CSC 252/452: Computer Organization
Fall 2024: Lecture 7

Instructor: Yanan Guo

Department of Computer Science
University of Rochester

Announcement

- Programming Assignment 2 is out
  - Details: https://www.cs.rochester.edu/courses/252/fall2024/labs/assignment2.html
  - Due on **Sep. 30th**, 11:59 PM
  - You (may still) have 3 slip days

Complete Memory Addressing Modes

- The General Form: D(Rb,Ri,S)
  - Memory address: Reg[Rb] + S * Reg[Ri] + D
  - E.g., `8(%eax, %ebx, 4)`; // address = `%eax` + 4 * `%ebx` + 8
  - D: Constant "displacement"
  - Rb: Base register: Any of 16 integer registers
  - Ri: Index register: Any, except for %rsp
  - S: Scale: 1, 2, 4, or 8
- What is `8(%eax, %ebx, 4)` used for?
- Special Cases

(Rb,Ri)	address = Reg[Rb]+Reg[Ri]
D(Rb,Ri)	address = Reg[Rb]+Reg[Ri]+D
(Rb,Ri,S)	address = Reg[Rb]+S*Reg[Ri]

Complete Memory Addressing Modes

- The General Form: D(Rb,Ri,S)
  - Memory address: Reg[Rb] + S * Reg[Ri] + D
  - E.g., **`8(%eax, %ebx, 4)`**; // address = **`%eax`** + 4 * **`%ebx`** + 8
  - D: Constant "displacement"
  - Rb: Base register: Any of 16 integer registers
  - Ri: Index register: Any, except for %rsp
  - S: Scale: 1, 2, 4, or 8
- What is **`8(%eax, %ebx, 4)`** used for?
- Special Cases

(Rb,Ri)	address = Reg[Rb]+Reg[Ri]
D(Rb,Ri)	address = Reg[Rb]+Reg[Ri]+D
(Rb,Ri,S)	address = Reg[Rb]+S*Reg[Ri]

Address Computation Instruction

```
leaq 4(%rsi,%rdi,2), %rax
```

↓

%rax = %rsi + %rdi * 2 + 4

- `leaq` Src, Dst
  - *Src* is address mode expression
  - Set *Dst* to address denoted by expression
  - No actual memory reference is made
- Uses
  - Computing addresses without a memory reference
    - E.g., translation of p = &x[i];

Some Arithmetic Operations (2 Operands)

Format	Computation	Notes
addq src, dest	Dest = Dest + Src	
subq src, dest	Dest = Dest - Src	
imulq src, dest	Dest = Dest * Src	
salq src, dest	Dest = Dest << Src	Also called **shlq**
sarq src, dest	Dest = Dest >> Src	Arithmetic shift
shrq src, dest	Dest = Dest >> Src	Logical shift
xorq src, dest	Dest = Dest ^ Src	
andq src, dest	Dest = Dest & Src	
orq src, dest	Dest = Dest | Src	

Some Arithmetic Operations (2 Operands)

No distinction between signed and unsigned (why?)

- Bit level behaviors for signed and unsigned arithmetic are exactly the same — assuming truncation

Some Arithmetic Operations (2 Operands)

No distinction between signed and unsigned (why?)

- Bit level behaviors for signed and unsigned arithmetic are exactly the same — assuming truncation

```
long signed_add
(long x, long y)
{
  long res = x + y;
  return res;
}
```

```
#x in %rdx, y in %rax
addq    %rdx, %rax
```

Some Arithmetic Operations (2 Operands)

No distinction between signed and unsigned (why?)

- Bit level behaviors for signed and unsigned arithmetic are exactly the same — assuming truncation

```
long signed_add
(long x, long y)
{
  long res = x + y;
  return res;
}
```

```
#x in %rdx, y in %rax
addq    %rdx, %rax
```

```
long unsigned_add
(unsigned long x, unsigned long y)
{
  unsigned long res = x + y;
  return res;
}
```

```
#x in %rdx, y in %rax
addq    %rdx, %rax
```

Some Arithmetic Operations (2 Operands)

No distinction between signed and unsigned (why?)

- Bit level behaviors for signed and unsigned arithmetic are exactly the same — assuming truncation

Bit-level

```
    010
+)  101
-------
    111
```

```
long signed_add
(long x, long y)
{
  long res = x + y;
  return res;
}
```

```
long unsigned_add
(unsigned long x, unsigned long y)
{
  unsigned long res = x + y;
  return res;
}
```

```
#x in %rdx, y in %rax
addq    %rdx, %rax
```

```
#x in %rdx, y in %rax
addq    %rdx, %rax
```

Some Arithmetic Operations (2 Operands)

No distinction between signed and unsigned (why?)

- Bit level behaviors for signed and unsigned arithmetic are exactly the same — assuming truncation

Bit-level	Signed
010	2
+) 101	+) -3
111	-1

```
long signed_add
(long x, long y)
{
  long res = x + y;
  return res;
}
```

```
#x in %rdx, y in %rax
addq    %rdx, %rax
```

```
long unsigned_add
(unsigned long x, unsigned long y)
{
  unsigned long res = x + y;
  return res;
}
```

```
#x in %rdx, y in %rax
addq    %rdx, %rax
```

Some Arithmetic Operations (2 Operands)

No distinction between signed and unsigned (why?)

- Bit level behaviors for signed and unsigned arithmetic are exactly the same — assuming truncation

Bit-level	Signed	Unsigned
010	2	2
+) 101	+) -3	+) 5
111	-1	7

```
long signed_add
(long x, long y)
{
  long res = x + y;
  return res;
}
```

```
long unsigned_add
(unsigned long x, unsigned long y)
{
  unsigned long res = x + y;
  return res;
}
```

```
#x in %rdx, y in %rax
addq     %rdx, %rax
```

```
#x in %rdx, y in %rax
addq     %rdx, %rax
```

Side Effect -- Set Condition Codes

`addq %rax, %rbx`

- Arithmetic instructions implicitly set condition codes (think of it as side effect)
  - **CF** set if `%rax + %rbx` generates a carry (i.e., unsigned overflow)
  - **ZF** set if `%rax + %rbx == 0`
  - **SF** set if `%rax + %rbx < 0`
  - **OF** set if `%rax + %rbx` overflows when `%rax` and `%rbx` are treated as signed numbers
    - `%rax > 0, %rbx > 0, and (%rax + %rbx) < 0), or`
    - `%rax < 0, %rbx < 0, and (%rax + %rbx) >= 0)`

Bit-level	Signed	Unsigned
111	-1	7
+) 010	+) 2	+) 2
1001	1	9

CF	ZF	SF	OF
1	0	0	0

Side Effect -- Set Condition Codes

`addq %rax, %rbx`

- Arithmetic instructions implicitly set condition codes (think of it as side effect)
  - **CF** set if `%rax + %rbx` generates a carry (i.e., unsigned overflow)
  - **ZF** set if `%rax + %rbx == 0`
  - **SF** set if `%rax + %rbx < 0`
  - **OF** set if `%rax + %rbx` overflows when `%rax` and `%rbx` are treated as signed numbers
    - `%rax > 0, %rbx > 0, and (%rax + %rbx) < 0), or`
    - `%rax < 0, %rbx < 0, and (%rax + %rbx) >= 0)`

	Bit-level	Signed	Unsigned
	011	3	3
+)	001	1	1
	100	-4	4

CF	ZF	SF	OF
0	0	1	1

Compare Instruction

`cmpq a, b`

- Computes $b - a$ (just like **sub**)
- Sets condition codes based on result, but…
- **Does not change b**
- All it does is setting condition codes!

How Should `cmpq` Set Condition Codes?

```
cmpq     %rsi, %rdi
```

`cmpq` *0xFF*, *0x80*

```
   10000000          -128
-) 11111111       -)   -1
   --------          ----
   10000001          -127
```

ZF Zero Flag (result is zero)

SF Sign Flag (result is negative)

OF Overflow Flag (result overflow)

ZF	SF	OF	CF
0	1	0	1

How Should `cmpq` Set Condition Codes?

```
cmpq     %rsi, %rdi
```

`cmpq` *0xFF*, *0x80*

```
    10000000          -128
-)  11111111      -)    -1
-------------     ----------
    10000001          -127
```

ZF Zero Flag (result is zero)

SF Sign Flag (result is negative)

OF Overflow Flag (result overflow)

ZF	SF	OF	CF
0	1	0	1

How Should `cmpq` Set Condition Codes?

`cmpq     %rsi, %rdi`

`cmpq` *0xFF*, *0x80*

```
    10000000          -128
-)  11111111       -)   -1
-------------      ---------
    10000001          -127
```

How to know if **`%rdi`** = **`%rsi`**?

Check `ZF`

ZF Zero Flag (result is zero)

SF Sign Flag (result is negative)

OF Overflow Flag (result overflow)

0	1	0	1
ZF	**SF**	**OF**	**CF**

How Should `cmpq` Set Condition Codes?

```
cmpq    %rsi, %rdi
```

`cmpq` *0xFF*, *0x80*

```
    10000000        -128
-)  11111111     -)   -1
------------     ---------
    10000001        -127
```

ZF Zero Flag (result is zero)

SF Sign Flag (result is negative)

OF Overflow Flag (result overflow)

0	1	0	1
ZF	**SF**	**OF**	**CF**

How to know if **`%rdi`** = **`%rsi`**?

Check `ZF`

How to know if **`%rdi < %rsi(signed)`**?

`%rdi` - `%rsi` < 0 and the result doesn't overflow, or

`%rdi` - `%rsi` > 0 and the result does overflow

or simply: (SF ^ OF)

How Should `cmpq` Set Condition Codes?

`cmpq      %rsi, %rdi`

`cmpq` *0xFF*, *0x80*

ZF Zero Flag (result is zero)

SF Sign Flag (result is negative)

OF Overflow Flag (result overflow)

0	1	0	1
ZF	**SF**	**OF**	**CF**

How to know if `%rdi` = `%rsi`?

Check `ZF`

How to know if `%rdi < %rsi(signed)`?

`%rdi` - `%rsi` < 0 and the result doesn't overflow, or

`%rdi` - `%rsi` > 0 and the result does overflow

or simply: (SF ^ OF)

How Should `cmpq` Set Condition Codes?

`cmpq      %rsi, %rdi`

`cmpq` *0xFF*, *0x80*

```
   10000000          -128
-) 01111111       -) 127
---------------   ---------
   00000001             1
```

ZF Zero Flag (result is zero)

SF Sign Flag (result is negative)

OF Overflow Flag (result overflow)

ZF	SF	OF	CF
0	1	0	1

How to know if **`%rdi`** = **`%rsi`**?

Check `ZF`

How to know if **`%rdi < %rsi(signed)`**?

`%rdi` - `%rsi` < 0 and the result doesn't overflow, or

`%rdi` - `%rsi` > 0 and the result does overflow

or simply: (SF ^ OF)

Reading Condition Codes

- SetX Instructions: `setl %al`
  - Set low-order byte of destination to 0 or 1 based on combinations of condition codes

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 (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
```

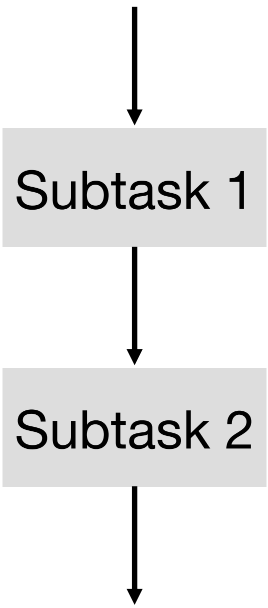
Today: Control Instructions

- Control: Conditional branches (**`if`**… **`else`**…)
- Control: Loops (for, while)
- Control: Switch Statements (**`case`**… **`switch`**…)

Three Basic Programming Constructs

Three Basic Programming Constructs

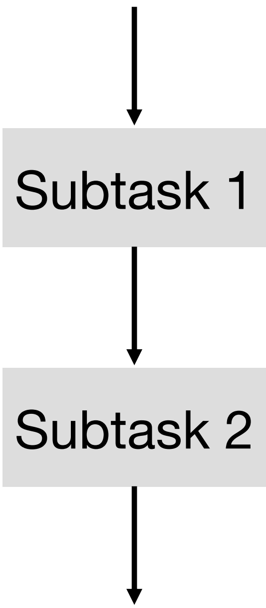
Sequential



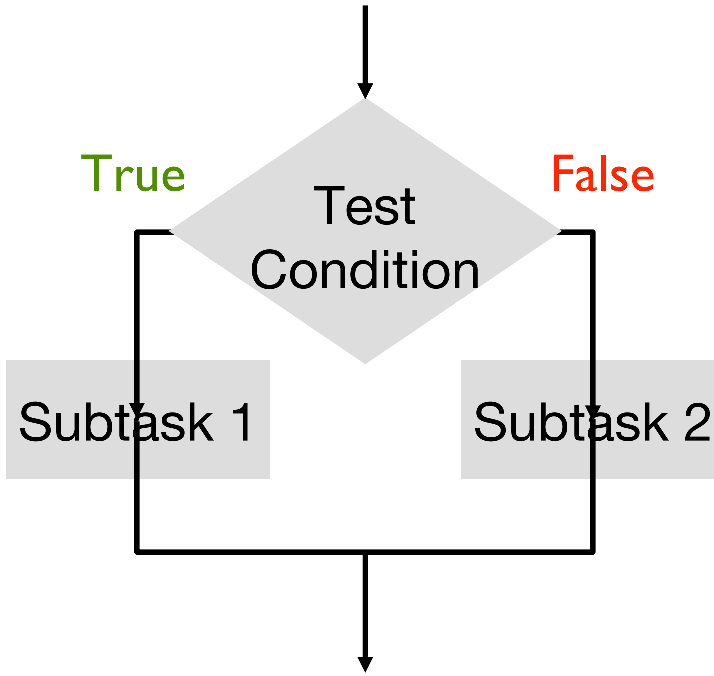

```
a = x + y;
y = a - c;
...
```

Three Basic Programming Constructs

Sequential



Conditional

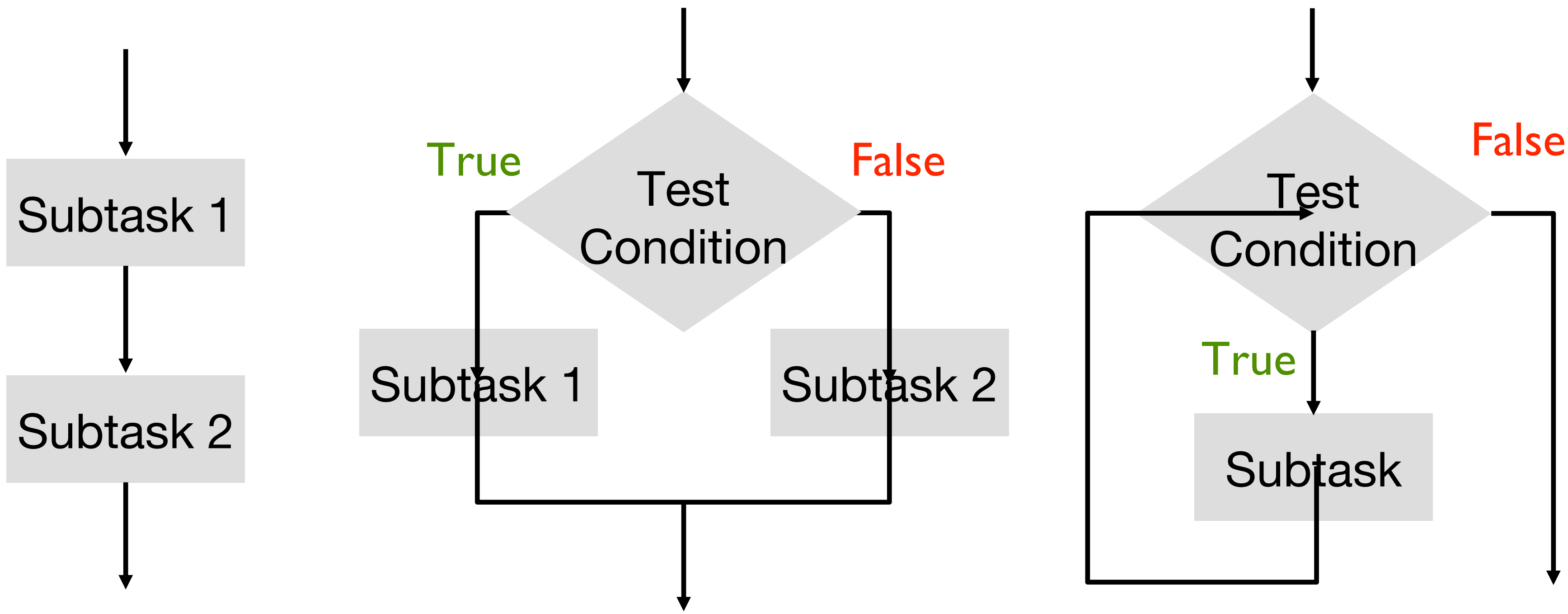



```
a = x + y;
y = a - c;
...
```

```
if (x > y) r = x - y;
else r = y - x;
```

Three Basic Programming Constructs

Sequential | **Conditional** | **Iterative**



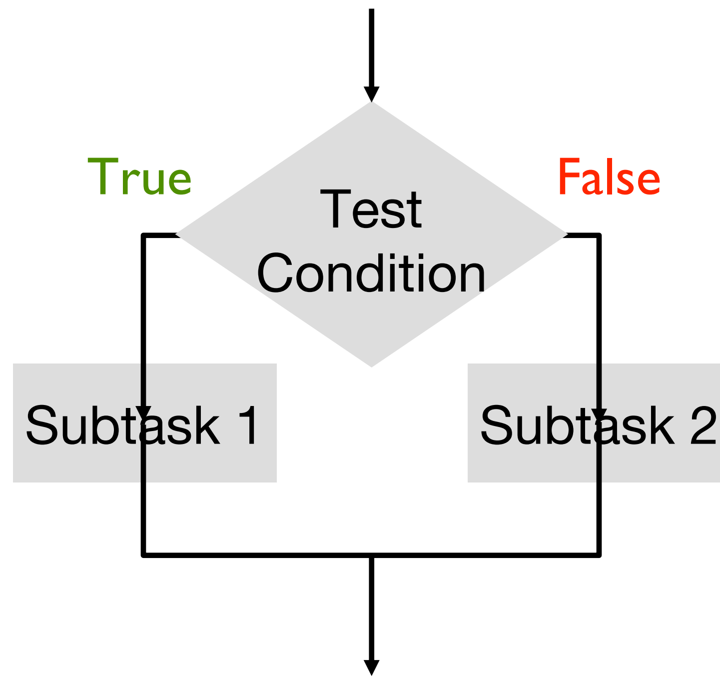

```
a = x + y;
y = a - c;
...
```

```
if (x > y) r = x - y;
else r = y - x;
```

```
while (x > 0) {
  x--;
}
```

Three Basic Programming Constructs

Conditional

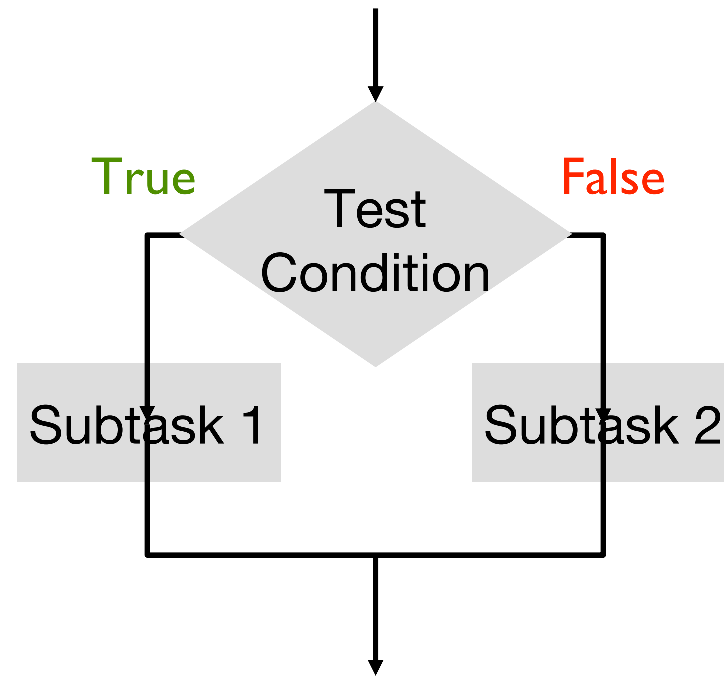



```
if (x > y) r = x - y;
else r = y - x;
```

Three Basic Programming Constructs

- Both conditional and iterative programming requires altering the sequence of instructions (control flow)

Conditional

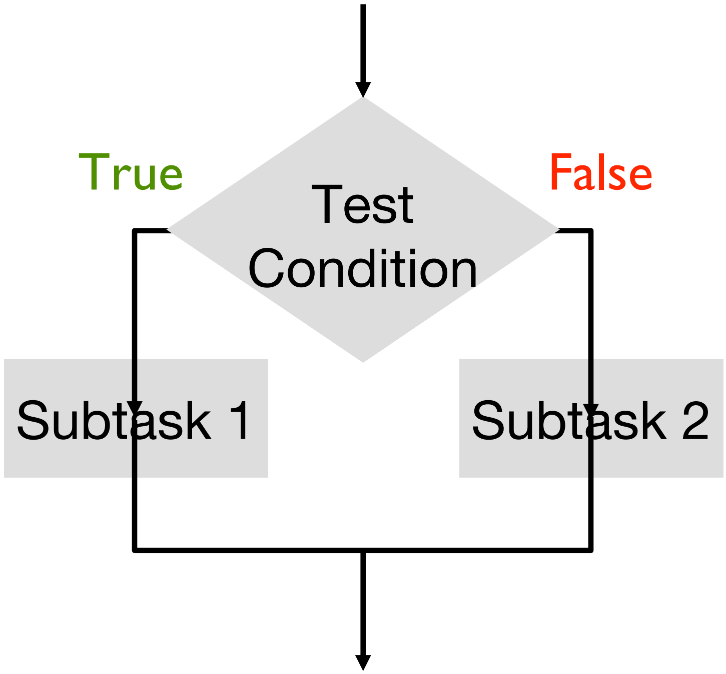



```
if (x > y) r = x - y;
else r = y - x;
```

Three Basic Programming Constructs

- Both conditional and iterative programming requires altering the sequence of instructions (control flow)
- We need a set of *control instructions* to do so

Conditional

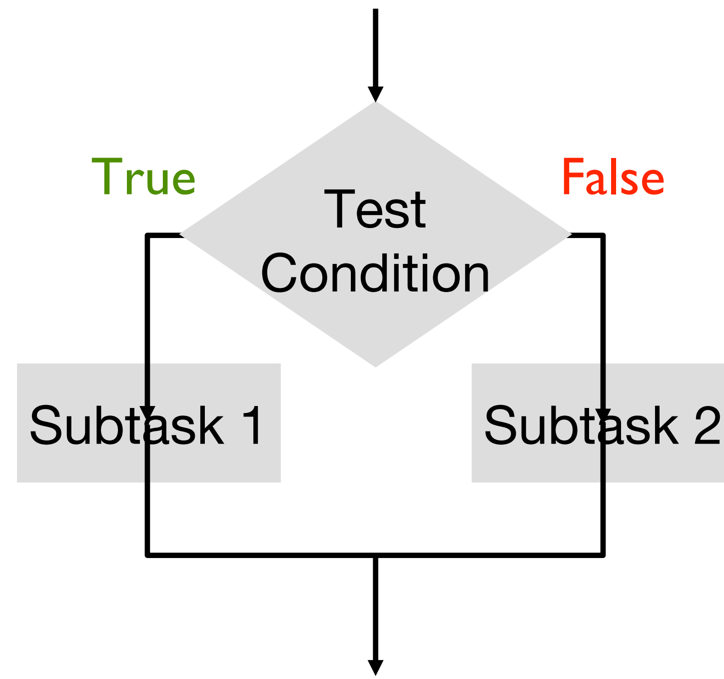



```
if (x > y) r = x - y;
else r = y - x;
```

Three Basic Programming Constructs

- Both conditional and iterative programming requires altering the sequence of instructions (control flow)
- We need a set of *control instructions* to do so
- Two fundamental questions:
- How to test condition and how to represent test results?
- How to alter control flow according to the test results?

Conditional




```
if (x > y) r = x - y;
else r = y - x;
```

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

Conditional Branch Example

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

Conditional Branch Example

```
gcc -Og -S -fno-if-conversion control.c
```

```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
```

Conditional Branch Example

```
gcc -Og -S -fno-if-conversion control.c
```

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

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

```
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
```

Conditional Branch Example

```
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;
}
```

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

```
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
```

Labels are symbolic names used to refer to instruction addresses.

Conditional Branch Example

```
gcc -Og -S -fno-if-conversion control.c
```

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

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

```
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
```

Labels are symbolic names used to refer to instruction addresses.

Conditional Branch Example

```
gcc -Og -S -fno-if-conversion control.c
```

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

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

```
absdiff:
   cmpq    %rsi,%rdi  # x:y
   jbe     .L4
   movq    %rdi,%rax
   subq    %rsi,%rax
   ret
.L4:               # x <= y
   movq    %rsi,%rax
   subq    %rdi,%rax
   ret
```

Labels are symbolic names used to refer to instruction addresses.

Conditional Jump Instruction

```
cmpq    %rsi, %rdi
jle     .L4
```

Conditional Jump Instruction

```
cmpq    %rsi, %rdi
jle     .L4
```

Jump to label if less than or equal to

Conditional Jump Instruction

```
cmpq    %rsi, %rdi
jle     .L4
```

Jump to label if less than or equal to

Semantics:

If `%rdi` is less than or equal to `%rsi` (both interpreted as **signed value**), jump to the part of the code with a label `.L4`

Conditional Jump Instruction

```
cmpq    %rsi, %rdi
jle     .L4
```

Jump to label if less than or equal to

Semantics:

If **`%rdi`** is less than or equal to **`%rsi`** (both interpreted as **signed value**), jump to the part of the code with a label **`.L4`**

- Under the hood:

Conditional Jump Instruction

```
cmpq    %rsi, %rdi
jle     .L4
```

Jump to label if less than or equal to

Semantics:

If **`%rdi`** is less than or equal to **`%rsi`** (both interpreted as **signed value**), jump to the part of the code with a label **`.L4`**

- Under the hood:
  - **`cmpq`** instruction sets the condition codes

Conditional Jump Instruction

```
cmpq    %rsi, %rdi
jle     .L4
```

Jump to label if less than or equal to

Semantics:

If **`%rdi`** is less than or equal to **`%rsi`** (both interpreted as **signed value**), jump to the part of the code with a label **`.L4`**

- Under the hood:
  - **`cmpq`** instruction sets the condition codes
  - **`jle`** reads and checks the **condition codes**

Conditional Jump Instruction

```
cmpq    %rsi, %rdi
jle     .L4
```

Jump to label if less than or equal to

Semantics:

If **`%rdi`** is less than or equal to **`%rsi`** (both interpreted as **signed value**), jump to the part of the code with a label **`.L4`**

- Under the hood:
  - **`cmpq`** instruction sets the condition codes
  - **`jle`** reads and checks the **condition codes**
  - If condition met, modify the Program Counter to point to the address of the instruction with a label **`.L4`**

Conditional Branch 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`	`x`
`%rsi`	`y`
`%rax`	Return value

```
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
```

0	0	0
ZF	SF	OF

Conditional Branch 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`	`x`
`%rsi`	`y`
`%rax`	Return value

```
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
```

`cmpq` sets ZF, SF, OF

`jle` checks ZF | (SF ^ OF)

0	0	0
ZF	SF	OF

Today: Control Instructions

- Control: Conditional branches (`if`… `else`…)
- Control: Loops (`for`, `while`)
- Control: Switch Statements (`case`… `switch`…)

"Do-While" Loop Example

- Popcount: Count number of 1's in argument `x`

`do-while` version

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

"Do-While" Loop Example

- Popcount: Count number of 1's in argument `x`

`do-while` version

```
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;
}
```

“Do-While” Loop Assembly

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

“Do-While” Loop Assembly

```
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, %rax    #  result = 0
.L2:                   # loop:
   movq    %rdi, %rdx
   andl    $1, %rdx    #  t = x & 0x1
   addq    %rdx, %rax  #  result += t
   shrq    $1, %rdi    #  x >>= 1
   jne     .L2         #  if (x) goto loop
   ret
```

“Do-While” Loop Assembly

```
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, %rax     #  result = 0
.L2:                    # loop:
   movq    %rdi, %rdx
   andl    $1, %rdx     #  t = x & 0x1
   addq    %rdx, %rax   #  result += t
   shrq    $1, %rdi     #  x >>= 1
   jne     .L2          #  if (x) goto loop
   ret
```

“Do-While” Loop Assembly

```
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, %rax     #  result = 0
.L2:                    # loop:
   movq    %rdi, %rdx
   andl    $1, %rdx     #  t = x & 0x1
   addq    %rdx, %rax   #  result += t
   shrq    $1, %rdi     #  x >>= 1
   jne     .L2          #  if (x) goto loop
   ret
```

"Do-While" Loop Assembly

```
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, %rax    #  result = 0
.L2:                   # loop:
   movq    %rdi, %rdx
   andl    $1, %rdx    #  t = x & 0x1
   addq    %rdx, %rax  #  result += t
   shrq    $1, %rdi    #  x >>= 1
   jne     .L2         #  if (x) goto loop
   ret
```

"Do-While" Loop Assembly

```
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, %rax    #  result = 0
.L2:                   # loop:
   movq    %rdi, %rdx
   andl    $1, %rdx    #  t = x & 0x1
   addq    %rdx, %rax  #  result += t
   shrq    $1, %rdi    #  x >>= 1
   jne     .L2         #  if (x) goto loop
   ret
```

"Do-While" Loop Assembly

```
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, %rax    #  result = 0
.L2:                   # loop:
   movq    %rdi, %rdx
   andl    $1, %rdx    #  t = x & 0x1
   addq    %rdx, %rax  #  result += t
   shrq    $1, %rdi    #  x >>= 1
   jne     .L2         #  if (x) goto loop
   ret
```

“Do-While” Loop Assembly

```
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, %rax     #  result = 0
.L2:                    # loop:
   movq    %rdi, %rdx
   andl    $1, %rdx     #  t = x & 0x1
   addq    %rdx, %rax   #  result += t
   shrq    $1, %rdi     #  x >>= 1
   jne     .L2          #  if (x) goto loop
   ret
```

"Do-While" Loop Assembly

```
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, %rax     #  result = 0
.L2:                    # loop:
   movq    %rdi, %rdx
   andl    $1, %rdx     #  t = x & 0x1
   addq    %rdx, %rax   #  result += t
   shrq    $1, %rdi     #  x >>= 1
   jne     .L2          #  if (x) goto loop
   ret
```

"Do-While" Loop Assembly

```
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, %rax     #  result = 0
.L2:                     # loop:
   movq     %rdi, %rdx
   andl     $1, %rdx     #  t = x & 0x1
   addq     %rdx, %rax   #  result += t
   shrq     $1, %rdi     #  x >>= 1
   jne      .L2          #  if (x) goto loop
   ret
```

“Do-While” Loop Assembly

```
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, %rax    #  result = 0
.L2:                   # loop:
   movq    %rdi, %rdx
   andl    $1, %rdx    #  t = x & 0x1
   addq    %rdx, %rax  #  result += t
   shrq    $1, %rdi    #  x >>= 1
   jne     .L2         #  if (x) goto loop
   ret
```

General “Do-While” Translation

`do-while` version

```
<before>;
do {
   body;
} while (A < B);
<after>;
```

`goto` Version

```
     <before>
.L1: <body>
    if (A < B)
      goto .L1
     <after>
```

General “Do-While” Translation

do-while version

```
<before>;
do {
   body;
} while (A < B);
<after>;
```

goto Version

```
     <before>
.L1: <body>
     if (A < B)
       goto .L1
     <after>
```

Replace with a conditional jump instruction

General “Do-While” Translation

do-while version

```
<before>;
do {
   body;
} while (A < B);
<after>;
```

goto Version

```
     <before>
.L1: <body>
     if (A < B)
       goto .L1
     <after>
```

Assembly Version

```
     <before>
.L1: <body>
     cmpq B, A
     jl .L1
     <after>
```

General “While” Translation

`while` version

```
<before>;
while (A < B) {
   body;
}
<after>;
```

General “While” Translation

`while` version

```
<before>;
while (A < B) {
   body;
}
<after>;
```

→

`goto` Version

```
     <before>
     goto .L2
.L1: <body>
.L2: if (A < B)
        goto .L1
     <after>
```

General “While” Translation

`while` version

```
<before>;
while (A < B) {
   body;
}
<after>;
```

`goto` Version

```
      <before>
      goto .L2
.L1:  <body>
.L2:  if (A < B)
        goto .L1
      <after>
```

Assembly Version

```
      <before>
      jmp .L2
.L1:  <body>
.L2:  cmpq A, B
      jg .L1
      <after>
```

General “While” Translation

`while` version

```
<before>;
while (A < B) {
   body;
}
<after>;
```

`goto` Version

```
     <before>
     goto .L2
.L1: <body>
.L2: if (A < B)
       goto .L1
     <after>
```

Assembly Version

```
     <before>
     jmp .L2
.L1: <body>
.L2: cmpq A, B
     jg .L1
     <after>
```

General “While” Translation

`while` version

```
<before>;
while (A < B) {
   body;
}
<after>;
```

`goto` Version

```
       <before>
       goto .L2
.L1:   <body>
.L2:   if (A < B)
         goto .L1
       <after>
```

Assembly Version

```
       <before>
       jmp .L2
.L1:   <body>
.L2:   cmpq A, B
       jg .L1
       <after>
```

"While" Loop Example

`while` version

```
long pcount_while
  (unsigned long x) {

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

}
```

“While” Loop Example

`while` version

```
long pcount_while
  (unsigned long x) {

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

}
```

`goto` Version

```
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;
}
```

“For” Loop Example

```
for (init; test; update){
  body
}
```

“For” Loop Example

```
for (init; test; update){
  body
}
```

```
//assume unsigned int is 4 bytes
long pcount_for (unsigned int x)
{

  size_t i;
  long result = 0;
  for (i = 0; i < 32; i++)
  {
    result += (x >> i) & 0x1;
  }
  return result;
}
```

“For” Loop Example

```
for (init; test; update){
  body
}
```

init

`i = 0`

```
//assume unsigned int is 4 bytes
long pcount_for (unsigned int x)
{

  size_t i;
  long result = 0;
  for (i = 0; i < 32; i++)
  {
    result += (x >> i) & 0x1;
  }
  return result;
}
```

"For" Loop Example

```
for (init; test; update){
  body
}
```

```
//assume unsigned int is 4 bytes
long pcount_for (unsigned int x)
{

  size_t i;
  long result = 0;
  for (i = 0; i < 32; i++)
  {
    result += (x >> i) & 0x1;
  }
  return result;
}
```

init

`i = 0`

test

`i < 32`

"For" Loop Example

```
for (init; test; update) {
  body
}
```

```
//assume unsigned int is 4 bytes
long pcount_for (unsigned int x)
{

  size_t i;
  long result = 0;
  for (i = 0; i < 32; i++)
  {
    result += (x >> i) & 0x1;
  }
  return result;
}
```

init

`i = 0`

test

`i < 32`

update

`i++`

"For" Loop Example

```
for (init; test; update){
  body
}
```

```
//assume unsigned int is 4 bytes
long pcount_for (unsigned int x)
{

  size_t i;
  long result = 0;
  for (i = 0; i < 32; i++)
  {
    result += (x >> i) & 0x1;
  }
  return result;
}
```

init

`i = 0`

test

`i < 32`

update

`i++`

body

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

Convert "For" Loop to "While" Loop

For Version

```
before;
for (init; test; update) {
  body;
}
after
```

Convert “For” Loop to “While” Loop

For Version

```
before;
for (init; test; update) {
  body;
}
after
```

While Version

```
before;
init;
while (test) {
    body;
    update;
}
after;
```

Convert “For” Loop to “While” Loop

For Version

```
before;
for (init; test; update) {
  body;
}
after
```

While Version

```
before;
init;
while (test) {
      body;
      update;
}
after;
```

Assembly Version

```
      before
      init
      jmp .L2
.L1:  body
      update
.L2:  cmpq A, B
      jg .L1
      after
```

Today: Control Instructions

- Control: Conditional branches (**`if`**… **`else`**…)
- Control: Loops (**`for`**, **`while`**)
- Control: Switch Statements (**`case`**… **`switch`**…)

Switch Statement Example

```
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;
    case 3:
        w += z;
        break;
    case 5:
    case 6:
        w -= z;
        break;
    default:
        w = 2;}
    return w;
}
```

Switch Statement Example

```
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;
    case 3:
        w += z;
        break;
    case 5:
    case 6:
        w -= z;
        break;
    default:
        w = 2;}
    return w;
}
```

Fall-through case

Switch Statement Example

```
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;
    case 3:
        w += z;
        break;
    case 5:
    case 6:
        w -= z;
        break;
    default:
        w = 2;}
    return w;
}
```

Fall-through case

Multiple case labels

Switch Statement Example

```
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;
    case 3:
        w += z;
        break;
    case 5:
    case 6:
        w -= z;
        break;
    default:
        w = 2;}
    return w;
}
```

Fall-through case

Multiple case labels

For missing cases, fall back to default

Switch Statement Example

```
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;
    case 3:
        w += z;
        break;
    case 5:
    case 6:
        w -= z;
        break;
    default:
        w = 2;}
    return w;
}
```

Fall-through case

Multiple case labels

For missing cases, fall back to default

Converting to a cascade of if-else statements is simple, but cumbersome with too many cases.

Implementing Switch Using Jump Table

Switch Form

```
switch(x) {
  case val_0:
    Block 0
  case val_1:
    Block 1

  ....
  case val_n-1:
    Block n–1
}
```

Implementing Switch Using Jump Table

Switch Form

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

Jump Targets

Targ0: Code Block 0

Targ1: Code Block 1

Targ2: Code Block 2

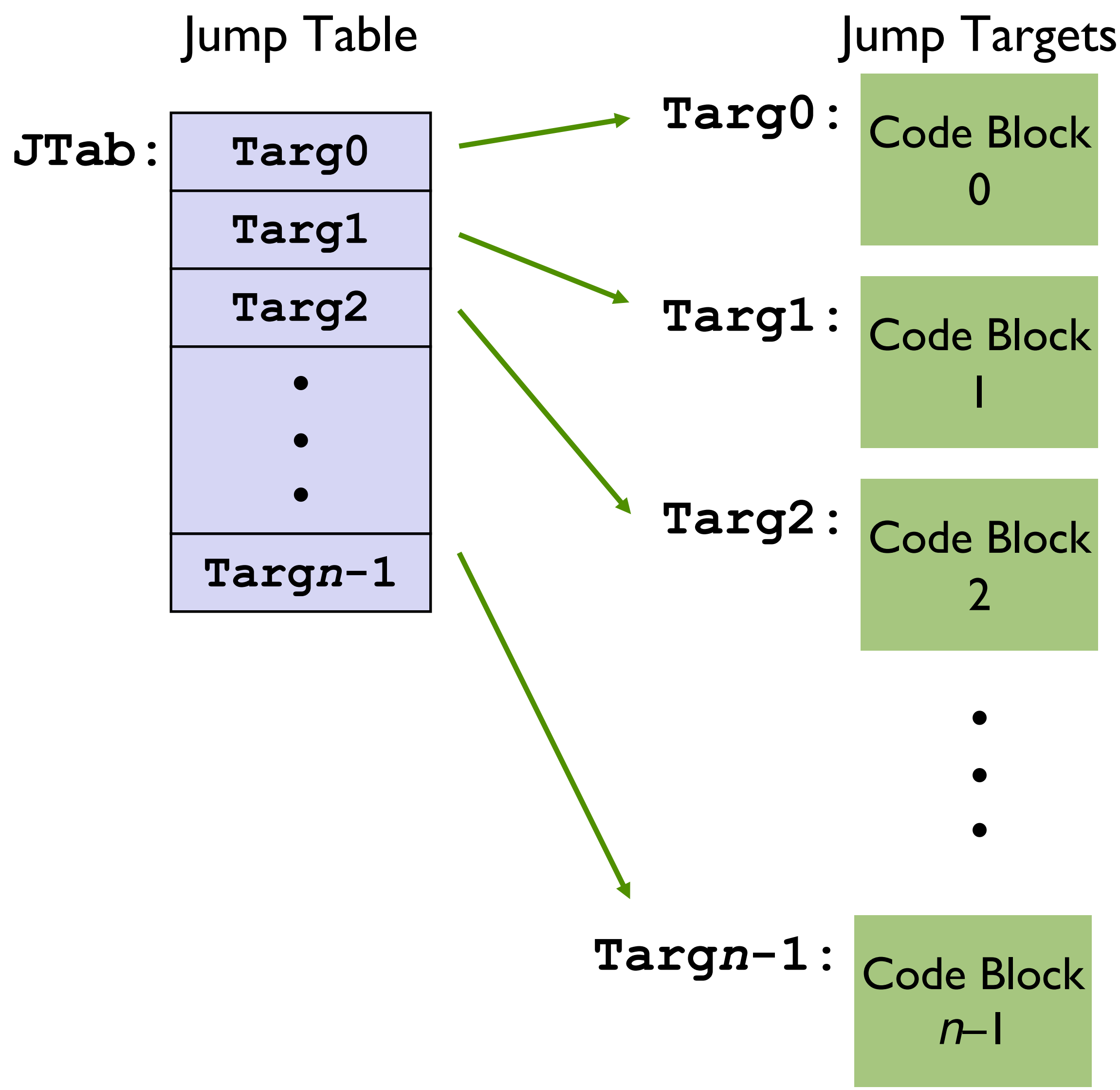
•
•
•

Targ*n*-1: Code Block *n*–1

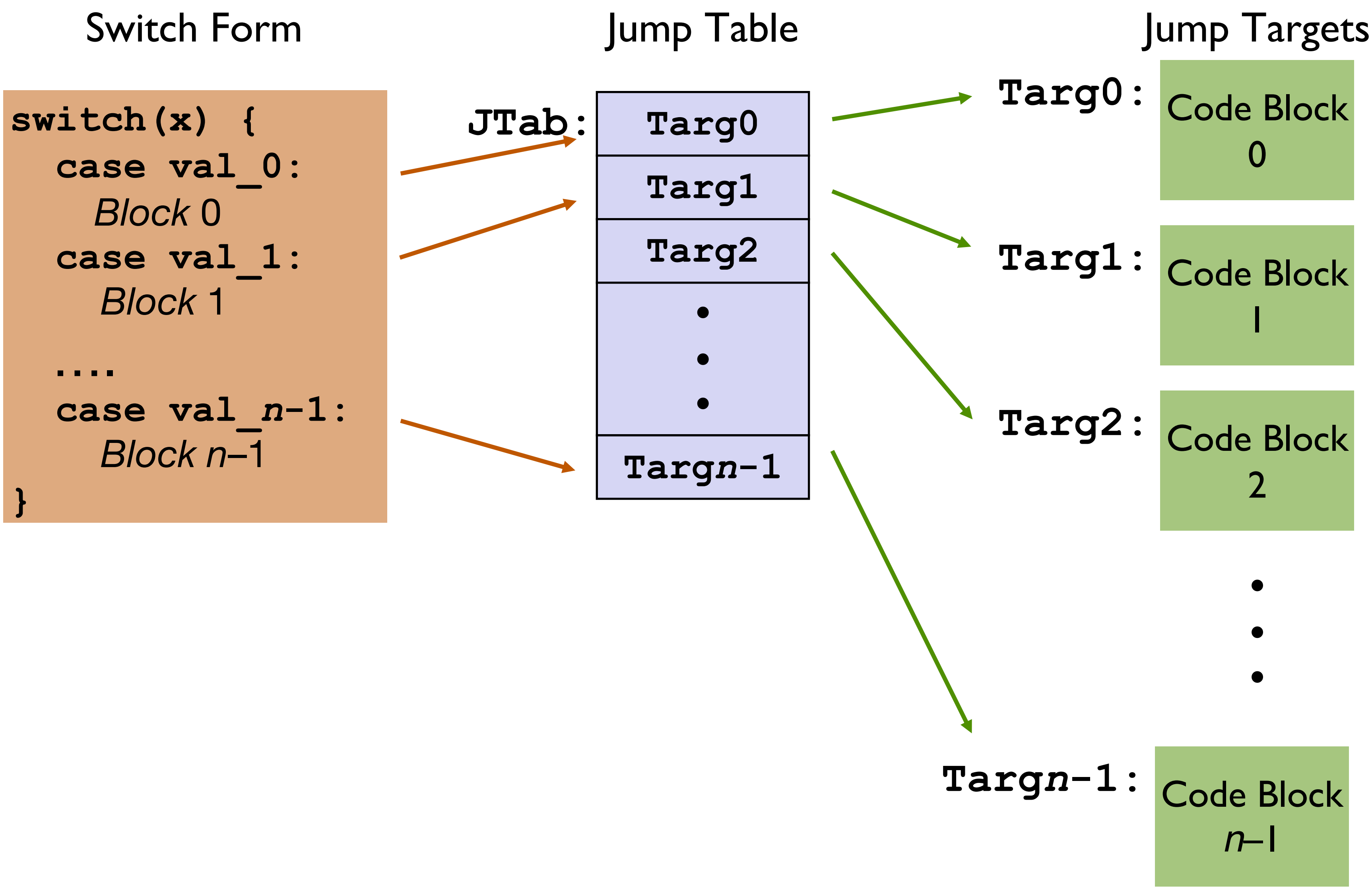
Implementing Switch Using Jump Table

Switch Form

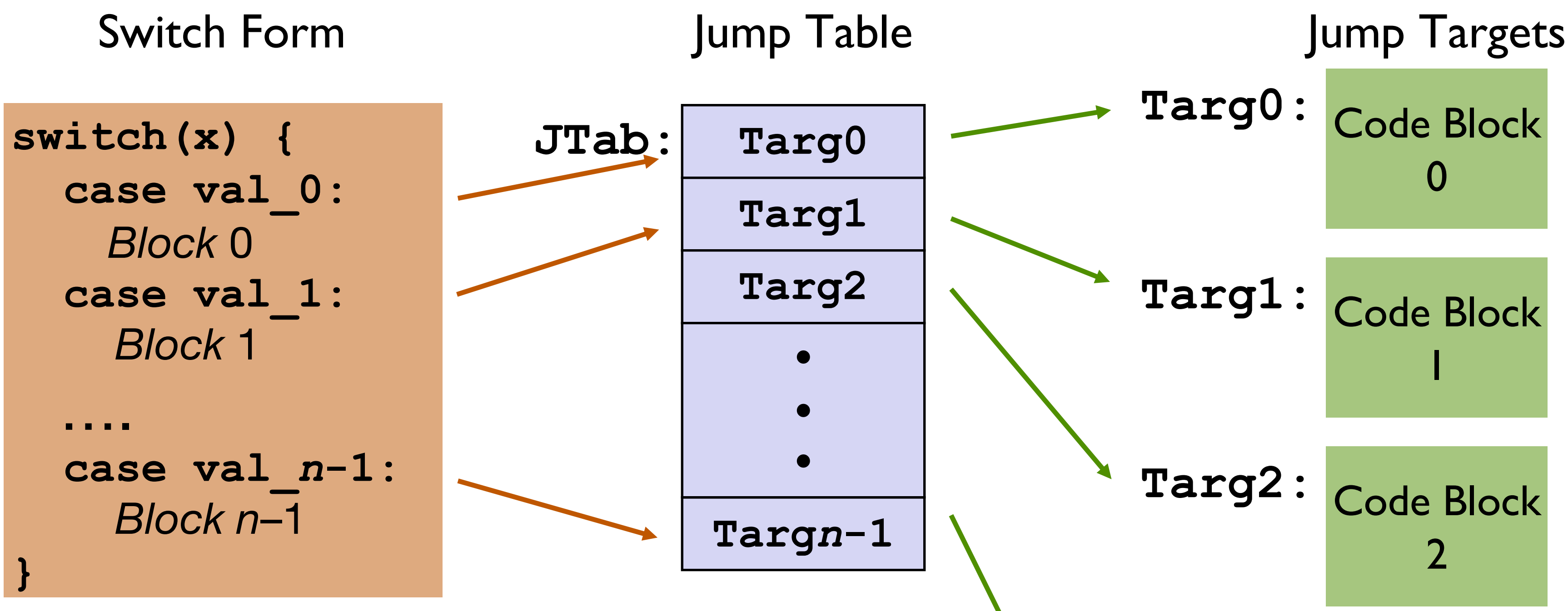
```
switch(x) {
  case val_0:
    Block 0
  case val_1:
    Block 1

  ....
  case val_n-1:
    Block n–1
}
```



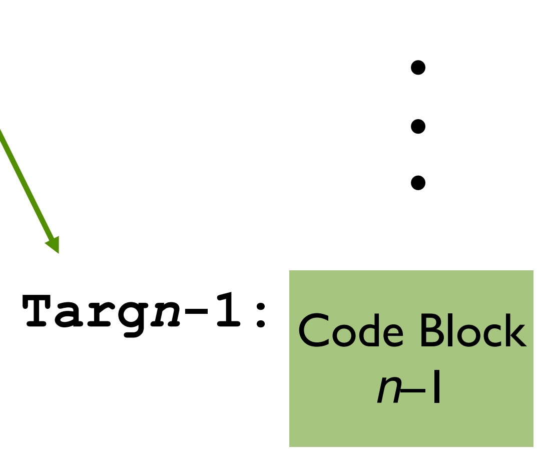
Implementing Switch Using Jump Table



Implementing Switch Using Jump Table



- Each code block starts from a unique address (Targ0, Targ1, …)
- Jump table stores all the target address
- Use the case value to index into the jump table to find where to jump to



Assembly Directives (Pseudo-Ops)

```
.L4:
  .quad .LD # x = 0
  .quad .L1 # x = 1
  .quad .L2 # x = 2
  .quad .L3 # x = 3
  .quad .LD # x = 4
  .quad .L5 # x = 5
  .quad .L5 # x = 6
```

- Directives:
  - Not real instructions, but assist assembler. Think of them as messages to help the assembler in the assembly process.

Assembly Directives (Pseudo-Ops)

```
.L4:
  .quad .LD # x = 0
  .quad .L1 # x = 1
  .quad .L2 # x = 2
  .quad .L3 # x = 3
  .quad .LD # x = 4
  .quad .L5 # x = 5
  .quad .L5 # x = 6
```

- .quad: tells the assembler to set aside the next 8 bytes in memory and initialize with the value of the operand (a label here, which itself is an address)

- Directives:
  - Not real instructions, but assist assembler. Think of them as messages to help the assembler in the assembly process.

Jump Table and Jump Targets

Jump Table

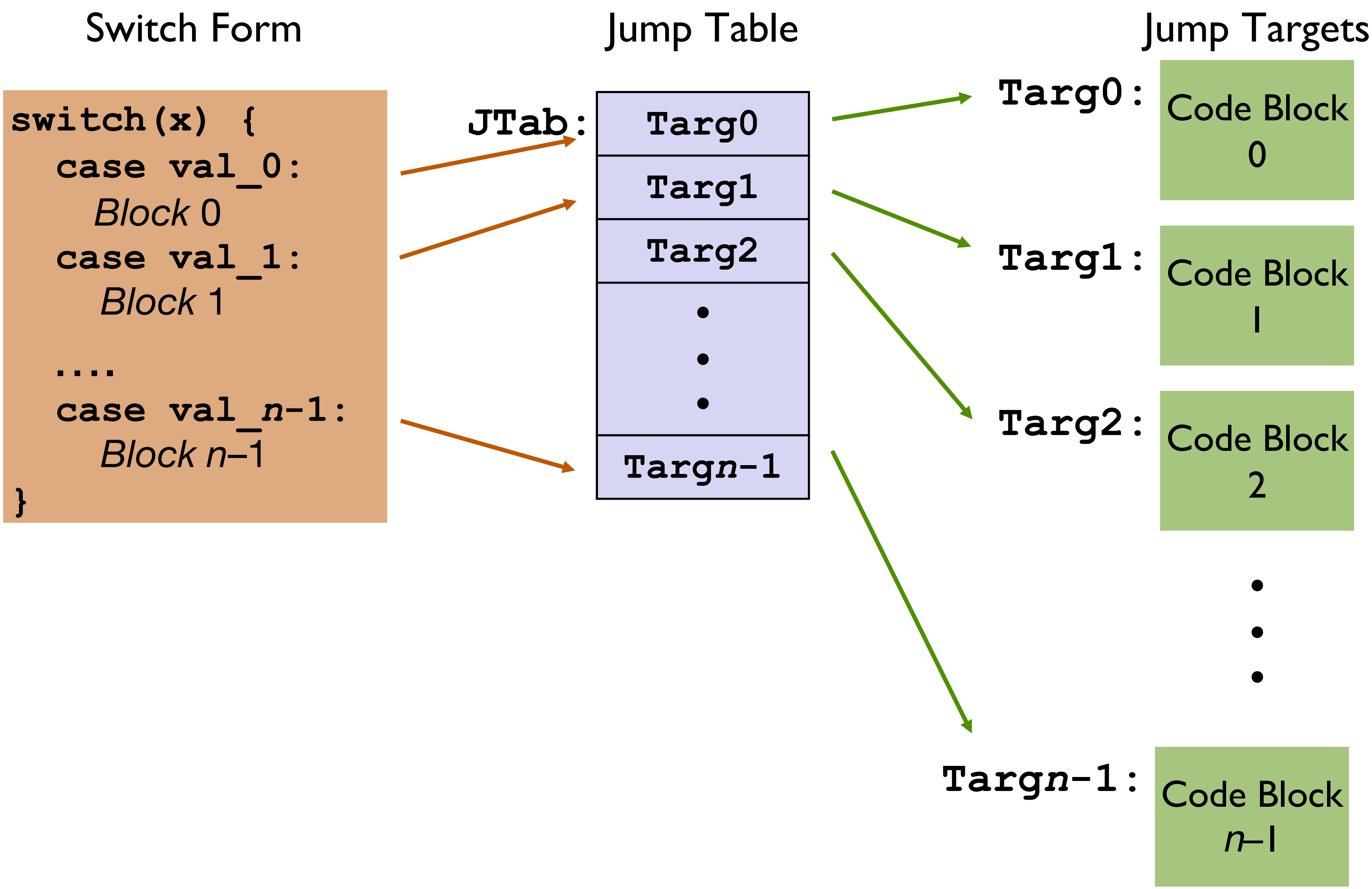
```
.L4:
  .quad .LD # x = 0
  .quad .L1 # x = 1
  .quad .L2 # x = 2
  .quad .L3 # x = 3
  .quad .LD # x = 4
  .quad .L5 # x = 5
  .quad .L5 # x = 6
```

`jmp .L3` will go to `.L3` and start executing from there

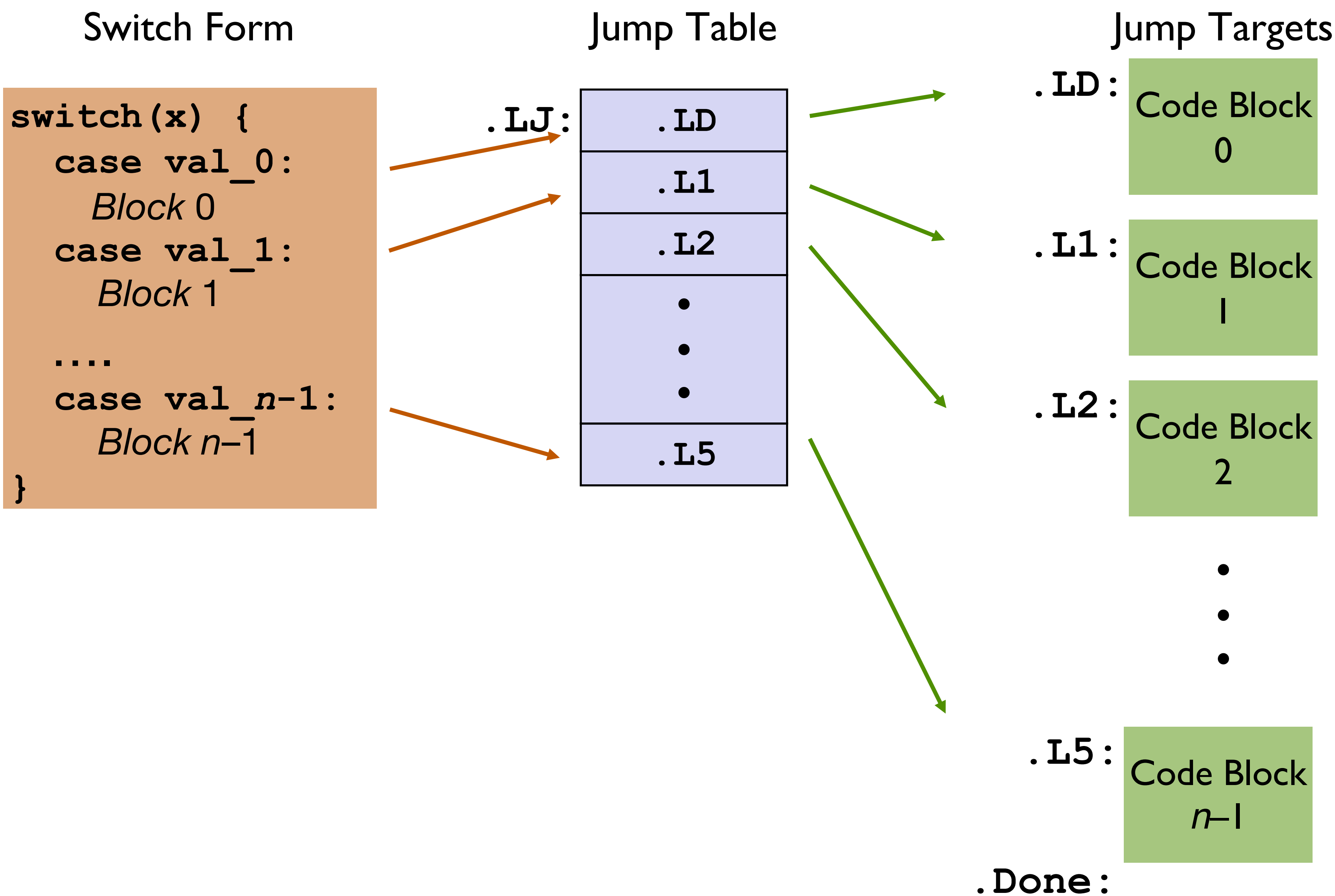
Jump Targets

```
.L1:                    # Case 1
   movq    %rsi, %rax
   imulq   %rdx, %rax
   jmp     .done
.L2:                    # Case 2
   movq    %rsi, %rax
   cqto
   idivq   %rcx
.L3:                    # Case 3
   addq    %rcx, %rax
   jmp     .done
.L5:                    # Case 5,6
   subq    %rdx, %rax
   jmp     .done
.LD:                    # Default
  movl     $2, %eax
  jmp      .done
```

Implementing Switch Using Jump Table



Implementing Switch Using Jump Table



Code Blocks (x == 1)

```
.L4:
  .quad .LD # x = 0
  .quad .L1 # x = 1
  .quad .L2 # x = 2
  .quad .L3 # x = 3
  .quad .LD # x = 4
  .quad .L5 # x = 5
  .quad .L5 # x = 6
```

Code Blocks (x == 1)

```
.L4:
  .quad .LD # x = 0
  .quad .L1 # x = 1
  .quad .L2 # x = 2
  .quad .L3 # x = 3
  .quad .LD # x = 4
  .quad .L5 # x = 5
  .quad .L5 # x = 6
```

```
switch(x) {
case 1:        // .L1
    w = y*z;
    break;
    …
}
```

Code Blocks (x == 1)

```
.L4:
  .quad .LD # x = 0
  .quad .L1 # x = 1
  .quad .L2 # x = 2
  .quad .L3 # x = 3
  .quad .LD # x = 4
  .quad .L5 # x = 5
  .quad .L5 # x = 6
```

```
switch(x) {
case 1:        // .L1
    w = y*z;
    break;
    …
}
```

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

Code Blocks (x == 1)

```
.L4:
  .quad .LD # x = 0
  .quad .L1 # x = 1
  .quad .L2 # x = 2
  .quad .L3 # x = 3
  .quad .LD # x = 4
  .quad .L5 # x = 5
  .quad .L5 # x = 6
```

```
switch(x) {
case 1:        // .L1
    w = y*z;
    break;
    …
}
```

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

```
.L1:
   movq    %rsi, %rax  # y
   imulq   %rdx, %rax  # y*z
   jmp     .done
```

Code Blocks (x == 1)

```
.L4:
  .quad .LD # x = 0
  .quad .L1 # x = 1
  .quad .L2 # x = 2
  .quad .L3 # x = 3
  .quad .LD # x = 4
  .quad .L5 # x = 5
  .quad .L5 # x = 6
```

```
switch(x) {
case 1:          // .L1
     w = y*z;
     break;
     …
}
```

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

```
.L1:
   movq    %rsi, %rax   # y
   imulq   %rdx, %rax   # y*z
   jmp     .done
```

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

```
.L4:
  .quad .LD # x = 0
  .quad .L1 # x = 1
  .quad .L2 # x = 2
  .quad .L3 # x = 3
  .quad .LD # x = 4
  .quad .L5 # x = 5
  .quad .L5 # x = 6
```

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

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

```
.L4:
  .quad .LD # x = 0
  .quad .L1 # x = 1
  .quad .L2 # x = 2
  .quad .L3 # x = 3
  .quad .LD # x = 4
  .quad .L5 # x = 5
  .quad .L5 # x = 6
```

```
switch(x) {
…
case 2:          // .L2
    w = y/z;
    /* Fall Through */
case 3:          // .L3
    w += z;
    break;
    …}
```

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

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

```
.L4:
  .quad .LD # x = 0
  .quad .L1 # x = 1
  .quad .L2 # x = 2
  .quad .L3 # x = 3
  .quad .LD # x = 4
  .quad .L5 # x = 5
  .quad .L5 # x = 6
```

```
switch(x) {
…
case 2:          // .L2
    w = y/z;
    /* Fall Through */
case 3:          // .L3
    w += z;
    break;
    …}
```

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

```
.L2:                          # Case 2
   movq     %rsi, %rax
   cqto
   idivq    %rcx              #  y/z

.L3:                          # Case 3
   addq     %rcx, %rax #  w += z
   jmp      .done
```

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

```
.L4:
  .quad .LD # x = 0
  .quad .L1 # x = 1
  .quad .L2 # x = 2
  .quad .L3 # x = 3
  .quad .LD # x = 4
  .quad .L5 # x = 5
  .quad .L5 # x = 6
```

```
switch(x) {
…
case 2:          // .L2
    w = y/z;
    /* Fall Through */
case 3:          // .L3
    w += z;
    break;
    …}
```

```
.L2:                          # Case 2
   movq    %rsi, %rax
   cqto
   idivq   %rcx               #  y/z

.L3:                          # Case 3
   addq    %rcx, %rax #  w += z
   jmp     .done
```

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

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

```
.L4:
  .quad .LD # x = 0
  .quad .L1 # x = 1
  .quad .L2 # x = 2
  .quad .L3 # x = 3
  .quad .LD # x = 4
  .quad .L5 # x = 5
  .quad .L5 # x = 6
```

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

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

```
.L4:
  .quad .LD # x = 0
  .quad .L1 # x = 1
  .quad .L2 # x = 2
  .quad .L3 # x = 3
  .quad .LD # x = 4
  .quad .L5 # x = 5
  .quad .L5 # x = 6
```

```
switch(x) {
…
case 5:  // .L5
case 6:  // .L5
    w -= z;
    break;
default: // .LD
    w = 2;}
```

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

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

```
.L4:
  .quad .LD # x = 0
  .quad .L1 # x = 1
  .quad .L2 # x = 2
  .quad .L3 # x = 3
  .quad .LD # x = 4
  .quad .L5 # x = 5
  .quad .L5 # x = 6
```

```
switch(x) {
…
case 5:  // .L5
case 6:  // .L5
    w -= z;
    break;
default: // .LD
    w = 2;}
```

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

```
.L5:                   # Case 5,6
  subq  %rdx, %rax #  w -= z
  jmp   .done
.LD:                   # Default:
  movl  $2, %eax     #  2
  jmp   .done
```

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

```
.L4:
  .quad .LD # x = 0
  .quad .L1 # x = 1
  .quad .L2 # x = 2
  .quad .L3 # x = 3
  .quad .LD # x = 4
  .quad .L5 # x = 5
  .quad .L5 # x = 6
```

```
switch(x) {
…
case 5:  // .L5
case 6:  // .L5
     w -= z;
     break;
default: // .LD
     w = 2;}
```

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

```
.L5:                      # Case 5,6
  subq   %rdx, %rax  #  w -= z
  jmp    .done
.LD:                      # Default:
  movl   $2, %eax    #  2
  jmp    .done
```

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

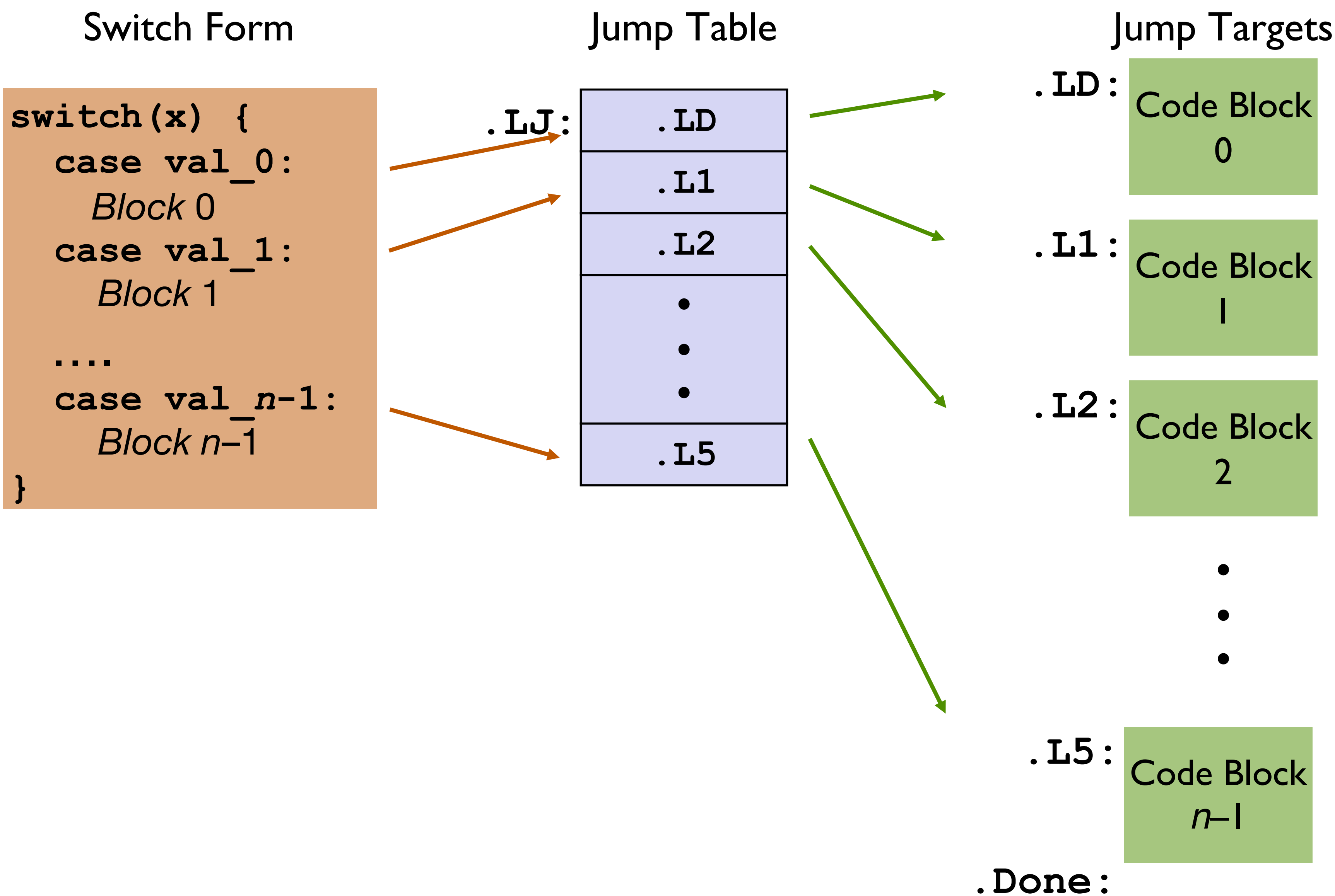
```
.L4:
  .quad .LD # x = 0
  .quad .L1 # x = 1
  .quad .L2 # x = 2
  .quad .L3 # x = 3
  .quad .LD # x = 4
  .quad .L5 # x = 5
  .quad .L5 # x = 6
```

```
switch(x) {
...
case 5:  // .L5
case 6:  // .L5
     w -= z;
     break;
default: // .LD
     w = 2;}
```

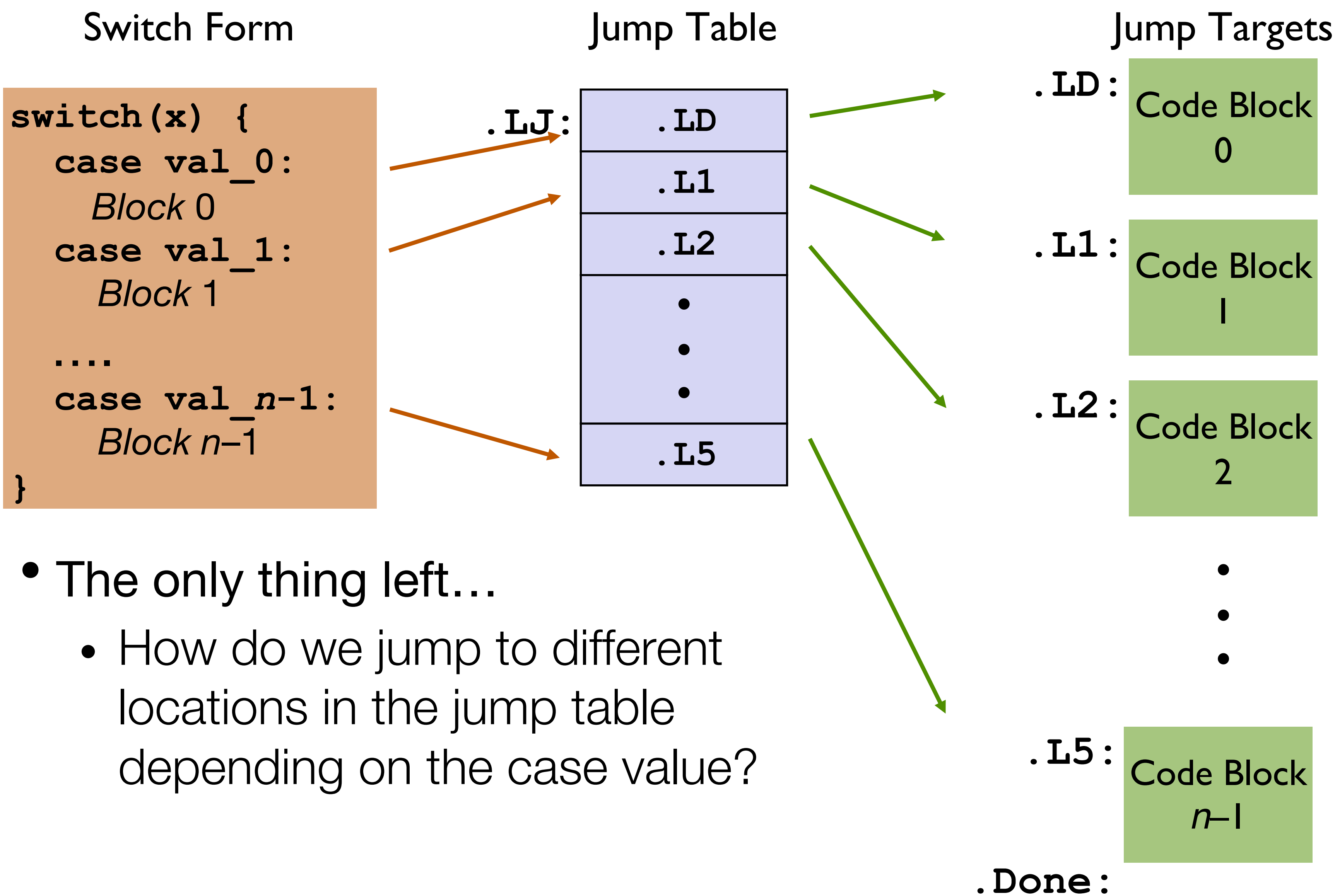
Register	Use(s)
`%rdi`	Argument **`x`**
`%rsi`	Argument **`y`**
`%rdx`	Argument **`z`**
`%rax`	Return value

```
.L5:                       # Case 5,6
  subq   %rdx, %rax #   w -= z
  jmp    .done
.LD:                       # Default:
  movl   $2, %eax     #   2
  jmp    .done
```

Implementing Switch Using Jump Table



Implementing Switch Using Jump Table



- The only thing left…
  - How do we jump to different locations in the jump table depending on the case value?

Indirect Jump Instruction

```
.LJ:
  .quad .LD # x = 0
  .quad .L1 # x = 1
  .quad .L2 # x = 2
  .quad .L3 # x = 3
  .quad .LD # x = 4
  .quad .L5 # x = 5
  .quad .L5 # x = 6
```

Indirect Jump Instruction

The address we want to jump to is stored at `.LJ + 8 * x`

```
.LJ:
  .quad .LD # x = 0
  .quad .L1 # x = 1
  .quad .L2 # x = 2
  .quad .L3 # x = 3
  .quad .LD # x = 4
  .quad .L5 # x = 5
  .quad .L5 # x = 6
```

Indirect Jump Instruction

The address we want to jump to is stored at `.LJ + 8 * x`

```
.LJ:
  .quad .LD # x = 0
  .quad .L1 # x = 1
  .quad .L2 # x = 2
  .quad .L3 # x = 3
  .quad .LD # x = 4
  .quad .L5 # x = 5
  .quad .L5 # x = 6
```

```
# assume x in %rdi
movq  .LJ(,%rdi,8), %rax
jmp   *%rax
```

Indirect Jump Instruction

The address we want to jump to is stored at `.LJ + 8 * x`

```
.LJ:
  .quad .LD # x = 0
  .quad .L1 # x = 1
  .quad .L2 # x = 2
  .quad .L3 # x = 3
  .quad .LD # x = 4
  .quad .L5 # x = 5
  .quad .L5 # x = 6
```

```
# assume x in %rdi
movq   .LJ(,%rdi,8), %rax
jmp    *%rax
```

- Indirect Jump: **`jmp *%rax`**
  - `%rax` specifies the address to jump to (PC = `%rax`)

Indirect Jump Instruction

The address we want to jump to is stored at `.LJ + 8 * x`

```
.LJ:
  .quad .LD # x = 0
  .quad .L1 # x = 1
  .quad .L2 # x = 2
  .quad .L3 # x = 3
  .quad .LD # x = 4
  .quad .L5 # x = 5
  .quad .L5 # x = 6
```

```
# assume x in %rdi
movq   .LJ(,%rdi,8), %rax
jmp    *%rax
```

- Indirect Jump: **`jmp *%rax`**
  - `%rax` specifies the address to jump to (PC = `%rax`)
- Direct Jump (**`jmp .LJ`**), directly specifies the jump address

Indirect Jump Instruction

The address we want to jump to is stored at `.LJ + 8 * x`

```
.LJ:
  .quad .LD # x = 0
  .quad .L1 # x = 1
  .quad .L2 # x = 2
  .quad .L3 # x = 3
  .quad .LD # x = 4
  .quad .L5 # x = 5
  .quad .L5 # x = 6
```

```
# assume x in %rdi
movq  .LJ(,%rdi,8), %rax
jmp   *%rax
```

- Indirect Jump: **`jmp *%rax`**
  - `%rax` specifies the address to jump to (PC = `%rax`)
- Direct Jump (**`jmp .LJ`**), directly specifies the jump address
- Indirect Jump specifies where the jump address is located

Indirect Jump Instruction

The address we want to jump to is stored at `.LJ + 8 * x`

```
.LJ:
  .quad .LD # x = 0
  .quad .L1 # x = 1
  .quad .L2 # x = 2
  .quad .L3 # x = 3
  .quad .LD # x = 4
  .quad .L5 # x = 5
  .quad .L5 # x = 6
```

```
# assume x in %rdi
movq   .LJ(,%rdi,8), %rax
jmp    *%rax
```

- Indirect Jump: **`jmp *%rax`**
  - `%rax` specifies the address to jump to (PC = `%rax`)
- Direct Jump (**`jmp .LJ`**), directly specifies the jump address
- Indirect Jump specifies where the jump address is located

An equivalent syntax in x86:

```
jmp       *.LJ(,%rdi,8)
```