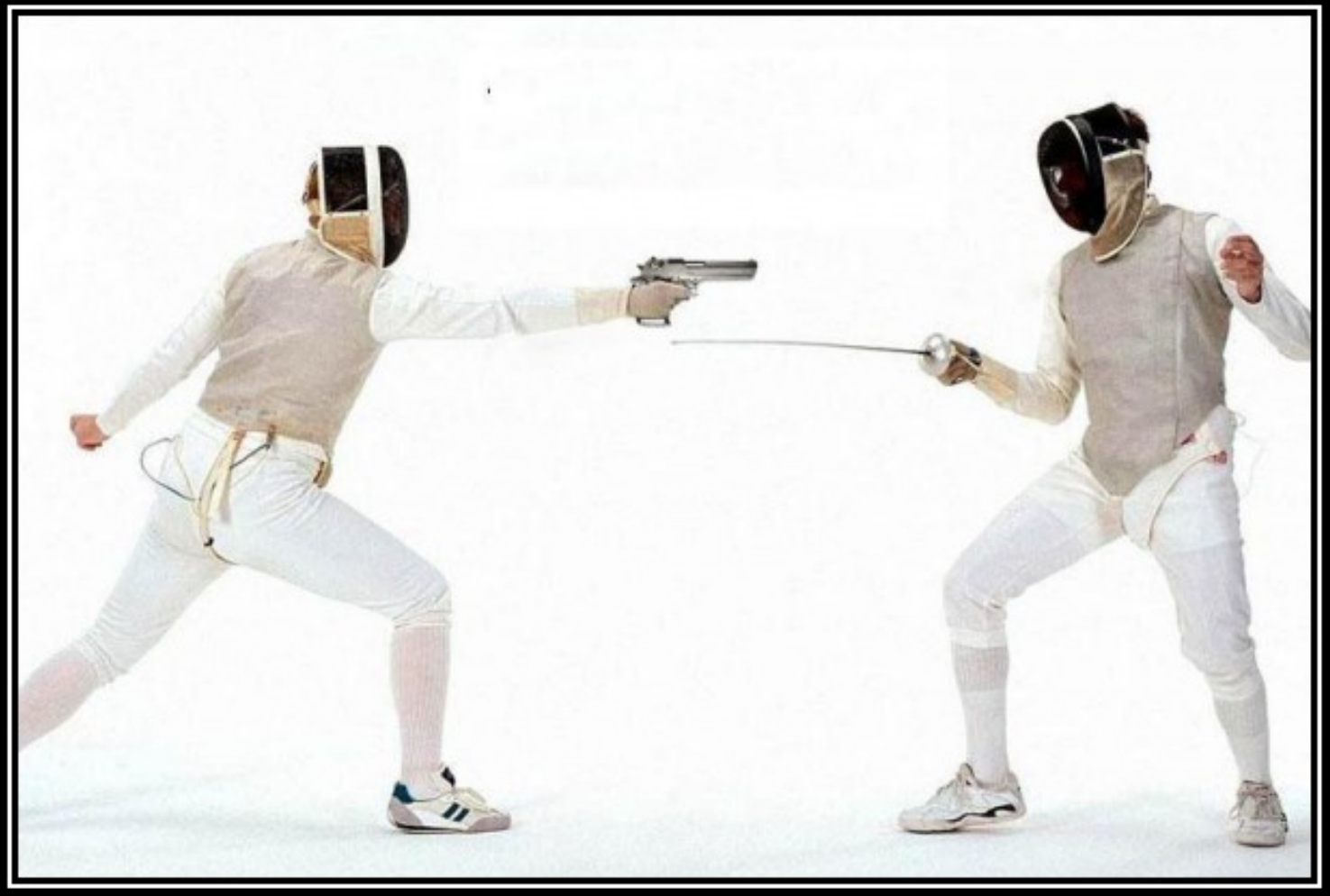


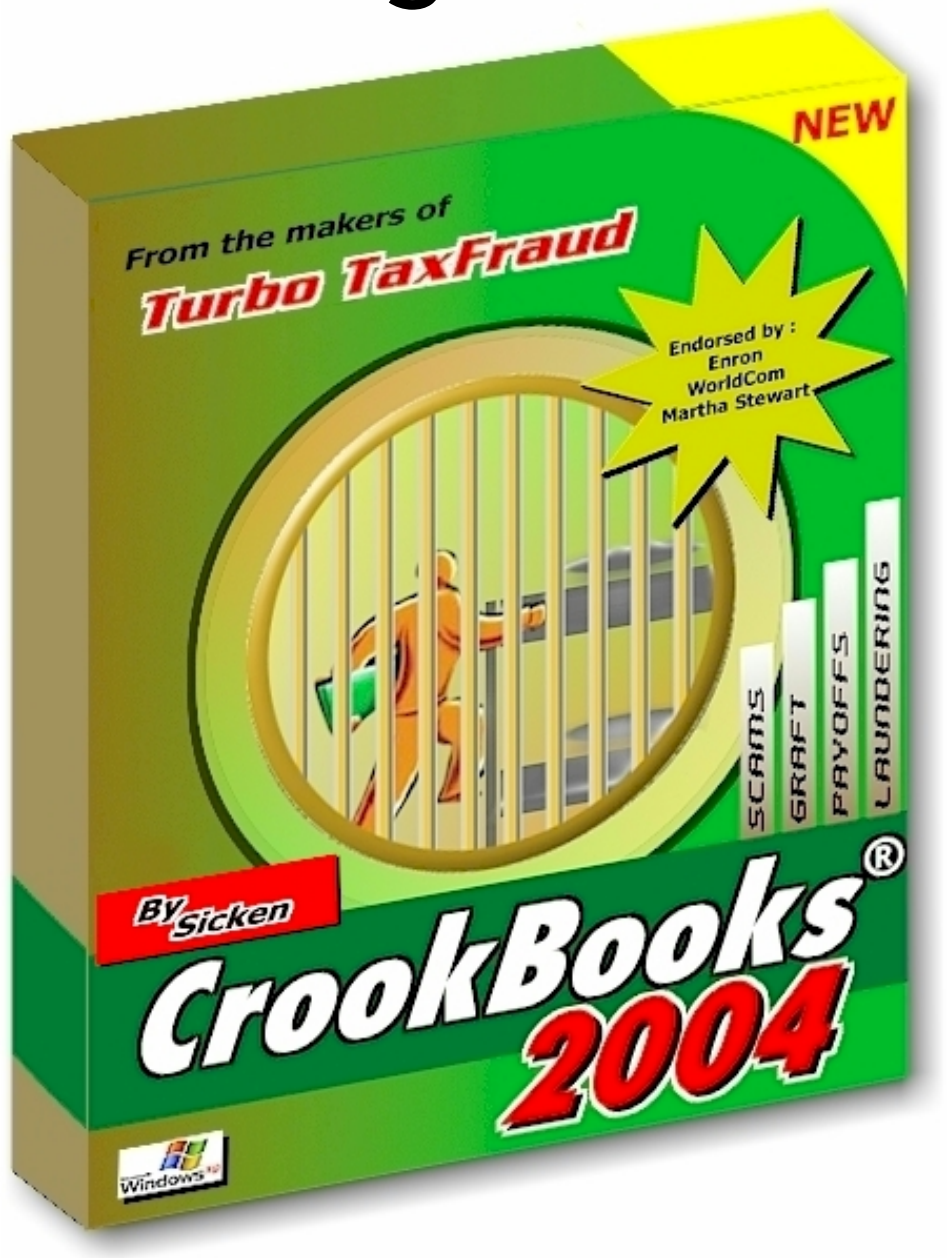
Language Security

Or: bringing a knife to a gun fight

One-Slide Summary

- A language's design principles and features have a strong influence on the security of programs written in that language.
- C's legacy of **null-terminated**, **stack-allocated** and **non-sized** buffers leads directly to one of the most common sorts of security vulnerabilities: the **buffer overrun**.
- What can be done?

Today: Hacking For Dummies?



Lecture Outline

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

Duck-billed Platitudes

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

C Design Principles

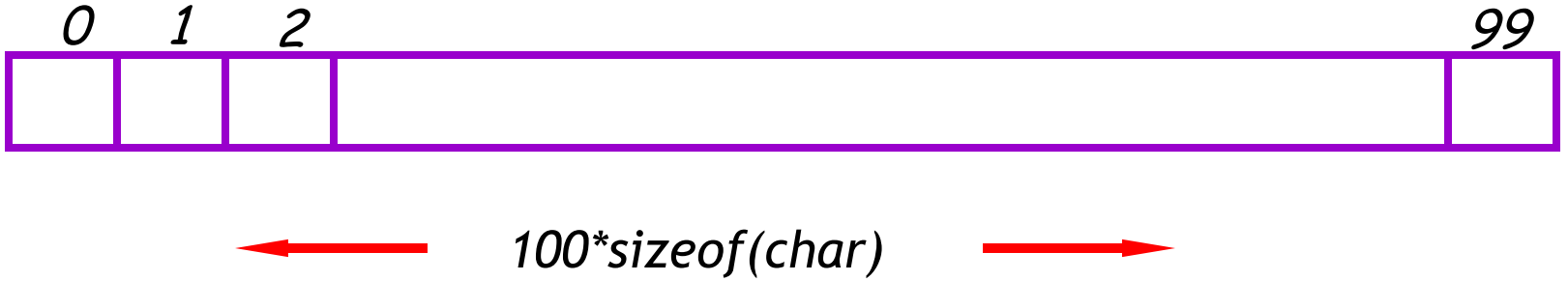
- Small language
- Maximum efficiency
- Safety less important

- Designed for the world in 1972
  - Weak machines
  - Trusted networks
  - *Tell me: how did those two factors influence C?*

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?

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

Indexing Out of Bounds

The following are all legal C (no parse errors, no type errors, etc.) and may generate no immediate run-time errors

```
char buffer[100];

buffer[-1] = ‘a’;
buffer[100] = ‘a’;
buffer[100000] = ‘a’;
```

Why Ask Why?

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

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

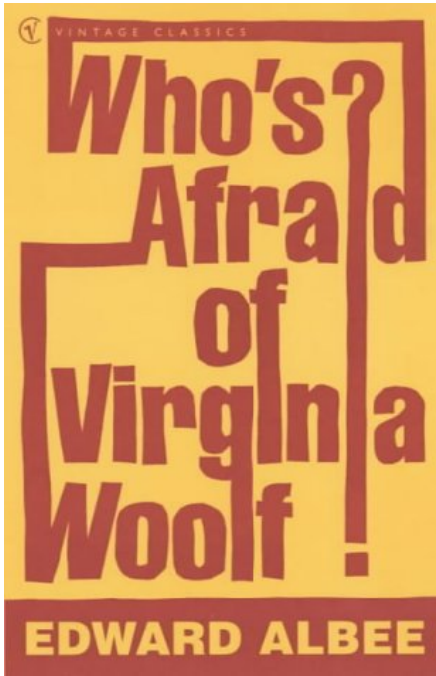
C vs. Java

- Typical work for a C array reference
  - Offset calculation
  - Memory operation (load or store)

- Typical work for a Java array reference
  - Offset calculation
  - Memory operation (load or store)
  - Array bounds check
  - Type compatibility check (for stores) (*why?*)

Buffer Overruns

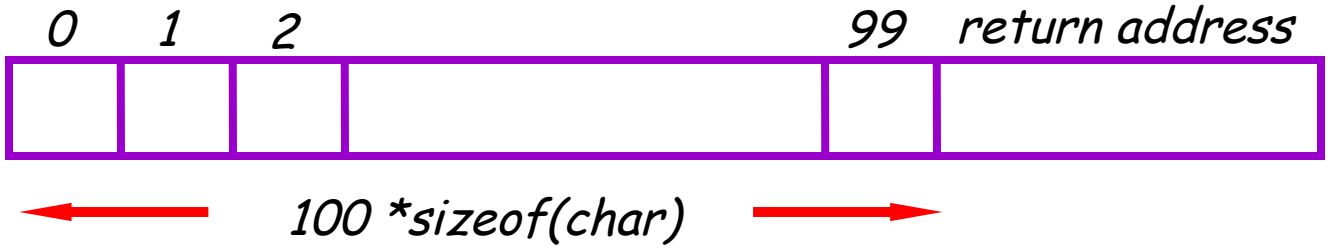
- A **buffer overrun** writes past the end of an array
- **Buffer** usually refers to a C array of char
  - But can be any array
- So who's afraid of a buffer overrun?
  - Cause a core dump
  - Can damage data structures
  - What else?



Stack Smashing

Buffer overruns can alter the control flow of your program!

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



An Overrun Vulnerability

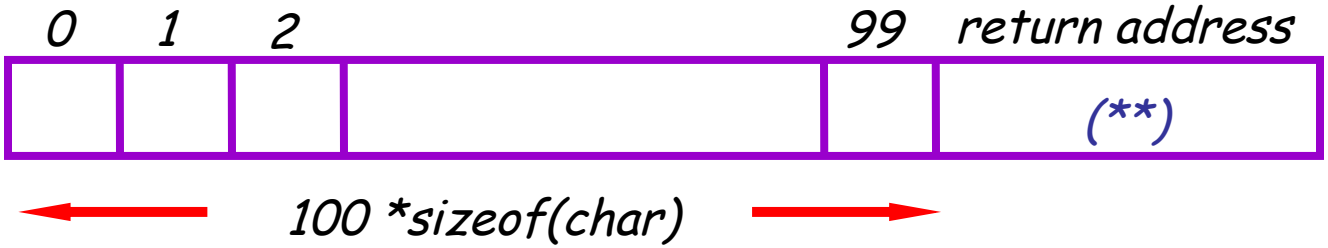
```
void foo(char in[]) {
  char buffer[100];
  int i = 0;
  for(i = 0; in[i] != '\0'; i++)
      buffer[i] = in[i];
  buffer[i] = '\0';
}
```

An Interesting Idea

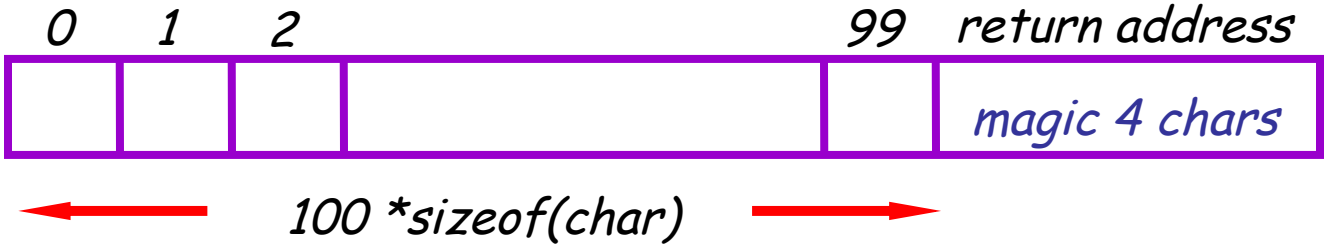
char in[104] = { 0,…,0, *magic 4 chars* }

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

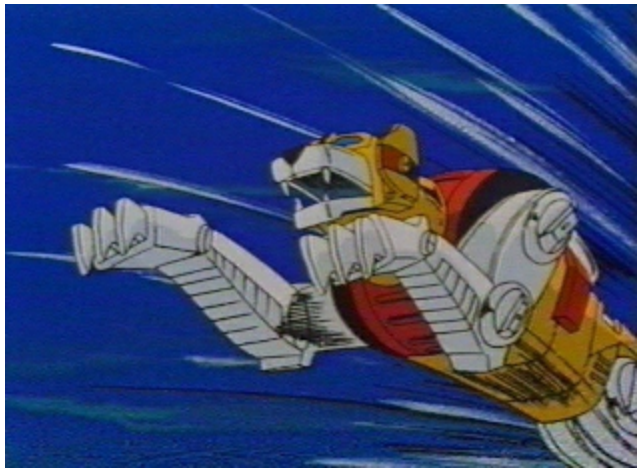
The Rest of the Story

- 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!

Useful Jumps

- Where to jump?



- We want to take control of the program
- How about to a system call?

The Plan

- Force a jump to the following code:
- In C: exec(“/bin/sh”);
- In x86 assembly:

```
        movl $LC0, (%esp)
        call _exec
LC0: .ascii “/bin/sh\0”
```

- In machine code: 0x20, 0x42, 0x00, …

The Plan

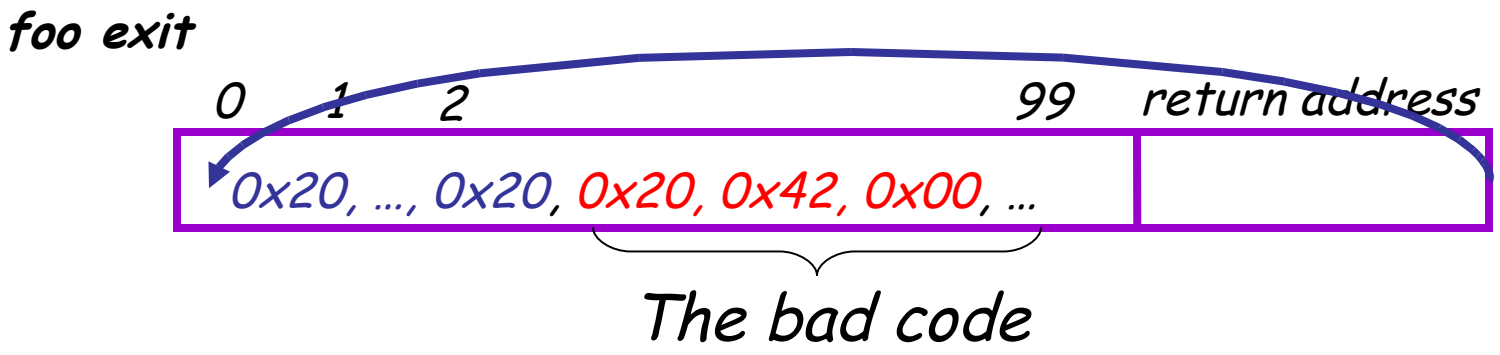
char in[104] = { 104 *magic chars* }

foo(in);

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

Guess the Location of the Injected Code

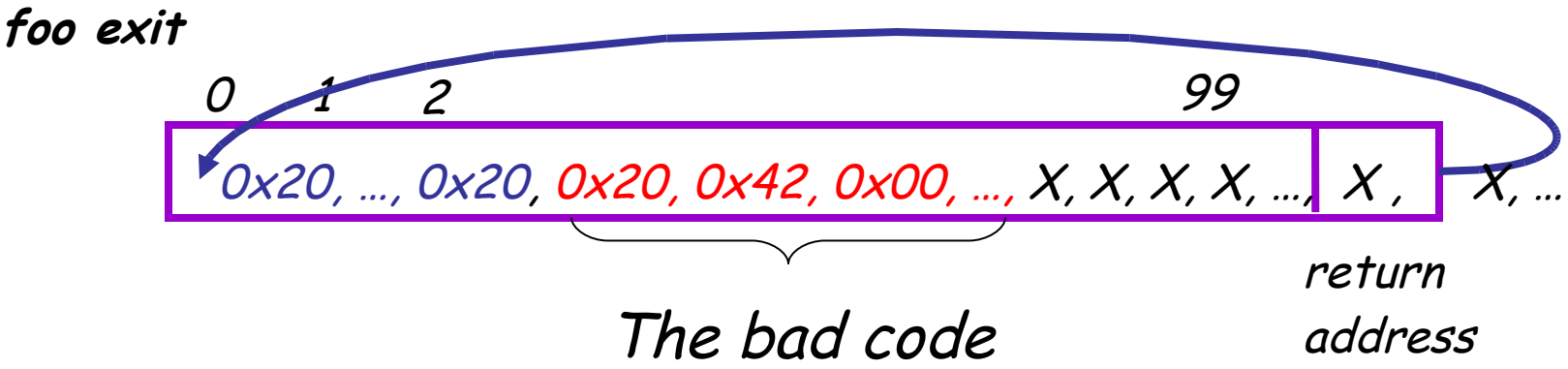
- Trial and error: gives you a ballpark
- Then pad the **injected code** with NOP
  - e.g. add r0, r1, 0x2020
    - stores result in r0 which is hardwired to 0 anyway
    - Encoded as 0x20202020



- 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 injected code carefully
  - Instead of “addiu r4,r0,0x0015”(code 0x20400015)
  - Use “addiu r4,r0,0x1126; subiu r4, r4,0x1111”

Q: Games (557 / 842)

- Name the company that manufactures **Barbie** (a $1.9 billion dollar a year industry in 2005 with two dolls being bought every second).

Q: General (447 / 842)

- This is a three-part deductive argument with an unstated assumption which must be true for the premises to lead to the conclusion. Examples include: *"There is no law against composing music when one has no ideas whatsoever. The music of Wagner, therefore, is perfectly legal."* or advertisements in which cars are draped with beautiful people.

Q: Music (132 / 842)

- This landmark 1986 metal album by Metallica includes the song **Welcome Home (Sanitarium)**. The Parents Music Resource Center pointed to the title song, which includes the lyrics *"Obey your master / Your life burns faster"* , as an explicit example of harmful content.

Q: Events (597 / 842)

- Identify the speaker: *"This is a court of law, young man, not a court of justice."* and *"I have no respect for the passion of equality, which seems to me merely idealizing envy."*

Q: Games (536 / 842)

- These 1912 ring-shaped hard candies traditionally came in five flavors and were packaged in "rolls" of fifteen pieces.

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 with respect to buffer overruns
  - Easy to do the wrong thing
  - Hard to do the right thing

The State of Hacking

- Buffer overruns are an attack of choice
  - 40-50% of new vulnerabilities are buffer overruns
  - Many recent attacks of this flavor: Code Red, Nimda, MS-SQL server, yada yada
  - "Buffer overflows have been the most common form of security vulnerability for the past ten years …" [OGI DARPA 2000]
  - From 2007 on, XSS and SQL-CIV are more popular, and buffer overruns are now #2
- Highly automated toolkits are available to exploit known buffer overruns
  - Look up "script kiddie"

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 white hats

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
- This is a popular research area; we'll present one idea at random [Wagner, Aiken, …]
  - You'll see more in later lectures

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 and array dereferences are very difficult to analyze statically
  - Where does *ptr 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
  - *Used* max number of bytes actually in use

- Use integer ranges
  - [x,y] = { x, x+1, …, y-1, y }
  - Alloc and used cannot be computed exactly

The Strategy

- For each program expression, write **constraints** capturing the alloc and used of its string subexpressions

- Solve the constraints for the entire program

- Check for each string variable s

$$\textbf{used(s)} \leq \textbf{alloc(s)}$$

The Constraints

char s[n];	n = alloc(s)
strcpy(dst,src)	used(src) ≤ used(dst)
p = strdup(s)	used(s) ≤ used(p) & alloc(s) ≤ alloc(p)
p[n] = '\0'	min(used(p),n+1)) ≤ used(p)

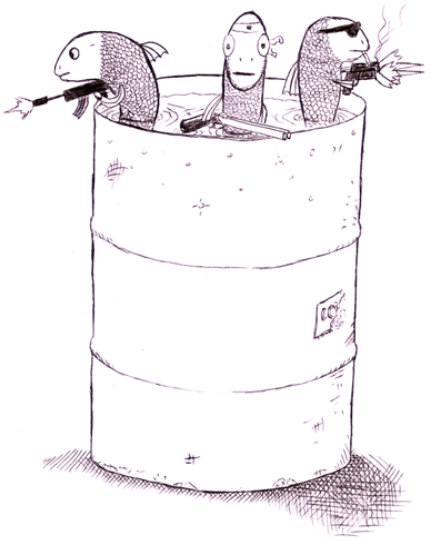
Constraint Solving

- Solving the constraints is akin to solving dataflow equations
  - Remember liveness? Constant propagation?
- Build a graph
  - Nodes are len(s), alloc(s)
  - Edges are constraints $\text{len}(s) \leq \text{len}(t)$
- Propagate information forward through the graph
  - Special handling of loops in the graph

Results

- This technique found new buffer overruns in *sendmail*
  - Which is like shooting fish in a barrel …
- Found new exploitable overruns in Linux *nettools* package

- Both widely used
- Previously hand-audited packages



Limitations

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

Summary

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

Homework

- Midterm 2 Next Tuesday In Class