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

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Preview 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`

Outline

Where overflows come from (cont'd)
More low-level problems
Classic code injection attacks
Announcements intermission
Shellcode techniques
Exploiting other vulnerabilities

More library attempts

- OpenBSD `strlcpy`, `strlcat`
  - Easier to use safely than "n" versions
  - Non-standard, but widely copied
- Microsoft-pushed `strcpy_s`, etc.
  - Now standardized in C11, but not in glibc
  - Runtime checks that `abort`
- Compute size and use `memcpy`
- C++ `std::string`, glib, etc.

Still a problem: truncation

- Unexpectedly dropping characters from the end of strings may still be a vulnerability
- E.g., if attacker pads paths with `///////` or `/./././.`
- Avoiding length limits is best, if implemented correctly

Off-by-one bugs

- `strlen` does not include the terminator
- Comparison with `<` vs. `<=`
- Length vs. last index
- `x++` vs. `++x`

Even more buffer/size mistakes

- Inconsistent code changes (use `sizeof`)
- Misuse of `sizeof` (e.g., on pointer)
- Bytes vs. wide chars (UCS-2) vs. multibyte chars (UTF-8)
- OS length limits (or lack thereof)

Other array problems

- Missing/wrong bounds check
  - One unsigned comparison suffices
  - Two signed comparisons needed
- Beware of clever loops
  - Premature optimization

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Integer overflow

- Fixed size result $\neq$ math result
- Sum of two positive `int`s negative or less than addend
- Also multiplication, left shift, etc.
- Negation of most-negative value
- `(low + high)/2`

Integer overflow example

```
int n = read_int();
obj *p = malloc(n * sizeof(obj));
for (i = 0; i < n; i++)
    p[i] = read_obj();
```

Signed and unsigned

- Unsigned gives more range for, e.g., `size_t`
- At machine level, many but not all operations are the same
- Most important difference: ordering
- In C, signed overflow is undefined behavior

Mixing integer sizes

- Complicated rules for implicit conversions
  - Also includes signed vs. unsigned
- Generally, convert before operation:
  - E.g., `1ULL << 63`
- Sign-extend vs. zero-extend
  - `char c = 0xff; (int)c`

Null pointers

- Vanilla null dereference is usually non-exploitable (just a DoS)
- But not if there could be an offset (e.g., field of struct)
- And not in the kernel if an untrusted user has allocated the zero page

Undefined behavior

- C standard "undefined behavior": anything could happen
- Can be unexpectedly bad for security
- Most common problem: compiler optimizes assuming undefined behavior cannot happen

Linux kernel example

```
struct sock *sk = tun->sk;
// ...
if (!tun)
    return POLLERR;
// more uses of tun and sk
```

Format strings

- `printf` format strings are a little interpreter
- `printf(fmt)` with untrusted `fmt` lets the attacker program it
- Allows:
  - Dumping stack contents
  - Denial of service
  - Arbitrary memory modifications!

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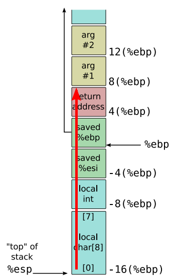
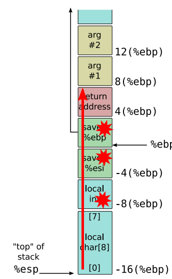
Overwriting the return address



Collateral damage



Collateral damage

- Stop the program from crashing early
- 'Overwrite' with same value, or another legal one
- Minimize time between overwrite and use

Other code injection targets

- Function pointers
  - Local, global, on heap
- `longjmp` buffers
- GOT (PLT) / import tables
- Exception handlers

Indirect overwrites

- Change a data pointer used to access a code pointer
- Easiest if there are few other uses
- Common examples
  - Frame pointer
  - C++ object vtable pointer

Non-sequential writes

- E.g. missing bounds check, corrupted pointer
- Can be more flexible and targeted
  - E.g., a *write-what-where* primitve
- More likely needs an absolute location
- May have less control of value written

Unexpected-size writes

- Attacks don't need to obey normal conventions
- Overwrite one byte within a pointer
- Use mis-aligned word writes to isolate a byte

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Memory layout question

In a 32-bit Linux/x86 program, which of these objects would have the lowest address (numerically least when considered as unsigned)?

A. An environment variable

B. The program name in `argv[0]`

C. A command-line argument in `argv[1]`

D. A local `float` variable in a function called by `main`

E. A local `char` array in `main`

Project meeting scheduling

- For pre-proposal due Wednesday night:
- Will pick a half-hour meeting slot, use for three different meetings
- List of about 70 slots on the web page
- Choose ordered list in pre-proposal, length inverse to popularity

HA1 materials posted

- Instructions PDF
- BCMTA source code
- VM instructions web page
- Discussion and submissions on Canvas

Getting your virtual machines

- Ubuntu 16.04 server, hosted on CSE Labs
  - 64-bit kernel but 32-bit BCMTA, `gcc -m32`
- One VM per group (up to 3 students)
- For allocation, send group list to Travis
- Don't put off until the last minute

Sequence of exploits

- Week 1 (9/20): bad feature, 10 points
- Week 2 (9/27): easier, 20 points
- Week 3 (10/4): harder, 30 points
- Week 4 (10/11): harder, 30 points
  - Plus, design suggestions (10 points)
- Week 5 (10/18): hardest, $10 \cdot n$ extra credit

Types of vulnerabilities

- OS interaction/logic errors
- Memory safety errors
  - E.g., exploit with control-flow hijacking
- Command-line and server modes available

Part of challenge: automation

- Must represent your attack as an exploit script
- Must be fully automatic
  - No user interaction
  - Works reliably, within 60 seconds
- Must work on a clean VM
- Use `test-exploit` script

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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

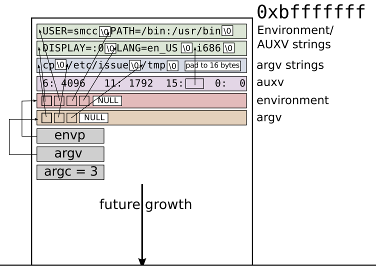
- Goal: make the shellcode an easier target to hit
- Long sequence of no-op instructions, real shellcode at the end
  - x86: 0x90 0x90 0x90 0x90 0x90 ... shellcode

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

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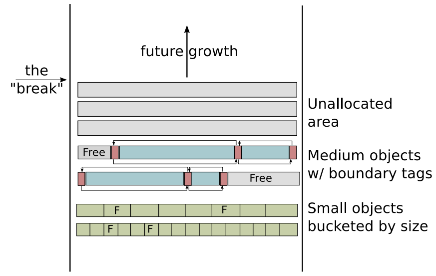
Non-control data overwrite

- 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

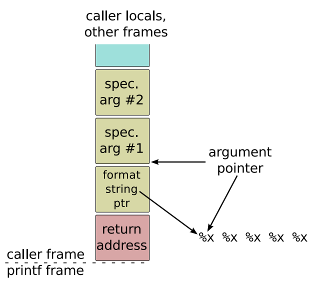
Null pointer dereference

- 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

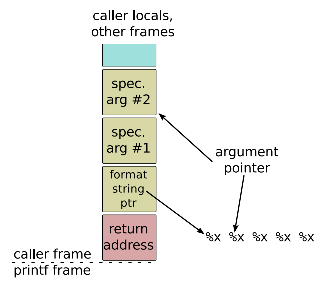
Format string attack

- 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

Next time

- Defenses and counter-attacks