Stack smashing analysis by abstract interpretation of binary code

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Outline

1 Introduction

2 Relational abstract interpretation of binary code

3 Stack smashing analysis

4 Conclusion
Stack smashing: vulnerable program

Example

```
#define MAX 12
void foo(char *bar)
{
    char c[MAX];
    strcpy(c, bar); // unsafe
}
int main(int argc, char **argv)
{
    foo(argv[1]);
    return 0;
}
```
Stack smashing: exploit

Figure: foo("AAAAAAAAAAAAAAAAAAAAAAAAAAAAAA\x08\x35\xC0\x80",24)

(Source Wikipedia)
Our approach: static analysis of binary code

We analyze the **binary code**:

- **Pros**
  - Can analyze closed-source programs;
  - No assumptions required about the compiler;

- **Cons**
  - Missing information:
    - No types;
    - No variables;
    - Program accesses **data locations**: registers, memory addresses;
    - Not your classic Abstract Interpretation;
  - Must handle different CPU instruction sets;
    - More tedious tooling.
Our contribution

1 Abstract Interpretation:
   - Of binary code;
   - With a relational abstract domain;
     ⇒ Supports statically unknown addresses.

2 AI-based analysis to prove the absence of return address corruption:
   - Track function return addresses in the program abstract state;
   - Fully-automated analysis.
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Reminder on abstract interpretation

Example

```c
int f(int s) {
    int x=4, y=3, s, o;

    if (s)
        o=x+y;
    else  o=x-y;
    // State here?
    return o;
}
```

- Two possible **concrete states** at end of function:
  - \( \{x = 4, y = 3, s = 0, o = 1\} \), \( \{x = 4, y = 3, s \neq 0, o = 7\} \)
- A valid **abstract state**: \( \{x = 4, y = 3, 1 \leq o \leq 7\} \)
- Properties proved on abstract state hold for any concrete state;
  - e.g. here we can prove that \( o > 0 \) at end of function.
POLYMAP, an abstract domain for binary code

With **POLYMAP**, we represent an abstract state as \((\langle c_1, \ldots, c_n \rangle, R^\#, \ast^\#)\):

- State variables (a.k.a dimensions) are added/removed as the analysis progresses;
- \( \langle c_1, \ldots, c_n \rangle \): constrains values of data locations (polyhedron);
- \( R^\# \), **register mapping**: maps polyhedra variables to registers;
- \( \ast^\# \), **memory mapping**: tracks addresses \( \mapsto \) values relationships.
## Tracking register contents

### Example

\[
\begin{align*}
(0) & : (\top, \emptyset, \emptyset) \\
\text{SET } r1, \ #1 & \quad (1) \\
\text{ADD } r1, \ r1, \ #1 & \quad (2)
\end{align*}
\]

- (0): \((\top, \emptyset, \emptyset)\)
- (1): \((\langle x_1 = 1 \rangle, \{r_1 : x_1\}, \emptyset)\)
- (2): \((\langle x_1 = 1, x_2 = x_1 + 1 \rangle, \{r_1 : x_2\}, \emptyset)\)

\(\Rightarrow\) We can remove \(x_1\): \((\langle x_2 = 2 \rangle, \{r_1 : x_2\}, \emptyset)\).
Tracking memory contents

Example

\[
\text{SET } r3, \#42 \quad (1) \\
\text{STORE } r3, [sp + \#4] \quad (2)
\]

- (1) \( (\langle x_1 = 42 \rangle, \{ r_3 : x_1, sp : x_2 \}, \emptyset) \)
- (2) \( (\langle x_1 = 42, x_3 = x_2 + 4, x_4 = x_1 \rangle, \{ r_3 : x_1, sp : x_2 \}, \{ x_3 : x_4 \}) \)
  \[\Rightarrow \star(x_3) = x_4\]
  \[\Rightarrow \text{Address } sp + 4 \text{ contains value } 42.\]
Abstract interpretation procedure: main difficulties

- **Aliasing**: two different variables corresponding to the same address
  - Impacts the interpretation of LOAD and STORE;
- **Unification**: 2 different variables in 2 different states corresponding to the same location:
  - When joining the states of two program branches, unify their mappings before joining the constraints.

For details

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Overview

Track more information during AI:
- Identify variables corresponding to return addresses;
- Track such variables for functions of the current call stack;
- Compare constraints at function call vs at function return.
Tracking return addresses

Our tool targets ARM:

- Return addresses are stored in the **link register** (LR);
- We consider:
  - Variable $lr_{\text{call}}$ mapped to LR at function call;
  - Variable $lr_{\text{ret}}$ mapped to LR at function return;
  - $p$ the polyhedron at function return;
  - $\Rightarrow$ Check that $p \subseteq \Diamond (lr_{\text{call}} = lr_{\text{ret}})$.
- Abstract state stores a stack of live return address variables;
  - $\Rightarrow$ Somehow, an **abstract shadow stack**.

Stack smashing analysis
Safe program

Example

```c
#define MAX 12

void foo(char *bar, int n)
{
    char c[MAX];
    if (n<MAX)
        strncpy(c, bar, n); // safe
}

int main(int argc, char **argv)
{
    foo(argv[1], atoi(argv[2]));
    return 0;
}
```

- Our tool Polymalys\(^1\) proves the **absence** of stack smashing;
- The same program with `strcpy` instead cannot be proved safe.

\(^1\)https://gitlab.cristal.univ-lille.fr/otawa-plugins/polymalys
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Summary

- Abstract interpretation of binary code;
  - Relevant memory addresses discovered during analysis;
  - Supports statically unknown memory addresses;
- Stack smashing detection;
  - Proves the absence of vulnerabilities
  - Fully automated;
- Limitations:
  - False negatives: invulnerable programs deemed vulnerable;
  - Scalability: AI with polyhedra=high complexity.