Parse this!
Summoning Context-Sensitive Inputs with Goblin

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Problem Introduction

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- Given an input specification, how to generate inputs?

Existing Approaches

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  - Mutations still blind to specification constraints

Wishlist

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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>
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7   <open-tag>  ::= '<'  <id> '>' | '<' <id> ' ' <attribute> '>'
8   <close-tag> ::= '</' <id> '>'
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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> |
2               <open-tag> <inner-tree> <close-tag>
3             { <open-tag>.<id> = <close-tag>.<id> }
4  ...
```
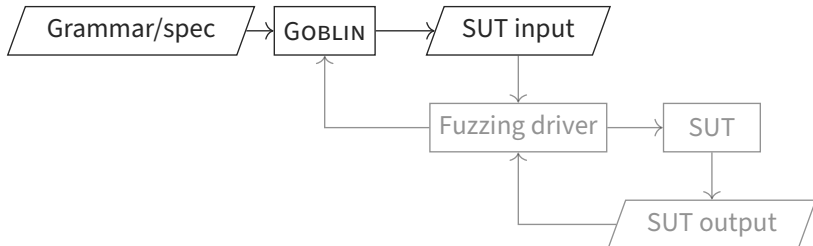
Input generation vs fuzzing

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

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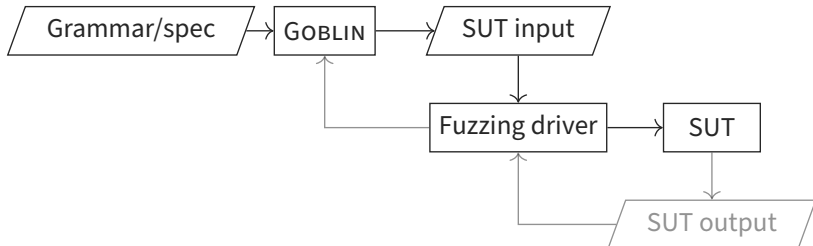
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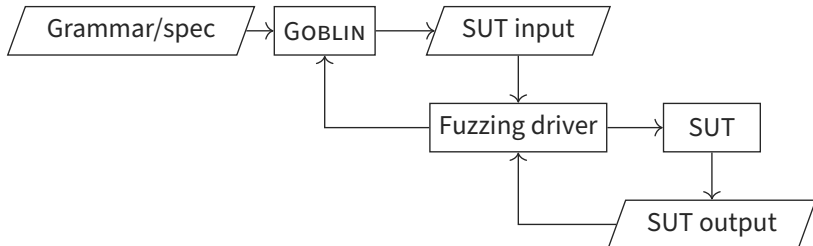
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GOBLIN by example: Language features

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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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 constraits 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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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
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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
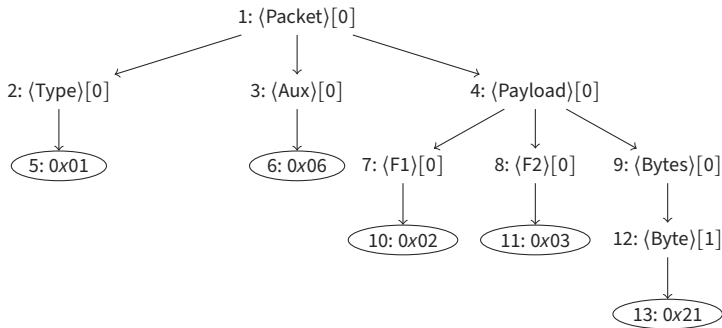
Semantics: Abstract syntax trees
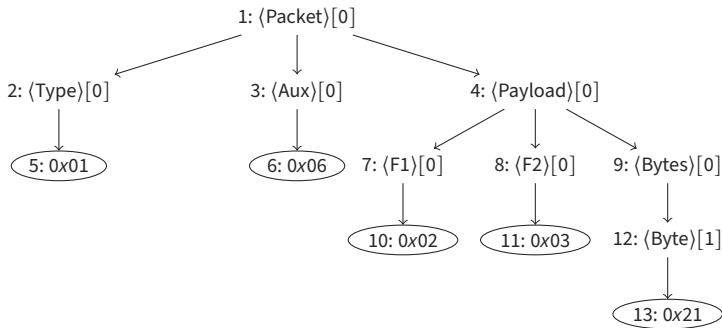
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Not a string `0x0106020321`

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- 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

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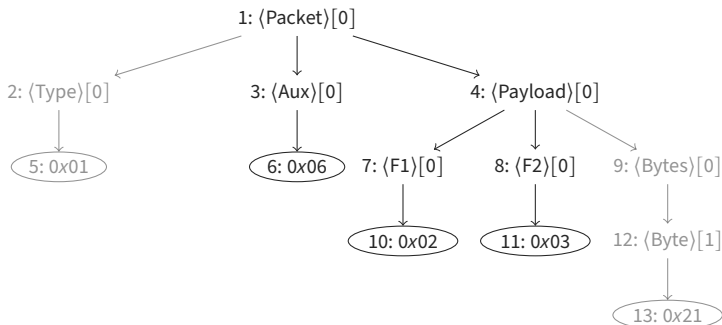
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$\}$

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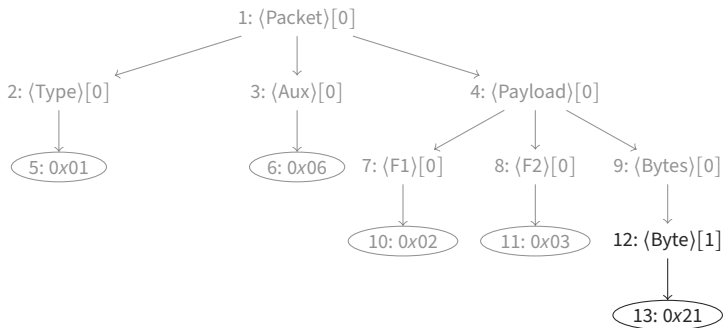
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```
1  <SAE_PACKET> ::= <COMMIT> | <CONFIRM>;
2  <COMMIT> ::= <FIELD> <RG_ID_LIST>;
3  <RG_ID_LIST> ::= <RG_ID> <RG_ID_LIST>;
4  <CONFIRM> ::= <FIELD1> <FIELD2>;
5  ...
```

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   – E.g., $\langle D \rangle > 0$ where $\langle D \rangle$ is derived

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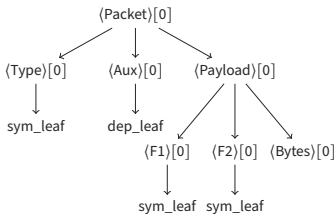
A derivation tree is an AST that may be open (or closed)

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

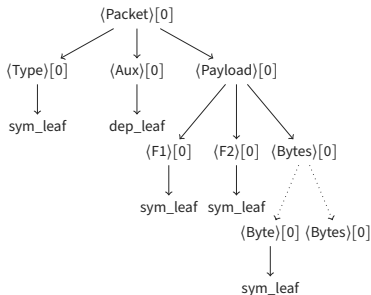# Search Algorithm: Main Concepts

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
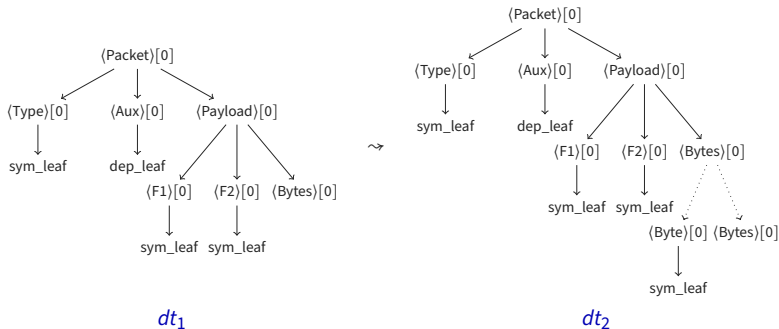2. Then instantiate with concrete values

dt_1 $\rightsquigarrow$ dt_2

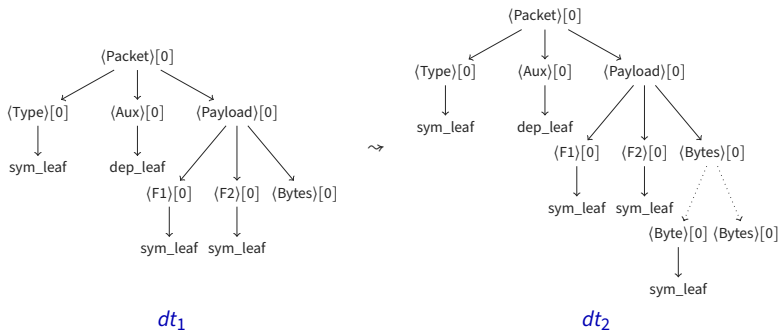# Search Algorithm: Main Concepts

Choosing an expansion is called a decision

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

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*

dt_1 $\rightsquigarrow$ dt_2
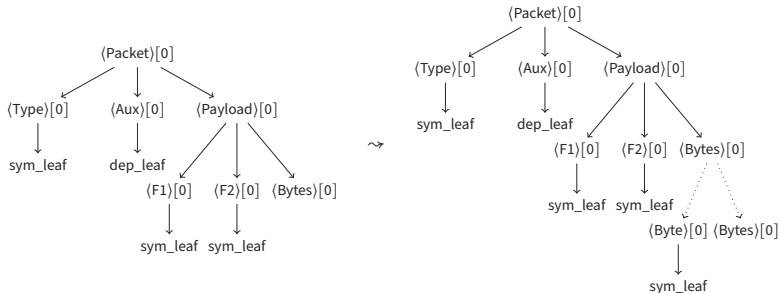
Search Algorithm: Main Concepts

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?

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Insight: use an incremental SMT backend

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- `(check-sat)`: check if conjunction of active assertions is SAT
- `(get-model)`: retrieve a concrete model

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Principles of constraint handling

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2. At each decision, `assert` all constraints associated with the expanded *dt* node and call `check-sat`

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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
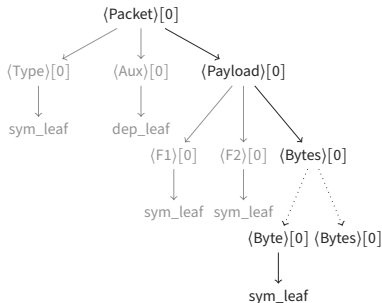
Search Algorithm: Main concepts

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
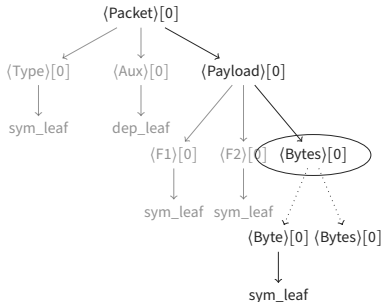
There are wrinkles...

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

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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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- 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 ~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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- 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

- 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

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

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

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

$\ldots$

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

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

Calculus

Can conceptualize as guarded rewrite rules on global state

Example rule expands a symbolic terminal

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

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 ∈ constraint set C do
17:             ASSERT if c is applicable
18:         if smt_check_sat() = UNSAT then
19:             if assertionLevel = 1 ∧ ¬bd? then
20:                 FAIL
21:             else if assertionLevel = 1 then
22:                 RESTARTUNSAT
23:             else
24:                 BACKTRACKUNSAT
```