Machine-Level Programming II: Control Flow

Today

- Condition codes
- Control flow structures

Next time

- Procedures

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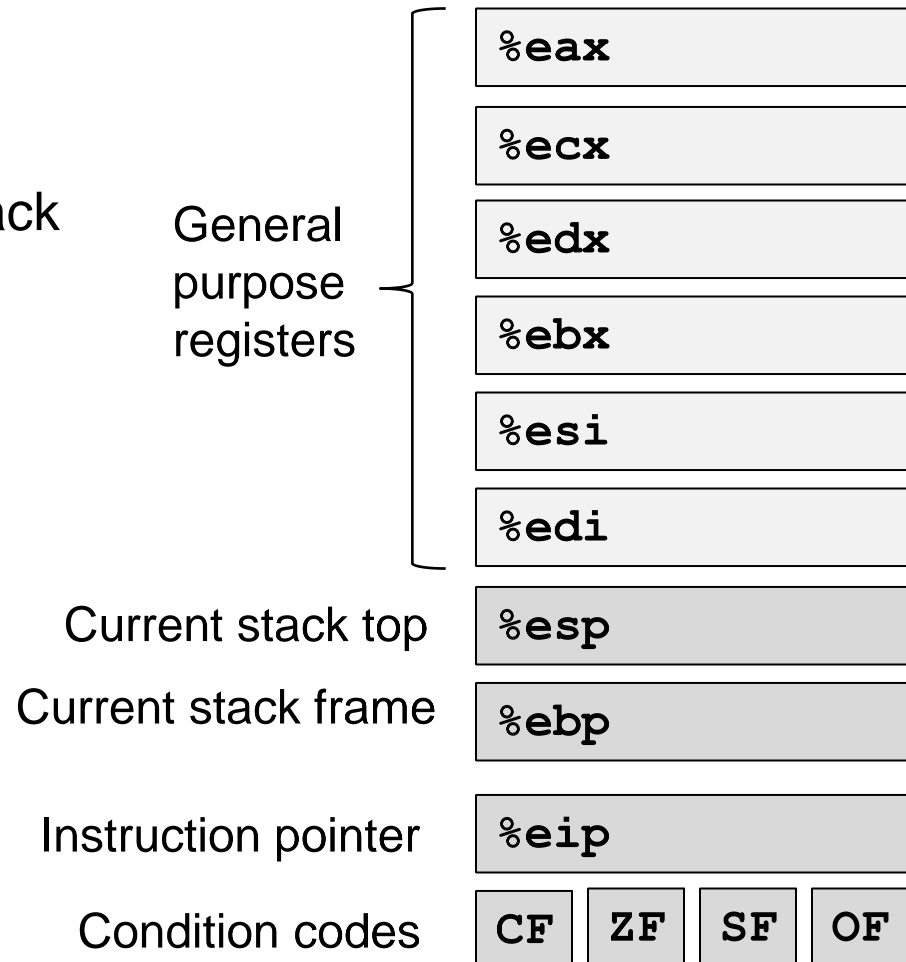
Processor state (ia32, partial)

- Information about currently executing program
  - Temporary data
  - Location of runtime stack
  - Location of current code control point
  - Status of recent tests



Condition codes (Implicit setting)

- Single bit registers

`CF`	Carry Flag	`SF`	Sign Flag
`ZF`	Zero Flag	`OF`	Overflow Flag

- Implicitly set by arithmetic operations

  `addl Src,Dest`

  C analog: t = a + b

  – `CF` set if carry out from most significant bit
    - Used to detect unsigned overflow

  – `ZF` set if t == 0

  – `SF` set if t < 0

  – `OF` set if two's complement overflow (positive or negative)

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

- Logical operations leave `CF` and `OF` set to 0
- Not set by `leal` instruction (*why?*)

Condition codes (Explicit setting: compare)

- Explicit setting by compare instruction

  `cmp{b,w,l} Src2,Src1`

  `cmpl b,a` like computing a-b without setting destination

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

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

Condition codes (Explicit setting: test)

- Explicit setting by test instruction

  `test{b,w,l}` *Src2*,*Src1*

  - Sets condition codes based on value of *Src1* `&` *Src2*
    - Useful to have one of the operands be a mask
  - `testl b,a` like `a & b` without setting destination
  - `ZF` set when `a & b == 0`
  - `SF` set when `a & b < 0`

Reading condition codes

- SetX Instructions
  - Set single byte based on combinations of condition codes
  - Note the suffixes do not indicate operand sizes, but conditions

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)

Reading condition codes

- SetX Instructions
  - Set single byte based on combinations of condition codes
  - One of 8 addressable byte registers
    - Embedded within first 4 integer registers
    - Does not alter remaining 3 bytes
    - Typically use movzbl to finish job

%eax	%ah	%al
%edx	%dh	%dl
%ecx	%ch	%cl
%ebx	%bh	%bl

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

Body

```
movl 12(%ebp),%eax   # eax = y
cmpl %eax,8(%ebp)    # Compare x : y
setg %al             # al = x > y
movzbl %al,%eax      # Zero rest of %eax
```

Note inverted ordering!

Jumping

- jX Instructions
  - Jump to different part of code depending on condition codes
  - `jmp` can be direct (to a label) or indirect (e.g. *(%eax), to M[R[%eax]]); everything else only direct

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

```
int max(int x, int y)
{
  if (x > y)
    return x;
  else
    return y;
}
```

```
max:
        pushl %ebp              Set
        movl %esp,%ebp          Up

        movl 8(%ebp),%edx
        movl 12(%ebp),%eax
        cmpl %eax,%edx          Body
        jle .L9
        movl %edx,%eax
.L9:

        leave                   Finish
        ret
```

Conditional branch example

```
int goto_max(int x, int y)
{
  int rval = y;
  int ok = (x <= y);
  if (ok)
    goto done;
  rval = x;
done:
  return rval;
}
```

- C allows “goto” as means of transferring control
  - Closer to machine-level programming style
- Generally considered bad coding style

```
    movl 8(%ebp),%edx     # edx = x
    movl 12(%ebp),%eax    # eax = y
    cmpl %eax,%edx        # x : y
    jle .L9               # if <= goto L9
    movl %edx,%eax        # eax = x   } Skipped when x ≤ y
  .L9:                    # Done:
```

Loops

- C provides different looping constructs
  - `do-while, while, for`
- No corresponding instruction in machine code
- Most compilers
  - Transform general loops into `do-while`
  - Then compile them into machine code

"Do-While" loop example

- Compute factorial of n (*n!*)

C Code

```
int fact_do (int x)
{
  int result = 1;
  do {
    result *= x;
    x = x-1;
  } while (x > 1);
  return result;
}
```

Goto Version

```
int fact_goto (int x)
{
  int result = 1;
loop:
  result *= x;
  x = x-1;
  if (x > 1)
    goto loop;
  return result;
}
```

- Use backward branch to continue looping
- Only take branch when "while" condition holds

“Do-While” loop compilation

Goto Version

```
int fact_goto
  (int x)
{
  int result = 1;
loop:
  result *= x;
  x = x-1;
  if (x > 1)
    goto loop;
  return result;
}
```

Assembly

```
fact_goto:
  pushl %ebp          # Setup
  movl %esp,%ebp      # Setup
  movl $1,%eax        # eax = 1
  movl 8(%ebp),%edx   # edx = x

.L2:
  imull %edx,%eax     # result *= x
  decl %edx           # x--
  cmpl $1,%edx        # Compare x : 1
  jg .L2              # if > goto loop

  leave               # Finish
  ret                 # Finish
```

- Registers

  `%edx   x`

  `%eax   result`

General "Do-While" translation

C Code

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

Goto Version

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

- *Body* can be any C statement
  - Typically compound statement:

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

- *Test* is expression returning integer
  - = 0 interpreted as false
  - ≠0 interpreted as true

"While" loop example #1

C Code

```
int fact_while
   (int x)
{
  int result = 1;
  while (x > 1) {
    result *= x;
    x = x-1;
  };
  return result;
}
```

First Goto Version

```
int fact_while_goto
   (int x)
{
  int result = 1;
loop:
  if (!(x > 1))
    goto done;
  result *= x;
  x = x-1;
  goto loop;
done:
  return result;
}
```

- *Is this code equivalent to the do-while version?*
- Must jump out of loop if test fails

Actual "While" loop translation

C Code

```
int fact_while(int x)
{
  int result = 1;
  while (x > 1) {
    result *= x;
    x = x-1;
  };
  return result;
}
```

- Historically used by GCC
- Uses same inner loop as do-while version
- Guards loop entry with extra test

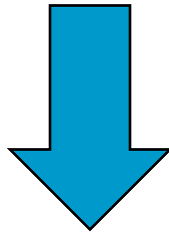
Second Goto Version

```
int fact_while_goto2
  (int x)
{
  int result = 1;
  if (!(x > 1))
    goto done;
loop:
  result *= x;
  x = x-1;
  if (x > 1)
    goto loop;
done:
  return result;
}
```

General "While" translation

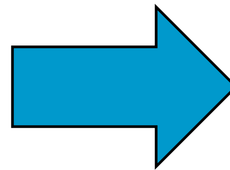
C Code

```
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:
```

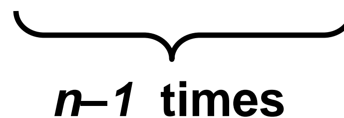
"For" loop example

```
/* Compute x raised to nonnegative power p */
int ipwr_for(int x, unsigned p) {
int result;
  for (result = 1; p != 0; p = p>>1) {
    if (p & 0x1)
      result *= x;
    x = x*x;
  }
  return result;
}
```

- Algorithm
  - Exploit property that $p = p_0 + 2p_1 + 4p_2 + \ldots 2^{n-1}p_{n-1}$
  - Gives: $x^p = z_0 \cdot z_1^{\ 2} \cdot (z_2^{\ 2})^{\ 2} \cdot \ldots \cdot (\ldots((z_{n-1}^{\ 2})^{\ 2})\ldots)^{\ 2}$

    $z_i = 1$ **when** $p_i = 0$

    $z_i = x$ **when** $p_i = 1$
  - Complexity $O(\log p)$



***n*–*1* times**

Example

$3^{10} = 3^2 * 3^8$

$= 3^2 * ((3^2)^2)^2$

`ipwr` computation

```
/* Compute x raised to nonnegative power p */
int ipwr_for(int x, unsigned p) {
int result;
  for (result = 1; p != 0; p = p>>1) {
    if (p & 0x1)
      result *= x;
    x = x*x;
  }
  return result;
}
```

result	x	p
1	3	10
1	9	5
9	81	2
9	6561	1
531441	43046721	0

"For" loop example

```
int result;
for (result = 1; p != 0; p = p>>1) {
    if (p & 0x1)
      result *= x;
    x = x*x;
}
```

General Form

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

Body

Init

```
result = 1
```

Test

```
p != 0
```

Update

```
p = p >> 1
```

Body

```
{
  if (p & 0x1)
    result *= x;
  x = x*x;
}
```

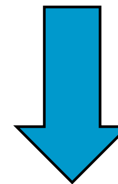
"For"→ "While"

For Version

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

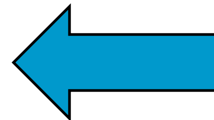
While Version

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



Do-While Version

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



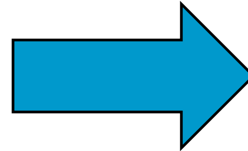
Goto Version

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

"For" loop compilation

Goto Version

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



```
   result = 1;
   if (p == 0)
      goto done;
loop:
   if (p & 0x1)
      result *= x;
   x = x*x;
   p = p >> 1;
   if (p != 0)
      goto loop;
done:
```

Init

```
result = 1
```

Test

```
p != 0
```

Update

```
p = p >> 1
```

Body

```
   {
      if (p & 0x1)
         result *= x;
      x = x*x;
   }
```

Switch statements

```
long switch_eg (long x, long y,
long z)
{
   long w = 1;
   switch(x) {
   case 1:
      w = y * x;
      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;
}
```

- A multi-way branching capability based on the value of an int
- Useful when many possible outcomes
- Switch cases
  - Multiple case labels
    - Here 5 & 6;
  - Fall through cases:
    - Here 2
  - Missing cases:
    - Here 4

Jump table structure

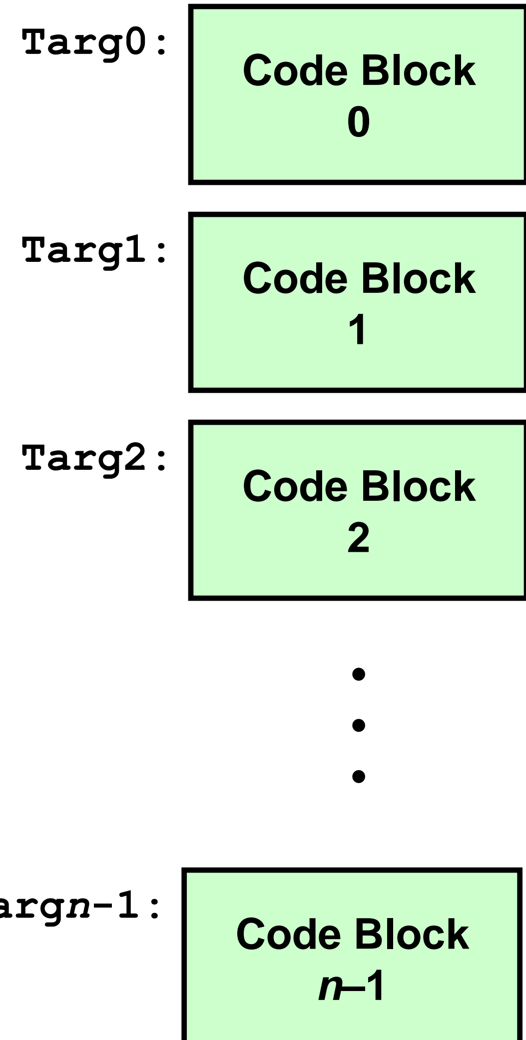
- An array where entry *i* is the address of a code segment to run when switch index equals *i*

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
• • •
Targn-1



Approx. translation

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

Switch statement example

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

Setup:

```
switch_eg:
   pushl %ebp
   movl %esp,%ebp
   pushl %ebx
   movl $1, %ebx
   movl 8(%ebp),%edx
   movl 16(%ebp), %ecx
   cmpl $6, %edx
   ja .L8
   jmp *.L9(,%edx,4)
```

Switch statement example

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

Jump table

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

Setup:

Indirect jump

```
switch_eg:
   pushl %ebp             # Setup
   movl %esp,%ebp         # Setup
   pushl %ebx             # Setup
   movl $1, %ebx          # w = 1
   movl 8(%ebp),%edx      # edx = x
   movl 16(%ebp), %ecx    # ecx = z
   cmpl $6, %edx          # Compare x-6 to 0
   ja .L8                 # if > goto default
   jmp *.L9(,%edx,4)      # goto JTab[x]
```

Assembly setup explanation

- Table structure
  - Each target requires 4 bytes
  - Base address at `.L9`

- Jumping

  `jmp .L8`

  - **Jump target is denoted by label `.L9`**

  `jmp *.L9(,%edx,4)`

  - **Start of jump table denoted by label `.L9`**
  - **Register `%edx` holds `op`**
  - **Must scale by factor of 4 to get offset into table (labels have 32-bits, 4 bytes on IA32)**
  - **Fetch target from effective Address `.L9 + op*4`**

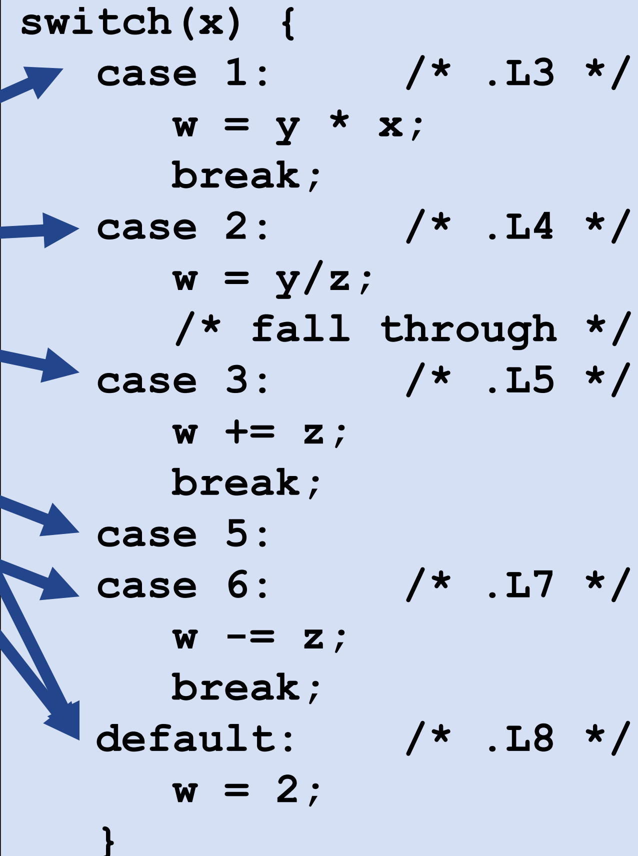
Jump table

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

Jump table

Jump table

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



```
switch(x) {
   case 1:       /* .L3 */
      w = y * x;
      break;
   case 2:       /* .L4 */
      w = y/z;
      /* fall through */
   case 3:       /* .L5 */
      w += z;
      break;
   case 5:
   case 6:       /* .L7 */
      w -= z;
      break;
   default:      /* .L8 */
      w = 2;
   }
```

Code block

```
switch(x) {
   case 1:         /* .L3 */
      w = y * x;
      break;
   case 2:         /* .L4 */
      w = y/z;
      /* fall through */
   case 3:         /* .L5 */
      w += z;
      break;
   case 5:
   case 6:         /* .L7 */
      w -= z;
      break;
   default:        /* .L8 */
      w = 2;
   }
```

```
.L3:
     movl     12(%ebp), %ebx
     imull    %edx, %ebx
     jmp      .L2
.L4:
     movl     12(%ebp), %eax
     cltd
     idivl    %ecx
     movl     %eax, %ebx
.L5:
     addl     %ecx, %ebx
     jmp      .L2
.L7:
     subl     %ecx, %ebx
     jmp      .L2
.L8:
     movl     $2, %ebx
```

- `imull` S R[%edx]:R[%eax] ← S * R[%eax]
- `cltd` R[%edx]:R[%eax] ←SignExtend(R[%eax])
  Convert to quad word for division
- `idivl` S R[%edx] ← R[%edx]:R[%eax] mod S
  R[%eax] ← R[%edx]:R[%eax] / S

Object code

- Setup
  – Label `.L8` becomes address `0x8048367`
  – Label `.L9` becomes address `0x8048470`

```
08048334 <switch_eg>:
8048334:       55                      push   %ebp
8048335:       89 e5                   mov    %esp,%ebp
8048337:       53                      push   %ebx
8048338:       8b 55 08                mov    0x8(%ebp),%edx
804833b:       8b 4d 10                mov    0x10(%ebp),%ecx
804833e:       bb 01 00 00 00          mov    $0x1,%ebx
8048343:       83 fa 06                cmp    $0x6,%edx
8048346:       77 1f                   ja     8048367 <switch_eg+0x33>
8048348:       ff 24 95 70 84 04 08    jmp    *0x8048470(,%edx,4)
```

Object code

- Jump table
  - Doesn't show up in disassembled code
  - Can inspect using GDB

```
gdb code-examples
(gdb) x/7xw 0x8048470
```

- E*x*amine *7* he*x*adecimal format "*w*ords" (4-bytes each)
- Use command "`help x`" to get format documentation

```
0x8048470:
    0x08048367
    0x0804834f
    0x08048357
    0x0804835f
    0x08048367
    0x08048363
    0x08048363
```

Disassembled targets

```
0x08048367
0x0804834f
0x08048357
0x0804835f
0x08048367
0x08048363
0x08048363
```

```
804834f:   8b 5d 0c            mov    0xc(%ebp),%ebx
8048352:   0f af da            imul   %edx,%ebx
8048355:   eb 15               jmp    804836c <switch_eg+0x38>
8048357:   8b 45 0c            mov    0xc(%ebp),%eax
804835a:   99                  cltd
804835b:   f7 f9               idiv   %ecx
804835d:   89 c3               mov    %eax,%ebx
804835f:   01 cb               add    %ecx,%ebx
8048361:   eb 09               jmp    804836c <switch_eg+0x38>
8048363:   29 cb               sub    %ecx,%ebx
8048365:   eb 05               jmp    804836c <switch_eg+0x38>
8048367:   bb 02 00 00 00      mov    $0x2,%ebx
804836c:   89 d8               mov    %ebx,%eax
804836e:   5b                  pop    %ebx
804836f:   c9                  leave
8048370:   c3                  ret
```

Sparse switch example

- Not practical to use jump table
  - Would require 1000 entries
- Obvious translation into if-then-else would have max. of 9 tests

```
/* Return x/111 if x is
   multiple && <= 999.
   -1 otherwise */
int div111(int x)
{
  switch(x) {
  case   0: return 0;
  case 111: return 1;
  case 222: return 2;
  case 333: return 3;
  case 444: return 4;
  case 555: return 5;
  case 666: return 6;
  case 777: return 7;
  case 888: return 8;
  case 999: return 9;
  default: return -1;
  }
}
```

Sparse switch code

- Compares x to possible case values
- Jumps different places depending on outcomes

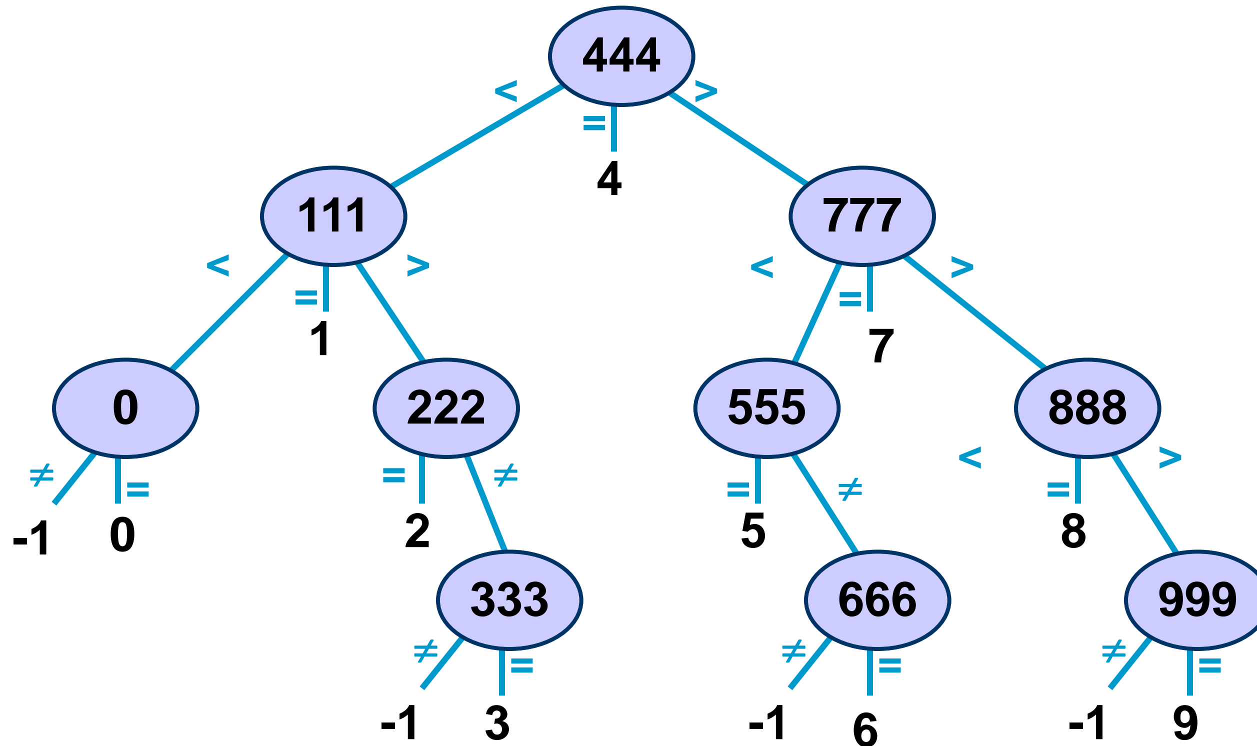
```
    movl 8(%ebp),%eax   # get x
    cmpl $444,%eax      # x:444
    je L8
    jg L16
    cmpl $111,%eax      # x:111
    je L5
    jg L17
    testl %eax,%eax     # x:0
    je L4
    jmp L14

    . . .
```

```
    . . .
L5:
    movl $1,%eax
    jmp L19
L6:
    movl $2,%eax
    jmp L19
L7:
    movl $3,%eax
    jmp L19
L8:
    movl $4,%eax
    jmp L19
    . . .
```

Sparse switch code structure

- Organizes cases as binary tree
- Logarithmic performance



Summarizing

- C Control
  - if-then-else, do-while, while, switch
- Assembler control
  - Jump & conditional jump
- Compiler
  - Must generate assembly code to implement more complex control
- Standard techniques
  - All loops → do-while form
  - Large switch statements use jump tables
- Conditions in CISC
  - Machines generally have condition code registers