Machine-Level Programming II: Control

COMP402127: Introduction to Computer Systems
https://xjtu-ics.github.io/

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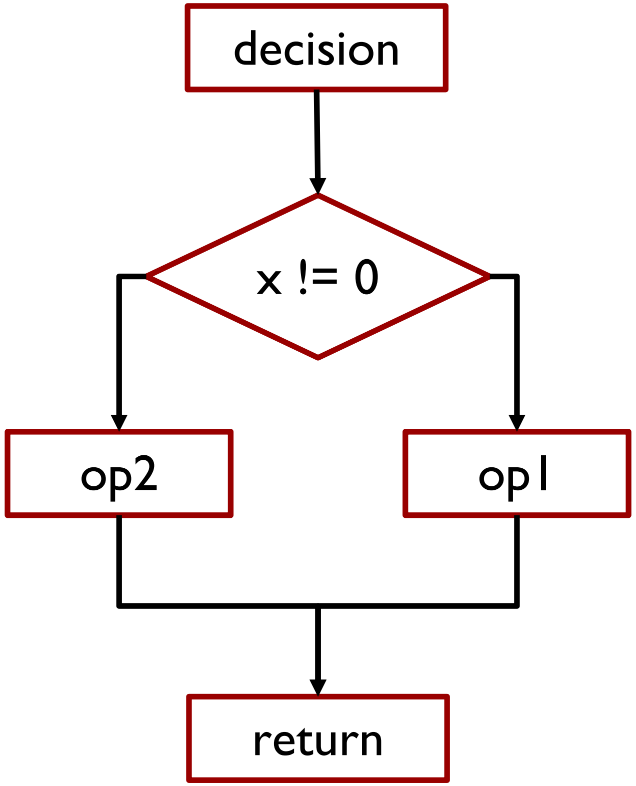
Today

- Basics of control flow
- Condition codes
- Conditional operations
- Loops
- Switch statements

Control flow

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

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



Control flow in assembly language

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

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

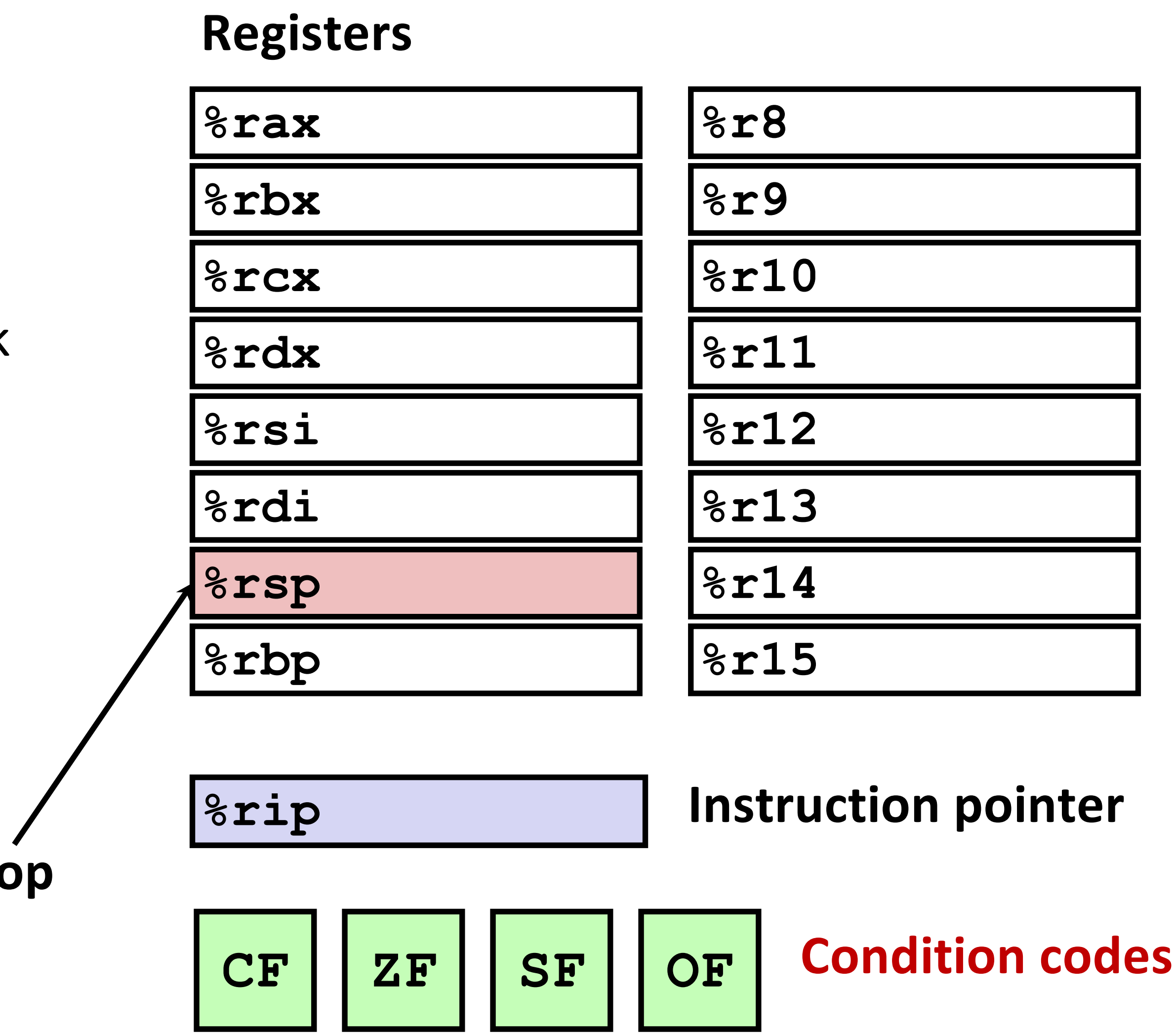
```
decision:
        subq    $8, %rsp
        testl   %edi, %edi
        je      .L2
        call    op1
        jmp     .L1
.L2:
        call    op2
.L1:
        addq    $8, %rsp
        ret
```

It's all done with GOTO!

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**)



Current stack top

Condition Codes (Implicit Setting)

Single bit registers

CF Carry Flag (for unsigned) **SF** Sign Flag (for signed)

ZF Zero Flag **OF** Overflow Flag (for signed)

Implicitly set (as side effect) of arithmetic operations

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

CF set if carry out from most significant bit (unsigned overflow)

ZF set if **`t == 0`**

SF set if **`t < 0`** (as signed)

OF set if two's-complement (signed) overflow
`(a>0 && b>0 && t<0) || (a<0 && b<0 && t>=0)`

Not set by `leaq` instruction

ZF set when

000000000000…00000000000

SF set when

```
1xxxxxxxxxxx…xxxxxxxxxxxx
```

CF set when

```
    yxxxxxxxxxxxx...
  + yxxxxxxxxxxxx...
  --------------------
  1 zxxxxxxxxxxxx...
```

Unsigned

OF set when

```
  wxxxxxxxxxxxx...
+ yxxxxxxxxxxxx...
------------------
  zxxxxxxxxxxxx...
```

Signed

$$w == y \ \&\& \ w \ != z$$

Compare Instruction

`cmp a, b`

Computes $b - a$ (just like `sub`)

Sets condition codes based on result, but…

Does not change $\boldsymbol{b}$

CF set if carry out from most significant bit (used for unsigned comparisons) (when b<a)

ZF set if b==a

SF set if (b-a) < 0 (as signed)

OF set if two’s-complement (signed overflow)

(b > 0 && a < 0 && (b-a) < 0) || (b < 0 && a > 0 && (b-a) > 0)

Used for `if (a < b) { … }`

whenever $a - b$ isn’t needed for anything else

Test Instruction

`test a, b`

Computes $b\&a$ (just like **`and`**)

Sets condition codes (only SF and ZF) based on result, but…

Does not change *b*

ZF Set when a&b == 0

SF Set when a&b < 0

Most common use: `test %rX, %rX`
to compare `%rX` to zero

Today

- Review of a few tricky bits from yesterday
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- **Conditional operations**
- Loops
- Switch statements

Reading Condition Codes

`SetX a`

Set low-order byte of **`a`** to 0 or 1 based on *combinations* of condition codes

Does not alter remaining 7 bytes

SetX	Condition	Description
`sete`	`ZF`	Equal / Zero
`setne`	`~ZF`	Not Equal / Not Zero
`sets`	`SF`	Negative
`setns`	`~SF`	Nonnegative
`setg`	`~(SF^OF)&~ZF`	Greater (Signed)
`setge`	`~(SF^OF)`	Greater or Equal (Signed)
`setl`	`(SF^OF)`	Less (Signed)
`setle`	`(SF^OF)|ZF`	Less or Equal (Signed)
`seta`	`~CF&~ZF`	Above (unsigned)
`setb`	`CF`	Below (unsigned)

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

SetX argument is always a low byte (%al, %r8b, etc.)

Reading Condition Codes (Cont.)

SetX Instructions:

Set single byte based on combination of condition codes

One of addressable byte registers

Does not alter remaining bytes

Typically use **movzbl** to finish job

32-bit instructions also set upper 32 bits to 0

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

Register	Use(s)
%rdi	Argument **x**
%rsi	Argument **y**
%rax	Return value

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

Reading Condition Codes (Cont.)

Beware weirdness **movzbl** (and others)

```
movzbl %al, %eax
```

0x00000000	0x000000	%al

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
```

Jumping

jX Instructions

Jump to different part of code depending on condition codes

jX	Condition	Description
`jmp`	`1`	Unconditional
`je`	`ZF`	Equal / Zero
`jne`	`~ZF`	Not Equal / Not Zero
`js`	`SF`	Negative
`jns`	`~SF`	Nonnegative
`jg`	`~(SF^OF)&~ZF`	Greater (Signed)
`jge`	`~(SF^OF)`	Greater or Equal (Signed)
`jl`	`(SF^OF)`	Less (Signed)
`jle`	`(SF^OF)|ZF`	Less or Equal (Signed)
`ja`	`~CF&~ZF`	Above (unsigned)
`jb`	`CF`	Below (unsigned)

Conditional Branch Example (Old Style)

I'll get to this shortly.

Generation

```
ICSServer> 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
```

Register	Use(s)
%rdi	Argument **x**
%rsi	Argument **y**
%rax	Return value

Expressing with Goto Code

- C allows goto statement
- 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;
}
```

General Conditional Expression Translation (Using Branches)

C Code

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

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

Goto Version

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

Create separate code regions for then & else expressions

Execute appropriate one

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Using Conditional Moves

Conditional Move Instructions

Instruction supports:

if (Test) Dest ← Src

Supported in post-1995 x86 processors

GCC tries to use them

But, only when known to be safe

Why?

Branches are very disruptive to instruction flow through pipelines

Conditional moves do not require control transfer

C Code

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

Goto Version

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

Conditional Move Example

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

Register	Use(s)
`%rdi`	Argument `x`
`%rsi`	Argument `y`
`%rax`	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
```

Bad Cases for Conditional Move

Expensive Computations

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

- Both values get computed
- Only makes sense when computations are very simple

Bad Performance

Risky Computations

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

- Both values get computed
- May have undesirable effects

Unsafe

Computations with side effects

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

- Both values get computed
- Must be side-effect free

Illegal

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"Do-While" Loop Example

C Code

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

Goto Version

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

- Count number of 1's in argument **x** ("popcount")
- Use conditional branch to either continue looping or to exit loop

"Do-While" Loop Compilation

Goto Version

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

Register	Use(s)
`%rdi`	Argument `x`
`%rax`	`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
    rep; ret
```

General "Do-While" Translation

C Code

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

Goto Version

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

Body:

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

General "While" Translation #1

"Jump-to-middle" translation

Used with –Og

While version

```
while (Test)
   Body
```

Goto Version

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

While Loop Example #1

C Code

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

Jump to Middle

```
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;
}
```

Compare to do-while version of function

Initial goto starts loop at test

General "While" Translation #2

While version

```
while (Test)
  Body
```

"Do-while" conversion

Used with –O1

Do-While Version

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

Goto Version

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

While Loop Example #2

C Code

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

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;
}
```

- Compare to do-while version of function
- Initial conditional guards entrance to loop

"For" Loop Form

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;
}
```

Init

```
i = 0
```

Test

```
i < WSIZE
```

Update

```
i++
```

Body

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

"For" Loop → While Loop

For Version

```
for (Init; Test; Update )
        Body
```

While Version

```
Init;
while (Test ) {
    Body
    Update;
}
```

For-While Conversion

Init

```
i = 0
```

Test

```
i < WSIZE
```

Update

```
i++
```

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" Loop Do-While Conversion

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;
}
```

Initial test can be optimized away

Goto Version

```
long pcount_for_goto_dw
  (unsigned long x) {
  size_t i;
  long result = 0;
  i = 0;                        Ini
  if (!(i < WSIZE))
    goto done;                  !Test
 loop:
  {
    unsigned bit =
      (x >> i) & 0x1;           Body
    result += bit;
  }
  i++;  Update
  if (i < WSIZE)                Test
    goto loop;
 done:
  return result;
}
```

Today

- Review of a few tricky bits from yesterday
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- Condition codes
- Conditional operations
- Loops
- **Switch statements**

```
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 Statement Example

- **Multiple case labels**
  - Here: 5 & 6
- **Fall through cases**
  - Here: 2
- **Missing cases**
  - Here: 4

Jump Table Structure

Switch Form

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

Translation (Extended C)

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

Jump Table

```
jtab: Targ0
      Targ1
      Targ2
        •
        •
        •
      Targn-1
```

Jump Targets

`Targ0:` Code Block 0

`Targ1:` Code Block 1

`Targ2:` Code Block 2

•
•
•

`Targn-1:` Code Block *n*–1

Switch Statement Example

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

Setup:

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

What range of values takes default?

Register	Use(s)
`%rdi`	Argument **`x`**
`%rsi`	Argument **`y`**
`%rdx`	Argument **`z`**
`%rax`	Return value

Note that **`w`** not initialized here

Switch Statement Example

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

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
```

Setup:

Indirect jump

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

Assembly Setup Explanation

Table Structure

Each target requires 8 bytes

Base address at **.L4**

Jumping

Direct: `jmp .L8`

Jump target is denoted by label **.L8**

Indirect: `jmp *.L4(,%rdi,8)`

Start of jump table: **.L4**

Must scale by factor of 8 (addresses are 8 bytes)

Fetch target from effective Address **.L4 + x*8**

Only for $0 \leq \mathbf{x} \leq 6$

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
```

Jump Table

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;
}
```

Code Blocks (x == 1)

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

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

Register	Use(s)
`%rdi`	Argument **x**
`%rsi`	Argument **y**
`%rdx`	Argument **z**
`%rax`	Return value

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;
```

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
   idivq    %rcx              #  y/z
   jmp      .L6               #  goto merge
.L9:                          # Case 3
   movl     $1, %eax          #  w = 1
.L6:                          # merge:
   addq     %rcx, %rax        #  w += z
   ret
```

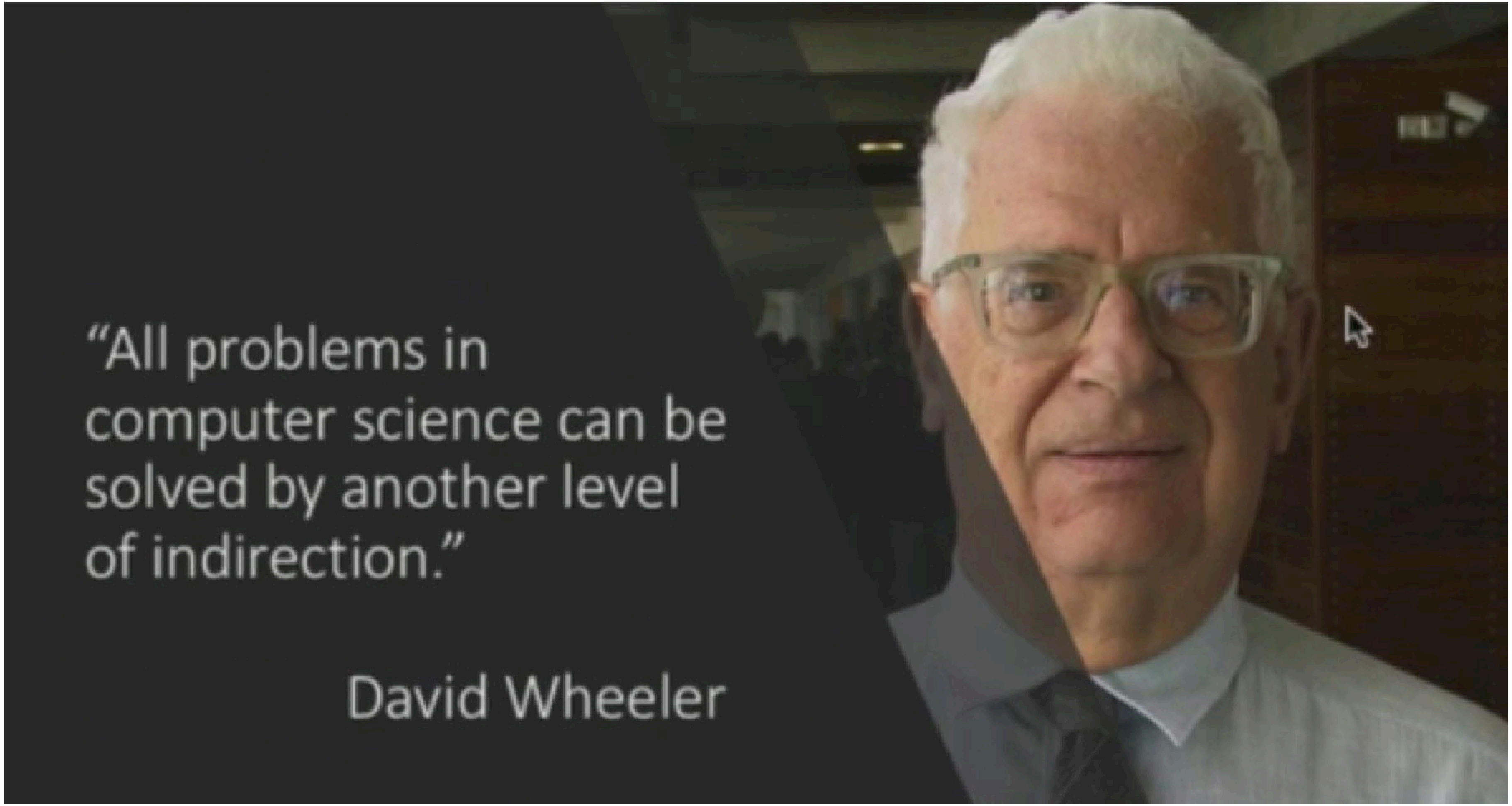
Register	Use(s)
%rdi	Argument **x**
%rsi	Argument **y**
%rdx	Argument **z**
%rax	Return value

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
```

Register	Use(s)
`%rdi`	Argument **x**
`%rsi`	Argument **y**
`%rdx`	Argument **z**
`%rax`	Return value


“All problems in
computer science can be
solved by another level
of indirection.”
David Wheeler

Summarizing

- **C Control**
  - If-then-else
  - Do-while
  - While, for
  - Switch
- **Assembler Control**
  - Conditional jump
  - Conditional move
  - Indirect jump (via dump tables)
  - Compiler generates code sequence to implement more complex control
- **Standard Techniques**
  - Loops converted to do-while or jump-to-middle form
  - Large switch statements use jump tables
  - Sparse switch statements may use decision trees (if-elseif-elseif-else)