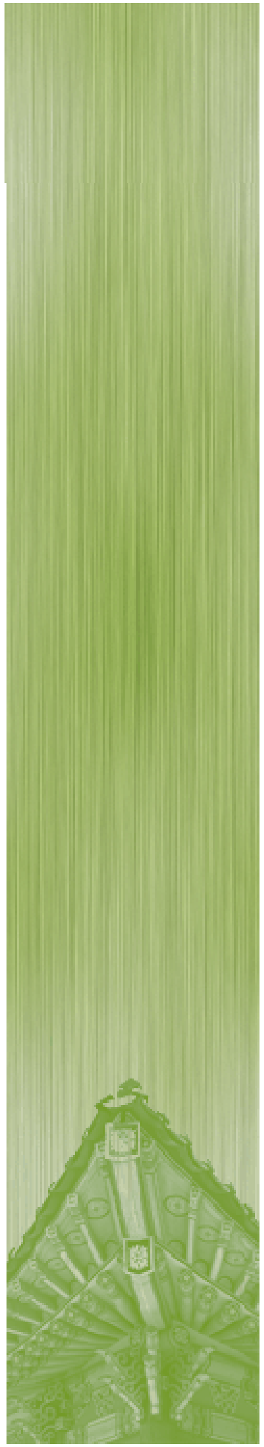

Assembly II: Control Flow

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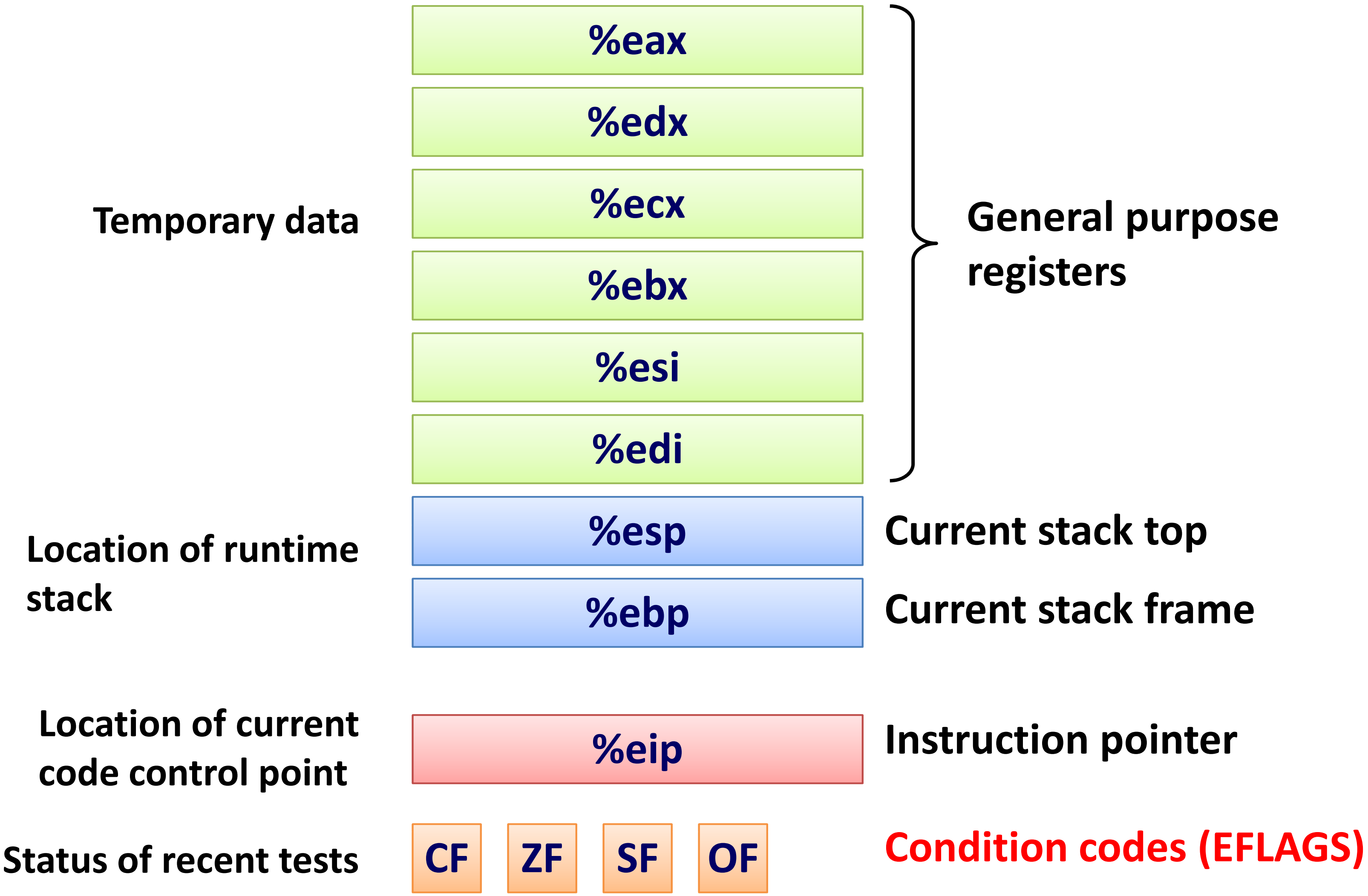
IA-32 Processor State



Temporary data

%eax

%edx

%ecx

%ebx

%esi

%edi

General purpose registers

Location of runtime stack

%esp — Current stack top

%ebp — Current stack frame

Location of current code control point

%eip — Instruction pointer

Status of recent tests

CF ZF SF OF — Condition codes (EFLAGS)

Setting Condition Codes (1)

- **Single bit registers**
  - CF (Carry), SF (Sign), ZF (Zero), OF (Overflow)
- **Implicitly set by arithmetic operations**
  - Example: **addl *Src*, *Dest*** (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
    - (a>0 && b>0 && t<0) || (a<0 && b<0 && t>0)
- **Not set by leal, incl, or decl instruction**

Setting Condition Codes (2)

- **Explicitly setting by compare instruction**
  - Example: **cmpl b, a**
  - Computes **(a – b)** without saving the result
  - 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)**

Setting Condition Codes (3)

- **Explicitly setting by test instruction**
  - Example: **testl b, a**
  - Sets condition codes based on value of **a** and **b**
    - Useful to have one of the operands be a mask
  - Computes **a & b** without setting destination
  - ZF set when **a & b == 0**
  - SF set when **a & b < 0**
  - CF and OF are cleared to 0

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 >)
jae	~CF	Above or Equal (Unsigned >=)
jb	CF	Below (Unsigned <)
jbe	CF | ZF	Below or Equal (Unsigned <=)

Reading Condition Codes (1)

- **setX instructions**
  - Set single byte based on combinations of condition codes

setX	Condition	Description
sete R_8	R_8 ← ZF	Equal / Zero
setne R_8	R_8 ← ~ZF	Not Equal / Not Zero
sets R_8	R_8 ← SF	Negative
setns R_8	R_8 ← ~SF	Nonnegative
setg R_8	R_8 ← ~(SF ^ OF) & ~ZF	Greater (Signed >)
setge R_8	R_8 ← ~(SF ^ OF)	Greater or Equal (Signed >=)
setl R_8	R_8 ← (SF ^ OF)	Less (Signed <)
setle R_8	R_8 ← (SF ^ OF) | ZF	Less or Equal (Signed <=)
seta R_8	R_8 ← ~CF & ~ZF	Above (Unsigned >)
setae R_8	R_8 ← ~CF	Above or Equal (Unsigned >=)
setb R_8	R_8 ← CF	Below (Unsigned <)
setbe R_8	R_8 ← CF | ZF	Below or Equal (Unsigned <=)

Reading Condition Codes (2)

- **setX instructions**
  - One of 8 addressable byte registers
    - **%ah, %al, %bh, %bl,**
      %ch, %cl, %dh, %dl
  - Does not alter remaining 3 bytes
  - Typically use **movzbl** to finish job

%eax	%ah	%al
%edx	%dh	%dl
%ecx	%ch	%cl
%ebx	%bh	%bl
%esi		
%edi		
%esp		
%ebp		

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

```
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!

Conditional Branch (1)

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

```
_max:
        pushl %ebp
        movl %esp,%ebp
```

Set Up

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

Body

```
        movl %ebp,%esp
        popl %ebp
        ret
```

Finish

Conditional Branch (2)

```
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
   L9:                    # Done:
```

Skipped when x ≤ y

“Do-While” Loop (1)

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 (2)

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

L11:
  imull %edx,%eax       # result *= x
  decl %edx             # x--
  cmpl $1,%edx          # Compare x : 1
  jg L11                # if > goto loop

  movl %ebp,%esp        # Finish
  popl %ebp             # Finish
  ret                   # Finish
```

- Registers

`%edx`	`x`
`%eax`	`result`

“Do-While” Loop (3)

- **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:

```
{
   Statement_1;
   Statement_2;
      …
   Statement_n;
}
```

- *Test* is expression returning integer

  = 0 interpreted as false   ≠ 0 interpreted as true

“While” Loop (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

"While" Loop (2)

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;
}
```

“While” Loop (3)

- **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 (1)

```
/* 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)

Example

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

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

“For” Loop (2)

```
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" Loop (3)

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 (4)

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;
}
```

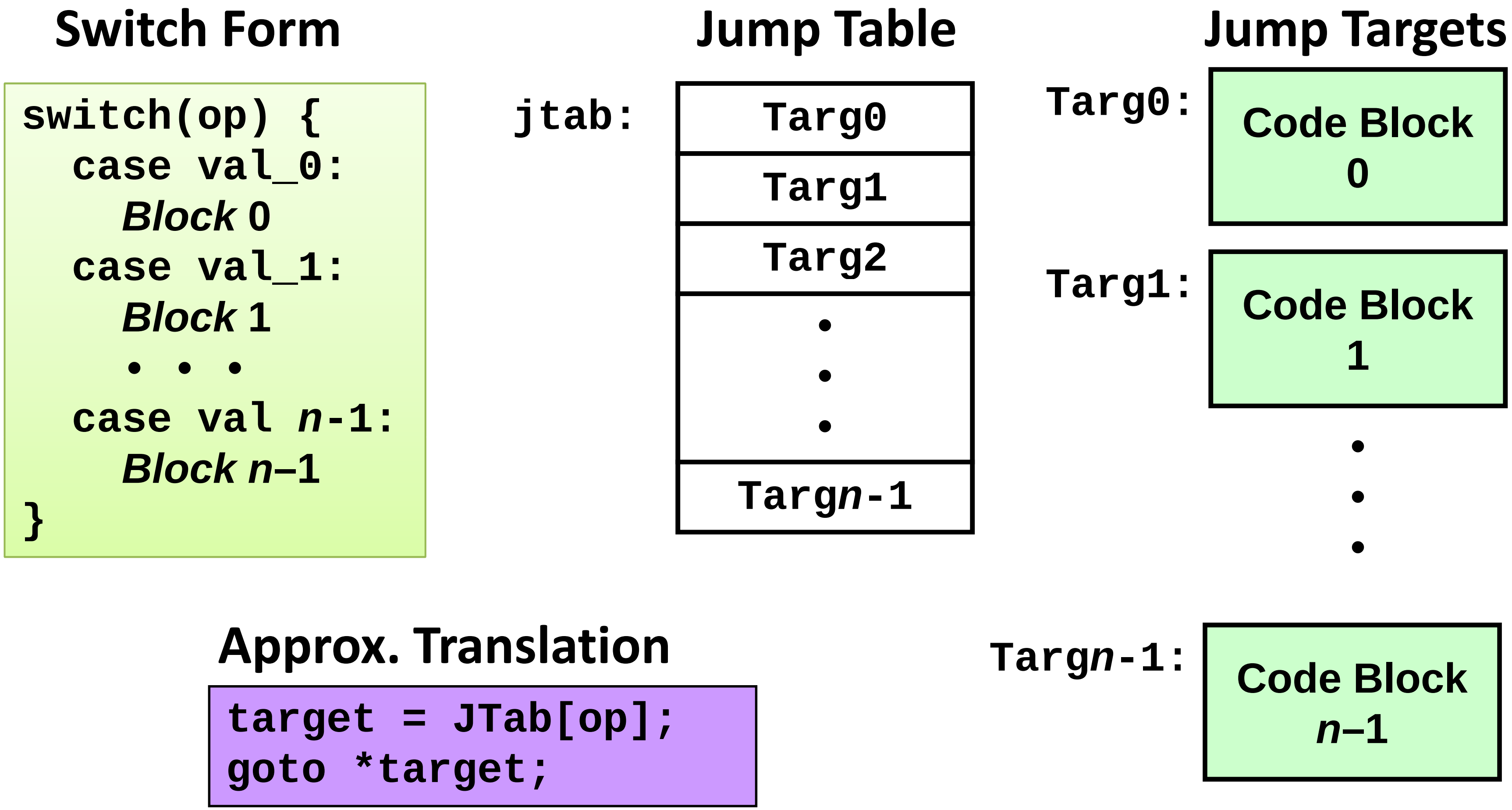
“Switch” Statement (1)

- **Implementation options**
  - Series of conditionals
    - Good if few cases
    - Slow if many
  - Jump table
    - Lookup branch target
    - Avoids conditionals
    - Possible when cases are small integer constants
  - GCC
    - Picks one based on case structure
  - Bug in example code
    - No default given

```
typedef enum {
   ADD, MULT, MINUS, DIV,
   MOD, BAD
}  op_type;

char unparse_symbol
(op_type op) {
  switch (op) {
  case ADD :  return '+';
  case MULT:  return '*';
  case MINUS: return '-';
  case DIV:   return '/';
  case MOD:   return '%';
  case BAD:   return '?';
  }
}
```

“Switch” Statement (2)

- **Jump table structure**



Switch Form

```
switch(op) {
  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
```

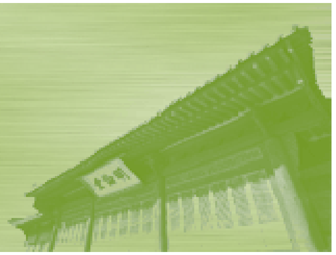
Jump Targets

```
Targ0:    Code Block 0

Targ1:    Code Block 1

            •
            •
            •

Targn-1:  Code Block n–1
```

Approx. Translation

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

“Switch” Statement (3)



Branching Possibilities

```
typedef enum {
   ADD, MULT, MINUS, DIV, MOD, BAD
}  op_type;

char unparse_symbol(op_type op)
{
  switch (op) {
    • • •
  }
}
```

Enumerated Values

ADD	0
MULT	1
MINUS	2
DIV	3
MOD	4
BAD	5

Setup:

```
unparse_symbol:
   pushl %ebp            # Setup
   movl %esp,%ebp        # Setup
   movl 8(%ebp),%eax     # eax = op
   cmpl $5,%eax          # Compare op : 5
   ja .L49               # If > goto done
   jmp *.L57(,%eax,4)    # goto Table[op]
```

“Switch” Statement (4)

- Symbolic labels
  - Labels of form **.LXX** translated into addresses by assembler
- Table structure
  - Each target requires 4 bytes, Base address at **.L57**
- Jumping
  - **jmp .L49**
    - Jump target is denoted by label **.L49**
  - **jmp *.L57(,%eax,4)**
    - Start of jump table denoted by label **.L57**
    - Register **%eax** holds **op**
    - Must scale by factor of 4 to get offset into table
    - Fetch target from effective address .**L57 + op * 4**

“Switch” Statement (5)

Table Contents

```
.section .rodata
   .align 4
.L57:
  .long .L51 #Op = 0
  .long .L52 #Op = 1
  .long .L53 #Op = 2
  .long .L54 #Op = 3
  .long .L55 #Op = 4
  .long .L56 #Op = 5
```

Enumerated Values

ADD	0
MULT	1
MINUS	2
DIV	3
MOD	4
BAD	5

Targets & Completion

```
.L51:
    movl $43,%eax # ’+’
    jmp .L49
.L52:
    movl $42,%eax # ’*’
    jmp .L49
.L53:
    movl $45,%eax # ’-’
    jmp .L49
.L54:
    movl $47,%eax # ’/’
    jmp .L49
.L55:
    movl $37,%eax # ’%’
    jmp .L49
.L56:
    movl $63,%eax # ’?’
    # Fall Through to .L49
```

“Switch” Statement (6)

Switch statement completion

```
.L49:                       # Done:
    movl %ebp,%esp          # Finish
    popl %ebp               # Finish
    ret                     # Finish
```

- What value returned when op is invalid?
  - Register %eax set to op at beginning of procedure
  - This becomes the return value

Advantage of jump table

- Can do k-way branch in O(1) operations

“Switch” Statement (7)

- **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.
   Return -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;
  }
}
```

"Switch" Statement (8)

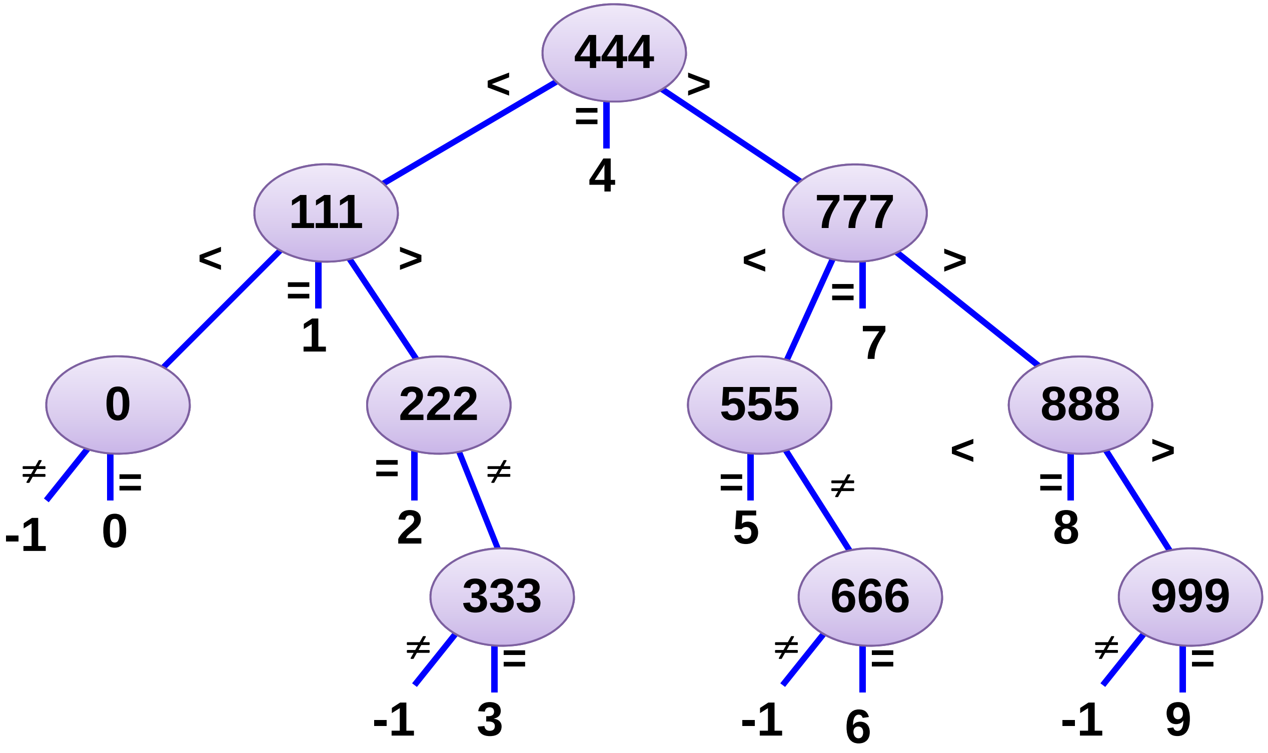
- Compares x to possible case values
- Jumps different places depending on outcomes

```
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
    . . .
```

"Switch" Statement (9)

- **Sparse switch code structure**
  - Organizes cases as binary tree
  - Logarithmic performance



Summary

C Control

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

Assembler control

- Jump
- Conditional jump
- Indirect jump

Compiler

- Must generate assembly code to implement more complex control

Standard techniques

- All loops converted to do-while form
- Large switch statements use jump tables

Conditions in CISC

- CISC machines generally have condition code registers

Conditions in RISC

- Use general registers to store condition information
- Special comparison instructions
- E.g., on Alpha: **cmple $16,1,$1**
  - Sets register $1 to 1 when $16 <= 1