CSci 5271
Introduction to Computer Security
Day 6: Low-level defenses and counterattacks, part 2

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Preview question

Which of these defense techniques would completely prevent a ROP attack from returning from an intended return instruction to an unintended gadget?

A. ASLR
B. A non-executable stack
C. Adjacent stack canaries
D. A shadow stack
E. A and C, but only if used together

Outline

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"
- First reading for today

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W⊕X (DEP)

Defenses in HA1

Return-oriented programming (ROP)

Announcements

BCECHO

Control-flow integrity (CFI)

More modern exploit techniques

BCMTA Makefile

```
CFLAGS := -g -Wall -m32 \
  -fno-stack-protector \
  -z execstack -z norelro
```

BCMTA Makefile

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```

- Standard non-security options

BCMTA Makefile

```
CFLAGS := -g -Wall -m32 \
  -fno-stack-protector \
  -z execstack -z norelro
```

- Turn off canaries

BCMTA Makefile

```
CFLAGS := -g -Wall -m32 \
  -fno-stack-protector \
  -z execstack -z norelro
```

- Allow execution on stack

BCMTA Makefile

```
CFLAGS := -g -Wall -m32 \
  -fno-stack-protector \
  -z execstack -z norelro
```

- Leave GOT writable

More HA1 VM unprotection

- Not in Makefile: disable ASLR
- Is done system-wide in VM
- For non-VM testing, can use `setarch i386 -R`

More HA1 VM unprotection

- Not in Makefile: disable /bin/sh privilege dropping
- Linux shells differ in whether they'll run setuid
- Recompiled `dash` with security check removed

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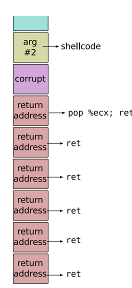
Basic new idea

- Treat the stack like a new instruction set
- "Opcodes" are pointers to existing code
- Generalizes return-to-libc with more programmability

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

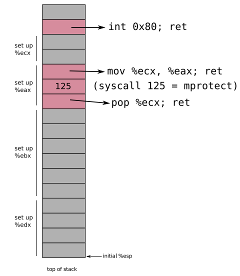
ret2pop (Müller)



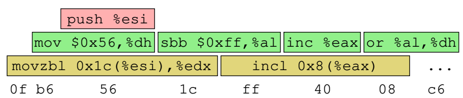
Gadgets

- Basic code unit in ROP
- Any existing instruction sequence that ends in a return
- Found by (possibly automated) search

Another partial example



Overlapping x86 instructions



- Variable length instructions can start at any byte
- Usually only one intended stream

Where gadgets come from

- Possibilities:
  - Entirely intended instructions
  - Entirely unaligned bytes
  - Fall through from unaligned to intended
- Standard x86 return is only one byte, 0xc3

Building instructions

- String together gadgets into manageable units of functionality
- Examples:
  - Loads and stores
  - Arithmetic
  - Unconditional jumps
- Must work around limitations of available gadgets

Hardest case: conditional branch

- Existing jCC instructions not useful
- But carry flag CF is
- Three steps:
  1. Do operation that sets CF
  2. Transfer CF to general-purpose register
  3. Add variable amount to `%esp`

Further advances in ROP

- Can also use other indirect jumps, overlapping not required
- Automation in gadget finding and compilers
- In practice: minimal ROP code to allow transfer to other shellcode

Anti-ROP: lightweight

- Check stack sanity in critical functions
- Check hardware-maintained log of recent indirect jumps (kBouncer)
- Unfortunately, exploitable gaps

Gaps in lightweight anti-ROP

- Three papers presented at 2014's USENIX Security
- Hide / flush jump history
- Very long loop → context switch
- Long "non-gadget" fragment
- (Later: call-preceded gadgets)

Anti-ROP: still research

- Modify binary to break gadgets
- Fine-grained code randomization
- Beware of adaptive attackers ("JIT-ROP")
- Next up: control-flow integrity

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StackGuard 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"

Exercise set 1

- Due Wednesday 11:59pm
- One member of each group submits a PDF via Canvas

BCMTA vulnerability found!

- The `-d` option and a recipient starting with `test` enabled a backdoor
- Caused message body to be sent directly to a shell

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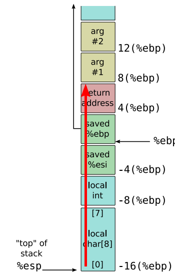
BCECHO code

```
void print_arg(char *str) {
  char buf[20]; int len;
  int buf_sz = (sizeof(buf)-sizeof(NULL))
               * sizeof(char *);
  len = strlcpy(buf, str, buf_sz);
  if (len > buf_sz) {
    fprintf(stderr,"Trucation occured "
            "when printing %s\n", str);
  }
  fwrite(buf, sizeof(char), len, stdout);
}
```

Attack planning

- Looks like candidate for classic stack-smash
- Where to put the attack value?
  - Via disassembly inspection
  - Via GDB
  - Via experimentation

Overwriting the return address



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Some philosophy

- Remember whitelist vs. blacklist?
- Rather than specific attacks, tighten behavior
  - Compare: type system; garbage collector vs. use-after-free
- CFI: apply to control-flow attacks

Basic CFI principle

- Each indirect jump should only go to a programmer-intended (or compiler-intended) target
- I.e., enforce call graph
- Often: identify disjoint target sets

Approximating the call graph

- One set: all legal indirect targets
- Two sets: indirect calls and return points
- n sets: needs possibly-difficult points-to analysis

Target checking: classic

- Identifier is a unique 32-bit value
- Can embed in effectively-nop instruction
- Check value at target before jump
- Optionally add shadow stack

Target checking: classic

```
cmp [ecx], 12345678h
jne error_label
lea ecx, [ecx+4]
jmp ecx
```

Challenge 1: performance

- In CCS'05 paper: 16% avg., 45% max.
  - Widely varying by program
  - Probably too much for on-by-default
- Improved in later research
  - Common alternative: use tables of legal targets

Challenge 2: compatibility

- Compilation information required
- Must transform entire program together
- Can't inter-operate with untransformed code

Recent advances: COTS

- Commercial off-the-shelf binaries
- CCFIR (Berkeley+PKU, Oakland'13): Windows
- CFI for COTS Binaries (Stony Brook, USENIX'13): Linux

COTS techniques

- CCFIR: use Windows ASLR information to find targets
- Linux paper: keep copy of original binary, build translation table

Control-Flow Guard

- CFI-style defense now in latest Windows systems
- Compiler generates tables of legal targets
- At runtime, table managed by kernel, read-only to user-space

Coarse-grained counter-attack

- "Out of Control" paper, Oakland'14
- Limit to gadgets allowed by coarse policy
  - Indirect call to function entry
  - Return to point after call site ("call-preceded")
- Use existing direct calls to `VirtualProtect`
- Also used against kBouncer

Control-flow bending counter-attack

- Control-flow attacks that still respect the CFG
- Especially easy without a shadow stack
- Printf-oriented programming generalizes format-string attacks

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Target #1: web browsers

- Widely used on desktop and mobile platforms
- Easily exposed to malicious code
- JavaScript is useful for constructing fancy attacks

Heap spraying

- How to take advantage of uncontrolled jump?
- Maximize proportion of memory that is a target
- Generalize NOP sled idea, using benign allocator
- Under W⊕X, can't be code directly

JIT spraying

- Can we use a JIT compiler to make our sleds?
- Exploit unaligned execution:
  - Benign but weird high-level code (bitwise ops. with constants)
  - Benign but predictable JITted code
  - Becomes sled + exploit when entered unaligned

JIT spray example

```
25 90 90 90 3c   and $0x3c909090,%eax
25 90 90 90 3c   and $0x3c909090,%eax
25 90 90 90 3c   and $0x3c909090,%eax
25 90 90 90 3c   and $0x3c909090,%eax
```

JIT spray example

```
90               nop
90               nop
90               nop
3c 25            cmp $0x25,%al
90               nop
90               nop
90               nop
3c 25            cmp $0x25,%al
```

Use-after-free

- Low-level memory error of choice in web browsers
- Not as easily audited as buffer overflows
- Can lurk in attacker-controlled corner cases
- JavaScript and Document Object Model (DOM)

Sandboxes and escape

- Chrome NaCl: run untrusted native code with SFI
  - Extra instruction-level checks somewhat like CFI
- Each web page rendered in own, less-trusted process
- But not easy to make sandboxes secure
  - While allowing functionality

Chained bugs in Pwnium 1

- Google-run contest for complete Chrome exploits
  - First edition in spring 2012
- Winner 1: 6 vulnerabilities
- Winner 2: 14 bugs and "missed hardening opportunities"
- Each got $60k, bugs promptly fixed

Next time

- Defensive design and programming
- Make your code less vulnerable the first time