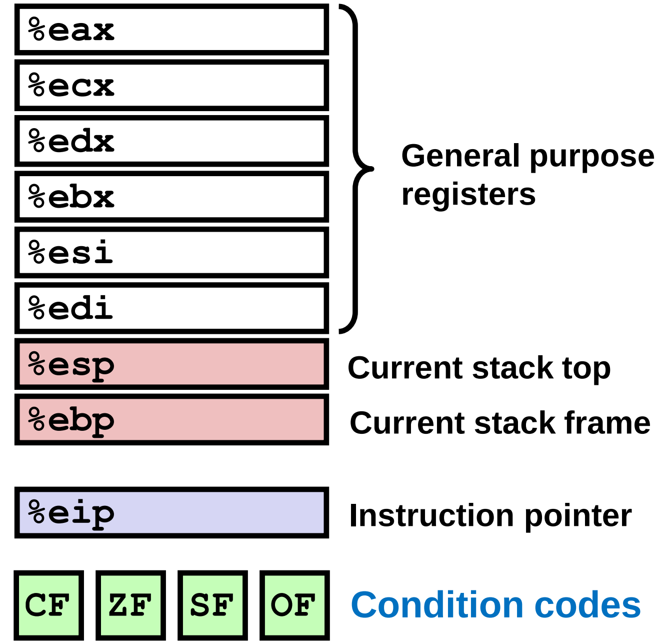
The HW/SW Interface

The x86 ISA:
Control Transfer Structures

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

Recap: Condition Codes



- Single bit registers

  CF Carry Flag (for unsigned)
  SF Sign Flag (for signed)
  ZF Zero Flag
  OF Overflow Flag (for signed)

- Implicitly set by arithmetic operations

  Example: **`addl/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 **`lea`** instruction

- Explicitly set by
  - **`cmp S2, S1`** set condition codes based on **`S1-S2`**
  - **`test S2, S1`** set condition codes based on **`S1 & S2`**

Recap: Condition Codes/Jumps

- setX: reading condition codes
  - set single byte, does not alter remaining 3 bytes
- jX: jump to different part of code depending on condition codes
- cmovX: conditional move

setX dest	jX target	cmovX S, reg	Condition	Description
	jmp		1	
sete	je	cmove	ZF	Equal / Zero
setne	jne	cmovne	~ZF	Not Equal / Not Zero
sets	js	cmovs	SF	Negative
setns	jns	cmovns	~SF	Nonnegative
setg	jg	cmovg	~(SF^OF)&~ZF	Greater (Signed)
setge	jge	cmovge	~(SF^OF)	Greater or Equal (Signed)
setl	jl	cmovl	(SF^OF)	Less (Signed)
setle	jle	cmovle	(SF^OF)|ZF	Less or Equal (Signed)
seta	ja	cmova	~CF&~ZF	Above (unsigned)
setb	jb	cmovg	CF	Below (unsigned)

Recap: if-else

```
if (cond) {
  true statements;
} else {
  false statements;
}
```

```
if (!cond) goto Else;
  true statements;
  goto Exit;
Else:
  false statements;
Exit:
```

```
    evaluate condition
    jX     .else
    true statements
    jmp .exit
.else:
    false statements
.exit:
```

Control Transfer Structures

- **Do-While Loops**
- While-Loops
- For-Loops
- Switch Statements

Acknowledgement: slides based on the cs:app2e material

“Do-While” Loop Example

C Code

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

Goto Version

```
int pcount_do(unsigned x)
{
  int 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

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

- Registers:

%edx	x
%ecx	result

```
  movl   $0, %ecx       #   result = 0
.L2:     # loop:
  movl   %edx, %eax
  andl   $1, %eax       #   t = x & 1
  addl   %eax, %ecx     #   result += t
  shrl   %edx           #   x >>= 1
  jne    .L2            #   If !0, goto loop
```

General “Do-While” Translation

C Code

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

Goto Version

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

- Body:

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

- Test returns integer
  - = 0 interpreted as false
  - ≠ 0 interpreted as true

Control Transfer Structures

- Do-While Loops
- **While-Loops**
- For-Loops
- Switch Statements

"While" Loop Example

C Code

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

Goto Version

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

- Is this code equivalent to the do-while version?
  - extra test *before* entering the loop

General “While” Translation

While version

```
while (Test)
   Body
```

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:
```

Control Transfer Structures

- Do-While Loops
- While-Loops
- **For-Loops**
- Switch Statements

"For" Loop Example

C Code

```
#define WSIZE 8*sizeof(int)
int pcount_for(unsigned x) {
  int i;
  int result = 0;
  for (i = 0; i < WSIZE; i++) {
    unsigned mask = 1 << i;
    result += (x & mask) != 0;
  }
  return result;
}
```

- Is this code equivalent to other versions?

"For" Loop Form

General Form

```
for ( Init; Test; Update )

      Body
```

```
for (i = 0; i < WSIZE; i++) {
    unsigned mask = 1 << i;
    result += (x & mask) != 0;
  }
```

Init

```
i = 0
```

Test

```
i < WSIZE
```

Update

```
i++
```

Body

```
{
  unsigned mask = 1 << i;
  result += (x & mask) != 0;
}
```

"For" Loop → While Loop

For Version

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

While Version

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

“For” Loop → … → Goto

For Version

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

While Version

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

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

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

"For" Loop Conversion Example

C Code

```
#define WSIZE 8*sizeof(int)
int pcount_for(unsigned x) {
  int i;
  int result = 0;
  for (i = 0; i < WSIZE; i++) {
    unsigned mask = 1 << i;
    result += (x & mask) != 0;
  }
  return result;
}
```

- Initial test can be optimized away

Goto Version

```
int pcount_for_gt(unsigned x) {
  int i;
  int result = 0;
  i = 0;                          Init
  if (!(i < WSIZE))               ! Test
    goto done;
 loop:
  {                               Body
    unsigned mask = 1 << i;
    result += (x & mask) != 0;
  }
  i++;  Update
  if (i < WSIZE)  Test
    goto loop;
 done:
  return result;
}
```

Control Transfer Structures

- Do-While Loops
- While-Loops
- For-Loops
- **Switch Statements**

CSE 컴퓨터공학부
Department of Computer Science & Engineering

```
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
}
```

Jump Table

jtab:

Targ0
Targ1
Targ2
• • •
Targ*n*-1

Jump Targets

Targ0: Code Block 0

Targ1: Code Block 1

Targ2: Code Block 2

•
•
•

Targ*n*-1: Code Block *n*–1

Approximate Translation

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

Switch Statement Example (IA32)

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

What range of values takes default?

Setup:

```
switch_eg:
   pushl   %ebp             # Setup
   movl    %esp, %ebp       # Setup
   movl    8(%ebp), %eax    # %eax = x
   cmpl    $6, %eax         # Compare x:6
   ja      .L2              # If unsigned > goto default
   jmp     *.L7(,%eax,4)    # Goto *JTab[x]
```

Note that **w** is not initialized here

Switch Statement Example (IA32)

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

Jump table

```
.section      .rodata
  .align 4
.L7:
  .long       .L2 # x = 0
  .long       .L3 # x = 1
  .long       .L4 # x = 2
  .long       .L5 # x = 3
  .long       .L2 # x = 4
  .long       .L6 # x = 5
  .long       .L6 # x = 6
```

Setup:

```
switch_eg:
  pushl  %ebp             # Setup
  movl   %esp, %ebp       # Setup
  movl   8(%ebp), %eax    # eax = x
  cmpl   $6, %eax         # Compare x:6
  ja     .L2              # If unsigned > goto default
  jmp    *.L7(,%eax,4)    # Goto *JTab[x]
```

Indirect jump

Assembly Setup Explanation

- Table Structure
  - Each target requires 4 bytes
  - Base address at **`.L7`**

- Jumping
  - **Direct:** **`jmp .L2`**
  - Jump target is denoted by label **`.L2`**

  - **Indirect:** **`jmp *.L7(,%eax,4)`**
  - Start of jump table: **`.L7`**
  - Must scale by factor of 4 (labels have 32-bits = 4 Bytes on IA32)
  - Fetch target from effective Address **`.L7 + eax*4`**
    - Only for $0 \le$ **`x`** ≤ 6

Jump table

```
.section   .rodata
  .align 4
.L7:
  .long    .L2 # x = 0
  .long    .L3 # x = 1
  .long    .L4 # x = 2
  .long    .L5 # x = 3
  .long    .L2 # x = 4
  .long    .L6 # x = 5
  .long    .L6 # x = 6
```

Jump Table

Jump table

```
.section   .rodata
  .align 4
.L7:
  .long    .L2 # x = 0
  .long    .L3 # x = 1
  .long    .L4 # x = 2
  .long    .L5 # x = 3
  .long    .L2 # x = 4
  .long    .L6 # x = 5
  .long    .L6 # x = 6
```

```
switch(x) {
case 1:       // .L3
    w = y*z;
    break;
case 2:       // .L4
    w = y/z;
    /* Fall Through */
case 3:       // .L5
    w += z;
    break;
case 5:
case 6:       // .L6
    w -= z;
    break;
default:      // .L2
    w = 2;
}
```

Handling Fall-Through

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

```
case 3:
        w = 1;
        goto merge;
```

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

merge:
        w += z;
```

Code Blocks (Partial)

```
switch(x) {
case 1:         // .L3
      w = y*z;
      break;
 . . .
case 3:        // .L5
    w += z;
    break;
  . . .
default:       // .L2
    w = 2;
}
```

```
.L2:      # Default
   movl  $2, %eax   # w = 2
   jmp   .L8        # Goto done

.L5:      # x == 3
   movl  $1, %eax   # w = 1
   jmp   .L9        # Goto merge

.L3:      # x == 1
   movl  16(%ebp), %eax   # z
   imull 12(%ebp), %eax   # w = y*z
   jmp   .L8               # Goto done
```

Code Blocks (Rest)

```
switch(x) {
  . . .
  case 2:  // .L4
      w = y/z;
      /* Fall Through */
  merge:    // .L9
      w += z;
      break;
  case 5:
  case 6:  // .L6
      w -= z;
      break;
}
```

```
.L4:      # x == 2
  movl  12(%ebp), %edx
  movl  %edx, %eax
  sarl  $31, %edx
  idivl 16(%ebp)   # w = y/z

.L9:      # merge:
  addl  16(%ebp), %eax # w += z
  jmp   .L8        # goto done

.L6:      # x == 5, 6
  movl  $1, %eax       # w = 1
  subl  16(%ebp), %eax # w = 1-z
```

Switch Code (Finish)

```
return w;
```

```
.L8:      # done:
   popl  %ebp
   ret
```

- Noteworthy Features
  - Jump table avoids sequencing through cases
    - Constant time, rather than linear
  - Use jump table to handle holes and duplicate tags
  - Use program sequencing to handle fall-through
  - Don't initialize w = 1 unless really need it

x86-64 Switch Implementation

- Same general idea, adapted to 64-bit code
- Table entries 64 bits (pointers)
- Cases use revised code

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

```
.L3:
  movq    %rdx, %rax
  imulq   %rsi, %rax
  ret
```

Jump Table

```
  .section  .rodata
  .align 8
.L7:
  .quad     .L2     # x = 0
  .quad     .L3     # x = 1
  .quad     .L4     # x = 2
  .quad     .L5     # x = 3
  .quad     .L2     # x = 4
  .quad     .L6     # X = 5
  .quad     .L6     # x = 6
```

IA32 Object Code

- Setup
  - Label **`.L2`** becomes address **`0x8048422`**
  - Label **`.L7`** becomes address **`0x8048660`**

Assembly Code

```
switch_eg:
  . . .
  ja     .L2              # If unsigned > goto default
  jmp    *.L7(,%eax,4)    # Goto *JTab[x]
```

Disassembled Object Code

```
08048410 <switch_eg>:
 . . .
 8048419:77 07              ja     8048422 <switch_eg+0x12>
 804841b:ff 24 85 60 86 04 08  jmp    *0x8048660(,%eax,4)
```

IA32 Object Code (cont.)

- Jump Table
  - Doesn't show up in disassembled code
  - Can inspect using GDB
  - **`gdb switch`**
  - **`(gdb) x/7xw 0x8048660`**
    - E*x*amine *7* he*x*adecimal format "*w*ords" (4-bytes each)
    - Use command "**`help x`**" to get format documentation

```
0x8048660:   0x08048422   0x08048432   0x0804843b   0x08048429
0x8048670:   0x08048422   0x0804844b   0x0804844b
```

IA32 Object Code (cont.)

- Deciphering Jump Table

```
0x8048660:    0x08048422    0x08048432    0x0804843b    0x08048429
0x8048670:    0x08048422    0x0804844b    0x0804844b
```

Address	Value	x
0x8048660	0x8048422	0
0x8048664	0x8048432	1
0x8048668	0x804843b	2
0x804866c	0x8048429	3
0x8048670	0x8048422	4
0x8048674	0x804844b	5
0x8048678	0x804844b	6

Disassembled Targets

```
8048422:    b8 02 00 00 00         mov     $0x2,%eax
8048427:    eb 2a                  jmp     8048453 <switch_eg+0x43>
8048429:    b8 01 00 00 00         mov     $0x1,%eax
804842e:    66 90                  xchg    %ax,%ax # noop
8048430:    eb 14                  jmp     8048446 <switch_eg+0x36>
8048432:    8b 45 10               mov     0x10(%ebp),%eax
8048435:    0f af 45 0c            imul    0xc(%ebp),%eax
8048439:    eb 18                  jmp     8048453 <switch_eg+0x43>
804843b:    8b 55 0c               mov     0xc(%ebp),%edx
804843e:    89 d0                  mov     %edx,%eax
8048440:    c1 fa 1f               sar     $0x1f,%edx
8048443:    f7 7d 10               idivl   0x10(%ebp)
8048446:    03 45 10               add     0x10(%ebp),%eax
8048449:    eb 08                  jmp     8048453 <switch_eg+0x43>
804844b:    b8 01 00 00 00         mov     $0x1,%eax
8048450:    2b 45 10               sub     0x10(%ebp),%eax
8048453:    5d                     pop     %ebp
8048454:    c3                     ret
```

Matching Disassembled Targets

Value
0x8048422
0x8048432
0x804843b
0x8048429
0x8048422
0x804844b
0x804844b

```
8048422:    mov     $0x2,%eax
8048427:    jmp     8048453 <switch_eg+0x43>
8048429:    mov     $0x1,%eax
804842e:    xchg    %ax,%ax
8048430:    jmp     8048446 <switch_eg+0x36>
8048432:    mov     0x10(%ebp),%eax
8048435:    imul    0xc(%ebp),%eax
8048439:    jmp     8048453 <switch_eg+0x43>
804843b:    mov     0xc(%ebp),%edx
804843e:    mov     %edx,%eax
8048440:    sar     $0x1f,%edx
8048443:    idivl   0x10(%ebp)
8048446:    add     0x10(%ebp),%eax
8048449:    jmp     8048453 <switch_eg+0x43>
804844b:    mov     $0x1,%eax
8048450:    sub     0x10(%ebp),%eax
8048453:    pop     %ebp
8048454:    ret
```

Control Transfer Structures: Summary

- C Control
  - if-then-else
  - do-while
  - while, for
  - switch

- Assembler Control
  - Conditional jump
  - Conditional move
  - Indirect jump
  - Compiler generates code sequence to implement more complex control

- Standard Techniques
  - Loops converted to do-while form
  - Large switch statements use jump tables
  - Sparse switch statements may use decision trees