Language Based Security

Lecture 19

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
  - Efficienty
  - Security

Recall: Platitude: A flat, dull, or trite remark, especially one uttered as if it were fresh or profound

C Design Principles

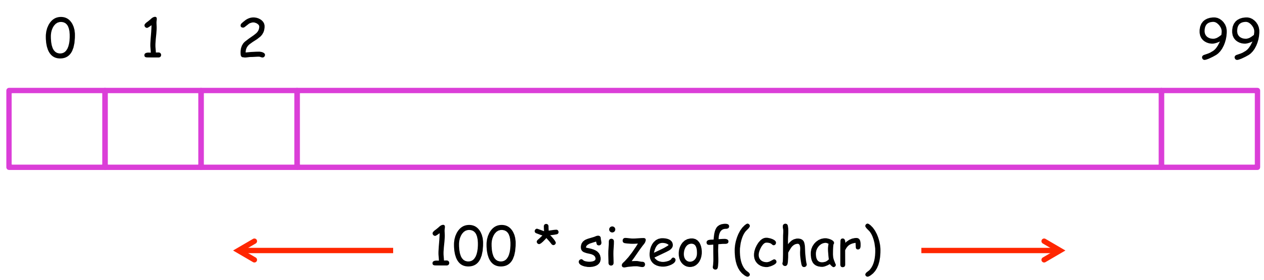
- Small language
- Maximum efficiency
- Safety less important

- 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

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

r1 = load &buf1;

r2 = load i;

r3 = r2 * 4;

r4 = r1 + r3;

store r4, 1

(note this last is NOT a MIPS instruction)

Discussion

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

Code Generation for Arrays with Bounds Checks

```
buf[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 typica 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)

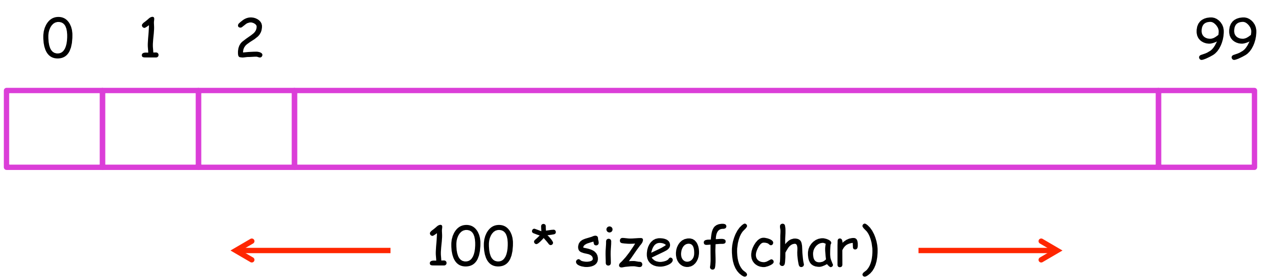
Buffer Overruns

- 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

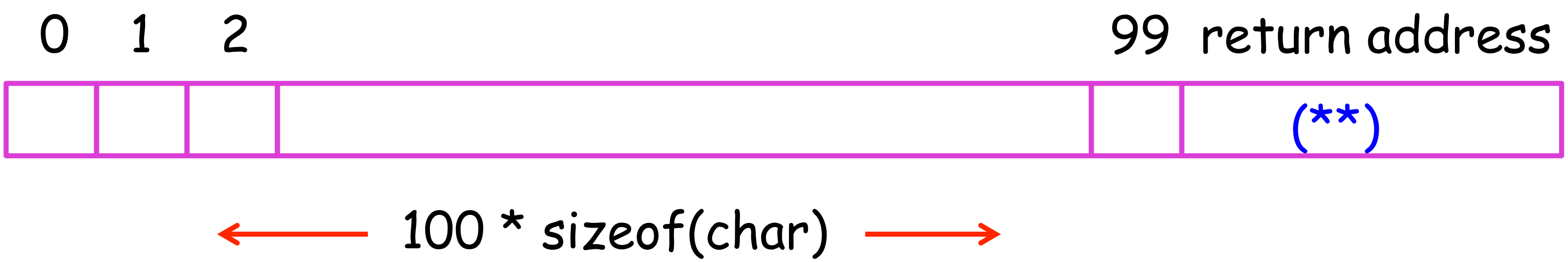
```
void foo(char buf1[]) {
    char buf2[100];
    int i = 0;
    for (i = 0; buf1[i] != '\0'; i++) {
            buff2[i] = buf1[i];
    }
    buf2[i] = '\0';
}
```

An Interesting Idea

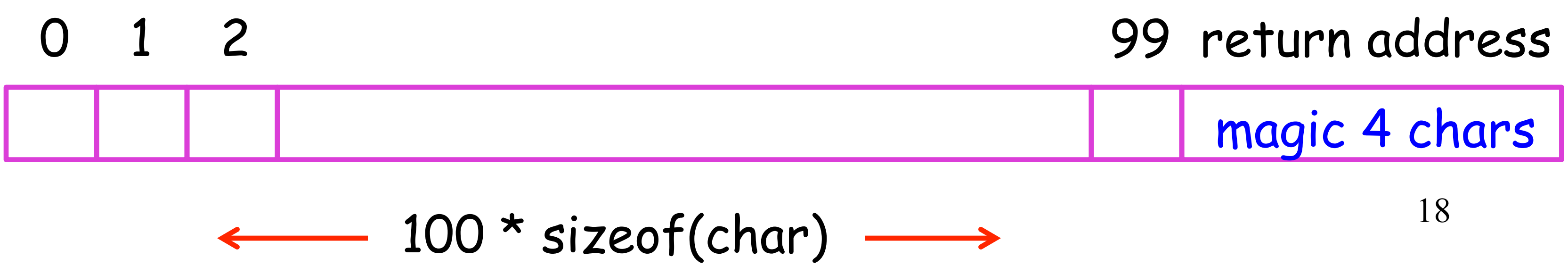
char buf[104] = { ' ',…, ' ', magic 4 chars }

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 chars to an int address

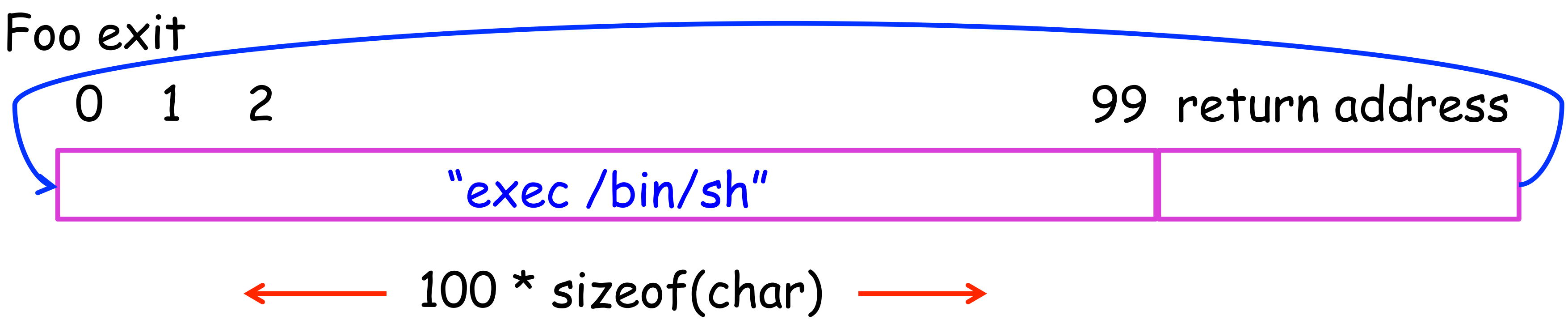
The Rest of the Story

- 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 bytes in the code (why?)

More Details

- Overwrite return address with start of buffer
  - Harder
  - Need to guess where buffer in called routine starts (trail & 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 … exec /bin/sh XXXXXXXXXXXXX"
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
  - Programs still apeear 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 are the attack of choice (sort of)
  - 40-50% of new vulnerabilities are buffer overrun exploits (though this figure varies)

- Highly automated toolkits available to exploit known buffer overruns
  - Google search for "buffer overruns" yields tens of thousands of hits!

The Sad Reality

- Even well-known buffer overruns are still widely exploited
  - Hard to get people to upgrade millions of vulnerable machines
    - And upgrading can sometimes create new vulnerabilities!

- 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

- Alex Aiken with David Wagner, Jeff Foster, and Eric Brewer
  - "A First Step Toward Automated Detection of Buffer Overrun Vulnerabilities", NDSS 2000

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 Abstact 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
  - Size allocated size of the buffer in bytes
  - Length number of bytes actually in use
- Use integer ranges $[x,y] = \{ x, x+1, \dots , y - 1, y \}$
  - Size & 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

len(s) <