

Parse this!

Summoning Context-Sensitive Inputs with GOBLIN

Rob Lorch Muhammad Daniyal Pirwani Dar

Cesare Tinelli Omar Chowdhury

The University of Iowa

Stony Brook University

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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

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

Context-free input generation

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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?

```
1 <xml-tree> ::= <openclose-tag> |
2                 <open-tag> <inner-tree> <close-tag>
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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>*
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- Given a context-sensitive grammar G , find x such that $x \in \mathcal{L}(G)$
- What is a context-sensitive grammar?

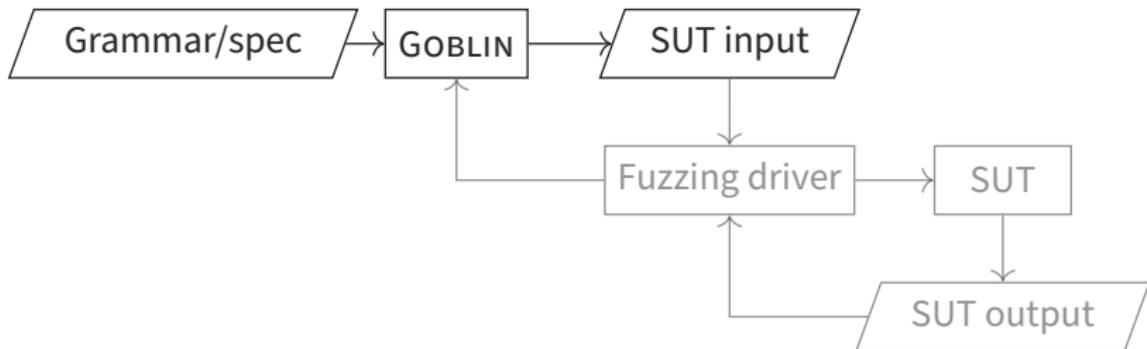
```
1 <xml-tree> ::= <openclose-tag> |
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4   ...
```

Input generation vs fuzzing

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

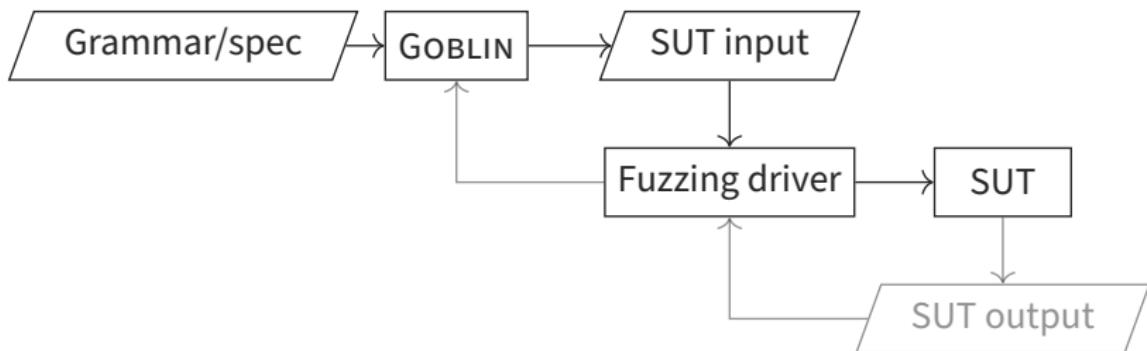
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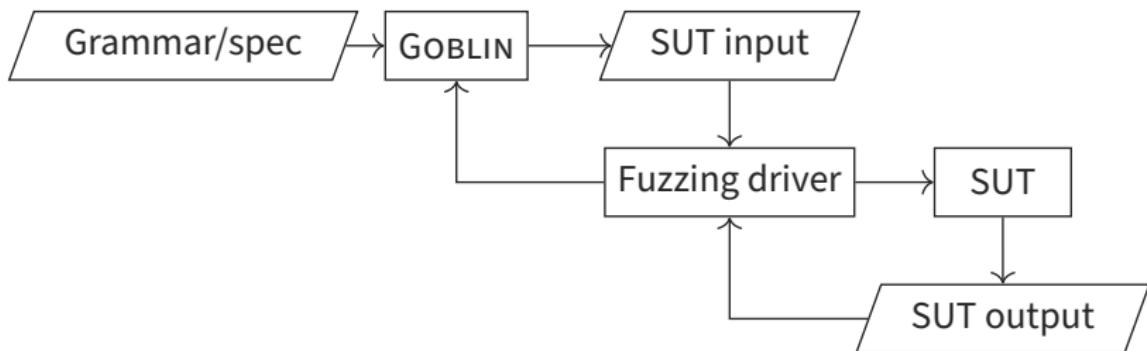
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GOBLIN by example: Language features

GOBLIN grammars have **production rules** as in CFGs

```
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**

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

```
1 <PACKET> ::= <TYPE> <AUX> <PAYLOAD>;
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5 <PAYLOAD> ::= <F1> <F2> <BYTES>;
6
7 <BYTES> ::= <BYTE> <BYTES> | <BYTE> | <OPT>;
8 <TYPE> :: BitVec(8) { <TYPE> = 0x01 or <TYPE> = 0x02; };
9 <BYTE> :: BitVec(8) { <BYTE> bvult 0x88; };
10 <AUX> :: BitVec(8);
11 <F1> :: BitVec(8); <F2> :: BitVec(8); <OPT> :: BitVec(4);
```

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; };
7 <BYTES> ::= <BYTE> <BYTES> | <BYTE> | <OPT>;
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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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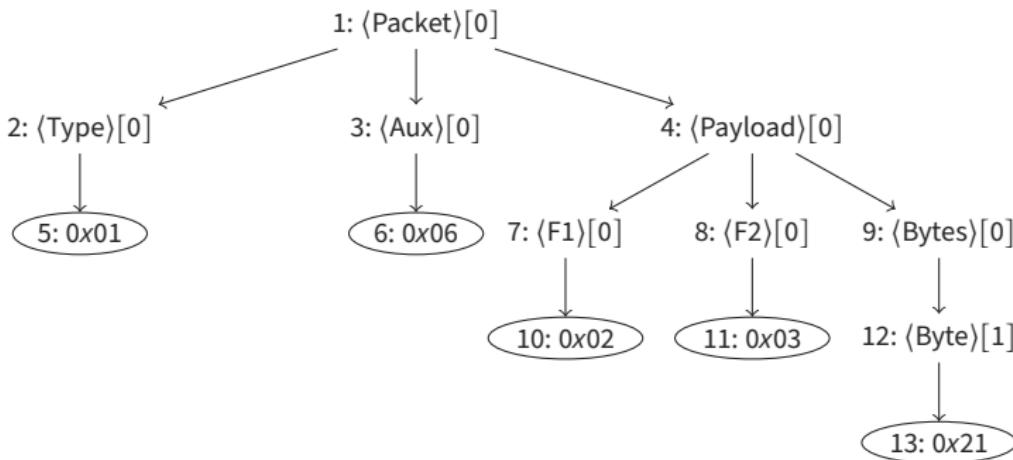
Derived fields with `<->` denote nonterminals that are directly computable, enforced syntactically
Cryptographic hashes, checksums, or any computable function

Semantics: Abstract syntax trees

GOBLIN generates **abstract syntax trees**, not strings

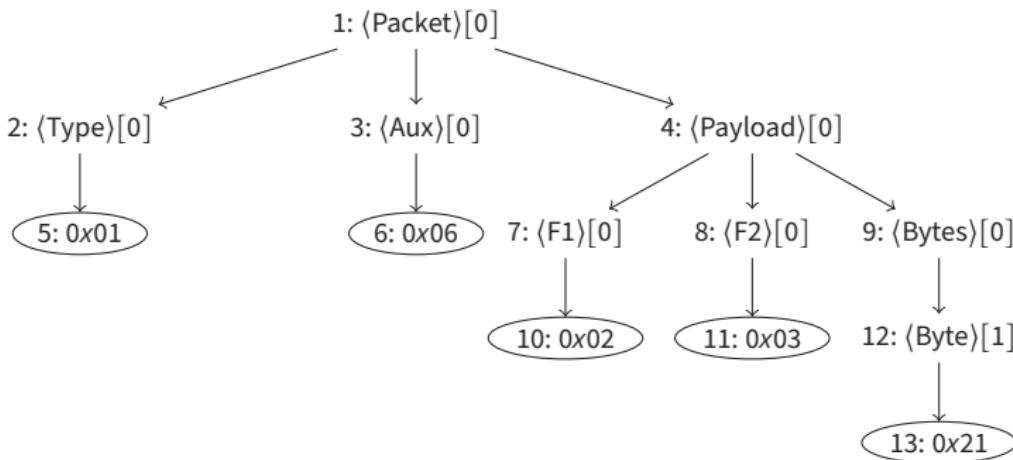
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The ADT view allows GOBLIN to natively support constraints over arbitrary SMT theories

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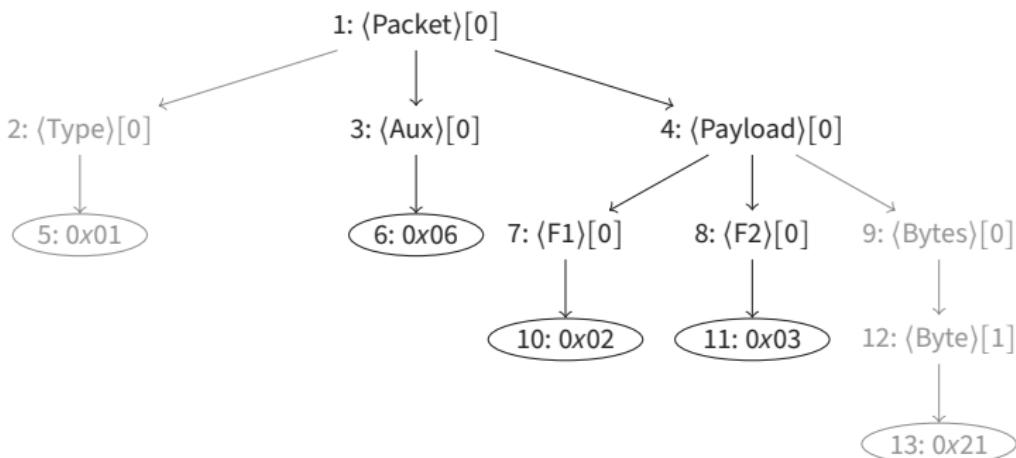
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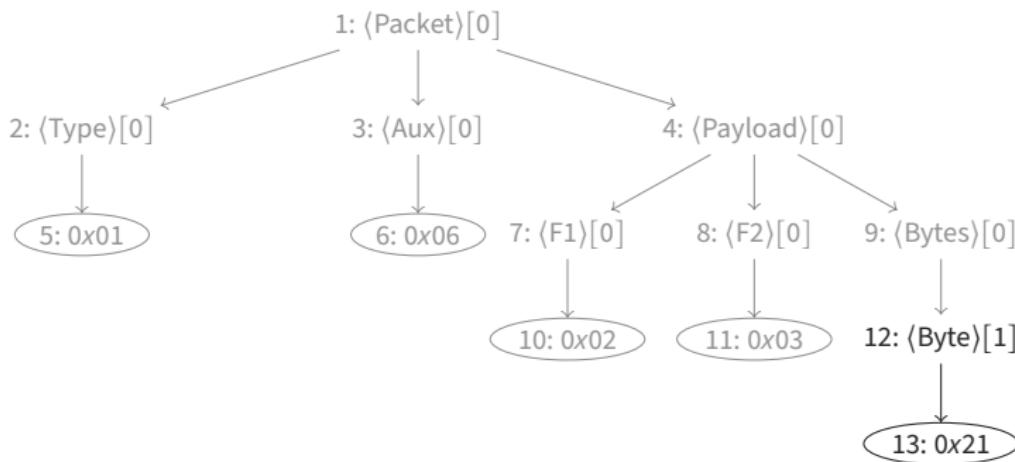
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```
1 <SAE_PACKET> ::= <COMMIT> | <CONFIRM>;
2 <COMMIT> ::= <FIELD> <RG_ID_LIST>;
3 <RG_ID_LIST> ::= <RG_ID> <RG_ID_LIST>;
4 <CONFIRM> ::= <FIELD1> <FIELD2>;
5 ...
```

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

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2. Disallow derived fields in semantic constraints
 - E.g., $\langle D \rangle > 0$ where $\langle D \rangle$ is derived

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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)

Search Algorithm: Main Concepts

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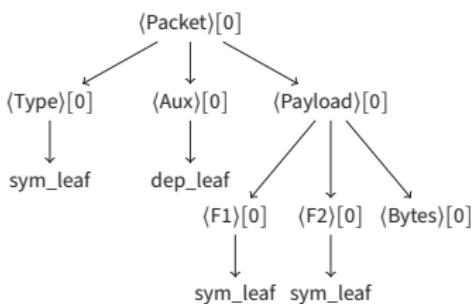
1. Build candidate dt via random walk until closed
2. Then instantiate with concrete values

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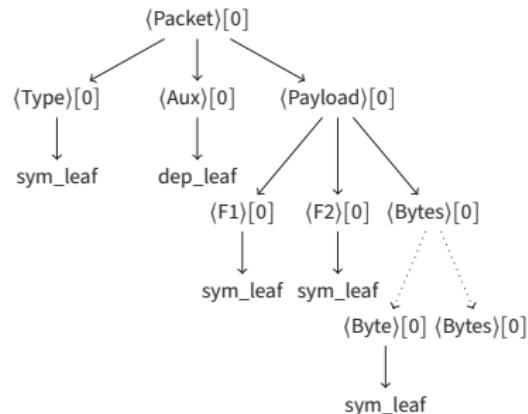
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dt_1

\rightsquigarrow

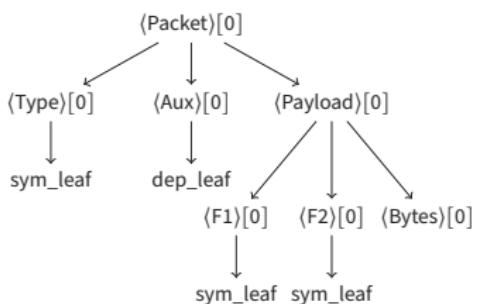


dt_2

Search Algorithm: Main Concepts

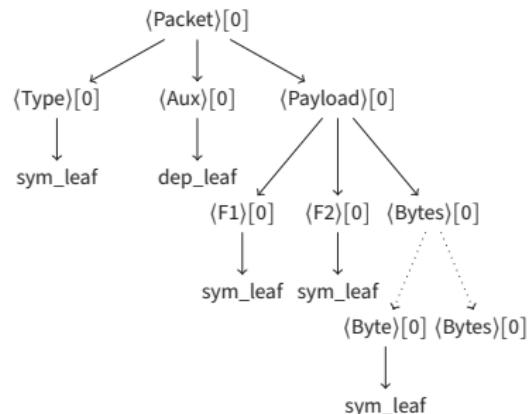
Choosing an expansion is called a **decision**

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



dt_1

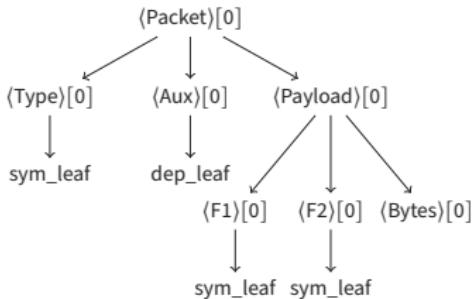
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dt_2

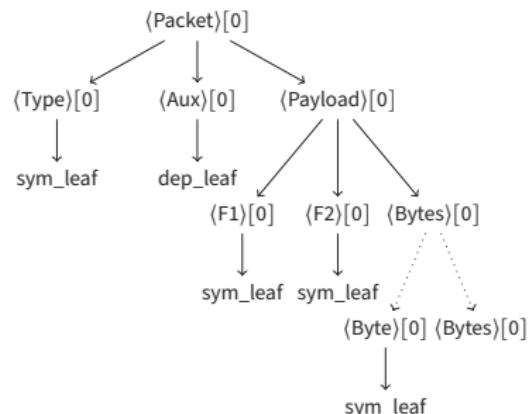
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Some “decisions” are **forced** (see solid arrows): symbolic terminals and nonterminals with exactly one production rule option
These are called **normalization steps** and are not stored in *ds*



dt₁

~



dt₂

Search Algorithm: Main Concepts

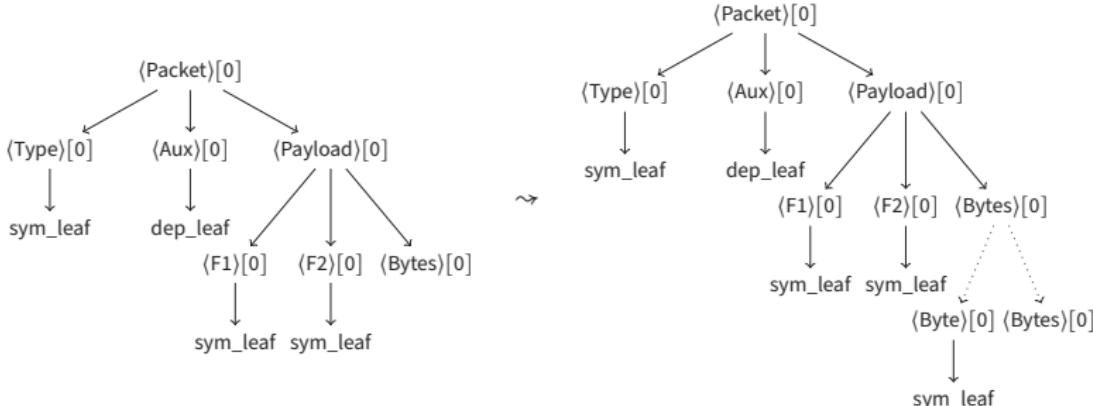
Termination is not guaranteed

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

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Insight: use an **incremental SMT** backend

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- `(assert c)`: assert a constraint

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

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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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1. Push an assertion frame at every decision
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**

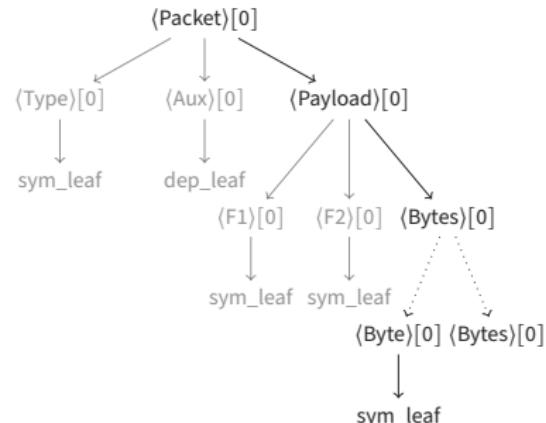
Search Algorithm: Main concepts

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

packet0_payload0_bytes0_opt0 >_{bv} 0x0



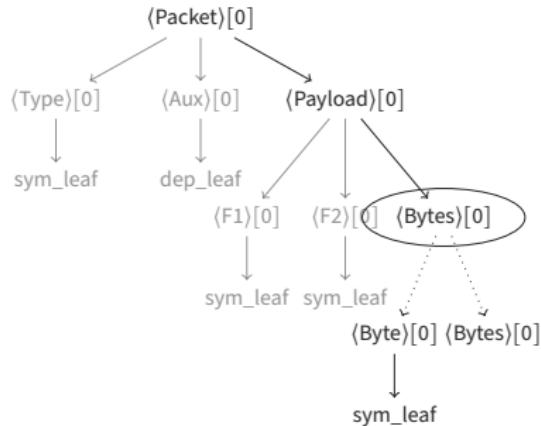
Search Algorithm: Main concepts

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

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Formal guarantees

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

Evaluation

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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

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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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- 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**

Local constraints for grammar mutation

- 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

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

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

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

...

Semantics: Satisfaction relation

Satisfaction relation $\models_{\mathcal{G}}$ captures whether or not a given constraint in \mathcal{G} is satisfied by a given AST

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

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

$\models_{\mathcal{G}} \neg \varphi$ 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 $tr \not\models_{\mathcal{G}} \varphi_1$ 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

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

Calculus

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

Example rule expands a symbolic terminal

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

Search algorithm pseudocode

```
1: initializeGlobalState()
2: while ¬allLeavesClosed( $dt$ ) do
3:   if there is more than one unvisited expansion then
4:     DECIDE
5:   else
6:     PROPAGATE
7:   while ¬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  $\wedge$  ¬bd? then
20:            FAIL
21:          else if assertionLevel = 1 then
22:            RESTARTUNSAT
23:          else
24:            BACKTRACKUNSAT
```