CSci 5271
Introduction to Computer Security
Low-level attacks and defenses

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Preview question

What two methods are mentioned in the StackGuard paper to prevent canary forgery?

A. "terminator canary" and "random canary"
B. "StackGhost" and "random XOR canary"
C. "stack layout randomization" and "entropy canary"
D. "StackGhost" and "PointGuard"
E. "Keccak" and "Rijndael"

Outline

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, cont'd
Exploiting other vulnerabilities
Return address protections
Announcements intermission
ASLR and counterattacks
W⊕X (DEP)

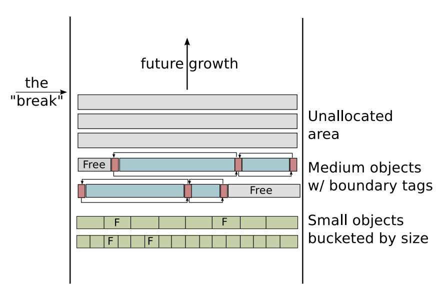
Non-control data overwrite

- 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

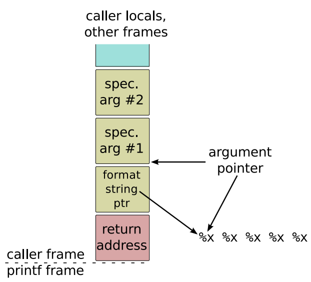
Null pointer dereference

- 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

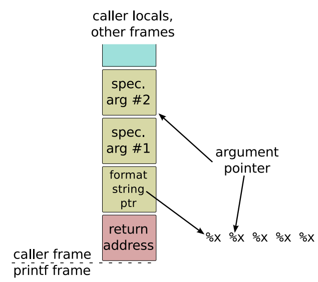
Format string attack

- 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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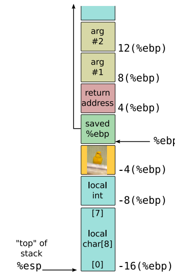
Canary in the coal mine

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: `%gs:0x14`

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

Outline

Shellcode techniques, cont'd

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Integer overflow question

Which of the following is not always true, when the variables are interpreted as 32-bit unsigned `int`s in C?

A. `x*y` is odd, if both `x` and `y` are odd

B. `x*y == y*x`

C. `x + x + x + x == 4*x`

D. `16*x >=x`

E. `x + (-x) == 0`

Pre-proposals due tonight

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

HA1 VMs now available

- Request from Travis if you have not already
- First exploit is due Friday evening
- Shouldn't be too hard to find, but allow time for trying out the VM and testing

BCECHO

- An even simpler buffer overflow example
- Can compile like BCMTA, install setuid root
- Will use for attack demo purposes next week

Outline

- Shellcode techniques, cont'd
- Exploiting other vulnerabilities
- Return address protections
- Announcements intermission
- ASLR and counterattacks
- 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 → 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`

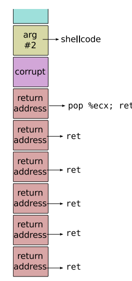
GOT hijack (Müller)

```
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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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)