assembly / ISAs

Changelog

Changes made in this version not seen in first lecture:

- 5 September 2017: slide 3: lea destination should have been rax, not rsp
- 5 September 2017: slide 10: signed result w/o truncation is $-2^{64} + 1$, not $-2^{64} - 1$
- 5 September 2017: slide 12: changed version B and C to use jge
- 5 September 2017: slide 14: fix bugs in third version: compare to 10 (not 9), end with %rbx set
- 8 September 2017: slide 11: use %rax, not %rbx

last time

AT&T syntax

```
movq (%rax,%rcx,4), %rbx =
mov RBX, QWORD PTR [RAX + RCX * 4]
```

C to assembly

- strategy — write with gotos first

condition codes

- set by arithmetic instructions + cmp or test
- used by conditional jump
- names based on subtraction (cmp)
- result = 0: equal; result positive: greater; result negative: less than
- ...more detail today

the quiz: ASM

```
movq %rsp, %rax
    # %rax ← %rsp = X
pushq %rax
    # %rsp ← %rsp - 8 = X - 8
    # memory[%rsp] = %rax
subq %rsp, %rax
    # %rax ← %rax - %rsp = X - (X - 8) = 8
leaq (%rax, %rax, 2), %rax
    # %rax ← %rax + %rax * 2 = 8 + 8 * 2 = 24
```

upcoming labs

this week: pointer-heavy code in C

use tool to find malloc/free-related mistakes

fix broken circular doubly-linked list implementation

next week: in-lab quiz

implement library functions strlen/strsep

no notes

last time

AT&T syntax

```
movq (%rax,%rcx,4), %rbx =
mov RBX, QWORD PTR [RAX + RCX * 4]
```

C to assembly

- strategy — write with gotos first

condition codes

- set by arithmetic instructions + cmp or test
- used by conditional jump
- names based on subtraction (cmp)
- result = 0: equal; result positive: greater; result negative: less than
- ...more detail today

condition codes and jumps

jg, **jle**, etc

named based on interpreting result of subtraction

zero: equal

negative: less than

positive: greater than

condition codes: closer look

x86 condition codes:

- `ZF` ("zero flag") — was result zero? (sub/cmp: equal)
- `SF` ("sign flag") — was result negative? (sub/cmp: less)
- `CF` ("carry flag") — did computation overflow (as unsigned)?
- `OF` ("overflow flag") — did computation overflow (as signed)?
- (and one more we won't talk about)

GDB: part of "eflags" register

set by cmp, test, arithmetic

closer look: condition codes (1)

```
  movq $-10, %rax
  movq $20, %rbx
  cmpq %rax, %rbx
// result = %rbx - %rax = 30
```

as signed: $20 - (-10) = 30$

as unsigned: $20 - (2^{64} - 10) = \cancel{-2^{64} - 30}\ 30$ (overflow!)

$\texttt{ZF} = 0$ (false) not zero rax and rbx not equal

closer look: condition codes (1)

```
  movq $-10, %rax
  movq $20, %rbx
  cmpq %rax, %rbx
// result = %rbx - %rax = 30
```

as signed: $20 - (-10) = 30$

as unsigned: $20 - (2^{64} - 10) = \cancel{-2^{64} - 30}\ 30$ (overflow!)

$\texttt{ZF} = 0$ (false) not zero rax and rbx not equal

closer look: condition codes (1)

```
  movq $-10, %rax
  movq $20, %rbx
  cmpq %rax, %rbx
// result = %rbx - %rax = 30
```

as signed: $20 - (-10) = 30$

as unsigned: $20 - (2^{64} - 10) = \cancel{-2^{64}} \cancel{- 30}\ 30$ (overflow!)

ZF $= 0$ (false)	not zero	rax and rbx not equal
SF $= 0$ (false)	not negative	rax $<=$ rbx

closer look: condition codes (1)

```
  movq $-10, %rax
  movq $20, %rbx
  cmpq %rax, %rbx
// result = %rbx - %rax = 30
```

as signed: $20 - (-10) = 30$

as unsigned: $20 - (2^{64} - 10) = \cancel{-2^{64} + 30}$ 30 (overflow!)

ZF $= 0$ (false)	not zero	rax and rbx not equal
SF $= 0$ (false)	not negative	rax <= rbx
OF $= 0$ (false)	no overflow as signed	correct for signed

closer look: condition codes (1)

```
  movq $-10, %rax
  movq $20, %rbx
  cmpq %rax, %rbx
// result = %rbx - %rax = 30
```

as signed: $20 - (-10) = 30$

as unsigned: $20 - (2^{64} - 10) = \cancel{-2^{64} - 30}\ 30$ (overflow!)

ZF $= 0$ (false)	not zero	rax and rbx not equal
SF $= 0$ (false)	not negative	rax <= rbx
OF $= 0$ (false)	no overflow as signed	correct for signed
CF $= 1$ (true)	overflow as unsigned	incorrect for unsigned

exercise: condition codes (2)

```
  // 2^63 - 1
  movq $0x7FFFFFFFFFFFFFFF, %rax
  // 2^63 (unsigned); -2**63 (signed)
  movq $0x8000000000000000, %rbx
  cmpq %rax, %rbx
// result = %rbx - %rax
```

ZF = ?

SF = ?

OF = ?

CF = ?

closer look: condition codes (2)

```
  // 2**63 - 1
  movq $0x7FFFFFFFFFFFFFFF, %rax
  // 2**63 (unsigned); -2**63 (signed)
  movq $0x8000000000000000, %rbx
  cmpq %rax, %rbx
// result = %rbx - %rax
```

as signed: $-2^{63} - \left(2^{63} - 1\right) = \cancel{-2^{64} + 1}\ 1$ (overflow)

as unsigned: $2^{63} - \left(2^{63} - 1\right) = 1$

$\mathrm{ZF} = 0$ (false) not zero rax and rbx not equal

closer look: condition codes (2)

```
  // 2**63 - 1
  movq $0x7FFFFFFFFFFFFFFF, %rax
  // 2**63 (unsigned); -2**63 (signed)
  movq $0x8000000000000000, %rbx
  cmpq %rax, %rbx
// result = %rbx - %rax
```

as signed: $-2^{63} - \left(2^{63} - 1\right) = \cancel{-2^{64} + 1}\ 1$ (overflow)

as unsigned: $2^{63} - \left(2^{63} - 1\right) = 1$

$\mathrm{ZF} = 0$ (false) not zero rax and rbx not equal

closer look: condition codes (2)

```
  // 2**63 - 1
  movq $0x7FFFFFFFFFFFFFFF, %rax
  // 2**63 (unsigned); -2**63 (signed)
  movq $0x8000000000000000, %rbx
  cmpq %rax, %rbx
// result = %rbx - %rax
```

as signed: $-2^{63} - \left(2^{63} - 1\right) = \cancel{-2^{64} + 1}\ 1$ (overflow)

as unsigned: $2^{63} - \left(2^{63} - 1\right) = 1$

ZF $= 0$ (false)	not zero	rax and rbx not equal
SF $= 0$ (false)	not negative	rax $<=$ rbx (if correct)

closer look: condition codes (2)

```
  // 2**63 - 1
  movq $0x7FFFFFFFFFFFFFFF, %rax
  // 2**63 (unsigned); -2**63 (signed)
  movq $0x8000000000000000, %rbx
  cmpq %rax, %rbx
// result = %rbx - %rax
```

as signed: $-2^{63} - \left(2^{63} - 1\right) = \cancel{-2^{64} + 1}\ 1$ (overflow)

as unsigned: $2^{63} - \left(2^{63} - 1\right) = 1$

ZF $= 0$ (false)	not zero	rax and rbx not equal
SF $= 0$ (false)	not negative	rax <= rbx (if correct)
OF $= 1$ (true)	overflow as signed	incorrect for signed

closer look: condition codes (2)

```
  // 2**63 - 1
  movq $0x7FFFFFFFFFFFFFFF, %rax
  // 2**63 (unsigned); -2**63 (signed)
  movq $0x8000000000000000, %rbx
  cmpq %rax, %rbx
// result = %rbx - %rax
```

as signed: $-2^{63} - \left(2^{63} - 1\right) = \cancel{-2^{64} + 1}\ 1$ (overflow)

as unsigned: $2^{63} - \left(2^{63} - 1\right) = 1$

ZF $= 0$ (false)	not zero	rax and rbx not equal
SF $= 0$ (false)	not negative	rax <= rbx (if correct)
OF $= 1$ (true)	overflow as signed	incorrect for signed
CF $= 0$ (false)	no overflow as unsigned	correct for unsigned

closer look: condition codes (3)

```
  movq  $-1, %rax
  addq  $-2, %rax
// result = -3
```

as signed: $-1 + (-2) = -3$

as unsigned: $(2^{64} - 1) + (2^{64} - 2) = \cancel{2^{65} - 3}$ $2^{64} - 3$ (overflow)

ZF $= 0$ (false) not zero result not zero

closer look: condition codes (3)

```
  movq  $-1, %rax
  addq  $-2, %rax
// result = -3
```

as signed: $-1 + (-2) = -3$

as unsigned: $(2^{64} - 1) + (2^{64} - 2) = \cancel{2^{65} - 3}$ $2^{64} - 3$ (overflow)

ZF $= 0$ (false)	not zero	result not zero
SF $= 1$ (true)	negative	result is negative
OF $= 0$ (false)	no overflow as signed	correct for signed
CF $= 1$ (true)	overflow as unsigned	incorrect for unsigned

while exercise

```
while (b < 10) { foo(); b += 1; }
```

Assume b is in callee-saved register %rbx. Which are correct assembly translations?

```
// version A
start_loop:
  call foo
  addq $1, %rbx
  cmpq $10, %rbx
  jl start_loop
```

```
// version B
start_loop:
  cmpq $10, %rbx
  jge end_loop
  call foo
  addq $1, %rbx
  jmp start_loop
end_loop:
```

```
// version C
start_loop:
  movq $10, %rax
  subq %rbx, %rax
  jge end_loop
  call foo
  addq $1, %rbx
  jmp start_loop
end_loop:
```

while to assembly (1)

```
while (b < 10) {
    foo();
    b += 1;
}
```

---

while to assembly (1)

```
while (b < 10) {
    foo();
    b += 1;
}
```

```
start_loop: if (b < 10) goto end_loop;
            foo();
            b += 1;
            goto start_loop;
end_loop:
```

while — levels of optimization

```
while (b < 10) { foo(); b += 1; }
```

```
start_loop:
  cmpq $10, %rbx
  jge end_loop
  call foo
  addq $1, %rbx
  jmp start_loop
end_loop:
    ...
    ...
    ...
    ...
```

while — levels of optimization

```
while (b < 10) { foo(); b += 1; }
```

```
start_loop:
  cmpq $10, %rbx
  jge end_loop
  call foo
  addq $1, %rbx
  jmp start_loop
end_loop:
    ...
    ...
    ...
    ...
```

```
  cmpq $10, %rbx
  jge end_loop
start_loop:
  call foo
  addq $1, %rbx
  cmpq $10, %rbx
  jne start_loop
end_loop:
    ...
    ...
    ...
```

while — levels of optimization

```
while (b < 10) { foo(); b += 1; }
```

```
start_loop:
  cmpq $10, %rbx
  jge end_loop
  call foo
  addq $1, %rbx
  jmp start_loop
end_loop:
    ...
    ...
    ...
    ...
```

```
  cmpq $10, %rbx
  jge end_loop
start_loop:
  call foo
  addq $1, %rbx
  cmpq $10, %rbx
  jne start_loop
end_loop:
    ...
    ...
    ...
```

```
  cmpq $10, %rbx
  jge end_loop
  movq $10, %rax
  subq %rbx, %rax
  movq %rax, %rbx
start_loop:
  call foo
  decq %rbx
  jne start_loop
  movq $10, %rbx
end_loop:
```

compiling switches (1)

```
switch (a) {
    case 1: ...; break;
    case 2: ...; break;
    ...
    default: ...
}
```

```
    // same as if statement?
    cmpq $1, %rax
    je code_for_1
    cmpq $2, %rax
    je code_for_2
    cmpq $3, %rax
    je code_for_3
    ...
    jmp code_for_default
```

compiling switches (2)

```
switch (a) {
    case 1: ...; break;
    case 2: ...; break;
    ...
    case 100: ...; break;
    default: ...
}
```

```
    // binary search
    cmpq $50, %rax
    jl code_for_less_than_50
    cmpq $75, %rax
    jl code_for_50_to_75
    ...
code_for_less_than_50:
    cmpq $25, %rax
    jl less_than_25_cases
    ...
```

compiling switches (3)

```
switch (a) {
    case 1: ...; break;
    case 2: ...; break;
    ...
    case 100: ...; break;
    default: ...
}
```

```
// jump table
cmpq $100, %rax
jg code_for_default
cmpq $1, %rax
jl code_for_default
jmp *table(,%rax,8)
```

```
table:
  // not instructions
  // .quad = 64-bit (4 x 16) constant
  .quad code_for_1
  .quad code_for_2
  .quad code_for_3
  .quad code_for_4
    ...
```

computed jumps

```
  cmpq $100, %rax
  jg code_for_default
  cmpq $1, %rax
  jl code_for_default
  // jump to memory[table + rax * 8]
    // table of pointers to instructions
  jmp *table(,%rax,8)
  // intel: jmp QWORD PTR[rax*8 + table]
  ...
table:
  .quad code_for_1
  .quad code_for_2
  .quad code_for_3
```

preview: our Y86 condition codes

`ZF` (zero flag), `SF` (sign flag)

just won't handle overflow/underflow

microarchitecture v. instruction set

microarchitecture — design of the hardware

- "generations" of Intel's x86 chips
- different microarchitectures for very low-power versus laptop/desktop
- changes in performance/efficiency

instruction set — interface visible by software

- what matters for software compatibility
- many ways to implement (but some might be easier)

selected instruction set design concerns

ease of creating efficient assembly/machine code

ease of designing efficient/cheap/low power/...hardware

flexibility for the future

ISAs being manufactured today

x86 — dominant in desktops, servers

ARM — dominant in mobile devices

POWER — Wii U, IBM supercomputers and some servers

MIPS — common in consumer wifi access points

SPARC — some Oracle servers, Fujitsu supercomputers

z/Architecture — IBM mainframes

Z80 — TI calculators

SHARC — some digital signal processors

Itanium — some HP servers (being retired)

RISC V — some embedded

...

ISA variation

instruction set	instr. length	# normal registers	*approx.* # instrs.
x86-64	1–15 byte	16	1500
Y86-64	1–10 byte	15	18
ARMv7	4 byte*	16	400
POWER8	4 byte	32	1400
MIPS32	4 byte	31	200
Itanium	41 bits*	128	300
Z80	1–4 byte	7	40
VAX	1–14 byte	8	150
z/Architecture	2–6 byte	16	1000
RISC V	4 byte*	31	500*

other choices: condition codes?

instead of:

```
cmpq %r11, %r12
je somewhere
```

could do:

```
/* _B_ranch if _EQ_ual */
beq  %r11, %r12, somewhere
```

other choices: addressing modes

ways of specifying operands. examples:

x86-64: `10(%r11,%r12,4)`

ARM: `%r11 << 3` (shift register value by constant)

VAX: `((%r11))` (register value is pointer to pointer)

other choices: number of operands

add `src1, src2, dest`

ARM, POWER, MIPS, SPARC, ...

add `src2, src1=dest`

x86, AVR, Z80, ...

VAX: both

other choices: instruction complexity

instructions that write multiple values?

- x86-64: **`push`**, **`pop`**, **`movsb`**, ...

more?

CISC and RISC

RISC — Reduced Instruction Set Computer

reduced from what?

CISC and RISC

RISC — Reduced Instruction Set Computer

reduced from what?

CISC — Complex Instruction Set Computer

some VAX instructions

`MATCHC` *haystackPtr*, *haystackLen*, *needlePtr*, *needleLen*
Find the position of the string in needle within haystack.

`POLY` *x*, *coefficientsLen*, *coefficientsPtr*
Evaluate the polynomial whose coefficients are pointed to by *coefficientPtr* at the value *x*.

`EDITPC` *sourceLen*, *sourcePtr*, *patternLen*, *patternPtr*
Edit the string pointed to by *sourcePtr* using the pattern string specified by *patternPtr*.

microcode

`MATCHC` *haystackPtr*, *haystackLen*, *needlePtr*, *needleLen*
Find the position of the string in needle within haystack.

loop in hardware???

typically: lookup sequence of microinstructions (“microcode”)

secret simpler instruction set

Why RISC?

complex instructions were usually not faster

complex instructions were harder to implement

compilers, not hand-written assembly

typical RISC ISA properties

fewer, simpler instructions

seperate instructions to access memory

fixed-length instructions

more registers

no “loops” within single instructions

no instructions with two memory operands

few addressing modes

Y86-64 instruction set

based on x86

omits most of the 1000+ instructions

leaves

`addq`	`jmp`	`pushq`
`subq`	`j`*CC*	`popq`
`andq`	`cmov`*CC*	`movq` (renamed)
`xorq`	`call`	`hlt` (renamed)
`nop`	`ret`	

much, much simpler encoding

Y86-64 instruction set

based on x86

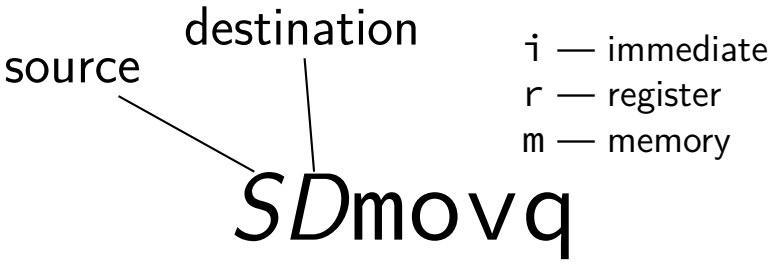
omits most of the 1000+ instructions

leaves

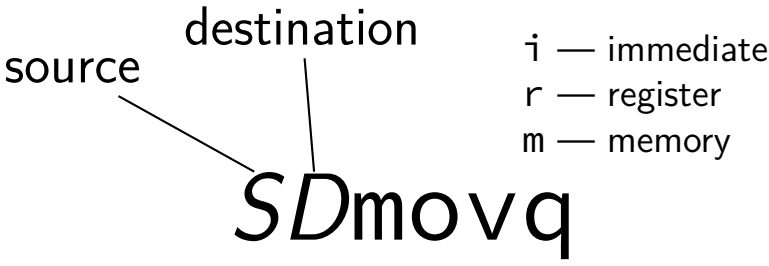
`addq`	`jmp`	`pushq`
`subq`	`j`*CC*	`popq`
`andq`	`cmov`*CC*	`movq` (renamed)
`xorq`	`call`	`hlt` (renamed)
`nop`	`ret`	

much, much simpler encoding

Y86-64: movq



Y86-64: movq

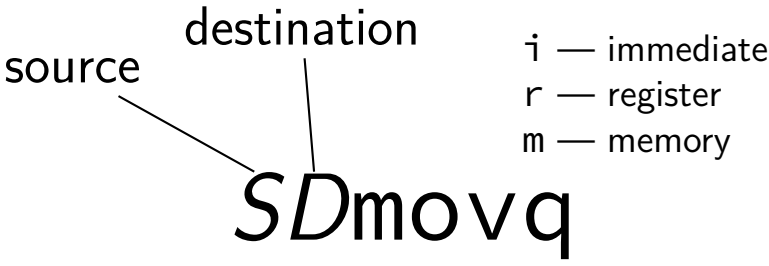


irmovq ~~immovq~~ ~~iimovq~~

rrmovq rmmovq ~~rimovq~~

mrmovq ~~mmmovq~~ ~~mimovq~~

Y86-64: movq



irmovq

~~immovq~~

rrmovq

rmmovq

mrmovq

~~mmmovq~~

Y86-64 instruction set

based on x86

omits most of the 1000+ instructions

leaves

`addq`	`jmp`	`pushq`
`subq`	`j`*`CC`*	`popq`
`andq`	`cmov`*`CC`*	`movq` (renamed)
`xorq`	`call`	`hlt` (renamed)
`nop`	`ret`	

much, much simpler encoding

cmovCC

conditional move

exist on x86-64 (but you probably didn't see them)

Y86-64: register-to-register only

instead of:

```
    jle skip_move
    rrmovq %rax, %rbx
skip_move:
    // ...
```

can do:

```
    cmovg %rax, %rbx
```

Y86-64 instruction set

based on x86

omits most of the 1000+ instructions

leaves

`addq`	`jmp`	`pushq`
`subq`	`j`*CC*	`popq`
`andq`	`cmov`*CC*	`movq` (renamed)
`xorq`	`call`	`hlt` (renamed)
`nop`	`ret`	

much, much simpler encoding

halt

(x86-64 instruction called `hlt`)

Y86-64 instruction `halt`

stops the processor

- otherwise — something's in memory "after" program!

real processors: reserved for OS

Y86-64: specifying addresses

Valid: `rmmovq %r11, 10(%r12)`

Y86-64: specifying addresses

Valid: `rmmovq %r11, 10(%r12)`

Invalid: ~~`rmmovq %r11, 10(%r12,%r13)`~~

Invalid: ~~`rmmovq %r11, 10(,%r12,4)`~~

Invalid: ~~`rmmovq %r11, 10(%r12,%r13,4)`~~

Y86-64: accessing memory (1)

r12 $\leftarrow$ memory[10 + r11] + r12

Invalid: ~~`addq 10(%r11), %r12`~~

Y86-64: accessing memory (1)

r12 $\leftarrow$ memory[10 + r11] + r12

Invalid: ~~`addq 10(%r11), %r12`~~

Instead:

```
mrmovq 10(%r11), %r11
/* overwrites %r11 */

addq %r11, %r12
```

Y86-64: accessing memory (2)

r12 ← memory[10 + 8 * r11] + r12

Invalid: ~~`addq 10(,%r11,8), %r12`~~

Y86-64: accessing memory (2)

r12 ← memory[10 + 8 * r11] + r12

Invalid: ~~`addq 10(,%r11,8), %r12`~~

Instead:

```
/* replace %r11 with 8*%r11 */
addq %r11, %r11
addq %r11, %r11
addq %r11, %r11

mrmovq 10(%r11), %r11
addq %r11, %r12
```

Y86-64 constants (1)

```
irmovq $100, %r11
```

only instruction with non-address constant operand

Y86-64 constants (2)

r12 $\leftarrow$ r12 + 1

Invalid: ~~`addq $1, %r12`~~

Y86-64 constants (2)

r12 $\leftarrow$ r12 + 1

Invalid: ~~`addq $1, %r12`~~

Instead, need an extra register:

```
irmovq $1, %r11
addq %r11, %r12
```

Y86-64: operand uniqueness

only one kind of value for each operand

instruction name tells you the kind

(why **movq** was 'split' into four names)

Y86-64: condition codes

ZF — value was zero?

SF — sign bit was set? i.e. value was negative?

this course: no OF, CF (to simplify assignments)

set by **addq**, **subq**, **andq**, **xorq**

not set by anything else

Y86-64: using condition codes

subq SECOND, FIRST (value = FIRST - SECOND)

j__ or cmov__	condition code bit test	value test
le	SF = 1 or ZF = 1	value ≤ 0
l	SF = 1	value < 0
e	ZF = 1	value $= 0$
ne	ZF = 0	value $\neq 0$
ge	SF = 0	value ≥ 0
g	SF = 0 and ZF = 0	value > 0

missing OF (overflow flag); CF (carry flag)

Y86-64: conditionals (1)

~~cmp~~, ~~test~~

Y86-64: conditionals (1)

~~`cmp`~~, ~~`test`~~

instead: use side effect of normal arithmetic

Y86-64: conditionals (1)

~~`cmp`~~, ~~`test`~~

instead: use side effect of normal arithmetic

instead of

```
cmpq %r11, %r12
jle somewhere
```

maybe:

```
subq %r11, %r12
jle
```

(but changes `%r12`)

push/pop

pushq %rbx

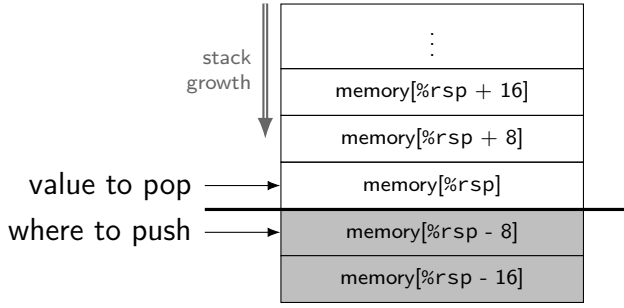
%rsp $\leftarrow$ %rsp $-$ 8

memory[%rsp] $\leftarrow$ %rbx

popq %rbx

%rbx $\leftarrow$ memory[%rsp]

%rsp $\leftarrow$ %rsp $+$ 8



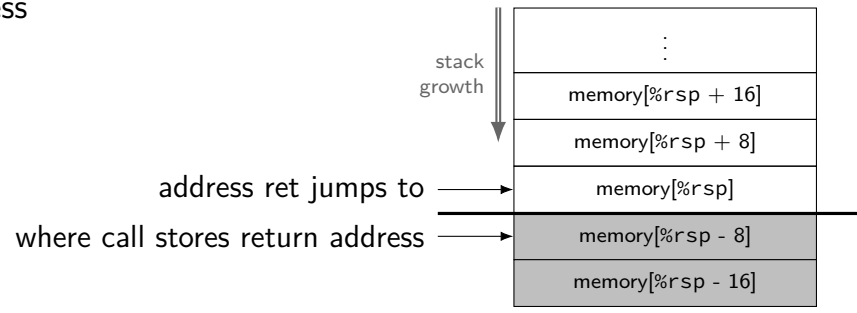
call/ret

`call` LABEL

push PC (next instruction address) on stack
jmp to LABEL address

`ret`

pop address from stack
jmp to that address



Y86-64 state

`%r`*XX* — 15 registers

- ~~`%r15`~~ missing
- smaller parts of registers missing

ZF (zero), SF (sign), ~~OF (overflow)~~

- book has OF, we'll not use it
- ~~CF~~ (carry) missing

`Stat` — processor status — halted?

PC — program counter (AKA instruction pointer)

main memory

typical RISC ISA properties

fewer, simpler instructions

seperate instructions to access memory

~~fixed-length instructions~~

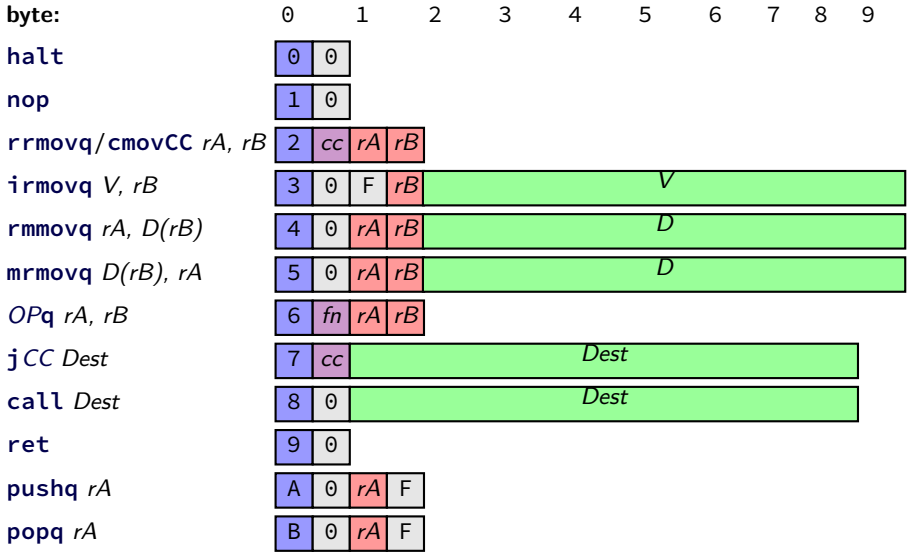
more registers

no “loops” within single instructions

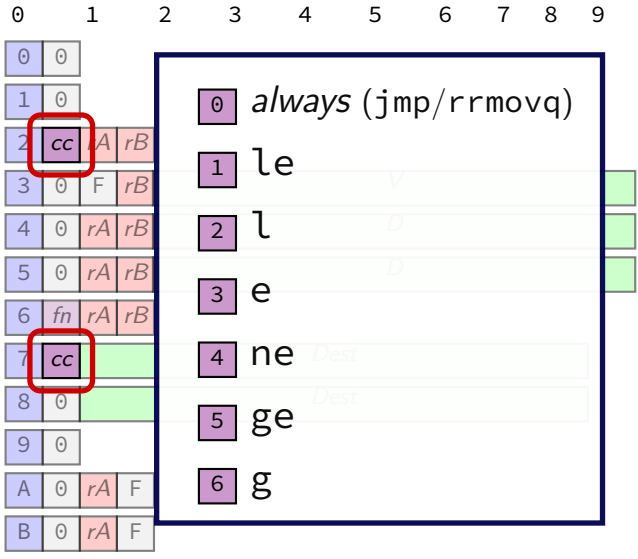
no instructions with two memory operands

few addressing modes

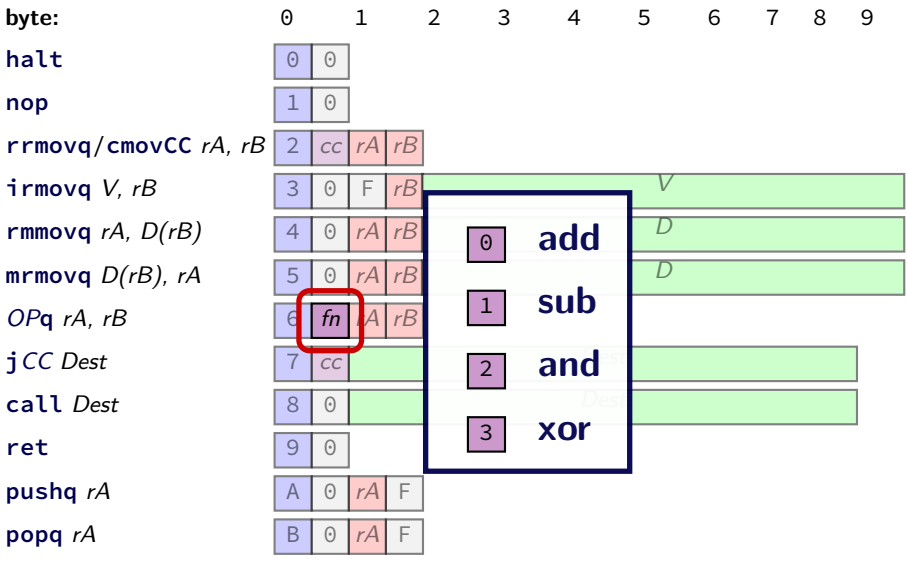
Y86-64 instruction formats



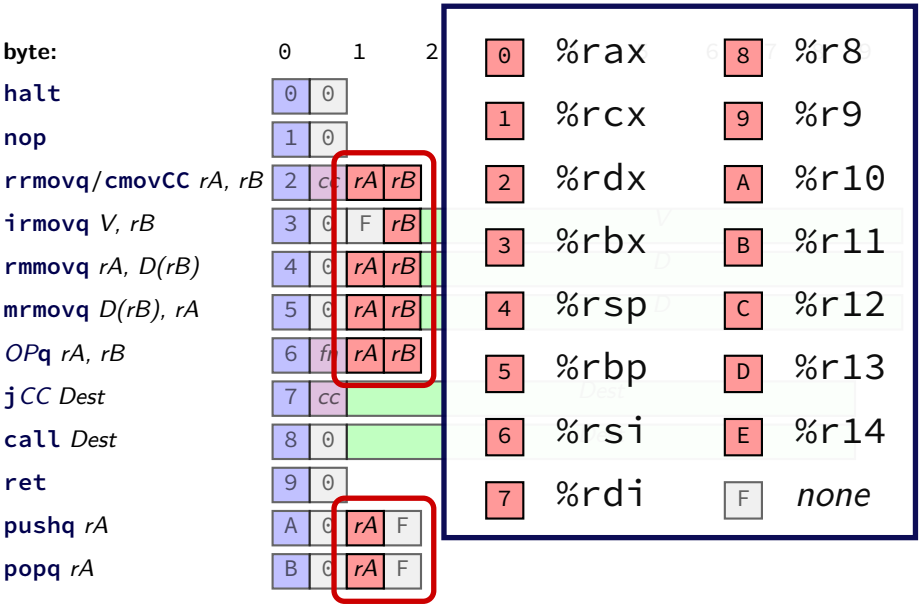
Secondary opcodes: `cmovcc`/`jcc`



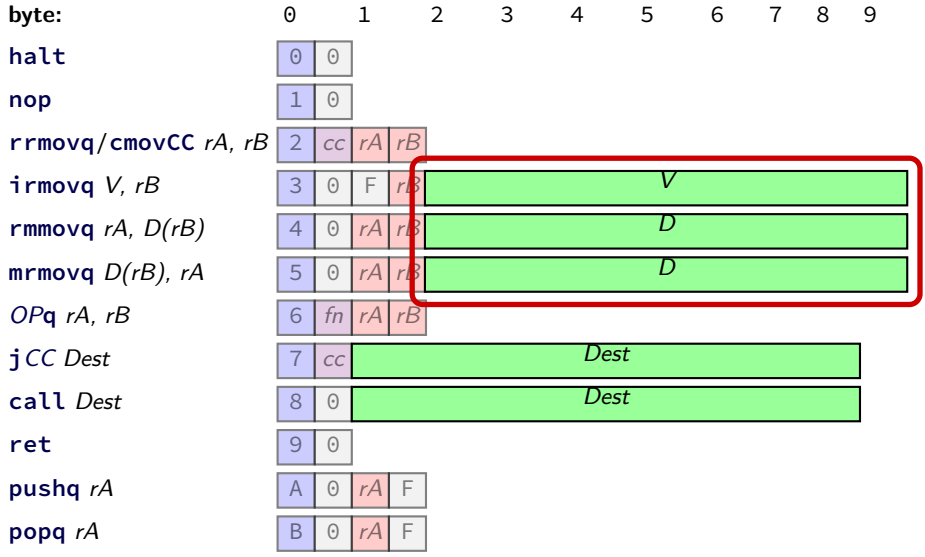
Secondary opcodes: *OP*q



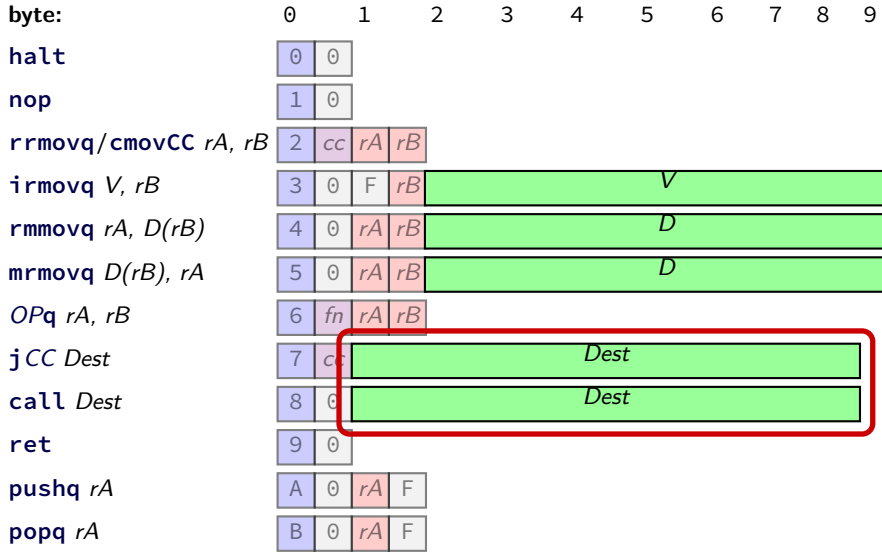
Registers: *rA, rB*



Immediates: *V, D, Dest*



Immediates: *V, D, Dest*



Y86-64 encoding (1)

```
long addOne(long x) {
    return x + 1;
}
```

x86-64:

```
    movq %rdi, %rax
    addq $1, %rax
    ret
```

Y86-64:

Y86-64 encoding (1)

```
long addOne(long x) {
    return x + 1;
}
```

x86-64:

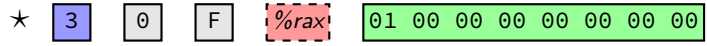
```
    movq %rdi, %rax
    addq $1, %rax
    ret
```

Y86-64:

```
    irmovq  $1,   %rax
    addq    %rdi, %rax
    ret
```

Y86-64 encoding (2)

```
addOne:
  irmovq  $1,   %rax
  addq    %rdi, %rax
  ret
```



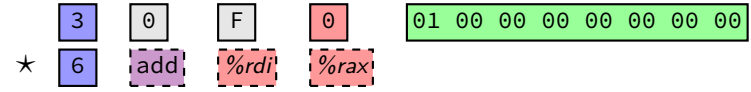
Y86-64 encoding (2)

```
addOne:
  irmovq  $1,   %rax
  addq    %rdi, %rax
  ret
```

★ 3 | 0 | F | 0 | 01 00 00 00 00 00 00 00

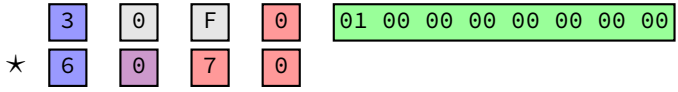
Y86-64 encoding (2)

```
addOne:
  irmovq  $1,   %rax
  addq    %rdi, %rax
  ret
```



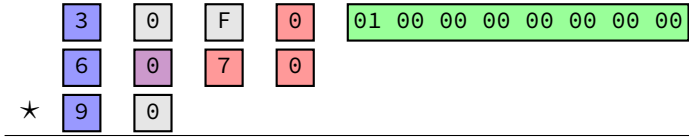
Y86-64 encoding (2)

```
addOne:
  irmovq  $1,   %rax
  addq    %rdi, %rax
  ret
```



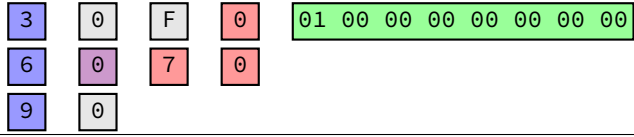
Y86-64 encoding (2)

```
addOne:
   irmovq   $1,    %rax
   addq     %rdi, %rax
   ret
```



Y86-64 encoding (2)

```
addOne:
   irmovq  $1,   %rax
   addq    %rdi, %rax
   ret
```




```
30 F0 01 00 00 00 00 00 00 00 60 70 90
```

Y86-64 encoding (3)

```
doubleTillNegative:
/* suppose at address 0x123 */
  addq    %rax, %rax
  jge doubleTillNegative
```

Y86-64 encoding (3)

```
doubleTillNegative:
/* suppose at address 0x123 */
  addq     %rax, %rax
  jge doubleTillNegative
```

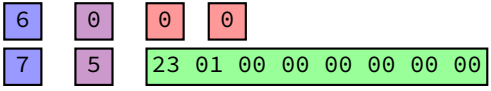
★ 6 add %rax %rax

Y86-64 encoding (3)

```
doubleTillNegative:
/* suppose at address 0x123 */
  addq     %rax, %rax
  jge doubleTillNegative
```

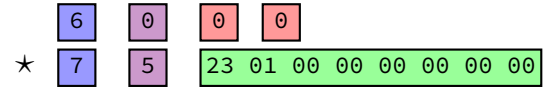
Y86-64 encoding (3)

```
doubleTillNegative:
/* suppose at address 0x123 */
  addq     %rax, %rax
  jge doubleTillNegative
```



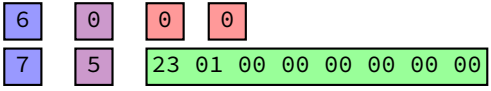
Y86-64 encoding (3)

```
doubleTillNegative:
/* suppose at address 0x123 */
  addq     %rax, %rax
  jge doubleTillNegative
```



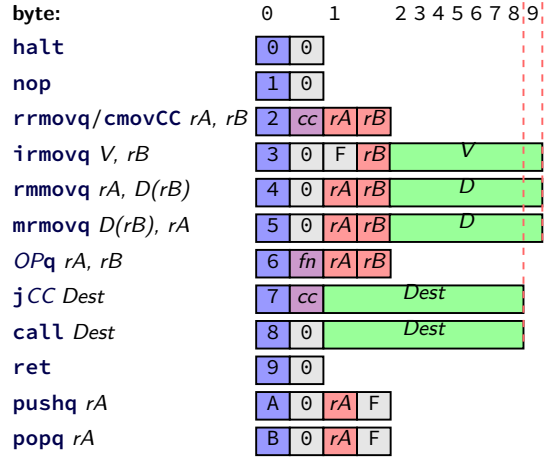
Y86-64 encoding (3)

```
doubleTillNegative:
/* suppose at address 0x123 */
  addq     %rax, %rax
  jge doubleTillNegative
```



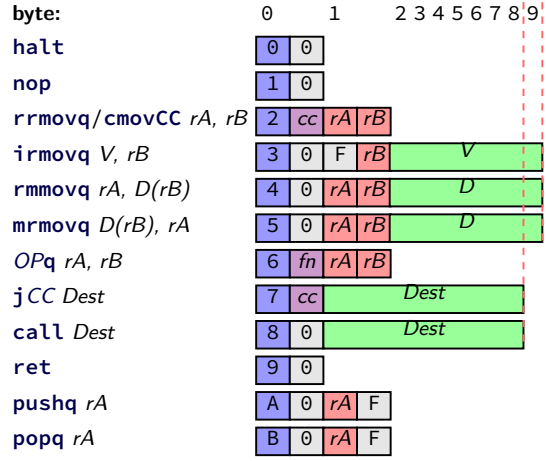
Y86-64 decoding

```
20 10 60 20 61 37 72 84 00 00 00 00 00 00 00 00
20 12 20 01 70 68 00 00 00 00 00 00 00 00
```



Y86-64 decoding

```
20 10 60 20 61 37 72 84 00 00 00 00 00 00 00 00
20 12 20 01 70 68 00 00 00 00 00 00 00 00
```

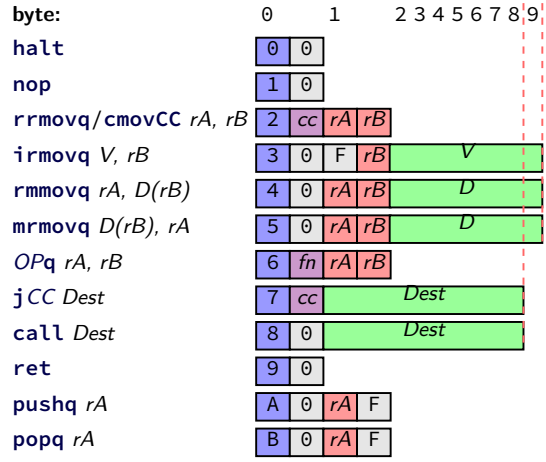


Y86-64 decoding

```
20 10 60 20 61 37 72 84 00 00 00 00 00 00 00
20 12 20 01 70 68 00 00 00 00 00 00 00
```

rrmovq %rcx, %rax

- 0 as cc: always
- 1 as reg: %rcx
- 0 as reg: %rax

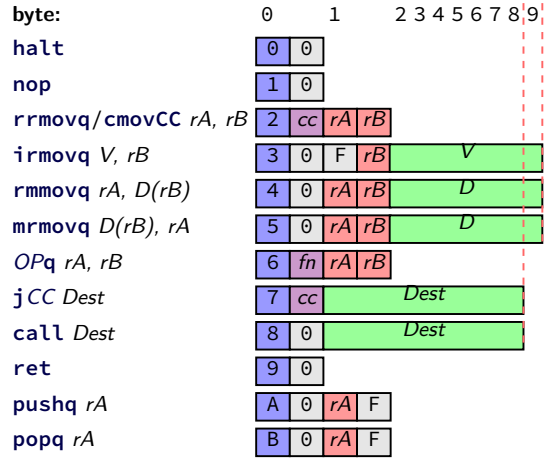


Y86-64 decoding

```
20 10 60 20 61 37 72 84 00 00 00 00 00 00 00
20 12 20 01 70 68 00 00 00 00 00 00 00
```

```
rrmovq %rcx, %rax
addq   %rdx, %rax
subq   %rbx, %rdi
```

- 0 as fn: add
- 1 as fn: sub

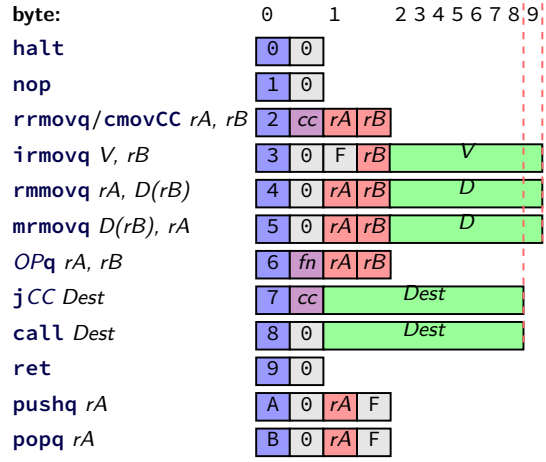


Y86-64 decoding

```
20 10 60 20 61 37 72 84 00 00 00 00 00 00 00
20 12 20 01 70 68 00 00 00 00 00 00 00
```

```
rrmovq %rcx, %rax
addq   %rdx, %rax
subq   %rbx, %rdi
jl     0x84
```

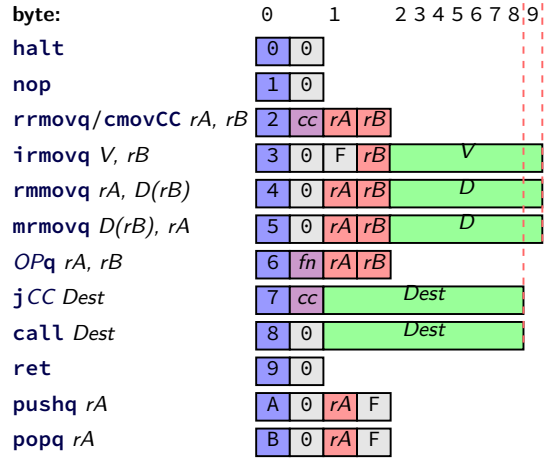
- 2 as cc: `l` (less than)
- hex 84 00… as little endian *Dest: 0x84*



Y86-64 decoding

```
20 10 60 20 61 37 72 84 00 00 00 00 00 00 00
20 12 20 01 70 68 00 00 00 00 00 00 00
```

```
rrmovq %rcx, %rax
addq   %rdx, %rax
subq   %rbx, %rdi
jl     0x84
rrmovq %rax, %rcx
jmp    0x68
```



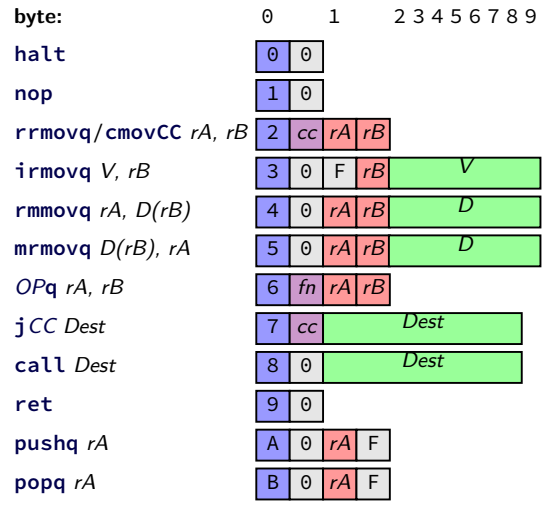
Y86-64: convenience for hardware

4 bits to decode instruction size/layout

(mostly) uniform placement of operands

jumping to zeroes (uninitialized?) by accident halts

no attempt to fit (parts of) multiple instructions in a byte



Y86-64

Y86-64: simplified, more RISC-y version of X86-64

minimal set of arithmetic

only movs touch memory

only jumps, calls, and movs take immediates

simple variable-length encoding

next time: implementing with circuits

backup slides

closer look: condition codes (3)

```
  movq  $-1, %rax
  testq %rax, %rax
// result = -1
```

ZF $= 0$ (false)	not zero	rax not zero
SF $= 1$ (true)	negative	rax is negative
OF $= 0$ (false)	no overflow as signed	operation can't overflow
CF $= 0$ (false)	no oveflow as unsigned	operation can't overflow

exercise: condition codes and jXX

`ZF` $= 0$ (false)
`SF` $= 1$ (true)
`OF` $= 0$ (false)
`CF` $= 1$ (true)

jle (signed less than equal) should do what?

ja (unsigned greater than) should do what?

logical operators

return 1 for true or 0 for false

```
( 1 && 1 ) == 1
( 2 && 4 ) == 1
( 1 && 0 ) == 0
( 0 && 0 ) == 0
(-1 && -2) == 1
("" && "") == 1
! 1        == 0
! 4        == 0
!-1        == 0
! 0        == 1
```

```
( 1 || 1 ) == 1
( 2 || 4 ) == 1
( 1 || 0 ) == 1
( 0 || 0 ) == 0
(-1 || -2) == 1
("" || "") == 1
```

recall: short-circuit (&&)

```
1 #include <stdio.h>
2 int zero() { printf("zero()\n"); return 0; }
3 int one() { printf("one()\n"); return 1; }
4 int main() {
5     printf("> %d\n", zero() && one());
6     printf("> %d\n", one() && zero());
7     return 0;
8 }
```

```
zero()
> 0
one()
zero()
> 0
```

AND	**false**	**true**
false	false	false
true	false	true

recall: short-circuit (&&)

```
1 #include <stdio.h>
2 int zero() { printf("zero()\n"); return 0; }
3 int one() { printf("one()\n"); return 1; }
4 int main() {
5     printf("> %d\n", zero() && one());
6     printf("> %d\n", one() && zero());
7     return 0;
8 }
```

```
zero()
> 0
one()
zero()
> 0
```

AND	**false**	**true**
false	false	false
true	false	true

recall: short-circuit (&&)

```
1 #include <stdio.h>
2 int zero() { printf("zero()\n"); return 0; }
3 int one() { printf("one()\n"); return 1; }
4 int main() {
5     printf("> %d\n", zero() && one());
6     printf("> %d\n", one() && zero());
7     return 0;
8 }
```

```
zero()
> 0
one()
zero()
> 0
```

AND	**false**	**true**
false	false	false
true	false	true

recall: short-circuit (&&)

```
1 #include <stdio.h>
2 int zero() { printf("zero()\n"); return 0; }
3 int one() { printf("one()\n"); return 1; }
4 int main() {
5     printf("> %d\n", zero() && one());
6     printf("> %d\n", one() && zero());
7     return 0;
8 }
```

```
zero()
> 0
one()
zero()
> 0
```

AND	**false**	**true**
false	false	false
true	false	true

recall: short-circuit (&&)

```
1 #include <stdio.h>
2 int zero() { printf("zero()\n"); return 0; }
3 int one() { printf("one()\n"); return 1; }
4 int main() {
5     printf("> %d\n", zero() && one());
6     printf("> %d\n", one() && zero());
7     return 0;
8 }
```

```
zero()
> 0
one()
zero()
> 0
```

AND	**false**	**true**
false	false	false
true	false	true

&& to assembly

```
return foo() && bar();
```

&& to assembly

```
return foo() && bar();
```

```
    result = foo();
    if (result == 0) goto skip_bar;
    result = bar();
skip_bar:
    result = (result != 0);
```

&& to assembly

```
return foo() && bar();
```

```
  call   foo
  testl  %eax, %eax // result is %eax (return val)
  je     skip_bar   // if result == 0 (equal for cmp)...
  call   bar
  testl  %eax, %eax // result is %eax (return val)
skip_bar:
  setne  %al        // set %al (low 8 bits of %eax)
                    // to 1 if result != 0, to 0 otherwise
  movzbl %al, %eax  // add zeroes to rest of %eax
```

recall: short-circuit (||)

```
1 #include <stdio.h>
2 int zero() { printf("zero()\n"); return 0; }
3 int one() { printf("one()\n"); return 1; }
4 int main() {
5     printf("> %d\n", zero() || one());
6     printf("> %d\n", one() || zero());
7     return 0;
8 }
```

```
zero()
one()
> 1
one()
> 1
```

OR	**false**	**true**
false	false	true
true	true	true

recall: short-circuit (||)

```
1 #include <stdio.h>
2 int zero() { printf("zero()\n"); return 0; }
3 int one() { printf("one()\n"); return 1; }
4 int main() {
5     printf("> %d\n", zero() || one());
6     printf("> %d\n", one() || zero());
7     return 0;
8 }
```

```
zero()
one()
> 1
one()
> 1
```

OR	**false**	**true**
false	false	true
true	true	true

recall: short-circuit (||)

```
1 #include <stdio.h>
2 int zero() { printf("zero()\n"); return 0; }
3 int one() { printf("one()\n"); return 1; }
4 int main() {
5     printf("> %d\n", zero() || one());
6     printf("> %d\n", one() || zero());
7     return 0;
8 }
```

```
zero()
one()
> 1
one()
> 1
```

OR	**false**	**true**
false	false	true
true	true	true

recall: short-circuit (||)

```
1 #include <stdio.h>
2 int zero() { printf("zero()\n"); return 0; }
3 int one() { printf("one()\n"); return 1; }
4 int main() {
5     printf("> %d\n", zero() || one());
6     printf("> %d\n", one() || zero());
7     return 0;
8 }
```

```
zero()
one()
> 1
one()
> 1
```

OR	**false**	**true**
false	false	true
true	true	true

recall: short-circuit (||)

```
1 #include <stdio.h>
2 int zero() { printf("zero()\n"); return 0; }
3 int one() { printf("one()\n"); return 1; }
4 int main() {
5     printf("> %d\n", zero() || one());
6     printf("> %d\n", one() || zero());
7     return 0;
8 }
```

```
zero()
one()
> 1
one()
> 1
```

OR	**false**	**true**
false	false	true
true	true	true

exercise

```
  movq $3, %rax
  movq $2, %rbx
start_loop:
  addq %rbx, %rbx
  cmpq $3, %rbx
  subq $1, %rax
  jg start_loop
```

What is the value of `%rbx` after this runs?

A. 2
B. 4
C. 8
D. 16
E. 32
F. something else

Y86-64: simple condition codes (1)

If `%r9` is -1 and `%r10` is 1:

`subq` `%r10, %r9`

r9 becomes $-1 - (1) = -2$.

- SF $= 1$ (negative)
- ZF $= 0$ (not zero)

`andq` `%r10, %r10`

r10 becomes 1

- SF $= 0$ (non-negative)
- ZF $= 0$ (not zero)

the quiz: C (1)

```
int array[3]; int *ptr;
```

`sizeof(ptr) == sizeof(int *)` (pointer size; lab: 8)

`sizeof(array) = 3 * sizeof(int)` (lab: $3 \times 4 = 12$)

the quiz: C (2)

```
typedef struct foo { ... } bar;
```

```
    struct foo a_variable_of_this_type;
```

common for, e.g., linked list

```
    bar a_variable_of_this_type;
```

wrong type: ~~`struct bar a_variable`~~

wrong type: ~~`foo a_variable`~~

```
typedef FIRST SECOND;
```

'`FIRST a_variable;`' same as '`SECOND a_variable;`'

exericse: || to assembly

```
if (foo() || bar()) quux();
```

```
  call   foo
  cmpl   $0, %eax
  ____   skip_bar   // (1)
  call   bar
  cmpl   $0, %eax
skip_bar:
  ____   skip_quux  // (2)
  call   quux
skip_quux:
```

What belongs in the blanks?

A. **jg/jle**
B. **jne/jne**
C. **jne/je**
D. **je/jne**
E. something else
F. there's no instructions that make this work