CS 261
Fall 2019

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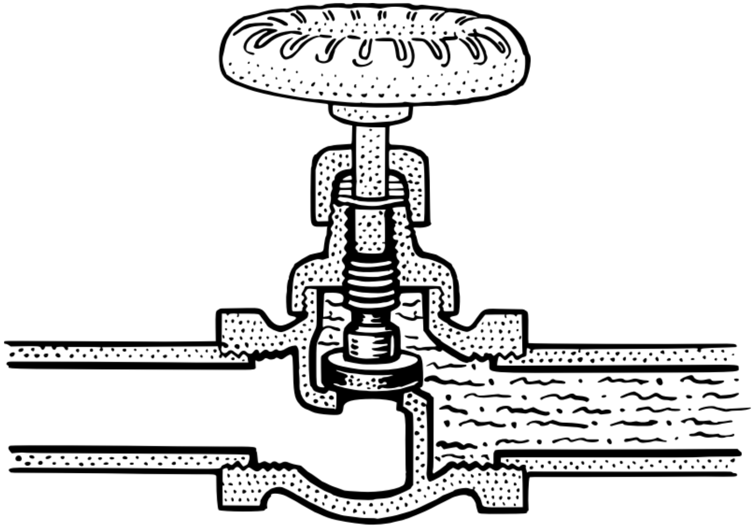

x86-64 Control Flow

Topics

- Condition codes
- Jumps
- Conditional moves
- Jump tables

Motivation

- We cannot translate the following C function to assembly, using only data movement and arithmetic operations
  - Fundamental requirement: ability to control the flow of program execution (i.e., decision-making)
  - Necessary for translating structured code

```
int min (int x, int y)
{
    if (x < y) {
        return x;
    } else {
        return y;
    }
}
```

Control flow

- The program counter (PC) tracks the address of the next instruction to be executed
  - To change the PC in assembly, use a jump instruction
    - Often the jump will be relative to the current PC value
  - In assembly, the target of a jump is usually a label, which is converted to a code address by the assembler
    - Labels are written using colon notation (e.g., "`L1:`")
  - However, unconditional jumps aren't sufficient for decision-making
    - In fact, the compiler can just re-arrange code to avoid them

```
    movl $2, %eax
    jmp L1
    movl $3, %eax      # never executed!
L1:
    movl $4, %eax
```

Conditional jumps

- Conditional jumps only jump under certain conditions
- In machine/assembly code, conditional jumps are often encoded using a **pair** of instructions
  - The **first** sets the condition codes of the CPU
    - On x86-64, the FLAGS register
    - Arithmetic/logical instructions do this as a side effect
    - Special-purpose instructions `cmp` and `test`
  - The **second** jumps base on the value of the condition codes
    - On x86-64, many variants: “jump-if-equal”, “jump-if-less-than”, etc.

```
cmpl %eax, %ecx        # means “compare %ecx with %eax”

jle pos1               # means “jump-if-less-than-or-equal”
```

Condition codes

- x86-64: special `%flags` register stores bits for these condition codes:
  - **CF** (carry): last operation resulted in a carry out **or borrow in**
    - (e.g, overflow for unsigned arithmetic)
  - **ZF** (zero): last operation resulted in a zero
  - **SF** (sign): last operation resulted in a negative value
  - **OF** (overflow): last operation caused a two's complement overflow (negative or positive)

- As well as a few we won't use:
  - **PF** (parity): last operation resulted in an even number of 1 bits in the eight least significant bits
  - **AF** (adjust): last operation resulted in a carry out for the four least significant bits
  - **IF** (interrupt): CPU will handle interrupts

- Use `$eflags` to reference this register in GDB
  - E.g., "`print $eflags`" or "`display $eflags`"

Aside: Subtraction

- In **addition**, the carry flag is set if a subtraction requires a carry out of the most significant (leftmost) bit
  - Basically, it's the "extra bit" necessary to represent the result
  - E.g., `1001 + 0001 = 1010` (CF=0)
  - E.g., `1111 + 0001 = 0000` (CF=1)

- In **subtraction**, the carry (borrow) flag is set if a subtraction requires a borrow into the most significant (leftmost) bit
  - E.g., `1000 - 0001 = 0111` (CF=0)
  - E.g., `0000 - 0001 = 1111` (CF=1)

Condition codes

- Special `cmp` and `test` instructions
  - `cmp` compares two values (computes arg_2 - arg_1)
    - **NOTE REVERSED ORDERING** – also, the result is not saved
    - Type-agnostic: all flags are set, but not all are relevant!
    - Does not change either operand
  - `test` checks for non-zero values (computes arg_2 & arg_1)
    - Often, the arguments are the same (or one is a bit mask)
    - Always sets carry and overflow flags to zero
    - Does not change either operand

```
cmpl %eax, %ecx          # means “compare %ecx with %eax”

testl $0xFF, %edx        # means “check low-order 8 bits of %edx”
```

Jump instructions

Instruction	Synonym	Jump condition	Description
jmp *Label*		1	Direct jump
jmp **Operand*		1	Indirect jump
je *Label*	jz	ZF	Equal / zero
jne *Label*	jnz	~ZF	Not equal / not zero
js *Label*		SF	Negative
jns *Label*		~SF	Nonnegative
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 or 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 <=)

Type difference

Figure 3.15 The jump instructions. These instructions jump to a labeled destination when the jump condition holds. Some instructions have "synonyms," alternate names for the same machine instruction.

Example

C code:

```
int min (int x, int y)
{
    if (x < y) {
        return x;
    } else {
        return y;
    }
}
```

x86-64 assembly:
(x in %edi, y in %esi)

```
min:
    cmpl  %esi, %edi
    jge   .L3
    movl  %edi, %eax
    ret
.L3:
    movl  %esi, %eax
    ret
```

Example

C code:

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        return x;
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x86-64 assembly:
(x in %edi, y in %esi)

```
min:       y       x
    cmpl  %esi, %edi
    jge   .L3
    movl  %edi, %eax
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   ret
.L3:
   movl  %esi, %eax
   ret
```

Control flow

- Compilers translate block-structured code to linear code using conditional jumps
  - We can simulate conditional jumps in C using the goto statement
    - General template: "`if (<cond>) goto <label>;`"
    - Syntax for labels is the same in C and assembly (colon notation)
- CS:APP: C “goto code” is code that uses only **`if/goto`** and **`goto`**
  - No blocks (and therefore no “else” blocks or explicit loops)
  - Not a good idea in general!
    - Famous letter by Dijkstra: "Go To Statement Considered Harmful"
  - However, it is useful for pedagogical purposes (closer to assembly)

Example

C code:

```
if (x < y) {
    printf("A");
} else {
    printf("B");
}
printf("C");
```

note inverted condition!

C goto code:

```
    if (x >= y) goto L1;
    printf("A");
    goto L2;
L1:
    printf("B");
L2:
    printf("C");
```

C code:

```
while (x < 5) {
    x = x – 1;
}
```

C goto code:

```
    goto L2;
L1:
    x = x – 1;
L2:
    if (x < 5) goto L1;
```

Conditionals (in goto code)

If/else

```
if (<test-expr>)
     <true-branch>
else
    <false-branch>
```

```
  if (!<test-expr>)
    goto false;
  <true-branch>
  goto done;
false:
  <false-branch>
done:
```

Nested if/else

```
if (<top-expr>)
     if (<test-expr>)
         <true-branch>
    else
        <false-branch>
else
    <else-branch>
```

```
  if (!<top-expr>)
    goto else;
  if (!<test-expr>)
    goto false;
  <true-branch>
  goto done;
false:
  <false-branch>
done:
  goto end;
else:
  <else-branch>
end:
```

Conditionals (in goto code)

```
if (<test-expr>)
    <true-branch>
else
    <false-branch>
```

```
  if (!<test-expr>)
    goto false;
  <true-branch>
  goto done;
false:
  <false-branch>
done:
```

If/else

```
if (<top-expr>)
    if (<test-expr>)
        <true-branch>
    else
        <false-branch>
else
    <else-branch>
```

```
  if (!<top-expr>)
    goto else;
  if (!<test-expr>)
    goto false;
  <true-branch>
  goto done;
false:
  <false-branch>
done:
  goto end;
else:
  <else-branch>
end:
```

Nested if/else

Conditional moves

- Similar to conditional jumps, but they move data if certain condition codes are set
  - Benefit: no branch prediction penalty
    - We'll see how this produces faster code in a few weeks
  - In C code: "`x = ( <cond> ? <tvalue> : <fvalue>)`"

```
  cmpq %rax, %rbx
  jg L01
  movq %rax, %rcx
  jmp L02
L01:
  movq %rbx, %rcx
L02:
```

```
movq   %rax, %rcx
cmpq   %rax, %rbx
cmovg  %rbx, %rcx
```

Conditional moves

- Similar to conditional jumps, but they move data if certain condition codes are set
  - Benefit: no branch prediction penalty
    - We'll see how this produces faster code in a few weeks
  - In C code: "x = (<*cond*> ? <*tvalue*> : <*fvalue*>)"

```
  cmpq %rax, %rbx
  jg L01
  movq %rax, %rcx
  jmp L02
L01:
  movq %rbx, %rcx
L02:
```

```
movq   %rax, %rcx
cmpq   %rax, %rbx
cmovg  %rbx, %rcx
```

Loops

- Basic idea: jump back to an earlier label
- Three basic forms:
  - Do-while loops
  - Jump-to-middle loops
  - Guarded-do loops
- Note: we’ll use goto code in C first
  - Just to avoid unnecessary complication
  - If you can translate a loop into goto code, it's then much easier to convert to assembly

Loops

```
do
    <body-statement>
while (<test-expr>);
```

```
loop:
  <body-statement>
  if (<test-expr>)
    goto loop;
```

Do-while loop

```
while (<test-expr>)
    <body-statement>
```

```
  goto test;
loop:
  <body-statement>
test:
  if (<test-expr>)
    goto loop
```

Jump-to-middle loop

```
  if (!<test-expr>)
    goto done
loop:
  <body-statement>
  if (<test-expr>)
    goto loop
done:
```

Guarded-do loop

Loops

```
do
    <body-statement>
while (<test-expr>);
```

```
loop:
  <body-statement>
  if (<test-expr>)
    goto loop;
```

Do-while loop

```
while (<test-expr>)
    <body-statement>
```

```
  goto test;
loop:
  <body-statement>
test:
  if (<test-expr>)
    goto loop
```

Jump-to-middle loop

```
  if (!<test-expr>)
    goto done
loop:
  <body-statement>
  if (<test-expr>)
    goto loop
done:
```

Guarded-do loop

Loops

```
for (<init-expr>; <test-expr>; <update-expr>)
    <body-statement>
```

```
  goto test;
loop:
  <body-statement>
test:
  if (<test-expr>)
    goto loop
```

Jump-to-middle loop

```
  if (!<test-expr>)
    goto done
loop:
  <body-statement>
  if (<test-expr>)
    goto loop
done:
```

Guarded-do loop

Loops

```
for (<init-expr>; <test-expr>; <update-expr>)
    <body-statement>
```

```
  <init-expr>
  goto test;
loop:
  <body-statement>
  <update-expr>
test:
  if (<test-expr>)
    goto loop
```

Jump-to-middle loop

```
  <init-expr>
  if (!<test-expr>)
    goto done;
loop:
  <body-statement>
  <update-expr>
  if (<test-expr>)
    goto loop
done:
```

Guarded-do loop

Switch statements

- One approach: convert to if/elseif code
  - Problem: performance varies based on ordering and actual runtime values!

```
switch (x) {
  case 10: do_blah();
           break;
  case 11: do_foo();
           break;
  case 13: do_bar();
           break;
  case 15: do_baz();
           break;
  default: error();
}
```

```
if (x == 10) {
    do_blah();
} else if (x == 11) {
    do_foo();
} else if (x == 13) {
    do_bar();
} else if (x == 15) {
    do_baz();
} else {
    error();
}
```

Switch statements

- Indexed indirect jump ("computed goto")
  - Jump to an address stored in a register
  - Implemented using a data structure called a jump table
  - Efficient when # of options is high and the value range is small

```
switch (x) {
  case 10: do_blah();
           break;
  case 11: do_foo();
           break;
  case 13: do_bar();
           break;
  case 15: do_baz();
           break;
  default: error();
}
```

Jump Table

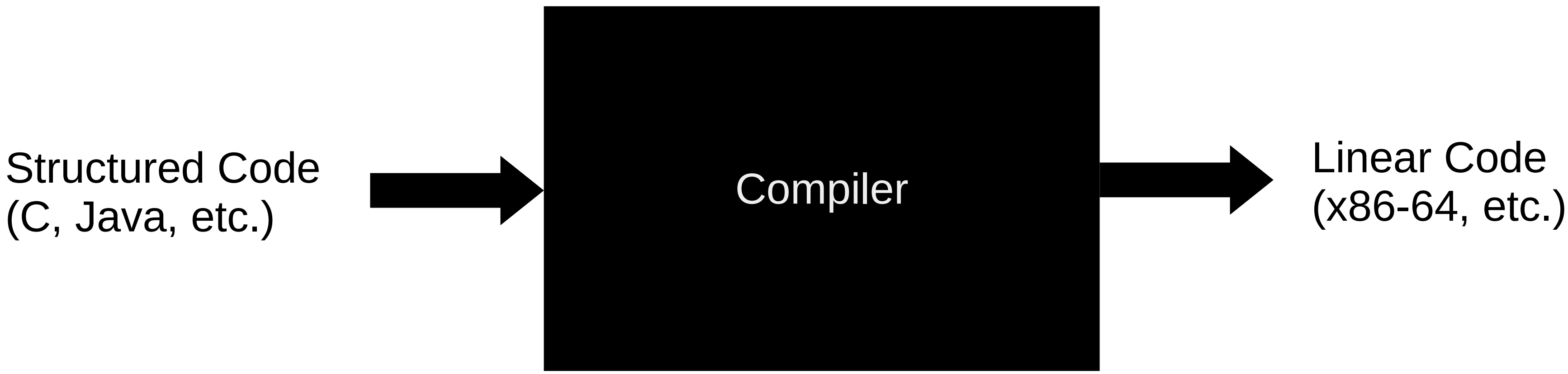
Index	Destination
0	0x400e51
1	0x400e88
2	0x401900
3	0x400f12
4	0x401900
5	0x400f34

x is in %rdx, address of jump table is in %rbx

```
subq $0xA, %rdx
movq (%rbx,%rdx,0x8), %rcx
jmp *%rcx
```

Related coursework

- We can **always** (and automatically!) translate from structured code to linear/goto code
  - This is what a compiler does!
  - If you're interested in learning more about how this works, plan to take CS 432 as your systems elective



Exercise

- Convert the following C function into x86-64 assembly:

```
int sum = 0;
int x = 1;
while (x < 10) {
    sum = sum + x;
    x = x + 1;
}
```