The SeaHorn Verification Framework

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Automated Software Analysis

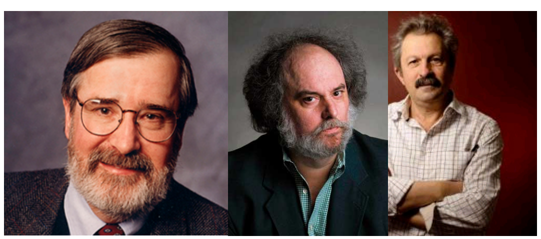
Program → Automated Analysis → Correct / Incorrect

Software Model Checking with Predicate Abstraction

e.g., Microsoft's SDV

Abstract Interpretation with Numeric Abstraction

e.g., ASTREE, Polyspace



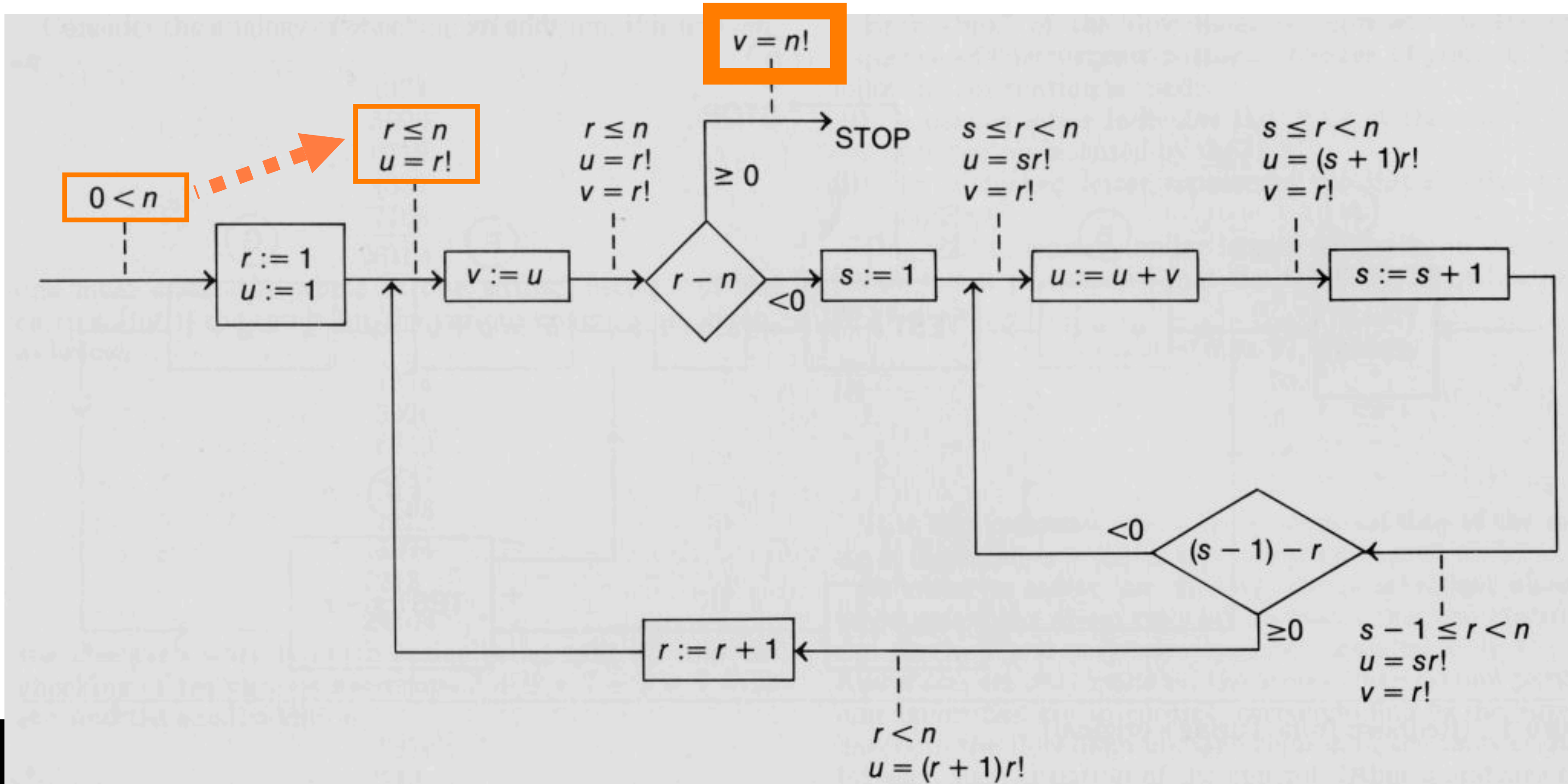
Turing, 1936: “undecidable”

Turing, 1949

Alan M. Turing. "Checking a large routine", 1949

How can one check a routine in the sense of making sure that it is right?

programmer should make a number of definite assertions which can be checked individually, and from which the correctness of the whole programme easily follows.

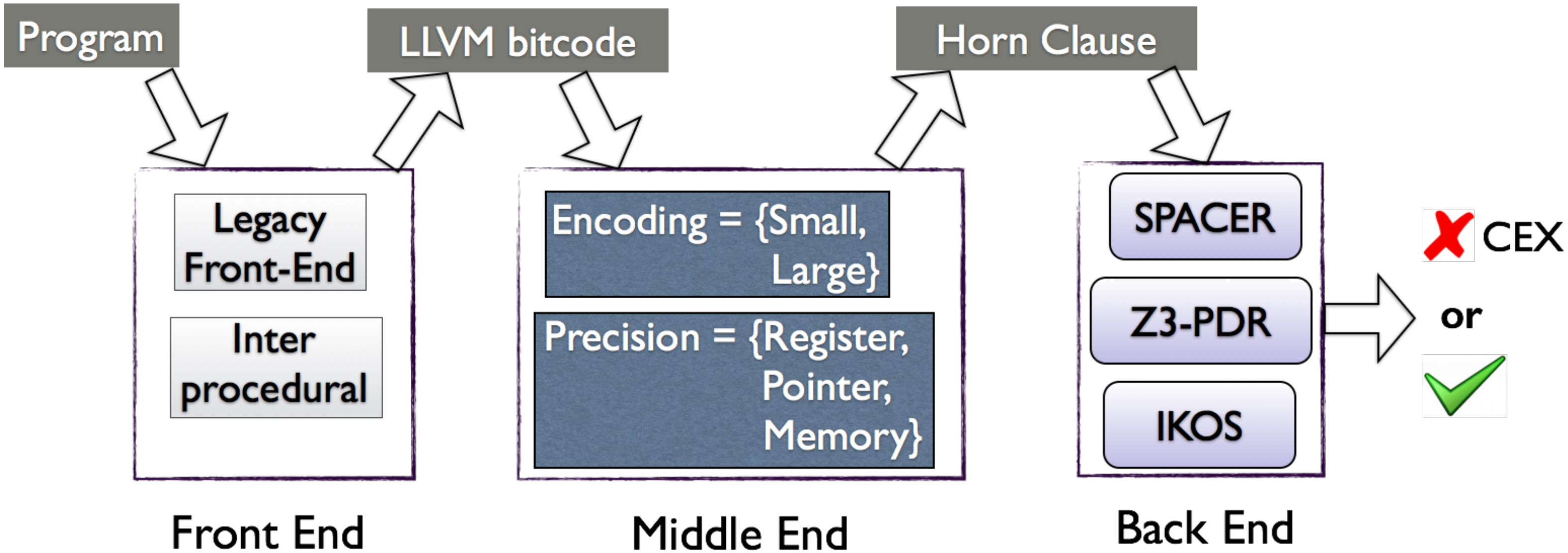


SeaHorn

A fully automated verification framework for LLVM-based languages.

http://seahorn.github.io

SeaHorn Verification Framework



Distinguishing Features

- LLVM front-end(s)
- Constrained Horn Clauses to represent Verification Conditions
- Comparable to state-of-the-art tools at SV-COMP'15

Goals

- be a state-of-the-art Software Model Checker
- be a framework for experimenting and developing CHC-based verification

Related Tools

CPAChecker

- Custom front-end for C
- Abstract Interpretation-inspired verification engine
- Predicate abstraction, invariant generation, BMC, k-induction

SMACK / Corral

- LLVM-based front-end
- Reduces C verification to Boogie
- Corral / Q verification back-end based on Bounded Model Checking with SMT

SeaHorn Usage

`> sea pf FILE.c`

Outputs `sat` for unsafe (has counterexample); `unsat` for safe

Additional options

- `--cex=trace.xml` outputs a counter-example in SV-COMP'15 format
- `--track={reg,ptr,mem}` track registers, pointers, memory content
- `--step={large,small}` verification condition step-semantics
  - *small* == basic block, *large* == loop-free control flow block
- `--inline` inline all functions in the front-end passes

Additional commands

- `sea smt` – generates CHC in extension of SMT-LIB2 format
- `sea clp` -- generates CHC in CLP format (under development)
- `sea lfe-smt` – generates CHC in SMT-LIB2 format using legacy front-end

Verification Pipeline

front-end

```
clang | pp | ms |opt | horn
```

compile

pre-process

mixed semantics

optimize

VC gen & solve

Constrained Horn Clauses (CHC)

Definition: A Constrained Horn Clause (CHC) is a formula of the form

$$\forall V . (\phi \wedge p_1[X_1] \wedge \ldots \wedge p_n[X_n] \rightarrow h[X]), \text{ where}$$

- ϕ is a constrained in a background theory A (e.g., arithmetic, arrays, SMT)
- $p_1, \ldots, p_n$, h are n-ary predicates
- $p_i[X]$ is an application of a predicate to first-order terms

We write clauses as rules, with all variables implicitly quantified

$$h[X] \leftarrow p_1[X_1], \ldots, p_n[X_n], \phi.$$

A model of a set of clauses Π is an interpretation of each predicate p_i that makes all clauses in Π valid

A set of clauses is satisfiable if it has a model, and is unsatisfiable otherwise

A model is A-definable, it each p_i is definable by a formula ψ_i in A

FROM PROGRAMS TO CLAUSES

Horn Clauses by Weakest Liberal Precondition

Prog = **def** Main(x) { body_M }, …, **def** P (x) { body_P }

wlp (x=E, Q) = **let** x=E **in** Q

wlp (**assert** (E) , Q) = E $\wedge$ Q

wlp (**assume**(E), Q) = E $\rightarrow$ Q

wlp (**while** E **do** S, Q) = I(w) $\wedge$

$\forall$w . ((I(w) $\wedge$ E) $\rightarrow$ wlp (S, I(w))) $\wedge$ ((I(w) $\wedge$ $\neg$E) $\rightarrow$ Q))

wlp (y = P(E), Q) = p_{pre}(E) $\wedge$ ($\forall$ r. p(E, r) $\rightarrow$ Q[r/y])

ToHorn (**def** P(x) {S}) = wlp (x0=x ; **assume** (p_{pre}(x)); S, p(x0, ret))

ToHorn (Prog) = wlp (Main(), true) $\wedge$ $\forall$\{P $\in$ Prog\} . ToHorn (P)

Horn Clauses by Dual WLP

Assumptions

- each procedure is represent by a control flow graph
  - i.e., statements of the form l_i:S ; goto l_j , where S is loop-free
- program is unsafe iff the last statement of Main() is reachable
  - i.e., no explicit assertions. All assertions are top-level.

For each procedure P(x), create predicates

- l(w) for each label, $p_{en}(x_0,x,w)$ for entry, $p_{ex}(x_0,r)$ for exit

The verification condition is a conjunction of clauses:

$p_{en}(x_0,x) \leftarrow x_0=x$

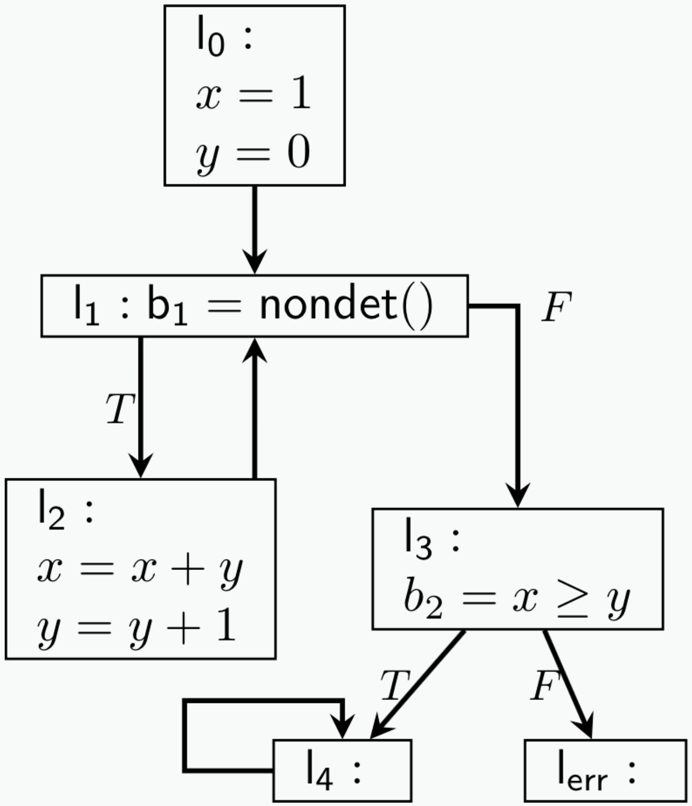
$l_i(x_0,w') \leftarrow l_j(x_0,w) \wedge \neg wlp(S, \neg(w=w'))$, for each statement l_i: S; goto l_j

$p(x_0,r) \leftarrow p_{ex}(x_0,r)$

$false \leftarrow Main_{ex}(x, ret)$

Example Horn Encoding

```
int x = 1;
int y = 0;
while (*) {
    x = x + y;
    y = y + 1;
}
assert(x >= y);
```



$$
\begin{aligned}
&\langle 1\rangle\ \mathsf{p}_0. \\
&\langle 2\rangle\ \mathsf{p}_1(x, y) \leftarrow \\
&\qquad\quad \mathsf{p}_0, x = 1, y = 0. \\
&\langle 3\rangle\ \mathsf{p}_2(x, y) \leftarrow \mathsf{p}_1(x, y)\ . \\
&\langle 4\rangle\ \mathsf{p}_3(x, y) \leftarrow \mathsf{p}_1(x, y)\ . \\
&\langle 5\rangle\ \mathsf{p}_1(x', y') \leftarrow \\
&\qquad\quad \mathsf{p}_2(x, y), \\
&\qquad\quad x' = x + y, \\
&\qquad\quad y' = y + 1. \\
&\langle 6\rangle\ \mathsf{p}_4 \leftarrow (x \geq y), \mathsf{p}_3(x, y). \\
&\langle 7\rangle\ \mathsf{p}_{err} \leftarrow (x < y), \mathsf{p}_3(x, y). \\
&\langle 8\rangle\ \mathsf{p}_4 \leftarrow \mathsf{p}_4.
\end{aligned}
$$

Large Step Encoding: Single Static Assignment

```
int x, y, n;

x = 0;
while (x < N) {
  if (y > 0)
    x = x + y;
  else
    x = x – y;
  y = -1 * y;
}
```

```
0: goto 1
1: x_0 = PHI(0:0, x_3:5);
   y_0 = PHI(y:0, y_1:5);
   if (x_0 < N) goto 2 else goto 6
2: if (y_0 > 0) goto 3 else goto 4

3: x_1 = x_0 + y_0; goto 5
4: x_2 = x_0 – y_0; goto 5

5: x_3 = PHI(x_1:3, x_2:4);
   y_1 = -1 * y_0;
   goto 1
6:
```

Example: Large Step Encoding

```
0: goto 1
1: x_0 = PHI(0:0, x_3:5);
   y_0 = PHI(y:0, y_1:5);
   if (x_0 < N) goto 2 else goto 6

2: if (y_0 > 0) goto 3 else goto 4

3: x_1 = x_0 + y_0; goto 5

4: x_2 = x_0 - y_0; goto 5

5: x_3 = PHI(x_1:3, x_2:4);
   y_1 = -1 * y_0;
   goto 1
6:
```

Example: Large Step Encoding

$x_1 = x_0 + y_0$
$x_2 = x_0 - y_0$
$y_1 = -1 * y_0$

```
1: x_0 = PHI(0:0, x_3:5);
   y_0 = PHI(y:0, y_1:5);
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   goto 1
```

Example: Large Step Encoding

$x_1 = x_0 + y_0$
$x_2 = x_0 - y_0$
$y_1 = -1 * y_0$

$B_2 \rightarrow x_0 < N$

$B_3 \rightarrow B_2 \wedge y_0 > 0$

$B_4 \rightarrow B_2 \wedge y_0 \leq 0$
$B_5 \rightarrow (B_3 \wedge x_3 = x_1) \vee (B_4 \wedge x_3 = x_2)$

$$\underbrace{B_5 \wedge x'_0 = x_3 \wedge y'_0 = y_1}$$

$p_1(x'_0, y'_0) \leftarrow p_1(x_0, y_0), \phi.$

```
1: x_0 = PHI(0:0, x_3:5);
   y_0 = PHI(y:0, y_1:5);
   if (x_0 < N) goto 2 else goto 6

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5: x_3 = PHI(x_1:3, x_2:4);
   y_1 = -1 * y_0;
   goto 1
```

Mixed Semantics

PROGRAM TRANSFORMATION

Mixed Semantics

[GWC'08,LQ'14]

Stack-free program semantics combining:

- operational (or small-step) semantics
  - i.e., usual execution semantics
- natural (or big-step) semantics: function summary [Sharir-Pnueli 81]
  - $(\sigma, \sigma`) \in ||f||$ iff the execution of f on input state σ terminates and results in state σ'
- some execution steps are big, some are small

Non-deterministic executions of function calls

- update top activation record using function summary, or
- enter function body, forgetting history records (i.e., no return!)

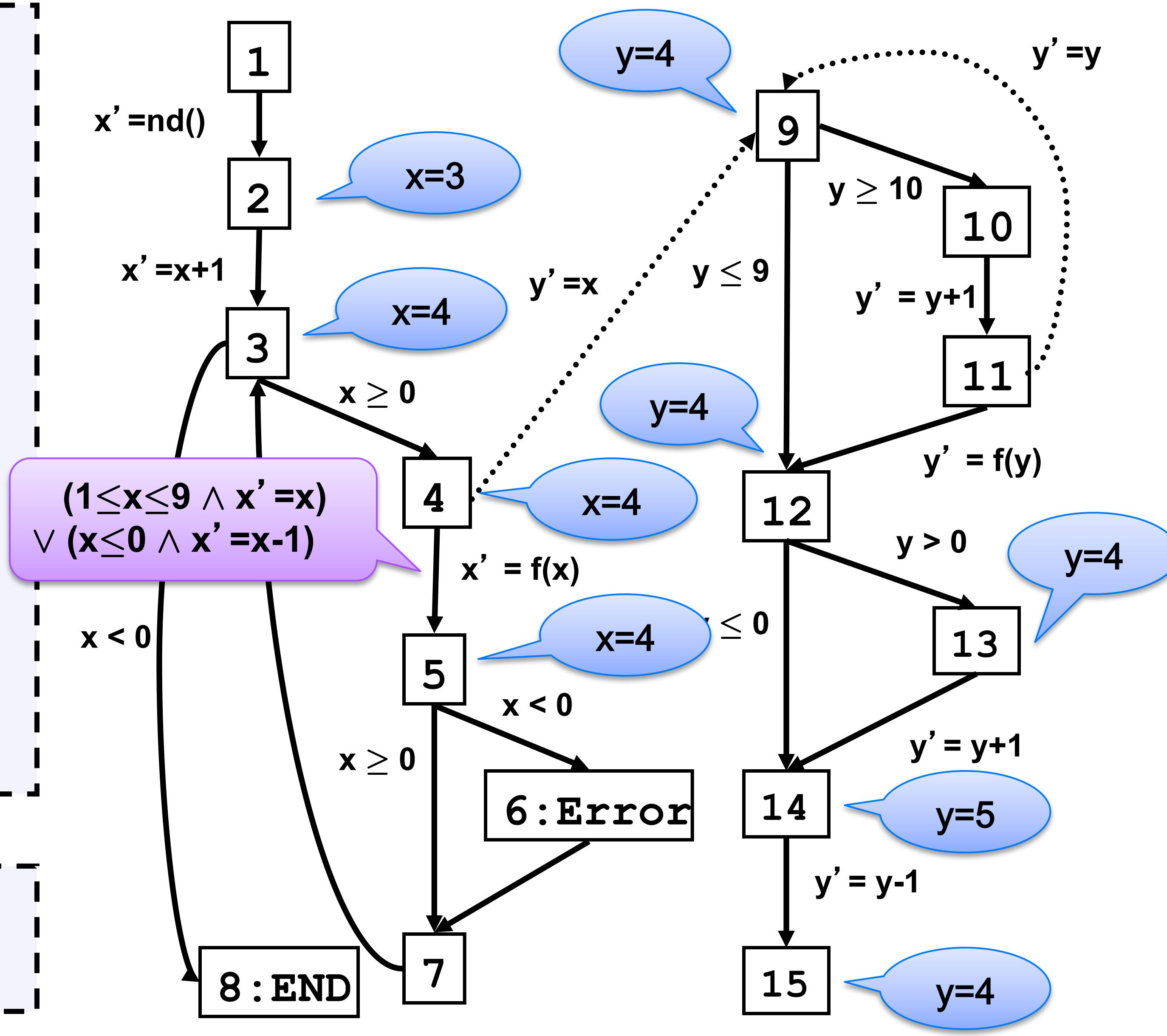
Preserves reachability and non-termination

Theorem: Let K be the operational semantics, K^m the stack-free semantics, and L a program location. Then,

$K \models EF\ (pc=L) \Leftrightarrow K^m \models EF\ (pc=L)$ and $K \models EG\ (pc \neq L) \Leftrightarrow K^m \models EG\ (pc \neq L)$

```
def main()
1: int x = nd();
2: x = x+1;
3: while(x>=0)
4:   x=f(x);
5:   if(x<0)
6:      Error;
7:
8: END;

def f(int y): ret y
9:  if(y,10){
10:    y=y+1;
11:    y=f(y);
12: else if(y>0)
13:   y=y+1;
14: y=y-1
15:
```



Summary of f(y)

$(1 \leq y \leq 9 \ \wedge \ y' = y)$
$\vee \ (y \leq 0 \ \wedge \ y' = y-1)$

Mixed Semantics as Program Transformation

$main$ ()
    $p1$ (); $p1$ ();
    assert ($c1$);
$p1$ ()
    $p2$ ();
    assert ($c2$);
$p2$ ()
    assert ($c3$);

Mixed Semantics

$main_{new}$ ()
    if (*) goto $p1_{entry}$;
    else $p1_{new}$ ();
    if (*) goto $p1_{entry}$;
    else $p1_{new}$ ();
    if ($\neg c1$) goto $error$;
    assume (false);

$p1_{entry}$:
    if (*) goto $p2_{entry}$;
    else $p2_{new}$ ();
    if ($\neg c2$) goto $error$;
$p2_{entry}$:
    if ($\neg c3$) goto $error$;
    assume (false);
$error$: assert (false);

$p1_{new}$ ()
    $p2_{new}$ ();
    assume ($c2$);
$p2_{new}$ ()
    assume ($c3$);

SOLVING CHC WITH SMT

Programs, Cexs, Invariants

A program *P = (V, Init, ρ, Bad)*

- Notation: $\mathcal{F}$(X) = ∃ ***u*** . (X ∧ ρ) ∨ Init

P is UNSAFE if and only if there exists a number *N* s.t.

$$Init(v_0) \wedge \left(\bigwedge_{i=0}^{N-1} \rho(v_i, v_{i+1}) \right) \wedge Bad(v_N) \;\not\Rightarrow\; \bot$$

P is SAFE if and only if there exists a *safe inductive invariant Inv s.t.*

$$\left.\begin{aligned} Init(u) &\Rightarrow Inv(u) \\ Inv(u) \wedge \rho(u, v) &\Rightarrow Inv(v) \end{aligned}\right\} \quad \boxed{\text{Inductive}}$$

$$Inv(u) \Rightarrow \neg Bad(u) \quad \boxed{\text{Safe}}$$

IC3/PDR Algorithm Overview

Input: Transition system $T = (\mathit{Init}, \mathit{Tr}, \mathit{Bad})$

$F_0 \leftarrow \mathit{Init}\,;\, N \leftarrow 0$

repeat

$\quad \boldsymbol{G} \leftarrow \textsc{PdrMkSafe}([F_0, \ldots, F_N], \mathit{Bad})$

$\quad$ **if** $\boldsymbol{G} = [\,]$ **then return** UNSAFE;

$\quad \forall 0 \leq i \leq N \cdot F_i \leftarrow \boldsymbol{G}[i]$

$\quad F_0, \ldots, F_N \leftarrow \textsc{PdrPush}([F_0, \ldots, F_N])$

$\quad$ `//` $F_0, \ldots, F_N$ `is a safe` δ`-trace`

$\quad$ **if** $\exists 0 \leq i \leq N \cdot F_i = \emptyset$ **then return** SAFE;

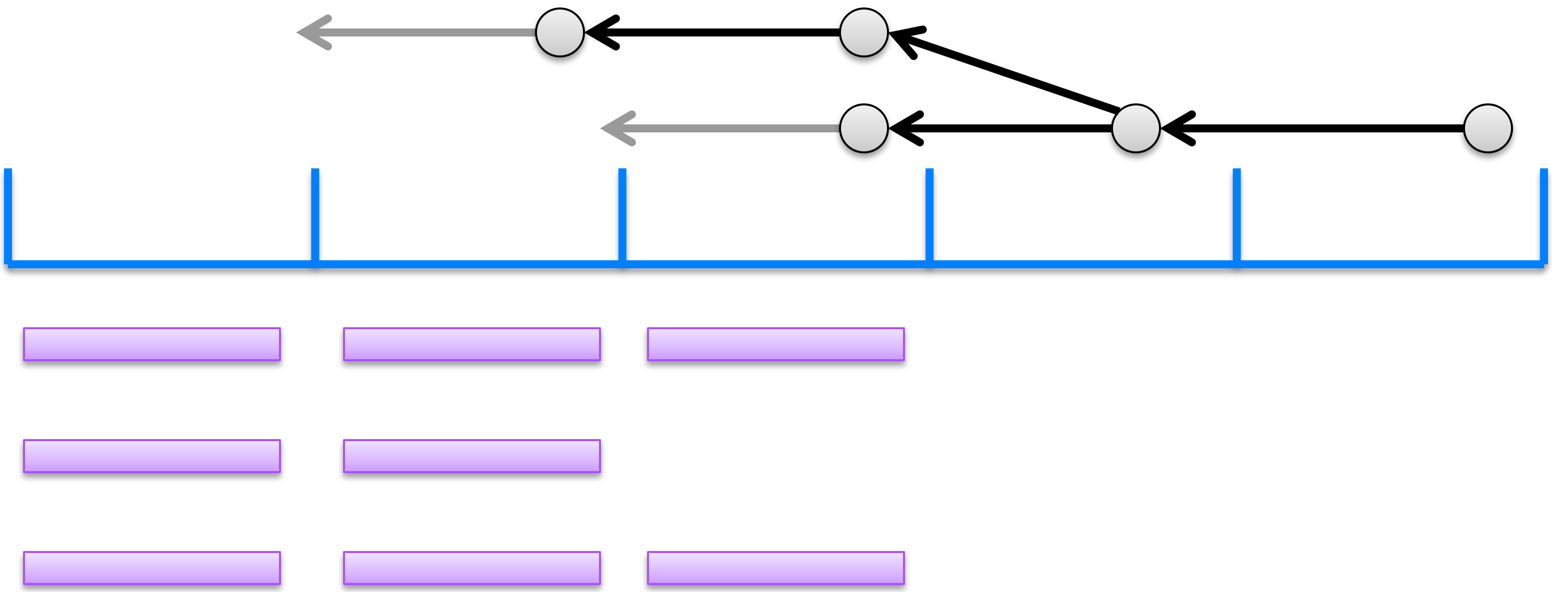
$\quad N \leftarrow N + 1\,;\, F_N \leftarrow \emptyset$

until ∞;

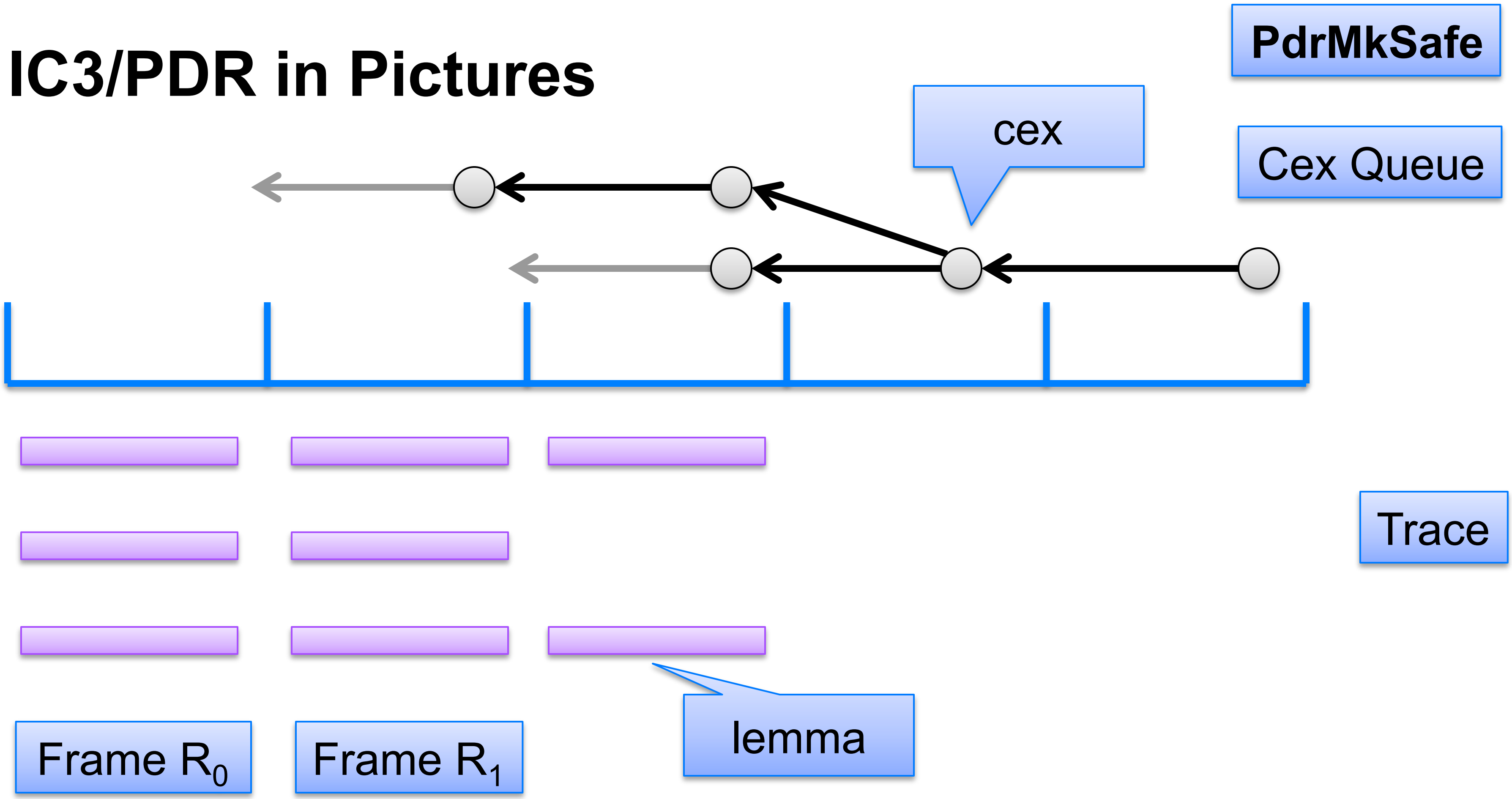
Aaron R. Bradley:SAT-Based Model Checking without Unrolling. VMCAI 2011: 70-87

IC3/PDR in Pictures

PdrMkSafe

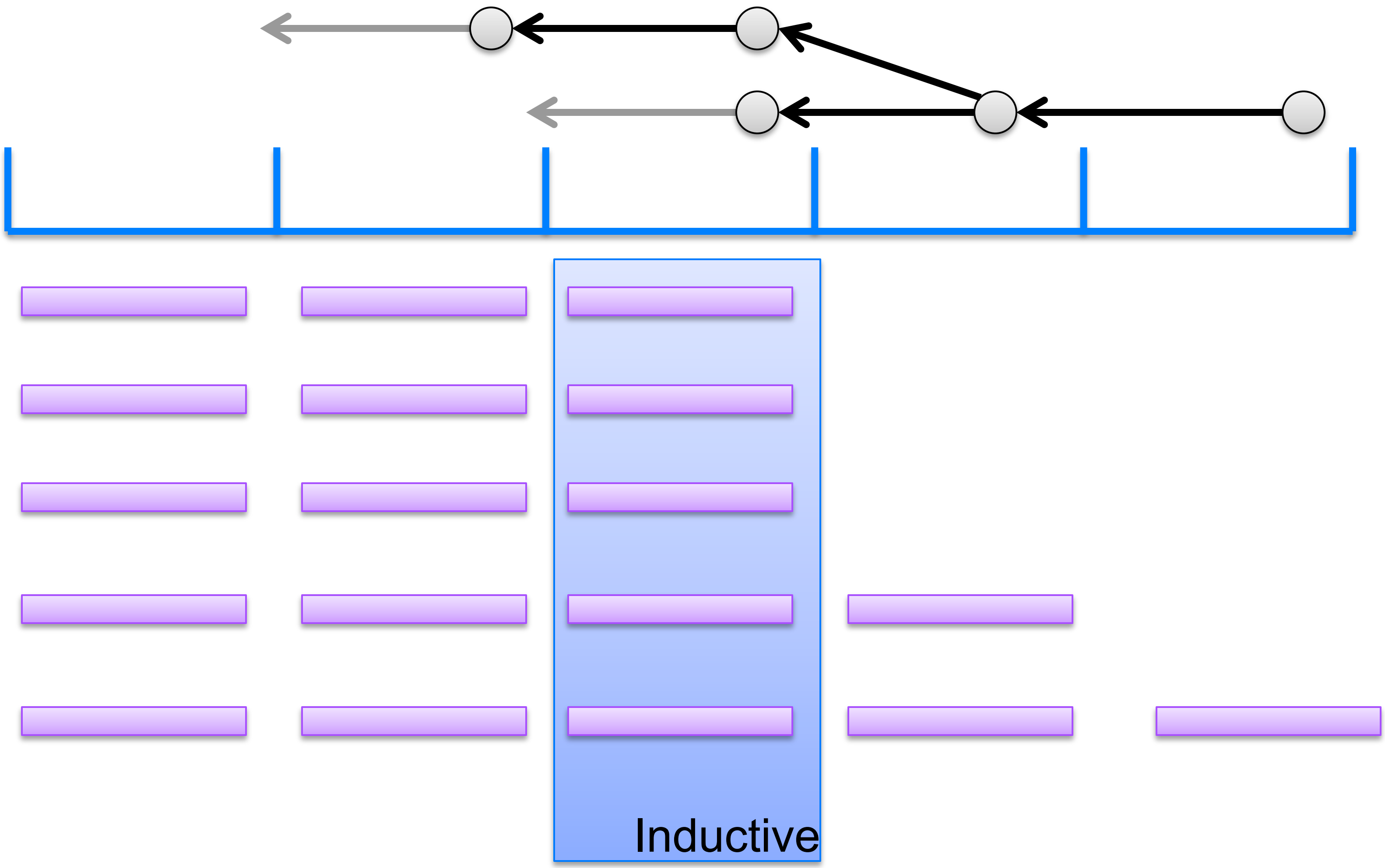


IC3/PDR in Pictures



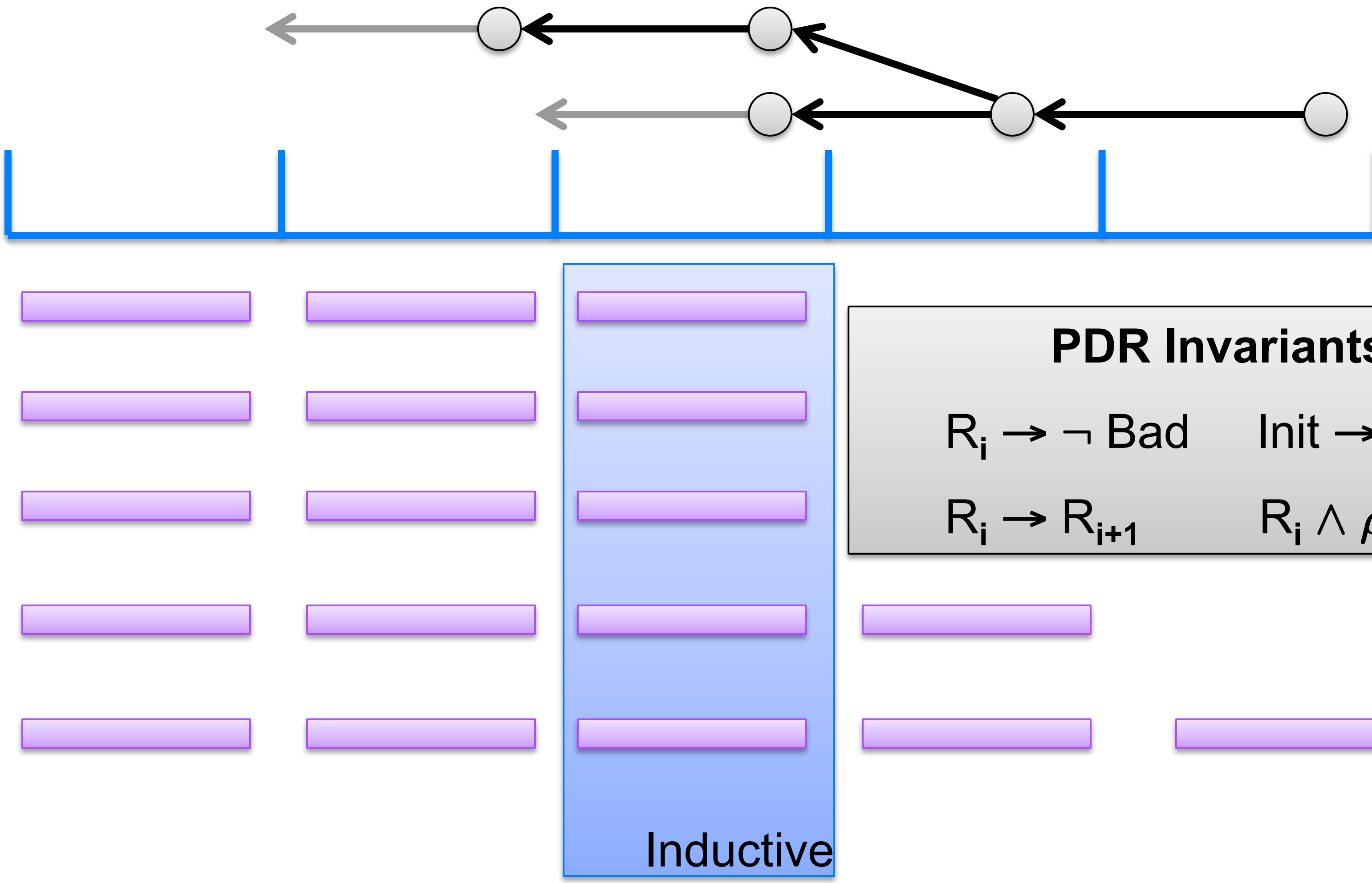
IC3/PDR in Pictures

PdrPush



IC3/PDR in Pictures

PdrPush



PDR Invariants

$R_i \rightarrow \neg$ Bad Init $\rightarrow R_i$

$R_i \rightarrow R_{i+1}$ $R_i \wedge \rho \rightarrow R_{i+1}$

IC3/PDR

Data: Q a queue of counter-examples. Initially, $Q = \emptyset$.
Data: N a level indication. Initially, $N = 0$.
Data: $R_0, R_1, \ldots, R_N$ is a trace. Initially, $R_0 = \mathit{Init}$.
repeat

Unreachable If there is an $i < N$ s.t. $R_{i+1} \rightarrow R_i$, return *Unreachable*.

Reachable If there is an m s.t. $\langle m, 0\rangle \in Q$ return *Reachable*.

Unfold If $R_N \rightarrow \neg \mathit{Bad}$, then set $N \leftarrow N + 1$, $R_N \leftarrow \top$.

Candidate If for some m, $m \rightarrow R_N \wedge \mathit{Bad}$, then add $\langle m, N\rangle$ to Q.

Decide If $\langle m, i+1\rangle \in Q$ and there are m_0 and m_1 s.t. $m_1 \rightarrow m$, $m_0 \wedge m_1'$ is satisfiable, and $m_0 \wedge m_1' \rightarrow \mathcal{F}(R_i) \wedge m'$, then add $\langle m_0, i\rangle$ to Q.

Conflict For $0 \leq i < N$: given a candidate model $\langle m, i+1\rangle \in Q$ and clause φ, such that $\neg\varphi \subseteq m$, if $\mathcal{F}(R_i \wedge \varphi) \rightarrow \varphi$, then add φ to R_j, for $j \leq i + 1$.

Leaf If $\langle m, i\rangle \in Q$, $0 < i < N$ and $\mathcal{F}(R_{i-1}) \wedge m'$ is unsatisfiable, then add $\langle m, i+1\rangle$ to Q.

Induction For $0 \leq i < N$, a clause $(\varphi \vee \psi) \in R_i$, $\varphi \notin R_{i+1}$, if $\mathcal{F}(R_i \wedge \varphi) \rightarrow \varphi$, then add φ to R_j, for each $j \leq i + 1$.

until ∞;

IC3/PDR

Data: Q a queue of counter-examples. Initially, $Q = \emptyset$.
Data: N a level indication. Initially, $N = 0$.
Data: $R_0, R_1, \ldots, R_N$ is a trace. Initially, $R_0 = Init$.
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Unreachable If there is an $i < N$ s.t. $R_{i+1} \rightarrow R_i$, return *Unreachable*.

Decide If $\langle m, i+1 \rangle \in Q$ and there are m_0 and m_1 s.t. $m_1 \rightarrow m$, $m_0 \wedge m_1'$ is satisfiable, and $m_0 \wedge m_1' \rightarrow \mathcal{F}(R_i) \wedge m'$, then add $\langle m_0, i \rangle$ to Q.

Conflict For $0 \leq i < N$: given a candidate model $\langle m, i+1 \rangle \in Q$ and clause φ, such that $\neg\varphi \subseteq m$, if $\mathcal{F}(R_i \wedge \varphi) \rightarrow \varphi$, then add φ to R_j, for $j \leq i+1$.

Induction For $0 \leq i < N$, a clause $(\varphi \vee \psi) \in R_i$, $\varphi \notin R_{i+1}$, if $\mathcal{F}(R_i \wedge \varphi) \rightarrow \varphi$, then add φ to R_j, for each $j \leq i+1$.

until ∞;

Extending PDR to Arithmetic: APDR

Decide$^{\mathcal{A}}$ If $\langle P, i+1\rangle \in Q$ and there is a model $m(\mathbf{v}, \mathbf{v}')$ s.t. $m \models \mathcal{F}(R_i) \wedge P'$, add $\langle P_{\downarrow}, i\rangle$ to Q, where $P_{\downarrow} \in \textsc{Mbp}(\mathbf{v}', m, \mathcal{F}(R_i) \wedge P')$.

Conflict$^{\mathcal{A}}$ For $0 \leq i < N$, given a counterexample $\langle P, i+1\rangle \in Q$ s.t. $\mathcal{F}(R_i) \wedge P'$ is unsatisfiable, add $P^{\uparrow} = \textsc{Itp}(\mathcal{F}(R_i)(\mathbf{v}_0, \mathbf{v}), P)$ to R_j for $j \leq i+1$.

Model Based Projection: MBP(***v***, m, F) [KGC'14]

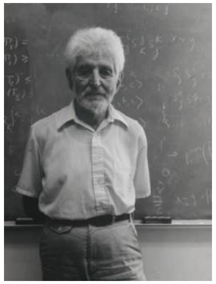
- generates an implicant of ∃ ***v*** . F that contains the model m

Counter-examples are monomials (conjunction of inequalities)

Lemmas are clauses (disjunction of inequalities)

APDR computes an (possibly non-convex) QFLRA invariant in CNF

Craig Interpolation Theorem



Theorem (Craig 1957)

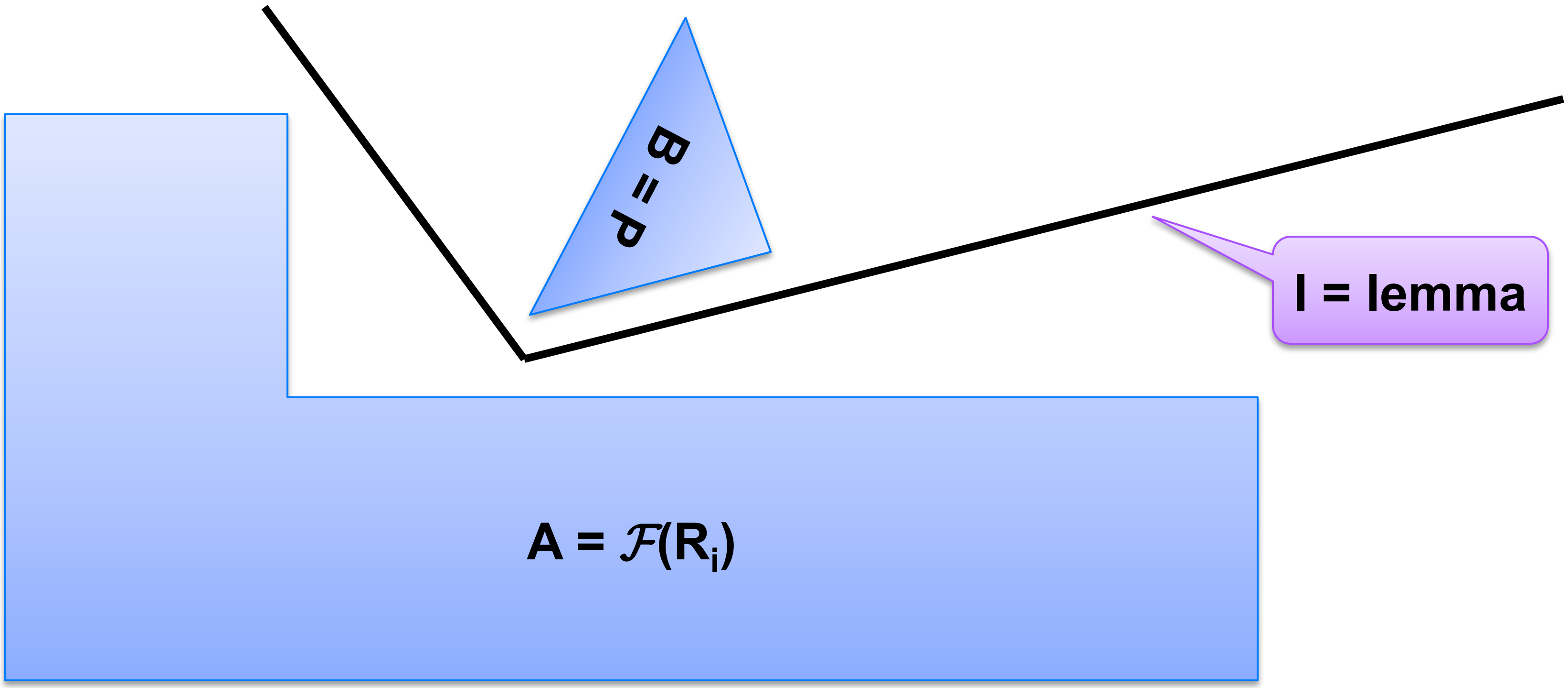
Let A and B be two First Order (FO) formulae such that $A \Rightarrow \neg B$, then there exists a FO formula I, denoted ITP(A, B), such that

$A \Rightarrow I$ $\quad\quad$ $I \Rightarrow \neg B$ $\quad\quad$ $atoms(I) \in atoms(A) \cap atoms(B)$

A Craig interpolant ITP(A, B) can be effectively constructed from a resolution proof of unsatisfiability of $A \wedge B$

In Model Cheching, Craig Interpolation Theorem is used to safely over-approximate the set of (finitely) reachable states

Craig Interpolation for Linear Arithmetic

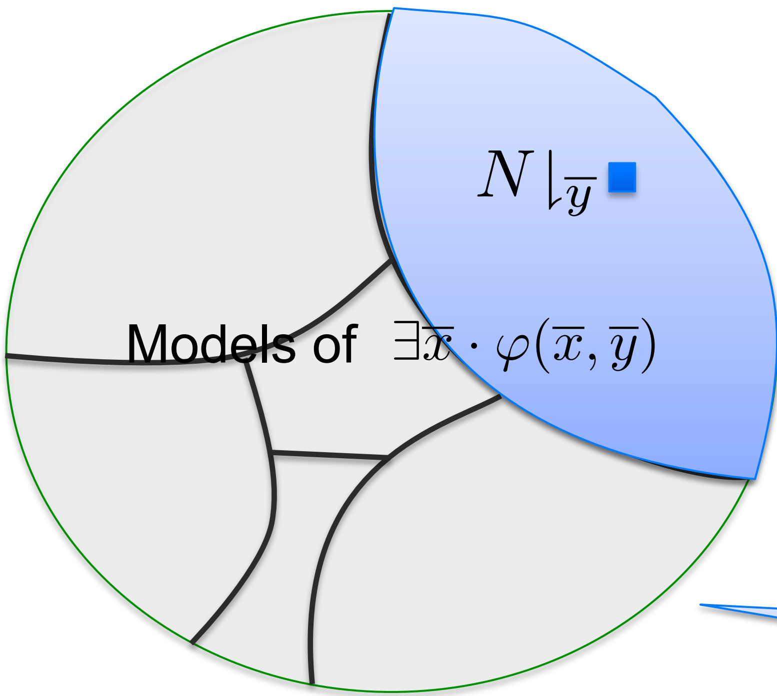


Useful properties of existing interpolation algorithms [CGS10] [HB12]

- $I \in ITP(A, B)$ then $\neg I \in ITP(B, A)$
- if A is syntactically convex (a monomial), then I is convex
- if B is syntactically convex, then I is co-convex (a clause)
- if A and B are syntactically convex, then I is a half-space

Model Based Projection

Expensive to find a quantifier-free $\psi(\overline{y}) \equiv \exists \overline{x} \cdot \varphi(\overline{x}, \overline{y})$



1. **find** $N \models \varphi(\overline{x}, \overline{y})$

   (e.g. specific pre-post pair that needs to be generalized)

2. **choose disjunct "covering" *N***

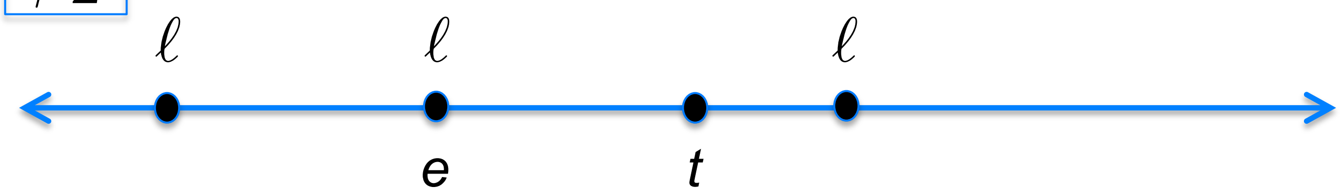
   using virtual substitution

Lazy Quantifier Elimination!

MBP for Linear Rational Arithmetic

$$\exists \ell \cdot (\boxed{\ell = e} \land \phi_1) \lor (\boxed{t < \ell} \land \ell < u) \lor (\ell < u \land \phi_2)$$

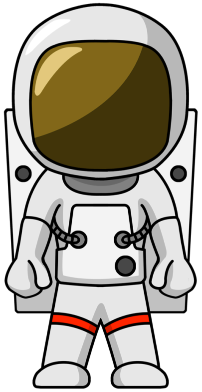
$$\begin{aligned} \equiv \quad & \boxed{(\phi_1 \lor (t < e \land e < u) \lor (e < u \land \phi_2))} \\ \lor \quad & \boxed{(t < u \lor (t < u \land \phi_2))} \\ \lor \quad & \boxed{\phi_2} \end{aligned}$$



pick a disjunct that covers a given model

[1] Cooper, *Theorem Proving in Arithmetic without Multiplication*, 1972
[2] Loos and Weispfenning, *Applying Linear Quantifier Elimination*, 1993
[3] Bjorner, *Linear Quantifier Elimination as an Abstract Decision Procedure*, 2010

Spacer: Solving CHC in Z3



Spacer: solver for SMT-constrained Horn Clauses

- stand-alone implementation in a fork of Z3
- http://bitbucket.org/spacer/code

Support for Non-Linear CHC

- model procedure summaries in inter-procedural verification conditions
- model assume-guarantee reasoning
- uses MBP to under-approximate models for finite unfoldings of predicates
- uses MAX-SAT to decide on an unfolding strategy

Supported SMT-Theories

- Best-effort support for arbitrary SMT-theories
  - data-structures, bit-vectors, non-linear arithmetic
- Full support for Linear arithmetic (rational and integer)
- Quantifier-free theory of arrays
  - only quantifier free models with limited applications of array equality

RESULTS

SV-COMP 2015

http://sv-comp.sosy-lab.org/2015/

4th Competition on Software Verification held (here!) at TACAS 2015

Goals

- Provide a snapshot of the state-of-the-art in software verification to the community.
- Increase the visibility and credits that tool developers receive.
- Establish a set of benchmarks for software verification in the community.

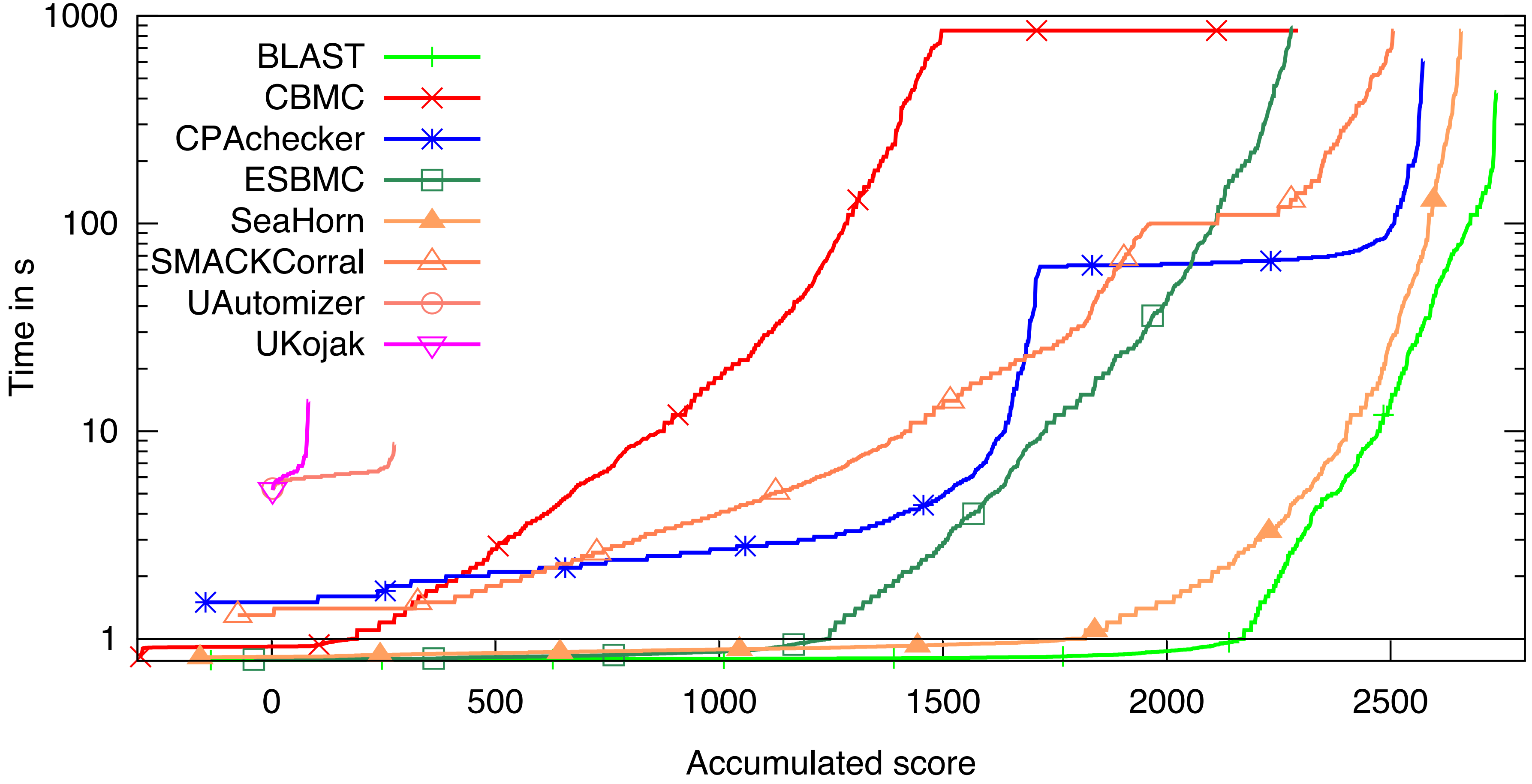
Participants:

- Over 22 participants, including most popular Software Model Checkers and Bounded Model Checkers

Benchmarks:

- C programs with error location (programs include pointers, structures, etc.)
- Over 6,000 files, each 2K – 100K LOC
- Linux Device Drivers, Product Lines, Regressions/Tricky examples
- http://sv-comp.sosy-lab.org/2015/benchmarks.php

Results for DeviceDriver category



Conclusion

SeaHorn (http://seahorn.github.io)

- a state-of-the-art Software Model Checker
- LLVM-based front-end
- CHC-based verification engine
- a framework for research in logic-based verification

The future

- making SeaHorn useful to users of verification technology
  – counterexamples, build integration, property specification, proofs, etc.
- targeting many existing CHC engines
  – specialize encoding and transformations to specific engines
  – communicate results between engines
- richer properties
  – termination, liveness, synthesis

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