inst.eecs.berkeley.edu/~cs61c

CS61C : Machine Structures

Lecture #1 – Introduction & Numbers

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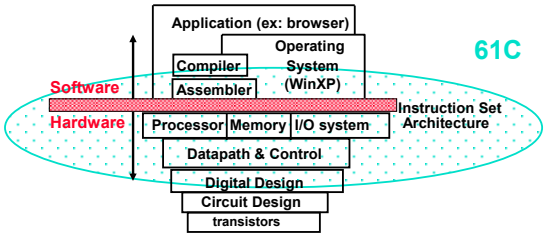
Are Computers Smart?

° To a programmer:
- Very complex operations/functions:
  - (map (lambda (x) (* x x)) '(1 2 3 4))
- Automatic memory management:
  - List l = new List;
- "Basic" structures:
  - Integers, floats, characters, plus, minus, print commands

Are Computers Smart?

° In real life:
- Only a handful of operations:
  - {and, or, not} or {nand, nor}
- No memory management.
- Only 2 values:
  - {0, 1} or {hi, lo} or {on, off}
  - 3 if you count <undef>

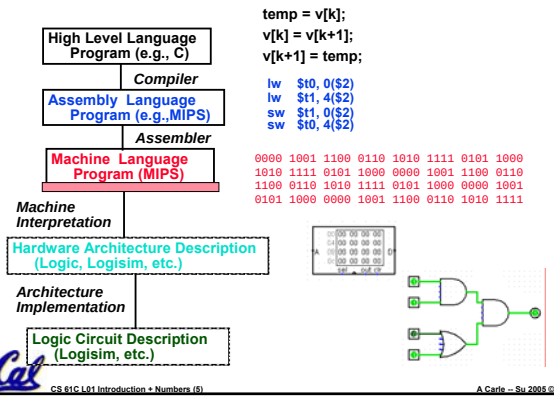
What are "Machine Structures"?



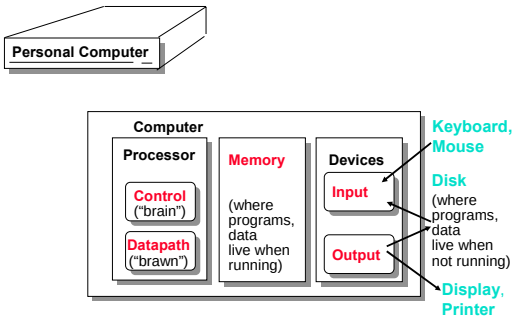
* Coordination of many

levels (layers) of abstraction

61C Levels of Representation



Anatomy: 5 components of any Computer



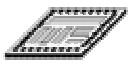
Overview of Physical Implementations

The hardware out of which we make systems.

- Integrated Circuits (ICs)
  - Combinational logic circuits, memory elements, analog interfaces.
- Printed Circuits (PC) boards
  - substrate for ICs and interconnection, distribution of CLK, Vdd, and GND signals, heat dissipation.
- Power Supplies
  - Converts line AC voltage to regulated DC low voltage levels.
- Chassis (rack, card case, ...)
  - holds boards, power supply, provides physical interface to user or other systems.
- Connectors and Cables.

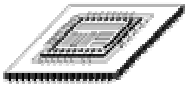
Integrated Circuits (2003 state-of-the-art)

Bare Die



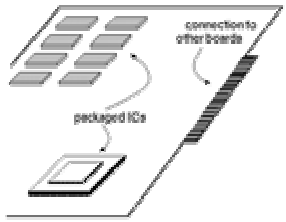
- Primarily Crystalline Silicon
- 1mm - 25mm on a side
- 2003 - feature size ~ 0.13μm = 0.13 x 10^{-6} m
- 100 - 400M transistors
- (25 - 100M "logic gates")
- 3 - 10 conductive layers
- "CMOS" (complementary metal oxide semiconductor) - most common.

Chip in Package



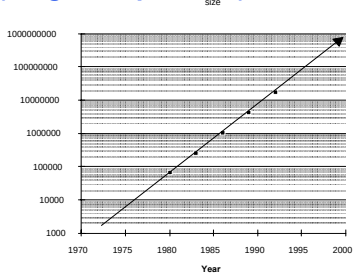
- Package provides:
  - spreading of chip-level signal paths to board-level
  - heat dissipation.
- Ceramic or plastic with gold wires.

Printed Circuit Boards



- fiberglass or ceramic
- 1-20 conductive layers
- 1-20in on a side
- IC packages are soldered down.

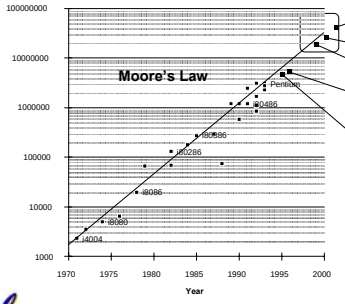
Technology Trends: Memory Capacity (Single-Chip DRAM)



year	size (Mbit)
1980	0.0625
1983	0.25
1986	1
1989	4
1992	16
1996	64
1998	128
2000	256
2002	512

- Now 1.4X/yr, or 2X every 2 years.
- 8000X since 1980!

Technology Trends: Microprocessor Complexity

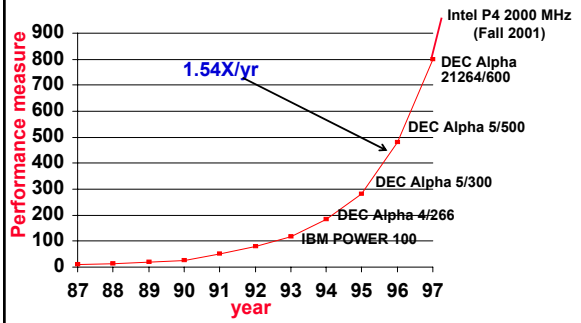


Itanium 2: 41 Million
Athlon (K7): 22 Million
Alpha 21264: 15 million
Pentium Pro: 5.5 million
PowerPC 620: 6.9 million
Alpha 21164: 9.3 million
Sparc Ultra: 5.2 million

2X transistors/Chip Every 1.5 years

Called "Moore's Law"

Technology Trends: Processor Performance



We'll talk about processor performance later on…

Computer Technology - Dramatic Change!

° **Memory**
  • DRAM capacity: 2x / 2 years (since '96); 64x size improvement in last decade.

° **Processor**
  • Speed 2x / 1.5 years (since '85); 100X performance in last decade.

° **Disk**
  • Capacity: 2x / 1 year (since '97) 250X size in last decade.

Computer Technology - Dramatic Change!

We'll see that Kilo, Mega, etc. are incorrect later!

° **State-of-the-art PC when you graduate: (at least…)**
  • Processor clock speed: 5000 MegaHertz (5.0 GigaHertz)
  • Memory capacity: 4000 MegaBytes (4.0 GigaBytes)
  • Disk capacity: 2000 GigaBytes (2.0 TeraBytes)
  • New units! Mega => Giga, Giga => Tera

(Tera => Peta, Peta => Exa, Exa => Zetta Zetta => Yotta = 10^{24})

CS61C: So what's in it for me?

° **Learn some of the big ideas in CS & engineering:**
  • 5 Classic components of a Computer
  • Data can be anything (integers, floating point, characters): a program determines what it is
  • Stored program concept: instructions just data
  • Principle of Locality, exploited via a memory hierarchy (cache)
  • Greater performance by exploiting parallelism
  • Principle of abstraction, used to build systems as layers
  • Compilation v. interpretation thru system layers
  • Principles/Pitfalls of Performance Measurement

Others Skills learned in 61C

° **Learning C**
  • If you know one, you should be able to learn another programming language largely on your own
  • Given that you know C++ or Java, should be easy to pick up their ancestor, C

° **Assembly Language Programming**
  • This is a skill you will pick up, as a side effect of understanding the Big Ideas

° **Hardware design**
  • We think of hardware at the abstract level, with only a little bit of physical logic to give things perspective
  • CS 150, 152 teach this

Course Lecture Outline

° Number representations
° C-Language (basics + pointers)
° Storage management
° Assembly Programming
° Floating Point
° `make`-ing an Executable
° Logic Design
° Introduction to Logisim
° CPU organization
° Pipelining
° Caches
° Virtual Memory
° Performance
° I/O Interrupts
° Disks, Networks
° Advanced Topics

Texts

° **Required:** ***Computer Organization and Design: The Hardware/Software Interface,*** ***Third Edition*****, Patterson and Hennessy (COD).** ***The second edition is far inferior, and is not suggested.***

° **Required:** ***The C Programming Language*****, Kernighan and Ritchie (K&R), 2nd edition**

° **Reading assignments on web page**

Administrivia

- We WILL have sections today (320 Soda)!
  - If you are currently waitlisted, attend section 103 at 5:00pm
  - Everyone on the waitlist will eventually be enrolled… but you may have to switch yourself to the 5:00 section.
- HW1 is available
  - Rather simple book problems, due by the end of the day on the 26th
- Office Hours are TBD
  - But, Andy will hold a quasi office hour here after class to address any questions anyone has about the course
- Full course policies + syllabus tomorrow

Decimal Numbers: Base 10

Digits: 0, 1, 2, 3, 4, 5, 6, 7, 8, 9

Example:

3271 =

$(3x10^3) + (2x10^2) + (7x10^1) + (1x10^0)$

Numbers: positional notation

- Number Base B ⇒ B symbols per digit:
  - Base 10 (Decimal): 0, 1, 2, 3, 4, 5, 6, 7, 8, 9
    Base 2 (Binary): 0, 1
- Number representation:
  - $d_{31}d_{30}$ ... d_1d_0 is a 32 digit number
  - value = $d_{31} \times B^{31} + d_{30} \times B^{30} + ... + d_1 \times B^1 + d_0 \times B^0$
- Binary: 0,1 (In binary digits called "bits")
  - 0b11010 = $1\times2^4 + 1\times2^3 + 0\times2^2 + 1\times2^1 + 0\times2^0$
    = 16 + 8 + 2
    = 26

#s often written 0b…

  - Here 5 digit binary # turns into a 2 digit decimal #
  - Can we find a base that converts to binary easily?

Hexadecimal Numbers: Base 16

- Hexadecimal:
  0, 1, 2, 3, 4, 5, 6, 7, 8, 9, A, B, C, D, E, F
  - Normal digits + 6 more from the alphabet
  - In C, written as 0x… (e.g., 0xFAB5)
- Conversion: Binary⇔Hex
  - 1 hex digit represents 16 decimal values
  - 4 binary digits represent 16 decimal values
  - ⇒1 hex digit replaces 4 binary digits
- One hex digit is a "nibble". Two is a "byte"
- Example:
  - 1010 1100 0011 (binary) = 0x_____ ?

Decimal vs. Hexadecimal vs. Binary

Examples:

1010 1100 0011 (binary)
= 0xAC3

10111 (binary)
= 0001 0111 (binary)
= 0x17

0x3F9
= 11 1111 1001 (binary)

How do we convert between hex and Decimal?

00	0	0000
01	1	0001
02	2	0010
03	3	0011
04	4	0100
05	5	0101
06	6	0110
07	7	0111
08	8	1000
09	9	1001
10	A	1010
11	B	1011
12	C	1100
13	D	1101
14	E	1110
15	F	1111

MEMORIZE!

Which base do we use?

- Decimal: great for humans, especially when doing arithmetic
- Hex: if human looking at long strings of binary numbers, its much easier to convert to hex and look 4 bits/symbol
  - Terrible for arithmetic on paper
- Binary: what computers use;
  you will learn how computers do +, -, *, /
  - To a computer, numbers always binary
  - Regardless of how number is written:
    32_{ten} == 32_{10} == 0x20 == 100000_2 == 0b100000
  - Use subscripts "ten", "hex", "two" in book, slides when might be confusing

What to do with representations of numbers?

° Just what we do with numbers!
- Add them
- Subtract them
- Multiply them
- Divide them
- Compare them

° Example: 10 + 7 = 17

```
    1  1
    1  0  1  0
+   0  1  1  1
-------------
1   0  0  0  1
```

- …so simple to add in binary that we can build circuits to do it!
- subtraction just as you would in decimal
- Comparison: How do you tell if X > Y ?

How to Represent Negative Numbers?

° So far, unsigned numbers

° Obvious solution: define leftmost bit to be sign!
- 0 ⇒ +, 1 ⇒ -
- Rest of bits can be numerical value of number

° This is ~ how YOU do signed numbers in decimal!

° Representation called sign and magnitude

° MIPS uses 32-bit integers. $+1_{ten}$ would be:

0000 0000 0000 0000 0000 0000 0000 0001

° And - 1_{ten} in sign and magnitude would be:

1000 0000 0000 0000 0000 0000 0000 0001

Shortcomings of sign and magnitude?

° Arithmetic circuit complicated
- Special steps depending whether signs are the same or not

° Also, two zeros
- 0x00000000 = $+0_{ten}$
- 0x80000000 = -0_{ten}
- What would two 0s mean for programming?

° Therefore sign and magnitude abandoned*

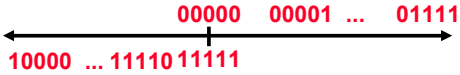
* Ask me about the star in two weeks!

Another try: complement the bits

° Example: $7_{10} = 00111_2$ $-7_{10} = 11000_2$

° Called One's Complement

° Note: positive numbers have leading 0s, negative numbers have leadings 1s.



° What is -00000 ? Answer: 11111

° How many positive numbers in N bits?

° How many negative ones?

Shortcomings of One's complement?

° Arithmetic still is somewhat complicated.

° Still two zeros
- 0x00000000 = $+0_{ten}$
- 0xFFFFFFFF = -0_{ten}

° Although used for awhile on some computer products, one's complement was eventually abandoned because another solution was better….

Another Attempt …

° Gedanken: Decimal Car Odometer

00003 ➔ 00002 ➔ 00001 ➔ 00000 ➔ 99999 ➔ 99998

° Binary Odometer:

00011 ➔ 00010 ➔ 00001 ➔ 00000 ➔ 11111 ➔ 11110

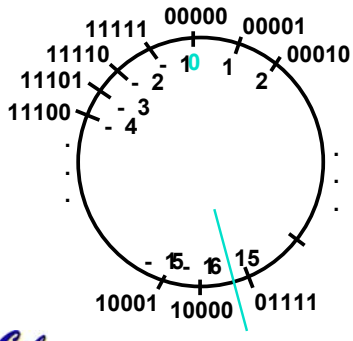
° With no obvious better alternative, pick representation that makes the math simple!
- 99999ten == -1ten
- 11111two == -1ten 11110two == -2ten

° This representation is Two's Complement

2's Complement Properties

- As with sign and magnitude, leading 0s ⇒ positive, leading 1s ⇒ negative
  - 000000...xxx is ≥ 0, 111111...xxx is < 0
  - except 1…1111 is -1, not -0 (as in sign & mag.)
- Only 1 Zero!

2's Complement Number "line": N = 5



- 2^{N-1} non-negatives
- 2^{N-1} negatives
- one zero
- how many positives?

Two's Complement for N=32

0000 ... 0000 0000 0000 0000$_{two}$ =	0$_{ten}$
0000 ... 0000 0000 0000 0001$_{two}$ =	1$_{ten}$
0000 ... 0000 0000 0000 0010$_{two}$ =	2$_{ten}$
...	
0111 ... 1111 1111 1111 1101$_{two}$ =	2,147,483,645$_{ten}$
0111 ... 1111 1111 1111 1110$_{two}$ =	2,147,483,646$_{ten}$
0111 ... 1111 1111 1111 1111$_{two}$ =	2,147,483,647$_{ten}$
1000 ... 0000 0000 0000 0000$_{two}$ =	–2,147,483,648$_{ten}$
1000 ... 0000 0000 0000 0001$_{two}$ =	–2,147,483,647$_{ten}$
1000 ... 0000 0000 0000 0010$_{two}$ =	–2,147,483,646$_{ten}$
...	
1111 ... 1111 1111 1111 1101$_{two}$ =	–3$_{ten}$
1111 ... 1111 1111 1111 1110$_{two}$ =	–2$_{ten}$
1111 ... 1111 1111 1111 1111$_{two}$ =	–1$_{ten}$

- One zero; 1st bit called sign bit
- 1 "extra" negative:no positive 2,147,483,648$_{ten}$

Kilo, Mega, Giga, Tera, Peta, Exa, Zetta, Yotta

`physics.nist.gov/cuu/Units/binary.html`

- Common use prefixes (all SI, except K [= k in SI])

Name	Abbr	Factor	SI size
Kilo	K	2^{10} = 1,024	10^3 = 1,000
Mega	M	2^{20} = 1,048,576	10^6 = 1,000,000
Giga	G	2^{30} = 1,073,741,824	10^9 = 1,000,000,000
Tera	T	2^{40} = 1,099,511,627,776	10^{12} = 1,000,000,000,000
Peta	P	2^{50} = 1,125,899,906,842,624	10^{15} = 1,000,000,000,000,000
Exa	E	2^{60} = 1,152,921,504,606,846,976	10^{18} = 1,000,000,000,000,000,000
Zetta	Z	2^{70} = 1,180,591,620,717,411,303,424	10^{21} = 1,000,000,000,000,000,000,000
Yotta	Y	2^{80} = 1,208,925,819,614,629,174,706,176	10^{24} = 1,000,000,000,000,000,000,000,000

- Confusing! Common usage of "kilobyte" means 1024 bytes, but the "correct" SI value is 1000 bytes
- Hard Disk manufacturers & Telecommunications are the only computing groups that use SI factors, so what is advertised as a 30 GB drive will actually only hold about 28 x 2^{30} bytes, and a 1 Mbit/s connection transfers 10^6 bps.

kibi, mebi, gibi, tebi, pebi, exbi, zebi, yobi

`en.wikipedia.org/wiki/Binary_prefix`

- New IEC Standard Prefixes [only to exbi officially]

Name	Abbr	Factor
kibi	Ki	2^{10} = 1,024
mebi	Mi	2^{20} = 1,048,576
gibi	Gi	2^{30} = 1,073,741,824
tebi	Ti	2^{40} = 1,099,511,627,776
pebi	Pi	2^{50} = 1,125,899,906,842,624
exbi	Ei	2^{60} = 1,152,921,504,606,846,976
zebi	Zi	2^{70} = 1,180,591,620,717,411,303,424
yobi	Yi	2^{80} = 1,208,925,819,614,629,174,706,176

As of this writing, this proposal has yet to gain widespread use…

- International Electrotechnical Commission (IEC) in 1999 introduced these to specify binary quantities.
  - Names come from shortened versions of the original SI prefixes (same pronunciation) and *bi* is short for "binary", but pronounced "bee" :-(
  - Now SI prefixes only have their base-10 meaning and never have a base-2 meaning.

The way to remember #s

- What is 2^{34}? How many bits addresses (I.e., what's `ceil` $\log_2$ = `lg` of) 2.5 TiB?
- Answer! 2^{XY} means…

X=0 ⇒ ---	Y=0 ⇒ 1
X=1 ⇒ kibi ~10^3	Y=1 ⇒ 2
X=2 ⇒ mebi ~10^6	Y=2 ⇒ 4
X=3 ⇒ gibi ~10^9	Y=3 ⇒ 8
X=4 ⇒ tebi ~10^{12}	Y=4 ⇒ 16
X=5 ⇒ tebi ~10^{15}	Y=5 ⇒ 32
X=6 ⇒ exbi ~10^{18}	Y=6 ⇒ 64
X=7 ⇒ zebi ~10^{21}	Y=7 ⇒ 128
X=8 ⇒ yobi ~10^{24}	Y=8 ⇒ 256
	Y=9 ⇒ 512

MEMORIZE!