Building Program Verifiers from Compilers and Theorem Provers

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Automated Software Analysis

Program \rightarrow \text{Automated Analysis} \rightarrow \text{Correct} \lor \text{Incorrect}

- Software Model Checking with Predicate Abstraction
  e.g., Microsoft’s SDV
- Abstract Interpretation with Numeric Abstraction
  e.g., ASTREE, Polyspace
Turing, 1936: “undecidable”
How can one check a routine in the sense of making sure that it is right? The 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,…
SeaHorn

A fully automated verification framework for LLVM-based languages.

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

front-end

clang | pp | ms | opt | horn

compile
pre-process
mixed semantics
optimize
VC gen & solve
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)
- $\phi$ 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 (true) {
    x = x + y;
    y = y + 1;
}
assert(x ≥ y);
```

```
\[\begin{align*}
\langle 1 \rangle & \; p_0. \\
\langle 2 \rangle & \; p_1(x, y) \leftarrow \; p_0, x = 1, y = 0. \\
\langle 3 \rangle & \; p_2(x, y) \leftarrow p_1(x, y). \\
\langle 4 \rangle & \; p_3(x, y) \leftarrow p_1(x, y). \\
\langle 5 \rangle & \; p_1(x', y') \leftarrow \; p_2(x, y), \quad x' = x + y, \quad y' = y + 1. \\
\langle 6 \rangle & \; p_4 \leftarrow (x ≥ y), p_3(x, y). \\
\langle 7 \rangle & \; p_{err} \leftarrow (x < y), p_3(x, y). \\
\langle 8 \rangle & \; p_4 \leftarrow p_4. \\
\langle 9 \rangle & \; \bot \leftarrow p_{err}. \\
\end{align*}\]
```
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 $\mathcal{I}$ is an interpretation of each predicate $p_i$ that makes all clauses in $\mathcal{I}$ valid.

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

A model is **$A$-definable**, if each $p_i$ is definable by a formula $\psi_i$ 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

\[
\begin{align*}
\text{Pre} & \Rightarrow \text{Inv} \\
\{\text{Inv} \land C\} \text{ Body} \{\text{Inv}\} \\
\text{Inv} \land \neg C & \Rightarrow \text{Post}
\end{align*}
\]

\[\{\text{Pre}\} \textbf{while} C \textbf{ do Body} \{\text{Post}\}\]

Function Application

\[
\begin{align*}
(\text{Pre} \land p=a) & \Rightarrow P \\
\{P\} \text{ Body}_F \{Q\} \\
(Q \land p,r=a,b) & \Rightarrow \text{Post}
\end{align*}
\]

\[\{\text{Pre}\} b = F(a) \{\text{Post}\}\]

Recursion

\[
\begin{align*}
\{\text{Pre}\} b = F(a) \{\text{Post}\} \\
\vdash \{\text{Pre}\} \text{ Body}_F \{\text{Post}\}
\end{align*}
\]

\[\{\text{Pre}\} b = F(a) \{\text{Post}\}\]
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 \( Post \)

\[ \{\text{Pre}\} \ P \ \{\text{Post}\} \ \text{is valid} \ \iff \ \text{Pre} \ \Rightarrow \ wlp \ (P, \ Post) \]
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 \land Q
wlp (assume(E), Q) = E \rightarrow Q
wlp (while E do S, Q) = I(w) \land
  \forall w . ((I(w) \land E) \rightarrow wlp (S, I(w))) \land ((I(w) \land \neg E) \rightarrow Q))
wlp (y = P(E), Q) = p_{pre}(E) \land (\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) \land \forall \{P \in Prog\}. ToHorn (P)
Example of a WLP Horn Encoding

\{\text{Pre: } y \geq 0}\}
\ x_0 = x; \\
\ y_0 = y; \\
\text{while } y > 0 \text{ do} \\
\quad x = x+1; \\
\quad y = y-1; \\
\{\text{Post: } x = x_0 + y_0}\}

ToHorn

C1: \ I(x,y,x,y) \leftarrow y \geq 0. \\
C2: \ I(x+1,y-1,x_0,y_0) \leftarrow I(x,y,x_0,y_0), \ y > 0. \\
C3: \ \text{false} \leftarrow I(x,y,x_0,y_0), \ y \leq 0, \ x \neq x_0 + y_0

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

Dual weakest liberal pre-condition

\[ \text{dual-wlp} (P, \text{Post}) = \neg \text{wlp} (P, \neg \text{Post}) \]

\( s \models \text{dual-wlp} (P, \text{Post}) \) iff there exists an execution of \( P \) that starts in \( s \) and ends in \( \text{Post} \)

\text{dual-wlp} (P, \text{Post}) is the weakest condition ensuring that an execution of \( P \) can reach a state in \( \text{Post} \)
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
  \( L_i; S \; ; \text{goto} \; L_j \)
  and \( S \) is control-free (i.e., assignments and procedure calls)
Horn Clauses by Dual WLP

Assumptions

- each procedure is represented by a control flow graph
  - i.e., statements of the form \( l_i : S ; \text{goto} \ l_j \), 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, \( p_{\text{en}}(x_0, x, w) \) for entry, \( p_{\text{ex}}(x_0, r) \) for exit

The verification condition is a conjunction of clauses:

\[
\begin{align*}
  p_{\text{en}}(x_0, x) & \iff x_0 = x \\
  l_i(x_0, w') & \iff l_j(x_0, w) \land \neg \text{wlp} (S, \neg (w = w')) \\
  p(x_0, r) & \iff p_{\text{ex}}(x_0, r) \\
  \text{false} & \iff \text{Main}_{\text{ex}}(x, \text{ret})
\end{align*}
\]
Example Horn Encoding

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

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

CFG

CPG

1
2
3
4
5
6

1

6
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

\[
x = \text{PHI} \left( v_0:bb_0, \ldots, v_n:bb_n \right)
\]

(phi-assignment)

“x gets \(v_i\) if previously executed block was \(bb_i\)”
Single Static Assignment: An Example

```c
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: $x_0 = \text{PHI}(0:0, x_3:5);$  
   $y_0 = \text{PHI}(y:0, y_1:5);$  
   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: $x_3 = \text{PHI}(x_1:3, x_2:4);$  
   $y_1 = -1 * y_0;$  
   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: \(x_0 = \text{PHI}(0:0, x_3:5);\)
   \(y_0 = \text{PHI}(y:0, y_1:5);\)
   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: \(x_3 = \text{PHI}(x_1:3, x_2:4);\)
   \(y_1 = -1 \times y_0;\)
   goto 1

6:
Large Step Encoding: Extract all Actions

\[ x_1 = x_0 + y_0 \]
\[ x_2 = x_0 - y_0 \]
\[ y_1 = -1 \times y_0 \]

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

2: \text{if} (y_0 > 0) \text{goto} 3 \text{ else goto} 4

3: \( x_1 = x_0 + y_0 \) \text{ goto} 5

4: \( x_2 = x_0 - y_0 \) \text{ goto} 5

5: \( x_3 = \text{PHI}(x_1:3, x_2:4); \)
   \( y_1 = -1 \times y_0; \)
   \text{goto} 1
Example: Encode Control Flow

\[ x_1 = x_0 + y_0 \]
\[ x_2 = x_0 - y_0 \]
\[ y_1 = -1 \times y_0 \]

\[ B_2 \rightarrow x_0 < N \]
\[ B_3 \rightarrow B_2 \land y_0 > 0 \]
\[ B_4 \rightarrow B_2 \land y_0 \leq 0 \]
\[ B_5 \rightarrow (B_3 \land x_3=x_1) \lor (B_4 \land x_3=x_2) \]

\[ B_5 \land x'_0=x_3 \land y'_0=y_1 \]

1: \[ x_0 = \text{PHI}(0:0, x_3:5); \]
   \[ y_0 = \text{PHI}(y:0, y_1:5); \]
   if (\(x_0 < N\)) goto 2 else goto 6

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

3: \[ x_1 = x_0 + y_0; \text{ goto } 5 \]

4: \[ x_2 = x_0 - y_0; \text{ goto } 5 \]

5: \[ x_3 = \text{PHI}(x_1:3, x_2:4); \]
   \[ y_1 = -1 \times y_0; \]
   goto 1

\[ p_1(x'_0,y'_0) \leftarrow p_1(x_0, y_0), \phi. \]
Mixed Semantics

PROGRAM TRANSFORMATION
Deeply nested assertions
Deeply nested assertions

Counter-examples are long
Hard to determine (from main) what is relevant
Mixed Semantics

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 \(\sigma\) terminates and results in state \(\sigma'\)
- 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,

\[
K \models \text{EF (pc=L)} \iff K^m \models \text{EF (pc=L)} \quad \text{and} \quad K \models \text{EG (pc\neq L)} \iff K^m \models \text{EG (pc\neq L)}
\]
```python
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≤y≤9 ∧ y′=y) ∨ (y≤0 ∧ y′=y-1)
```

```
Mixed Semantics as Program Transformation

```plaintext
main ()
    p1 (); p1 ();
    assert (c1);
    p1 ()
    p2 ();
    assert (c2);
    p2 ()
    assert (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 `error()` 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 $P = (V, \text{Init}, \rho, \text{Bad})$

- Notation: $\mathcal{F}(X) = \exists u . (X \land \rho) \lor \text{Init}$

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

$$\text{Init}(v_0) \land \left( \bigwedge_{i=0}^{N-1} \rho(v_i, v_{i+1}) \right) \land \text{Bad}(v_N) \nRightarrow \bot$$

$P$ is SAFE if and only if there exists a safe inductive invariant $\text{Inv}$ s.t.

\[
\begin{align*}
\text{Init}(u) & \Rightarrow \text{Inv}(u) \\
\text{Inv}(u) \land \rho(u, v) & \Rightarrow \text{Inv}(v) \\
\text{Inv}(u) & \Rightarrow \neg \text{Bad}(u)
\end{align*}
\]

\{ Inductive \}

\{ Safe \}
IC3/PDR Algorithm Overview

**Input:** Safety problem \( \langle \text{Init}(X), \text{Tr}(X, X'), \text{Bad}(X) \rangle \)

\[
F_0 \leftarrow \text{Init} \; ; \; N \leftarrow 0 \; \text{repeat} \; \; \\
\text{G} \leftarrow \text{PdrMkSafe}([F_0, \ldots, F_N], \text{Bad}) \; \; \\
\text{if } G = [ ] \text{ then return } \text{Reachable}; \; \\
\forall 0 \leq i \leq N \cdot F_i \leftarrow G[i] \; \\
F_0, \ldots, F_N \leftarrow \text{PdrPush}([F_0, \ldots, F_N]) \; \\
\text{if } \exists 0 \leq i < N \cdot F_i = F_{i+1} \text{ then return } \text{Unreachable}; \; \\
N \leftarrow N + 1 \; ; \; F_N \leftarrow \emptyset \; \\
\text{until } \infty; \]

**bounded safety**

**strengthen result**
IC3/PDR in Pictures
IC3/PDR in Pictures

Frame R₀ → Frame R₁

lemma

cex

PdrMkSafe

Cex Queue

Trace
IC3/PDR in Pictures

PdrPush
IC3/PDR in Pictures

PDR Invariants

\[ R_i \rightarrow \neg \text{Bad} \]
\[ \text{Init} \rightarrow R_i \]
\[ R_i \rightarrow R_{i+1} \]
\[ R_i \wedge \rho \rightarrow R_{i+1} \]
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

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
Results for DeviceDriver category

```
<table>
<thead>
<tr>
<th>Software</th>
<th>Time in s</th>
</tr>
</thead>
<tbody>
<tr>
<td>BLAST</td>
<td>0</td>
</tr>
<tr>
<td>CBMC</td>
<td>500</td>
</tr>
<tr>
<td>CPAchecker</td>
<td>1000</td>
</tr>
<tr>
<td>ESBMC</td>
<td>1500</td>
</tr>
<tr>
<td>SeaHorn</td>
<td>2000</td>
</tr>
<tr>
<td>SMACKCorral</td>
<td>2500</td>
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<tr>
<td>UAutomizer</td>
<td></td>
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<td>UKojak</td>
<td></td>
</tr>
</tbody>
</table>
```

Accumulated score vs. Time in s graph showing performance of different tools.
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