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

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

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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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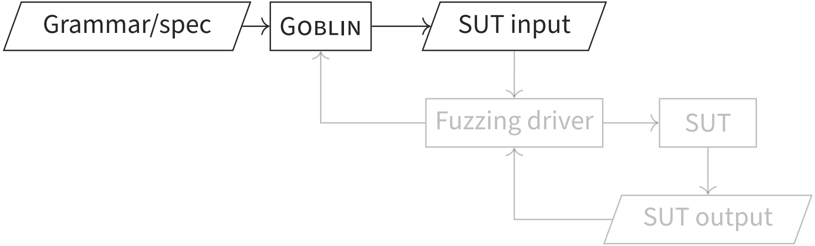

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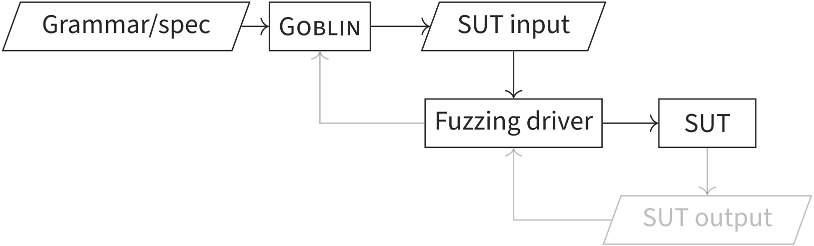

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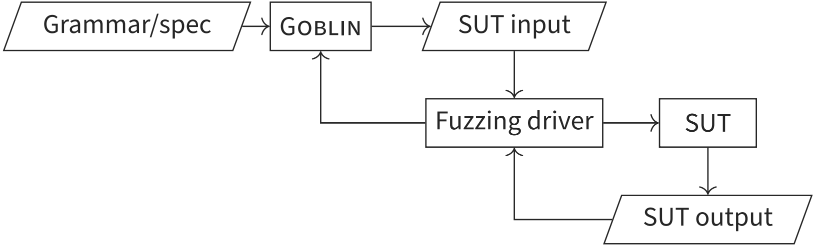
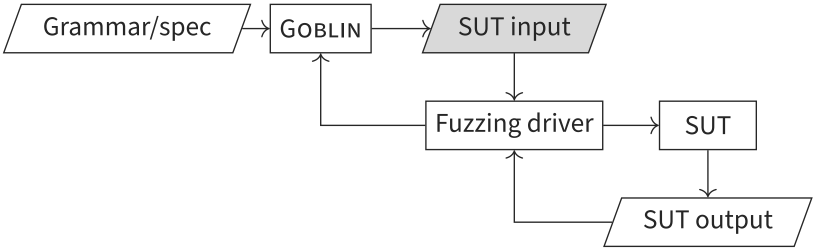


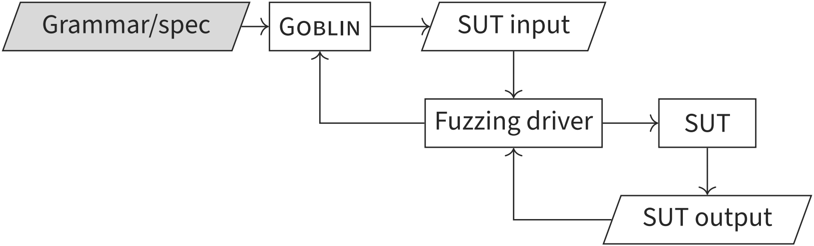
Input generation vs fuzzing

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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Structure-aware mutations

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```

Prior work cannot tie global constraints to mutations

Prior work

Tool	Constraint type	Philosophy	Search algo	Supported theories
GOBLIN	Local	Minimalist	Constraint solving	All
ISLa	Global	Maximalist	Constraint solving	Strings
Fandango	Global	Maximalist	Genetic algo	All

Fandango constraints may be non-monotonic (no monotonically decreasing notion of distance for constraint satisfaction) and time 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)

Language features: Production rules

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



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

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




```

Language features: Type annotations

Language features: Type annotations

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);
```

Language features: Refinement types

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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;};
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<F1> :: BitVec(8); <F2> :: BitVec(8); <OPT> :: BitVec(4);
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Language features: Semantic constraints

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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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Language features: Dot notation

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Reference child nonterminals with dot notation

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Dot notation is partial and implicitly universally quantified

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Cryptographic hashes, checksums, or any computable function

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But try telling an SMT solver to find x such that $\mathrm{hash}(x) = y$...

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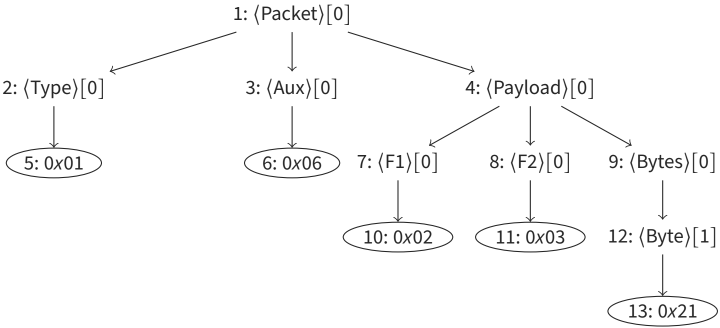

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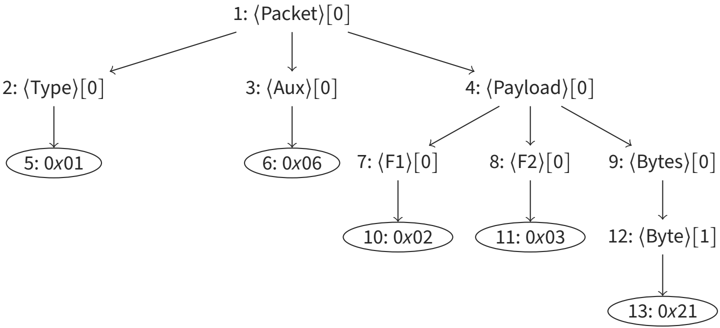

Not a string `0x0106020321`

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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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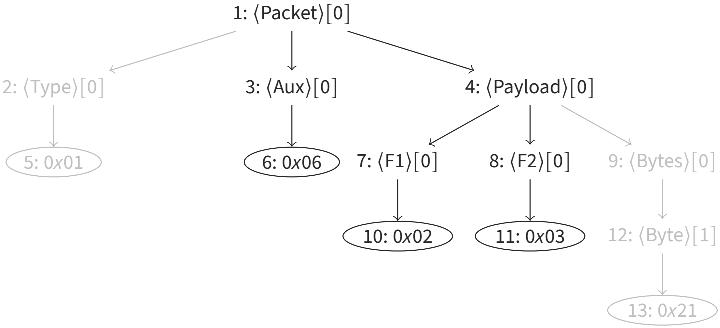

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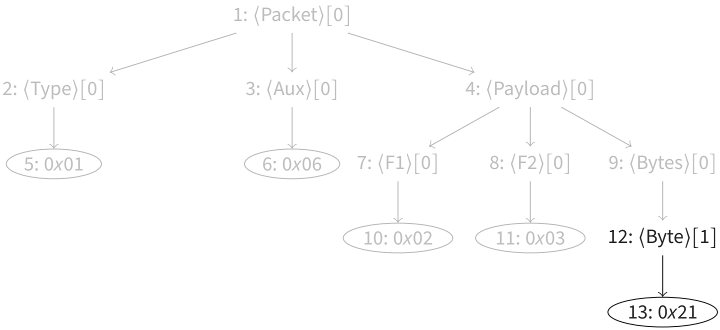

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How does Goblin find t such that $t \in \mathcal{L}_{\text{AST}}(G)$?

General workflow:

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

Derived Field Checks

Derived fields $\langle F \rangle \leftarrow e$ must be computable without constraint solving

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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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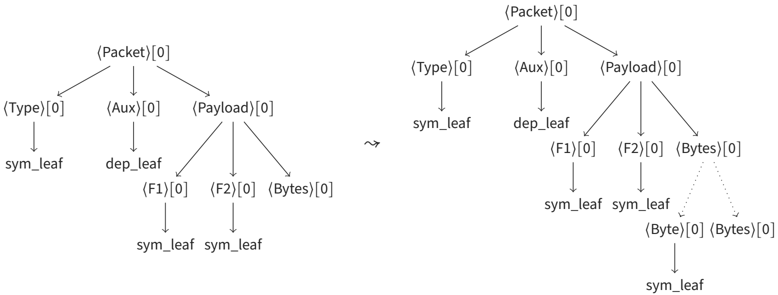


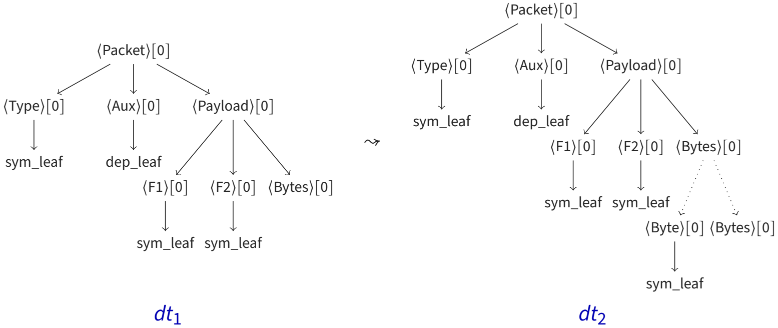
dt_1 dt_2

Search Algorithm: Main Concepts

Choosing an expansion is called a decision

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

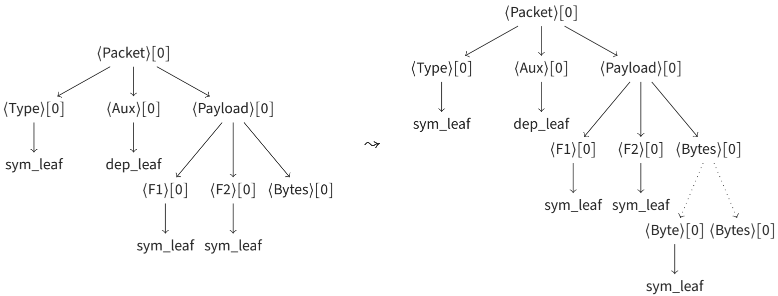
Version control helps you undo mistakes!



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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Idea: Bound search depth with IDS

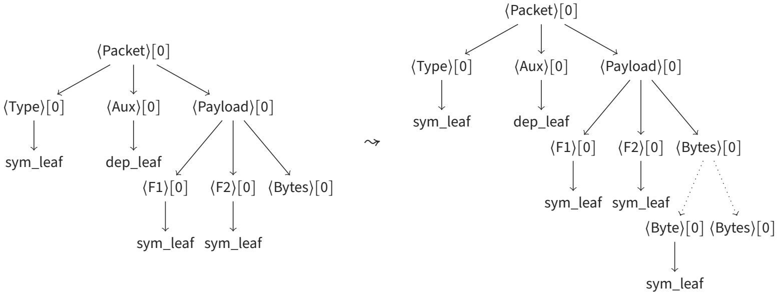
Search Algorithm: Main Concepts

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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How to extend the context-free algorithm to handle constraints?

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- `(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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Principles of constraint handling

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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

But wait, there's more...

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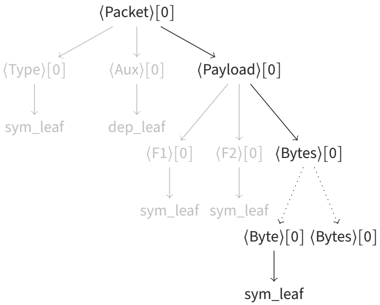
```
<PACKET> ::= <TYPE> <AUX> <PAYLOAD> { ... };
<PAYLOAD> ::= <F1> <F2> <BYTES>
 { <BYTES>.<OPT> bvugt 0x0; };
<BYTES> ::= <BYTE> <BYTES> | <BYTE> | <OPT>; ...
```

$\text{packet0\_payload0\_bytes0\_opt0} >_{bv} 0x0$

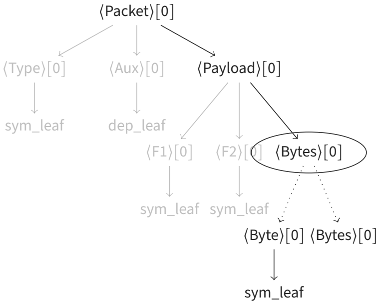


Search Algorithm: Main concepts

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

$\text{packet0\_payload0\_bytes0\_opt0} >_{bv} 0x0$



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

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

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
```