第3章 程序的机器级表示
Machine-Level Programming II: Control

100076202： 计算机系统导论
II： 控制
II: Control

任课教师:
宿红毅　张艳　黎有琦　颜珂

原作者:
Randal E. Bryant and David R. O’Hallaron

回忆：内存操作数和LEA
Recall:Memory operands and LEA

在大多数指令中，内存操作数访问内存 In most instructions, a memory operand accesses memory

汇编 Assembly	等价C语言 C equivalent
mov 6(%rbx,%rdi,8), %ax	ax = *(rbx + rdi*8 + 6)
add 6(%rbx,%rdi,8), %ax	ax += *(rbx + rdi*8 + 6)
xor %ax, 6(%rbx,%rdi,8)	*(rbx + rdi*8 + 6) ^= ax

LEA特殊性：它不访问内存 LEA is special: it *doesn't* access memory

汇编 Assembly	等价C语言 C equivalent
lea 6(%rbx,%rdi,8), %rax	rax = rbx + rdi*8 + 6

为何使用LEA Why use LEA?

- CPU设计师倾向使用：计算一个对象的指针 CPU designers' intended use: calculate a pointer to an object
  - 数组元素，或许 An array element, perhaps
  - 例如 传递一个数组元素给另一个函数 For instance, to pass just one array element to another function

汇编 Assembly	等价C语言 C equivalent
lea (%rbx,%rdi,8), %rax	rax = &rbx[rdi]

- 编译器设计人员喜欢用它实现普通计算 Compiler authors like to use it for ordinary arithmetic
  - 可以在一条指令中做复杂的计算 It can do complex calculations in one instruction
  - x86仅有的几个三操作数指令之一 It's one of the only three-operand instructions the x86 has
  - 并不影响条件码（我们后面再讨论）It doesn't touch the condition codes (we'll come back to this)

汇编 Assembly	等价C语言 C equivalent
lea (%rbx,%rbx,2), %rax	rax = rbx * 3

旁注：指令后缀
Sidebar: instruction suffixes

- 多数x86指令可以写或不写后缀 Most x86 instructions can be written with or without a suffix
  - `imul    %rcx, %rax`
  - `imulq   %rcx, %rax`

没有区别

There’s no difference!

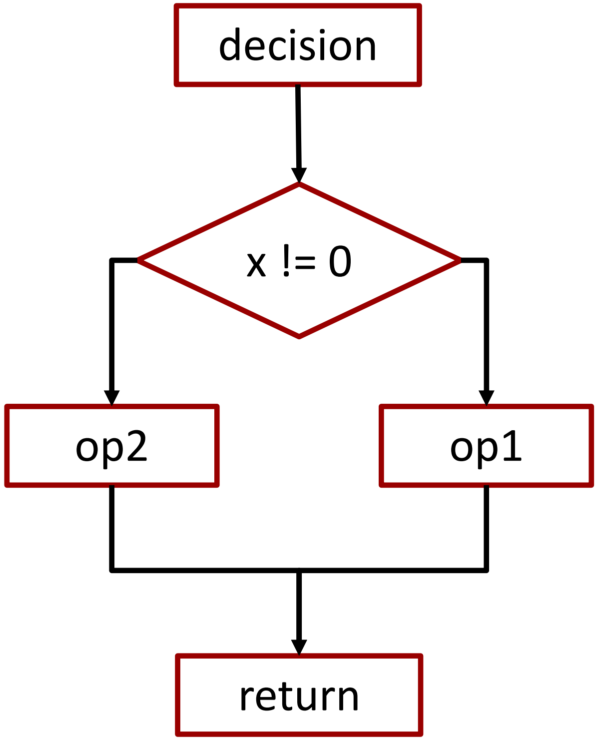
- 后缀指明操作的大小 The suffix indicates the operation size
  - b=byte, w=short, l=int, q=long
  - 如果出现，必须和寄存器名字相匹配 If present, must match register names
- 编译器产生的汇编输出(gcc –S)通常有后缀 Assembly output from the compiler (gcc –S)
  usually has suffixes
- 反汇编转储通常省略后缀 Disassembly dumps (objdump –d, gdb ‘disas’) usually omit suffixes
- Intel手册总是省略后缀 Intel’s manuals always omit the suffixes


CONTROL... CONTROL...
YOU MUST LEARN CONTROL

控制流 Control flow

```
extern void op1(void);
extern void op2(void);

void decision(int x) {
    if (x) {
        op1();
    } else {
        op2();
    }
}
```



汇编语言的控制流
Control flow in assembly language

```c
extern void op1(void);
extern void op2(void);

void decision(int x) {
    if (x) {
        op1();
    } else {
        op2();
    }
}
```

```asm
decision:
        subq    $8, %rsp
        testl   %edi, %edi
        je      .L2
        call    op1
        jmp     .L1
.L2:
        call    op2
.L1:
        addq    $8, %rsp
        ret
```

汇编语言的控制流
Control flow in assembly language

```c
extern void op1(void);
extern void op2(void);

void decision(int x) {
    if (x) {
        op1();
    } else {
        op2();
    }
}
```

```
decision:
        subq    $8, %rsp
        testl   %edi, %edi
        je      .L2
        call    op1
        jmp     .L1
.L2:
        call    op2
.L1:
        addq    $8, %rsp
        ret
```

用GOTO语句来实现 It's all done with GOTO!

议题

- **控制：条件码 Control: Condition codes**
- 条件分支 Conditional branches
- 循环 Loops
- Switch语句 Switch Statements

处理器状态（x86-64，部分）
Processor State (x86-64, Partial)

- **关于当前执行程序的信息**
  Information about currently executing program
  - 临时数据 Temporary data
    (**`%rax`**, …)
  - 运行时栈位置 Location of runtime stack
    (**`%rsp`**)
  - 当前代码控制点位置Location of current code control point
    (**`%rip`**, …)
  - 最近测试的状态 Status of recent tests
    (**CF, ZF, SF, OF**)

寄存器 **Registers**

`%rax`	`%r8`
`%rbx`	`%r9`
`%rcx`	`%r10`
`%rdx`	`%r11`
`%rsi`	`%r12`
`%rdi`	`%r13`
`%rsp`	`%r14`
`%rbp`	`%r15`

当前栈顶
Current stack top

`%rip`

指令指针
Instruction pointer

CF	ZF	SF	OF

条件码
Condition codes

在授课过程中需记住什么
What to remember during lecture

设置条件码 Set Condition Codes	
• 操作：例如addq Operations: e.g. `addq` • 比较：Compare: `cmp a,b` 类似做b-a like doing `b-a` • 测试：Test: `test a,b` 类似做a&b like doing `a&b`	根据条件码跳转：je（相等跳转）jg（大于跳转）等 Jump based on condition codes: `je` (jump if equal), `jg` (greater), etc. 根据条件码设置寄存器的低字节为0/1 Set low order byte of a register to 0/1 based on condition codes 如果条件码置位则传送一个值 `mov` a value if a condition code is set

我们将深入研究，但是请像做炸弹实验一样阅读

We’ll dive in, but read as you do bomb lab!

条件码（隐式设置）Condition Codes (Implicit Setting)

- **单个比特位寄存器 Single bit registers**
  - **CF** 进位标志Carry Flag (对无符号数 for unsigned) **SF** 符号标志 Sign Flag (对有符号数 for signed)
  - **ZF** 零标志 Zero Flag **OF** 溢出标志 Overflow Flag (对有符号数for signed)
- **由算术运算隐式设置（看成副作用） Implicitly set (think of it as side effect) by arithmetic operations**

  举例：Example: `addq` *Src,Dest* ↔ `t = a+b`

  CF set 如果从最高有效位进位（无符号溢出） if carry out from most significant bit (unsigned overflow)

  ZF set 如果结果为零 if `t == 0`

  SF set 如果结果小于零（有符号数） if `t < 0` (as signed)

  OF set 如果补码（有符号数）溢出 if two's-complement (signed) overflow
  `(a>0 && b>0 && t<0) || (a<0 && b<0 && t>=0)`
- **leaq指令不设置条件码 Not set by `leaq` instruction**

ZF set when

000000000000...00000000000

SF set when

```
  yxxxxxxxxxxxx...
+ yxxxxxxxxxxxx...
------------------
  1xxxxxxxxxxxx...
```

对于有符号数计算，该标志报告结果为负数

For signed arithmetic, this reports when result is a negative number

CF set when

```
    1xxxxxxxxxxxxx...
+   1xxxxxxxxxxxxx...          进位 Carry
---------------------
1   xxxxxxxxxxxxxx...
```

```
1   0xxxxxxxxxxxxx...
-   1xxxxxxxxxxxxx...          借位 Borrow
---------------------
    1xxxxxxxxxxxxx...
```

对于无符号数计算，该标志报告产生溢出

For unsigned arithmetic, this reports overflow

OF set when

```
   yxxxxxxxxxxxxx...     a
+  yxxxxxxxxxxxxx...     b
   -----------------
   zxxxxxxxxxxxxx...     t
```

$$z = \sim y$$

```
(a>0 && b>0 && t<0) || (a<0 && b<0 && t>=0)
```

对于有符号数计算，该标志报告溢出

For signed arithmetic, this reports overflow

条件码（显式设置：比较指令）
Condition Codes (Explicit Setting: Compare)

- **由比较指令显式设置 Explicit Setting by Compare Instruction**
  - **`cmpq`** *Src2*, *Src1*
  - **`cmpq b,a`** 类似计算a-b，只是不设置目的操作数 like computing **`a-b`** without setting destination

  - **CF set** 如果从最高有效位进位（用于无符号数比较） if carry out from most significant bit (used for unsigned comparisons)
  - **ZF set** 如果相等 if **`a == b`**
  - **SF set** 如果小于（有符号数） if **`(a-b) < 0`** (as signed)
  - **OF set** 如果补码（有符号数）溢出 if two’s-complement (signed) overflow
`(a>0 && b<0 && (a-b)<0) || (a<0 && b>0 && (a-b)>0)`

条件码（显式设置：测试指令）
Condition Codes (Explicit Setting: Test)

- **由测试指令显式设置 Explicit Setting by Test instruction**
  - `testq` *Src2*, *Src1*
    - `testq b,a` 类似计算与操作，但是不设置目的操作数 like computing `a&b` without setting destination
  - 根据与运算的值设置条件码 Sets condition codes based on value of *Src1* & *Src2*
  - 对于用一个操作数作为掩码很有用 Useful to have one of the operands be a mask
  - **ZF set** 当与结果为0时 when `a&b == 0`
  - **SF set** 当与结果小于0时 when `a&b < 0`

非常常用 Very often:

```
testq  %rax,%rax
```

读取条件码 Reading Condition Codes

SetX指令 SetX Instructions

- 根据条件码组合设置目的操作数低字节成0或1 Set low-order byte of destination to 0 or 1 based on combinations of condition codes
- 不要改变剩余的7个字节 Does not alter remaining 7 bytes

SetX	条件 Condition	描述 Description
`sete`	`ZF`	等于/零 Equal / Zero
`setne`	`~ZF`	不等/不为零 Not Equal / Not Zero
`sets`	`SF`	负数 Negative
`setns`	`~SF`	非负 Nonnegative
`setg`	`~(SF^OF)&~ZF`	大于（有符号）Greater (Signed)
`setge`	`~(SF^OF)`	大于或等于（有符号数）Greater or Equal (Signed)
`setl`	`(SF^OF)`	小于（有符号数）Less (Signed)
`setle`	`(SF^OF)|ZF`	小于或等于（有符号数）Less or Equal (Signed)
`seta`	`~CF&~ZF`	高于（无符号数）Above (unsigned)
`setb`	`CF`	低于（无符号数）Below (unsigned)

示例：setl（有符号数小于）
Example: setl (Signed <)

- 情况 Condition: SF^OF

SF	OF	SF ^ OF	隐含 Implication
0	0	0	没有溢出，SF隐含着不小于 No overflow, so SF implies not <
1	0	1	没有溢出，SF隐含着小于 No overflow, so SF implies <
0	1	1	溢出，SF隐含着负溢，即小于 Overflow, so SF implies negative overflow, i.e. <
1	1	0	溢出，SF隐含着正溢，即不小于 Overflow, so SF implies positive overflow, i.e. not <

负溢的情况 negative overflow case

```
  1xxxxxxxxxxxxx...   a
- 0xxxxxxxxxxxxx...   b
---------------------
  0xxxxxxxxxxxxx...   t
```

x86-64整数寄存器 x86-64 Integer Registers

%rax	%al	%r8	%r8b
%rbx	%bl	%r9	%r9b
%rcx	%cl	%r10	%r10b
%rdx	%dl	%r11	%r11b
%rsi	%sil	%r12	%r12b
%rdi	%dil	%r13	%r13b
%rsp	%spl	%r14	%r14b
%rbp	%bpl	%r15	%r15b

- 可以引用低字节 Can reference low-order byte

读取条件码 Reading Condition Codes (Cont.)

- **SetX指令 SetX Instructions:**
  - 根据条件码的组合设置单个字节 Set single byte based on combination of condition codes
- **可寻址的字节寄存器之一 One of addressable byte registers**
  - 不会修改剩余的字节 Does not alter remaining bytes
  - 典型地使用movzbl(0扩展字节到双字)来完成工作 Typically use **`movzbl`** to finish job
    - 32位指令也设置高32位为0 32-bit instructions also set upper 32 bits to 0

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

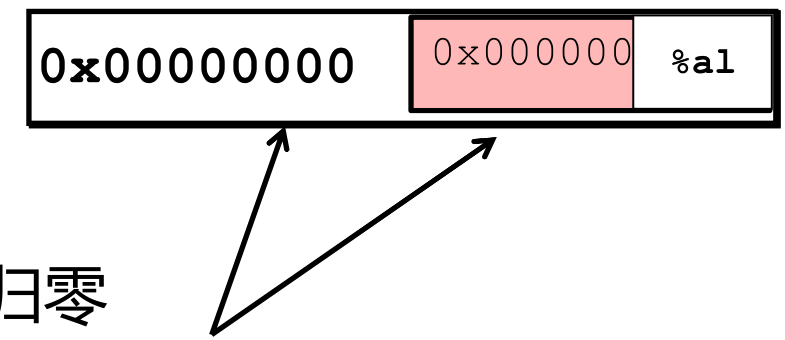
寄存器 Register	用途 Use(s)
`%rdi`	参数x Argument **`x`**
`%rsi`	参数y Argument **`y`**
`%rax`	返回值 Return value

```
    cmpq   %rsi, %rdi    # Compare x:y
    setg   %al           # Set when >
    movzbl %al, %eax     # Zero rest of %rax
    ret
```

显式读取条件码（续）
Explicit Reading Condition Codes (Cont.)

当心怪异movzbl（和其它）Beware weirdness **movzbl** (and others)

movzbl %al, %eax



全部归零
Zapped to all 0's

Use(s)
Argument **x**
Argument **y**
Return value

```
cmpq   %rsi, %rdi    # Compare x:y
setg   %al           # Set when >
movzbl %al, %eax     # Zero rest of %rax
ret
```

议题

- 控制：条件码 Control: Condition codes
- **条件分支 Conditional branches**
- 循环 Loops
- Switch语句 Switch Statements

跳转指令 Jumping

- **跳转指令 jX Instructions**
  - 根据条件码跳转到代码的不同部分 Jump to different part of code depending on condition codes

jX	条件 Condition	描述 Description
`jmp`	`1`	无条件 Unconditional
`je`	`ZF`	相等/零 Equal / Zero
`jne`	`~ZF`	不等/非零 Not Equal / Not Zero
`js`	`SF`	负数 Negative
`jns`	`~SF`	非负数 Nonnegative
`jg`	`~(SF^OF)&~ZF`	大于（有符号数） Greater (Signed)
`jge`	`~(SF^OF)`	大于或等于（有符号数）Greater or Equal (Signed)
`jl`	`(SF^OF)`	小于（有符号数）Less (Signed)
`jle`	`(SF^OF)|ZF`	小于或等于（有符号数）Less or Equal (Signed)
`ja`	`~CF&~ZF`	高于Above（无符号数） (unsigned)
`jb`	`CF`	低于Below（无符号数） (unsigned)

条件分支示例（旧版风格）
Conditional Branch Example (Old Style)

- 生成 Generation

Get to this shortly

```
shark> gcc -Og -S -fno-if-conversion control.c
```

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

```
absdiff:
   cmpq    %rsi, %rdi   # x:y
   jle     .L4
   movq    %rdi, %rax
   subq    %rsi, %rax
   ret
.L4:               # x <= y
   movq    %rsi, %rax
   subq    %rdi, %rax
   ret
```

寄存器 Register	用途 Use(s)
%rdi	参数x Argument x
%rsi	参数y Argument y
%rax	返回值 Return value

用Goto代码表达 Expressing with Goto Code

- C语言允许使用goto语句 C allows goto statement
- 跳转到标号指示的位置 Jump to position designated by label

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

```
long absdiff_j
  (long x, long y)
{
    long result;
    int ntest = x <= y;
    if (ntest) goto Else;
    result = x-y;
    goto Done;
 Else:
    result = y-x;
 Done:
    return result;
}
```

通用条件表达式翻译（使用分支）General Conditional Expression Translation (Using Branches)

C语言代码 C Code

```
val = Test ? Then_Expr : Else_Expr;
```

```
val = x>y ? x-y : y-x;
```

Goto版本 Goto Version

```
  ntest = !Test;
  if (ntest) goto Else;
  val = Then_Expr;
  goto Done;
Else:
  val = Else_Expr;
Done:
  . . .
```

- 为then和else表达式分别创建代码区 Create separate code regions for then & else expressions
- 执行适当的一个代码区 Execute appropriate one

使用条件传送指令 Using Conditional Moves

- **条件传送指令 Conditional Move Instructions**
  - 指令支持：Instruction supports:

    if (Test) Dest ← Src
  - 在1995年之后的x86处理器得到支持 Supported in post-1995 x86 processors
  - GCC尝试使用这些指令 GCC tries to use them
    - 但是，仅仅当知道这样是在安全的情况下才行 But, only when known to be safe
- **为何? Why?**
  - 指令流通过流水线时分支是非常容易引起混乱的 Branches are very disruptive to instruction flow through pipelines
  - 条件传送不需要控制转移 Conditional moves do not require control transfer

C代码 C Code

```
val = Test
    ? Then_Expr
    : Else_Expr;
```

Goto版本 Goto Version

```
result = Then_Expr;
eval = Else_Expr;
nt = !Test;
if (nt) result = eval;
return result;
```

条件传送指令

- 只有条件成立时，才进行传送；否则，无操作

指令	条件	描述
cmove	ZF	相等/零
cmovne	~ZF	不相等/非零
cmovs	SF	负数
cmovns	~SF	非负数
cmovg	~(SF^OF)&~ZF	大于（有符号>)
cmovge	~(SF^OF)	大于或等于（有符号>=)
cmovl	SF^OF	小于（有符号<)
cmovle	(SF^OF)|ZF	小于或等于（有符号<=)
cmova	~CF&~ZF	高于（无符号>)
cmovae	~CF	高于或相等（无符号>=)
cmovb	CF	低于（无符号<)
cmovbe	CF|ZF	低于或相等（无符号<=)

条件传送示例 Conditional Move Example

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

寄存器 Register	用途 Use(s)
`%rdi`	参数x Argument **x**
`%rsi`	参数y Argument **y**
`%rax`	返回值 Return value

```
absdiff:
   movq    %rdi, %rax   # x
   subq    %rsi, %rax   # result = x-y
   movq    %rsi, %rdx
   subq    %rdi, %rdx   # eval = y-x
   cmpq    %rsi, %rdi   # x:y
   cmovle  %rdx, %rax   # if <=, result = eval
   ret
```

何时这样做比较糟糕?
When is this bad?

对于条件传送糟糕的情况
Bad Cases for Conditional Move

需大量的计算 **Expensive Computations**

```
val = Test(x) ? Hard1(x) : Hard2(x);
```

- **两个值都需要计算 Both values get computed**
- **仅当计算非常简单时才有意义 Only makes sense when computations are very simple**

糟糕的性能

Bad Performance

计算存在风险 **Risky Computations**

```
val = p ? *p : 0;
```

- 两个值都得到计算 **Both values get computed**
- 可能有不期望的效果 **May have undesirable effects**

不安全 Unsafe

计算有副作用 **Computations with**

```
val = x > 0 ? x*=7 : x+=3;
```

- 两个值都得到计算 **Both values get computed**
- 必须保证没有副作用 **Must be side-effect free**

不正确 Illegal

练习

`cmpq b,a` like computing `a-b` w/o setting dest

subq	Src,Dest	Dest = Dest - Src
xorq	Src,Dest	Dest = Dest ^ Src

- **CF set** if carry/borrow out from most significant bit (used for unsigned comparisons)
- **ZF set** if `a == b`
- **SF set** if `(a-b) < 0` (as signed)
- **OF set** if two's-complement (signed) overflow

SetX	Condition	Description
`setl`	`SF^OF`	Less (signed)

	`%rax`	SF	CF	OF	ZF
`xorq %rax, %rax`	`0x0000 0000 0000 0000`	0	0	0	1
`subq $1, %rax`	`0xFFFF FFFF FFFF FFFF`	1	1	0	0
`cmpq $2, %rax`	`0xFFFF FFFF FFFF FFFF`	1	0	0	0
`setl %al`	`0xFFFF FFFF FFFF FF01`	1	0	0	0
`movzbl %al, %eax`	`0x0000 0000 0000 0001`	1	0	0	0

Note: **`setl`** and **`movzblq`** do not modify condition codes

议题

- 控制：条件码 Control: Condition codes
- 条件分支 Conditional branches
- **循环 Loops**
- Switch语句 Switch Statements

Do-While循环示例
"Do-While" Loop Example

C代码 C Code

```
long pcount_do
  (unsigned long x) {
  long result = 0;
  do {
    result += x & 0x1;
    x >>= 1;
  } while (x);
  return result;
}
```

Goto版本Goto Version

```
long pcount_goto
  (unsigned long x) {
  long result = 0;
 loop:
  result += x & 0x1;
  x >>= 1;
  if(x) goto loop;
  return result;
}
```

- **计算参数x中1的个数 Count number of 1's in argument x ("popcount")**
- **使用条件分支要么继续循环要么退出循环**
  branch to either continue looping or to exit l

X86作为CISC有popcount指令 x86 being CISC has a popcount instruction

通用“Do-While”翻译
General “Do-While” Translation

C代码 C Code

```
do
    Body
    while (Test);
```

Goto版本 Goto Version

```
loop:
    Body
    if (Test)
        goto loop
```

- **循环体 Body:**

```
{
   Statement1;
   Statement2;
      …
   Statementn;
}
```

Do-While循环翻译
“Do-While” Loop Compilation

Goto版本 Goto Version

```
long pcount_goto
  (unsigned long x) {
  long result = 0;
 loop:
  result += x & 0x1;
  x >>= 1;
  if(x) goto loop;
  return result;
}
```

寄存器 Register	用途 Use(s)
`%rdi`	参数x Argument `x`
`%rax`	结果 `result`

```
    movl    $0, %eax     #  result = 0
.L2:                    # loop:
    movq    %rdi, %rdx
    andl    $1, %edx     #  t = x & 0x1
    addq    %rdx, %rax   #  result += t
    shrq    %rdi         #  x >>= 1
    jne     .L2          #  if (x) goto loop
    rep; ret
```

通用“While”循环翻译方法#1
General “While” Translation #1

- “跳转到中间”翻译方法 **“Jump-to-middle” translation**
- 使用编译参数 **Used with –Og**

While版本 While version

```
while (Test)
    Body
```

Goto版本 Goto Version

```
    goto test;
loop:
    Body
test:
    if (Test)
        goto loop;
done:
```

While循环示例 While Loop Example #1

跳转到中间版本

C代码 C Code

```
long pcount_while
  (unsigned long x) {
  long result = 0;
  while (x) {
    result += x & 0x1;
    x >>= 1;
  }
  return result;
}
```

Jump to Middle Version

```
long pcount_goto_jtm
  (unsigned long x) {
  long result = 0;
  goto test;
 loop:
  result += x & 0x1;
  x >>= 1;
 test:
  if(x) goto loop;
  return result;
}
```

- **相较于该函数的do-while版本 Compare to do-while version of function**
- **初始跳转到从测试开始循环 Initial goto starts loop at test**

通用“While”翻译方法#2
General “While” Translation #2

While版本 While version

```
while (Test)
    Body
```

Do-While版本 Do-While Version

```
  if (!Test)
    goto done;
  do
    Body
    while(Test);
done:
```

- “Do-while”转换 “Do-while” conversion
- 使用编译参数 Used with –O1

Goto版本 Goto Version

```
  if (!Test)
    goto done;
loop:
  Body
  if (Test)
    goto loop;
done:
```

While循环示例 While Loop Example #2

C代码 C Code

```
long pcount_while
  (unsigned long x) {
  long result = 0;
  while (x) {
    result += x & 0x1;
    x >>= 1;
  }
  return result;
}
```

Do-While版本 Do-While Version

```
long pcount_goto_dw
  (unsigned long x) {
  long result = 0;
  if (!x) goto done;
 loop:
  result += x & 0x1;
  x >>= 1;
  if(x) goto loop;
 done:
  return result;
}
```

- 初始条件检测在循环入口 **Initial conditional guards entrance to loop**
- 相较于该函数的**do-while**版本 **Compare to do-while version of function**
  - 删除跳转到中间这个过程。是好是坏? Removes jump to middle. When is this good or bad?

"For"循环形式 "For" Loop Form

通用格式 General Form

for (*Init*; *Test*; *Update*)

Body

```
#define WSIZE 8*sizeof(int)
long pcount_for
  (unsigned long x)
{
  size_t i;
  long result = 0;
  for (i = 0; i < WSIZE; i++)
  {
    unsigned bit =
      (x >> i) & 0x1;
    result += bit;
  }
  return result;
}
```

初始 Init

```
i = 0
```

测试 Test

```
i < WSIZE
```

更新 Update

```
i++
```

循环体 Body

```
{
  unsigned bit =
      (x >> i) & 0x1;
  result += bit;
}
```

“For”循环转换成While循环
“For” Loop → While Loop

For循环版本 For Version

```
for (Init; Test; Update)

        Body
```

While循环版本 While Version

```
Init;

while (Test) {

    Body

    Update;

}
```

For-While转换 For-While Conversion

初始 Init

```
i = 0
```

测试 Test

```
i < WSIZE
```

更新 Update

```
i++
```

循环体 Body

```
{
  unsigned bit =
      (x >> i) & 0x1;
  result += bit;
}
```

```
long pcount_for_while
  (unsigned long x)
{
  size_t i;
  long result = 0;
  i = 0;
  while (i < WSIZE)
  {
    unsigned bit =
      (x >> i) & 0x1;
    result += bit;
    i++;
  }
  return result;
}
```

“For”循环到Do-While循环转换

“For” Loop Do-While Conversion

C代码 C Code

```
long pcount_for
  (unsigned long x)
{
  size_t i;
  long result = 0;
  for (i = 0; i < WSIZE; i++)
  {
    unsigned bit =
      (x >> i) & 0x1;
    result += bit;
  }
  return result;
}
```

- 初始测试可以优化掉 Initial test can be optimized away

Goto版本 Goto Version

```
long pcount_for_goto_dw
  (unsigned long x) {
  size_t i;
  long result = 0;
  i = 0;                      初始 Init
  if (!(i < WSIZE))
    goto done;                非终止测试 ! Test
 loop:
  {
    unsigned bit =
      (x >> i) & 0x1;         循环体 Body
    result += bit;
  }
  i++                         更新 Update
  if (i < WSIZE)
    goto loop;                测试 Test
 done:
  return result;
}
```

议题

- 控制：条件码 Control: Condition codes
- 条件分支 Conditional branches
- 循环 Loops
- **Switch（开关）语句 Switch Statements**

```c
long switch_eg
   (long x, long y, long z)
{
    long w = 1;
    switch(x) {
    case 1:
        w = y*z;
        break;
    case 2:
        w = y/z;
        /* Fall Through */
    case 3:
        w += z;
        break;
    case 5:
    case 6:
        w -= z;
        break;
    default:
        w = 2;
    }
    return w;
}
```

Switch语句示例 Switch Statement Example

- 多个情况标签 **Multiple case labels**
  - 此处：5和6 Here: 5 & 6
- 落入其它情况 **Fall through cases**
  - 此处：2 Here: 2
- 缺失的情况 **Missing cases**
  - 此处：4 Here: 4

跳转表结构 Jump Table Structure

开关形式 Switch Form

```
switch(x) {
  case val_0:
    Block 0
  case val_1:
    Block 1
    • • •
  case val_n-1:
    Block n–1
}
```

跳转表 Jump Table

jtab:
Targ0
Targ1
Targ2
• • •
Targ*n*-1

跳转目标 Jump Targets

Targ0: Code Block 0

Targ1: Code Block 1

Targ2: Code Block 2

• • •

Targ*n*-1: Code Block *n*–1

翻译 Translation (Extended C)

```
goto *JTab[x];
```

开关语句示例 Switch Statement Example

```
long switch_eg(long x, long y, long z)
{
    long w = 1;
    switch(x) {
      . . .
    }
    return w;
}
```

组织方式 **Setup:**

```
switch_eg:
    movq    %rdx, %rcx
    cmpq    $6, %rdi     # x:6
    ja      .L8
    jmp     *.L4(,%rdi,8)
```

默认值的范围是多少？ **What range of values takes default?**

寄存器 Register	用途 Use(s)
`%rdi`	参数x Argument **`x`**
`%rsi`	参数y Argument **`y`**
`%rdx`	参数z Argument **`z`**
`%rax`	返回值 Return value

注意w此处没有初始化 Note that **`w`** not initialized here

开关语句示例 Switch Statement Example

```
long switch_eg(long x, long y, long z)
{
    long w = 1;
    switch(x) {
      . . .
    }
    return w;
}
```

跳转表 **Jump table**

```
.section    .rodata
  .align 8
.L4:
  .quad     .L8   # x = 0
  .quad     .L3   # x = 1
  .quad     .L5   # x = 2
  .quad     .L9   # x = 3
  .quad     .L8   # x = 4
  .quad     .L7   # x = 5
  .quad     .L7   # x = 6
```

组织方式 **Setup:**

```
switch_eg:
    movq    %rdx, %rcx
    cmpq    $6, %rdi         # x:6
    ja      .L8              # Use default
    jmp     *.L4(,%rdi,8)    # goto *JTab[x]
```

间接跳转 ***Indirect jump***

汇编程序组织方式解释
Assembly Setup Explanation

- 跳转表结构 **Table Structure**
  - 每个目标需要8字节 Each target requires 8 bytes
  - 基地址在.L4处 Base address at **`.L4`**

- 跳转 **Jumping**
  - 直接跳转 **Direct:** **`jmp .L8`**
  - 跳转目标由标号.L8指示 Jump target is denoted by label **`.L8`**

  - 间接跳转 **Indirect:** **`jmp *.L4(,%rdi,8)`**
  - 跳转表从.L4开始 Start of jump table: **`.L4`**
  - 必须用8做比例因子（地址是8字节） Must scale by factor of 8 (addresses are 8 bytes)
  - 从有效地址获取目标 Fetch target from effective Address **`.L4 + x*8`**
    - 仅在范围内 Only for $0 \le \mathbf{x} \le 6$

跳转表 **Jump table**

```
.section    .rodata
  .align 8
.L4:
  .quad     .L8   # x = 0
  .quad     .L3   # x = 1
  .quad     .L5   # x = 2
  .quad     .L9   # x = 3
  .quad     .L8   # x = 4
  .quad     .L7   # x = 5
  .quad     .L7   # x = 6
```

跳转表 Jump Table

跳转表 Jump table

```
.section    .rodata
  .align 8
.L4:
  .quad     .L8    # x = 0
  .quad     .L3    # x = 1
  .quad     .L5    # x = 2
  .quad     .L9    # x = 3
  .quad     .L8    # x = 4
  .quad     .L7    # x = 5
  .quad     .L7    # x = 6
```

```
switch(x) {
case 1:        // .L3
    w = y*z;
    break;
case 2:        // .L5
    w = y/z;
    /* Fall Through */
case 3:        // .L9
    w += z;
    break;
case 5:
case 6:        // .L7
    w -= z;
    break;
default:       // .L8
    w = 2;
}
```

代码块（x等于1时） Code Blocks (x == 1)

```
  switch(x) {
  case 1:        // .L3
        w = y*z;
        break;
   . . .
}
```

```
.L3:
   movq    %rsi, %rax  # y
   imulq   %rdx, %rax  # y*z
   ret
```

寄存器 Register	用途 Use(s)
`%rdi`	参数x Argument **`x`**
`%rsi`	参数y Argument **`y`**
`%rdx`	参数z Argument **`z`**
`%rax`	返回值 Return value

处理落入其它情况 Handling Fall-Through

```
long w = 1;
   . . .
switch(x) {
   . . .
case 2:
    w = y/z;
    /* Fall Through */
case 3:
    w += z;
    break;
   . . .
}
```

```
case 2:
    w = y/z;
    goto merge;
```

```
case 3:
        w = 1;

merge:
        w += z;
```

代码块（当x为2，3时）
Code Blocks (x == 2, x == 3)

```
long w = 1;
   . . .
switch(x) {
   . . .
case 2:
    w = y/z;
    /* Fall Through */
case 3:
    w += z;
    break;
   . . .
}
```

```
.L5:                        # Case 2
   movq     %rsi, %rax
   cqto                     # 扩展为8字节
   idivq    %rcx            #  y/z
   jmp      .L6             #  goto merge
.L9:                        # Case 3
   movl     $1, %eax        #  w = 1
.L6:                        # merge:
   addq     %rcx, %rax      #  w += z
   ret
```

寄存器 Register	用途 Use(s)
%rdi	参数x Argument **x**
%rsi	参数y Argument **y**
%rdx	参数z Argument **z**
%rax	返回值 Return value

代码块（当x为5，6时）
Code Blocks (x == 5, x == 6, default)

```
  switch(x) {
    . . .
    case 5:  // .L7
    case 6:  // .L7
        w -= z;
        break;
    default: // .L8
        w = 2;
}
```

```
.L7:                     # Case 5,6
  movl   $1, %eax        #  w = 1
  subq   %rdx, %rax      #  w -= z
  ret
.L8:                     # Default:
  movl   $2, %eax        #  2
  ret
```

寄存器 Register	用途 Use(s)
`%rdi`	参数x Argument **x**
`%rsi`	参数y Argument **y**
`%rdx`	参数z Argument **z**
`%rax`	返回值 Return value

练习 Exercise

```
void switch2(long x, long *dest){
  long val = 0;
  switch (x) {
    ...
   Body of switch statement omitted
  }
  *dest = val;
}
```

- switch 语句内情况标号的值分别是多少?
- C代码中哪些情况有多个标号?

```
switch2:
    addq   $1, %rdi
    cmpq   $8, %rdi
    ja     .L2
    jmp    *.L4(,%rdi,8)
```

```
.L4:
     .quad .L9   # x = -1
     .quad .L5   # x = 0
     .quad .L6   # x = 1
     .quad .L7   # x = 2
     .quad .L2   # x = 3
     .quad .L7   # x = 4
     .quad .L8   # x = 5
     .quad .L2   # x = 6
     .quad .L5   # x = 7
```

小结 Summarizing

- C语言控制 C Control
  - if-then-else
  - do-while
  - while, for
  - switch
- 汇编器控制 Assembler Control
  - 条件跳转 Conditional jump
  - 条件传送 Conditional move
  - 间接跳转（通过跳转表） Indirect jump (via jump tables)
  - 编译器生成代码序列实现更复杂的控制 Compiler generates code sequence to implement more complex control
- 标准技术 Standard Techniques
  - 循环转换成do-while或跳转到中间的形式 Loops converted to do-while or jump-to-middle form
  - 大型switch语句使用跳转表 Large switch statements use jump tables
  - 稀疏switch语句可能使用决策树（if-elseif-elseif-else） Sparse switch statements may use decision trees (if-elseif-elseif-else)

小结 Summary

- **本次议题**
  - 控制：条件码 Control: Condition codes
  - 条件分支和条件传送 Conditional branches & conditional moves
  - 循环 Loops
  - Switch语句 Switch statements
- **下次议题 Next Time**
  - 栈 Stack
  - 调用/返回 Call / return
  - 过程调用准则 Procedure call discipline

找到二进制跳转表
Finding Jump Table in Binary

```
 00000000004005e0 <switch_eg>:
4005e0:        48 89 d1                mov    %rdx,%rcx
4005e3:        48 83 ff 06             cmp    $0x6,%rdi
4005e7:        77 2b                   ja     400614 <switch_eg+0x34>
4005e9:        ff 24 fd f0 07 40 00    jmpq   *0x4007f0(,%rdi,8)
4005f0:        48 89 f0                mov    %rsi,%rax
4005f3:        48 0f af c2             imul   %rdx,%rax
4005f7:        c3                      retq
4005f8:        48 89 f0                mov    %rsi,%rax
4005fb:        48 99                   cqto
4005fd:        48 f7 f9                idiv   %rcx
400600:        eb 05                   jmp    400607 <switch_eg+0x27>
400602:        b8 01 00 00 00          mov    $0x1,%eax
400607:        48 01 c8                add    %rcx,%rax
40060a:        c3                      retq
40060b:        b8 01 00 00 00          mov    $0x1,%eax
400610:        48 29 d0                sub    %rdx,%rax
400613:        c3                      retq
400614:        b8 02 00 00 00          mov    $0x2,%eax
400619:        c3                      retq
```

找到二进制跳转表（续）
Finding Jump Table in Binary (cont.)

```
 00000000004005e0 <switch_eg>:
 . . .
 4005e9:       ff 24 fd f0 07 40 00     jmpq   *0x4007f0(,%rdi,8)
 . . .
```

```
 % gdb switch
(gdb) x /8xg 0x4007f0
0x4007f0:       0x0000000000400614      0x00000000004005f0
0x400800:       0x00000000004005f8      0x0000000000400602
0x400810:       0x0000000000400614      0x000000000040060b
0x400820:       0x000000000040060b      0x2c646c25203d2078
(gdb)
```

找到二进制跳转表（续）
Finding Jump Table in Binary (cont.)

```
 % gdb switch
(gdb) x /8xg 0x4007f0
0x4007f0:       0x0000000000400614      0x00000000004005f0
0x400800:       0x00000000004005f8      0x0000000000400602
0x400810:       0x0000000000400614      0x000000000040060b
0x400820:       0x000000000040060b      0x2c646c25203d2078
```

```
  . . .
  4005f0:      48 89 f0             mov    %rsi,%rax
  4005f3:      48 0f af c2          imul   %rdx,%rax
  4005f7:      c3                   retq
  4005f8:      48 89 f0             mov    %rsi,%rax
  4005fb:      48 99                cqto
  4005fd:      48 f7 f9             idiv   %rcx
  400600:      eb 05                jmp    400607 <switch_eg+0x27>
  400602:      b8 01 00 00 00       mov    $0x1,%eax
  400607:      48 01 c8             add    %rcx,%rax
  40060a:      c3                   retq
  40060b:      b8 01 00 00 00       mov    $0x1,%eax
  400610:      48 29 d0             sub    %rdx,%rax
  400613:      c3                   retq
  400614:      b8 02 00 00 00       mov    $0x2,%eax
  400619:      c3                   retq
```