Q: Exploit Hardening Made Easy


CS 6301-001: Language-based Security
Dr. Kevin Hamlen
Attacker’s Dilemma

• Problem Scenario
  – Attack target is a server running some known native code software (e.g., Apache web server).
  – Attacker knows exact software version, but has no physical access or remote privileges.
  – Attacker wishes to “take control” of process (e.g., make it divulge or delete private files).

• Significant assumption: Attacker knows a vulnerability (e.g., buffer overflow bug).
  – Defender doesn’t know it (vulnerability is zero-day) or hasn’t patched it yet.

• How can the attacker leverage this vulnerability to do more than just crash the process?
Anatomy of a Software Hack

• Usually two parts
  – “Exploit” – Maneuver process into executing bug
    • Example: Provide a long input string to overflow the buffer.
    • Let’s assume we already know how to do that part.
  – “Payload” – Leverage bug to convince process to execute attacker-supplied code

• Three kinds of payloads (in order of increasing sophistication):
  – direct code injection
  – jump-to-libc
  – return-oriented programming (ROP)
Code-injection Example

void main(int argc, char *argv[])
{
    char buf[64];
    strcpy(buf, argv[1]);
    ...
    return;
}

lea eax,[ebp-48h]
push eax
call <system>
.data "erase"
.data "*.*"
.data "aaaaa..."
.data "aaaa"
<addr of buf>

8D 45 B8 lea eax,[ebp-48h]
50                    push eax
FF 15 BC 82 2F 01 call <system>
65 72 61 73 65 20 .data "erase"
2A 2E 2A 20          .data "*.*"
61 (x24)             .data "aaaaa..."
61 61 61 61          .data "aaaa"
30 FB 1F 00          <addr of buf>

buf (64 bytes)

saved EBP (4 bytes)
saved EIP (4 bytes)
argv (4 bytes)
argc (4 bytes)
bottom of stack (higher addresses)
top of stack (lower addresses)
Code-injection Example

void main(int argc, char *argv[])
{
    char buf[64];
    strcpy(buf, argv[1]);
    ...
    return;
}

lea eax,[ebp-48h]
push eax
call <system>
.data "erase"
.data "*.*"
.data "aaaaa..."
.data "aaaa"
<addr of buf>

lea eax,[ebp-48h]
push eax
call <system>
 erase *.* aaaaaaaa
 aaaaaaaaaaaaaaaaa

lea eax,[ebp-48h]
push eax
call <system>
<addr of buf>

argv (4 bytes)
argc (4 bytes)
bottom of stack (higher addresses)

8D 45 B8 50 FF 15 BC 82 2F 01 65 72 61 73 65 20 2A 2E 2A 61 (x24) 61 61 61 61 30 FB 1F 00 8D 45 B8 50 FF 15 BC 82 2F 01 65 72 61 73 65 20 2A 2E 2A 61 (x24) 61 61 61 61 30 FB 1F 00
Code-injection Example

void main(int argc, char *argv[]) {
    char buf[64];
    strcpy(buf, argv[1]);
    ... 
    return;
}

lea eax,[ebp-48h]
push eax
call <system>
.data "erase"
.data "*.*"
.data "aaaaaaa..."
.data "aaaa"
<addr of buf>

8D 45 B8 lea eax,[ebp-48h]
50 push eax
FF 15 BC 82 2F 01 call <system>
65 72 61 73 65 20 .data "erase"
2A 2E 2A 20 .data "*.*"
61 (x24) .data "aaaaaaa...
61 61 61 61 .data "aaaa"
30 FB 1F 00 <addr of buf>

bottom of stack (higher addresses)
argc (4 bytes)
argv (4 bytes)
top of stack (lower addresses)

erase *.* aaaaaaaaaaaa
aaaaaaaaaaaaaaaaaaa
aaaaa

<addr of buf>
Code-injection Example

```c
void main(int argc, char *argv[])
{
    char buf[64];
    strcpy(buf, argv[1]);
    ...
    return;
}
```

8D 45 B8              lea eax,[ebp-48h]
50                     push eax
FF 15 BC 82 2F 01      call <system>
65 72 61 73 65 20      .data “erase”
2A 2E 2A 20            .data “*.*”
61 (x24)               .data “aaaaa…”
61 61 61 61            .data “aaaa”
30 FB 1F 00            <addr of buf>

lea eax,[ebp-48h]
push eax
call <system>
```

Erasing...```
Code-injection Example

```c
void main(int argc, char *argv[]) {
    char buf[64];
    strcpy(buf, argv[1]);
    ...
    return;
}
```

```assembly
8D 45 B8                         lea eax,[ebp-48h]
50                                push eax
FF 15 BC 82 2F 01                call <system>
65 72 61 73 65 20                .data “erase”
2A 2E 2A 20                      .data “*. *”
61 (x24)                         .data “aaaaa...”
61 61 61 61                      .data “aaaa”
30 FB 1F 00                      <addr of buf>
```

```assembly
lea eax,[ebp-48h]
push eax
call <system>
erase *. * aaaaaaaa
  aaaaaaaaaaaaaaaaa
```

```
bottom of stack (higher addresses)
<addr of “erase *. * ...”>
<addr of buf>
argv (4 bytes)
aaaa
```
Code-injection Example

void main(int argc, char *argv[])
{
    char buf[64];
    strcpy(buf, argv[1]);
    ...
    return;
}
Defense: W⊕X Pages

• Data Execution Prevention (DEP)
  – disallow writable & executable permission on any one page of process memory
  – stack is writable but non-executable by default
  – now default on most Windows & Linux systems

• Counter-attack
  – don’t insert any code onto the stack
  – jump *directly to existing dangerous code*
    • usually library code, since there are many dangerous things there, and libraries are common to many applications
  – called “jump-to-libc”
Return-to-libc Example

```c
void main(int argc, char *argv[])
{
    char buf[64];
    strcpy(buf, argv[1]);
    ...
    return;
}
```

### Stack Diagram
- **buf (64 bytes)**
- **argv (4 bytes)**
- **argc (4 bytes)**
- **saved EBP (4 bytes)**
- **saved EIP (4 bytes)**

### Memory Contents
- **.data “erase”**
- **.data “*. *”**
- **.data “aaaa...”**
- **.data <system>**
- **.data <buf>**

### Instruction Pointer (EIP)
- **bottom of stack (higher addresses)**
- **top of stack (lower addresses)**
Return-to-libc Example

```c
void main(int argc, char *argv[])
{
    char buf[64];
    strcpy(buf, argv[1]);
    ... 
    return;
}
```
Return-to-libc Example

```c
void main(int argc, char *argv[])
{
    char buf[64];
    strcpy(buf, argv[1]);
    ...
    return;
}
```

```plaintext
data "erase"
data "*.*
.data "aaaa..."
data <system>
data "aaaa..."
data <buf>
```

```
65 72 61 73 65 20 .data "erase"
2A 2E 2A 20 .data "*.*
61 (x58) .data "aaaa..."
BC 82 2F 01 .data <system>
61 (x8) .data "aaaa..."
30 FB 1F 00 .data <buf>
```
Return-to-libc Example

```c
void main(int argc, char *argv[])
{
    char buf[64];
    strcpy(buf, argv[1]);
    ...
    return;
}
```

top of stack (lower addresses)

|       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| erase | erase | erase | erase | erase | erase | erase | erase | erase | erase | erase | erase | erase | erase | erase | erase | erase |
| *.*   | *.*   | *.*   | *.*   | *.*   | *.*   | *.*   | *.*   | *.*   | *.*   | *.*   | *.*   | *.*   | *.*   | *.*   | *.*   | *.*   |
| aaaaa | aaaaa | aaaaa | aaaaa | aaaaa | aaaaa | aaaaa | aaaaa | aaaaa | aaaaa | aaaaa | aaaaa | aaaaa | aaaaa | aaaaa | aaaaa | aaaaa |

65 72 61 73 65 20 .data "erase"
2A 2E 2A 20       .data "*.*  
61 (x58)           .data "aaaa..."
BC 82 2F 01       .data <system>
61 (x8)           .data "aaaa..."
30 FB 1F 00       .data <buf>
Return-to-libc Example

```c
libc::system(char *cmd)
{
    <passes cmd to the shell!>
}
```

```
65 72 61 73 65 20 .data "erase"
2A 2E 2A 20 .data ".*.*"
61 (x58) .data "aaaa..."
BC 82 2F 01 .data <system>
61 (x8) .data "aaaa..."
30 FB 1F 00 .data <buf>
```

```
erase *.*

aaaaaaa...
```

```
addr of <system>
aaaa
aaaa
addr of <buf>
```
Defense: Hide the Libraries

• Address Space Layout Randomization (ASLR)
  – Loader chooses starting address of each library *at load-time* (not compile-time)
  • Libraries already compiled with this capability, so that loader can avoid address space conflicts
  • Note that application main modules do NOT typically have this capability!
  – Tweak the loader to choose the address semi-randomly
  – Result: Attacker cannot reliably predict where libraries are, so cannot reliably jump to any particular code!

• Counter-attack: Return-Oriented Programming
  – Payload jumps to main module code instead of libraries.
  – Challenge: Far less dangerous code there (typically).
  – Can the attacker really do much damage?
Return-Oriented Programming

• Key insight: Exploit the “ret” instruction
  – Semantics of ret: Pop the address atop the stack and jump there.
  – Attacker controls the stack...
  – So attacker can control where ALL ret instructions jump henceforth!

• Can string together ret-ending code fragments already present in the main module to implement an attack payload!
ROP Example

```c
void main(int argc, char *argv[])
{
    char buf[64];
    strcpy(buf, argv[1]);
    ...
    return;
}
```

```
61 72 61 73 65 20 .data “erase ”
2A 2E 2A 20 .data “.*.*”
61 (x58) .data “aaaa…”
BC 82 2F 04 .data <addr1>
61 61 61 61 .data “aaaa”
82 8C 2E 04 .data <addr2>
82 8C 2E 04 .data <addr2>
7F 22 30 04 .data <addr3>
```

Diagram:
- Top of stack (lower addresses)
  - `buf` (64 bytes)
- Bottom of stack (higher addresses)
  - Saved EBP (4 bytes)
  - Saved EIP (4 bytes)
  - `argv` (4 bytes)
  - `argc` (4 bytes)
  - Caller’s stack frame
```
void main(int argc, char *argv[]) {
    char buf[64];
    strcpy(buf, argv[1]);
    ...
    return;
}
```

<table>
<thead>
<tr>
<th>top of stack (lower addresses)</th>
</tr>
</thead>
<tbody>
<tr>
<td>erase .<em>.</em></td>
</tr>
<tr>
<td>aaaaaaaa...</td>
</tr>
<tr>
<td>aaaa</td>
</tr>
<tr>
<td>&lt;addr1&gt;</td>
</tr>
<tr>
<td>aaaa</td>
</tr>
<tr>
<td>&lt;addr2&gt;</td>
</tr>
<tr>
<td>&lt;addr2&gt;</td>
</tr>
<tr>
<td>&lt;addr3&gt;</td>
</tr>
</tbody>
</table>

ROP Example

```
61 72 61 73 65 20 .data "erase"
2A 2E 2A 20 .data ".*.*"
61 (x58) .data "aaaa..."
BC 82 2F 04 .data <addr1>
61 61 61 61 .data "aaaa"
82 8C 2E 04 .data <addr2>
82 8C 2E 04 .data <addr2>
7F 22 30 04 .data <addr3>
```
ROP Example

init_display: ...
< ... 1024 bytes ... >

system: ...

addr2: add eax, 512
ret
...
addr1: mov eax, [init_display]
call eax
pop ebx
ret
...
addr3: call eax
ret

top of stack (lower addresses)
erase *.*
aaaaaaa...

aaaa

<addr1>

aaaa

<addr2>

<addr2>

<addr3>
ROP Example

init_display: ...
< ... 1024 bytes ... >
system: ...

addr2: add eax, 512
ret
...
addr1: mov eax, [init_display]
call eax
pop ebx
ret
...
addr3: call eax
ret

top of stack (lower addresses)
erase *.*
aaaaaaaa...

eax = init_display
init_display: ...

< ... 1024 bytes ... >

system: ...

addr2: add eax, 512
ret

addr1: mov eax, [init_display]
call eax
pop ebx
ret

addr3: call eax
ret

top of stack (lower addresses)

erase *.*
aaaaaaaa...

eax = init_display
ROP Example

init_display: ...

< ... 1024 bytes ... >

system: ...

addr2: add eax, 512
ret

addr1: mov eax, [init_display]
call eax
pop ebx
ret

addr3: call eax
ret

eax = init_display

top of stack (lower addresses)

erase *.*

aaaaaaa...

aaaa

<addr1+5>

aaaa

<addr2>

<addr2>

<addr3>
ROP Example

init_display: ...
< ... 1024 bytes ... >
system: ...

addr2: add eax, 512
ret
...
addr1: mov eax, [init_display]
call eax
call eax
pop ebx
ret
...
addr3: call eax
ret
eax = init_display

top of stack (lower addresses)
erase *.*
aaaaaaa...

aaaa
<addr1+5>
aaaa
<addr2>
<addr2>
<addr3>
ROP Example

init_display: ...
< ... 1024 bytes ... >
system: ...

addr2: add eax, 512
ret
...
addr1: mov eax, [init_display]
call eax
pop ebx
ret
...
addr3: call eax
ret

eax = init_display

top of stack (lower addresses)
erase *.*
aaaaaaaa...

aaaa

<addr1+5>
aaaa

<addr2>
<addr2>
<addr3>
**ROP Example**

<table>
<thead>
<tr>
<th>init_display: ...</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; ... 1024 bytes ... &gt;</td>
</tr>
<tr>
<td>system: ...</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>addr2: add eax, 512</th>
</tr>
</thead>
<tbody>
<tr>
<td>ret</td>
</tr>
<tr>
<td>...</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>addr1: mov eax, [init_display]</th>
</tr>
</thead>
<tbody>
<tr>
<td>call eax</td>
</tr>
<tr>
<td>pop ebx</td>
</tr>
<tr>
<td>ret</td>
</tr>
<tr>
<td>...</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>addr3: call eax</th>
</tr>
</thead>
<tbody>
<tr>
<td>ret</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>top of stack (lower addresses)</th>
</tr>
</thead>
<tbody>
<tr>
<td>erase <em>.</em> *</td>
</tr>
<tr>
<td>aaaaaaaa...</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>eax = init_display + 512</th>
</tr>
</thead>
</table>

```
eax = init_display + 512
```

```
init_display: ...
< ... 1024 bytes ... >
system: ...
```

```
addr2: add eax, 512
ret
...
```

```
addr1: mov eax, [init_display]
call eax
pop ebx
ret
...
```

```
addr3: call eax
ret
```
ROP Example

init_display: ...
< ... 1024 bytes ... >
system: ...

addr2:  
...  
add eax, 512  
ret  
...  

addr1:  
mov eax, [init_display]  
call eax  
call eax  
pop ebx  
ret  
...  

addr3:  
call eax  
ret  

eax = init_display+512  

top of stack (lower addresses)

erase *.*  
aaaaaaaa...  

aaaa  
<addr1+5>  
aaaa  
<addr2>  
<addr2>  
<addr3>
ROP Example

init_display: ...
< ... 1024 bytes ... >
system: ...

addr2: add eax, 512
ret
... 
addr1: mov eax, [init_display]
call eax
call eax
pop ebx
ret
... 
addr3: call eax
ret

eax = init_display+1024 = system !!!
top of stack (lower addresses)

erase *.*
aaaaaaa...

<addr1+5>
aaaa
<addr2>
<addr2>
<addr3>
ROP Example

init_display: ...
< ... 1024 bytes ... >

system: ...

addr2: add eax, 512
ret
...

addr1: mov eax, [init_display]
call eax
pop ebx
ret
...

addr3: call eax
ret

eax = init_display+1024 = system !!!

top of stack (lower addresses)
erase *.*

aaaa

<addr1+5>

aaaa

<addr2>

<addr2>

<addr3>
### ROP Example

```
addr1: mov eax, [init_display]
call eax
pop ebx
ret
```

```
addr2: add eax, 512
ret
```

```
addr3: call eax
ret
```

```
init_display: ...
< ... 1024 bytes ... >
system: ...
```

```
eax = init_display+1024 = system !!!
```

<table>
<thead>
<tr>
<th>top of stack (lower addresses)</th>
</tr>
</thead>
<tbody>
<tr>
<td>erase <em>.</em></td>
</tr>
<tr>
<td>aaaaaaaaa...</td>
</tr>
<tr>
<td>aaaaa</td>
</tr>
<tr>
<td>&lt;addr1+5&gt;</td>
</tr>
<tr>
<td>aaaaa</td>
</tr>
<tr>
<td>&lt;addr2&gt;</td>
</tr>
<tr>
<td>&lt;addr2&gt;</td>
</tr>
<tr>
<td>&lt;addr3&gt;</td>
</tr>
</tbody>
</table>
ROP Attack Surface

• Gadgets: Every `ret`-ending byte sequence at a known location is available to attacker
  – Gadgets need not be intended, reachable code! Any bytes will do!
  – Can string gadgets together in any sequence
  – Can encode loops (because gadgets can push new addresses)

• Research questions:
  – What payloads are possible from gadget-sequencing?
  – Given a victim program and desired payload, is there a way to systematically discover a gadget-implementation?
Q: An ROP Payload Compiler

Figure 2: An overview of Q’s design.
Q Stages

• Gadget Discovery
  – find gadgets of various “types” in victim program

• Gadget Arrangement
  – infer general gadget sequences that suffice to implement payload
  – not all inferred sequences may be present in victim

• Gadget Assignment
  – match discovered gadgets to inferred arrangements

• Payload Printing
  – output a complete, working assignment
  – usable as malicious input to victim program
Gadget “Types”

<table>
<thead>
<tr>
<th>Name</th>
<th>Input</th>
<th>Parameters</th>
<th>Semantic Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>NoOpG</td>
<td>—</td>
<td>—</td>
<td>Does not change memory or registers</td>
</tr>
<tr>
<td>JumpG</td>
<td>AddrReg</td>
<td>Offset</td>
<td>EIP ← AddrReg + Offset</td>
</tr>
<tr>
<td>MoveRegG</td>
<td>InReg, OutReg</td>
<td>—</td>
<td>OutReg ← InReg</td>
</tr>
<tr>
<td>LoadConstG</td>
<td>OutReg, Value</td>
<td>—</td>
<td>OutReg ← Value</td>
</tr>
<tr>
<td>ArithmeticG</td>
<td>InReg1, InReg2, OutReg</td>
<td>◊_b</td>
<td>OutReg ← InReg1 ◊_b InReg2</td>
</tr>
<tr>
<td>LoadMemG</td>
<td>AddrReg, OutReg</td>
<td># Bytes, Offset</td>
<td>OutReg ← M[AddrReg + Offset]</td>
</tr>
<tr>
<td>StoreMemG</td>
<td>AddrReg, InReg</td>
<td># Bytes, Offset</td>
<td>M[AddrReg + Offset] ← InReg</td>
</tr>
<tr>
<td>ArithmeticLoadG</td>
<td>OutReg, AddrReg</td>
<td># Bytes, Offset, ◊_b</td>
<td>OutReg ◊_b ← M[AddrReg + Offset]</td>
</tr>
<tr>
<td>ArithmeticStoreG</td>
<td>InReg, AddrReg</td>
<td># Bytes, Offset, ◊_b</td>
<td>M[AddrReg + Offset] ◊_b ← InReg</td>
</tr>
</tbody>
</table>

- **Challenge:** Given an arbitrary gadget, how to infer its “type” from the table above?
- **Open Research Question:** Is there a better list of “types”? Why just these “types”?
Weakest Precondition

• Hoare Logic:
  – Notation “[A]C[B]” means “If the program state satisfies A, then code C eventually terminates in a program state satisfying B.
  – Example: [x=3 ∧ y=1] x:=x+y [x=4 ∧ y=1]
  – Example: [x=y] x:=x+y [x=2y]
  – Example: [true] x:=3 [x=3]
  – A = “precondition” and B = “postcondition”

• Weakest Precondition [Dijkstra, CACM’75]
  – For any C and B, there are many A satisfying [A]C[B].
  – Weakest possible precondition is “true” (no assumptions)
WP and Gadget Discovery

• Weakest Precondition Algorithm
  – known, easy algorithm for non-looping instructions
  – Example: [?] mov r1, r2 [r1=7]
    • A = “r2=7”
  – Generalized: [?] mov r1, r2 [B]
    • A = substitute “r2” for all “r1” in B

• Each gadget “type” is really a post-condition
  – MovRegG: r1=r2
  – [?] mov r1, r2 [r1=r2]
    • A = “r2=r2” = true

• Strategy: Gadget C has type B if WP(C,B)=true
More Nifty Science in Q

• Gadget arrangement based on *every-munch* (a take-all version of *maximal munch*)

• Various tricky register allocation problems
  – register clobbering avoidance
  – register matching

• Basically a full compiler for a very weird instruction set that it has to learn each time!
• With just 20KB of code to mine, Q is 80% successful at finding ROP payloads
• Others have found that at least 33% of all binaries contain Turing-complete gadget sets!
Next Time

• Some embarrassing failures of diversity- and obfuscation-based defenses