- Times out for simple examples (equality, set membership)

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GOBLIN by example: Language features

GOBLIN's **minimalist** design philosophy positions it as an **intermediate language** (compile target), not a **user-facing language** (future work)

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```
1 <PACKET> ::= <TYPE> <AUX> <PAYLOAD>;  
2  
3  
4  
5 <PAYLOAD> ::= <F1> <F2> <BYTES>;  
6  
7 <BYTES> ::= <BYTE> <BYTES> | <BYTE> | <OPT>;  
8  
9  
10  
11
```

GOBLIN by example: Language features

Use **symbolic terminals** (in teal) with **type annotations** rather than concrete terminals. Capture **abstract syntax**, not **concrete syntax**

```
1 <PACKET> ::= <TYPE> <AUX> <PAYLOAD>;
2
3
4
5 <PAYLOAD> ::= <F1> <F2> <BYTES>;
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7 <BYTES> ::= <BYTE> <BYTES> | <BYTE> | <OPT>;
8 <TYPE> :: BitVec(8);
9 <BYTE> :: BitVec(8);
10 <AUX> :: BitVec(8);
11 <F1> :: BitVec(8); <F2> :: BitVec(8); <OPT> :: BitVec(4);
```

GOBLIN by example: Language features

Constrain symbolic terminals with **refinement types**

```
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5 <PAYLOAD> ::= <F1> <F2> <BYTES>;
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7 <BYTES> ::= <BYTE> <BYTES> | <BYTE> | <OPT>;
8 <TYPE> :: BitVec(8) { <TYPE> = 0x01 or <TYPE> = 0x02; };
9 <BYTE> :: BitVec(8) { <BYTE> bvult 0x88; };
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GOBLIN by example: Language features

Attach **semantic constraints** to production rules

Support types/functions/predicates with **SMT-LIB** analogues

```
1 <PACKET> ::= <TYPE> <AUX> <PAYLOAD>
2 { <AUX> <- <PAYLOAD>.<F1> bvmul <PAYLOAD>.<F2>;
3 <TYPE> = 0x01 => (<PAYLOAD>.<BYTES>.<BYTE> bvugt 0x20
4 and <PAYLOAD>.<BYTES>.<BYTE> bvult 0x7E); };
5 <PAYLOAD> ::= <F1> <F2> <BYTES>
6 { <BYTES>.<OPT> bvugt 0x0; };
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Reference child nonterminals with dot notation

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GOBLIN by example: Language features

Dot notation is **partial** and **implicitly universally quantified**

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Many constraints are not amenable to automated constraint solving with an SMT engine

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Derived fields with <- denote nonterminals that are directly computable, enforced syntactically
Cryptographic hashes, checksums, or any computable function

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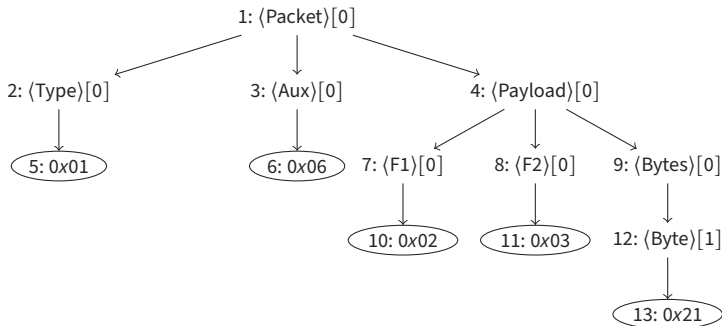
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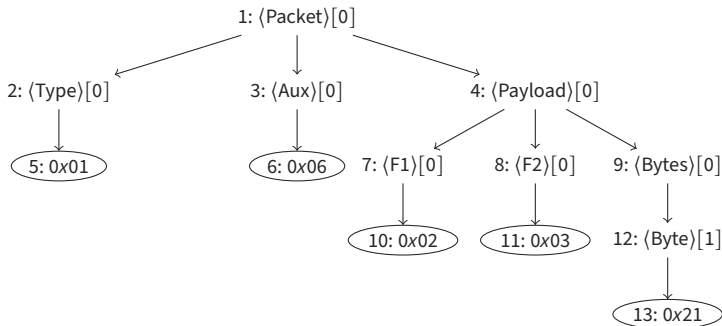
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Not a string 0x0106020321

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- AST semantics position GOBLIN as a generator of constrained **algebraic datatype** (ADT) terms

The ADT view allows GOBLIN to natively support constraints over arbitrary SMT theories

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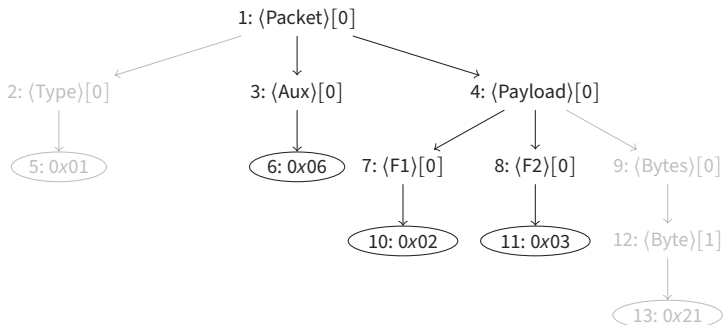
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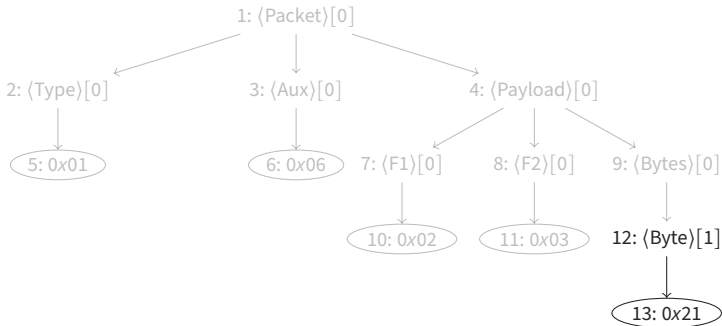
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How does GOBLIN find t such that $t \in \mathcal{L}_{\text{AST}}(G)$?

General workflow:

1. Context-free wellformedness and other syntactic checks
2. Type checking
3. Desugar refinement types
4. Disambiguate constraints
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```
1 <SAE_PACKET> ::= <COMMIT> | <CONFIRM>;
2 <COMMIT> ::= <FIELD> <RG_ID_LIST>;
3 <RG_ID_LIST> ::= <RG_ID> <RG_ID_LIST>;
4 <CONFIRM> ::= <FIELD1> <FIELD2>;
5 ...
```

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1. Disallow **cyclic dependencies** (e.g. $\langle A \rangle \leftarrow T[\langle B \rangle], \langle B \rangle \leftarrow T[\langle A \rangle]$)
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 - Two stages of computation
 - E.g., $\langle D \rangle > 0$ where $\langle D \rangle$ is derived

Abstract derived fields

We remove derived fields from G before the main search; compute them after constraint solving

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```
1 <PACKET> ::= <TYPE> <AUX> <PAYLOAD>
2   { <AUX> <- <PAYLOAD>.<F1> bvmul <PAYLOAD>.<F2>;
3   ...
```



```
1 <PACKET> ::= <TYPE> dep_sym_leaf <PAYLOAD>
2   { ...
```

Search Algorithm: Main Concepts

Start with context-free case

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A **derivation tree** is an AST that may be **open** (or **closed**)

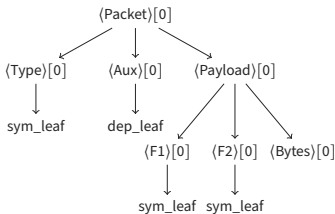
1. Build candidate *dt* via random walk until closed (as in XML)
2. Then instantiate with concrete values

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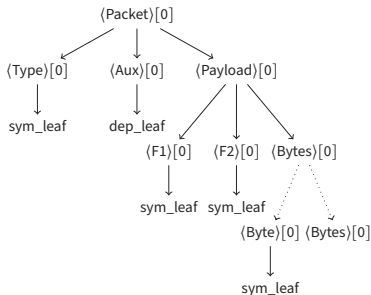
A **derivation tree** is an AST that may be **open** (or **closed**)

1. Build candidate **dt** via random walk until closed (as in XML)
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dt_1

\sim

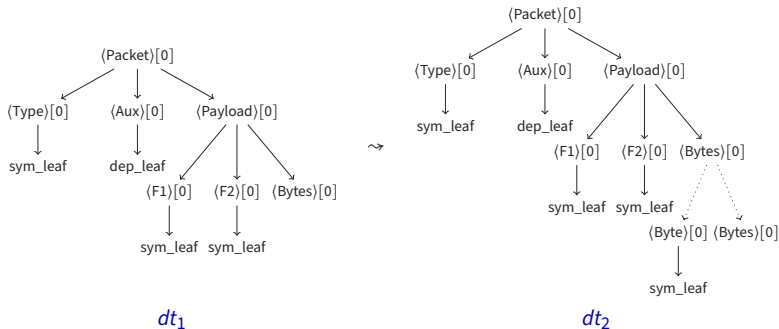


dt_2

Search Algorithm: Main Concepts

Choosing an expansion is called a **decision**

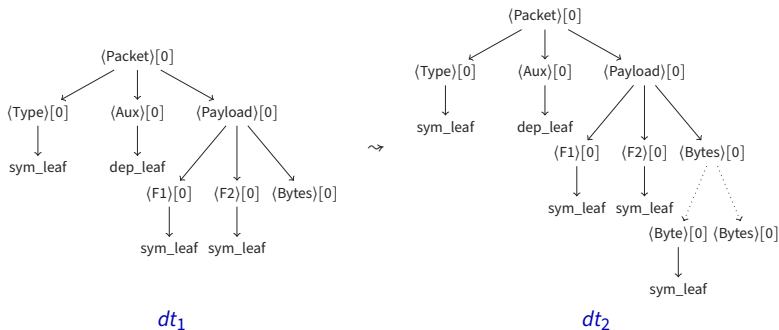
Decisions are recorded in a **decision stack** $ds = [dt_1, dt_2]$



Search Algorithm: Main Concepts

Some “decisions” are **forced** (see solid arrows): symbolic terminals and nonterminals with exactly one production rule option

These are called **normalization steps** and are not stored in *ds*



Search Algorithm: Main Concepts

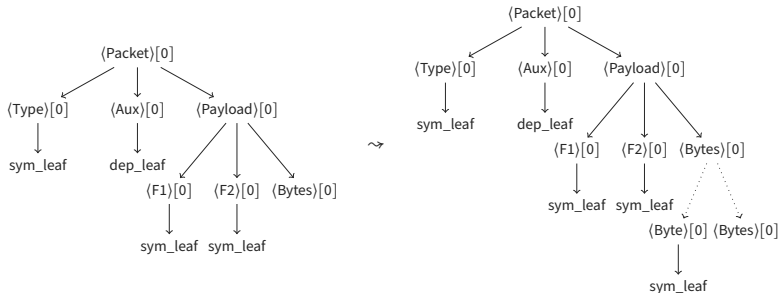
Termination is not guaranteed

Pick a **depth limit** L and associate a **search depth** with each dt

Backtrack once L is exceeded by popping ds

Record visited expansions and do not revisit

Restart and increment L if backtracking and $ds = []$



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- `(push 1)`: push an assertion level

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- `(get-model)`: retrieve a concrete model

Search Algorithm: Main Concepts

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2. At each decision, `assert` all constraints associated with the expanded `dt` node and call `check-sat`
3. Backtrack and pop an assertion level if `check-sat` yields **UNSAT**
4. Do not commit to concrete values; call `get-model` once `dt` is closed; then instantiate

Search Algorithm: Main concepts

There are wrinkles...

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1. Constraints must be **disambiguated** and **universalized**

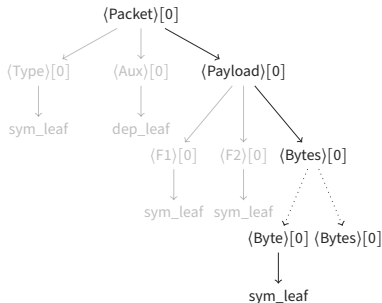
Search Algorithm: Main concepts

There are wrinkles...

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```
1 <PACKET> ::= <TYPE> <AUX> <PAYLOAD> { ... };  
2 <PAYLOAD> ::= <F1> <F2> <BYTES>  
3 { <BYTES>.<OPT> bvugt 0x0; };  
4 <BYTES> ::= <BYTE> <BYTES> | <BYTE> | <OPT>; ...
```

packet0_payload0_bytes0_opt0 >_{bv} 0x0



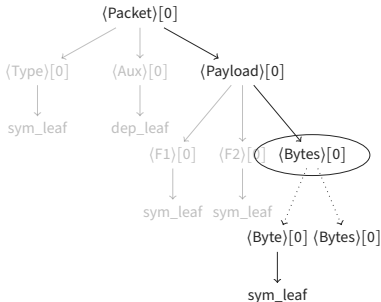
Search Algorithm: Main concepts

There are wrinkles...

2. This constraint is not **applicable**!

- Can it be applicable after a future decision?
- Extra constraint set **C** to store inapplicable constraints
- Remove from **C** when backtracking

`packet0_payload0_bytes0_opt0 >bv 0x0`



1. Existing approaches to input generation
2. Syntax and language features
3. Semantics
4. GOBLIN workflow
 - Well-formedness checks
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5. **Formal guarantees**
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We prove the calculus satisfies **solution soundness**, **refutation soundness**, and **solution completeness**

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Case study 1, 2, 3: Compare directly with prior work, ISLa

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- XML, ScriptSize C, and CSV input generation
- Matching tags, definition before use, and column count
- Measure **efficiency** in inputs generated per minute and **diversity** in **k-path coverage** for $k = 3$ (percentage of paths of length 3 traversed through the grammar)
- Outperform prior work by **~10 – 100%** in all metrics, save for efficiency of CSV inputs

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- 36x improvement in efficiency
- Able to produce outputs for more than twice the number of grammars ($\sim 24,000$ / $\sim 97,000$ up to $\sim 49,000$ / $\sim 97,000$)

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- Divide and conquer/parallel approaches
- CDCL-style backjumping

Thanks! Questions?

`robert-lorch@uiowa.edu`

`github.com/lorchrob/goblin`

Structural constraints

Every element of the second list is present in the first

```
1  <S> ::= <L1> <L2>
2      { <L2>.<_defs_down> = <L1>.<_defs_up>; };
3  <L1> ::= <_defs_up> <str> <L1>
4      { <_defs_up> = set.union(set.singleton(<str>),
5                                <L1>.<_defs_up>); }
6      | <_defs_up> <str>
7      { <_defs_up> = set.singleton(<str>); };
8  <L2> ::= <_defs_down> <str> <L2>
9      { set.member(<str>, <_defs_down>);
10      <L2>.<_defs_down> = <_defs_down>; }
11     | <_defs_down> <str>
12     { set.member(<str>, <_defs_down>); };
13 <str> :: String;
14 <_defs_down> :: Set(String);
15 <_defs_up> :: Set(String);
```


Prior Work

- ISLa, most similar in spirit
 - Only natively supports string constraints
 - Global constraints not amenable to **grammar mutations**
- Fandango
 - Uses **genetic algorithms** with built-in fitness functions
 - Constraints may be **non-monotonic** (no monotonically decreasing notion of distance for constraint satisfaction)
 - Times out for simple examples (equality, set membership)
 - Times out with SAECRED grammars

Related Work

- Parser generator libraries (e.g. ANTLR, yacc) handle context sensitivity but are for **parsing** rather than generation
- Attribute grammars handle context sensitivity but work focuses on **parsing** and theoretical results
- Property-based testing does not support **general context-sensitive constraints** over inputs
- SyGuS does not natively support **constraints over non-top-level nonterminals**

Grammar mutations

How to perform structure-aware mutations on context-sensitive grammars?

- **Crossover mutation** swapping `GROUP_ID` and `RG_LIST`
- **Local constraints** are easier to maintain

```
1  COMMIT ::= SEQ GROUP_ID SCALAR
2      { GROUP_ID is equal to 13 and SEQ is greater than 4 }
3  RG_CONT ::= RG_LENGTH RG_TY RG_LIST
4      { RG_LENGTH is the length of RG_LIST }
5  ...
6  ~
7  COMMIT ::= SEQ RG_LIST SCALAR
8      { SEQ is greater than 4 }
9  RG_CONT ::= RG_LENGTH RG_TY GROUP_ID
10     { GROUP_ID is equal to 13 }
11  ...
```

Semantics: Interpretation function

Interpretation function $\mathcal{I}_{tr}(t)$ outputs denotation of term t in AST tr

\mathcal{I}_{tr} also maps function and predicate symbols to their fixed interpretations

$$\mathcal{I}_{tr}(f(t_1, \dots, t_n)) = \top \text{ if some } \mathcal{I}_{tr}(t_i) = \top$$

$$\mathcal{I}_{tr}(f(t_1, \dots, t_n)) = \mathcal{I}_{tr}(f)(\mathcal{I}_{tr}(t_1), \dots, \mathcal{I}_{tr}(t_n))$$

$$l_{tr}(\langle nt \rangle[i].\langle nt_expr \rangle) = l_{tr'}(\langle nt_expr \rangle) \text{ for } tr' \text{ rooted at the only } v \in \text{get_children}(tr, \text{root}(tr)) \text{ such that } \ell(v) = \langle nt \rangle[i]$$

...

Semantics: Satisfaction relation

Satisfaction relation \models_G captures whether or not a given constraint in G is satisfied by a given AST

$\models_G \varphi$ if $\mathcal{I}_{tr}(t_i) = \top$ for some subterm t_i of φ ; otherwise,

$\models_G p(t_1, \dots, t_n)$ if $(\mathcal{I}_{tr}(t_1), \dots, \mathcal{I}_{tr}(t_n)) \in \mathcal{I}_{tr}(p)$

$\models_G \neg\varphi$ if $\not\models_G \varphi$

$tr \models_G \varphi_1 \wedge \varphi_2$ if $tr \models_G \varphi_1$ and $tr \models_G \varphi_2$

$tr \models_G \varphi_1 \vee \varphi_2$ if $tr \models_G \varphi_1$ or $tr \models_G \varphi_2$

$tr \models_G \varphi_1 \Rightarrow \varphi_2$ if $tr \not\models_G \varphi_1$ or $tr \models_G \varphi_2$

Semantics: Denotation of G

Semantics of a GOBLIN input G is the set of syntactically valid ASTs which satisfy all the constraints

$$\llbracket G \rrbracket = \{t \mid t \in \mathcal{L}_{\text{AST}}(G) \wedge \forall (\text{nt}, _, \text{constraints}) \in R. \\ \forall s \in \text{get_subtrees}(t, \text{nt}). \forall \varphi \in \text{constraints}. s \models_{\mathcal{G}} \text{resolve}(\varphi)\}$$

Calculus

Can conceptualize as **guarded rewrite rules** on global state

Example rule expands a symbolic terminal

$$\text{NORMALIZE}_{\text{TA}} \frac{v \in \text{open_leaves}(DT) \quad \text{depth}(DT) \leq L \quad \ell(v), \tau \in \Gamma}{DT' \leftarrow \text{expand}_G(DT, v, [])}$$

Search algorithm pseudocode

```
1: initializeGlobalState()
2: while  $\neg$ allLeavesClosed(dt) do
3:   if there is more than one unvisited expansion then
4:     DECIDE
5:   else
6:     PROPAGATE
7:   while  $\neg$ is_normalized(dt) do
8:     NORMALIZEPR (if applicable)
9:     NORMALIZETA (if applicable)
10:  if current search depth d > depth limit L then
11:    if assertionLevel = 1 then
12:      RESTARTDEPTH
13:    else
14:      BACKTRACKDEPTH
15:  else
16:    for all c  $\in$  constraint set C do
17:      ASSERT if c is applicable
18:    if smt_check_sat() = UNSAT then
19:      if assertionLevel = 1  $\wedge$   $\neg$ bd? then
20:        FAIL
21:      else if assertionLevel = 1 then
22:        RESTARTUNSAT
23:      else
24:        BACKTRACKUNSAT
```