Today's topics

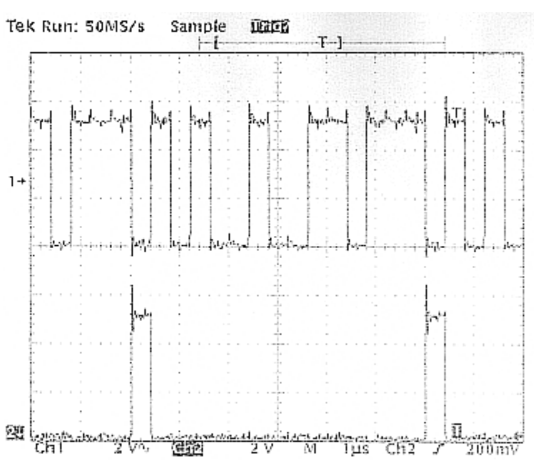
- Binary Numbers
  - Brookshear 1.1-1.6
- Computer Architecture
  - Notes from David A. Patterson and John L. Hennessy, *Computer Organization and Design: The Hardware/Software Interface*, Morgan Kaufmann, 1997.
  - http://computer.howstuffworks.com/pc.htm
- Slides from Prof. Marti Hearst of UC Berkeley SIMS
- Upcoming
  - Operating Systems
    - Brookshear 3.1-3.4
  - Security
    - GI, 11 & Brookshear 3.7

Digital Computers

- What are computers made up of?
  - Lowest level of abstraction: atoms
  - Higher level: transistors
- Transistors
  - Invented in 1951 at Bell Labs
  - An electronic switch
  - Building block for all modern electronics
  - Transistors are packaged as Integrated Circuits (ICs)
  - 40 million transistors in 1 IC

Binary Digits (Bits)

- Yes or No
- On or Off
- One or Zero
- 10010010



More on binary

- Byte
  - A sequence of bits
  - 8 bits = 1 byte
  - 2 bytes = 1 word (sometimes 4 or 8 bytes)
- Powers of two
- How do binary numbers work?

Decimal (Base 10) Numbers

- Each digit in a decimal number is chosen from ten symbols:
  { 0, 1, 2, 3, 4, 5, 6, 7, 8, 9 }
- The position (right to left) of each digit represents a power of ten.
- *Example*: Consider the decimal number 2307

```
          2   3   0   7
          ↑   ↑   ↑   ↑
position: 3   2   1   0
```

$2307 = 2\times10^3 + 3\times10^2 + 0\times10^1 + 7\times10^0$

Binary (Base 2) Numbers

- Each digit in a binary number is chosen from two symbols:
  { 0, 1 }
- The position (right to left) of each digit represents a power of two.
- *Example*: Convert binary number 1101 to decimal

```
          1   1   0   1
          ↑   ↑   ↑   ↑
position: 3   2   1   0
```

$1101 = 1\times2^3 + 1\times2^2 + 0\times2^1 + 1\times2^0$

$= 1\times8 + 1\times4 + 0\times2 + 1\times1 = 8 + 4 + 1 = 13$

Powers of Two

Decimal	Binary	Power of 2
1	1	2^0
2	10	2^1
4	100	2^2
8	1000	2^3
16	10000	2^4
32	100000	2^5
64	1000000	2^6
128	10000000	2^7

Famous Powers of Two

Kilobyte (KB)	1024 or 2^{10} bytes	1,024 bytes	Thousands of bytes
Megabyte (MB)	1024^2 or 2^{20} bytes	1,048,578 bytes	Millions of bytes
Gigabyte (GB)	1024^3 or 2^{30} bytes	1,073,741,824 bytes	Billions of bytes
Terabyte (TB)	1024^4 or 2^{40} bytes	1,099,511,627,776 bytes	Trillions of bytes

Images from http://courses.cs.vt.edu/~csonline/MachineArchitecture/Lessons/Circuits/index.html

Other Number Systems

Binary	Octal	Decimal	Hexadecimal
0000	0	0	0
0001	1	1	1
0010	2	2	2
0011	3	3	3
0100	4	4	4
0101	5	5	5
0110	6	6	6
0111	7	7	7
1000	10	8	8
1001	11	9	9
1010	12	10	A
1011	13	11	B
1100	14	12	C
1101	15	13	D
1110	16	14	E
1111	17	15	F
Base-2	*Base-8*	*Base-10*	*Base-16*

Images from http://courses.cs.vt.edu/~csonline/MachineArchitecture/Lessons/Circuits/index.html

Binary Addition

Rule 1	Rule 2	Rule 3	Rule 4
0 + 0 = 0	0 + 1 = 1	1 + 0 = 1	1 + 1 = 10

Also: 1 + 1 + 1 = 1 with a carry of 1

Images from http://courses.cs.vt.edu/~csonline/MachineArchitecture/Lessons/Circuits/index.html

Adding Binary Numbers

```
   101
+   10
--------
   111
```

- 101 + 10 = ($1\times2^2 + 0\times2^1 + 1\times2^0$) + ($1\times2^1 + 0\times2^0$)
  = (1×4 + 0×2 + 1×1) + (1×2 + 0×1)
- Add like terms: There is one 4, one 2, one 1
  = 1×4 + 1×2 + 1×1 = 111

Adding Binary Numbers

```
 1 1     ← carry
   111
+  110
---------
  1101
```

- 111 + 110 = ($1\times2^2 + 1\times2^1 + 1\times2^0$) + ($1\times2^2 + 1\times2^1 + 0\times2^0$)
  = (1×4 + 1×2 + 1×1) + (1×4 + 1×2 + 0×1)
- Add like terms: There are two 4s, two 2s, one 1
  = 2×4 + 2×2 + 1×1
  = 1×8 + 1×4 + 0×2 + 1×1 = 1101
- BinaryNumber Applet

Converting Decimal to Binary

Decimal	→ → conversion → →	Binary
0	$0 = 0\times2^0$	0
1	$1 = 1\times2^0$	1
2	$2 = 1\times2^1 + 0\times2^0$	10
3	$3 = 2+1 = 1\times2^1 + 0\times2^0$	11
4	$4 = 1\times2^2 + 0\times2^1 + 0\times2^0$	100
5	$5 = 4+1 = 1\times2^2 + 0\times2^1 + 1\times2^0$	101
6	$6 = 4+2 = 1\times2^2 + 1\times2^1 + 0\times2^0$	110
7	$7 = 4+2+1 = 1\times2^2 + 1\times2^1 + 1\times2^0$	111
8	$8 = 1\times2^2 + 0\times2^2 + 0\times2^1 + 0\times2^0$	1000

Converting Decimal to Binary

- Repeated division by two until the quotient is zero
- *Example*: Convert decimal number 54 to binary

Division	remainder
0	→ 1
2) 1	→ 1
2) 3	→ 0
2) 6	→ 1
2) 13	→ 1
2) 27	→ 0
2) 54	

Binary representation of 54 is 110110

Converting Decimal to Binary

Division	remainder
0	→ 1
2) 1	→ 1
2) 3	→ 0
2) 6	→ 1
2) 13	→ 1
2) 27	→ 0
2) 54	

- 1 32 = 0 plus 1 thirty-two
- 6 8s = 1 32 plus 1 sixteen
- 3 16s = 3 16 plus 0 eights
- 13 4s = 6 8s plus 1 four
- 27 2s = 13 4s plus 1 two
- 54 = 27 2s plus 0 ones

- Subtracting highest power of two
- 1s in positions 5,4,2,1

$54 - 2^5 = 22$

$22 - 2^4 = 6$ → 110110

$6 - 2^2 = 2$

$2 - 2^1 = 0$

Problems

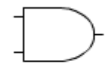
- Convert 1011000 to decimal representation
- Add the binary numbers 1011001 and 10101 and express their sum in binary representation
- Convert 77 to binary representation

Boolean Logic

- AND, OR, NOT, NOR, NAND, XOR
- Each operator has a set of rules for combining two binary inputs
  - These rules are defined in a Truth Table
  - (This term is from the field of Logic)
- Each implemented in an electronic device called a gate
  - Gates operate on inputs of 0's and 1's
  - These are more basic than operations like addition
  - Gates are used to build up circuits that
    - Compute addition, subtraction, etc
    - Store values to be used later
    - Translate values from one format to another

Truth Tables

AND gate

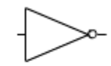


Input		Output
0	0	0
0	1	0
1	0	0
1	1	1

OR gate

Input		Output
0	0	0
0	1	1
1	0	1
1	1	1

NOT gate



Input	Output
0	1
1	0

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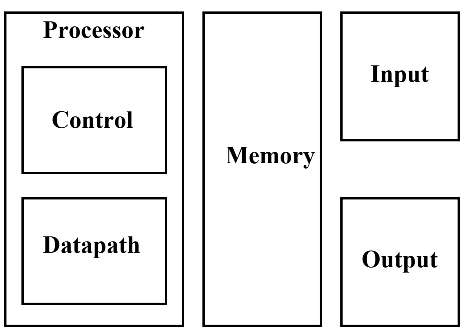
The Big Picture

- Since 1946 all computers have had 5 components
  - The Von Neumann Machine



- What is computer architecture?

  Computer Architecture = Machine Organization + Instruction Set Architecture + ...

Fetch, Decode, Execute Cycle

- Computer instructions are stored (as bits) in memory
- A program's execution is a loop
  - Fetch instruction from memory
  - Decode instruction
  - Execute instruction
- Cycle time
  - Measured in hertz (cycles per second)
  - 2 GHz processor can execute this cycle up to 2 billion times a second
  - Not all cycles are the same though…

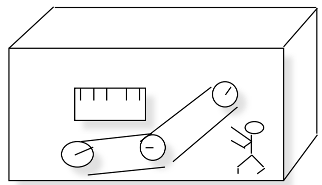
Organization

- Capabilities & Performance Characteristics of Principal Functional Units (Fus)
  - (e.g., Registers, ALU, Shifters, Logic Units, ...)
- Ways in which these components are interconnected
- Information flows between components
- Logic and means by which such information flow is controlled.
- Choreography of FUs to realize the ISA

Logic Designer's View

ISA Level

FUs & Interconnect



Memory bottleneck

- CPU can execute dozens of instruction in the time it takes to retrieve one item from memory
- Solution: Memory Hierarchy
  - Use fast memory
  - Registers
  - Cache memory
  - Rule: small memory is fast, large memory is small

What is Realtime?

- Response time
  - Panic
    - How to tell "I am still computing"
    - Progress bar
- Flicker
  - Fusion frequency
- Update rate vs. refresh rate
  - Movie film standards (24 fps projected at 48 fps)
- Interactive media
  - Interactive vs. non-interactive graphics
    - computer games vs. movies
    - animation tools vs. animation
  - Interactivity => real-time systems
    - system must respond to user inputs without any perceptible delay (A Primary Challenge in VR)

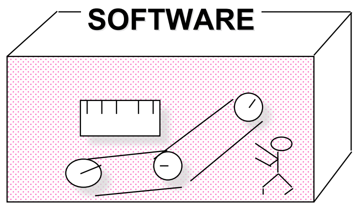
A great idea in computer science

- Temporal locality
  - Programs tend to access data that has been accessed recently (i.e. close in *time*)
- Spatial locality
  - Programs tend to access data at an address near recently referenced data (i.e. close in *space*)
- Useful in graphics and virtual reality as well
  - Realistic images require significant computational power
  - Don't need to represent distant objects as well
- Efficient distributed systems rely on locality
  - Memory access time increases over a network
  - Want to acess data on local machine

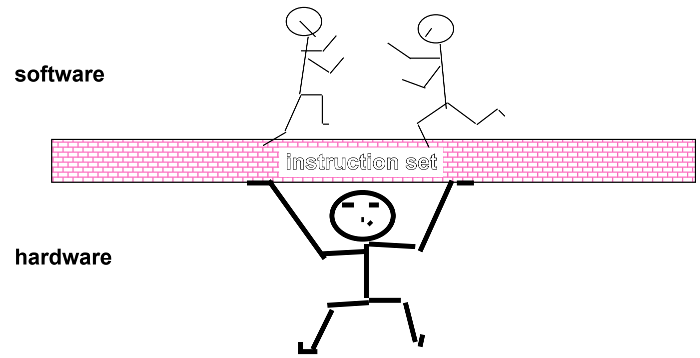
Instruction Set Architecture

... the attributes of a [computing] system as seen by the programmer, *i.e.* the conceptual structure and functional behavior, as distinct from the organization of the data flows and controls the logic design, and the physical implementation.
– Amdahl, Blaaw, and Brooks, 1964

- -- Organization of Programmable Storage
- -- Data Types & Data Structures: Encodings & Representations
- -- Instruction Set
- -- Instruction Formats
- -- Modes of Addressing and Accessing Data Items and Instructions
- -- Exceptional Conditions

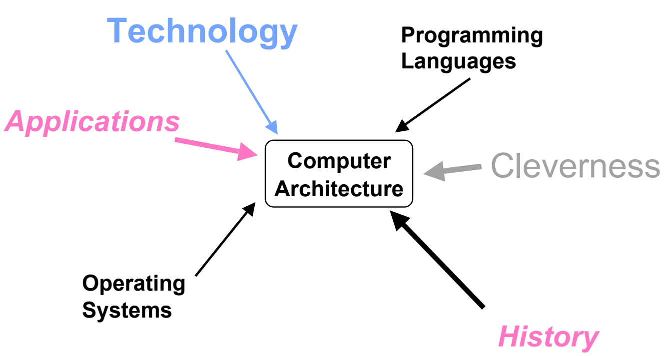


The Instruction Set: a Critical Interface



- What is an example of an Instruction Set architecture?

Forces on Computer Architecture



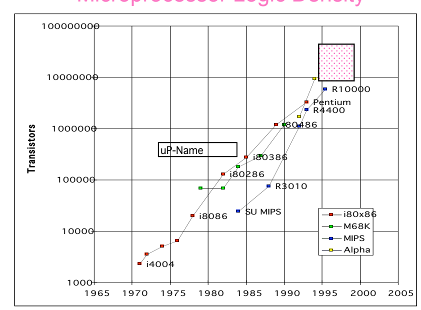
Technology

DRAM chip capacity

DRAM

Year	Size
1980	64 Kb
1983	256 Kb
1986	1 Mb
1989	4 Mb
1992	16 Mb
1996	64 Mb
1999	256 Mb
2002	1 Gb
2004	4 Gb

Microprocessor Logic Density

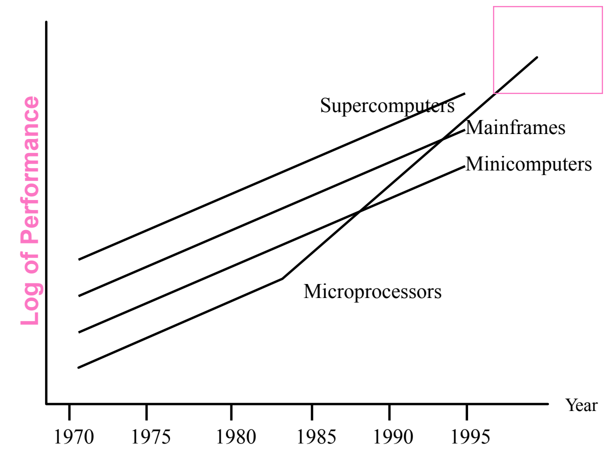


- In ~1985 the single-chip processor (32-bit) and the single-board computer emerged
  - => workstations, personal computers, multiprocessors have been riding this wave since
- Now, we have multicore processors

Technology => dramatic change

- Processor
  - logic capacity: about 30% per year
  - clock rate: about 20% per year
- Memory
  - DRAM capacity: about 60% per year (4x every 3 years)
  - Memory speed: about 10% per year
  - Cost per bit: improves about 25% per year
- Disk
  - capacity: about 60% per year
  - Total use of data: 100% per 9 months!
- Network Bandwidth
  - Bandwidth increasing more than 100% per year!

Performance Trends



Laws?

- Define each of the following. What has its effect been on the advancement of computing technology?
  - Moore's Law
  - Amdahl's Law
  - Metcalfe's Law