Lecture 2

Great Ideas in Computer Architecture (a.k.a. Machine Structures)

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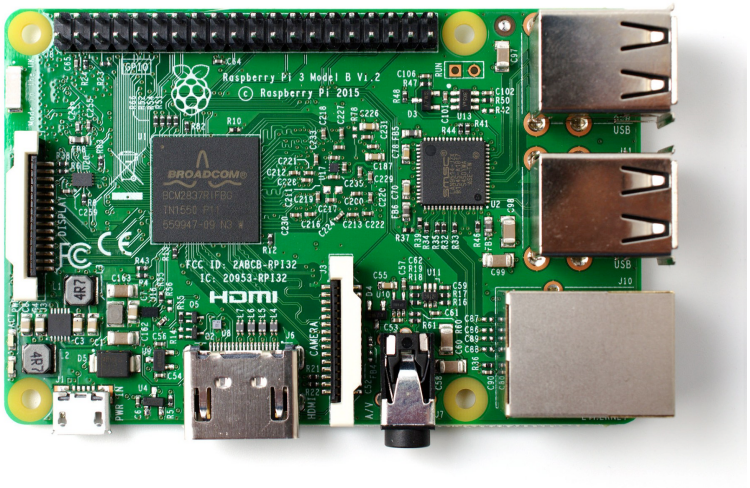
Administrivia

- Teaching Assistants: In Today!
- Lectures are recorded. Waitlist/Concurrent Enrollment may have to view recordings.
- Office hours to be announced soon (webpage)
- Lab0 online (soon), including instructions for Raspberry PI!



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About 61C (recap)

- CS61C: Understand 6 great ideas in computer architecture to enable high performance programming via parallelism.
- Understand computers from transistor-level up to programming-language level (‚dispell the magic‘)

New:

- Work with small computing boards for connection to the Internet of Things and Maker world (at no additional cost).

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Agenda

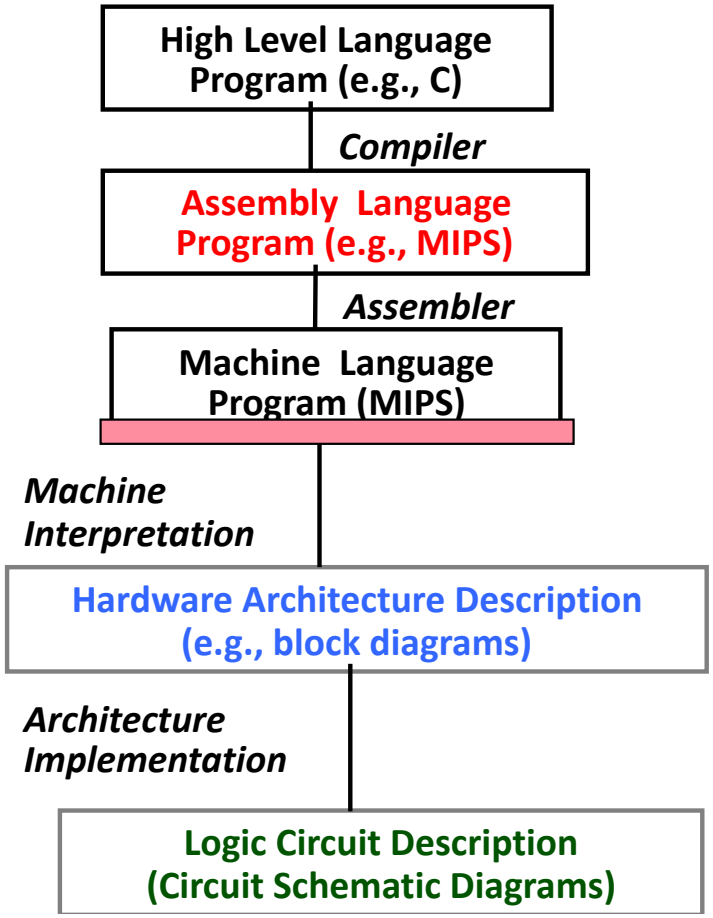
- Great Ideas in Computer Architecture
- Everything is a Number

5 Great Ideas in Computer Architecture

1. Abstraction
   (Layers of Representation/Interpretation)
2. Moore's Law (Designing through trends)
3. Principle of Locality (Memory Hierarchy)
4. Parallelism & Amdahl's law (which limits it)
5. Dependability via Redundancy

Great Idea #1: Abstraction (Levels of Representation/Interpretation)

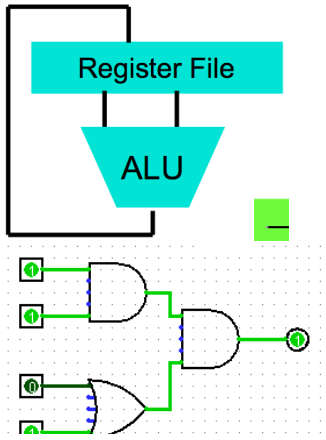

```
lw    $t0, 0($2)
lw    $t1, 4($2)
sw    $t1, 0($2)
sw    $t0, 4($2)
```




```
temp = v[k];
v[k] = v[k+1];
v[k+1] = temp;
```

Anything can be represented as a *number*, i.e., data or instructions

```
0000 1001 1100 0110 1010
1010 1111 0101 1000 0000
1100 0110 1010 1111 0101
0101 1000 0000 1001 1100
```



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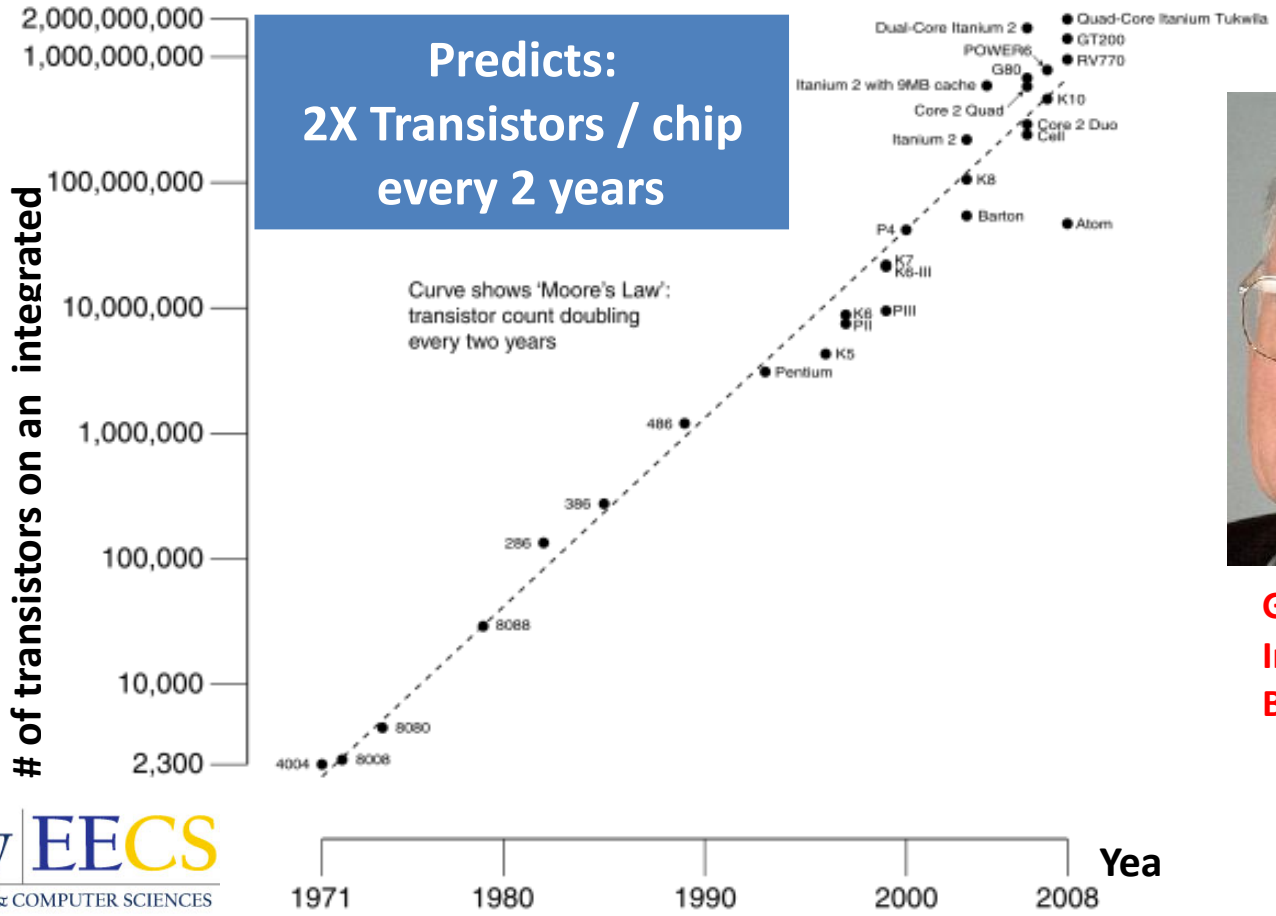
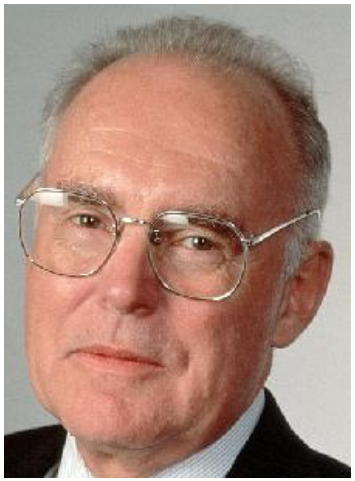
#2: Moore's Law





Gordon Moore
Intel Cofounder
B.S. Cal 1950!

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Interesting Times

- Moore's Law relied on the cost of transistors scaling down as technology scaled to smaller and smaller feature sizes.
  - And the resulting transistors resulted in increased single-task performance
- But single-task performance improvements hit a brick wall years ago...
- And now the newest, smallest fabrication processes <14nm, might have greater cost/transistor!!!! So, why shrink????

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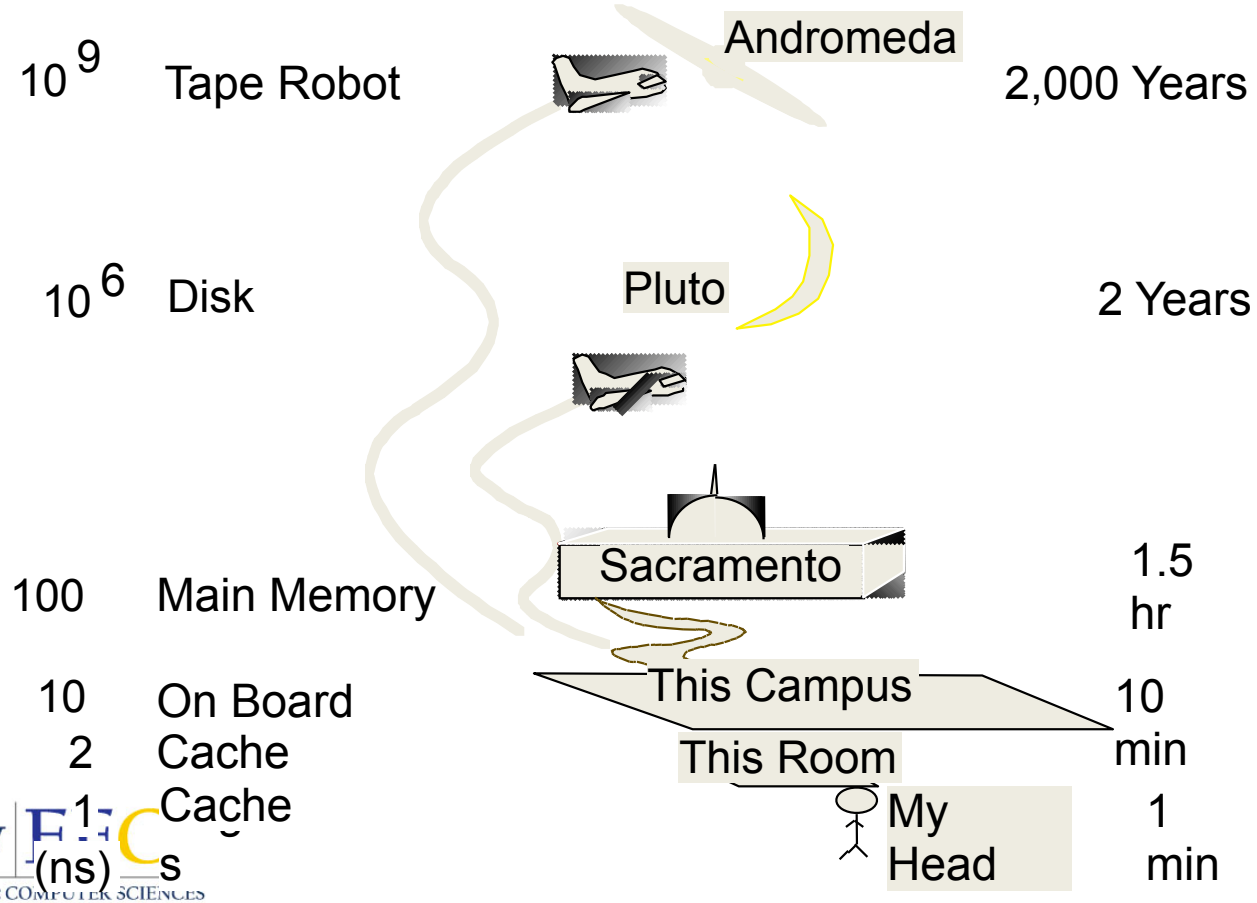
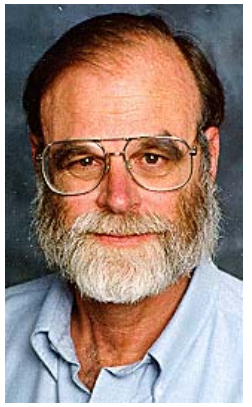
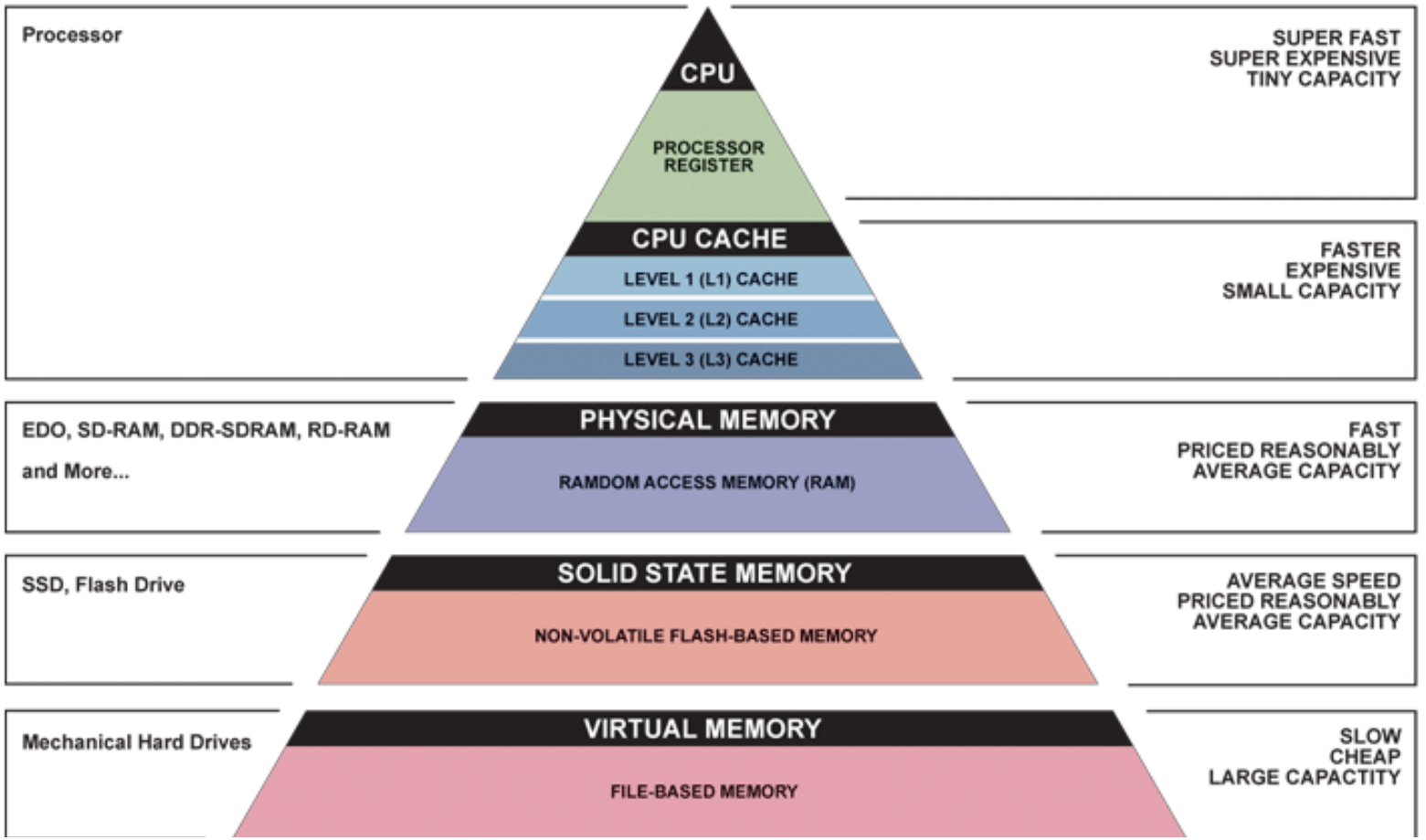
Jim Gray's Storage Latency Analogy: How Far Away is the Data?





Jim Gray
Turing Award
B.S. Cal 1966
Ph.D. Cal 1969!

Great Idea #3: Principle of Locality/ Memory Hierarchy



If your computer doesn't have an SSD, get one!

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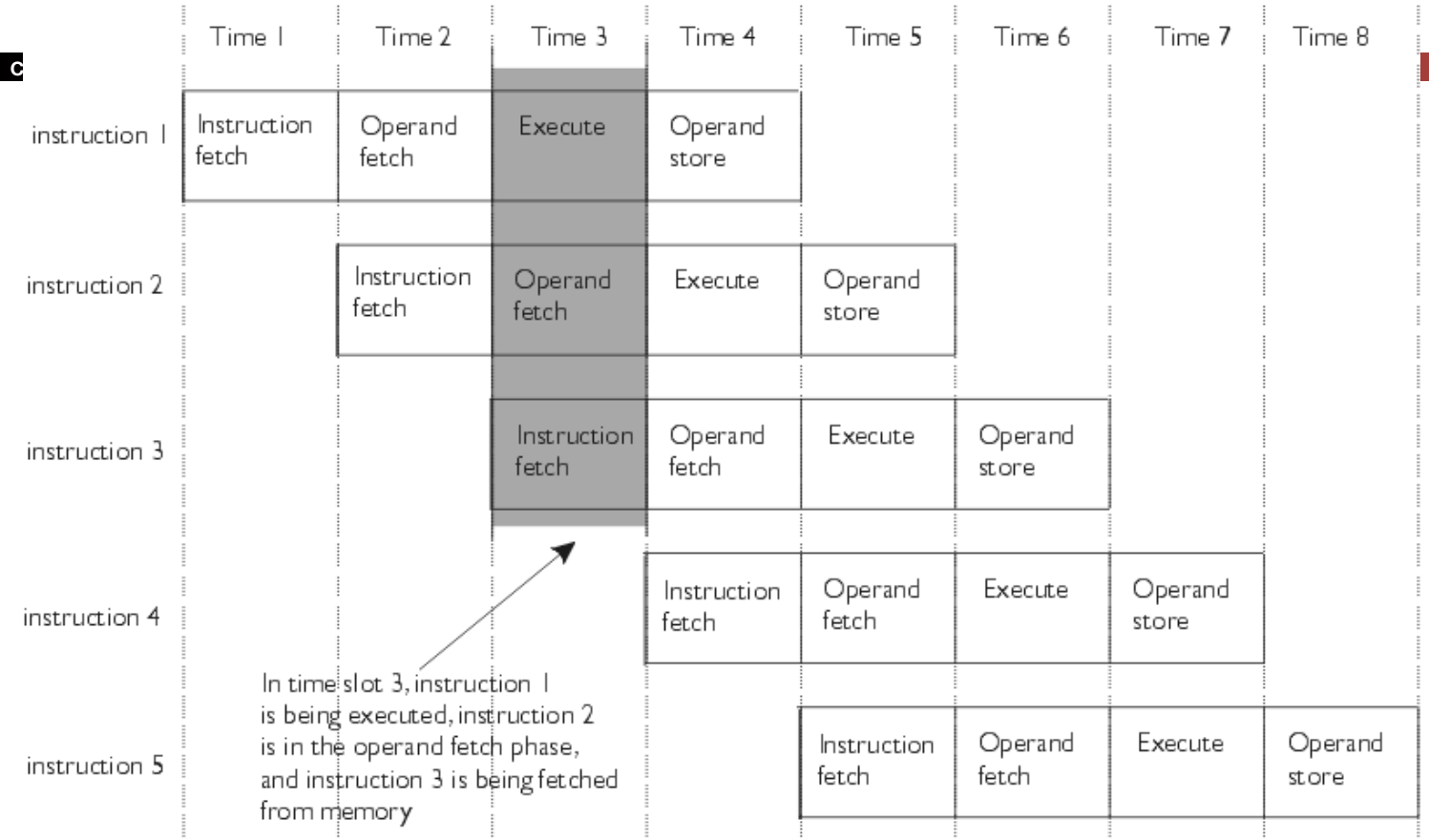
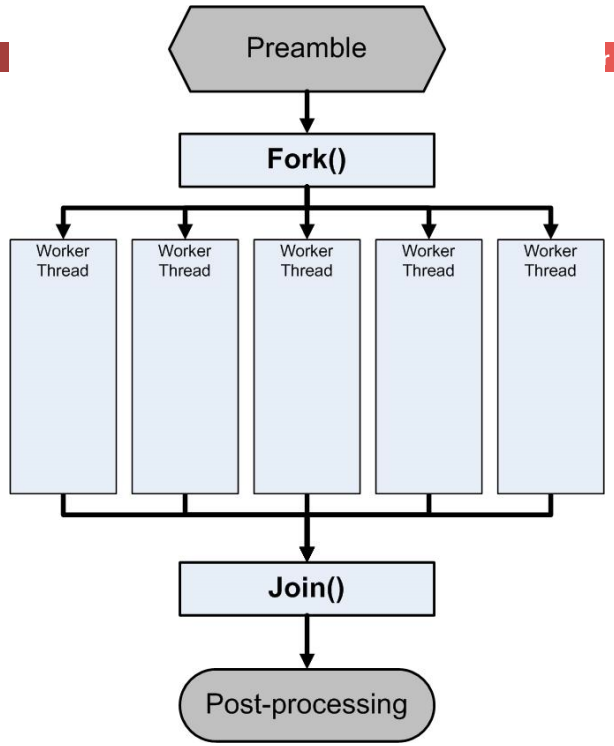
Great Idea #4: Parallelism





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The Caveat: Amdahl's Law

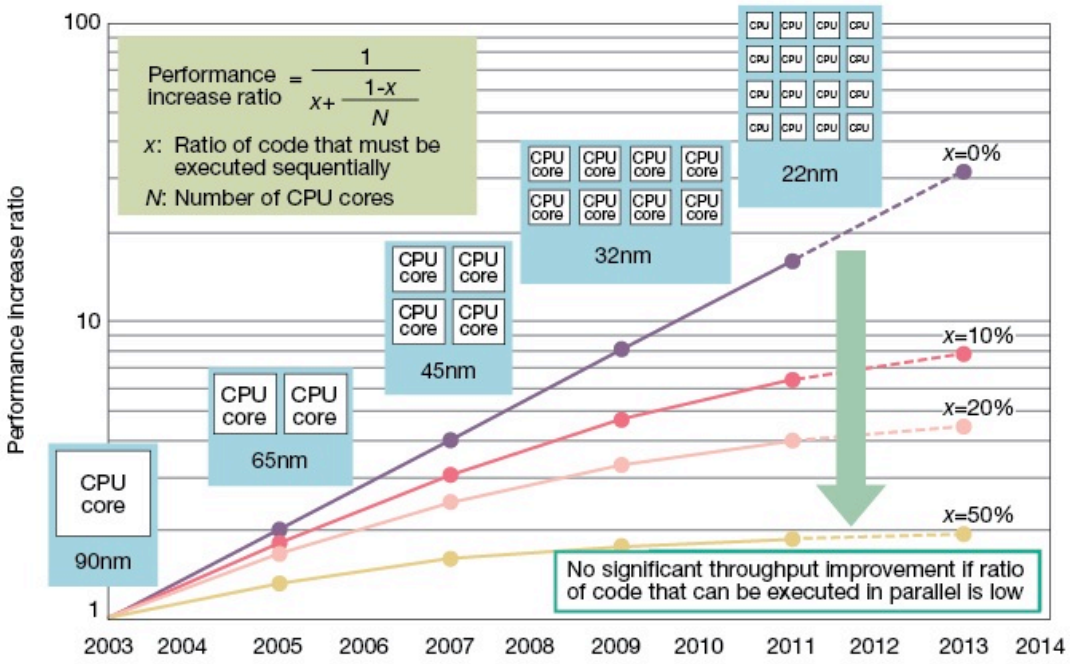

Fig 3 Amdahl's Law an Obstacle to Improved Performance Performance will not rise in the same proportion as the increase in CPU cores. Performance gains are limited by the ratio of software processing that must be executed sequentially. Amdahl's Law is a major obstacle in boosting multicore microprocessor performance. Diagram assumes no overhead in parallel processing. Years shown for design rules based on Intel planned and actual technology. Core count assumed to double for each rule generation.

Gene Amdahl
Computer Pioneer

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Great Idea #5: Failures Happen, so...

- 4 disks/server, 50,000 servers
- Failure rate of disks: 2% to 10% / year
  - Assume 4% annual failure rate
- On average, how often does a disk fail?

a) 1 / month
b) 1 / week
c) 1 / day
d) 1 / hour

Coping with Failures

- 4 disks/server, 50,000 servers
- Failure rate of disks: 2% to 10% / year
  - Assume 4% annual failure rate
- On average, how often does a disk fail?

a) 1 / month
b) 1 / week
c) 1 / day
d) 1 / hour

50,000 x 4 = 200,000 disks
200,000 x 4% = 8000 disks fail
365 days x 24 hours = 8760 hours

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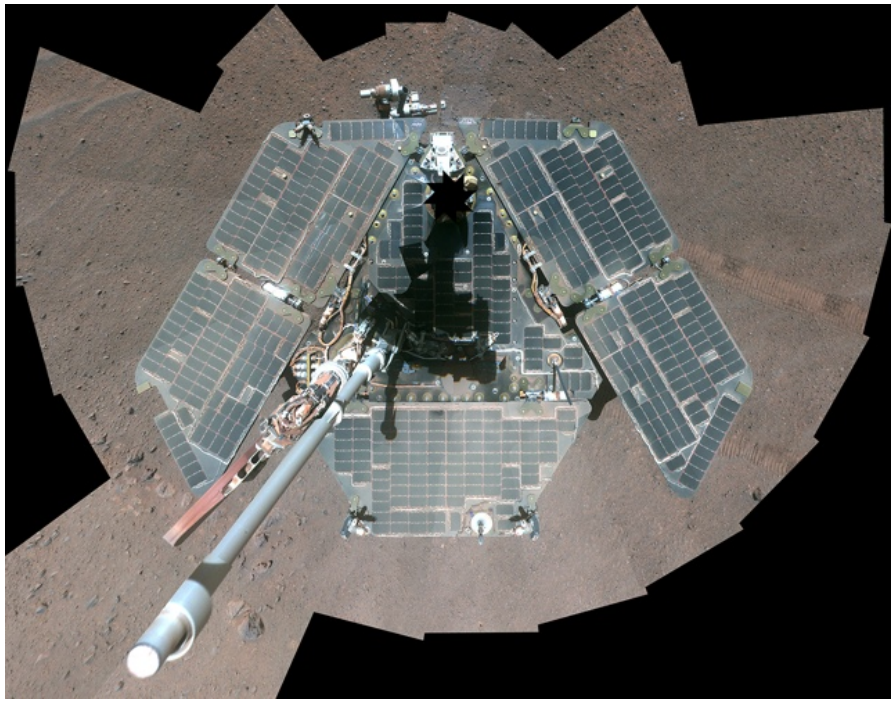
NASA Fixing Rover's Flash Memory

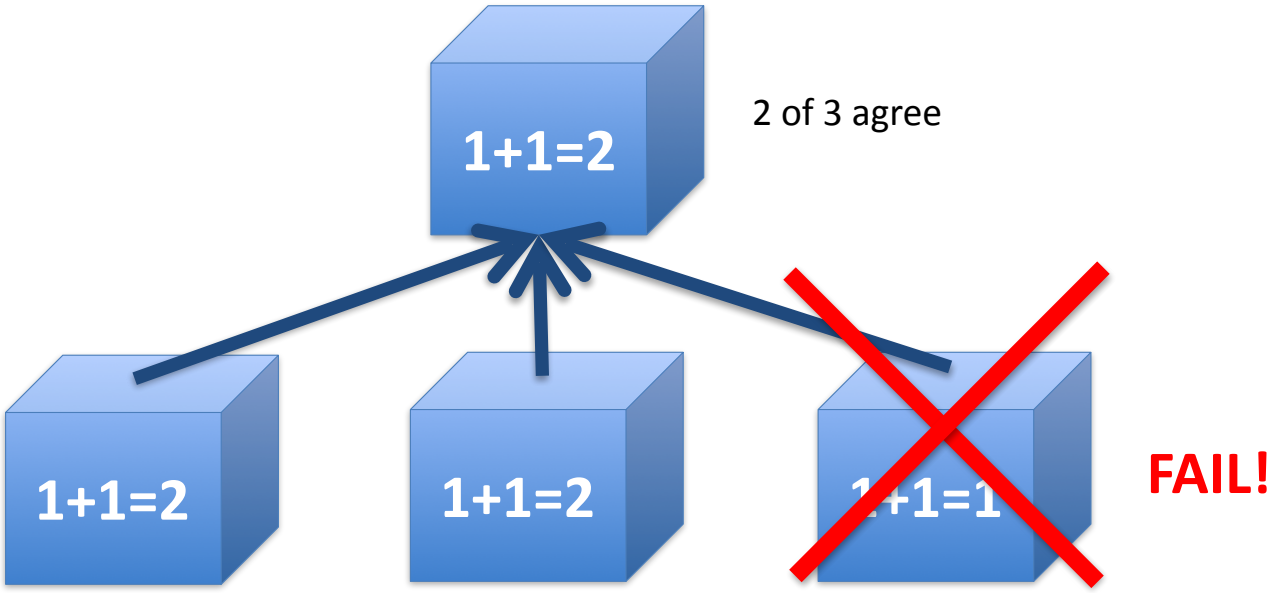
- Opportunity still active on Mars after >10 years
- But flash memory worn out
- New software update to avoid using worn out memory banks



http://www.engadget.com/2014/12/30/nasa-opportunity-rover-flash-fix/

Great Idea #5: Dependability via Redundancy

- Redundancy so that a failing piece doesn't make the whole system fail



Increasing transistor density reduces the cost of redundancy

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Great Idea #5: Dependability via Redundancy

- Applies to everything from datacenters to storage to memory to instructors
  - Redundant datacenters so that can lose 1 datacenter but Internet service stays online
  - Redundant computers was Google's original internal innovation
  - Redundant disks so that can lose 1 disk but not lose data (Redundant Arrays of Independent Disks/RAID)
  - Redundant memory bits of so that can lose 1 bit but no data (Error Correcting Code/ECC Memory/"Chipkill" memory)
  - Redundant instructors so one of us can travel while the other teaches ;-)

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Summary: Great Ideas in Computer Architecture

1. Abstraction
   (Layers of Representation/Interpretation)
2. Moore's Law
3. Principle of Locality/Memory Hierarchy
4. Parallelism
5. Performance Measurement and Improvement
6. Dependability via Redundancy

Agenda

- Great Ideas in Computer Architecture
- Everything is a Number

Key Concepts

- Inside computers, everything is a number
- But numbers usually stored with a fixed size
  - 8-bit bytes, 16-bit half words, 32-bit words, 64-bit double words, …
- Integer and floating-point operations can lead to results too big/small to store within their representations: *overflow/underflow*

Number Representation

- Value of i-th digit is $d \times Base^i$ where i starts at 0 and increases from right to left:
- $123_{10} = 1_{10} \times 10_{10}^2 + 2_{10} \times 10_{10}^1 + 3_{10} \times 10_{10}^0$

  $= 1\text{x}100_{10} + 2\text{x}10_{10} + 3\text{x}1_{10}$

  $= 100_{10} + 20_{10} + 3_{10}$

  $= 123_{10}$
- Binary (Base 2), Hexadecimal (Base 16), Decimal (Base 10) different ways to represent an integer
  - We'll use 1_{two}, 5_{ten}, 10_{hex} to be clearer

    (vs. 1_2, 4_8, 5_{10}, 10_{16})

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Number Representation

- Hexadecimal digits: 0,1,2,3,4,5,6,7,8,9,A,B,C,D,E,F
- $FFF_{hex} = 15_{ten} \times 16_{ten}^{2} + 15_{ten} \times 16_{ten}^{1} + 15_{ten} \times 16_{ten}^{0}$
  $= 3840_{ten} + 240_{ten} + 15_{ten}$
  $= 4095_{ten}$
- $1111\ 1111\ 1111_{two} = FFF_{hex} = 4095_{ten}$
- May put blanks every group of binary, octal, or hexadecimal digits to make it easier to parse, like commas in decimal

Signed and Unsigned Integers

- C, C++, and Java have *signed integers*, e.g., 7, -255:

```
int x, y, z;
```

- C, C++ also have *unsigned integers*, which are used for addresses
- 32-bit word can represent 2^{32} binary numbers
- Unsigned integers in 32 bit word represent 0 to 2^{32}-1 (4,294,967,295)

Unsigned Integers

$0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0000_{two} = 0_{ten}$
$0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0001_{two} = 1_{ten}$
$0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0010_{two} = 2_{ten}$
... ...
$0111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1101_{two} = 2{,}147{,}483{,}645_{ten}$
$0111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1110_{two} = 2{,}147{,}483{,}646_{ten}$
$0111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1111_{two} = 2{,}147{,}483{,}647_{ten}$
$1000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0000_{two} = 2{,}147{,}483{,}648_{ten}$
$1000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0001_{two} = 2{,}147{,}483{,}649_{ten}$
$1000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0010_{two} = 2{,}147{,}483{,}650_{ten}$
... ...
$1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1101_{two} = 4{,}294{,}967{,}293_{ten}$
$1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1110_{two} = 4{,}294{,}967{,}294_{ten}$
$1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1111_{two} = 4{,}294{,}967{,}295_{ten}$

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Signed Integers and Two's-Complement Representation

- Signed integers in C; want ½ numbers <0, want ½ numbers >0, and want one 0
- *Two's complement* treats 0 as positive, so 32-bit word represents 2^{32} integers from
  -2^{31} (–2,147,483,648) to $2^{31}-1$ (2,147,483,647)
  - Note: one negative number with no positive version
  - Book lists some other options, all of which are worse
  - Every computer uses two's complement today
- *Most-significant bit* (leftmost) is the *sign bit*, since 0 means positive (including 0), 1 means negative
  - Bit 31 is most significant, bit 0 is least significant

Two's-Complement Integers

Sign Bit

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

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Ways to Make Two's Complement

- For N-bit word, complement to 2_{ten}^{N}
  - For 4 bit number $3_{ten}=0011_{two}$,

    two's complement (i.e. -3_{ten}) would be

    $16_{ten}-3_{ten}=13_{ten}$ or $10000_{two} - 0011_{two} = 1101_{two}$
    - Here is an easier way:
      - Invert all bits and add 1
      - Computers actually do it like this, too

3_{ten} 0011_{two}

Bitwise complement 1100_{two}

$+ \quad 1_{two}$

-3_{ten} 1101_{two}

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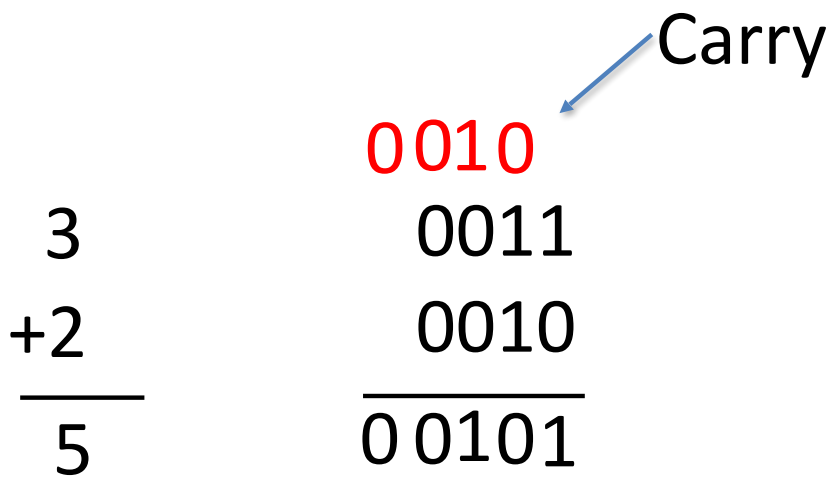
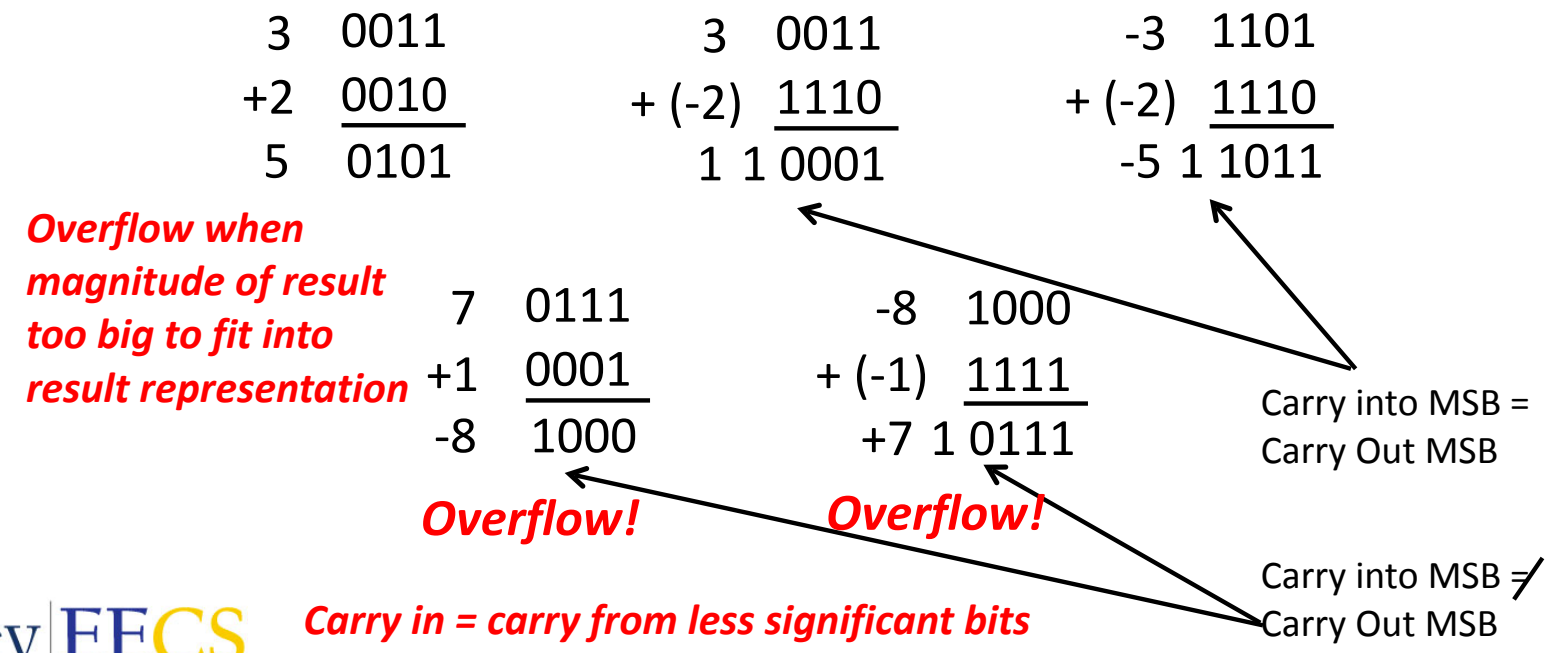
Binary Addition Example



Two's-Complement Examples

- Assume for simplicity 4 bit width, -8 to +7 represented



Carry in = carry from less significant bits
Carry out = carry to more significant bits

Lecture 2

Suppose we had a 5-bit word. What integers can be represented in two's complement?

- ☐ -32 to +31
- ☐ 0 to +31
- ☐ -16 to +15
- ☐ -15 to +16

Lecture 2

Suppose we had a 5-bit word. What integers can be represented in two's complement?

- ☐ -32 to +31
- ☐ 0 to +31
- ☐ -16 to +15
- ☐ -15 to +16

Summary: Number Representations

- Everything in a computer is a number, in fact only 0 and 1.
- Integers are interpreted by adhering to fixed length
- Negative numbers are represented with Two's complement
- Overflows can be detected utilizing the carry bit.