Parse this!

Summoning Context-Sensitive Inputs with Goblin

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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?

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  - Mutations still blind to specification constraints

Wishlist

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2. Expressiveness of tailor-made fuzzers

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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?

```
<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>*
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  - And evaluated in the context of real fuzzing workflows
- Given a context-sensitive grammar G, find x such that $x \in \mathcal{L}(G)$
- What is a context-sensitive grammar?

```
<xml-tree> ::= <openclose-tag> |
               <open-tag> <inner-tree> <close-tag>
             { <open-tag>.<id> = <close-tag>.<id> }
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Input generation vs fuzzing

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

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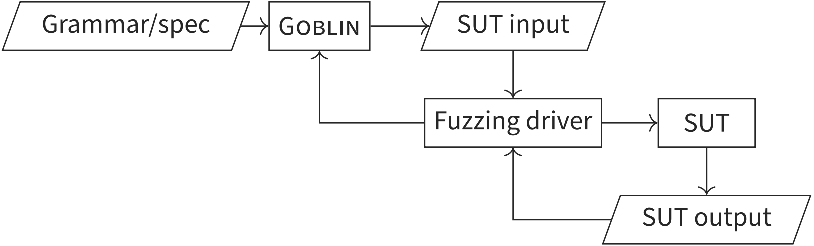

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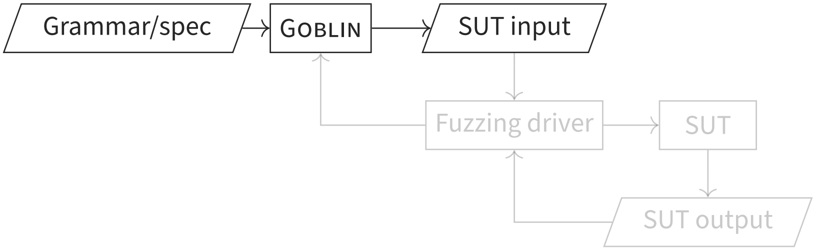

From now on we only discuss input generation

GOBLIN by example: Language features

GOBLIN grammars have production rules as in CFGs

```
<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);
<F1> :: BitVec(8); <F2> :: BitVec(8); <OPT> :: BitVec(4);
```

GOBLIN by example: Language features

Attach semantic constraits 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; };
<BYTES> ::= <BYTE> <BYTES> | <BYTE> | <OPT>;
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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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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

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Cryptographic hashes, checksums, or any computable function

Semantics: Abstract syntax trees

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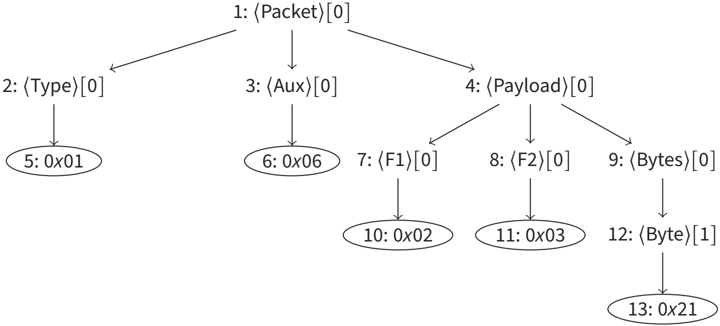

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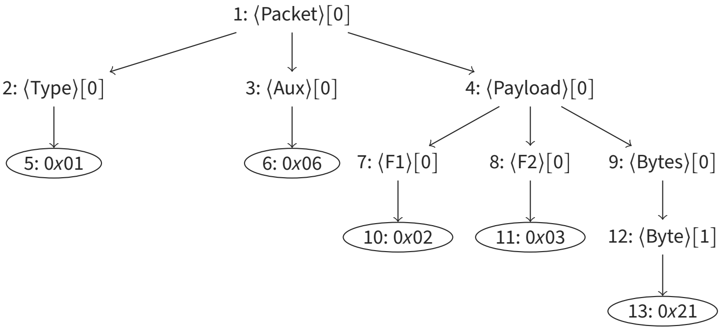

Not a string `0x0106020321`

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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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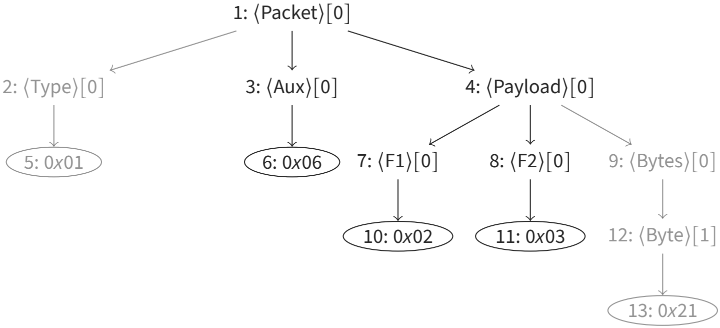

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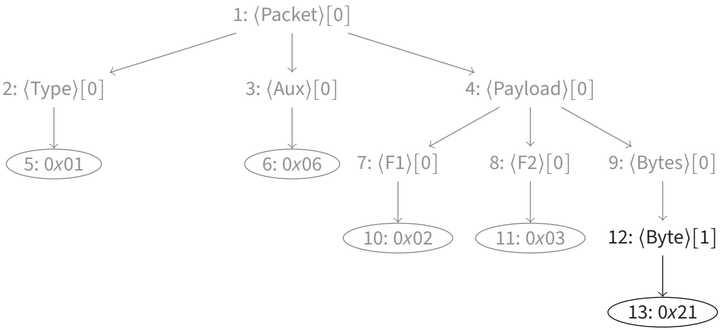

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8. Serialize

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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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   - (*ii*) Include vertex for each RHS nonterminal/symbolic terminal
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2. Disallow derived fields in semantic constraints
   - 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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```
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...
```

$\rightsquigarrow$

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

Search algorithm

Formal guarantees

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

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We prove the calculus satisfies solution soundness, refutation soundness, and solution completeness

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- 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)

Evaluation

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

- 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

Evaluation

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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)

Discussion and future work

- User-facing language
  - Synthesized and inherited attributes
  - User-defined recursive functions
  - Built-ins like `length(.)`

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- CDCL-style backjumping

Thanks! Questions?

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`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

Local constraints for grammar mutation

- 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 $\mathcal{I}_{tr}(t_i) = \top$

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

$I_{tr}(\langle \mathrm{nt} \rangle[i].\langle \mathrm{nt\_expr} \rangle) = I_{tr'}(\langle \mathrm{nt\_expr} \rangle)$ for tr' rooted at the only

$v \in \mathrm{get\_children}(\mathrm{tr}, \mathrm{root}(\mathrm{tr}))$ such that $\ell(v) = \langle \mathrm{nt} \rangle[i]$

$\ldots$

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

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

Calculus

Can conceptualize as guarded rewrite rules on global state

Example rule expands a symbolic terminal

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

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
```