Software Security: Buffer Overflow Defenses

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Admin

• Assignments:
  • Homework 1: Due today at 11:59pm
  • Lab 1: Sign up, granting access ~once per day, see forum
Summary of Printf Risks

• Printf takes a variable number of arguments
  • E.g., printf(“Here’s an int: %d”, 10);

• Assumptions about input can lead to trouble
  • E.g., printf(buf) when buf=“Hello world” versus when buf=“Hello world %d”
  • Can be used to advance printf’s internal stack pointer
  • Can read memory
    • E.g., printf(“%x”) will print in hex format whatever printf’s internal stack pointer is pointing to at the time
  • Can write memory
    • E.g., printf(“Hello%n”); will write “5” to the memory location specified by whatever printf’s internal SP is pointing to at the time
How Can We Attack This?

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

What should the string returned by readUntrustedInput() contain??

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

What should the string returned by readUntrustedInput() contain??
<table>
<thead>
<tr>
<th></th>
<th>Saved FP</th>
<th>ret/IP</th>
<th>&amp;buf</th>
<th>buf</th>
<th>Saved FP</th>
<th>ret/IP</th>
<th>Caller’s frame</th>
</tr>
</thead>
</table>

- **Printf’s frame**
- **Foo’s frame**
Using `%n` to Overwrite Return Address

**In `foo()`'s stack frame:**

- Buffer with attacker-supplied input “string”
- “... `attackString%n`”, attack code
- `%n` will write the number of characters in `attackString` into `RET`
- 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

**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)

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.

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

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The exploitation twilight zone

• During an exploitation attempt sometimes you have to ‘let it run’
  • Overflow a buffer
  • Change things
  • Let program run for ‘a bit’
  • Everything triggers!

• Printf exploit a perfect example
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 tomorrow
Buffer Overflow: Causes and Cures

• Classical 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. …
Defense: 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 ret (IP) with address of any library routine
  • Arrange stack to look like arguments

• Does not look like a huge threat
  • ...

• Canvas in-class activity, Jan 13!
return-to-libc

- Overwrite saved ret (IP) with address of any library routine
  - Arrange stack to look like arguments

- Does not look like a huge threat
  - ...
  - We can call any function we want!
  - Say, exec 😊
return-to-libc on Steroids

- Insight: Overwritten saved EIP need not point to the *beginning* of a library routine
- **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 (SP)
    - Guess what? Its value is under attacker’s control!
  - Use it as the new value for IP
    - Now control is transferred to an address of attacker’s choice!
  - Increment SP 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
Defense: 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

Diagram:
- buf
- canary
- sfp
- ret addr
- Top of stack
- Frame of the calling function
- Pointer to previous frame
- Return execution to this address
- Local variables
Defense: 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

- **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 `copy(dst, buf)` where attacker controls both dst and buf
  - Example: dst is a local pointer variable

```
buf &dst canary sfp RET
```
Return execution to this address

```
BadPointer, attack code &RET canary sfp RET
```
Overwrite destination of strcpy with RET position

strcpy will copy BadPointer here
Defense: 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
Defense: 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)

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

- ASLR more effective on 64-bit architectures
Attacking ASLR

• **NOP sleds** 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
Defense: Shadow stacks

• Idea: don’t store return addresses on the stack!

• Store them on... a **different stack**!
  • A *hidden* stack

• On function call/return
  • Store/retrieve the return address from shadow stack

• Maybe encrypt/randomize the shadow stack data?
Challenges With Shadow Stacks

• Where do we put the shadow stack?
  • Can the attacker figure out where it is?

• How fast is it to store/retrieve from the shadow stack?

• How big is the shadow stack?

• Is this compatible with all software?
Other Possible Solutions

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