Algorithmic Logic-Based Verification with SeaHorn

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based on joint work with Anvesh Komuravelli, and Nikolaj Bjørner

Automated Software Analysis

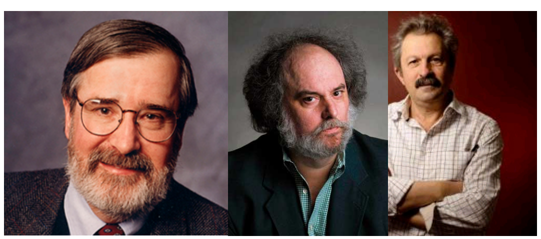
Program → Automated Analysis → Correct / Incorrect

Software Model Checking with Predicate Abstraction

e.g., Microsoft's SDV

Abstract Interpretation with Numeric Abstraction

e.g., ASTREE, Polyspace



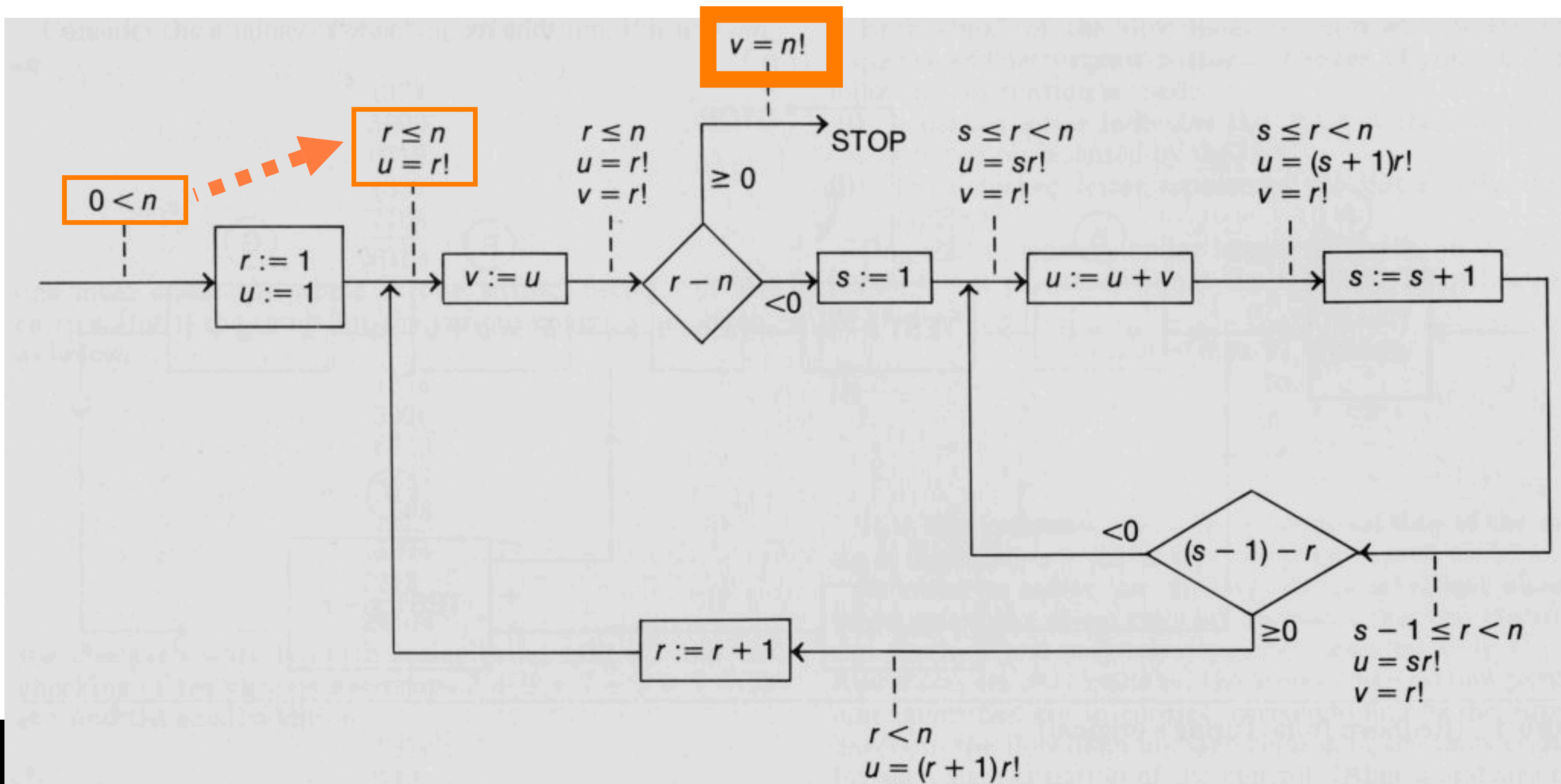
Turing, 1936: “undecidable”

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.



Three-Layers of a Program Verifier

Compiler

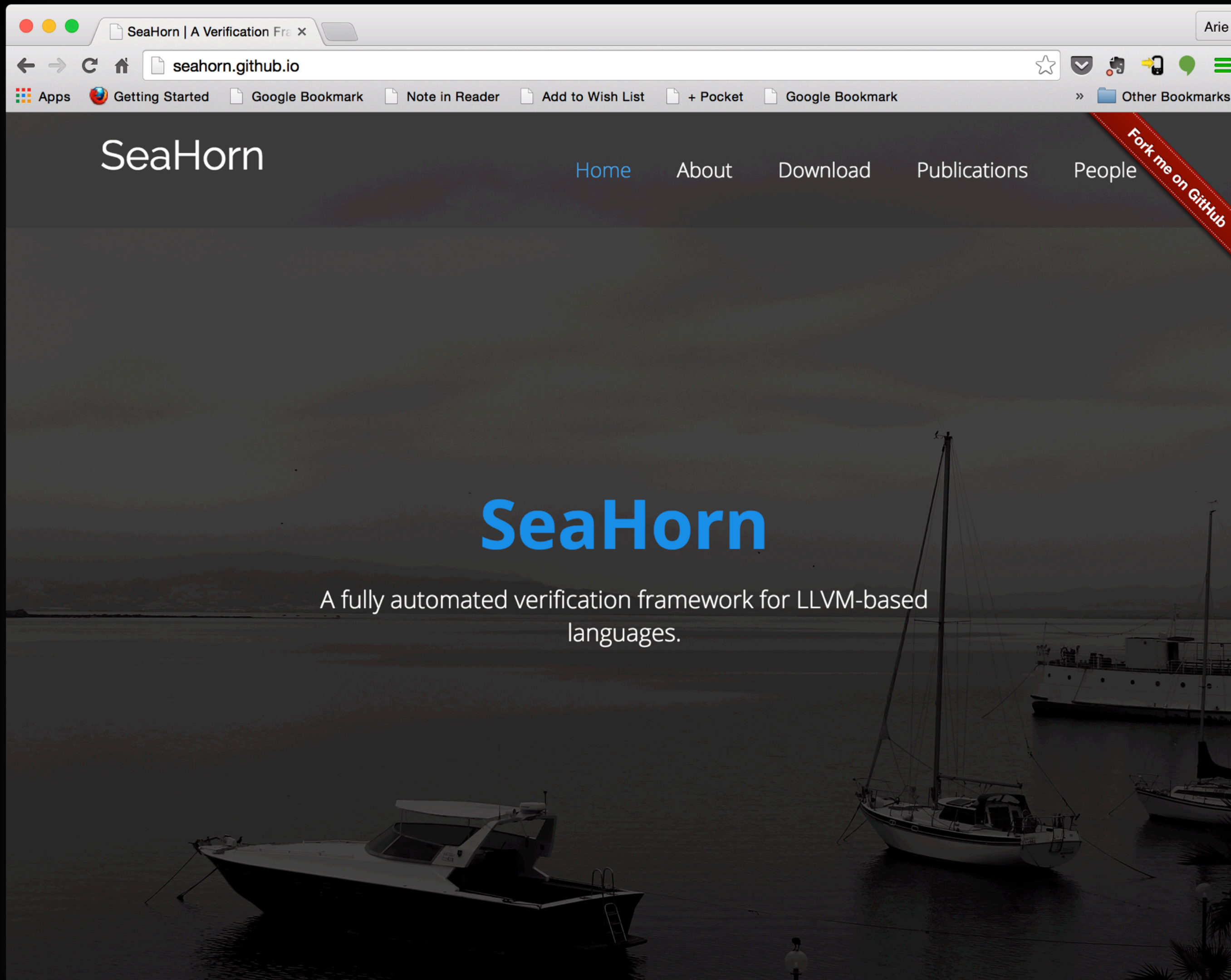
- compiles surface syntax a target machine
- embodies syntax with semantics

Verification Condition Generator

- transforms a program and a property to a verification condition in logic
- employs different abstractions, refinements, proof-search strategies, etc.

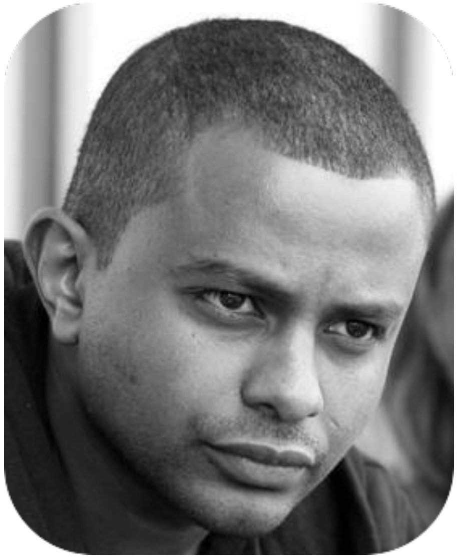
Automated Theorem Prover / Reasoning Engine

- discharges verification conditions
- general purpose constraint solver
- SAT, SMT, Abstract Interpreter, Temporal Logic Model Checker,…



http://seahorn.github.io

SeaHorn Verification Framework



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The Plan

Introduction

Architecture and Usage

Demonstration

Constrained Horn Clauses as an Intermediate Representation

From Programs to Logic

- generating verification conditions

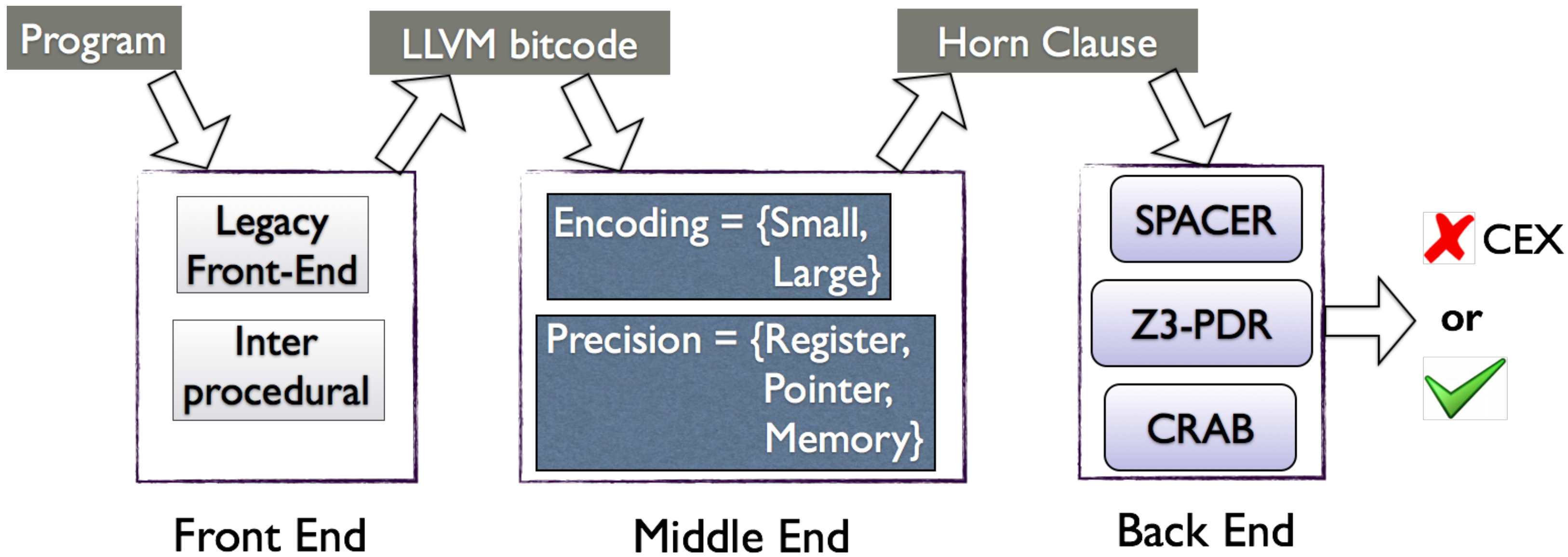
Program Transformations for Verification

Solving Constrained Horn Clauses

- synthesizing inductive invariants and procedure summaries

Conclusion

SeaHorn Verification Framework



Key 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

UFO

- LLVM-based front-end (partially reused in SeaHorn)
- Combines Abstract Interpretation with Interpolation-Based Model Checking
- (no longer actively developed)

SeaHorn Philosophy

Build a state-of-the-art Software Model Checker

- useful to "average" users
  - user-friendly, efficient, trusted, certificate-producing, …
- useful to researchers in verification
  - modular design, clean separation between syntax, semantics, and logic, …

Stand on the shoulders of giants

- reuse techniques from compiler community to reduce verification effort
  - SSA, loop restructuring, induction variables, alias analysis, …
  - static analysis and abstract interpretation
- reduce verification to logic
  - verification condition generation
  - Constrained Horn Clauses

Build reusable logic-based verification technology

- "SMT-LIB" for program verification

SeaHorn Usage

```
> sea pf FILE.c
```

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

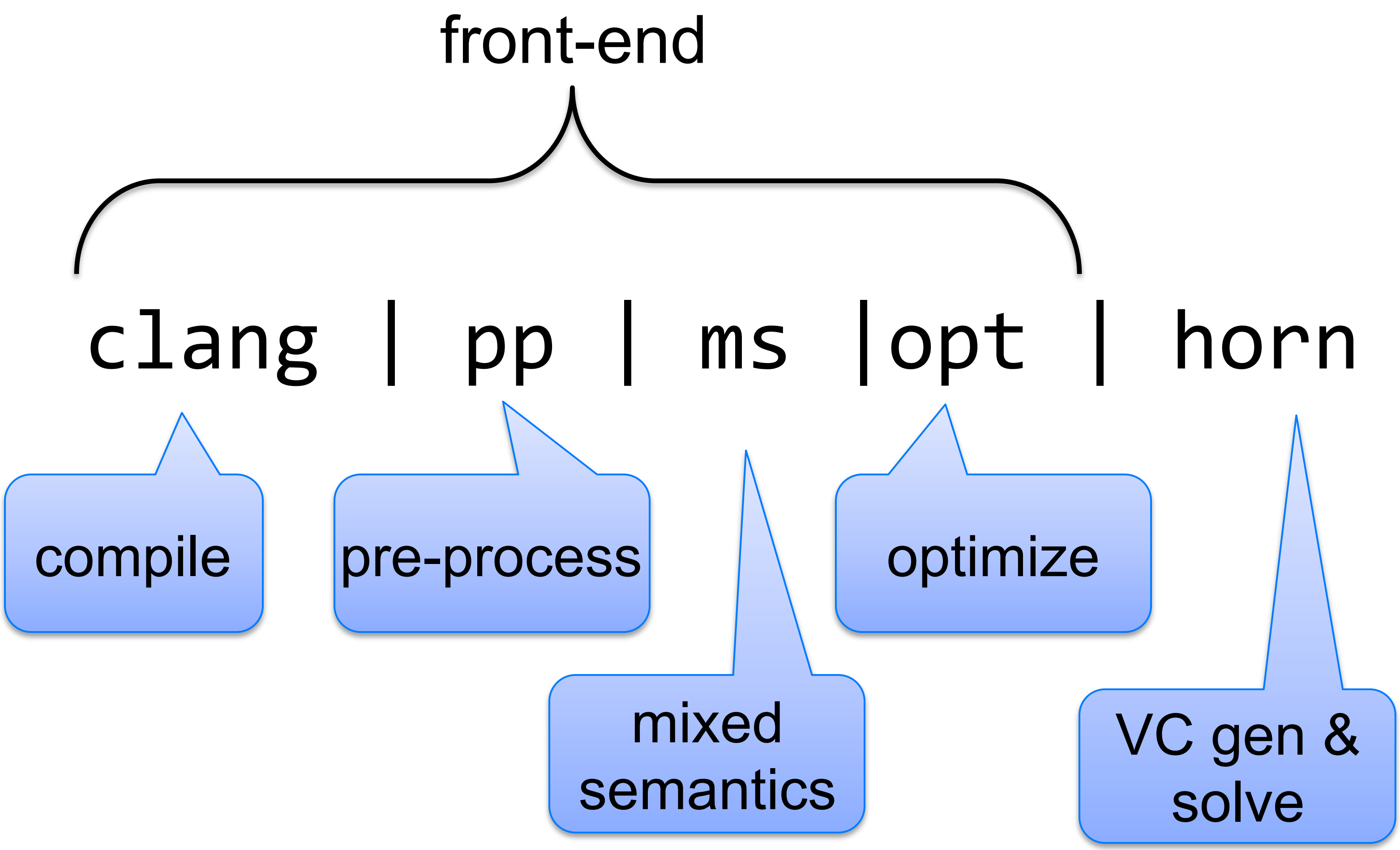
Additional options

- `--cex=trace.xml` outputs a counter-example in SV-COMP'15 format
- --show-invars displays computed invariants
- `--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



DEMO

From Programming to Modeling

Extend C programming language with 3 modeling features

Assertions

- assert(e) – aborts an execution when e is false, no-op otherwise

```
void assert (_Bool b) { if (!b) abort(); }
```

Non-determinism

- nondet_int() – returns a non-deterministic integer value

```
int nondet_int () { int x; return x; }
```

Assumptions

- assume(e) – "ignores" execution when e is false, no-op otherwise

```
void assume (_Bool e) { while (!e) ;  }
```

Constrained Horn Clauses

INTERMEDIATE REPRESENTATION

Constrained Horn Clauses (CHC)

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

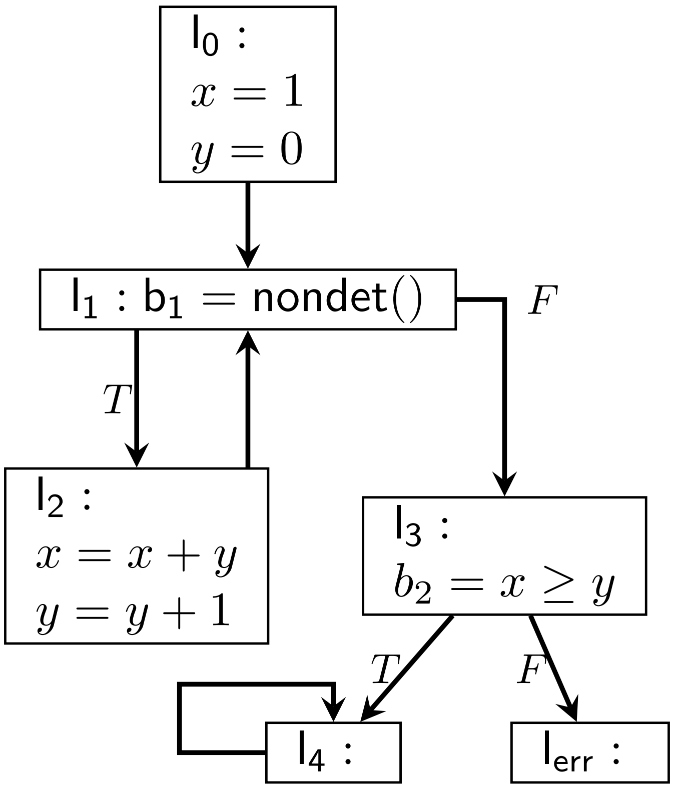
$$\forall V . (\phi \land p_1[X_1] \land \ldots \land p_n[X_n] \rightarrow h[X]),$$

where

- A is a background theory (e.g., Linear Arithmetic, Arrays, Bit-Vectors, or combinations of the above)
- ϕ is a constrained in the background theory A
- $p_1, \ldots, p_n$, h are n-ary predicates
- $p_i[X]$ is an application of a predicate to first-order terms

Example Horn Encoding

$$
\begin{array}{l}
\text{int } x = 1; \\
\text{int } y = 0; \\
\text{while } (*) \ \{ \\
\quad x = x + y; \\
\quad y = y + 1; \\
\} \\
\text{assert}(x \geq y);
\end{array}
$$



$\langle 1 \rangle$ p_0.

$\langle 2 \rangle$ $p_1(x, y) \leftarrow$
$p_0, x = 1, y = 0.$

$\langle 3 \rangle$ $p_2(x, y) \leftarrow p_1(x, y)$.

$\langle 4 \rangle$ $p_3(x, y) \leftarrow p_1(x, y)$.

$\langle 5 \rangle$ $p_1(x', y') \leftarrow$
$p_2(x, y),$
$x' = x + y,$
$y' = y + 1.$

$\langle 6 \rangle$ $p_4 \leftarrow (x \geq y), p_3(x, y).$

$\langle 7 \rangle$ $p_{err} \leftarrow (x < y), p_3(x, y).$

$\langle 8 \rangle$ $p_4 \leftarrow p_4.$

$\langle 9 \rangle$ $\bot \leftarrow p_{err}.$

CHC Terminology

head | body | constraint

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

Query $\mathit{false} \leftarrow p_1[X_1], \ldots, p_n[X_n], \phi.$

Fact $h[X] \leftarrow \phi.$

Linear CHC $h[X] \leftarrow p[X_1], \phi.$

Non-Linear CHC $h[X] \leftarrow p_1[X_1], \ldots, p_n[X_n], \phi.$ for $n > 1$

CHC Satisfiability

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

Example Horn Encoding

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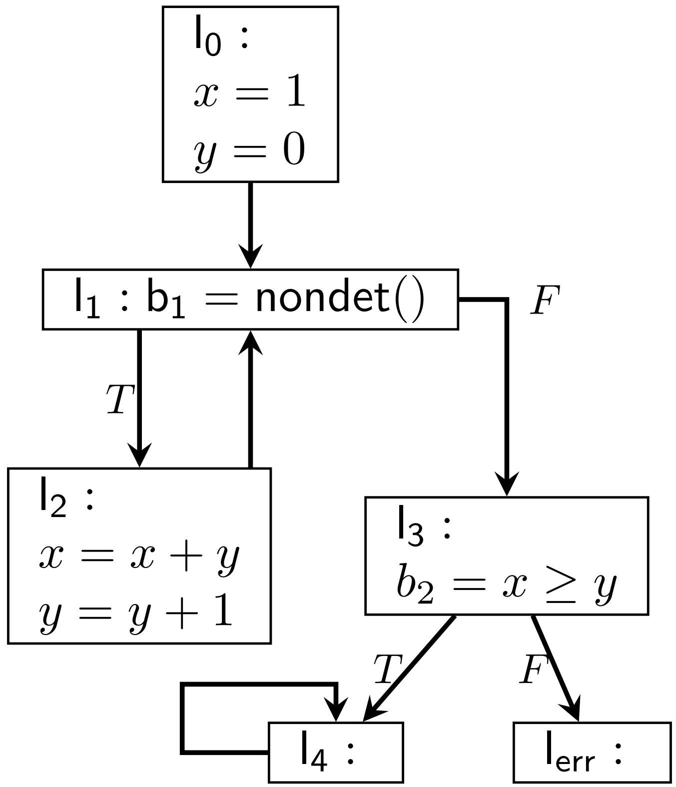


$$
\begin{array}{ll}
\langle 1 \rangle & p_0. \\
\langle 2 \rangle & p_1(x, y) \leftarrow \\
& \quad p_0, x = 1, y = 0. \\
\langle 3 \rangle & p_2(x, y) \leftarrow p_1(x, y)\ . \\
\langle 4 \rangle & p_3(x, y) \leftarrow p_1(x, y)\ . \\
\langle 5 \rangle & p_1(x', y') \leftarrow \\
& \quad p_2(x, y), \\
& \quad x' = x + y, \\
& \quad y' = y + 1. \\
\langle 6 \rangle & p_4 \leftarrow (x \geq y), p_3(x, y). \\
\langle 7 \rangle & p_{err} \leftarrow (x < y), p_3(x, y). \\
\langle 8 \rangle & p_4 \leftarrow p_4. \\
\langle 9 \rangle & \bot \leftarrow p_{err}.
\end{array}
$$

Relationship between CHC and Verification

A program satisfies a property iff corresponding CHCs are satisfiable

- satisfiability-preserving transformations == safety preserving

Models for CHC correspond to verification certificates

- inductive invariants and procedure summaries

Unsatisfiability (or derivation of FALSE) corresponds to counterexample

- the resolution derivation (a path or a tree) is the counterexample

CAVEAT: In SeaHorn the terminology is reversed

- SAT means there exists a counterexample – a BMC at some depth is SAT
- UNSAT means the program is safe – BMC at all depths are UNSAT

FROM PROGRAMS TO CLAUSES

Hoare Triples

A Hoare triple {Pre} P {Post} is valid iff every terminating execution of *P* that starts in a state that satisfies *Pre* ends in a state that satisfies *Post*

Inductive Loop Invariant

$$\frac{Pre \Rightarrow Inv \qquad \{Inv \wedge C\}\ Body\ \{Inv\} \qquad Inv \wedge \neg C \Rightarrow Post}{\{Pre\}\ \textbf{while}\ C\ \textbf{do}\ Body\ \{Post\}}$$

Function Application

$$\frac{(Pre \wedge p=a) \Rightarrow P \qquad \{P\}\ Body_F\ \{Q\} \qquad (Q \wedge p,r=a,b) \Rightarrow Post}{\{Pre\}\ b = F(a)\ \{Post\}}$$

Recursion

$$\frac{\{Pre\}\ b = F(a)\ \{Post\} \vdash \{Pre\}\ Body_F\ \{Post\}}{\{Pre\}\ b = F(a)\ \{Post\}}$$

Weakest Liberal Pre-Condition

Validity of Hoare triples is reduced to FOL validity by applying a **predicate transformer**

Dijkstra's weakest liberal pre-condition calculus [Dijkstra'75]

wlp (P, Post)

weakest pre-condition ensuring that executing P ends in Post

{Pre} P {Post} is valid $\Leftrightarrow$ Pre $\Rightarrow$ **wlp** (P, Post)

A Simple Programming Language

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

body  ::= stmt (; stmt)*

stmt  ::= x = E | assert (E) | assume (E) |
          while E do S | y = P(E) |
          L:stmt | goto L              (optional)

E     := expression over program variables
```

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)

Example of a WLP Horn Encoding

$\{Pre:\ y \geq 0\}$
$\quad x_o = x;$
$\quad y_o = y;$
$\quad \textbf{while}\ y > 0\ \textbf{do}$
$\qquad x = x+1;$
$\qquad y = y-1;$
$\{Post:\ x = x_o + y_o\}$

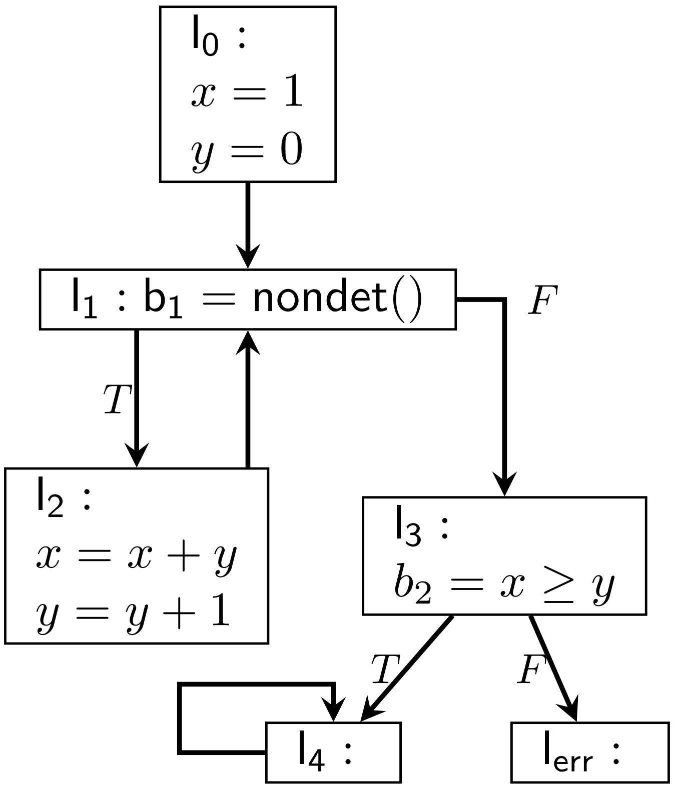
ToHorn

$C1:\ I(x,y,x,y) \leftarrow y \geq 0.$
$C2:\ I(x+1,y-1,x_o,y_o) \leftarrow I(x,y,x_o,y_o),\ y>0.$
$C3:\ false \leftarrow I(x,y,x_o,y_o),\ y \leq 0,\ x \neq x_o + y_o$

$\{y \geq 0\}\ P\ \{x = x_{old} + y_{old}\}$ is **true** iff the query C_3 is **satisfiable**

Example Horn Encoding

$\text{int } x = 1;$
$\text{int } y = 0;$
$\text{while } (*)\ \{$
$\quad x = x + y;$
$\quad y = y + 1;$
$\}$
$\text{assert}(x \geq y);$



$\langle 1 \rangle\ \mathsf{p}_0.$

$\langle 2 \rangle\ \mathsf{p}_1(x, y) \leftarrow$
$\qquad \mathsf{p}_0, x = 1, y = 0.$

$\langle 3 \rangle\ \mathsf{p}_2(x, y) \leftarrow \mathsf{p}_1(x, y)\ .$

$\langle 4 \rangle\ \mathsf{p}_3(x, y) \leftarrow \mathsf{p}_1(x, y)\ .$

$\langle 5 \rangle\ \mathsf{p}_1(x', y') \leftarrow$
$\qquad \mathsf{p}_2(x, y),$
$\qquad x' = x + y,$
$\qquad y' = y + 1.$

$\langle 6 \rangle\ \mathsf{p}_4 \leftarrow (x \geq y), \mathsf{p}_3(x, y).$

$\langle 7 \rangle\ \mathsf{p}_{err} \leftarrow (x < y), \mathsf{p}_3(x, y).$

$\langle 8 \rangle\ \mathsf{p}_4 \leftarrow \mathsf{p}_4.$

$\langle 9 \rangle\ \bot \leftarrow \mathsf{p}_{err}.$

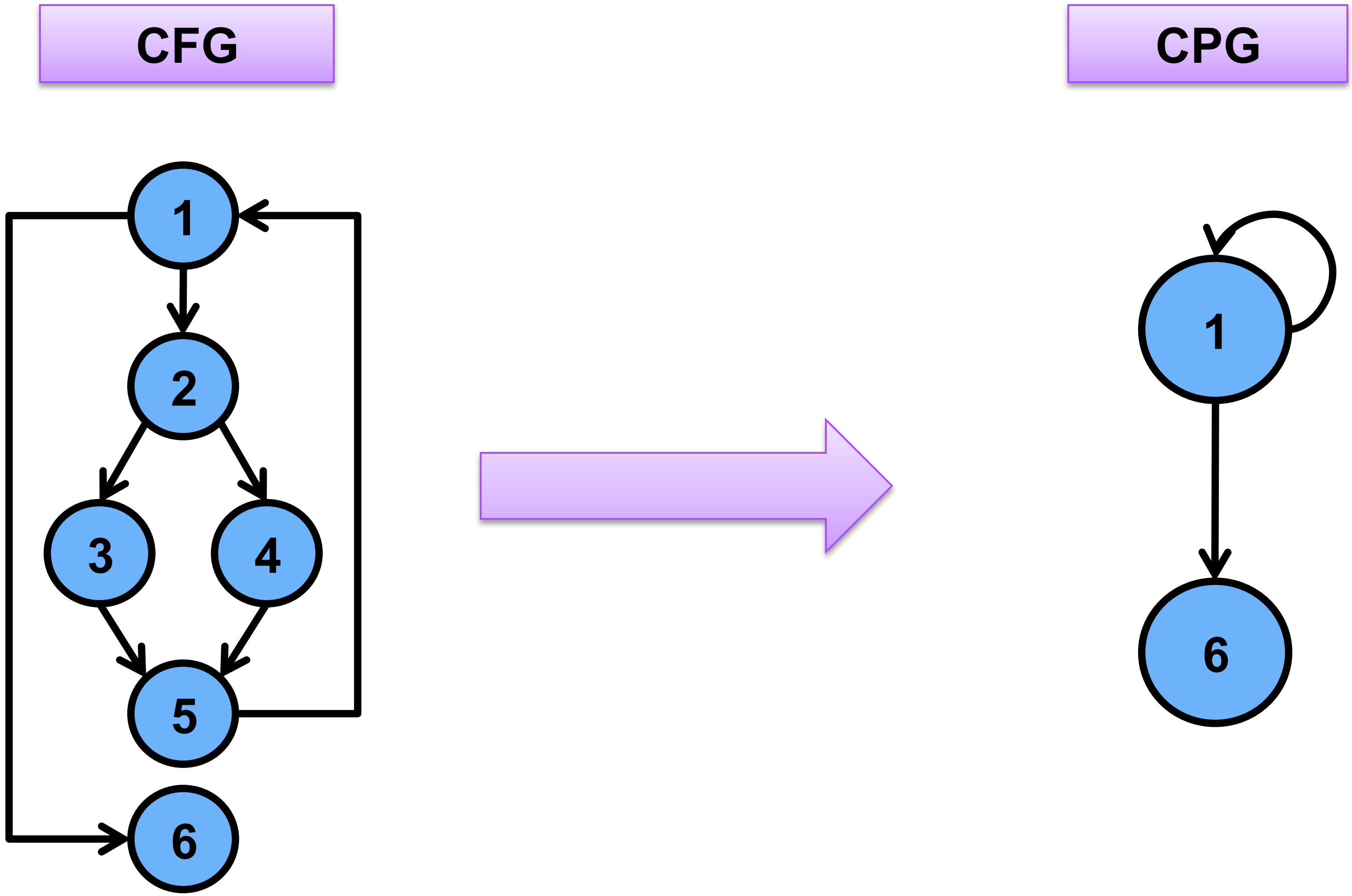
From CFG to Cut Point Graph

A *Cut Point Graph* hides (summarizes) fragments of a control flow graph by (summary) edges

Vertices (called, *cut points*) correspond to *some* basic blocks

An edge between cut-points *c* and *d* summarizes all finite (loop-free) executions from *c* to *d* that do not pass through any other cut-points

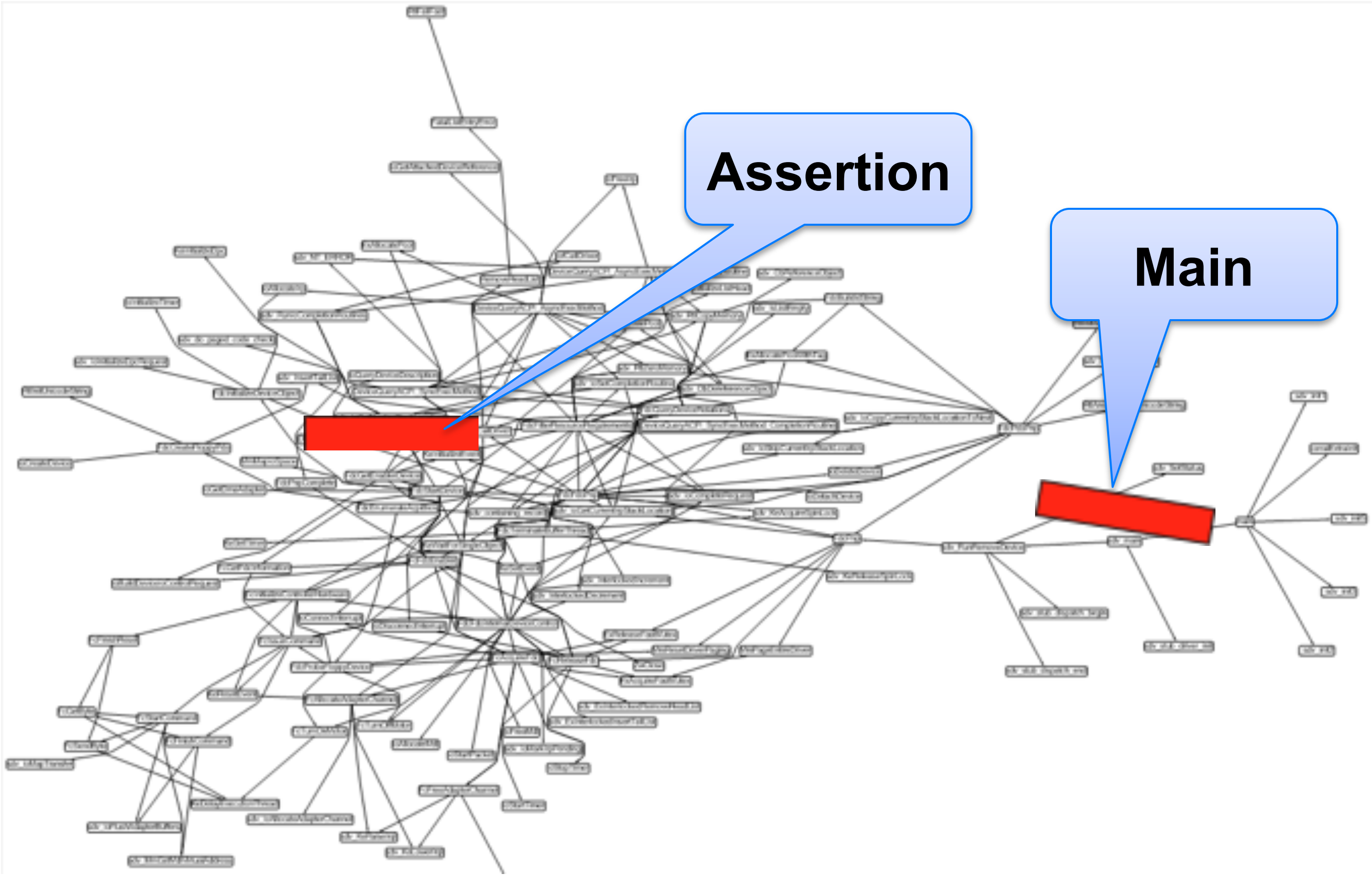
Cut Point Graph Example



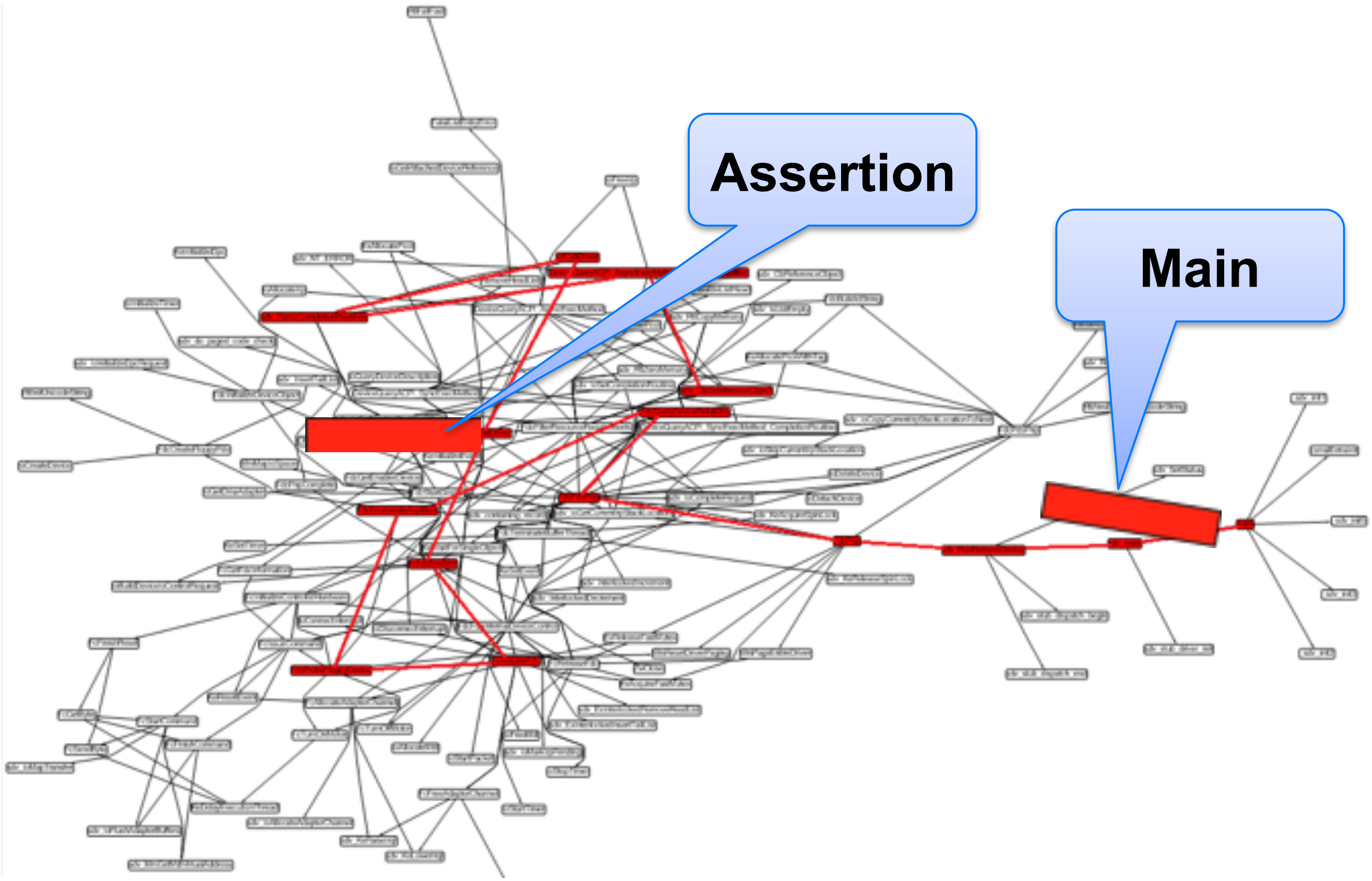
Mixed Semantics

PROGRAM TRANSFORMATION

Deeply nested assertions



Deeply nested assertions



Counter-examples are long

Hard to determine (from main) what is relevant

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!)

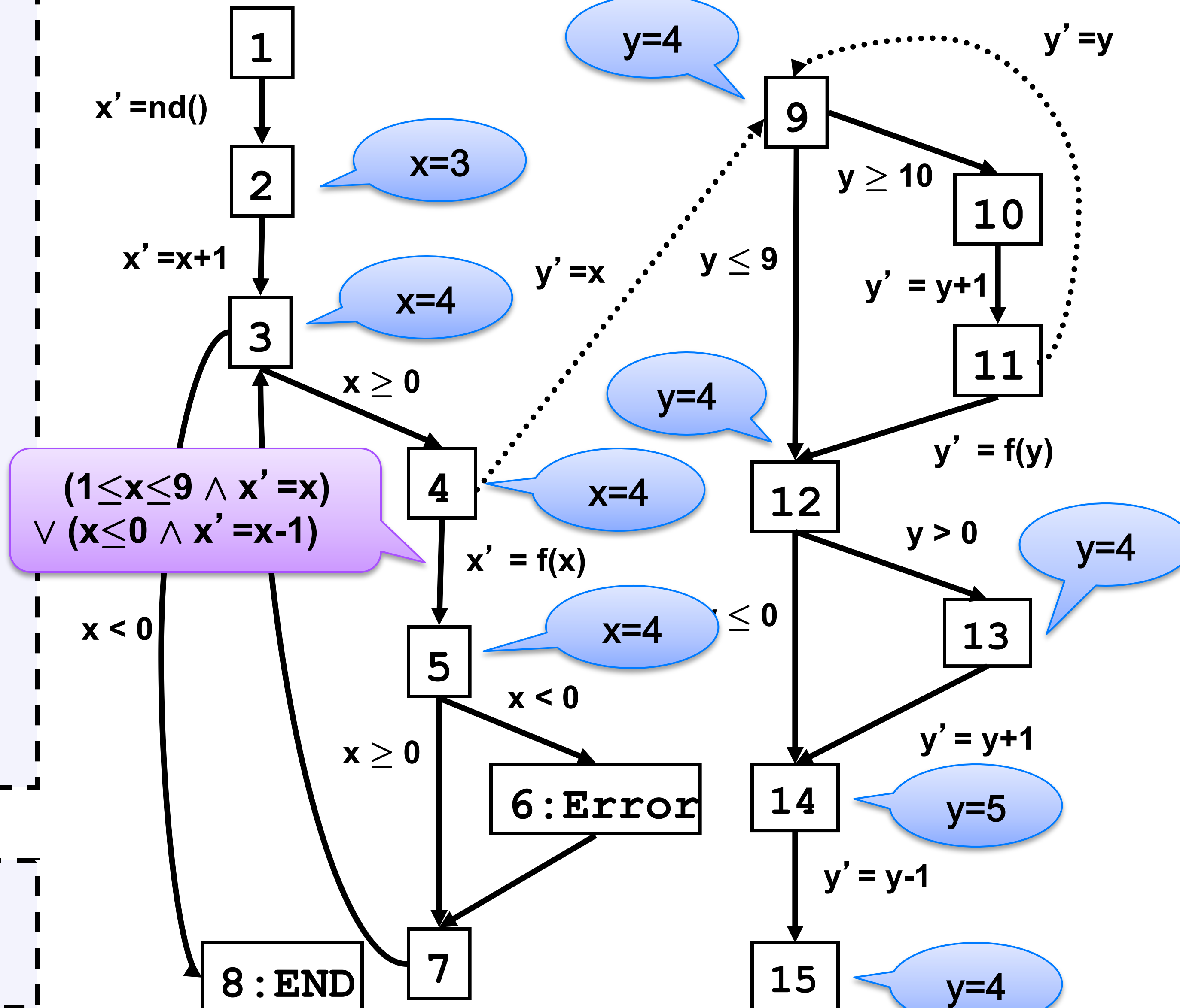
Preserves reachability and non-termination

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)

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

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 ($c3$);

Mixed Semantics: Summary

Every procedure is inlined at most once

- in the worst case, doubles the size of the program
- can be restricted to only inline functions that directly or indirectly call errror() function

Easy to implement at compiler level

- create “failing” and “passing” versions of each function
- reduce “passing” functions to returning paths
- in main(), introduce new basic block bb.F for every failing function F(), and call failing.F in bb.F
- inline all failing calls
- replace every call to F to non-deterministic jump to bb.F or call to passing F

Increases context-sensitivity of context-insensitive analyses

- context of failing paths is explicit in main (because of inlining)
- enables / improves many traditional analyses

SOLVING CHC WITH SMT

Programs, Cexs, Invariants

A program *P = (V, Init, ρ, Bad)*

- Notation: $\mathcal{F}(X) = \exists \boldsymbol{u} . (X \wedge \rho) \vee Init$

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.*

$$Init(u) \Rightarrow Inv(u)$$

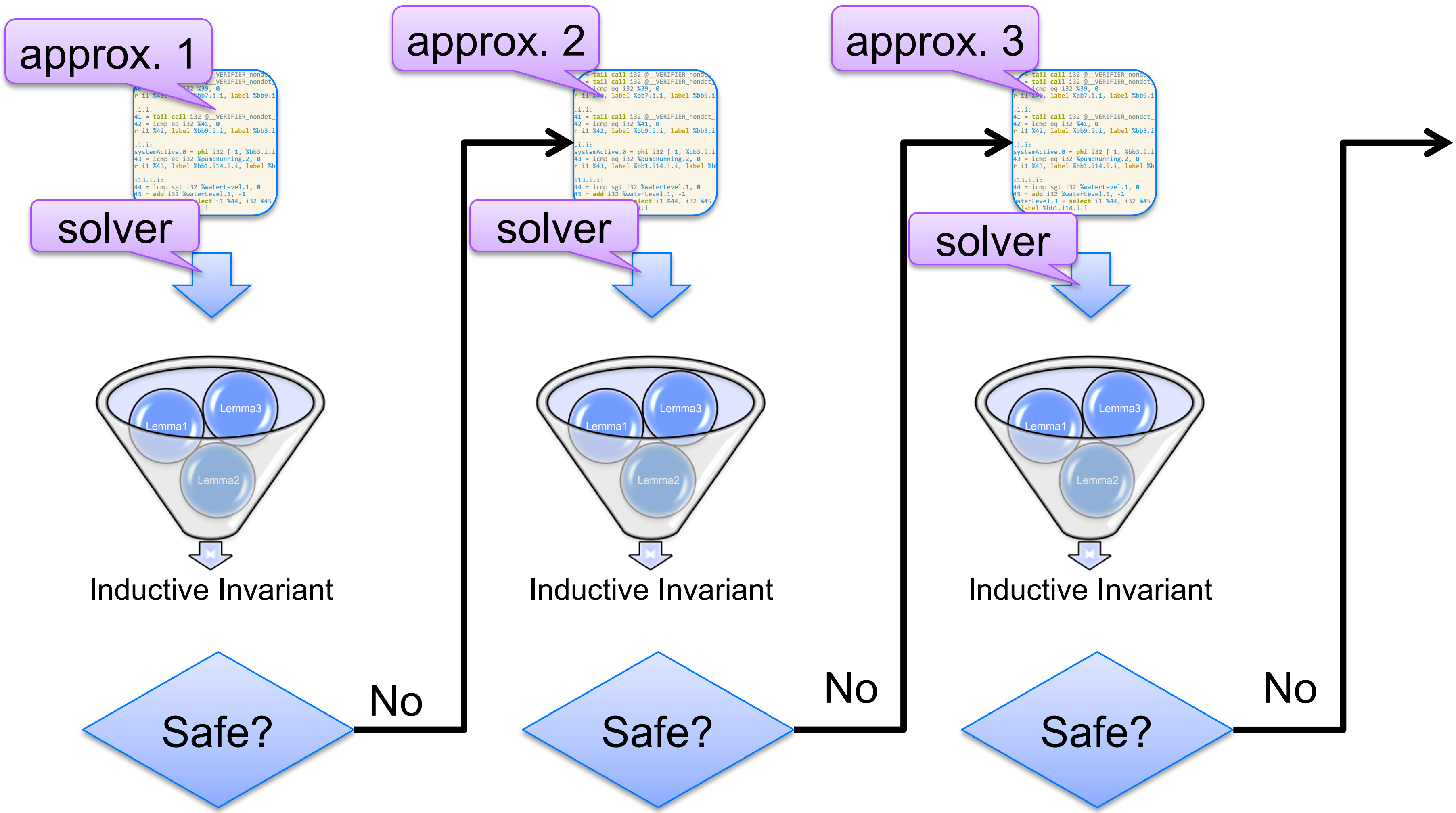
$$Inv(u) \wedge \rho(u, v) \Rightarrow Inv(v)$$

} Inductive

$$Inv(u) \Rightarrow \neg Bad(u)$$

Safe

Verification by Evolving Approximations



IC3/PDR Algorithm Overview

bounded safety

Input: Safety problem $\langle Init(X), Tr(X, X'), Bad(X) \rangle$

$F_0 \leftarrow Init\,; N \leftarrow 0$ **repeat**

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

$\quad$ **if** $\mathbf{G} = [\,]$ **then return** $Reachable$;

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

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

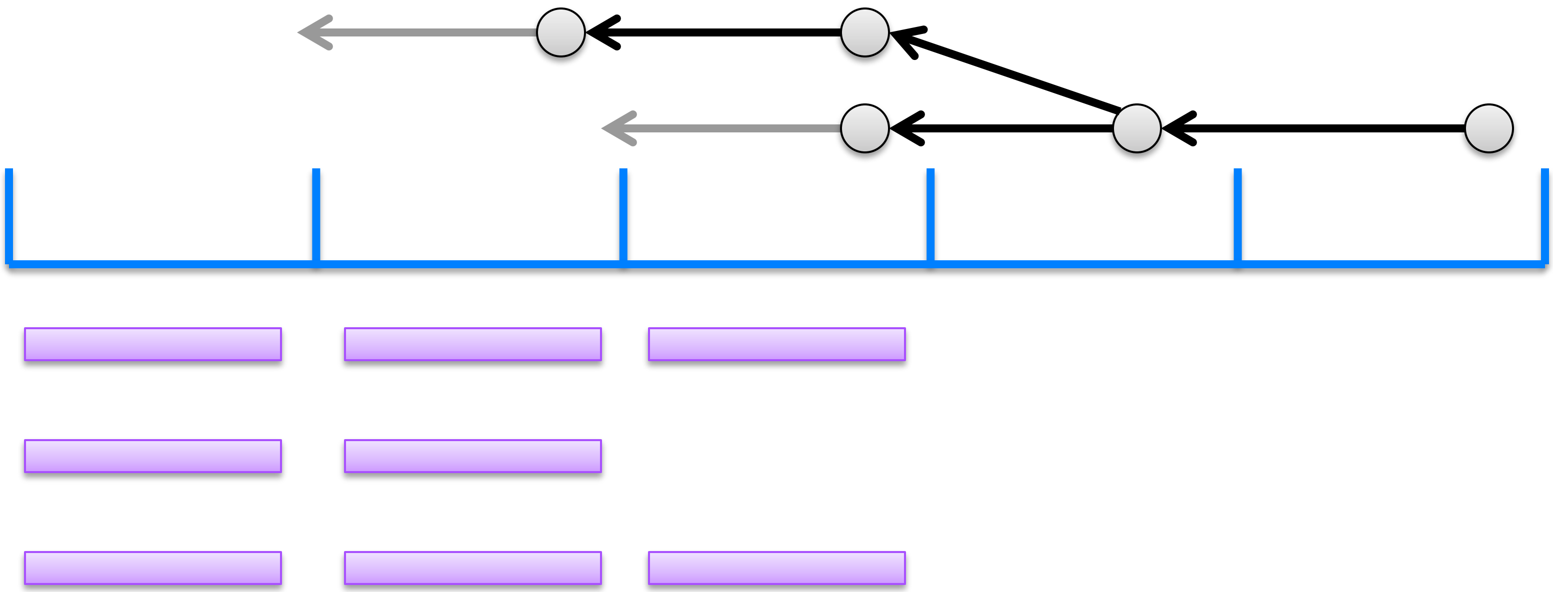
$\quad$ **if** $\exists 0 \leq i < N \cdot F_i = F_{i+1}$ **then return** $Unreachable$;

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

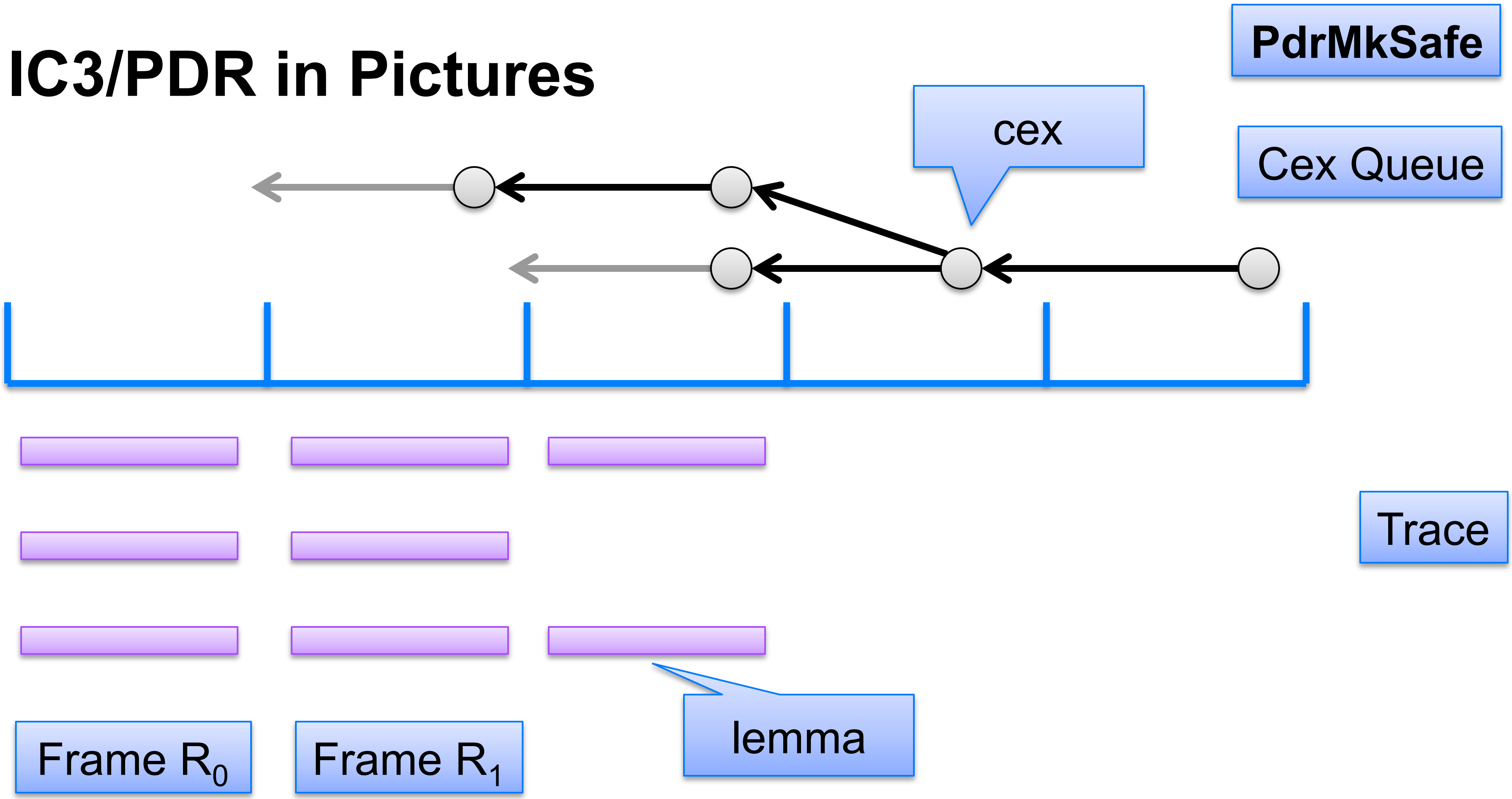
until ∞;

strengthen result

IC3/PDR in Pictures

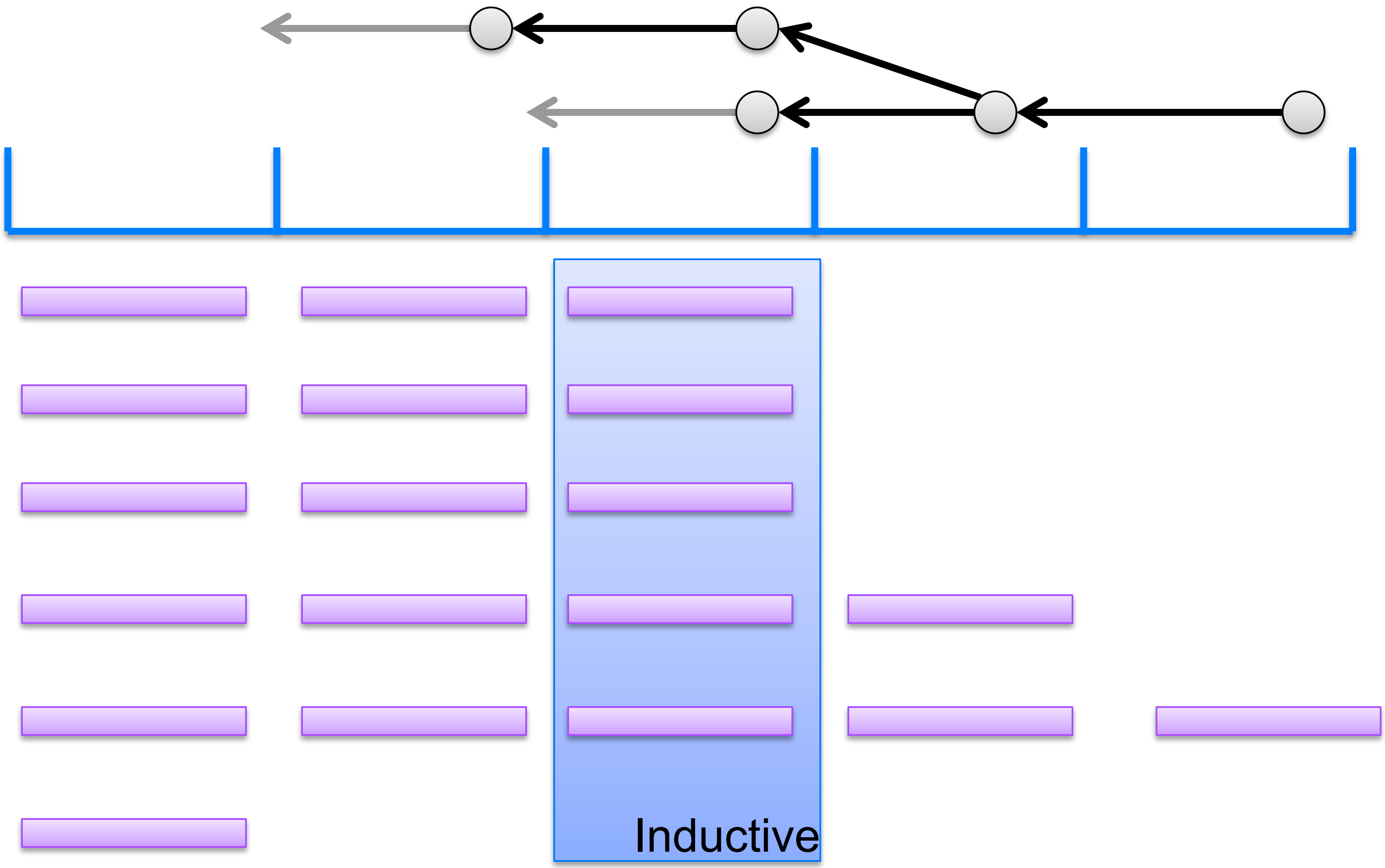


IC3/PDR in Pictures



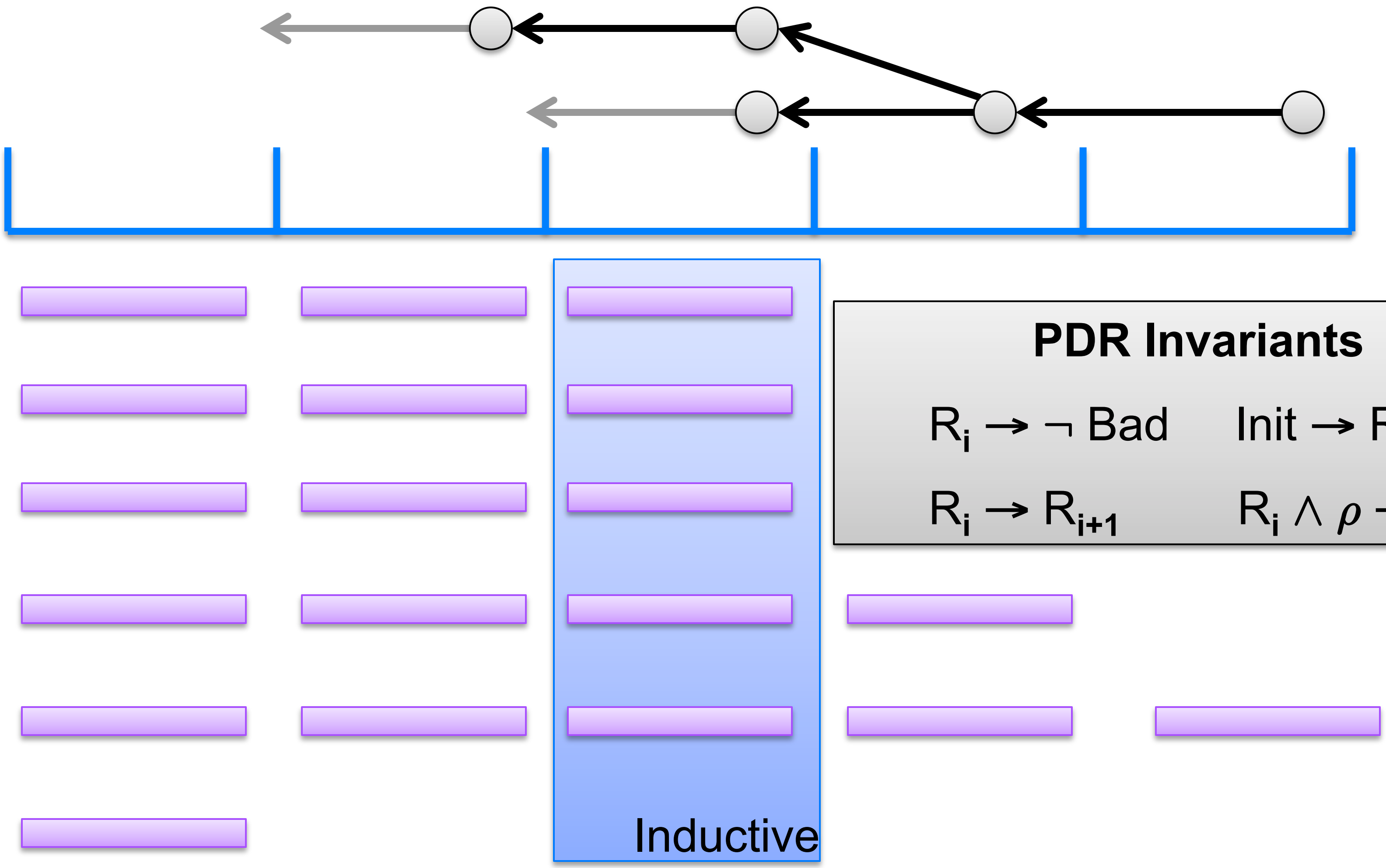
IC3/PDR in Pictures

PdrPush



IC3/PDR in Pictures

PdrPush

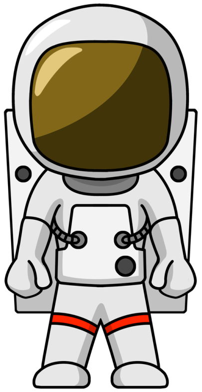


PDR Invariants

$R_i \rightarrow \neg \text{Bad}$ $\quad$ $\text{Init} \rightarrow R_i$

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

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

CRAB: Cornucopia of Abstractions

A library of abstract domains build on top of NASA Ikos (Inference Kernel for Open Static Analyzers)

A language-independent intermediate representation

Many abstract domains

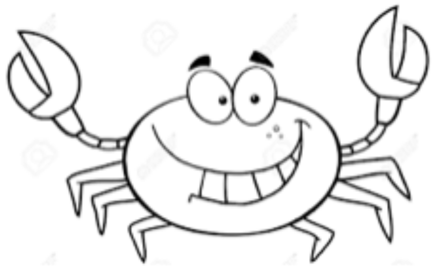
- intervals (with congruences) (with uninterpreted functions)
- zones, dbms, octagons
- pointer analysis with offsets
- array analysis with smashing

Fixpoint iteration library

- precise interleaving between widening and narrowing
- extensible with thresholds

Efficient reusable data-structure

- simple API for integrating new abstract domains



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.

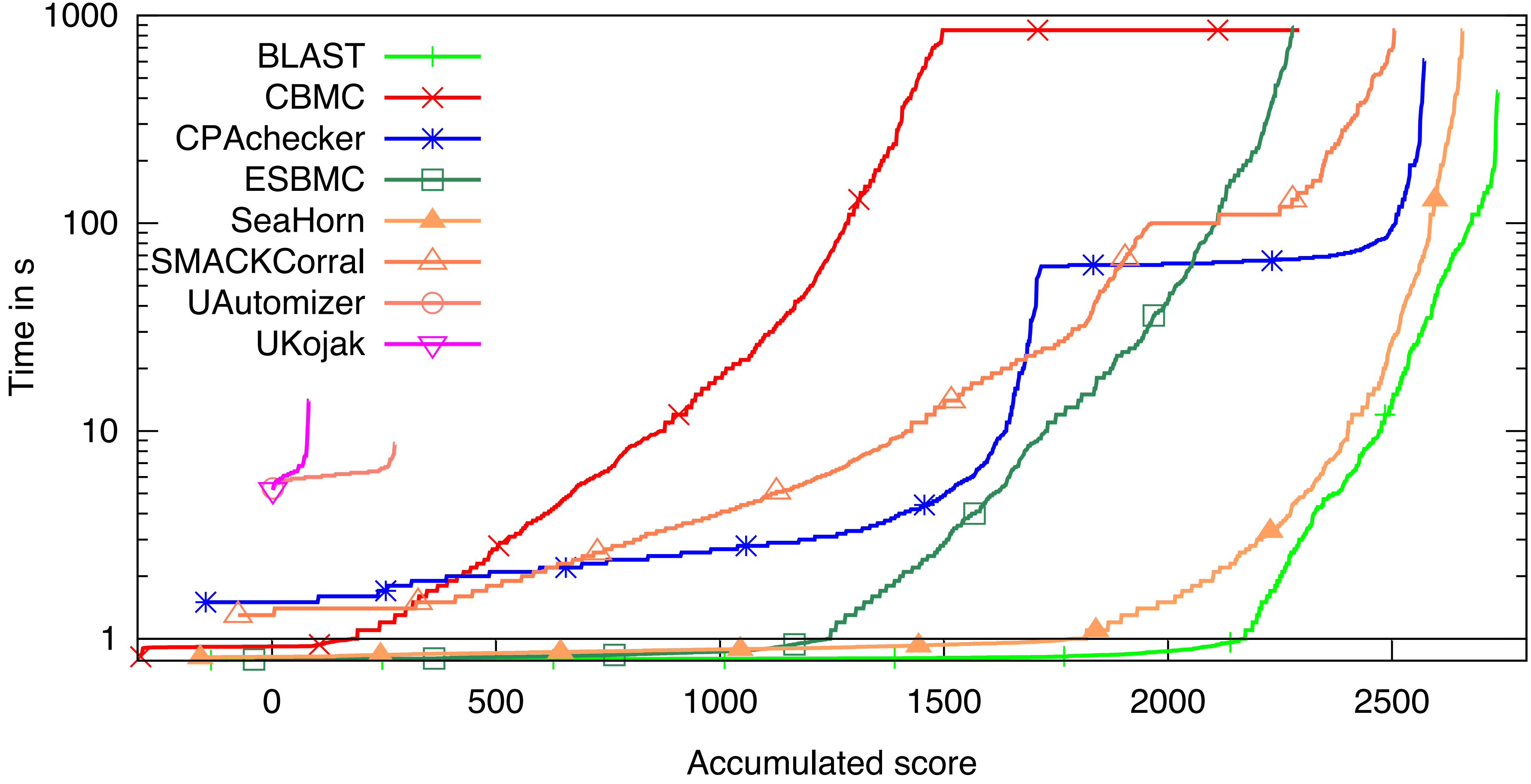
Participants:

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

Benchmarks:

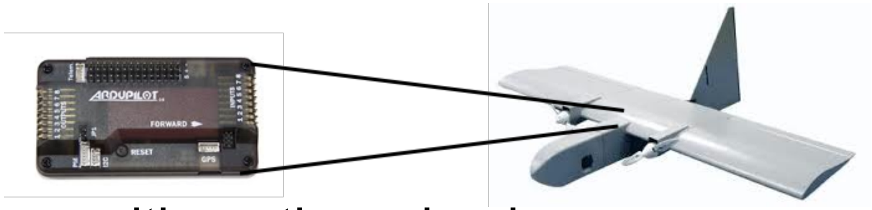
- C programs with error location (programs include pointers, structures, etc.)
- Over 6,000 files, each 2K – 100K LOC
- Linux Device Drivers, Product Lines, Regressions/Tricky examples
- http://sv-comp.sosy-lab.org/2015/benchmarks.php

Results for DeviceDriver category



Detecting Buffer Overflow in Auto-pilot software

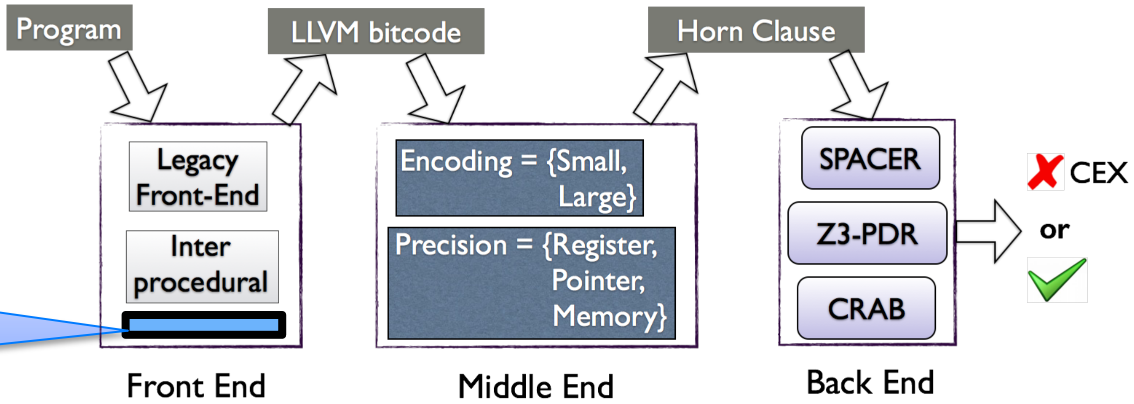
Show absence of Buffer Overflows in
- paparazzi and mnav autopilots



Automatically instrument buffer accesses with runtime checks

Use SeaHorn to validate that run-time checks never fail
- somewhat slower than pure abstract interpretation
- much more precise!

LLVM Pass to insert BO checks



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

Available postdoctoral positions

What: development and application of SeaHorn

Where: CMU/NASA Silicon Valley Campus

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