Imperial College London

113: Architecture

Spring 2018

Lecture: Machine-Level Programming III

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Recap from yesterday

- Which conditional statement properly fills in the following blank?

```
if (__________) {...} else {...}
```

```
cmpq    $1, %rsi        # %rsi = j
setg    %dl             # %dl =
cmpq    %rdi, %rsi      # %rdi = i
setl    %al             # %al =
orb     %al, %dl        # arithmetic op
je      .else           #   sets flags
```

1. j > 1 || j < i
2. j > 1 && j < i
3. j ≤ 1 || j ≥ i
4. j ≤ 1 && j ≥ i

Today: Control flow (loops, switch)

- **Loops**
  - **`do-while`**
  - **`while`**
  - **`for`**
- `switch`

Compiling loops

C/Java code:

```
while (sum != 0) {
  <loop body>
}
```

Assembly code:

```
loopTop:  testq   %rax, %rax
          je      loopDone
          <loop body code>
          jmp     loopTop
loopDone:
```

- Other loops compiled similarly
  - We will cover variations in coming slides
- Most important to consider:
  - When should the condition be evaluated? (`while` vs. `do-while`)
  - How much jumping is involved? (we don't want to break control flow too much)

"do-while" loop example

C/Java, factorial

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

`goto` *version, factorial*

```
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 the branch when "`while`" condition holds

"do-while" loop compilation to asm

goto version, factorial

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

Assembly

```
fact_do:

  movl   $1, %eax      # eax = 1
.L2:
  imull  %edi, %eax    # eax = eax*edi
  subl   $1, %edi      # edi -= 1
  cmpl   $1, %edi      # compare 1 & edi
  jg     .L2           # jump if greater
  rep ret              # return
```

Register	Use
%edi	x
%eax	Result

http://repzret.org/p/repzret/

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

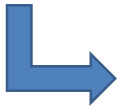
General "do-while" translation

C/Java code

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

`goto` *version*

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



- Body:

```
{
   Statement_1;
   Statement_2;
   ...
   Statement_n;
}
```

General "`while`" translation

- "*Jump-to-middle*" translation
- Used with `-Og`. Recent technique for GCC.

C/Java code

```
While (Test)
  Body
```

`goto` *version*

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

"while" loop example #1

C/Java, factorial

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

`goto` *version*

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

Assembly

```
fact_while:
  movl   $1, %eax
  jmp    .L4
.L3:
  imull %edi, %eax
  decl   %edx
.L4:
  cmpl   $1, %edx
  jg     .L3
  rep ret
```

Register	Use
%edi	Argument x
%eax	Result

- Uses same inner loop as `do-while` version
- Initial `goto` starts loop at `test`

General "while" translation #2

- "do-while" conversion
- Used with **–O1**

`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:
```

"while" loop example #2

C/Java, factorial

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

goto *version*

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

Assembly

Register	Use
%edi	Argument x
%eax	Result

```
fact_while:
  movl   $1, %eax
  cmpl   $1, %edi
  jle    .L4
.L3:
  imull %edi, %eax
  subl   $1, %edi
  cmpl   $1, %edi
  jne    .L3
.L4:
  ret
```

- Uses same inner loop as `do-while` version
- Guards loop entry with extra test

Implementing loops

- Mostly translated into form based on "`do-while`"
- Optimizer can make use of "jump-to-middle"

- Why the difference?
  - Compiler originally developed for machine where all operations were costly
  - Updated for machine where unconditional branches incur (almost) no overhead

"for" loop example

Code factorial – `for` loop

```
int fact_for(int n)
{
  int i;
  int result = 1;
  for (i = 2; i <= n; i++){
    result *= i;
  }
  return result;
}
```

`for` *loop general form*

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

```
Init:   i = 2;
Test:   i <= n;
Update: i++;
Body:   result *= i;
```

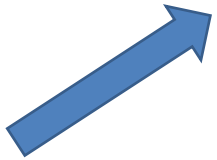
"for" loop form

C/Java `for` *loop code*

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

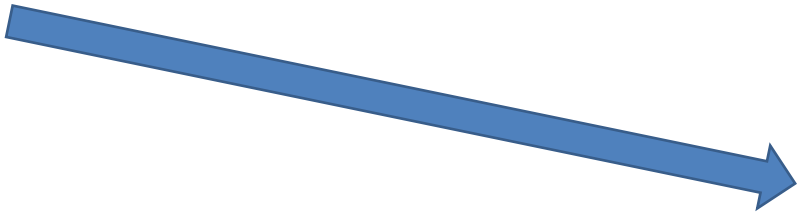
`while` *version*

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



`do-while` *GOTO*

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



goto-middle **GOTO**

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

"for" loop example: translation to goto

Code factorial (`for`* loop)*

```
for (i = 2; i <= n; i++)
{
  result *= i;
}
```

`do-while` *GOTO*

```
  i = 2;
  if (!(i <= n))
    goto done;
loop:
  result *= i;
  i++;
  if (i <= n)
    goto loop;
done:
```

`jump-in-middle` *GOTO*

```
  i = 2;
  goto test;
loop:
  result *= i;
  i++;
test:
  if (i <= n)
    goto loop;
done:
```

Caveat for `break` and `continue`

- C and Java have `break` and `continue`
- Conversion works fine for `break`
  - jump to same label as loop exit condition
- But not for `continue`, would skip doing ***Update,*** which it should do with for loops.
  - Introduce a new label at ***Update***

Today: Control flow (loops, switch)

- Loops
  - `do-while`
  - `while`
  - `for`
- **`switch`**
  - **Compact `switch` statements**
  - **Sparse `switch` statements**

Compact "switch" statement example

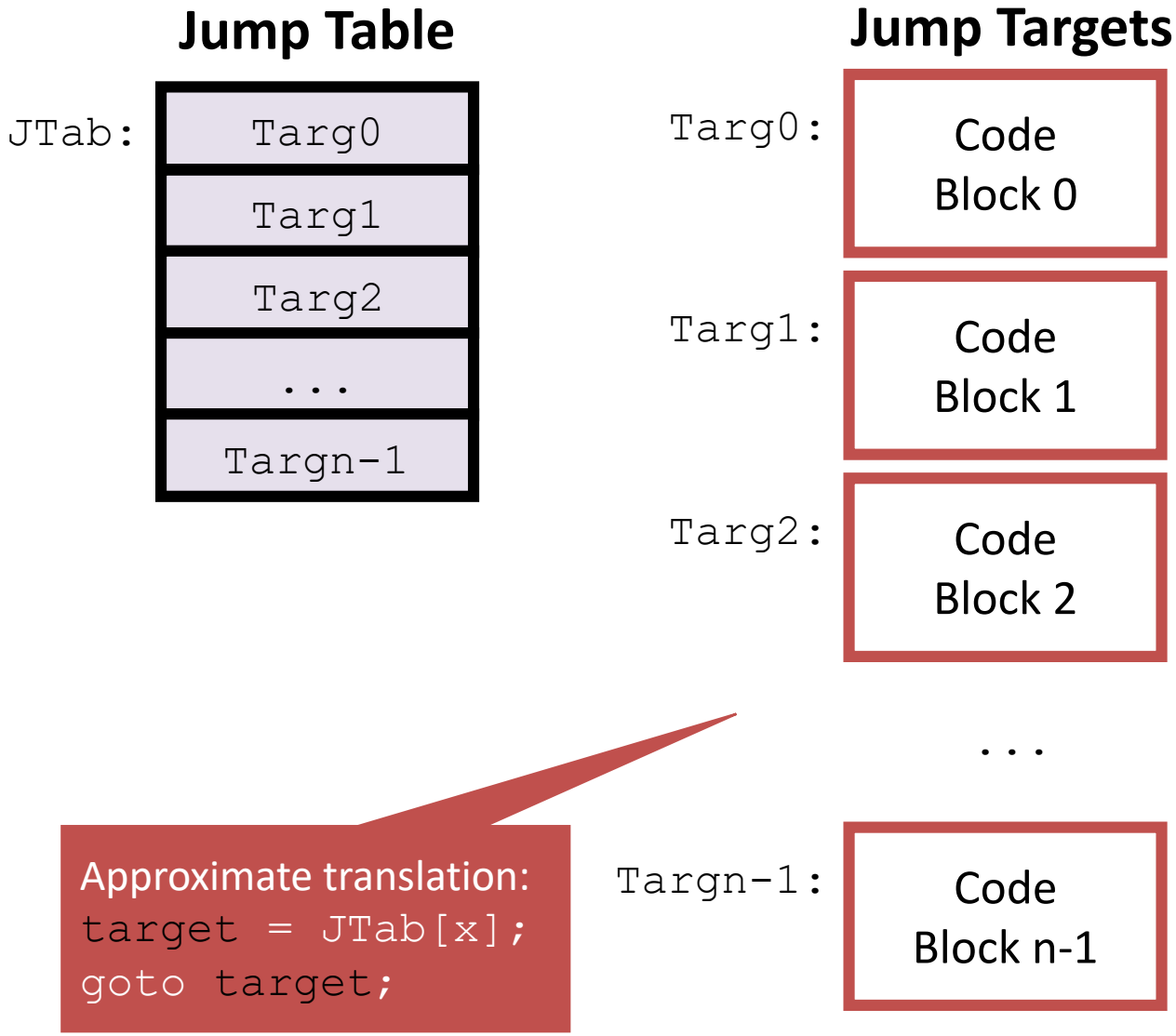
```
long switch_ex(long x, long y, long z){
    long w = 1;
    switch (x) {
        case 1:
            w = y*z;
            break;
        case 2:
            w = y/z; // fall through
        case 3:
            w += z;
            break;
        case 5:
        case 6:
            w -= z;
       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

- Multiple case labels
  - here: 5 and 6
- Fall through cases
  - here: 2
- Missing cases
  - here: 4
- Implemented with
  - Jump table
  - Indirect jump instruction

Jump Table structure

Switch form

```
switch (x) {
  case val_0:
    block 0
  case val_1:
    block 1
    ...
  case val_n-1:
    block n-1
}
```



Switch statement example

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

```
switch_ex:
    movq   %rdx, %rcx
    cmpg   $6, %rdi          # x:6
    ja     .L8               # default
    jmp    *.L4(,%rdi,8)     # jump table
```

Indirect jump
`*.Label(expression)`

`ja` **j**ump **a**bove – unsigned
catches negative default cases

Register	Use
%rdi	x
%rsi	y
%rdx	z
%rax	Return val 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
```

Assembly setup explanation

- **Jump table structure**
  - Each target requires 8 bytes (address)
  - Base address at `.L4`
- **Direct jump:** `jmp .L8`
  - Jump target is denoted by label `.L8`
- **Indirect jump:** `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 $0 \leq x \leq 6$

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

Declaring data, not instructions

8-byte memory alignment

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
```

This data is 64-bits wide

```
long switch_ex(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;
}
```

Code Blocks (x==1,x==2,x==3)

```
long switch_ex(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 2:
    w = y/z;
    goto merge;
```

```
case 3:
    w = 1;
merge:
    w += z;
```

Register	Use
%rdi	x
%rsi	y
%rdx	z
%rax	Return val w

```
.L3:
    movq   %rdx, %rax      # z
    imulq  %rsi, %rax      # y*z
    ret
.L5:                       # case 2
    movq    %rsi, %rax     # y in rax
    cqto                   # div prep
    idivq   %rcx           # y/z
    jmp     .L6            # goto merge
.L9:                       # case 3
    movl    $1, %eax       # w = 1
.L6:                       # merge:
    addq    %rcx, %rax     # w += z
    ret
```

Code Blocks (x==5, x==6, default)

```
long switch_ex(long x, long y, long z){

    long w = 1;

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

Register	Use
%rdi	x
%rsi	y
%rdx	z
%rax	Return val w

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

Question

- Would you implement this with a jump table?

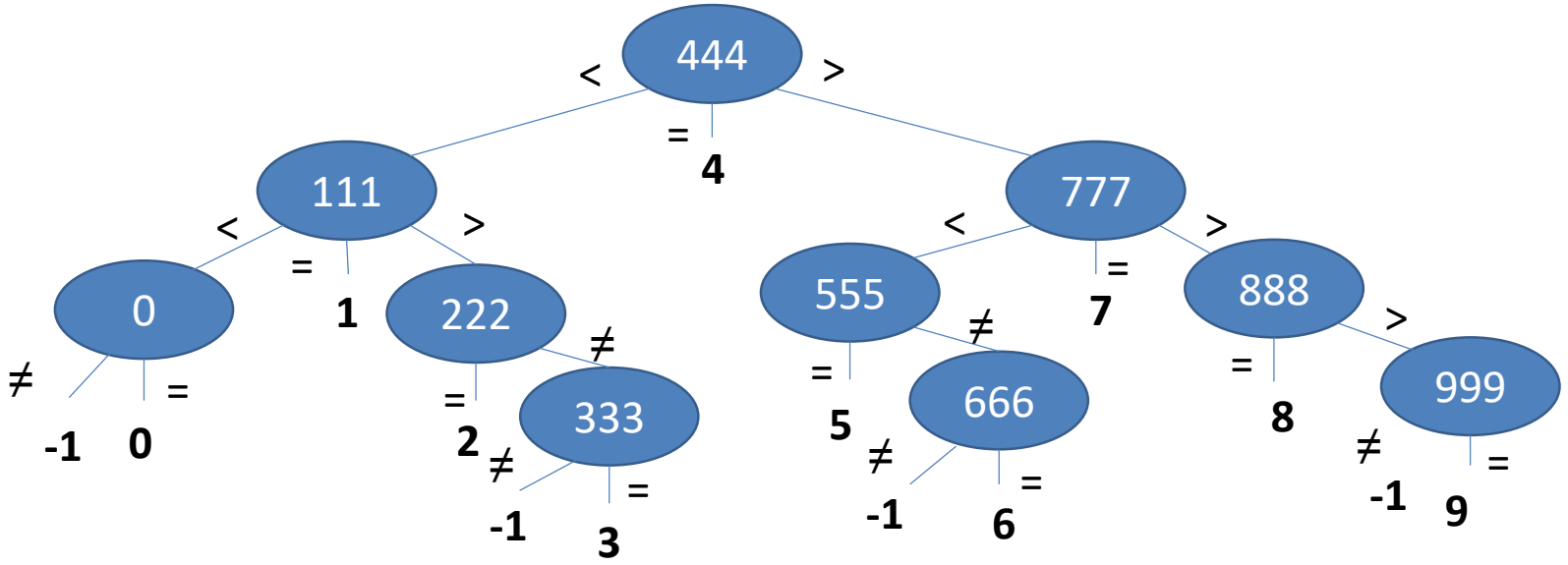
```
switch (x) {
    case 0:     <some code>
                break;
    case 10:    <some code>
                break;
    case 32767: <some code>
                break;
    default:    <some code>
                break;
}
```

- Probably not:
  - 32768-entry jump table is too big (256KiB) for only 4 cases
  - For comparison, text of this statement is 193 B

Sparse `switch` statements

```
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;
    }
}
```

- Not practical to use a jump table:
  - would require 1000 entries
- Obvious translation into if-then-else
  - would have maximum of 9 tests
- Sparse switch code structure
  - organizes the cases as a binary tree



Sparse `switch` statements

```
div111:
    cmpl    $444, %edi
    je      .L3
    jle     .L28
    cmpl    $777, %edi
    je      .L10
    jg      .L11
    cmpl    $555, %edi
    movl    $5, %eax
    je      .L1
    cmpl    $666, %edi
    movl    $6, %eax
    jne     .L2
.L1:
    rep ret
```

```
.L28:
    cmpl    $111, %edi
    movl    $1, %eax
    je      .L1
    jle     .L29
    cmpl    $222, %edi
    movl    $2, %eax
    je      .L1
    cmpl    $333, %edi
    movl    $3, %eax
    je      .L1
.L2:
    movl    $-1, %eax
.L11:
    cmpl    $888, %edi
    movl    $8, %eax
    je      .L1
```

```
    cmpl    $999, %edi
    movl    $9, %eax
    jne     .L2
    rep ret
.L29:
    xorl    %eax, %eax
    testl   %edi, %edi
    jne     .L2
    rep ret
.L10:
    movl    $7, %eax
    ret
.L3:
    movl    $4, %eax
    ret
```

Summary

- **Control flow**
  - `if-then-else`
  - `do-while`
  - `while`, `for`
  - `switch`
- **Assembler control flow**
  - conditional jump
  - conditional move
  - indirect jump
  - compiler must generate assembly code to implement more complex control flow
- **Standard techniques**
  - Loops converted to
    - `do-while`
    - Jump-to-middle
  - Large `switch` statements use jump tables
  - Sparse `switch` statements may use decision trees
- **Conditions in CISC (x86)**
  - CISC machines generally have condition code registers