

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

Problem Introduction

- Some software systems have highly **complex input formats** (e.g. compilers, file renderers, network protocol stacks)

Problem Introduction

- Some software systems have highly **complex input formats** (e.g. compilers, file renderers, network protocol stacks)
- Complex input formats are difficult for testing, especially **automated testing**

Problem Introduction

- Some software systems have highly **complex input formats** (e.g. compilers, file renderers, network protocol stacks)
- Complex input formats are difficult for testing, especially **automated testing**
- We will discuss techniques for **automated input generation** of software with complex input formats

Problem Introduction

- Some software systems have highly **complex input formats** (e.g. compilers, file renderers, network protocol stacks)
- 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?

Existing Approaches

- Use context-free grammars (CFGs) to capture input structure

Existing Approaches

- Use context-free grammars (CFGs) to capture input structure
 - HTTP requests, DNS packets, LangFuzz

Existing Approaches

- Use context-free grammars (CFGs) to capture input structure
 - HTTP requests, DNS packets, LangFuzz
 - Can only handle context-free aspects of the spec

Existing Approaches

- Use context-free grammars (CFGs) to capture input structure
 - HTTP requests, DNS packets, LangFuzz
 - Can only handle context-free aspects of the spec
 - Consider packet format with fields f_1 and f_2 s.t. $f_1 = |f_2|$

Existing Approaches

- Use context-free grammars (CFGs) to capture input structure
 - HTTP requests, DNS packets, LangFuzz
 - Can only handle context-free aspects of the spec
 - Consider packet format with fields f_1 and f_2 s.t. $f_1 = |f_2|$
- Tools tailor-made for system under test (SUT)

Existing Approaches

- Use context-free grammars (CFGs) to capture input structure
 - HTTP requests, DNS packets, LangFuzz
 - Can only handle context-free aspects of the spec
 - Consider packet format with fields f_1 and f_2 s.t. $f_1 = |f_2|$
- Tools tailor-made for system under test (SUT)
 - CSmith

Existing Approaches

- Use context-free grammars (CFGs) to capture input structure
 - HTTP requests, DNS packets, LangFuzz
 - Can only handle context-free aspects of the spec
 - Consider packet format with fields f_1 and f_2 s.t. $f_1 = |f_2|$
- Tools tailor-made for system under test (SUT)
 - CSmith
 - Lacks generality!

Existing Approaches

- Use context-free grammars (CFGs) to capture input structure
 - HTTP requests, DNS packets, LangFuzz
 - Can only handle context-free aspects of the spec
 - Consider packet format with fields f_1 and f_2 s.t. $f_1 = |f_2|$
- Tools tailor-made for system under test (SUT)
 - CSmith
 - Lacks generality!
- Coverage-guided mutation

Existing Approaches

- Use context-free grammars (CFGs) to capture input structure
 - HTTP requests, DNS packets, LangFuzz
 - Can only handle context-free aspects of the spec
 - Consider packet format with fields f_1 and f_2 s.t. $f_1 = |f_2|$
- Tools tailor-made for system under test (SUT)
 - CSmith
 - Lacks generality!
- Coverage-guided mutation
 - How to generate an initial corpus?

Existing Approaches

- Use context-free grammars (CFGs) to capture input structure
 - HTTP requests, DNS packets, LangFuzz
 - Can only handle context-free aspects of the spec
 - Consider packet format with fields f_1 and f_2 s.t. $f_1 = |f_2|$
- Tools tailor-made for system under test (SUT)
 - CSmith
 - Lacks generality!
- Coverage-guided mutation
 - How to generate an initial corpus?
 - What if no access to coverage information?

Existing Approaches

- Use context-free grammars (CFGs) to capture input structure
 - HTTP requests, DNS packets, LangFuzz
 - Can only handle context-free aspects of the spec
 - Consider packet format with fields f_1 and f_2 s.t. $f_1 = |f_2|$
- Tools tailor-made for system under test (SUT)
 - CSmith
 - Lacks generality!
- Coverage-guided mutation
 - How to generate an initial corpus?
 - What if no access to coverage information?
 - Mutations still blind to specification constraints

Wishlist

1. Generality of CFG-based approaches

Wishlist

1. Generality of CFG-based approaches
2. Expressiveness of tailor-made fuzzers

Wishlist

1. Generality of CFG-based approaches
2. Expressiveness of tailor-made fuzzers

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

Context-free input generation

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

Context-free input generation

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

```
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>
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>*
```

Introducing GOBLIN

- Presenting GOBLIN

Introducing GOBLIN

- Presenting GOBLIN
 - A context-sensitive input generation tool, supported by

Introducing GOBLIN

- Presenting GOBLIN
 - A context-sensitive input generation tool, supported by
 - A new DSL with a formal semantics

Introducing GOBLIN

- Presenting GOBLIN
 - A context-sensitive input generation tool, supported by
 - A new DSL with a formal semantics
 - A new search algorithm to address the underlying problem

Introducing GOBLIN

- Presenting GOBLIN
 - A context-sensitive input generation tool, supported by
 - A new DSL with a formal semantics
 - A new search algorithm to address the underlying problem
 - Supporting constraint solving over arbitrary SMT theories

Introducing GOBLIN

- Presenting GOBLIN
 - A context-sensitive input generation tool, supported by
 - A new DSL with a formal semantics
 - A new search algorithm to address the underlying problem
 - Supporting constraint solving over arbitrary SMT theories
 - And evaluated in the context of real fuzzing workflows

Introducing GOBLIN

- Presenting GOBLIN
 - A context-sensitive input generation tool, supported by
 - A new DSL with a formal semantics
 - A new search algorithm to address the underlying problem
 - Supporting constraint solving over arbitrary SMT theories
 - And evaluated in the context of real fuzzing workflows
- Given a context-sensitive grammar G , find x such that $x \in \mathcal{L}(G)$

Introducing GOBLIN

- Presenting GOBLIN
 - A context-sensitive input generation tool, supported by
 - A new DSL with a formal semantics
 - A new search algorithm to address the underlying problem
 - Supporting constraint solving over arbitrary SMT theories
 - 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?

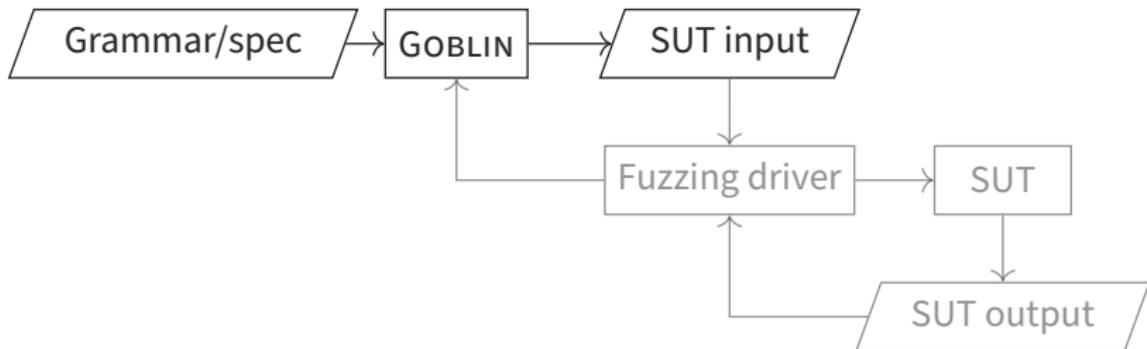
```
1 <xml-tree> ::= <openclose-tag> |
2           <open-tag> <inner-tree> <close-tag>
3           { <open-tag>.<id> = <close-tag>.<id> }
4   ...
```

Input generation vs fuzzing

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

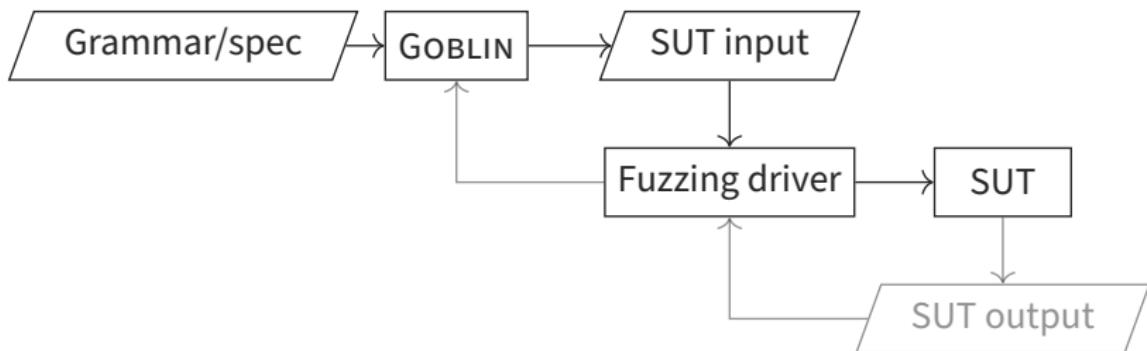
Input generation vs fuzzing

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



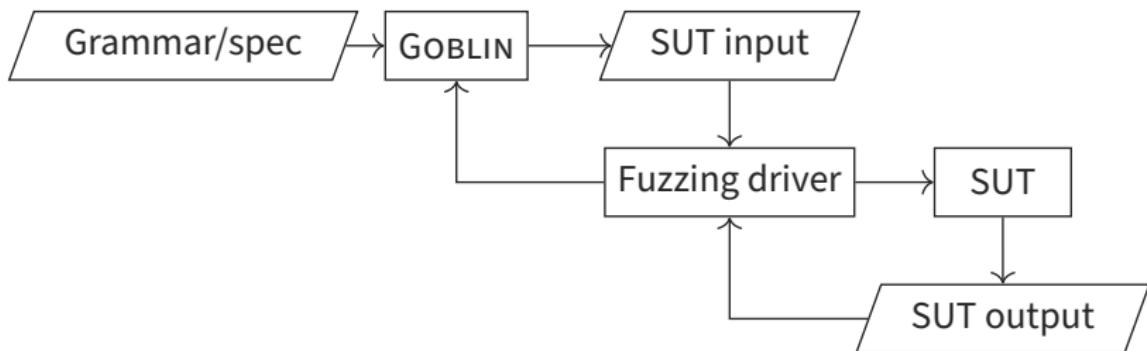
Input generation vs fuzzing

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



Input generation vs fuzzing

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



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>;  
2  
3  
4  
5 <PAYLOAD> ::= <F1> <F2> <BYTES>;  
6  
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>;
2
3
4
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>;
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

Reference child nonterminals with **dot notation**

```
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>;
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

Dot notation is **partial** and implicitly universally quantified

```
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>;
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

Many constraints are not amenable to automated constraint solving with an SMT engine

```
1 <PACKET> ::= <TYPE> <AUX> <PAYLOAD>
2 { <AUX> <- <PAYLOAD>.<F1> bvmul <PAYLOAD>.<F2>;
3 ...
4 <PAYLOAD> ::= <F1> <F2> <BYTES>
5 ...
```

GOBLIN by example: Language features

Many constraints are not amenable to automated constraint solving with an SMT engine

```
1 <PACKET> ::= <TYPE> <AUX> <PAYLOAD>
2 { <AUX> <- <PAYLOAD>. <F1> bvmul <PAYLOAD>. <F2>;
3 ...
4 <PAYLOAD> ::= <F1> <F2> <BYTES>
5 ...
```

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

GOBLIN by example: Language features

Many constraints are not amenable to automated constraint solving with an SMT engine

```
1 <PACKET> ::= <TYPE> <AUX> <PAYLOAD>
2 { <AUX> <- <PAYLOAD>.<F1> bvmul <PAYLOAD>.<F2>;
3 ...
4 <PAYLOAD> ::= <F1> <F2> <BYTES>
5 ...
```

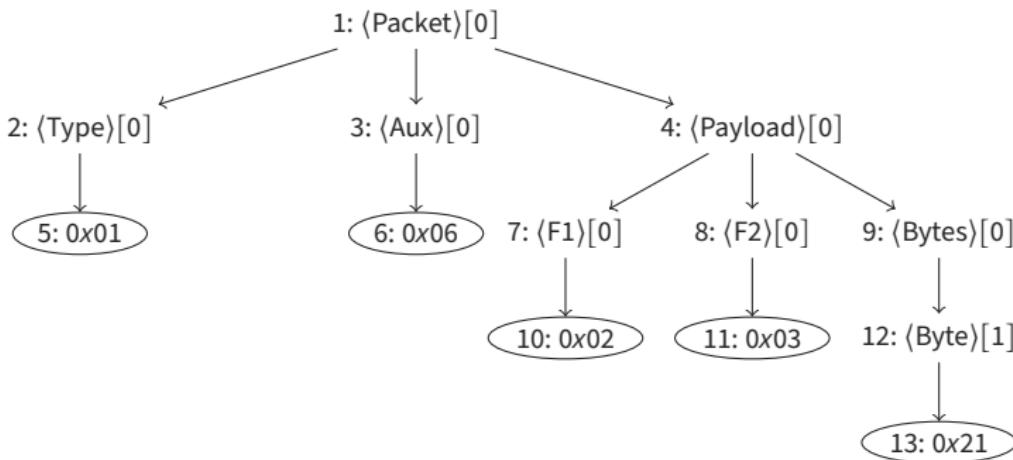
Derived fields with `<->` denote nonterminals that are directly computable, enforced syntactically
Cryptographic hashes, checksums, or any computable function

Semantics: Abstract syntax trees

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

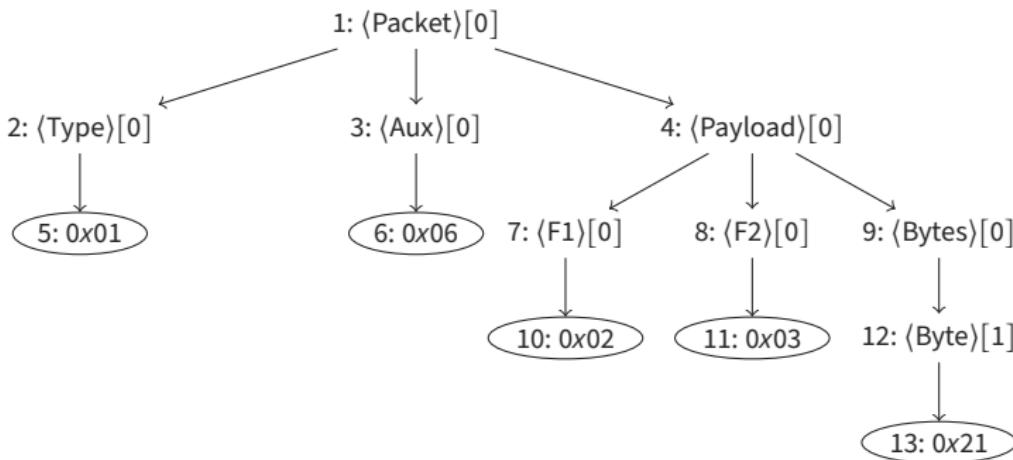
Semantics: Abstract syntax trees

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



Semantics: Abstract syntax trees

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



Not a string `0x0106020321`

Semantics: Abstract syntax trees

- Without the AST view, prior work natively **only supports string constraints**

Semantics: Abstract syntax trees

- Without the AST view, prior work natively **only supports string constraints**
- AST semantics position GOBLIN as a generator of constrained **algebraic datatype** (ADT) terms

Semantics: Abstract syntax trees

- Without the AST view, prior work natively **only supports string constraints**
- 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

Semantics

The **semantics** of a goblin input G are the set of ASTs that respect (*i*) G 's context-free syntactic constraints and G 's (*ii*) context-sensitive semantic constraints

Semantics

The **semantics** of a goblin input G are the set of ASTs that respect (*i*) G 's context-free syntactic constraints and G 's (*ii*) context-sensitive semantic constraints

$$\mathcal{L}_{\text{AST}}(G) = \{t \mid$$

1. t is rooted at the start symbol

Semantics

The **semantics** of a goblin input G are the set of ASTs that respect (i) G 's context-free syntactic constraints and G 's (ii) context-sensitive semantic constraints

$$\mathcal{L}_{\text{AST}}(G) = \{t \mid$$

1. t is rooted at the start symbol
2. Each $v \in V(t)$ is either

Semantics

The **semantics** of a goblin input G are the set of ASTs that respect (i) G 's context-free syntactic constraints and G 's (ii) context-sensitive semantic constraints

$$\mathcal{L}_{\text{AST}}(G) = \{t \mid$$

1. t is rooted at the start symbol
2. Each $v \in V(t)$ is either
 - a. A non-leaf with children representing a production rule application in G ,

Semantics

The **semantics** of a goblin input G are the set of ASTs that respect (i) G 's context-free syntactic constraints and G 's (ii) context-sensitive semantic constraints

$$\mathcal{L}_{\text{AST}}(G) = \{t \mid$$

1. t is rooted at the start symbol
2. Each $v \in V(t)$ is either
 - a. A non-leaf with children representing a production rule application in G ,
 - b. A non-leaf representing a type annotation in G , or

Semantics

The **semantics** of a goblin input G are the set of ASTs that respect (i) G 's context-free syntactic constraints and G 's (ii) context-sensitive semantic constraints

$$\mathcal{L}_{\text{AST}}(G) = \{t \mid$$

1. t is rooted at the start symbol
2. Each $v \in V(t)$ is either
 - a. A non-leaf with children representing a production rule application in G ,
 - b. A non-leaf representing a type annotation in G , or
 - c. A well-typed leaf

Semantics

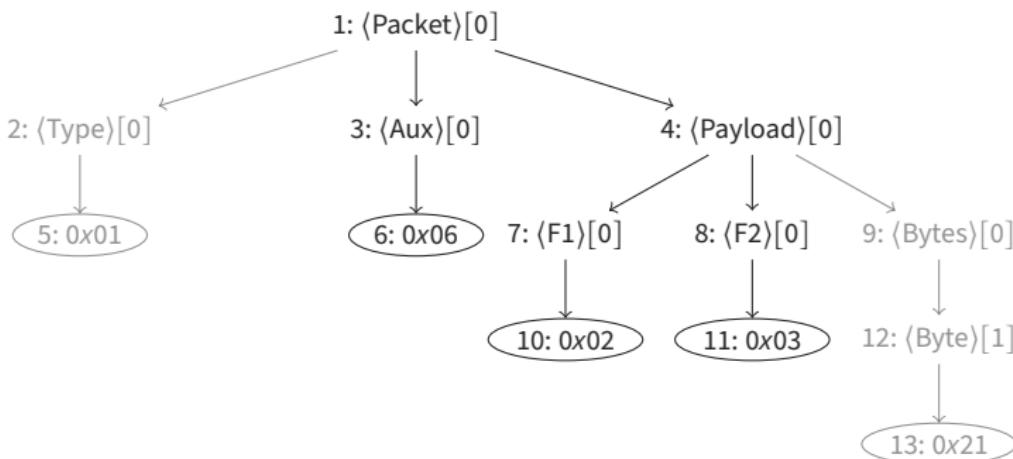
The **semantics** of a goblin input G are the set of ASTs that respect (i) G 's context-free syntactic constraints and G 's (ii) context-sensitive semantic constraints

$$\mathcal{L}_{\text{AST}}(G) = \{t \mid$$

1. t is rooted at the start symbol
 2. Each $v \in V(t)$ is either
 - a. A non-leaf with children representing a production rule application in G ,
 - b. A non-leaf representing a type annotation in G , or
 - c. A well-typed leaf
 3. t satisfies the constraints at every production rule application
- }

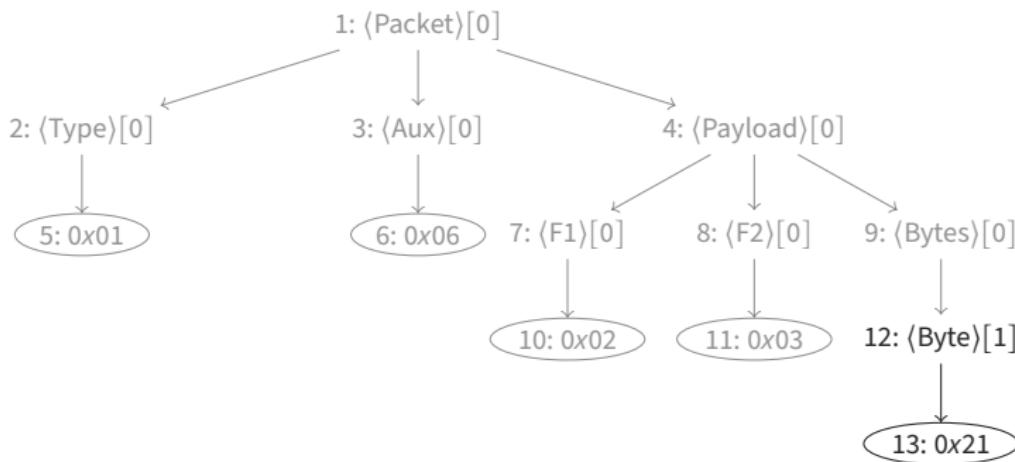
Semantics: Constraint Satisfaction

```
1 <PACKET> ::= <TYPE> <AUX> <PAYLOAD>
2 { <AUX> <- <PAYLOAD>.F1 bvmul <PAYLOAD>.F2;
3 ...
4 <PAYLOAD> ::= <F1> <F2> <BYTES>
5 ...
```



Semantics: Constraint Satisfaction

```
1 ...
2 <BYTE> :: BitVec(8) { <BYTE> bvult 0x88; };
3 ...
```



GOBLIN Workflow

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

GOBLIN Workflow

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

General workflow:

GOBLIN Workflow

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

General workflow:

1. Context-free wellformedness and other syntactic checks

GOBLIN Workflow

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

General workflow:

1. Context-free wellformedness and other syntactic checks
2. Type checking

GOBLIN Workflow

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

General workflow:

1. Context-free wellformedness and other syntactic checks
2. Type checking
3. Desugar refinement types

GOBLIN Workflow

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

General workflow:

1. Context-free wellformedness and other syntactic checks
2. Type checking
3. Desugar refinement types
4. Disambiguate constraints

GOBLIN Workflow

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

General workflow:

1. Context-free wellformedness and other syntactic checks
2. Type checking
3. Desugar refinement types
4. Disambiguate constraints
5. Abstract derived fields

GOBLIN Workflow

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

General workflow:

1. Context-free wellformedness and other syntactic checks
2. Type checking
3. Desugar refinement types
4. Disambiguate constraints
5. Abstract derived fields
6. Main search algorithm

GOBLIN Workflow

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

General workflow:

1. Context-free wellformedness and other syntactic checks
2. Type checking
3. Desugar refinement types
4. Disambiguate constraints
5. Abstract derived fields
6. Main search algorithm
7. Compute derived fields

GOBLIN Workflow

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

General workflow:

1. Context-free wellformedness and other syntactic checks
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

- Context-free language emptiness (e.g., $S \rightarrow S$) is a modeling issue, stemming from non-wellfounded recursion

Context-Free Wellformedness

- Context-free language emptiness (e.g., $S \rightarrow S$) is a modeling issue, stemming from non-wellfounded recursion
- We perform a more general check called context-free wellformedness

Context-Free Wellformedness

- Context-free language emptiness (e.g., $S \rightarrow S$) is a modeling issue, stemming from non-wellfounded recursion
 - We perform a more general check called context-free wellformedness
1. Iteratively expand a set N of nonterminals known to be able to produce finite derivations until reaching a fixpoint

Context-Free Wellformedness

- Context-free language emptiness (e.g., $S \rightarrow S$) is a modeling issue, stemming from non-wellfounded recursion
 - We perform a more general check called context-free wellformedness
1. Iteratively expand a set N of nonterminals known to be able to produce finite derivations until reaching a fixpoint
 2. Check every reachable nonterminal is in N

Context-Free Wellformedness

- Context-free language emptiness (e.g., $S \rightarrow S$) is a modeling issue, stemming from non-wellfounded recursion
 - We perform a more general check called context-free wellformedness
1. Iteratively expand a set N of nonterminals known to be able to produce finite derivations until reaching a fixpoint
 2. Check every reachable nonterminal is in N

```
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 ...
```

Derived Field Checks

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

Derived Field Checks

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

1. Disallow cyclic dependencies (e.g. $\langle A \rangle \rightarrow T[\langle B \rangle]$, $\langle B \rangle \rightarrow T[\langle A \rangle]$)

Derived Field Checks

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

1. Disallow cyclic dependencies (e.g. $\langle A \rangle \rightarrow T[\langle B \rangle]$, $\langle B \rangle \rightarrow T[\langle A \rangle]$)
 - (i) Build a directed graph for each prod rule

Derived Field Checks

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

1. Disallow cyclic dependencies (e.g. $\langle A \rangle \rightarrow T[\langle B \rangle]$, $\langle B \rangle \rightarrow T[\langle A \rangle]$)
 - (i) Build a directed graph for each prod rule
 - (ii) Include vertex for each RHS nonterminal/symbolic terminal

Derived Field Checks

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

1. Disallow cyclic dependencies (e.g. $\langle A \rangle \rightarrow T[\langle B \rangle]$, $\langle B \rangle \rightarrow T[\langle A \rangle]$)
 - (i) Build a directed graph for each prod rule
 - (ii) Include vertex for each RHS nonterminal/symbolic terminal
 - (iii) Check for cycles

Derived Field Checks

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

1. Disallow cyclic dependencies (e.g. $\langle A \rangle \rightarrow T[\langle B \rangle]$, $\langle B \rangle \rightarrow T[\langle A \rangle]$)
 - (i) Build a directed graph for each prod rule
 - (ii) Include vertex for each RHS nonterminal/symbolic terminal
 - (iii) Check for cycles
2. Disallow derived fields in semantic constraints

Derived Field Checks

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

1. Disallow **cyclic dependencies** (e.g. $\langle A \rangle \rightarrow T[\langle B \rangle]$, $\langle B \rangle \rightarrow T[\langle A \rangle]$)
 - (i) Build a directed graph for each prod rule
 - (ii) Include vertex for each RHS nonterminal/symbolic terminal
 - (iii) Check for cycles
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

Abstract derived fields

We remove derived fields from G before the main search; compute them after constraint solving

```
1 <PACKET> ::= <TYPE> <AUX> <PAYLOAD>
2   { <AUX> <- <PAYLOAD>.<F1> bvmul <PAYLOAD>.<F2>;
3   ...
```

~>

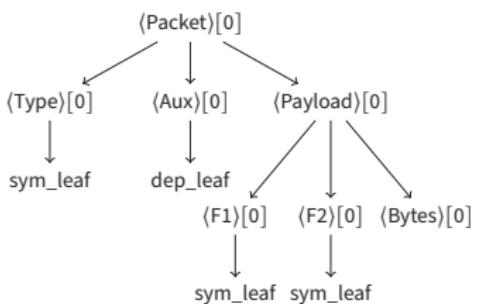
```
1 <PACKET> ::= <TYPE> dep_sym_leaf <PAYLOAD>
2   { ...
```

Search Algorithm: Main Concepts

Start with context-free case

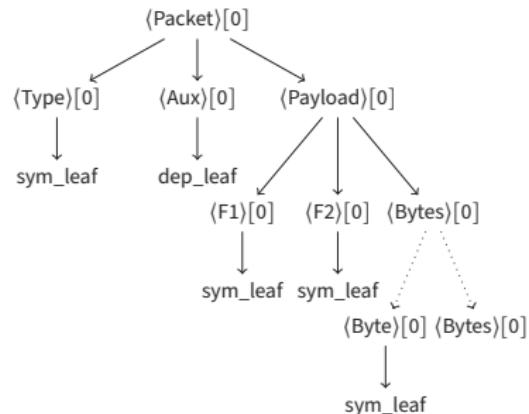
A derivation tree is an AST that may be open (or closed)

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



dt_1

\rightsquigarrow

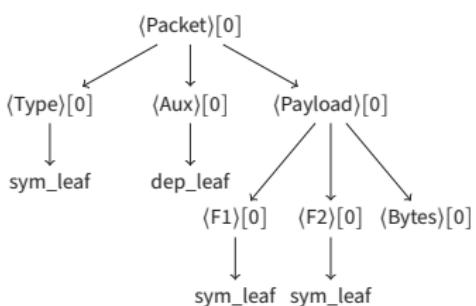


dt_2

Search Algorithm: Main Concepts

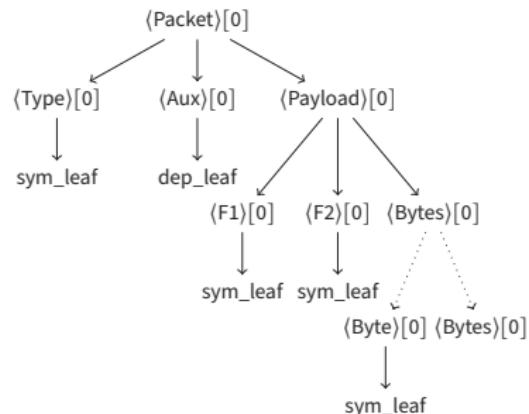
Choosing an expansion is called a **decision**

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



dt_1

\rightsquigarrow

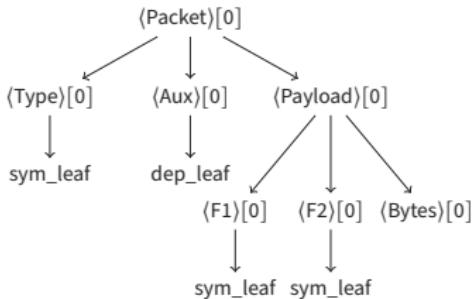


dt_2

Search Algorithm: Main Concepts

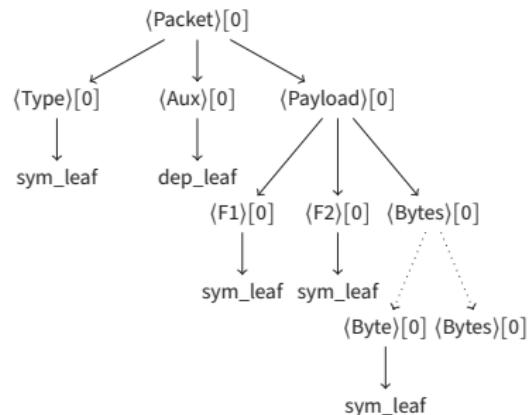
Some “decisions” are **forced**: symbolic terminals and nonterminals with exactly one production rule option

These are called **normalization steps** and are not stored in *ds*



dt₁

~



dt₂

Search Algorithm: Main Concepts

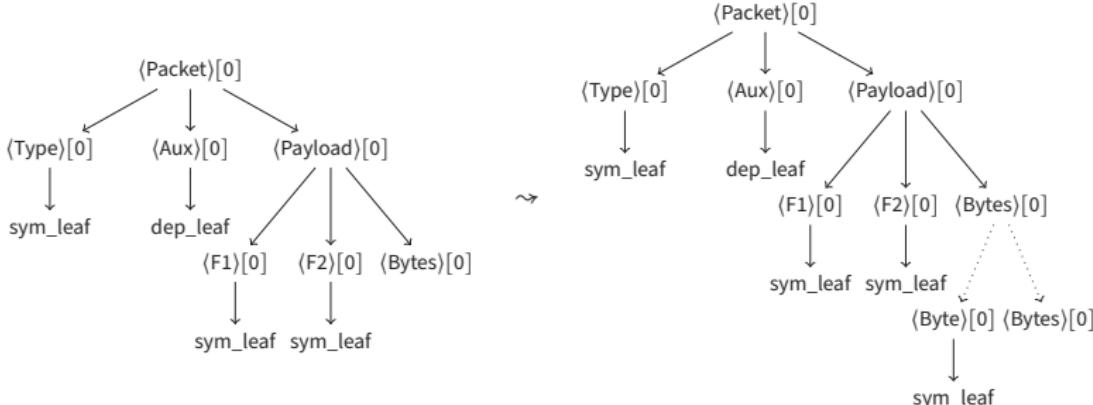
Termination is not guaranteed

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 $ds = []$



Search Algorithm: Main Concepts

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

Search Algorithm: Main Concepts

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

Insight: use an **incremental SMT** backend

Search Algorithm: Main Concepts

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

Insight: use an **incremental SMT** backend

Solver interface

Search Algorithm: Main Concepts

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

Insight: use an **incremental SMT** backend

Solver interface

- `(assert c)`: assert a constraint

Search Algorithm: Main Concepts

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

Insight: use an **incremental SMT** backend

Solver interface

- `(assert c)`: assert a constraint
- `(push 1)`: push an assertion level

Search Algorithm: Main Concepts

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

Insight: use an **incremental SMT** backend

Solver interface

- `(assert c)`: assert a constraint
- `(push 1)`: push an assertion level
- `(pop 1)`: undo assertions in last assertion level (backtrack)

Search Algorithm: Main Concepts

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

Insight: use an **incremental SMT** backend

Solver interface

- `(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**

Search Algorithm: Main Concepts

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

Insight: use an **incremental SMT** backend

Solver interface

- `(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

Search Algorithm: Main Concepts

Principles of constraint handling

1. Push an assertion frame at every decision

Search Algorithm: Main Concepts

Principles of constraint handling

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`

Search Algorithm: Main Concepts

Principles of constraint handling

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**

Search Algorithm: Main Concepts

Principles of constraint handling

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

Search Algorithm: Main concepts

There are wrinkles...

Search Algorithm: Main concepts

There are wrinkles...

1. Constraints must be **disambiguated** and **universalized**

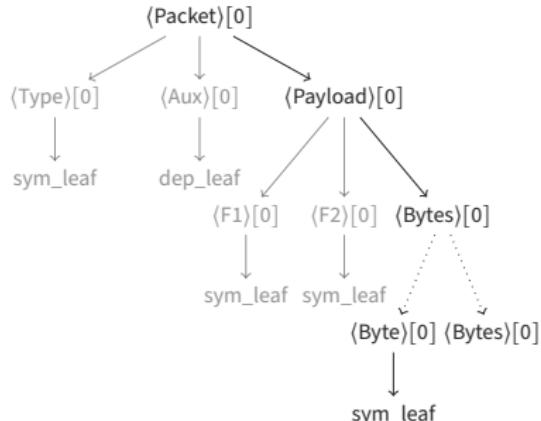
Search Algorithm: Main concepts

There are wrinkles...

1. Constraints must be **disambiguated** and **universalized**

```
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



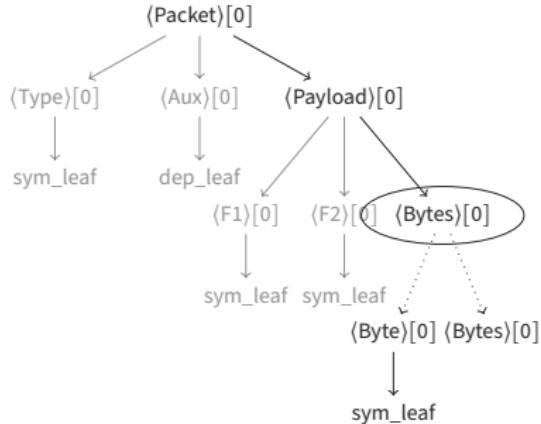
Search Algorithm: Main concepts

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

packet0_payload0_bytes0_opt0 >_{bv} 0x0



Formal guarantees

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

Formal guarantees

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

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

Evaluation

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

Evaluation

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

- XML, ScriptSize C, and CSV input generation

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

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)

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

Case study 4

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

Evaluation

Case study 4

- WiFi SAE packet input generation (SAECRED's SyGuS engine;
GOBLIN predecessor)
- Handle **bit vector SMT constraints** not expressible in ISLa

Evaluation

Case study 4

- WiFi SAE packet input generation (SAECRED's SyGuS engine; GOBLIN predecessor)
- Handle **bit vector SMT constraints** not expressible in ISLa
- 36x improvement in efficiency

Evaluation

Case study 4

- 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(.)`

Discussion and future work

- User-facing language
 - Synthesized and inherited attributes
 - User-defined recursive functions
 - Built-ins like `length(.)`
- More powerful type system (e.g., polymorphism)

Discussion and future work

- User-facing language
 - Synthesized and inherited attributes
 - User-defined recursive functions
 - Built-ins like `length(.)`
- More powerful type system (e.g., polymorphism)
- AI abstraction/refinement algorithms

Discussion and future work

- User-facing language
 - Synthesized and inherited attributes
 - User-defined recursive functions
 - Built-ins like `length(.)`
- More powerful type system (e.g., polymorphism)
- AI abstraction/refinement algorithms
- Finite model finding and CLP engines

Discussion and future work

- User-facing language
 - Synthesized and inherited attributes
 - User-defined recursive functions
 - Built-ins like `length(.)`
- More powerful type system (e.g., polymorphism)
- AI abstraction/refinement algorithms
- Finite model finding and CLP engines
- Divide and conquer/parallel approaches

Discussion and future work

- User-facing language
 - Synthesized and inherited attributes
 - User-defined recursive functions
 - Built-ins like `length(.)`
- More powerful type system (e.g., polymorphism)
- AI abstraction/refinement algorithms
- 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

```
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
```