CSE 484 / CSE M 584: Computer Security and Privacy

Software Security: Buffer Overflow Defenses

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Admin

• Assignments:
  – Ethics form: **Due today at 11:59pm**!
  – Homework 1: Due Friday at 5pm
  – Lab 1: Sign up, make sure you can access ASAP

• Looking forward
  – Friday: Guest lecture (David Aucsmith)
  – Next week: Finish software security, start crypto
How Can We Attack This?

```c
foo() {
    char buf[...];
    strncpy(buf, readUntrustedInput(), sizeof(buf));
    printf(buf); //vulnerable
}
```

If format string contains % then printf will expect to find arguments here...

What should readUntrustedInput() return??

The diagram illustrates the frames of the caller and the function being called. The `printf` function is in the caller's frame, and `foo` is in the callee's frame. The call stack is shown with `ret/IP`, `Saved FP`, and `Addr 0xFF...F` fields.
Using %n to Overwrite Return Address

Buffer with attacker-supplied input “string”

“... attackString%n”, attack code

&RET

SFP

RET

This portion contains enough % symbols to advance printf’s internal stack pointer

Number of characters in attackString must be equal to ... what?

When %n happens, make sure the location under printf’s stack pointer contains address of RET; %n will write the number of characters in attackString into RET

Return execution to this address

C allows you to concisely specify the “width” to print, causing printf to pad by printing additional blank characters without reading anything else off the stack.

Example: printf(“%5d”, 10) will print three spaces followed by the integer: “ 10”

That is, %n will print 5, not 2.

Key idea: do this 4 times with the right numbers to overwrite the return address byte-by-byte.

(4x %n to write into &RET, &RET+1, &RET+2, &RET+3)
Recommended Reading

• It will be hard to do Lab 1 without:
  – Reading (see course schedule):
    • Smashing the Stack for Fun and Profit
    • Exploiting Format String Vulnerabilities
  – Attending section this week, next week
Buffer Overflow: Causes and Cures

• Typical memory exploit involves code injection
  – Put malicious code at a predictable location in memory, usually masquerading as data
  – Trick vulnerable program into passing control to it

• Possible defenses:
  1. Prevent execution of untrusted code
  2. Stack “canaries”
  3. Encrypt pointers
  4. Address space layout randomization
  5. Code analysis
  6. ...
Executable Space Protection

- Mark all writeable memory locations as non-executable
  - Example: Microsoft’s Data Execution Prevention (DEP)
  - This blocks many code injection exploits

- Hardware support
  - AMD “NX” bit (no-execute), Intel “XD” bit (executed disable) (in post-2004 CPUs)
  - Makes memory page non-executable

- Widely deployed
  - Windows XP SP2+ (2004), Linux since 2004 (check distribution), OS X 10.5+ (10.4 for stack but not heap), Android 2.3+
What Does “Executable Space Protection” Not Prevent?

- Can still corrupt stack ...
  - ... or function pointers
  - ... or critical data on the heap

- As long as RET points into existing code, executable space protection will not block control transfer!
  ➔ return-to-libc exploits
return-to-libc

- Overwrite saved EIP with address of any library routine
  - Arrange stack to look like arguments

- Does not look like a huge threat
  - Attacker cannot execute arbitrary code
  - But ... ?
    - Can still call critical functions, like exec

- See lab 1, sploit 8 (extra credit)
return-to-libc on Steroids

• Insight: Overwritten saved EIP need not point to the \textit{beginning} of a library routine

• \textbf{Any} existing instruction in the code image is fine
  – Will execute the sequence starting from this instruction

• What if instruction sequence contains RET?
  – Execution will be transferred... to where?
  – Read the word pointed to by stack pointer (ESP)
    • Guess what? Its value is under attacker’s control!
  – Use it as the new value for EIP
    • Now control is transferred to an address of attacker’s choice!
  – Increment ESP to point to the next word on the stack
Chaining RETs for Fun and Profit

• Can chain together sequences ending in RET
  – Krahmer, “x86-64 buffer overflow exploits and the borrowed code chunks exploitation technique” (2005)

• What is this good for?

• Answer [Shacham et al.]: everything
  – Turing-complete language
  – Build “gadgets” for load-store, arithmetic, logic, control flow, system calls
  – Attack can perform arbitrary computation using no injected code at all – return-oriented programming
Return-Oriented Programming
Run-Time Checking: StackGuard

- Embed "canaries" (stack cookies) in stack frames and verify their integrity prior to function return
  - Any overflow of local variables will damage the canary
Run-Time Checking: StackGuard

• Embed “canaries” (stack cookies) in stack frames and verify their integrity prior to function return
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  buf ➔ canary ➔ sfp ➔ ret addr ➔ Frame of the calling function
  Top of stack
  
  Local variables ➔ Pointer to previous frame ➔ Return execution to this address

• Choose random canary string on program start
  – Attacker can’t guess what the value of canary will be

• Terminator canary: “\0”, newline, linefeed, EOF
  – String functions like strcpy won’t copy beyond “\0”
StackGuard Implementation

• StackGuard requires code recompilation
• Checking canary integrity prior to every function return causes a performance penalty
  – For example, 8% for Apache Web server at one point in time
• StackGuard can be defeated
  – A single memory write where the attacker controls both the value and the destination is sufficient
Defeating StackGuard

• Suppose program contains `strcpy(dst, buf)` where attacker controls both `dst` and `buf`  
  – Example: `dst` is a local pointer variable

![Diagram of StackGuard vulnerability]

- `strcpy` will copy `BadPointer` here
- Return execution to this address
- Overwrite destination of `strcpy` with RET position
- `BadPointer, attack code`
PointGuard

• Attack: overflow a function pointer so that it points to attack code

• Idea: encrypt all pointers while in memory
  – Generate a random key when program is executed
  – Each pointer is XORed with this key when loaded from memory to registers or stored back into memory
    • Pointers cannot be overflowed while in registers

• Attacker cannot predict the target program’s key
  – Even if pointer is overwritten, after XORing with key it will dereference to a “random” memory address
Normal Pointer Dereference

1. Fetch pointer value
2. Access data referenced by pointer

![Diagram showing normal pointer dereference]

Corrupted pointer
1. Fetch pointer value
2. Access attack code referenced by corrupted pointer

![Diagram showing corrupted pointer dereference]

[Cowan]
PointGuard Dereference

Memory

1. Fetch pointer value
2. Access data referenced by pointer

CPU

Decrypt

0x1234

Encrypt 0x7239

pointer

Data

0x1234

Memory

1. Fetch pointer value
2. Access random address; segmentation fault and crash

CPU

Decrypt

0x9786

Decrypts to random value

Corrupted pointer 0x7239
0x1340

Data

Attack code

0x1234 0x1340 0x9786
PointGuard Issues

- Must be very fast
  - Pointer dereferences are very common

- Compiler issues
  - Must encrypt and decrypt only pointers
  - If compiler “spills” registers, unencrypted pointer values end up in memory and can be overwritten there

- Attacker should not be able to modify the key
  - Store key in its own non-writable memory page

- PG’d code doesn’t mix well with normal code
  - What if PG’d code needs to pass a pointer to OS kernel?
ASLR: Address Space Randomization

• Randomly arrange address space of key data areas for a process
  – Base of executable region
  – Position of stack
  – Position of heap
  – Position of libraries

• Introduced by Linux PaX project in 2001
• Adopted by OpenBSD in 2003
• Adopted by Linux in 2005
ASLR: Address Space Randomization

• Deployment (examples)
  – Linux kernel since 2.6.12 (2005+)
  – Android 4.0+
  – iOS 4.3+ ; OS X 10.5+
  – Microsoft since Windows Vista (2007) (not by default)

• Attacker goal: Guess or figure out target address (or addresses)

• ASLR more effective on 64-bit architectures
Attacking ASLR

- **NOP slides** and **heap spraying** to increase likelihood for custom code (e.g., on heap)
- Brute force attacks or memory disclosures to map out memory on the fly
  - Disclosing a single address can reveal the location of all code within a library, depending on the ASLR implementation
Other Possible Solutions

• Use safe programming languages, e.g., Java
  – What about legacy C code?
  – (Though Java doesn’t magically fix all security issues 😊)
• Static analysis of source code to find overflows
• Dynamic testing: “fuzzing”