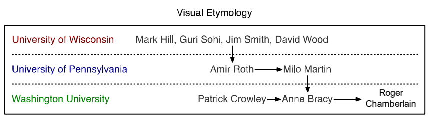
CSE 560
Computer Systems Architecture

Introduction



Administrative Stuff

- Instructor: Roger Chamberlain
  - Office – Jolley 210 Email – roger@wustl.edu
  - Office Hours – 4pm to 5pm Mondays and Wednesdays
- TAs: Chenfeng Zhao, Bryan Orabutt
  - Office Hours – TBD, at least some on Thur and Fri
- Please use Piazza over email for asking questions
  - Emails get lost in the pile, Piazza posts don't
- Webpage: https://www.cse.wustl.edu/~roger/560m.html
- Optional Text: J.-L. Baer, *Microprocessor Architecture: From Simple Pipelines to Chip Multiprocessors*, Cambridge University Press, 2010

Grading Logistics

- Three elements
  - Practice problems – approx. once per week
  - Assignments – typically simulation experiments
  - Two exams – equal coverage, no comprehensive final
- Practice problems
  - Solutions posted about one week after problems are posted
  - No impact on grade, but they are practice for exams
- Assignments
  - 4 or 5 during the course of the semester
- Exams
  - Closed book, one-page crib sheet is allowed
- Grading:
  - Assignments 20%
  - Exams – Oct 16, Dec 4 40% each (in class)

What is Computer Architecture?

"*Computer Architecture* is the science and art of selecting and interconnecting hardware components to create computers that meet functional, performance and cost goals."

- Old WWW Computer Architecture Page

An analogy to architecture of buildings…

What is ~~Computer~~ Architecture?

The role of a ***building*** architect:

Materials
Steel
Concrete
Brick
Wood
Glass

Design

Plans

Construction

Buildings
Houses
Offices
Apartments
Stadiums
Museums

Goals
Function
Cost
Safety
Ease of Construction
Energy Efficiency
Fast Build Time
Aesthetics

What is Computer Architecture?

The role of a *computer* architect:

Technology
Logic Gates
SRAM
DRAM
Circuit Techniques
Packaging
Magnetic Storage
Flash Memory

Design

Plans

Manufacturing

Computer
Desktop
Servers
PDAs
Mobile Phones
Supercomputers
Game Consoles
Embedded

Goals
Function
Performance
Reliability
Cost/Manufacturability
Energy Efficiency
Time to Market

Important Differences…

- Age of discipline: 60 years (vs. 5,000 years)
- Automated mass production
  - Advances magnified over millions of chips
- Boot-strapping effect
  - Better computers help design next generation

  When Seymour Cray was told that Apple had just purchased a Cray computer that would be used in designing the next Macintosh, he thought for a minute, and replied that that seemed reasonable, since he was using a Macintosh to design the next Cray.
- Rate of change
  - Technology, Applications, Goals changing **quickly**

Survey Time

Which of the following statements is true?

A: If you can verify that a chip works correctly, you can be sure it will continue to work correctly in the future.

B: Chip manufacturing today has much better yield (of working chips) than it did decades ago.

C: Building reliable (correctly working) chips today is easier than it was decades ago.

D: It costs ~$300,000,000 to build a fabrication plant.

E: If you have an idea that can make a CPU run at a higher frequency, you should definitely implement it (i.e., it's always a good idea).

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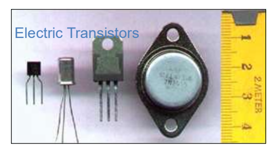
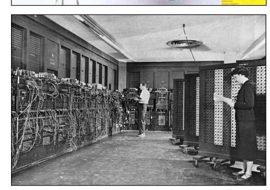
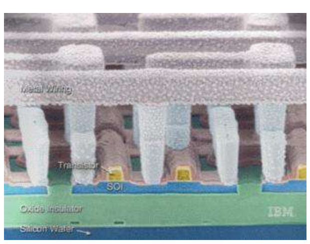
Bunch of fab shots

Old-school Transistors → Old-school Computers





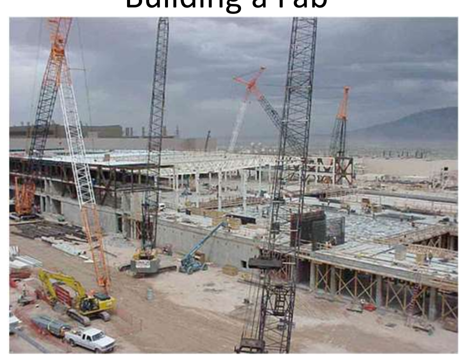
Modern Transistor



IBM SOI Technology

From slides © Krste Asanovic, MIT

Building a Fab



Intel Fab 11x project, Submicron Manufacturing Facility, Rio Rancho, New Mexico: Aug 28, 2000

Building a Fab

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Building a Fab

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Inside a Fab

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Inside a Fab

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Inside a Fab

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Inside a Fab

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Inside a Fab

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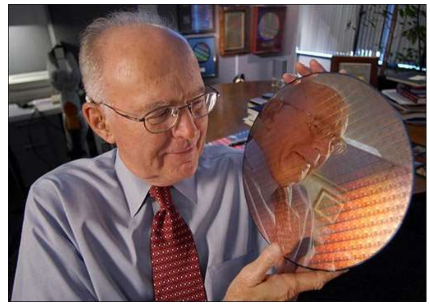
Gordon Moore with a Wafer



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Design Goals (1)

- **Functional**
  - Correctness – harder than software
  - What functions should it support?
- **Reliable**
  - Does it ***continue*** to perform correctly?
  - Hard fault vs. transient fault
  - Desktop vs. server vs. space probe reliability
- **High performance**
  - "Fast" — only meaningful in the context of set of tasks
  - Not just GHz – truck vs. sports car analogy
  - Impossible: fastest possible design for all programs

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Design Goals (2)

- **Low cost:** engineer's dime/fool's dollar
  - Per unit manufacturing cost (wafer cost)
  - Cost of making first chip after design (mask cost)
  - Design cost (huge design teams, why? Two reasons…)
- **Low power/energy – "the new performance"**
  - Energy in (battery life, cost of electricity)
  - Energy out (cooling and related costs)
- **Challenge: balancing these goals**
  - Balance constantly changing
  - Focus for us: **Performance**

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Shaping Force: Applications/Domains

Another shaping force: **applications** (usage and context)
Different domains → different needs → different designs

- **Scientific**: weather prediction, genome sequencing
  - 1st computing application domain: ballistics tables
  - **Need:** large memory, heavy-duty floating point
  - Examples: Cray XC, IBM BlueGene

  Making a comeback → anything that works on lots of data
- **Commercial**: database/web serving, e-commerce, Google
  - **Need:** data movement, high memory + I/O bandwidth
  - E.g., Intel Xeon, AMD Opteron

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Question for Later

Which of the following is a correct quote?

1. "I think there is a world market for maybe five computers." Thomas J. Watson, chairman of the board, IBM, 1943
2. "There is no reason for any individual to have a computer in his home." Ken Olson, founder, Digital Equipment Corp., 1972

A: only 1 is correct
B: only 2 is correct
C: both are correct quotes
D: neither are correct quotes

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More Applications/Domains

- **Desktop**: home office, multimedia, games
  - **Need:** integer, memory b/w, integrated graphics/network?
  - Examples: Intel Core 2, Core i7, AMD Athlon, PowerPC G5
- **Mobile**: laptops, mobile phones
  - **Need:** **low power**, integer performance, integrated wireless
  - Laptops: Intel Core 2 Mobile, Atom, AMD Turion
  - Examples: ARM chips by Samsung and others, Intel Atom
- **Embedded**: microcontrollers in automobiles, door knobs
  - **Need:** low power, **low cost**
  - Examples: ARM chips, dedicated digital signal processors (DSPs)
  - Over 1 billion ARM cores sold in 2006 (at least one per phone)
- **Deeply Embedded**: disposable "smart dust" sensors
  - **Need:** extremely low power, extremely low cost

Application Specific Designs

- This class mostly about **general-purpose CPUs**
  - Processor that can do anything, run a full OS, *etc.*
  - *E.g.*, Intel Core i7, AMD Opteron, IBM Power, ARM
- In contrast to **application-specific chips**
  - Or ASICs (Application specific integrated circuits)
  - Implement critical domain-specific functionality in hardware
    - Examples: video encoding, cryptography
  - General rules
    - \- Hardware is less flexible than software
    - \+ Hardware more effective (speed, power, cost) than software
    - \+ Domain specific more "parallel" than general purpose
      - *But general mainstream processors becoming more parallel!*
- **Trend:** from specific to general (for a specific domain)

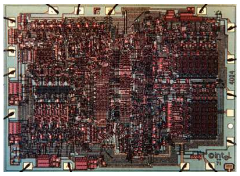
Revolution I: The Microprocessor

- **Microprocessor revolution:** 16-bit processor on 1 chip!
  - 1970s, ~25K transistors
  - Performance advantages: fewer slow chip-crossings
  - Cost advantages: one "stamped-out" component
- **Out with the old**
  - Microprocessor-based systems replace supercomputers, "mainframes", "minicomputers", *etc.*
- **In with the new**
  - Desktops, CD/DVD players, laptops, game consoles, set-top boxes, cell phones, digital camera, ipods, GPS…

First Microprocessor

Intel 4004 (1971)

- Application: calculators
- Technology: 10 μm PMOS
- 2300 transistors
- 13 mm^2
- 108 kHz
- 12 Volts
- 4-bit data
- Single-cycle datapath

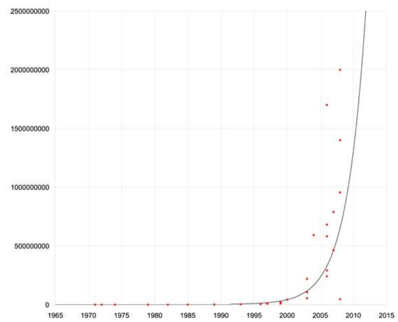


Pinnacle of Single-Core Microprocessors

Intel Pentium4 (2003)

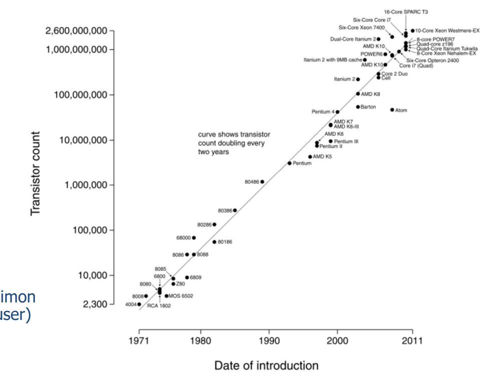
- Application: desktop/server
- Technology: 0.09 μm CMOS (1/100X)
- 55M transistors (20,000X)
- 101 mm^2 (10X)
- 3.4 GHz (10,000X)
- 1.2 Volts (1/10X)
- 32/64-bit data (16X)
- 22-stage pipelined datapath
- 4 instructions per cycle (superscalar)
- Two levels of on-chip cache
- data-parallel (SIMD) instructions, hyper-threading

Transistor Counts: Bad Graph



Transistor Counts: Good Graph

Microprocessor Transistor Counts 1971-2011 & Moore's Law



Source: wgsimon (wikipedia user)

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What to do with all these transistors?

First things first: expressiveness

- Widen the datapath (4004: 4 bits → Pentium4: 64 bits)

- More powerful instructions
  - To amortize overhead of fetch and decode
  - To simplify programming (done by hand then)

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Revolution II: Implicit parallelism

Extract implicit instruction-level parallelism (ILP)

- Hardware parallelizes, software is oblivious

Round 1:

- **Pipelining** → increased clock frequency
- **Caches**: became necessary as frequencies increased
- Integrated floating-point

Round 2:

- Deeper pipelines and **branch speculation**
- Multiple issue (**superscalar**)
- Dynamic scheduling (**out-of-order execution**)

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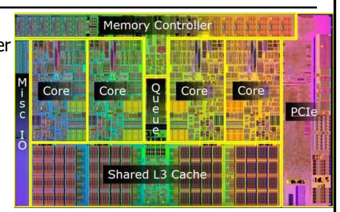
Relatively Recent Multicore Processor

Intel Core i7 (2009)

- Application: desktop/server
- Technology: 45nm (1/2x)

- 774M transistors (12x)
- 296 mm2 (3x)
- 3.2 GHz to 3.6 Ghz (~1x)
- 0.7 to 1.4 Volts (~1x)



- 128-bit data (2x)
- 14-stage pipelined datapath (0.5x)
- 4 instructions per cycle (~1x)
- Three levels of on-chip cache
- data-parallel vector (SIMD) instructions, hyperthreading
- **Four-core multicore** (4x)

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Revolution III: Explicit Parallelism

Support explicit data & thread level parallelism

- HW provides parallel resources, SW specifies usage
- Why? Diminishing returns on ILP

Round 1: Vector instructions…, Intel's SSE

- One instruction → 4 parallel multiplies

Round 2: Support for multi-threaded programs

- Coherent caches, hardware synchronization primitives

Round 3: Support for multiple concurrent threads on chip

- Single-core **multi-threading** → **multi-core**

Round 4: highly parallel Graphics processing units (GPUs)

- Converging with general-purpose processors (CPUs)?
- AMD bought ATI, Intel making GPUs

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Constant Change

<u>Technology</u>
Logic Gates
SRAM
DRAM
Circuit Techniques
Packaging
Magnetic Storage
Flash Memory

<u>Applications/Domains</u>
Desktop
Servers
PDAs
Mobile Phones
Supercomputers
Game Consoles
Embedded

<u>Constraints</u>
Function
Performance
Reliability
Cost/Manufacturability
Energy Efficiency
Time to Market

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Technology Disruptions

Classic examples:

- The transistor
- Microprocessor

More recent examples:

- Multicore processors
- Flash-based solid-state storage

Near-term potentially disruptive technologies:

- Phase-change memory (non-volatile memory)
- Chip stacking (also called 3D die stacking)

Disruptive "end-of-scaling"

- "If something can't go on forever, it must stop eventually"
- Can we continue to shrink transistors for ever?
- Even if more transistors, not getting as energy efficient as fast

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Pervasive Idea: Abstraction and Layering

- **Abstraction**: divide complex systems into objects with:
  - **Interface:** for the common folk
  - **Implementation**: "black box" for the specialists
  - E.g., car, only mechanics understand implementation
- **Layering**
  - Implement X using interface of layer just below
  - Ignore lower layers (sometimes helps)
- **Inertia**: a dark side of layering
  - Interfaces become stagnant ("standards")
  - – Getting layers to cooperate (Intel & Microsoft)
  - *"Company X now making product Y"*
- **Opacity**: hard to reason about performance across layers

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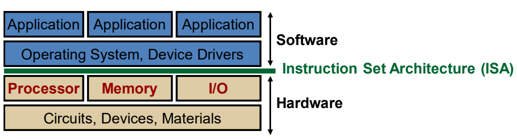
Abstraction, Layering, and Computers



- **Computer architecture**
  - Define **ISA** to facilitate software implementation layers
- This course mostly about **computer organization**
  - Design **Processor**, **Memory**, I/O to implement **ISA**
- Touch on compilers & OS (N+1), circuits (N-1) as well

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Survey Time

Which of the following statements is false?

A: A programmer needs to understand how a processor handles memory traffic to ensure program correctness.

B: The number of companies designing their own chips gets smaller every year.

C: A programmer must understand how a particular chip's functional units work to ensure program correctness.

D: If a programmer doesn't care about performance, she doesn't gain much by understanding the architecture her program is running on.

E: All of them are false.

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Why Study Computer Architecture?

- **Understand where computers are going**
  - Future capabilities drive the (computing) world
  - Real impact: better computers make more things possible
- **Get a (design or research) hardware job**
  - Intel, AMD, IBM, ARM, Apple, NVIDIA, NEC, Samsung
- **Get a (design or research) software job**
  - Best software designers understand hardware
  - Need to understand hardware to write fast software

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Course Goals

- **Understand "big ideas" in computer architecture**
  - Including spectre and meltdown security lapses!
- **Be a better scientist:** this is a *great* scientific playground
  - Good & bad engineering
  - Experimental evaluation/analysis ("science" in CS)
    - Computer performance and metrics
    - Quantitative data and experiments
    - Experimental design & Results presentation
- **Get your geek on**: think/speak like a computer architect
  - Possibly whether you want to or not ☺

Earlier Question

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But back then, #2 was right.