U. Wisconsin CS/ECE 752
Advanced Computer Architecture I

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Unit 0: Introduction

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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." - WWW Computer Architecture Page

- An analogy to architecture of buildings…

What is ~~Computer~~ Architecture?

The role of a building architect:

Construction

Materials → Design → Plans → Construction → **Buildings**

Materials
- Steel
- Concrete
- Brick
- Wood
- Glass

Design

Plans

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:

Manufacturing

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

Design

Plans

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

Computer
PCs
Servers
PDAs
Mobile Phones
Supercomputers
Game Consoles
Embedded

Three important differences: age (~70 years vs thousands), rate of change, automated mass production (magnifies design)

Design Goals

- Functional
  - Needs to be correct
  - What functions should it support (Turing completeness aside)
- Reliable
  - Does it continue to perform correctly?
  - Hard fault vs transient fault
  - Space probe vs PC reliability
- High performance
  - "Fast" is only meaningful in the context of a set of important tasks
  - Not just "Gigahertz"
  - Impossible goal: fastest possible design for all programs

Design Goals

- Low cost
  - Per unit manufacturing cost (wafer cost)
  - Cost of making first chip after design (mask cost)
  - Design cost (huge design teams)
- Low power
  - Energy in (battery life, cost of electricity)
  - Energy out (cooling and related costs)
  - Static vs dynamic power, sleep modes, peak vs average
- Challenge: balancing the relative importance of these goals
  - And the balance is constantly changing

Constant Change

“Technology”

Logic Gates
SRAM
DRAM
Circuit Techniques
Packaging
Magnetic Storage
Flash Memory

Applications/Domains

PCs
Servers
PDAs
Mobile Phones
Supercomputers
Game Consoles
Embedded

Goals

Function
Performance
Reliability
Cost/Manufacturability
Energy Efficiency
Time to Market

- Absolute improvement, **different rates of change**, **cyclic**
- Better computers help design the next generation

Rapid Change

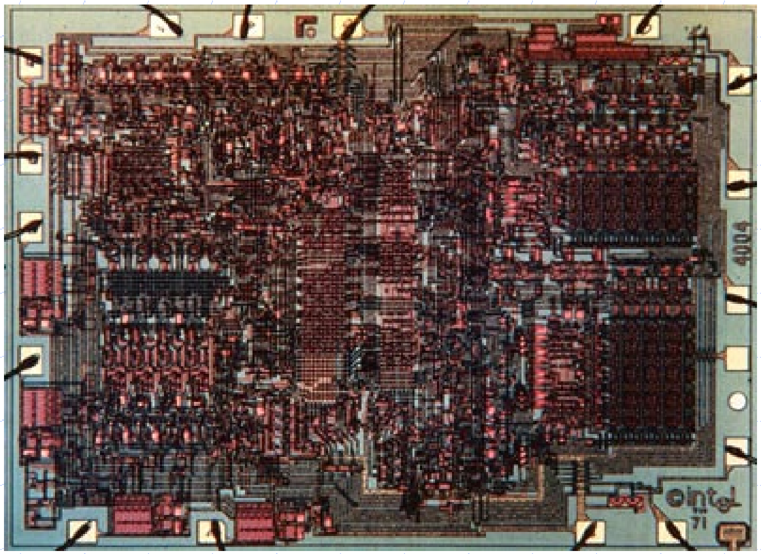
	1971–1980	1981–1990	1991–2000	2008	2018
Transistors (M)	0.01–0.1	0.1–1	1–100	300-1000	10000
Clock (MHz)	0.2–2	2–20	20–1000	3500	4000
MIPS	<0.2	0.2–20	20–2000	7000	10000

- Exciting: perhaps the fastest moving field … ever
  - Processors vs. cars
    - 1985: processors = 1 MIPS, cars = 60 MPH
    - 2000: processors = 500 MIPS, cars = 30,000 MPH?

- Another exciting field? ML
  - Guess what: many ML advances are computational

First Microprocessor

- Connect a few transistors together to make…



- Intel 4004
  - 1971 (first microprocessor)
  - 4-bit data
  - 2300 transistors
  - 10 μm PMOS
  - 108 KHz
  - 12 V
  - 13 mm^2

Circa 2005 Microprocessor

- Or a few more to form…

- Intel Pentium4 + HT
  - 2003
  - 32/64-bit data
  - 55M transistors
  - 0.90 μm CMOS
  - 3.4 GHz
  - 1.2 V
  - 101 mm^2

By end of course, this will make sense!

- Pentium 4 specifications: what do each of these mean?
  - Technology
    - 55M transistors, 0.90 μm CMOS, 101 mm^2, 3.4 GHz, 1.2 V
  - Performance
    - 1705 SPECint, 2200 SPECfp
  - ISA
    - X86+MMX/SSE/SSE2/SSE3 (X86 translated to RISC uops inside)
  - Memory hierarchy
    - 64KB 2-way insn trace cache, 16KB D$, 512KB–2MB L2
    - MESI-protocol coherence controller, processor consistency
  - Pipeline
    - 22-stages, dynamic scheduling/load speculation, renaming
    - 1K-entry BTB, 8Kb hybrid direction predictor, 16-entry RAS
    - 2-way hyper-threading
  - Circa 2020: Apple M1

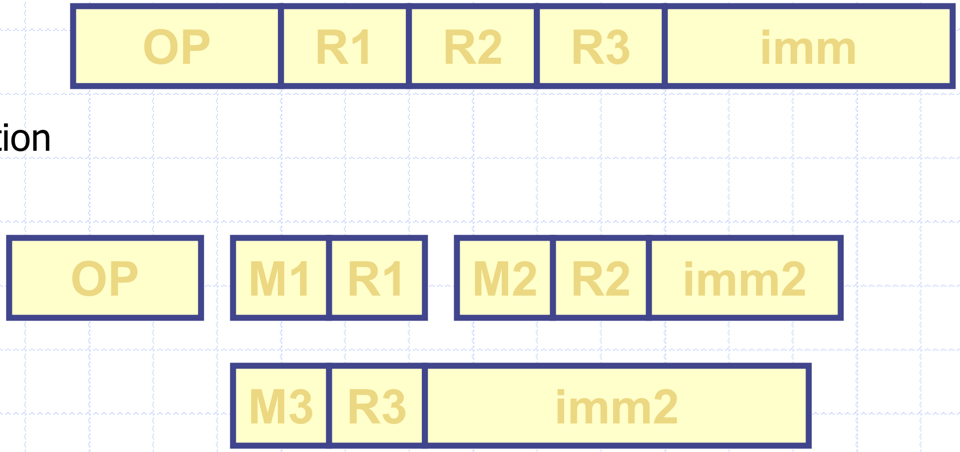
Layers of abstraction

- Architects need to understand computers at many levels
  - Instruction Set Architecture
  - Microarchitecture
  - Systems Architecture
  - Technology
  - Applications

- Good architects are "Jacks of most trades"

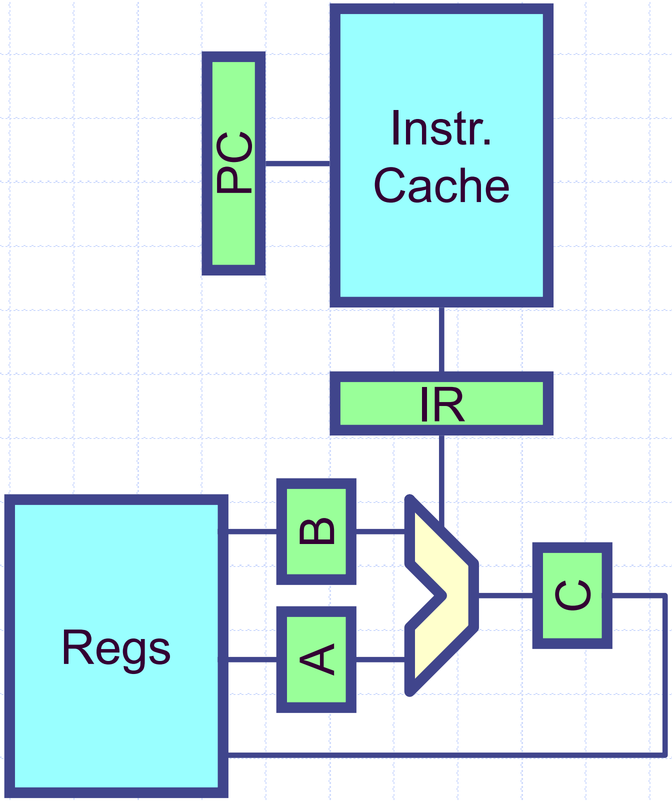
Instruction Set Architecture

- Hardware/Software interface
  - Software impact
    - support OS functions
      - restartable instructions
      - memory relocation and protection
    - a good compiler target
      - simple
      - orthogonal
    - Dense
      - Improve memory performance
  - Hardware impact
    - admits efficient implementation
      - across generations
    - admits parallel implementation
      - no 'serial' bottlenecks
  - Abstraction without interpretation



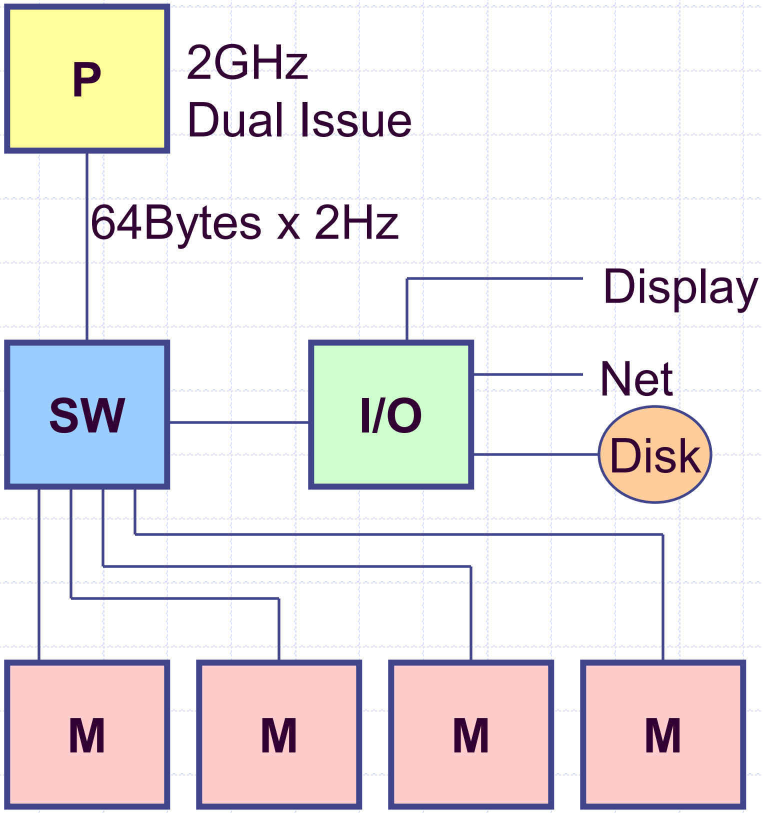
Microarchitecture

- Register-transfer-level (RTL) design
- Implement instruction set
- Exploit capabilities of technology
  - locality and concurrency
- Iterative process
  - generate proposed architecture
  - estimate cost
  - measure performance
- Still emphasis is on overcoming sequential nature of programs
  - deep pipelining
  - multiple issue
  - dynamic scheduling
  - branch prediction/speculation



System-Level Design

- Design at the level of processors, memories, and interconnect.
- More important to application performance, cost and power than CPU design
- Feeds and speeds
  - constrained by IC pin count, module pin count, and signaling rates
- System balance
  - for a particular application
- Driven by
  - performance/cost goals
  - available components (cost/perf)
  - technology constraints



Large-system example

- Google Datacenter: Oregon/Washington border
- Cheap electricity: Columbia river
- Cheap cooling: Columbia river
- Cheap b/w: surplus optic network from tech-boom era
- Amazon, Google, and Microsoft

Technology Trends

- Processor (SRAM)
  - Density: ~30%, Speed: ~20%
- Memory (DRAM)
  - Density: ~60%, Speed: ~4%
- Disk
  - Density: ~60%, Speed: ~10%

- **Changing quickly and with respect to each other!!**
  - Fundamentally changes design
  - Different tradeoffs

- Exciting: constant re-evaluation and re-design

Shaping Force: Applications/Domains

- Another shaping force: **applications**
  - Applications and application domains have different requirements
    - Domain: group with similar character
  - Lead to different designs

- **Scientific**: weather prediction, genome sequencing
  - First computing application domain: naval ballistics firing tables
  - Need: large memory, heavy-duty floating point
  - Examples: CRAY T3E, IBM BlueGene

- **Commercial**: database/web serving, e-commerce
  - Need: data movement, high memory + I/O bandwidth
  - Examples: Sun Enterprise Server, AMD Opteron, Intel Xeon, IBM Power

More Recent Applications/Domains

- **Desktop**: home office, multimedia, games
  - Need: integer, memory bandwidth, integrated graphics/network?
  - Examples: Intel Core i9
- **Mobile**: laptops
  - Need: **low power**, integer performance, integrated wireless?
  - Examples: Intel Core m3, Apple M1

- **Embedded**: PDAs, cell phones, automobiles, door knobs
  - Need: low power, **low cost**, integrated DSP?
  - Examples: Apple A11
- **Sensors**: disposable “smart dust”
  - Need: extremely low power, extremely low cost
- AI: from data centers to servers to mobiles

Application Specific Designs

- This course is mostly about **general-purpose CPUs**
  - CPU that can do anything, specifically run a full OS
- Large, profitable segment of **application-specific CPUs**
  - Implement some critical domain-specific functionality in hardware
    - Graphics engines, physics engines, AI hardware

  \+ Much more effective (performance, power, cost) than software

  \+ General rule: hardware is better than software

Why Study Computer Architecture?

- **Understand where computers are going**
  - Future capabilities drive the computing world
  - Forced to think 5+ years in the future
- **Exposure to high-level design**
  - Less about "design" than "what to design"
  - Engineering, science, art
  - Architects paint with broad strokes
  - The best architects understand all the levels
    - Devices, circuits, architecture, compilers, applications
- **Understand hardware for software tuning**
- **Real-world impact**
  - no computer architecture $\rightarrow$ no computers!
- **Get a job** (design or research)

Course Prerequisites

- CS/ECE 552 Basic Architecture
  - Logic: gates, boolean functions, latches, memories
  - Datapath: ALU, register file, memory interface, muxes
  - Control: single-cycle control, micro-code
  - Caches & pipelining (will go into these in more detail here)
  - Some familiarity with assembly language
  - Hennessy & Patterson's "Computer Organization and Design"
- Also
  - CS 537 Operating Systems (processes, threads, & virtual memory)
  - C/Unix programming

Some Course Goals

- **Exposure to the "big ideas" in computer architecture**
- Exposure to examples of good (and some bad) engineering
- Understanding computer performance and metrics
  - Empirical evaluation
  - Understanding quantitative data and experiments
- "Research" exposure
  - Read research literature (i.e., papers)
  - Course project
  - Cutting edge proposals
- Non-goals: "how computers work", detailed design
- Let's look at course home page…