Computer Architecture

Lecture 2: Fundamental Concepts and ISA

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Based on original slides by Prof. Onur Mutlu

What Do I Expect From You?

"Chance favors the prepared mind."

(Louis Pasteur)

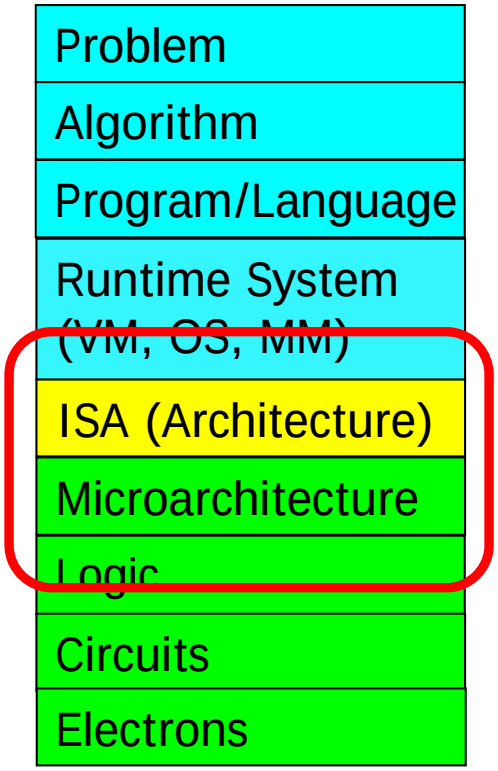
"كل عامل ميسر لعمله" (محمد، صلي الله عليه وسلم)

Agenda for Today

- Review
- Why study computer architecture?
- ISA
- Microarchitecture
- Computer Architecture
- Next Lecture

REVIEW

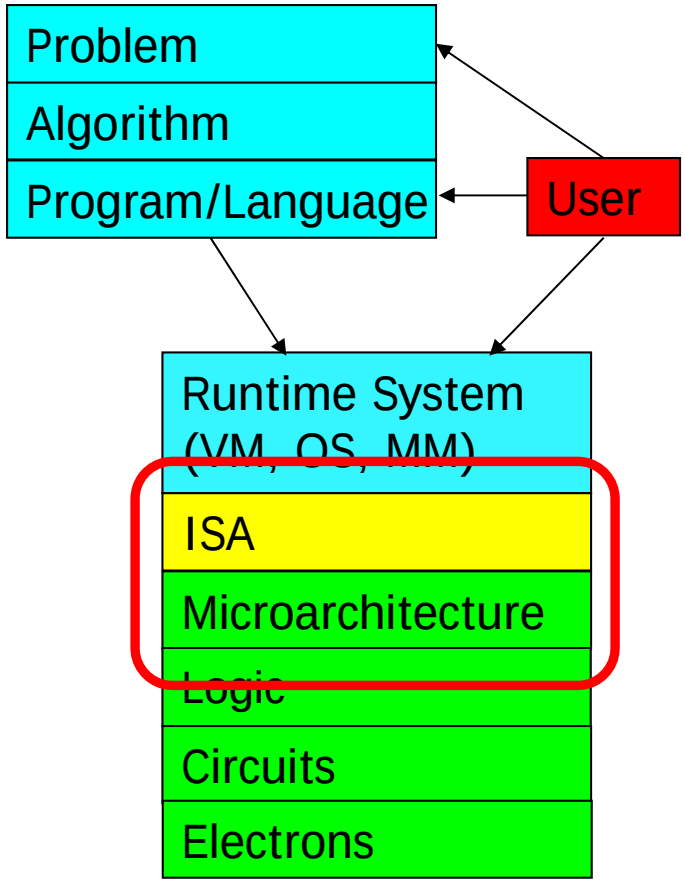
Review: Comp. Arch. in Levels of Transformation



- Read: Patt, "Requirements, Bottlenecks, and Good Fortune: Agents for Microprocessor Evolution," Proceedings of the IEEE 2001.

Review: Levels of Transformation, Revisited

- A user-centric view: computer designed for users

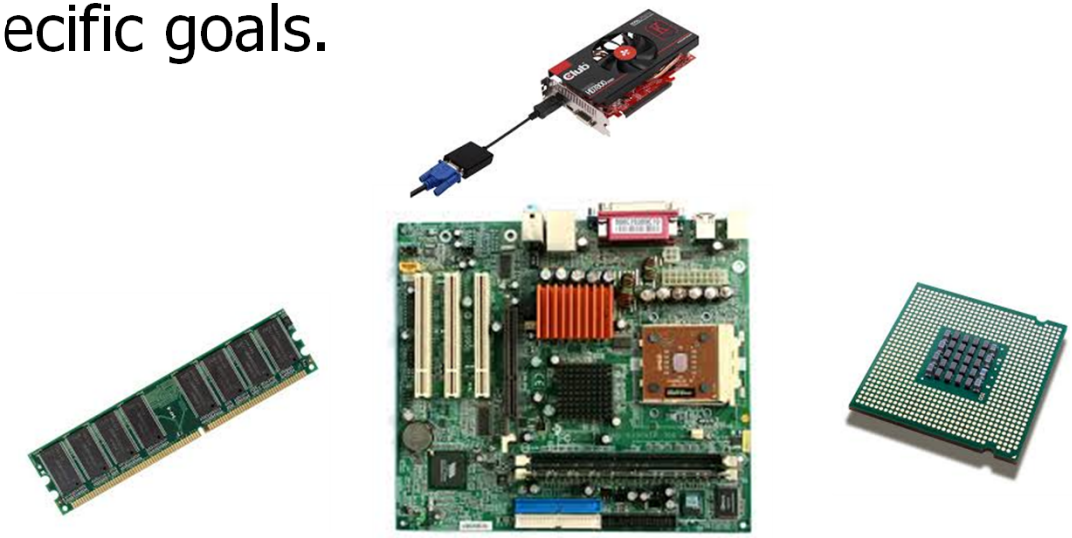


- The entire stack should be optimized for user

WHY STUDY COMPUTER ARCHITECTURE?

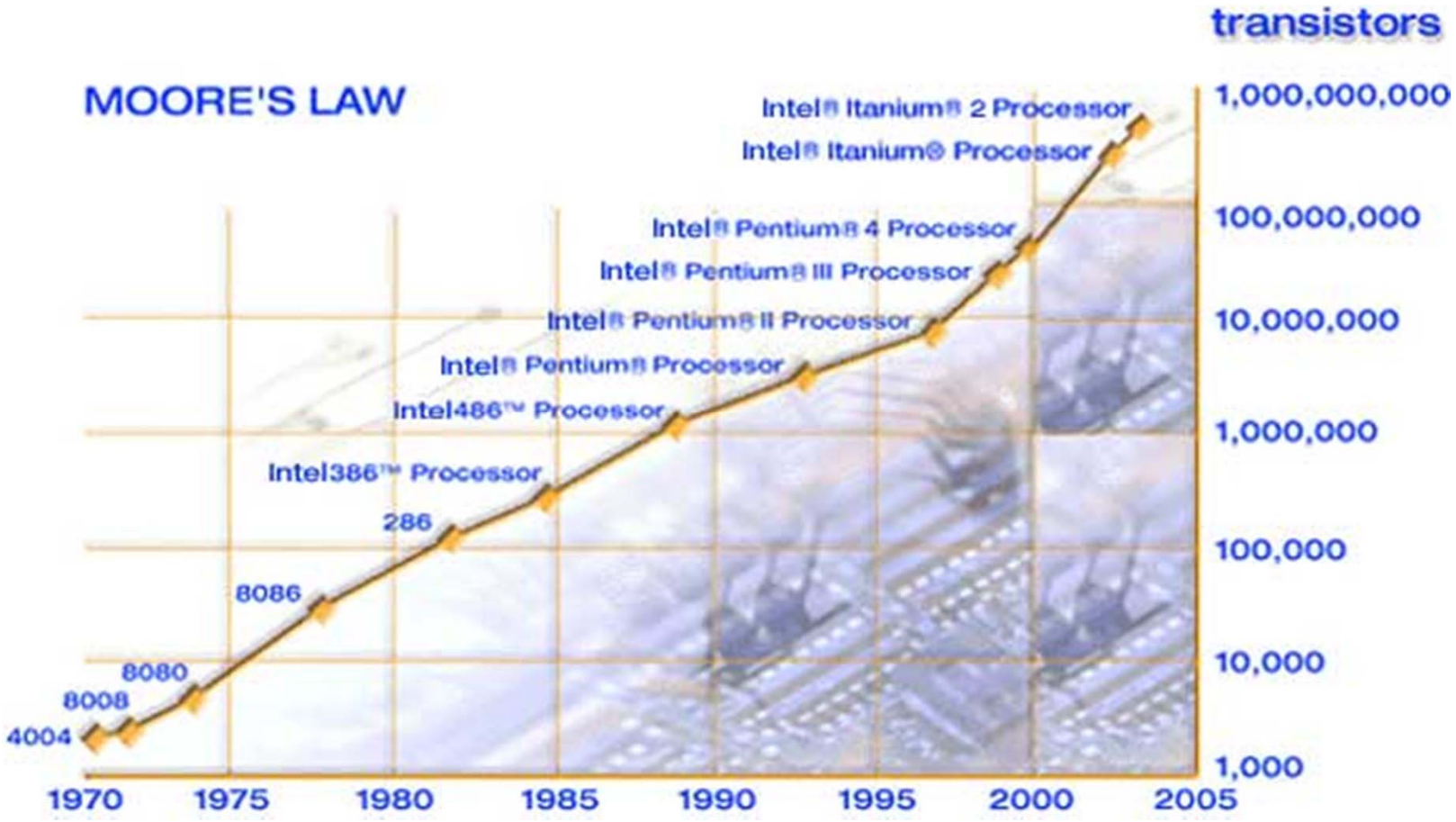
Why study Computer Architecture?

- The science and art of designing, selecting, and interconnecting hardware components and designing the hardware/software interface to create a computing system that meets functional, performance, energy consumption, cost, and other specific goals.



- We will soon distinguish between the terms *architecture*, and *microarchitecture*.

An Enabler: Moore's Law

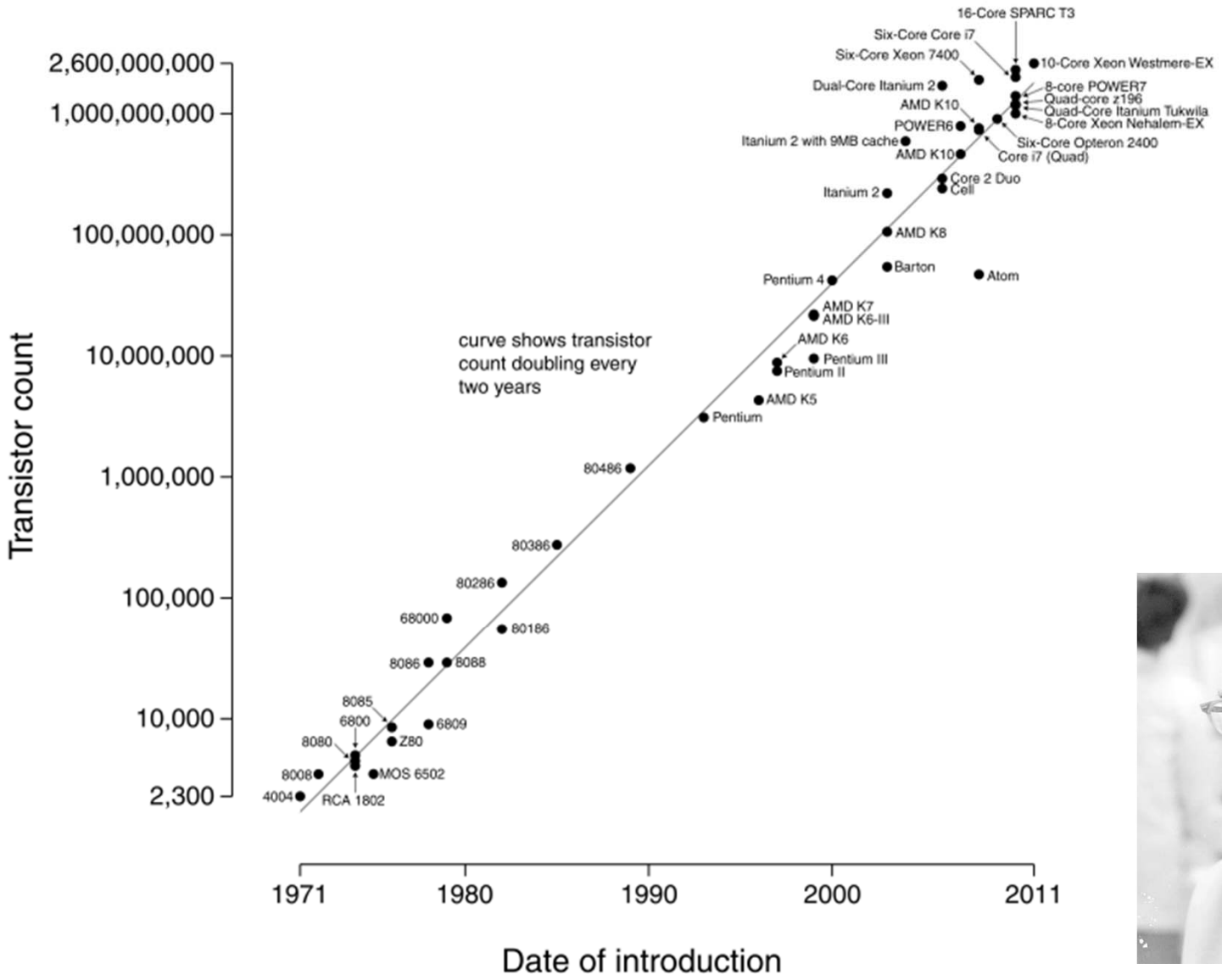


Moore, "Cramming more components onto integrated circuits," Electronics Magazine, 1965.

Component counts double every other year

Image source: Intel

Microprocessor Transistor Counts 1971-2011 & Moore's Law



Number of transistors on an integrated circuit doubles ~ every two years

Image source: Wikipedia

What Do We Use These Transistors for?

- Your readings for this week should give you an idea...

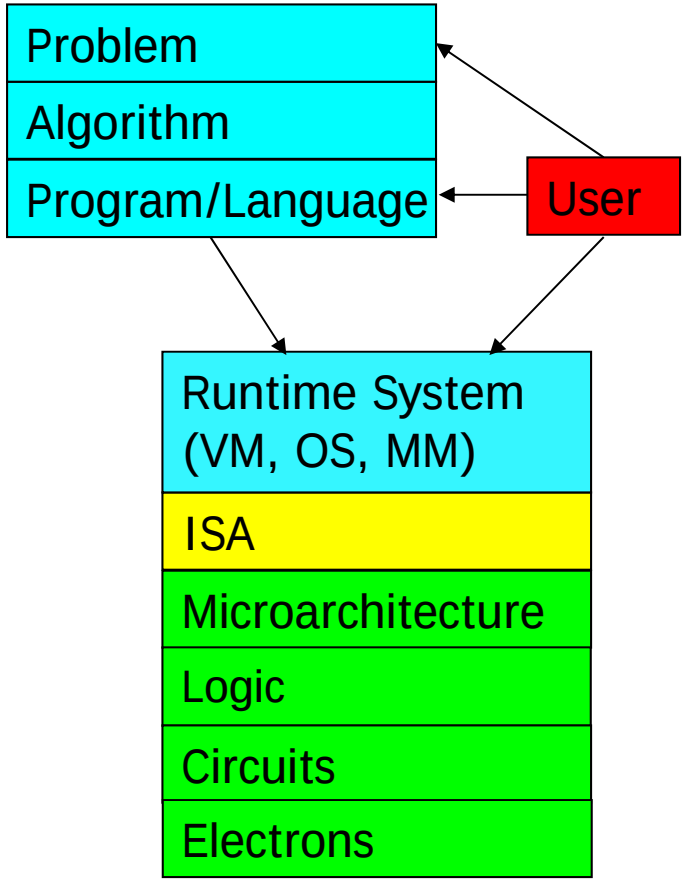
- Patt, "Requirements, Bottlenecks, and Good Fortune: Agents for Microprocessor Evolution," Proceedings of the IEEE 2001.

Computer Architecture Today

- Today is a very exciting time to study computer architecture
- Industry is in a large paradigm shift (to multi-core and beyond) – many different potential system designs possible
- Many difficult problems *motivating* and *caused by* the shift
  - Power/energy constraints
  - Complexity of design → multi-core?
  - Difficulties in technology scaling → new technologies?
    - Memory wall/gap
    - Reliability wall/issues
    - Programmability wall/problem
- No clear, definitive answers to these problems

Computer Architecture Today (II)

- These problems affect all parts of the computing stack – if we do not change the way we design systems



- You can invent new paradigms for computation, communication, and storage

Course Goals

- Goal 1: To familiarize those interested in computer system design with both fundamental operation principles and design tradeoffs of processor, memory, and platform architectures in today's systems.
  - Strong emphasis on fundamentals and design tradeoffs.

- Goal 2: To provide the necessary background and experience to design, implement, and evaluate a modern processor by performing hands-on RTL and C-level implementation.
  - Strong emphasis on functionality and hands-on design.

- Goal 3: Think critically (in solving problems), and broadly across the levels of transformation

… but, first …

- Let's understand the fundamentals...

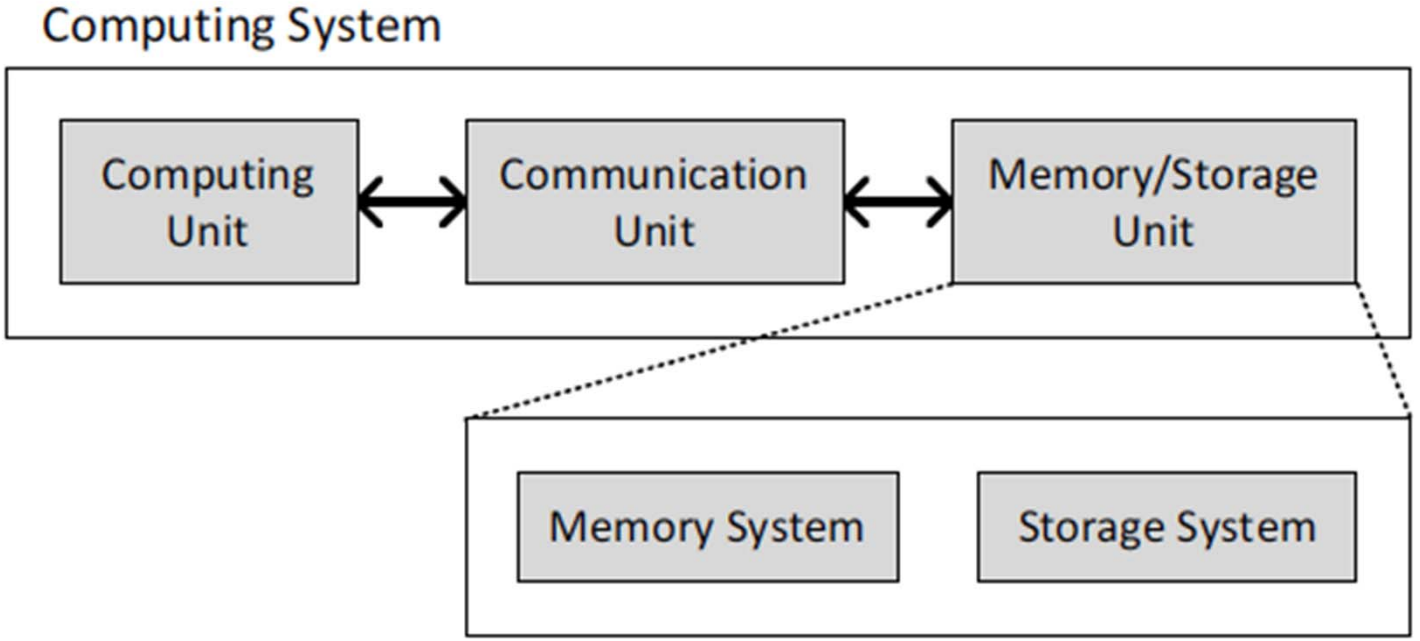
- You can change the world only if you understand it well enough...
  - Especially the past and present dominant paradigms
  - And, their advantages and shortcomings -- tradeoffs

INSTRUCTION SET ARCHITECTURE (ISA)

What is A Computer?

- Three key components

- Computation
- Communication
- Storage (memory)



The Von Neumann Model/Architecture

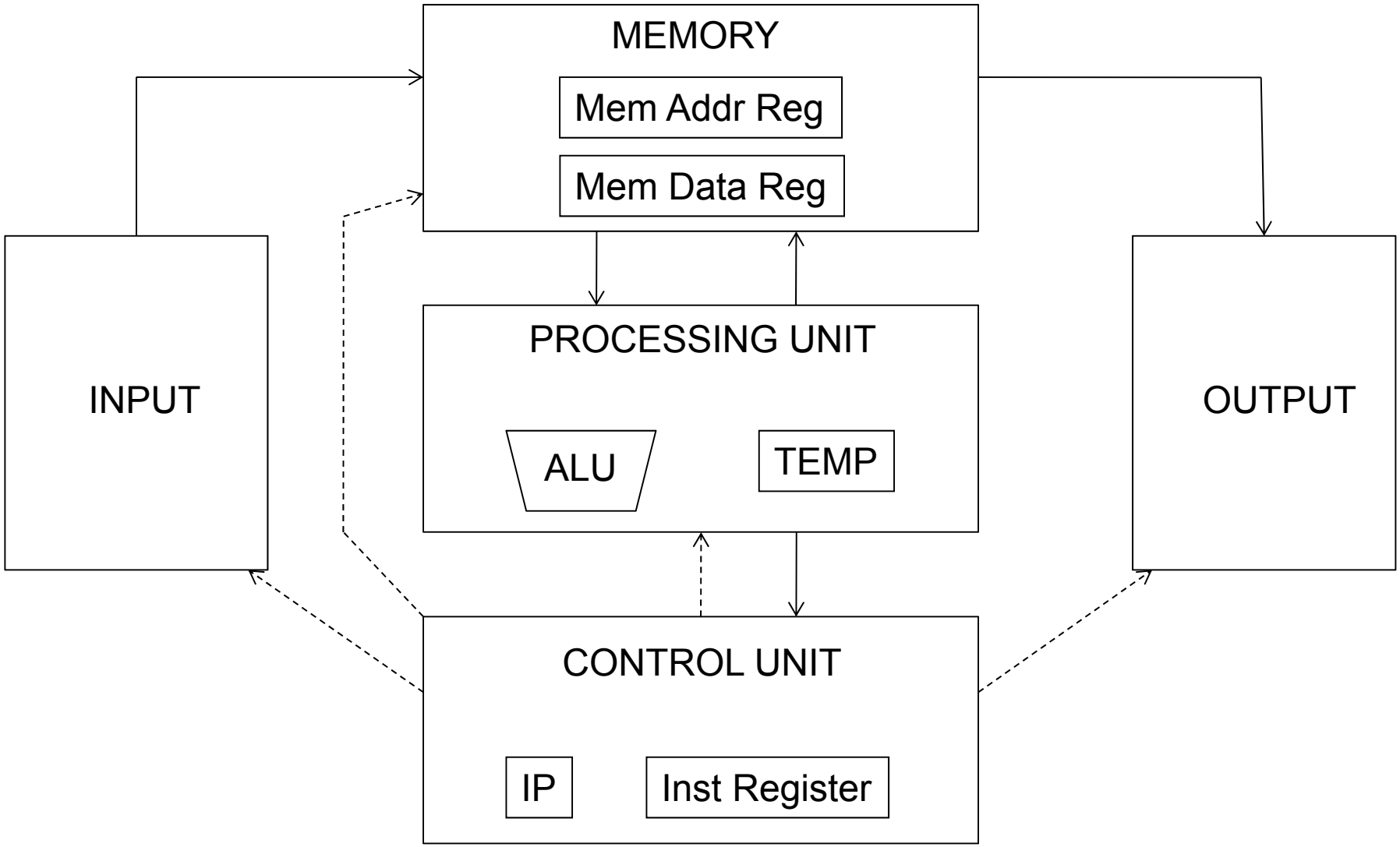
- Also called *stored program computer* (instructions in memory). Two key properties:

- Stored program
  - Instructions stored in a linear memory array
  - Memory is unified between instructions and data
    - The interpretation of a stored value depends on the control signals

When is a value interpreted as an instruction?

- Sequential instruction processing
  - One instruction processed (fetched, executed, and completed) at a time
  - Program counter (instruction pointer) identifies the current instr.
  - Program counter is advanced sequentially except for control transfer instructions

The von Neumann Model (of a Computer)



The Dataflow Model (of a Computer)

- Von Neumann model: An instruction is fetched and executed in control flow order
  - As specified by the instruction pointer
  - Sequential unless explicit control flow instruction

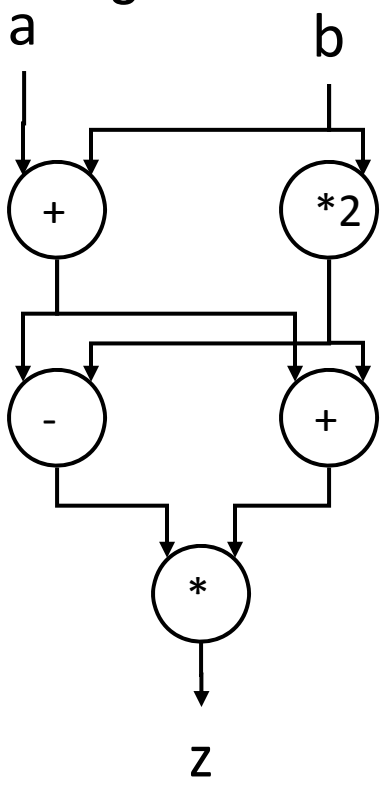
- Dataflow model: An instruction is fetched and executed in data flow order
  - i.e., when its operands are ready
  - i.e., there is no instruction pointer
  - Instruction ordering specified by data flow dependence
    - Each instruction specifies “who” should receive the result
    - An instruction can “fire” whenever all operands are received
  - Potentially many instructions can execute at the same time
    - Inherently more parallel

von Neumann vs Dataflow

- Consider a von Neumann program
  - What is the significance of the program order?
  - What is the significance of the storage locations?

```
v  = a + b;
w = b * 2;
x  = v - w
y  = v + w
z  = x * y
```

Sequential



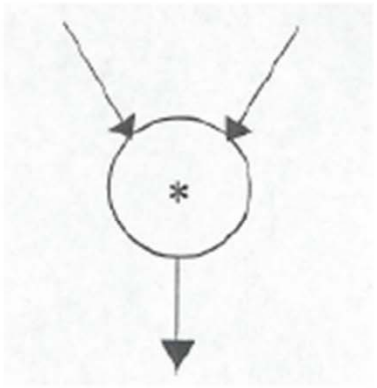
Dataflow

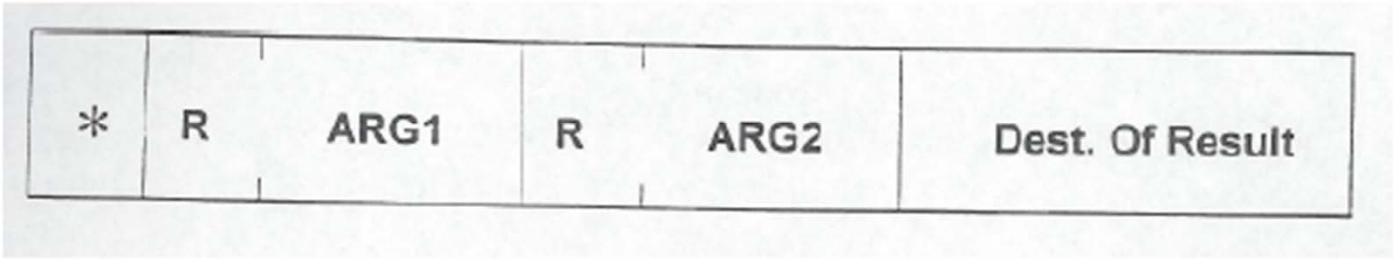
- Which model is more natural to you as a programmer?

More on Data Flow

- In a data flow machine, a program consists of data flow nodes
  - A data flow node fires (fetched and executed) when all it inputs are ready
    - i.e. when all inputs have tokens

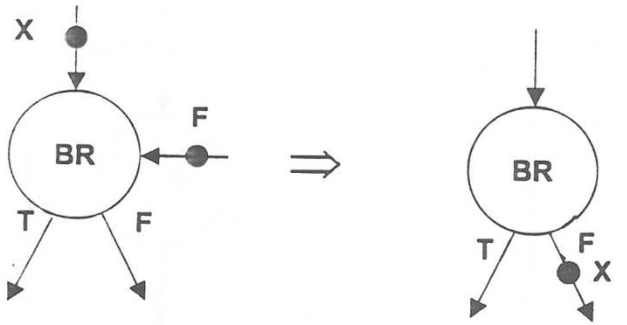
- Data flow node and its ISA representation



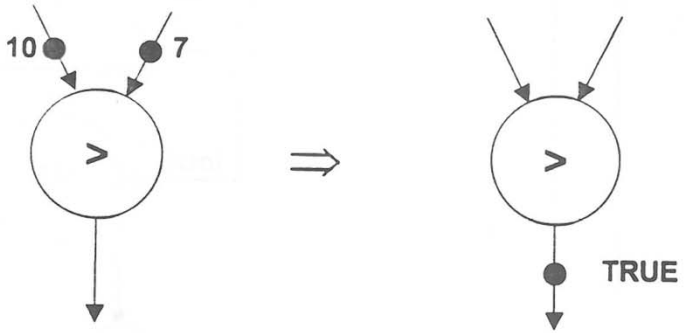


Data Flow Nodes

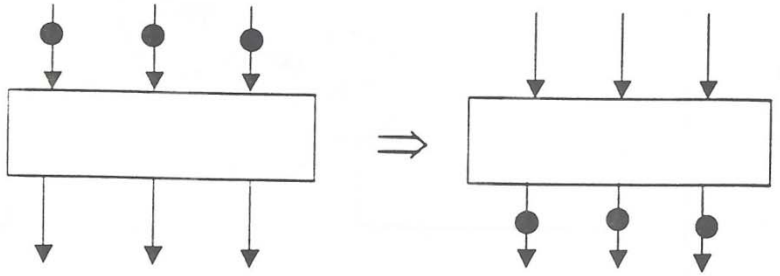
*Conditional



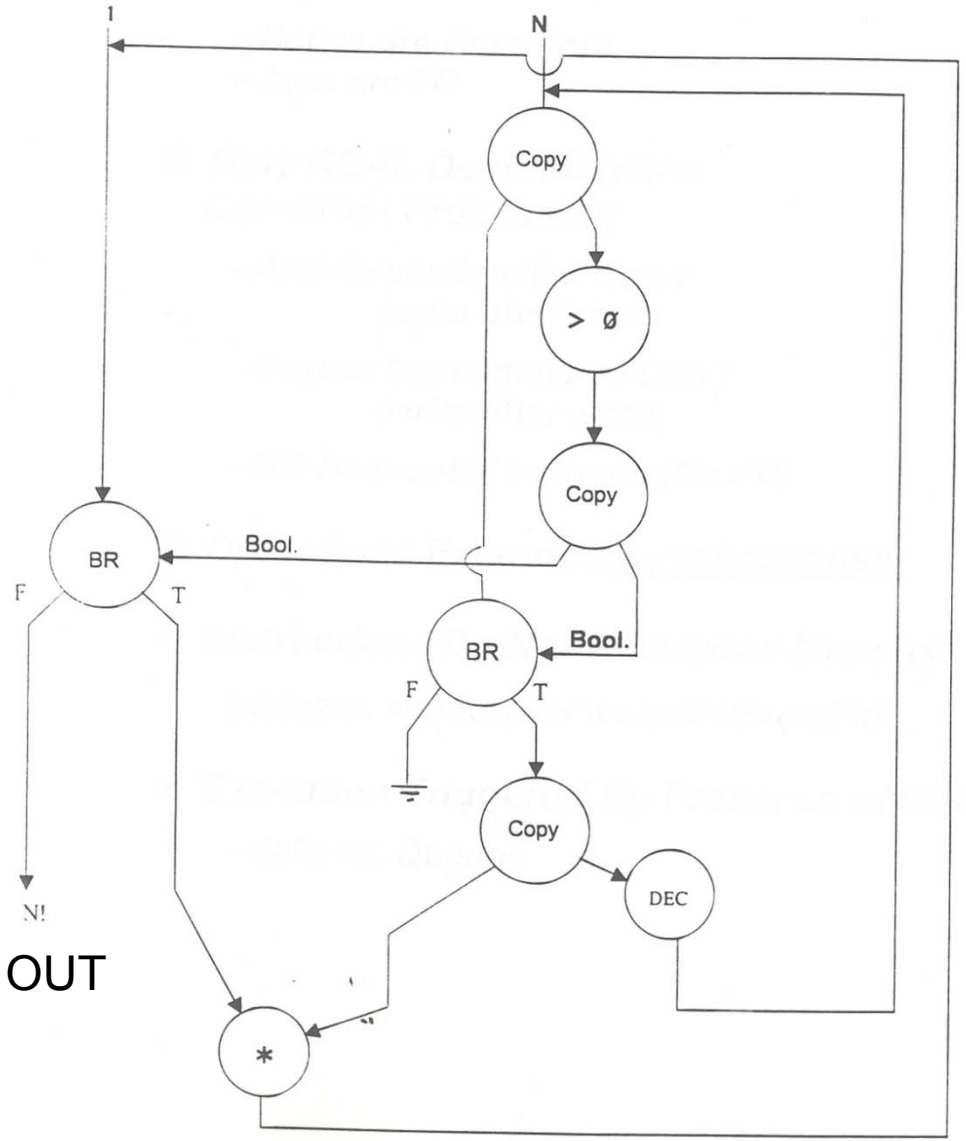
*Relational



*Barrier Synch



An Example Data Flow Program



ISA-level Tradeoff: Instruction Pointer

- Do we need an instruction pointer in the ISA?
  - Yes: Control-driven, sequential execution
    - An instruction is executed when the IP points to it
    - IP automatically changes sequentially (except for control flow instructions)
  - No: Data-driven, parallel execution
    - An instruction is executed when all its operand values are available (data flow)

- Tradeoffs: MANY high-level ones
  - Ease of programming (for average programmers)?
  - Ease of compilation?
  - Performance: Extraction of parallelism?
  - Hardware complexity?

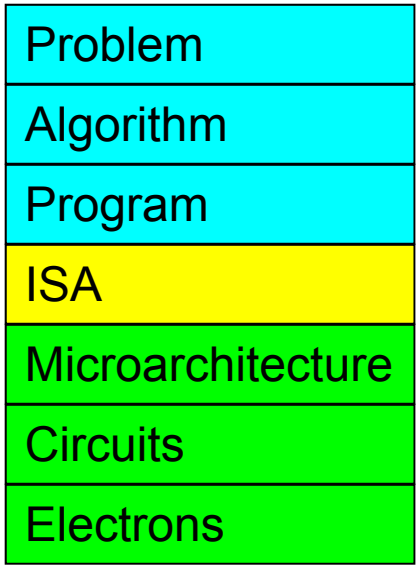
Remember

- Von Neumann and Data-flow is just models
- All major instruction set architectures today use this Von Neumann model
  - x86, ARM, MIPS, SPARC, Alpha, POWER

MICROARCHITECTURE

ISA vs. Microarchitecture

- What is part of ISA vs. Uarch?
  - Gas pedal: interface for "acceleration"
  - Internals of the engine: implement "acceleration"
- ISA
  - Agreed upon interface between software and hardware (SW/compiler assumes, HW promises)
  - What programmer needs to know to write and debug system/user programs and to specify to user a sequential control-flow or a data-flow execution order.
- Microarchitecture
  - Specific implementation of an ISA
  - Not visible to the software or the programmer
- Microprocessor
  - **ISA, uarch**, circuits
  - "Architecture" = ISA + microarchitecture



ISA Example

- Instructions
  - Opcodes, Addressing Modes, Data Types
  - Instruction Types and Formats
  - Registers, Condition Codes
- Memory
  - Address space, Addressability, Alignment
  - Virtual memory management
- Call, Interrupt/Exception Handling
- Access Control, Priority/Privilege
- I/O: memory-mapped vs. instr.
- Task/thread Management
- Power and Thermal Management
- Multi-threading support, Multiprocessor support

Intel® 64 and IA-32 Architectures
Software Developer's Manual

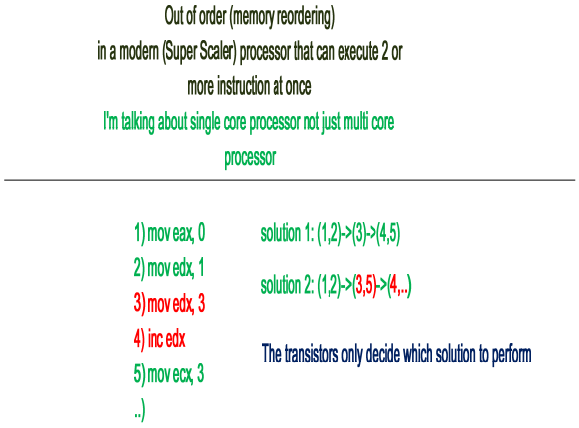
Microarchitecture Example

- Underneath (at the microarchitecture level), the execution model of almost all *implementations (or, microarchitectures)* is very different
  - Pipelined instruction execution: *Intel 80486 uarch*
  - Multiple instructions at a time: *Intel Pentium uarch*
  - Out-of-order execution: *Intel Pentium Pro uarch*
  - Separate instruction and data caches
- Implementation (uarch) can be various as long as it satisfies the specification (ISA)
  - Add instruction vs. Adder implementation
    - Bit serial, ripple carry, carry lookahead adders are all part of microarchitecture
  - x86 ISA has many implementations: 286, 386, 486, Pentium, Pentium Pro, Pentium 4, Core, ...

Microarchitecture Tradeoff: control vs. data driven

- A similar tradeoff (control vs. data-driven execution) can be made at the microarchitecture level

- Microarchitecture: How the underlying implementation actually executes instructions
  - Microarchitecture can execute instructions in any order as long as it obeys the semantics specified by the ISA when making the instruction results visible to software
    - Programmer should see the order specified by the ISA



Review Questions (ISA or Uarch)?

- ADD instruction's opcode
- Number of general purpose registers
- Number of ports to the register file
- Number of cycles to execute the MUL instruction
- Whether or not the machine employs pipelined instruction execution

Remember

- Microarchitecture: Implementation of the ISA under specific design constraints and goals

- Microarchitecture usually changes faster than ISA
  - Few ISAs (x86, ARM, SPARC, MIPS, Alpha) but many uarchs
  - *Why?*
    - *Abstraction!*

COMPUTER ARCHITECTURE

What is Computer Architecture?

- **ISA+implementation definition:** The science and art of designing, selecting, and interconnecting hardware components and designing the hardware/software interface to create a computing system that meets functional, performance, energy consumption, cost, and other specific goals.

- **Traditional (only ISA) definition:** "The term *architecture* is used here to describe the attributes of a system as seen by the programmer, i.e., the conceptual structure and functional behavior as distinct from the organization of the dataflow and controls, the logic design, and the physical implementation." *Gene Amdahl*, IBM Journal of R&D, April 1964