Language Security

Lecture 18

Lecture Outline

- Beyond compilers
  - Looking at other issues in programming language design and tools
- C
  - Arrays
  - Exploiting buffer overruns
  - Detecting buffer overruns

Platitudes

- Language design has influence on
  - Safety
  - Efficiency
  - Security

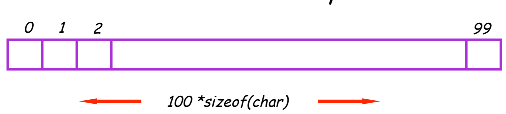
C Design Principles

- Small language
- Maximum efficiency
- Safety less important
- Designed for the world in 1972
  - Weak machines
  - Trusted networks

Arrays in C

```
char buffer[100];
```

Declares and allocates an array of 100 chars



C Array Operations

```
char buf1[100], buf2[100];
```

Write:

```
buf1[0] = 'a';
```

Read:

```
return buf2[0];
```

What's Wrong with this Picture?

```
int i = 0;
for(i = 0; buf1[i] != '\0'; i++)
  { buf2[i] = buf1[i]; }
buf2[i] = '\0';
```


Indexing Out of Bounds

The following are all legal C and may generate no run-time errors

```
char buffer[100];

buffer[-1] = 'a';
buffer[100] = 'a';
buffer[100000] = 'a';
```


Why?

- Why does C allow out of bounds array references?
  - Proving at compile-time that all array references are in bounds is very difficult (impossible in C)
  - Checking at run-time that all array references are in bounds is expensive

Code Generation for Arrays

```
buf1[i] = 1;   /* buf1 has type int[] */

r1 = load &buf1;
r2 = load i;
r3 = r2 * 4;
r4 = r1 + r3
store r4, 1
```


Discussion

- 5 instructions worst case
- Often &buf1 and i already in registers
  - Saves 2 instructions
- Many machines have indirect loads/stores
  - store r1[r3], 1
  - Saves 1 instruction
- Best case 2 instructions
  - Offset calculation and memory operation

Code Generation for Arrays with Bounds Checks

```
buf1[i] = 1;   /* buf1 has type int[] */

r1 = load &buf1;
r2 = load i;
r3 = r2 * 4;
if r3 < 0 then error;
r5 = load limit of buf1;
if r3 >= r5 then error;
r4 = r1 + r3
store r4, 1
```

Discussion

- Lower bounds check can often be removed
  - Easy to prove statically that index is positive
- Upper bounds check hard to remove
  - Leaves a conditional in instruction stream
- In C, array limits not stored with array
  - Knowing the array limit for a given reference is non-trivial

C vs. Java

- C array reference typical case
  - Offset calculation
  - Memory operation (load or store)
- Java array reference typical case
  - Offset calculation
  - Memory operation (load or store)
  - Array bounds check
  - Type compatibility check (for stores)

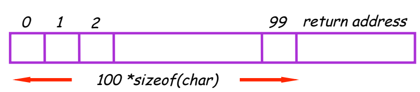
Buffer Overruns

- A buffer overrun writes past the end of an array
- *Buffer* usually refers to a C array of char
  - But can be any array
- So who's afraid of a buffer overrun?
  - Can damage data structures
  - Cause a core dump
  - What else?

Stack Smashing

Buffer overruns can alter the control flow of your program!

```
char buffer[100];    /* stack allocated array */
```



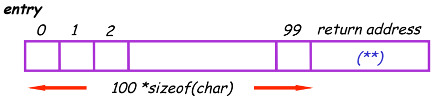
An Overrun Vulnerability

```
void foo(char buf1[]) {
  char buf2[100];
  int i = 0;
  for(i = 0; buf1[i] != '\0'; i++)
     { buf2[i] = buf1[i]; }
  buf2[i] = '\0';
}
```

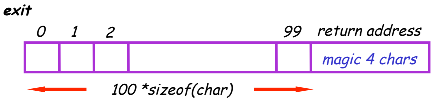

An Interesting Idea

char buf[104] = { ' ',…,' ', *magic 4 chars* }
foo(buf);   (**)

Foo entry



Foo exit



Discussion

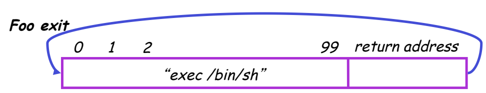
- So we can make foo jump wherever we like.
- How is this possible?
- Unanticipated interaction of two features:
  - Unchecked array operations
  - Stack-allocated arrays
    - Knowledge of frame layout allows prediction of where array and return address are stored
  - Note the "magic cast" from char's to an address

The Rest of the Story

- We can make foo jump anywhere.
- But where is a useful place to jump?
- Idea: Put our own code in the buffer and jump there!

The Plan

char buf[104] = { 104 *magic chars* }
foo(buf);



Details

- "exec /bin/sh"
  - Easy to write in assembly code
  - Make all jumps relative
- Be careful not to have null's in the code (why?)

More Details

- Overwrite return address with start of buffer
  - Harder
  - Need to guess where buffer in called routine starts (trial & error)
  - Pad front of buffer with NOPs
    - Guess need not be exact; just land somewhere in NOPs

And More Details

- Overwrite return address
  - Don't need to know exactly where return address is
  - Just pad end of buffer with multiple copies of new return address X

char buf[104] =
  "NOPS … /bin/exec sh XXXXXXXXXX"
foo(buf);

The State of C Programming

- Buffer overruns are common
  - Programmers must do their own bounds checking
  - Easy to forget or be off-by-one or more
  - Program still appears to work correctly
- In C wrt to buffer overruns
  - Easy to do the wrong thing
  - Hard to do the right thing

The State of Hacking

- Buffer overruns widely known since the 1980's
  - Remain a popular attack today
- Highly automated toolkits available to exploit known buffer overruns
  - Search for "buffer overruns" yields > 100,000 hits

The Sad Reality

- Even well-known buffer overruns are still exploited
  - Hard to get people to upgrade millions of vulnerable machines
- We assume that there are many more unknown buffer overrun vulnerabilities
  - At least unknown to the good guys

How Do We Prevent Buffer Overruns?

- Many proposed techniques!
  - A research Rorschach test
- A brief survey
  - Language design
  - Static analysis
  - Dynamic analysis

Language Design

- Enforce data abstractions!
- How?
  - Type safety
    - The guarantee that if e:T, then e evaluates to a value of type T
    - No unsafe casts
  - Memory safety
    - Array bounds checking
    - No computation on pointers
    - Automatic memory management

Tools for Static Memory Safety

- Bug finding tools
  - Detect common patters of buffer overruns
  - Use heuristics
    - Focus on scenarios likely to be real overruns, rather than obscure scenarios that might not be
    - Avoid *false positives*
- Verification
  - Formally prove memory safety
  - Can require deep understanding of the program's semantics

Dynamic Memory Safety

- Many proposals
- Sandboxing
  - Confine all memory references in the program to it's own data space
  - Guarantees damage is limited to the program itself
- Code and data randomization
  - Give everyone a slightly different binary and data layout
  - Variation minimizes chances an attack can work on all copies of a program

Summary

- Programming language knowledge useful beyond compilers
- Useful for programmers
  - Understand what you are doing!
- Useful for tools other than compilers
  - Big research direction