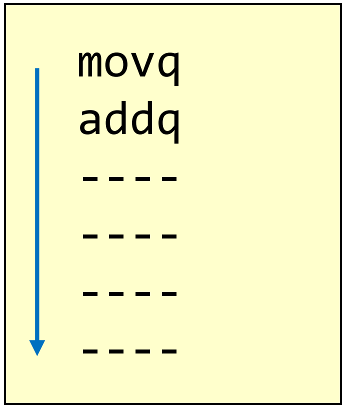
CS356 Unit 5

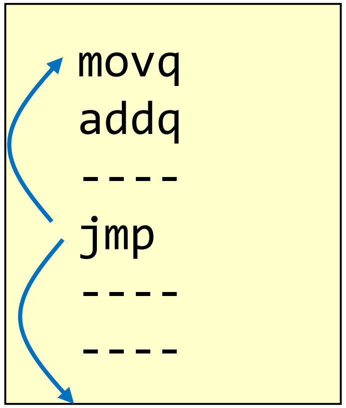
x86 Control Flow

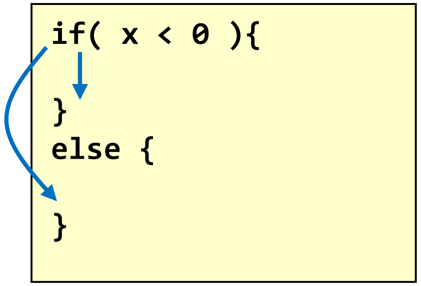
JUMP/BRANCHING OVERVIEW

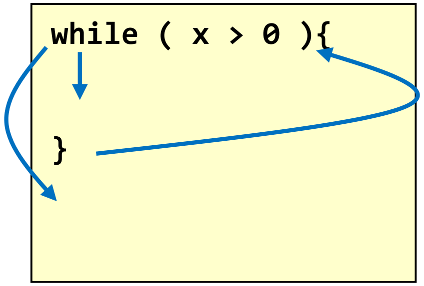
Concept of Jumps/Branches

- Assembly is executed in sequential order by default
- Jump instruction (aka "branches") cause execution to skip ahead or back to some other location
- Jumps are used to implement control structures like if statements & loops



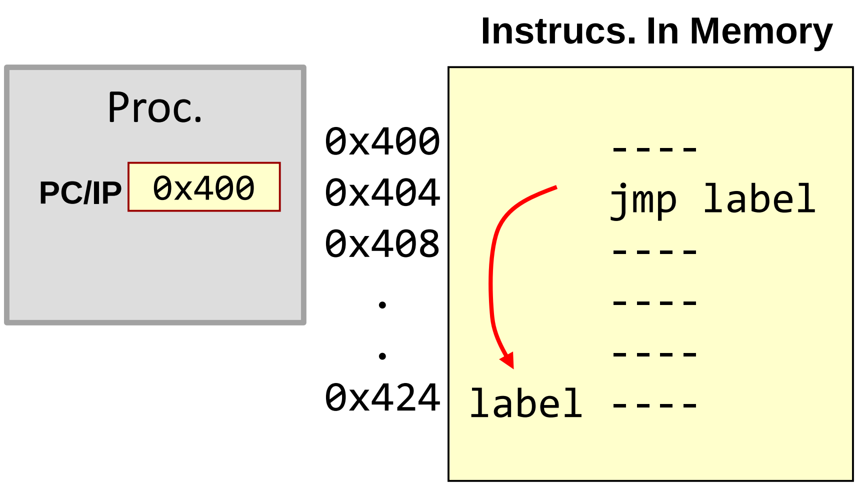




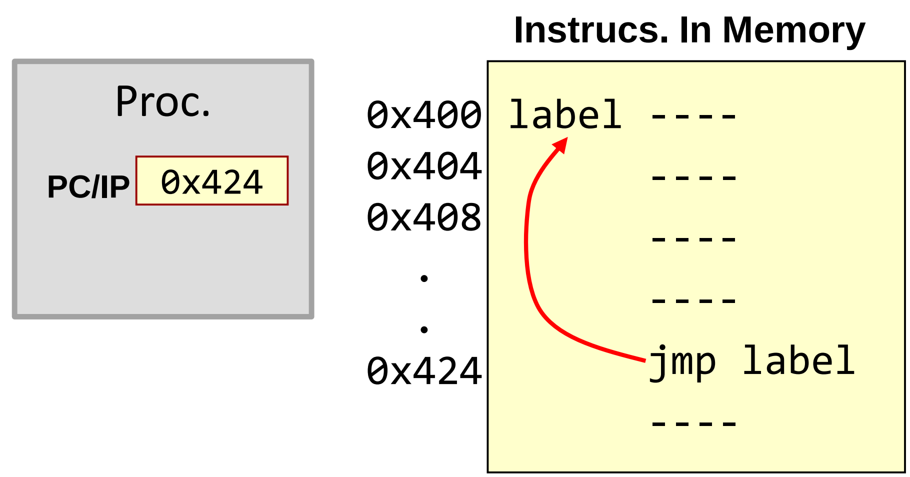


Jump/Branch Instructions

- Jump (aka "branch") instructions allow us to jump backward or forward in our code
- How? By manipulating the Program Counter (PC)
- Operation: PC = PC + displacement
  - Compiler/programmer specifies a "label" for the instruction to branch to; then the assembler will determine the displacement



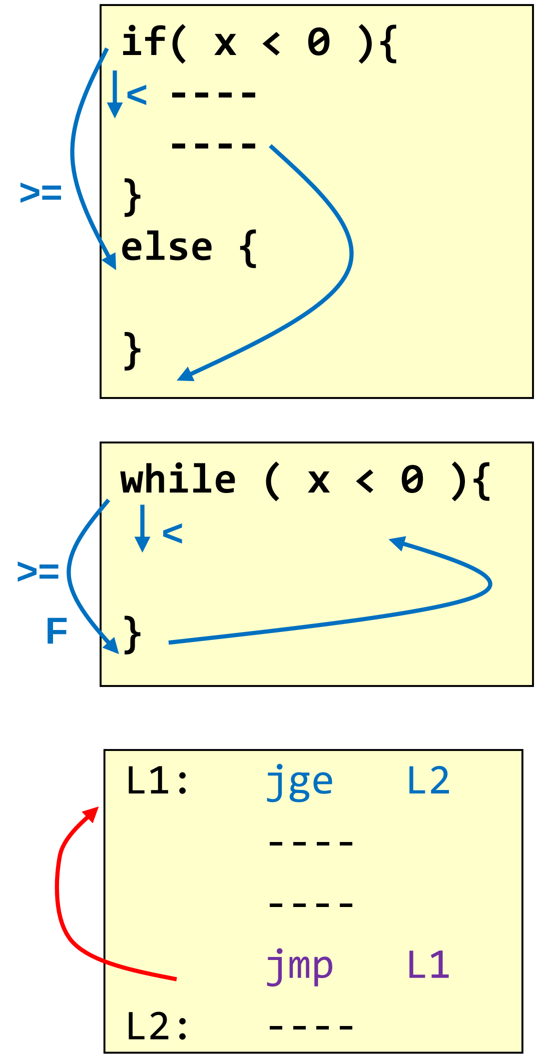
Jump Forward => Conditional



Jump Back => Loop

Conditional vs. Unconditional Jumps

- Two kinds of jumps/branches
- Conditional
  - Jump only if a condition is true, otherwise continue sequentially
  - x86 instructions: `je, jne, jge, …` (see next slides)
  - **Need a way to compare and check conditions**
  - Needed for if, while, for
- Unconditional
  - Always jump to a new location
  - x86 instruction: `jmp label`



x86 View

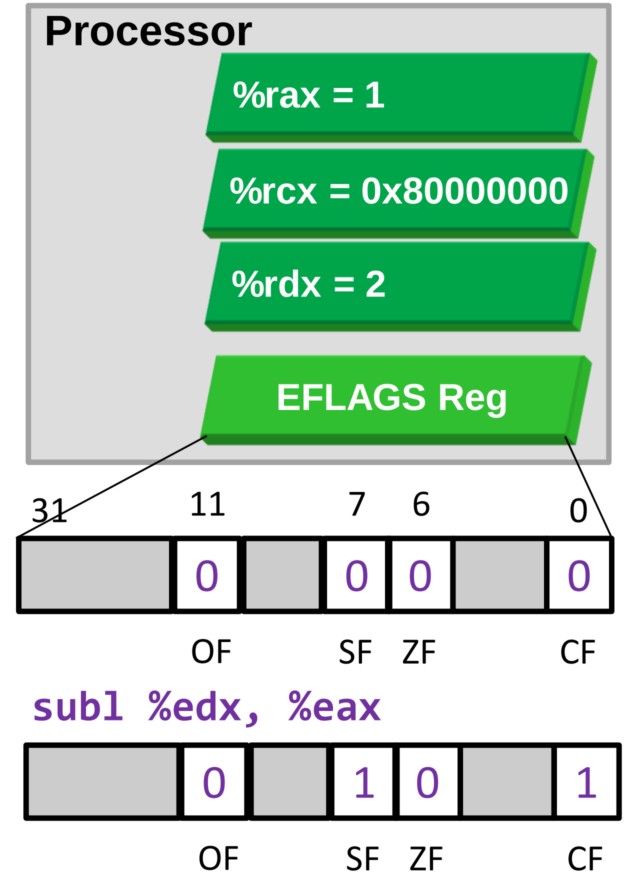
Condition Codes

MAKING A DECISION

Condition Codes (Flags)

CS:APP 3.6.1

- The processor hardware performs several tests on the result of most instructions
- Each test generates a True/False (1 or 0) outcome which are recorded in various bits of the FLAGS register in the process
- The tests and associated bits are:
  - SF = Sign Flag
    - Tests if the result is negative (just a copy of the MSB of the result of the instruction)
  - ZF = Zero Flag
    - Tests if the result is equal to 0
  - OF = 2's complement Overflow Flag
    - Set if signed overflow has occurred
  - CF = ~~Carry Flag~~ Unsigned Overflow
    - Not just the carry-out; 1 if unsigned overflow
    - Unsigned Overflow: if (ADD and Cout=1) or (SUB and Cout=0)



`cmp` and `test` Instructions

- `cmp[bwql] src1, src2`
  - Compares src2 to src1 (e.g. `src2 < src1`, `src2 == src1`)
  - Performs (`src2 - src1`) **and sets the condition codes** based on the result
  - src1 & src2 is not changed (subtraction result is only used for condition codes and then discarded)
- `test[bwql] src1, src2`
  - Performs (`src1 & src2`) **and sets condition codes**
  - src2 is not changed
  - Often used with the src1 = src2 (i.e. `test %eax, %eax`) to check if a value is 0 or negative

Condition Code Exercises

Processor Registers

0000 0000 0000 0001	rax
0000 0000 0000 0000	rbx
0000 0000 0000 8801	rcx
0000 0000 0000 0002	rdx

EFLAGS Reg

31	11		7	6		0
	?		?	?		?
	OF		SF	ZF		CF

– addl $0x7fffffff,%rdx

0000 0000 8000 0001 rdx

OF	SF	ZF	CF
1	1	0	0

– andb %al, %bl

0000 0000 0000 0000 rbx

OF	SF	ZF	CF
0	0	1	0

– addb $0xff, %al

0000 0000 0000 0000 rax

OF	SF	ZF	CF
0	0	1	1

– cmpw $0x7000, %cx

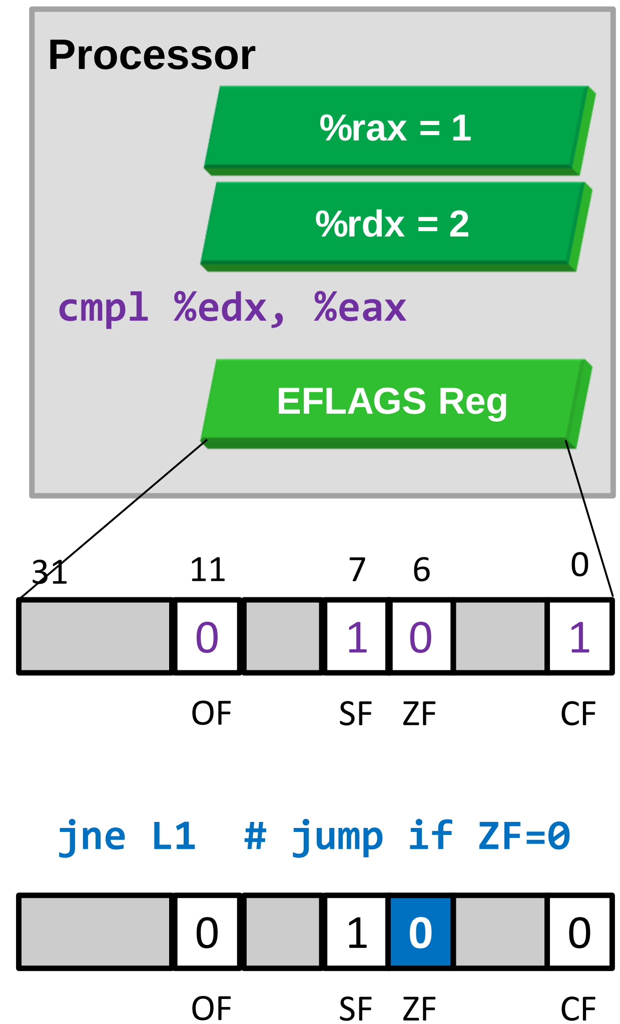
0000 0000 0000 1801 result

0000 0000 0000 8801 rcx

OF	SF	ZF	CF
1	0	0	0

Conditional Branches

- Comparison in x86 is *usually* a 2-step (2-instruction) process
- Step 1:
  - Execute an instruction that will compare or examine the data (e.g. cmp, test, etc.)
  - Results of comparison will be saved in the EFLAGS register via the condition codes
- Step 2:
  - Use a conditional jump (je, jne, jl, etc.) that will check for a certain comparison result of the previous instruction



Conditional Jump Instructions

CS:APP 3.6.3

- Figure 3.15 from CS:APP, 3e

Instruction	Synonym	Jump Condition	Description
`jmp label`			
`jmp *(Operand)`			
`je label`	`jz`	ZF	Equal / zero
`jne label`	`jnz`	~ZF	Not equal / not zero
`js label`		SF	Negative
`jns label`		~SF	Non-negative
`jg label`	`jnle`	~(SF ^ OF) & ~ZF	Greater (signed >)
`jge label`	`jnl`	~(SF ^ OF)	Greater or Equal (signed >=)
`jl label`	`jnge`	(SF ^ OF)	Less (signed <)
`jle label`	`jng`	(SF ^ OF) | ZF	Less of equal (signed <=)
`ja label`	`jnbe`	~CF & ~ZF	Above (unsigned >)
`jae label`	`jnb`	~CF	Above or equal (unsigned >=)
`jb label`	`jnae`	CF	Below (unsigned <)
`jbe label`	`jna`	CF | ZF	Below or equal (unsigned <=)

Reminder: For all jump instructions other than jmp (which is unconditional), some previous instruction (cmp, test, etc.) is needed to set the condition codes to be examined by the jmp

Condition Code Exercises

Processor Registers

0000 0000 0000 0001	rax
0000 0000 0000 0002	rbx
0000 0000 ffff fffe	rcx
0000 0000 0000 0000	rdx

Order:
__1__
__2__
__5___
__6___
__3,7_
__4,8_
____9_

```
f1:
    testl %edx, %edx
    je    L2
L1: cmpw  %bx, %ax
    jge   L3
L2: incl  %ecx
    js    L1
L3: ret
```

OF	SF	ZF	CF				
0	0	1	0				
0	1	0	1				
0	1	0	0	0	0	1	1

Control Structure Examples 1

CS:APP 3.6.5

```
// x = %edi, y = %esi, res = %rdx
void func1(int x, int y, int *res)
{
  if(x < y) *res = x;
  else *res = y;

}
```

gcc -S -Og func1.c

```
func1:
        cmpl    %esi, %edi
        jge     .L2
        movl    %edi, (%rdx)
        ret
.L2:
        movl    %esi, (%rdx)
        ret
```

```
// x = %edi, y = %esi, res = %rdx
void func2(int x, int y, int *res)
{
  if(x == -1 || y == -1)
    *res = y-1;
  else if(x > 0 && y < x)
    *res = x+1;
  else
    *res = 0;

}
```

gcc -S -O3 func2.c

```
func2:
        cmpl    $-1, %edi
        je      .L6
        cmpl    $-1, %esi
        je      .L6
        testl   %edi, %edi
        jle     .L5
        cmpl    %esi, %edi
        jle     .L5
        addl    $1, %edi
        movl    %edi, (%rdx)
        ret
.L5:
        movl    $0, (%rdx)
        ret
.L6:
        subl    $1, %esi
        movl    %esi, (%rdx)
        ret
```

Control Structure Examples 2

CS:APP 3.6.7

```
// str = %rdi
int func3(char str[])
{
  int i = 0;
  while(str[i] != 0){
    i++;
  }
  return i;
}
```

gcc -S -Og func3.c

```
func3:
        movl    $0, %eax
        jmp     .L2
.L3:
        addl    $1, %eax
.L2:
        movslq  %eax, %rdx
        cmpb    $0, (%rdi,%rdx)
        jne     .L3
        ret
```

```
// dat = %rdi, len = %esi
int func4(int dat[], int len)
{
  int i, min = dat[0];
  for(i=1; i < len; i++){
    if(dat[i] < min){
      min = dat[i];
    }
  }
  return min;
}
```

gcc -S -Og func4.c

```
func4:
        movl    (%rdi), %eax
        movl    $1, %edx
        jmp     .L2
.L4:
        movslq  %edx, %rcx
        movl    (%rdi,%rcx,4), %ecx
        cmpl    %ecx, %eax
        jle     .L3
        movl    %ecx, %eax
.L3:
        addl    $1, %edx
.L2:
        cmpl    %esi, %edx
        jl      .L4
        ret
```

Branch Displacements

CS:APP 3.6.4

- **Recall**: Jumps perform PC = PC + displacement
- Assembler converts jumps and labels to appropriate displacements
- Examine the disassembled output (below) especially the machine code in the left column
  - Displacements are in the 2nd byte of the instruction
  - Recall: PC increments to point at next instruction while jump is fetched and **BEFORE the jump is executed**

```
// dat = %rdi, len = %esi
int func4(int dat[], int len)
{
  int i, min = dat[0];
  for(i=1; i < len; i++){
    if(dat[i] < min){
      min = dat[i];
    }
  }
  return min;
}
```

C Code

```
0000000000000000 <func4>:
   0:   8b 07                   mov    (%rdi),%eax
   2:   ba 01 00 00 00          mov    $0x1,%edx
   7:   eb 0f                   jmp    18 <func4+0x18>
   9:   48 63 ca                movslq %edx,%rcx
   c:   8b 0c 8f                mov    (%rdi,%rcx,4),%ecx
   f:   39 c8                   cmp    %ecx,%eax
  11:   7e 02                   jle    15 <func4+0x15>
  13:   89 c8                   mov    %ecx,%eax
  15:   83 c2 01                add    $0x1,%edx
  18:   39 f2                   cmp    %esi,%edx
  1a:   7c ed                   jl     9 <func4+0x9>
  1c:   f3 c3                   retq
```

x86 Disassembled Output

```
func4:
        movl    (%rdi), %eax
        movl    $1, %edx
        jmp     .L2
.L4:
        movslq  %edx, %rcx
        movl    (%rdi,%rcx,4), %ecx
        cmpl    %ecx, %eax
        jle     .L3
        movl    %ecx, %eax
.L3:
        addl    $1, %edx
.L2:
        cmpl    %esi, %edx
        jl      .L4
        ret
```

x86 Assembler

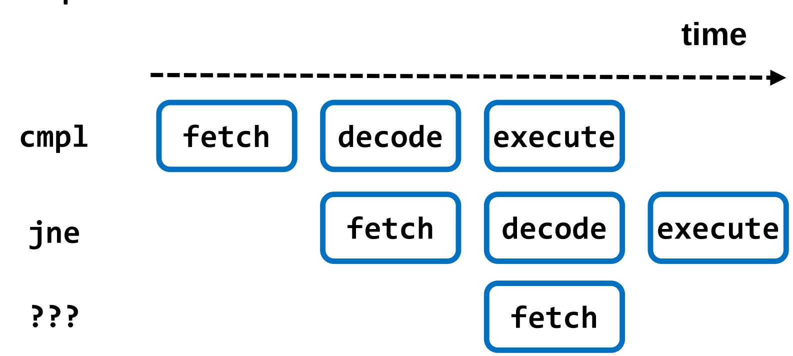
CONDITIONAL MOVES

Cost of Jumps

CS:APP 3.6.6

- Fact: Modern processors execute multiple instructions at one time
  - While earlier instructions are executing the processor can be fetching and decoding later instructions
  - This overlapped execution is known as **pipelining** and is key to obtaining good performance
- Problem: Conditional jumps limit pipelining because when we reach a jump, the comparison results it relies on may not be computed yet
  - It is unclear which instruction to fetch next
  - To be safe we have to stop and wait for the jump condition to be known

```
func1:
        cmpl    $-1, %edi
        je      .L6
        cmpl    $-1, %esi
        je      .L6
        testl   %edi, %edi
        jle     .L5
        cmpl    %esi, %edi
        jl      .L5
        addl    $1, %edi
        movl    %edi, (%rdx)
        ret
.L5:
        movl    $0, (%rdx)
        ret
.L6:
        subl    $1, %esi
        movl    %esi, (%rdx)
        ret
```



Cost of Jumps

- Solution: When modern processors reach a jump before the comparison condition is known, it will predict whether the jump condition will be true (aka "branch prediction") and "speculatively" execute down the chosen path
  - If the guess is right…we win and get good performance
  - If the guess is wrong…we lose and will have to throw away the wrongly fetched/decoded instructions once we realize the jump was mispredicted

Currently executing

Fetching here

Should we go sequentially or jump?

```
func1:
        cmpl    $-1, %edi
        je      .L6
        cmpl    $-1, %esi
        je      .L6
        testl   %edi, %edi
        jle     .L5
        cmpl    %esi, %edi
        jl      .L5
        addl    $1, %edi
        movl    %edi, (%rdx)
        ret
.L5:
        movl    $0, (%rdx)
        ret
.L6:
        subl    $1, %esi
        movl    %esi, (%rdx)
        ret
```

Conditional Move Concept

- Potential better solution: Be more pipelining friendly and compute both results and only store the correct result when the condition is known
- Allows for pure sequential execution
  - With jumps, we had to choose which instruction to fetch next
  - With conditional moves, we only need to choose whether to save or discard a computed result

```
int cmove1(int x, int* res)
{
  if(x > 5) *res = x+1;
  else *res = x-1;
}
```

C Code

```
cmove1:
        cmpl    $5, %edi
        jle     .L2
        addl    $1, %edi
        movl    %edi, (%rsi)
        ret
.L2:
        subl    $1, %edi
        movl    %edi, (%rsi)
        ret
```

With Jumps (-Og Optimization)

```
int cmove1(int x)
{
  int then_val = x+1;
  int temp = x-1;
  if(x > 5) temp = then_val;
  *res = temp;
}
```

Equivalent C code

```
cmove1:
        leal    1(%rdi), %edx
        leal    -1(%rdi), %eax
        cmpl    $6, %edi
        cmovge  %edx, %eax
        movl    %eax, (%rsi)
        ret
```

With Conditional Moves (-O3 Optimization)

Conditional Move Instruction

- Similar to `(cond) ? x : y`
- Syntax: `cmov[cond] src, reg`
  - Cond = Same conditions as jumps (e, ne, l, le, g, ge)
  - Destination must be a register
  - If condition is true, reg = src
  - If condition is false, reg is unchanged (i.e. instruction has no effect)

```
if(test-expr)
   res = then-expr
else
   res = else-expr
```

```
Let v = then-expr
Let res = else-expr
Let t = test-expr
if(t) res = v  // cmov in assembly
```

Conditional Move Instructions

- Figure 3.18 from CS:APP, 3e

Instruction	Synonym	Jump Condition	Description
`cmove label`	`cmovz`	ZF	Equal / zero
`cmovne label`	`cmovnz`	~ZF	Not equal / not zero
`cmovs label`		SF	Negative
`cmovns label`		~SF	Non-negative
`cmovg label`	`cmovnle`	~(SF ^ OF) & ~ZF	Greater (signed >)
`cmovge label`	`cmovnl`	~(SF ^ OF)	Greater or Equal (signed >=)
`cmovl label`	`cmovnge`	(SF ^ OF)	Less (signed <)
`cmovle label`	`cmovng`	(SF ^ OF) | ZF	Less of equal (signed <=)
`cmova label`	`cmovnbe`	~CF & ~ZF	Above (unsigned >)
`cmovae label`	`cmovnb`	~CF	Above or equal (unsigned >=)
`cmovb label`	`cmovnae`	CF	Below (unsigned <)
`cmovbe label`	`cmovna`	CF | ZF	Below or equal (unsigned <=)

Reminder: Some previous instruction (cmp, test, etc.) is needed to set the condition codes to be examined by the cmov

Conditional Move Exercises

Processor Registers

0000 0000 0000 0001	rax
0000 0000 0000 0000	rbx
0000 0000 0000 8801	rcx
0000 0000 0000 0002	rdx

- `cmpl  $8,%edx`
- `cmovl %rcx,%edx`

		OF	SF	ZF	CF
0000 0000 0000 8801	rdx	0	1	0	1

- `test  %rax,%rax`
- `cmove %rcx,%rax`

		OF	SF	ZF	CF
0000 0000 0000 0001	rax	0	0	0	0

Important Notes:

- No size modifier is added to cmov, but instead the register names specify the size
- Byte-size conditional moves are not support (only 16-, 32- or 64-bit conditional moves)

Limitations of Conditional Moves

- If code in then and else have side effects then executing both would violate the original intent
- If large amounts of code in then or else branches, then doing both may be more time consuming

```
int badcmove1(int x, int y)
{
   int z;
   if(x > 5) z = x++; // side effect
   else z = y;
   return z+1;
}

void badcmove2(int x, int y)
{
   int z;
   if(x > 5) {
     /* Lots of code */
   }
   else {
     /* Lots of code */
   }
}
```

C Code

ASIDE: ASSEMBLER DIRECTIVES

Labels and Instructions

- The optional label in front of an instruction evaluates to the address where the instruction or data starts in memory and can be used in other instructions

```
        .text
func4:  movl   %eax,8(%rdx)
.L1:    add    $1,%eax
        jne    .L1
        jmp    func4
```

Assembly Source File

Instruction	Address
movl	0x400000 = func4
add	0x400003 = .L1
jne	0x400006
jmp	0x400008

Assembler finds what address each instruction starts at…

```
              .text
0:            movl   %eax,8(%rdx)
3:            add    $1,%eax
6:            jne    0x400003 (-5)
8:            jmp    0x400000 (-10)
```

…and replaces the labels with their corresponding address

Assembler Directives

- Start with `.` (e.g. `.text`, `.quad`, `.long`)
- Similar to pre-processor statements (#include, #define, etc.) and global variable declarations in C/C++
  - Text and data segments
  - Reserving & initializing global variables and constants
  - Compiler and linker status
- Direct the assembler in how to assemble the actual instructions and how to initialize memory when the program is loaded

An Example

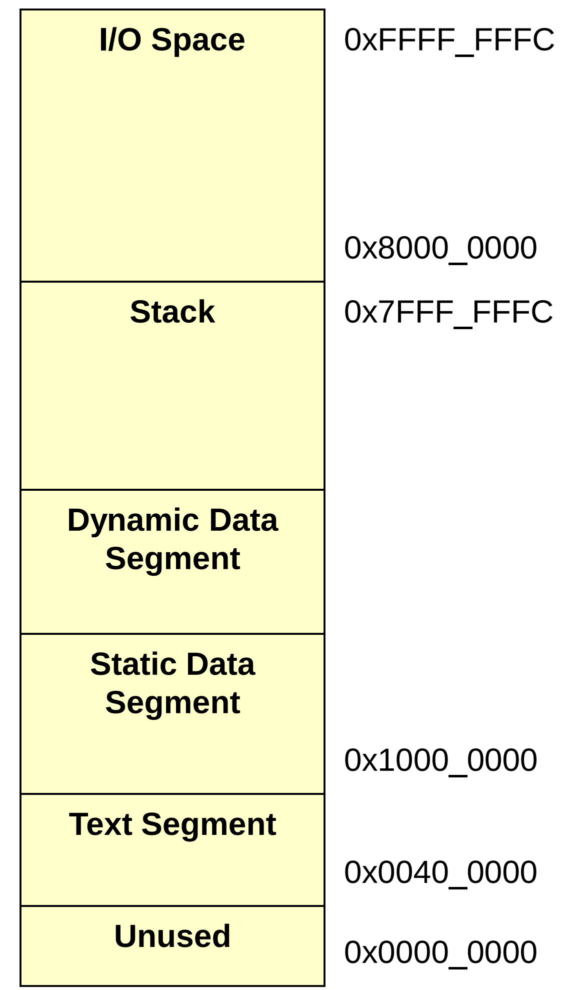
- Directives specify
  - Where to place the information (.text, .data, etc.)
  - What names (symbols) are visible to other files in the program (.globl)
  - Global data variables & their size (.byte, .long, .quad, .string)
  - Alignment requirements (.align)

```
int x[4] = {1,2,3,4};
char* str = "Hello";
unsigned char z = 10;
double grades[10];

int func()
{
  return 1;
}
```

```
        .text
        .globl   func
func:
        movl     $1, %eax
        ret

        .globl z
        .data
z:
        .byte    10

        .globl   str
        .string "Hello"

        .data
        .align 8
str:
        .quad    .LC0

        .globl   x
        .align 16
x:
        .long    1
        .long    2
        .long    3
        .long    4
```

Text and Data Segments

- .text directive indicates the following instructions should be placed in the program area of memory
- .data directive indicates the following data declarations will be placed in the data memory segment



Static Data Directives

- Fills memory with specified data when program is loaded
- Format:

(*Label*:)   .*type_id*   *val_0,val_1,…,val_n*

- type_id = {.byte, .value, .long, .quad, .float, .double}
- Each value in the comma separated list will be stored using the indicated size
  - Example: `myval:  .long  1, 2, 3`
    - Each value 1, 2, 3 is stored as a word (i.e. 32-bits)
    - Label "`myval`" evaluates to the start address of the first word (i.e. of the value 1)

Indirect jumps with jump tables

SWITCH TABLES

Switch with Direct Jumps

CS:APP 3.6.8

```
void switch1(unsigned x, int* res)
{
  switch(x%8)
    {
    case 0:
      *res = x+5;
      break;
    case 1:
      *res = x-3;
      break;
    case 2:
      *res = x+12;
      break;
    default:
      *res = x+7;
      break;

    }
}
```

```
switch1:
        movl    %edi, %eax
        andl    $7, %eax
        cmpl    $1, %eax
        je      .L3
        cmpl    $1, %eax
        jb      .L4
        cmpl    $2, %eax
        je      .L5
        jmp     .L7
.L4:
        addl    $5, %edi
        movl    %edi, (%rsi)
        ret
.L3:
        subl    $3, %edi
        movl    %edi, (%rsi)
        ret
.L5:
        addl    $12, %edi
        movl    %edi, (%rsi)
        ret
.L7:
        addl    $7, %edi
        movl    %edi, (%rsi)
        ret
```

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Switch w/ Indirect Jumps (Jump Tables)

```
// x = %edi, res = %rsi
void switch2(unsigned x, int* res)
{
  switch(x%8)
    {
    case 0:
      *res = x+5;
      break;
    case 1:
      *res = x-3;
      break;
    case 2:
      *res = x+12;
      break;
    case 3:
      *res = x+7;
      break;
    case 4:
      *res = x+5;
      break;
    case 5:
      *res = x-3;
      break;
    case 6:
      *res = x+12;
      break;
    case 7:
      *res = x+7;
      break;

    }
}
```

jump to
*(table[x%8])

1000 0ef0	
	0040 008a
	0040 0090
	0040 0096
	0040 009c
	0040 00a2
	0040 00a8
	0040 00ae
	0040 00b4

```
switch2:
        movl    %edi, %eax
        andl    $7, %eax
        movl    %eax, %eax
        jmp     *.L4(,%rax,8)
        .section
        .rodata
        .align 8
        .align 4
.L4: 1000 0ef0
        .quad   .L3
        .quad   .L5
        .quad   .L6
        .quad   .L7
        .quad   .L8
        .quad   .L9
        .quad   .L10
        .quad   .L11
        .text
.L3: 0040 008a
        addl    $5, %edi
        movl    %edi, (%rsi)
        ret
.L5: 0040 0090
        subl    $3, %edi
        movl    %edi, (%rsi)
        ret
.L6: 0040 0096
        addl    $12, %edi
        movl    %edi, (%rsi)
        ret
.L7: 0040 009c
        addl    $7, %edi
        movl    %edi, (%rsi)
        ret
```

```
.L8:  0040 00a2
        addl    $5, %edi
        movl    %edi, (%rsi)
        ret
.L9:  0040 00a8
        subl    $3, %edi
        movl    %edi, (%rsi)
        ret
.L10: 0040 00ae
        addl    $12, %edi
        movl    %edi, (%rsi)
        ret
.L11: 0040 00b4
        addl    $7, %edi
        movl    %edi, (%rsi)
        ret
```