CSC 252: Computer Organization
Spring 2018: Lecture 7

Instructor: Yuhao Zhu

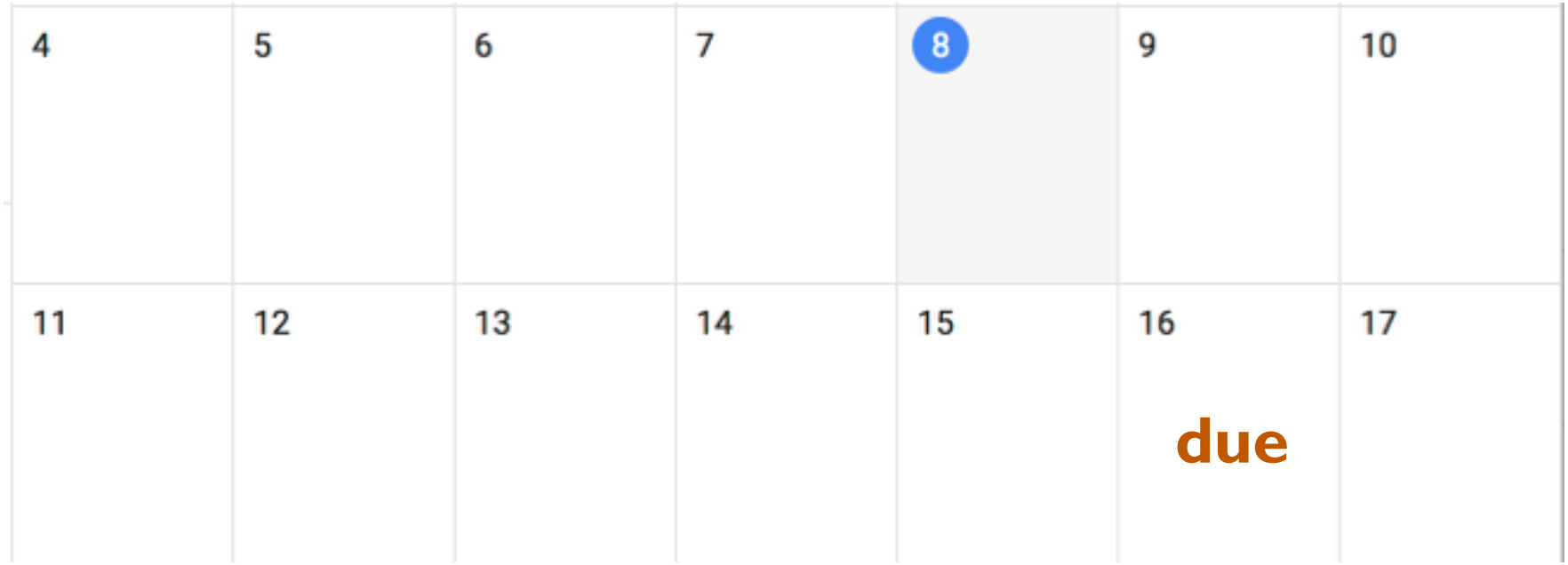
Department of Computer Science
University of Rochester

Action Items:

- **Assignment 2 is out**

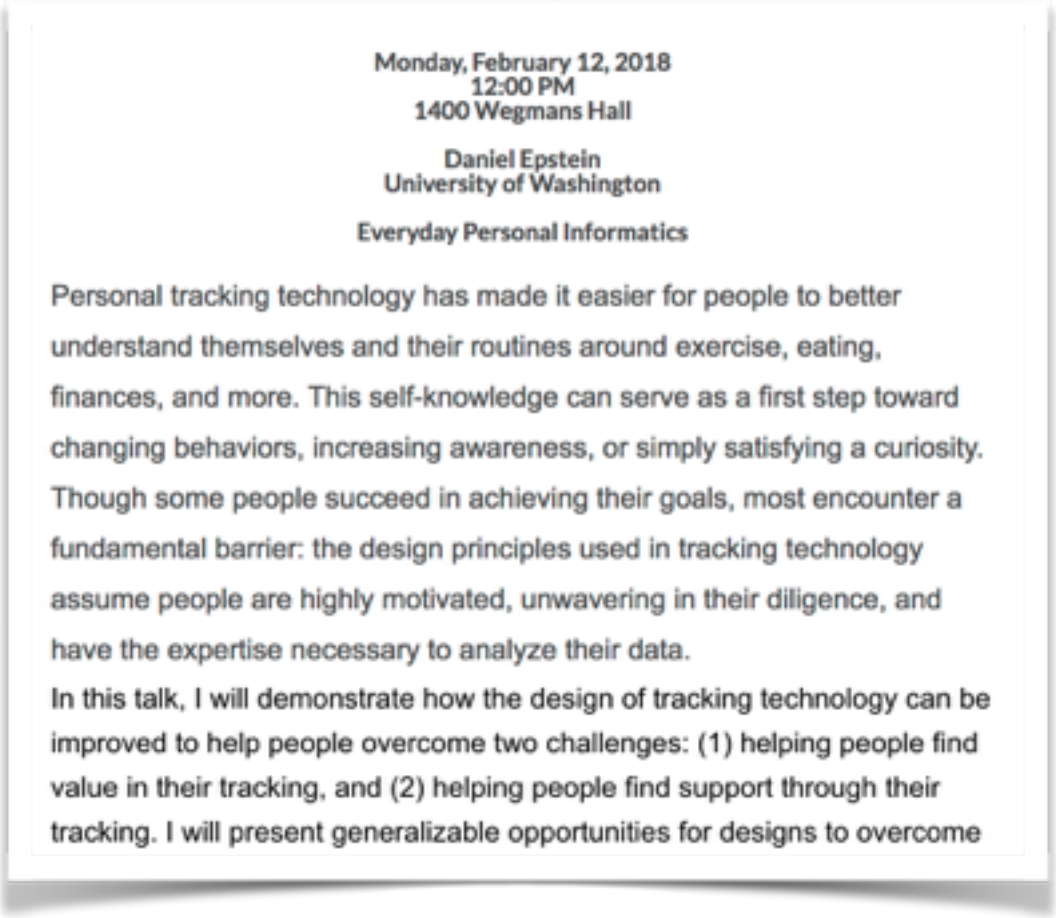
Announcement

- Programming Assignment 2 is out
  - Due on **Feb 16, 11:59 PM**
  - You may still have 3 slip days…



Announcement

- There is a faculty candidate talk on Monday



Monday, February 12, 2018
12:00 PM
1400 Wegmans Hall

Daniel Epstein
University of Washington

Everyday Personal Informatics

Personal tracking technology has made it easier for people to better understand themselves and their routines around exercise, eating, finances, and more. This self-knowledge can serve as a first step toward changing behaviors, increasing awareness, or simply satisfying a curiosity. Though some people succeed in achieving their goals, most encounter a fundamental barrier: the design principles used in tracking technology assume people are highly motivated, unwavering in their diligence, and have the expertise necessary to analyze their data.

In this talk, I will demonstrate how the design of tracking technology can be improved to help people overcome two challenges: (1) helping people find value in their tracking, and (2) helping people find support through their tracking. I will present generalizable opportunities for designs to overcome

www.cs.rochester.edu/dept/seminar/view/dept/2018/02/12/1196/Daniel_Epstein/Everyday_Personal_Informatics.html

Conditional Branch Example

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```
long absdiff
   (long x, long y)
{
   long result;
   if (x > y)
     result = x-y;
   else
     result = y-x;
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absdiff:
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    ret
.L4:                  # x <= y
    movq    %rsi,%rax
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```

Labels (.L4) are symbolic names referring to memory addresses.

Conditional Jump Instruction

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jle     .L4
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Jump to label if less than or equal to

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  - **`cmpq`** instruction sets the condition codes
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  - If condition met, modify the Program Counter to point to the address of the instruction with a label **`.L4`**

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ZF Zero Flag (result is zero)

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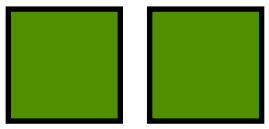
SF Sign Flag (result is negative)



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`cmpq` *0xFF, 0x80*

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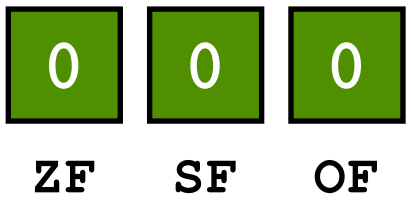

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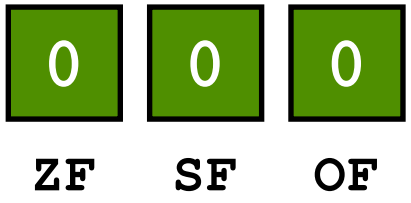

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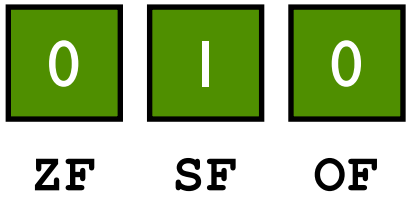

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  - `%rdi - %rsi` < 0 and the result doesn't overflow, or
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- `%rdi <= %rsi` if and only if
  - ZF is set, or
  - SF is set but OF is not set, or
  - SF is not set, but OF is set
- or simply: ZF | (SF ^ OF)

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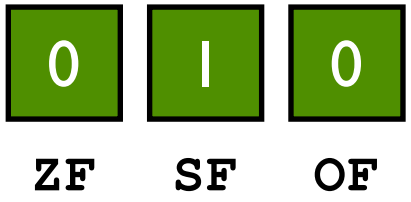

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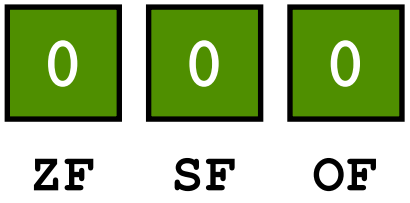

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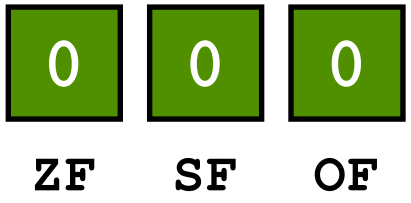
`cmpq` sets ZF, SF, OF

`jle` checks ZF | (SF ^ OF)



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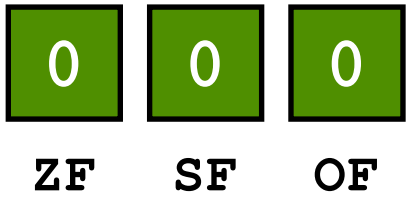

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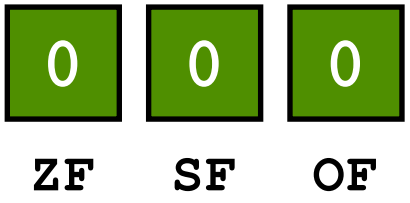

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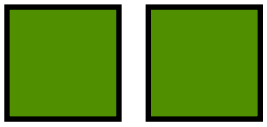
CF Carry Flag (for unsigned)



How Should `cmpq` Set Condition Codes?

`cmpq %rsi, %rdi`

- How do we know **`%rdi`** <= **`%rsi`**? This time for unsigned values
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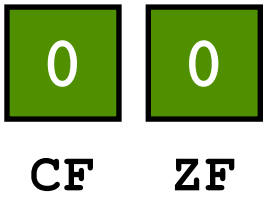

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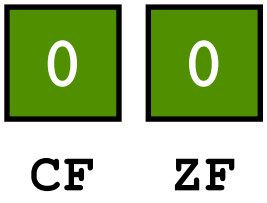

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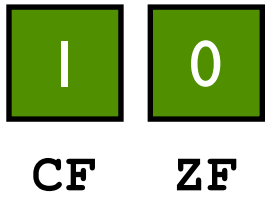

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- `%rdi <= %rsi` (as unsigned) if and only if:
  - ZF is set, or
  - CF is set
- or simply: ZF | CF
- This is what `jbe` checks

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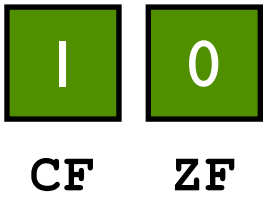

Putting It All Together

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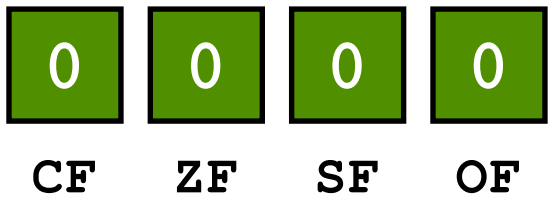

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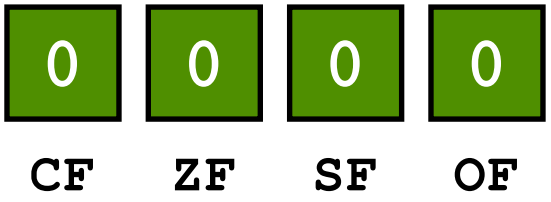

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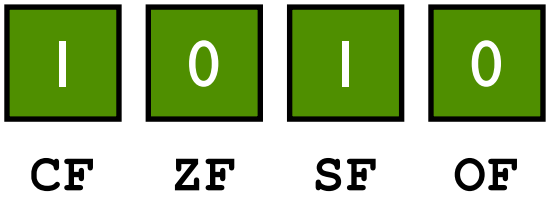

Putting It All Together

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

- `cmpq` sets all 4 condition codes simultaneously
- ZF, SF, and OF are used when comparing signed value (e.g., `jle`)

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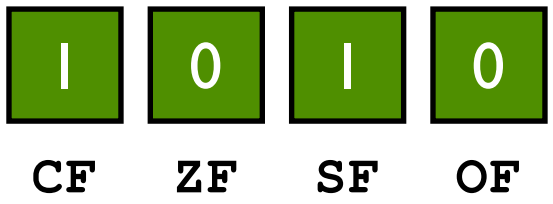

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cmpq    %rsi,%rdi          cmpq    %rsi,%rdi
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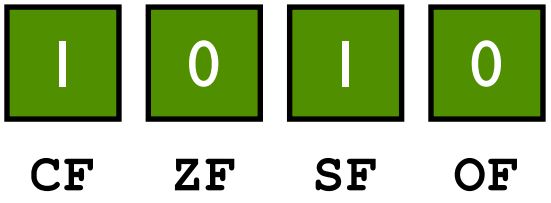
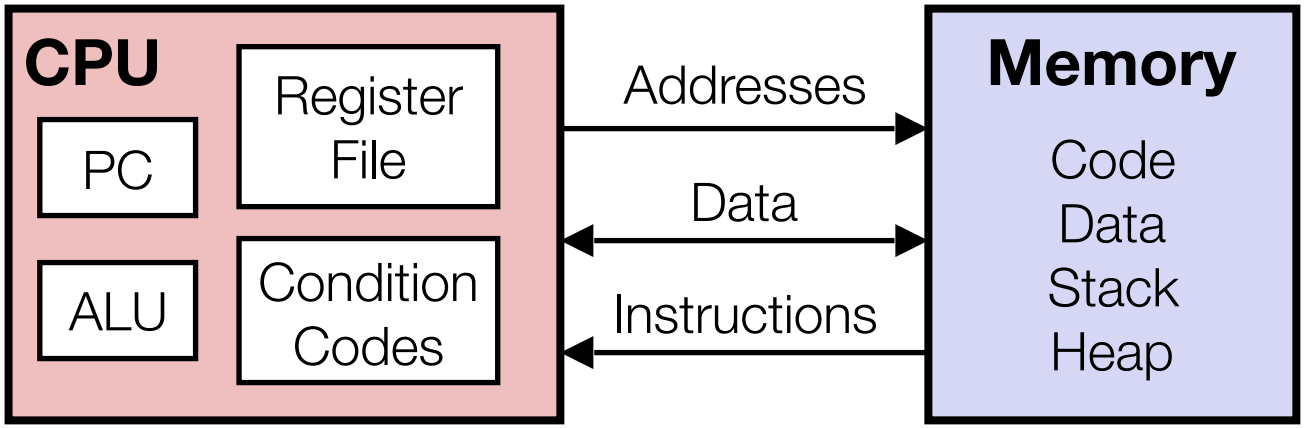
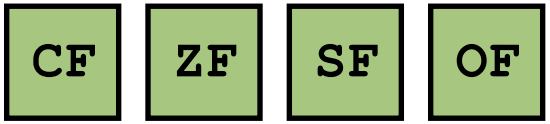


Condition Codes Hold Test Results

Assembly Programmer's Perspective of a Computer



- Condition Codes
  - Hold the status of most recent test
  - 4 common condition codes in x86-64
  - A set of special registers (more often: bits in one single register)
  - Sometimes also called: Status Register, Flag Register



CF Carry Flag

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OF Overflow Flag (for signed)

Jump Instructions

- Jump to different part of code (designated by a label) depending on condition codes

jle	`(SF^OF)|ZF`	Less or Equal (Signed)

jbe	`CF|ZF`	Below or Equal (unsigned)

Jump Instructions

Instruction	Jump 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)

Explicit Set Condition Codes: Test

`testq %rsi, %rdi`

- Explicit Setting by Test Instruction
  - **`test b,a`** like computing **`a&b`**, but instead of setting the result, it sets condition codes
  - Similar to **`cmpq b, a`**, except **`cmpq b, a`** does **`a-b`**

  - **ZF (Zero Flag):** set if `a & b == 0`
  - **SF (Sign Flag):** set if `a & b < 0`
  - OF and CF are always set to 0

Implicit Set Condition Codes

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addq %rax, %rbx
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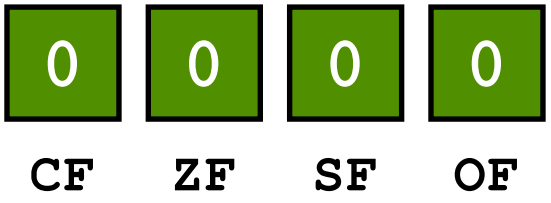
`addq` *0xFF, 0x80*

```
   10000000
+) 11111111
-----------
  c01111111
```



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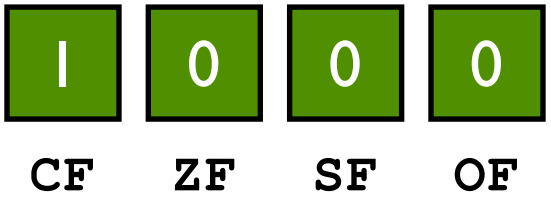

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1	0	0	1
CF	ZF	SF	OF

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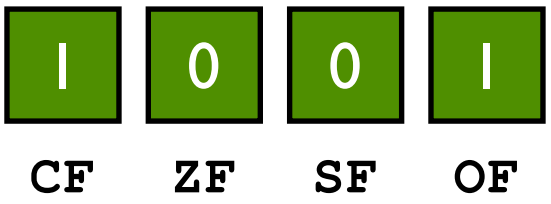

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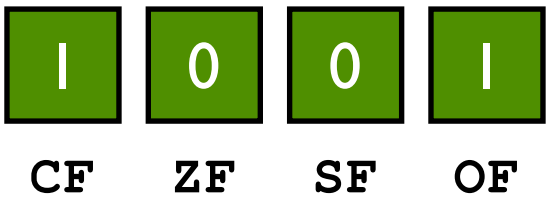

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Questions?

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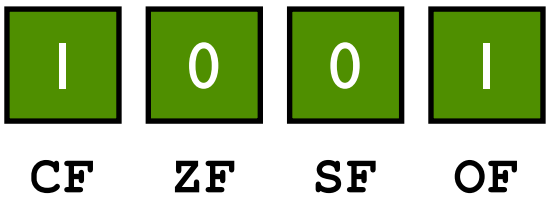

Today: Compute and Control Instructions

- Arithmetic & logical operations
- Control: Condition codes
- Conditional branches (`if`… `else`…)
- Loops (`for`, `do`… `while`)
- 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);
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`goto` Version

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“Do-While” Loop Assembly

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Register	Use(s)
%rdi	Argument x
%rax	result

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   movl    $0, %rax    #  result = 0
.L2:                   # loop:
   movq    %rdi, %rdx
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   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    %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     %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
}
```

```
#define WSIZE 8*sizeof(unsigned)
long pcount_for (unsigned int x)
{

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

}
```

“For” Loop Example

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

init

```
i = 0
```

```
#define WSIZE 8*sizeof(unsigned)
long pcount_for (unsigned int x)
{

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

}
```

“For” Loop Example

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

init

```
i = 0
```

test

```
i < WSIZE
```

```
#define WSIZE 8*sizeof(unsigned)
long pcount_for (unsigned int x)
{

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

}
```

“For” Loop Example

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

```
#define WSIZE 8*sizeof(unsigned)
long pcount_for (unsigned int x)
{

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

}
```

init

```
i = 0
```

test

```
i < WSIZE
```

update

```
i++
```

“For” Loop Example

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

```
#define WSIZE 8*sizeof(unsigned)
long pcount_for (unsigned int x)
{

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

}
```

init

```
i = 0
```

test

```
i < WSIZE
```

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

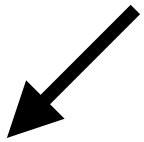
```
before;
for (init; test; update) {
  body;
}
after
```

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
```



Convert "For" Loop to "While" Loop

For Version

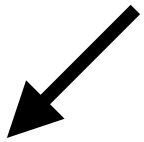
```
before;
for (init; test; update) {
  body;
}
after
```

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
```



Questions?

Today: Compute and Control Instructions

- Arithmetic & logical operations
- Control: Condition codes
- Conditional branches (`if`… `else`…)
- Loops (`for`, `do`… `while`)
- 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;
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        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;
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        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:
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        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

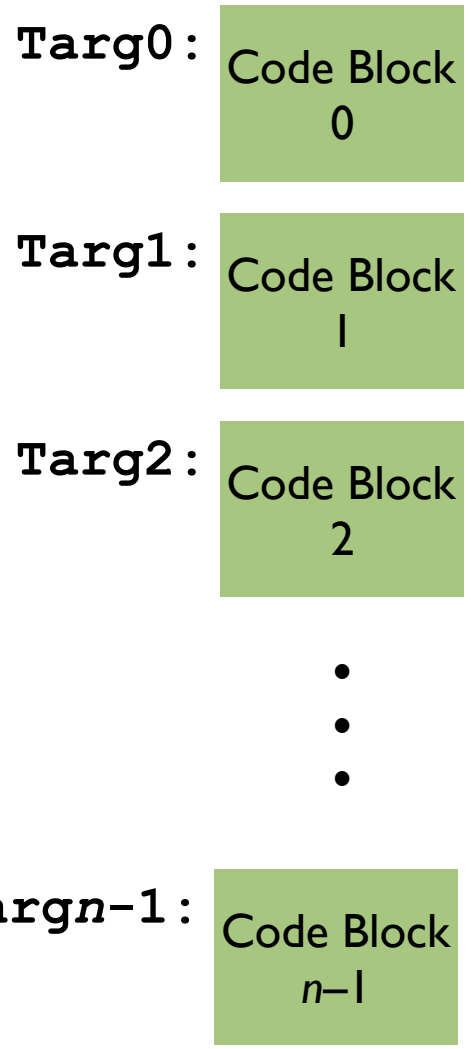
```
switch(x) {
  case val_0:
    Block 0
  case val_1:
    Block 1

  ....
  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
}
```

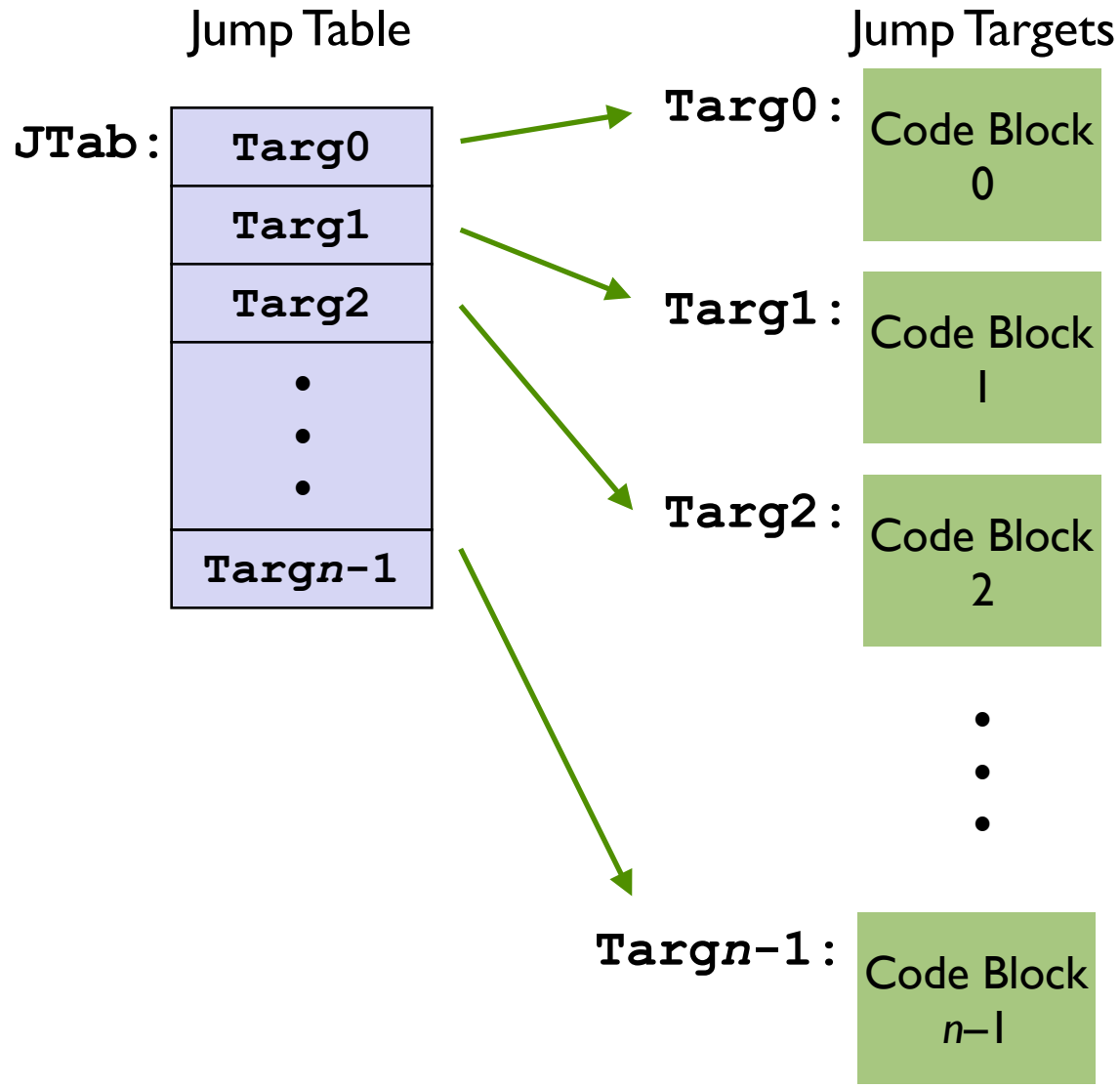
Jump Targets



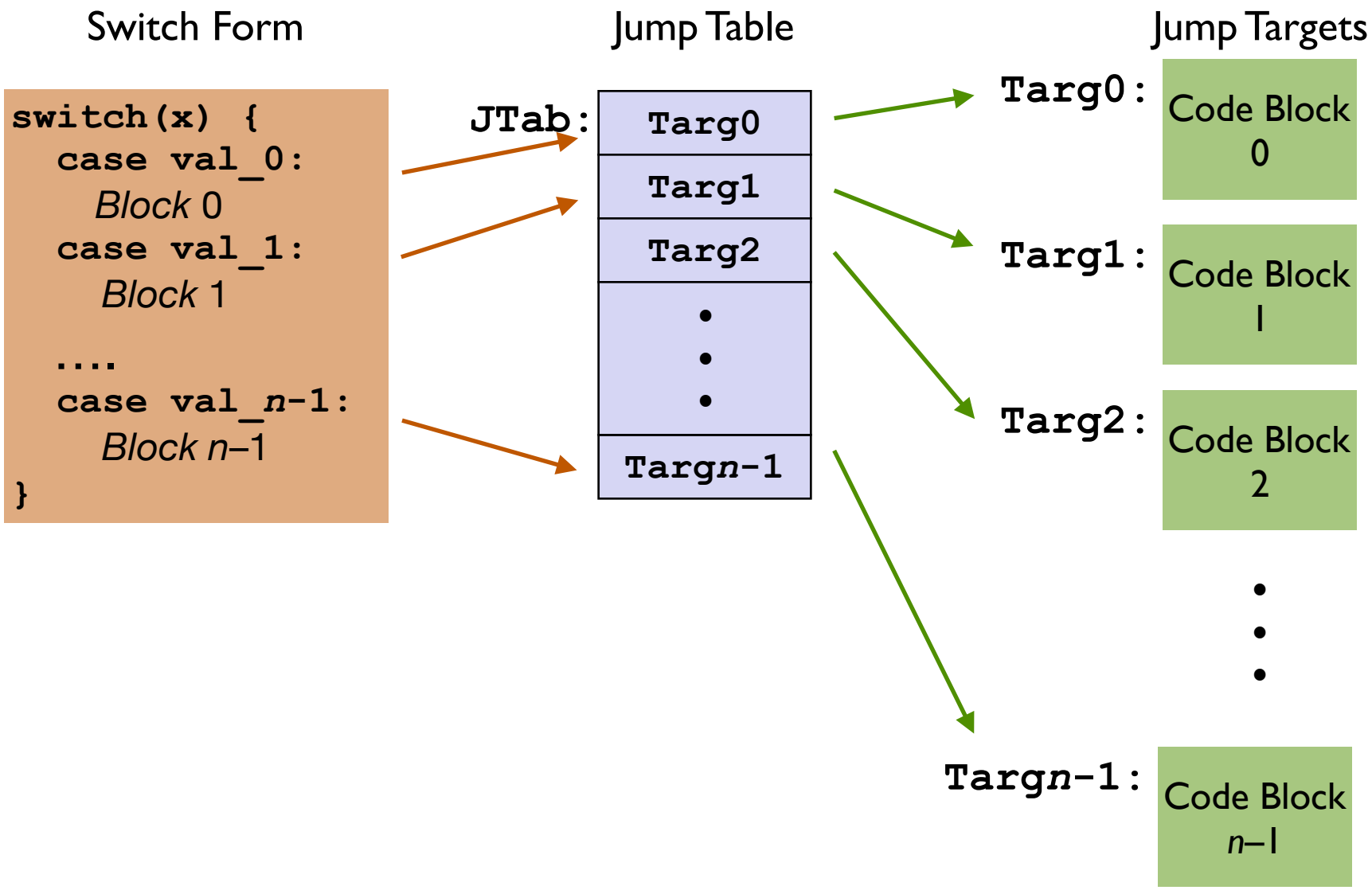
Implementing Switch Using Jump Table

Switch Form

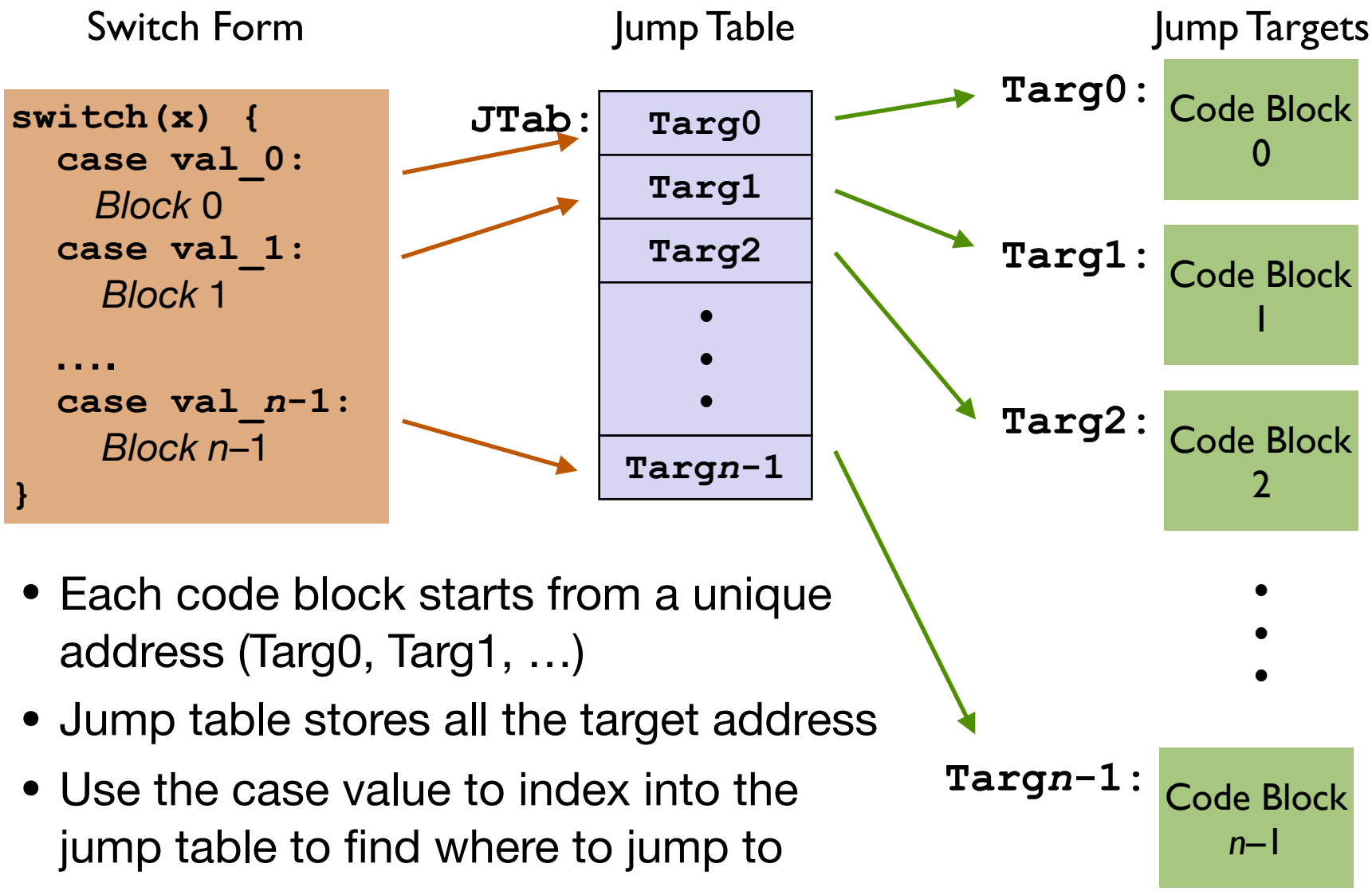
```
switch(x) {
  case val_0:
    Block 0
  case val_1:
    Block 1

  ....
  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

Jump Table in Assembly

```
.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
```

```
switch(x) {
case 1:       // .L3
    w = y*z;
    break;
case 2:       // .L5
    w = y/z;
    /* Fall Through */
case 3:       // .L9
    w += z;
    break;
case 5:
case 6:       // .L7
    w -= z;
    break;
default:      // .L8
    w = 2;
}
```

Jump Table in Assembly

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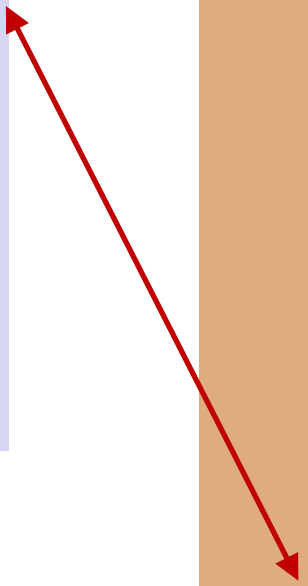

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Jump Table in Assembly

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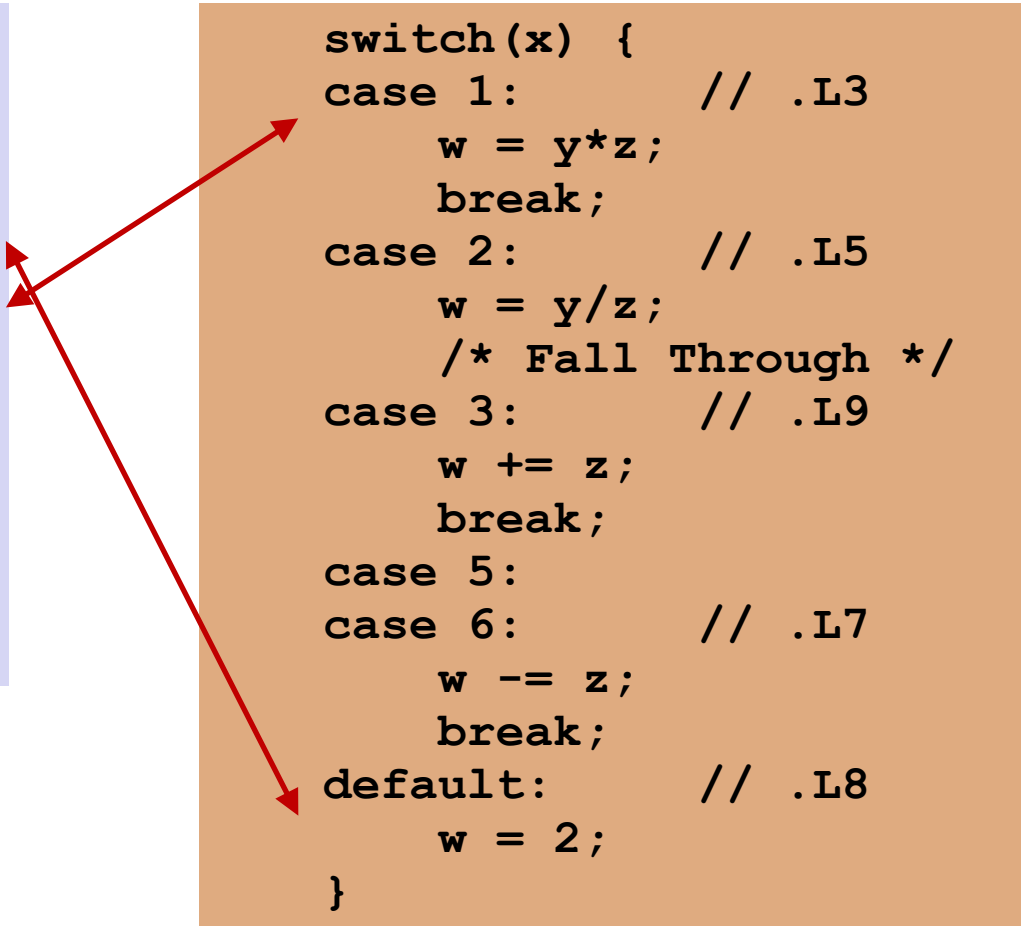
```



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switch(x) {
case 1:       // .L3
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    break;
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    w = y/z;
    /* Fall Through */
case 3:       // .L9
    w += z;
    break;
case 5:
case 6:       // .L7
    w -= z;
    break;
default:      // .L8
    w = 2;
}
```

Jump Table in Assembly

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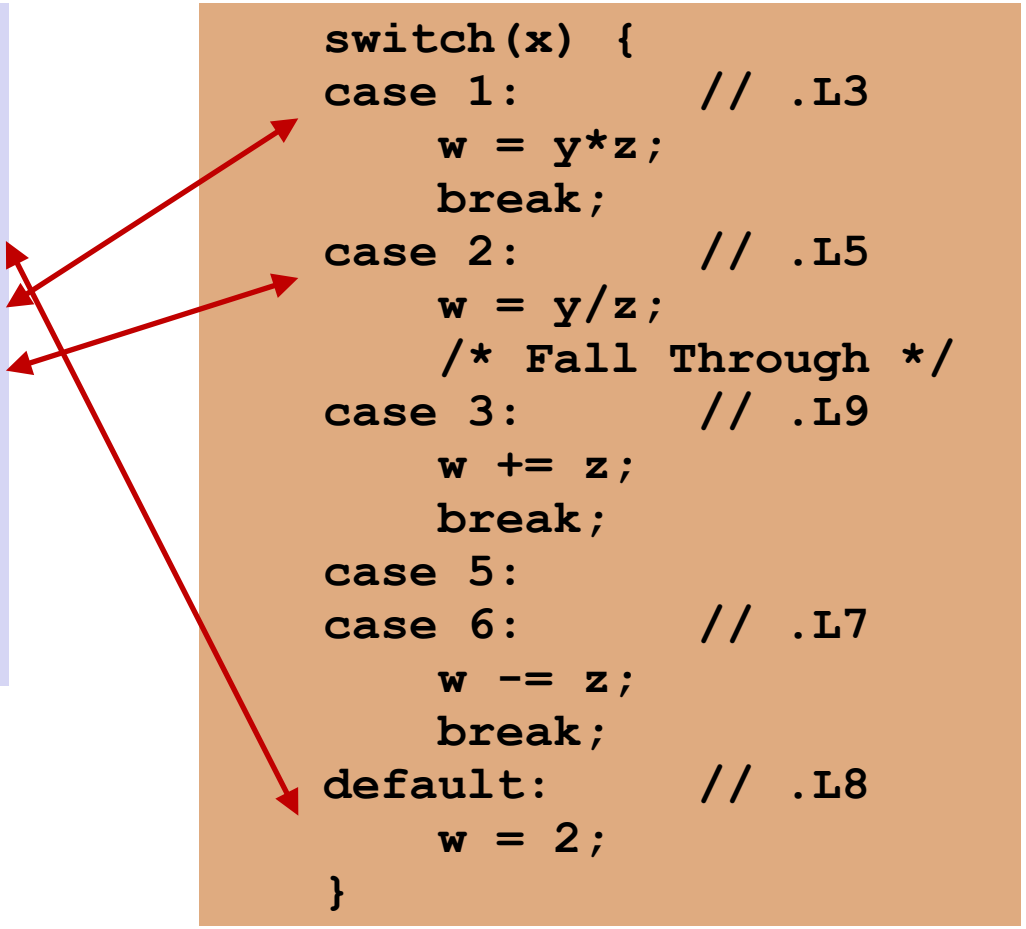
```



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    /* Fall Through */
case 3:       // .L9
    w += z;
    break;
case 5:
case 6:       // .L7
    w -= z;
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default:      // .L8
    w = 2;
}
```

Jump Table in Assembly

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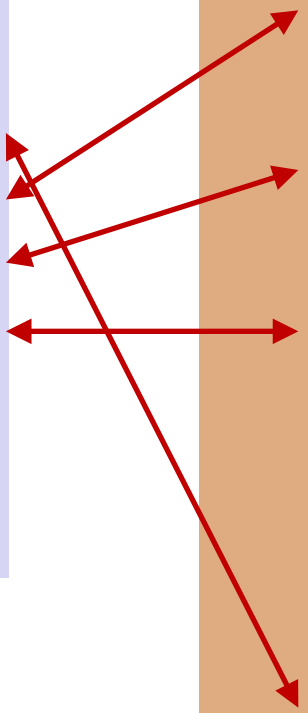
  .quad .L7 # x = 6
```



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    break;
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Jump Table in Assembly

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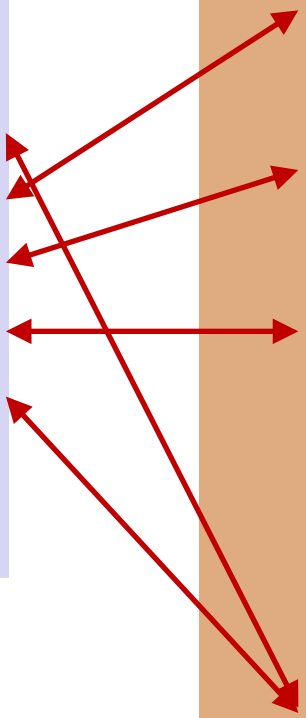

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    w -= z;
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Jump Table in Assembly

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  .quad .L7 # x = 5
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```

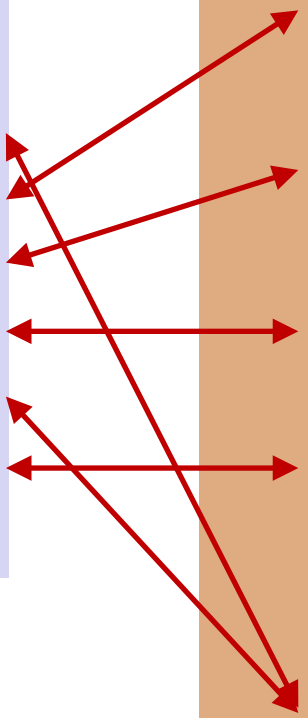

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case 1:       // .L3
    w = y*z;
    break;
case 2:       // .L5
    w = y/z;
    /* Fall Through */
case 3:       // .L9
    w += z;
    break;
case 5:
case 6:       // .L7
    w -= z;
    break;
default:      // .L8
    w = 2;
}
```

Jump Table in Assembly

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.section  .rodata
  .align 8
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  .quad .L7 # x = 6
```

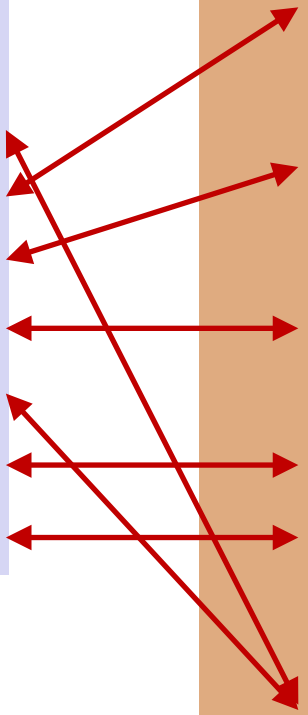

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switch(x) {
case 1:       // .L3
    w = y*z;
    break;
case 2:       // .L5
    w = y/z;
    /* Fall Through */
case 3:       // .L9
    w += z;
    break;
case 5:
case 6:       // .L7
    w -= z;
    break;
default:      // .L8
    w = 2;
}
```

Assembly Directives (Pseudo-Ops)

```
.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
```

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

Assembly Directives (Pseudo-Ops)

```
.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
```

- .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.

Assembly Directives (Pseudo-Ops)

```
.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
```

- .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)
- .align: tells the assembler that addresses of the the following data will be aligned to 8 bytes

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  .quad .L9 # x = 3
  .quad .L8 # x = 4
  .quad .L7 # x = 5
  .quad .L7 # x = 6
```

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

- .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)
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- .section: denotes different parts of the object file

Assembly Directives (Pseudo-Ops)

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  .align 8
.L4:
  .quad .L8 # x = 0
  .quad .L3 # x = 1
  .quad .L5 # x = 2
  .quad .L9 # x = 3
  .quad .L8 # x = 4
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```

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

- .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)
- .align: tells the assembler that addresses of the the following data will be aligned to 8 bytes
- .section: denotes different parts of the object file
- .rodata: read-only data section

Code Blocks (x == 1)

```
.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
```

Code Blocks (x == 1)

```
.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
```

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

Code Blocks (x == 1)

```
.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
```

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

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

Code Blocks (x == 1)

```
.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
```

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

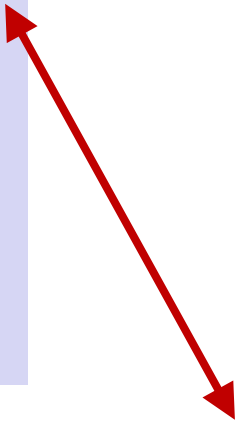
Register	Use(s)
%rdi	Argument x
%rsi	Argument y
%rdx	Argument z
%rax	Return value

```
.L3:
   movq     %rsi, %rax   # y
   imulq    %rdx, %rax   # y*z
   jmp      .done
```

Code Blocks (x == 1)

```
.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
```

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



```
.L3:
   movq     %rsi, %rax   # y
   imulq    %rdx, %rax   # y*z
   jmp      .done
```

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

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

```
.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
```

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

```
.section  .rodata
  .align 8
.L4:
  .quad .L8 # x = 0
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  .quad .L5 # x = 2
  .quad .L9 # x = 3
  .quad .L8 # x = 4
  .quad .L7 # x = 5
  .quad .L7 # x = 6
```

```
switch(x) {
…
case 2:         // .L5
    w = y/z;
    /* Fall Through */
case 3:         // .L9
    w += z;
    break;
    …
}
```

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

```
.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
```

```
switch(x) {
…
case 2:          // .L5
    w = y/z;
    /* Fall Through */
case 3:          // .L9
    w += z;
    break;
    …
}
```

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

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

```
.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
```

```
switch(x) {
…
case 2:          // .L5
    w = y/z;
    /* Fall Through */
case 3:          // .L9
    w += z;
    break;
    …
}
```

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

```
.L5:                        # Case 2
   movq     %rsi, %rax
   cqto
   idivq    %rcx           #  y/z

.L9:                        # Case 3
   addq     %rcx, %rax #  w += z
   jmp      .done
```

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

```
.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
```

```
switch(x) {
…
case 2:          // .L5
    w = y/z;
    /* Fall Through */
case 3:          // .L9
    w += z;
    break;
    …
}
```

```
.L5:                        # Case 2
    movq     %rsi, %rax
    cqto
    idivq    %rcx           #  y/z

.L9:                        # 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)

```
.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
```

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

```
.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
```

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

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

```
.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
```

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

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

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

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.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
```

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

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

```
.L7:                    # Case 5,6
  subq  %rdx, %rax #  w -= z
  jmp   .done
.L8:                    # Default:
  movl  $2, %eax    #  2
  jmp   .done
```

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

```
.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
```

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

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

```
.L7:                    # Case 5,6
  subq   %rdx, %rax #   w -= z
  jmp    .done
.L8:                    # Default:
  movl   $2, %eax    #   2
  jmp    .done
```

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

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     w -= z;
     break;
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%rdi	Argument x
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.L7:                    # Case 5,6
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.L8:                    # Default:
  movl   $2, %eax    #  2
  jmp    .done
```

Jump Table and Jump Targets

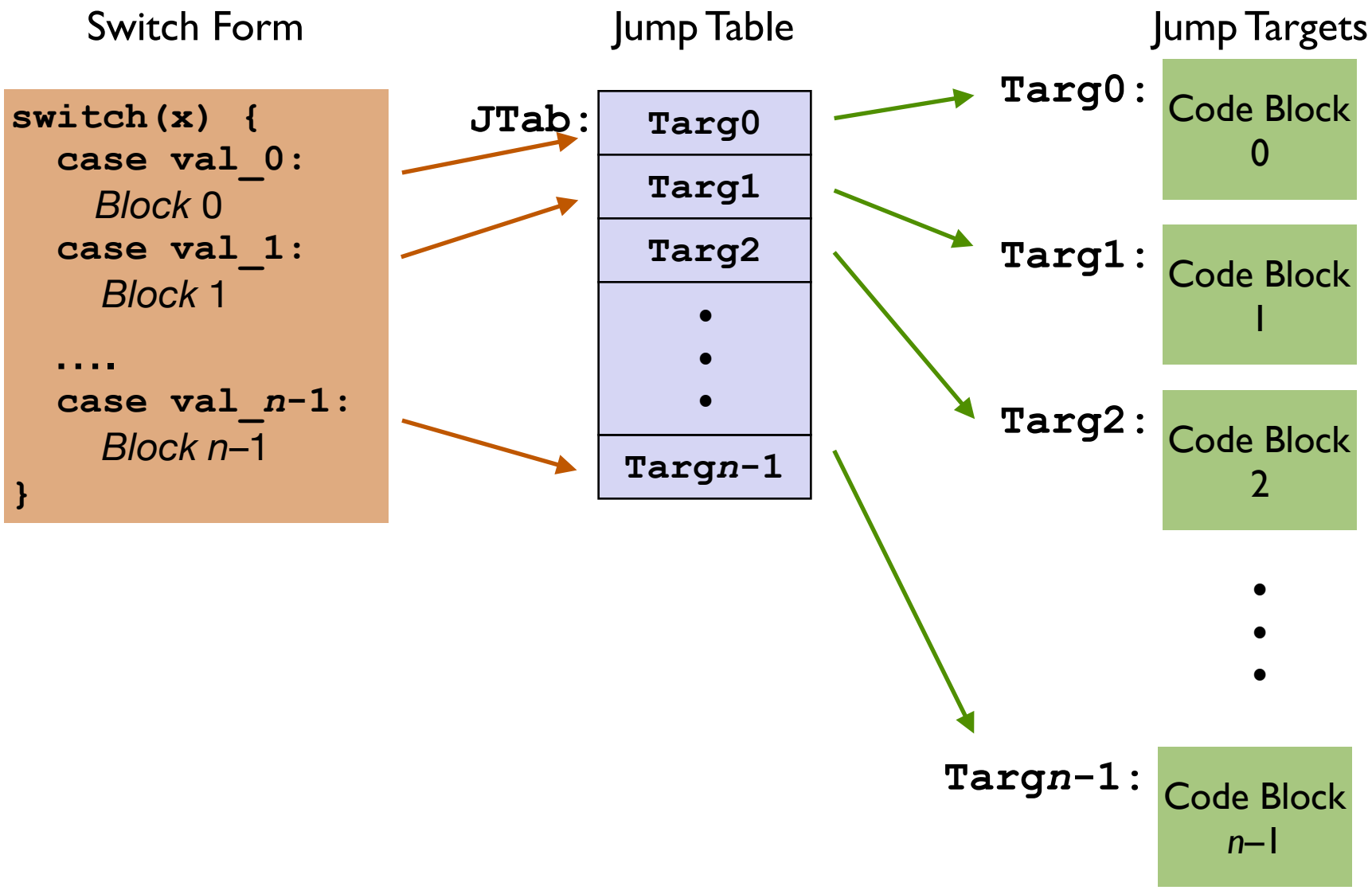
Jump Table

```
.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
```

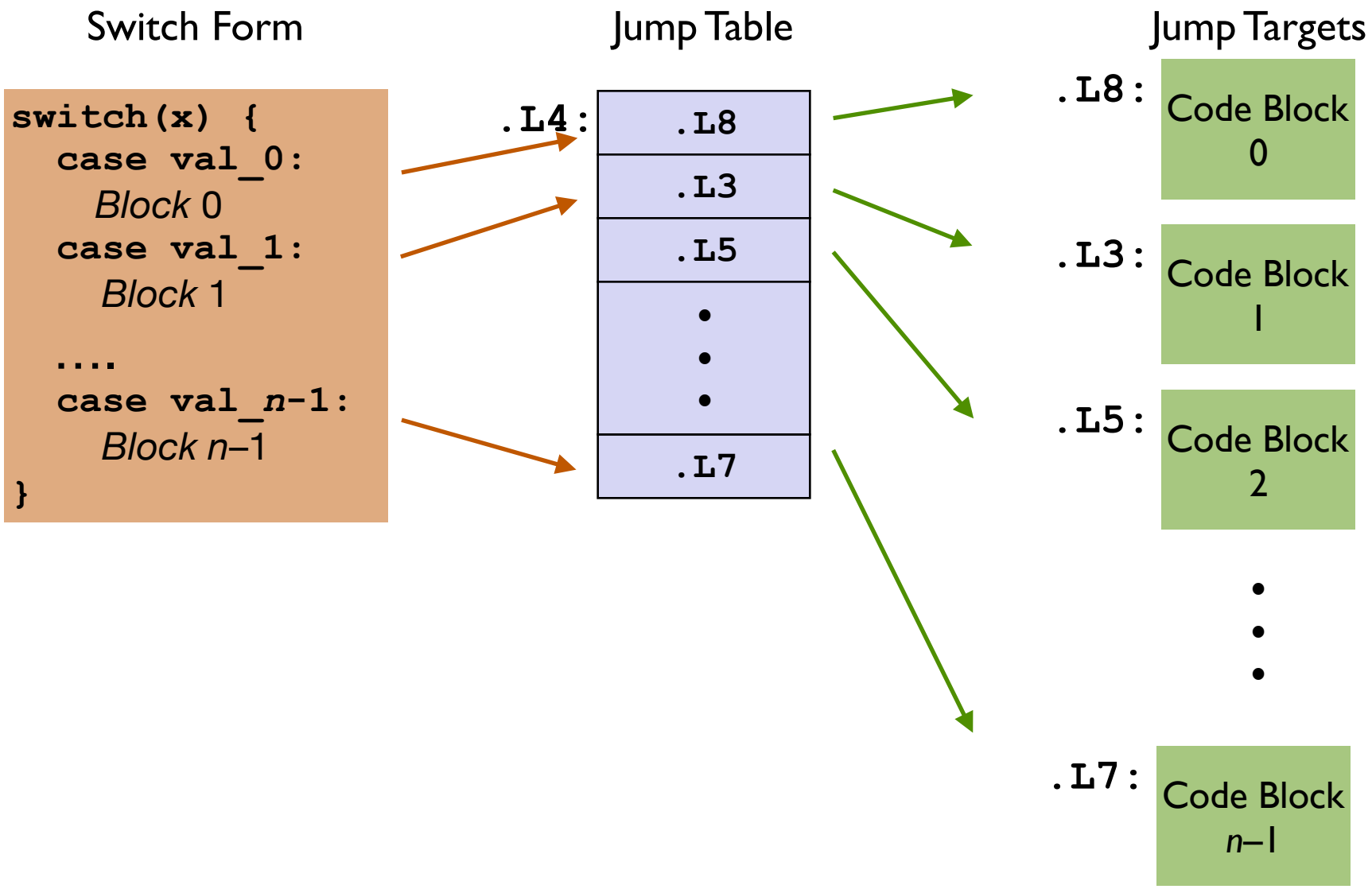
Jump Targets

```
.L3:                    # Case 1
   movq    %rsi, %rax
   imulq   %rdx, %rax
   jmp     .done
.L5:                    # Case 2
   movq    %rsi, %rax
   cqto
   idivq   %rcx
.L9:                    # Case 3
   addq    %rcx, %rax
   jmp     .done
.L7:                    # Case 5,6
   subq    %rdx, %rax
   jmp     .done
.L8:                    # Default
  movl     $2, %eax
  jmp     .done
```

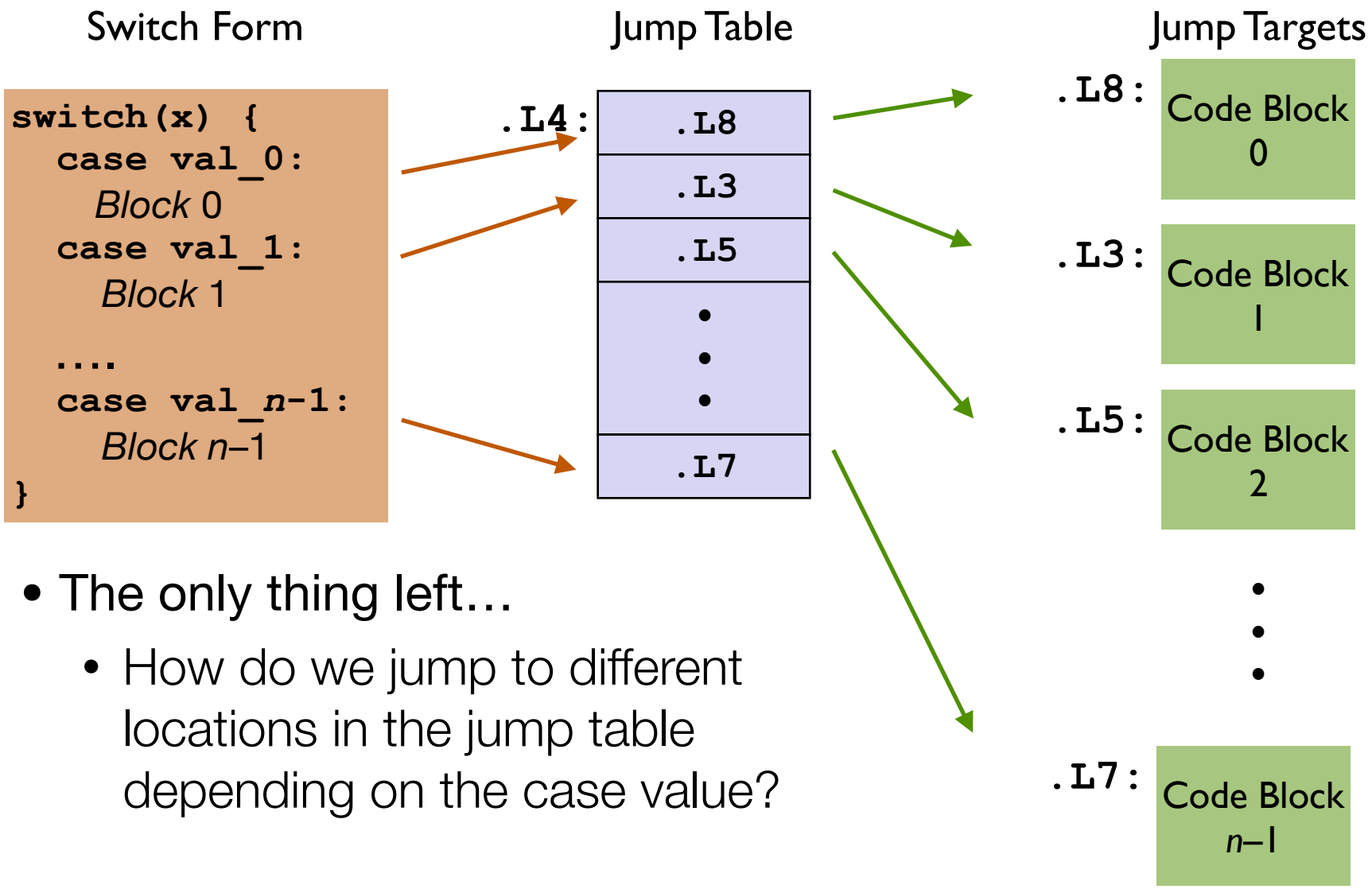
Implementing Switch Using Jump Table



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

```
.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
```

Indirect Jump Instruction

Address we want = .L4 + 8 * x

```
.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
```

Indirect Jump Instruction

Address we want = .L4 + 8 * x

```
# assume x in %rdi
movq   .L4(,%rdi,8), %rax
jmp    *%rax
```

```
.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
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```

Indirect Jump Instruction

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.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
```

Address we want = .L4 + 8 * `x`

```
# assume x in %rdi
movq   .L4(,%rdi,8), %rax
jmp    *%rax
```

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

Indirect Jump Instruction

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.section  .rodata
  .align 8
.L4:
  .quad .L8 # x = 0
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  .quad .L8 # x = 4
  .quad .L7 # x = 5
  .quad .L7 # x = 6
```

Address we want = .L4 + 8 * `x`

```
# assume x in %rdi
movq  .L4(,%rdi,8), %rax
jmp   *%rax
```

- Indirect Jump: **`jmp *%rax`**
  - `%rax` specifies the address to jump to (PC = `%rax`)
- Direct Jump (**`jmp .L4`**), directly specifies the jump address

Indirect Jump Instruction

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.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
```

Address we want = .L4 + 8 * `x`

```
# assume x in %rdi
movq  .L4(,%rdi,8), %rax
jmp   *%rax
```

- Indirect Jump: **`jmp *%rax`**
  - `%rax` specifies the address to jump to (PC = `%rax`)
- Direct Jump (**`jmp .L4`**), directly specifies the jump address
- Indirect Jump specifies where the jump address is located

Indirect Jump Instruction

```
.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
```

Address we want = .L4 + 8 * `x`

```
# assume x in %rdi
movq  .L4(,%rdi,8), %rax
jmp   *%rax
```

- Indirect Jump: **`jmp *%rax`**
  - `%rax` specifies the address to jump to (PC = `%rax`)
- Direct Jump (**`jmp .L4`**), directly specifies the jump address
- Indirect Jump specifies where the jump address is located

```
jmp     *.L4(,%rdi,8)
```