CS 110
Computer Architecture
(a.k.a. Machine Structures)
Lecture 1: *Course Introduction*

Instructor:
Sören Schwertfeger

http://shtech.org/courses/ca/

School of Information Science and Technology SIST

ShanghaiTech University

Slides based on UC Berkley's CS61C

Agenda

- Thinking about Machine Structures
- Great Ideas in Computer Architecture
- What you need to know about this class
- Everything is a Number

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CS 110 is NOT really about C Programming

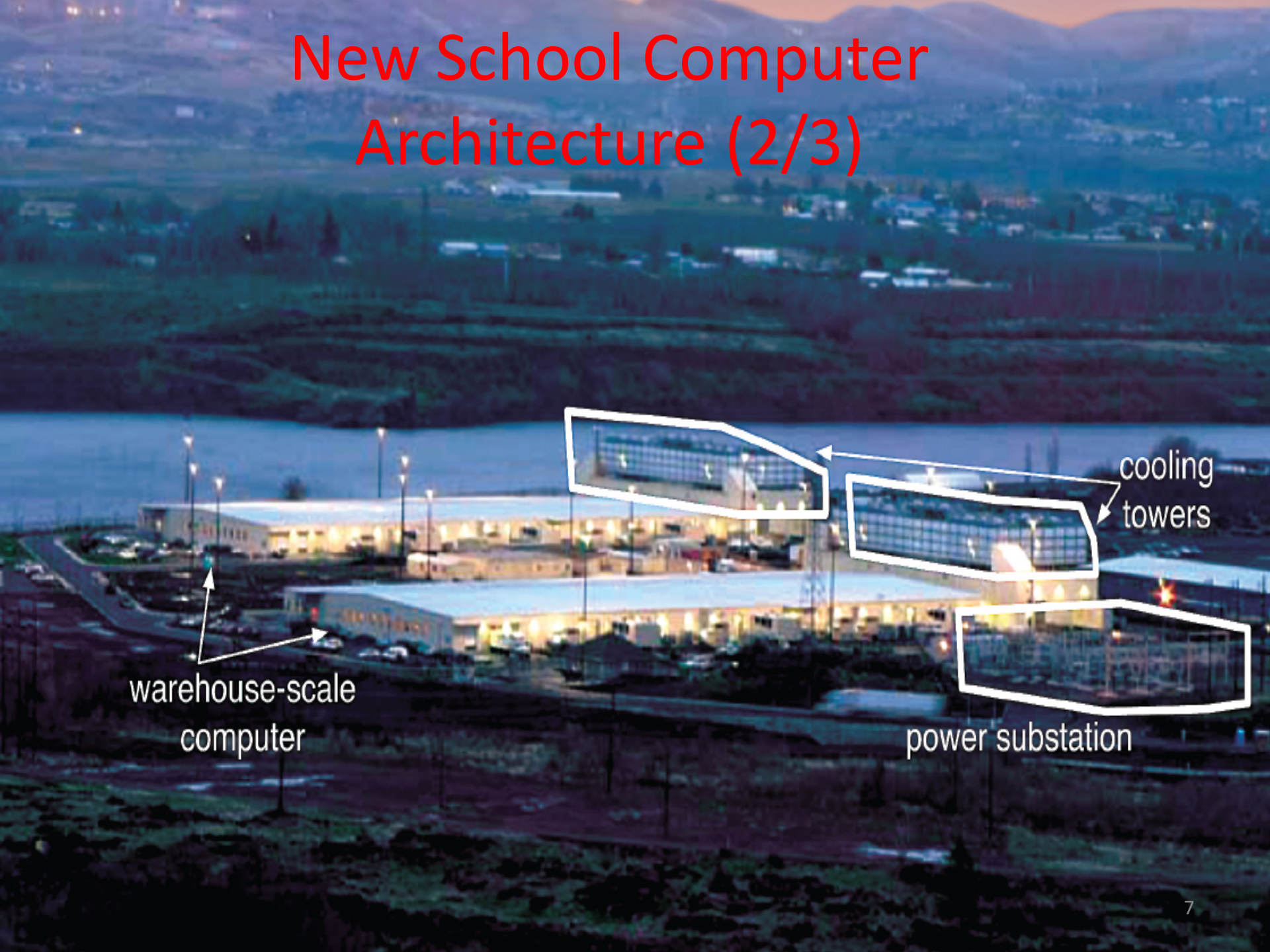
- It is about the *hardware-software interface*
  - What does the programmer need to know to achieve the highest possible performance
- C is close to the underlying hardware, unlike languages like Scheme, Python, Java!
  - Allows us to talk about key hardware features in higher level terms
  - Allows programmer to explicitly harness underlying hardware parallelism for high performance

Old School Computer Architecture

New School Computer Architecture (1/3)

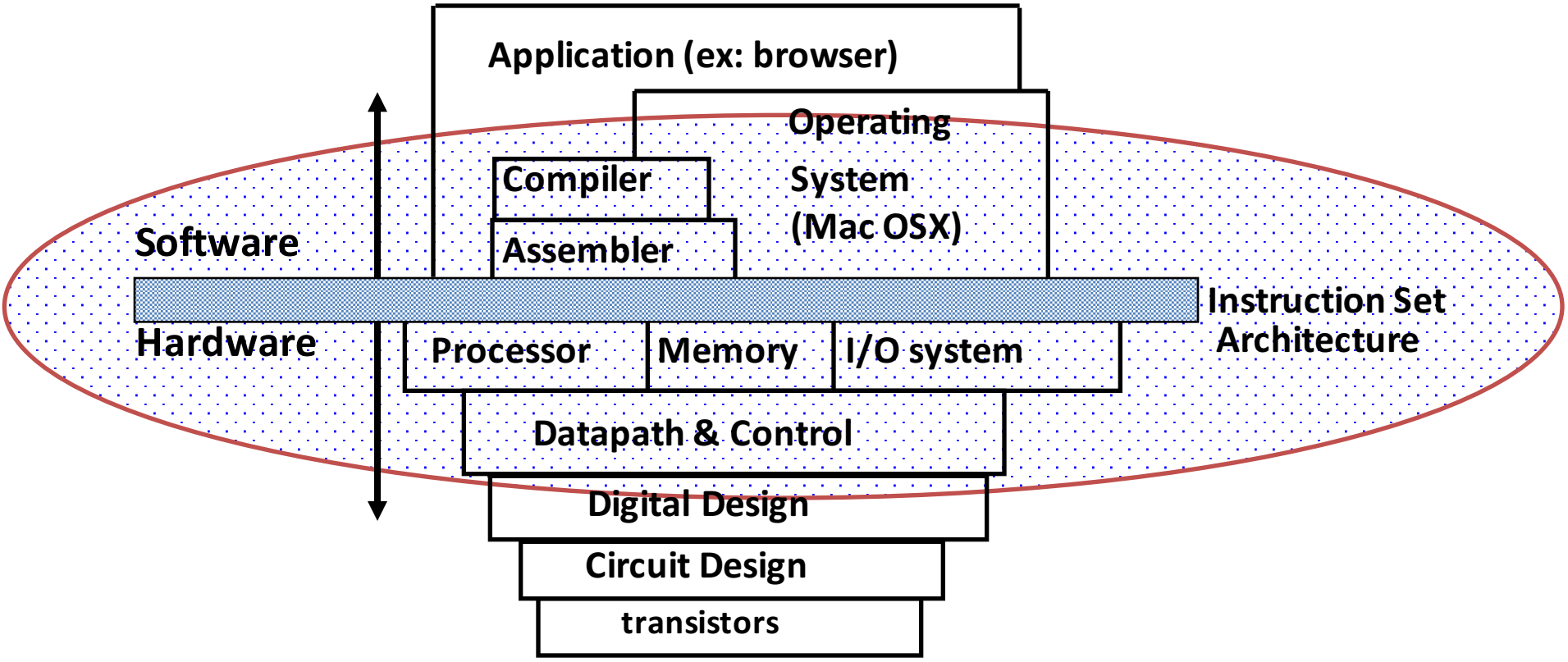
Personal Mobile Devices

New School Computer Architecture (2/3)



New School Computer Architecture (3/3)

Old School Machine Structures



New-School Machine Structures (It's a bit more complicated!)

Software | *Hardware*

- Parallel Requests
  - Assigned to computer
  - e.g., Search "cats"
- Parallel Threads
  - Assigned to core
  - e.g., Lookup, Ads
- Parallel Instructions
  - >1 instruction @ one time
  - e.g., 5 pipelined instructions
- Parallel Data
  - >1 data item @ one time
  - e.g., Add of 4 pairs of words
- Hardware descriptions
  - All gates functioning in parallel at same time

Harness Parallelism & Achieve High Performance

Warehouse -Scale Computer

Smart Phone

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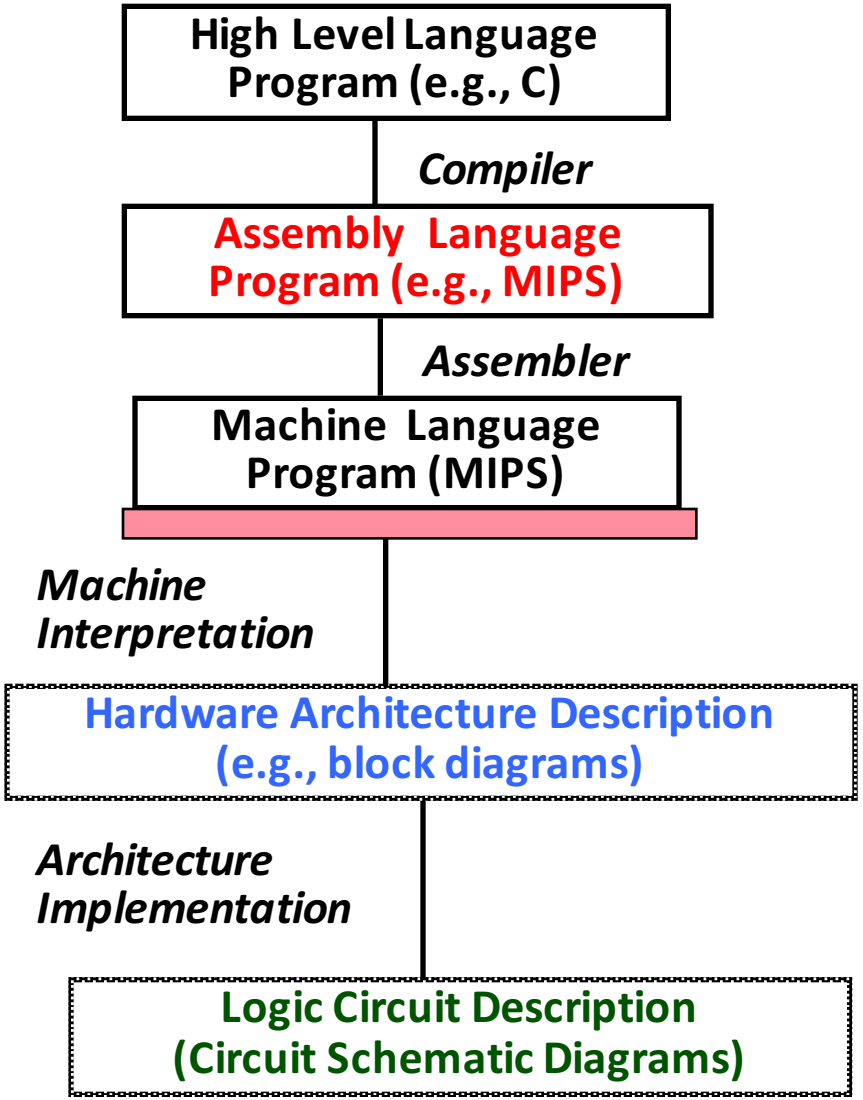
6 Great Ideas in Computer Architecture

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

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

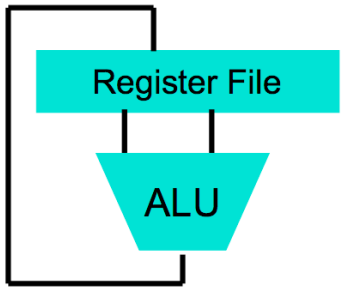


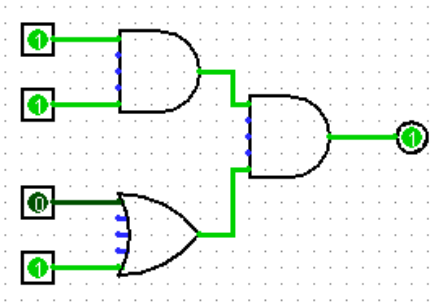

```
temp = v[k];
v[k] = v[k+1];
v[k+1] = temp;
```

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

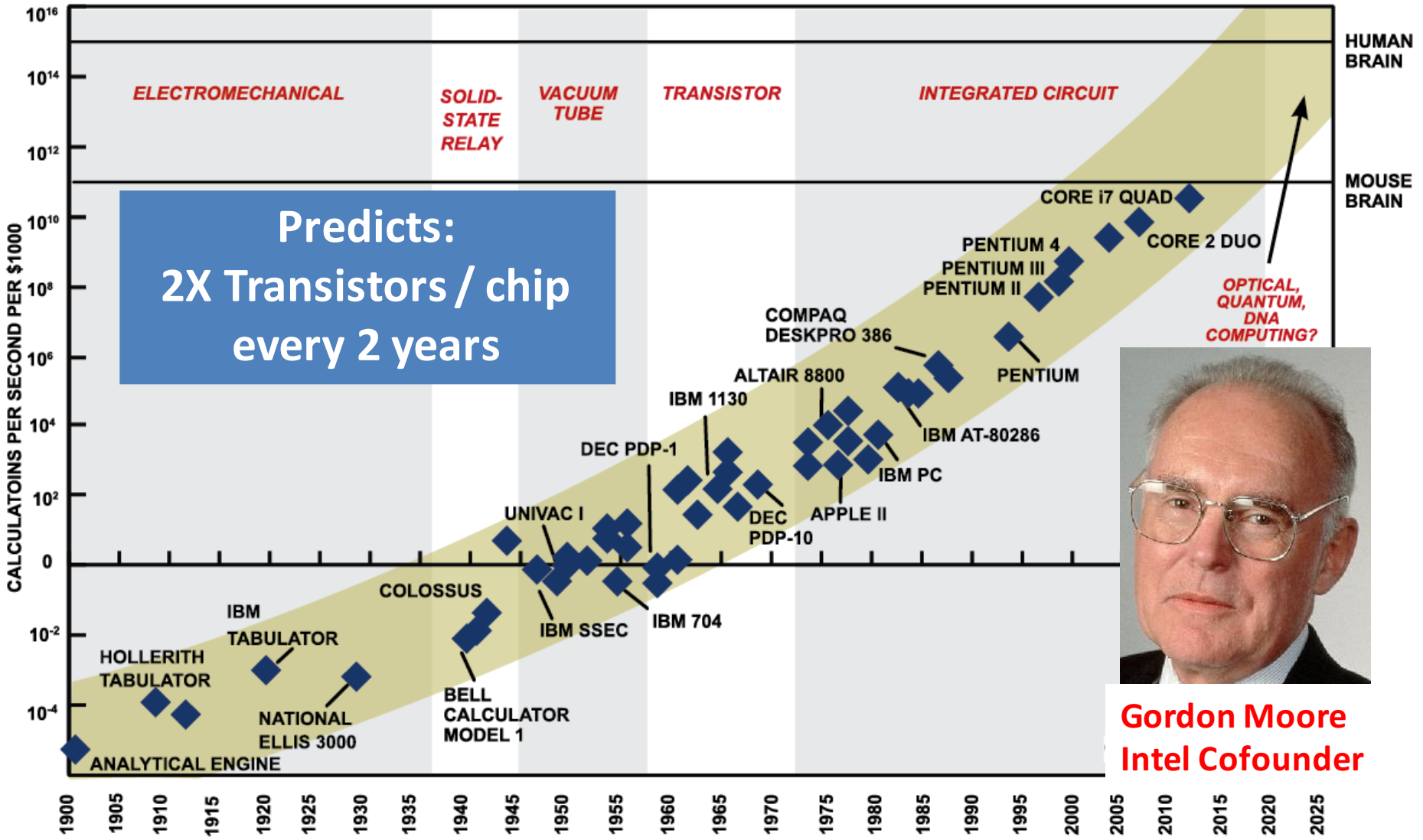
Anything can be represented as a *number*, i.e., data or instructions

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





#2: Moore's Law



Gordon Moore
Intel Cofounder

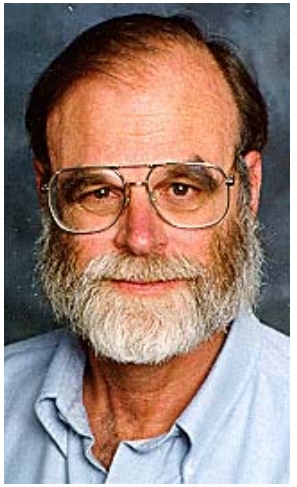
SOURCE: RAY KURZWEIL, "THE SINGULARITY IS NEAR: WHEN HUMANS TRANSCEND BIOLOGY", P.67, *THE VIKING PRESS*, 2006. DATAPOINTS BETWEEN 2000 AND 2012 REPRESENT BCA ESTIMATES.

Interesting Times

Moore's Law relied on the cost of transistors scaling down as technology scaled to smaller and smaller feature sizes.

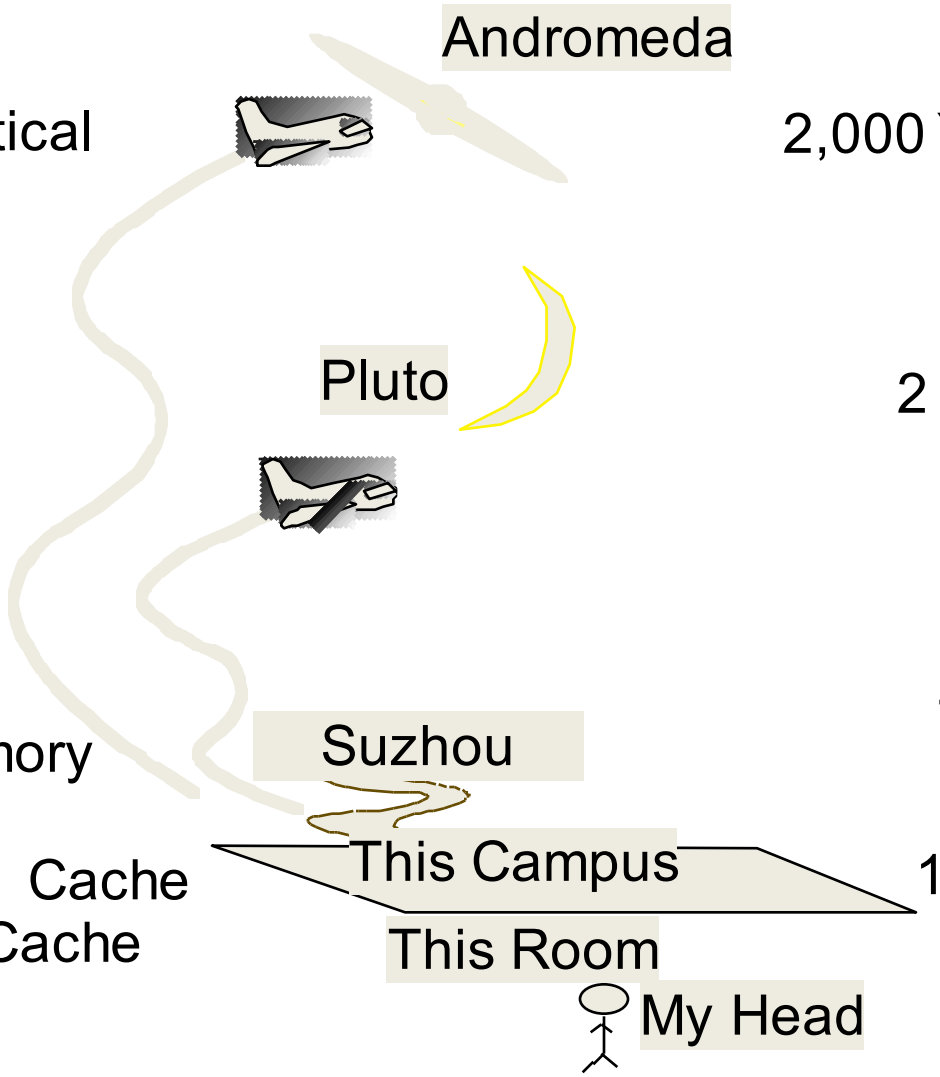
BUT newest, smallest fabrication processes <14nm, might have greater cost/transistor !!!!
So, why shrink????

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

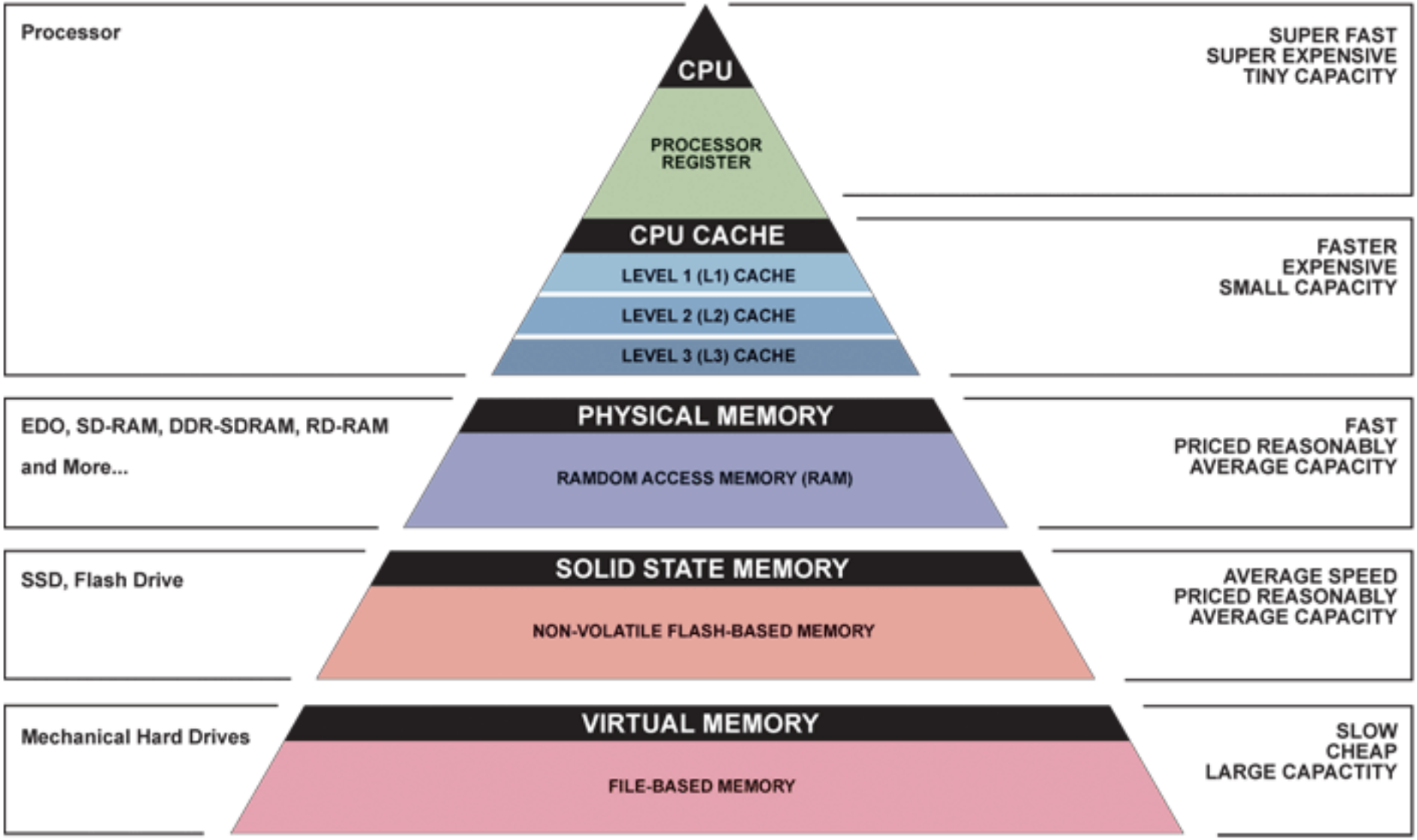


Jim Gray
Turing Award

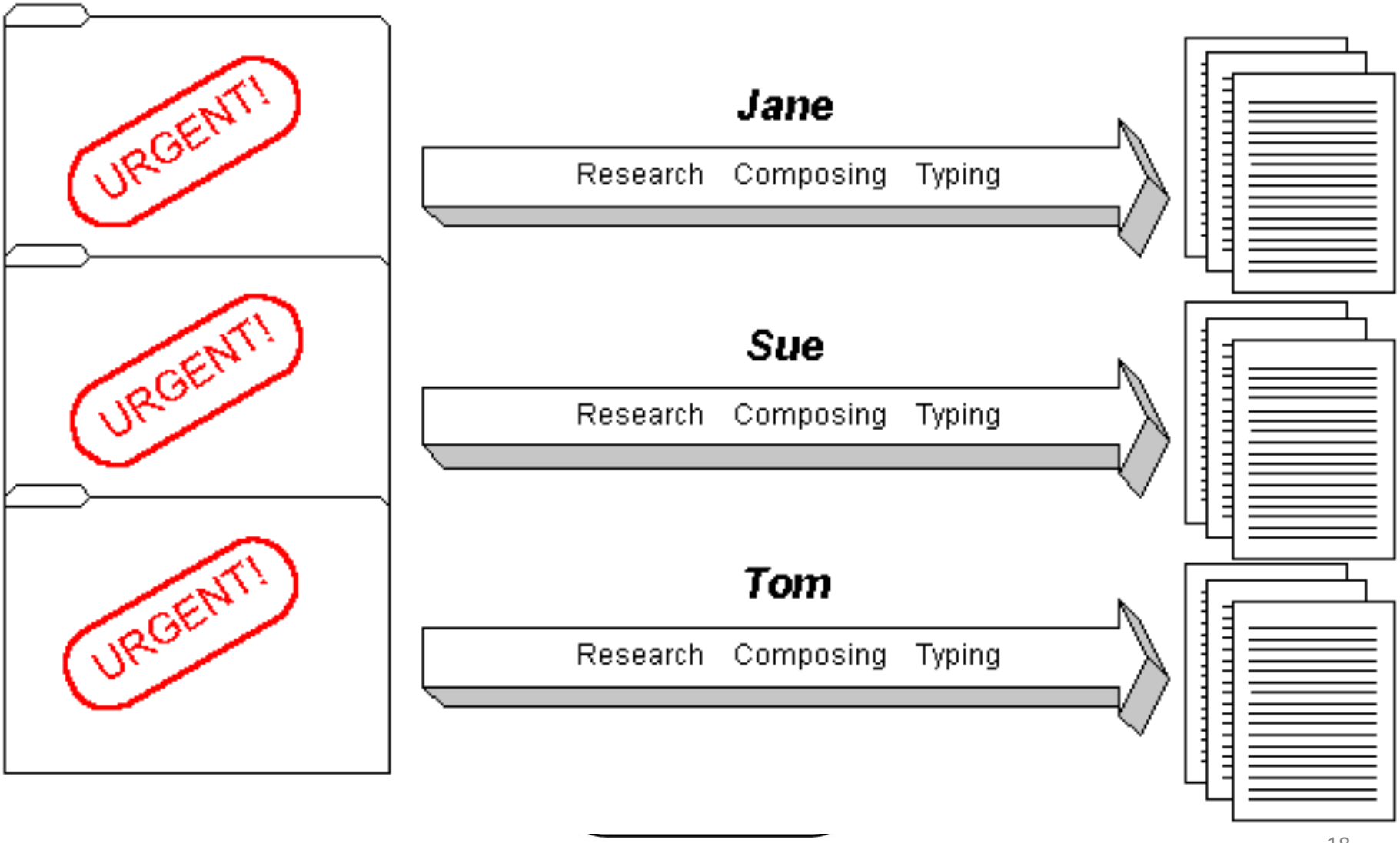
10^9	Tape /Optical Robot	2,000 Years
10^6	Disk	2 Years
100	Main Memory	1.5 hr
10	On Board Cache	10 min
2	On Chip Cache	
1	Registers	1 min
(ns)		



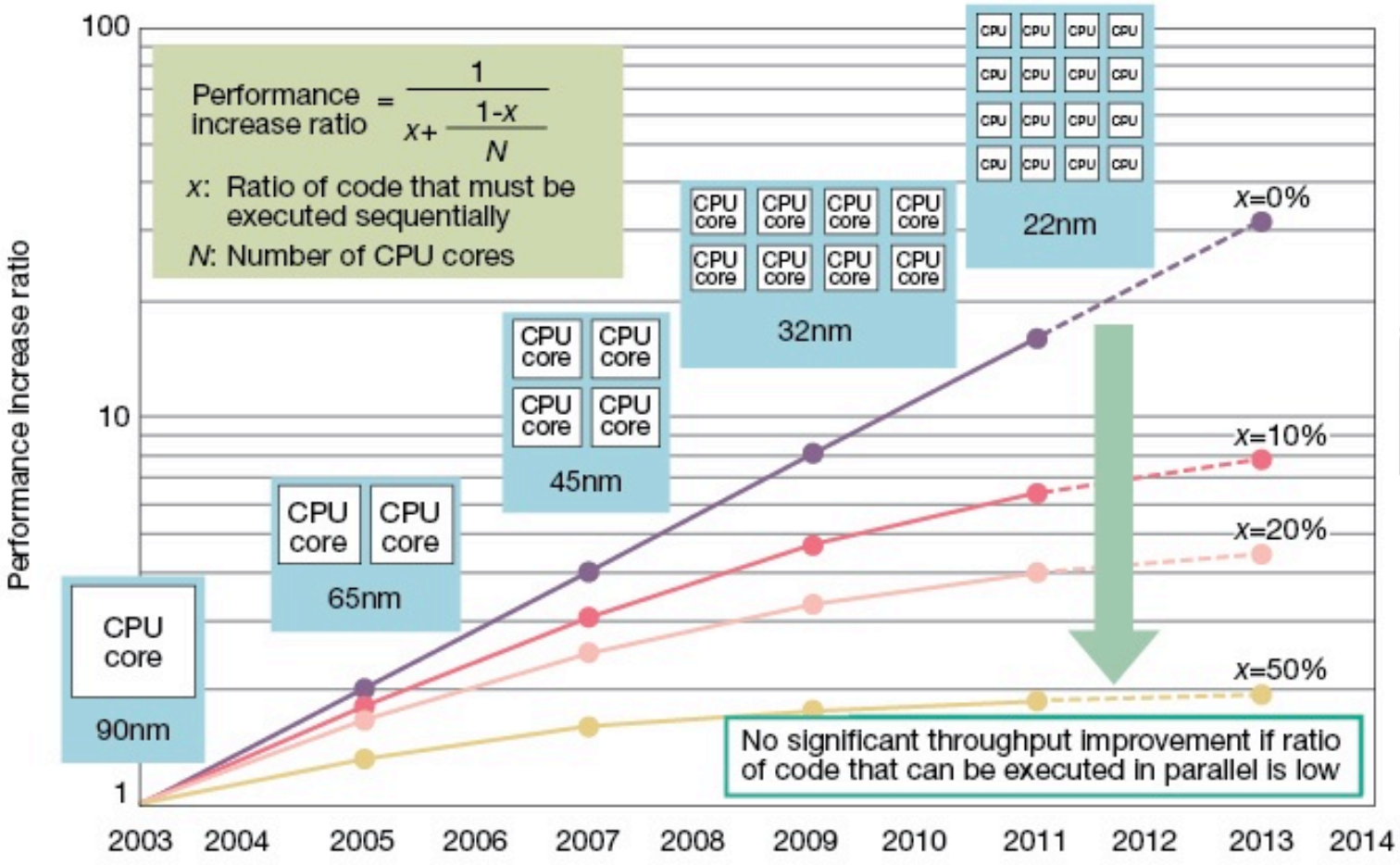
Great Idea #3: Principle of Locality/ Memory Hierarchy



Great Idea #4: Parallelism



Caveat: Amdahl's Law



Gene Amdahl
Computer Pioneer

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.

Great Idea #5: Performance Measurement and Improvement

- Tuning application to underlying hardware to exploit:
  - Locality
  - Parallelism
  - Special hardware features, like specialized instructions (e.g., matrix manipulation)
- Latency
  - How long to set the problem up
  - How much faster does it execute once it gets going
  - It is all about *time to finish*

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

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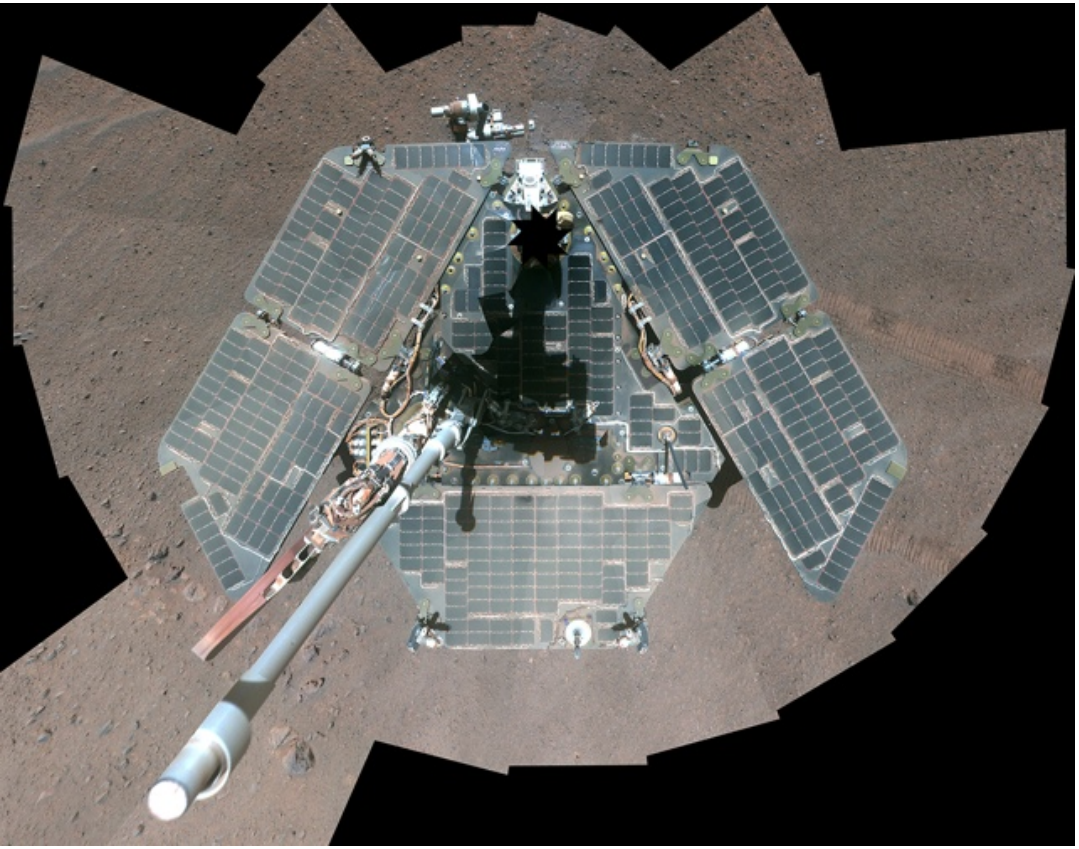
50,000 x 4 = 200,000 disks

200,000 x 4% = 8000 disks fail

365 days x 24 hours = 8760 hours

NASA Fixing Rover's Flash Memory



Opportunity still active on Mars after >10 years

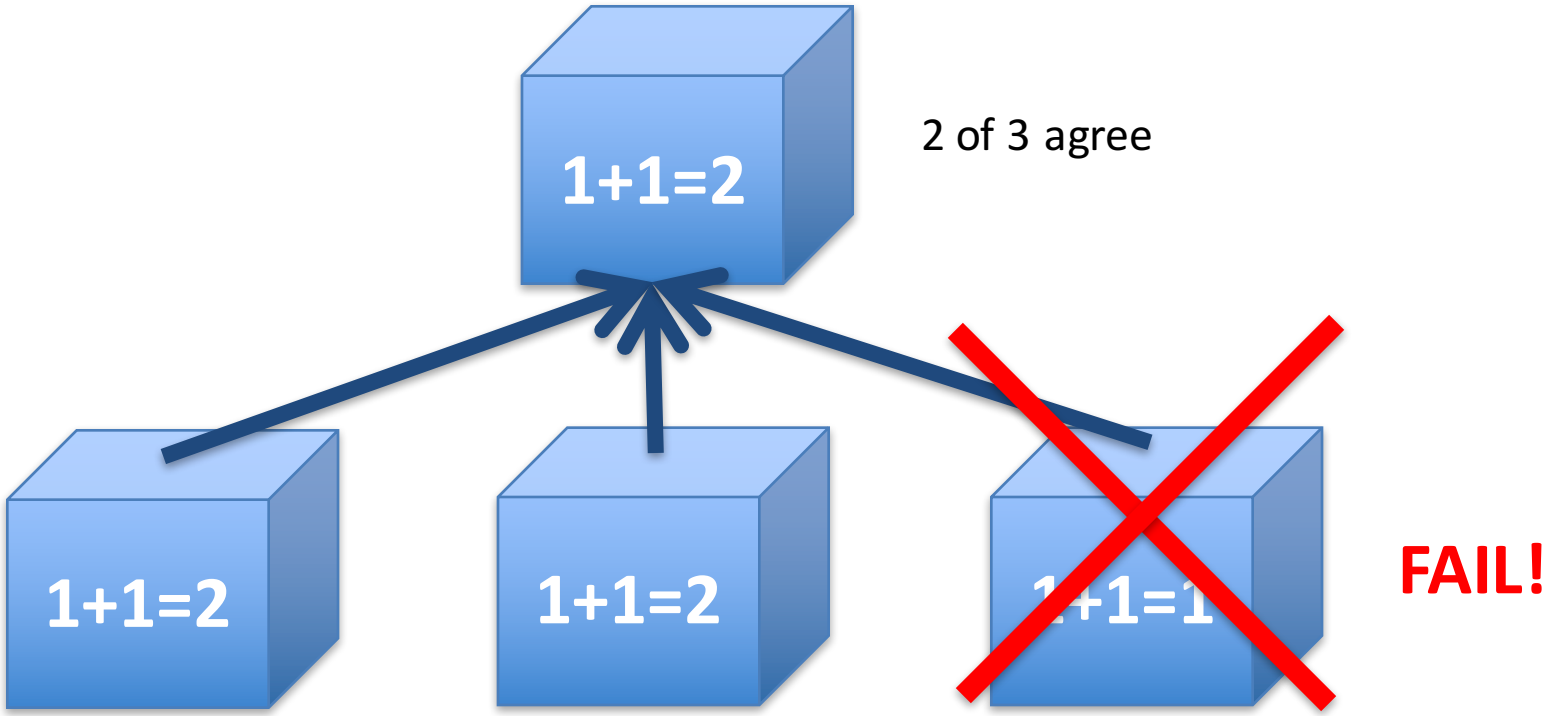
But flash memory worn out

New software update to avoid using worn out memory banks

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

Great Idea #6: Dependability via Redundancy

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



Increasing transistor density reduces the cost of redundancy

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 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)

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Weekly Schedule

Lecture	Tuesday, 08:15-09:55. room: H2 109
Lecture	Friday, 10:15-11:55. room: H2 109
Discussions	Tuesday, 18:40-20:20. 教学楼309.
Lab 1	Monday, 15:00-16:40. 教学楼308
Lab 2	Tuesday, 15:00-16:40. 教学楼309
Lab 3	Thursday, 15:00-16:40. 行政楼405

Course Information

- Course Web: http://shtech.org/course/ca/
- Acknowledgement: Instructors of UC Berkeley's CS61C: http://www-inst.eecs.berkeley.edu/~cs61c/
- Instructor:
  - Sören Schwertfeger
- Teaching Assistants: (see webpage)
- Textbooks: Average 15 pages of reading/week
  - Patterson & Hennessey, *Computer Organization and Design*, 5th Edition (Chinese version is 4th edition – significant differences!)
  - Kernighan & Ritchie, *The C Programming Language*, 2nd Edition
  - Barroso & Holzle, *The Datacenter as a Computer, 2nd Edition*
- Piazza:
  - Every announcement, discussion, clarification happens there

Course Grading

- Projects: 33%
- Homework: 17%
- Lab: 10%
- Exams: 35%
  - Midterm 1: 7.5%
  - Midterm 2: 7.5%
  - Final: 20%
- Participation: 5%

Late Policy … Slip Days!

- Assignments due at 11:59:59 PM
- You have 3 slip day tokens (NOT hour or min)
- Every day your project or homework is late (even by a minute) we deduct a token
- After you've used up all tokens, it's 25% deducted per day.
  - No credit if more than 3 days late
  - Save your tokens for projects, worth more!!
- No need for sob stories, just use a slip day!
- Gradebot is open till 3 days after due date!
- If you need more time (slip days plus deduction) send the TA and Prof. an email!

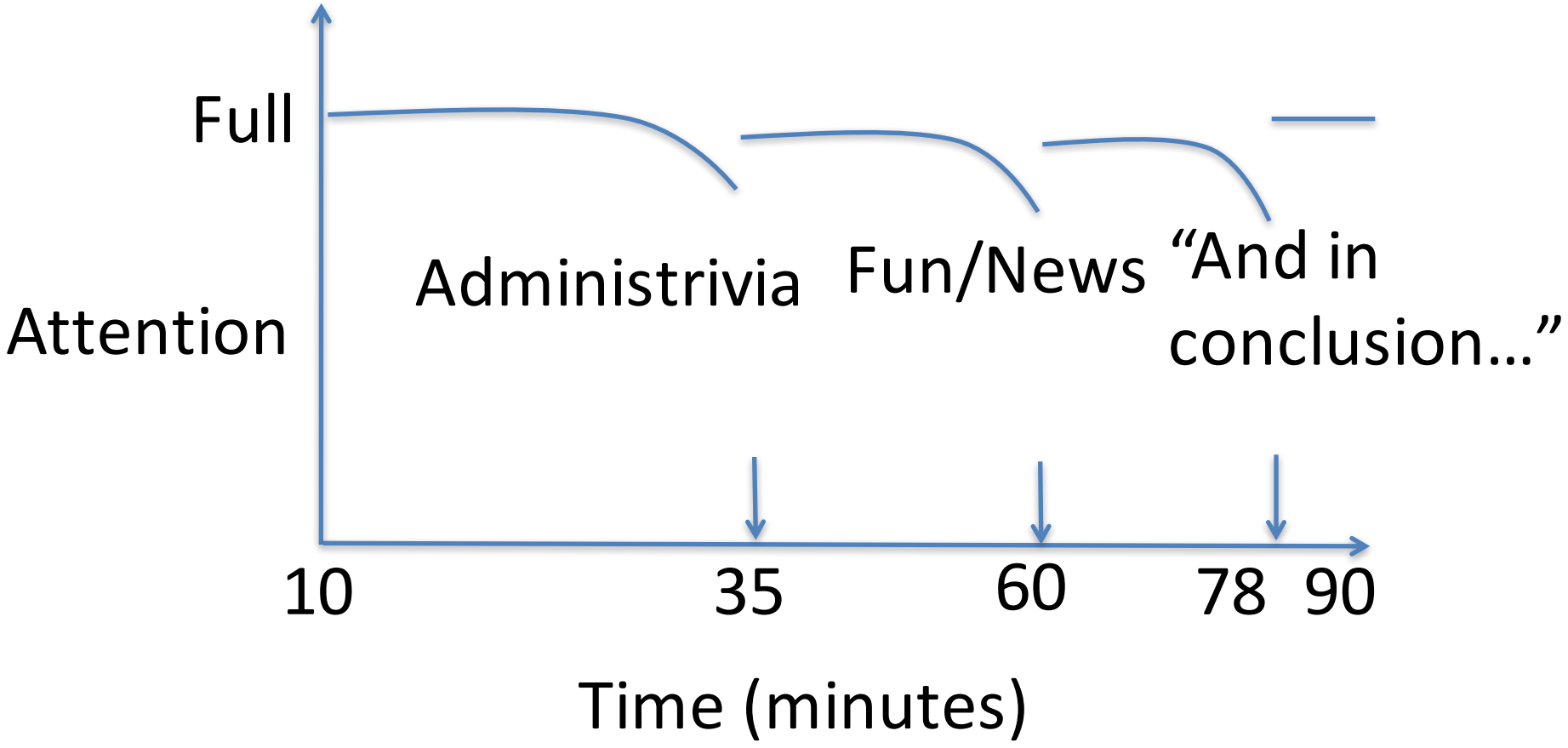
Policy on Assignments and Independent Work

- **ALL PROJECTS WILL BE DONE WITH A PARTNER**
- With the exception of laboratories and assignments that explicitly permit you to work in groups, all homework and projects are to be YOUR work and your work ALONE.
- PARTNER TEAMS MAY NOT WORK WITH OTHER PARTNER TEAMS
- You are encouraged to discuss your assignments with other students, and credit will be assigned to students who help others, particularly by answering questions on Piazza, but we expect that what you hand in is yours.
- It is NOT acceptable to copy solutions from other students.
- It is NOT acceptable to copy (or start your) solutions from the Web.
- It is NOT acceptable to use PUBLIC github archives (giving your answers away)
- We have tools and methods, developed over many years, for detecting this. You WILL be caught, and the penalties WILL be severe.
- **At the minimum F in the course**, and a letter to your university record documenting the incidence of cheating.
- **Both Giver and Receiver are equally culpable and suffer equal penalties**

Discussion & Labs & HW1

- First discussion today! Tuesday, 18:40-20:20 教学楼309
  - Topic: Number representation
  - Let us know what topics you'd like to have covered!
  - Topic next discussion: C
- Labs: Find a partner for your lab-work and the projects – from you lab class!
  - Send an email to Xu Qingwen (xuqw)
  - Labs start next week
- HW1 will be posted on Friday.

Architecture of a typical Lecture



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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:
- $123_{10} = 1_{10} \times 10_{10}^{2} + 2_{10} \times 10_{10}^{1} + 3_{10} \times 10_{10}^{0}$

  $= 1x100_{10} + 2x10_{10} + 3x1_{10}$

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

  $= 123_{10}$
- Binary (Base 2), Hexadecimal (Base 16), Decimal (Base 10) different ways to represent an integer
  - We use 1_{two}, 5_{ten}, 10_{hex} to be clearer (vs. 1_2, 4_8, 5_{10}, 10_{16})

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*, e.g. 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) (4 Gig)

Unsigned Integers

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

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

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

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}

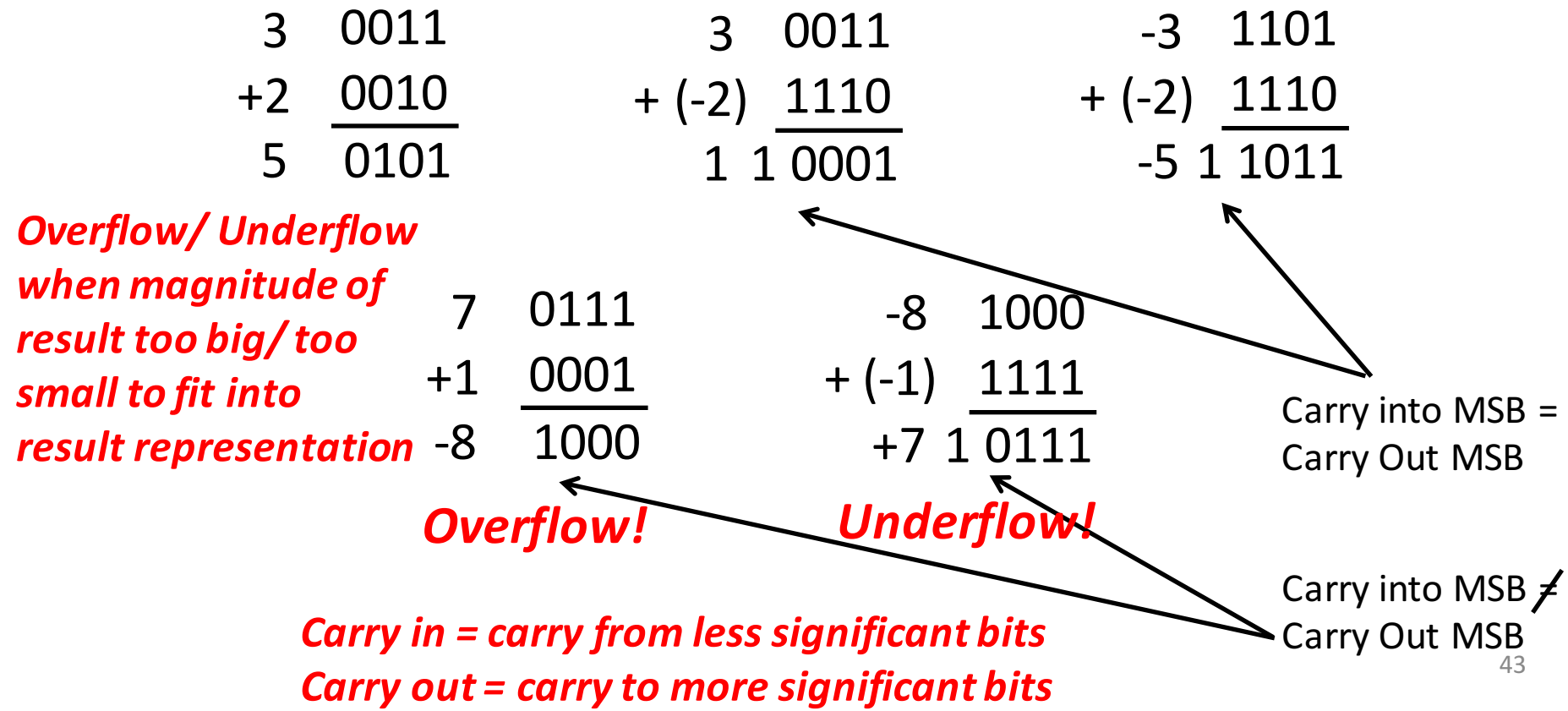
Bitwise complement 1100_{two}

$+ \quad 1_{two}$

-3_{ten} 1101_{two}

Two's-Complement Examples

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



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**

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

- Computer Architecture: Learn 6 great ideas in computer architecture to enable high performance programming via parallelism, not just learn C
  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
- Everything is a Number!