x86-64 Programming III & The Stack

CSE 351 Autumn 2017

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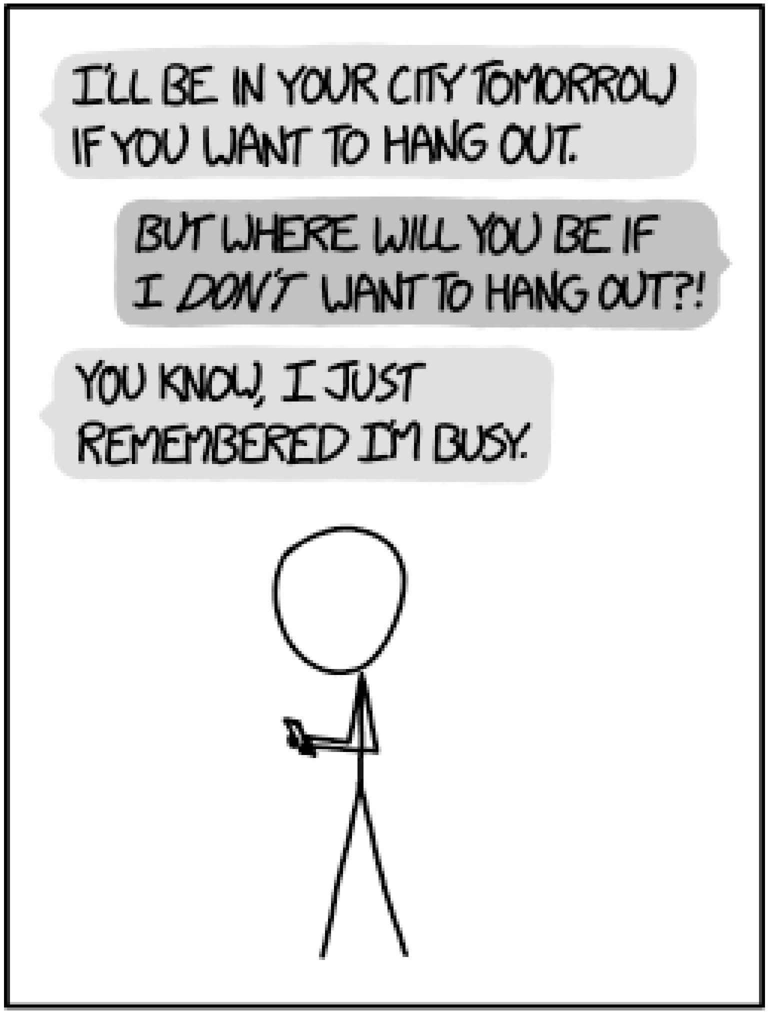

I'LL BE IN YOUR CITY TOMORROW IF YOU WANT TO HANG OUT.
BUT WHERE WILL YOU BE IF I *DON'T* WANT TO HANG OUT?!
YOU KNOW, I JUST REMEMBERED I'M BUSY.

WHY I TRY NOT TO BE PEDANTIC ABOUT CONDITIONALS.

http://xkcd.com/1652/

Administrivia

- Homework 2 due Friday (10/20)
- Lab 2 due next Friday (10/27)

- Section tomorrow on Assembly and GDB
  - Bring your laptops!

- Midterm: 10/30, 5pm in KNE 120
  - You will be provided a fresh reference sheet
  - You get 1 *handwritten*, double-sided cheat sheet (letter)
  - Midterm Clobber Policy: replace midterm score with score on midterm portion of the final if you “do better”

x86 Control Flow

- Condition codes
- Conditional and unconditional branches
- **Loops**
- Switches

Expressing with Goto Code

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

conditional jump

unconditional jump →

labels (addresses)

```
long absdiff_j(long x, long y)
{
    long result;
    int ntest = (x <= y);
    if (ntest) goto Else;
    result = x-y;
    goto Done;
 Else:
    result = y-x;
 Done:
    return result;
}
```

cmp

jle

jmp

- C allows `goto` as means of transferring control (`jump`)
  - Closer to assembly programming style
  - Generally considered bad coding style

Compiling Loops

C/Java code:

Test

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

Assembly code:

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

!Test

- Other loops compiled similarly
  - Will show variations and complications in coming slides, but may skip a few examples in the interest of time
- Most important to consider:
  - When should conditionals be evaluated? (*while* vs. *do-while*)
  - How much jumping is involved?

Compiling Loops

C/Java code:

```
while ( Test ) {
    Body
}
```

Goto version

```
Loop: if ( !Test )  goto Exit;
      Body
      goto Loop;
Exit:
```

- What are the Goto versions of the following?
  - Do…while: Test and Body
  - For loop: Init, Test, Update, and Body

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

```
     "i=0"  "i<n"  "i++"
for (Init; Test; Update) {
    Body
}
```

Do…while

```
Loop:  Body
       if (Test)  goto Loop;
```

For loop

```
      Init
Loop: if (!Test)  goto Exit;
      Body
      Update
      goto Loop;
Exit:
```

Compiling Loops

all jump instructions update the program counter (%rip)

While Loop:

Test

C:

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

sum == 0

x86-64:

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

~Test

Do-while Loop:

C:

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

Test

x86-64:

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

Test

While Loop (ver. 2):

Test

C:

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

x86-64:

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

~Test

do-while loop

Test

For Loop → While Loop

For Version

```
for (Init; Test; Update)

      Body
```

While Version

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

Caveat: C and Java have `break` *and* `continue`

- *Conversion works fine for* `break`
  - *Jump to same label as loop exit condition*
- *But not* `continue`*: would skip doing Update, which it should do with for-loops*
  - *Introduce new label at Update*

x86 Control Flow

- Condition codes
- Conditional and unconditional branches
- Loops
- **Switches**

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

Switch Statement Example

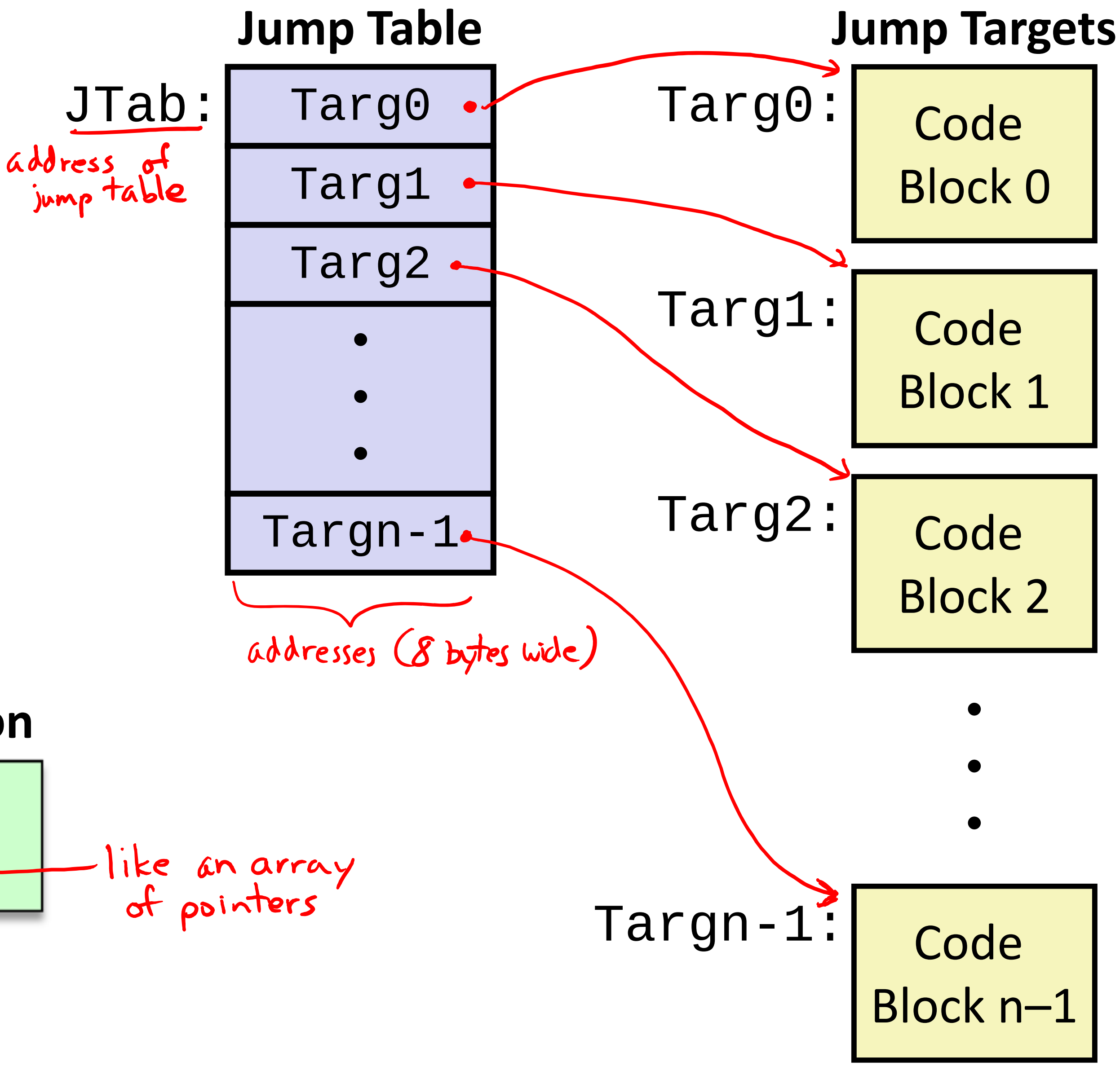
- Multiple case labels
    - Here: 5 & 6
- Fall through cases
    - Here: 2
- Missing cases
    - Here: 4

- Implemented with:
    - *Jump table*
    - *Indirect jump instruction*

Jump Table Structure

Switch Form

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



Approximate Translation

```
target = JTab[x];
goto target;
```

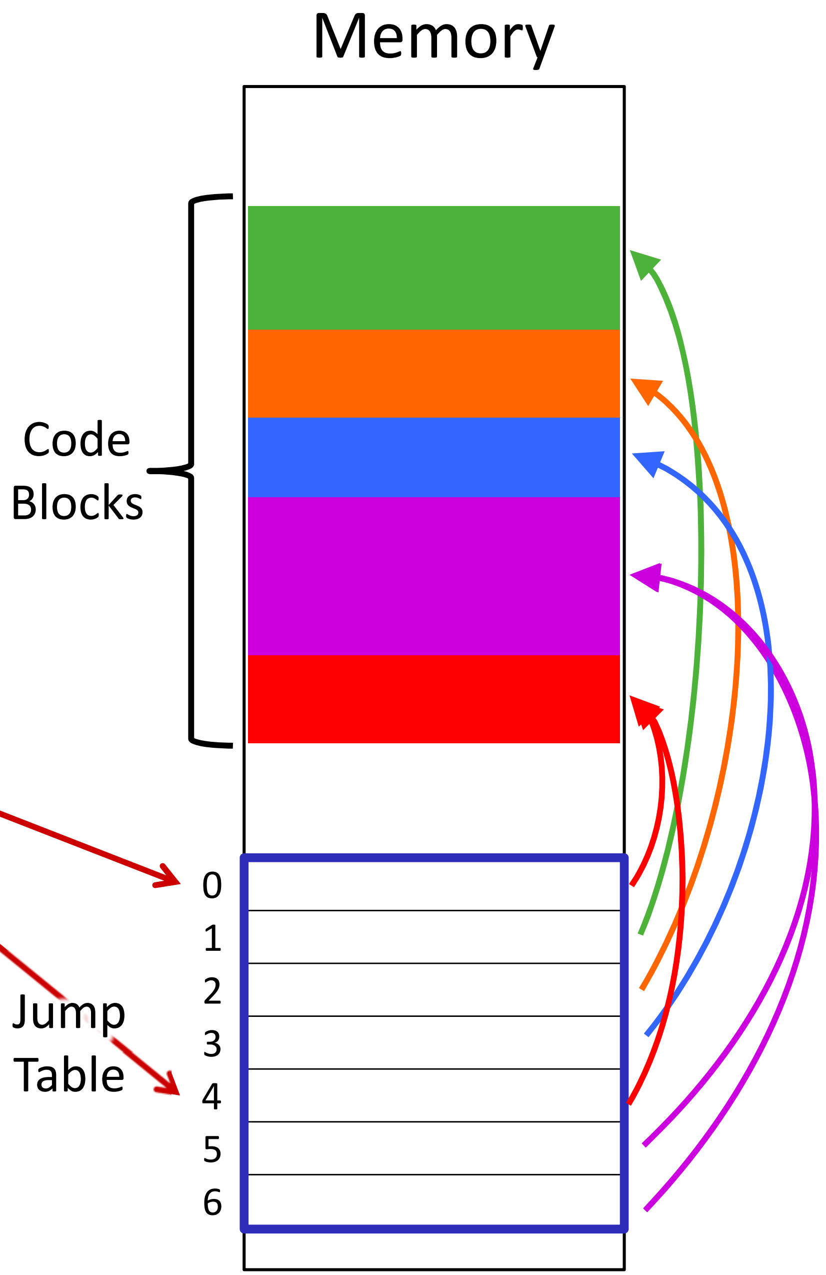
Jump Table Structure

C code:

```
switch (x) {
   case 1: <some code>
           break;
   case 2: <some code>
   case 3: <some code>
           break;
   case 5:
   case 6: <some code>
           break;
   default: <some code>
}
```

Use the jump table when x ≤ 6:

```
if (x <= 6)
   target = JTab[x];
   goto target;
else
   goto default;
```



Switch Statement Example

Register	Use(s)
%rdi	1st argument (x)
%rsi	2nd argument (y)
%rdx	3rd argument (z)
%rax	Return value

where?

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

Note compiler chose to not initialize w

a b

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

jump to default case if x>6 (unsigned)

Take a look!

https://godbolt.org/g/DnOmXb

jump above – unsigned > catches negative default cases

-1 > 6U → jump to default case

Switch Statement Example

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

Jump table

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

address

following data is a "quad word" = 8 bytes

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

Indirect jump

D + Ri * S

addr of jump table

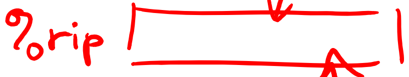
x

sizeof (void*)

Assembly Setup Explanation

- Table Structure
  - Each target requires 8 bytes (address)
  - Base address at `.L4`

- **Direct jump:** `jmp .L8`
  - Jump target is denoted by label `.L8`



- **Indirect jump:** `jmp *.L4(,%rdi,8)`

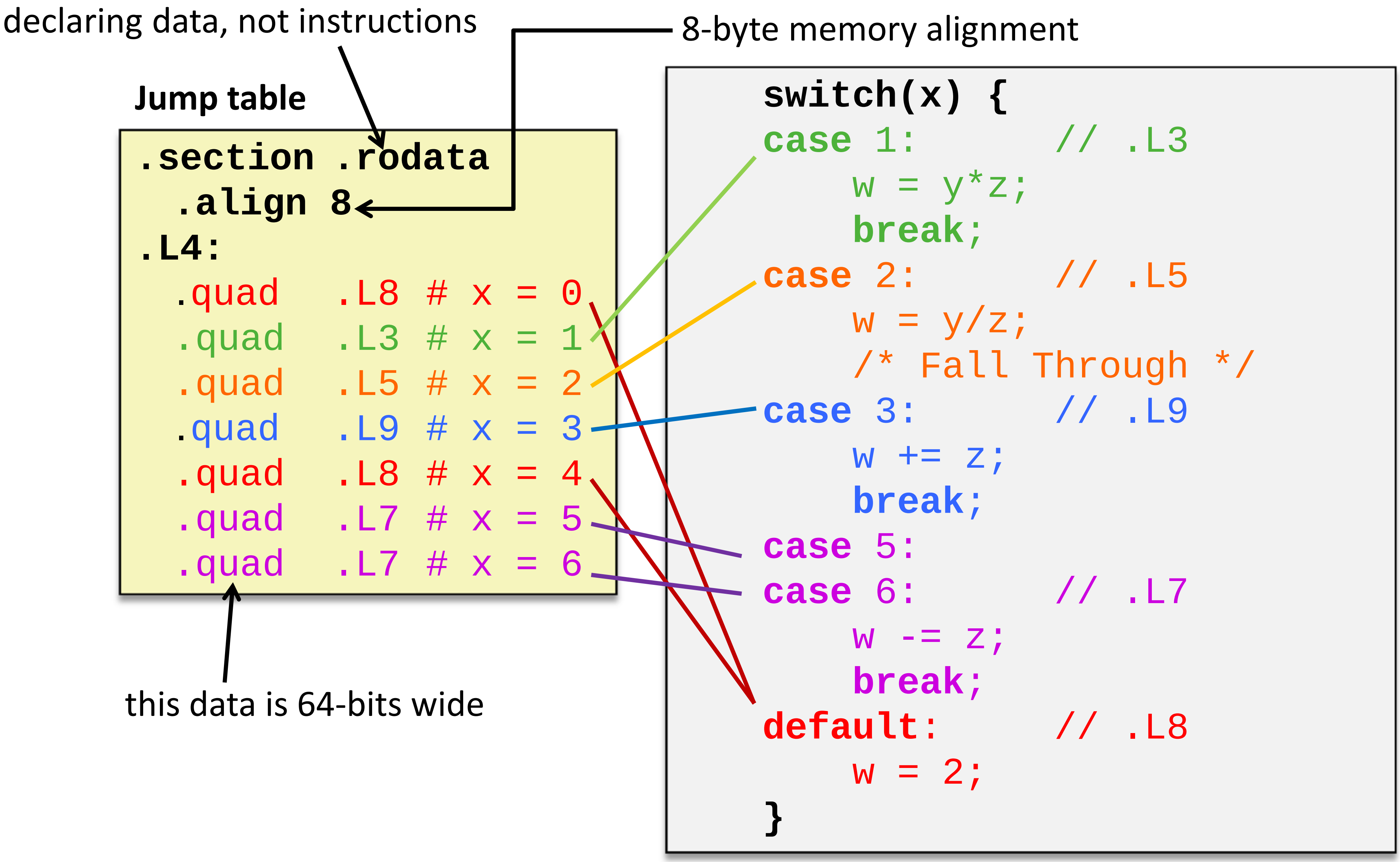
Mem[D+ Reg[Ri]*S]

  - Start of jump table: `.L4`
  - Must scale by factor of 8 (addresses are 8 bytes)
  - Fetch target from effective address `.L4 + x*8`
    - Only for $0 \le x \le 6$

Jump table

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

Jump Table



declaring data, not instructions

8-byte memory alignment

Jump table

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

this data is 64-bits wide

```
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;
}
```

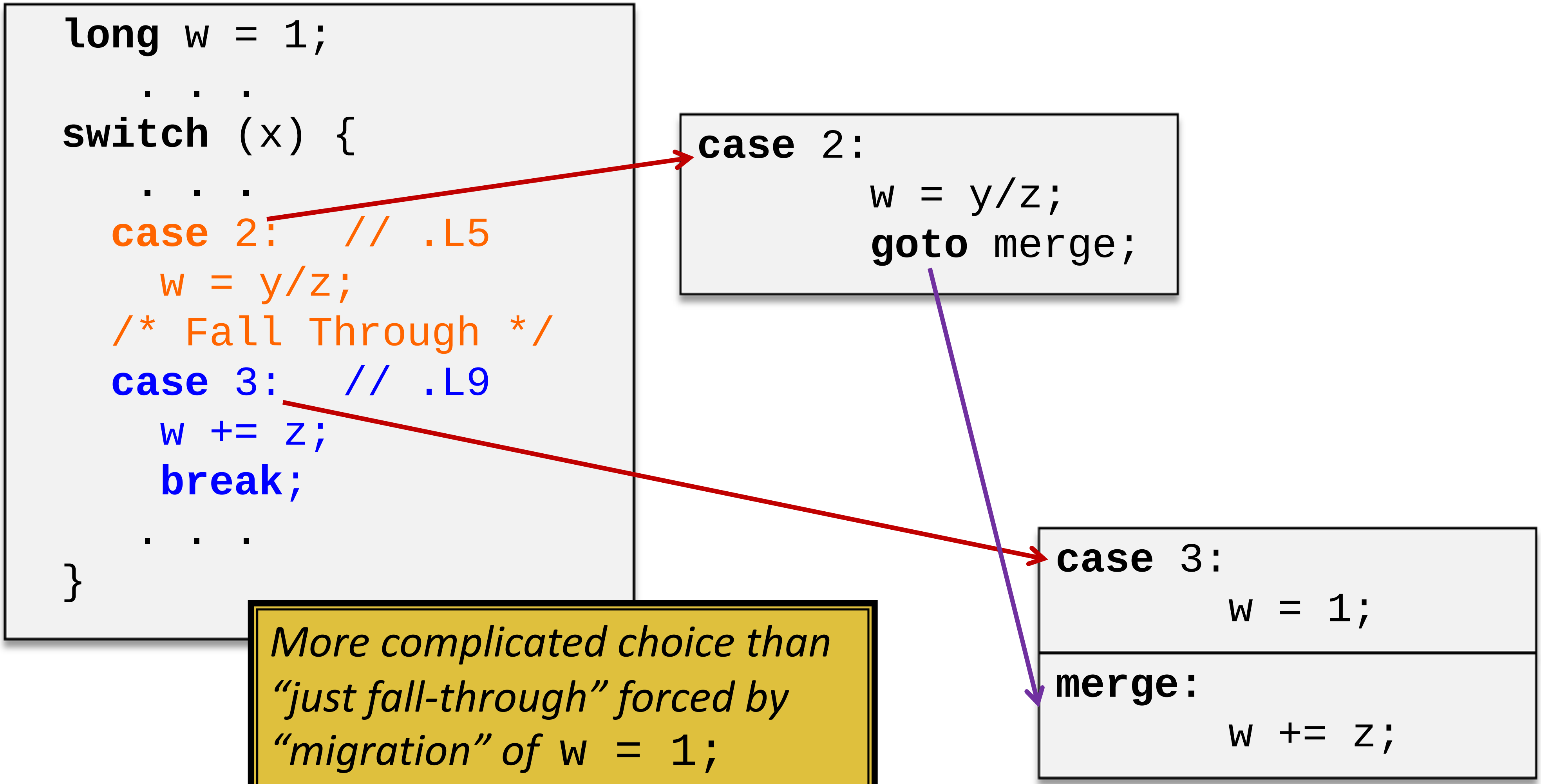
Code Blocks (x == 1)

Register	Use(s)
%rdi	1st argument (x)
%rsi	2nd argument (y)
%rdx	3rd argument (z)
%rax	Return value

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

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

Handling Fall-Through



```
long w = 1;
   . . .
switch (x) {
   . . .
  case 2:   // .L5
    w = y/z;
  /* Fall Through */
  case 3:   // .L9
    w += z;
    break;
   . . .
}
```

```
case 2:
       w = y/z;
       goto merge;
```

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

More complicated choice than "just fall-through" forced by "migration" of `w = 1;`

- *Example compilation trade-off*

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

Register	Use(s)
%rdi	1st argument (x)
%rsi	2nd argument (y)
%rdx	3rd argument (z)
%rax	Return value

```
long w = 1;
   . . .
switch (x) {
   . . .
  case 2:   // .L5
    w = y/z;
  /* Fall Through */
  case 3:   // .L9
    w += z;
    break;
   . . .
}
```

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

Code Blocks (rest)

Register	Use(s)
%rdi	1st argument (x)
%rsi	2nd argument (y)
%rdx	3rd argument (z)
%rax	Return value

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

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

Roadmap

C:

```
car *c = malloc(sizeof(car));
c->miles = 100;
c->gals = 17;
float mpg = get_mpg(c);
free(c);
```

Java:

```
Car c = new Car();
c.setMiles(100);
c.setGals(17);
float mpg =
    c.getMPG();
```

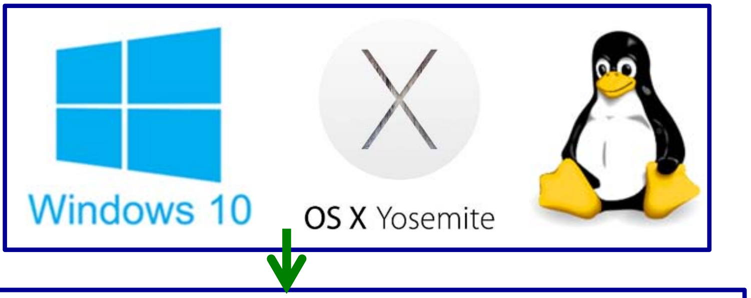
Assembly language:

```
get_mpg:
    pushq   %rbp
    movq    %rsp, %rbp
    ...
    popq    %rbp
    ret
```

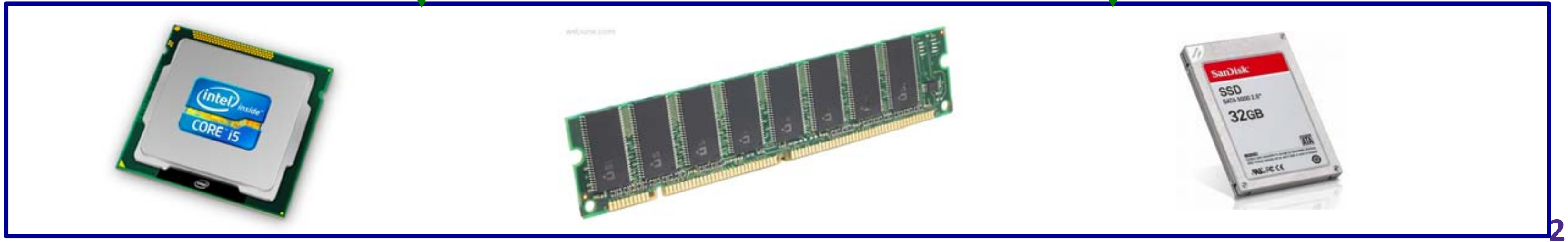
Machine code:

```
0111010000011000
100011010000010000000010
1000100111000010
110000011111101000011111
```

OS:



Computer system:

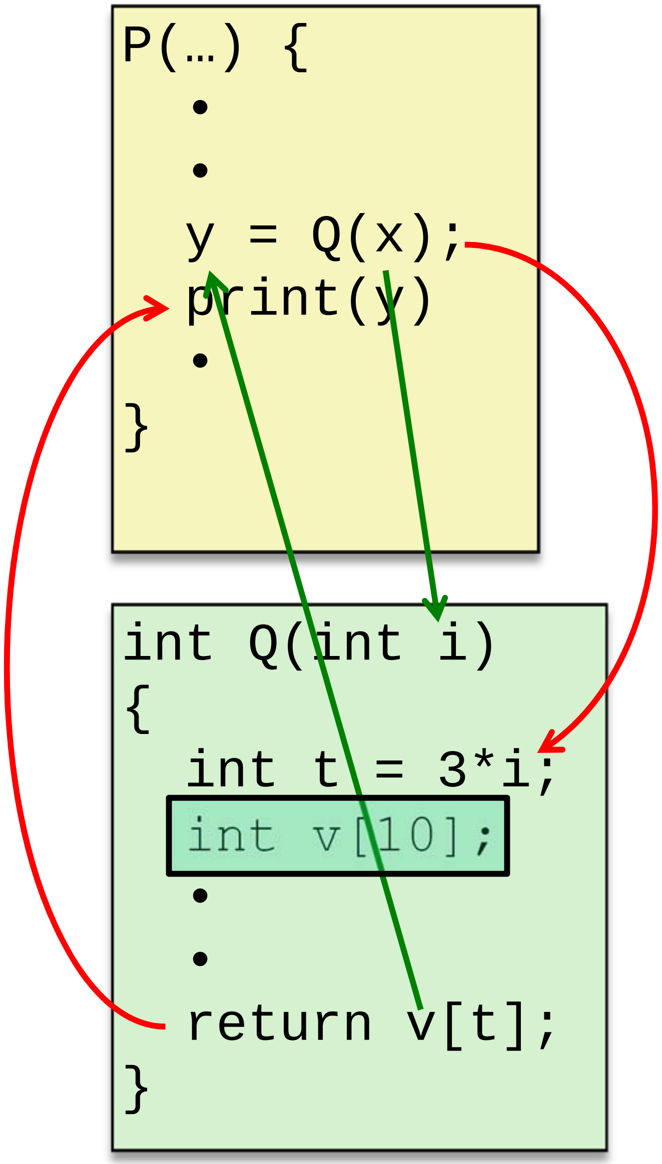


Memory & data
Integers & floats
x86 assembly
Procedures & stacks
Executables
Arrays & structs
Memory & caches
Processes
Virtual memory
Memory allocation
Java vs. C

Mechanisms required for *procedures*

1) Passing control
   - To beginning of procedure code
   - Back to return point
2) Passing data
   - Procedure arguments
   - Return value
3) Memory management
   - Allocate during procedure execution
   - Deallocate upon return

- All implemented with machine instructions!
  - An x86-64 procedure uses only those mechanisms required for that procedure



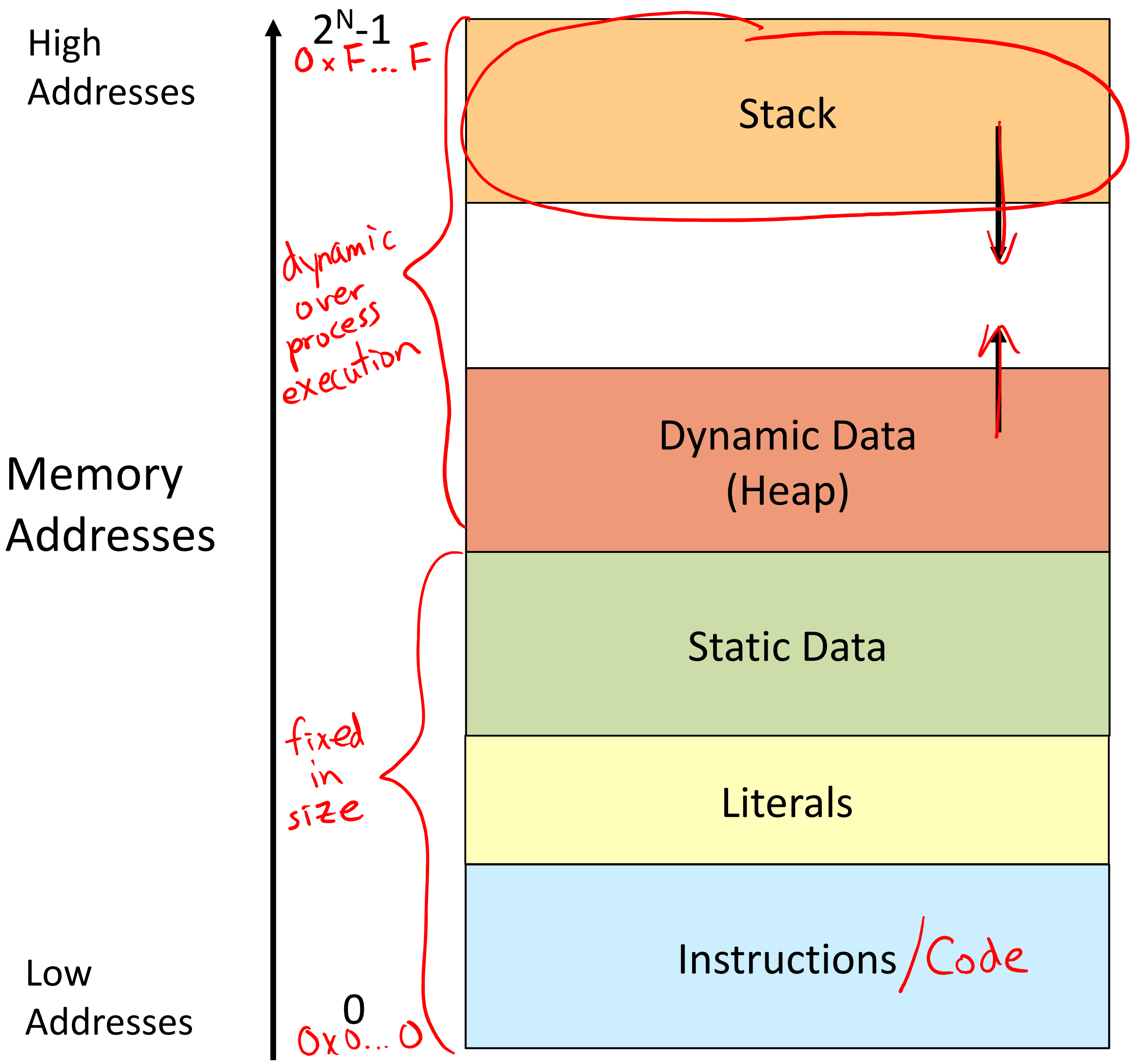
```
P(…) {
  •
  •
  y = Q(x);
  print(y)
  •
}
```

```
int Q(int i)
{
  int t = 3*i;
  int v[10];
  •
  •
  return v[t];
}
```

Procedures

- **Stack Structure**
- Calling Conventions
  - Passing control
  - Passing data
  - Managing local data
- Register Saving Conventions
- Illustration of Recursion

Simplified Memory Layout



Stack: local variables; procedure context

Dynamic Data (Heap): variables allocated with *new* or *malloc*

Static Data: *static* variables (including global variables (C))

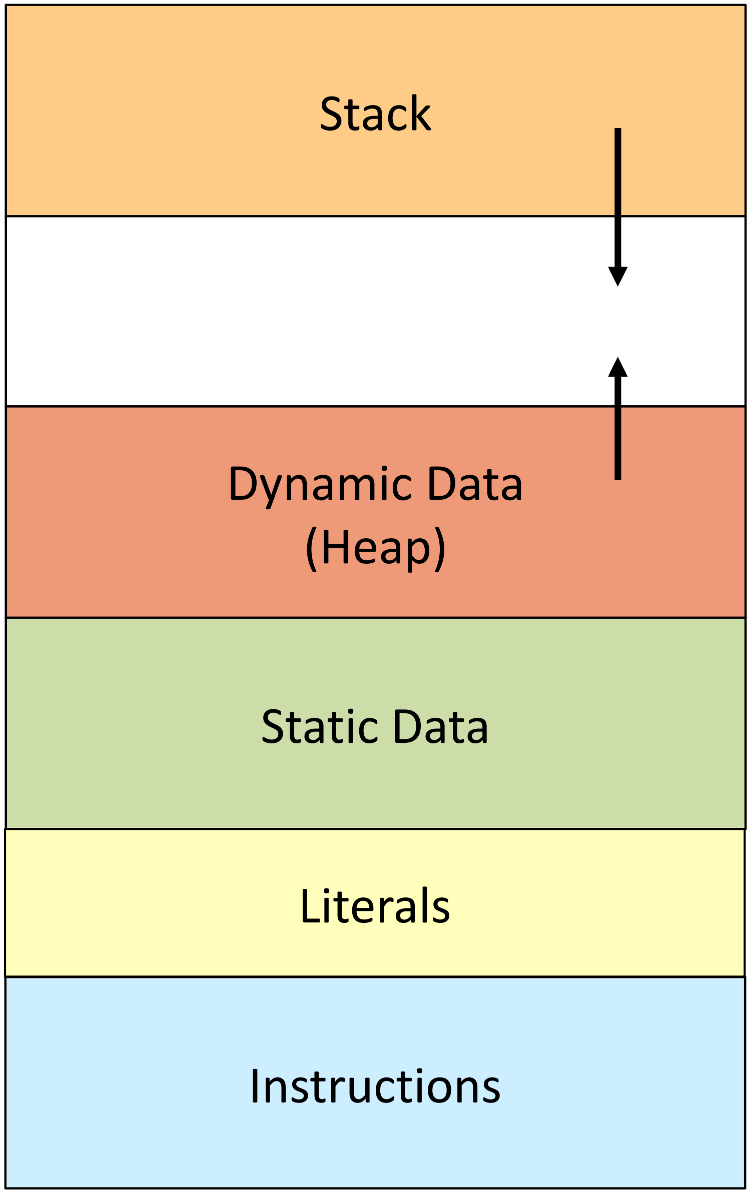
Literals: large constants (*e.g.* "example")

Instructions: program code

Memory Permissions

segmentation faults?

accessing memory in a way that you are not allowed to

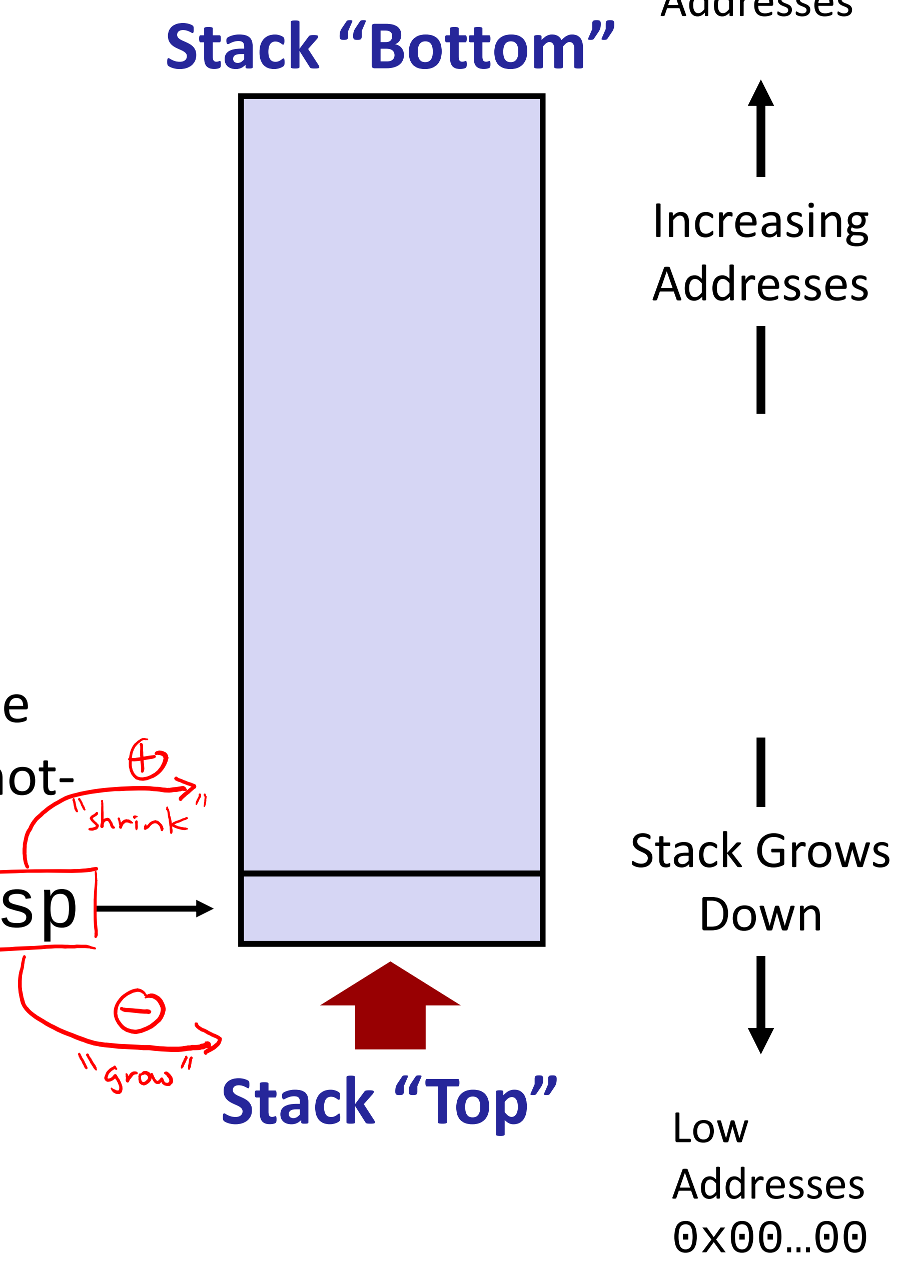


writable; not executable	Stack	Managed "automatically" (by compiler)
		← grow towards each other to maximize use of space
writable; not executable	Dynamic Data (Heap)	Managed by programmer
writable; not executable	Static Data	Initialized when process starts
read-only; not executable	Literals	Initialized when process starts
read-only; executable	Instructions	Initialized when process starts

x86-64 Stack

Last In, First Out (LIFO)

- Region of memory managed with stack "discipline"
  - Grows toward lower addresses
  - Customarily shown "upside-down"
- Register `%rsp` contains *lowest* stack address
  - `%rsp` = address of *top* element, the most-recently-pushed item that is not-yet-popped



Stack Pointer: `%rsp`

x86-64 Stack: Push

- `pushq` *src*
  ↑ size specifier
  - Fetch operand at *src*
    - *Src* can be reg, memory, immediate
  - ***Decrement*** `%rsp` by 8
  - Store value at address given by `%rsp`

- Example:
  - **`pushq %rcx`**
  - Adjust `%rsp` and store contents of `%rcx` on the stack

Registers

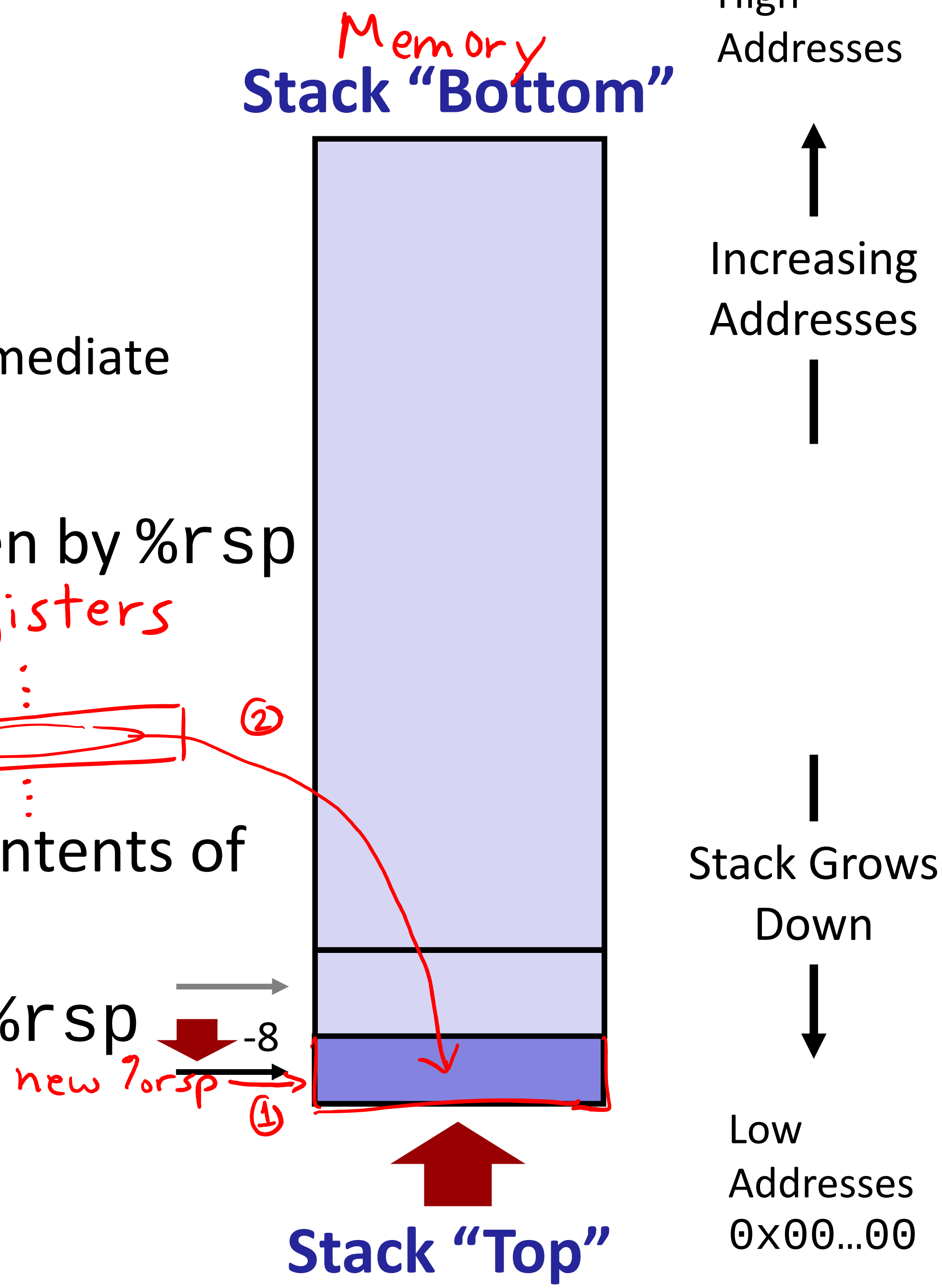
%rcx

②

Stack Pointer: `%rsp`

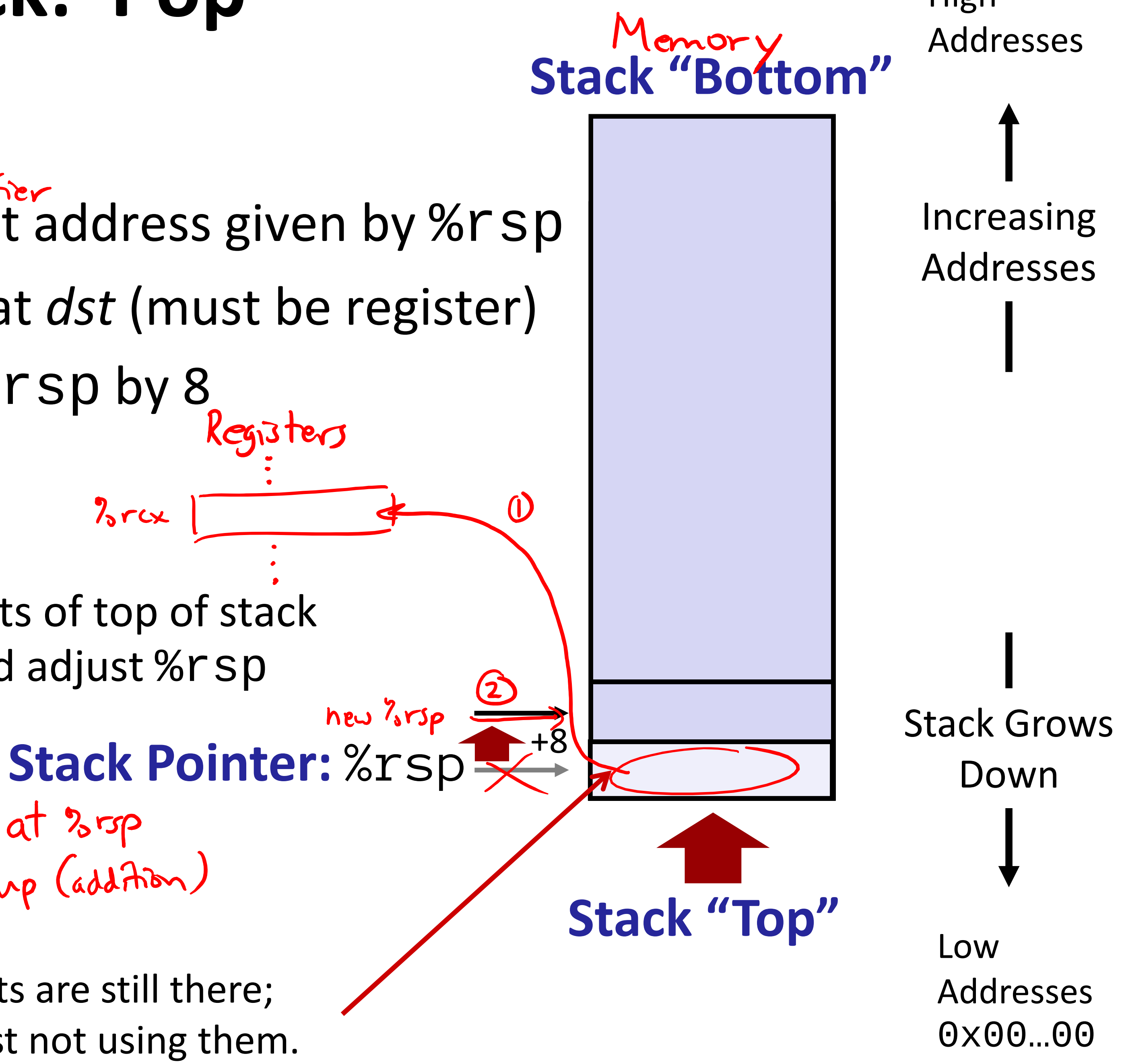
① move %rsp down (subtract)

② store src at %rsp



x86-64 Stack: Pop

- popq *dst*
  ↑ size specifier
  - Load value at address given by %rsp
  - Store value at *dst* (must be register)
  - ***Increment*** %rsp by 8
- Example:
  - **popq %rcx**
  - Stores contents of top of stack into %rcx and adjust %rsp



① read out data at %rsp

② move %rsp up (addition)

Those bits are still there; we're just not using them.