A Static Analysis Method for Detecting Buffer Overflow Vulnerabilities

Testing programs for vulnerabilities

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Overview

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Buffer overflow

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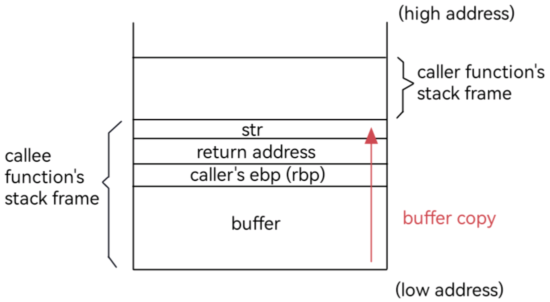
Definition

Occurs when data > fixed-length block of memory

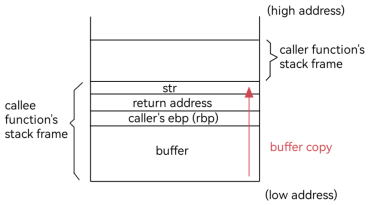


- commonly seen
- easy to be unaware of
- can be fatal

Exploitation

The techniques to exploit a buffer overflow vulnerability vary by architecture, by operating system and by memory region.

Take stack buffer overflow as an example:



- use extra data to overwrite return address
- point to a malicious program

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Overview

Symbolic execution is a way of executing a program abstractly

- assume symbolic values for inputs

$$a = 1, b = a + 2$$
$$\Rightarrow a = \alpha, b = \alpha + \beta$$

- focuses on execution paths

Good points

- multiple possible inputs can be covered by doing one execution
- avoid reporting false warnings

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Demo

Here is a piece of C code:

```
void foo(int *arr, int n, int h) {
    ASSUME(n > 0, capacity(arr) >= n);
    int idx;
    if (h != 0) {
        idx = 0;
    } else {
        idx = n;
    }
    print(arr[idx]);
}
```

`ASSUME` is a annotation that represents constraints on the inputs.

A programmer familiar with C may see that `print(arr[idx])` can cause buffer overflow when the capacity of `arr` is exactly `n` and it also happens that `h` is 0.

Let's see how symbolic execution can find this vulnerability.

Initialization

```
void foo(int *arr, int n, int h) {
    ASSUME(n > 0, capacity(arr) >= n);
    int idx;
    if (h != 0) {
        idx = 0;
    } else {
        idx = n;
    }
    print(arr[idx]);
}
```

$$E = \{arr \mapsto \mathtt{ptr}(0, arr_{cap}), n \mapsto n', h \mapsto h'\}$$

$$P = n' > 0 \land arr_{cap} \geq n'$$

Declaration

```
void foo(int *arr, int n, int h) {
    ASSUME(n > 0, capacity(arr) >= n);
    int idx;
    if (h != 0) {
        idx = 0;
    } else {
        idx = n;
    }
    print(arr[idx]);
}
```

$$E = \{arr \mapsto \mathtt{ptr}(0, arr_{cap}), n \mapsto n', h \mapsto h', idx \mapsto idx'\}$$

$$P = n' > 0 \land arr_{cap} \geq n'$$

Branching and assignment

```
void foo(int *arr, int n, int h) {
    ASSUME(n > 0, capacity(arr) >= n);
    int idx;
    if (h != 0) {
        idx = 0;
    } else {
        idx = n;
    }
    print(arr[idx]);
}
```

$$E_1 = \{arr \mapsto \mathtt{ptr}(0, arr_{cap}), n \mapsto n', h \mapsto h', idx \mapsto 0\}$$

$$P_1 = n' > 0 \wedge arr_{cap} \geq n' \wedge h' \neq 0$$

$$E_2 = \{arr \mapsto \mathtt{ptr}(0, arr_{cap}), n \mapsto n', h \mapsto h', idx \mapsto n'\}$$

$$P_2 = n' > 0 \wedge arr_{cap} \geq n' \wedge h' = 0$$

Branch merging

```
void foo(int *arr, int n, int h) {
    ASSUME(n > 0, capacity(arr) >= n);
    int idx;
    if (h != 0) {
        idx = 0;
    } else {
        idx = n;
    }
    print(arr[idx]);
}
```

$$E_1 = \{arr \mapsto \mathtt{ptr}(0, arr_{cap}), n \mapsto n', h \mapsto h', idx \mapsto 0\}$$

$$E_2 = \{arr \mapsto \mathtt{ptr}(0, arr_{cap}), n \mapsto n', h \mapsto h', idx \mapsto n'\}$$

$$E = \{arr \mapsto \mathtt{ptr}(0, arr_{cap}), n \mapsto n', h \mapsto h', idx \mapsto \mathtt{if}\ h' \neq 0\ \mathtt{then}\ 0\ \mathtt{else}\ n'\}$$

$$P = n' > 0 \wedge arr_{cap} \geq n'$$

Memory access

```
void foo(int *arr, int n, int h) {
    ASSUME(n > 0, capacity(arr) >= n);
    int idx;
    if (h != 0) {
        idx = 0;
    } else {
        idx = n;
    }
    print(arr[idx]);
}
```

$$E = \{arr \mapsto \mathtt{ptr}(0, arr_{cap}), n \mapsto n', h \mapsto h', idx \mapsto \mathtt{if}\ h' \neq 0\ \mathtt{then}\ 0\ \mathtt{else}\ n'\}$$

$$P = n' > 0 \wedge arr_{cap} \geq n'$$

$$C = P \wedge ((\mathtt{if}\ h' \neq 0\ \mathtt{then}\ 0\ \mathtt{else}\ n') < 0 \vee (\mathtt{if}\ h' \neq 0\ \mathtt{then}\ 0\ \mathtt{else}\ n') \geq arr_{cap})$$

C is satisfiable! Consider $n' = arr_{cap} = 1, h' = 0$

Satisfiability solving

z3 is a SMT solver, which can "magically" solve the final problem.

You may use its Python binding like this:

```
import z3

n = z3.Int('n')
h = z3.Int('h')
idx = z3.If(h!=0, 0, n)
cap = z3.Int('cap')
s = z3.Solver()
s.add(z3.And(n>0, cap>=n, z3.Or(idx<0, idx>=cap)))
if s.check() == z3.sat:
    print(s.model())
```

It will outputs a model `[h = 0, n = 1, cap = 1]`.

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