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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  - Mutations still blind to specification constraints

Wishlist

An input generation approach that gives...

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1. Generality of CFG-based approaches

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

Context-free input generation

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```
<xml-tree> ::= <openclose-tag> |
               <open-tag> <inner-tree> <close-tag>

<inner-tree> ::= <TEXT> | <xml-tree>
               | <inner-tree> <inner-tree>

<open-tag>  ::= ‘<’  <id> ‘>’ | ‘<’ <id> ‘ ’ <attribute> ‘>’
<close-tag> ::= ‘</’ <id> ‘>’

<openclose-tag> := ‘<’ <id> ‘/>’
                 | ‘<’ <id> ‘ ’ <attribute> ‘/>’

<attribute> ::= <id> ‘="’ <TEXT > ‘"’
              | <attribute> ‘ ’ <attribute>

<id> ::= <ID-START-CHAR> <ID-CHAR>*
```

Context-free input generation

Termination? (Mostly) well-formed inputs?

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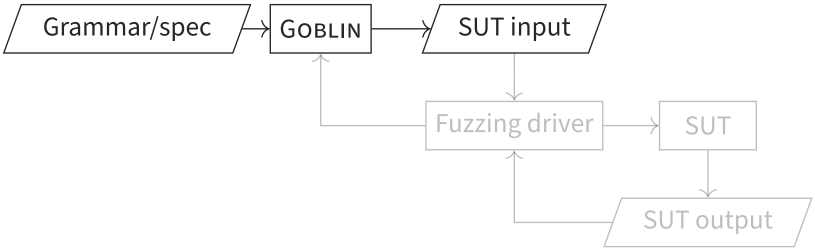

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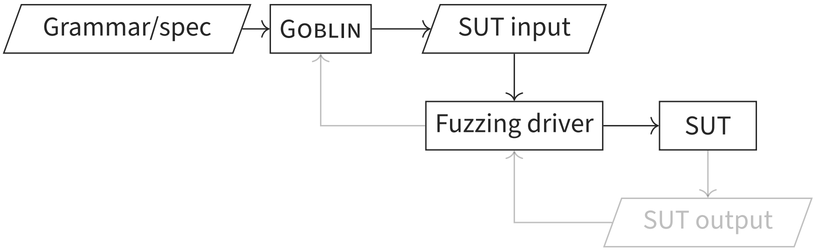

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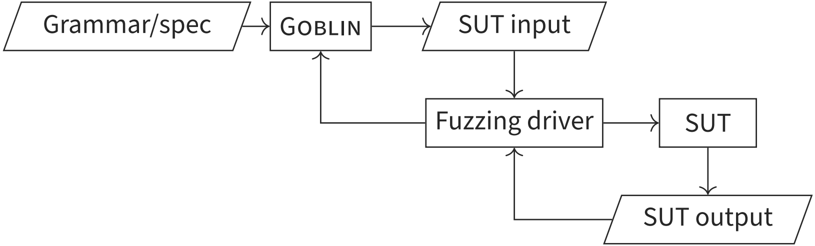
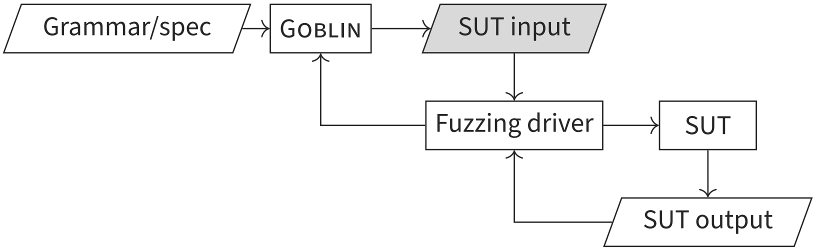


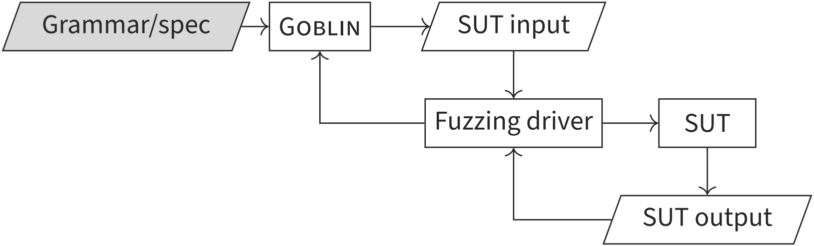
Input generation vs fuzzing

Most tools perform mutations at the byte level



Input generation vs fuzzing

Some tools perform structure-aware mutations (ATFuzz, SAECRED)



Structure-aware mutations

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

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Crossover mutation swapping `GROUP_ID` and `RG_LIST`

```
COMMIT ::= SEQ GROUP_ID SCALAR
  { GROUP_ID is equal to 13  and  SEQ is greater than 4 }
RG_CONT ::= RG_LENGTH RG_TY RG_LIST
  { RG_LENGTH is the length of RG_LIST }
...
⇝
COMMIT ::= SEQ RG_LIST SCALAR
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Prior work cannot tie global constraints to mutations

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- 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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```
<PACKET> ::= <TYPE> <AUX> <PAYLOAD>;



<PAYLOAD> ::= <F1> <F2> <BYTES>;

<BYTES> ::= <BYTE> <BYTES> | <BYTE> | <OPT>;




```

Goblin by example: Language features

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

```
<PACKET> ::= <TYPE> <AUX> <PAYLOAD>;



<PAYLOAD> ::= <F1> <F2> <BYTES>;

<BYTES> ::= <BYTE> <BYTES> | <BYTE> | <OPT>;
<TYPE> :: BitVec(8);
<BYTE> :: BitVec(8);
<AUX> :: BitVec(8);
<F1> :: BitVec(8); <F2> :: BitVec(8); <OPT> :: BitVec(4);
```

Goblin by example: Language features

Constrain symbolic terminals with refinement types

```
<PACKET> ::= <TYPE> <AUX> <PAYLOAD>;



<PAYLOAD> ::= <F1> <F2> <BYTES>;

<BYTES> ::= <BYTE> <BYTES> | <BYTE> | <OPT>;
<TYPE> :: BitVec(8) { <TYPE> = 0x01 or <TYPE> = 0x02; };
<BYTE> :: BitVec(8) { <BYTE> bvult 0x88;};
<AUX> :: BitVec(8);
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GOBLIN by example: Language features

Attach semantic constraints to production rules

Support types/functions/predicates with SMT-LIB analogues

```
<PACKET> ::= <TYPE> <AUX> <PAYLOAD>
  { <AUX> <- <PAYLOAD>.<F1> bvmul <PAYLOAD>.<F2>;
    <TYPE> = 0x01 => (<PAYLOAD>.<BYTES>.<BYTE> bvugt 0x20
                and <PAYLOAD>.<BYTES>.<BYTE> bvult 0x7E); };
<PAYLOAD> ::= <F1> <F2> <BYTES>
 { <BYTES>.<OPT> bvugt 0x0; };
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Goblin by example: Language features

Reference child nonterminals with dot notation

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Dot notation is partial and implicitly universally quantified

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Derived fields with `<-` denote nonterminals that are directly computable, enforced syntactically

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Cryptographic hashes, checksums, or any computable function

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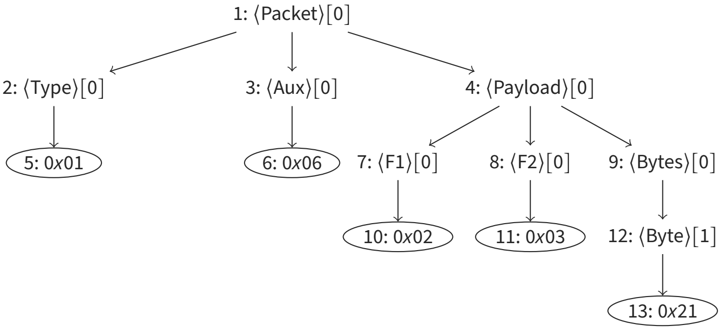

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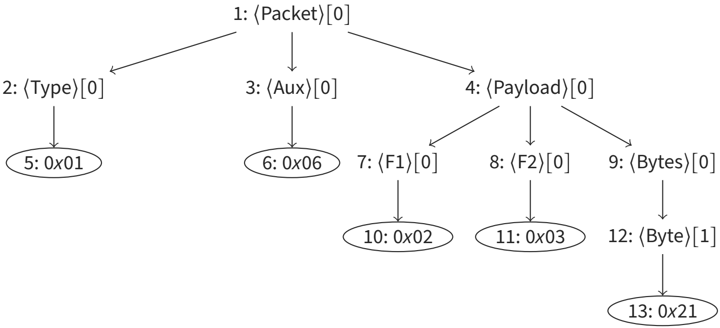

Not a string `0x0106020321`

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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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3. t satisfies the constraints at every production rule application

$\}$

Semantics: Constraint Satisfaction

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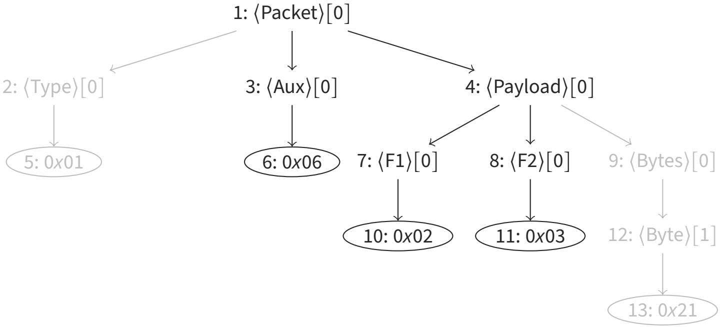

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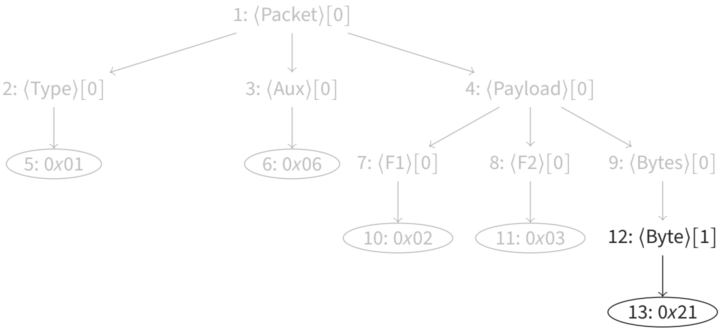

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2. Type checking
3. Desugar refinement types
4. Disambiguate constraints
5. Abstract derived fields
6. Main search algorithm
7. Compute derived fields
8. Serialize

Context-Free Wellformedness

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```
<SAE_PACKET> ::= <COMMIT> | <CONFIRM>;
<COMMIT> ::= <FIELD> <RG_ID_LIST>;
<RG_ID_LIST> ::= <RG_ID> <RG_ID_LIST>;
<CONFIRM> ::= <FIELD1> <FIELD2>;
...
```

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1. Disallow cyclic dependencies (e.g. $\langle A \rangle \leftarrow T[\langle B \rangle], \langle B \rangle \leftarrow T[\langle A \rangle]$)
2. Disallow derived fields in semantic constraints
   - 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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```
<PACKET> ::= <TYPE> <AUX> <PAYLOAD>
  { <AUX> <- <PAYLOAD>.<F1> bvmul <PAYLOAD>.<F2>;
...
```

$\rightsquigarrow$

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

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)

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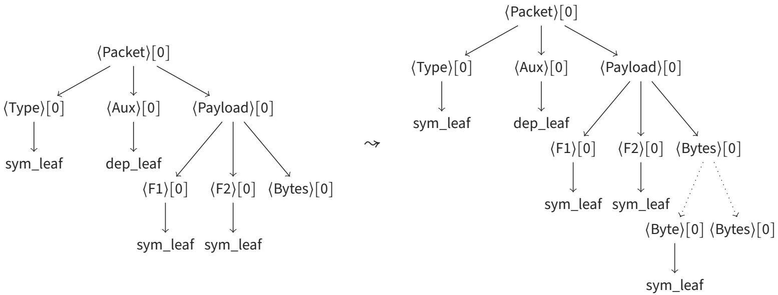


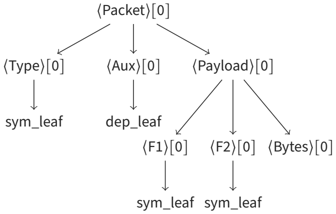
dt_1 dt_2

Search Algorithm: Main Concepts

Choosing an expansion is called a decision

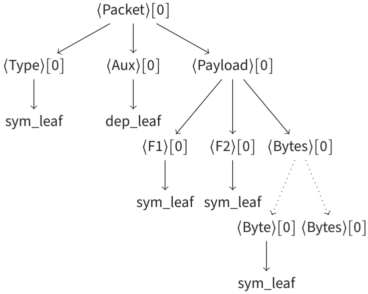
Decisions are recorded in a decision stack $ds = [dt_1, dt_2]$

Version control helps you undo mistakes!



dt_1

$\rightsquigarrow$

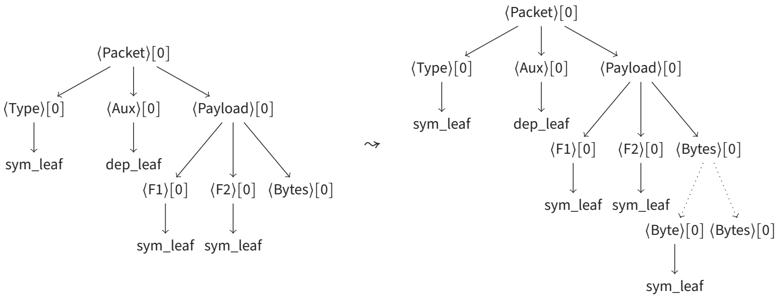


dt_2

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*



dt_1 dt_2

Search Algorithm: Main Concepts

Termination is not guaranteed…

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Termination is not guaranteed...

Idea: Bound search depth with IDS

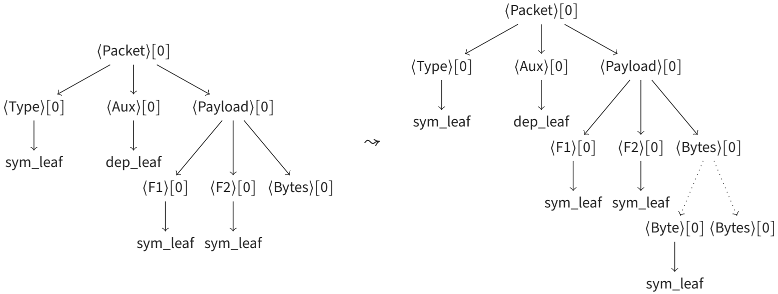
Search Algorithm: Main Concepts

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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- `(assert c)`: assert a constraint
- `(push 1)`: push an assertion level
- `(pop 1)`: undo assertions in last assertion level (backtrack)
- `(check-sat)`: check if conjunction of active assertions is SAT
- `(get-model)`: retrieve a concrete model

Search Algorithm: Main Concepts

Principles of constraint handling

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Idea: utilize incrementality of SMT engine to repair flawed candidate solutions (fear of commitment)

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2. At each decision, `assert` all constraints associated with the expanded *dt* node and call `check-sat`

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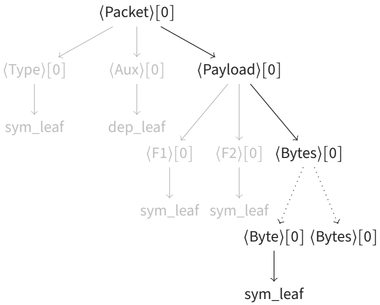
```
<PACKET> ::= <TYPE> <AUX> <PAYLOAD> { ... };
<PAYLOAD> ::= <F1> <F2> <BYTES>
 { <BYTES>.<OPT> bvugt 0x0; };
<BYTES> ::= <BYTE> <BYTES> | <BYTE> | <OPT>; ...
```

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

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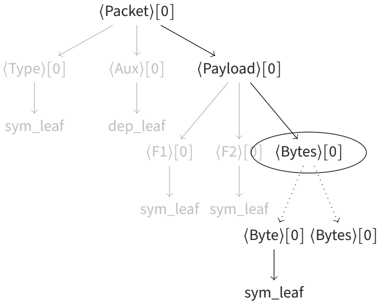

1. Existing approaches to input generation
2. Syntax and language features
3. Semantics
4. GOBLIN workflow
   - Well-formedness checks
   - Derived fields
   - Main search algorithm
5. **Formal guarantees**
6. Evaluation
7. Discussion and future work

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In the paper, we formalize the GOBLIN search procedure as a calculus comprised of 11 inference rules

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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 $\sim 10 - 100\%$ in all metrics, save for efficiency of CSV inputs

Evaluation

Case study 4

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- WiFi SAE packet input generation (SAECRED's SyGuS engine; GOBLIN predecessor)

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- WiFi SAE packet input generation (SAECRED's SyGuS engine; GOBLIN predecessor)
- Handle bit vector SMT constraints not expressible in ISLa
- 36x improvement in efficiency
- Able to produce outputs for more than twice the number of grammars (~24,000 / ~97000 up to ~49,000 / ~97,000)

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4. GOBLIN workflow
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Discussion and future work

- User-facing language
  - Synthesized and inherited attributes
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- Finite model finding and CLP engines
- 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

```
<S> ::= <L1> <L2>
      { <L2>.<_defs_down> = <L1>.<_defs_up>; };
<L1> ::= <_defs_up> <str> <L1>
       { <_defs_up> = set.union(set.singleton(<str>),
                                 <L1>.<_defs_up>); }
       | <_defs_up> <str>
       { <_defs_up> = set.singleton(<str>); };
<L2> ::= <_defs_down> <str> <L2>
       { set.member(<str>, <_defs_down>);
         <L2>.<_defs_down> = <_defs_down>; }
       | <_defs_down> <str>
       { set.member(<str>, <_defs_down>); };
<str> :: String;
<_defs_down> :: Set(String);
<_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

```
COMMIT ::= SEQ GROUP_ID SCALAR
  { GROUP_ID is equal to 13  and  SEQ is greater than 4 }
RG_CONT ::= RG_LENGTH RG_TY RG_LIST
  { RG_LENGTH is the length of RG_LIST }
...
⇝
COMMIT ::= SEQ RG_LIST SCALAR
  { SEQ is greater than 4 }
RG_CONT ::= RG_LENGTH RG_TY GROUP_ID
  { GROUP_ID is equal to 13 }
...
```

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

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

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

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

$\ldots$

Semantics: Satisfaction relation

Satisfaction relation $\models_{\mathcal{G}}$ 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,

$\models_{\mathcal{G}} p(t_1, \ldots, t_n)$ if $(\mathcal{I}_{tr}(t_1), \ldots, \mathcal{I}_{tr}(t_n)) \in \mathcal{I}_{tr}(p)$

$\models_{\mathcal{G}} \neg\varphi$ if $\not\models_{\mathcal{G}} \varphi$

$tr \models_{\mathcal{G}} \varphi_1 \wedge \varphi_2$ if $tr \models_{\mathcal{G}} \varphi_1$ and $tr \models_{\mathcal{G}} \varphi_2$

$tr \models_{\mathcal{G}} \varphi_1 \vee \varphi_2$ if $tr \models_{\mathcal{G}} \varphi_1$ or $tr \models_{\mathcal{G}} \varphi_2$

$tr \models_{\mathcal{G}} \varphi_1 \Rightarrow \varphi_2$ if $tr \not\models_{G} \varphi_1$ or $tr \models_{\mathcal{G}} \varphi_2$

Semantics: Denotation of G

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

$$\begin{aligned}[\![G]\!] = \{t \mid\ & t \in \mathcal{L}_{\mathsf{AST}}(G) \wedge \forall(\mathsf{nt}, \_, \mathsf{constraints}) \in R. \\ & \forall s \in \mathsf{get\_subtrees}(t, \mathsf{nt}).\ \forall \varphi \in \mathsf{constraints}.\ s \vDash_{\mathcal{G}} \mathsf{resolve}(\varphi)\}\end{aligned}$$

Calculus

Can conceptualize as guarded rewrite rules on global state

Example rule expands a symbolic terminal

$$\textsc{NormalizeTA}\ \frac{v \in \text{open\_leaves}(DT) \quad \text{depth}(DT) \leq L \quad \ell(v), \tau \in \Gamma}{DT' \leftarrow \text{expand}_G(DT, v, [\,])}$$

Search algorithm pseudocode

```
initializeGlobalState()
while ¬allLeavesClosed(dt) do
    if there is more than one unvisited expansion then
        DECIDE
    else
        PROPAGATE
    while ¬is_normalized(dt) do
        NORMALIZEPR (if applicable)
        NORMALIZETA (if applicable)
    if current search depth d > depth limit L then
        if assertionLevel = 1 then
            RESTARTDEPTH
        else
            BACKTRACKDEPTH
    else
        for all c ∈ constraint set C do
            ASSERT if c is applicable
        if smt_check_sat() = UNSAT then
            if assertionLevel = 1 ∧ ¬bd? then
                FAIL
            else if assertionLevel = 1 then
                RESTARTUNSAT
            else
                BACKTRACKUNSAT
```