YSC4230: Programming Language Design and Implementation

Week 2: x86Lite

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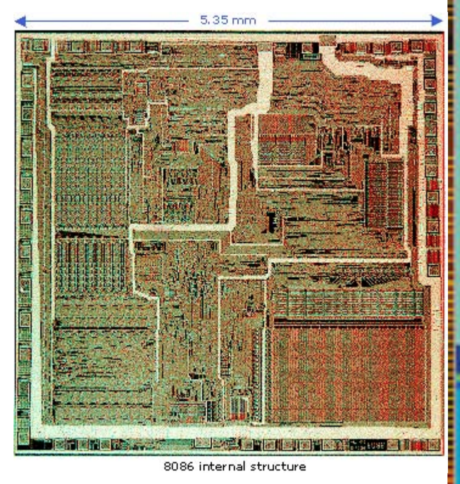
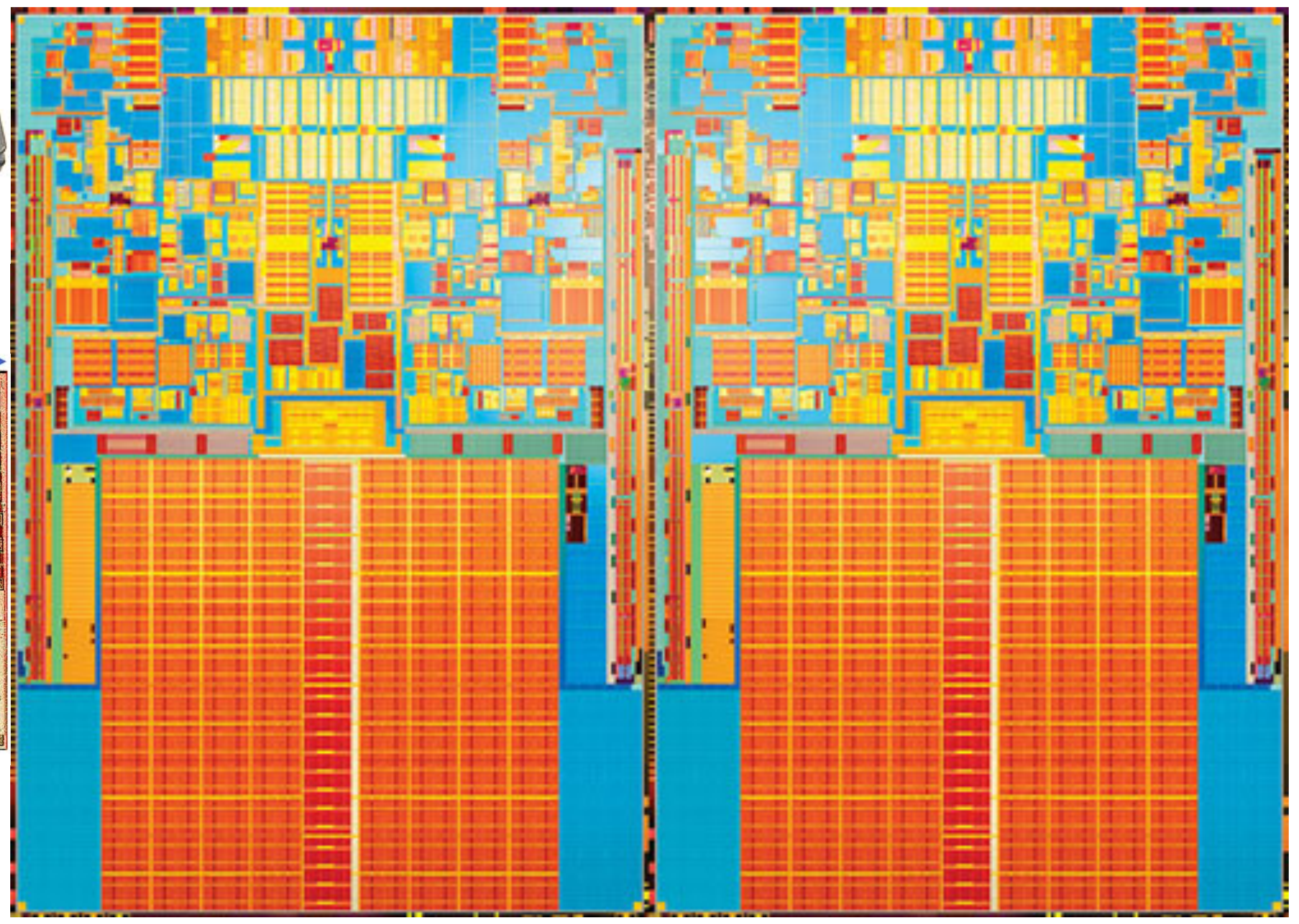
Week 2: x86Lite

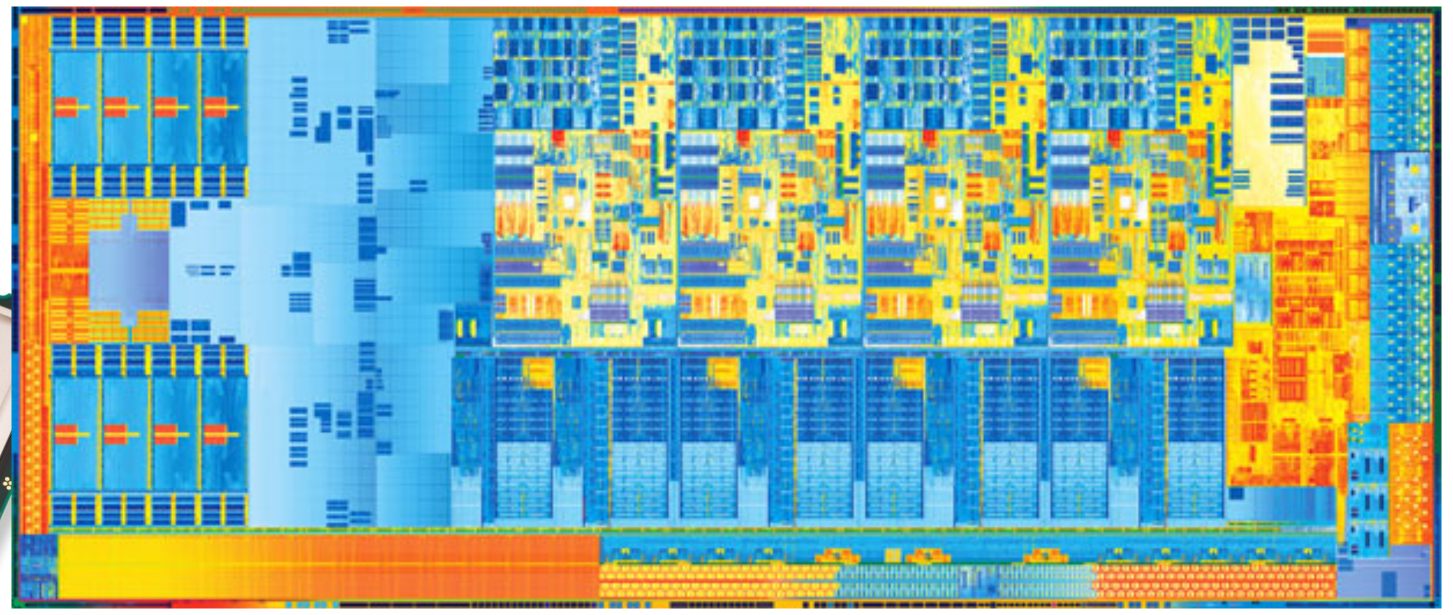
(the target architecture for this module)

Intel's X86 Architecture

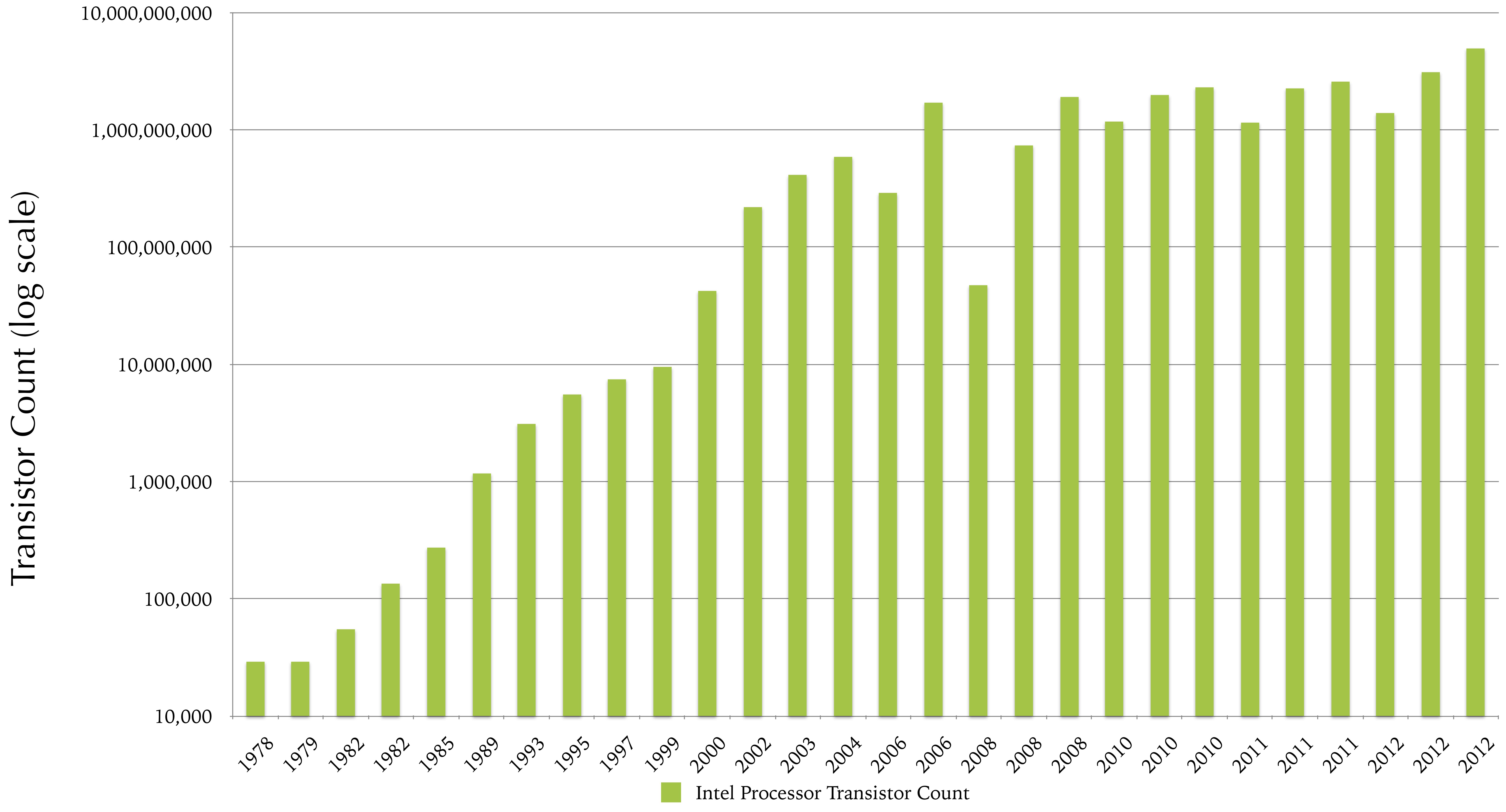
- 1978: Intel introduces 8086
- 1982: 80186, 80286
- 1985: 80386
- 1989: 80486 (100MHz, 1μm)
- 1993: Pentium
- 1995: Pentium Pro
- 1997: Pentium II/III
- 2000: Pentium 4
- 2003: Pentium M, Intel Core
- 2006: Intel Core 2
- 2008: Intel Core i3/i5/i7
- 2011: SandyBridge / IvyBridge
- 2013: Haswell
- 2014: Broadwell
- 2015: Skylake (core i3/i5/i7/i9) (2.4GHz, 14nm)
- 2016: Xeon Phi







Intel Processor Transistor Count

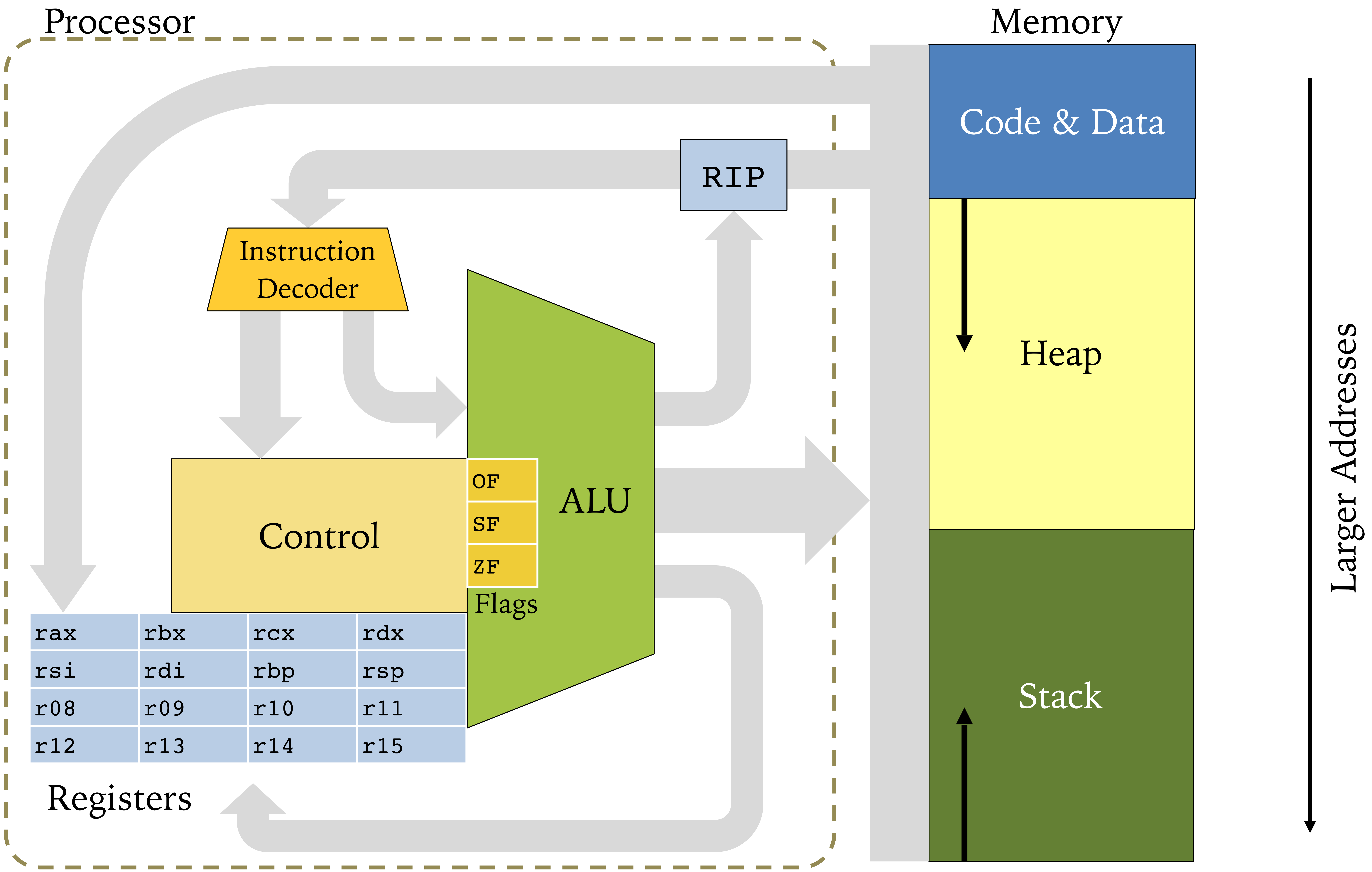


X86 vs. X86lite

- X86 assembly is *very* complicated:
  - 8-, 16-, 32-, 64-bit values + floating points, etc.
  - Intel 64 and IA 32 architectures have a *huge* number of functions
  - “CISC” complex instructions
  - Machine code: instructions range in size from 1 byte to 17 bytes
  - Lots of hold-over design decisions for backwards compatibility
  - Hard to understand, there is a large book about optimizations at just the instruction-selection level

- X86lite is a *very* simple subset of X86:
  - Only 64 bit signed integers (no floating point, no 16bit, no …)
  - Only about 20 instructions
  - Sufficient as a target language for general-purpose computing

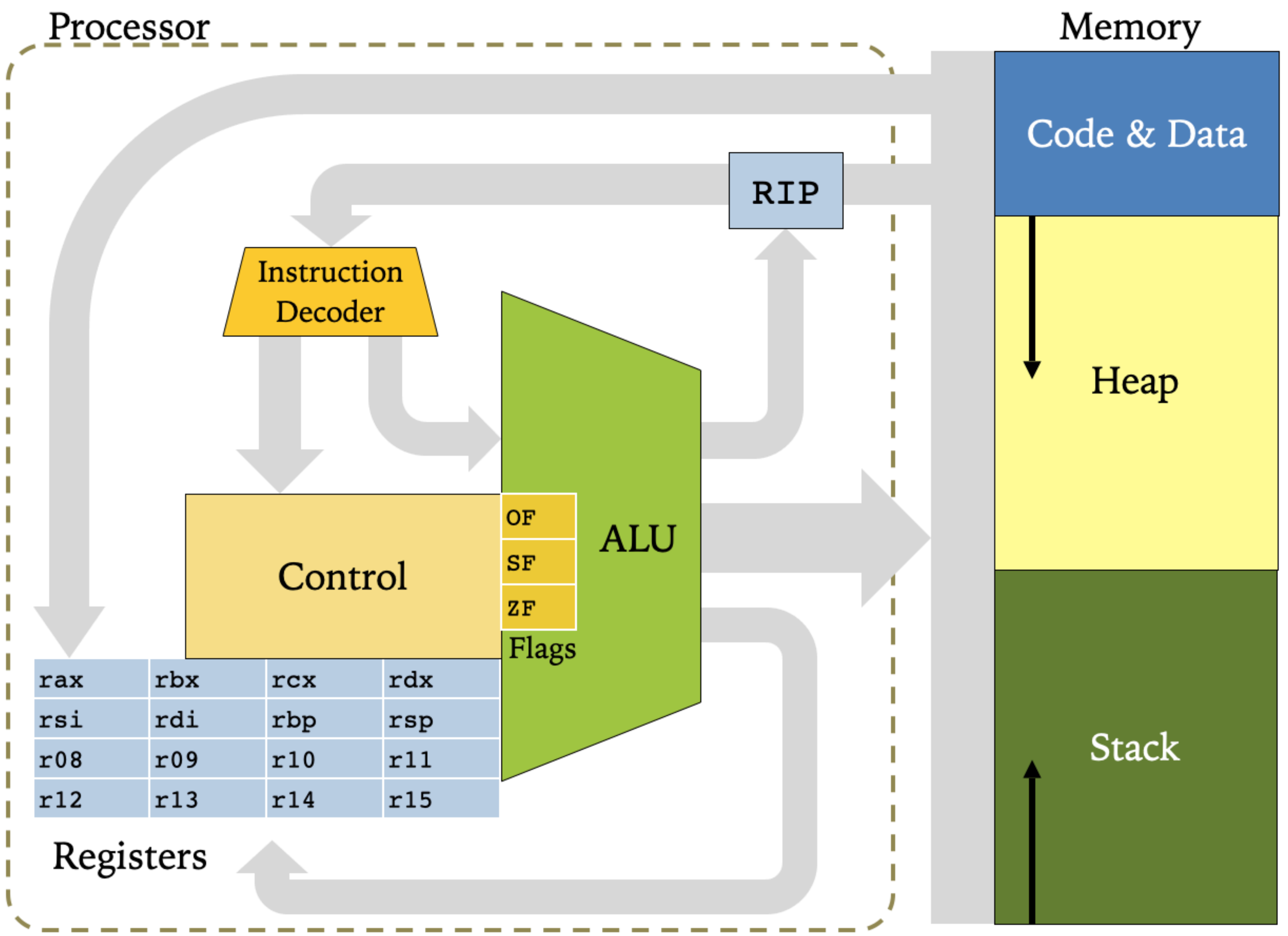
X86 Schematic



X86lite Machine State: Registers

- Register File: 16 64-bit registers

– `rax`	general purpose accumulator
– `rbx`	base register, pointer to data
– `rcx`	counter register for strings & loops
– `rdx`	data register for I/O
– `rsi`	pointer register, string source register
– `rdi`	pointer register, string destination register
– `rbp`	base pointer, points to the stack frame
– `rsp`	stack pointer, points to the top of the stack
– `r08-r15`	general purpose registers



- `rip` a "virtual" register, points to the current instruction
  - `rip` is manipulated only indirectly via jumps and return.

Simplest instruction: `mov`

- `movq` SRC`,` DEST copy SRC into DEST

- Here, DEST and SRC are *operands*
- DEST is treated as a *location*
  - A location can be a register or a memory address
- SRC is treated as a *value*
  - A value is the *contents* of a register or memory address
  - A value can also be an *immediate* (constant) or a label

- `movq $4, %rax` // move the 64-bit immediate value `4` into `rax`
- `movq %rbx, %rax` // move the contents of `rbx` into `rax`

A Note About Instruction Syntax

- X86 presented in *two* common syntax formats

- AT&T notation: source *before* destination
  - Prevalent in the Unix/Mac ecosystems
  - Immediate values prefixed with '`$`'
  - Registers prefixed with '`%`'
  - Mnemonic suffixes: `movq` vs. `mov`
    - `q` = quadword (4 words)
    - `l` = long (2 words)
    - `w` = word
    - `b` = byte

```
movq $5, %rax

movl $5, %eax
```

src dest

Note: X86lite uses the AT&T notation and the 64-bit only version of the instructions and registers.

- Intel notation: destination *before* source
  - Used in the Intel specification / manuals
  - Prevalent in the Windows ecosystem
  - Instruction variant determined by register name

```
mov rax, 5

mov eax, 5
```

dest src

X86lite Arithmetic instructions

• `negq` DEST	two's complement negation
• `addq` SRC, DEST	DEST ← DEST + SRC
• `subq` SRC, DEST	DEST ← DEST – SRC
• `imulq` SRC, Reg	Reg ← Reg * SRC (truncated 128-bit mult.)

Examples as written in:

```
addq %rbx, %rax     // rax ← rax + rbx
subq $4, rsp        // rsp ← rsp - 4
```

- Note: Reg (in `imulq`) must be a register, not a memory address

X86lite Logic/Bit manipulation Operations

• `notq` DEST	logical negation
• `andq` SRC, DEST	DEST ← DEST && SRC
• `orq` SRC, DEST	DEST ← DEST || SRC
• `xorq` SRC, DEST	DEST ← DEST xor SRC
• `sarq` Amt, DEST	DEST ← DEST >> amt (arithmetic shift right)
• `shlq` Amt, DEST	DEST ← DEST << amt (arithmetic shift left)
• `shrq` Amt, DEST	DEST ← DEST >>> amt (bitwise shift right)

The difference between arithmetic and bitwise shift is that the former preserves the sign.

X86 Operands

Operands are the values operated on by the assembly instructions

• Imm	64-bit literal signed integer "immediate" `42, 0x3de7`
• Lbl	a "label" representing a machine address, to be resolved by the assembler/linker/loader `_factorial, .L2`
• Reg	One of the 16 registers, the value of a register is of its contents %rax, %r04
• Ind	[base:Reg][index:Reg,scale:int32][disp] "Indirect" machine address (see next slide) `(%rax), -8(%rbp)`

X86 Addressing

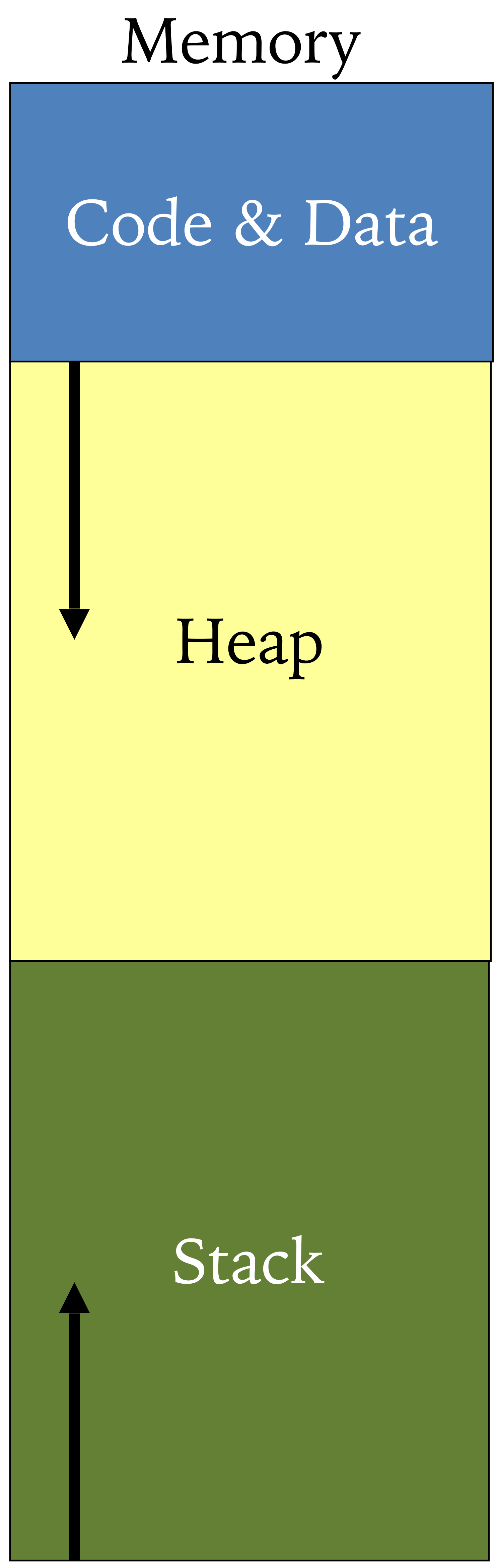
- In general, there are three components of an indirect address
  - Base: a machine address stored in a register
  - Index * scale: a variable offset from the base
  - Disp: a constant offset (displacement) from the base

- addr(ind) = Base + [Index * scale] + Disp
  - When used as a *location*, ind denotes the address addr(ind)
  - When used as a *value*, ind denotes Mem[addr(ind)], the contents of the memory address

- Example: `-4(%rsp)` denotes address: `rsp` – 4
- Example: `(%rax, %rcx, 4)` denotes address: `rax` + `4*rcx`
- Example: `12(%rax, %rcx, 4)` denotes address: `rax` + `4*rcx +12`

- Note: Index cannot be `rsp`

Note: X86lite does not need this full generality. It does not use index * scale.

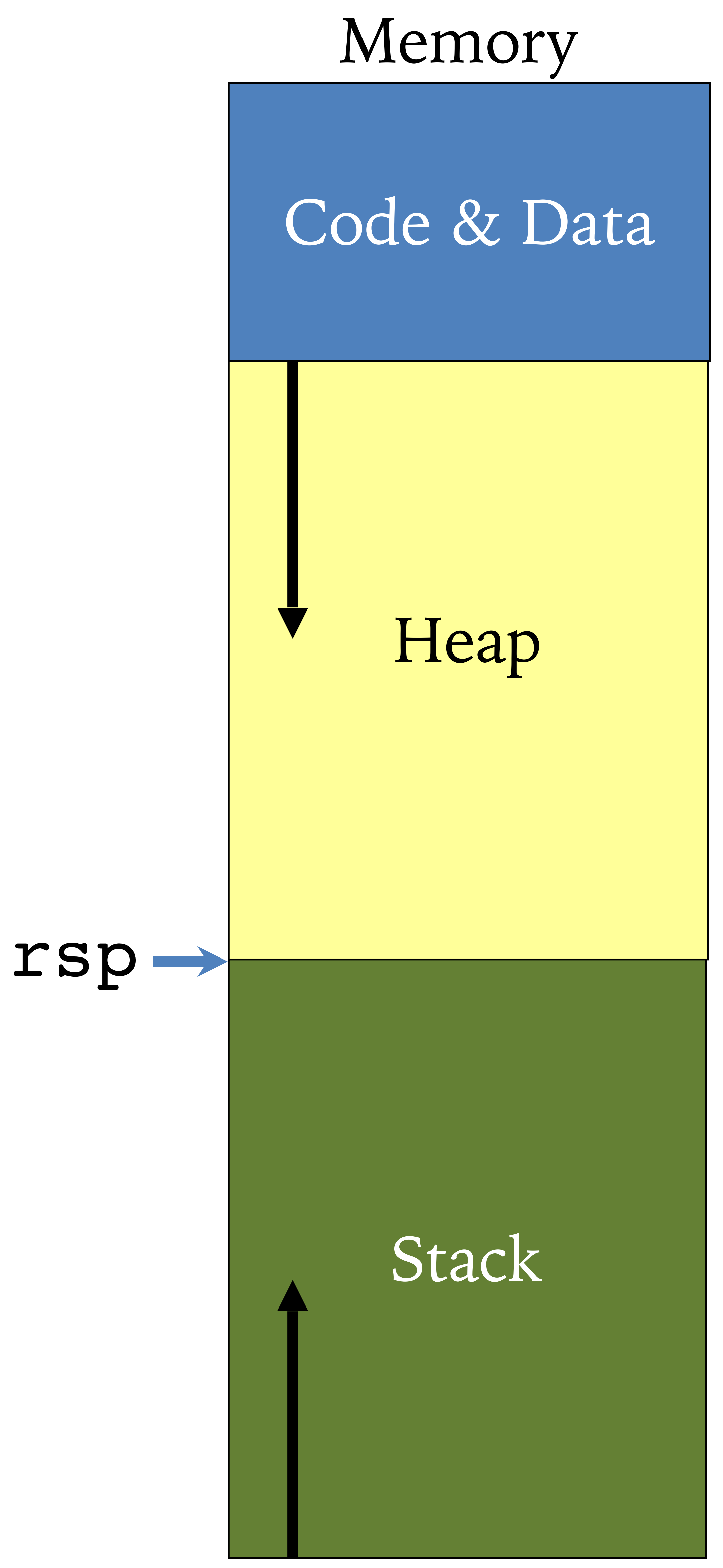


X86lite Memory Model

- The X86lite memory consists of 2^{64} bytes.
- X86lite treats the memory as consisting of 64-bit (8-byte) quadwords.
- Therefore: legal X86lite memory addresses consist of 64-bit, quadword-aligned pointers.
  - All memory addresses are evenly divisible by 8

- `leaq` Ind, DEST   DEST ← addr(Ind)   loads a pointer into DEST

- By convention, there is a stack that grows from high addresses to low addresses
- The register `rsp` points to the top of the stack
  - `pushq` SRC   `rsp` ← `rsp` - 8; Mem[`rsp`] ← SRC
  - `popq` DEST   DEST ← Mem[`rsp`]; `rsp` ← `rsp` + 8



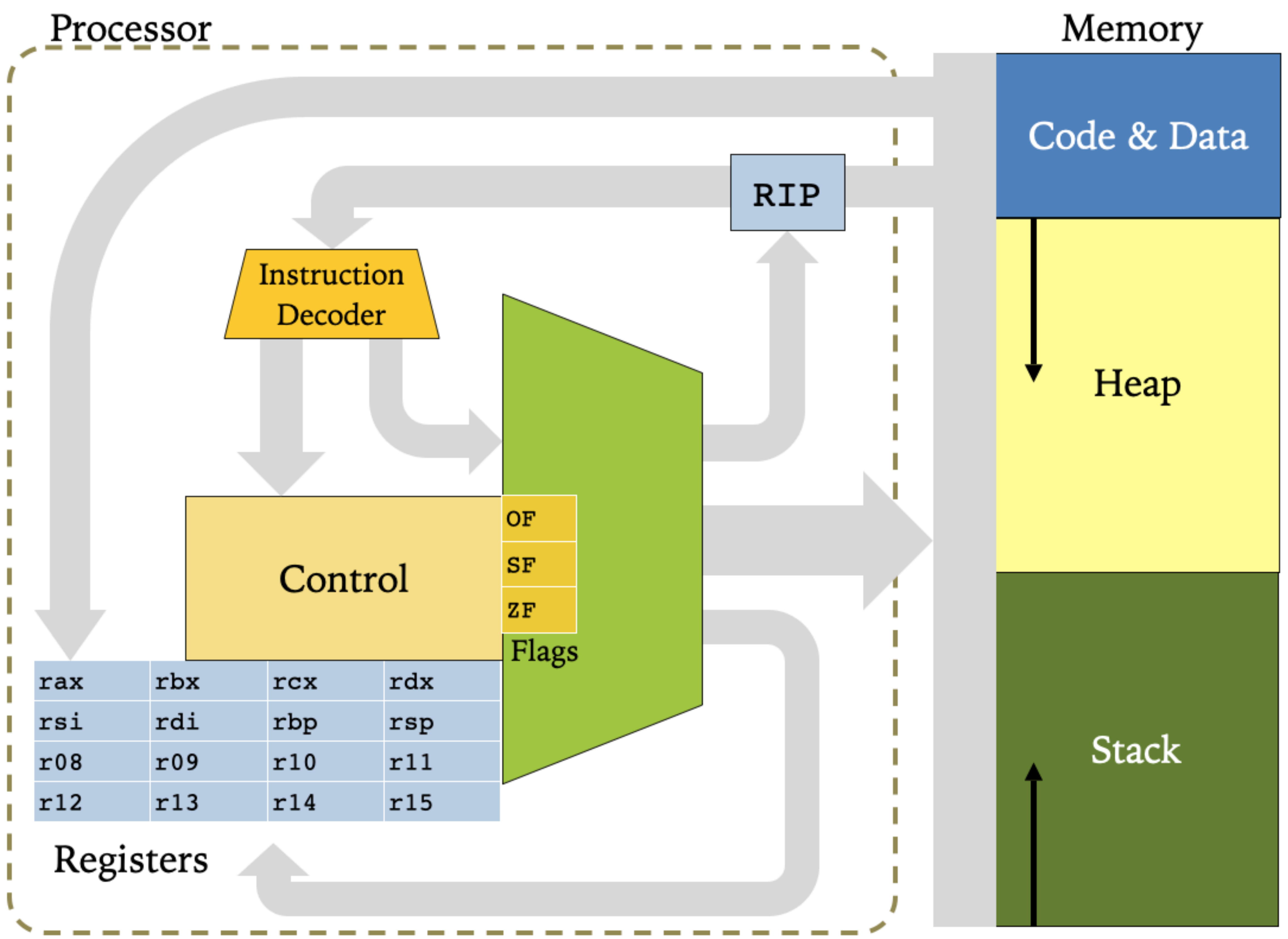
Comparisons and Conditioning

X86lite State: Flags & Condition Codes

- X86 instructions set flags as a side effect
- X86lite has only 3 flags:
  - `OF`: "overflow" set when the result is too big/small to fit in 64-bit reg.
  - `SF`: "sign" set to the sign or the result (0=positive, 1 = negative)
  - `ZF`: "zero" set when the result is 0

- From these flags, we can define *Condition Codes*
  - You can think of Cond. Codes as of additional registers, whose value changes depending on the current flags

- E.g., `cmpq` SRC1, SRC2 computes SRC1 – SRC2 to set the flags
- Now we can check conditional codes:
  - `eq` equality holds when `ZF` is set
  - `neq` inequality holds when (not `ZF`)
  - `lt` less than holds when `SF` <> `OF`
    - Equivalently: ((`SF` && not `OF`) || (not `SF` && `OF`))
  - `ge` greater or equal holds when (not lt) holds, i.e. (SF = OF)
  - `le` than or equal holds when `SF` <> `OF` or `ZF`
  - `gt` greater than holds when (not le) holds,
    - i.e. (SF = OF) && not(ZF)



Conditional Instructions

• `cmpq` SRC1, SRC2	Compute SRC2 – SRC1, set condition flags
• `setb` CC DEST	DEST's lower byte ← if CC then 1 else 0
• `j`CC SRC	`rip` ← if CC then SRC else do nothing

- Example:

`cmpq %rcx, %rax`	Compare `rax` to `ecx`
`jeq __truelbl`	If `rax` = `rcx` then jump to `__truelbl`

Code Blocks & Labels

- X86 assembly code is organized into *labeled blocks*:

```
label1:
        <instruction>
        <instruction>
        …
        <instruction>

label2:
        <instruction>
        <instruction>
        …
        <instruction>
```

  Labels indicate code locations that can be jump targets (either through conditional branch instructions or function calls).

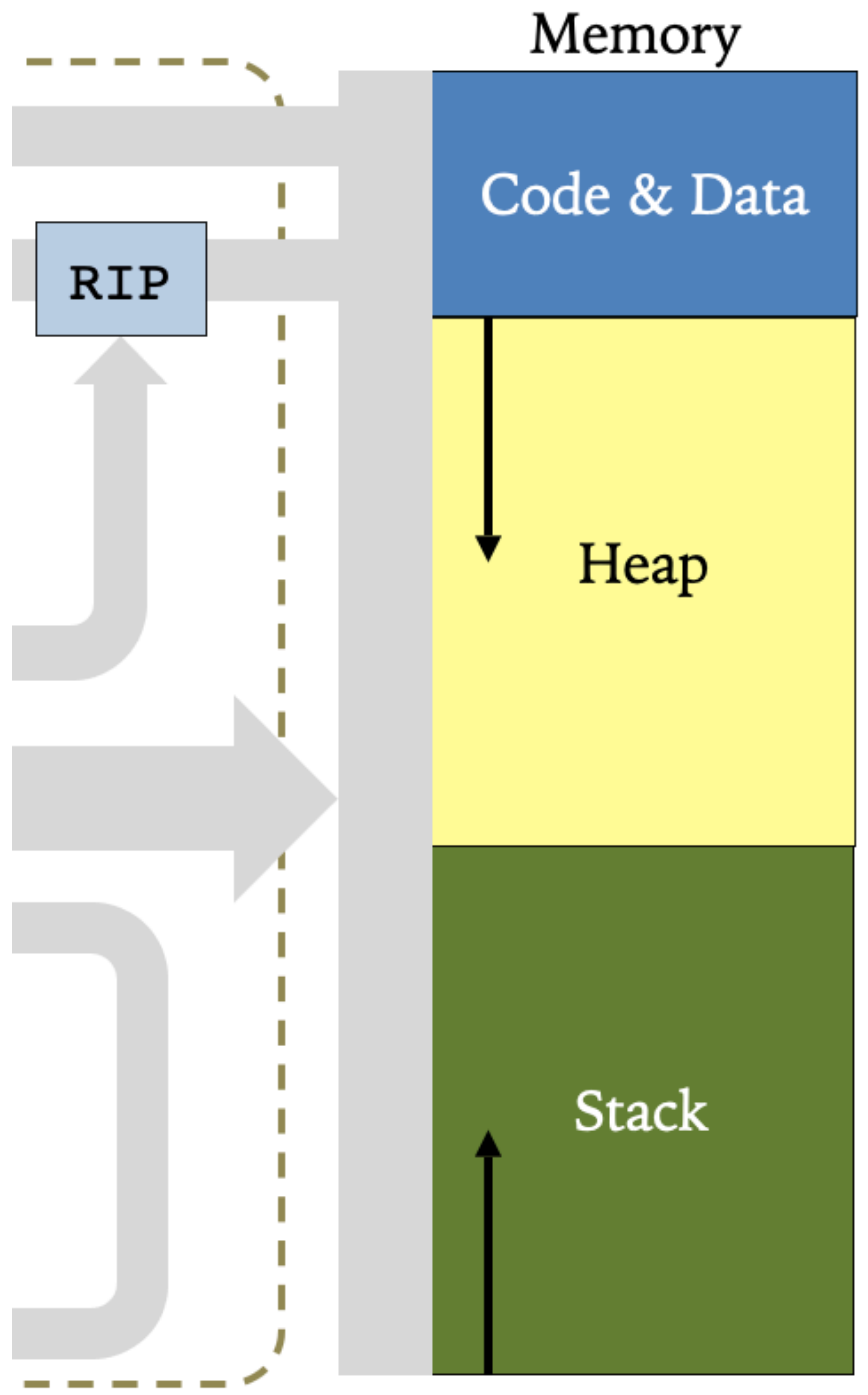
- Labels are translated away by the linker and loader – instructions live in the heap in the "code segment"

- An X86 program begins executing at a designated code label (usually "main").

Basic Control Flow

Jumps, Calls, and Return

- `jmp` SRC — `rip` ← SRC — Jump to location in SRC
- `callq` SRC — Push `rip`; `rip` ← SRC
  - Call a procedure: Push the program counter to the stack (decrementing `rsp`) and then jump to the machine instruction at the address given by SRC.
- `retq` — Pop into `rip`
  - Return from a procedure: Pop the current top of the stack into `rip` (incrementing `rsp`).
  - This instruction effectively jumps to the address at the top of the stack



Loop-based Factorial in Assembly

```
.globl  _program
_program:
    movq    $1, %rax
    movq    $6, %rdi
loop:
    cmpq    $0, %rdi
    je  exit
    imulq   %rdi, %rax
    decq    %rdi
    jmp loop
exit:
    retq
```

```
int program() {
  int acc = 1;
  int n   = 6;
  while (0 < n) {
    acc = acc * n;
    n = n - 1;
  }
  return acc;
}
```

Demo: Hand-Coded x86Lite

- https://github.com/ysc4230/week-02-x86lite
- Basic definitions: `x86.ml`
- Linking with assembly: `test.c`
- Example program, simple output, factorial

Compiling, Linking, Running

- To use hand-coded X86:
  1. Compile OCaml program `main1.ml` to the executable
  2. Run it, redirecting the output to some .s file, e.g.:
     ```
     ./main1.native >> prog.s
     ```
  3. Use gcc (or clang) to compile & link with `test.c:`
     ```
     gcc -o test test.c prog.s
     ```
  4. You should be able to run the resulting executable:
     ```
     ./test
     ```

Next lecture

- Compiling simple programs to X86lite
- Intermediate Representations