CSci 5271
Introduction to Computer Security
Day 5: Low-level defenses and counterattacks

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Outline

Basic definition

- Shellcode: attacker supplied instructions implementing malicious functionality
- Name comes from example of starting a shell
- Often requires attention to machine-language encoding

Classic execve `/bin/sh`

- `execve(fname, argv, envp)` system call
- Specialized syscall calling conventions
- Omit unneeded arguments
- Doable in under 25 bytes for Linux/x86

Avoiding zero bytes

- Common requirement for shellcode in C string
- Analogy: broken 0 key on keyboard
- May occur in other parts of encoding as well

More restrictions

- No newlines
- Only printable characters
- Only alphanumeric characters
- "English Shellcode" (CCS'09)

Transformations

- Fold case, escapes, Latin1 to Unicode, etc.
- Invariant: unchanged by transformation
- Pre-image: becomes shellcode only after transformation

Multi-stage approach

- Initially executable portion unpacks rest from another format
- Improves efficiency in restricted environments
- But self-modifying code has pitfalls

NOP sleds

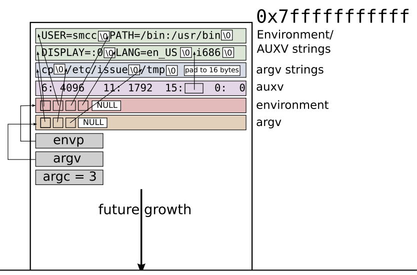
- Goal: make the shellcode an easier target to hit
- Long sequence of no-op instructions, real shellcode at the end
  - x86: 0x90 0x90 0x90 0x90 0x90 . . . shellcode

Where to put shellcode?

- In overflowed buffer, if big enough
- Anywhere else you can get it
  - Nice to have: predictable location
- Convenient choice of Unix local exploits:

Where to put shellcode?

Environment variables



Code reuse

- If can't get your own shellcode, use existing code
- Classic example: `system` implementation in C library
  - "Return to libc" attack
- More variations on this later

Outline

Shellcode techniques

Exploiting other vulnerabilities

Return address protections

Announcements intermission

ASLR and counterattacks

W⊕X (DEP)

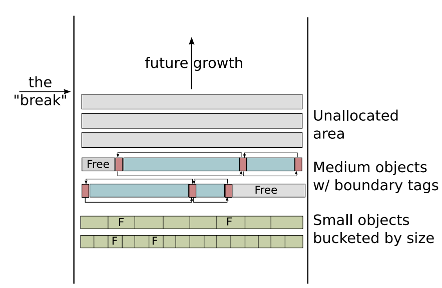
Non-control data overwrite

- Overwrite other security-sensitive data
- No change to program control flow
- Set user ID to 0, set permissions to all, etc.

Heap meta-data

- Boundary tags similar to doubly-linked list
- Overwritten on heap overflow
- Arbitrary write triggered on `free`
- Simple version stopped by sanity checks

Heap meta-data



Use after free

- Write to new object overwrites old, or vice-versa
- Key issue is what heap object is reused for
- Influence by controlling other heap operations

Integer overflows

- Easiest to use: overflow in small (8-, 16-bit) value, or only overflowed value used
- 2GB write in 100 byte buffer
  - Find some other way to make it stop
- Arbitrary single overwrite
  - Use math to figure out overflowing value

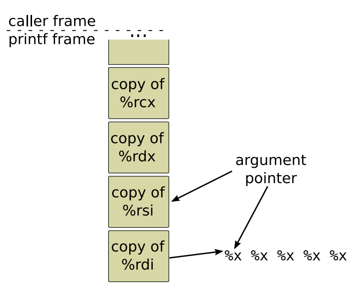
Null pointer dereference

- Add offset to make a predictable pointer
  - On Windows, interesting address start low
- Allocate data on the zero page
  - Most common in user-space to kernel attacks
  - Read more dangerous than a write

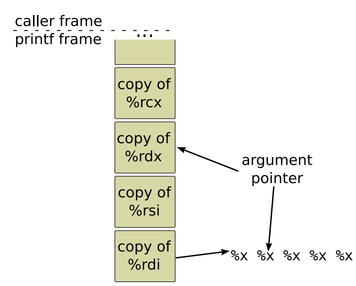
Format string attack

- Attacker-controlled format: little interpreter
- Step one: add extra integer specifiers, dump stack
  - Already useful for information disclosure

Format string attack layout



Format string attack layout



Format string attack: overwrite

- %n specifier: store number of chars written so far to pointer arg
- Advance format arg pointer to other attacker-controlled data
- Control number of chars written with padding
- On x86, use unaligned stores to create pointer

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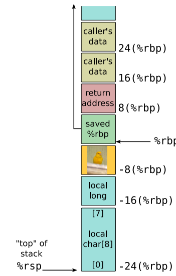
Canary in the coal mine

Adjacent canary idea



Terminator canary

- Value hard to reproduce because it would tell the copy to stop
- StackGuard: 0x00 0D 0A FF
  - 0: String functions
  - newline: `fgets()`, etc.
  - -1: `getc()`
  - carriage return: similar to newline?
- Doesn't stop: `memcpy`, custom loops

Random canary

- Can't reproduce because attacker can't guess
- For efficiency, usually one per execution
- Ineffective if disclosed

XOR canary

- Want to protect against non-sequential overwrites
- XOR return address with value c at entry
- XOR again with c before return
- Standard choice for c: see random canary

Further refinements

- More flexible to do earlier in compiler
- Rearrange buffers after other variables
  - Reduce chance of non-control overwrite
- Skip canaries for functions with only small variables
  - Who has an overflow bug in an 8-byte array?

What's usually not protected?

- Backwards overflows
- Function pointers
- Adjacent structure fields
- Adjacent static data objects

Where to keep canary value

- Fast to access
- Buggy code/attacker can't read or write
- Linux/x86-64: `%fs:0x28`

Complex anti-canary attack

- Canary not updated on `fork` in server
- Attacker controls number of bytes overwritten

Complex anti-canary attack

- Canary not updated on `fork` in server
- Attacker controls number of bytes overwritten
- ANRY BNRY CNRY DNRY ENRY FNRY
- search $2^{32} \longrightarrow$ search $4 \cdot 2^8$

Shadow return stack

- Suppose you have a safe place to store the canary
- Why not just store the return address there?
- Needs to be a separate stack
- Ultimate return address protection

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Pre-proposals due tonight

- Most groups formed?
- One PDF per group, include schedule choices
- Submit via Canvas by 11:59pm

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W⊕X (DEP)

Basic idea

- "Address Space Layout Randomization"
- Move memory areas around randomly so attackers can't predict addresses
- Keep internal structure unchanged
  - E.g., whole stack moves together

Code and data locations

- Execution of code depends on memory location
- E.g., on 32-bit x86:
  - Direct jumps are relative
  - Function pointers are absolute
  - Data must be absolute

Relocation (Windows)

- Extension of technique already used in compilation
- Keep table of absolute addresses, instructions on how to update
- Disadvantage: code modifications take time on load, prevent sharing

PIC/PIE (GNU/Linux)

- "Position-Independent Code / Executable"
- Keep code unchanged, use register to point to data area
- Disadvantage: code complexity, register pressure hurt performance

What's not covered

- Main executable (Linux 32-bit PIC)
- Incompatible DLLs (Windows)
- Relative locations within a module/area

Entropy limitations

- Intuitively, *entropy* measures amount of randomness, in bits
- Random 32-bit int: 32 bits of entropy
- ASLR page aligned, so at most $32 - 12 = 20$ bits of entropy
- Other constraints further reduce possibilities

Leakage limitations

- If an attacker learns the randomized base address, can reconstruct other locations
- Any stack address $\rightarrow$ stack unprotected, etc.

GOT hijack (Müller)

- Main program fixed, libc randomized
- PLT in main program used to call libc
- Rewire PLT to call attacker's favorite libc functions
- E.g., turn `printf` into `system`

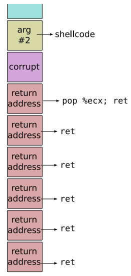
GOT hijack (Müller)

```
printf@plt:     jmp *0x8049678
...
system@plt:     jmp *0x804967c
...
0x8049678: <addr of printf in libc>
0x804967c: <addr of system in libc>
```

ret2pop (Müller)

- Take advantage of shellcode pointer already present on stack
- Rewrite intervening stack to treat the shellcode pointer like a return address
  - A long sequence of chained returns, one pop

ret2pop (Müller)



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- Shellcode techniques
- Exploiting other vulnerabilities
- Return address protections
- Announcements intermission
- ASLR and counterattacks
- W⊕X (DEP)

Basic idea

- Traditional shellcode must go in a memory area that is
  - writable, so the shellcode can be inserted
  - executable, so the shellcode can be executed
- But benign code usually does not need this combination
- W xor X, really $\neg(W \wedge X)$

Non-writable code, $X \rightarrow \neg W$

- E.g., read-only .text section
- Has been standard for a while, especially on Unix
- Lets OS efficiently share code with multiple program instances

Non-executable data, $W \rightarrow \neg X$

- Prohibit execution of static data, stack, heap
- Not a problem for most programs
  - Incompatible with some GCC features no one uses
  - Non-executable stack opt-in on Linux, but now near-universal

Implementing $W \oplus X$

- Page protection implemented by CPU
  - Some architectures (e.g. SPARC) long supported $W \oplus X$
- x86 historically did not
  - One bit controls both read and execute
  - Partial stop-gap "code segment limit"
- Eventual obvious solution: add new bit
  - NX (AMD), XD (Intel), XN (ARM)

One important exception

- Remaining important use of self-modifying code: just-in-time (JIT) compilers
  - E.g., all modern JavaScript engines
- Allow code to re-enable execution per-block
  - `mprotect`, `VirtualProtect`
  - Now a favorite target of attackers

Counterattack: code reuse

- Attacker can't execute new code
- So, take advantage of instructions already in binary
- There are usually a lot of them
- And no need to obey original structure

Classic return-to-libc (1997)

- Overwrite stack with copies of:
  - Pointer to libc's `system` function
  - Pointer to `"/bin/sh"` string (also in libc)
- The `system` function is especially convenient
- Distinctive feature: return to entry point

Chained return-to-libc

- Shellcode often wants a sequence of actions, e.g.
  - Restore privileges
  - Allow execution of memory area
  - Overwrite system file, etc.
- Can put multiple fake frames on the stack
  - Basic idea present in 1997, further refinements

Beyond return-to-libc

- Can we do more? Oh, yes.
- Classic academic approach: what's the most we could ask for?
- Here: "Turing completeness"
- How to do it: reading for Monday

Next slides

- Return-oriented programming (ROP)
  - And counter-defenses
- Control-flow integrity (CFI)