Lecture 3

CIS 341: COMPILERS

Announcements

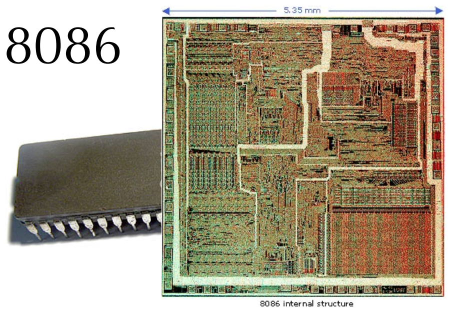
- HW1: Hellocaml!
  - is due *tonight* at 11:59:59pm.

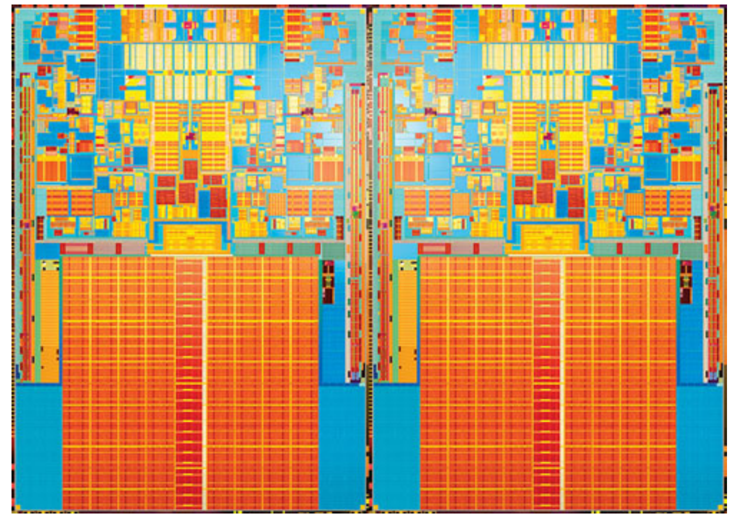
- HW2: X86lite
  - Will be available soon… look for an announcement on Piazza
  - Pair-programming project

The target architecture for CIS341

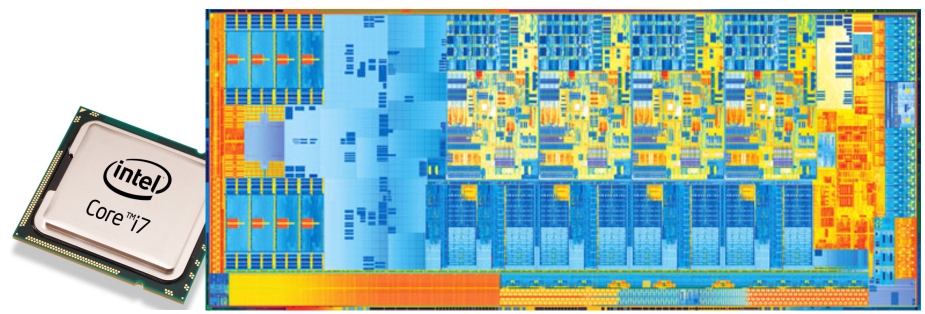
X86LITE

Intel's X86 Architecture



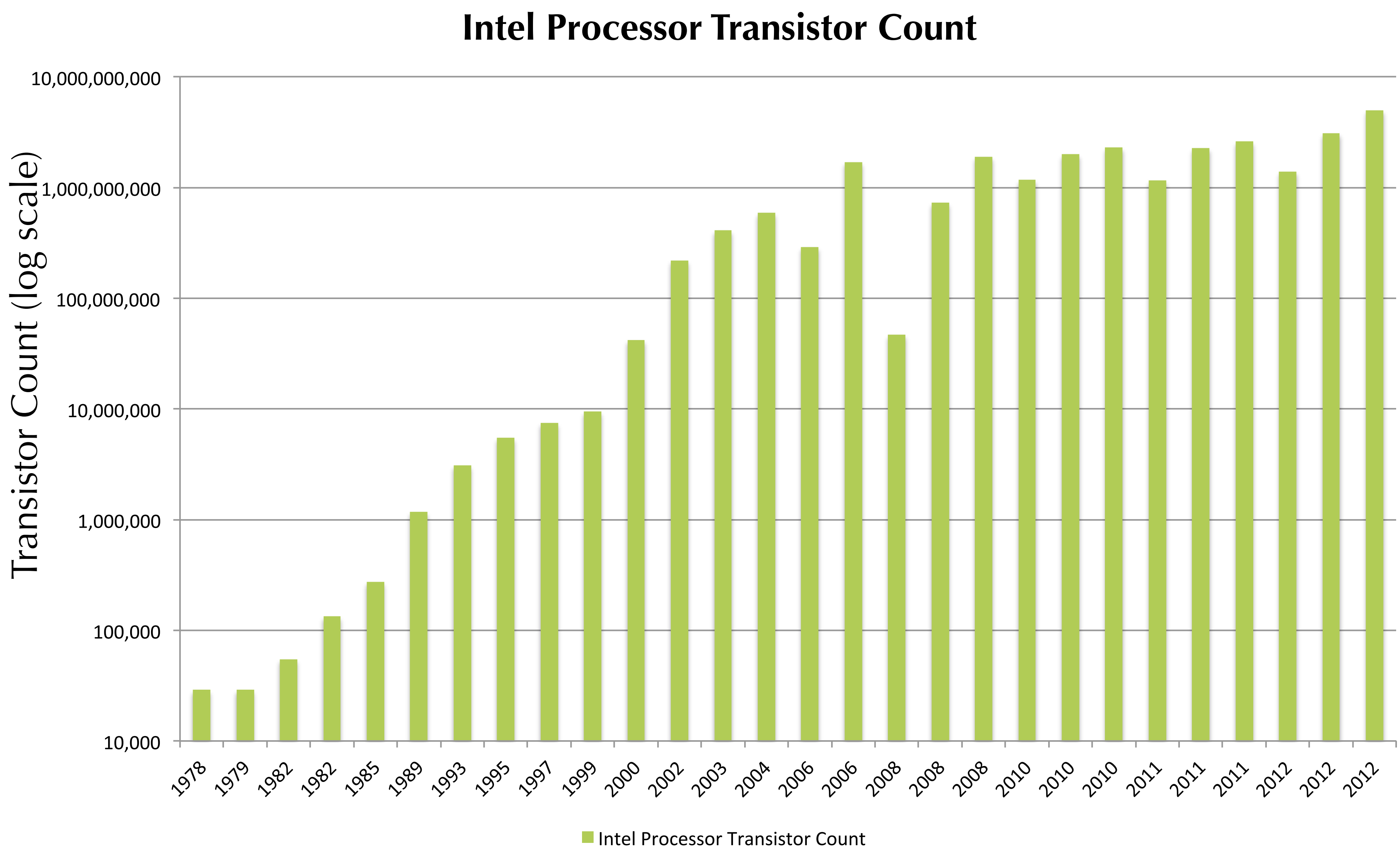


- 1978: Intel introduces 8086
- 1982: 80186, 80286
- 1985: 80386
- 1989: 80486
- 1993: Pentium
- 1995: Pentium Pro
- 1997: Pentium II/III
- 2000: Pentium 4
- 2003: Pentium M, Intel Core
- 2006: Intel Core 2
- 2008: Intel Core i3/i5/i7
- 2011: SandyBridge / IvyBridge
- 2013: Haswell



- AMD has a parallel line of processors

X86 Evolution & Moore's Law

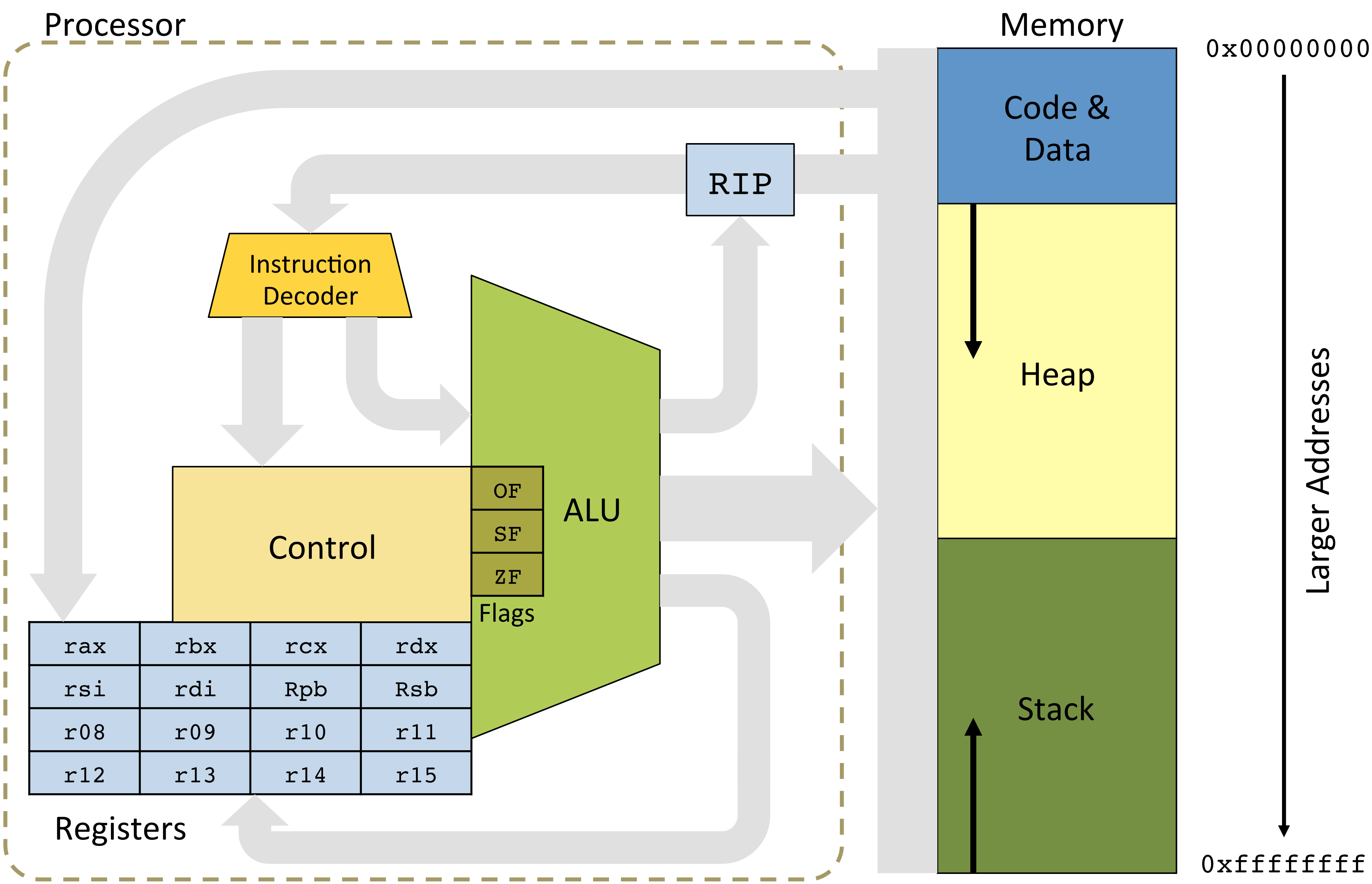


X86 vs. X86lite

- 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)

X86 Operands

- Operands are the values operated on by the assembly instructions

- Imm — 64-bit literal signed integer "immediate"

- Lbl — a "label" representing a machine address
  the assembler/linker/loader resolve labels

- Reg — One of the 16 registers, the value of a register is its contents

- Ind — [base:Reg][index:Reg,scale:int32][disp]
  machine address (see next slide)

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 numbered `0x00000000` through `0xffffffff`.
- 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` ← `rps - 8`; Mem[`rsp`] ← SRC
  - `popq` DEST DEST ← Mem[`rsp`]; `rsp` ← `rsp` + 8

X86lite State: Condition Flags & 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*
  - To compare SRC1 and SRC2, compute SRC1 – SRC2 to set the flags
  - `e` equality holds when **ZF** is set
  - `ne` inequality holds when (not **ZF**)
  - `g` greater than holds when (not **ZF**) and (not **SF**)
  - `l` less than holds when **SF** <> **OF**
    - Equivalently: ((**SF** && not **OF**) || (not **SF** && **OF**))
  - `ge` greater or equal holds when (not **SF**)
  - `le` than or equal holds when **SF** <> **OF** or **ZF**

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").

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 fallthrough
- Example:

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

Jumps, Call 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

See file: x86.ml

IMPLEMENTING X86LITE

See: runtime.c

DEMO: HANDCODING X86LITE

Compiling, Linking, Running

- To use hand-coded X86:
  1. Compile main.ml (or something like it) to either native or bytecode
  2. Run it, redirecting the output to some .s file, e.g.:
     ./handcoded.native >> test.s
  3. Use gcc to compile & link with runtime.c:
     gcc -o test runtime.c test.s
  4. You should be able to run the resulting exectuable:
     ./test

- If you want to debug in gdb:
  - Call gcc with the –g flag too