HARVARD
School of Engineering
and Applied Sciences

Machine Programming 2: Control flow

CS61, Lecture 4

Prof. Stephen Chong

September 13, 2011

Announcements

- Assignment 1 due today, 11:59pm
  - Hand in at front during break or email it to cs61-staff@seas.harvard.edu
  - If you need to use late days, you must email us **before** deadline
- Sections started yesterday
  - Contact course staff if you haven't been assigned a section
  - Please try to attend your assigned section
  - On **trial basis**, we are allowing students to attend other sections.
- Infrastructure
  - Some issues yesterday and this morning, have been resolved

Office Hours and New Course Staff

- Office hours posted on website
- New course staff

Gabrielle Ehrlich

Randy Miller

Today

- Data types
  - Register names
- Control flow
  - jmp
  - Condition flags
  - Loops
  - Switch statements

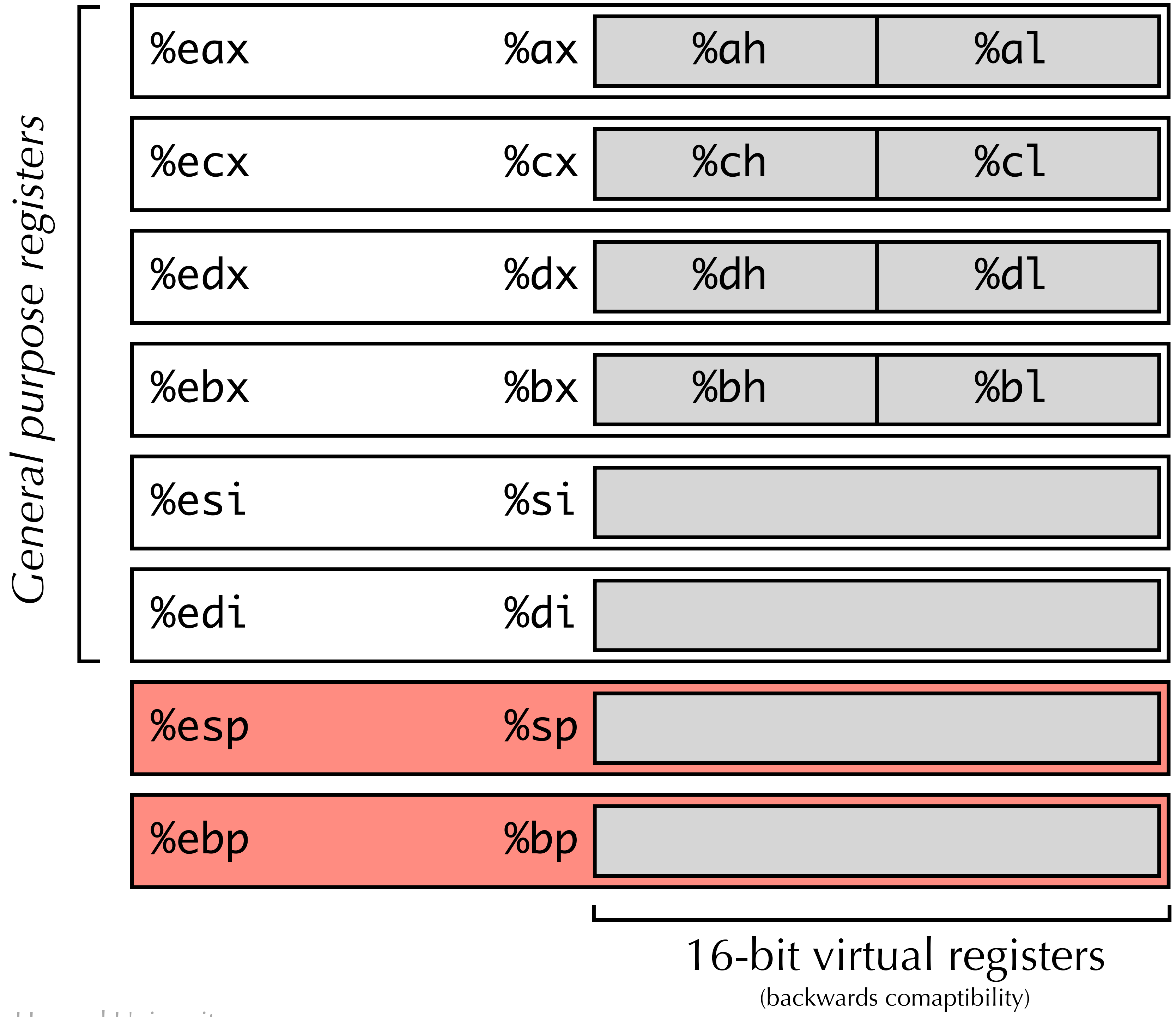
Data types

- All examples have dealt with 4-byte integers
  - Instructions `addl`, `subl`, `movl`, etc.
  - The "`l`" (ell) at the end represents "`long`" ... which is the x86 data type that holds an int.
- Many instructions can operate on different data types:
  - `addb` – byte, 8 bits (C type: char, unsigned char)
  - `addw` – word, 16 bits (C type: short, unsigned short)
  - `addl` – long, 32 bits (C type: int, unsigned int, long, unsigned long)

Register names

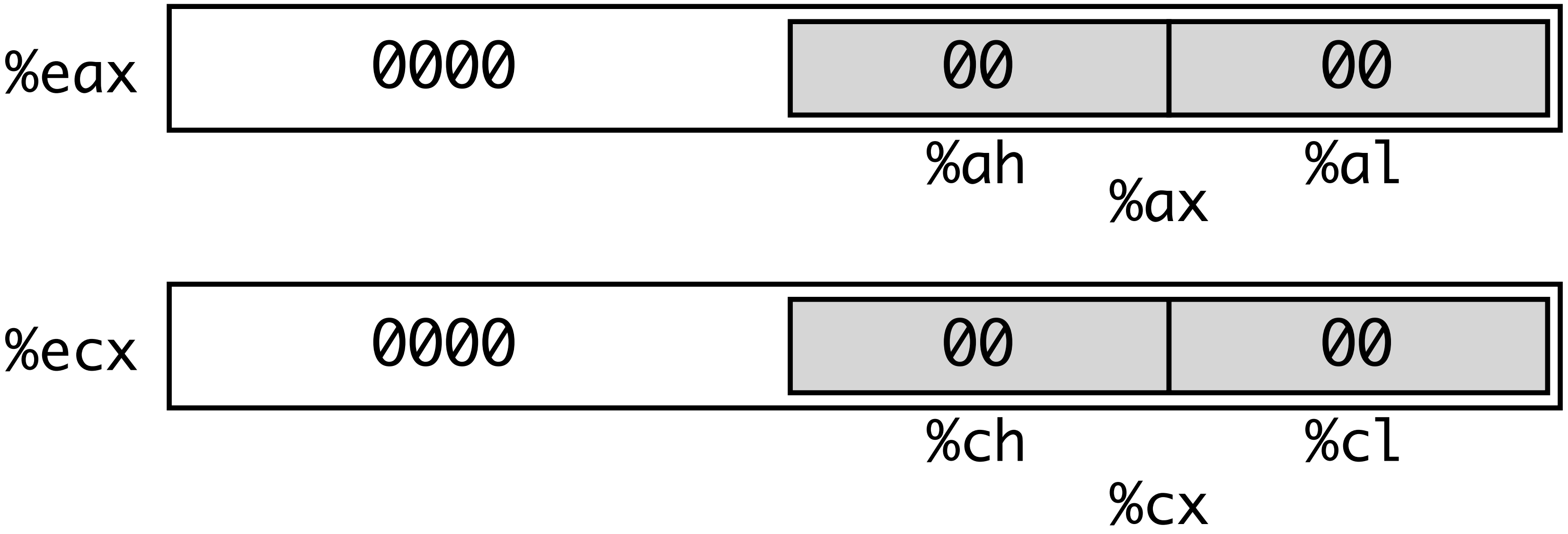
- Registers `%eax`, `%ecx`, `%edx`, `%ebx`, `%esi`, `%edi`, `%esp`, `%ebp` are all 32-bit
- Sometimes we handle data smaller than 32 bits
    - Have names for addressing just some bits of a register
        - Historical, due to development of IA32 from 8 and 16 bit architectures

Register names



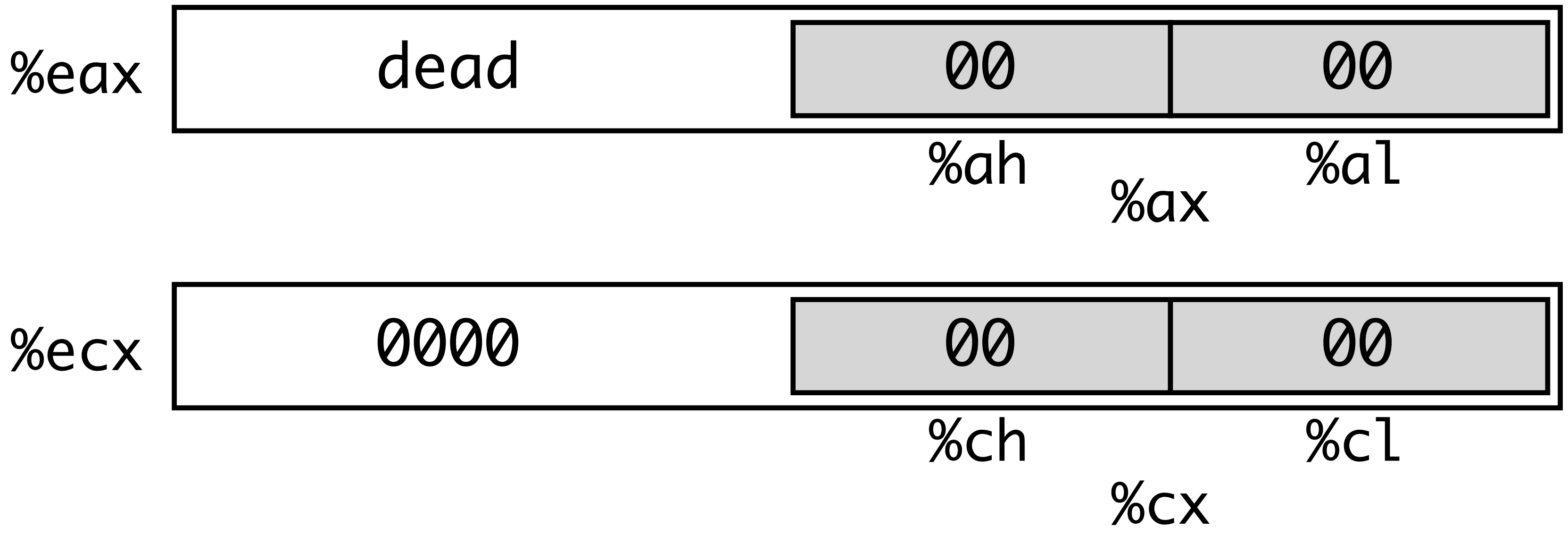
				Origin (mostly obsolete)
%eax	%ax	%ah	%al	*accumulate*
%ecx	%cx	%ch	%cl	*counter*
%edx	%dx	%dh	%dl	*data*
%ebx	%bx	%bh	%bl	*base*
%esi	%si			*source index*
%edi	%di			*destination index*
%esp	%sp			***stack pointer***
%ebp	%bp			***base pointer***

Register name example



```
movl   $0xdead0000, %eax
movb   $0xef, %al
movb   $0xbe, %ah
movl   %eax, %ecx
```

Register name example



%eax dead 00 00

%ah %al

%ax

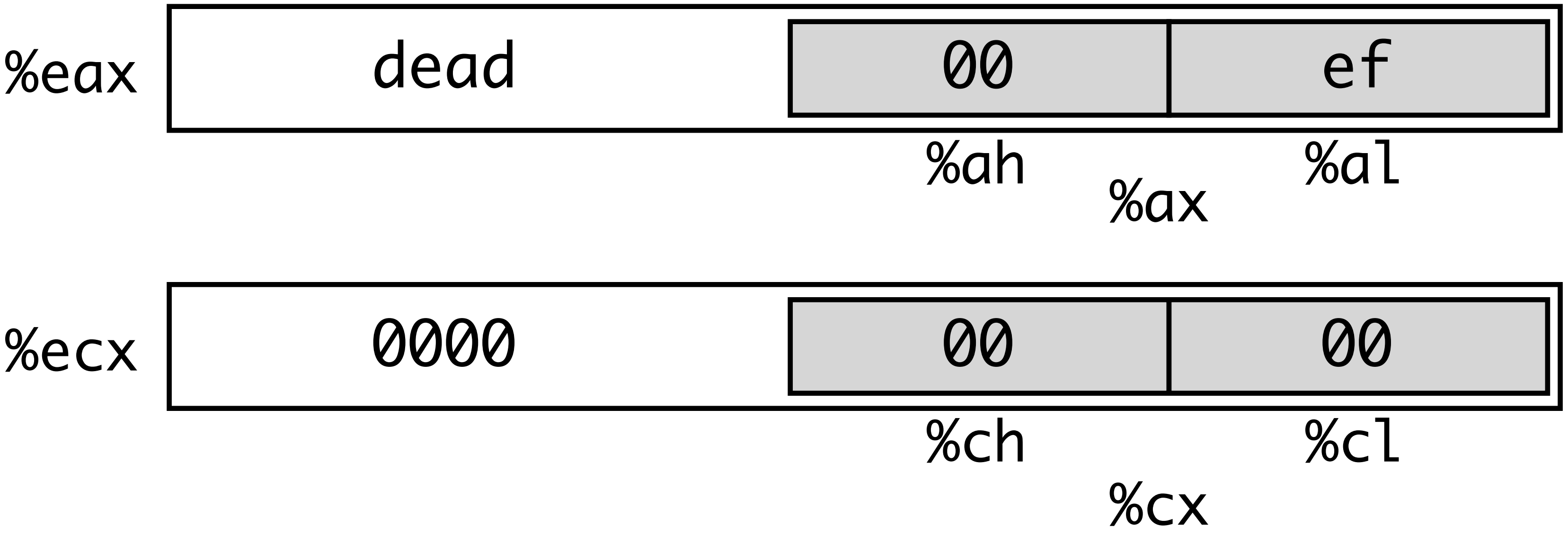
%ecx 0000 00 00

%ch %cl

%cx

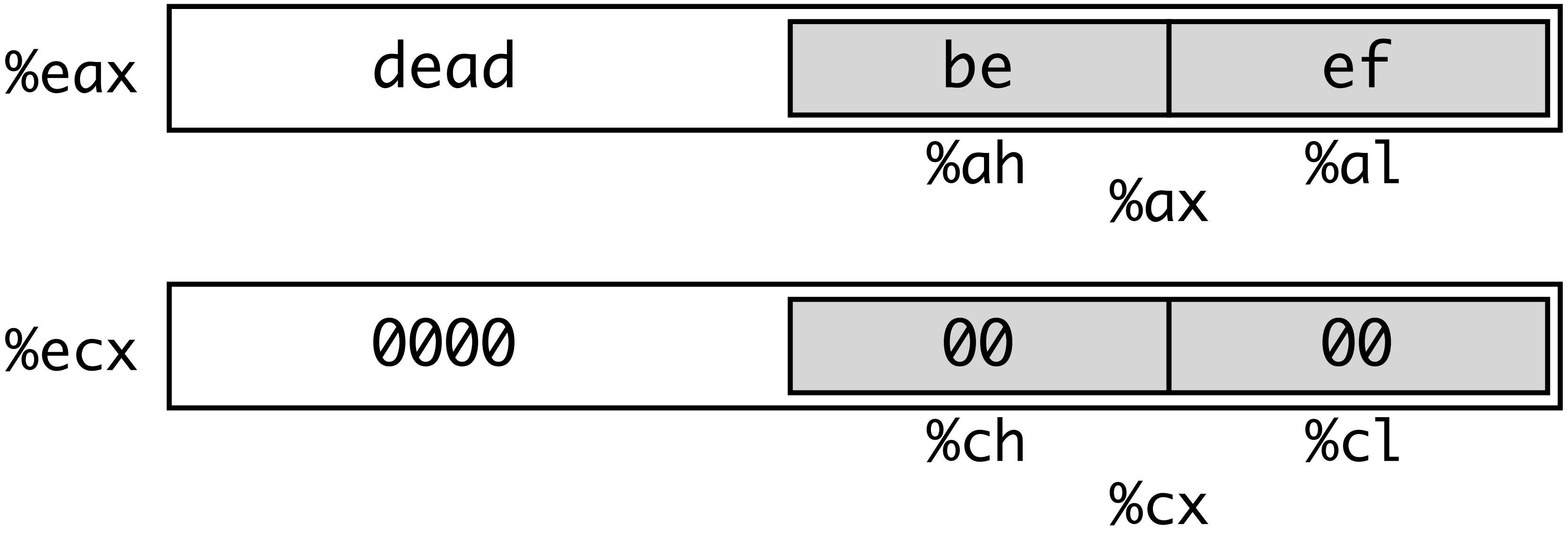
```
movl   $0xdead0000, %eax
movb   $0xef, %al
movb   $0xbe, %ah
movl   %eax, %ecx
```

Register name example



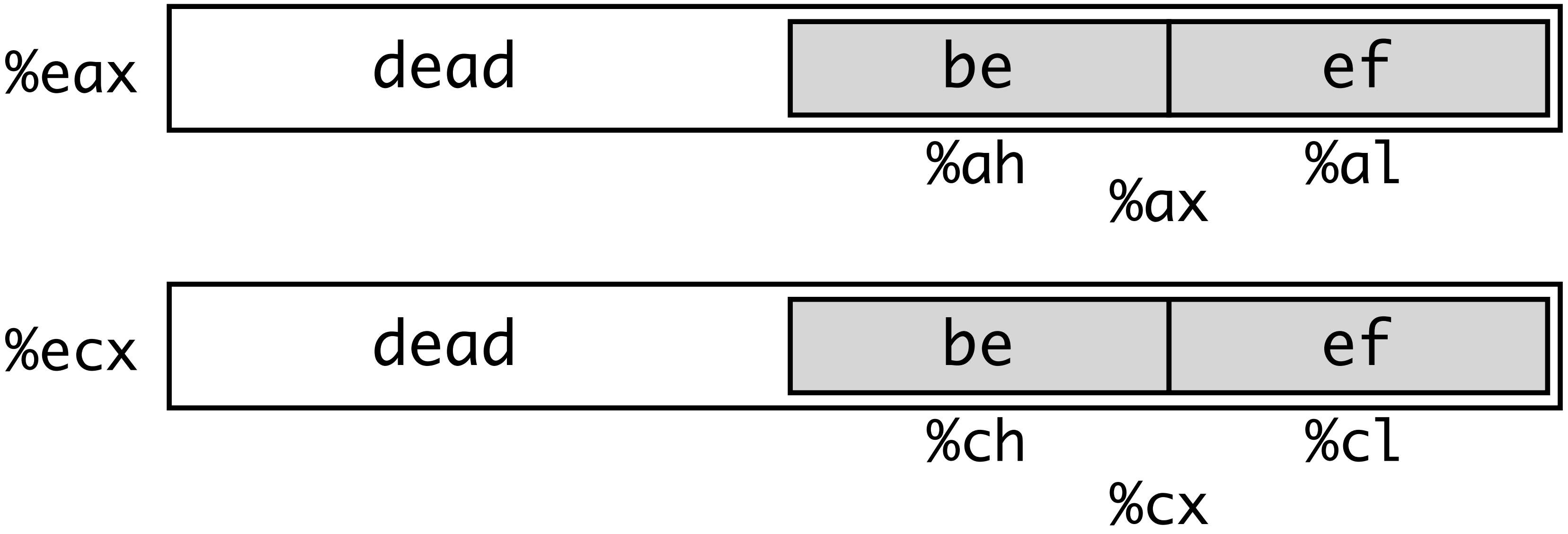
```
movl    $0xdead0000, %eax
movb    $0xef, %al
movb    $0xbe, %ah
movl   %eax, %ecx
```

Register name example



```
movl    $0xdead0000, %eax
movb    $0xef, %al
movb    $0xbe, %ah
movl    %eax, %ecx
```

Register name example



%eax dead be ef

%ah %ax %al

%ecx dead be ef

%ch %cx %cl

```
movl    $0xdead0000, %eax
movb    $0xef, %al
movb    $0xbe, %ah
movl    %eax, %ecx
```

Today

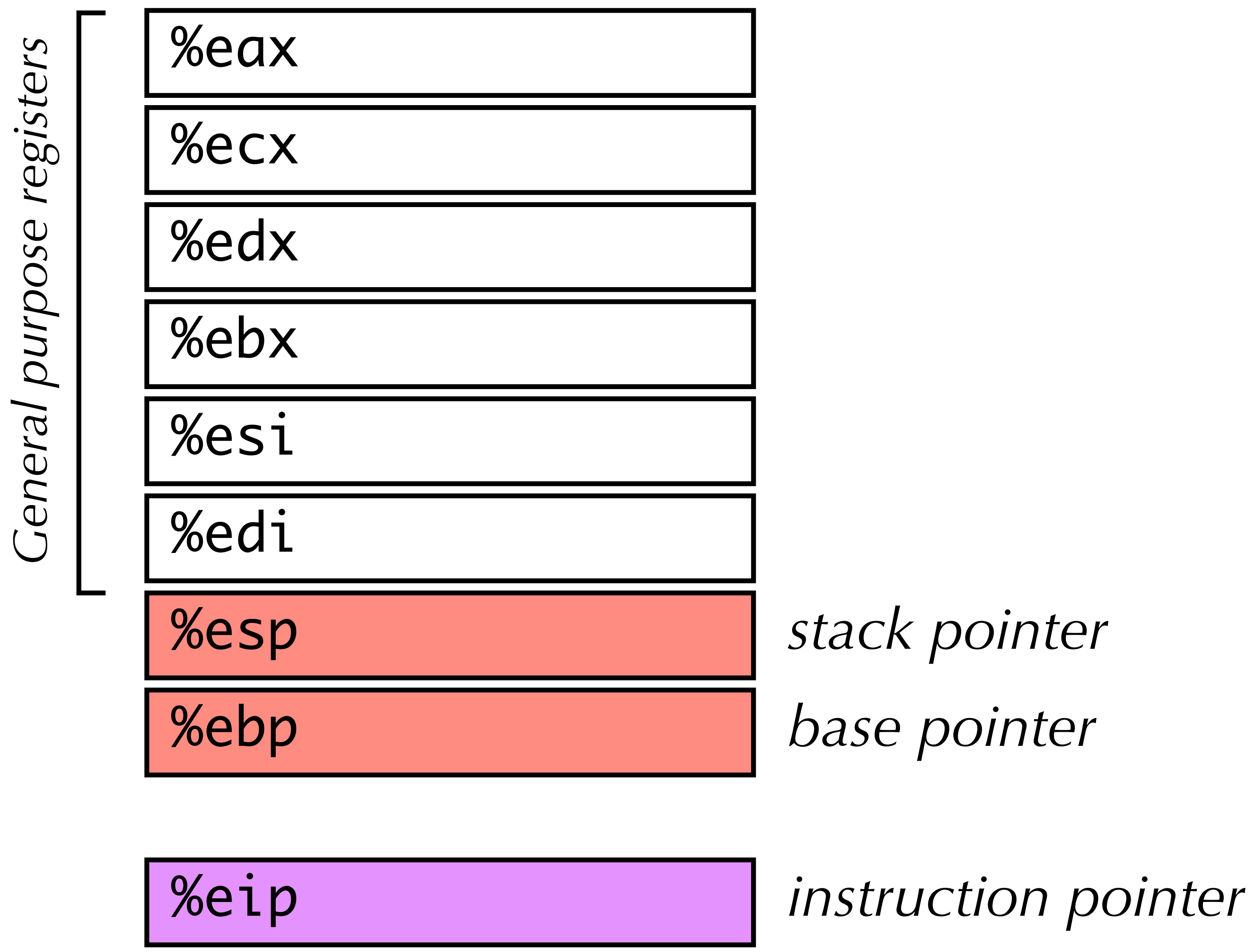
- Data types
  - Register names
- Control flow
  - jmp
  - Condition flags
  - Loops
  - Switch statements

Control flow

- **Control flow** is the general term for any code that controls which parts of a program are executed.
- Examples in C
  - `if (`*expr*`) { ... } else { ... }`
  - `do { .... } while (`*expr*`);`
  - `while (`*expr*`) { .... }`
  - `for (`*expr1*`; `*expr2*`; `*expr3*`) { ... }`
  - C "`goto`" statement
  - `switch (`*expr*`) { case `*val1*`: ...; case `*val1*`: ...; default: ...; }`

Processor state

- Control flow is about how the value of the instruction pointer changes



Simplest case: jmp instruction

- Operation `jmp` *label* causes processor to “jump” to a new instruction and execute from there

```
.L3:
        movl    12(%ebp), %eax          eax = arg2
        addl    8(%ebp), %eax           eax += arg1
        movl    %eax, -4(%ebp)          temp = eax
        jmp     .L6                     goto .L6
.L5:
        movl    12(%ebp), %eax          eax = arg2
        imull   8(%ebp), %eax           eax *= arg1
        movl    %eax, -4(%ebp)          temp = eax
.L6:
        movl    -4(%ebp), %eax          eax = temp
        leave                           return
        ret
```

- The label (“.L6”) is just a symbolic reference to a specific instruction in the program.
- Once compiled to a binary, the .L6 will be replaced by a memory address.

Symbolic labels

- The assembler replaces symbolic labels with the actual memory address when converting to machine code.
  - They are just “placeholders” for memory addresses.

Output from gcc -S

```
.L3:
        movl    12(%ebp), %eax
        addl    8(%ebp), %eax
        movl    %eax, -4(%ebp)
        jmp     .L6
.L5:
        movl    12(%ebp), %eax
        imull   8(%ebp), %eax
        movl    %eax, -4(%ebp)
.L6:
        movl    -4(%ebp), %eax
        leave
        ret
```

Output from objdump

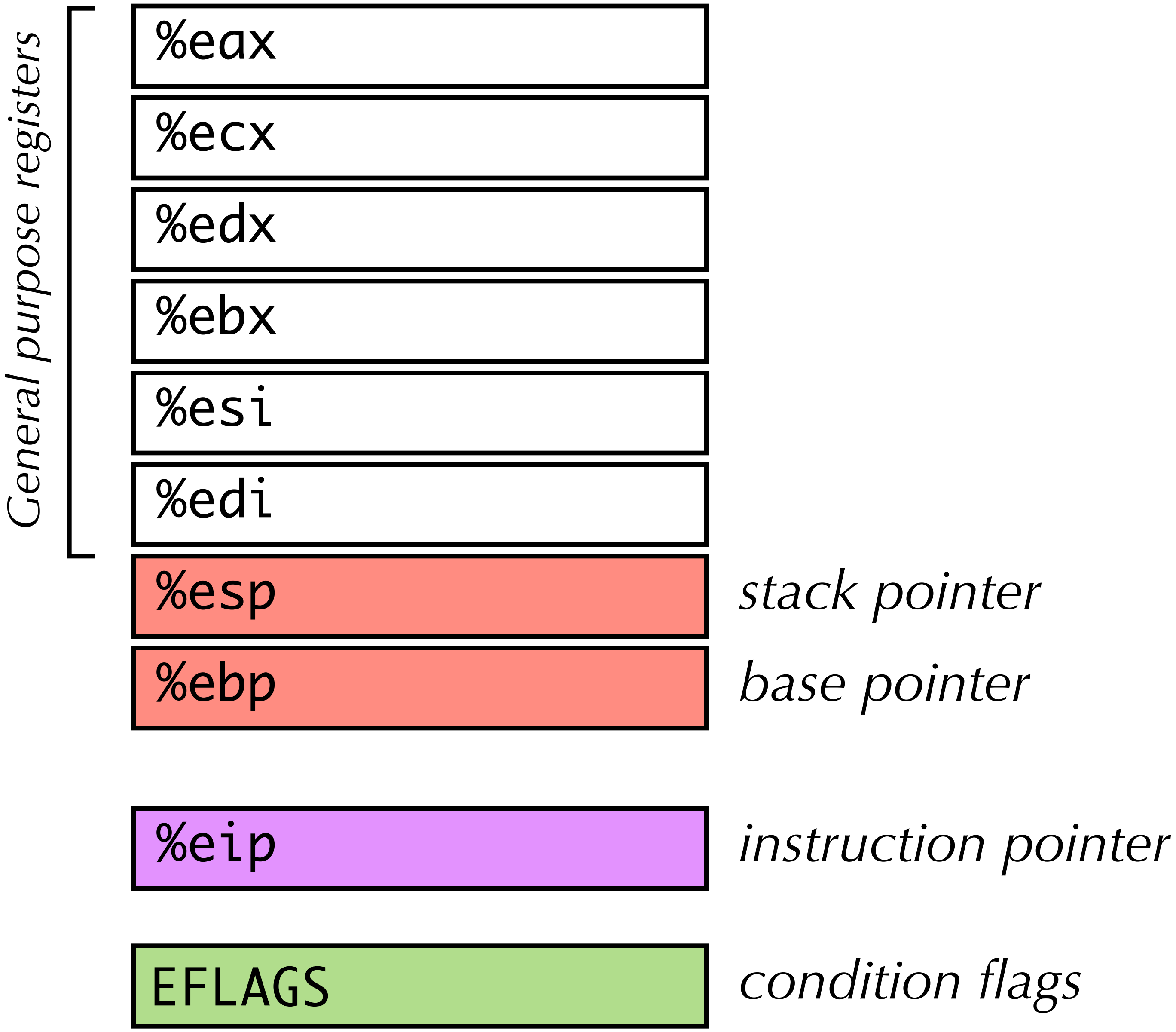
```
08048476: movl    12(%ebp), %eax
08048477: addl    8(%ebp), %eax
08040479: movl    %eax, -4(%ebp)
0804847c: jmp     08048489

0804847f: movl    12(%ebp), %eax
08048481: imull   8(%ebp), %eax
08048487: movl    %eax, -4(%ebp)

08048489: movl    -4(%ebp), %eax
0804848d: leave
0804848e: ret
```

Conditional branching

- `jmp` basically implements goto
  - Always same control flow
- How do we implement if statements, loops, etc?
  - Not always the same control flow
- Two kinds of instructions
- Comparison instructions (`cmpl`, `testl`, etc.)
  - Compare values of two registers
  - Set **condition flags** based on result
- Conditional branch instructions (`je`, `jne`, `jg`, etc.)
  - Jump depending on current value of condition flags

Condition flags

- Bits maintained by the processor representing result of previous arithmetic instruction
- Used for many purposes: To determine if there has been overflow, whether the result is zero, etc.
- Stored in a special "EFLAGS" register within processor



Condition flags

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- Used for many purposes: To determine if there has been overflow, whether the result is zero, etc.
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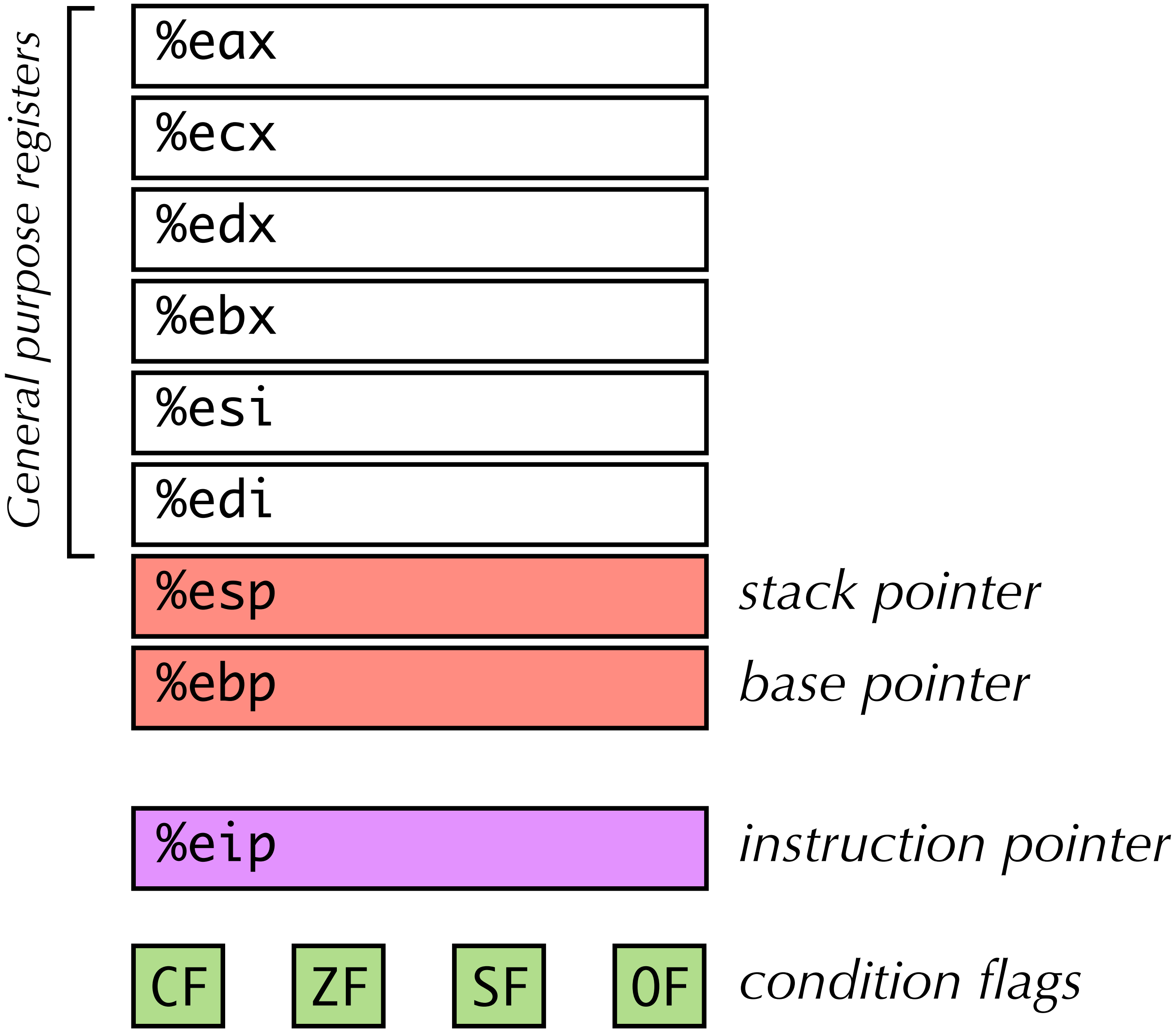


Some x86 condition flags

- CF: Carry Flag
  - The most recent operation generated a carry bit out of the MSB
  - Indicates an overflow when performing unsigned integer arithmetic
- OF: Overflow flag
  - The most recent operation caused a 2‘s complement overflow (either positive or negative)
  - Indicates an overflow when performing signed integer arithmetic
- SF: Sign flag
  - The most recent operation yielded a negative value
  - Equal to MSB of result; which indicates the sign of a two's complement integer
  - 0 means result was positive, 1 means negative
- ZF: Zero flag
  - The most recent operation yielded zero
- Condition flags are set **implicitly** by every arithmetic operation.
- Can also be set **explicitly** by comparison instructions.

Comparison instructions

- `cmpl` *src1, src2*
  - Compares value of *src1* and *src2*
  - *src1*, *src2* can be registers, immediate values, or contents of memory.
  - Computes (*src2* – *src1*) without modifying either operand
    - like "`subl` *src1, src2*" without changing *src2*
  - But, sets the condition flags based on the result of the subtraction.
- `testl` *src1, src2*
  - Like `cmpl`, but computes (*src1* & *src2*) instead of subtracting them.

Condition flags example

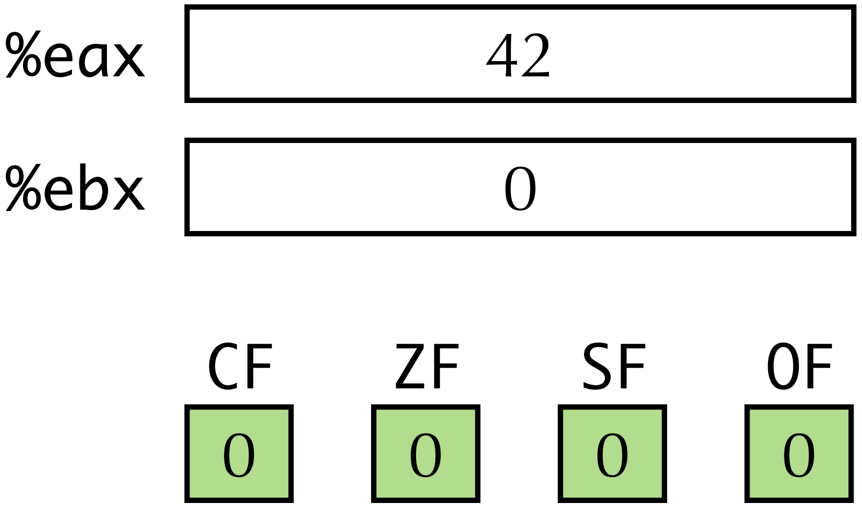
```
movl $42, %eax
movl $6, %ebx
mull $7, %ebx
cmpl %eax, %ebx
```

%eax	0
%ebx	0

CF	ZF	SF	OF
0	0	0	0

Condition flags example

```
movl $42, %eax
movl $6, %ebx
mull $7, %ebx
cmpl %eax, %ebx
```



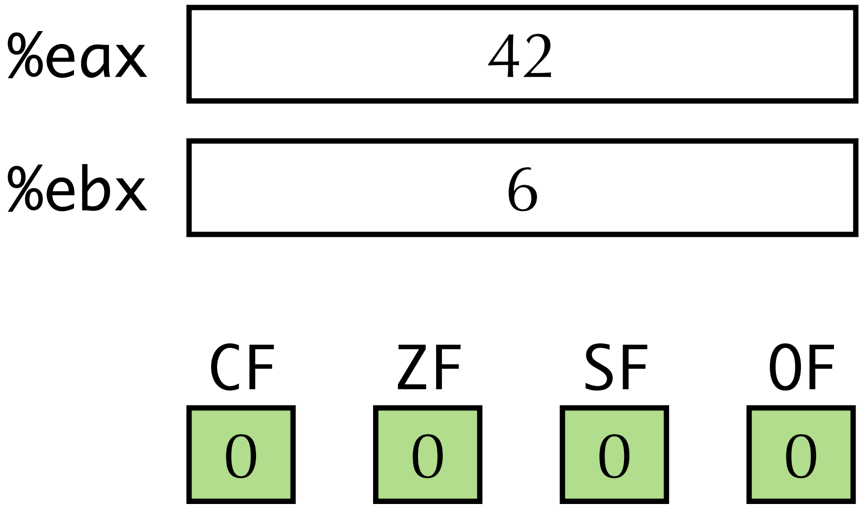
%eax 42

%ebx 0

CF	ZF	SF	OF
0	0	0	0

Condition flags example

```
movl $42, %eax
movl $6, %ebx
mull $7, %ebx
cmpl %eax, %ebx
```



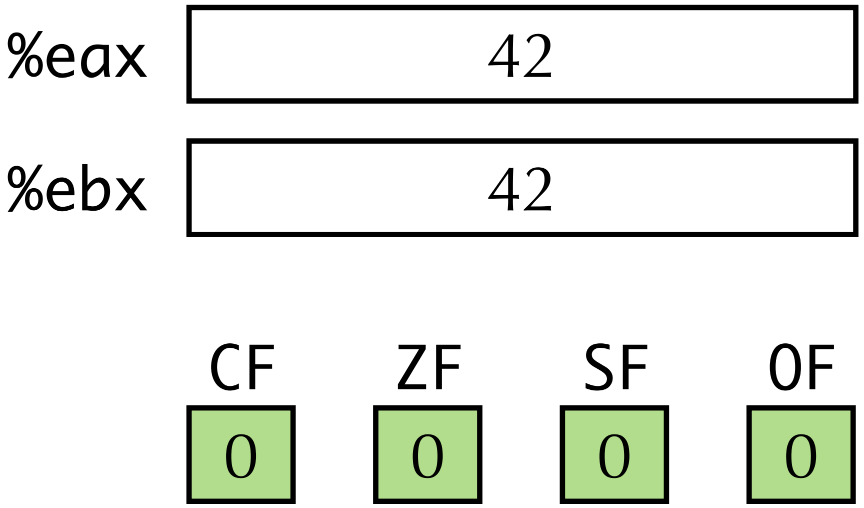
%eax 42

%ebx 6

CF	ZF	SF	OF
0	0	0	0

Condition flags example

```
movl $42, %eax
movl $6, %ebx
mull $7, %ebx
cmpl %eax, %ebx
```



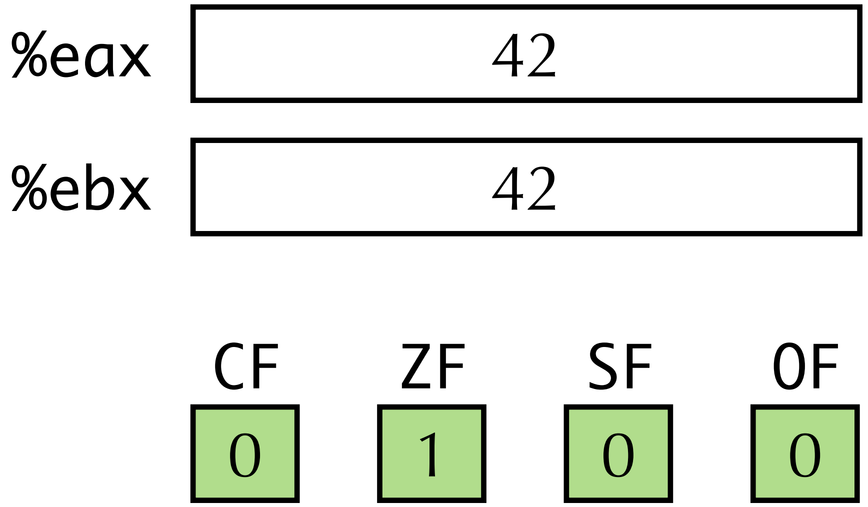
%eax 42

%ebx 42

CF	ZF	SF	OF
0	0	0	0

Condition flags example

```
movl $42, %eax
movl $6, %ebx
mull $7, %ebx
cmpl %eax, %ebx
```



%eax 42

%ebx 42

CF	ZF	SF	OF
0	1	0	0

- Recall: `cmpl %eax, %ebx` computes `%ebx` – `%eax` and sets the flags
  - `%ebx` is not modified by the `cmpl` instruction (unlike `subl`)
- Condition flags are set after every instruction!
  - See x86 manual or textbook for details of which flags are affected by each instruction
  - In this example, the flags were only changed by the `cmpl` instruction

Another example

- Consider `cmpl %eax, %ebx`
  - computes %ebx – %eax
- How do we determine the relationship between %ebx and %eax based on the condition flags?
- Suppose `%ebx` is ***equal to*** `%eax`
  - Then %ebx – %eax is zero, and so ZF = 1

Another example

- Suppose %ebx is ***greater than*** %eax
  - Since %ebx > %eax result cannot be zero ⇒ ZF = 0
  - Suppose no overflow occurs (i.e., OF = 0)
    - %ebx > %eax if and only if result is positive
    - ⇒ SF = 0 (indicating positive)
  - Suppose overflow occurs (i.e., OF =1)
    - %ebx > %eax if and only if result is negative
    - ⇒ SF = 1 (indicating negative)
- %ebx is greater than %eax
  if and only if ZF=0, and SF equal to OF
  if and only if ~(SF ^ OF) & ~ZF

Reading condition flags

- Operation `setX` *dest* sets single byte based on condition code

SetX	Synonyms	Condition	Description
`sete`	`setz`	dest = ZF	Equal/zero
`setne`	`setnz`	dest = ~ZF	Not equal/non-zero
`sets`		dest = SF	Negative
`setns`		dest = ~SF	Not negative
`setg`	`setnle`	dest = ~(SF ^ OF) & ~ZF	Greater than (signed >)
`setge`	`netnl`	dest = ~(SF ^ OF)	Greater than or equal (signed ≥)
`setl`	`setnge`	dest = SF ^ OF	Less than (signed <)
`setle`	`setng`	dest = (SF ^ OF) | ZF	Less than or equal (signed ≤)
`seta`	`setnbe`	dest = ~CF & ~ZF	Above (unsigned >)
`setb`	`setnae`	dest = CF	Below (unsigned <)

Conditional jumps

- Operation `jX` *label* jumps to label if condition *X* is satisfied

Instruction	Synonyms	Jump condition	Description
`jmp`		1	
`je`	`jz`	ZF	Equal/zero
`jne`	`jnz`	~ZF	Not equal/non-zero
`js`		SF	Negative
`jns`		~SF	Not negative
`jg`	`jnle`	~(SF ^ OF) & ~ZF	Greater than (signed >)
`jge`	`jnl`	~(SF ^ OF)	Greater than or equal (signed ≥)
`jl`	`jnge`	SF ^ OF	Less than (signed <)
`jle`	`jng`	(SF ^ OF) | ZF	Less than or equal (signed ≤)
`ja`	`jnbe`	~CF & ~ZF	Above (unsigned >)
`jb`	`jnae`	CF	Below (unsigned <)

Condition flags example

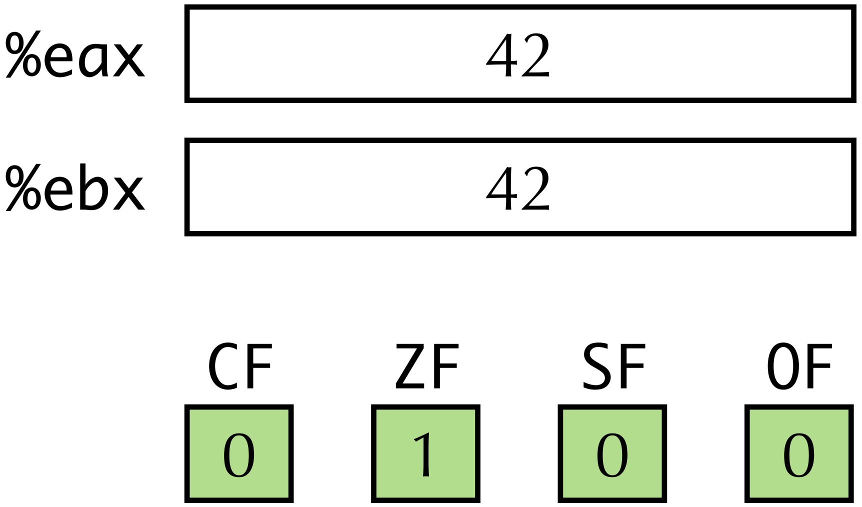
```
movl $42, %eax
movl $6, %ebx
mull $7, %ebx
cmpl %eax, %ebx
```

%eax	42
%ebx	42

CF	ZF	SF	OF
0	1	0	0

Condition flags example

```
movl $42, %eax
movl $6, %ebx
mull $7, %ebx
cmpl %eax, %ebx
jz   0x80459845
movl $33, %eax

…
```



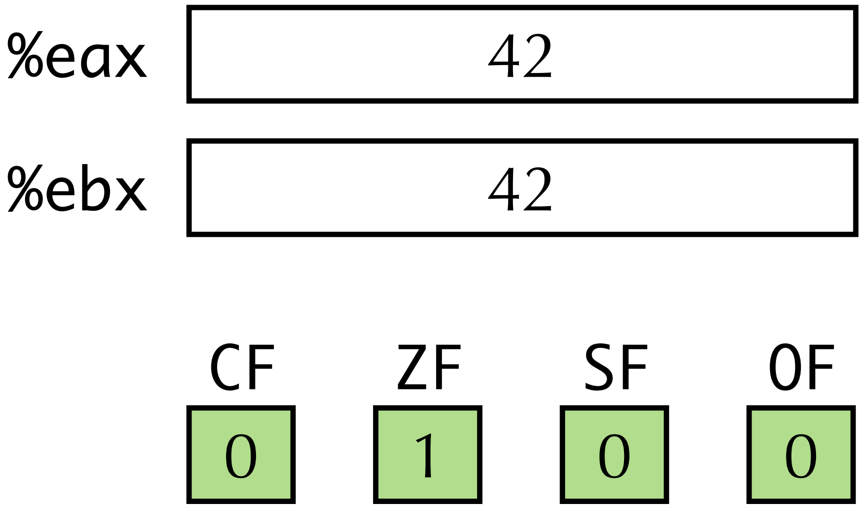
%eax 42

%ebx 42

CF	ZF	SF	OF
0	1	0	0

Condition flags example

```
movl $42, %eax
movl $6, %ebx
mull $7, %ebx
cmpl %eax, %ebx
jz   0x80459845
movl $33, %eax

…
```



- Instruction `jz 0x80459845` will set instruction pointer to `0x80459845` if ZF=1.
- Otherwise, execution continues after the instruction
  - i.e., with `movl $33, %eax`

More examples

- What do the following examples do?

```
movl $0xffffffff, %eax
addl $0x1, %eax
jz 0x08045900
...
```

Jump if -1 + 1 is zero

```
movl $6, %eax
subl $10, %eax
jl 0x08045900
...
```

Jump if 6 is less than 10

Given `cmpl` *src*, *dest*, what is the relationship of *dest* to *src*?

```
movl $0x42, %eax
movl $0x77, %ebx
subl %ebx, %eax
js 0x08045900
...
```

Jump if 0x42 – 0x77 is negative

Example: absdiff

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

```
absdiff:
    pushl   %ebp
    movl    %esp, %ebp
    movl    8(%ebp), %edx
    movl    12(%ebp), %eax
    cmpl    %eax, %edx
    jle     .L7
    subl    %eax, %edx
    movl    %edx, %eax
.L8:
    leave
    ret
.L7:
    subl    %edx, %eax
    jmp     .L8
```

Set up

Body 1

Finish

Body 2

Example: absdiff

```
int absdiff_goto(int x, int y)
{
    int result;
    if (x <= y) goto Else;
    result = x-y;
  Exit:
    return result;
  Else:
    result = y-x;
    goto Exit;
}
```

- C allows “goto” as a control flow mechanism
  - Closer to machine-level programming
  - Generally considered bad programming style

```
absdiff:
    pushl   %ebp
    movl    %esp, %ebp
    movl    8(%ebp), %edx
    movl    12(%ebp), %eax
    cmpl    %eax, %edx
    jle     .L7
    subl    %eax, %edx
    movl    %edx, %eax
.L8:
    leave
    ret
.L7:
    subl    %edx, %eax
    jmp     .L8
```

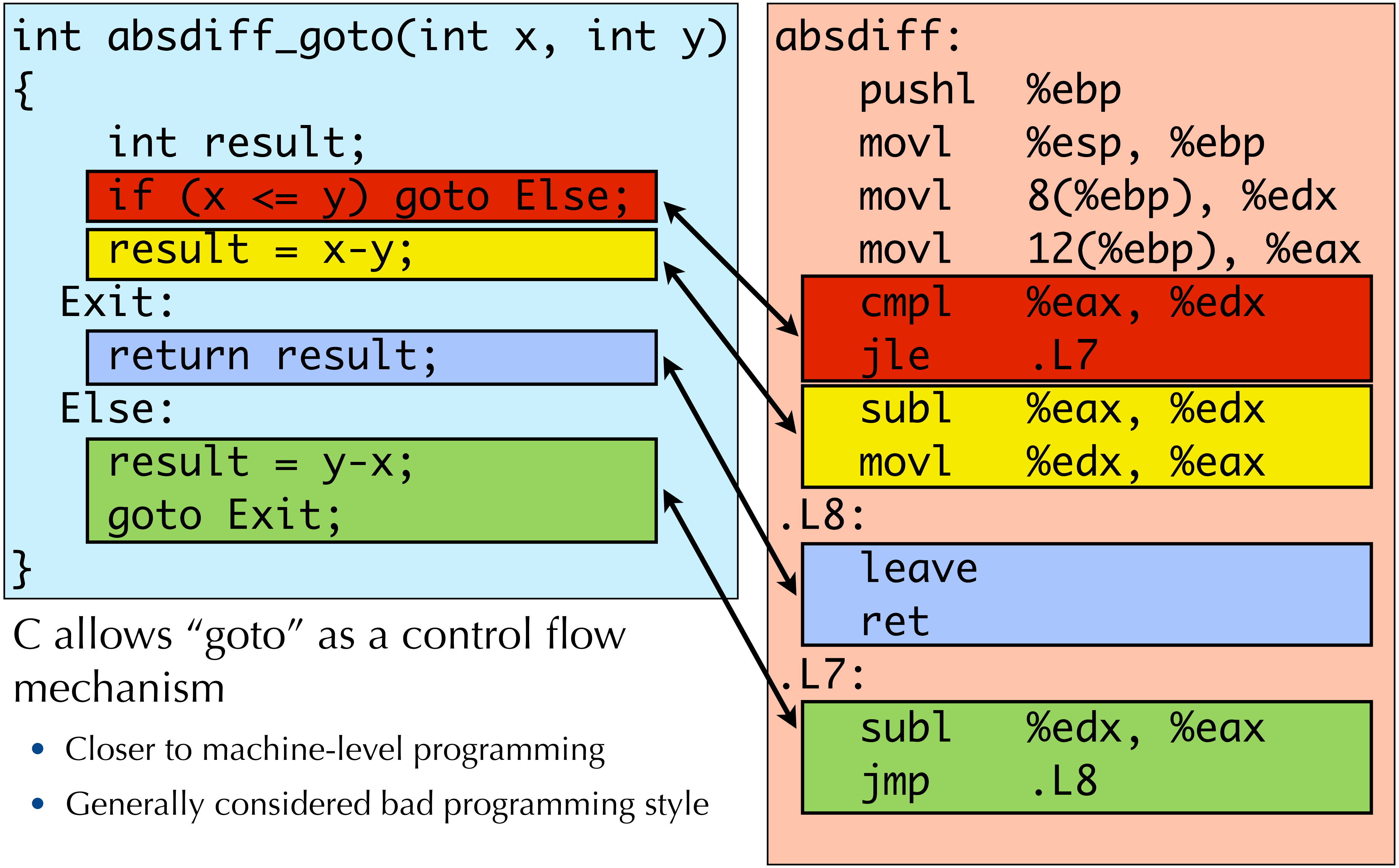
Set up

Body 1

Finish

Body 2

Example: absdiff



```
int absdiff_goto(int x, int y)
{
    int result;
    if (x <= y) goto Else;
    result = x-y;
  Exit:
    return result;
  Else:
    result = y-x;
    goto Exit;
}
```

```
absdiff:
    pushl   %ebp
    movl    %esp, %ebp
    movl    8(%ebp), %edx
    movl    12(%ebp), %eax
    cmpl    %eax, %edx
    jle     .L7
    subl    %eax, %edx
    movl    %edx, %eax
.L8:
    leave
    ret
.L7:
    subl    %edx, %eax
    jmp     .L8
```

%edx = x
%eax = y

- C allows “goto” as a control flow mechanism
    - Closer to machine-level programming
    - Generally considered bad programming style

Today

- Data types
  - Register names
- Control flow
  - jmp
  - Condition flags
  - Loops
  - Switch statements

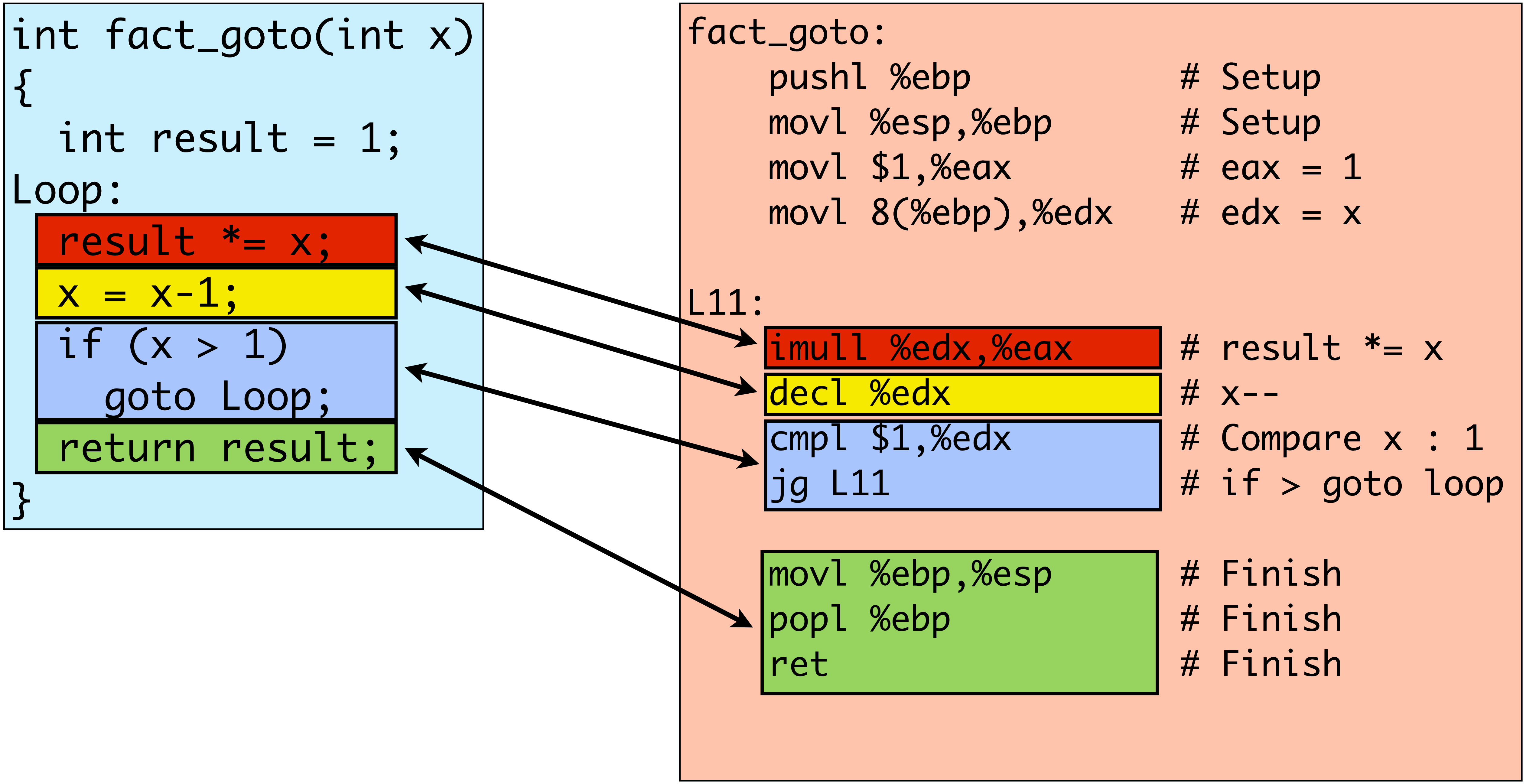
Implementing loops

```
int fact_do(int x)
{
  int result = 1;
  do {
    result *= x;
    x = x-1;
  } while (x > 1);

  return result;
}
```

```
int fact_goto(int x)
{
  int result = 1;
Loop:
  result *= x;
  x = x-1;
  if (x > 1)
    goto Loop;
  return result;
}
```

- Two equivalent programs to compute factorial
- Goto version uses backwards branch to continue loop
  - Only takes branch if `while` condition (`x > 1`) is true

Do-while loop compilation



```
int fact_goto(int x)
{
  int result = 1;
Loop:
  result *= x;
  x = x-1;
  if (x > 1)
    goto Loop;
  return result;
}
```

```
fact_goto:
    pushl %ebp            # Setup
    movl %esp,%ebp        # Setup
    movl $1,%eax          # eax = 1
    movl 8(%ebp),%edx     # edx = x

L11:
    imull %edx,%eax       # result *= x
    decl %edx             # x--
    cmpl $1,%edx          # Compare x : 1
    jg L11                # if > goto loop

    movl %ebp,%esp        # Finish
    popl %ebp             # Finish
    ret                   # Finish
```

While loops version 1

C code

```
int fact_while(int x)
{
  int result = 1;
  while (x > 1) {


    result *= x;
    x = x-1;
  };

  return result;
}
```

Goto version 1

```
int fact_while_goto(int x)
{
  int result = 1;
Loop:
  if (!(x > 1))
    goto Done;
  result *= x;
  x = x-1;
  goto Loop;
Done:
  return result;
}
```

- How is this different from the do-while version?

While loops version 2

C code

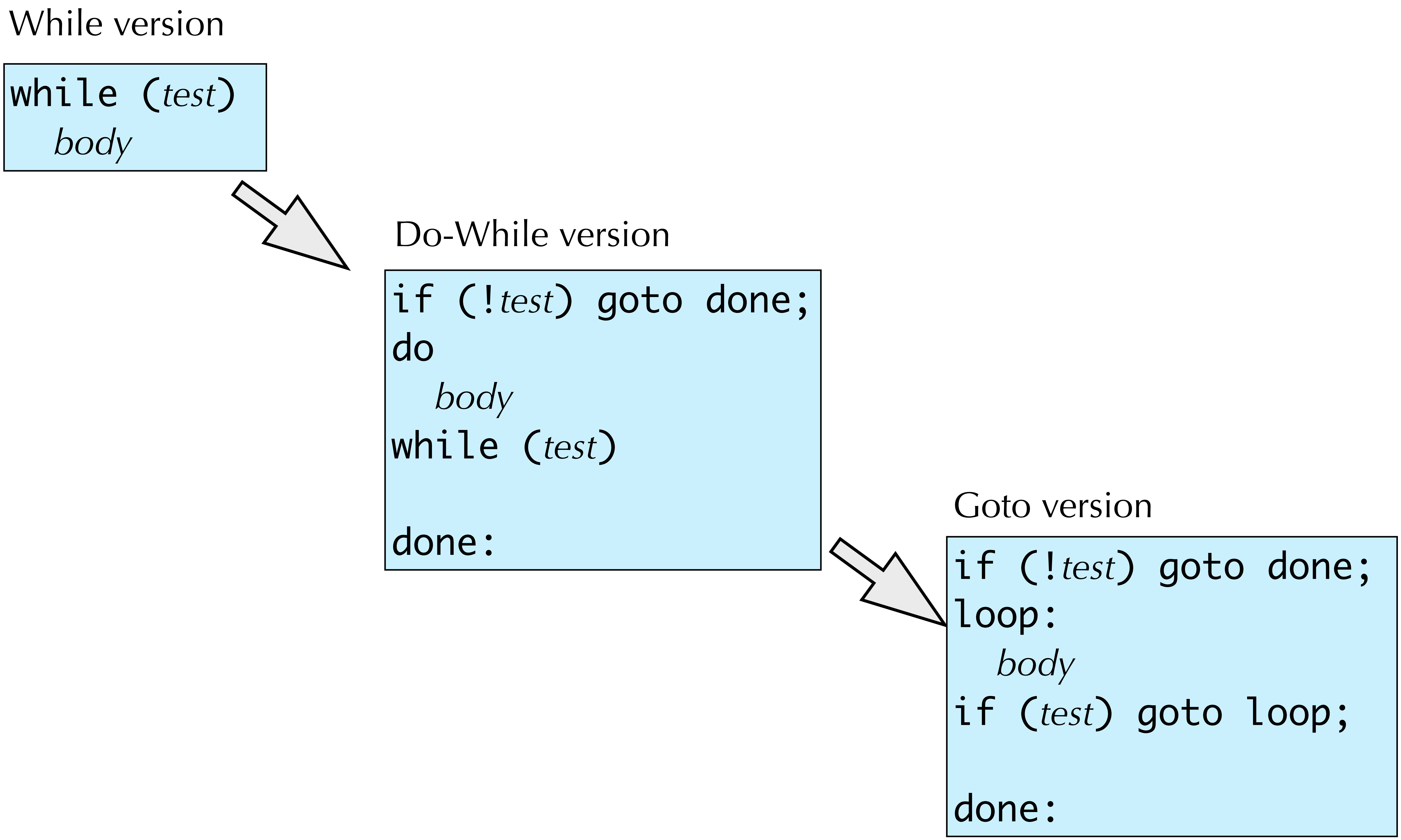
```
int fact_while(int x)
{
  int result = 1;
  while (x > 1) {


    result *= x;
    x = x-1;
  };

  return result;
}
```

Goto version 2

```
int fact_while_goto2(int x)
{
  int result = 1;
  if (!(x > 1))
    goto Done;
Loop:
  result *= x;
  x = x-1;
  if (x > 1)
    goto Loop;
Done:
  return result;
}
```

- Historically used by GCC
- Uses same inner loop as do-while version
- Guards loop entry with extra test

While loops version 2



While version

```
while (test)
   body
```

Do-While version

```
if (!test) goto done;
do
   body
while (test)

done:
```

Goto version

```
if (!test) goto done;
loop:
   body
if (test) goto loop;

done:
```

While loops version 3

C code

```
int fact_while(int x)
{
  int result = 1;
  while (x > 1) {


    result *= x;
    x = x-1;
  };

  return result;
}
```

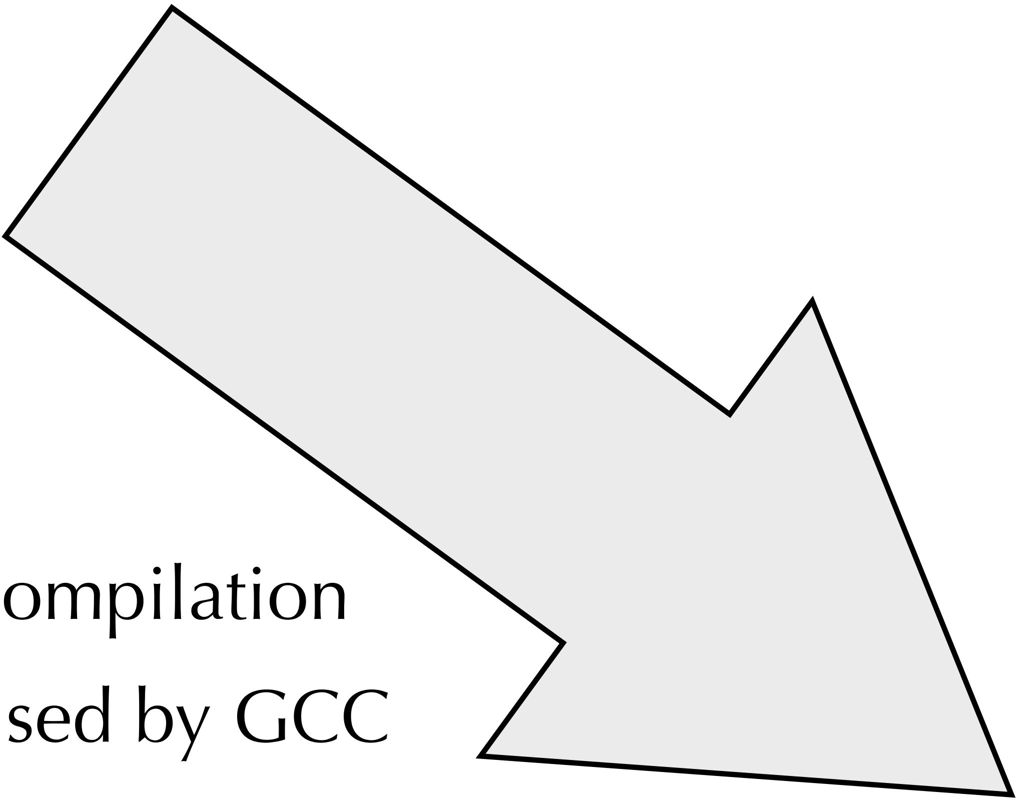
Goto version 3

```
int fact_while_goto3(int x)
{
  int result = 1;
  goto middle;
loop:
  result *= x;
  x = x-1;
middle:
  if (x > 1)
    goto loop;
  return result;
}
```

While loops version 3

While version

```
while (test)
    body
```

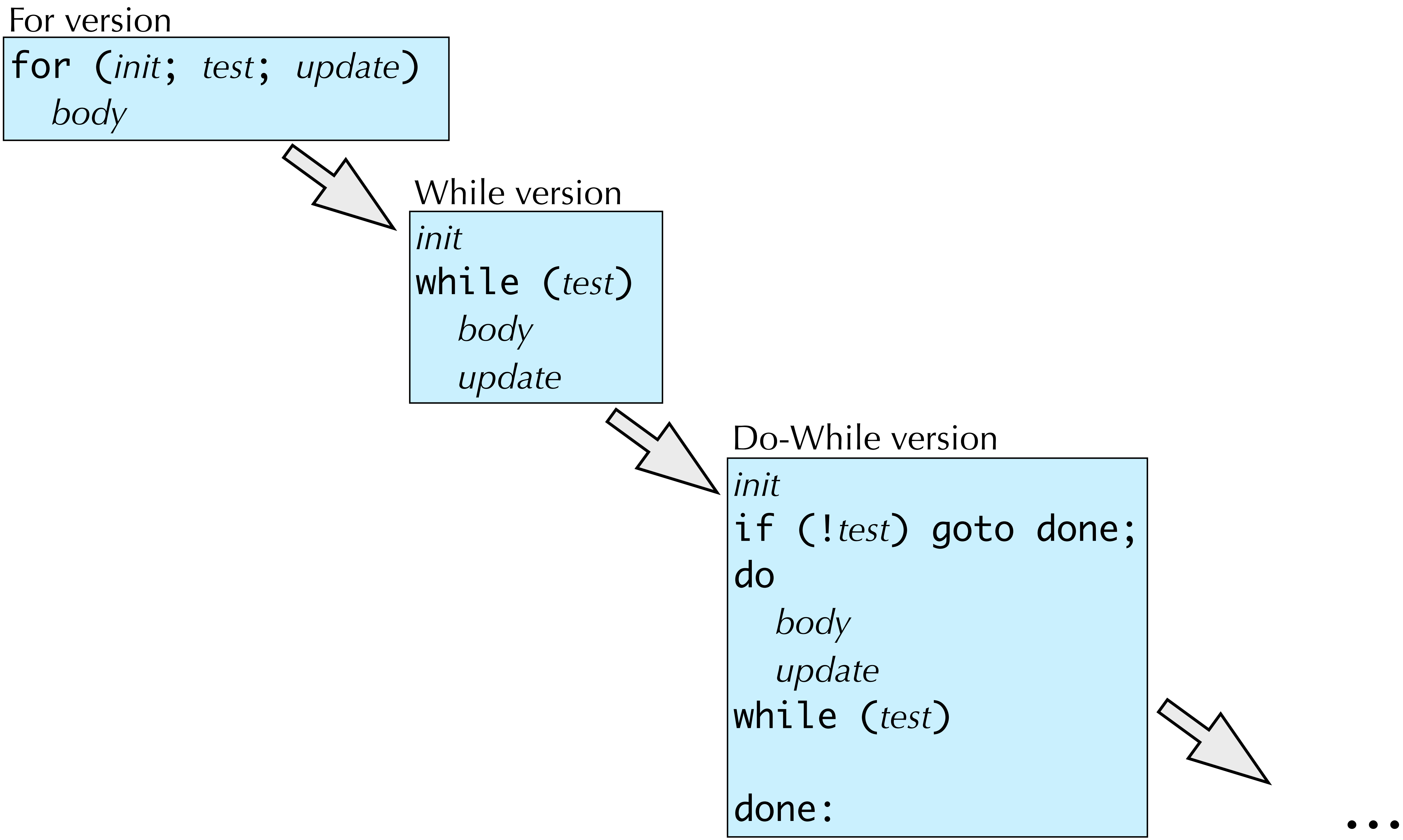


- “Jump to middle” compilation
- Recent technique used by GCC
- Avoids duplicating test code
- Unconditional goto incurs no performance penalty

Goto version

```
goto middle;
loop:
   body
middle:
   if (test) goto loop;

done:
```

Compiling for loops



For version

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

While version

```
init
while (test)
   body
   update
```

Do-While version

```
init
if (!test) goto done;
do
   body
   update
while (test)

done:
```

…

Switch statements

- Switch statements can be complex…
  - Many cases to consider
  - Can have “fall through”
    - No break at end of case 2
  - Can have missing cases
  - Can have `default` case
- How to compile?
  - Series of conditionals?
    - Works, but a lot of code, and expensive
  - **Jump table**
    - List of jump targets indexed by x
    - Less code, and fast!

```
int switchexample(int x) {
    int y;
    switch(x) {
      case 1:
        y = x; break;
      case 2:
        y = 2*x;
        /* Fall through! */
      case 3:
        y = 3*x; break;
      /* No case 4! */
      case 5:
         y = 5*x; break;
      default:
         y = x; break;
    }
    return y;
}
```

Jump table structure

Switch code

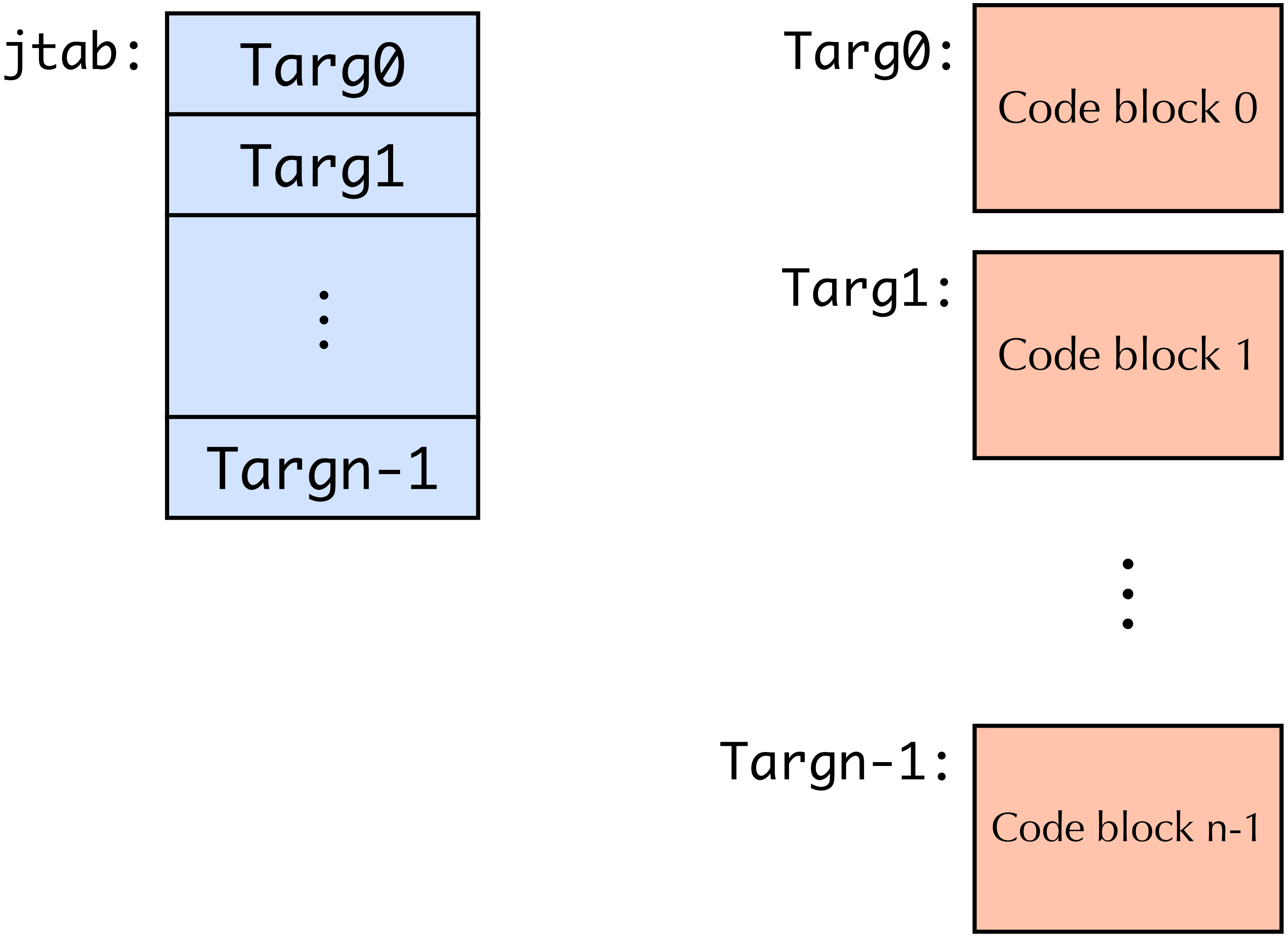
```
switch(x) {
  case val_0:
    Block_0
  case val_1:
    Block_1
  ...
  case val_n-1:
    Block_n-1
}
```

Approximate translation

```
target = jtab[x];
goto *target;
```

Jump table

Jump targets



jtab:

Targ0

Targ1

⋮

Targn-1

Targ0: Code block 0

Targ1: Code block 1

⋮

Targn-1: Code block n-1

Using a jump table

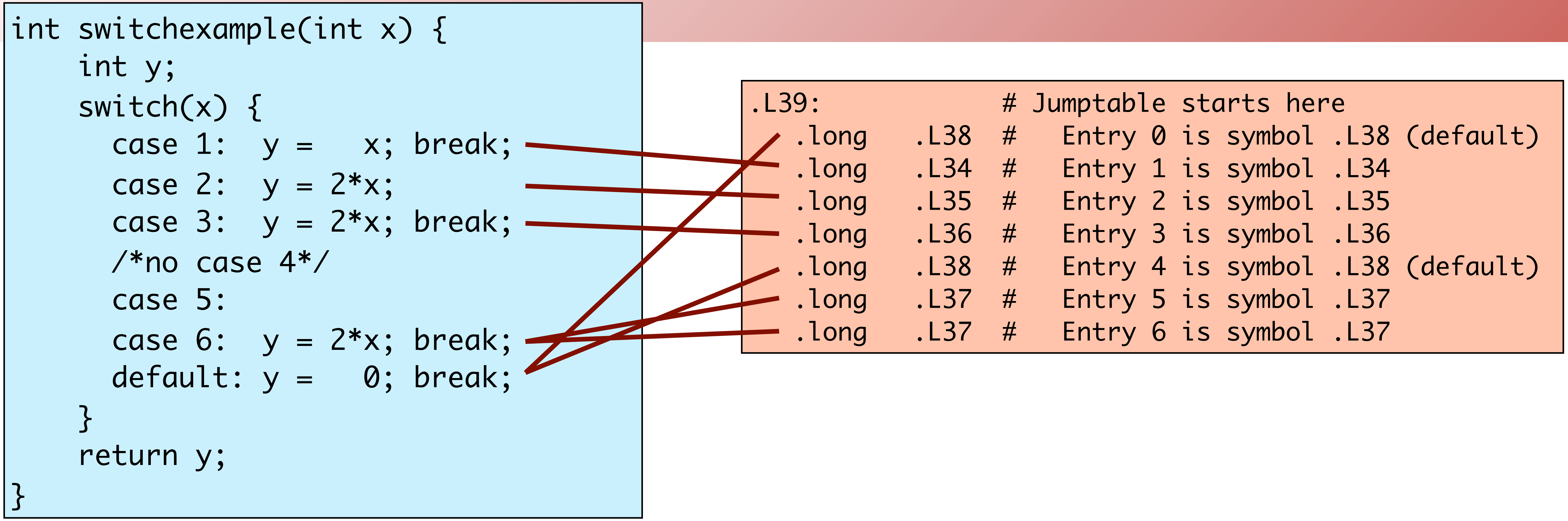
```
int switchexample(int x) {
    int y;
    switch(x) {
      case 1:   y =   x; break;
      case 2:   y = 2*x;
      case 3:   y = 2*x; break;
      /*no case 4*/
      case 5:
      case 6:   y = 2*x; break;
      default: y =   0; break;
    }
    return y;
}
```

`jmp  *`*src* is an **indirect jump**. Always jumps to the address that *src* evaluates to.

Why multiply x by 4?

```
pushl   %ebp                # Setup
movl    %esp, %ebp
subl    $16, %esp
cmpl    $6, 8(%ebp)         # Check if 'x' is > 6
ja      .L38                # If so, jump to .L38 (default case)
movl    8(%ebp), %eax       # %eax = x
sall    $2, %eax            # Shift left by 2 (multiply by 4)
movl    .L39(%eax), %eax    # Move jumptable[x] to eax
jmp     *%eax               # Jump to this address
```

Using a jump table

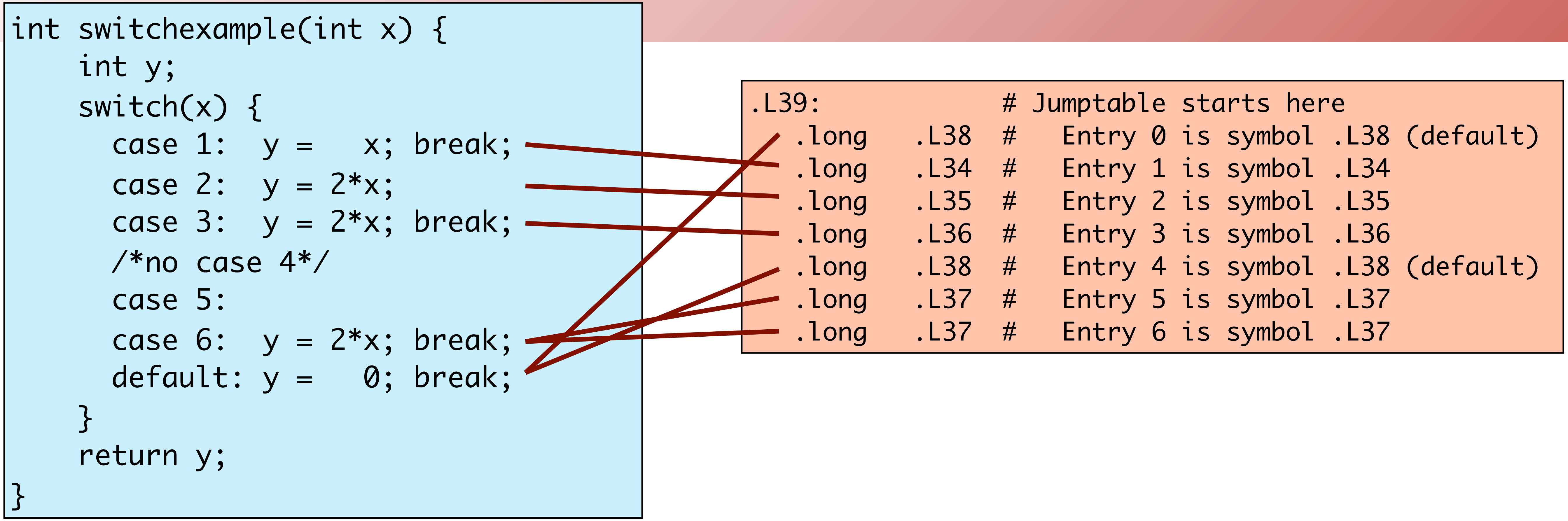


```
int switchexample(int x) {
    int y;
    switch(x) {
      case 1:  y =   x; break;
      case 2:  y = 2*x;
      case 3:  y = 2*x; break;
      /*no case 4*/
      case 5:
      case 6:  y = 2*x; break;
      default: y =   0; break;
    }
    return y;
}
```

```
.L39:               # Jumptable starts here
   .long    .L38  #   Entry 0 is symbol .L38 (default)
   .long    .L34  #   Entry 1 is symbol .L34
   .long    .L35  #   Entry 2 is symbol .L35
   .long    .L36  #   Entry 3 is symbol .L36
   .long    .L38  #   Entry 4 is symbol .L38 (default)
   .long    .L37  #   Entry 5 is symbol .L37
   .long    .L37  #   Entry 6 is symbol .L37
```

```
   pushl   %ebp                # Setup
   movl    %esp, %ebp
   subl    $16, %esp
   cmpl    $6, 8(%ebp)         # Check if 'x' is > 6
   ja      .L38                # If so, jump to .L38 (default case)
   movl    8(%ebp), %eax       # %eax = x
   sall    $2, %eax            # Shift left by 2 (multiply by 4)
   movl    .L39(%eax), %eax    # Move jumptable[x] to eax
   jmp     *%eax               # Jump to this address
```

Using a jump table



```
int switchexample(int x) {
    int y;
    switch(x) {
      case 1:  y =   x; break;
      case 2:  y = 2*x;
      case 3:  y = 2*x; break;
      /*no case 4*/
      case 5:
      case 6:  y = 2*x; break;
      default: y =   0; break;
    }
    return y;
}
```

```
.L39:               # Jumptable starts here
   .long     .L38   #    Entry 0 is symbol .L38 (default)
   .long     .L34   #    Entry 1 is symbol .L34
   .long     .L35   #    Entry 2 is symbol .L35
   .long     .L36   #    Entry 3 is symbol .L36
   .long     .L38   #    Entry 4 is symbol .L38 (default)
   .long     .L37   #    Entry 5 is symbol .L37
   .long     .L37   #    Entry 6 is symbol .L37
```

```
.L34:                              # Case for Entry 1 (x == 1)
   movl     8(%ebp), %eax          # %eax = x
   movl     %eax, -4(%ebp)         # y = %eax
   jmp      .L40                   # Jump out of 'switch'
```

Sparse switch statement

```
/* Return x/111 if x is multiple
   && <= 999.  -1 otherwise */
int div111(int x)
{
  switch(x) {
  case   0: return 0;
  case 111: return 1;
  case 222: return 2;
  case 333: return 3;
  case 444: return 4;
  case 555: return 5;
  case 666: return 6;
  case 777: return 7;
  case 888: return 8;
  case 999: return 9;
  default: return -1;
  }
}
```

- Jump tables work fine when...
  - Small number of jump targets
  - Mostly contiguous (few missing cases)
- Inefficient to use a jump table if the switch space is "sparse"
  - Example would require a jump table of 1000 entries, 990 of which all point to the same "default" case.
- Could use simple translation to multiple conditional branches
  - No more than 9 tests would be required

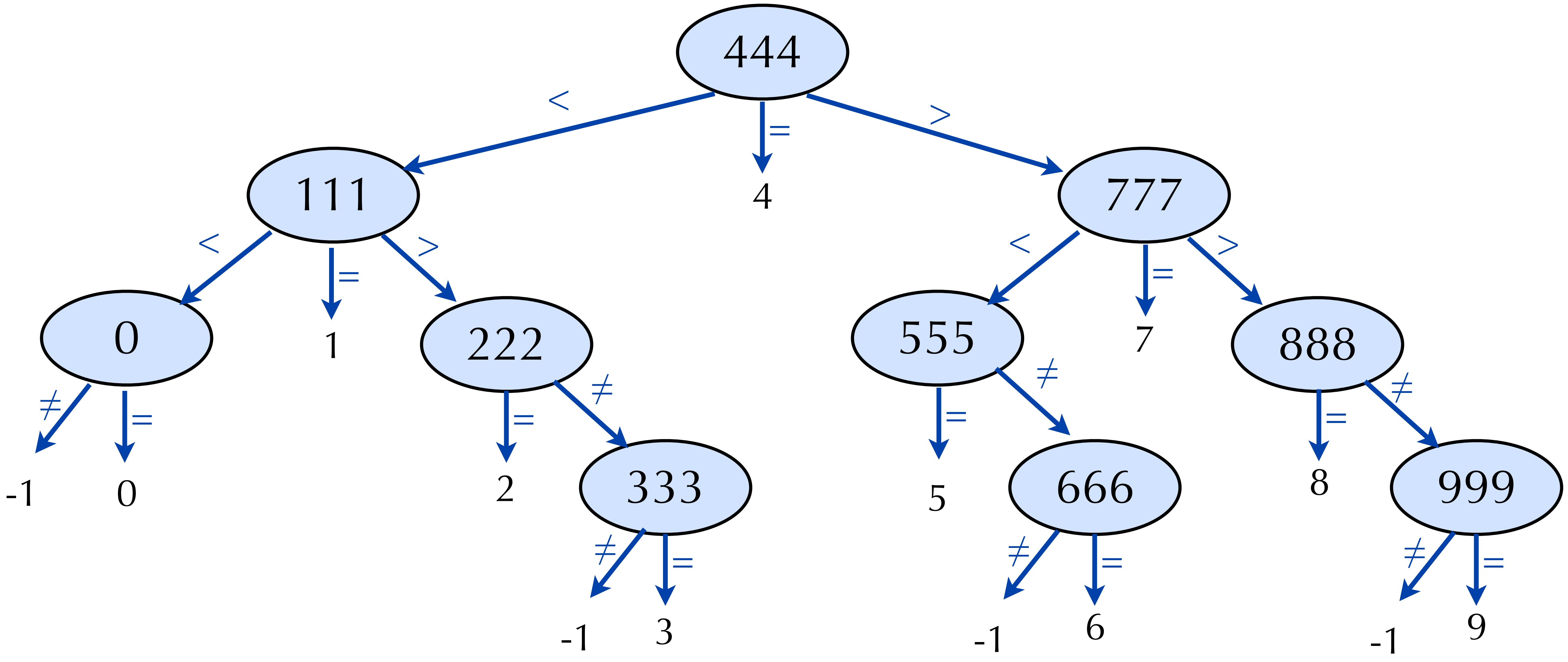
Better approach: branch tree

- Compare x to possible case values
- Jump to different target depending on outcome of each test

```
movl 8(%ebp),%eax      # get x
cmpl $444,%eax         # Compare to 444
je .L8
jg .L16
cmpl $111,%eax         # Compare to 111
je .L5
jg .L17
testl %eax,%eax        # Compare to 0
je .L4
jmp .L14
...
```

```
        ...
.L5:
        movl $1,%eax
        jmp .L19
.L6:
        movl $2,%eax
        jmp .L19
.L7:
        movl $3,%eax
        jmp .L19
.L8:
        movl $4,%eax
        jmp .L19
        ...
```

Branch tree structure



- Organizes cases as binary tree
- Logarithmic performance to find right case
  - Better than linear!

Next lecture

- Procedures
  - Implementing procedure calls
  - Using the stack
  - Storing and accessing local variables
  - Saving and restoring registers
  - Recursive procedures
- x86_64