

Language Security

Lecture 40
(from notes by G. Necula)

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Lecture Outline

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

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Platitudes

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

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C Design Principles

- Small language
- Maximum efficiency
- Safety less important
- Designed for the world as it was in 1972
 - Weak machines
 - Superhuman programmers (or so they thought)
 - Trusted networks

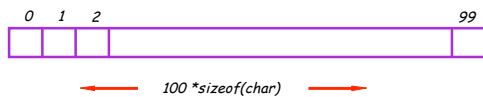
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Arrays in C

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

Declares and allocates an array of 100 chars



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C Array Operations

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

Write:

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

Read:

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

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What's Wrong with this Picture?

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

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Indexing Out of Bounds

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

```
char buffer[100];

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

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Why?

- Why does C allow out-of-bounds array references?
 - Proving at compile-time that all array references are in bounds is impossible in most languages
 - Checking at run-time that all array references are in bounds is "expensive"
 - But it is even more expensive to skip the checks

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Code Generation for Arrays

- The C code:

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

- The assembly code:

```
Regular C
r1 = &buf1;
r2 = load i;
r3 = r2 * 4;
```

```
r4 = r1 + r3
store r4, 1
```

```
C with bounds checks
r1 = &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
```

Costly!

Finding the array limits is non-trivial

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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 some arrays)

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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 cause a core dump
 - Can damage data structures
 - What else?

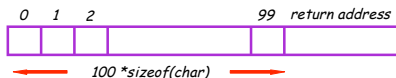
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Stack Smashing

Buffer overruns can alter the control flow of your program!

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



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An Overrun Vulnerability

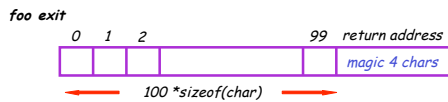
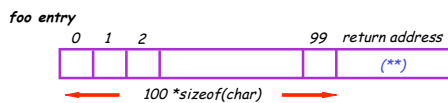
```
void foo(char in[]) {
    char buffer[100];
    int i = 0;
    for(i = 0; in[i] != '\0'; i++)
        { buffer[i] = in[i]; }
    buffer[i] = '\0';
}
```

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An Interesting Idea

```
char in[104] = { '\t', ..., '\t', magic 4 chars }
foo(in); (**)
```



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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 and return addresses
 - Knowledge of frame layout allows prediction of where array and return address are stored
 - Note the "magic cast" from char's to an address

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The Rest of the Story

- Say that `foo` is part of a network server and the `in` originates in a received message
 - Some remote user can make `foo` jump anywhere!
- But where is a "useful" place to jump?
 - Idea: Jump to some code that gives you control of the host system (e.g. code that spawns a shell)
- But where to put such code?
 - Idea: Put the code in the same buffer and jump there!

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The Plan

- We'll make the code jump to the following code:
- In C: `exec("/bin/sh");`
- In assembly (pretend):

```
mov $a0, 15 ; load the syscall code for "exec"
mov $a1, &ldata ; load the command
syscall ; make the system call
ldata: .byte '/', 'b', 'i', 'n', '/', 's', 'h', '\0' ; null-terminated
```
- In machine code: `0x20, 0x42, 0x00, ...`

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The Plan

```
char in[104] = { 104 magic chars }
foo(in);
```



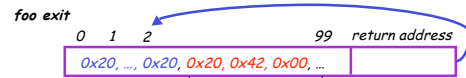
- The last 4 bytes in "in" must equal the start of `buffer`
- Its position might depend on many factors !

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Guess the Location of the Injected Code

- Trial & error: gives you a ballpark
- Then pad the injected code with NOP
 - E.g. add `$0, $1, 0x2020`
 - stores result in `$0` which is hardcoded to 0 anyway
 - Encoded as `0x20202020`



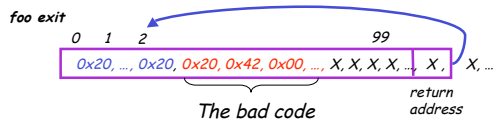
- Works even with an approximate address of `buffer` !

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More Problems

- We do not know exactly where the return address is
 - Depends on how the compiler chose to allocate variables in the stack frame
- Solution: pad the buffer at the end with many copies of the "magic return address X"



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Even More Problems

- The most common way to copy the bad code in a stack buffer is using string functions: `strcpy`, `strcat`, etc.
- This means that `buf` cannot contain `0x00` bytes
 - Why?
- Solution:
 - Rewrite the code carefully
 - Instead of `"addiu $4,$0,0x0015"` (code `0x20400015`)
 - Use `"addiu $4,$0,0x1126; subiu $4,$4,0x1111"`

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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 w.r.t. to buffer overruns
 - Easy to do the wrong thing
 - Hard to do the right thing

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The State of Hacking

- Buffer overruns are the attack of choice
 - 40-50% of new vulnerabilities are buffer overrun exploits
 - Many recent attacks of this flavor: Code Red, Nimda, MS-SQL server
- Highly automated toolkits available to exploit known buffer overruns
 - Search for "buffer overruns" yields > 25,000 hits

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The Sad Reality

- Even well-known buffer overruns are still widely 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

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Static Analysis to Detect Buffer Overruns

- Detecting buffer overruns *before* distributing code would be better
- Idea: Build a tool similar to a type checker to detect buffer overruns
- Joint work by Alex Aiken, David Wagner, Jeff Foster, at Berkeley

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Focus on Strings

- Most important buffer overrun exploits are through string buffers
 - Reading an untrusted string from the network, keyboard, etc.
- Focus the tool only on arrays of characters

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Idea 1: Strings as an Abstract Data Type

- A problem: Pointer operations & array dereferences are very difficult to analyze statically
 - Where does `*a` point?
 - What does `buf[j]` refer to?
- Idea: Model effect of string library functions directly
 - Hard code effect of `strcpy`, `strcat`, etc.

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Idea 2: The Abstraction

- Model buffers as pairs of integer ranges
 - *Alloc* min allocated size of the buffer in bytes
 - *Length* max number of bytes actually in use
- Use integer ranges $[x,y] = \{x, x+1, \dots, y-1, y\}$
 - Alloc & length cannot be computed exactly

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The Strategy

- For each program expression, write constraints capturing the *alloc* and *len* of its string subexpressions
- Solve the constraints for the entire program
- Check for each string variable *s*
 $len(s) \leq alloc(s)$

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The Constraints

```
char s[n];           n ≤ alloc(s)
strcpy(dst,src)     len(src) ≤ len(dst)

p = strdup(s)       len(s) ≤ len(p) &
                   len(s) ≤ alloc(p)

p[n] = '\0'         n+1 ≤ len(p)
```

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Constraint Solving

- Solving the constraints is akin to solving dataflow equations (e.g., constant propagation)
- Build a graph
 - Nodes are $len(s)$, $alloc(s)$
 - Edges are constraints $len(s) ≤ len(t)$
- Propagate information forward through the graph
 - Special handling of loops in the graph

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Using Solutions

- Once you've solved constraints to extract as much information as possible, look to see if $len(s) ≤ alloc(s)$ is necessarily true. If not, may have a problem.
- For example, if b is parameter about which we know nothing, then in

```
char s[100];
strcpy(s, b);
```

assertion $len(s) ≤ alloc(s)$ will not simplify to True.

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Results

- Found new buffer overruns in sendmail
- Found new exploitable overruns in Linux nettools package
- Both widely used, previously hand-audited packages

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Limitations

- Tool produces many false positives
 - 1 out of 10 warnings is a real bug
- Tool has false negatives
 - Unsound---may miss some overruns
- But still productive to use

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Summary

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

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