The Hardware/Software Interface

x86-64 Programming III

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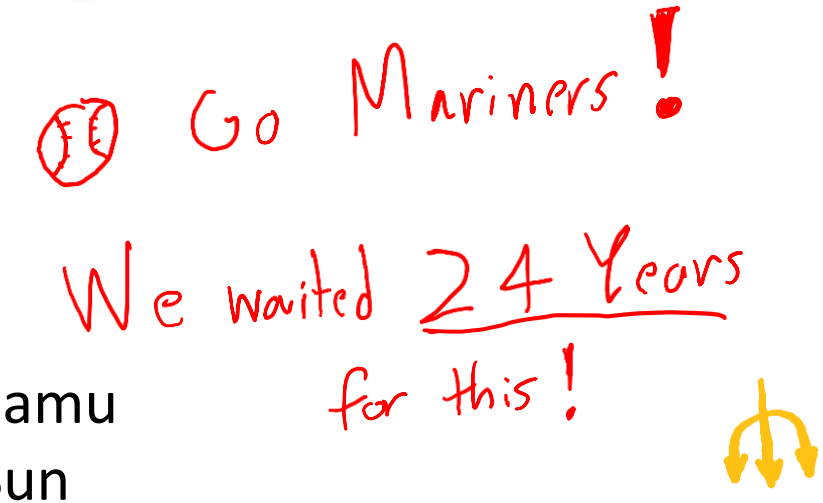
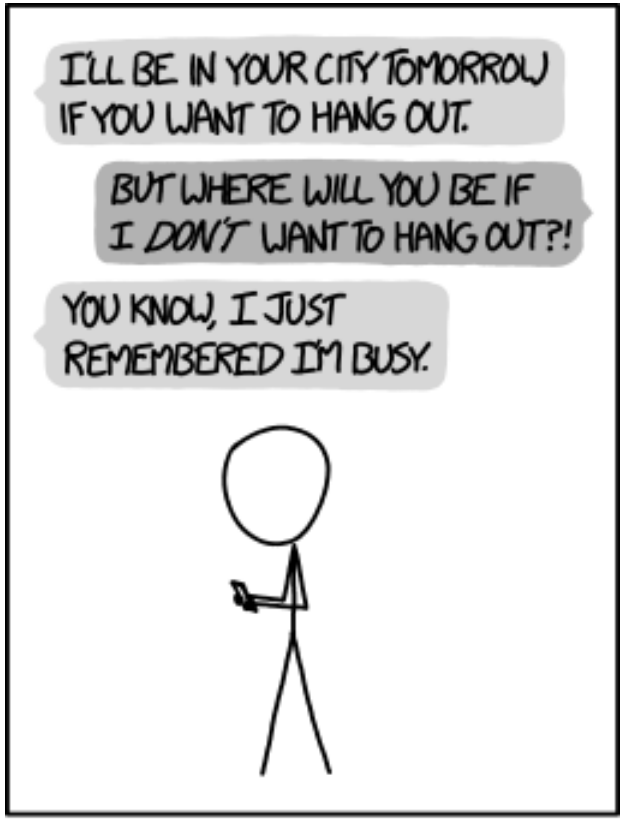




WHY I TRY NOT TO BE PEDANTIC ABOUT CONDITIONALS.

http://xkcd.com/1652/

Relevant Course Information

- Lab submissions that fail the autograder get a **ZERO**
  - No excuses – make full use of tools & Gradescope's interface
  - Leeway on Lab 1a won't be given moving forward

- Lab 2 (x86-64) released Wednesday
  - Learn to trace x86-64 assembly and use GDB

- Midterm is in two weeks (10/27, 5:30pm, location dependent on section)
  - No lecture that day
  - You will be provided a fresh midterm reference sheet
    - Study and use this NOW so you are comfortable with it when the exam comes around
  - Form study groups and look at past exams!

Lab Extra Credit

- Lab 2 and several other labs have "extra credit"
  - These are meant to be fun extensions to the labs – you are not expected to attempt these extra components

- Extra credit points *don't* affect your lab grades
  - From the course policies: "These will be accumulated over the course and may be used to bump up borderline grades at the end of the quarter at the discretion of the instructor(s)."
  - Make sure you finish the rest of the lab before attempting any extra credit

Lecture Outline (1/4)

- **Control Flow**
- Condition Codes
- Conditionals
- Instruction Set Philosophies, Revisited

Control Flow (1/2)

```
long max(long x, long y) {
  long max;
  if (x > y) {
    max = x;
  } else {
    max = y;
  }
  return max;
}
```

```
max:
   ???
   movq    %rdi, %rax  # if case
   ???
   ???
   movq    %rsi, %rax  # else case
   ???
   ret
```

Variable	Register
x	%rdi
y	%rsi
return value	%rax

Control Flow (2/2)

```
long max(long x, long y) {
  long max;
  if (x > y) {
    max = x;
  } else {
    max = y;
  }
  return max;
}
```

Conditional jump

Unconditional jump

```
max:
  if x <= y then jump to else
  movq    %rdi, %rax
  jump to done
else:
  movq    %rsi, %rax
done:
  ret
```

if TRUE

if FALSE

Variable	Register
x	%rdi
y	%rsi
return value	%rax

Conditionals and Control Flow

- **Conditional jump:** Jump to somewhere else if some *condition* is true, otherwise execute next instruction
- **Unconditional jump:** *Always* jump when you get to this instruction

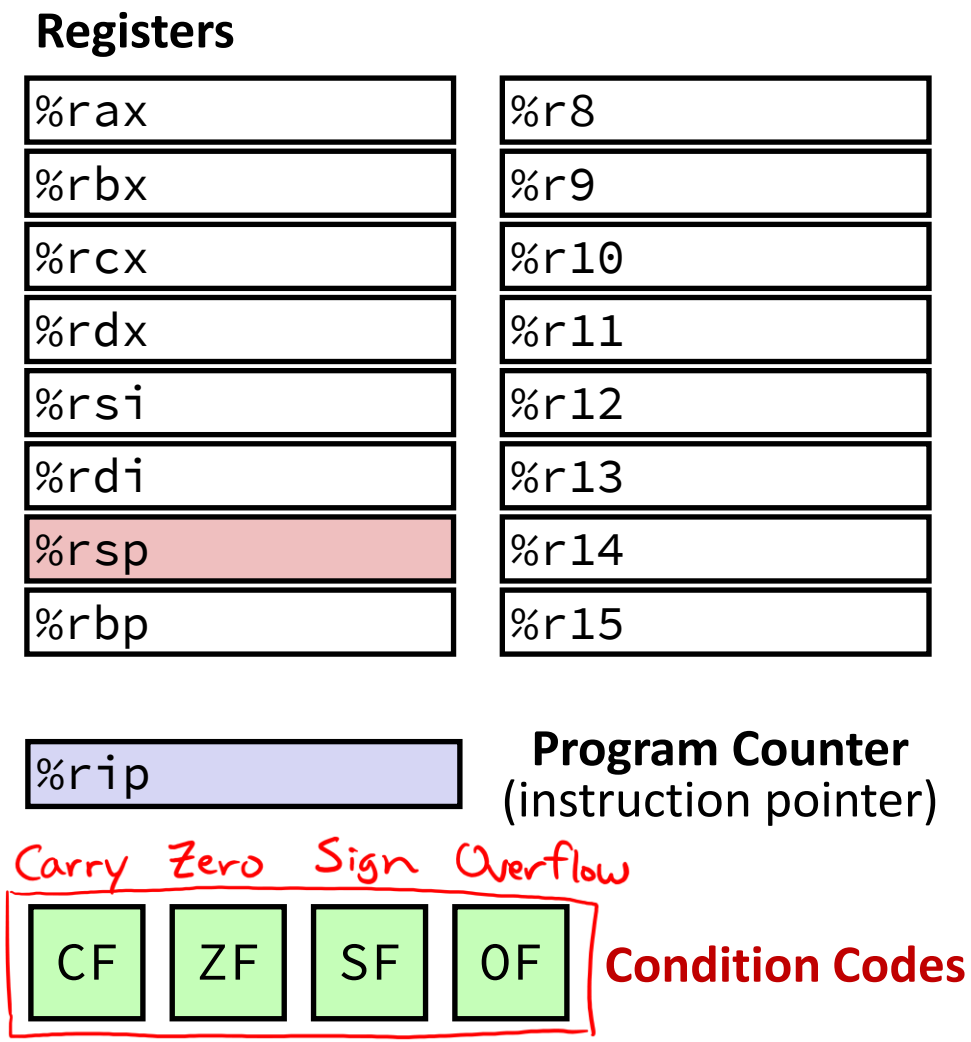
- With just these two types of jumps, we can implement most control flow constructs in higher-level languages:
  - **`if`** (*condition*) **`then`** {…} **`else`** {…}
  - **`while`** (*condition*) {…}
  - **`do`** {…} **`while`** (*condition*)
  - **`for`** (*initialization*; *condition*; *iterative*) {…}
  - **`switch`** {…}

Lecture Outline (2/4)

- Control Flow
- **Condition Codes**
- Conditionals
- Instruction Set Philosophies, Revisited

Processor State (x86-64, partial)

- Information about currently executing program
  - Temporary data (`%rax`, …)
  - Location of runtime stack (`%rsp`)
  - Location of current code control point (`%rip`, …)
  - Status of recent tests (**`CF`**, **`ZF`**, **`SF`**, **`OF`**)
    - Single bit registers:



Condition Codes (Review)

- Condition codes are set based on the result of the *previous* instruction(s)
  - These are automatically updated by your CPU as instructions are executed
  - Some instructions don't affect the condition codes (*e.g.*, `mov`, `ret`, `lea`)

- **Carry:** `CF=1` if result had *unsigned* overflow
- **Zero:** `ZF=1` if result was 0
- **Sign:** `SF=1` if result was negative (*i.e.*, same as sign bit)
- **Overflow:** `OF=1` if result had *signed* overflow

Implicit Setting (Review)

- *Implicitly* set by **arithmetic** and **logical** operations as side effect
  - Notable exception: `lea` (beware! 🙄)

- Example: `%al=0x80`, execute **addb** `%al, %al`

compute: 0b 1000 0000
+ 0b 1000 0000
---
1 0000 0000

stores 0x00 in %al ⟹

CF = 1 (carry out from MSB)
ZF = 1 (== 0)
SF = 0 (non-negative)
OF = 1 (⊖ + ⊖ = ⊕)

CF	*Carry Flag*	ZF	*Zero Flag*	SF	*Sign Flag*	OF	*Overflow Flag*

Explicit Setting (Review)

- *Explicitly* set by **`cmp`** and **`test`**, whose purposes are to change the condition codes *without storing their results*
  - `cmp` is equivalent result to `sub` (`-`); `test` is equivalent result to `and` (`&`)

- Example: `%al=0x83` and `%bl=0x8C`, execute **`testb`** `%al, %bl`

compute: 0b 1000 0011
& 0b 1000 1100
1000 0000

result is 0x80,
but %bl is unchanged!

⇒

CF = 0 (no carry out)
ZF = 0 (!= 0)
SF = 1 (MSB is 1)
OF = 0 (no overflow)

CF	*Carry Flag*	ZF	*Zero Flag*	SF	*Sign Flag*	OF	*Overflow Flag*

Lecture Outline (3/4)

- Control Flow
- Condition Codes
- **Conditionals**
- Instruction Set Philosophies, Revisited

Jump and Set Families (Review)

- `j* target`
  - Jumps to ***target*** (an address) based on condition codes

- `set* dst`
  - Set low-order byte of `dst` to 0x00 or 0x01 based on condition codes and does not alter remaining 7 bytes

- Typically come as the second in a pair of instructions:
  1) Set the condition codes
  2) Uses the condition codes to do something

Instruction Condition Table (Review)

- `j*/set*` Instructions – focus on description, not formula

don't worry about the details

Jump Instr	Set Instr	Condition	Description
jmp *target*	*n/a*	1	Unconditional
je *target*	**sete** *dst*	ZF	Equal to 0
jne *target*	**setne** *dst*	~ZF	Not Equal to 0
js *target*	**sets** *dst*	SF	Signed/Negative
jns *target*	**setns** *dst*	~SF	Not Signed/Nonnegative
jg *target*	**setg** *dst*	~(SF^OF)&~ZF	Greater Than 0 (Signed)
jge *target*	**setge** *dst*	~(SF^OF)	Greater Than or Equal to 0 (Signed)
jl *target*	**setl** *dst*	(SF^OF)	Less Than 0 (Signed)
jle *target*	**setle** *dst*	(SF^OF)|ZF	Less Than or Equal to 0 (Signed)
ja *target*	**seta** *dst*	~CF&~ZF	Above 0 (unsigned “>”)
jb *target*	**setb** *dst*	CF	Below 0 (unsigned “<“)

Choosing Instruction Pairs

- Find correct form of condition in table, use corresponding instrs
  - Instruction #1 = chosen operation, Instruction #2 = row heading
  - Recall: `cmp` performs `sub`
    `test` performs `and`

- Examples:
  - `x >= y` →
    ```
    x - y >= 0
    ```
    →
    ```
    cmp y, x
    jge target
    ```
  - `x == 3` →
    ```
    x - 3 == 0
    ```
    ```
    cmp 3, x
    je target
    ```
  - `x` →
    ```
    x & x != 0
    ```
    ```
    test x, x
    jne target
    ```

		(op) s, d
je /sete	"Equal"	d (op) s == 0
jne/setne	"Not equal"	d (op) s != 0
js /sets	"Signed" (negative)	d (op) s < 0
jns/setns	"Not signed" (nonnegative)	d (op) s >= 0
jg /setg	"Greater"	d (op) s > 0
jge/setge	"Greater or equal"	d (op) s >= 0
jl /setl	"Less"	d (op) s < 0
jle/setle	"Less or equal"	d (op) s <= 0
ja /seta	"Above" (unsigned >)	d (op) s > 0U
jb /setb	"Below" (unsigned <)	d (op) s < 0U

Set Example

```
int gt(long x, long y) {
  return x > y;
}
```

x - y > 0

Variable	Register
x	%rdi
y	%rsi
return value	%rax

cmp y, x → cmp %rsi, %rdi

set g ___ → setg %al

```
cmpq    %rsi, %rdi   # set flags on x - y
setg    %al          # %al = (x-y>0)
movzbl  %al, %eax    # %rax = (x>y)
ret
```

- %al is lowest byte of %rax
- Uses movz to finish job, since set* only changes lowest byte of register

Labels (Review)

```
swap:
    movq   (%rdi), %rax
    movq   (%rsi), %rdx
    movq   %rdx, (%rdi)
    movq   %rax, (%rsi)
    ret
```

```
max:
    movq %rdi, %rax
    cmpq %rsi, %rdi
    jg   done
    movq %rsi, %rax
done:
    ret
```

- A jump changes the program counter (`%rip`)
  - `%rip` tells the CPU the *address* of the next instruction to execute
- **Labels** give us a way to refer to a specific instruction in our assembly/machine code
  - Associated with the *next* instruction found in the assembly code (ignores whitespace)
  - Each ***use*** of the label will eventually be replaced with something that indicates the final address of the instruction that it is associated with

Jump Example (Writing)

```
if (x < 3) {
  return 1;
}
return 2;
```

do this if x ≥ 3

Variable	Register
x	%rdi
return value	%rax

```
  cmpq $3, %rdi
  jge T2
T1:  # x < 3
  movq $1, %rax
  ret
T2:  # !(x < 3)
  movq $2, %rax
  ret
```

(if)

(else)

		① cmp a, b (3, x)	test a, b
je	"Equal"	b-a == 0	b&a == 0
jne	"Not equal"	b-a != 0	b&a != 0
js	"Signed" (negative)	b-a < 0	b&a < 0
jns	"Not signed" (nonnegative)	b-a >= 0	b&a >= 0
jg	"Greater"	b-a > 0	b&a > 0
② **jge**	"Greater or equal"	b-a >= 0 (x ≥ 3)	b&a >= 0
jl	"Less"	b-a < 0	b&a < 0
jle	"Less or equal"	b-a < 0	b&a <= 0
ja	"Above" (unsigned >)	b $>_U$ a	b&a > 0U
jb	"Below" (unsigned <)	b $<_U$ a	b&a < 0U

Jump Example (Reading)

```
mystery:
        movl    %edi, %eax      # ret = x
        testl   %edi, %edi      # x & x
        js      .L3             # jump if x < 0
.L2:    ret
.L3:    negl    %eax            # negate x
        jmp     .L2
```

Variable	Register
x	%edi
return value	%eax

```
int mystery(int x) {
  if ( x < 0 ) {
    return -x;
  } else {
    return x;
  }
}
```

		cmp a, b	test a, b
je	"Equal"	b-a == 0	b&a == 0
jne	"Not equal"	b-a != 0	b&a != 0
js	"Signed" (negative)	b-a < 0	b&a < 0
jns	"Not signed" (nonnegative)	b-a >= 0	b&a >= 0
jg	"Greater"	b-a > 0	b&a > 0
jge	"Greater or equal"	b-a >= 0	b&a >= 0
jl	"Less"	b-a < 0	b&a < 0
jle	"Less or equal"	b-a < 0	b&a <= 0
ja	"Above" (unsigned >)	b $>_U$ a	b&a > 0U
jb	"Below" (unsigned <)	b $<_U$ a	b&a < 0U

Polling Question

Register	Use(s)
%rdi	1st argument (x)
%rsi	2nd argument (y)
%rax	return value

```
long absdiff(long x, long y) {
  long result;
  if (x > y)
    result = x-y;
  else
    result = y-x;
  return result;
}
```

A.
```
cmpq   %rsi, %rdi
jle    .L4
```
x-y

B.
```
cmpq   %rsi, %rdi
jg     .L4
```
x-y

C.
```
testq  %rsi, %rdi
jle    .L4
```
x&y

D.
```
testq  %rsi, %rdi
jg     .L4
```
x&y

```
absdiff:
    ____________________
    ____________________
                          # x > y:
    movq    %rdi, %rax
    subq    %rsi, %rax
    ret
.L4:                      # x <= y:
    movq    %rsi, %rax    x-y <= 0
    subq    %rdi, %rax
    ret
```
less than or equal to (le)

Lecture Outline (4/4)

- Control Flow
- Condition Codes
- Conditionals
- **Instruction Set Philosophies, Revisited**

Instruction Set Philosophies, Revisited

- *Complex Instruction Set Computing* (CISC):
  Add more and more elaborate and specialized instructions as needed
  - **Design goals:** complete tasks in as few instructions as possible; minimize memory accesses for instructions

- *Reduced Instruction Set Computing* (RISC):
  Keep instruction set small and regular
  - **Design goals:** build fast hardware; instructions should complete in few clock cycles (ideally 1); minimize complexity and maximize performance

- How different are these two philosophies, really?

Instruction Set Philosophies, Revisited

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- *Reduced Instruction Set Computing* (RISC):
  Keep instruction set small and regular
  - **Design goals:** build fast hardware; instructions should complete in few clock cycles (ideally 1); minimize complexity and maximize performance

- How different are these two philosophies, really?
  - Both pursue **efficiency** (**minimalism** is a means to an end)

Mainstream ISAs, Revisited

x86	
Designer	Intel, AMD
Bits	16-bit, 32-bit and 64-bit
Introduced	1978 (16-bit), 1985 (32-bit), 2003 (64-bit)
Design	CISC
Type	Register–memory
Encoding	Variable (1 to 15 bytes)
Branching	Condition code
Endianness	Little

ARM	
Introduced	1985
Encoding	AArch64/A64 and AArch32/A32 use 32-bit instructions, T32 (Thumb-2)

RISC-V	
Designer	University of California, Berkeley
Bits	32 · 64 · 128
Introduced	2010
Design	RISC
Type	Load-store
Encoding	Variable
Endianness	Little[1][3]

Does anything feel "off" about this landscape?

Windows desktop/laptops
(Core i3, i5, i7, Ryzen)
x86-64 Instruction Set

Smartphone-like devices
(iPhone, Android, Raspberry Pi)
Apple products (ca. 2020-)
(Macbook, Mac Mini)
ARM Instruction Set

Mostly research
(some traction in embedded)
RISC-V Instruction Set

Tech Monopolization (Oligopolization)

- How many “dominant” ISAs are there?
  - 2: x86, ARM
- How many “dominant” phone brands are there?
  - 3: Samsung, Apple, Xiaomi
- How many “dominant” operating systems are there?
  - 3-ish: Windows, iOS/macOS, Android/Linux
- How many “dominant” chip manufacturers are there?
  - 3: TSMC, Samsung, Intel

- It wasn’t always this way!
  - Combination of antitrust policies and (lack of) enforcement

Discussion Questions

- Discuss the following question(s) in groups of 3-4 students
  - I will call on a few groups afterwards so please be prepared to share out
  - Be respectful of others' opinions and experiences

- How do you feel about tech oligopolization?
  - What are the benefits and disadvantages of this landscape for (1) the dominant companies and (2) the consumers?

  - These big tech companies are now worth billions of dollars. What might we try if we wanted to break up the oligopolization?

Summary (1/2)

- Control flow in x86 determined by Condition Codes
  - Showed **C**arry, **Z**ero, **S**ign, and **O**verflow, though others exist
  - Set flags with arithmetic & logical instructions (implicit) or Compare/Test (explicit)
  - **Set instructions** (`set*`) read out flag values (0/1)
  - **Jump instructions** (`j*`) use flag values to determine next instruction to execute
  - Result of 1st instruction gets compared against 0 in a way determined by 2nd instruction:

			`(op) s, d`	`cmp a, b`	`test a, b`
je	**sete**	"Equal"	`d (op) s == 0`	`b-a == 0`	`b&a == 0`
jne	**setne**	"Not equal"	`d (op) s != 0`	`b-a != 0`	`b&a != 0`
js	**sets**	"Signed" (negative)	`d (op) s < 0`	`b-a < 0`	`b&a < 0`
jns	**setns**	"Not signed" (nonnegative)	`d (op) s >= 0`	`b-a >= 0`	`b&a >= 0`
jg	**setg**	"Greater"	`d (op) s > 0`	`b-a > 0`	`b&a > 0`
jge	**setge**	"Greater or equal"	`d (op) s >= 0`	`b-a >= 0`	`b&a >= 0`
jl	**setl**	"Less"	`d (op) s < 0`	`b-a < 0`	`b&a < 0`
jle	**setle**	"Less or equal"	`d (op) s <= 0`	`b-a < 0`	`b&a <= 0`
ja	**seta**	"Above" (unsigned >)	`d (op) s > 0U`	$b >_U a$	`b&a > 0U`
jb	**setb**	"Below" (unsigned <)	`d (op) s < 0U`	$b <_U a$	`b&a < 0U`

Summary (2/2)

- **Labels** (*e.g.*, `main`, `.L0`) refer to an instruction address and used as jump targets in assembly

Bonus: Compound Conditional Example

```
if (x < 3 && x == y) {
  return 1;
} else {
  return 2;
}
```

```
  cmpq  $2, %rdi
  setle %dl
  cmpq  %rsi, %rdi
  sete  %al
  testb %al, %dl
  je    T2
T1: # x <= 2 && x == y:
  movl  $1, %eax
  ret
T2: # else
  movl  $2, %eax
  ret
```

Variable	Register
x	%rdi
y	%rsi
return value	%rax

		cmp a, b	test a, b
je	"Equal"	b-a == 0	b&a == 0
jne	"Not equal"	b-a != 0	b&a != 0
js	"Signed" (negative)	b-a < 0	b&a < 0
jns	"Not signed" (nonnegative)	b-a >= 0	b&a >= 0
jg	"Greater"	b-a > 0	b&a > 0
jge	"Greater or equal"	b-a >= 0	b&a >= 0
jl	"Less"	b-a < 0	b&a < 0
jle	"Less or equal"	b-a < 0	b&a <= 0
ja	"Above" (unsigned >)	$b >_U a$	b&a > 0U
jb	"Below" (unsigned <)	$b <_U a$	b&a < 0U