

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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**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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7 <open-tag>   ::= '<' <id> '>' | '<' <id> ' ' <attribute> '>'  
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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?

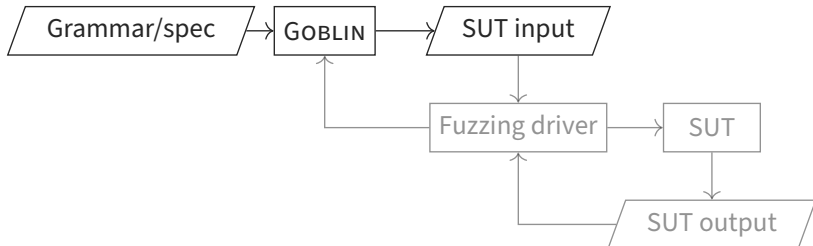
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1 <xml-tree> ::= <openclose-tag> |  
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Input generation vs fuzzing

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

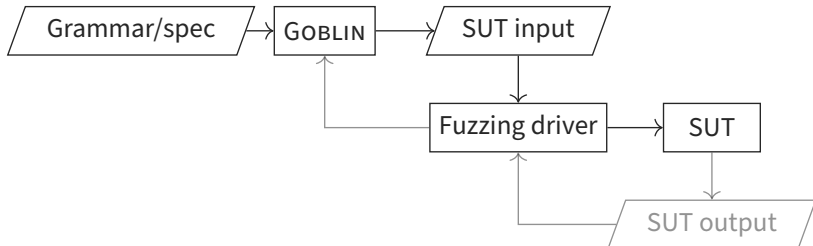
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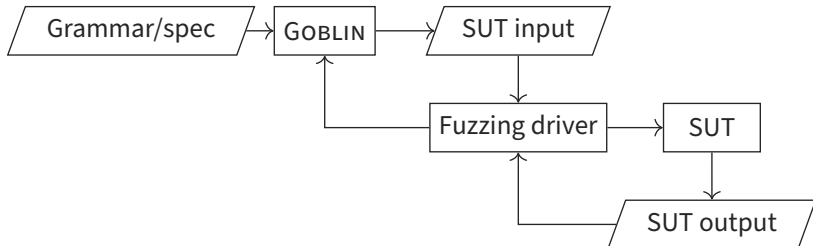
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GOBLIN by example: Language features

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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3
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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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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);
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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; };
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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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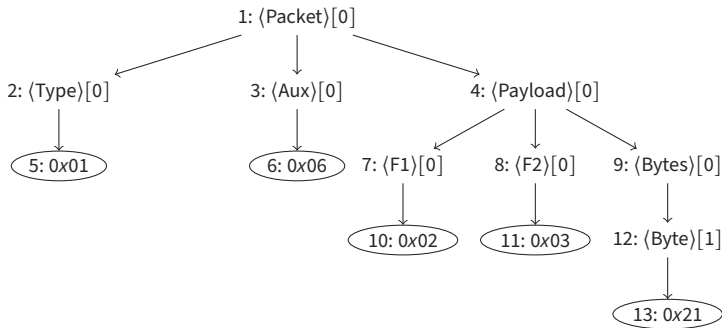
Derived fields with <- denote nonterminals that are directly computable, enforced syntactically
Cryptographic hashes, checksums, or any computable function

Semantics: Abstract syntax trees

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

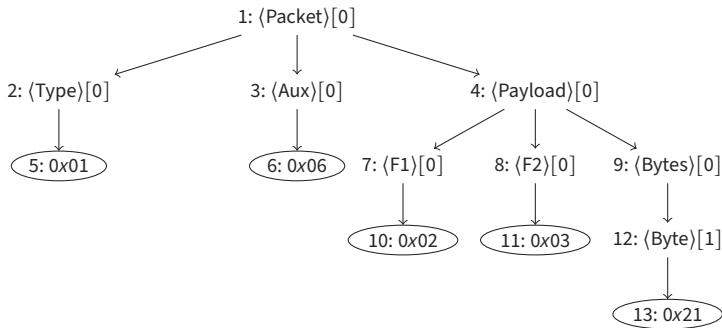
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The ADT view allows GOBLIN to natively support constraints over arbitrary SMT theories

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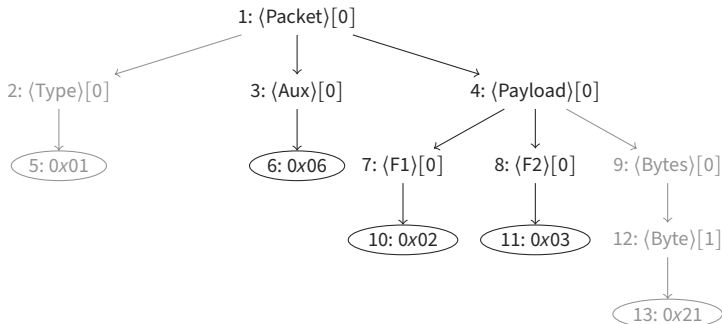
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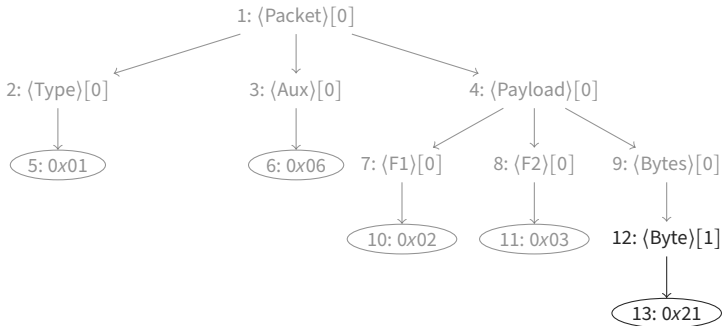
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```
1 <SAE_PACKET> ::= <COMMIT> | <CONFIRM>;
2 <COMMIT> ::= <FIELD> <RG_ID_LIST>;
3 <RG_ID_LIST> ::= <RG_ID> <RG_ID_LIST>;
4 <CONFIRM> ::= <FIELD1> <FIELD2>;
5 ...
```

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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> 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

Start with **context-free case**

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

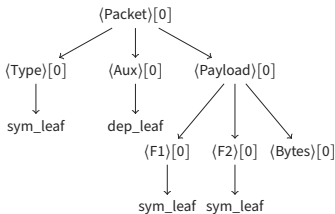
1. Build candidate *dt* via random walk until closed
2. Then instantiate with concrete values

Search Algorithm: Main Concepts

Start with **context-free** case

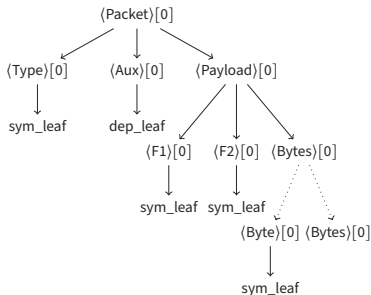
A **derivation tree** is an AST that may be **open** (or **closed**)

1. Build candidate **dt** via random walk until closed
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dt_1

\sim

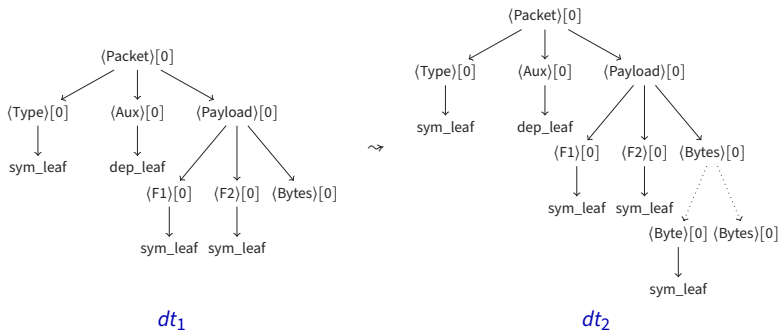


dt_2

Search Algorithm: Main Concepts

Choosing an expansion is called a **decision**

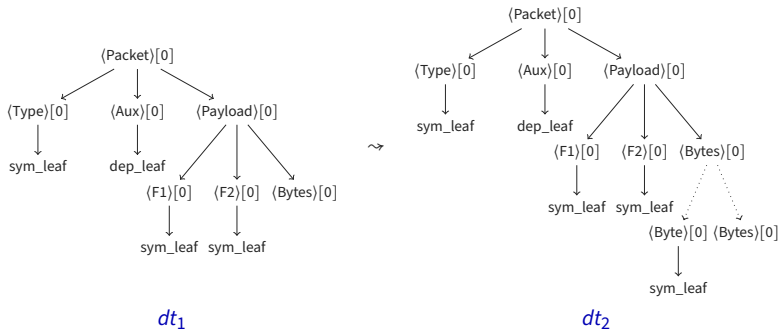
Decisions are recorded in a **decision stack** $ds = [dt_1, dt_2]$



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*



Search Algorithm: Main Concepts

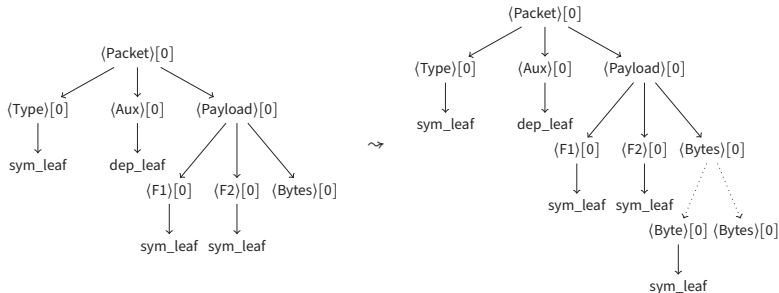
Termination is not guaranteed

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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- `(assert c)`: assert a constraint

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

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- `(get-model)`: retrieve a concrete model

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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...

Search Algorithm: Main concepts

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

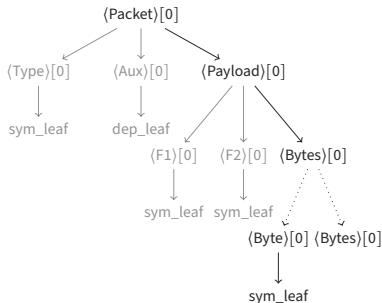
Search Algorithm: Main concepts

There are wrinkles...

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

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

packet0_payload0_bytes0_opt0 >_{bv} 0x0

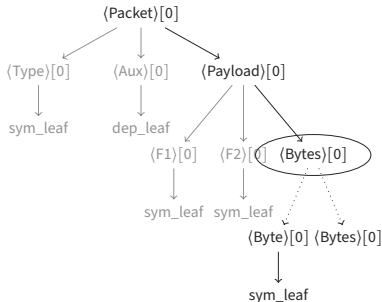


Search Algorithm: Main concepts

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

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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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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

Case study 4

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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 ($\sim 24,000$ / $\sim 97,000$ up to $\sim 49,000$ / $\sim 97,000$)

Discussion and future work

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

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- 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

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

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

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

...

Semantics: Satisfaction relation

Satisfaction relation \models_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,

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

$\models_G \neg\varphi$ if $\not\models_G \varphi$

$tr \models_G \varphi_1 \wedge \varphi_2$ if $tr \models_G \varphi_1$ and $tr \models_G \varphi_2$

$tr \models_G \varphi_1 \vee \varphi_2$ if $tr \models_G \varphi_1$ or $tr \models_G \varphi_2$

$tr \models_G \varphi_1 \Rightarrow \varphi_2$ if $tr \not\models_G \varphi_1$ or $tr \models_G \varphi_2$

Semantics: Denotation of G

Semantics of a GOBLIN input G is the set of syntactically valid ASTs which satisfy all the constraints

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

Calculus

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

Example rule expands a symbolic terminal

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

Search algorithm pseudocode

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