CSC 252: Computer Organization Spring 2023: Lecture 8

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Announcement

- Programming assignment 2 is out. It's in x86 assembly language. Details at: https://www.cs.rochester.edu/courses/252/spring2023/labs/assignment2.html.

22	23	24	25	26	27	28
29	30	31	Feb 1	2	3 Today	4
5	6	7	8	9	10	11
12	13 Due	14	15	16	17	18

Announcement

- You might still have three slip days.
- Read the instructions before getting started!!!
    - You get 1/4 point off for every wrong answer
    - Maxed out at 10
- TAs are best positioned to answer your questions about programming assignments!!!
- Programming assignments do NOT repeat the lecture materials. They ask you to synthesize what you have learned from the lectures and work out something new.
- Logics and arithmetics problem set: https://www.cs.rochester.edu/courses/252/spring2023/handouts.html.
    - Not to be turned in.

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
    subq    %rdi,%rax
    ret
```

`cmpq` sets ZF, SF, OF

`jle` checks ZF | (SF ^ OF)

0	0	0
ZF	SF	OF

Conditional Branch Example

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

Register	Use(s)
`%rdi`	`x`
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absdiff:
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.L4:                    # x <= y
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```

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

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

0	0	0
ZF	SF	OF

Conditional Jump Instruction

```
cmpq    %rsi, %rdi
jbe     .L4
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Jump to label if below or equal to

Conditional Jump Instruction

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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`

Conditional Jump Instruction

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

Jump to label if below or equal to

- Semantics of **`jbe`**:
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- Under the hood:

Conditional Jump Instruction

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cmpq    %rsi, %rdi
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- Semantics of **`jbe`**:
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- Under the hood:
    - **`cmpq`** instruction sets the condition codes

Conditional Jump Instruction

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

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

How Should `cmpq` Set Condition Codes?

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

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

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```
cmpq     %rsi, %rdi
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- Calculate `%rdi - %rsi`
- `%rdi == %rsi` if and only if `%rdi - %rsi == 0`

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ZF Zero Flag (result is zero)

`ZF`

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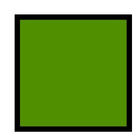

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ZF Zero Flag (result is zero)

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

ZF

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- How do we know **`%rdi`** <= **`%rsi`**? This time for unsigned values
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   C010
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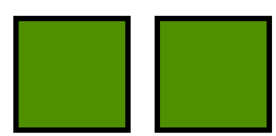
ZF Zero Flag (result is zero)

CF Carry Flag (for unsigned)



CF   **ZF**

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11111111 10000000

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

ZF Zero Flag (result is zero)

CF Carry Flag (for unsigned)

0	0
CF	**ZF**

How Should **cmpq** Set Condition Codes?

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- Calculate `%rdi - %rsi`
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11111111 10000000

cmpq *0xFF*, *0x80*

```
    10000000   <---  128
-)  11111111   <---  255
-----------
   c10000001
```

ZF Zero Flag (result is zero)

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CF	ZF
0	0

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- How do we know **`%rdi`** <= **`%rsi`**? This time for unsigned values
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`cmpq` *0xFF, 0x80*

```
    10000000  ←  128
-)  11111111  ←  255
---------------
   c10000001
```

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CF	ZF
1	0

How Should `cmpq` Set Condition Codes?

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cmpq      %rsi, %rdi
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- Calculate `%rdi - %rsi`
- `%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

ZF Zero Flag (result is zero)

CF Carry Flag (for unsigned)

CF	ZF
1	0

Putting It All Together

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- `cmpq` sets all 4 condition codes simultaneously

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ZF Zero Flag

CF Carry Flag

SF Sign Flag

OF Overflow Flag (for signed)

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

Putting It All Together

- `cmpq` sets all 4 condition codes simultaneously

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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`)

11111111 10000000

cmpq *0xFF*, *0x80*

```
    10000000
-)  11111111
------------
   c10000001
```

ZF Zero Flag

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OF Overflow Flag (for signed)

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Putting It All Together

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

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    10000000
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ZF Zero Flag

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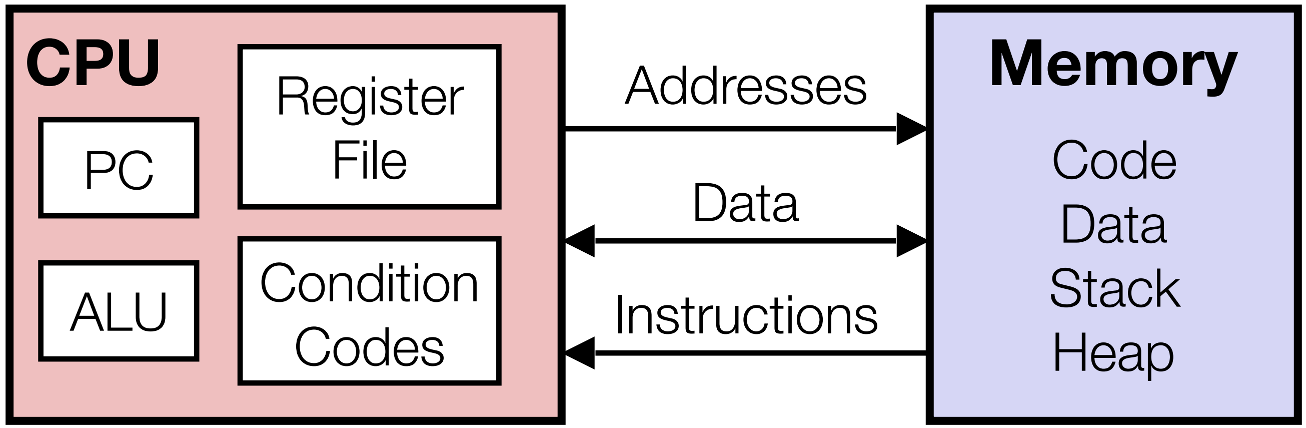
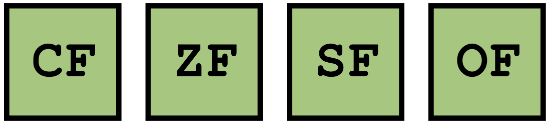
CF	ZF	SF	OF
1	0	1	0

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

SF Sign Flag

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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    - `%rax > 0, %rbx > 0, and (%rax + %rbx) < 0), or`

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`addq` *0xFF*, *0x80*

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

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

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`addq` *0xFF*, *0x80*

`jle .L4`

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

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```
if((x+y)<0) {
    …
}
```

`addq` *0xFF, 0x80*

`jle .L4`

CF	ZF	SF	OF
1	0	0	1

Today: Control Instructions

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

“Do-While” Loop Example

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

`do-while` version

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

“Do-While” Loop Example

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}
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`goto` Version

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

“Do-While” Loop Assembly

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

"Do-While" Loop Assembly

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

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

```
   movl    $0, %rax    #  result = 0
.L2:                   # loop:
   movq    %rdi, %rdx
   andl    $1, %rdx    #  t = x & 0x1
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“Do-While” Loop Assembly

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“Do-While” Loop Assembly

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  (unsigned long x) {
  long result = 0;
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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
}
```

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

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

}
```

init

`i = 0`

test

`i < 32`

“For” Loop Example

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

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

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

}
```

init

`i = 0`

test

`i < 32`

update

`i++`

"For" Loop Example

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

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

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

}
```

init

```
i = 0
```

test

```
i < 32
```

update

```
i++
```

body

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

Convert “For” Loop to “While” Loop

For Version

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

Convert “For” Loop to “While” Loop

For Version

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

While Version

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

Convert “For” Loop to “While” Loop

For Version

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

While Version

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

Assembly Version

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

Today: Control Instructions

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

Switch Statement Example

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

Switch Statement Example

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

Fall-through case

Switch Statement Example

```
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    long w = 1;
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Fall-through case

Multiple case labels

Switch Statement Example

```
long switch_eg (long x, long y, long z)
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    long w = 1;
    switch(x) {
    case 1:
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    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

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    }
    return w;
}
```

Fall-through case

Multiple case labels

For missing cases, fall back to default

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

Implementing Switch Using Jump Table

Switch Form

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

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

Implementing Switch Using Jump Table

Switch Form

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

Jump Targets

Targ0: Code Block 0

Targ1: Code Block 1

Targ2: Code Block 2

•
•
•

Targ*n*-1: Code Block *n*–1

Implementing Switch Using Jump Table

Switch Form

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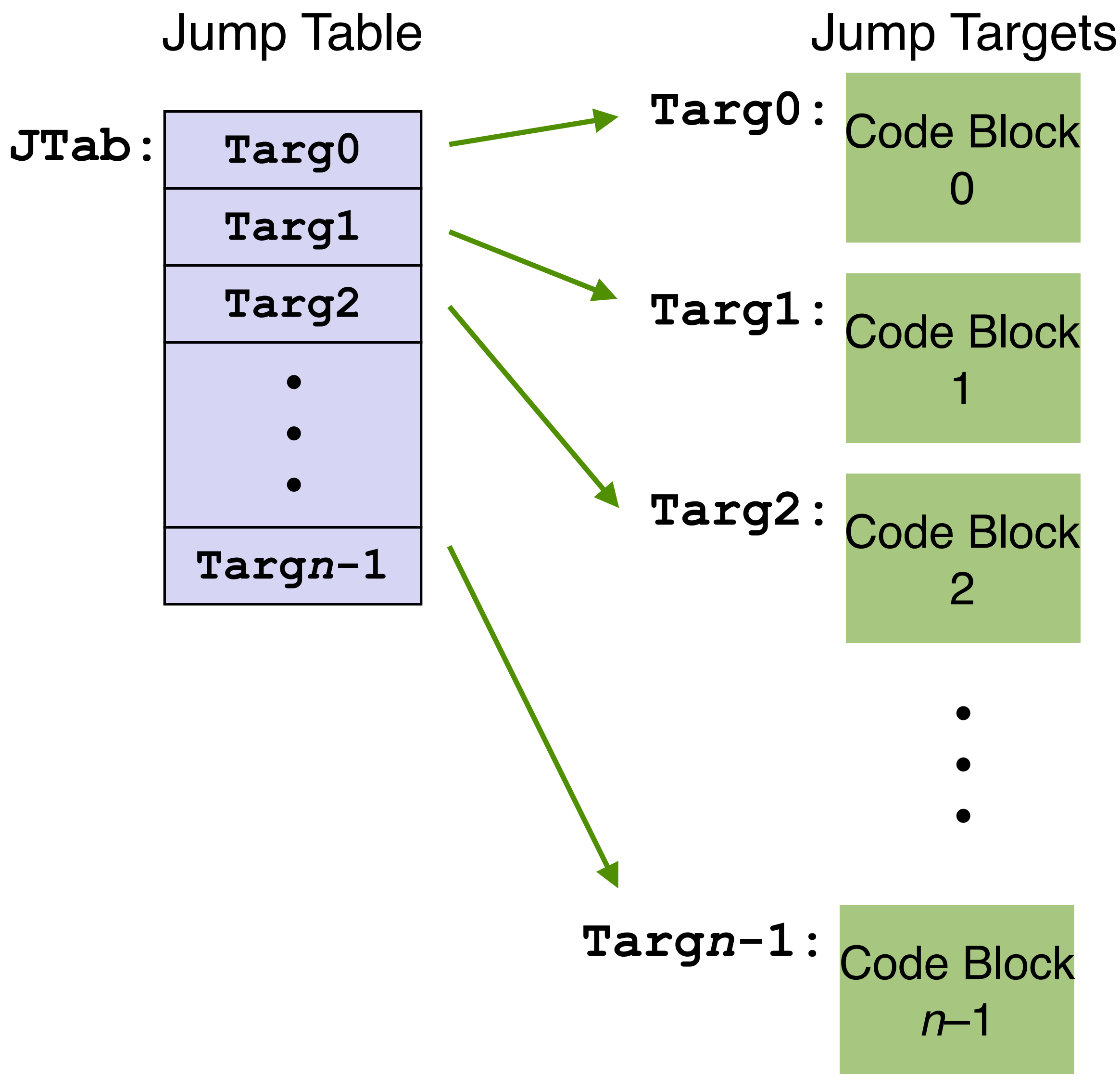
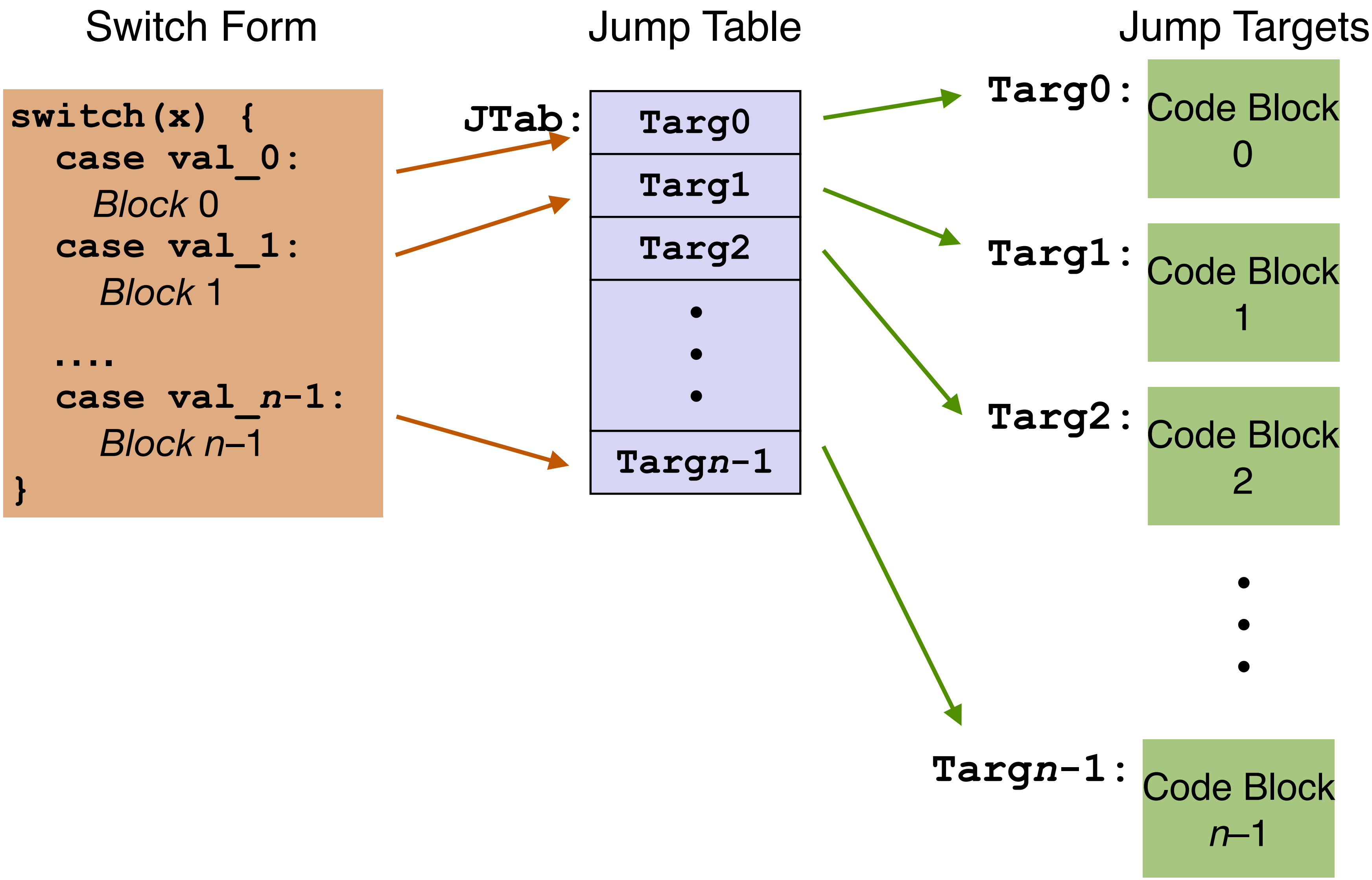
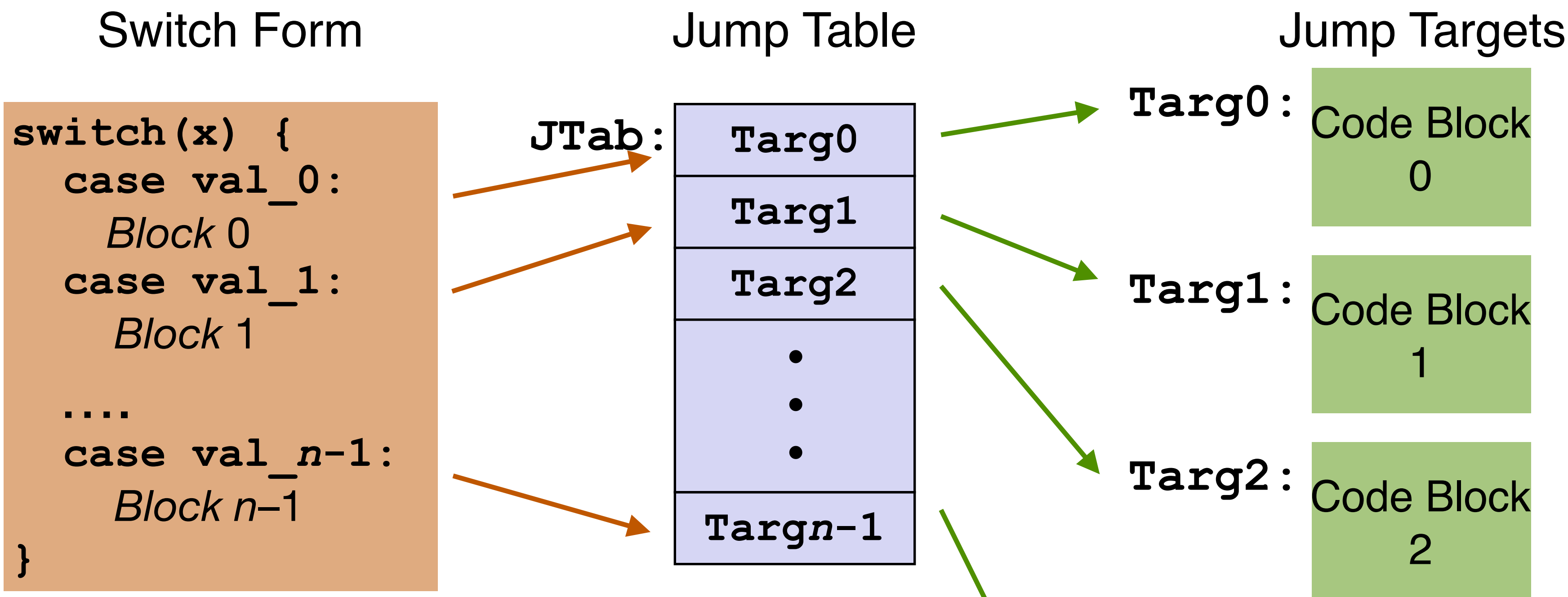
```



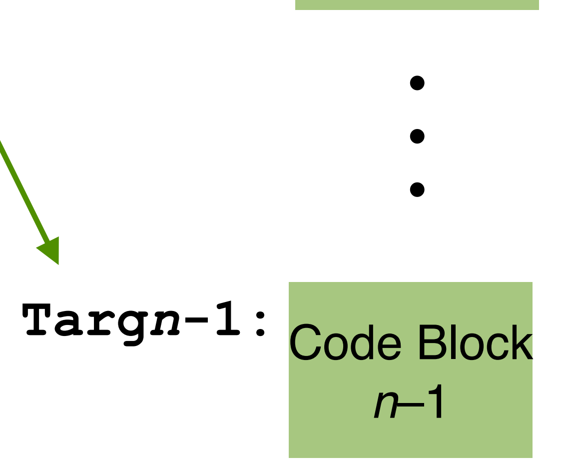
Implementing Switch Using Jump Table



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



Assembly Directives (Pseudo-Ops)

```
.section  .rodata
  .align 8
.L4:
  .quad .LD # x = 0
  .quad .L1 # x = 1
  .quad .L2 # x = 2
  .quad .L3 # x = 3
  .quad .LD # x = 4
  .quad .L5 # x = 5
  .quad .L5 # x = 6
```

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

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

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- .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

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- .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

Jump Table and Jump Targets

Jump Table

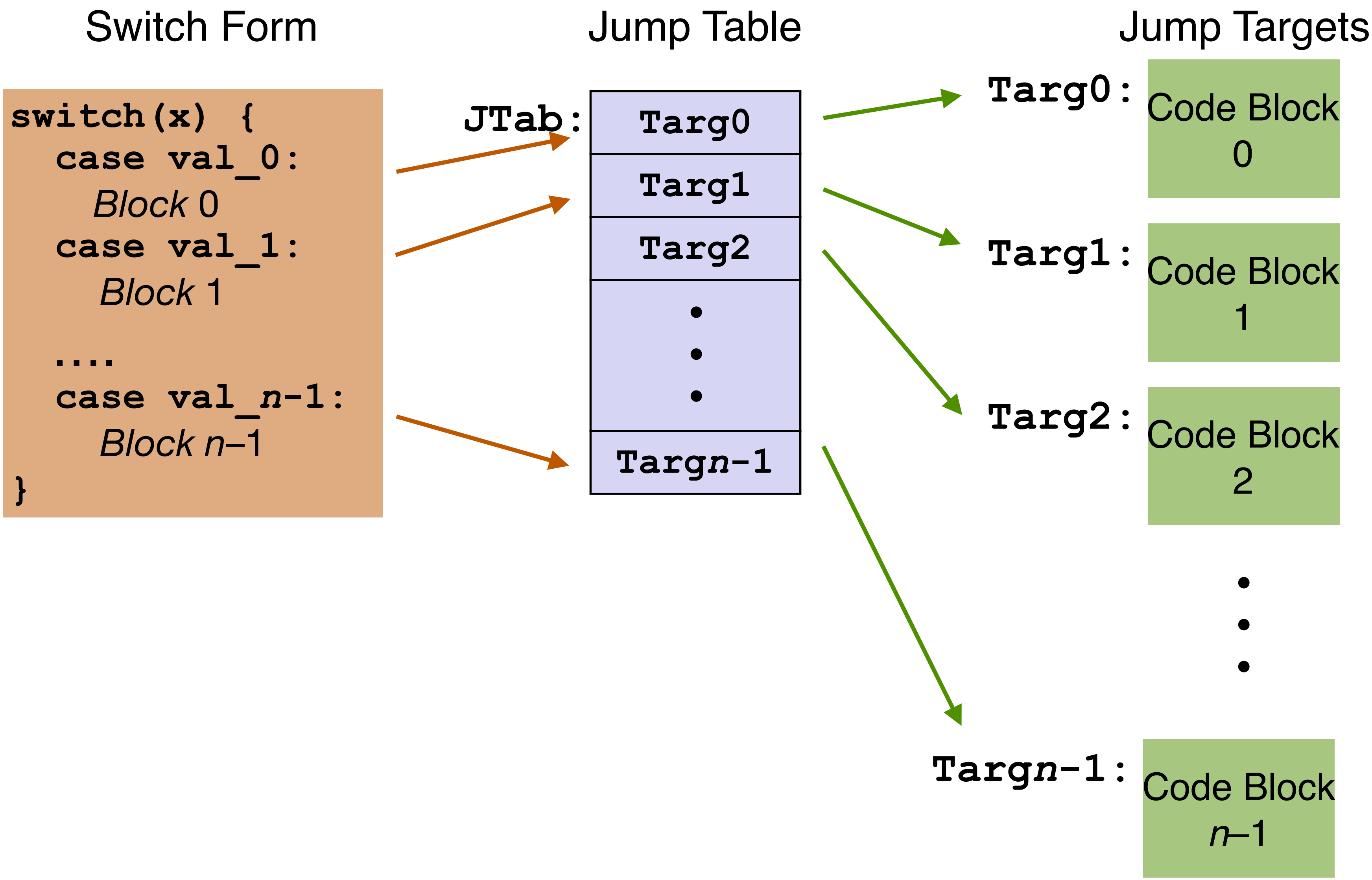
```
.section   .rodata
  .align 8
.L4:
  .quad .LD # x = 0
  .quad .L1 # x = 1
  .quad .L2 # x = 2
  .quad .L3 # x = 3
  .quad .LD # x = 4
  .quad .L5 # x = 5
  .quad .L5 # x = 6
```

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

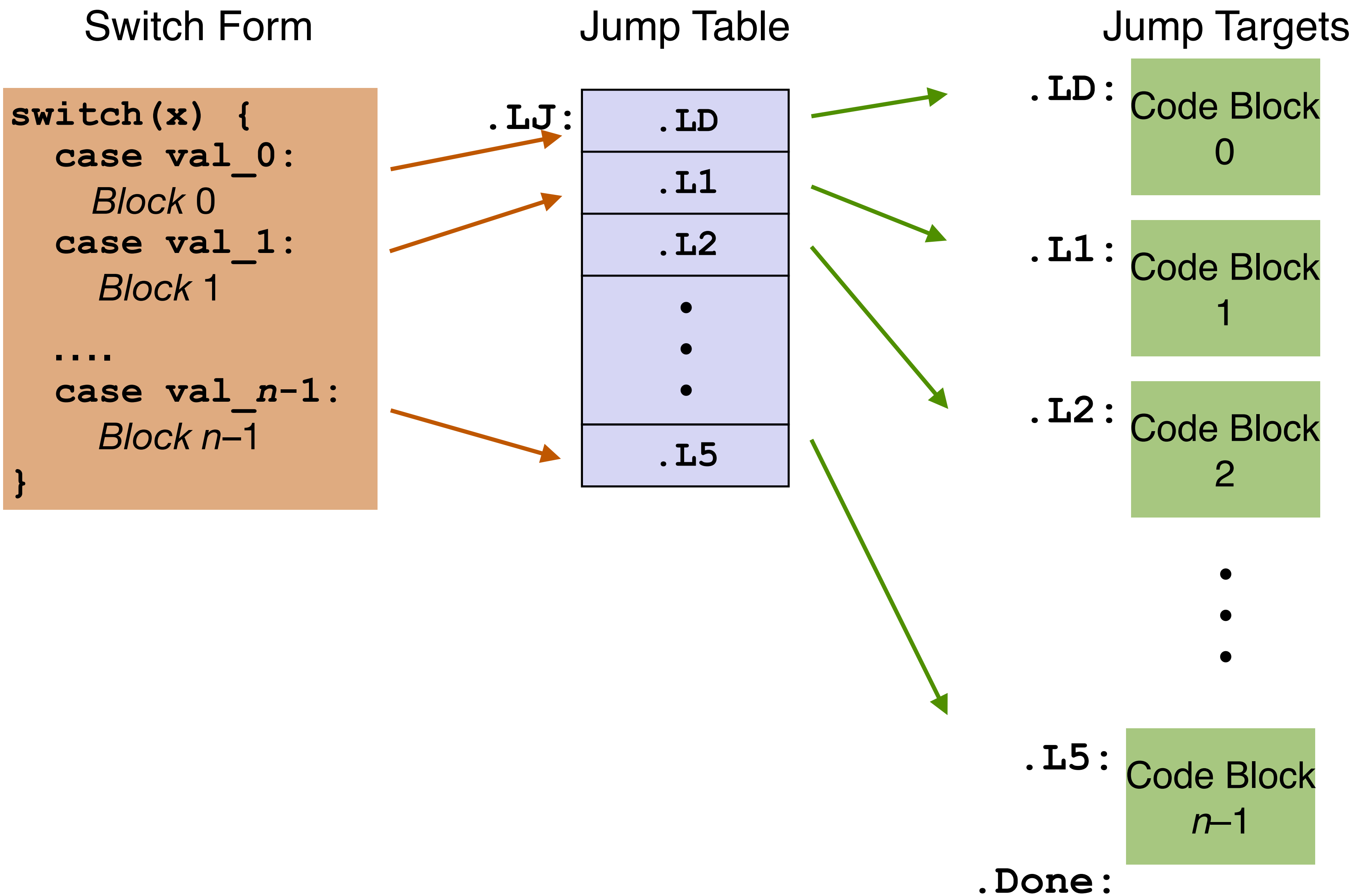
Jump Targets

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

Implementing Switch Using Jump Table



Implementing Switch Using Jump Table



Code Blocks (x == 1)

```
.section  .rodata
 .align 8
.L4:
 .quad .LD # x = 0
 .quad .L1 # x = 1
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  .quad .L3 # x = 3
  .quad .LD # x = 4
  .quad .L5 # x = 5
  .quad .L5 # x = 6
```

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

Code Blocks (x == 1)

```
.section  .rodata
  .align 8
.L4:
  .quad .LD # x = 0
  .quad .L1 # x = 1
  .quad .L2 # x = 2
  .quad .L3 # x = 3
  .quad .LD # x = 4
  .quad .L5 # x = 5
  .quad .L5 # x = 6
```

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

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

Code Blocks (x == 1)

```
.section  .rodata
  .align 8
.L4:
  .quad .LD # x = 0
  .quad .L1 # x = 1
  .quad .L2 # x = 2
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```

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

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

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

Code Blocks (x == 1)

```
.section  .rodata
  .align 8
.L4:
  .quad .LD # x = 0
  .quad .L1 # x = 1
  .quad .L2 # x = 2
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  .quad .LD # x = 4
  .quad .L5 # x = 5
  .quad .L5 # x = 6
```

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

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

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

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

```
.section   .rodata
  .align 8
.L4:
  .quad .LD # x = 0
  .quad .L1 # x = 1
  .quad .L2 # x = 2
  .quad .L3 # x = 3
  .quad .LD # x = 4
  .quad .L5 # x = 5
  .quad .L5 # x = 6
```

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

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

```
.section  .rodata
  .align 8
.L4:
  .quad .LD # x = 0
  .quad .L1 # x = 1
  .quad .L2 # x = 2
  .quad .L3 # x = 3
  .quad .LD # x = 4
  .quad .L5 # x = 5
  .quad .L5 # x = 6
```

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

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

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

```
.section  .rodata
  .align 8
.L4:
  .quad .LD # x = 0
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  .quad .L3 # x = 3
  .quad .LD # x = 4
  .quad .L5 # x = 5
  .quad .L5 # x = 6
```

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

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

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

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

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

```
.section  .rodata
  .align 8
.L4:
  .quad .LD # x = 0
  .quad .L1 # x = 1
  .quad .L2 # x = 2
  .quad .L3 # x = 3
  .quad .LD # x = 4
  .quad .L5 # x = 5
  .quad .L5 # x = 6
```

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

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

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

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

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

```
.section   .rodata
  .align 8
.L4:
  .quad .LD # x = 0
  .quad .L1 # x = 1
  .quad .L2 # x = 2
  .quad .L3 # x = 3
  .quad .LD # x = 4
  .quad .L5 # x = 5
  .quad .L5 # x = 6
```

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

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

```
.section  .rodata
  .align 8
.L4:
  .quad .LD # x = 0
  .quad .L1 # x = 1
  .quad .L2 # x = 2
  .quad .L3 # x = 3
  .quad .LD # x = 4
  .quad .L5 # x = 5
  .quad .L5 # x = 6
```

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

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

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

```
.section  .rodata
  .align 8
.L4:
  .quad .LD # x = 0
  .quad .L1 # x = 1
  .quad .L2 # x = 2
  .quad .L3 # x = 3
  .quad .LD # x = 4
  .quad .L5 # x = 5
  .quad .L5 # x = 6
```

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

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

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

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

```
.section  .rodata
  .align 8
.L4:
  .quad .LD # x = 0
  .quad .L1 # x = 1
  .quad .L2 # x = 2
  .quad .L3 # x = 3
  .quad .LD # x = 4
  .quad .L5 # x = 5
  .quad .L5 # x = 6
```

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

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

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

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

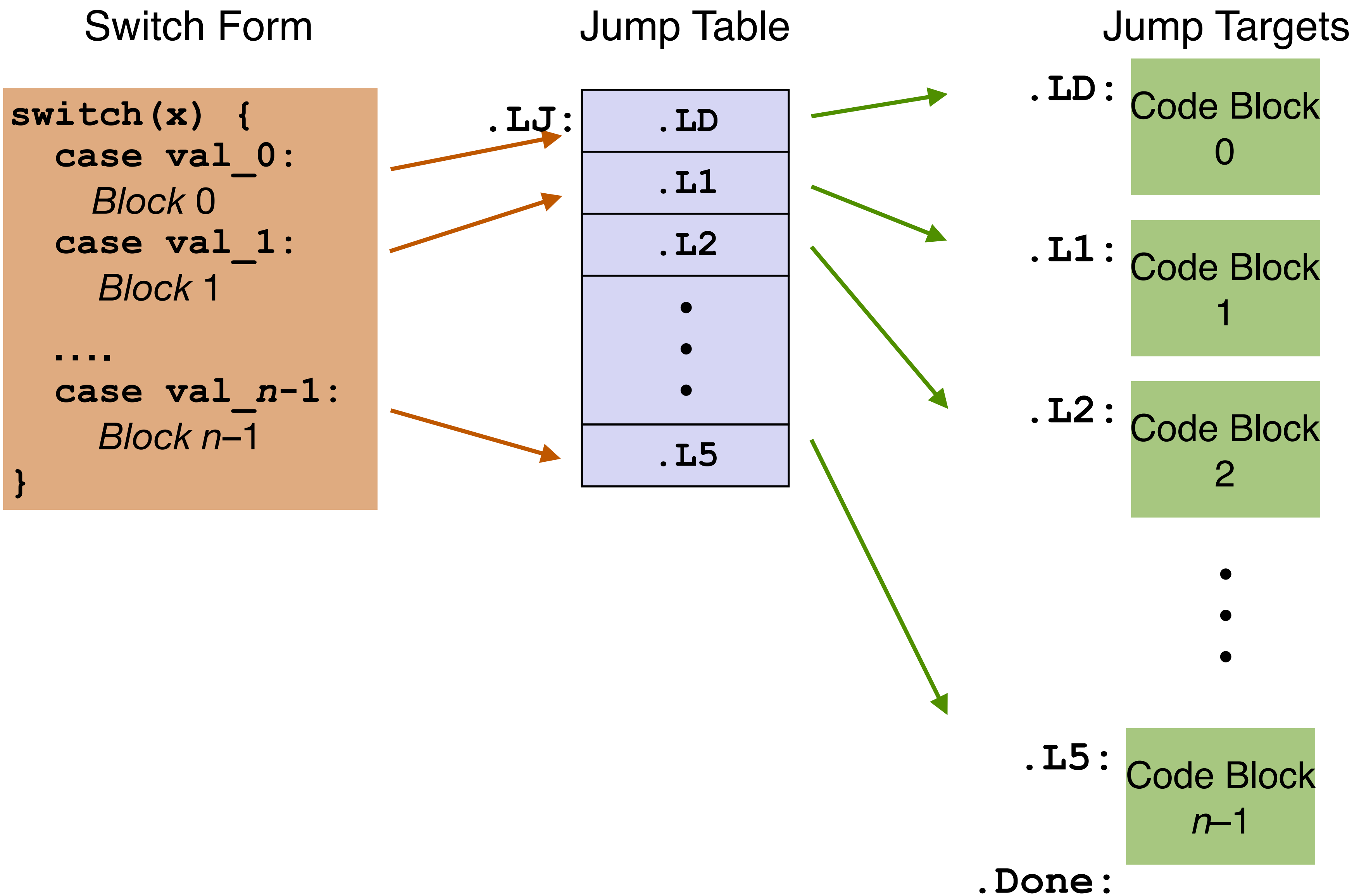
```
.section   .rodata
  .align 8
.L4:
  .quad .LD #  x = 0
  .quad .L1 #  x = 1
  .quad .L2 #  x = 2
  .quad .L3 #  x = 3
  .quad .LD #  x = 4
  .quad .L5 #  x = 5
  .quad .L5 #  x = 6
```

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

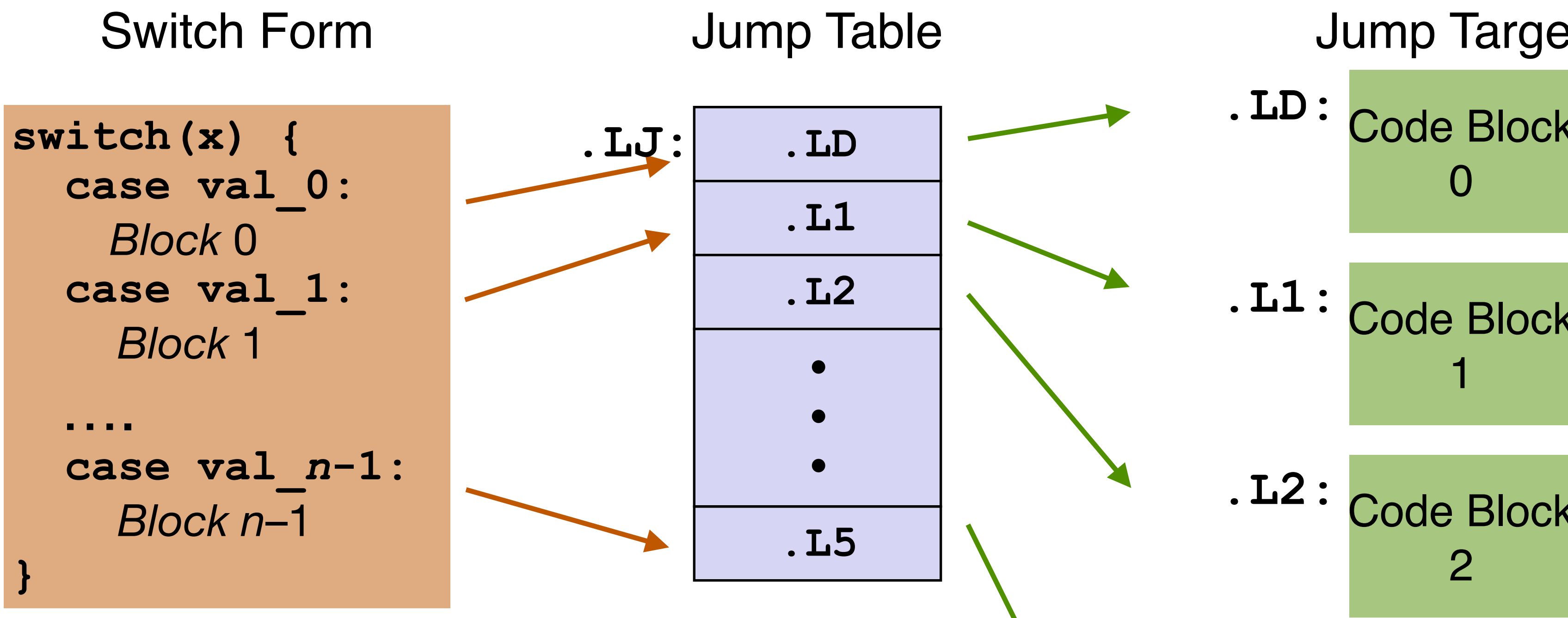
Register	Use(s)
`%rdi`	Argument **x**
`%rsi`	Argument **y**
`%rdx`	Argument **z**
`%rax`	Return value

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

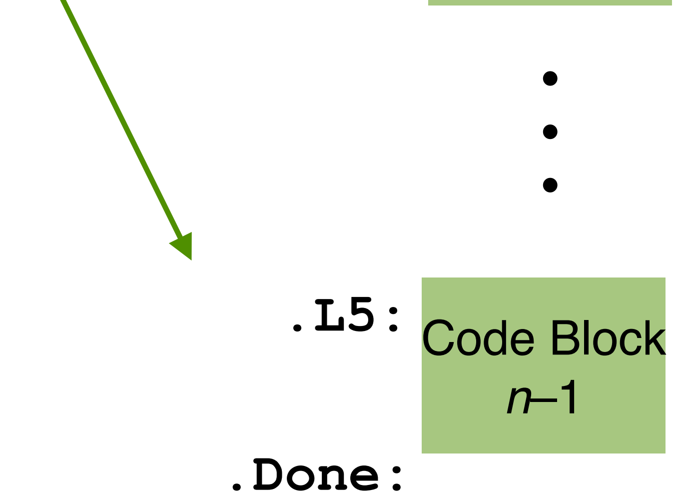
Implementing Switch Using Jump Table



Implementing Switch Using Jump Table



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



Indirect Jump Instruction

```
.section  .rodata
  .align 8
.LJ:
  .quad .LD # x = 0
  .quad .L1 # x = 1
  .quad .L2 # x = 2
  .quad .L3 # x = 3
  .quad .LD # x = 4
  .quad .L5 # x = 5
  .quad .L5 # x = 6
```

Indirect Jump Instruction

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

```
.section  .rodata
  .align 8
.LJ:
  .quad .LD # x = 0
  .quad .L1 # x = 1
  .quad .L2 # x = 2
  .quad .L3 # x = 3
  .quad .LD # x = 4
  .quad .L5 # x = 5
  .quad .L5 # x = 6
```

Indirect Jump Instruction

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

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

Indirect Jump Instruction

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

```
.section   .rodata
  .align 8
.LJ:
  .quad .LD # x = 0
  .quad .L1 # x = 1
  .quad .L2 # x = 2
  .quad .L3 # x = 3
  .quad .LD # x = 4
  .quad .L5 # x = 5
  .quad .L5 # x = 6
```

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

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

Indirect Jump Instruction

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

```
.section   .rodata
  .align 8
.LJ:
  .quad .LD # x = 0
  .quad .L1 # x = 1
  .quad .L2 # x = 2
  .quad .L3 # x = 3
  .quad .LD # x = 4
  .quad .L5 # x = 5
  .quad .L5 # x = 6
```

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

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

Indirect Jump Instruction

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

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.section   .rodata
  .align 8
.LJ:
  .quad .LD # x = 0
  .quad .L1 # x = 1
  .quad .L2 # x = 2
  .quad .L3 # x = 3
  .quad .LD # x = 4
  .quad .L5 # x = 5
  .quad .L5 # x = 6
```

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

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

Indirect Jump Instruction

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

```
.section   .rodata
  .align 8
.LJ:
  .quad .LD # x = 0
  .quad .L1 # x = 1
  .quad .L2 # x = 2
  .quad .L3 # x = 3
  .quad .LD # x = 4
  .quad .L5 # x = 5
  .quad .L5 # x = 6
```

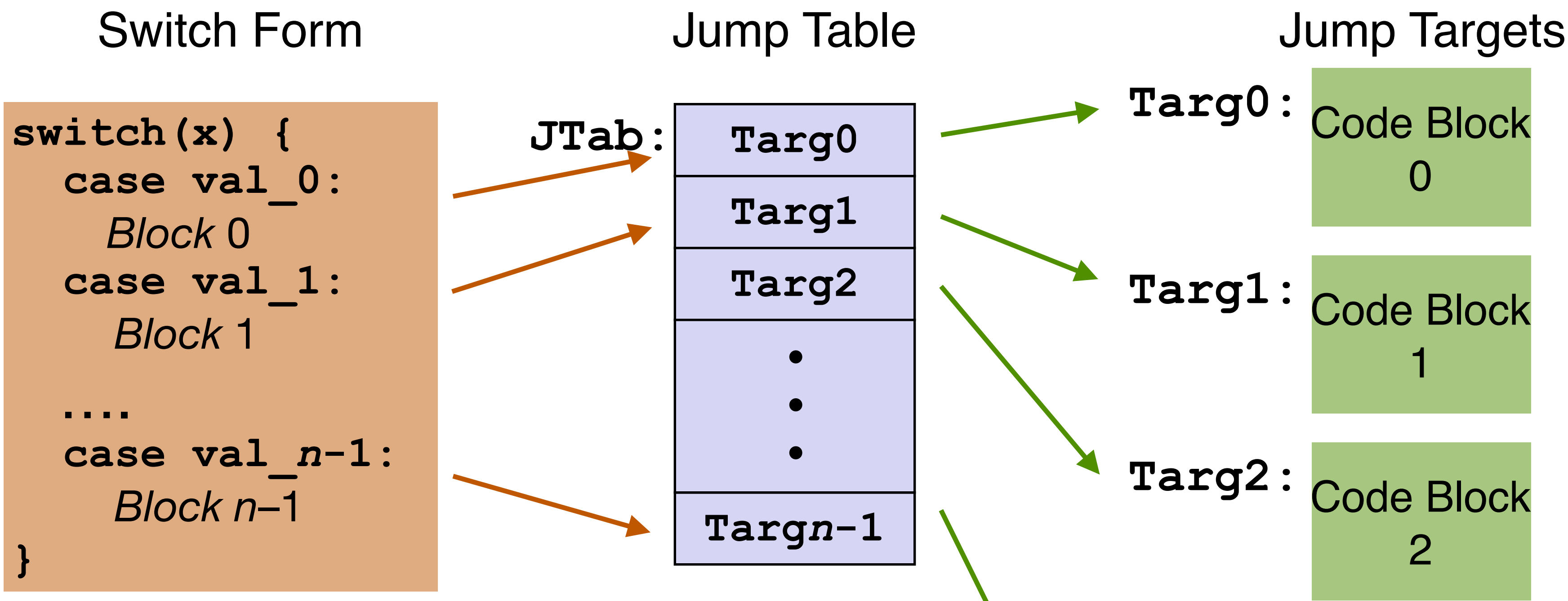
```
# assume x in %rdi
movq   .LJ(,%rdi,8), %rax
jmp    *%rax
```

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

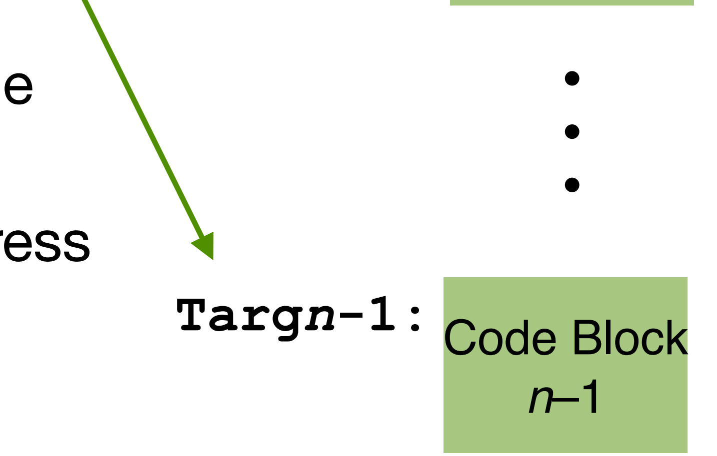
An equivalent syntax in x86:

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

Summary



- 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

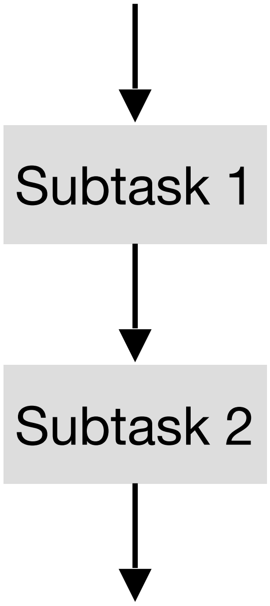


Not The Only Way

- Jump table might not the most efficient implementation; certainly not the only way to implement switch-case.
- What if x can take a very large value range. Do we need to have a giant jump table?
- Let's say x can be any integer from 1 to 1 million, but anything between 8 and 1 million fall back to the default case. Can we avoid a 1 million entry jump table (which isn't too bad if you calculate the size)?
    - Have an if-else check first followed by an 8-entry table.

Summary

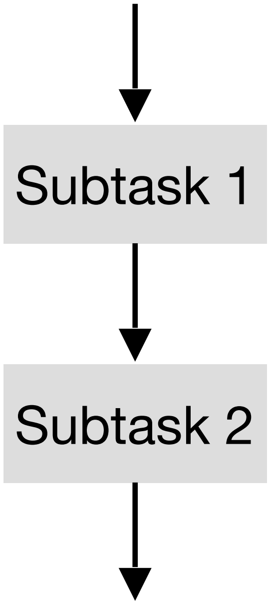
Sequential




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

Summary

Sequential




```
a = x + y;
y = a - c;
…
```

Memory

```
.section .text

…

<subtask 1>

…

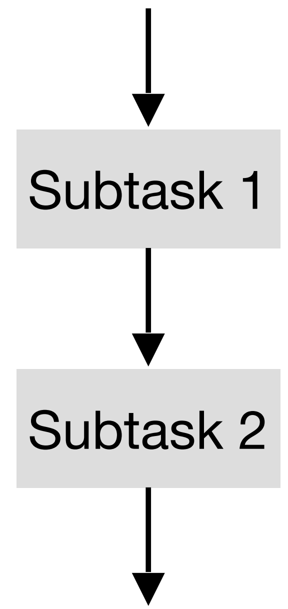
…

<subtask 2>

…
```

Summary

Sequential




```
a = x + y;
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…
```

Memory

```
.section .text

…

<subtask 1>

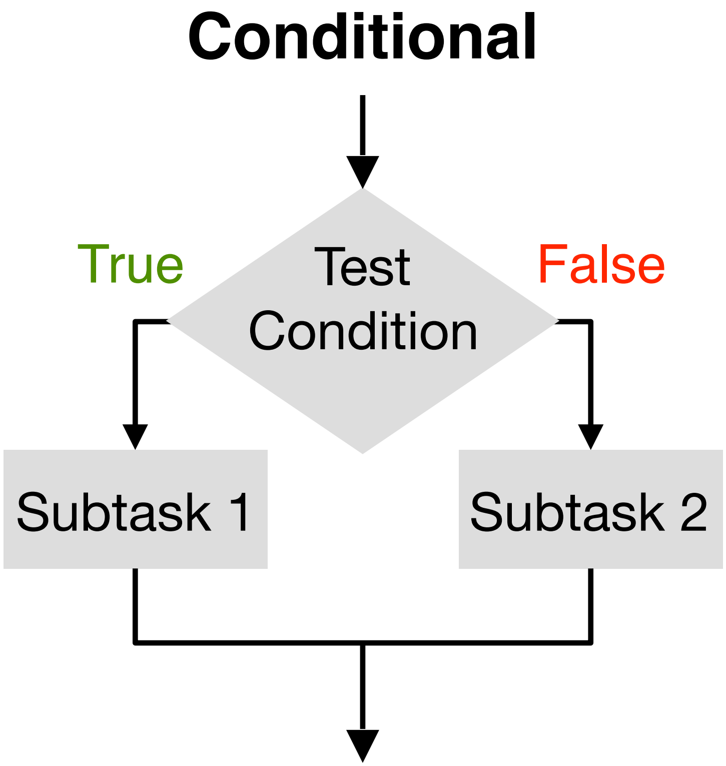
…

…

<subtask 2>

…
```

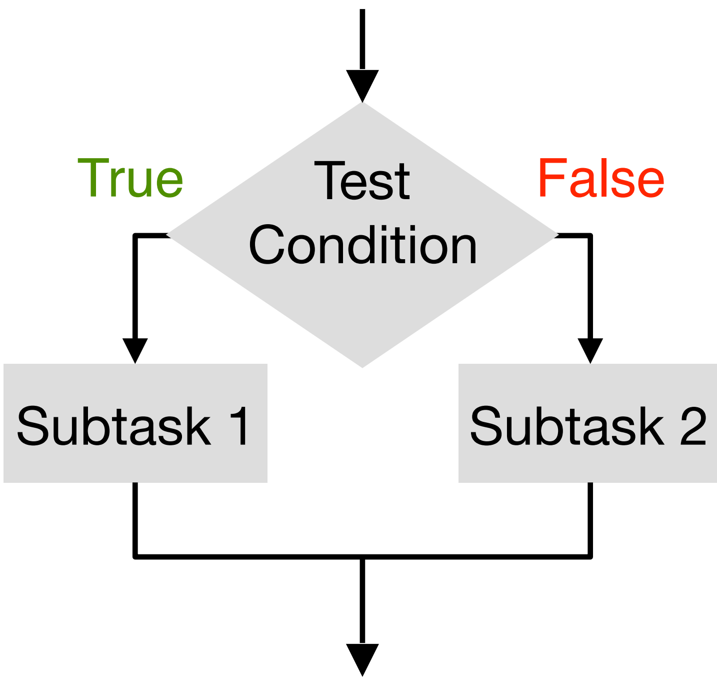
Summary




```
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>

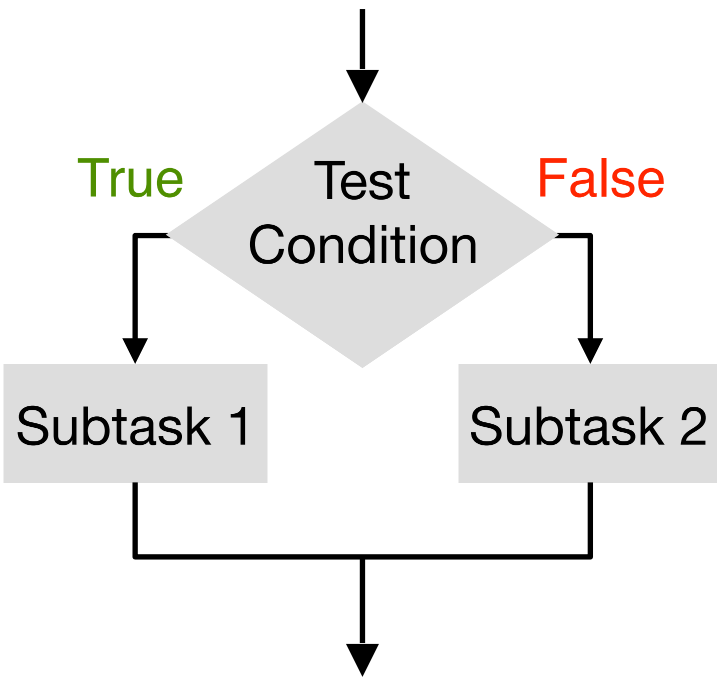
…

jmp .done
.L2 <subtask 2>

…
.done
```

Summary

Conditional




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

Memory

```
.section .text

…
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…

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…
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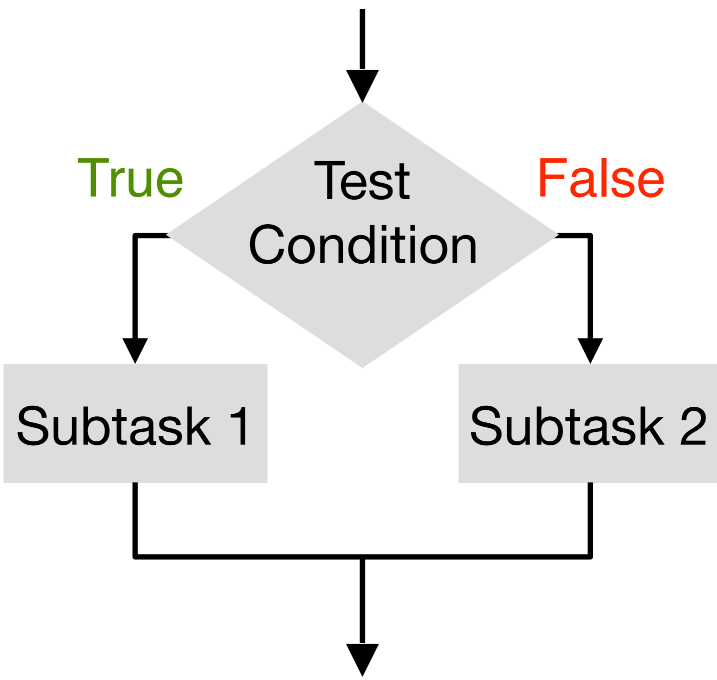
```

Summary

Conditional




```
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Memory

```
.section .text

…
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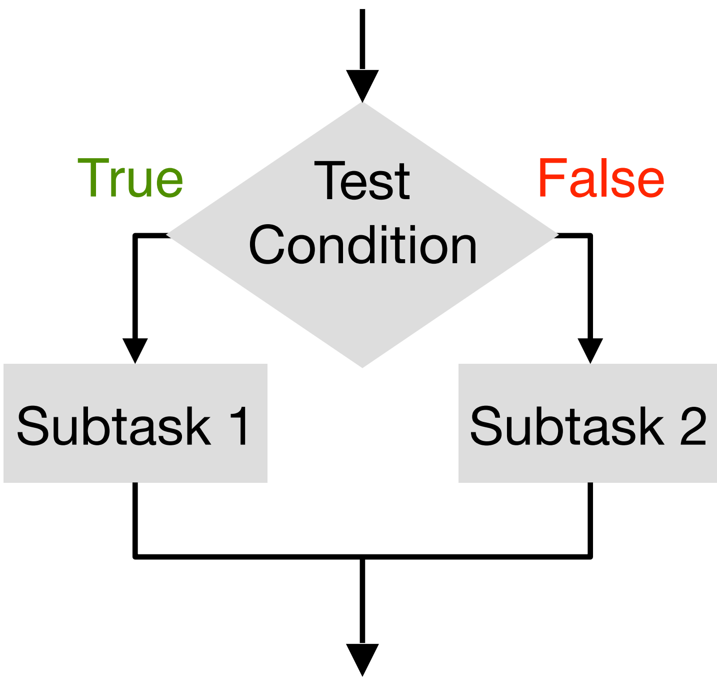
Summary

Conditional

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Memory

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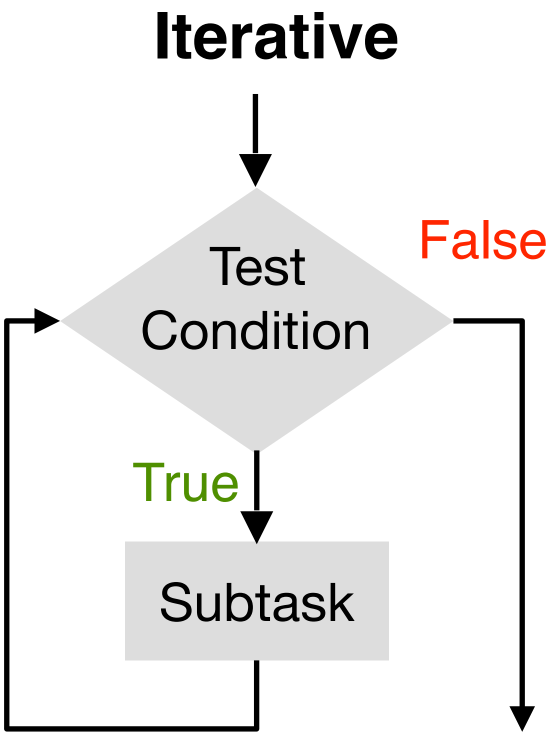
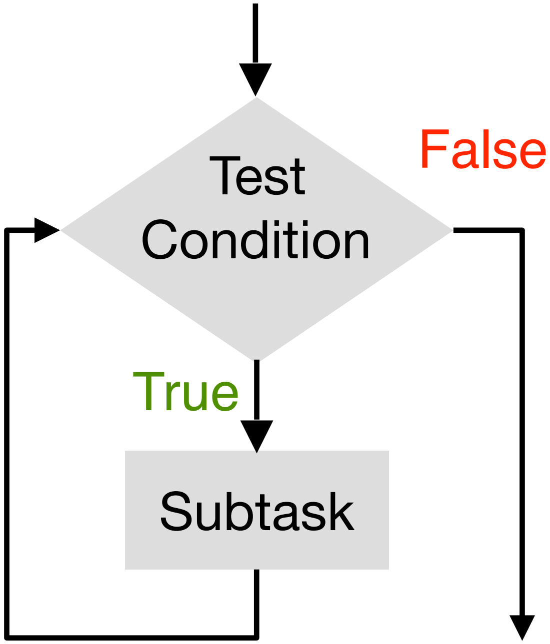
Summary




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

Summary

Iterative




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

Memory

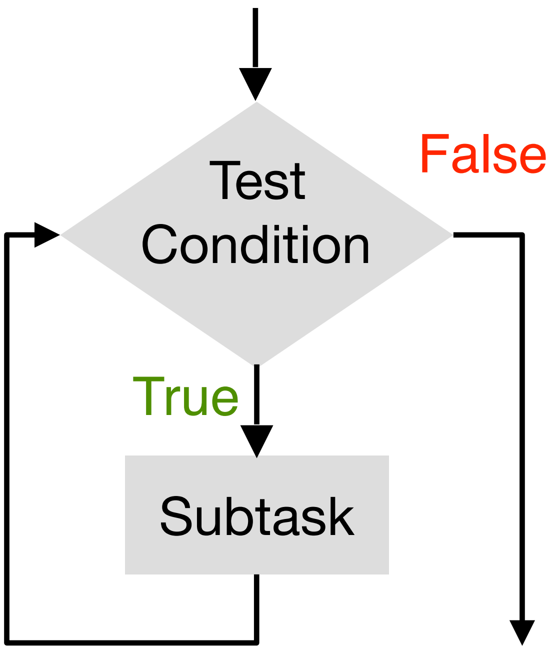
```
.section .text

…
addq
jmp .L2
.L1:

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

Summary

Iterative




```
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   x--;
}
```

Memory

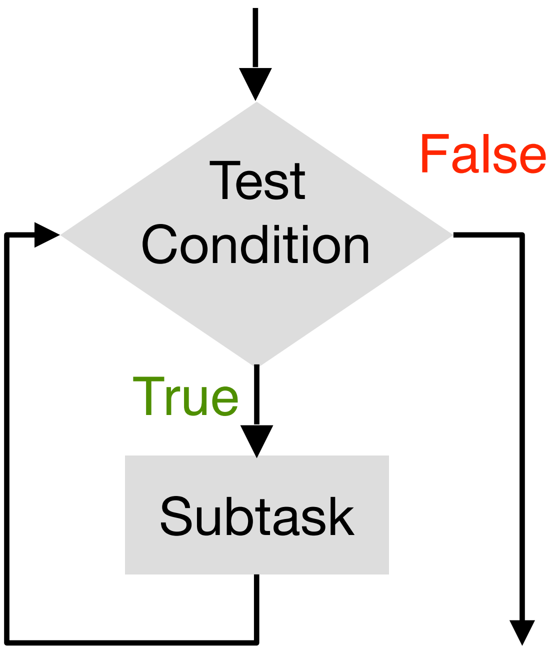
```
.section .text

…
addq
jmp .L2
.L1:

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

Summary

Iterative

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Memory

```
.section .text

…
addq
jmp .L2
.L1:

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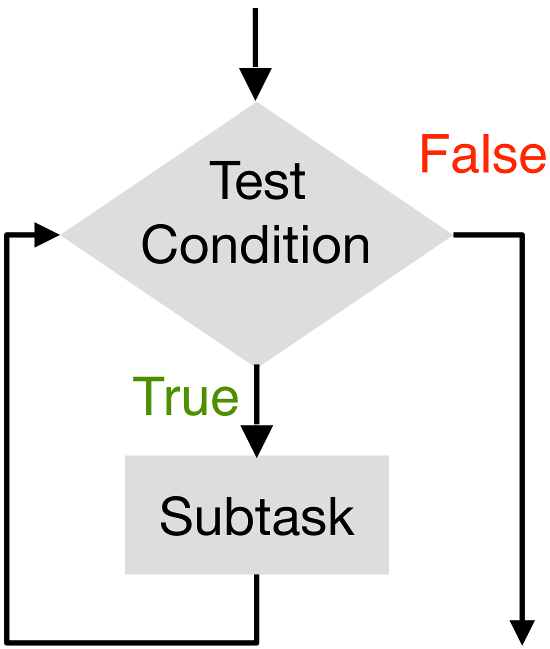
…
…
```

Summary

Iterative

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```

Memory

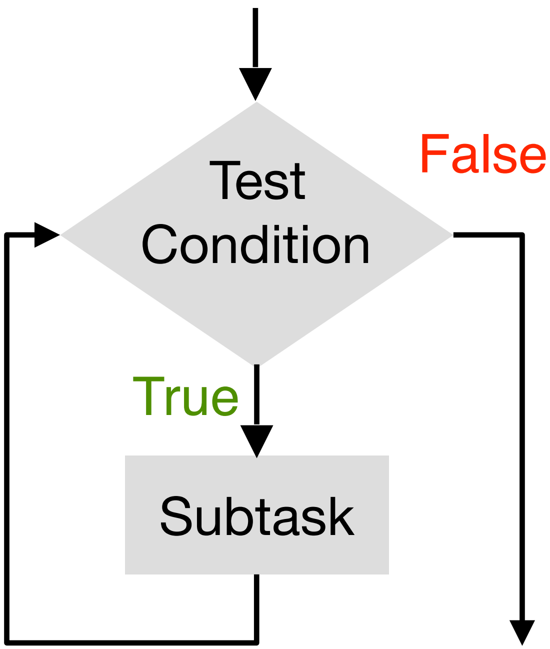
```
.section .text

…
addq
jmp .L2
.L1:

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

Summary

Iterative

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Memory

```
.section .text

…
addq
jmp .L2
.L1:

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