Building Program Verifiers from Compilers and Theorem Provers

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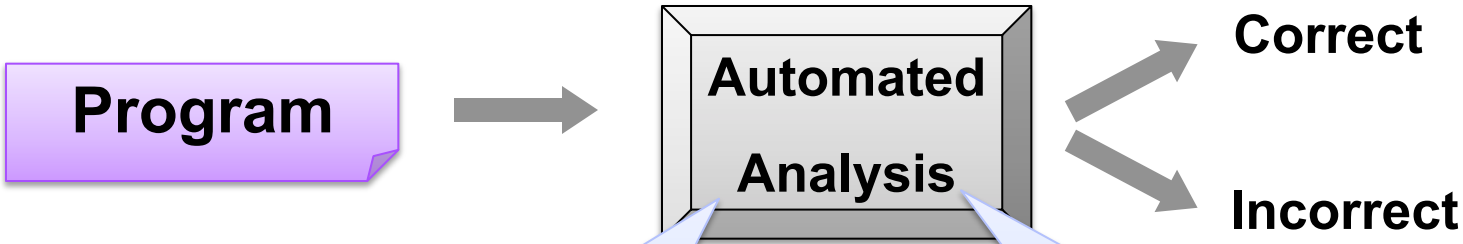
Automated Software Analysis

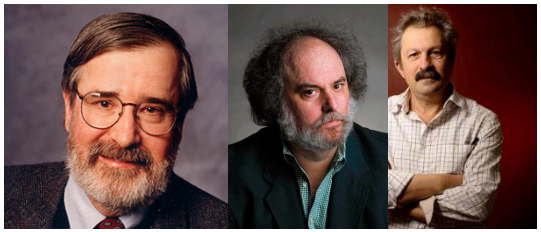


Software Model Checking with Predicate Abstraction

e.g., Microsoft's SDV

Abstract Interpretation with Numeric Abstraction

e.g., ASTREE, Polyspace



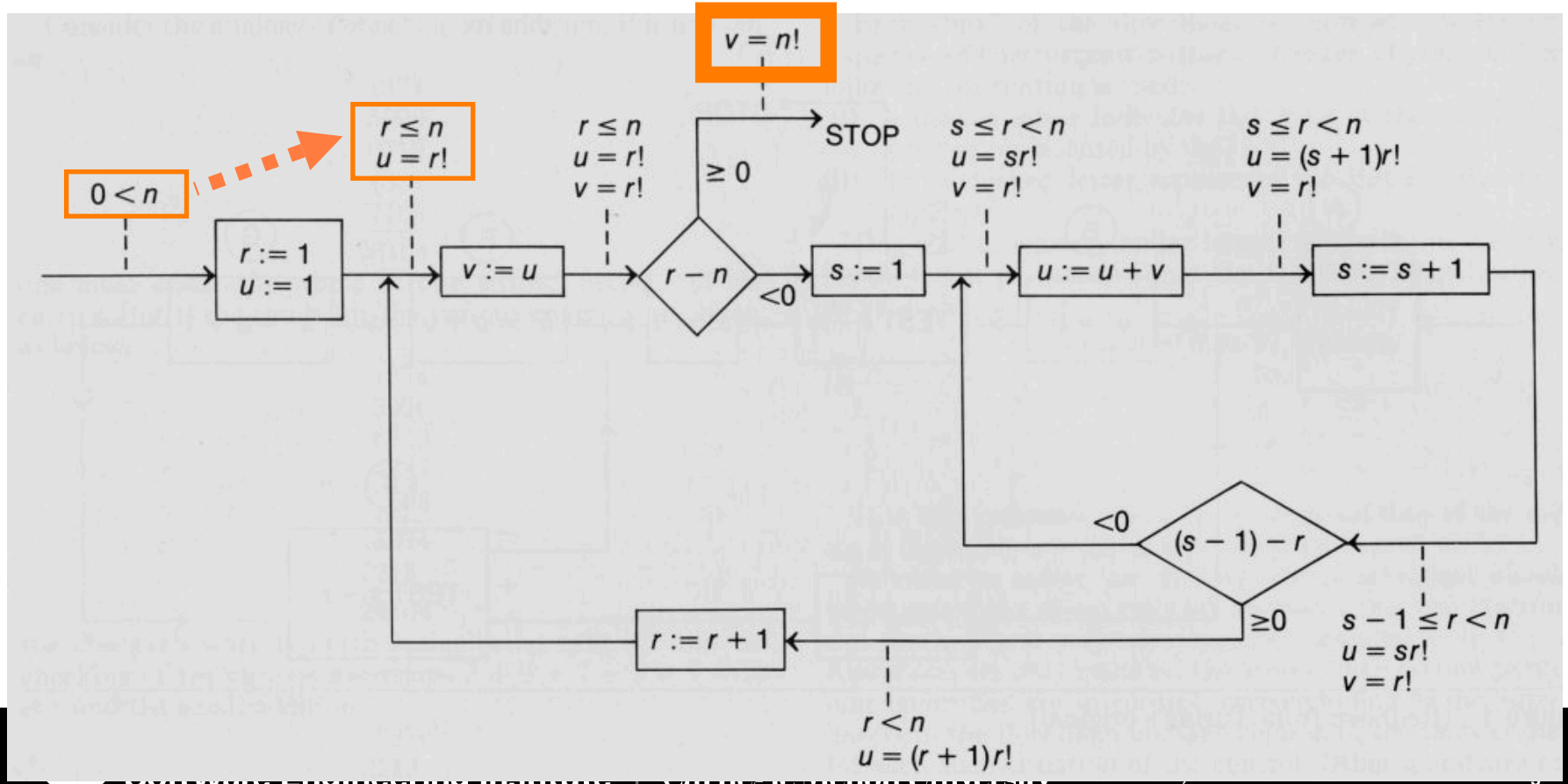
Turing, 1936: “undecidable”

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?

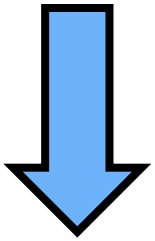
programmer should make a number of definite assertions which can be checked individually, and from which the correctness of the whole programme easily follows.



Three-Layers of a Program Verifier

Compiler

- compiles surface syntax to some machine
- embodies syntax with semantics

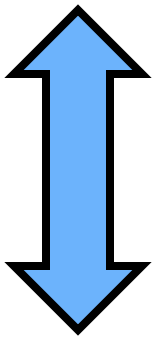


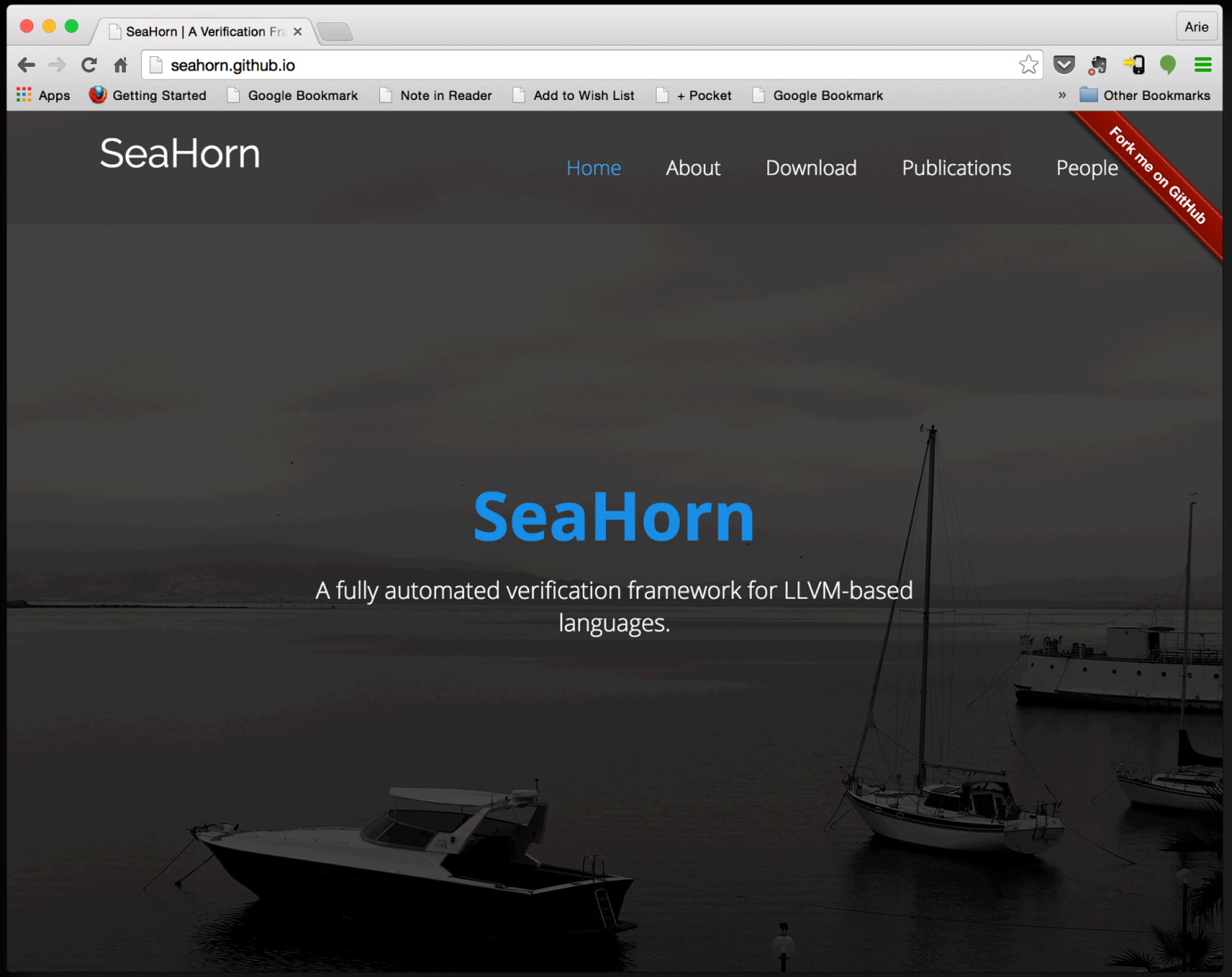
Verification Condition Generator

- transforms a program and a property to 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 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

The Plan

This Lecture

- front-end: verification conditions, constrained horn clauses
- from verification problems to decision problems in logic

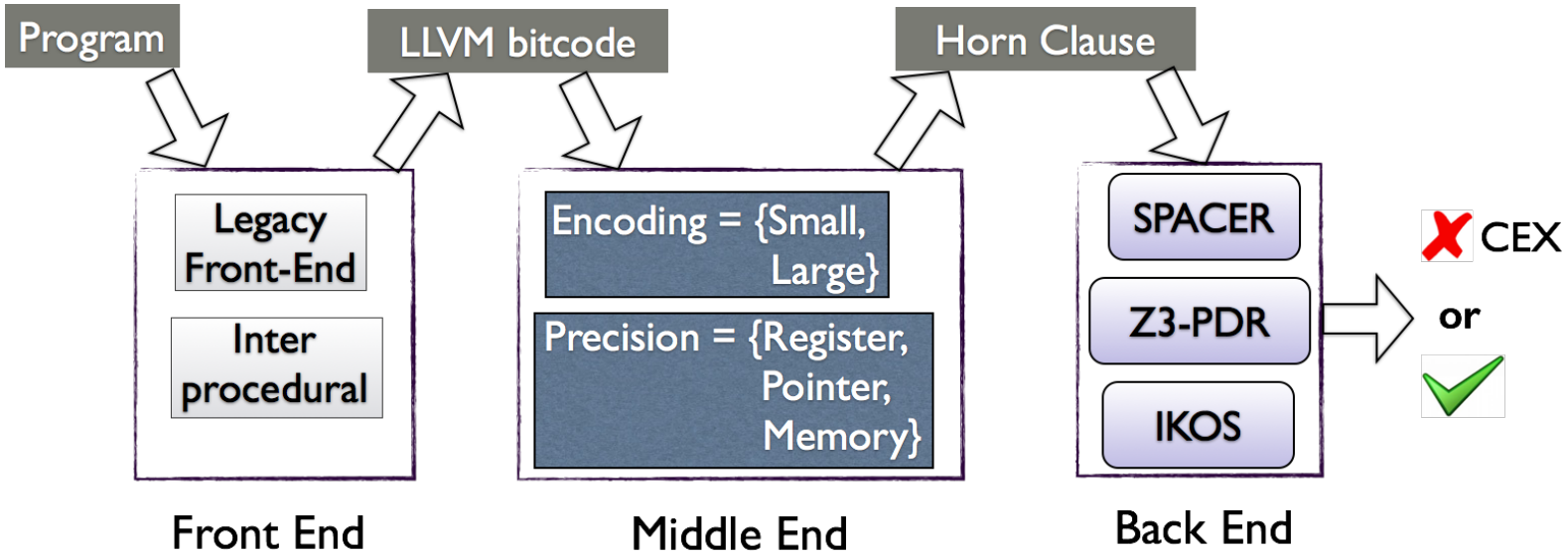
Next Lecture

- back-end: solving verification conditions
- IC3/PDR algorithms and extensions for software verification
- http://arieg.bitbucket.org/pdf/gurfinkel_ssft15.pdf

Labs

- we will play with tools
- get binary distribution from github.com/seahorn/seahorn
- get seahorn-tutorial repo from github.com/seahorn-tutorial
- pre-requisites: recent Linux or OSX + clang-3.6
- can use provided VM to satisfy the pre-requisites

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

UFO

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

SeaHorn Usage

`> sea pf FILE.c`

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

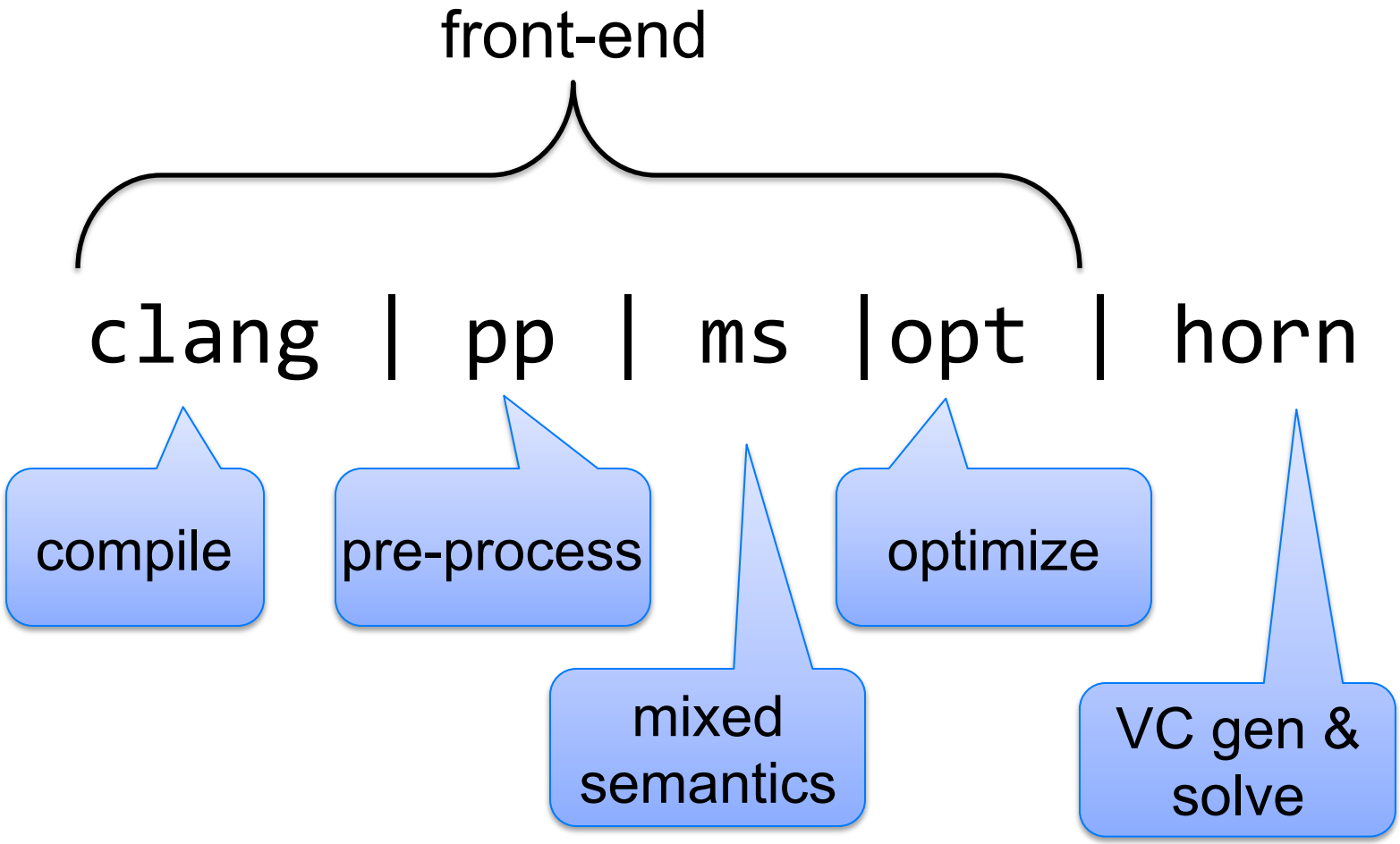
Additional options

- `--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



Constrained Horn Clauses

INTERMEDIATE REPRESENTATION

Constrained Horn Clauses (CHC)

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

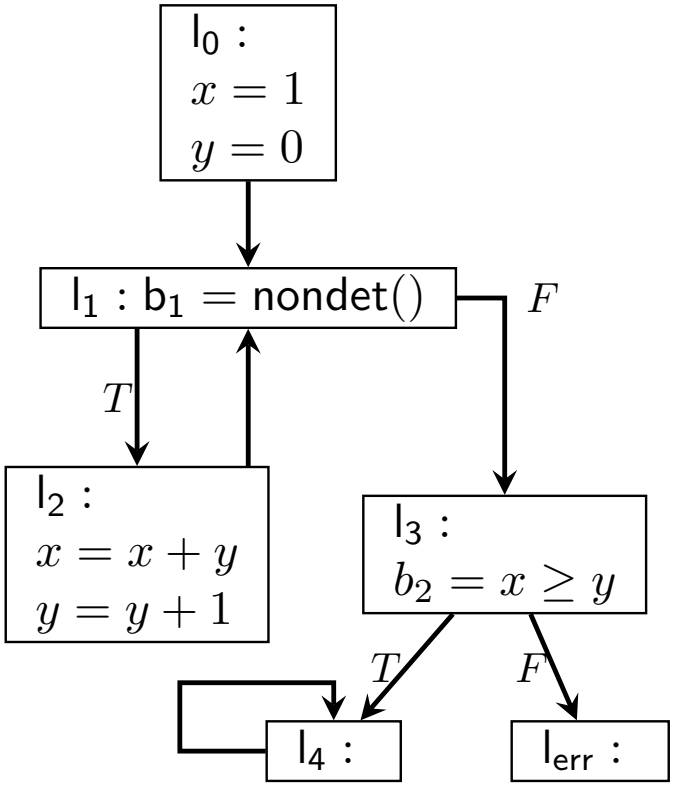
$$\forall V . (\phi \wedge p_1[X_1] \wedge \ldots \wedge p_n[X_n] \rightarrow h[X]),$$

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

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



$\langle 1 \rangle$ p_0.

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

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

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$x' = x + y$,
$y' = y + 1$.

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

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

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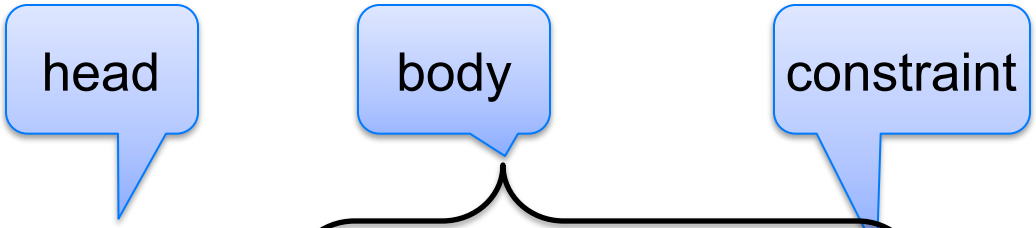
$\langle 9 \rangle$ $\bot \leftarrow \mathsf{p}_{\mathsf{err}}$.

CHC Terminology



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

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

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

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

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

Function Application

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

Recursion

$$\frac{\{\text{Pre}\}\ \text{b = F(a)}\ \{\text{Post}\}\ \vdash \{\text{Pre}\}\ \text{Body}_{\text{F}}\ \{\text{Post}\}}{\{\text{Pre}\}\ \text{b = F(a)}\ \{\text{Post}\}}$$

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))

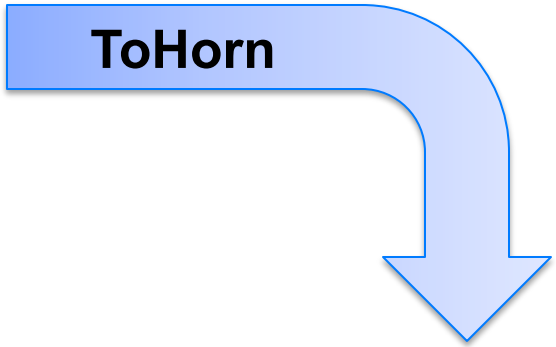
wlp (y = P(E), Q) = p_{pre}(E) $\wedge$ ($\forall$ r. p(E, r) $\rightarrow$ Q[r/y])

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≥ 0}
 x_o = x;
 y_o = y;
 while y > 0 do
    x = x+1;
    y = y-1;
{Post: x=x_o+y_o}
```




```
C1: I(x,y,x,y) ← y>=0.
C2: I(x+1,y-1,x_o,y_o) ← I(x,y,x_o,y_o), y>0.
C3: false ← I(x,y,x_o,y_o), y≤0, x≠x_o+y_o
```

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

Dual WLP

Dual weakest liberal pre-condition

$$\textbf{dual-wlp}\ (P, Post) \;=\; \neg\textbf{wlp}\ (P, \neg Post)$$

s ⊨ **dual-wlp** (P, Post) iff there exists an execution of P that starts in s and ends in Post

dual-wlp (P, Post) is the weakest condition ensuring that an execution of P can reach a state in Post

Control Flow Graph

A CFG is a graph of basic blocks

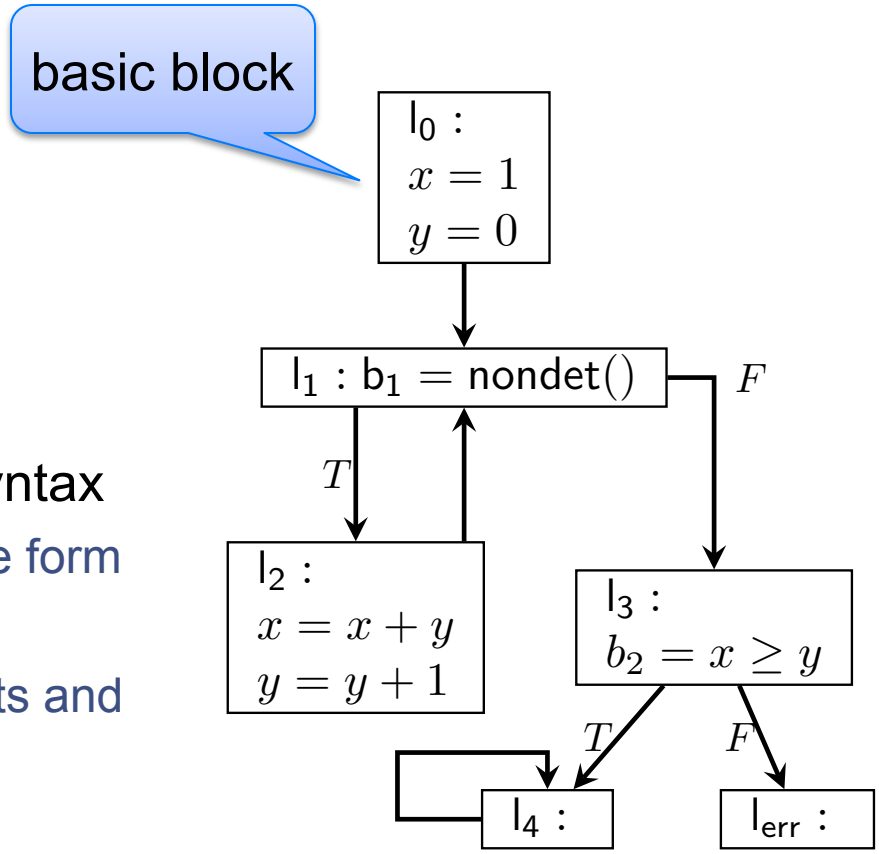
- edges represent different control flow

A CFG corresponds to a program syntax

- where statements are restricted to the form

  L_i:S ; goto L_j

  and S is control-free (i.e., assignments and procedure calls)



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:

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

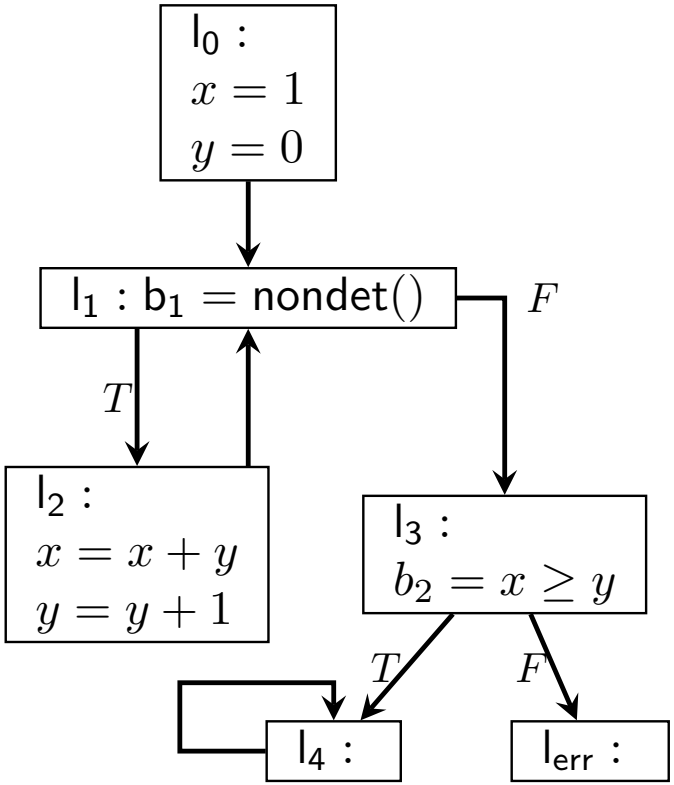
$l_i(x_0,w') \leftarrow l_j(x_0,w) \wedge \neg wlp(S, \neg(w=w'))$, for each statement l_i: S; goto l_j

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

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

Example Horn Encoding

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



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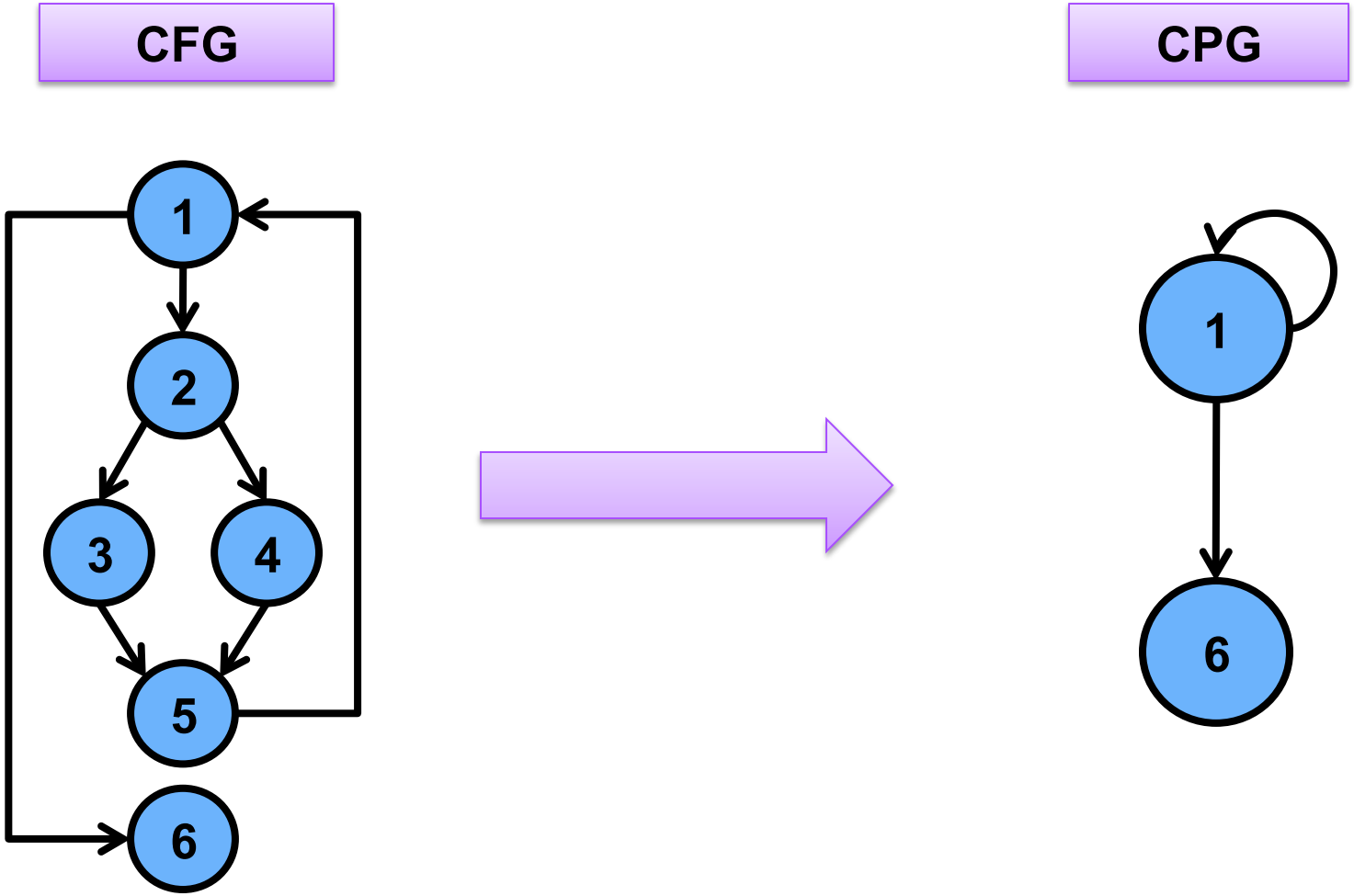
From CFG to Cut Point Graph

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



From CFG to Cut Point Graph

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

Cut Point Graph preserves reachability of (not-summarized) control location.

Summarizing loops is undecidable! (Halting program)

A *cutset summary* summarizes all location except for a *cycle cutset* of a CFG. Computing minimal cutset summary is NP-hard (minimal feedback vertex set).

A reasonable compromise is to summarize everything but heads of loops. (Polynomial-time computable).

Single Static Assignment

SSA == every value has a unique assignment (a *definition*)

A procedure is in SSA form if every variable has exactly one definition

SSA form is used by many compilers

- explicit def-use chains
- simplifies optimizations and improves analyses

PHI-function are necessary to maintain unique definitions in branching control flow

$$x = PHI (v_0:bb_0, \ldots, v_n:bb_n)) \qquad \text{(phi-assignment)}$$

"x gets v_i if previously executed block was bb_i"

Single Static Assignment: An Example

```
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:
```

val:bb

Large Step Encoding

Problem: Generate a compact verification condition for a loop-free block of code

```
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:
```

Large Step Encoding: Extract all Actions

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

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

Example: Encode Control Flow

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

$B_2 \rightarrow x_0 < N$

$B_3 \rightarrow B_2 \wedge y_0 > 0$

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

$B_5 \wedge x'_0 = x_3 \wedge y'_0 = y_1$

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

```
1: x_0 = PHI(0:0, x_3:5);
   y_0 = PHI(y:0, y_1:5);
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5: x_3 = PHI(x_1:3, x_2:4);
   y_1 = -1 * y_0;
   goto 1
```
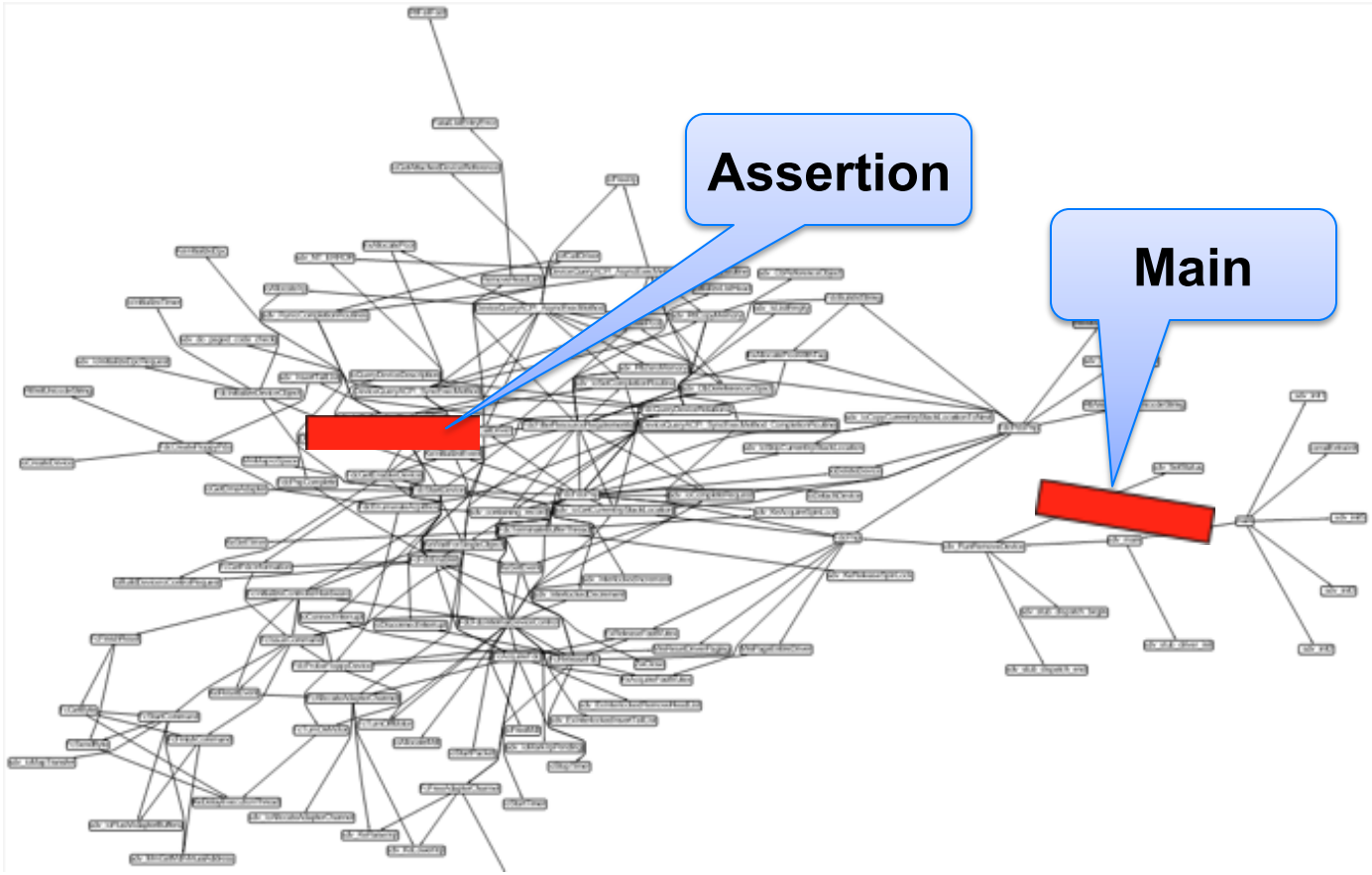
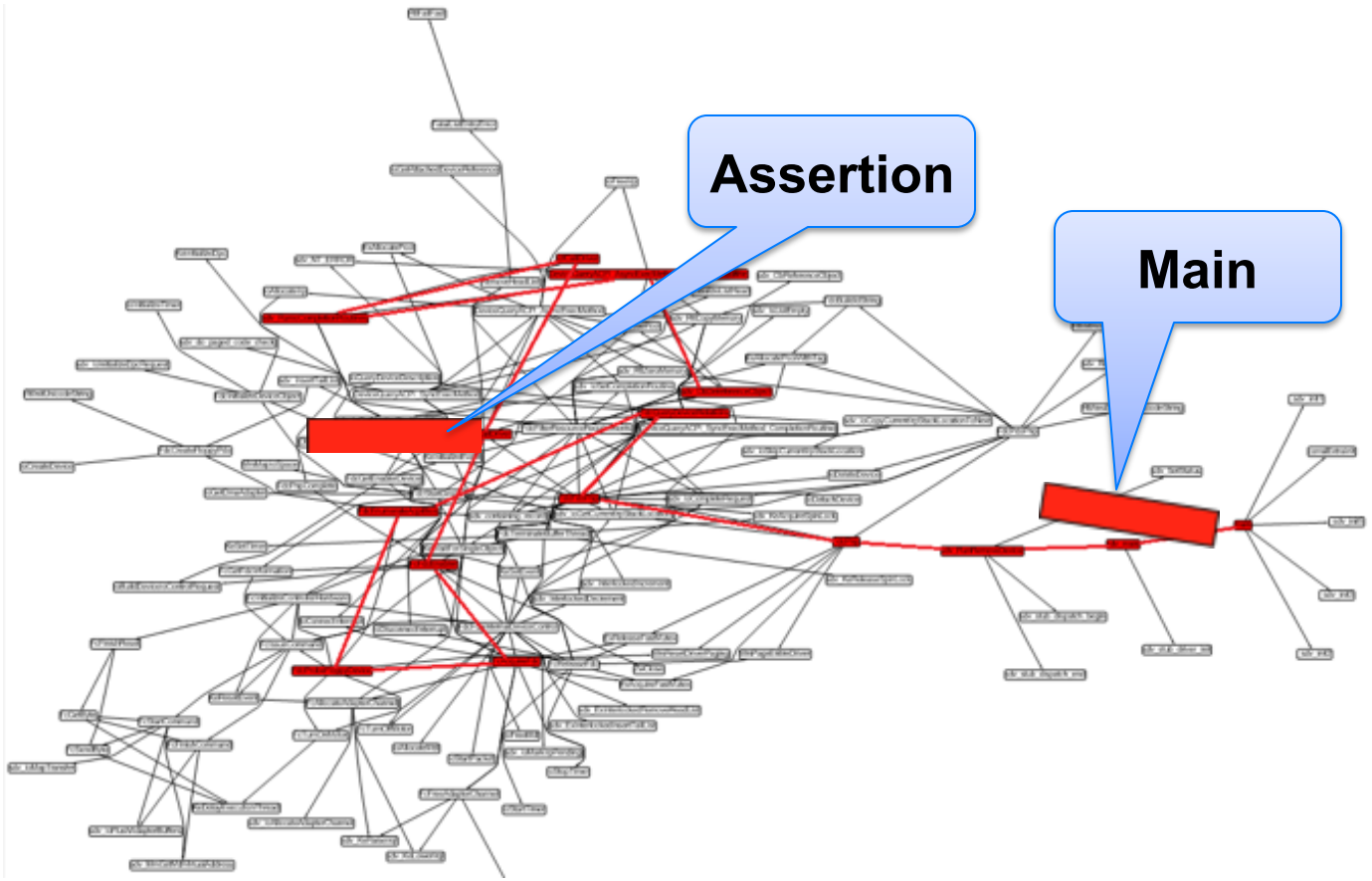

Mixed Semantics

PROGRAM TRANSFORMATION

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

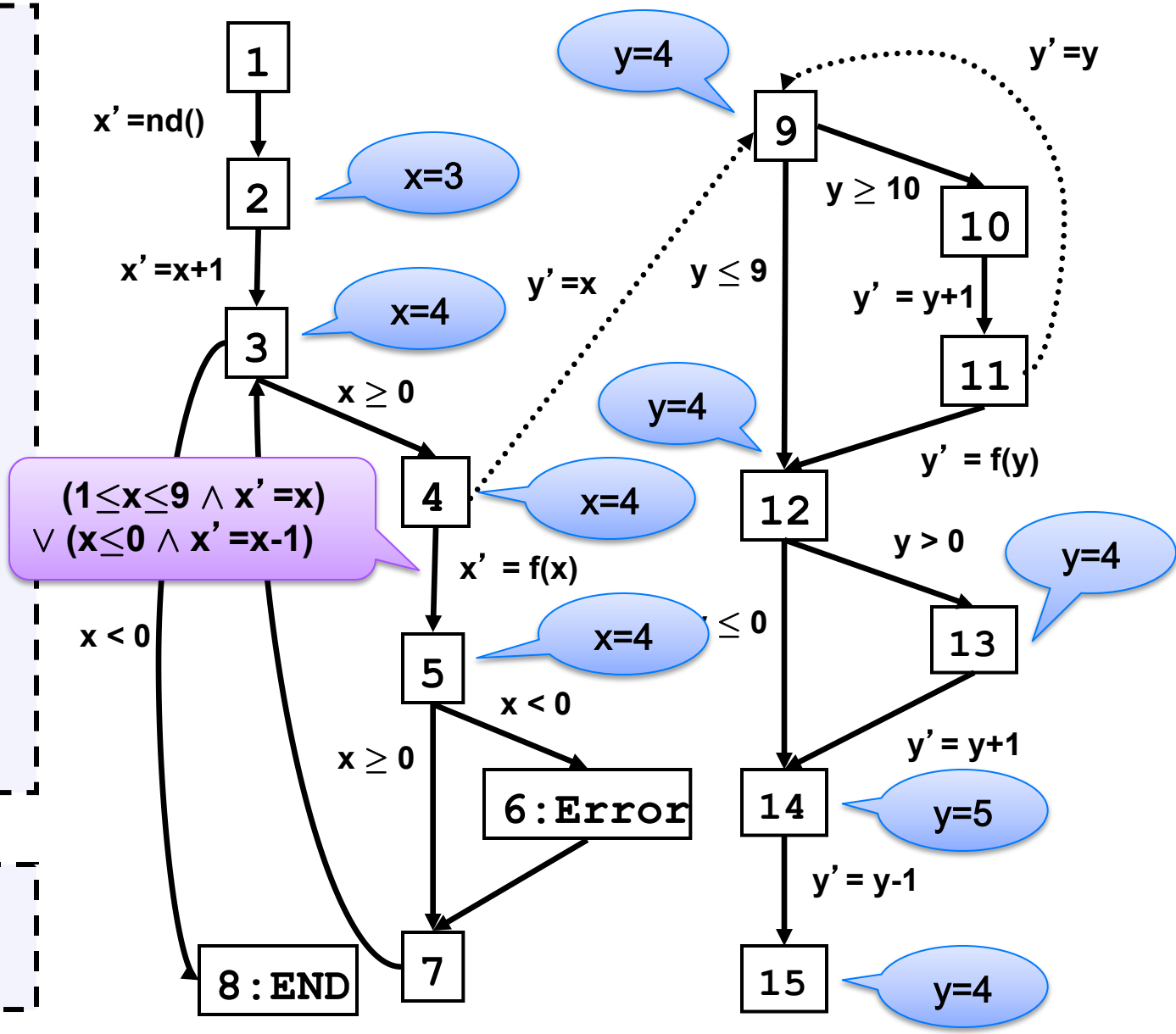
- update top activation record using function summary, or
- enter function body, forgetting history records (i.e., no return!)

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:
```

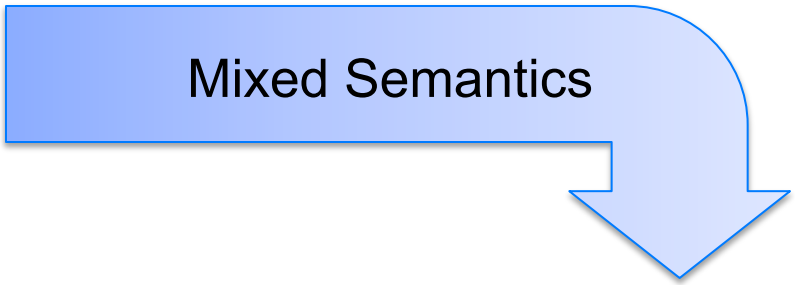


Summary of f(y)

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

Mixed Semantics as Program Transformation

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




```
main_new ()
    if (*) goto p1_entry;
    else p1_new ();
    if (*) goto p1_entry;
    else p1_new ();
    if (¬c1) goto error;
    assume (false);

p1_entry :
    if (*) goto p2_entry;
    else p2_new ();
    if (¬c2) goto error;
p2_entry :
    if (¬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: $\mathcal{F}(X) = \exists\ \boldsymbol{u}\ .\ (X \wedge \rho) \vee \text{Init}$

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

IC3/PDR Algorithm Overview

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

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

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

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

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

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

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

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

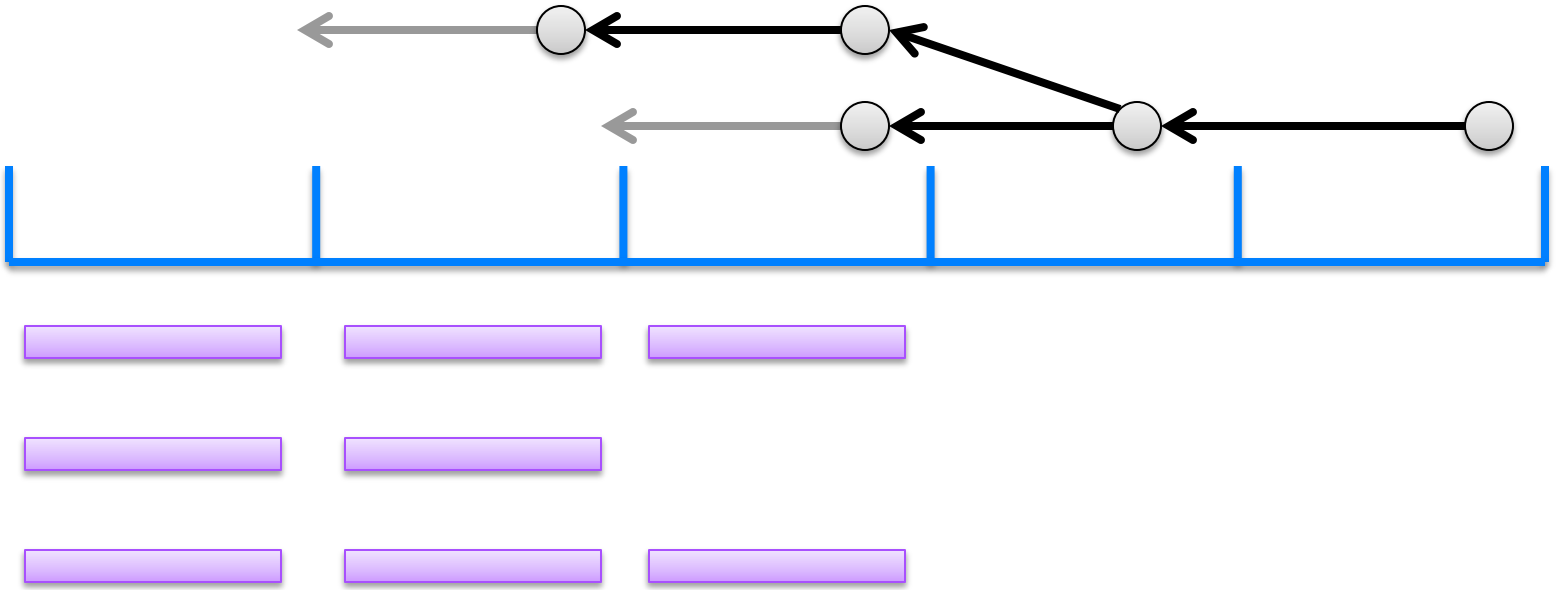
until ∞;

bounded safety

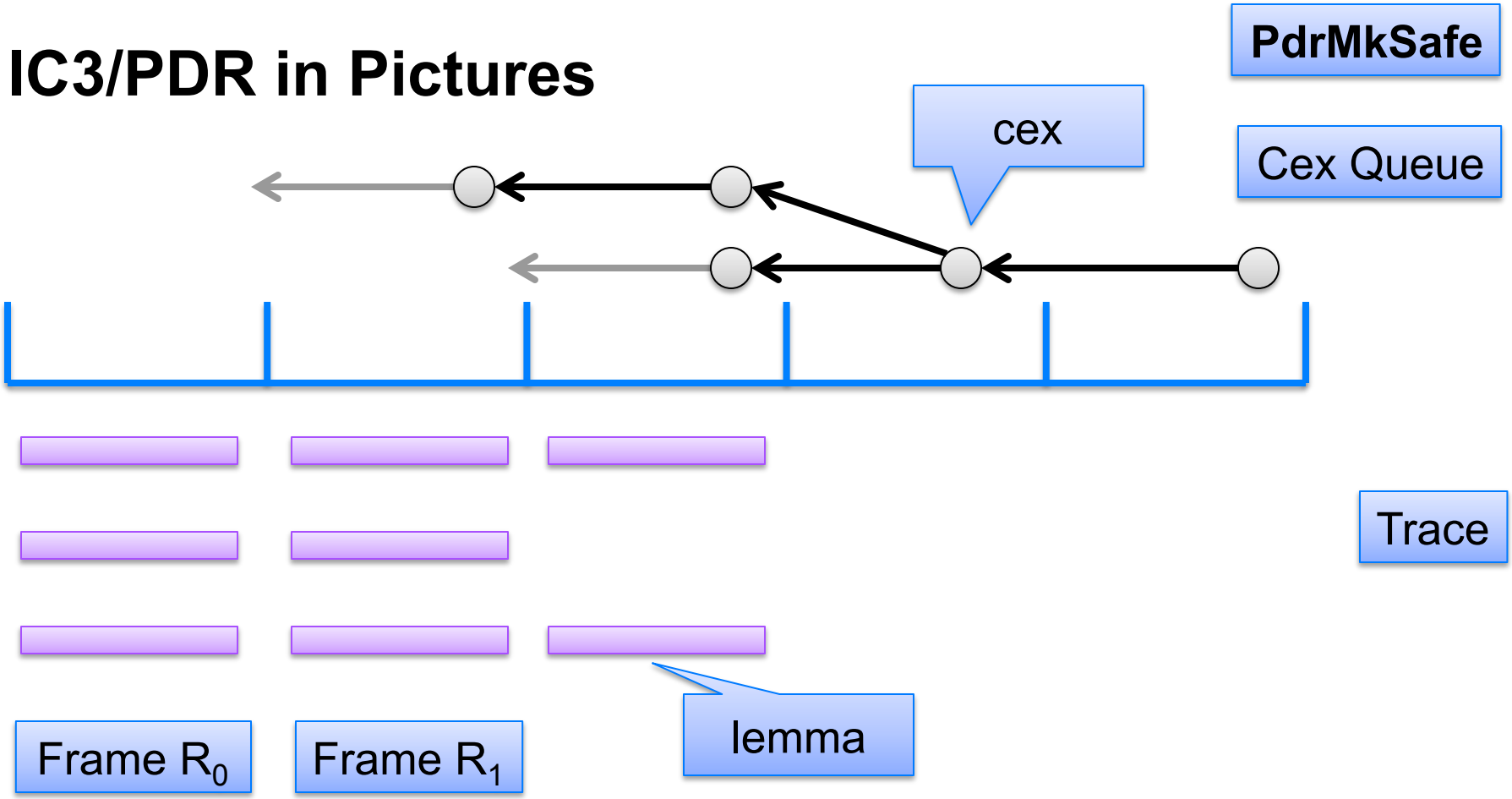
strengthen result

IC3/PDR in Pictures

PdrMkSafe

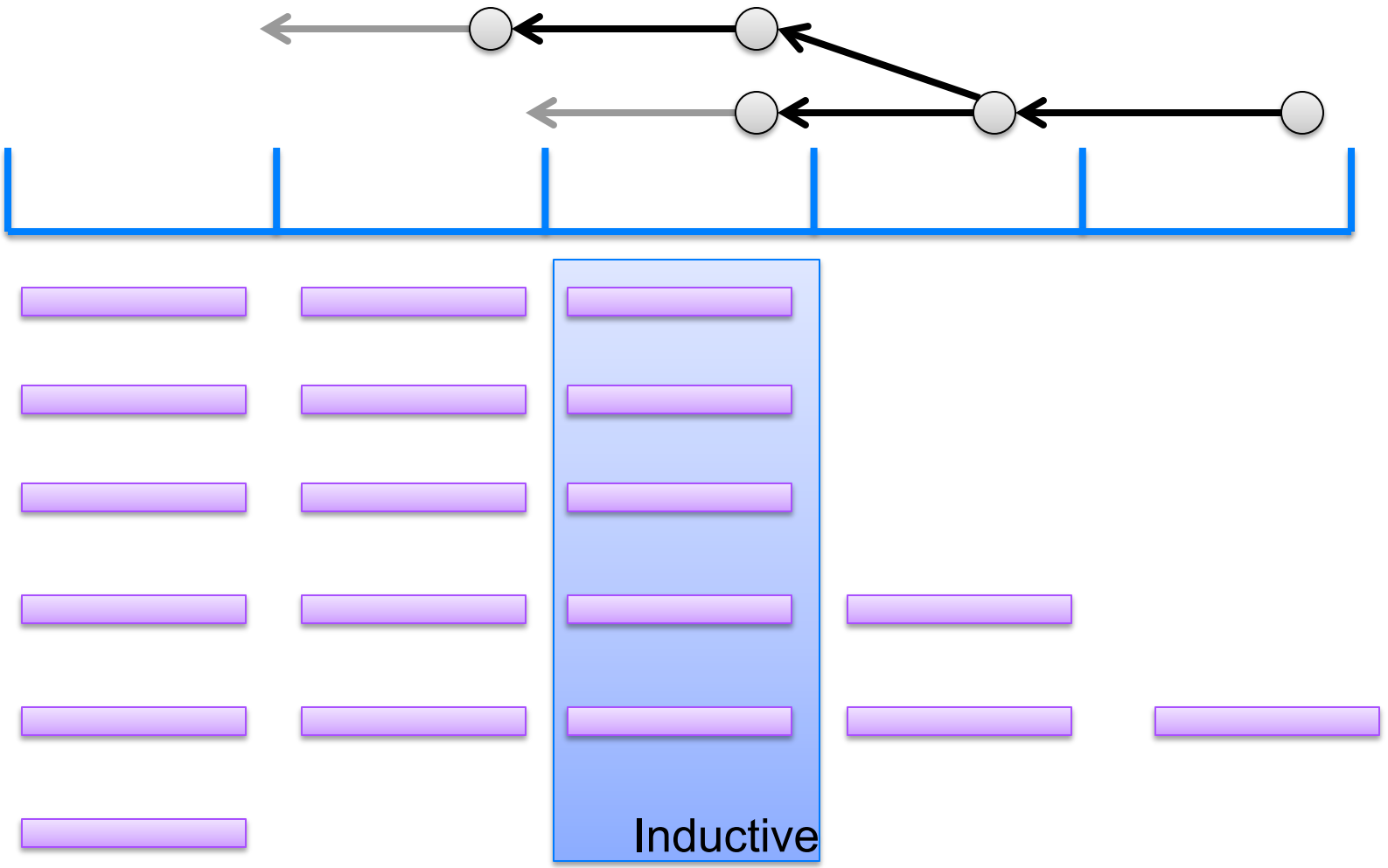


IC3/PDR in Pictures



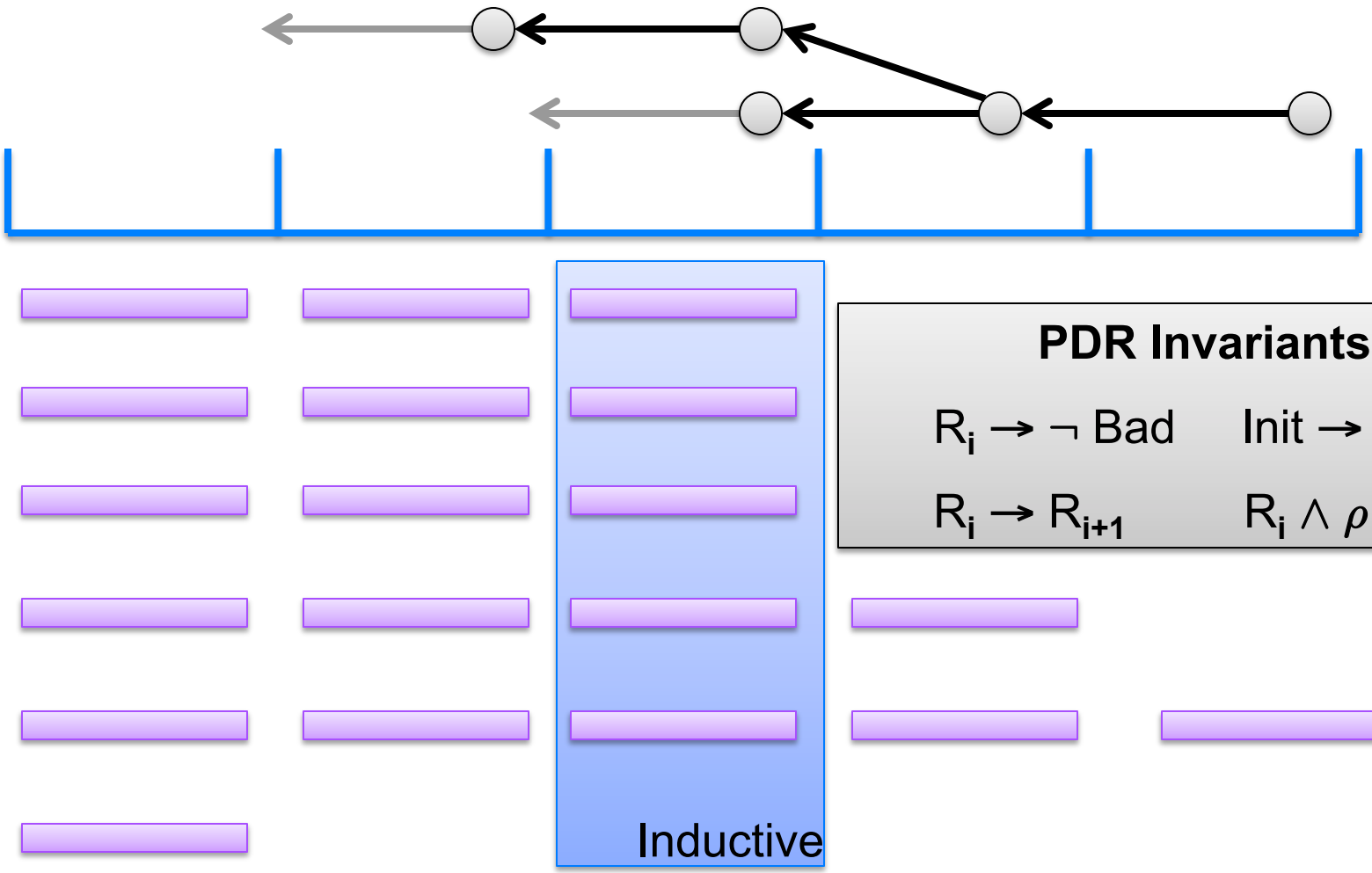
IC3/PDR in Pictures

PdrPush



IC3/PDR in Pictures

PdrPush

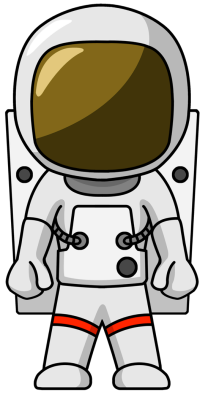


PDR Invariants

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

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

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.

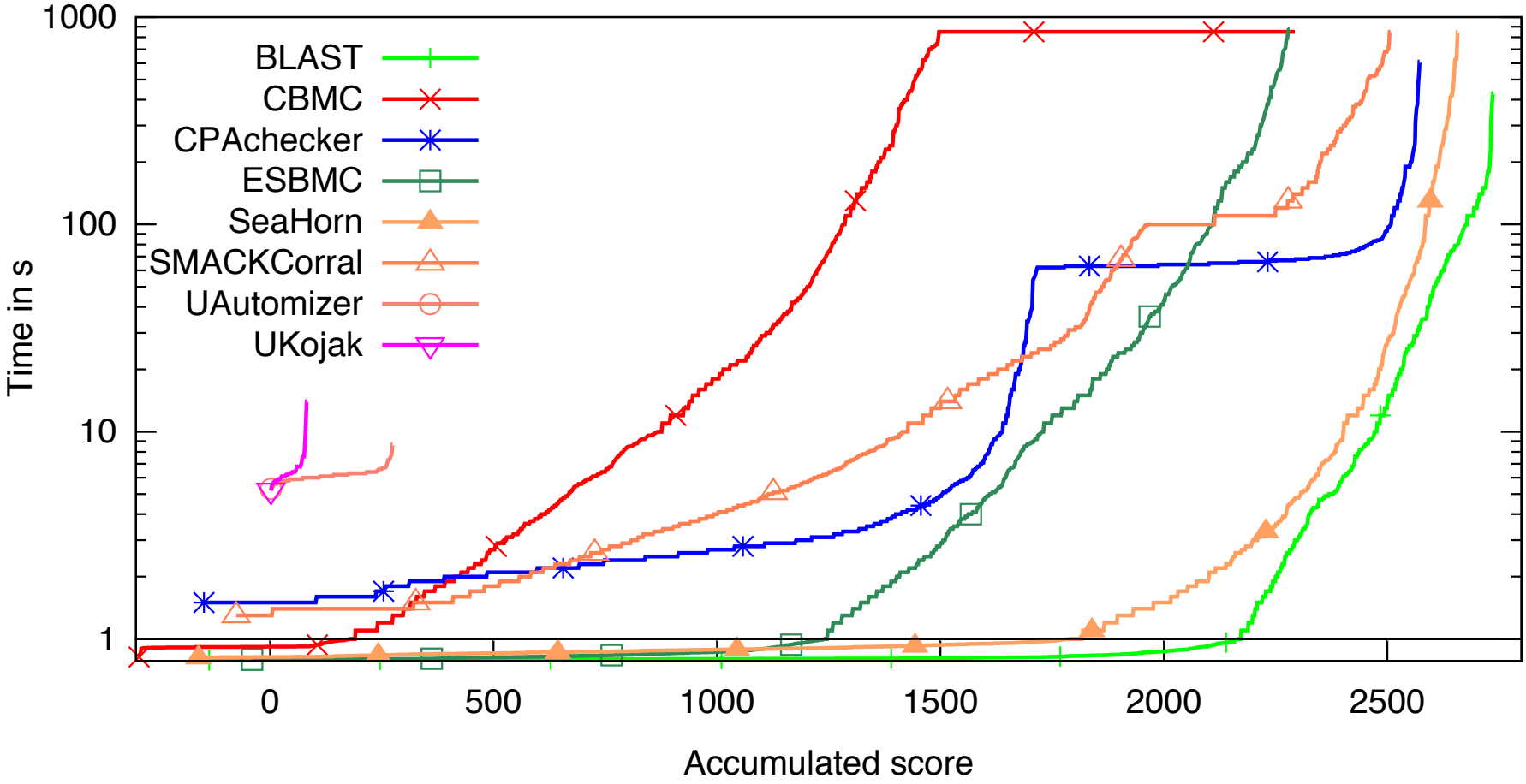
Participants:

- 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

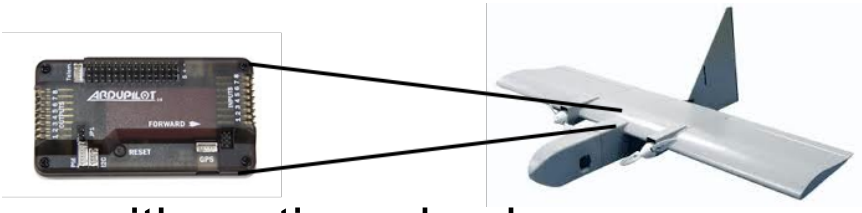
Results for DeviceDriver category



Detecting Buffer Overflow in Auto-pilot software

Show absence of Buffer Overflows in

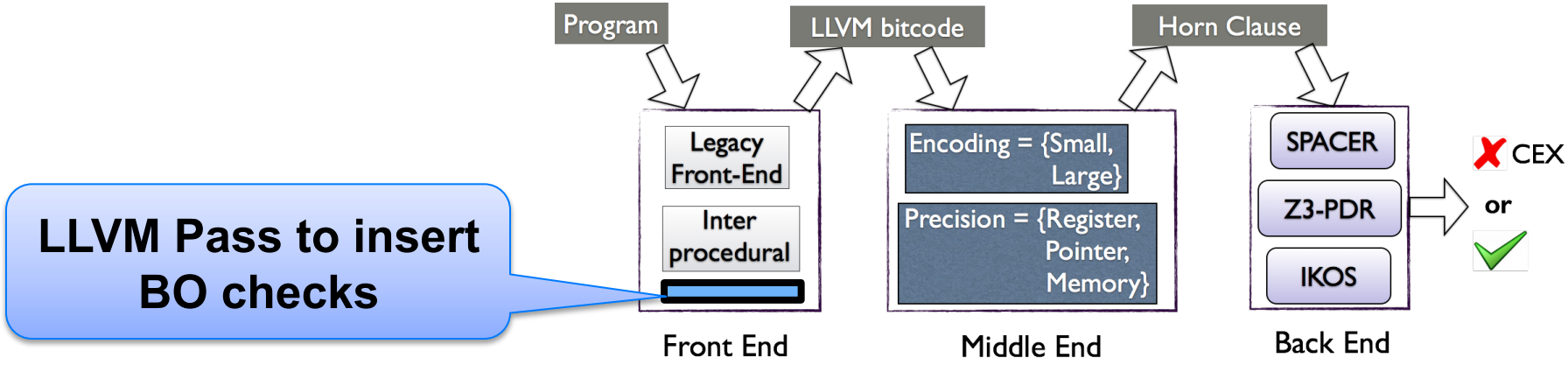
- paparazzi and mnav autopilots



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!



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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