CSC 252: Computer Organization
Spring 2019: Lecture 7

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University of Rochester

Action Items:

- **Assignment 2 is out**

Announcement

- Programming Assignment 2 is out
  - Due on **Feb 15, 11:59 PM**
  - You may still have 3 slip days…

3	4	5	6	7 **Today**	8	9
10	11	12	13	14	15 **Due**	16

Announcement

- Programming Assignment 2 is out
  - Due on **Feb 15, 11:59 PM**
  - You may still have 3 slip days…
- **Late submissions get 0 unless you use slip days.** But you have to tell us ahead of time.
- If you code doesn't compile, you get 0. So test your code on the CSUG machine.

Data Movement

```
movq    (%rdi), %rdx
```

- Semantics:
  - Move (really, **copy**) data store in memory location whose address is the value stored in **`%rdi`** to register **`%rdx`**

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movq    %rdx, (%rdi)
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Data Movement

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movq    %rdx, (%rdi)
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```

Accessing memory and doing computation in one instruction. OK in x86, but not all ISAs allow that (e.g., ARM).

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addq    8(%rdi), %rdx
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```

Illegal in x86 (and almost all other ISAs). Could make microarchitecture implementation inefficient/inelegant. More on this later.

Today: Control Instructions

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

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
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```

Register	Use(s)
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Labels are symbolic names used to refer to instruction addresses.

Conditional Branch Example

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

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Conditional Jump Instruction

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- Semantics of **`jle`**:
  - Treat the data in **`%rdi`** and **`%rsi`** as **signed values**.
  - If **`%rdi`** is less than or equal to **`%rsi`**, jump to the part of the code with a label **`.L4`**

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- Under the hood:

Conditional Jump Instruction

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- Under the hood:
  - **`cmpq`** instruction sets the **condition codes (a.k.a., status flags)**

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- Under the hood:
  - **`cmpq`** instruction sets the **condition codes (a.k.a., status flags)**
  - **`jle`** reads and checks the status flags

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

How Should `cmpq` Set Condition Codes?

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cmpq    %rsi, %rdi
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No Overflow

```
   001          1
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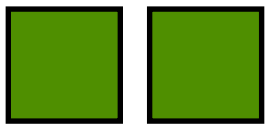
ZF Zero Flag (result is zero)

SF Sign Flag (result is negative)



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`cmpq` *0xFF, 0x80*

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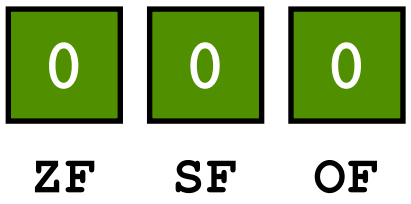

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`cmpq` *0xFF, 0x80*

10000000	**-128**
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10000001	**-127**

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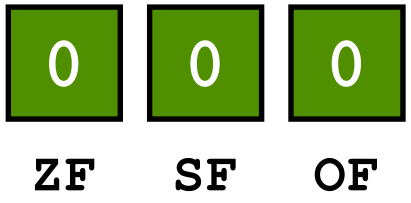

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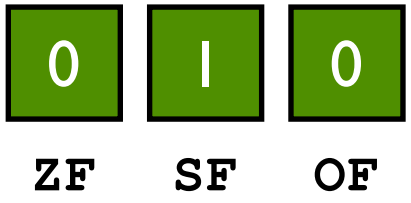

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  - `%rdi - %rsi` < 0 and the result doesn't overflow, or
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- `%rdi <= %rsi` if and only if
  - ZF is set, or
  - SF is set but OF is not set, or
  - SF is not set, but OF is set
- or simply: ZF |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

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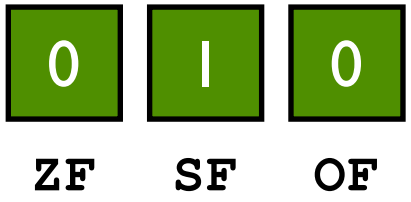

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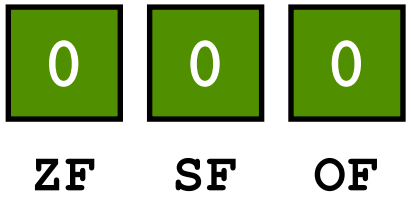

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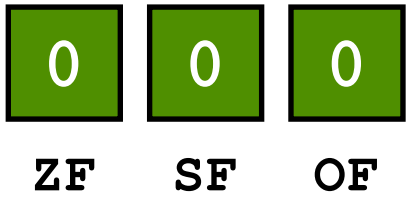
`cmpq` sets ZF, SF, OF

`jle` checks ZF | (SF ^ OF)



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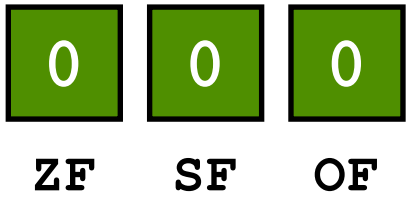

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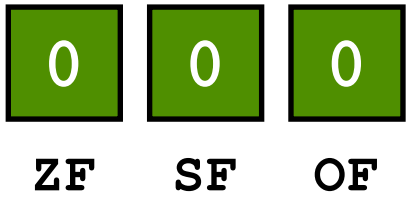

Conditional Jump Instruction

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Jump to label if
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Conditional Jump Instruction

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- Semantics of **`jbe`**:
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  - If **`%rdi`** is less than or equal to **`%rsi`**, jump to the part of the code with a label **`.L4`**

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- Under the hood:

Conditional Jump Instruction

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  - If **`%rdi`** is less than or equal to **`%rsi`**, jump to the part of the code with a label **`.L4`**
- Under the hood:
  - **`cmpq`** instruction sets the condition codes

Conditional Jump Instruction

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

Jump to label if below or equal to

- Semantics of **`jbe`**:
  - Treat the data in **`%rdi`** and **`%rsi`** as **unsigned values**.
  - If **`%rdi`** is less than or equal to **`%rsi`**, jump to the part of the code with a label **`.L4`**
- Under the hood:
  - **`cmpq`** instruction sets the condition codes
  - **`jbe`** reads and checks the condition codes

Conditional Jump Instruction

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How Should `cmpq` Set Condition Codes?

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```
   001    <---   1
-) 111    <---   7
-------
  C010
```

ZF

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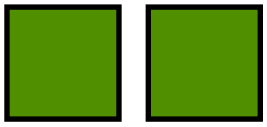

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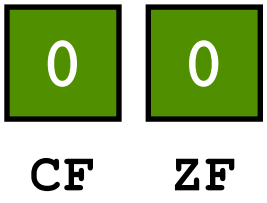

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-----------------------
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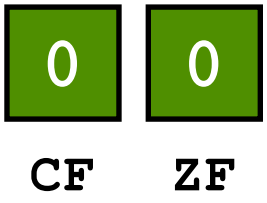

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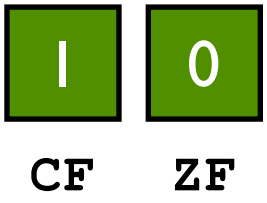

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- `%rdi == %rsi` if and only if `%rdi - %rsi == 0`
- `%rdi < %rsi` if a carry is generated during subtraction

- `%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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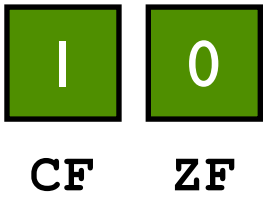

Putting It All Together

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- `cmpq` sets all 4 condition codes simultaneously

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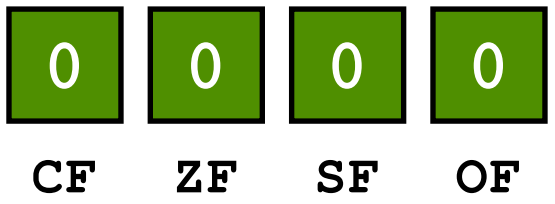
CF Carry Flag

SF Sign Flag

OF Overflow Flag (for signed)



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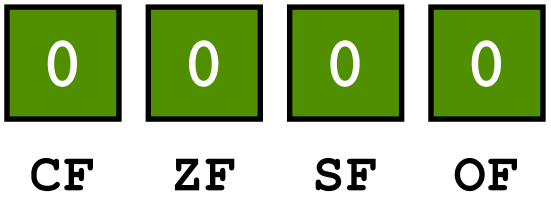

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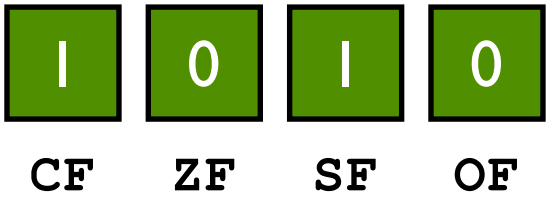

Putting It All Together

```
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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```
    10000000
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-------------
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```

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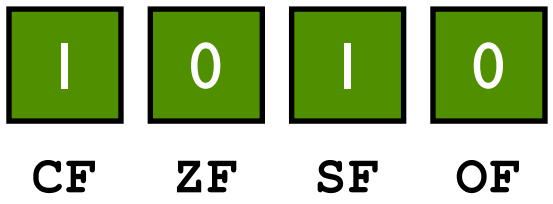

Putting It All Together

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

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```
    10000000
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-------------
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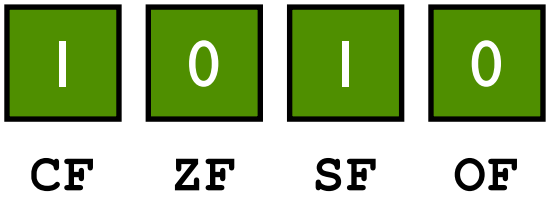
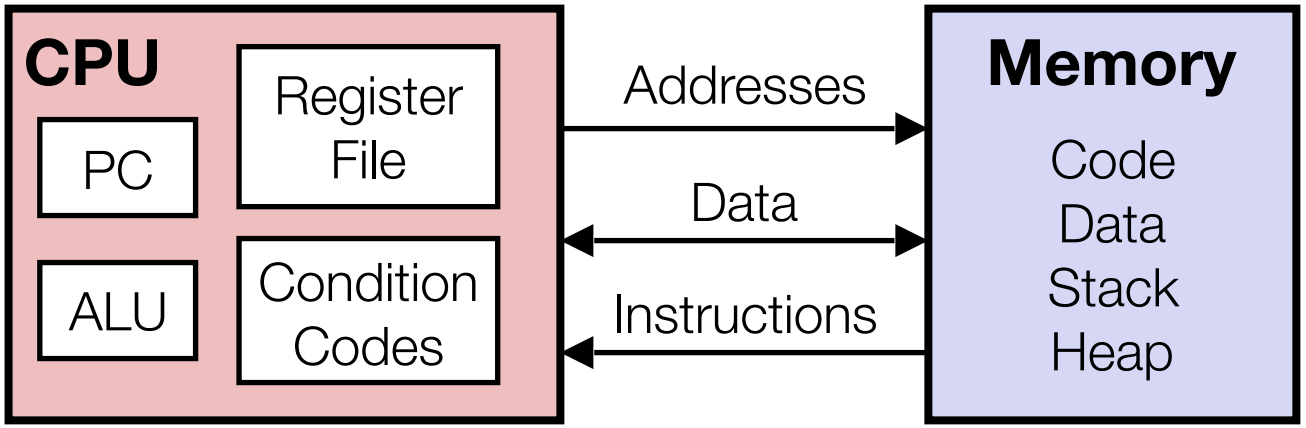
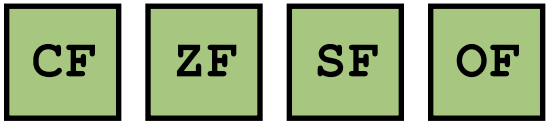


Condition Codes Hold Test Results

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

ZF Zero 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)

Implicit Set Condition Codes

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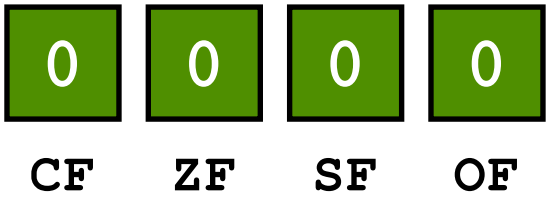
`addq` *0xFF, 0x80*

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



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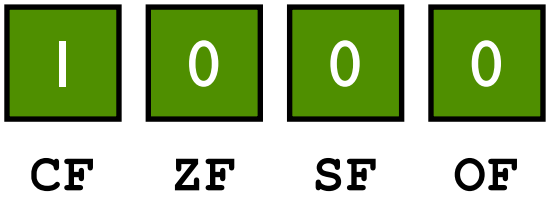

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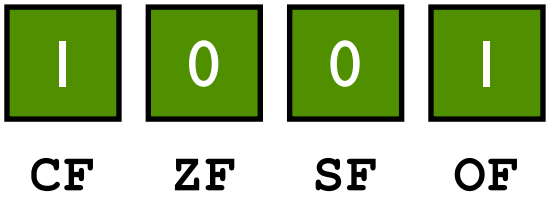

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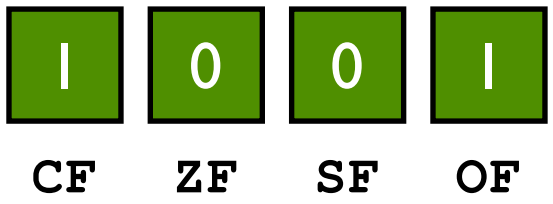

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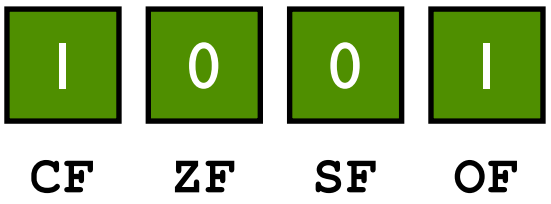

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Questions?

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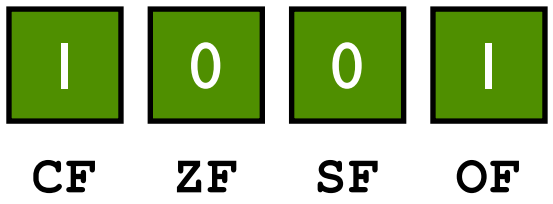

Today: Control Instructions

- 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;
}
```

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`goto` Version

```
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 loop:
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  x >>= 1;
  if(x) goto loop;
  return result;
}
```

“Do-While” Loop Assembly

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```

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
```

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   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
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“Do-While” Loop Assembly

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“Do-While” Loop Assembly

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“Do-While” Loop Assembly

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“Do-While” Loop Assembly

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   movq    %rdi, %rdx
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   addq    %rdx, %rax  #  result += t
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“Do-While” Loop Assembly

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“Do-While” Loop Assembly

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   movl    $0, %rax    #  result = 0
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   movq    %rdi, %rdx
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   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
}
```

init

```
i = 0
```

test

```
i < WSIZE
```

```
//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 < WSIZE
```

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 < 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

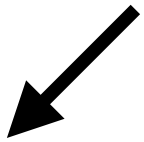
```
before;
for (init; test; update) {
  body;
}
after
```

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: 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:
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        w += z;
        break;
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    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)
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    long w = 1;
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    case 1:
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        w += z;
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    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)
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    case 1:
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        w += z;
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    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)
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    long w = 1;
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    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

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
}
```

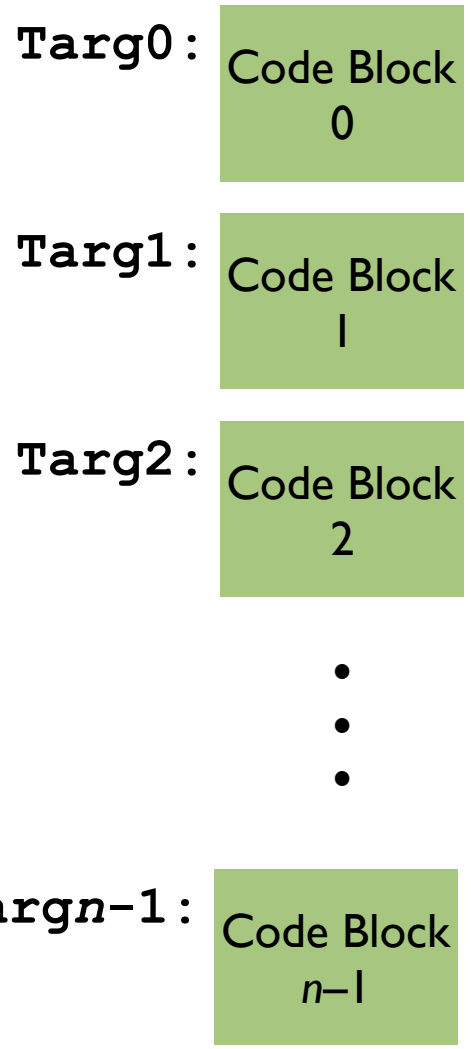
Implementing Switch Using Jump Table

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:
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  ....
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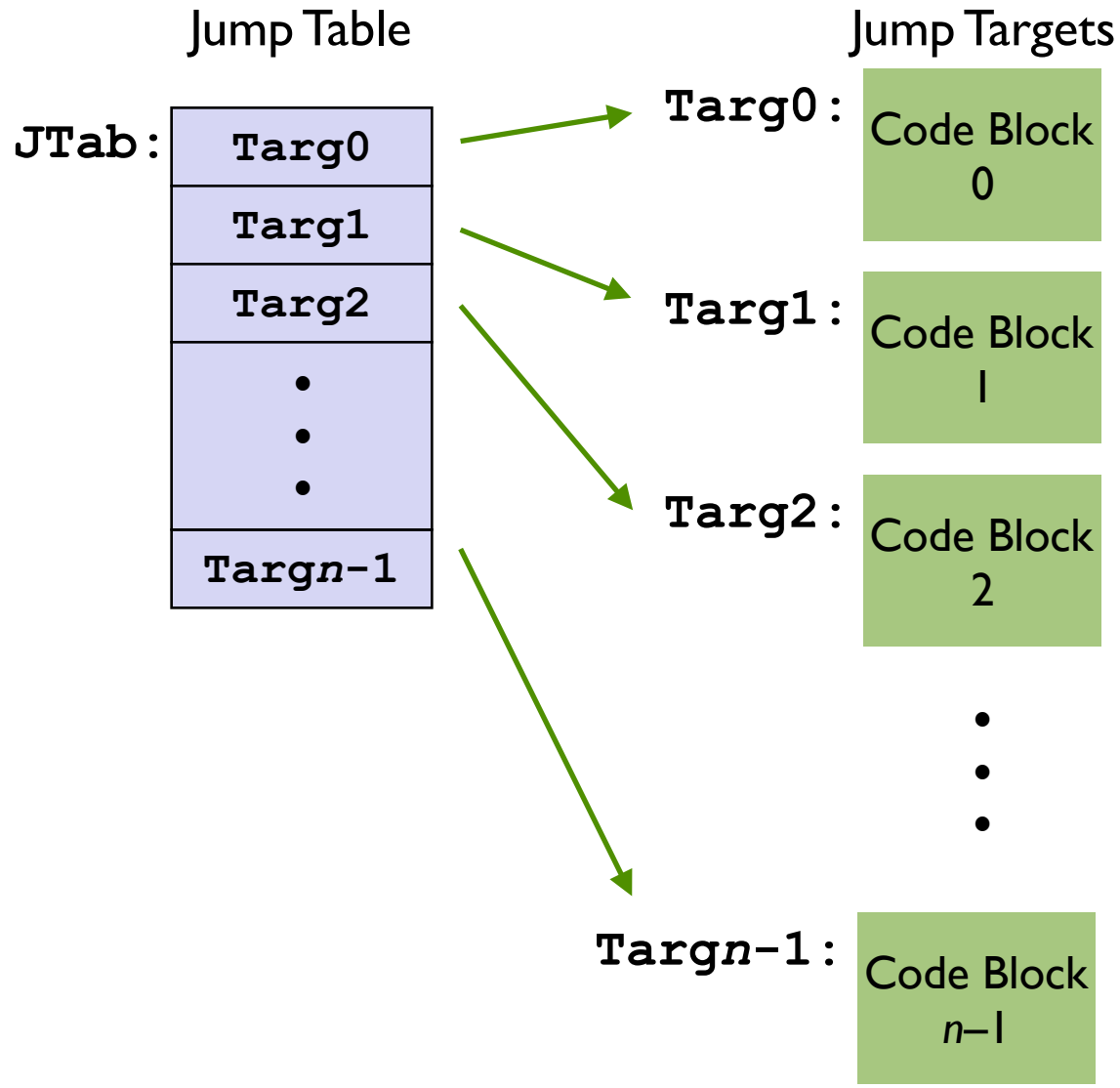
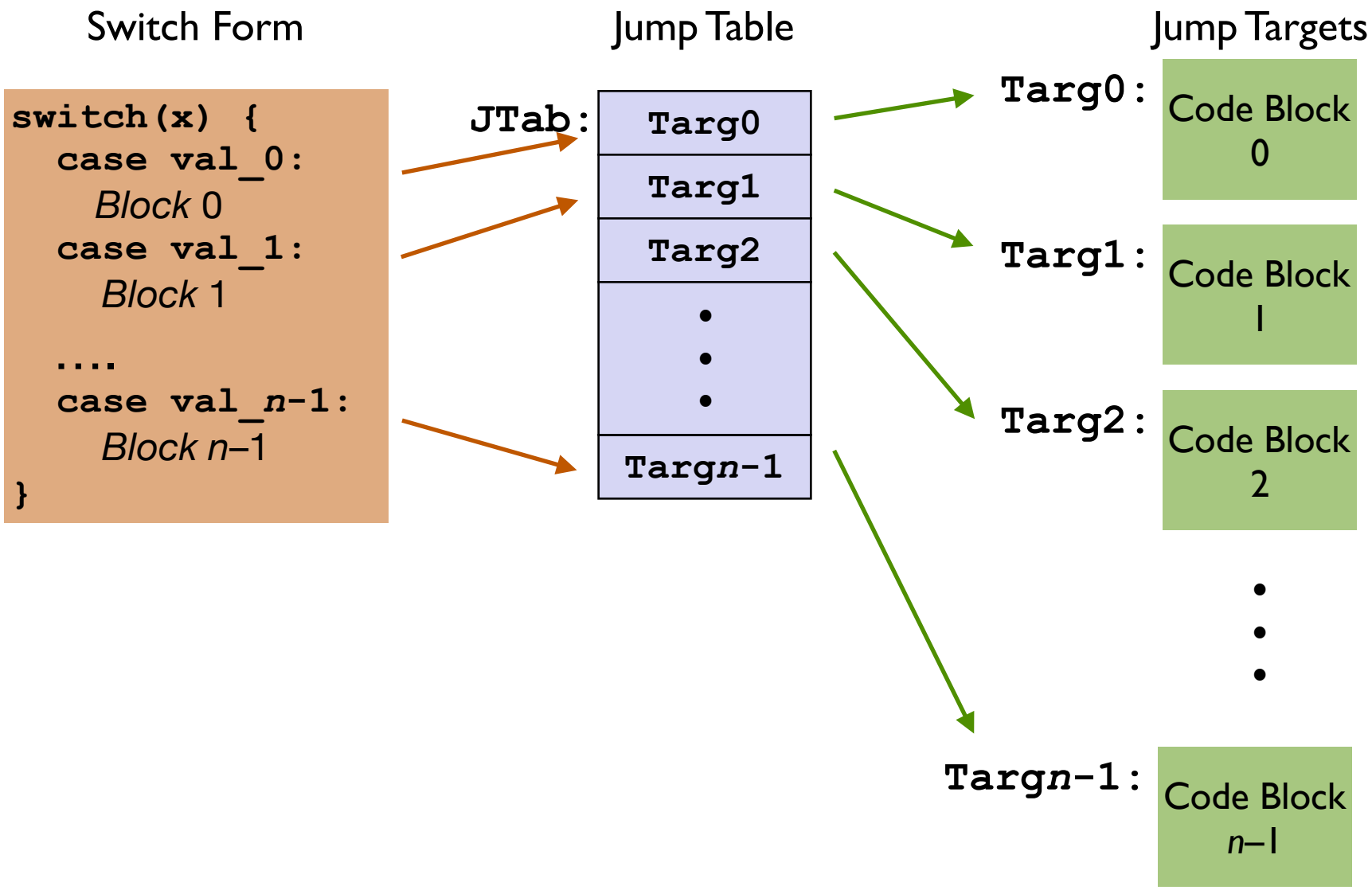
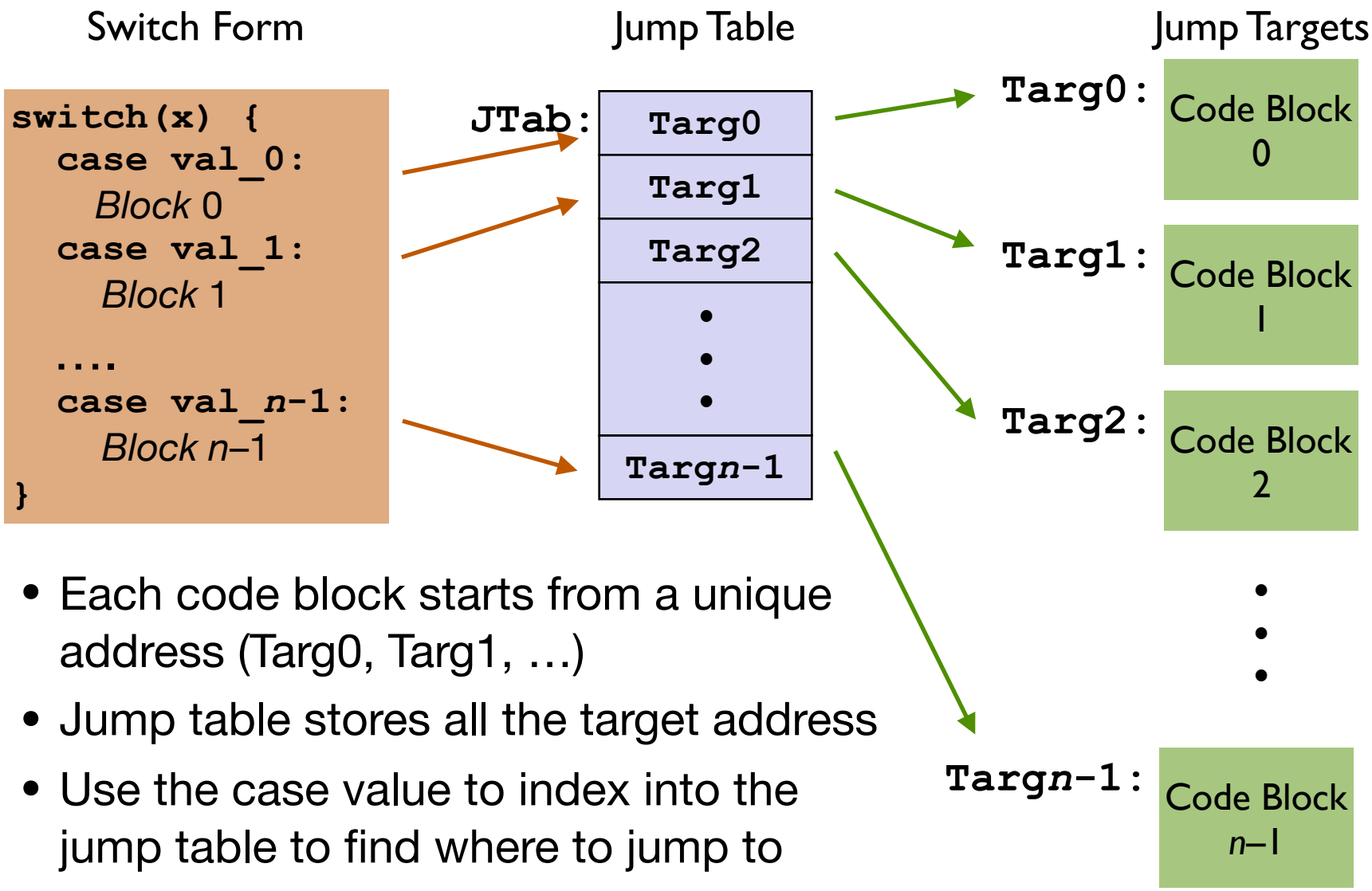


Implementing Switch Using Jump Table



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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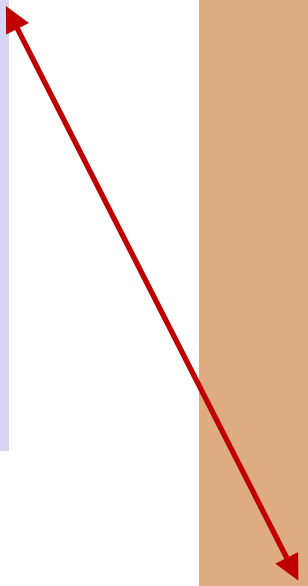

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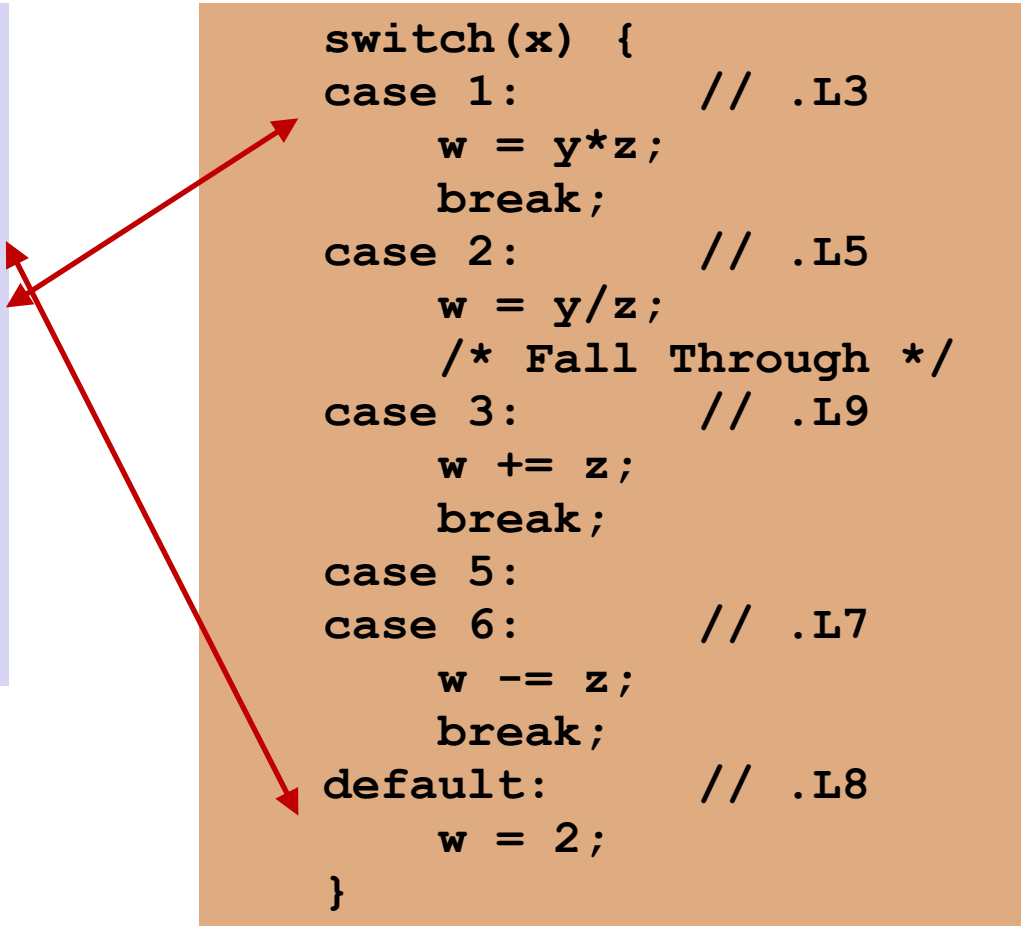
```



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    /* Fall Through */
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case 6:       // .L7
    w -= z;
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Jump Table in Assembly

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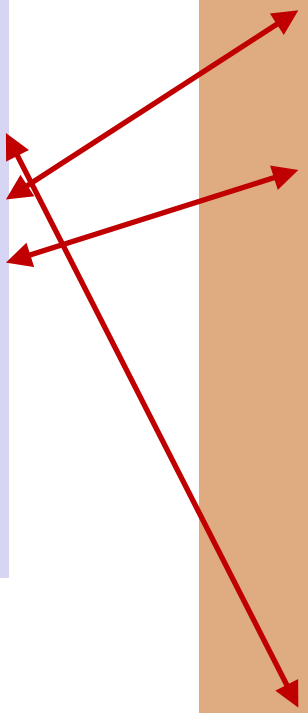
```



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    /* Fall Through */
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    w -= z;
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}
```

Jump Table in Assembly

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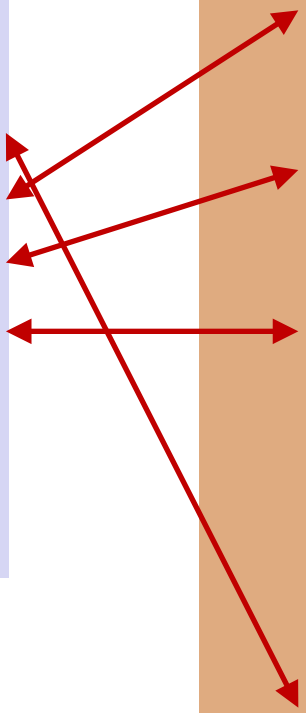
  .quad .L7 # x = 6
```



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case 1:       // .L3
    w = y*z;
    break;
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    w += z;
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    w -= z;
    break;
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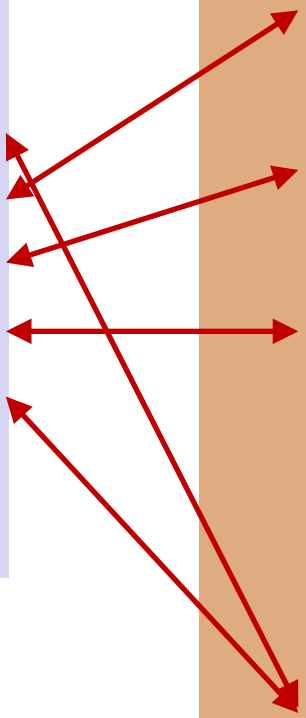

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    w = y/z;
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    w += z;
    break;
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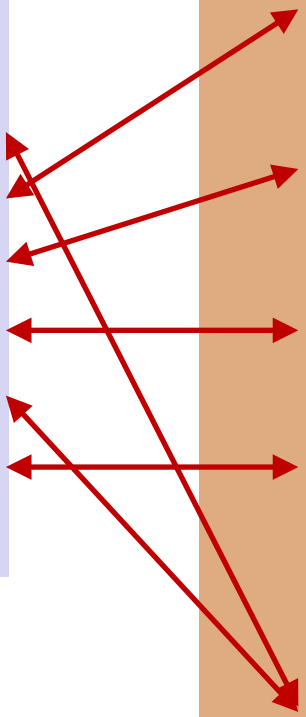
case 6:       // .L7
    w -= z;
    break;
default:      // .L8
    w = 2;
}
```

Jump Table in Assembly

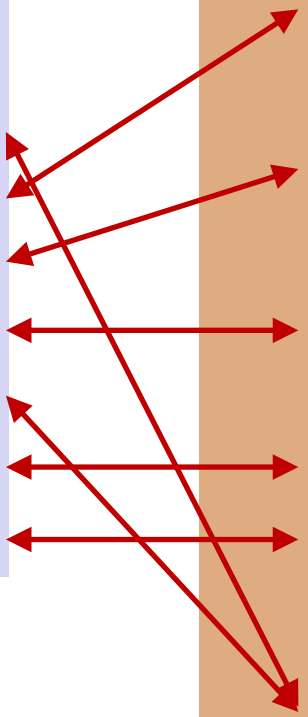
```
.section  .rodata
  .align 8
.L4:
  .quad .L8 # x = 0
  .quad .L3 # x = 1
  .quad .L5 # x = 2
  .quad .L9 # x = 3
  .quad .L8 # x = 4
  .quad .L7 # x = 5
  .quad .L7 # x = 6
```



```
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

```
.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;
}
```

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)

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

Assembly Directives (Pseudo-Ops)

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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
```

- .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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  - 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
```

- 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

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.

- .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;
     …
}
```

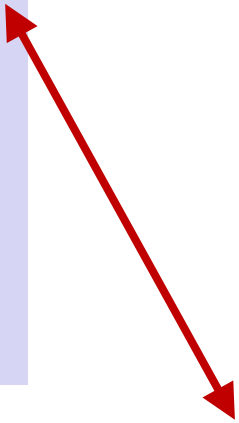
Register	Use(s)
%rdi	Argument x
%rsi	Argument y
%rdx	Argument z
%rax	Return value

```
.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;
     …
}
```



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 == 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
  .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;
    …
}
```

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)

```
.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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.section   .rodata
  .align 8
.L4:
  .quad .L8 # x = 0
  .quad .L3 # x = 1
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  .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
```

Jump Table and Jump Targets

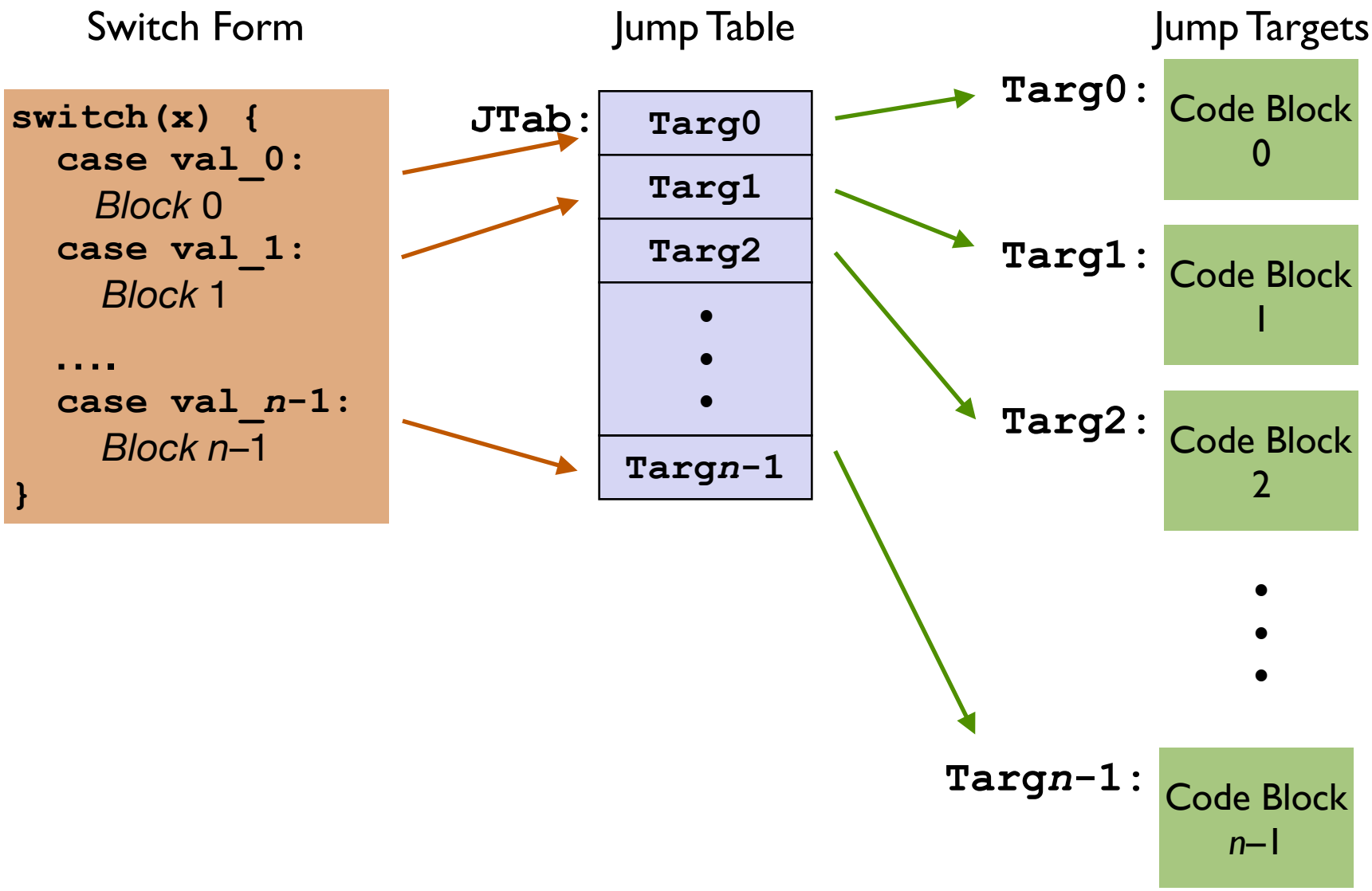
Jump Table

```
.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
```

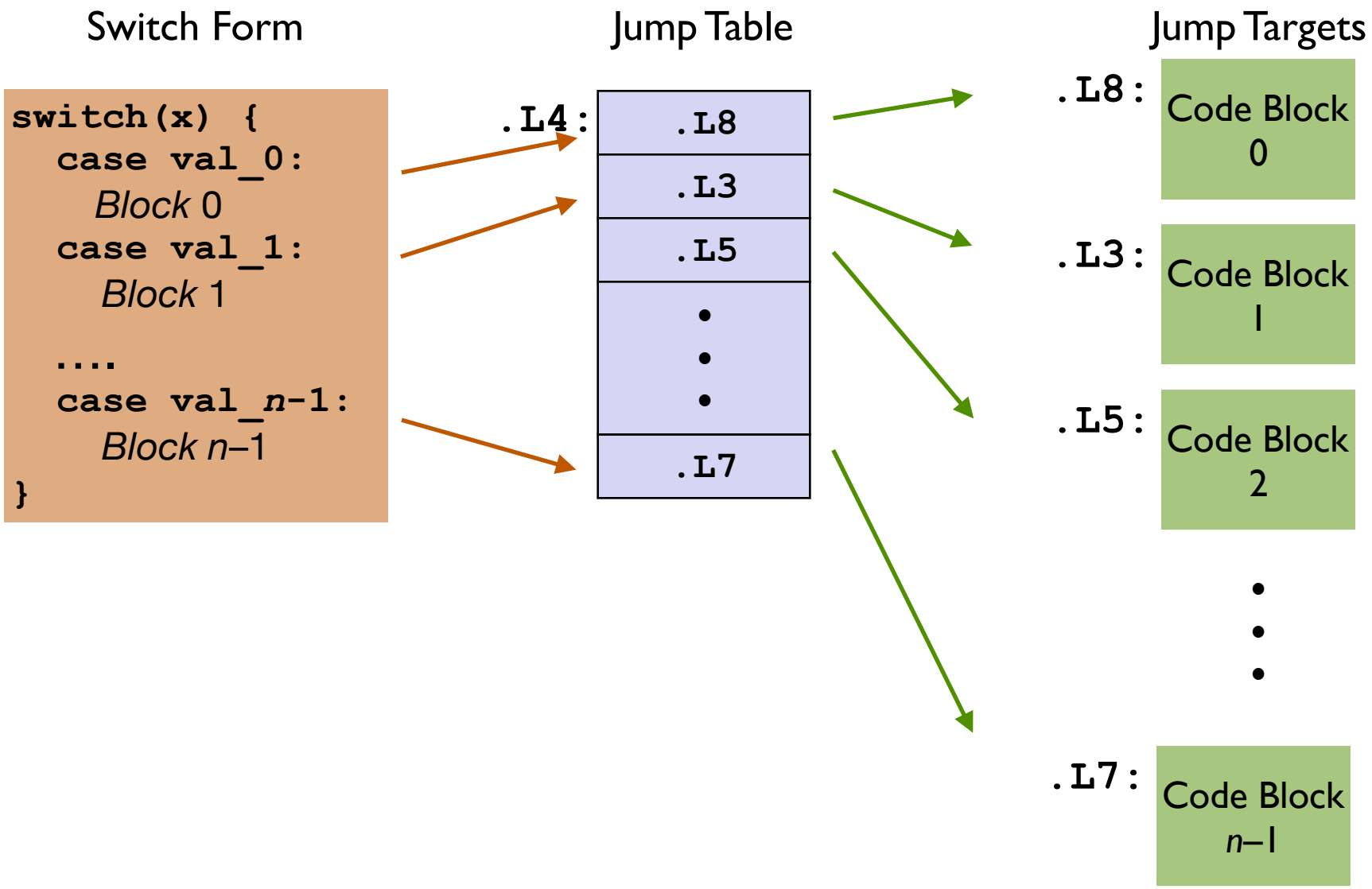
Jump Targets

```
.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
```

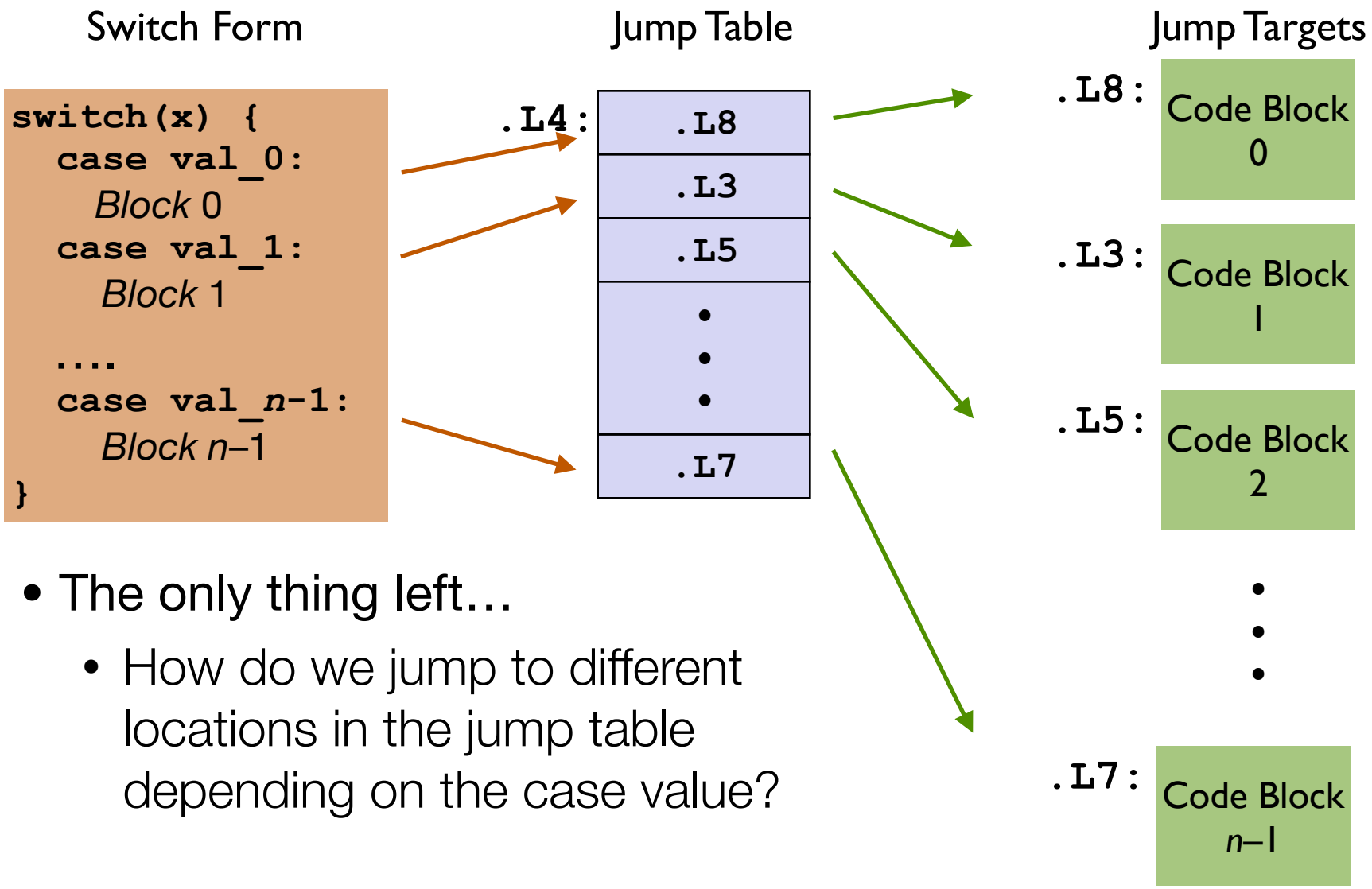
Implementing Switch Using Jump Table



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
  .quad .L7 # x = 6
```

Indirect Jump Instruction

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.section  .rodata
  .align 8
.L4:
  .quad .L8 # x = 0
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  .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

```
.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 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

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`

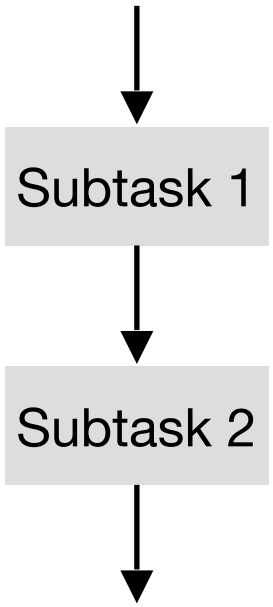
```
# assume x in %rdi
movq  .L4(,%rdi,8), %rax
jmp   *%rax
```

- 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)
```

Summary

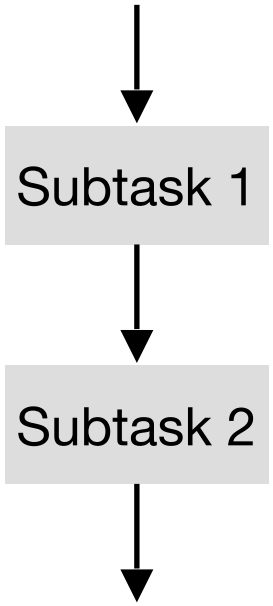
Sequential




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

Summary

Sequential




```
a = x + y;
y = a - c;
…
```

Memory

```
.section .text

…

<subtask 1>

…

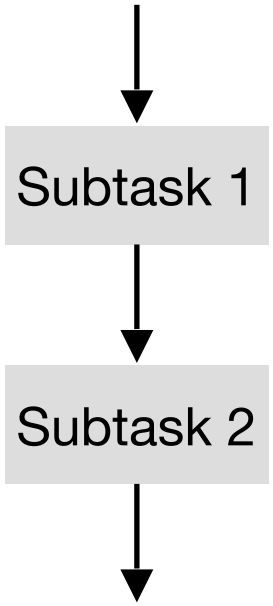
…

<subtask 2>

…
```

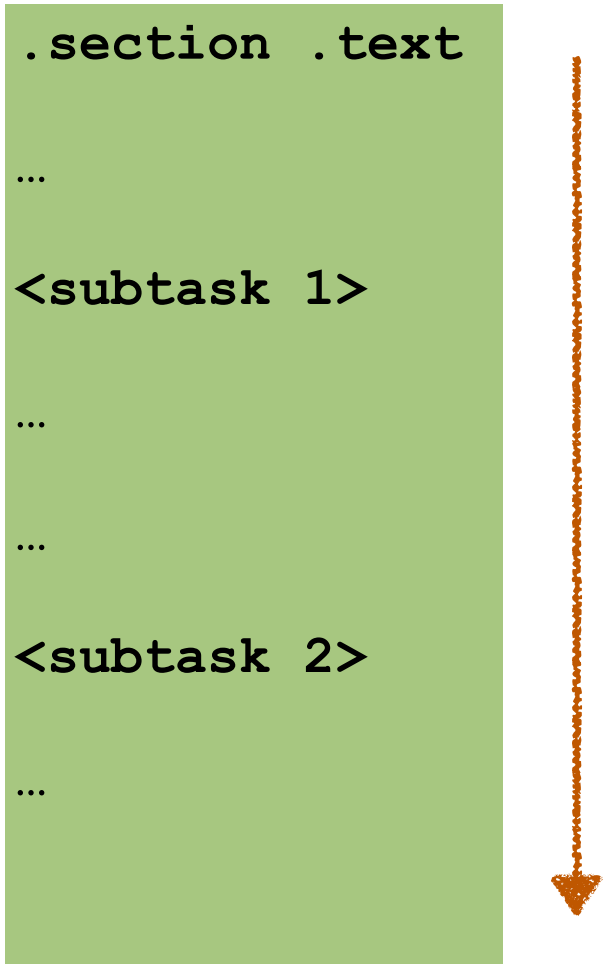
Summary

Sequential

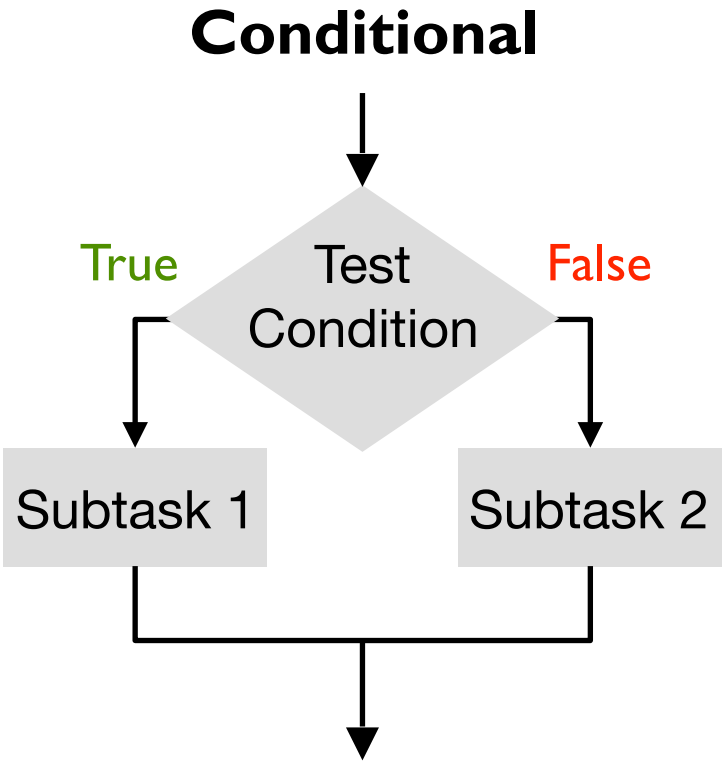



```
a = x + y;
y = a - c;
…
```

Memory



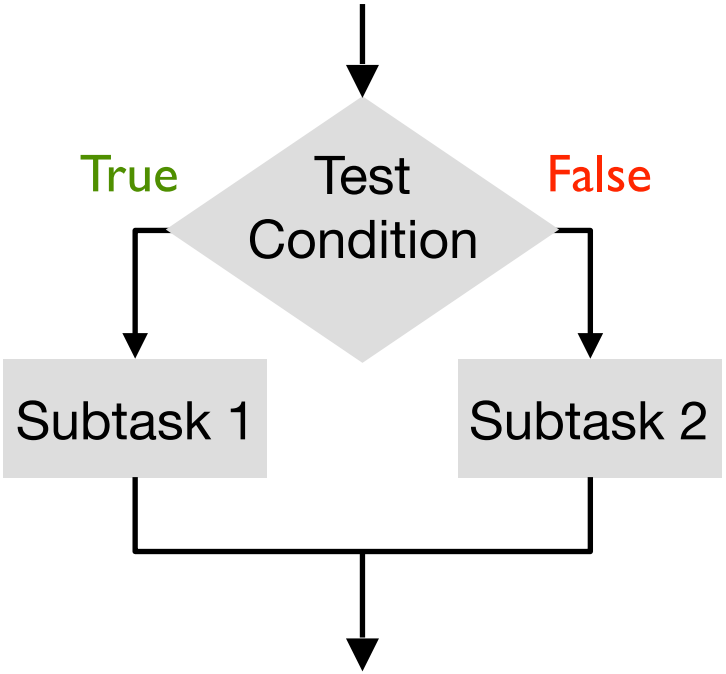
Summary




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

Summary

Conditional




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

Memory

```
.section .text

…
cmpq
jle .L2
.L1 <subtask 1>

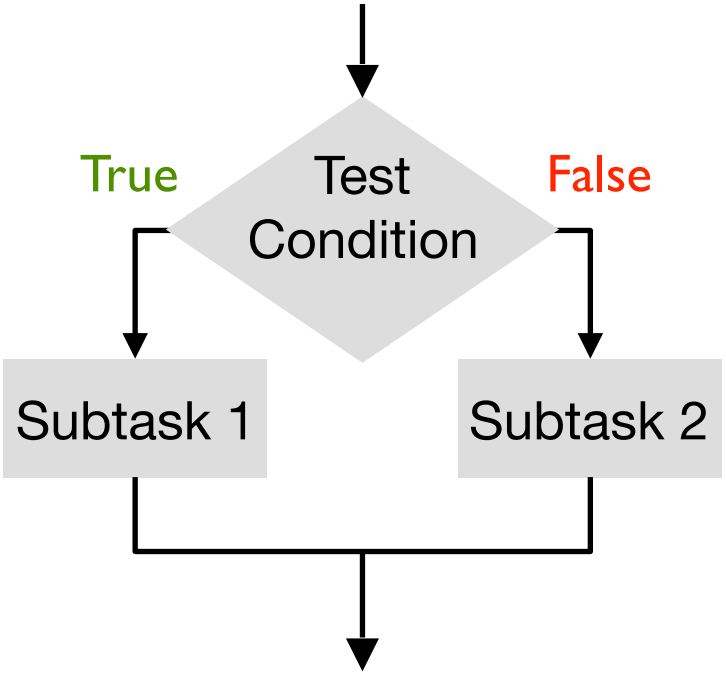
…

jmp .done
.L2 <subtask 2>

…
.done
```

Summary

Conditional




```
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```

Memory

```
.section .text

…
cmpq
jle .L2
.L1 <subtask 1>

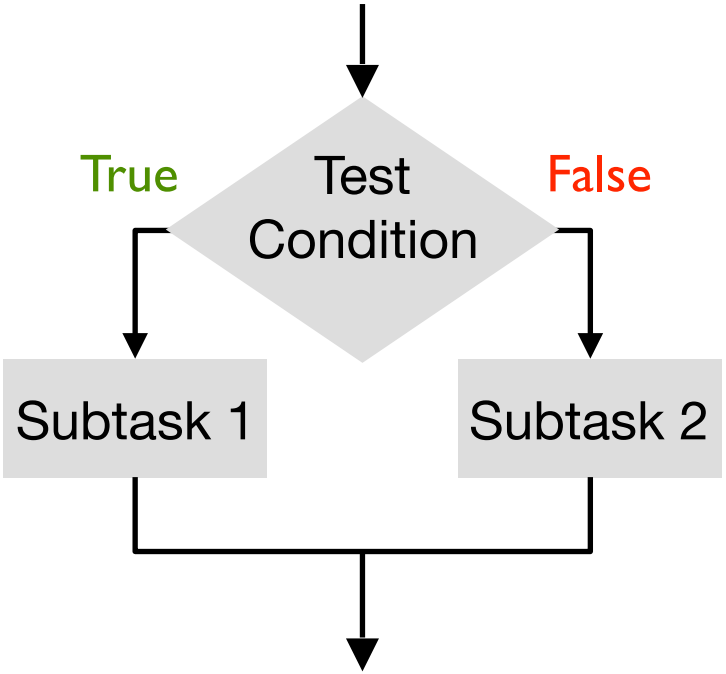
…

jmp .done
.L2 <subtask 2>

…
.done
```

Summary

Conditional




```
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else r = y - x;
```

Memory

```
.section .text

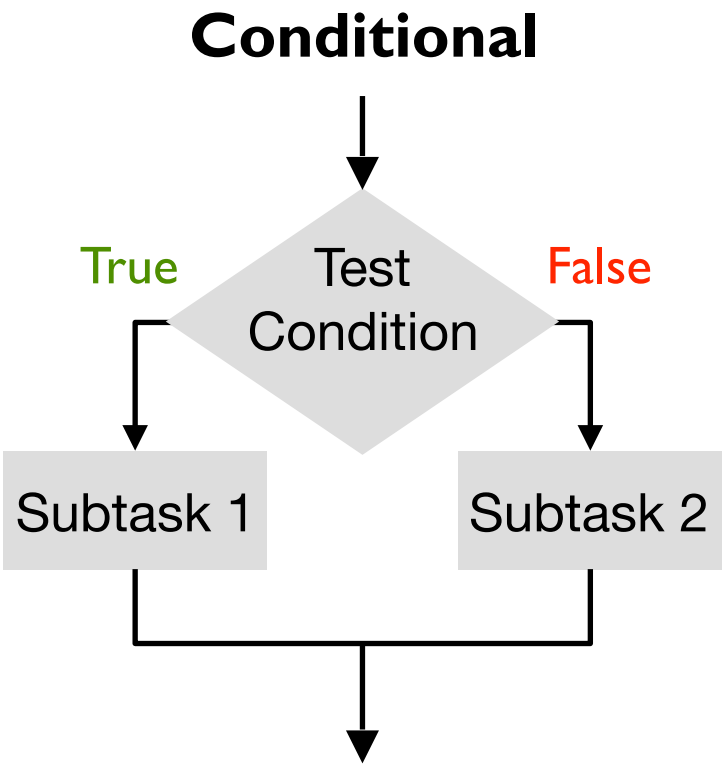
…
cmpq
jle .L2
.L1 <subtask 1>

…

jmp .done
.L2 <subtask 2>

…
.done
```

Summary

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else r = y - x;
```

Memory

```
.section .text

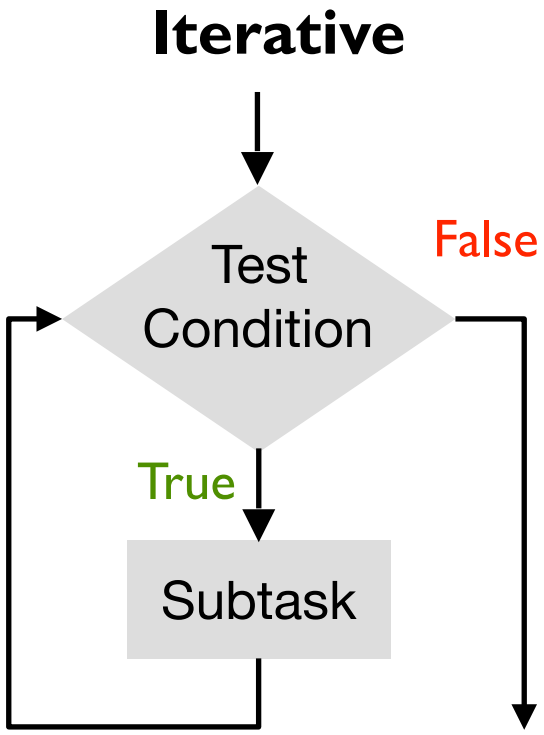
…
cmpq
jle .L2
.L1 <subtask 1>

…

jmp .done
.L2 <subtask 2>

…
.done
```

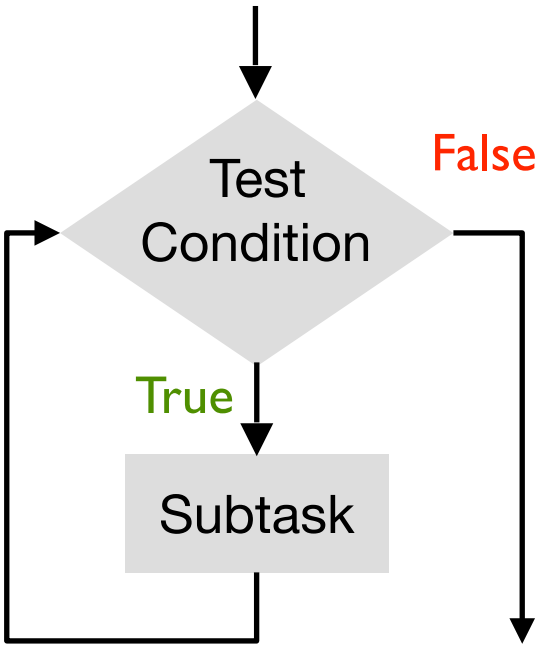
Summary




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

Summary

Iterative




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

Memory

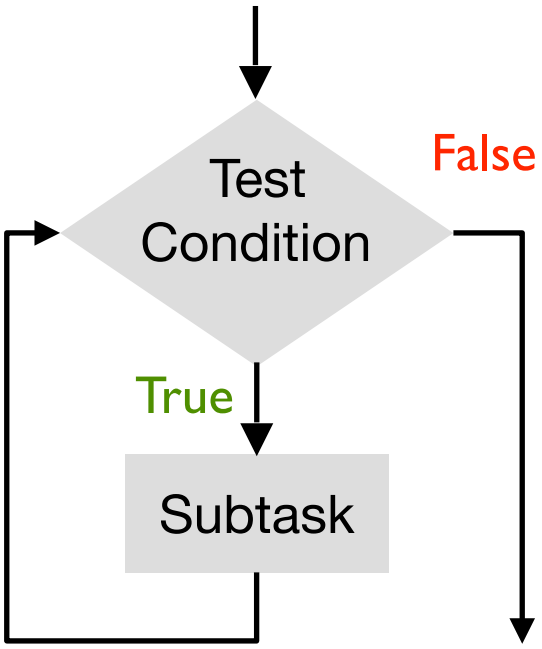
```
.section .text

…
addq
jmp .L2
.L1:

…
  <subtask>
…
.L2:
  cmpq A, B
  jg .L1
…
…
```

Summary

Iterative

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Memory

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.section .text

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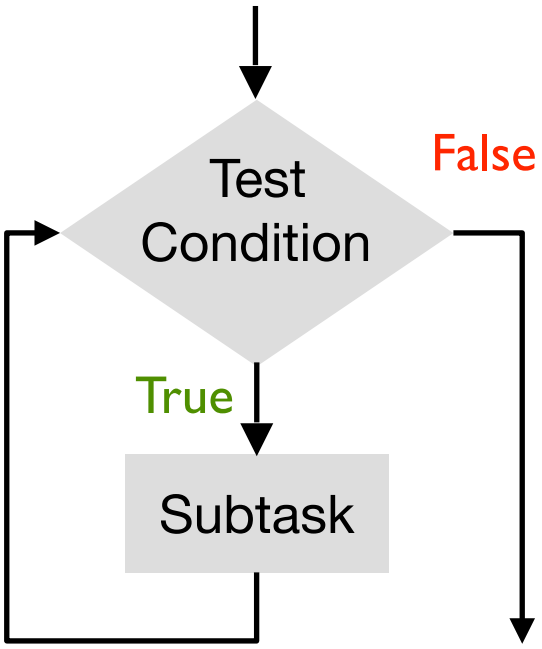
addq
jmp .L2
.L1:

…
  <subtask>
…
.L2:
  cmpq A, B
  jg .L1
…
…
```

Summary

Iterative

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Memory

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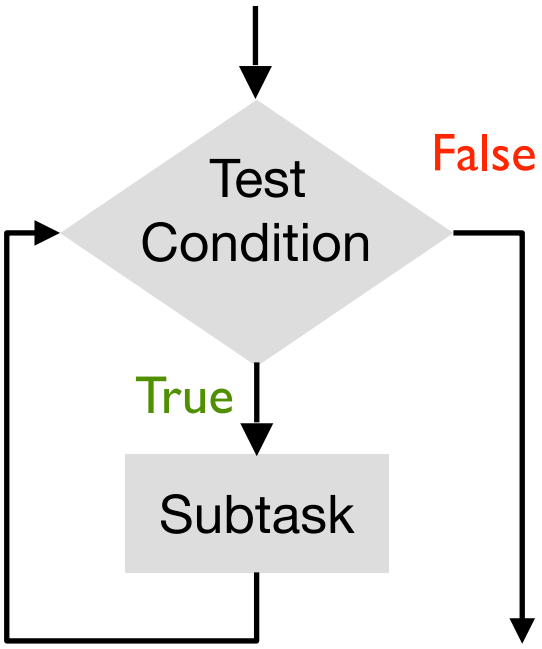
addq
jmp .L2
.L1:

…
  <subtask>
…
.L2:
  cmpq A, B
  jg .L1
…
…
```

Summary

Iterative

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Memory

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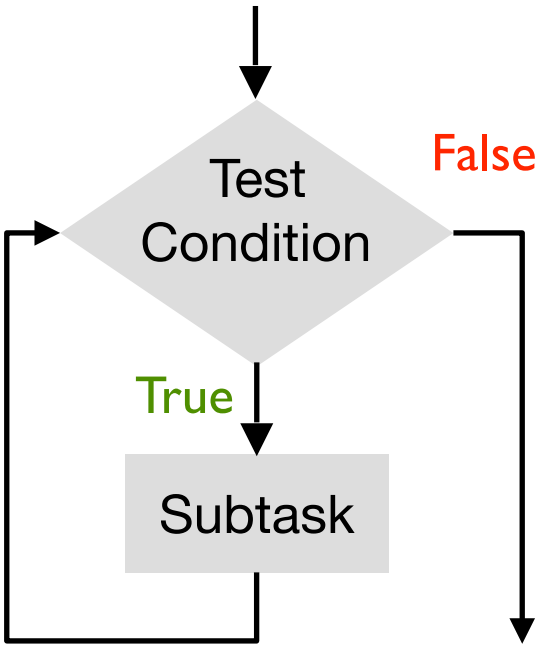
addq
jmp .L2
.L1:

…
  <subtask>
…
.L2:
  cmpq A, B
  jg .L1
…
…
```

Summary

Iterative

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Memory

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…
addq
jmp .L2
.L1:

…
  <subtask>
…
.L2:
  cmpq A, B
  jg .L1
…
…
```