

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

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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

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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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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>*
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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?

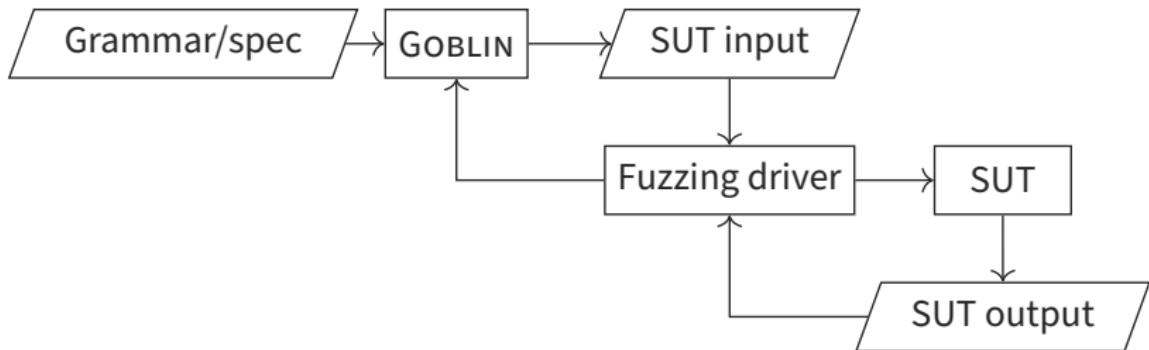
```
1 <xml-tree> ::= <openclose-tag> |
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4   ...
```

Input generation vs fuzzing

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

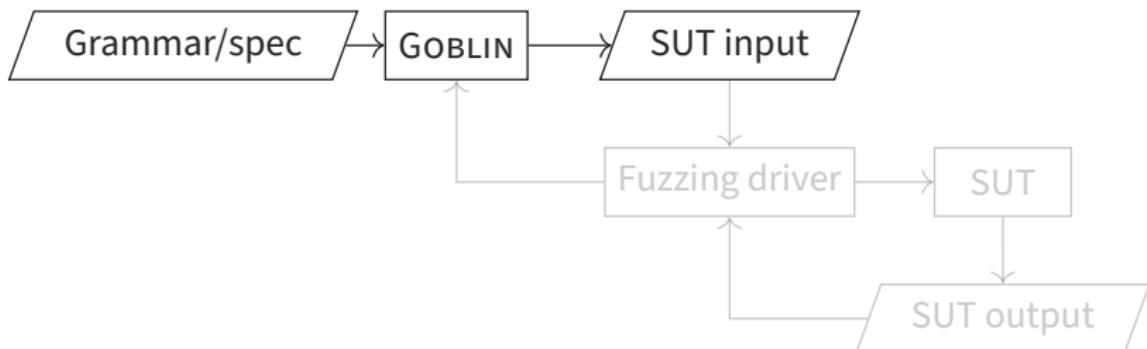
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Input generation vs fuzzing

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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

```
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>;  
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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

```
1 <PACKET> ::= <TYPE> <AUX> <PAYLOAD>;
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3
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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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GOBLIN by example: Language features

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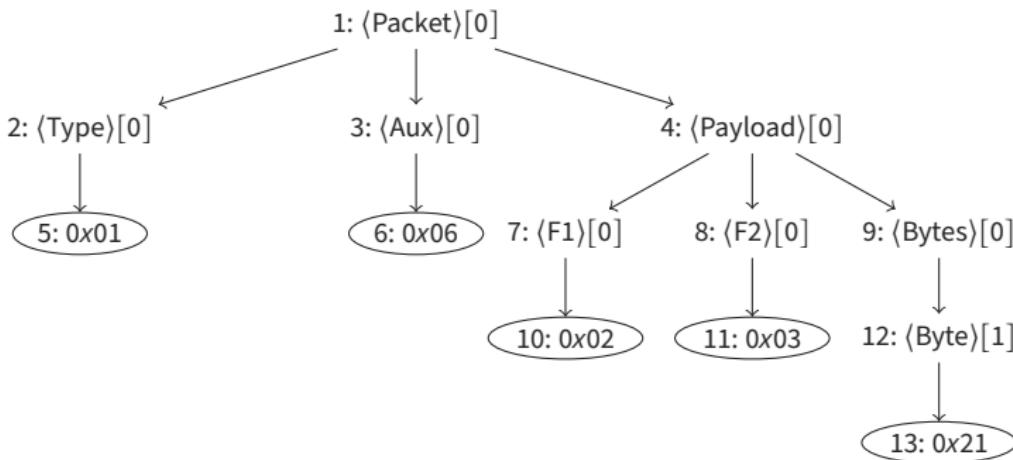
Derived fields with `<->` denote nonterminals that are directly computable, enforced syntactically
Cryptographic hashes, checksums, or any computable function

Semantics: Abstract syntax trees

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

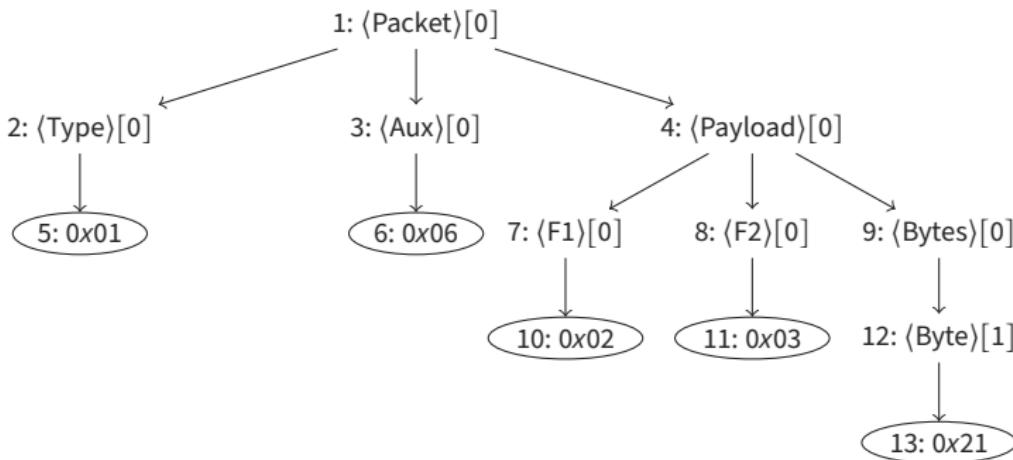
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Not a string `0x0106020321`

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

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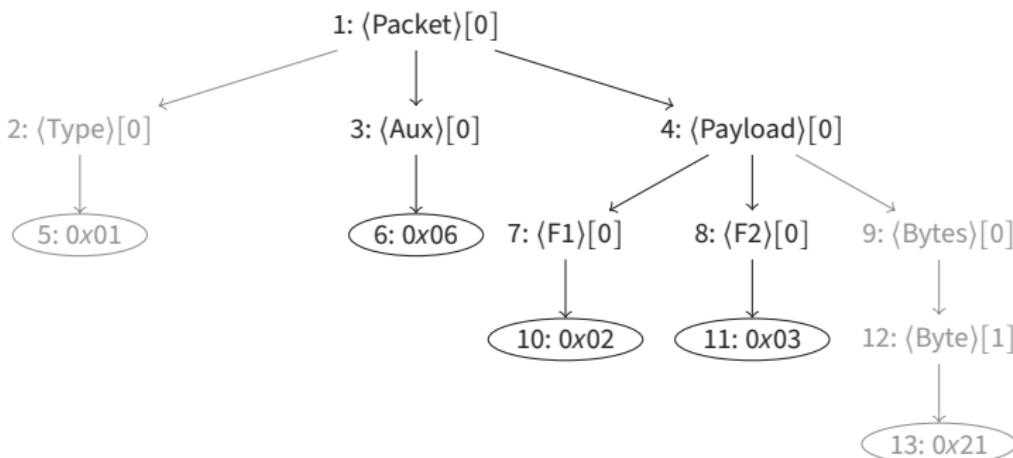
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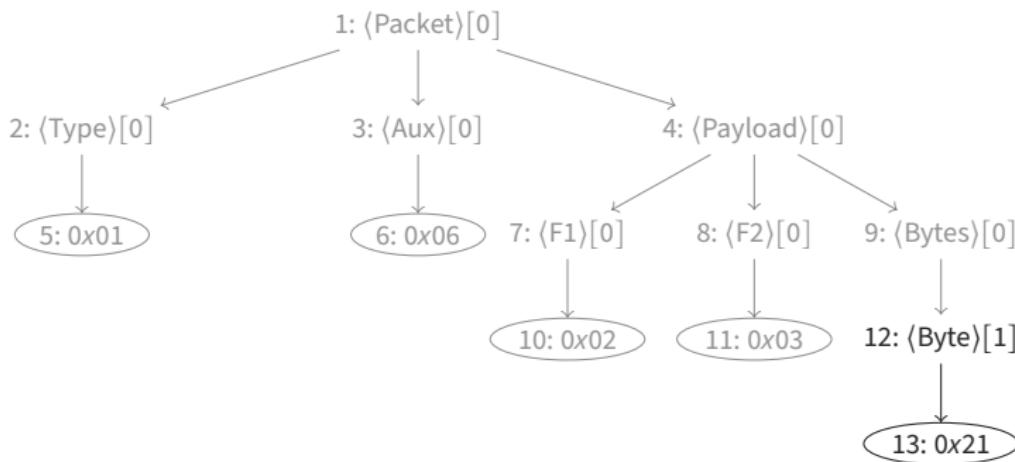
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```
1 <SAE_PACKET> ::= <COMMIT> | <CONFIRM>;
2 <COMMIT> ::= <FIELD> <RG_ID_LIST>;
3 <RG_ID_LIST> ::= <RG_ID> <RG_ID_LIST>;
4 <CONFIRM> ::= <FIELD1> <FIELD2>;
5 ...
```

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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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3   ...
```

~>

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

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**

Evaluation

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

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- XML, ScriptSize C, and CSV input generation

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- 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

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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?

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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

Semantics: Interpretation function

Semantics: Satisfaction relation

Semantics: Denotation of G

Search algorithm pseudocode

Calculus

Can conceptualize as guarded rewrite rules on global state