Extending enumerative function synthesis via SMT-driven classification

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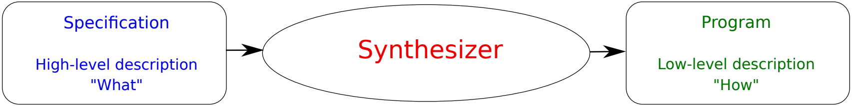
Program synthesis: "The Holy Grail of Computer Science"



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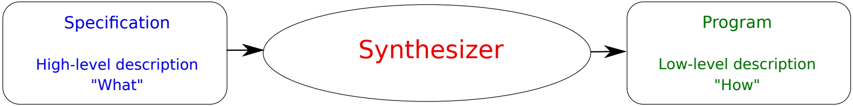

In	Out
0	1
1	2
2	4
3	8

$$P(x) =$$

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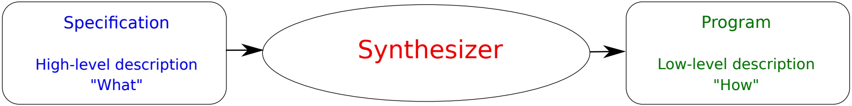

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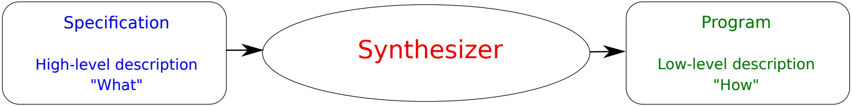

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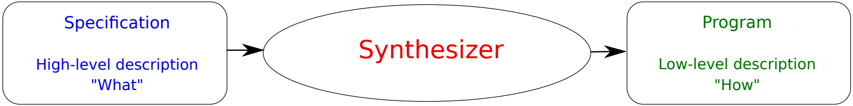

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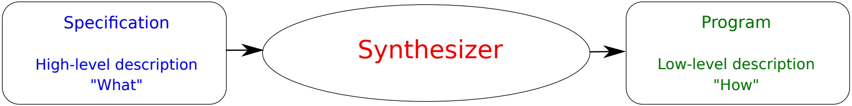

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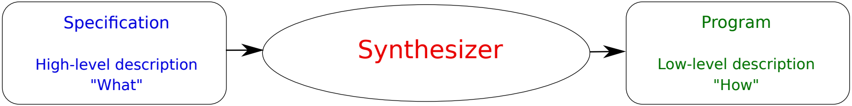

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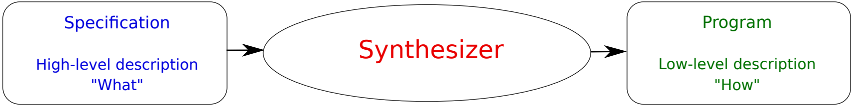

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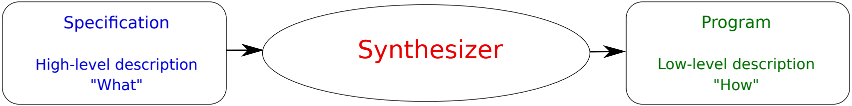

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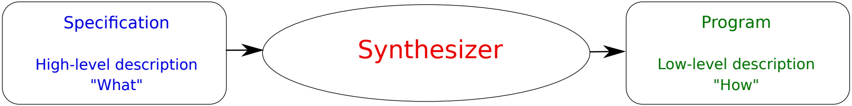

- Main challenges:
  - Exploring search space
  - Capturing intention

- Three main characteristics
  - How to write specification
  - How to constrain search space
  - How to guide the search

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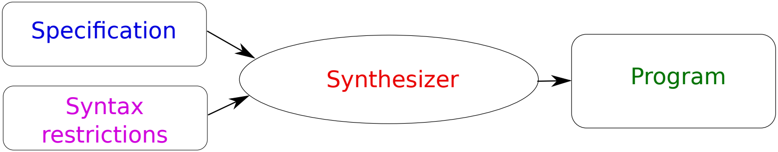
Some applications of program synthesis

- ▷ Superoptimization [SSA13], [NRB+19], ...
- ▷ Program repair [NWK+17], [LCL+17], ...
- ▷ Programming by examples [Gul11], [FMG+17] ...
- ▷ Circuit synthesis [EWW16], ...
- ▷ Loop invariant synthesis [GLM+14], [PSM16], ...
- ▷ ...

Syntax-Guided Synthesis (SyGuS) [ABJ+13]



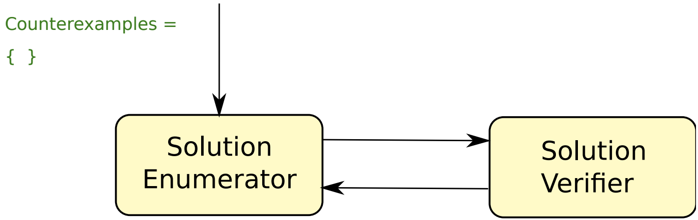
- ▷ Specification is given by (second-order) $\mathcal{T}$-formula: $\exists f.\, \forall \bar{x}.\, \varphi[f, \bar{x}]$
- ▷ Syntactic restrictions given by context-free grammar R

Enumerative CEGIS

Consider the example:

$$\varphi \quad = \quad f(x, x) \simeq x + 1 \wedge f(x, x+1) \simeq x$$

$$R \quad = \quad \begin{array}{l} A \to 0 \mid 1 \mid x \mid y \mid A + A \mid \mathrm{ite}(B, A, A) \\ B \to A \leq A \mid \neg B \end{array}$$



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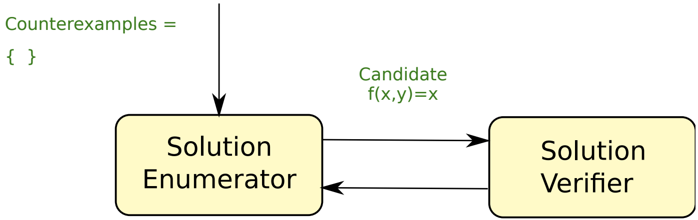

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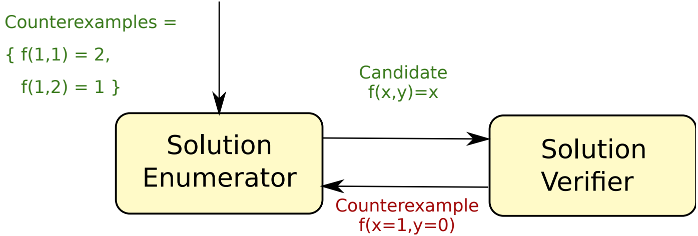

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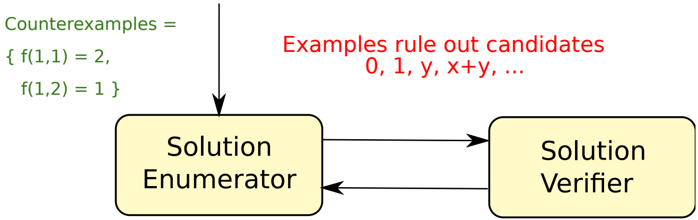

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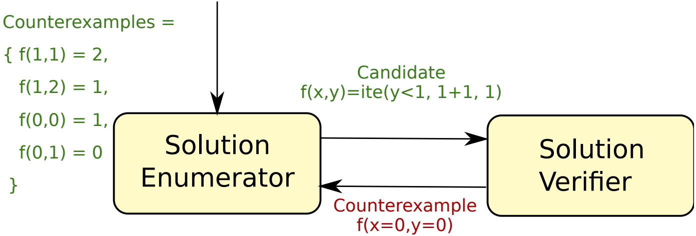

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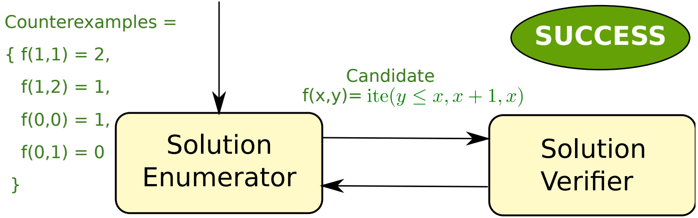

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Scalability issues

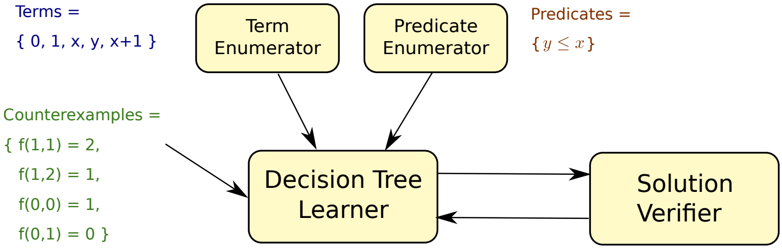
Enumerative techniques are effective but limited by the explosion of the enumeration space as term size increases

For this bit-vector grammar, enumerating

- Terms of size $= 1$: .05 seconds
- Terms of size $= 2$: .6 seconds
- Terms of size $= 3$: 48 seconds
- Terms of size $= 4$: 5.8 hours
- Terms of size $= 5$: ??? (100+ days)

```
(synth-fun f ((s (BitVec 4))
              (t (BitVec 4)))
 (BitVec 4) (
 (Start (BitVec 4) (
  s t #x0
  (bvneg  Start)
  (bvnot  Start)
  (bvadd  Start Start)
  (bvmul  Start Start)
  (bvand  Start Start)
  (bvlshr Start Start)
  (bvor   Start Start)
  (bvshl  Start Start)))))
```

Divide and conquer (D&C) [ARU17; NSM18]



- ▷ Generate partial solutions correct on subset of input
- ▷ Unify partial solutions via decision tree learning

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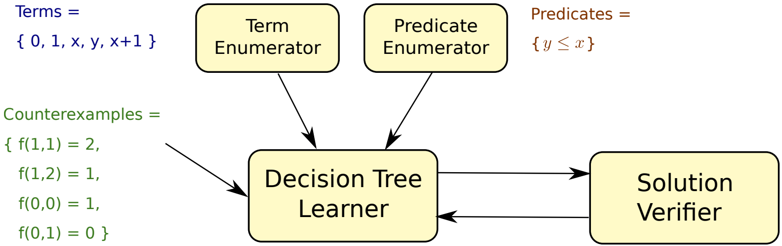

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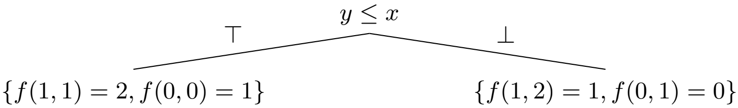

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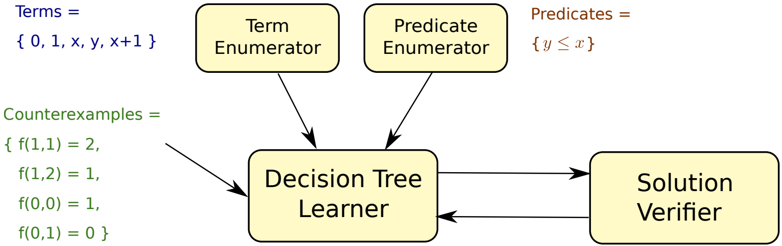

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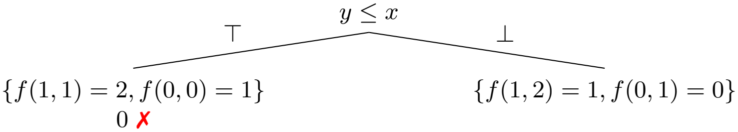

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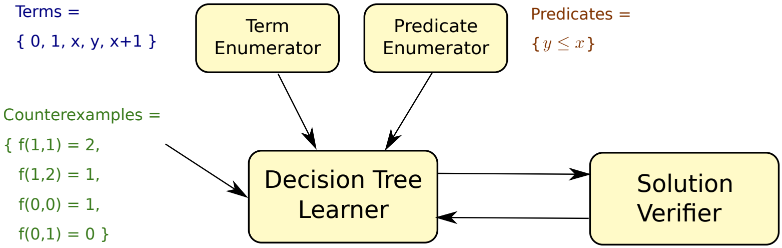

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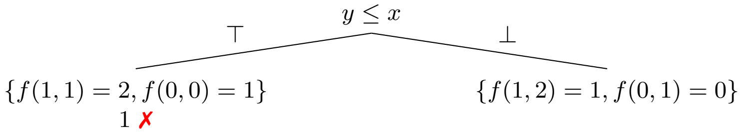

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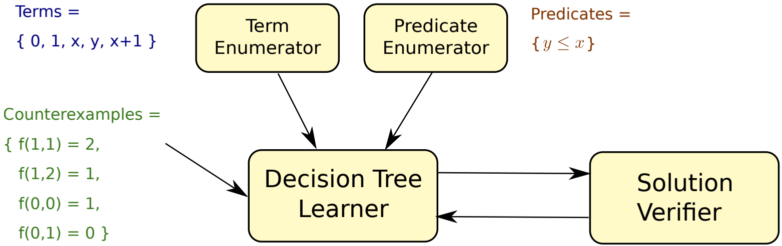

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$$y \le x$$

$\top$ $\bot$

$\{f(1,1) = 2, f(0,0) = 1\}$ $\{f(1,2) = 1, f(0,1) = 0\}$

x ✗

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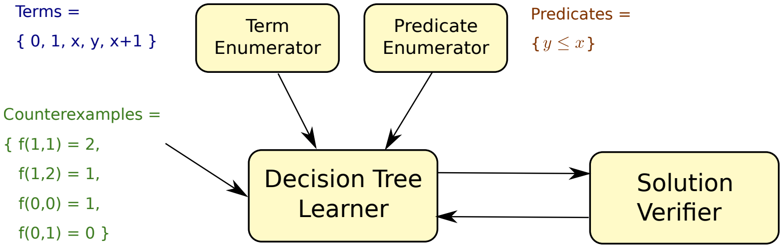

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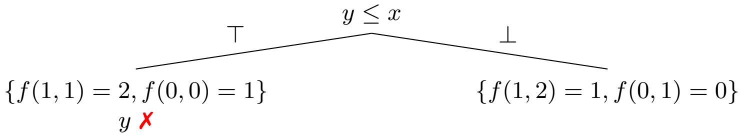

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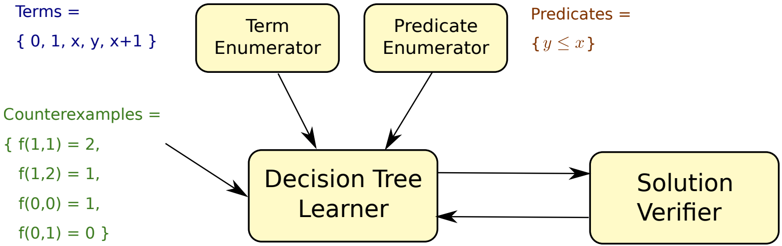

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$$y \leq x$$

$\top$: $\{f(1,1) = 2, f(0,0) = 1\}$ — $x + 1$ ✓

$\bot$: $\{f(1,2) = 1, f(0,1) = 0\}$

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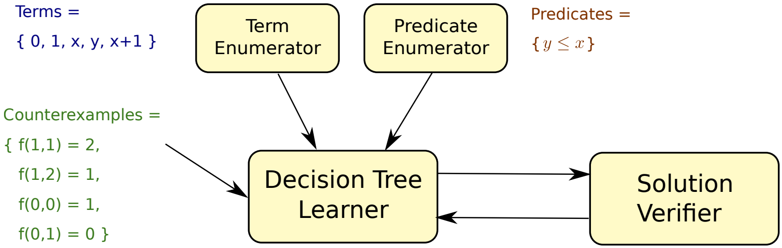

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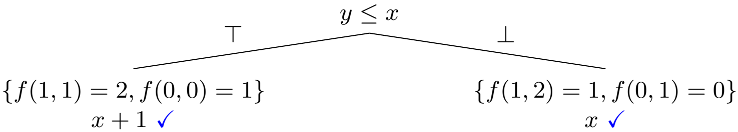

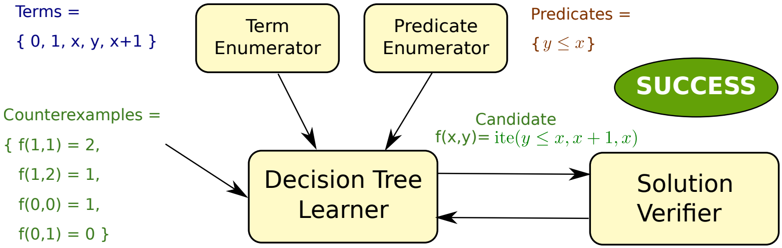

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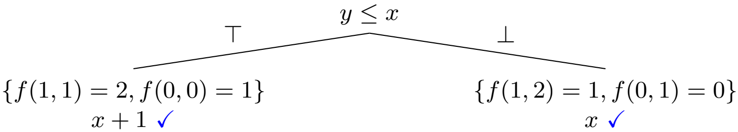

- D&C provides much better scalability

However...

- D&C can only be applied to point-wise specifications
  - Each input valuation is specified independently

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Consider augmenting the previous example:

$$\begin{aligned}\varphi = \quad & f(x, x) \simeq x+1 \land f(x, x+1) \simeq x \\ \land \quad & f(x, y) \simeq x+1 \Rightarrow f(x+2, y) \simeq x\end{aligned}$$

Counterexample $\{x \mapsto 1, y \mapsto 0\}$ yields the constraints:

$$f(1, 1) \simeq 2 \quad \land \quad f(1, 2) \simeq 1 \quad \land \quad f(1, 0) \simeq 2 \Rightarrow f(3, 0) \simeq 1$$

- A solution for $f(1, 0)$ restricts the solution for $f(3, 0)$
- Breaks assumption that partial solutions can be found *indepedently*

Challenges

- This limitation excludes interesting classes of synthesis problems
  - Invariants: $I(x) \wedge T(x, x') \Rightarrow I(x')$
  - Ranking functions: $rank(x') < rank(x)$
  - Modular arithmetic functions: $f(x) \simeq f(x+n)$
  - ...
- Extending D&C to arbitrary (non-point-wise) specifications:
  - Find a term assignment consistent with point dependencies
  - Correctly classify points according to term assignment

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Decision tree learning

- SMT-based solution-complete strategy
- Heuristic strategy

SMT solving for SyGuS

Satisfiability Modulo Theories (SMT)

First-order formulas in CNF:

$$\begin{array}{rcl} t & ::= & x \mid f(t,\ldots,t) \\ \varphi & ::= & p(t,\ldots,t) \mid \neg\varphi \mid \varphi \vee \varphi \mid \forall x_1 \ldots x_n.\, \varphi \end{array}$$

Given a formula φ in FOL and background theories $\mathcal{T}_1, \ldots, \mathcal{T}_n$, finding a model $\mathcal{M}$ giving an *interpretation* to all terms and predicates such that $\mathcal{M} \models_{\mathcal{T}_1,\ldots,\mathcal{T}_n} \varphi$

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Example

Is φ satisfiable modulo *equality* and *arithmetic*?

$$\varphi \;=\; (x_1 \geq 0) \wedge (x_1 < 1) \quad \wedge \quad (f(x_1) \not\simeq f(0) \quad \vee \quad x_3 + x_1 > x_3 + 1)$$

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$$\varphi \quad \models_{\text{LIA}} \quad x_1 \simeq 0$$

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$$\varphi \;=\; \underbrace{(x_1 \geq 0) \wedge (x_1 < 1)}_{\text{LIA}} \;\wedge\; (\underbrace{f(x_1) \not\simeq f(0)}_{\text{EUF}} \;\vee\; \underbrace{x_3 + x_1 > x_3 + 1}_{\text{LIA}})$$

$$\begin{array}{rcl} \varphi & \models_{\text{LIA}} & x_1 \simeq 0 \\ x_1 \simeq 0 & \models_{\text{EUF}} & f(x_1) \simeq f(0) \end{array}$$

Satisfiability Modulo Theories (SMT)

First-order formulas in CNF:

$$\begin{array}{lcl} t & ::= & x \mid f(t,\ldots,t) \\ \varphi & ::= & p(t,\ldots,t) \mid \neg\varphi \mid \varphi \vee \varphi \mid \forall x_1 \ldots x_n.\, \varphi \end{array}$$

Given a formula φ in FOL and background theories $\mathcal{T}_1, \ldots, \mathcal{T}_n$, finding a model $\mathcal{M}$ giving an *interpretation* to all terms and predicates such that $\mathcal{M} \models_{\mathcal{T}_1,\ldots,\mathcal{T}_n} \varphi$

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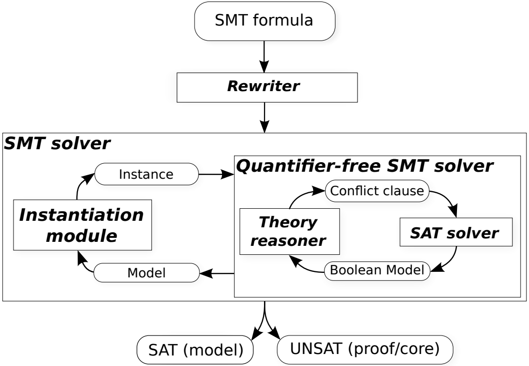
Therefore $\models_{\text{EUF}\cup\text{LIA}} \neg\varphi$

SMT solving [BT18]

- Decidability depends on the theories being used
- Efficient decision procedures
  - Equality and uninterpreted functions (Congruence Closure (CC)) [NO80], [DST80]
  - Algebraic datatypes (CC + Injectivity, Distinctness, Exhaustiveness, Acyclicity) [BST07]
  - Linear arithmetic (Simplex) [DM06]
  - Bit-vectors (Bit-blasting)
  - Combination of theories (Nelson-Oppen)
  - ...
- Boolean search leverages SAT solvers
- Users may define their own theories
  - New operators as uninterpreted functions + Axioms

CDCL($\mathcal{T}$) architecture



- Rewriter simplifies terms

  $x + 0 \to x$ $\quad$ $\mathsf{a} \not\approx \mathsf{a} \to \bot$ $\quad$ $(\text{str.replace}\ x\ (\text{str.++}\ x\ x)\ y) \to x$
- SAT solver enumerates models for Boolean skeleton of formula
- Theory solvers check consistency in the theory
- Instantiation module selects relevant instances

Enumerative SyGuS in SMT [RKT+17], [RVB+18]

- Encode problem using a deep embedding into datatypes

$$\varphi \quad = \quad f(x,\, x) \simeq x + 1 \,\wedge\, f(x,\, x+1) \simeq x$$

$$R \quad = \quad \begin{array}{l} A \to 0 \mid 1 \mid x \mid y \mid A + A \mid \mathrm{ite}(B,\, A,\, A) \\ B \to A \leq A \mid \neg B \end{array}$$

  Becomes

$$\llbracket \varphi \rrbracket \quad = \quad \mathrm{eval}_{\mathrm{a}}(d, x, x) \simeq x + 1 \,\wedge\, \mathrm{eval}_{\mathrm{a}}(d, x, x+1) \simeq x$$

$$\llbracket R \rrbracket \quad = \quad \begin{array}{ll} \mathrm{a} & = \mathrm{Zero} \mid \mathrm{One} \mid \mathrm{X} \mid \mathrm{Y} \mid \mathrm{Plus(a, a)} \mid \mathrm{Ite(b,\, a,\, a)} \\ \mathrm{b} & = \mathrm{Leq(a,\, a)} \mid \mathrm{Neg(b)} \end{array}$$

- eval maps datatype terms to their corresponding theory terms
  - $\mathrm{eval}_{\mathrm{a}}(\mathrm{Plus}(\mathrm{X}, \mathrm{X}), 2, 3)$ is interpreted as $(x + x)\{x \mapsto 2, y \mapsto 3\} = 4$

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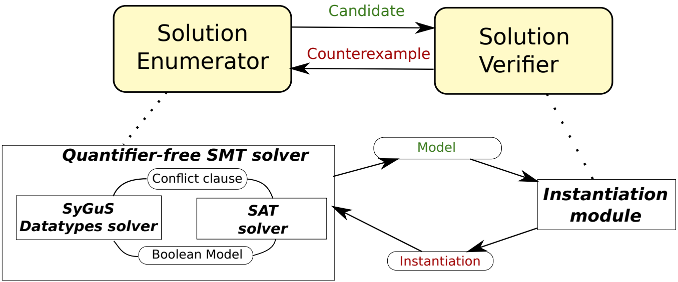
- A solution is a model in which e.g.
  - $d = \mathrm{Ite}(\mathrm{Leq}(\mathrm{Y},\, \mathrm{X}),\, \mathrm{Plus}(\mathrm{X}, \mathrm{One}),\, \mathrm{X})$, corresponding to
  - $f = \lambda xy.\, \mathrm{ite}(y \leq x,\, x + 1,\, x)$

Enumerative SyGuS in SMT [RKT+17], [RVB+18]



- An instantiation module checks candidates against the specification
  - Generates lemmas witnessing why a candidate failed
- A specialized datatypes solver for SyGuS generates candidate solutions
  - Must satisfy all lemmas
  - Dedicated pruning
  - Parameterizable fairness criteria for enumeration

Unif+PI: a general divide-and-conquer framework for SyGuS solving

Recapping

- D&C can only be applied to point-wise specifications
  - Each input valuation is specified independently
- Extending D&C to arbitrary (non-point-wise) specifications requires:
  - Find a term assignment consistent with point dependencies

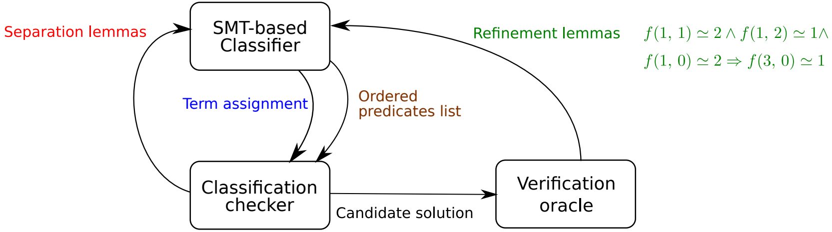
SMT solving

  - Correctly classify points according to term assignment

Decision tree learning

- SMT-based solution-complete strategy
- Heuristic strategy

Unif+PI: Synthesis via Pointwise-Indepentent unification

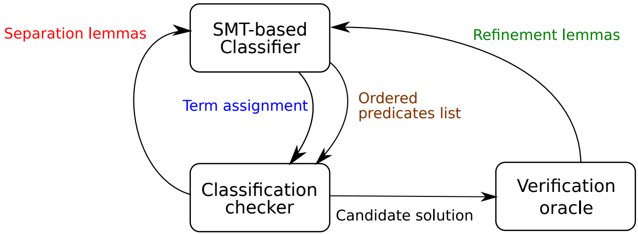


- *SMT-based classifier*
  - Assigns terms to points so that lemmas hold

$$f(1,\,1) \mapsto y + y, \quad \{f(1,\,0),\, f(3,\,0),\, f(1,\,2)\} \mapsto x$$

  - Generates ordered list of predicates to *separate* points: $P_1 \mapsto x \neq y$
- *Classification checker*: whether corresponding decision tree correctly classifies sample
  - Failures are encoded as *separation lemmas*

Unif+PI: Synthesis via Pointwise-Indepentent unification



▷ Successful candidates that are not verified lead to refinement lemmas and the learning restarts

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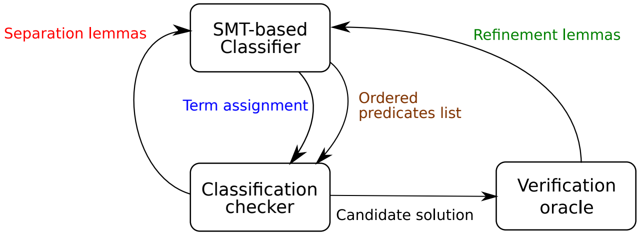

- Successful candidates that are not verified lead to refinement lemmas and the learning restarts
- Bounded *solution-completeness* and *minimality* results due to exhaustive enumeration of possible classifiers according to
  - *size* and *number* of distinct terms to be assigned
  - *size* and *number* of distinct predicates

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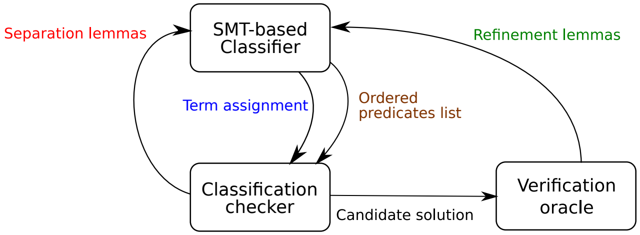

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- Bounded *solution-completeness* and *minimality* results due to exhaustive enumeration of possible classifiers according to
  - *size* and *number* of distinct terms to be assigned
  - *size* and *number* of distinct predicates
- Our fairness criteria are $size = log_2(\#terms)$, $\#pred = \#terms - 1$

Consider again:

$$\begin{aligned} \varphi = & \quad f(x, x) \simeq x + 1 \land f(x, x+1) \simeq x \\ \land & \quad f(x, y) \simeq x + 1 \Rightarrow f(x+2, y) \simeq x \end{aligned}$$

- Initially a single term of size 0 will be a trivial successful classifier

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$$f(1,\,1) \simeq 2 \quad \wedge \quad f(1,\,0) \simeq 2 \Rightarrow f(3,\,0) \simeq 1 \quad \wedge \quad f(1,\,2) \simeq 1$$

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- This classifier fails on the sample, yielding a separation lemma

$$P_1 \simeq \top \Rightarrow f(1, 1) \simeq f(1, 0)$$

$$\begin{array}{rcl} \varphi_R & = & f(1,\,1) \simeq 2 \quad \wedge \quad f(1,\,0) \simeq 2 \Rightarrow f(3,\,0) \simeq 1 \quad \wedge \quad f(1,\,2) \simeq 1 \\ \varphi_S & = & P_1 \simeq \top \Rightarrow f(1,\,1) \simeq f(1,\,0) \end{array}$$

- Given this constraints and current threshold the next candidate classifier produced is:

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$f(1,1)$

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$$f(1,1),\, f(1,0),\, f(3,0) \diamond f(1,2) \;\rightarrow$$

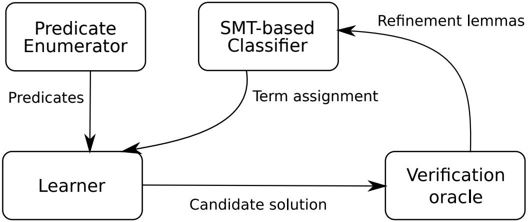
$$y \leq x$$

$\top$ $\qquad$ $\bot$

$$f(1,1),\, f(1,0),\, f(3,0) \qquad\qquad f(1,2)$$

- As the classification succeeds, a candidate is generated
- The candidate fails, so the process restarts with new refinement lemmas
- Eventually finds solution $f = \lambda xy.\, \mathrm{ite}(x \leq y,\, \mathrm{ite}(y \leq x,\, x+1,\, x),\, y)$

Unif+PI with unconstrained predicate enumeration



- Unif+PI+E uses SMT solver only to produce term assignments
  - Relies on standard decision tree learning to classify a labeled sample
  - Predicates chosen from enumerated pool with information-gain heuristic
  - Separation conflicts solved when new predicates are enumerated

- Often sacrificing completeness and minimality allows problems to be solved more efficiently

Experimental results

Setup

- Benchmarks (all over LIA)
  - 127 invariant synthesis benchmarks from SyGuS-COMP'18
  - 440 invariant synthesis benchmarks from test suite of Kind 2
- Three configurations of CVC4SY

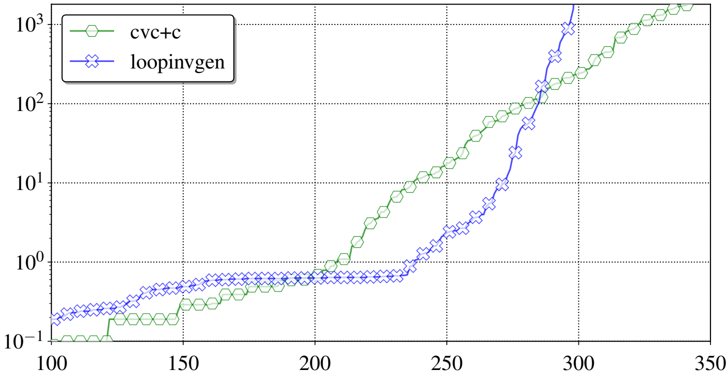
CVC+C	enumerative CEGIS [RBN+19]
CVC+UPI	Unif+PI
CVC+UPI+E	Unif+PI+E

- LOOPINVGEN [PM17] and CVC+C as baselines
- 1800s timeout, 8gb RAM

Full data at `http://cvc4.cs.stanford.edu/papers/FMCAD2019-UnifPI/`

Summary

	Solved	Unique	Total time	Fastest	Shortest
CVC+C	**341**	30	436251s	245	259
LOOPINVGEN	298	7	433273s	261	**289**



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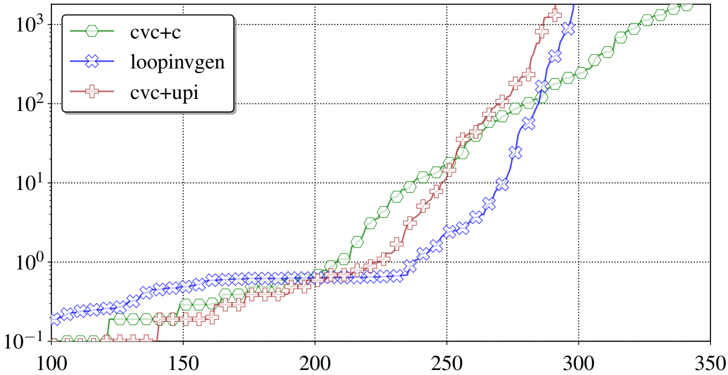

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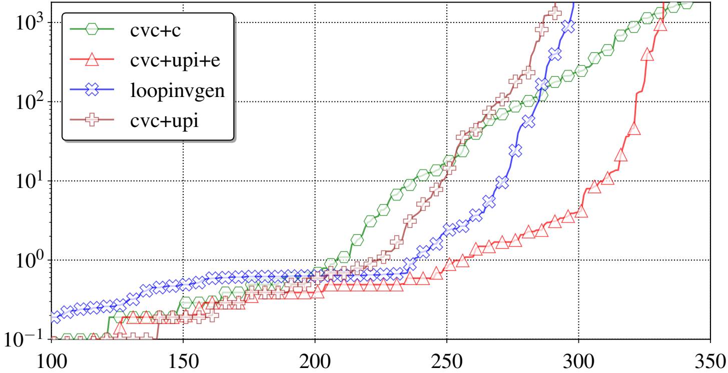
CVC-PORT	400	-	31476s	379	306



Advantages and disadvantages of Unif+PI

- CVC+UPI and CVC+UPI+E thrive when invariants can be built from combination of small literals
- CVC+C is superior when invariant is a single complex literal
  - 29 of its 30 unique solves are such cases
- CVC+UPI and CVC+UPI+E also suffer from dependence on samples
  - Sometimes search is biased towards simple classifiers when only a more complex one would suffice

Inv Track (829)

Solver	Solved	Fastest	Smallest	Score
CVC4-su	**592**	423	264	**4493**
LoopInvGen	512	**442**	**364**	4250
LoopInvGen-gplearn	511	411	349	4137
CVC4-Fast	522	319	243	3810
CVC4-Smart	539	283	260	3804
OASIS	538	20	317	3067
DryadSynth	277	161	39	1907

- ▷ 829 benchmarks from the literature in loop invariant synthesis
- ▷ 3600s timeout

Injecting some welcome realism

- Kind 2 employs in cooperation:
  - IC3 [Bra11]
  - k-induction [SSS00]
  - Generation of auxiliary invariants [KGT11]
- Kind 2 solves all the 480 benchmarks it its test suite in less than 120s
- Considering k-induction in isolation, CVC-PORT is competitive

	Solved	Unique	Time (commonly solved)
CVC-PORT	**323**	**82**	109.6
Kind 2 (k-induction)	313	72	**9.6**

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- We consider this encouraging given our framework is
  - not theory-specific
  - single-threaded
  - not optimized for reachability

Conclusions

Conclusions

- New enumerative function synthesis framework via divide and conquer
  - No dependence on point-wise specifications
  - Powered by SMT-driven classification algorithms
  - Implemented in CVC4SY
- Experimental evaluation shows significant gains w.r.t. previous SyGuS techniques for invariant synthesis

Future work

- Improving classification
  - Using constraint solving for synthesizing term assignments
  - Only considering relevant arguments when synthesizing predicates

$$f(0, 0, 0, 1, 2, 1, 0) \diamond f(1, 0, 0, 5, 2, 1, 3)$$

    - Can drastically reduce search space

- Improving sample
  - Reducing noise: make points as similar as possible

$$f(1, 0, 0, 1, 2, 1, 0) \diamond f(1, 0, 0, 5, 2, 1, 0)$$

  - Improve diversity via clustering analysis: only add new points to sample that are sufficiently different

Extending enumerative function synthesis via SMT-driven classification

Haniel Barbosa, Andrew Reynolds, Daniel Larraz, Cesare Tinelli

UFMG

The University of Iowa

Lógicos em Quarentena

2020-04-30, The Internet

Extra slides

Invariant Synthesis

```
Add(Int x, y) {
  z := x; i := 0;
  assume(y > 0);
  while (i < y) {
    z := z + 1;
    i := i + 1;
  }
  return z;
}
```

Post-condition:
$\forall x, y:\ z = x + y$

Result is the sum of the inputs

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Invariant?

Post-condition:
$\forall x, y : \; z = x + y$

Result is the sum of the inputs

Verification:

$$
\begin{array}{lcl}
z = x \wedge i = 0 \wedge y > 0 & \rightarrow & Inv(x,\, y,\, z,\, i) \\
Inv(x,\, y,\, z,\, i) \wedge i < y \wedge z' = z + 1 \wedge i' = i + 1 & \rightarrow & Inv(x,\, y,\, z',\, i') \\
Inv(x,\, y,\, z,\, i) \wedge i \geq y & \rightarrow & z = x + y
\end{array}
$$

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  while (i < y) {
    z := z + 1;
    i := i + 1;
  }
  return z;
}
```

$$Inv(x,\, y,\, z,\, i)$$
$$z = x + i$$
$$z \le x + y$$

Post-condition:
$\forall x, y:\ z = x + y$

Result is the sum of the inputs

Verification:

$$\begin{array}{lcl}
z = x \wedge i = 0 \wedge y > 0 & \rightarrow & Inv(x,\, y,\, z,\, i) \\
Inv(x,\, y,\, z,\, i) \wedge i < y \wedge z' = z + 1 \wedge i' = i + 1 & \rightarrow & Inv(x,\, y,\, z',\, i') \\
Inv(x,\, y,\, z,\, i) \wedge i \ge y & \rightarrow & z = x + y
\end{array}$$

Invariant Synthesis in SyGuS

- State-of-the-art: LoopInvGen [PM17]: *data-driven* loop invariant inference with automatic feature synthesis
  - Precondition inference from sets of "good" and "bad" states
    - Feature synthesis for solving conflicts
  - PAC (*probably approximately correct*) algorithm for building candidate invariants
- "Bad" states are dependent on model of initial condition (no guaranteed convergence)
- No support for implication counterexamples

Invariant Synthesis with Unif+PI

- Refinement lemmas allows derivation of three kinds on data points:
  - "good points" (invariant must always hold)
  - "bad points" (invariant can never hold)
  - "implication points" (if invariant holds in first point it must hold in second)
- Native support for implication counterexamples
- Straightforward usage of classic information gain heuristic to build candidate solutions with decision tree learning
  - SMT solver "resolves" implication counterexample points as "good" and "bad"
  - Out-of-the-box Shannon entropy

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