Language Security

Lecture 40

(from notes by G. Necula)

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
  - Efficiency
  - Safety
  - Security

C Design Principles

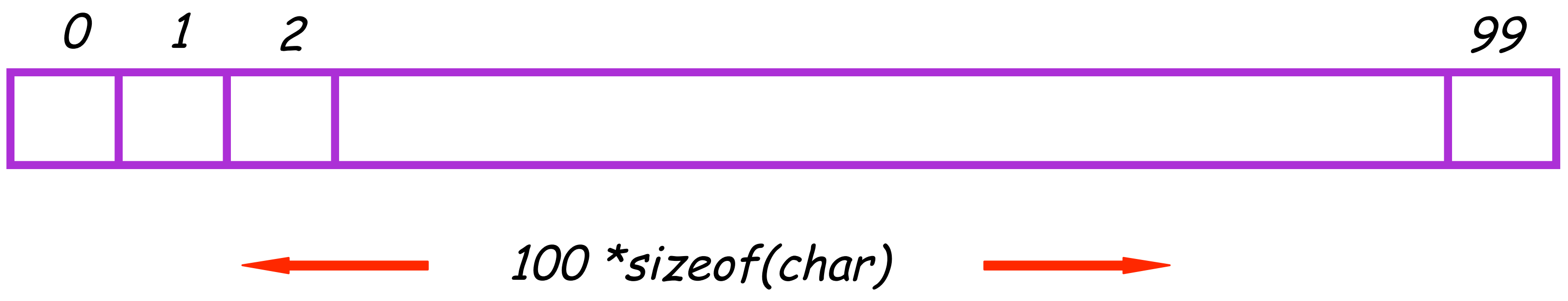
- Small language
- Maximum efficiency
- Safety less important

- Designed for the world as it was in 1972
  - Weak machines
  - Superhuman programmers (or so they thought)
  - Trusted networks

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

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’;
```

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

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

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)

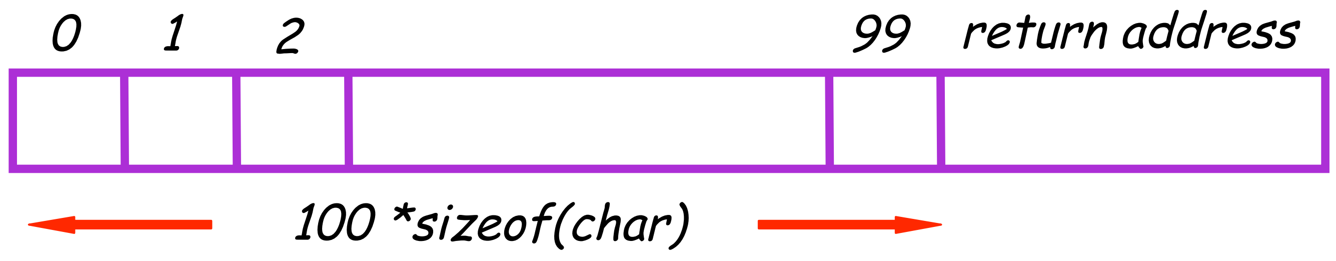
Buffer Overruns

- 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?

Stack Smashing

Buffer overruns can alter the control flow of your program!

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



An Overrun Vulnerability

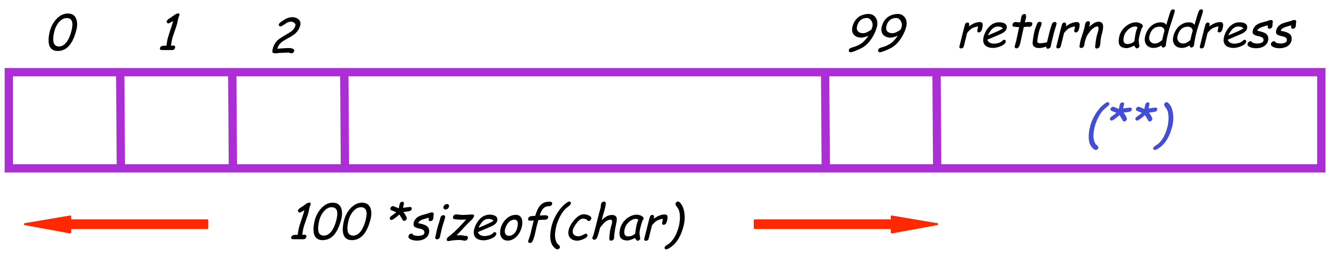
```
void foo(char in[]) {
   char buffer[100];
   int i = 0;
   for(i = 0; in[i] != '\0'; i++)
        { buffer[i] = in[i]; }
   buffer[i] = '\0';
}
```

An Interesting Idea

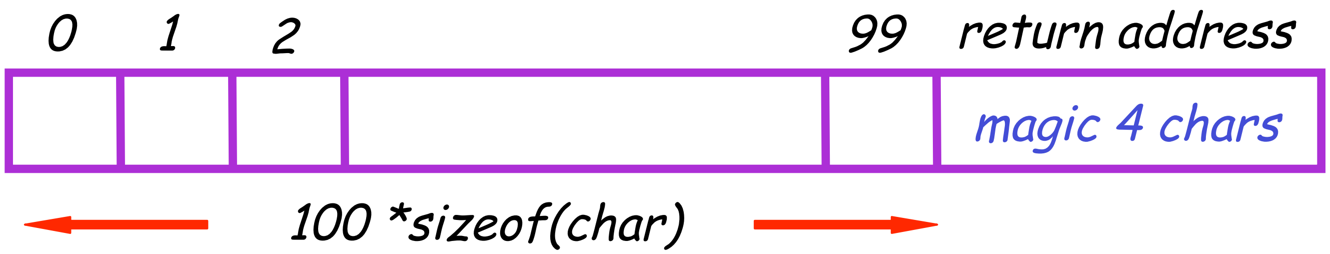
char in[104] = { ' ',…,' ', *magic 4 chars* }

foo(in); (**)

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 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

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!

The Plan

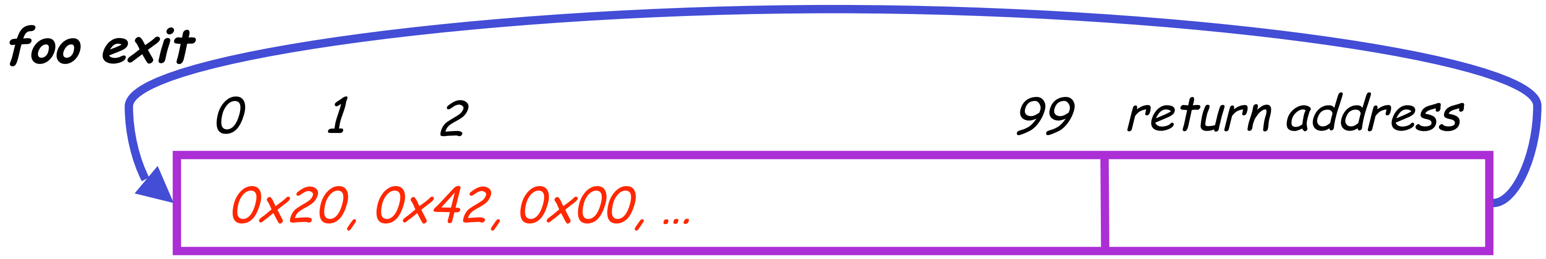
- We'll make the code jump to the following code:
- In C: exec("/bin/sh");
- In assembly (pretend):

```
    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, …

The Plan

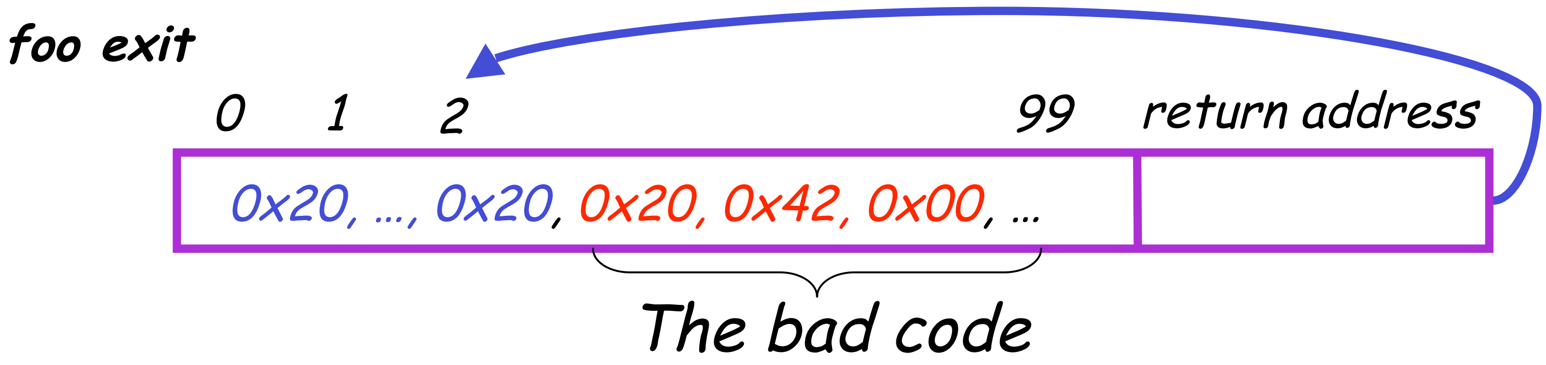
```
char in[104] = {  104 magic chars }
foo(in);
```



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

Guess the Location of the Injected Code

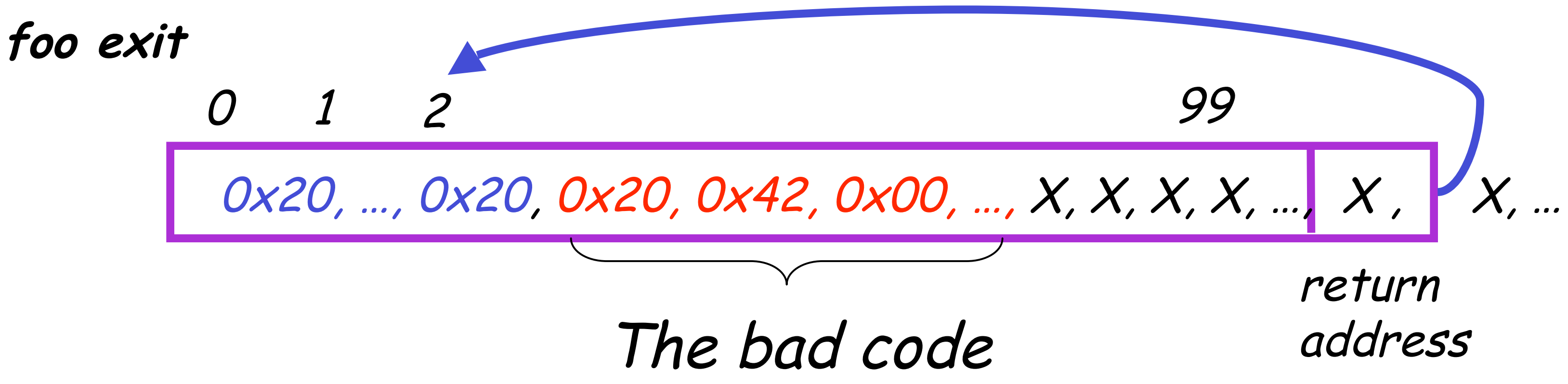
- Trial & error: gives you a ballpark
- Then pad the injected code with NOP
  - E.g. add $0, $1, 0x2020
    - stores result in $0 which is hardwired to 0 anyway
    - Encoded as 0x20202020



- Works even with an approximate address of buffer !

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"



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"

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

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

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

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

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

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.

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, …, y-1, y }
  - Alloc & length cannot be computed exactly

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

$$\text{len}(s) \le \text{alloc}(s)$$

The Constraints

`char s[n];`	$n \le alloc(s)$
`strcpy(dst,src)`	$len(src) \le len(dst)$
`p = strdup(s)`	$len(s) \le len(p)$ & $len(s) \le alloc(p)$
`p[n] = '\0'`	$n+1 \le len(p)$

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

Using Solutions

- Once you've solved constraints to extract as much information as possible, look to see if

  $\text{len}(s) \leq \text{alloc}(s)$

  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 $\text{len}(s) \leq \text{alloc}(s)$ will not simplify to True.

Results

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

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

Summary

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