UFR IM²AG

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Software security, secure programming

Static Analysis (in a nutshell)

Master M2 Cybersecurity

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Static Analysis

Main objective:

statically compute some information about (an approximation of) the program behavior

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- under-approximate the pgm behaviour
  $\rightarrow$ result is complete (no false negatives), but unsound ($\exists$ false negative)
- non-terminating analysis
  $\rightarrow$ **if** the analysis terminates, **then** the result is sound and complete

What static analysis can be used for ?

General applications

- compiler optimization
  e.g., active variables, available expressions, constant propagations, etc.
- program verification
  e.g., invariant, post-conditions, etc.
- worst-case execution time computation
- parallelization
- etc.

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In the "software security" context

- disassembling
  e.g., what are the targets of a dynamic jump
  (`be eax`, content of `eax` ?)
- error and vulnerability detection
  memory error (Null-pointer dereference, out-of-bound array access), use-after-free, arithmetic overflow, etc.

Outline

How to proceed ?

Typical problems

- need to reason on a set of executions (not on a single one)

  ex: `x = y * z`

  → compute values of `x` for all possible values of `y` and `z` ?
- need to cope with loops

  ex: `while (x < y) do ... end`

  → infer the loop behavior for all possible values of `x` and `y` ?

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A solution: over-approximate the program behavior

1. propagate an abstract state (over approximating the memory content)

   e.g., $x > 0$, $p \neq NULL$, $x \leq y + z$, p and q are aliases, etc.

   → depends on the properties you want to check !
2. **safely** merge memory abstract states produced from ≠ paths
3. make loop iterations always finite

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Pb: How to find a suitable abstract domains ?

→ accuracy vs scalability trade-offs . . .

Outline

A basic programming language

Syntax

$$
\begin{array}{lcl}
\text{Exp} & ::= & x \mid n \mid \text{op}\,(\text{Exp}, \ldots \text{Exp}) \\
\text{Stm} & ::= & x := \text{Exp} \\
 & ::= & \text{Stm}\ ;\ \text{Stm} \\
 & ::= & \text{skip} \\
 & ::= & \text{if}\ \ \text{Exp}\ \ \text{then}\ \ \text{Stm}\ \ \text{else}\ \ \text{Stm} \\
 & ::= & \text{while}\ \ \text{Exp}\ \ \text{do}\ \ \text{Stm}\ \ \text{end} \\
 & ::= & \text{assert}\ \ \text{Exp}
\end{array}
$$

In practice : arrays, structures, pointers, procedures, etc.

Axiomatic Semantics

$\Rightarrow$ programs viewed as *predicate transformers* where predicates are *assertions* on program variables (Hoare, Dijkstra 1976).

- Weakest Preconditions (*wp*) : backward computation
  Example :
  $$x \geq 0 \ \{x := x + 1;\} \ x > 0$$

- Strongest Postcondition (*sp*) : forward computation
  Example :
  $$x \geq 0 \ \{x := x + 1;\} \ x > 0$$

Weakest precondition / Strongest postcondition

Let I a statement, P, R, $'$, R' some predicats

The weakest precondition $P = wp(I, R)$ is such that:

$$\forall P' \; (P' \Rightarrow wp(I, R)) \Rightarrow (P' \Rightarrow P)$$

A precondition P' stronger than $x \geq 0$: $x > 5$.

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The strongest postcondition $R = sp(R, I)$ is such that:

$$\forall R' \ (sp(P, I) \Rightarrow R' \Rightarrow (R \Rightarrow R')$$

A postcondition R' weaker than $x \geq 0$: $x > -2$.

Substitution - free/bounded variables

Free and bounded variables

A variable x is bounded (resp. free) within formula F iff F contains an occurrence of x which is (resp. which is not) within the scope of a quantifier.

Example:

$$\varphi \equiv P(y, x) \land \forall x \ . \ Q(x, y)$$

$\hookrightarrow$ there is both a free and a bounded occurrence of x in φ

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Substitution

$P[E/x]$ is the formula P in which all free occurrences of variable x have been replaced by the term E.

Example:

$$(\varphi[x+1/x])[f/y] \equiv P(f, x+1) \wedge \ \forall x \ . \ Q(x, f)$$

Computing weakest preconditions: basic instructions

Statement	*def.*	**WP**
$wp(\text{skip}, R)$	$\hat{=}$	R
$wp(x := e, R)$	$\hat{=}$	$R[e/x]$
$wp(i_1 \; ; \; i_2, R)$	$\hat{=}$	$wp(i_1, wp(i_2, R))$
$wp(\text{assert}(e), R)$	$\hat{=}$	$e \wedge R$

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Examples:

1. $wp(x := x + 1, x > 0)$
2. $wp(z := 2\ ;\ y := z + 1\ ;\ x := z + y,\ x \in 3..8)$

Another way to write WPs

R
skip;

$R[e/x]$
$\mathbf{x} := \mathbf{e}$;

$wp(i_1, wp(i_2, R))$
$\mathbf{i_1}$;
$wp(i_2, R)$
$\mathbf{i_2}$;

$P \wedge R$
assert(**P**)

Example

$2 + 2 + 1 \in 3..8$

z:=2 ;

$z + z + 1 \in 3..8$

y:=z+1 ;

$z + y \in 3..8$

x:=z+y;

$x \in 3..8$

Computing weakest precondition: conditional statement

$$wp(\text{if } P \text{ then } i_1 \text{ else } i_2 \text{ end}, R) \\ \hat{=} \; (P \Rightarrow wp(i_1, R)) \land (\neg P \Rightarrow wp(i_2, R))$$

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Examples:

- Define $wp(\text{if } e \text{ then } i \text{ end }, R)$.

Computing weakest precondition: conditional statement

$$\boxed{\begin{array}{c} wp(\text{if } P \text{ then } i_1 \text{else } i_2 \text{ end}, R) \\ \hat{=} (P \Rightarrow wp(i_1, R)) \wedge (\neg P \Rightarrow wp(i_2, R)) \end{array}}$$

Examples:

- Define $wp(\text{if } e \text{ then } i \text{ end }, R)$.
- What does the following program compute ? Prove the result ...

  begin
  if $x > y$ then $m := x$ else $m := y$ end ;
  if $z > m$ then $m := z$ end
  end

Solution (1)

$(x > y \Rightarrow F_1[x/m]) \wedge (\neg(x > y) \Rightarrow] F_1[y/m])$ $= F_2$

if $x > y$

$F_1[x/m]$

then $m := x$

$F_1[y/m]$

else $m := y$ end ;

$(z > m \Rightarrow R_1[z/m]) \wedge (\neg(z > m) \Rightarrow R_1)$ $= F_1$

if $z > m$

$R_1[z/m]$;

then $m := z$

R_1 ;

else skip ;

end

R_1

Solution (2)

Postcondition :

$$(m = x \vee m = y \vee m = z) \wedge m \geq x \wedge m \geq y \wedge m \geq z$$

Let's process $R_1 = m \geq x$.

Computing F_1 :

$$(z > m \Rightarrow m[z/m] \geq x) \wedge (\neg(z > m) \Rightarrow m \geq x)$$

which can be rewritten:

$$(z > m \Rightarrow z \geq x) \wedge (\neg(z > m) \Rightarrow m \geq x)$$

Solution (3)

Computing F_2:

$$(x > y \;\Rightarrow\; F_1[x/m]) \wedge (\neg(x > y) \;\Rightarrow\; F_1[y/m])$$

leading to:

$$\begin{array}{lll}
(x > y \wedge \; z > x & \Rightarrow z \geq x) & \wedge \\
(x > y \wedge \; \neg(z > x) & \Rightarrow x \geq x) & \wedge \\
(\neg(x > y) \wedge \; z > y & \Rightarrow x \geq x) & \wedge \\
(\neg(x > y) \wedge \; \neg(z > y) & \Rightarrow y \geq x) &
\end{array}$$

Each of these 4 propositions is equivalent to **true**.

Computing weakest precondition: iteration

$$wp(\text{while } b \text{ do } S \text{ end }, R) \quad ?$$

Partial correctness

→ compute the WP **assuming the loop will terminate**

- need to reason about an arbitrary number of iteration;
- find a loop invariant I such that:
  1. I is preserved by the loop body:
  $$I \wedge b \Rightarrow wp(S, I)$$
  2. if and when the loop terminates, the post-condition holds:
  $$I \wedge \neg b \Rightarrow R$$

Then

$$wp(\text{while } b \text{ do } S \text{ end }, R) = I$$

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Then

$$wp(\text{while } b \text{ do } S \text{ end }, R) = I$$

Total correctness: prove that the loop **do** terminate . . .
need to introduce a loop variant
(i.e, a measure strictly decreasing at each iteration towards a limit).

Example

Prove the following program using WP

```
{x=n && n>0}
  y := 1 ;
  while x <> 1 do
     y := y*x ;
     x := x-1 ;
   end
{y=n! && n>0}
```

Implementing WP computation ?

1. WP computation:
   - based on the program structure (Abstract Syntax Tree)
   - leaves $\leadsto$ root, following the instruction structure

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1. WP computation:
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   - leaves $\rightsquigarrow$ root, following the instruction structure
2. Decidability problems:
   - simplification and proof of formula
     undecidable in general, heuristics . . .
   - invariant generation
     undecidable in general, only specific invariant can be generated in some restricted conditions (i.e., inductive invariants)

Accurracy vs Effectiveness trade-off

Assertion language

Theories	Complexity	Rappels
First order logic	undecidable	Interactive provers
Booleans	decidable	state enumeration
Intervals	quasi linear	approximation
Polyhedras	exponential	(better) approximation

Tools:
Frama-C/WP (proofs), Frama-C/Value (intervals), Polyspace (polyhedras) . . .

Outline

A general framework : abstract interpretation

Although this theory has been invented here in Grenoble . . .

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. . . let's jump to Dillig's slides (from UT Austin, Texas) !

Outline

Overview

Principles

Weakest Preconditions

Abstract Interpretation

Value-Set Analysis (VSA)

Conclusion

Analysis example: Value-Set Analysis

Objective:

compute a (super)-set of possible values of each variable at each program location . . .

$$Env(x, l) = \text{value set of variable } \texttt{x} \text{ at program location } \texttt{l}$$

Several possible abstract domains to express these sets:

- bounded value sets (k-sets)
  ex: $Env(x, l) = \{0, 4, 9, 10\}, Env(y, l) = \{1\}, Env(z, l) = \top$
- intervals
  ex: $Env(x, l) = [2, 8], Env(y, l) = [-\infty, 7], Env(z, l) = [-\infty, +\infty]$
- differential bounded matrix (DBM)
  ex : $Env(l) = x - y < 10 \wedge z < 0$
- polyhedra (conjonction of linear equations)
  ex: $Env(l) = x + y \geq 10 \wedge z < 0$
- etc.

VSA with intervals (example 1)

```
1. x := x+y ;
if x>0 then
     2. y:= x + 2
else
     3. y:= -x
4. fi
5. return x+y
```

Asumming (pre-condition) that:

$$x \in [-3, 3], y \in [-1, 5]$$

compute $Env(x, l)$ and $Env(y, l)$ for each program location l
what is the set of return values ?

Computing intervals on expressions

Syntax of expressions

$$e \rightarrow n \mid x \mid e + e \mid e \times e \mid \ldots$$

Computation rules

$Val(e, Env)$ is the interval associated to $\mathtt{e}$ within Env

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$$e \to n \mid x \mid e + e \mid e \times e \mid \ldots$$

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$$Val(n, Env) \quad = \quad [n, n]$$

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$$\begin{aligned} Val(n, Env) &= [n, n] \\ Val(x, Env) &= Env(x) \end{aligned}$$

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$$\begin{array}{rcl} Val(n, Env) & = & [n, n] \\ Val(x, Env) & = & Env(x) \\ Val(e1 + e2, Env) & = & [a + c, b + d] \text{ where} \\ & & \quad Val(e1, Env) = [a, b] \wedge Val(e2, Env) = [c, d] \end{array}$$

Computing intervals on expressions

Syntax of expressions

$$e \to n \mid x \mid e + e \mid e \times e \mid \ldots$$

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\begin{aligned}
Val(n, Env) &= [n, n] \\
Val(x, Env) &= Env(x) \\
Val(e1 + e2, Env) &= [a + c, b + d] \text{ where} \\
& \quad Val(e1, Env) = [a, b] \wedge Val(e2, Env) = [c, d] \\
Val(e1 \times e2, Env) &= [x, y] \text{ where} \\
& \quad Val(e1, Env) = [a, b] \wedge Val(e2, Env) = [c, d] \\
& \quad x = min(a \times c, a \times d, b \times c, b \times d) \\
& \quad y = max(a \times c, a \times d, b \times c, b \times d)
\end{aligned}
$$

Intervals propagation

Propagation rules along the statement syntax:

- assignment

$$\{\mathit{Env}1\}\ \mathrm{x} := \mathrm{e}\ \{\mathit{Env}2\}$$

where

$$\mathit{Env}2(x) = \mathit{Val}(e, \mathit{Env}1) \wedge \mathit{Env}2(y) = \mathit{Env}1(x) \ \text{ for } \ y \neq x$$

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- sequence

$$\{Env1\}\ \texttt{s1}; \texttt{s2}\ \{Env2\}$$

where

$$\{Env1\}\ \texttt{s1}\ \{Env3\} \wedge \{Env3\}\ s2\ \{Env2\}$$

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$$\{Env1\}\ \texttt{s1; s2}\ \{Env2\}$$

  where

$$\{Env1\}\ \texttt{s1}\ \{Env3\} \wedge \{Env3\}\ s2\ \{Env2\}$$

- conditionnal

$$\{Env\}\ \texttt{if (b) then s1 else s2}\ \{Env'\}$$

  where
  - {Env ∩ Val(b, Env)} s1 {Env1}
  - {Env ∩ Val(¬ b, Env)} s2 {Env2}
  - Env' = Env1 ⊔ Env2
    ($Env'(x)$ is the smallest interval containing $Env1(x)$ and $Env2(x)$, $\forall x$)

Iteration ? (example 1)

```
1. x : = 0 ;
while (x < 2) do
  2. x := x+1
3. end
4. return x
```

compute $Env(x, l)$ for each program location l, where . . .

$$Env(x, 2) = Env(x, 1) \sqcup Env(x, 3)$$

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Actually, what we aim to compute is the least solution of function *Env*, i.e:

$$Env^0(\bot, l) \sqcup Env^1(\bot, l) \sqcup Env^2(\bot, l) \sqcup \ldots \sqcup Env^k(\bot, l) \sqcup \ldots$$

Iteration ? (example 2)

```
1. x : = 0 ;
while (x < 1000) do
  2. x := x+1
3. end
4. return x
```

Compute $Env(x, l)$ for each program location l . . .

Iteration ? (example 2)

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1. x : = 0 ;
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  2. x := x+1
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Compute $Env(x, l)$ for each program location l ...

What happens if we replace `x := x+1` by `x := x-1` ?

Iteration ? (example 2)

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Compute $Env(x, l)$ for each program location l . . .

What happens if we replace `x := x+1` by `x := x-1` ?

How to cope with such **loooong**, or even **infinite**, computations ?

A practical solution : Widening & Narrowing operators

See Hakjoo Oh slides . . .

Outline

Challenges for static analysis

Accuracy vs scalability trade-off . . .

- inter-procedural analysis (+ recursivity . . .)
- multi-threading
- dynamic memory allocation
- modular reasonning
- libraries (+ legacy code)
- etc.

Application to vulnerability detection ?

Clearly may provide some useful features:

- out-of-bounds array access
- arithmetic overflows
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- use-after-free
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But still some limitations:

- exploitability analysis (beyond standard program semantics) ?
- relevant and accurate memory model (for heap and stack)
- self-modifying code (e.g., malwares)
- binary code analysis (see next slide !)

Static analysis on binary code

Static analysis relies on a (clear) program semantics

- can be done at the assembly-level (or IR)
- but disassembling is undecidable . . .
- . . . and disassemblers may rely on static analysis !
  (to retrieve the program CFG)

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Static analysis on low-level code is difficult

- no types (a single type for value, addresses, data, code, . . .)
- address computation is pervasive . . .
  ex: `mov eax, [ecx + 42]`
- function bounds cannot always be retrieved
  $\rightarrow$ many un-initialized memory locations
- sacalability issues
- etc.

What help for “security analysis” ?

“security analysis” = vulnerability detection

A pragmatic approach:

1. annotate the code with “vulnerability checks” (e.g., `frama-c -rte`) i.e., assertions to detect integer overflows, invalid memory accesses (arrays, pointers), etc

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   $\rightarrow$ reveals a lot of hot spots (= unchecked assertions)

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   → consider **proving** (some of) these assertions ?

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⇒ a set of potential vulnerabilities remains, to be discharged by other means, possibly on a **program slice**
(false positive ? real bug but harmless w.r.t security ? real vulnerability ?)

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4. run the VSA again . . .

⇒ a set of potential vulnerabilities remains, to be discharged by other means, possibly on a **program slice**
(false positive ? real bug but harmless w.r.t security ? real vulnerability ?)

Rk: some static analysis tools also provide bug finding facilities
(i.e., no false postives, . . . but false negatives instead)

Tool examples

Disclaimer: non limitative nor objective list ! (see wikipedia for more info)

Source-level tools

- Astrèe
- Coverity, **Polyspace**, CodeSonar, HP Fortify, VeraCode
- **Frama-C**, Fluctuat
- etc, etc, . . .

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Some binary-level tools

- x86-CodeSurfer
- VeraCode
- Angr
- **BinSec plateform**
- etc ?

You can see also:

- the CERT webpages
- the Microsoft “Secure Development Lifecycle” . . .