

Machine Learning's Slides

Author: Pannenets.F

Date: December 12, 2020

Je reviendrai et je serai des millions. «Spartacus»

0.1 Introduction

Computer Architecture (计算机体系结构)

Lecture #1 – Introduction



Lecturer Yuanqing Cheng (成元庆)

School of Microelectronics

Beihang University

www.cadetlab.cn

“I stand on the shoulders of giants...”



**Prof
David
Patterson**



**Prof
Dan
Garcia**

**Thanks to these talented folks (& many others)
whose contributions have helped make this
course a really tremendous course!**

What are prerequisites of this course ?

- **Programming languages ?**
- **Data structures ?**
- **Digital logic design ?**

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

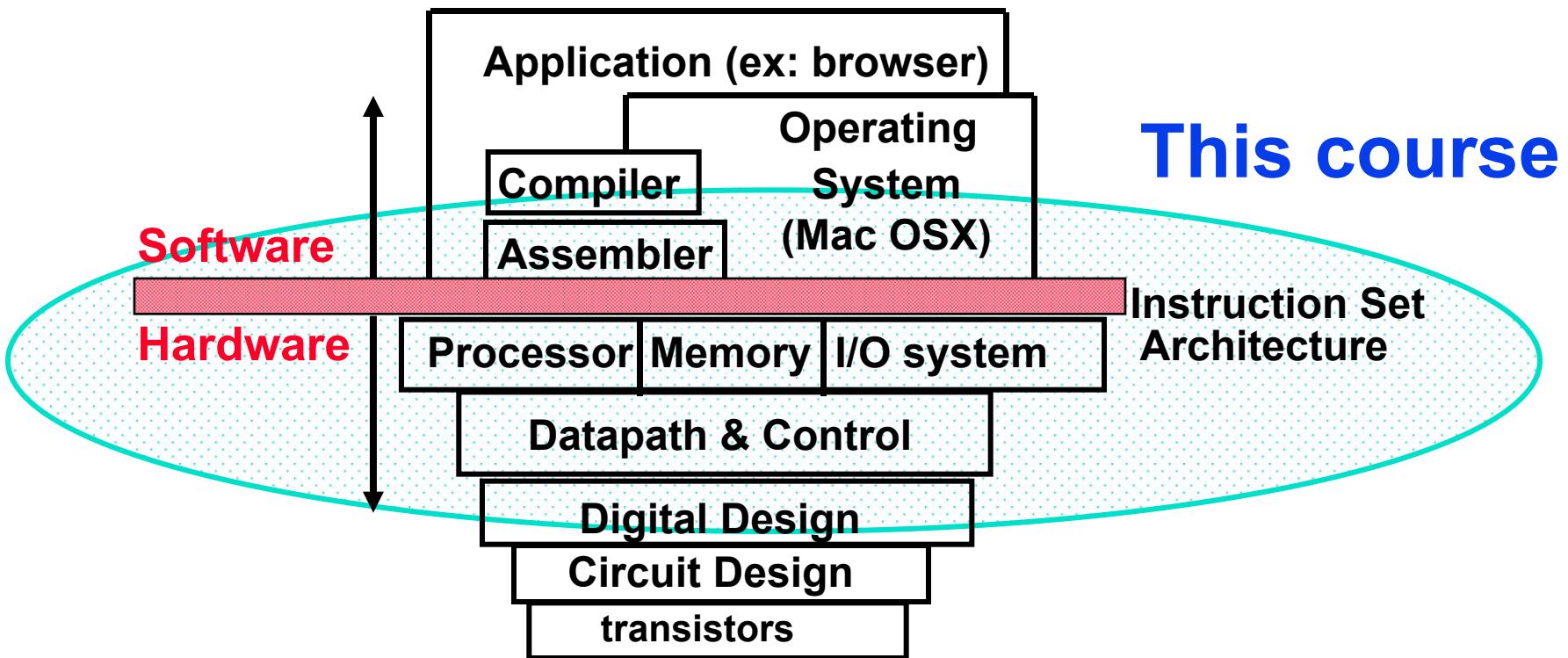


Are Computers Smart?

- In real life at the lowest level:
 - Only a handful of operations:
 - {and, or, not}
 - No automatic memory management.
 - Only 2 values:
 - {0, 1} or {low, high} or {off, on}

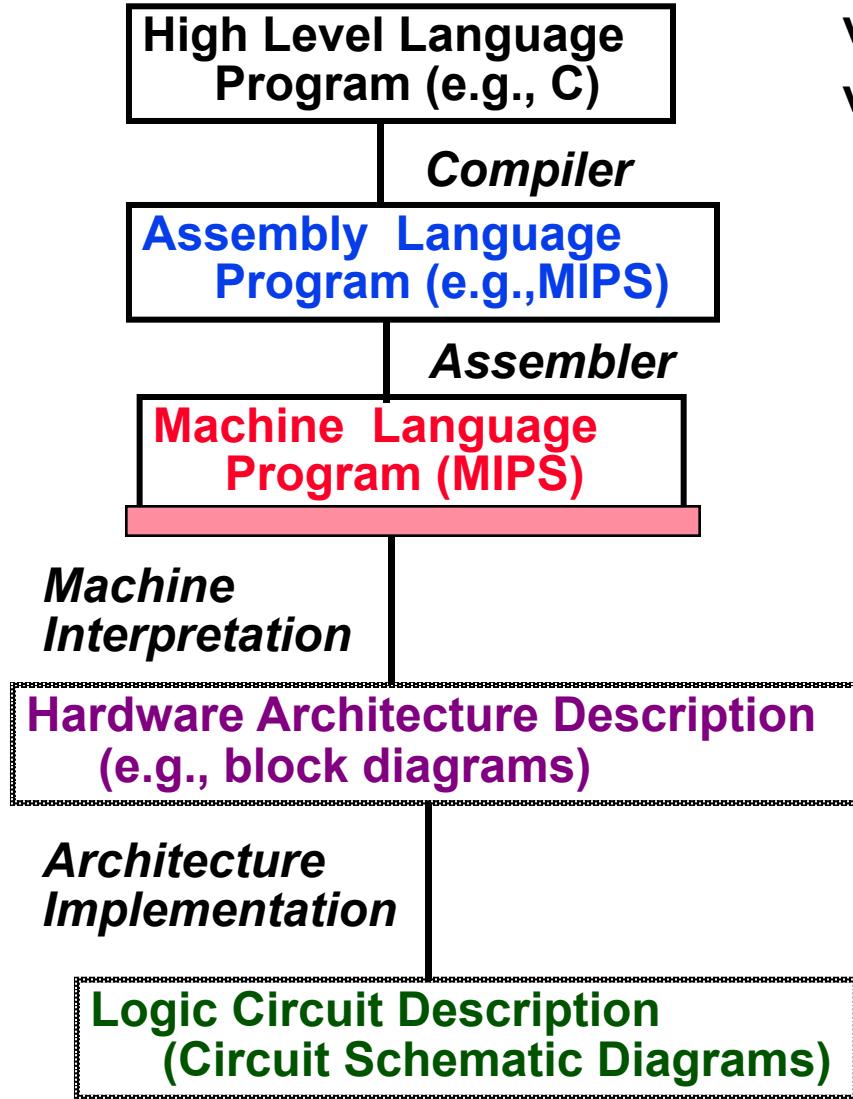


What are “Computer Architecture”?



**Coordination of many
*levels (layers) of abstraction***

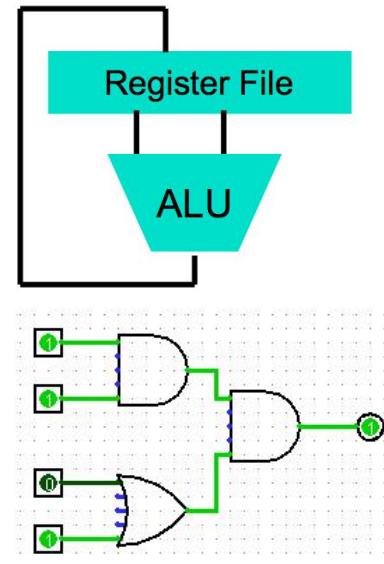
Levels of Representation



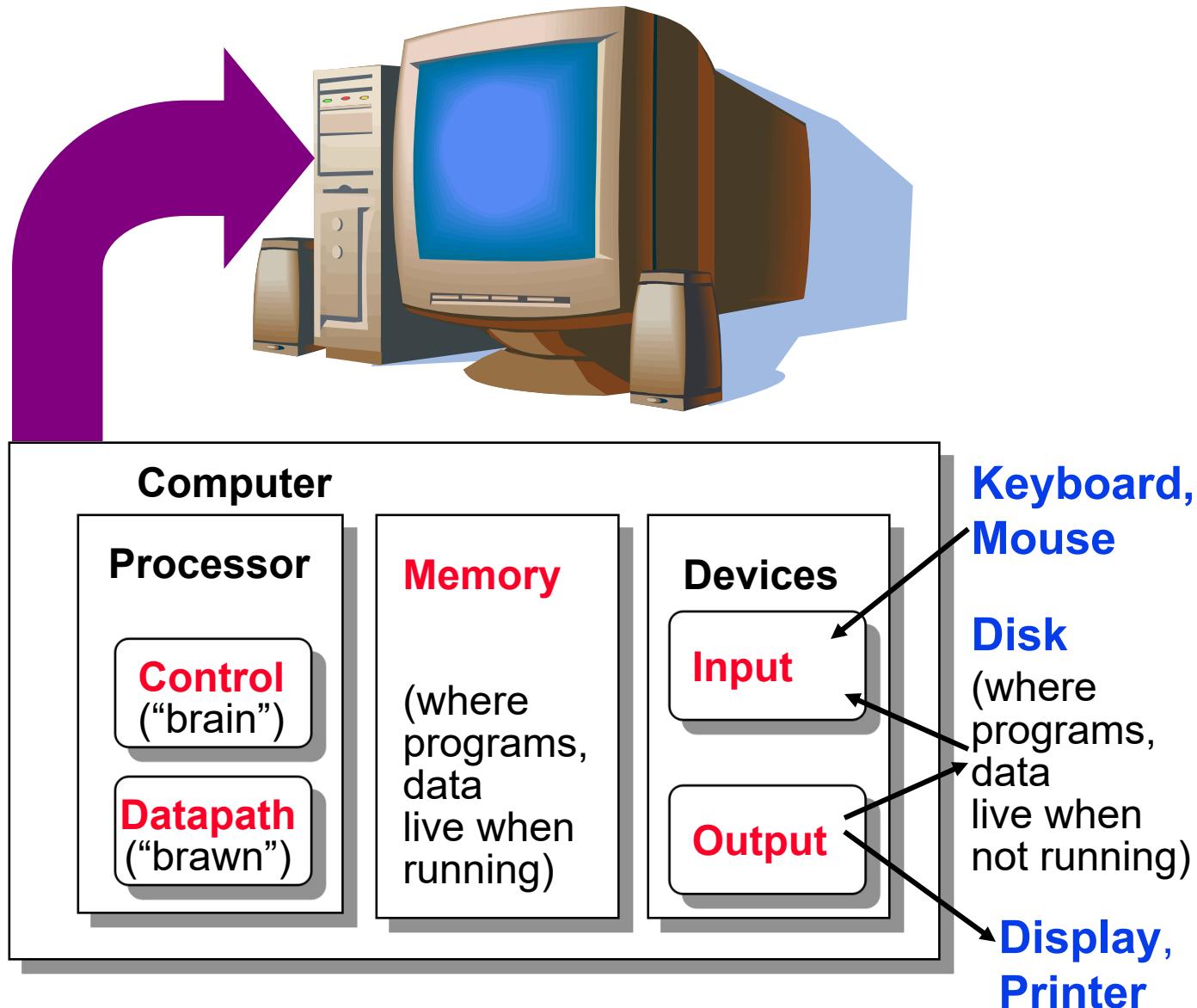
`temp = v[k];
v[k] = v[k+1];
v[k+1] = temp;`

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

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



Anatomy: 5 components of any Computer



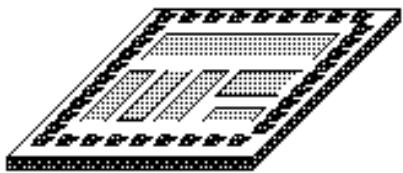
Overview of Physical Implementations

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.**

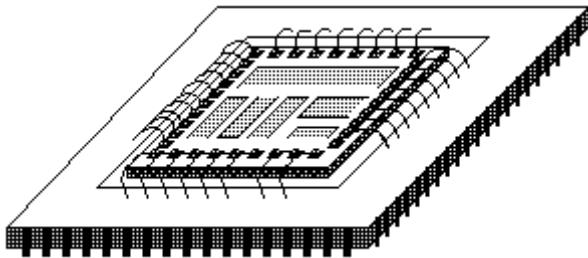
Integrated Circuits (2020 state-of-the-art)

Bare Die



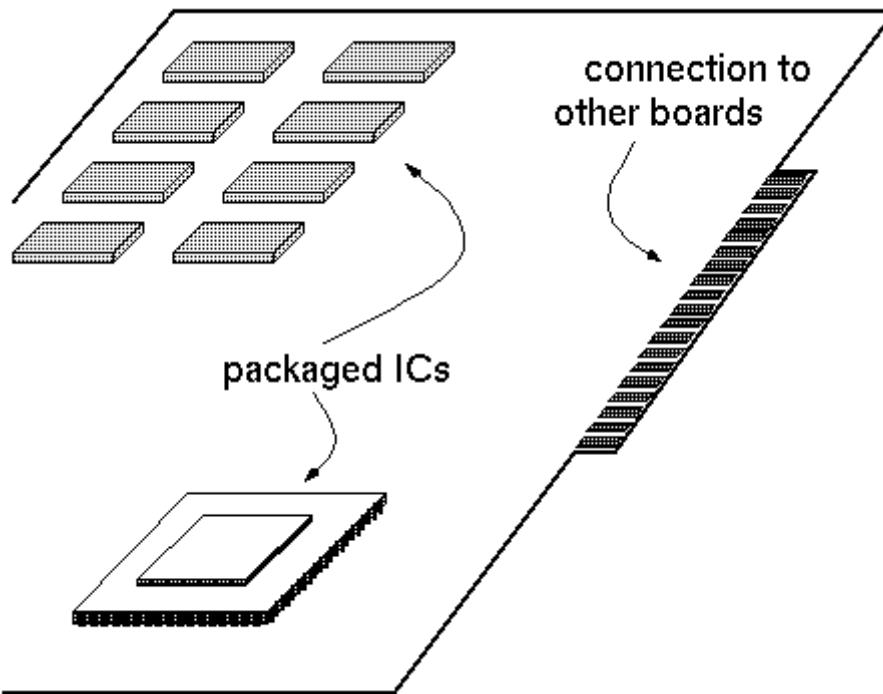
- Primarily Crystalline Silicon
- 1mm - 25mm on a side
- feature size $\sim 14/7$ nm
- Billions of transistors
- (25 - 100M “logic gates”)
- 3 - 12 conductive layers
- “CMOS” (complementary metal oxide semiconductor) - most common.

Chip in Package



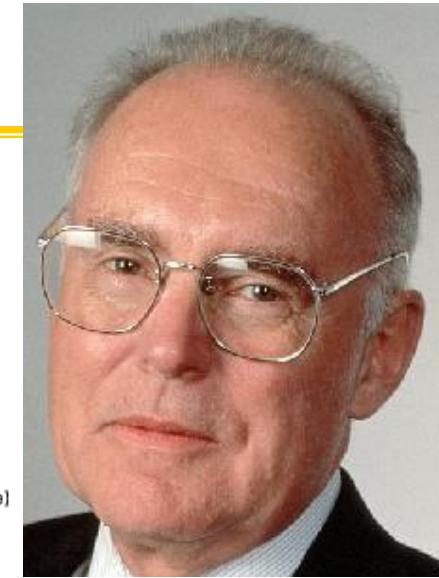
- Package provides:
 - spreading of chip-level signal paths to board-level
 - heat dissipation.
- Ceramic or plastic with gold wires.

Printed Circuit Boards

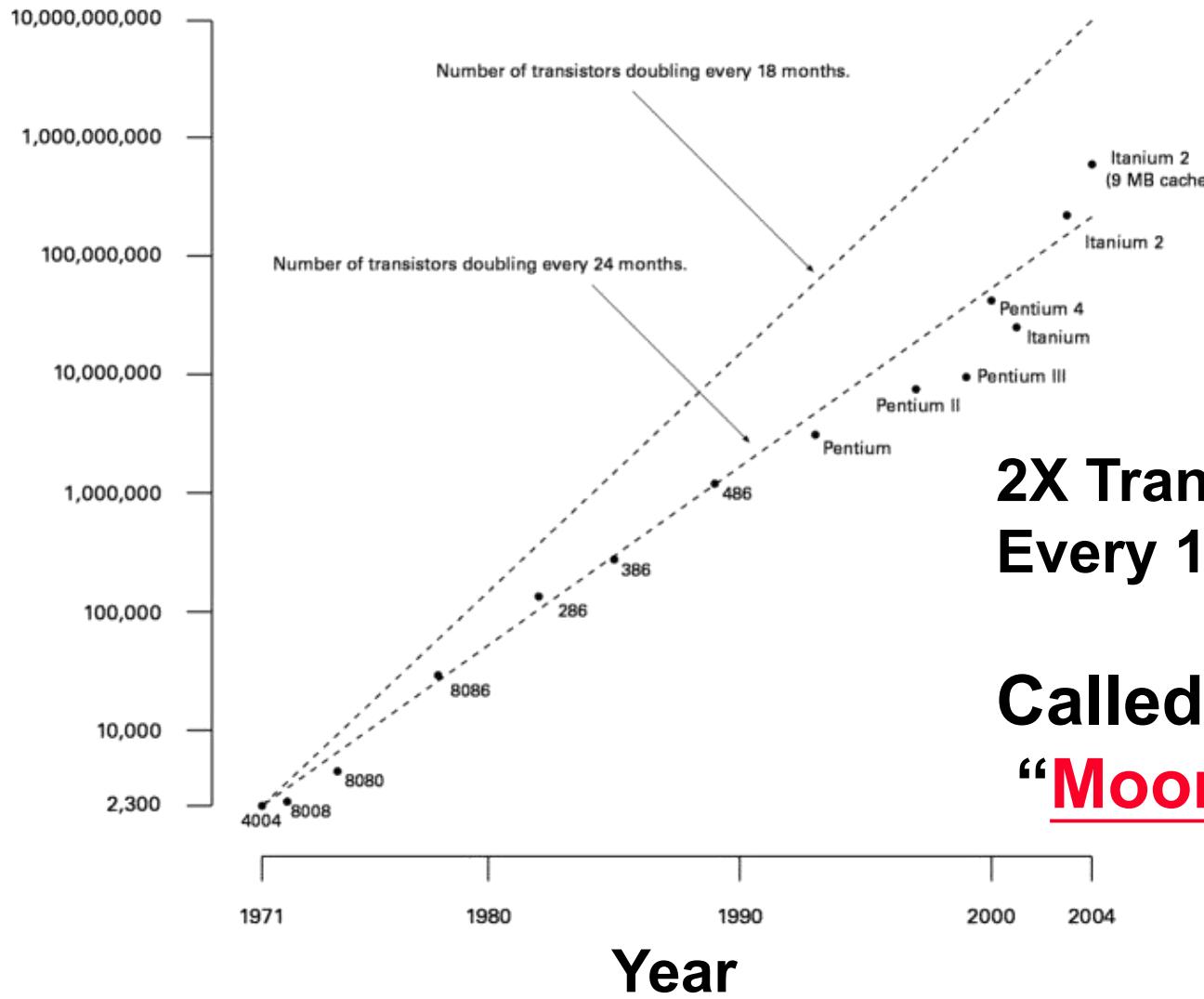


- **fiberglass or ceramic**
- **1-20 conductive layers**
- **1-20 in on a side**
- **IC packages are soldered down.**
- **Provides:**
 - Mechanical support
 - Distribution of power and heat.

Technology Trends: Microprocessor Complexity



of transistors on an IC

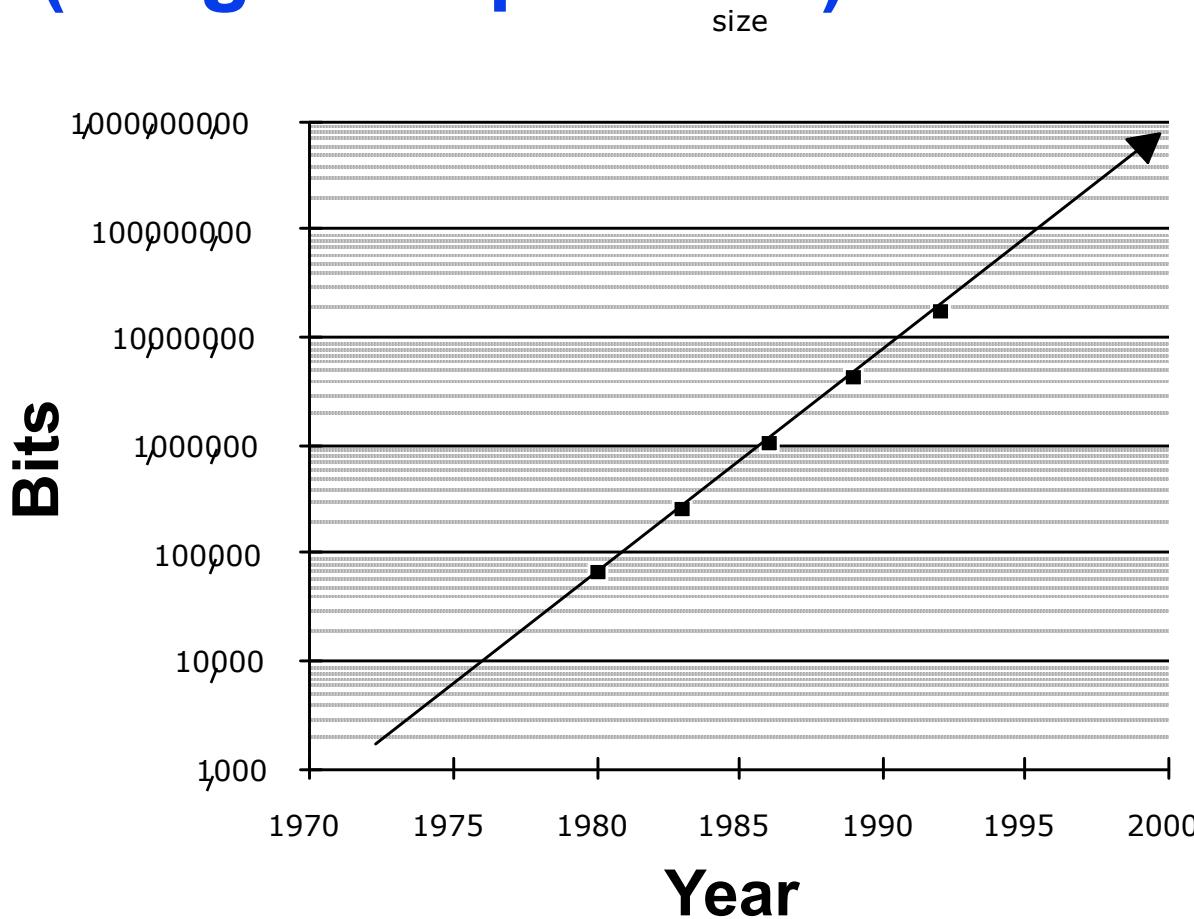


Gordon Moore
Intel Cofounder!

2X Transistors / Chip
Every 1.5 years

Called
“Moore’s Law”

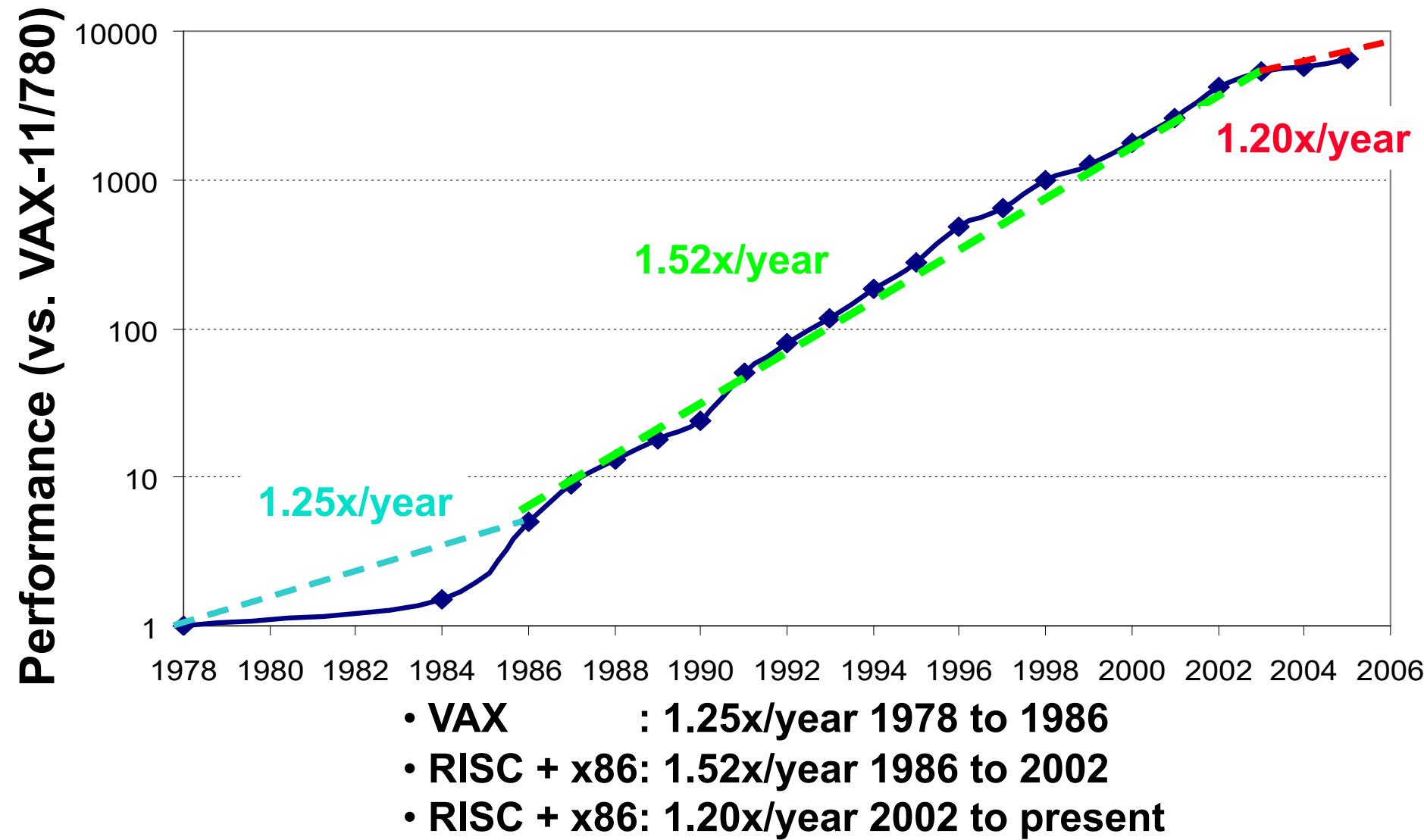
Technology Trends: Memory Capacity (Single-Chip DRAM)



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

year	size (Mbit)
1980	0.0625
1983	0.25
1986	1
1989	4
1992	16
1996	64
1998	128
2000	256
2002	512
2004	1024
2006	2048 (2Gbit)
2010	8192 (8Gbit)

Technology Trends: Uniprocessor Performance (SPECint)



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); **[slowing!]**
Now almost remain the same.
- Disk
 - Capacity: 2x / 1 year (since '97)
250X size in last decade.

Computer Technology - Dramatic Change!

You just learned the difference between (Kilo, Mega, ...) and (Kibi, Mebi, ...)!

- State-of-the-art PC :
(at least...)

- Processor clock speed: 4,000 **MegaHertz**
(4.0 **GigaHertz**)
- Memory capacity: 65,536 **MebiBytes**
(64.0 **GibiBytes**)
- Disk capacity: 2,000 **GigaBytes**
(2.0 **TeraBytes**)
- New units! **Mega** ⇒ **Giga**, **Giga** ⇒ **Tera**

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

Computer arch. : So, what's in it for me?

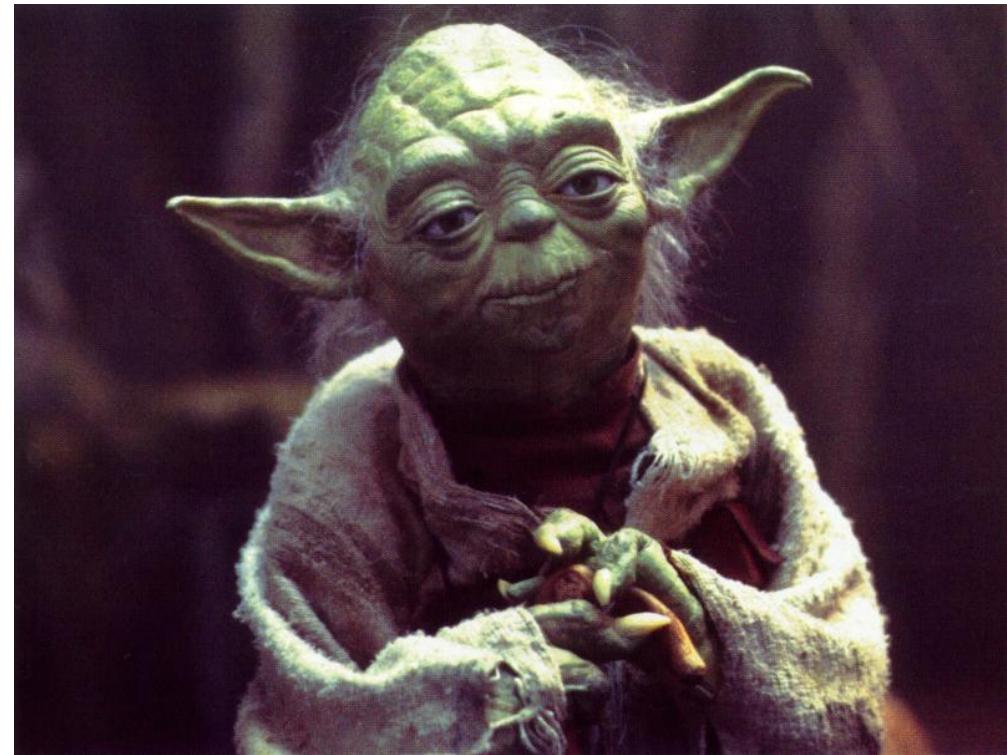
- Learn some of the big ideas in CS & Engineering:
 - Principle of abstraction
 - Used to build systems as layers
 - 5 Classic components of a Computer
 - Data can be anything
 - Integers, floating point, characters, ...
 - A program determines what it is
 - Stored program concept: instructions just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

Others Skills learned in this course

- **Enhance C programming skill**
 - If you know one, you should be able to learn another programming language largely on your own
 - If you know C++ or Java, it 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'll learn just the basics of hardware design
 - We'll this in more detail in following courses

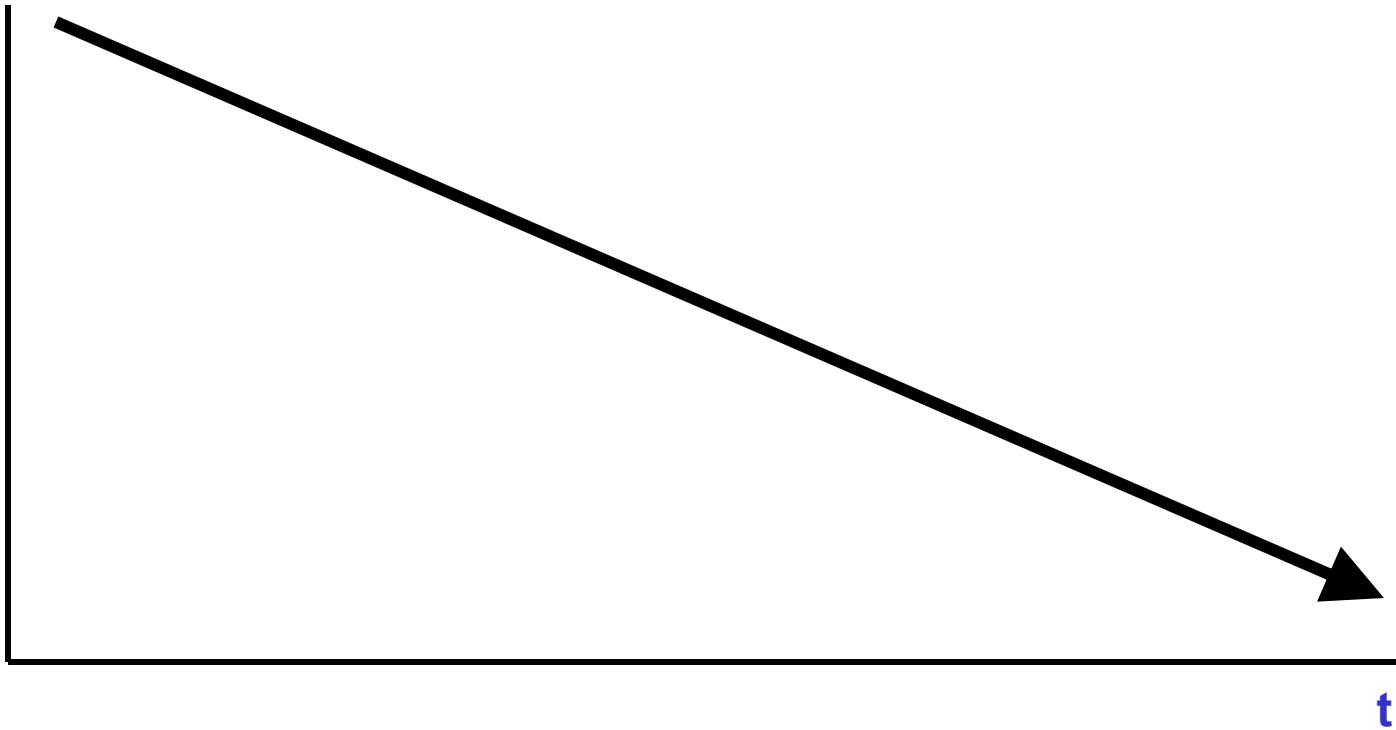
Yoda says...

**“Always in
motion is the
future...”**



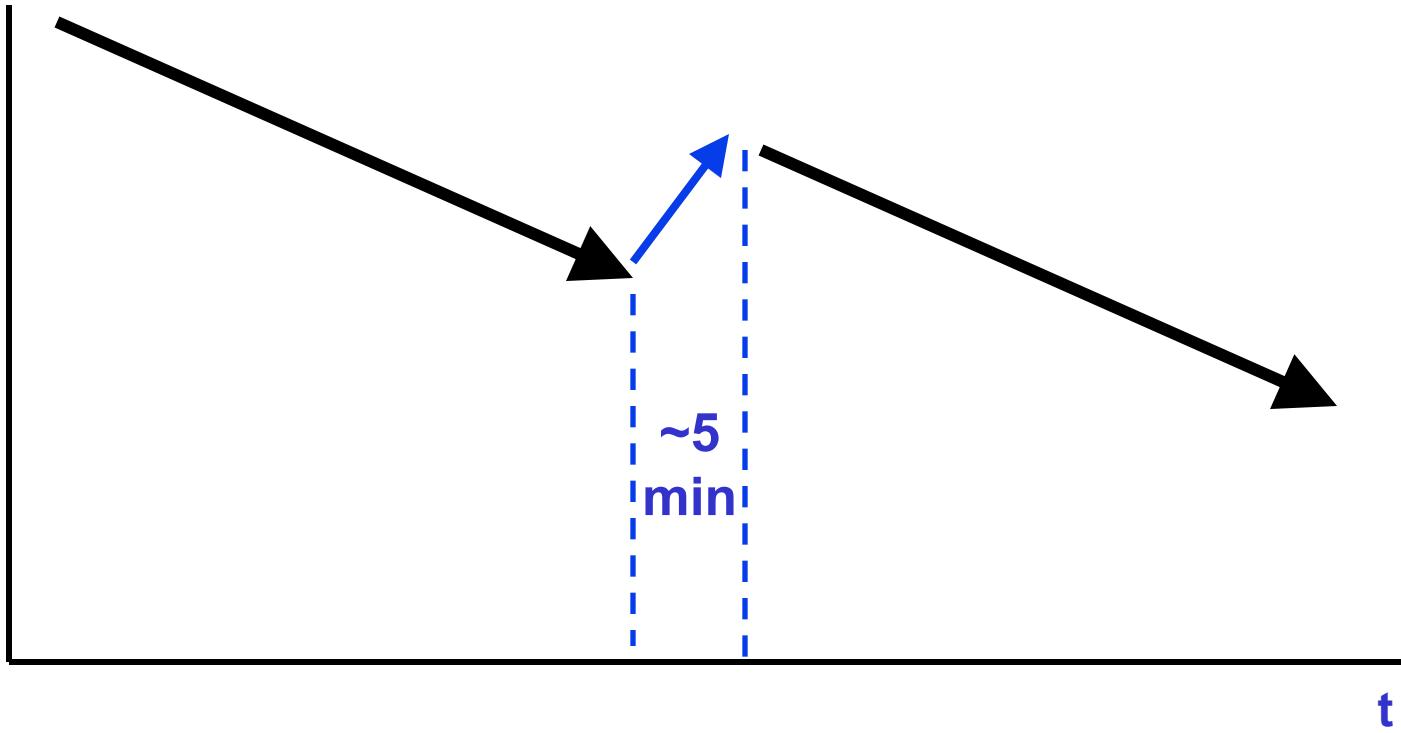
**Our schedule may change slightly depending on some factors.
This includes lectures, assignments & labs...**

What is this?



Attention over time!

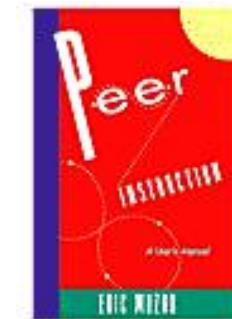
What is this?!



Attention over time!

Tried-and-True Technique: Peer Instruction

- Increase real-time learning in lecture, test understanding of concepts vs. details
- As complete a “segment” ask multiple choice question
 - 1-2 minutes to decide yourself
 - 3 minutes in pairs/triples to reach consensus. Teach others!
 - 5-7 minute discussion of answers, questions, clarifications



Extra Credit: EPA!

- **Effort**
 - Attending my or my TA's office hours, completing all assignments, turning in HW, doing reading quizzes
- **Participation**
 - Attending lecture and voting in Peer Instruction
 - Asking great questions in discussion and lecture and making it more interactive
- **Altruism**
 - Helping others in lab or wechat
- **EPA! extra credit points have the potential to bump students up to the next grade level!**

Course Problems...Cheating

- What is cheating?
 - Studying together in groups is encouraged.
 - Turned-in work must be completely your own.
 - Common examples of cheating: running out of time on a assignment and then pick up output, take homework from box and copy, person asks to borrow solution “just to take a look”, copying an exam question, ...
 - You’re not allowed to work on homework/projects/exams with anyone (other than ask Qs walking out of lecture)
 - Both “giver” and “receiver” are equally culpable
- Cheating points: **0 EPA, negative points for that assignment / project / exam (e.g., if it’s worth 10 pts, you get -10) In most cases, F in the course. .**

My goal as an instructor

- To make your experience in this course as enjoyable & informative as possible
 - Enthusiasm, graphics & technology-in-the-news in lecture
 - Fun, challenging projects & HW
 - Pro-student policies
- To be a good-teaching man
 - Please give me feedback so I improve!
Why am I not excellent teacher for you? I will listen!!



Teaching Assistants

- **Jiacheng Ni**



Summary

- Continued rapid improvement in computing
 - 2X every 2.0 years in memory size;
every 1.5 years in processor speed;
every 1.0 year in disk capacity;
 - Moore's Law enables processor
(2X transistors/chip ~1.5-2 yrs)
- 5 classic components of all computers

Control Datapath Memory Input Output



Processor

Reference slides

You ARE responsible for the material on these slides (they're just taken from the reading anyway) ; we've moved them to the end and off-stage to give more breathing room to lecture!

Course Lecture Outline

- Machine Representations
 - Numbers (integers, reals)
 - Assembly Programming
 - Compilation, Assembly
- Processors & Hardware
 - Logic Circuit Design
 - CPU organization
 - Pipelining
- Memory Organization
 - Caches
 - Virtual Memory
- I / O
 - Interrupts
 - Disks, Networks
- Advanced Topics
 - Performance
 - Virtualization
 - Parallel Programming

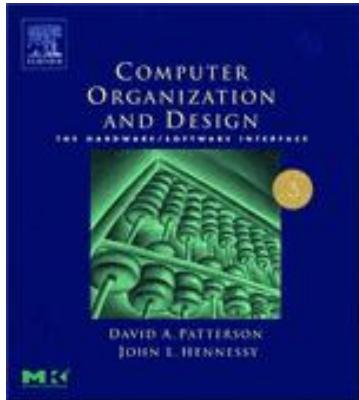
Homeworks and Projects

- Homework exercises
- Projects
- All exercises, reading, homeworks, projects on course web page
www.cadetlab.cn/courses
- We will DROP your lowest HW, Lab!
- Only one final exam

Your final grade

- **Grading (max: 100 pts)**
 - 20pts = 20% Homework
 - 20pts = 20% Projects
 - 50pts = 50% Final exam
 - 10pts = 10% Attendance
 - Extra EPA points (5pts)

Texts



- Required: *Computer Organization and Design: The Hardware/Software Interface*, Third Edition, Patterson and Hennessy (COD).
- Reading assignments on web page

Peer Instruction and Just-in-time-learning

- **Read textbook**
 - Reduces examples have to do in class
 - Get more from lecture (also good advice)
- **Fill out 3-question on web**
 - Graded for effort, not correctness...
 - This counts toward EPA score

0.2 Numbers

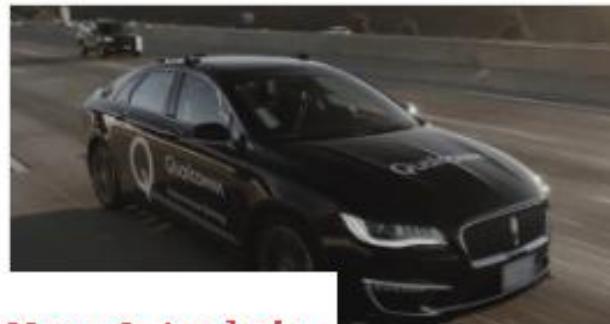
Computer Architecture (计算机体系结构)

Lecture #2 – Number Representation



Lecturer Yuanqing Cheng (成元庆)

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News & Analysis

Qualcomm Prepares to Take
Nvidia for a Ride

Review



- Continued rapid improvement in computing
 - 2X every 2.0 years in memory size;
every 1.5 years in processor speed;
every 1.0 year in disk capacity;
 - Moore's Law enables processor
(2X transistors/chip every 2 yrs)
- 5 classic components of all computers

a b c d e
Control Datapath Memory Input Output



What'll be the most
important part of a computer
in the future?

Putting it all in perspective...

“If the automobile had followed the same development cycle as the computer,

– *Robert X. Cringely*



Data input: Analog → Digital

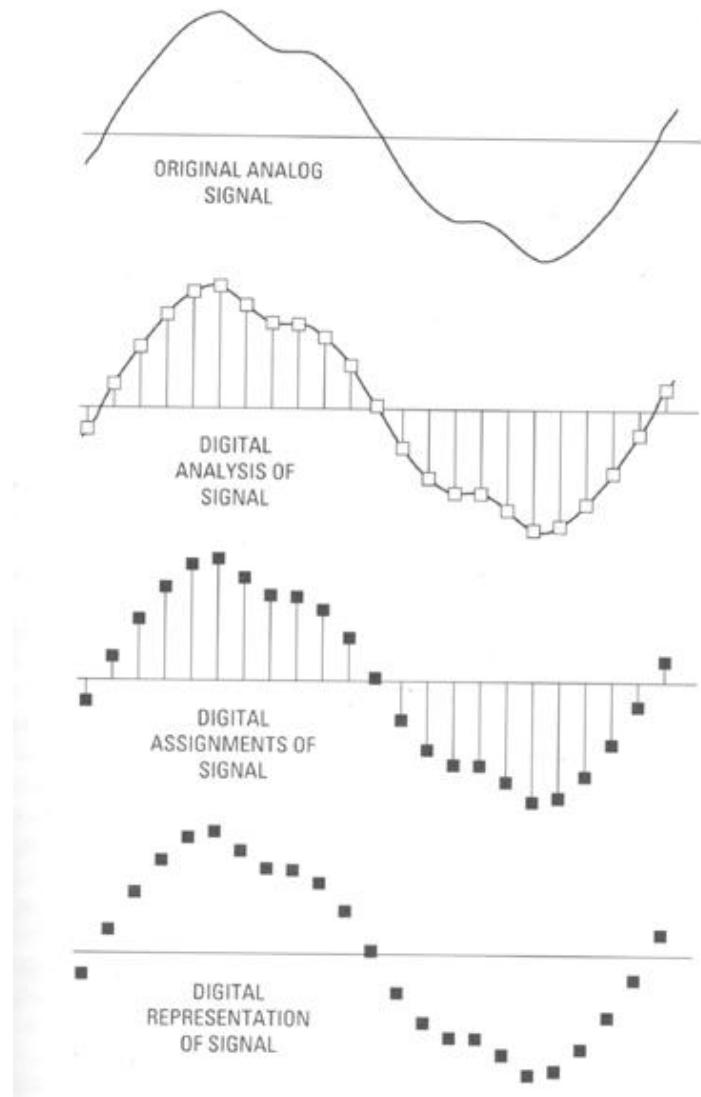
- Real world is analog!
- To import analog information, we must do two things

- Sample

- E.g., for a CD, every 44,100ths of a second, we ask a music signal how loud it is.

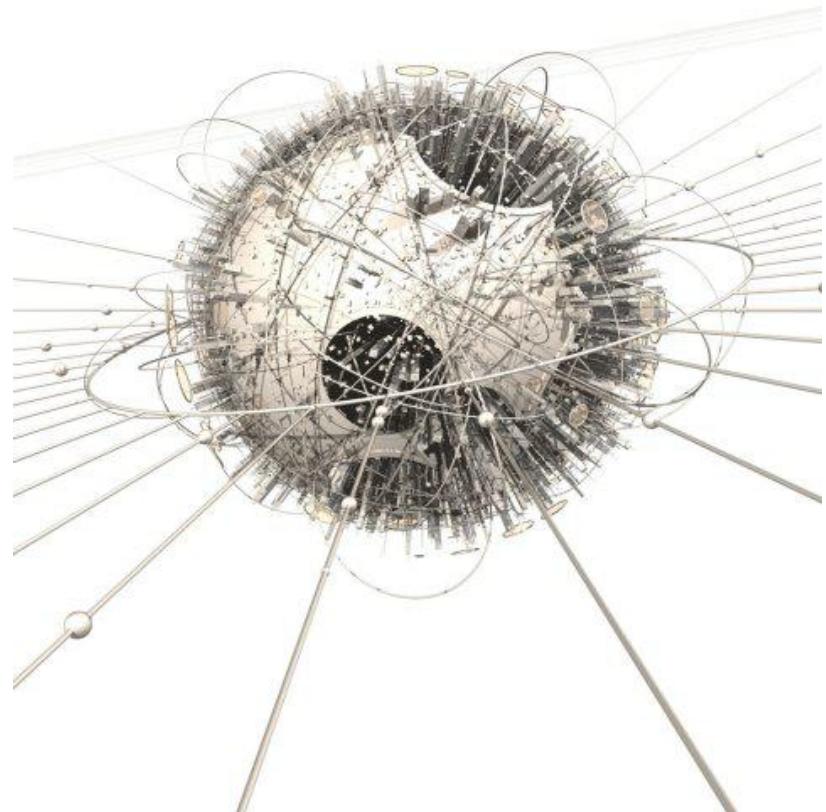
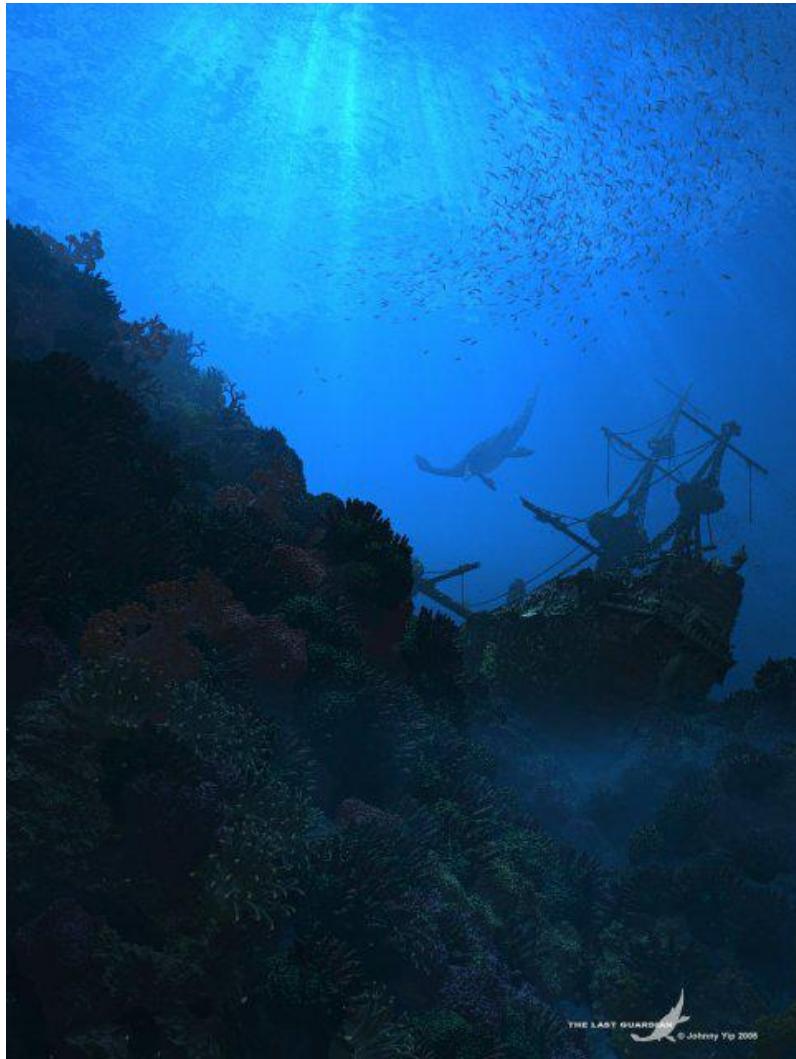
- Quantize

- For every one of these samples, we figure out where, on a 16-bit (65,536 tic-mark) “yardstick”, it lies.



www.joshuadysart.com/journal/archives/digital_sampling.gif

Digital data not nec born Analog...



hof.povray.org

BIG IDEA: Bits can represent anything!!

- Characters?

- 26 letters \Rightarrow 5 bits ($2^5 = 32$)
- upper/lower case + punctuation
 \Rightarrow 7 bits (in 8) ("ASCII")
- standard code to cover all the world's languages \Rightarrow 8,16,32 bits ("Unicode")
www.unicode.com



- Logical values?

- 0 \Rightarrow False, 1 \Rightarrow True

- colors ? Ex: Red (00) Green (01) Blue (11)

- locations / addresses? commands?

- MEMORIZE: N bits \Leftrightarrow at most 2^N things

How many bits to represent π ?



- a) 1
- b) 9 ($\pi = 3.14$, so that's 011 “.” 001 100)
- c) 64 (Since Macs are 64-bit machines)
- d) Every bit the machine has!
- e) ∞

What to do with representations of numbers?

- Just what we do with numbers!

- Add them

1 1

- Subtract them

1 0 1 0

- Multiply them

+ 0 1 1 1

- Divide them

- Compare them

1 0 0 0 1

- Example: $10 + 7 = 17$

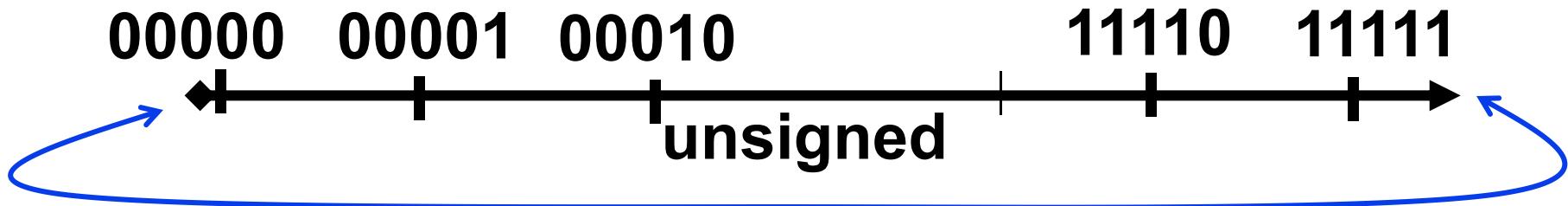
- ...so simple to add in binary that we can build circuits to do it!

- subtraction just as you would in decimal

- Comparison: How do you tell if $X > Y$?

What if too big?

- Binary bit patterns above are simply **representatives** of numbers. Strictly speaking they are called “numerals”.
- Numbers really have an ∞ number of digits
 - with almost all being same (00...0 or 11...1) except for a few of the rightmost digits
 - Just don't normally show leading digits
- If result of add (or -, *, /) cannot be represented by these rightmost HW bits, **overflow** is said to have occurred.



How to Represent Negative Numbers?

(C's `unsigned int`, C99's `uintN_t`)

- So far, unsigned numbers

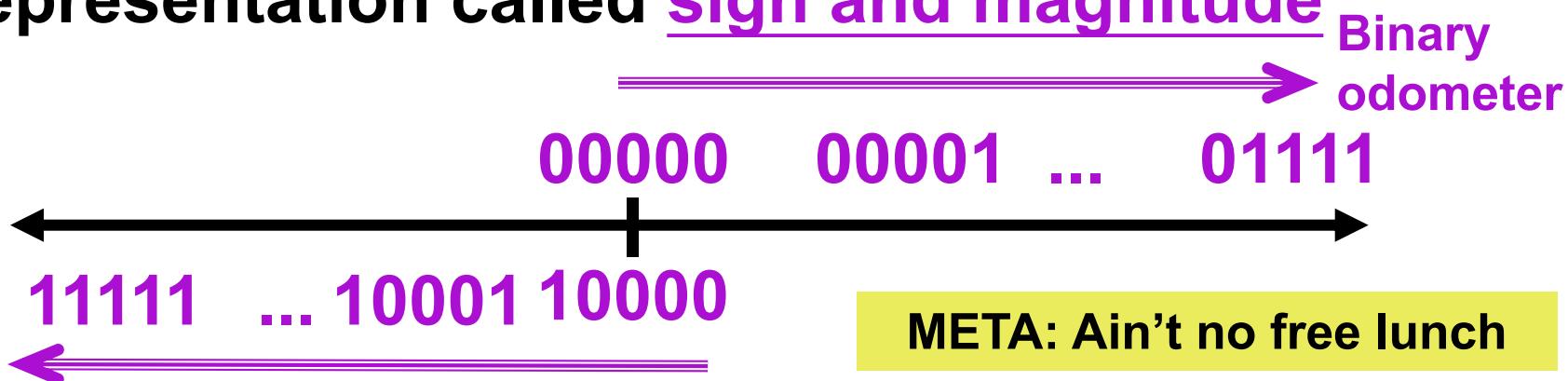


- Obvious solution: define leftmost bit to be sign!

- $0 \rightarrow +$ $1 \rightarrow -$

- Rest of bits can be numerical value of number

- Representation called sign and magnitude

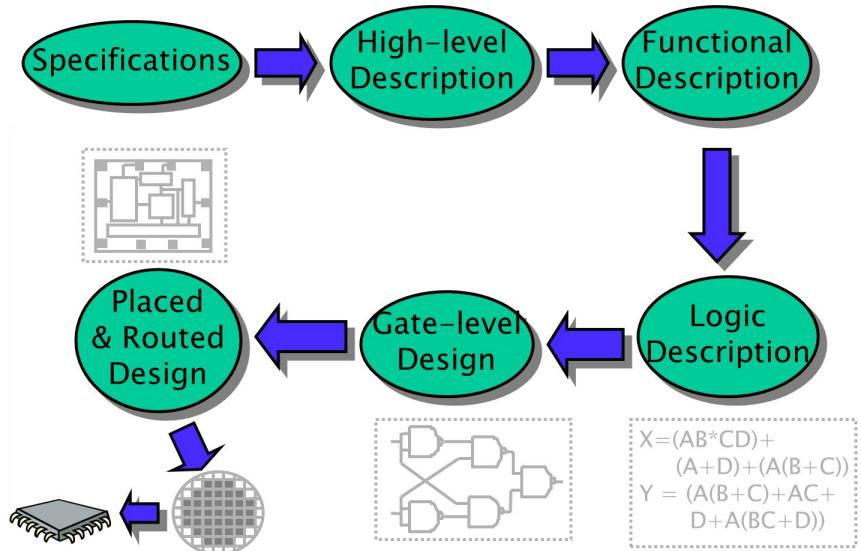


Shortcomings of sign and magnitude?

- Arithmetic circuit complicated
 - Special steps depending whether signs are the same or not
- Also, two zeros
 - $0x00000000 = +0_{\text{ten}}$
 - $0x80000000 = -0_{\text{ten}}$
 - What would two 0s mean for programming?
- Also, incrementing “binary odometer”, sometimes increases values, and sometimes decreases!
- Therefore sign and magnitude abandoned

Great EDA course I supervise

- Introduction to VLSI Design Automation
 - The first EDA course in Beihang University
 - Learn physical design or design automation of ICs
 - Prereqs (data structures, programming language, algorithms, VLSI design)
 - <http://www.cadetlab.cn/courses>

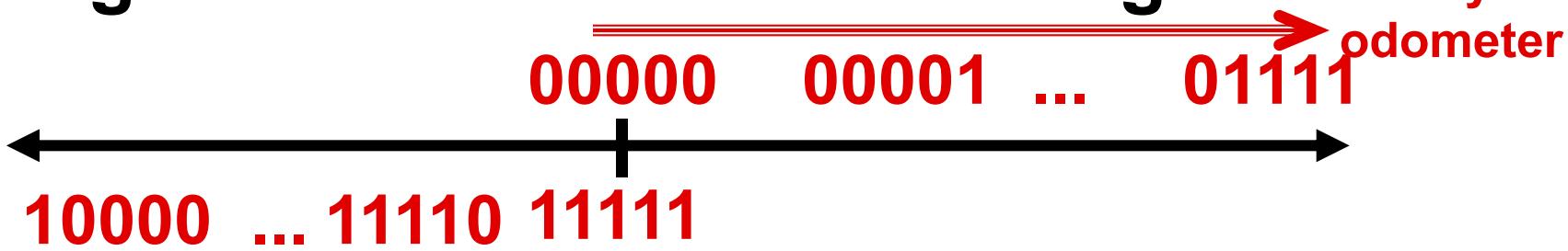


Another try: complement the bits

- 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 numbers?

Shortcomings of One's complement?

- Arithmetic still a somewhat complicated.
- Still two zeros
 - $0x00000000 = +0_{ten}$
 - $0xFFFFFFF = -0_{ten}$
- Although used for a while on some computer products, one's complement was eventually abandoned because another solution was better.

Standard Negative # Representation

- Problem is the negative mappings “overlap” with the positive ones (the two 0s). Want to shift the negative mappings left by one.
 - Solution! For negative numbers, complement, then add 1 to the result
- As with sign and magnitude, & one’s compl. leading 0s is positive, leading 1s is negative
 - 000000...xxx is ≥ 0 , 111111...xxx is < 0
 - except 1...1111 is -1, not -0 (as in sign & mag.)
- This representation is Two’s Complement
 - This makes the hardware simple!
(C’s int, aka a “signed integer”)

(Also C’s short, long long, ..., C99’s `intN_t`)

Two's Complement Formula

- Can represent positive and negative numbers in terms of the bit value times a power of 2:

$$d_{31} \times -(2^{31}) + d_{30} \times 2^{30} + \dots + d_2 \times 2^2 + d_1 \times 2^1 + d_0 \times 2^0$$

- Example: 1101_{two} in a nibble?

$$= 1 \times -(2^3) + 1 \times 2^2 + 0 \times 2^1 + 1 \times 2^0$$

$$= -2^3 + 2^2 + 0 + 2^0$$

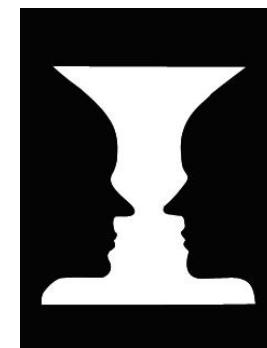
$$= -8 + 4 + 0 + 1$$

$$= -8 + 5$$

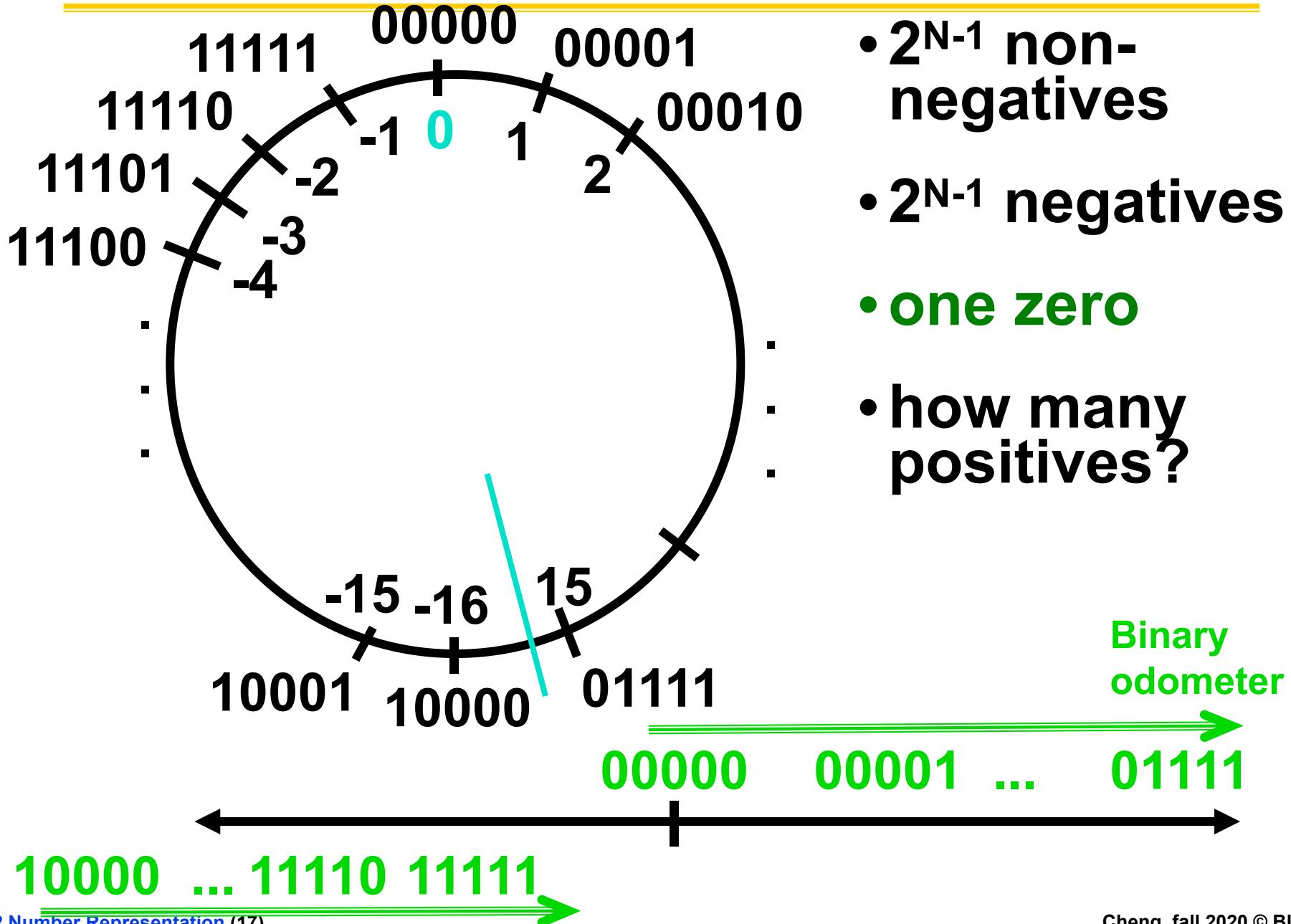
$$= -3_{\text{ten}}$$

Example: -3 to +3 to -3
(again, in a nibble):

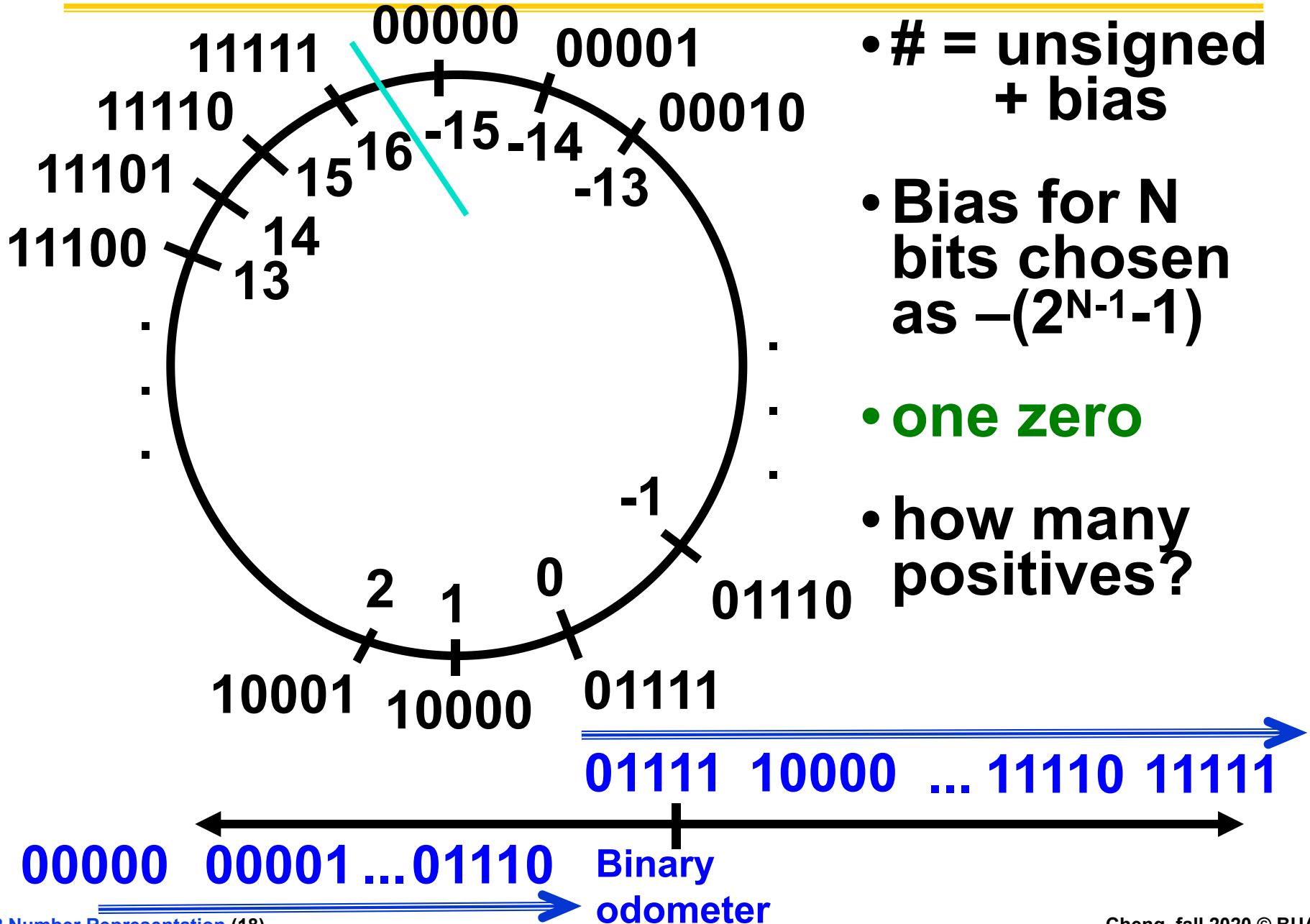
$$\begin{array}{ll} x: & 1101_{\text{two}} \\ x': & 0010_{\text{two}} \\ +1: & 0011_{\text{two}} \\ ()': & 1100_{\text{two}} \\ +1: & 1101_{\text{two}} \end{array}$$



2's Complement Number “line”: N = 5



Bias Encoding: N = 5 (bias = -15)



How best to represent -12.75?



- a) 2s Complement (but shift binary pt)
- b) Bias (but shift binary pt)
- c) Combination of 2 encodings
- d) Combination of 3 encodings
- e) We can't

Shifting binary point means “divide number by some power of 2. E.g., $11_{10} = 1011.0_2 \rightarrow 10.110_2 = (11/4)_{10} = 2.75_{10}$

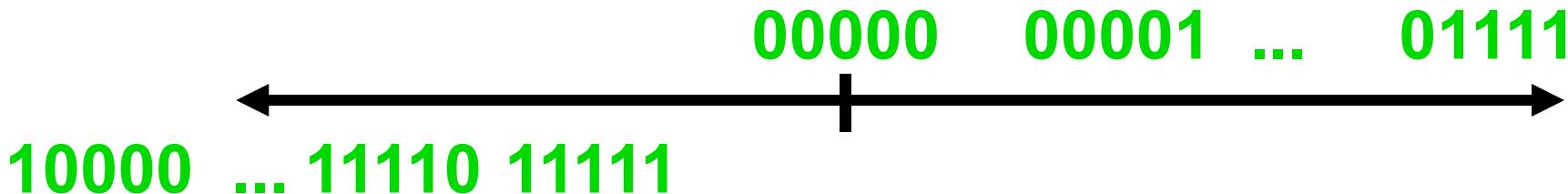
And in summary...

META: We often make design decisions to make HW simple

- We represent “things” in computers as particular bit patterns: **N bits $\Rightarrow 2^N$ things**
- These 5 integer encodings have different benefits; 1s complement and sign/mag have most problems.
- **unsigned** (C99’s `uintN_t`) :



- **2's complement** (C99’s `intN_t`) universal, learn!
-



- **Overflow:** numbers ∞ ; computers finite, errors!

META: Ain't no free lunch

REFERENCE: 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:
 - $32_{\text{ten}} == 32_{10} == 0x20 == 100000_2 == 0b100000$
 - Use subscripts “ten”, “hex”, “two” in book, slides when might be confusing

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}

Two's comp. shortcut: Sign extension

- Convert 2's complement number rep. using n bits to more than n bits
- Simply **replicate** the most significant bit (sign bit) of smaller to fill new bits
 - 2's comp. positive number has infinite 0s
 - 2's comp. negative number has infinite 1s
 - Binary representation hides leading bits; sign extension restores some of them
 - 16-bit -4_{ten} to 32-bit:

1111 1111 1111 1100_{two}

1111 1111 1111 1111 1111 1111 1111 1100_{two}

0.3 MIPS Arithmetic

Computer Architecture (计算机体系结构)

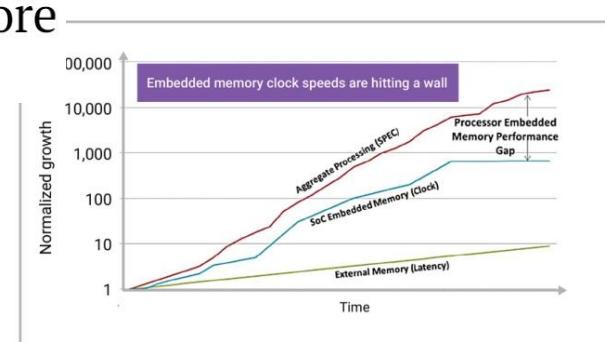
Lecture #3 – Introduction to MIPS Assembly language : Arithmetic



Lecturer Yuanqing Cheng (成元庆)

www.cadetlab.cn

Meeting Increasing Performance Requirements in Embedded Applications with Scalable Multicore Processors



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- These 5 integer encodings have different benefits; 1s complement and sign/mag have most problems.
- **unsigned** (C99’s `uintN_t`) :

00000 00001 ... 01111 10000 ... 11111
← →

- **2's complement** (C99’s `intN_t`) universal, learn!
-

00000 00001 ... 01111
← →
10000 ... 11110 11111

- **Overflow:** numbers ∞ ; computers finite, errors!

Assembly Language

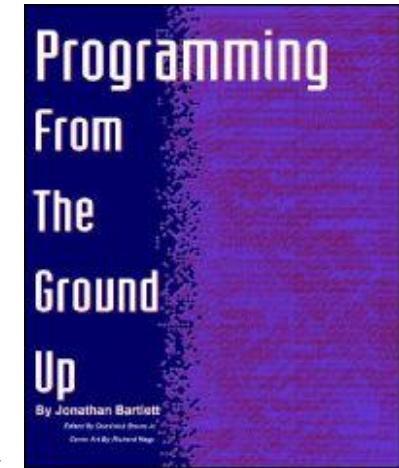
- Basic job of a CPU: execute lots of *instructions*.
- Instructions are the primitive operations that the CPU may execute.
- Different CPUs implement different sets of instructions. The set of instructions a particular CPU implements is an *Instruction Set Architecture (ISA)*.
 - Examples: Intel 80x86 (Pentium 4), IBM/Motorola PowerPC (Macintosh), MIPS, Intel IA64, ...

Book: *Programming From the Ground Up*

*"A new book was just released which is based on a new concept - teaching computer science through assembly language (Linux x86 assembly language, to be exact). This book teaches how the machine itself operates, rather than just the language. I've found that the key difference between mediocre and excellent programmers is whether or not they know assembly language. **Those that do tend to understand computers themselves at a much deeper level.***

*Although [almost!] unheard of today, this concept isn't really all that new -- there used to not be much choice in years past. Apple computers came with only BASIC and assembly language, and there were books available on assembly language for kids. This is why the old-timers are often viewed as 'wizards': they **had** to know assembly language programming."*

-- slashdot.org comment, 2004-02-05



Instruction Set Architectures

- Early trend was to add more and more instructions to new CPUs to do elaborate operations
 - VAX architecture had an instruction to multiply polynomials!
- RISC philosophy (Cocke IBM, Patterson, Hennessy, 1980s) – Reduced Instruction Set Computing
 - Keep the instruction set small and simple, makes it easier to build fast hardware.
 - Let software do complicated operations by composing simpler ones.

MIPS Architecture

- MIPS – semiconductor company that built one of the first commercial RISC architectures



- We will study the MIPS architecture in some detail in this class (also used in upper division courses CS 152, 162, 164)
- Why MIPS instead of Intel 80x86?
 - MIPS is simple, elegant. Don't want to get bogged down in gritty details.
 - MIPS widely used in embedded apps, x86 little used in embedded, and more embedded computers than PCs



Most HP LaserJet workgroup printers are driven by MIPS-based™ 64-bit processors.

Assembly Variables: Registers (1/4)

- Unlike HLL like C or Java, assembly cannot use variables
 - Why not? Keep Hardware Simple
- Assembly Operands are registers
 - limited number of special locations built directly into the hardware
 - operations can only be performed on these!
- Benefit: Since registers are directly in hardware, they are very fast (faster than 1 billionth of a second)

Assembly Variables: Registers (2/4)

- Drawback: Since registers are in hardware, there are a predetermined number of them
 - Solution: MIPS code must be very carefully put together to efficiently use registers
- 32 registers in MIPS
 - Why 32? Smaller is faster
- Each MIPS register is 32 bits wide
 - Groups of 32 bits called a word in MIPS

Assembly Variables: Registers (3/4)

- Registers are numbered from 0 to 31
- Each register can be referred to by number or name
- Number references:
 \$0, \$1, \$2, ... \$30, \$31

Assembly Variables: Registers (4/4)

- By convention, each register also has a name to make it easier to code
- For now:

$\$16 - \$23 \rightarrow \$s0 - \$s7$

(correspond to C variables)

$\$8 - \$15 \rightarrow \$t0 - \$t7$

(correspond to temporary variables)

Later will explain other 16 register names

- In general, use names to make your code more readable

C, Java variables vs. registers

- In C (and most High Level Languages) variables declared first and given a type
 - Example:

```
int fahr, celsius;
char a, b, c, d, e;
```
- Each variable can ONLY represent a value of the type it was declared as (cannot mix and match int and char variables).
- In Assembly Language, the registers have no type; operation determines how register contents are treated

Comments in Assembly

- Another way to make your code more readable: comments!
- Hash (#) is used for MIPS comments
 - anything from hash mark to end of line is a comment and will be ignored
 - This is just like the C99 //
- Note: Different from C.
 - C comments have format
/* comment */
so they can span many lines

Assembly Instructions

- In assembly language, each statement (called an Instruction), executes exactly one of a short list of simple commands
- Unlike in C (and most other High Level Languages), each line of assembly code contains at most 1 instruction
- Instructions are related to operations (=, +, -, *, /) in C or Java
- Ok, enough already...gimme my MIPS!

MIPS Addition and Subtraction (1/4)

- **Syntax of Instructions:**

1 2,3,4

where:

- 1) operation by name
- 2) operand getting result (“destination”)
- 3) 1st operand for operation (“source1”)
- 4) 2nd operand for operation (“source2”)

- **Syntax is rigid:**

- 1 operator, 3 operands
- Why? Keep Hardware simple via regularity

Addition and Subtraction of Integers (2/4)

- **Addition in Assembly**

- Example: `add $s0,$s1,$s2` (in MIPS)
Equivalent to: $a = b + c$ (in C)

where MIPS registers `$s0,$s1,$s2` are associated with C variables `a, b, c`

- **Subtraction in Assembly**

- Example: `sub $s3,$s4,$s5` (in MIPS)
Equivalent to: $d = e - f$ (in C)

where MIPS registers `$s3,$s4,$s5` are associated with C variables `d, e, f`

Addition and Subtraction of Integers (3/4)

- How do the following C statement?

a = b + c + d - e;

- Break into multiple instructions

add \$t0, \$s1, \$s2 # *temp* = *b* + *c*

add \$t0, \$t0, \$s3 # *temp* = *temp* + *d*

sub \$s0, \$t0, \$s4 # *a* = *temp* - *e*

- Notice: A single line of C may break up into several lines of MIPS.
- Notice: Everything after the hash mark on each line is ignored (comments)

Addition and Subtraction of Integers (4/4)

- How do we do this?

$$f = (g + h) - (i + j);$$

- Use intermediate temporary register

add \$t0,\$s1,\$s2	# <i>temp</i> = $g + h$
add \$t1,\$s3,\$s4	# <i>temp</i> = $i + j$
sub \$s0,\$t0,\$t1	# $f = (g+h) - (i+j)$

Register Zero

- One particular immediate, the number zero (0), appears very often in code.
- So we define register zero (\$0 or **\$zero**) to always have the value 0; eg

add \$s0,\$s1,\$zero (in MIPS)

f = g (in C)

where MIPS registers \$s0,\$s1 are associated with C variables f, g

- defined in hardware, so an instruction

add \$zero,\$zero,\$s0

will not do anything!

Immediates

- **Immediates are numerical constants.**
- **They appear often in code, so there are special instructions for them.**
- **Add Immediate:**

addi \$s0,\$s1,10 (in MIPS)

f = g + 10 (in C)

where MIPS registers \$s0,\$s1 are associated with C variables f, g

- **Syntax similar to add instruction, except that last argument is a number instead of a register.**

Immediates

- There is no Subtract Immediate in MIPS: Why?
- Limit types of operations that can be done to absolute minimum
 - if an operation can be decomposed into a simpler operation, don't include it
 - `addi ..., -x = subi ..., x => so no subi`
 - `addi $s0,$s1,-10 (in MIPS)`
 $f = g - 10 \text{ (in C)}$
where MIPS registers `$s0, $s1` are associated with C variables `f, g`

Peer Instruction

- 1) Since there are only 8 local (\$s) and 8 temp (\$t) variables, we can't write MIPS for C exprs that contain > 16 vars.
- 2) If p (stored in \$s0) were a pointer to an array of ints, then p++ ; would be addi \$s0 \$s0 1

	12
a)	FF
b)	FT
c)	TF
d)	TT
e)	dunno

“And in Conclusion...”

- In MIPS Assembly Language:
 - Registers replace C variables
 - One Instruction (simple operation) per line
 - Simpler is Better
 - Smaller is Faster
- New Instructions:
`add, addi, sub`
- New Registers:
C Variables: `$s0 - $s7`
Temporary Variables: `$t0 - $t9`
Zero: `$zero`

0.4 Data Transfer & Decisions



Computer Architecture (计算机体系结构)

Lecture 4 – Introduction to MIPS Data Transfer & Decisions I

Lecturer
Yuanqing
Cheng

2020-09-11



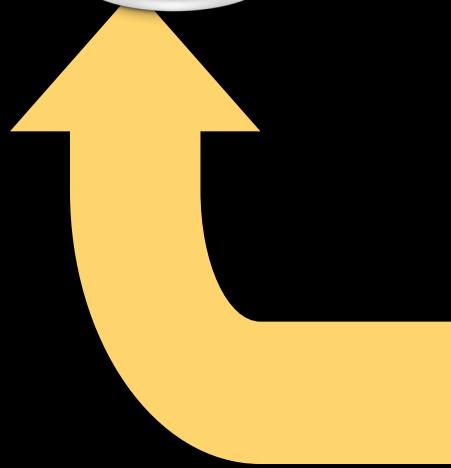
Review

- In MIPS Assembly Language:
 - Registers replace variables
 - One Instruction (simple operation) per line
 - Simpler is Better, Smaller is Faster
- New Instructions:
add, addi, sub
- New Registers:
C Variables: \$s0 - \$s7
Temporary Variables: \$t0 - \$t7
Zero: \$zero

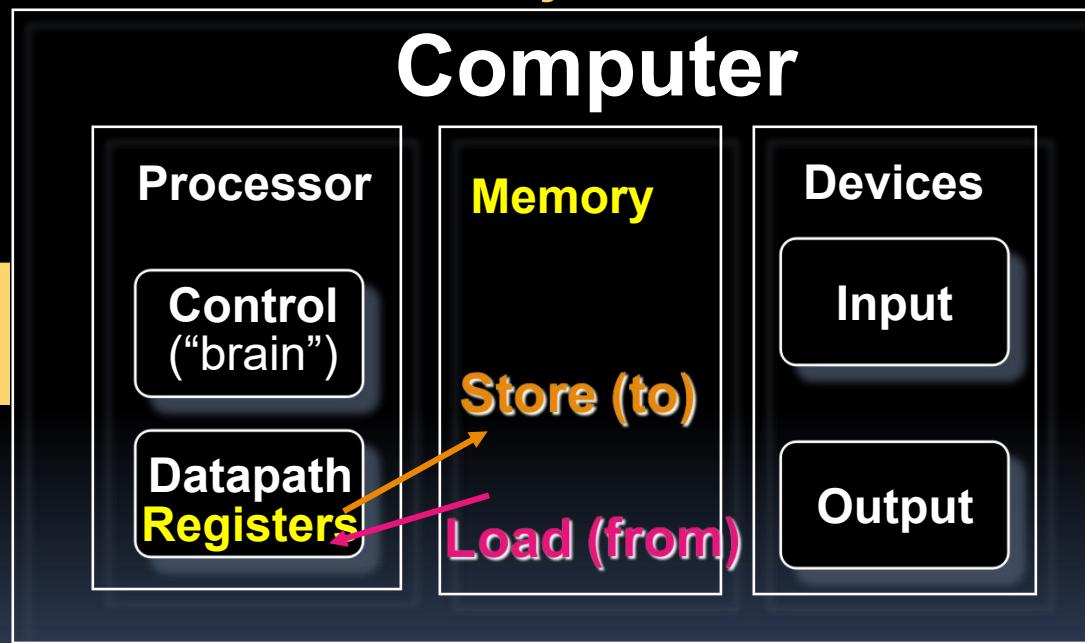
Assembly Operands: Memory

- C variables map onto registers; what about large data structures like arrays?
- 1 of 5 components of a computer: **memory** contains such data structures
- But MIPS arithmetic instructions only operate on registers, never directly on memory.
- **Data transfer instructions** transfer data between registers and memory:
 - **Memory to register**
 - **Register to memory**

Anatomy: 5 components of any Computer



Registers are in the datapath of the processor; if operands are in memory, we must transfer them to the processor to operate on them, and then transfer back to memory when done.



These are “data transfer” instructions...

Data Transfer: Memory to Reg (1/4)

- To transfer a word of data, we need to specify two things:
 - Register: specify this by # (\$0 - \$31) or symbolic name (\$s0, ..., \$t0, ...)
 - Memory address: more difficult
 - Think of memory as a single one-dimensional array, so we can address it simply by supplying a pointer to a memory address.
 - Other times, we want to be able to offset from this pointer.
- Remember: “Load FROM memory”

Data Transfer: Memory to Reg (2/4)

- To specify a memory address to copy from, specify two things:
 - A register containing a pointer to memory
 - A numerical offset (**in bytes**)
- The desired memory address is the sum of these two values.
- Example: **8 (\$t0)**
 - specifies the memory address pointed to by the value in \$t0, plus 8 bytes

Data Transfer: Memory to Reg (3/4)

- Load Instruction Syntax:

1 2 , 3 (4)

- where

- 1) operation name
- 2) register that will receive value
- 3) numerical offset in bytes
- 4) register containing pointer to memory

- MIPS Instruction Name:

- **lw** (meaning Load Word, so 32 bits or one word are loaded at a time)

Data Transfer: Memory to Reg (4/4)



Example: **lw \$t0, 12(\$s0)**

This instruction will take the pointer in \$s0, add 12 bytes to it, and then load the value from the memory pointed to by this calculated sum into register \$t0

- Notes:
 - \$s0 is called the base register
 - 12 is called the offset
 - offset is generally used in accessing elements of array or structure: base reg points to beginning of array or structure (note offset must be a constant known at assembly time)

Data Transfer: Reg to Memory

- Also want to store from register into memory
 - Store instruction syntax is identical to Load's
- MIPS Instruction Name:
sw (meaning Store Word, so 32 bits or one word is stored at a time)

- Example: **sw \$t0,12(\$s0)**
This instruction will take the pointer in \$s0, add 12 bytes to it, and then store the value from register \$t0 into that memory address
- Remember: “**Store INTO memory**”

Pointers v. Values

- **Key Concept:** A register can hold any 32-bit value. That value can be a (signed) int, an unsigned int, a pointer (memory addr), and so on
 - E.g., If you write: `add $t2,$t1,$t0` then \$t0 and \$t1 better contain values that can be added
 - E.g., If you write: `lw $t2,0($t0)` then \$t0 better contain a pointer
- Don't mix these up!

Addressing: Byte vs. Word

- Every word in memory has an address, similar to an **index** in an array
- Early computers numbered words like C numbers elements of an array:
 - **Memory [0]** , **Memory [1]** , **Memory [2]** , ...


Called the “address” of a word
- Computers needed to access 8-bit bytes as well as words (4 bytes/word)
- Today machines address memory as bytes, (i.e., “**Byte Addressed**”) hence 32-bit (4 byte) word addresses differ by 4
 - **Memory [0]** , **Memory [4]** , **Memory [8]**

Compilation with Memory

- What offset in `lw` to select `A[5]` in C?
- $4 \times 5 = 20$ to select `A[5]`: byte v. word
- Compile by hand using registers:

`g = h + A[5];`

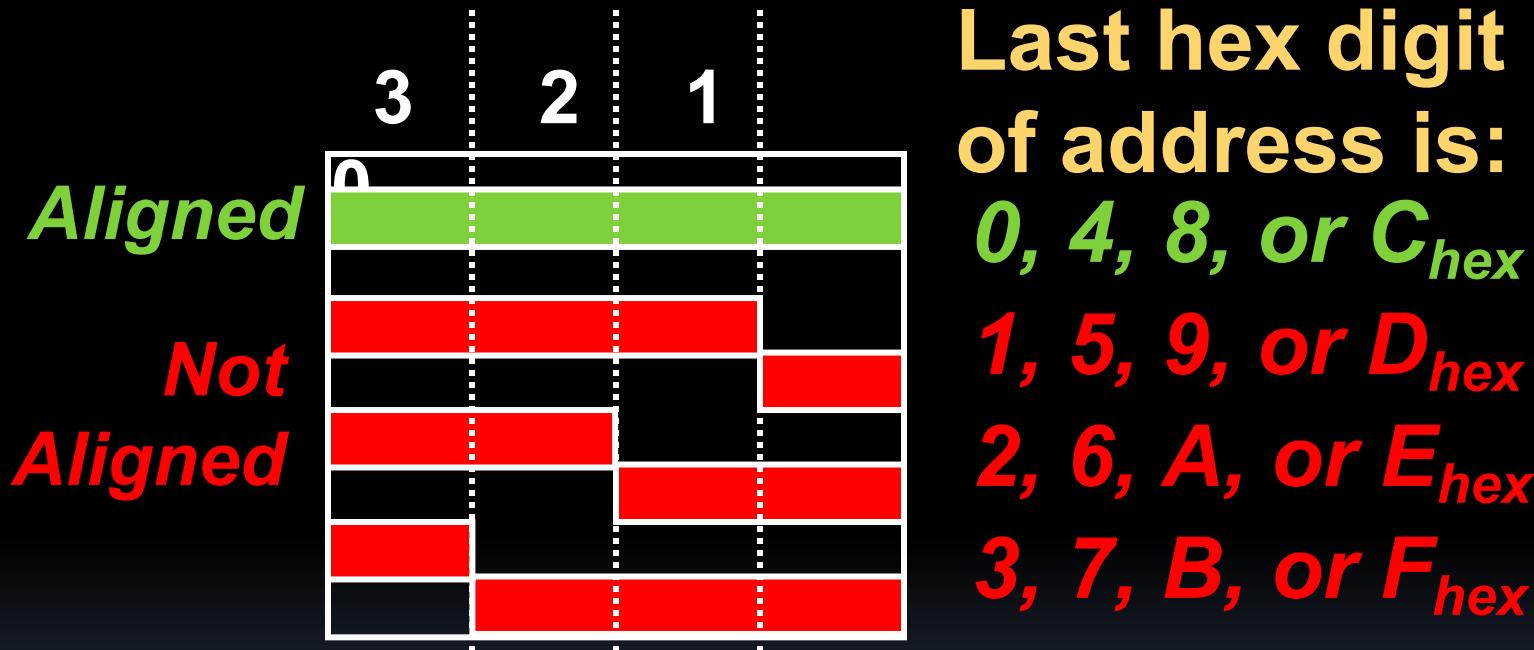
- `g: $s1, h: $s2, $s3: base address of A`
- 1st transfer from memory to register:
`lw $t0, 20($s3) # $t0 gets A[5]`
 - Add 20 to `$s3` to select `A[5]`, put into `$t0`
- Next add it to `h` and place in `g`
`add $s1, $s2, $t0 # $s1 = h+A[5]`

Notes about Memory

- Pitfall: Forgetting that sequential word addresses in machines with byte addressing do not differ by 1.
 - Many an assembly language programmer has toiled over errors made by assuming that the address of the next word can be found by incrementing the address in a register by 1 instead of by the word size in bytes.
 - Also, remember that for both **lw** and **sw**, the sum of the base address and the offset must be a multiple of 4 (to be word aligned)

More Notes about Memory: Alignment

- MIPS requires that all words start at byte addresses that are multiples of 4 bytes



- Called **Alignment**: objects fall on address that is multiple of their size

Role of Registers vs. Memory

- What if more variables than registers?
 - Compiler tries to keep most frequently used variable in registers
 - Less common variables in memory: **spilling**
- Why not keep all variables in memory?
 - Smaller is faster:
registers are faster than memory
 - Registers more versatile:
 - MIPS arithmetic instructions can read 2, operate on them, and write 1 per instruction
 - MIPS data transfer only read or write 1 operand per instruction, and no operation

So Far...

- All instructions so far only manipulate data...we've built a **calculator** of sorts.
- In order to build a **computer**, we need ability to make decisions...
- C (and MIPS) provide labels to support “**goto**” jumps to places in code.
 - C: Horrible style; MIPS: Necessary!
- Heads up: pull out some papers and pens, you'll do an in-class exercise!

C Decisions: if Statements

- 2 kinds of if statements in C

`if (condition) clause`

`if (condition) clause1 else clause2`

- Rearrange 2nd if into following:

`if (condition) goto L1;
 clause2;`

`goto L2;`

`L1: clause1;`

`L2:`

- Not as elegant as if-else, but same meaning

MIPS Decision Instructions

- Decision instruction in MIPS:

`beq register1, register2, L1`

`beq` is “Branch if (registers are) equal”

Same meaning as (using C):

`if (register1==register2) goto L1`

- Complementary MIPS decision instruction

`bne register1, register2, L1`

`bne` is “Branch if (registers are) not equal”

Same meaning as (using C):

`if (register1!=register2) goto L1`

- Called conditional branches

MIPS Goto Instruction

- In addition to conditional branches, MIPS has an unconditional branch:

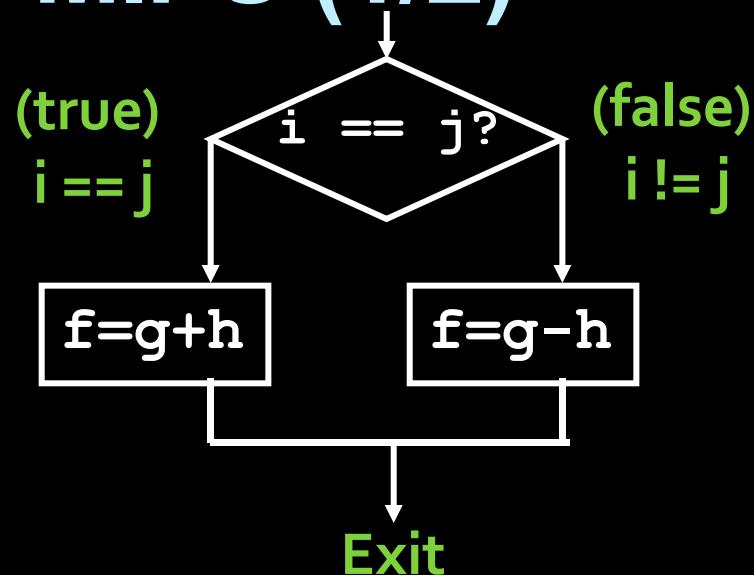
`j label`

- Called a Jump Instruction: jump (or branch) directly to the given label without needing to satisfy any condition
- Same meaning as (using C): `goto label`
- Technically, it's the same effect as:
`beq $0,$0,label`
since it always satisfies the condition.

Compiling C if into MIPS (1/2)

- Compile by hand

```
if (i == j) f=g+h;  
else f=g-h;
```



- Use this mapping:

f: \$s0

g: \$s1

h: \$s2

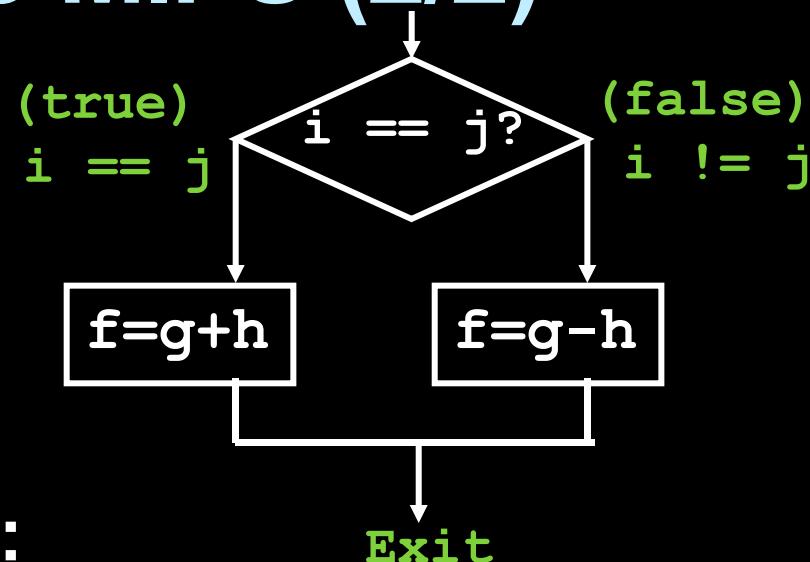
i: \$s3

j: \$s4

Compiling C if into MIPS (2/2)

- Compile by hand

```
if (i == j) f=g+h;  
else f=g-h;
```



- Final compiled MIPS code:

```
beq $s3,$s4,True    # branch i==j  
sub $s0,$s1,$s2      # f=g-h (false)  
j Fin                # goto Fin  
True: add $s0,$s1,$s2 # f=g+h (true)  
Fin:
```

Note: Compiler automatically creates labels to handle decisions (branches). Generally not found in HLL code.

Peer

We want to translate $*x = *y$ into MIPS
Instruction
(x, y ptrs stored in: $\$s0 \ \$s1$)

```
1: add $s0,    $s1, zero
2: add $s1,    $s0, zero
3: lw  $s0, 0($s1)
4: lw  $s1, 0($s0)
5: lw  $t0, 0($s1)
6: sw $t0, 0($s0)
7: lw  $s0, 0($t0)
8: sw $s1, 0($t0)
```

- a) 1 or 2
- b) 3 or 4
- c) 5→6
- d) 6→5
- e) 7→8

“And in Conclusion...”

- Memory is byte-addressable, but `lw` and `sw` access one word at a time.
- A pointer (used by `lw` and `sw`) is just a memory address, we can add to it or subtract from it (using offset).
- A Decision allows us to decide what to execute at run-time rather than compile-time.
- C Decisions are made using conditional statements within `if`, `while`, `do while`, `for`.
- MIPS Decision making instructions are the conditional branches: `beq` and `bne`.
- New Instructions:
`lw`, `sw`, `beq`, `bne`, `j`

0.5 Addition to Data Transfer



Computer Architecture (计算机体系结构)

Lecture 5 Introduction to MIPS : Decisions II

Lecturer
Yuanqing
Cheng

2020-09-14

Germany Taking the Autobahn to
Autonomy



Review

- Memory is byte-addressable, but **lw** and **sw** access one word at a time.
- A pointer (used by **lw** and **sw**) is just a memory address, so we can add to it or subtract from it (using offset).
- A Decision allows us to decide what to execute at run-time rather than compile-time.
- C Decisions are made using conditional statements within **if**, **while**, **do while**, **for**.
- MIPS Decision making instructions are the conditional branches: **beq** and **bne**.
- New Instructions:

lw, sw, beq, bne, j

Last time: Loading, Storing bytes 1/2

- In addition to word data transfers (**lw**, **sw**), MIPS has **byte** data transfers:
 - load byte: **lb**
 - store byte: **sb**
- same format as **lw**, **sw**
- E.g., **lb \$s0, 3(\$s1)**
 - *contents of memory location with address = sum of “3” + contents of register s1 is copied to the low byte position of register s0.*

Loading, Storing bytes 2/2

- What do with other 24 bits in the 32 bit register?

- lb: sign extends to fill upper 24 bits



- Normally don't want to sign extend chars
- MIPS instruction that doesn't sign extend when loading bytes:
 - load byte unsigned: **lbu**

Overflow in Arithmetic (1/2)

- Reminder: Overflow occurs when there is a mistake in arithmetic due to the limited precision in computers.
- Example (4-bit unsigned numbers):

$$\begin{array}{r} 15 \\ + 3 \\ \hline 18 \end{array}$$

$$\begin{array}{r} 1111 \\ + 0011 \\ \hline 10010 \end{array}$$

- But we don't have room for 5-bit solution, so the solution would be 0010, which is +2, and wrong.

Overflow in Arithmetic (2/2)

- Some languages detect overflow (Ada), some don't (C)
- MIPS solution is 2 kinds of arithmetic instructs:
 - These cause overflow to be detected
 - add (**add**)
 - add immediate (**addi**)
 - subtract (**sub**)
 - These do not cause overflow detection
 - add unsigned (**addu**)
 - add immediate unsigned (**addiu**)
 - subtract unsigned (**subu**)
- Compiler selects appropriate arithmetic
 - MIPS C compilers produce **addu**, **addiu**, **subu**

Two “Logic” Instructions

- Here are 2 more new instructions
- Shift Left: **sll \$s1,\$s2,2**
#s1=s2<<2
 - Store in $\$s1$ the value from $\$s2$ shifted 2 bits to the left (they fall off end), inserting 0's on right; $<<$ in C.
 - Before: $0000\ 0002_{\text{hex}}$
 $0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0010_{\text{two}}$
 - After: $0000\ 0008_{\text{hex}}$
 $0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 1000_{\text{two}}$
 - What arithmetic effect does shift left have?
- Shift Right: **srl** is opposite shift; **>>**

Loops in C/Assembly (1/3)

- Simple loop in C; **A[]** is an array of ints

```
do { g = g + A[i];  
     i = i + j;  
 } while (i != h);
```

- Rewrite this as:

```
Loop: g = g + A[i];  
      i = i + j;  
      if (i != h) goto Loop;
```

- Use this mapping:

g, h, i, j, base of A
\$s1, \$s2, \$s3, \$s4, \$s5

Loops in C/Assembly (2/3)

- Final compiled MIPS code:

```
Loop: sll $t1,$s3,2      # $t1= 4*I  
      addu $t1,$t1,$s5    # $t1=addr A+4i  
      lw   $t1,0($t1)     # $t1=A[i]  
      addu $s1,$s1,$t1    # g=g+A[i]  
      addu $s3,$s3,$s4    # i=i+j  
      bne $s3,$s2,Loop    # goto Loop  
                      # if i!=h
```

- Original code:

```
Loop: g = g + A[i];  
      i = i + j;  
      if (i != h) goto Loop;
```

Loops in C/Assembly (3/3)

- There are three types of loops in C:
 - **while**
 - **do... while**
 - **for**
- Each can be rewritten as either of the other two, so the method used in the previous example can be applied to these loops as well.
- Key Concept: Though there are multiple ways of writing a loop in MIPS, the key to decision-making is conditional branch

Inequalities in MIPS (1/4)

- Until now, we've only tested equalities (`==` and `!=` in C). General programs need to test `<` and `>` as well.
- Introduce MIPS Inequality Instruction:
 - “Set on Less Than”
 - Syntax: `slt reg1, reg2, reg3`
 - Meaning: `reg1 = (reg2 < reg3);`

```
if (reg2 < reg3)
    reg1 = 1;
else reg1 = 0;
```

Same thing...

“set” means “change to 1”,
“reset” means “change to 0”.

Inequalities in MIPS (2/4)

- How do we use this? Compile by hand:

```
if (g < h) goto Less; #g:$s0, h:$s1
```

- Answer: compiled MIPS code...

```
slt $t0,$s0,$s1 # $t0 = 1 if g<h  
bne $t0,$0,Less # goto Less  
# if $t0!=0  
# (if (g<h) ) Less:
```

- Register **\$0** always contains the value 0, so **bne** and **beq** often use it for comparison after an **slt** instruction.
- A **slt → bne** pair means **if (... < ...)** **goto...**

Inequalities in MIPS (3/4)

- Now we can implement $<$,
but how do we implement $>$, \leq and \geq ?
- We could add 3 more instructions, but:
 - MIPS goal: Simpler is Better
- Can we implement \leq in one or more
instructions using just **slt** and **branches**?
 - What about $>?$
 - What about $\geq?$

Inequalities in MIPS (4/4)

```
# a:$s0, b:$s1
slt $t0,$s0,$s1 # $t0 = 1 if a<b
beq $t0,$0,skip # skip if a >= b
    <stuff>      # do if a<b
skip:
```

Two independent variations possible:

Use **slt \$t0,\$s1,\$s0** instead of
slt \$t0,\$s0,\$s1

Use **bne** instead of **beq**

Immediates in Inequalities

- There is also an immediate version of **slt** to test against constants: **slti**
 - Helpful in **for** loops

C **if** (g >= 1) **goto** Loop

M

I **slti** \$t0,\$s0,1 **#** \$t0 = 1 if
P **#** \$s0<1 (g<1)

S **beq** \$t0,\$0,Loop **#** goto Loop
 # if \$t0==0
 # (if (g>=1))

An **slt** → **beq** pair means **if (... ≥ ...) goto...**

What about unsigned numbers?

- Also **unsigned** inequality instructions:

sltu, sltiu

...which sets result to 1 or 0 depending on unsigned comparisons

- What is value of \$t0, \$t1?

$(\$s0 = \text{FFFF FFFA}_{\text{hex}}, \$s1 = 0000 \text{ FFFA}_{\text{hex}})$

slt \$t0, \$s0, \$s1

sltu \$t1, \$s0, \$s1

MIPS Signed vs. Unsigned – diff

meanings!

■ MIPS terms Signed/Unsigned “overloaded”:

- Do/Don't sign extend
 - (**lb**, **lbu**)
- Do/Don't overflow
 - (**add**, **addi**, **sub**, **mult**, **div**)
 - (**addu**, **addiu**, **subu**, **multu**, **divu**)
- Do signed/unsigned compare
 - (**slt**, **slti/sltu**, **sltiu**)

Peer Instruction

```
Loop: addi $s0,$s0,-1      # i = i - 1
      slti $t0,$s1,2        # $t0 = (j < 2)
      beq  $t0,$0 ,Loop     # goto Loop if $t0 == 0
      slt   $t0,$s1,$s0       # $t0 = (j < i)
      bne   $t0,$0 ,Loop     # goto Loop if $t0 != 0
```

(\$s0=i, \$s1=j)

What C code properly fills in
the blank in loop below?

do {i--;} while(_);

a	a	b	b	c	c	d	d	e	e	2	2	2	2	2	2	2	&&	&&	&&	i	i	i	i	i	i
										>	>	>	>	>	>	>									
										>	>	>	>	>	>	>									
										>	>	>	>	>	>	>									
										>	>	>	>	>	>	>									

“And in conclusion...”

- To help the **conditional branches** make decisions concerning inequalities, we introduce: “Set on Less Than” called **slt, slti, sltu, sltiu**
- One can store and load (signed and unsigned) **bytes** as well as words with **lb, lbu**
- Unsigned add/sub **don't cause overflow**
- New MIPS Instructions:
sll, srl, lb, lbu
slt, slti, sltu, sltiu
addu, addiu, subu

Bonus Slides

Example: The C Switch Statement

(1/3)

- Choose among four alternatives depending on whether `k` has the value 0, 1, 2 or 3.

Compile this C code:

```
switch (k) {  
    case 0: f=i+j; break; /* k=0 */  
    case 1: f=g+h; break; /* k=1 */  
    case 2: f=g-h; break; /* k=2 */  
    case 3: f=i-j; break; /* k=3 */  
}
```

Example: The C Switch Statement

(2/3)

This is complicated, so **simplify**.

- Rewrite it as a chain of if-else statements, which we already know how to compile:

```
if (k==0) f=i+j;  
else if (k==1) f=g+h;  
else if (k==2) f=g-h;  
else if (k==3) f=i-j;
```

- Use this mapping:

```
f:$s0, g:$s1, h:$s2,  
i:$s3, j:$s4, k:$s5
```

Example: The C Switch Statement

▪ (3/3)

▪ Final compiled MIPS code:

```
bne $s5,$0,L1      # branch k!=0
add $s0,$s3,$s4    #k==0 so f=i+j
j Exit            # end of case so Exit
L1: addi $t0,$s5,-1 # $t0=k-1
bne $t0,$0,L2      # branch k!=1
add $s0,$s1,$s2    #k==1 so f=g+h
j Exit            # end of case so Exit
L2: addi $t0,$s5,-2 # $t0=k-2
bne $t0,$0,L3      # branch k!=2
sub $s0,$s1,$s2    #k==2 so f=g-h
j Exit            # end of case so Exit
L3: addi $t0,$s5,-3 # $t0=k-3
bne $t0,$0,Exit    # branch k!=3
sub $s0,$s3,$s4    # k==3 so f=i-j
```

Exit:

0.6 Function



Computer Architecture (计算机体系结构)

Lecture 6 – Introduction to MIPS : Decisions II

Lecturer
Yuanqing
Cheng

2020-09-14

Review

- In order to help the conditional branches make decisions concerning inequalities, we introduce a single instruction: “Set on Less Than” called **slt**, **slti**, **sltu**, **sltiu**
- One can store and load (signed and unsigned) **bytes** as well as words
- Unsigned add/sub **don't cause overflow**
- New MIPS Instructions:
 - sll**, **srl**, **lb**, **sb**
 - slt**, **slti**, **sltu**, **sltiu**
 - addu**, **addiu**, **subu**

C functions

```
main() {  
    int i,j,k,m;  
    ...  
    i = mult(j,k); ...  
    m = mult(i,i); ...  
}
```

What information must compiler/programmer keep track of?

```
/* really dumb mult function */  
  
int mult (int mcand, int mlier){  
    int product = 0;  
    while (mlier > 0) {  
        product = product + mcand;  
        mlier = mlier -1; }  
    return product;  
}
```

What instructions can accomplish this?

Function Call Bookkeeping

- Registers play a major role in keeping track of information for function calls.
- Register conventions:
 - Return address **\$ra**
 - Arguments **\$a0, \$a1, \$a2, \$a3**
 - Return value **\$v0, \$v1**
 - Local variables **\$s0, \$s1, ... , \$s7**
- The stack is also used; more later.

Instruction Support for Functions

(1/6)

```
sum(a,b); . . . /* a,b:$s0,$s1 */
```

```
}
```

```
C int sum(int x, int y) {  
    return x+y;  
}
```

address (shown in decimal)

M 1000

I 1004

P 1008

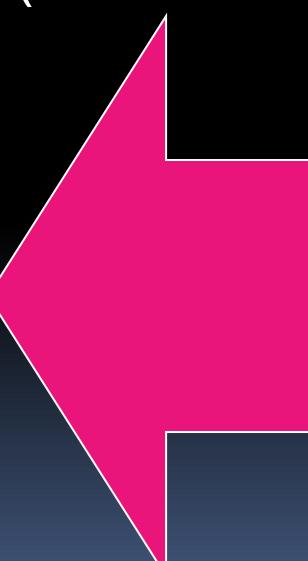
S 1012

1016

...

2000

2004



In MIPS, all instructions are 4 bytes, and stored in memory just like data. So here we show the addresses of where the programs are stored.

Instruction Support for Functions (2/6)

```
... sum(a,b); ... /* a,b:$s0,$s1 */  
}  
C int sum(int x, int y) {  
    return x+y;  
}
```

address (shown in decimal)

MIPS

```
1000 add $a0,$s0,$zero # x = a  
1004 add $a1,$s1,$zero # y = b  
1008 addi $ra,$zero,1016 #$ra=1016  
1012 j sum #jump to sum  
1016  
...  
2000 sum: add $v0,$a0,$a1  
2004 jr $ra # new instruction
```

Instruction Support for Functions (3/6)

```
... sum(a,b); ... /* a,b:$s0,$s1 */  
}  
int sum(int x, int y) {  
    return x+y;  
}
```

- Question: Why use **jr** here? Why not use **j**?
- Answer: **sum** might be called by many places, so we can't return to a fixed place. The calling proc to **sum** must be able to say "return here" somehow.

M
I
P
S



```
2000 sum: add $v0,$a0,$a1  
2004 jr $ra          # new instruction
```

Instruction Support for Functions (4/6)

- Single instruction to jump and save return address: jump and link (**jal**)
- **Before:**

```
1008 addi $ra,$zero,1016 #$ra=1016
1012 j sum                      #goto sum
```
- **After:**

```
1008 jal sum    # $ra=1012, goto sum
```
- Why have a **jal**?
 - Make the common case fast: function calls very common.
 - Don't have to know where code is in memory with **jal**!

Instruction Support for Functions (5/6)

- Syntax for `jal` (jump and link) is same as for `j` (jump):

`jal label`

- `jal` should really be called `laJ` for “link and jump”:
 - Step 1 (link): Save address of *next* instruction into `$ra`
 - Why next instruction? Why not current one?
 - Step 2 (jump): Jump to the given label

Instruction Support for Functions (6/6)

- Syntax for **jr** (jump register):

jr register

- Instead of providing a label to jump to, the **jr** instruction provides a register which contains an address to jump to.
- Very useful for function calls:
 - **jal** stores return address in register (**\$ra**)
 - **jr \$ra** jumps back to that address

Nested Procedures (1/2)

```
int sumSquare(int x, int y) {  
    return mult(x,x)+ y;  
}
```

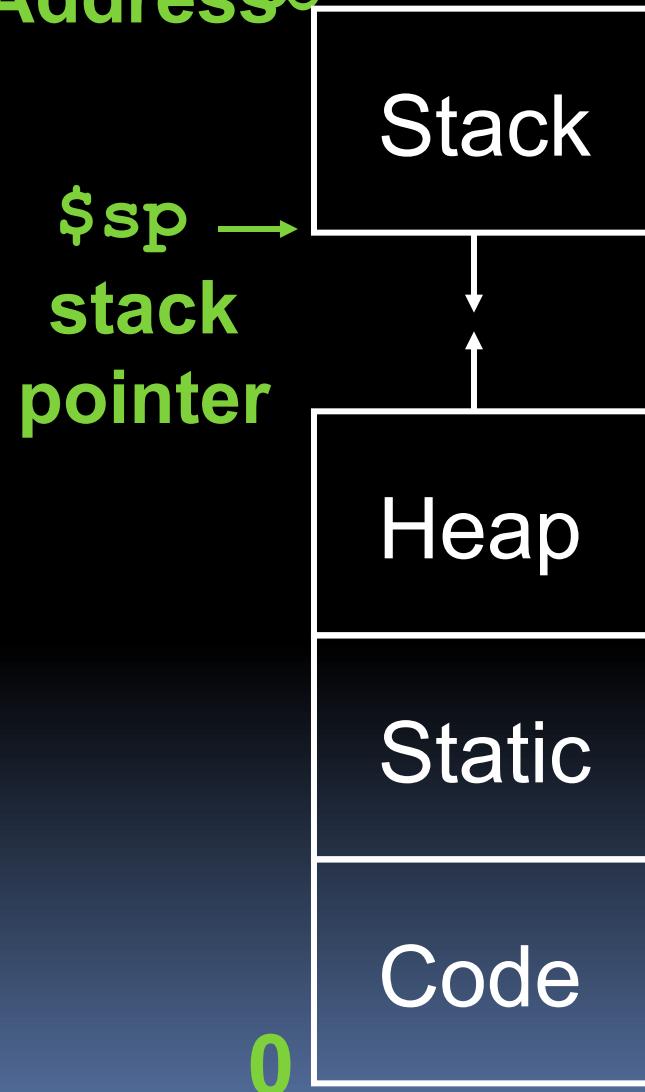
- Something called **sumSquare**, now **sumSquare** is calling **mult**.
- So there's a value in \$ra that **sumSquare** wants to jump back to, but this will be overwritten by the call to **mult**.
- Need to save **sumSquare** return address before call to **mult**.

Nested Procedures (2/2)

- In general, may need to save some other info in addition to `$ra`.
- When a C program is run, there are 3 important memory areas allocated:
 - **Static:** Variables declared once per program, cease to exist only after execution completes.
E.g., C globals
 - **Heap:** Variables declared dynamically via `malloc`
 - **Stack:** Space to be used by procedure during execution; this is where we can save register values

C memory Allocation review

Address[∞]



Space for saved procedure information

Explicitly created space,
i.e., malloc ()

Variables declared once per program; e.g., globals

Program

Using the Stack (1/2)

- So we have a register **\$sp** which always points to the last used space in the stack.
- To use stack, we decrement this pointer by the amount of space we need and then fill it with info.
- So, how do we compile this?

```
int sumSquare(int x, int y) {  
    return mult(x,x)+ y;  
}
```

Using the Stack (2/2)

- Hand-compile `int sumSquare(int x, int y) {
sumSquare:
 return mult(x,x)+ y; }`

“push”

```
addi $sp,$sp,-8 # space on stack  
sw $ra, 4($sp) # save ret addr  
sw $a1, 0($sp) # save y  
add $a1,$a0,$zero # mult(x,x)  
jal mult # call mult  
lw $a1, 0($sp) # restore y  
add $v0,$v0,$a1 # mult() +y  
“pop” lw $ra, 4($sp) # get ret addr  
addi $sp,$sp,8 # restore stack  
jr $ra
```

mult: ...

Steps for Making a Procedure Call

1. Save necessary values onto stack.
2. Assign argument(s), if any.
3. `jal` call
4. Restore values from stack.

Rules for Procedures

- Called with a **jal** instruction,
returns with a **jr \$ra**
- Accepts up to 4 arguments in
\$a0, \$a1, \$a2 and **\$a3**
- Return value is always in **\$v0**
(and if necessary in **\$v1**)
- Must follow **register conventions**

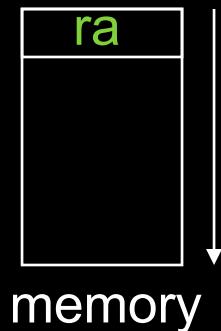
So what are they?

Basic Structure of a Function

Prologue

```
entry_label:  
addi $sp,$sp, -framesize  
sw $ra, framesize-4($sp) # save $ra  
save other regs if need be
```

Body . . . (call other functions...)



Epilogue

```
restore other regs if need be  
lw $ra, framesize-4($sp) # restore $ra  
addi $sp,$sp, framesize  
jr $ra
```

MIPS Registers

The constant 0	\$0	\$zero
Reserved for Assembler	\$1	\$at
Return Values	\$2-\$3	\$v0-
\$v1		
Arguments	\$4-\$7	
\$a0-\$a3		
Temporary		\$8-\$15
	\$t0-\$t7	
Saved		\$s0-
\$s7	\$16-\$23	
More Temporary	\$24-\$25	\$t8-\$t9
Used by Kernel	\$26-27	\$k0-
\$k1		
Global Pointer	\$28	\$gp
Stack Pointer	\$29	\$sp
Frame Pointer	\$30	\$fp
Return Address	\$31	
\$ra		

Other Registers

- **\$at**: may be used by the assembler at any time; unsafe to use
- **\$k0-\$k1**: may be used by the OS at any time; unsafe to use
- **\$gp, \$fp**: don't worry about them
- Note: Feel free to read up on **\$gp** and **\$fp** in Appendix A, but you can write perfectly good MIPS code without them.

Peer Instruction

```
int fact(int n) {  
    if(n == 0) return 1; else return(n*fact(n-1)); }
```

When translating this to MIPS...

- 1) We COULD copy \$a0 to \$a1 (& then not store \$a0 or \$a1 on the stack) to store n across recursive calls.
- 2) We MUST save \$a0 on the stack since it gets changed.
- 3) We MUST save \$ra on the stack since we need to know where to return to...

1	2	3
a)	FFF	
b)	FFT	
c)	FTF	
c)	FTT	
d)	TFF	
d)	TFT	
e)	TTF	
e)	TTT	

“And in Conclusion...”

- Functions called with **jal**, return with **jr \$ra**.
- The stack is your friend: Use it to save anything you need. Just leave it the way you found it!
- Instructions we know so far...
 - Arithmetic: **add**, **addi**, **sub**, **addu**, **addiu**, **subu**
 - Memory: **lw**, **sw**, **lb**, **sb**
 - Decision: **beq**, **bne**, **slt**, **slti**, **sltu**, **sltiu**
 - Unconditional Branches (Jumps): **j**, **jal**, **jr**
- Registers we know so far
 - All of them!

0.7 Logic



Computer Architecture (计算机体系结构)

Lecture 7 – Introduction to MIPS Procedures II & Logical Ops

Lecturer
Yuanqing
Cheng

2020-09-18

Review

- Functions called with **jal**, return with **jr \$ra**.
- The stack is your friend: Use it to save anything you need. Just leave it the way you found it!
- Instructions we know so far...
 - Arithmetic: **add**, **addi**, **sub**, **addu**, **addiu**, **subu**
 - Memory: **lw**, **sw**, **lb**, **sb**
 - Decision: **beq**, **bne**, **slt**, **slti**, **sltu**, **sltiu**
 - Unconditional Branches (Jumps): **j**, **jal**, **jr**
- Registers we know so far
 - All of them!
 - There are CONVENTIONS when calling procedures!

Register Conventions (1/4)

- CalleR: the calling function
- CalleE: the function being called
- When callee returns from executing, the caller needs to know which registers may have changed and which are guaranteed to be unchanged.
- Register Conventions: A set of generally accepted rules as to which registers will be unchanged after a procedure call (`jal`) and which may be changed.

Register Conventions (2/4) – saved

- \$0: No Change. Always 0.
- \$s0-\$s7: Restore if you change. Very important, that's why they're called saved registers. If the callee changes these in any way, it must restore the original values before returning.
- \$sp: Restore if you change. The stack pointer must point to the same place before and after the `jal` call, or else the caller won't be able to restore values from the stack.
- HINT -- All saved registers start with S!

Register Conventions (2/4) – volatile

- **\$ra: Can Change.** The `jal` call itself will change this register. Caller needs to save on stack if nested call.
- **\$v0-\$v1: Can Change.** These will contain the new returned values.
- **\$a0-\$a3: Can change.** These are volatile argument registers. Caller needs to save if they are needed after the call.
- **\$t0-\$t9: Can change.** That's why they're called temporary: any procedure may change them at any time. Caller needs to save if they'll need them afterwards.

Register Conventions (4/4)

- What do these conventions mean?
 - If function **R** calls function **E**, then function **R** must save any temporary registers that it may be using onto the stack before making a `jal` call.
 - Function **E** must save any **S** (saved) registers it intends to use before garbling up their values
- Remember: caller/callee need to save only temporary/saved registers **they are using**, not all registers.

Parents leaving for weekend analogy (1/5)

- Parents (`main`) leaving for weekend
- They (`caller`) give keys to the house to kid (`callee`) with the rules (`calling conventions`):
 - You can trash the temporary room(s), like the den and basement (`registers`) if you want, we don't care about it
 - BUT you'd better leave the rooms (`registers`) that we want to save for the guests untouched. “these rooms better look the same when we return!”
- Who hasn't heard this in their life?

Parents leaving for weekend analogy (2/5)

- Kid now “owns” rooms (`registers`)
- Kid wants to use the `saved` rooms for a wild, wild party (`computation`)
- What does kid (`callee`) do?
 - Kid takes what was in these rooms and puts them in the garage (`memory`)
 - Kid throws the party, `trashes everything` (except garage, who ever goes in there?)
 - Kid restores the rooms the parents wanted `saved after the party` by `replacing the items from the garage` (`memory`) back into those `saved rooms`

Parents leaving for weekend analogy (3/5)

- Same scenario, except before parents return and kid replaces **saved** rooms...
- Kid (**callee**) has left valuable stuff (**data**) all over.
 - Kid's friend (**anothercallee**) wants the house for a party **when the kid** is away
 - Kid knows that friend might **trash** the place destroying valuable stuff!
 - Kid remembers rule parents taught and now becomes the “heavy” (**caller**), instructing friend (**callee**) on good rules (**conventions**) of house.

Parents leaving for weekend analogy (4/5)

- If kid had data in **temporary rooms** (which were going to be trashed), there are three options:
 - Move items directly to garage (**m em ory**)
 - Move items to **saved rooms** whose contents have already been moved to the garage (**m em ory**)
 - Optimize lifestyle (**code**) so that the amount you've got to move stuff back and forth from garage (**m em ory**) is minimized.
 - Mantra: “Minimize register footprint”
- Otherwise: “Dude, where’s my data?!”

Parents leaving for weekend analogy (5/5)

- Friend now “owns” rooms (registers)
- Friend wants to use the saved rooms for a wild, wild party (com putation)
- What does friend (callee) do?
 - Friend takes what was in these rooms and puts them in the garage (m em ory)
 - Friend throws the party, trashes everything (except garage)
 - Friend restores the rooms the kid wanted saved after the party by replacing the items from the garage (m em ory) back into those saved rooms

Bitwise Operations

- So far, we've done arithmetic (**add**, **sub**, **addi**), mem access (**lw** and **sw**), & branches and jumps.
- All of these instructions view contents of register as a single quantity (e.g., signed or unsigned int)
- **New Perspective:** View register as 32 raw bits rather than as a single 32-bit number
 - Since registers are composed of 32 bits, wish to access individual bits (or groups of bits) rather than the whole.
- Introduce two new classes of instructions

Logical Operators (1/3)

- Two basic logical operators:
 - AND: outputs 1 only if **all** inputs are 1
 - OR: outputs 1 if **at least one** input is 1
- Truth Table: standard table listing all possible combinations of inputs and resultant output

A	B	A AND B	A OR B
0	0	0	0
0	1	0	1
1	0	0	1
1	1	1	1

Logical Operators (2/3)

- Logical Instruction Syntax:
 - 1 2,3,4
 - where
 - 1) operation name
 - 2) register that will receive value
 - 3) first operand (register)
 - 4) second operand (register) or immediate (numerical constant)
- In general, can define them to accept > 2 inputs, but in the case of MIPS assembly, these accept exactly 2 inputs and produce 1 output
 - Again, rigid syntax, simpler hardware

Logical Operators (3/3)

- Instruction Names:
 - **and, or**: Both of these expect the third argument to be a register
 - **andi, ori**: Both of these expect the third argument to be an immediate
- MIPS Logical Operators are all **bitwise**, meaning that bit 0 of the output is produced by the respective bit 0's of the inputs, bit 1 by the bit 1's, etc.
 - C: Bitwise AND is **&** (e.g., ***z = x & y;***)
 - C: Bitwise OR is **|** (e.g., ***z = x | y;***)

Uses for Logical Operators (1/3)

- Note that **anding** a bit with 0 produces a 0 at the output while **anding** a bit with 1 produces the original bit.
- This can be used to create a **mask**.
 - Example:

1011 0110 1010 0100 0011

mask: 0000 0000 0000 0000 0000

- The result of **anding** these:

0000 0000 0000 0000 0000

1101 1001 1010

1111 1111 1111

1101 1001 1010

mask last 12 bits

Uses for Logical Operators (2/3)

- The second bitstring in the example is called a **mask**. It is used to isolate the rightmost 12 bits of the first bitstring by masking out the rest of the string (e.g. setting to all 0s).
- Thus, the **and** operator can be used to set certain portions of a bitstring to 0s, while leaving the rest alone.
 - In particular, if the first bitstring in the above example were in \$t0, then the following instruction would mask it:

andi \$t0,\$t0,0xFFFF

Uses for Logical Operators (3/3)

- Similarly, note that **oring** a bit with 1 produces a 1 at the output while **oring** a bit with 0 produces the original bit.
- Often used to force certain bits to 1s.
 - For example, if \$t0 contains 0x12345678, then after this instruction:

```
ori $t0, $t0, 0xFFFF
```

... \$t0 will contain 0x1234~~FFFF~~FFF
 - (i.e., the high-order 16 bits are untouched, while the low-order 16 bits are forced to 1s).

Peer Instruction

```
r: ...      # R/W $s0,$v0,$t0,$a0,$sp,$ra,mem  
...          ##### PUSH REGISTER(S) TO STACK?  
jal e      # Call e  
...          # R/W $s0,$v0,$t0,$a0,$sp,$ra,mem  
jr $ra      # Return to caller of r  
  
e: ...      # R/W $s0,$v0,$t0,$a0,$sp,$ra,mem  
jr $ra      # Return to r
```

What does **r** have to push on the stack before “**jal e**”?

- a) 1 of (\$s0,\$sp,\$v0,\$t0,\$a0,\$ra)
- b) 2 of (\$s0,\$sp,\$v0,\$t0,\$a0,\$ra)
- c) 3 of (\$s0,\$sp,\$v0,\$t0,\$a0,\$ra)
- d) 4 of (\$s0,\$sp,\$v0,\$t0,\$a0,\$ra)
- e) 5 of (\$s0,\$sp,\$v0,\$t0,\$a0,\$ra)

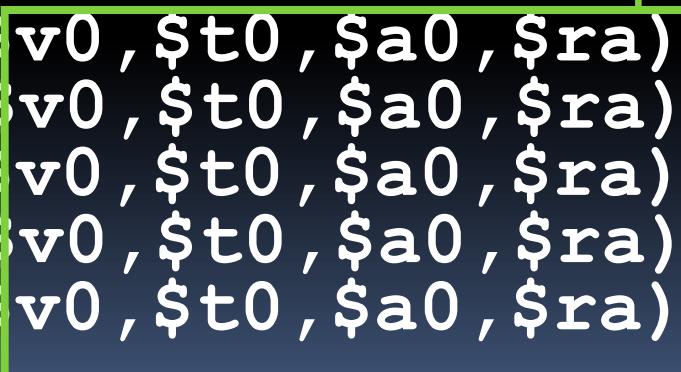
Peer Instruction Answer

```
r: ...      # R/W $s0,$v0,$t0,$a0,$sp,$ra,mem  
...          ##### PUSH REGISTER(S) TO STACK?  
jal e      # Call e  
...          # R/W $s0,$v0,$t0,$a0,$sp,$ra,mem  
jr $ra      # Return to caller of r  
  
e: ...      # R/W $s0,$v0,$t0,$a0,$sp,$ra,mem  
jr $ra      # Return to r
```

What does **r** have to push on the stack before “**jal e**”?

Saved Volatile! -- need to push

- a) 1 of (\$s0,\$sp,\$v0,\$t0,\$a0,\$ra)
- b) 2 of (\$s0,\$sp,\$v0,\$t0,\$a0,\$ra)
- c) 3 of (\$s0,\$sp,\$v0,\$t0,\$a0,\$ra)
- d) 4 of (\$s0,\$sp,\$v0,\$t0,\$a0,\$ra)
- e) 5 of (\$s0,\$sp,\$v0,\$t0,\$a0,\$ra)



“And in Conclusion...”

- **Register Conventions:** Each register has a purpose and limits to its usage. Learn these and follow them, even if you’re writing all the code yourself.
- Logical and Shift Instructions
 - Operate on bits individually, unlike arithmetic, which operate on entire word.
 - Use to isolate fields, either by masking or by shifting back and forth.
 - Use shift left logical, **sll**, for multiplication by powers of 2
 - Use shift right logical, **srl**, for division by powers of 2 of unsigned numbers (**unsigned int**)
 - Use shift right arithmetic, **sra**, for division by powers of 2 of signed numbers (**int**)
- New Instructions:
and, andi, or, ori, sll, srl, sra

Bonus slides

- These are extra slides that used to be included in lecture notes, but have been moved to this, the “bonus” area to serve as a supplement.
- The slides will appear in the order they would have in the normal presentation

Bonus

Shift Instructions (review) (1/4)

- Move (shift) all the bits in a word to the left or right by a number of bits.
 - Example: shift right by 8 bits

0001 0010 0011 0100 0101 0110 0111 1000

0000 0000 0001 0010 0011 0100 0101 0110

- Example: shift left by 8 bits

0001 0010 0011 0100 0101 0110 0111 1000

0011 0100 0101 0110 0111 1000 0000 0000

Shift Instructions (2/4)

- Shift Instruction Syntax:

1 2,3,4

...where

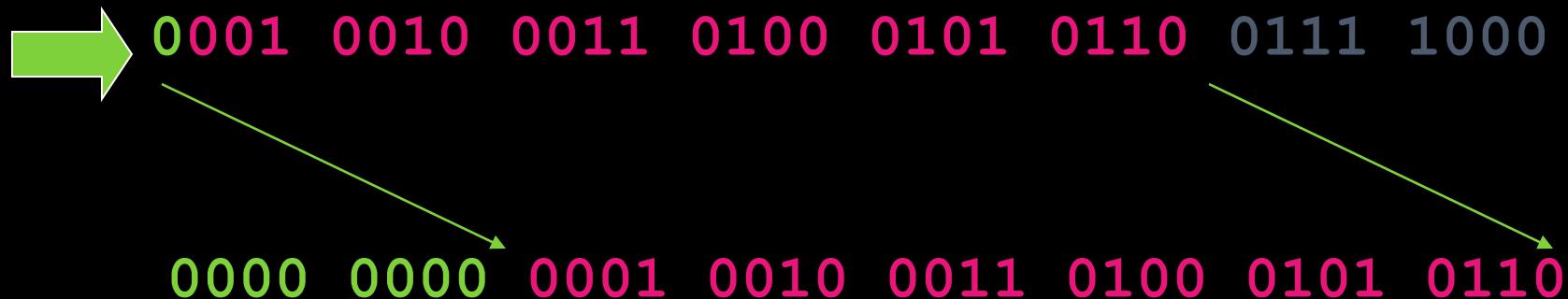
- 1) operation name
- 2) register that will receive value
- 3) first operand (register)
- 4) shift amount (constant < 32)

- MIPS shift instructions:

1. **sll** (shift left logical): shifts left and fills emptied bits with 0s
2. **srl** (shift right logical): shifts right and fills emptied bits with 0s
3. **sra** (shift right arithmetic): shifts right and fills emptied bits by sign extending

Shift Instructions (3/4)

- Example: shift right arithmetic by 8 bits



- Example: shift right arithmetic by 8 bits



Shift Instructions (4/4)

- Since shifting may be faster than multiplication, a good compiler usually notices when C code multiplies by a power of 2 and compiles it to a shift instruction:
`a *= 8;` (in C)
would compile to:
`sll $s0,$s0,3` (in MIPS)
- Likewise, shift right to divide by powers of 2 (rounds towards $-\infty$)
 - remember to use `sra`

Example: Fibonacci Numbers 1/8

- The Fibonacci numbers are defined as follows: $F(n) = F(n - 1) + F(n - 2)$, $F(0)$ and $F(1)$ are defined to be 1
- In scheme, this could be written:

```
(define (Fib n)          (cond      (= n 0) 1)
      (= n 1) 1)
      (else (+ (Fib (-n 1))
                (Fib (-n 2))))))
```

Example: Fibonacci Numbers 2/8

- Rewriting this in C we have:

```
int fib (int n) {  
    if(n == 0) {  
        return 1; }  
    if(n == 1) { return 1; }  
    return (fib (n - 1) + fib (n - 2));  
}
```

Example: Fibonacci Numbers 3/8

- Now, let's translate this to MIPS!
- You will need space for three words on the stack
- The function will use one \$s register, \$s0
- Write the Prologue:

fib:

```
addi $sp, $sp, -12    # Space for three words
sw $ra, 8($sp)         # Save return address
sw $s0, 4($sp)         # Save s0
```

Example: Fibonacci Numbers 4/8

- ° Now write the Epilogue:

fin:

```
lw $s0, 4($sp)      # Restore $s0
lw $ra, 8($sp)      # Restore return address
addi $sp, $sp, 12    # Pop the stack frame
jr $ra               # Return to caller
```



Example: Fibonacci Numbers 5/8

- Finally, write the body. The C code is below. Start by translating the lines indicated in the comments

```
int fib (int n) {  
    if(n == 0) { return 1; } /*Translate Me!*/ if(n == 1)  
    { return 1; } /*Translate Me!*/ return (fib (n - 1) + fib (n -  
    2));  
}  
  
addi $v0, $zero, 1          # $v0 = 1  
beq $a0, $zero, fin        #  
addi $t0, $zero, 1          # $t0 = 1  
beq $a0, $t0, fin          #
```

Continued on next slide. . .



Example: Fibonacci Numbers 6/8

- ° Almost there, but be careful, this part is tricky!

```
int fib (int n) {  
    ...  
    return (fib (n -1) + fib (n -2));  
}
```

```
addi $a0, $a0, -1          # $a0 = n - 1  
sw $a0, 0($sp)              # Need $a0 after jal  
jal fib                     # fib(n - 1)  
lw $a0, 0($sp)              # restore $a0  
addi $a0, $a0, -1          # $a0 = n - 2
```



Example: Fibonacci Numbers 7/8

- ° Remember that \$vo is caller saved!

```
int fib (int n) {  
    . . .  
    return (fib (n -1) + fib (n -2));  
}
```

```
add $s0, $v0, $zero      # Place fib(n - 1)  
                          # somewhere it won't get  
                          # clobbered  
jal fib                  # fib(n - 2)  
add $v0, $v0, $s0          # $v0 = fib(n-1) + fib(n-2)
```

To the epilogue and beyond. . . .



Example: Fibonacci Numbers 8/8

- ° Here's the complete code for reference:

```
fib: addi $sp, $sp, -12
      sw $ra, 8($sp)
      sw $s0, 4($sp)
      addi $v0, $zero, 1
      beq $a0, $zero, fin
      addi $t0, $zero, 1
      beq $a0, $t0, fin
      addi $a0, $a0, -1
      sw $a0, 0($sp)
      jal fib
```

```
           lw $a0, 0($sp)
           addi $a0, $a0, -1
           add $s0, $v0, $zero
           jal fib
           add $v0, $v0, $s0
           fin: lw $s0, 4($sp)
                  lw $ra, 8($sp)
                  addi $sp, $sp, 12
                  jr $ra
```



Bonus Example: Compile This (1/5)

```
main() {  
    int i,j,k,m; /* i-m:$s0-$s3 */  
    ...  
    i = mult(j,k); ...  
    m = mult(i,i); ...  
}  
  
int mult (int mcand, int mlier) {  
    int product;  
  
    product = 0;  
    while (mlier > 0) {  
        product += mcand;  
        mlier -= 1; }  
    return product;  
}
```

Bonus Example: Compile This (2/5)

__start:

...

```
add $a0,$s1,$0      # arg0 = j
add $a1,$s2,$0      # arg1 = k
jal mult            # call mult
add $s0,$v0,$0      # i = mult()
```

```
add $a0,$s0,$0      # arg0 = i
add $a1,$s0,$0      # arg1 = i
jal mult            # call mult
add $s3,$v0,$0      # m = mult()
```

...

```
j __exit    main() {
              int i,j,k,m; /* i-m:$s0-$s3 */
              ...
              i = mult(j,k); ...
              m = mult(i,i); ... }
```

Bonus Example: Compile This (3/5)

- Notes:
 - **main** function ends with a jump to **__exit**, not **jr \$ra**, so there's no need to save **\$ra** onto stack
 - all variables used in **main** function are saved registers, so there's no need to save these onto stack

Bonus Example: Compile This (4/5)

mult:

Loop:

add	\$t0,\$0,\$0	# <i>prod=0</i>
slt	\$t1,\$0,\$a1	# <i>mlr > 0?</i>
beq	\$t1,\$0,Fin	# <i>no=>Fin</i>
add	\$t0,\$t0,\$a0	# <i>prod+=mc</i>
addi	\$a1,\$a1,-1	# <i>mlr-=1</i>
j	Loop	# <i>goto Loop</i>

Fin:

add	\$v0,\$t0,\$0	# <i>\$v0=prod</i>
jr	\$ra	# <i>return</i>

```
int mult (int mcand, int mlier) {
    int product = 0;
    while (mlier > 0)  {
        product += mcand;
        mlier -= 1; }
    return product;
}
```

Bonus Example: Compile This

(5/5)

Notes:

- no `jal` calls are made from `mult` and we don't use any saved registers, so we don't need to save anything onto stack
- temp registers are used for intermediate calculations (could have used s registers, but would have to save the caller's on the stack.)
- `$a1` is modified directly (instead of copying into a temp register) since we are free to change it
- result is put into `$v0` before returning (could also have modified `$v0` directly)

0.8 Representation



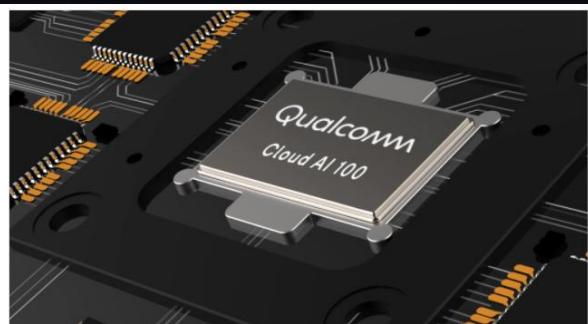
Computer Architecture (计算机体系结构)

Lecture 8 MIPS Instruction Representation I

Lecturer
Yuanqing
Chen

2020-09-18

Qualcomm Cloud AI 100 Promises Impressive Performance per Watt for Near-Edge AI



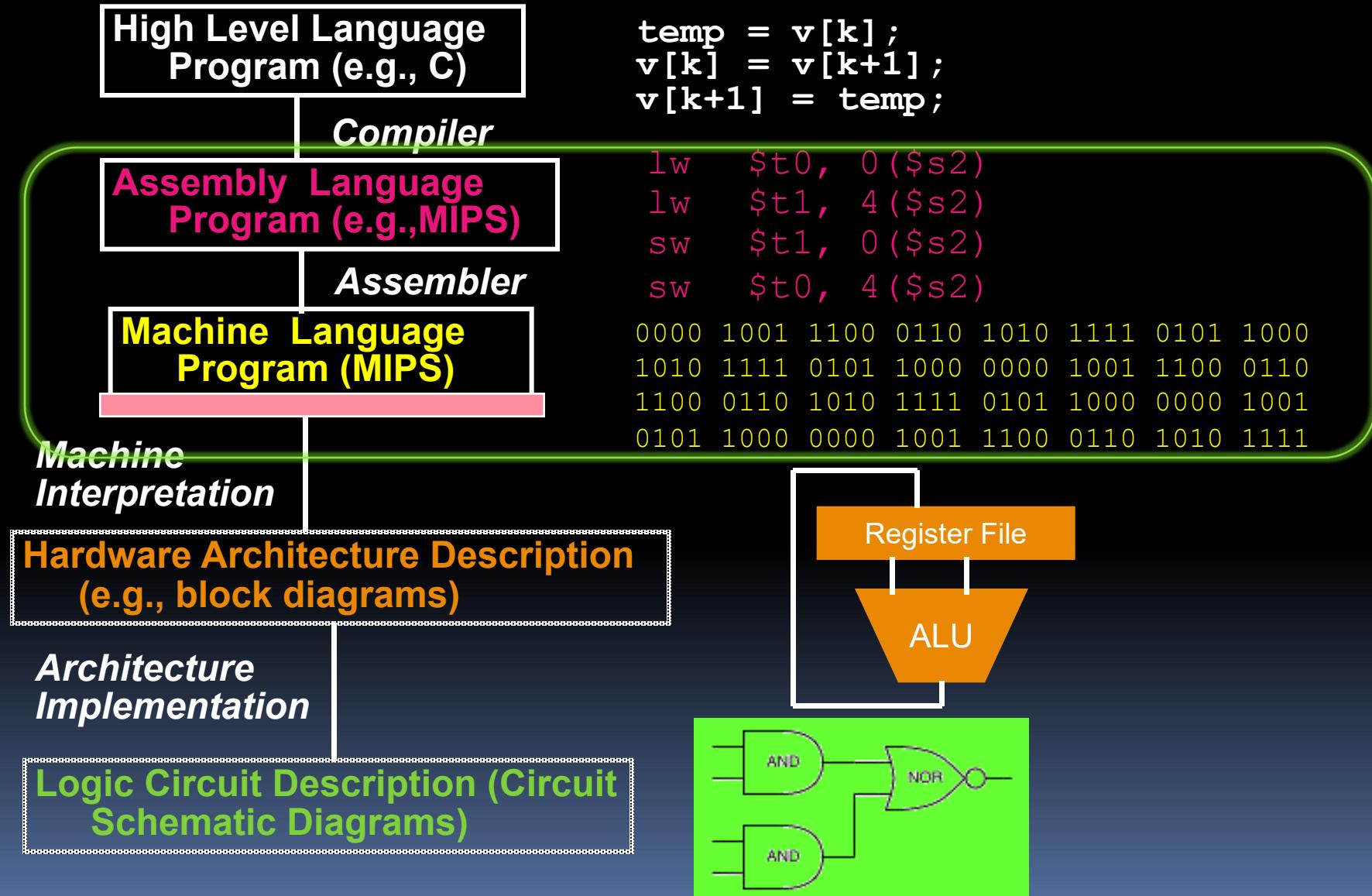
Qualcomm's Cloud AI 100 is targeted at near-edge applications including enterprise data centers and 5G infrastructure (Image: Qualcomm)



Review

- **Register Conventions:** Each register has a purpose and limits to its usage. Learn these and follow them, even if you're writing all the code yourself.
- **Logical and Shift Instructions**
 - Operate on bits individually, unlike arithmetic, which operate on entire word.
 - Use to isolate fields, either by masking or by shifting back and forth.
 - Use shift left logical, **sll**, for multiplication by powers of 2
 - Use shift right logical, **srl**, for division by powers of 2 of unsigned numbers (**unsigned int**)
 - Use shift right arithmetic, **sra**, for division by powers of 2 of signed numbers (**int**)
- **New Instructions:**
and, andi, or, ori, sll, srl, sra

Levels of Representation (abstractions)



Overview – Instruction

Representation

Big Idea: stored program

- consequences of stored program
- Instructions as numbers
- Instruction encoding
- MIPS instruction format for Add instructions
- MIPS instruction format for Immediate, Data transfer instructions

Big Idea: Stored-Program Concept

- Computers built on 2 key principles:
 - Instructions are represented as bit patterns - can think of these as numbers.
 - Therefore, entire programs can be stored in memory to be read or written just like data.
- Simplifies SW/HW of computer systems:
 - Memory technology for data also used for programs

Consequence #1: Everything

Addressed

Since all instructions and data are stored in memory, everything has a memory address: instructions, data words

- both branches and jumps use these
- C pointers are just memory addresses: they can point to anything in memory
 - Unconstrained use of addresses can lead to nasty bugs; up to you in C; limits in Java
- One register keeps address of instruction being executed: **“Program Counter” (PC)**
 - Basically a pointer to memory: Intel calls it Instruction Address Pointer, a better name

Consequence #2: Binary

Compatibility

- Programs are distributed in binary form
 - Programs bound to specific instruction set
 - Different version for Macintoshes and PCs
- New machines want to run old programs (“binaries”) as well as programs compiled to new instructions
- Leads to “backward compatible” instruction set evolving over time
- Selection of Intel 8086 in 1981 for 1st IBM PC is major reason latest PCs still use 80x86 instruction set (Pentium 4); could still run program from 1981 PC today

Instructions as Numbers (1/2)

- Currently all data we work with is in words (32-bit blocks):
 - Each register is a word.
 - **lw** and **sw** both access memory one word at a time.
- So how do we represent instructions?
 - Remember: Computer only understands 1s and 0s, so “**add \$t0,\$0,\$0**” is meaningless.
 - MIPS wants simplicity: since data is in words, make instructions be words too

Instructions as Numbers (2/2)

- One word is 32 bits, so divide instruction word into “**fields**”.
- Each field tells processor something about instruction.
- We could define different fields for each instruction, but MIPS is based on simplicity, so define 3 basic types of instruction formats:
 - R-format
 - I-format
 - J-format

Instruction Formats

- **I-format**: used for instructions with immediates, **lw** and **sw** (since offset counts as an immediate), and branches (**beq** and **bne**),
 - (but not the shift instructions; later)
- **J-format**: used for **j** and **jal**
- **R-format**: used for all other instructions
- It will soon become clear why the instructions have been partitioned in this way.

R-Format Instructions (1/5)

- Define “**fields**” of the following number of bits each: $6 + 5 + 5 + 5 + 5 + 6 = 32$

6	5	5	5	5	6
---	---	---	---	---	---

- For simplicity, each field has a name:

opcode	rs	rt	rd	shamt	funct
--------	----	----	----	-------	-------

- Important:** On these slides and in book, each field is viewed as a 5- or 6-bit unsigned integer, not as part of a 32-bit integer.
 - Consequence: 5-bit fields can represent any number 0-31, while 6-bit fields can represent any number 0-63.

R-Format Instructions (2/5)

- What do these field integer values tell us?
 - `opcode`: partially specifies what instruction it is
 - Note: This number is equal to 0 for all R-Format instructions.
 - `funct`: combined with `opcode`, this number exactly specifies the instruction
- Question: Why aren't `opcode` and `funct` a single 12-bit field?
 - We'll answer this later.

R-Format Instructions (3/5)

- More fields:
 - rs (Source Register): *generally* used to specify register containing first operand
 - rt (Target Register): *generally* used to specify register containing second operand (note that name is misleading)
 - rd (Destination Register): *generally* used to specify register which will receive result of computation

R-Format Instructions (4/5)

- Notes about register fields:
 - Each register field is exactly 5 bits, which means that it can specify any unsigned integer in the range 0-31. Each of these fields specifies one of the 32 registers by number.
 - The word “generally” was used because there are exceptions that we’ll see later. E.g.,
 - **mult** and **div** have nothing important in the **rd** field since the dest registers are **hi** and **lo**
 - **mfhi** and **mflo** have nothing important in the **rs** and **rt** fields since the source is determined by the instruction (see COD)

R-Format Instructions (5/5)

- Final field:
 - shamt: This field contains the amount a shift instruction will shift by. Shifting a 32-bit word by more than 31 is useless, so this field is only 5 bits (so it can represent the numbers 0-31).
 - This field is set to 0 in all but the shift instructions.
- For a detailed description of field usage for each instruction, see green insert in COD (You can bring with you to all exams)

R-Format Example (1/2)

- MIPS Instruction:

add \$8 , \$9 , \$10

opcode = 0 (look up in table in book)

funct = 32 (look up in table in book)

rd = 8 (destination)

rs = 9 (first *operand*)

rt = 10 (second *operand*)

shamt = 0 (not a shift)

R-Format Example (2/2)

- MIPS Instruction:

add \$8,\$9,\$10

Decimal number per field representation:

0	9	10	8	0	32
---	---	----	---	---	----

Binary number per field representation:

000000	01001	01010	01000	00000	100000
--------	-------	-------	-------	-------	--------

hex

hex representation:

012A 4020_{hex}

decimal representation:

19, 546, 144_{ten}

Called a Machine Language Instruction

Administrivia

- Remember to look at Appendix A (also on SPIM website), for MIPS assembly language details, including “assembly directives”, etc.

I-Format Instructions (1/4)

- What about instructions with immediates?
 - 5-bit field only represents numbers up to the value 31: immediates may be much larger than this
 - Ideally, MIPS would have only one instruction format (for simplicity): unfortunately, we need to compromise
- Define new instruction format that is partially consistent with R-format:
 - First notice that, if instruction has immediate, then it uses at most 2 registers.

I-Format Instructions (2/4)

- Define “fields” of the following number of bits each: $6 + 5 + 5 + 16 = 32$ bits



- Again, each field has a name:



- Key Concept:** Only one field is inconsistent with R-format. Most importantly, opcode is still in same location.

I-Format Instructions (3/4)

- What do these fields mean?
 - `opcode`: same as before except that, since there's no `funct` field, `opcode` uniquely specifies an instruction in I-format
 - This also answers question of why R-format has two 6-bit fields to identify instruction instead of a single 12-bit field: in order to be consistent as possible with other formats while leaving as much space as possible for immediate field.
 - `rs`: specifies a register operand (if there is one)
 - `rt`: specifies register which will receive result of computation (this is why it's called the *target* register "rt") or other operand for some instructions.

I-Format Instructions (4/4)

- The Immediate Field:
 - **addi, slti, sltiu**, the immediate is sign-extended to 32 bits. Thus, it's treated as a signed integer.
 - 16 bits → can be used to represent immediate up to 2^{16} different values
 - This is large enough to handle the offset in a typical **lw** or **sw**, plus a vast majority of values that will be used in the **slti** instruction.
 - We'll see what to do when the number is too big in our next lecture...

I-Format Example (1/2)

- MIPS Instruction:

addi \$21,\$22,-50

opcode = 8 (look up in table in book)

rs = 22 (register containing operand)

rt = 21 (target register)

immediate = -50 (by default, this is decimal)

I-Format Example (2/2)

- MIPS Instruction:

addi \$21,\$22,-50

Decimal/field representation:

8	22	21	-50
---	----	----	-----

Binary/field representation:

001000	10110	10101	1111111111001110
--------	-------	-------	------------------

hexadecimal representation: 22D5

~~decimal representation:~~

584,449,998_{ten}

Peer Instruction

Which instruction has same representation as 35_{ten} ?

- a) add \$0, \$0, \$0

opcode	rs	rt	rd	shamt	funct

- b) subu \$s0,\$s0,\$s0

opcode	rs	rt	rd	shamt	funct

- c) lw \$0, 0(\$0)

opcode	rs	rt	offset		

- d) addi \$0, \$0, 35

opcode	rs	rt	immediate		

- e) subu \$0, \$0, \$0

opcode	rs	rt	rd	shamt	funct

Registers numbers and names:

0: \$0, .. 8: \$t0, 9:\$t1, ..15: \$t7, 16: \$s0, 17: \$s1, .. 23: \$s7

Opcodes and function fields (if necessary)

add: opcode = 0, funct = 32

subu: opcode = 0, funct = 35

addi: opcode = 8

lw: opcode = 35

Peer Instruction Answer

Which instruction has same representation as 35_{ten} ?

a) add \$0, \$0, \$0

0	0	0	0	0	32
---	---	---	---	---	----

b) subu \$s0,\$s0,\$s0

0	16	16	16	0	35
---	----	----	----	---	----

c) lw \$0, 0(\$0)

35	0	0			0
----	---	---	--	--	---

d) addi \$0, \$0, 35

8	0	0			35
---	---	---	--	--	----

e) subu \$0, \$0, \$0

0	0	0	0	0	35
---	---	---	---	---	----

Registers numbers and names:

0: \$0, .. 8: \$t0, 9:\$t1, ..15: \$t7, 16: \$s0, 17: \$s1, .. 23: \$s7

Opcodes and function fields (if necessary)

add: opcode = 0, funct = 32

subu: opcode = 0, funct = 35

addi: opcode = 8

lw: opcode = 35

In conclusion...

- Simplifying MIPS: Define instructions to be same size as data word (one word) so that they can use the same memory (compiler can use lw and sw).
- Computer actually stores programs as a series of these 32-bit numbers.
- **MIPS Machine Language Instruction:** 32 bits representing a single instruction

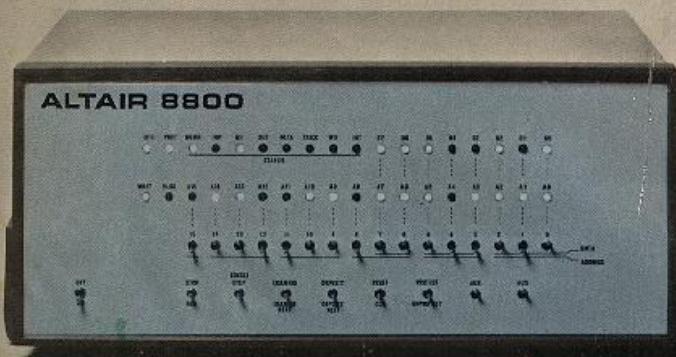
R	opcode	rs	rt	rd	shamt	funct
I	opcode	rs	rt		immediate	



EXCLUSIVE!

ALTAIR 8800

The most powerful minicomputer project ever presented—can be built for under \$400



BY H. EDWARD ROBERTS AND WILLIAM YATES

THE era of the computer in every home—a favorite topic among science-fiction writers—has arrived! It's made possible by the POPULAR ELECTRONICS/MITS Altair 8800, a full-blown computer that can hold its own against sophisticated minicomputers now on the market. And it doesn't cost several thousand dollars. In fact, it's in a color TV-receiver's price class—under \$400 for a complete kit.

The Altair 8800 is not a "demonstrator" or souped-up calculator. It is the most powerful computer ever presented as a construction project in any electronics magazine. In many ways, it represents a revolutionary development in electronic design and thinking.

The Altair 8800 is a parallel 8-bit word/16-bit address computer with an instruction cycle time of 2 μ s. Its central

processing unit is a new LSI chip that is many times more powerful than previous IC processors. It can accommodate 256 inputs and 256 outputs, all directly addressable, and has 78 basic machine instructions (as compared with 40 in the usual minicomputer). This means that you can write an extensive and detailed program. The basic computer has 256 words of memory, but it can be economically expanded for 65,000 words. Thus, with full expansion, up to 65,000 subroutines can all be going at the same time.

The basic computer is a complete system. The program can be entered via switches located on the front panel, providing a LED readout in binary format. The very-low-cost terminal presented in POPULAR ELECTRONICS last month can also be used.

PROCESSOR DESCRIPTION

Processor: 8 bit parallel
Max. memory: 65,000 words (all directly addressable)
Instruction cycle time: 2 μ s (min.)
Inputs and outputs: 256 (all directly addressable)
Number of basic machine instructions: 78 (181 with variants)
Add/subtract time: 2 μ s
Number of subroutine levels: 65,000
Interrupt structure: 8 hardware vectored levels plus software levels
Number of auxiliary registers: 8 plus stack pointer, program counter and accumulator
Memory type: semiconductor (dynamic or static RAM, ROM, PROM)
Memory access time: 850 ns static RAM; 420 or 150 ns dynamic Ram

0.9 Formats of Instructions



Lecturer
Yuanqing
Cheng

Computer Architecture (计算机体系结构)

Lecture 9 MIPS Instruction Representation II

2020-09-21



Memory Technologies Confront Edge AI's Diverse Challenges

Edge AI applications are many and varied, which means that there are nearly endless options for memory for edge applications.

Review

- Simplifying MIPS: Define instructions to be same size as data word (one word) so that they can use the same memory (compiler can use `lw` and `sw`).
- Computer actually stores programs as a series of these 32-bit numbers.
- **MIPS Machine Language Instruction:** 32 bits representing a single instruction

R	opcode	rs	rt	rd	shamt	funct
I	opcode	rs	rt		immediate	

I-Format Problems (0/3)

- Problem 0: Unsigned # sign-extended?
 - addiu, sltiu, **sign-extends** immediates to 32 bits. Thus, # is a “signed” integer.
- Rationale
 - addiu so that can add w/out overflow
 - See K&R pp. 230, 305
 - sltiu suffers so that we can have easy HW
 - Does this mean we'll get wrong answers?
 - Nope, it means assembler has to handle any unsigned immediate $2^{15} \leq n < 2^{16}$ (I.e., with a 1 in the 15th bit and 0s in the upper 2 bytes) as it does for numbers that are too large. \Rightarrow

I-Format Problem (1/3)

- Problem:
 - Chances are that addi, lw, sw and slti will use immediates small enough to fit in the immediate field.
 - ...but what if it's too big?
 - We need a way to deal with a 32-bit immediate in any I-format instruction.

I-Format Problem (2/3)

- Solution to Problem:
 - Handle it in software + new instruction
 - Don't change the current instructions: instead, add a new instruction to help out

- New instruction:

lui register, immediate

- stands for Load Upper Immediate
- takes 16-bit immediate and puts these bits in the upper half (high order half) of the register
- sets lower half to 0s

I-Format Problems (3/3)

- Solution to Problem (continued):

- So how does lui help us?
 - Example:

```
addiu $t0,$t0, 0xABABCD
```

...becomes

```
lui $at 0xABAB
ori $at, $at, 0xCD
addu $t0,$t0,$at
```

- Now each I-format instruction has only a 16-bit immediate.
 - Wouldn't it be nice if the assembler would do this for us automatically? (later)

Branches: PC-Relative Addressing

(1/5) Use I-Format

opcode	rs	rt	immediate
--------	----	----	-----------

- opcode **specifies** beq **versus** bne
- rs **and** rt **specify registers to compare**
- What can immediate specify?
 - immediate is only 16 bits
 - PC (Program Counter) has byte address of current instruction being executed;
32-bit pointer to memory
 - So immediate cannot specify entire address to branch to.

Branches: PC-Relative Addressing

(2/5)

How do we typically use branches?

- Answer: if-else, while, for
- Loops are generally small: usually up to 50 instructions
- Function calls and unconditional jumps are done using jump instructions (`j` and `jal`), not the branches.
- Conclusion: may want to branch to anywhere in memory, but a branch often changes **PC** by a small amount

Branches: PC-Relative Addressing

(3/5)

■ Solution to branches in a 32-bit instruction:
PC-Relative Addressing

- Let the 16-bit immediate field be a signed two's complement integer to be *added* to the PC if we take the branch.
- Now we can branch $\pm 2^{15}$ bytes from the PC, which should be enough to cover almost any loop.
- Any ideas to further optimize this?

Branches: PC-Relative Addressing

(4/5)

Note: Instructions are words, so they're word aligned (byte address is always a multiple of 4, which means it ends with 00 in binary).

- So the number of bytes to add to the PC will always be a multiple of 4.
- So specify the immediate in words.
- Now, we can branch $\pm 2^{15}$ words from the PC (or $\pm 2^{17}$ bytes), so we can handle loops 4 times as large.

Branches: PC-Relative Addressing

(5/5)

Branch Calculation:

- If we **don't** take the branch:

$$PC = PC + 4 = \text{byte address of next instruction}$$

- If we **do** take the branch:

$$PC = (PC + 4) + (\text{immediate} * 4)$$

- Observations

- Immediate field specifies the number of words to jump, which is simply the number of instructions to jump.
- Immediate field can be positive or negative.
- Due to hardware, add immediate to $(PC+4)$, not to PC; will be clearer why later in course

Branch Example (1/3)

- MIPS Code:

```
Loop: beq    $9, $0, End
      addu   $8, $8, $10
      addiu  $9, $9, -1
      j       Loop
```

End:

- **beq branch is I-Format:**

opcode = 4 (look up in table)

rs = 9 (first operand)

rt = 0 (second operand)

immediate = ???

Branch Example (2/3)

- MIPS Code:

```
Loop: beq    $9, $0, End
      addu   $8, $8, $10
      addiu  $9, $9, -1
      j      Loop
```

End:

- immediate Field:

- Number of **instructions** to add to (or subtract from) the PC, starting at the instruction *following* the branch.
- In beq **case**, immediate = 3

Branch Example (3/3)

- MIPS Code:

```
Loop: beq    $9, $0, End
      addu   $8, $8, $10
      addiu  $9, $9, -1
      j       Loop
```

End:

decimal representation:

4	9	0	3
---	---	---	---

binary representation:

000100	01001	00000	0000000000000011
--------	-------	-------	------------------

Questions on PC-addressing

- Does the value in branch field change if we move the code?
- What do we do if destination is $> 2^{15}$ instructions away from branch?
- Why do we need different addressing modes (different ways of forming a memory address)? Why not just one?

J-Format Instructions (1/5)

- For branches, we assumed that we won't want to branch too far, so we can specify *change* in PC.
- For general jumps (`j` and `jal`), we may jump to *anywhere* in memory.
- Ideally, we could specify a 32-bit memory address to jump to.
- Unfortunately, we can't fit both a 6-bit opcode and a 32-bit address into a single 32-bit word, so we compromise.

J-Format Instructions (2/5)

- Define two “fields” of these bit widths:

6 bits

26 bits

- As usual, each field has a name:

opcode

target address

- Key Concepts

- Keep opcode field identical to R-format and I-format for consistency.
- Collapse all other fields to make room for large target address.

J-Format Instructions (3/5)

- For now, we can specify 26 bits of the 32-bit bit address.
- Optimization:
 - Note that, just like with branches, jumps will only jump to word aligned addresses, so last two bits are always 00 (in binary).
 - So let's just take this for granted and not even specify them.

J-Format Instructions (4/5)

- Now specify 28 bits of a 32-bit address
- Where do we get the other 4 bits?
 - By definition, take the 4 highest order bits from the PC.
 - Technically, this means that we cannot jump to *anywhere* in memory, but it's adequate 99.9999...% of the time, since programs aren't that long
 - only if straddle a 256 MB boundary
 - If we absolutely need to specify a 32-bit address, we can always put it in a register and use the jr instruction.

J-Format Instructions (5/5)

- Summary:
 - New PC = { PC[31..28], target address, 00 }
- Understand where each part came from!
- Note: { , , } means concatenation
 - { 4 bits , 26 bits , 2 bits } = 32 bit address
 - { 1010, 111111111111111111111111, 00 } =
1010111111111111111111111111111100
 - Note: Book uses ||

Peer Instruction Question

(for A,B) When combining two C files into one executable, recall we can compile them independently & then merge them together.

- 1) **Jump** insts don't require any changes.
- 2) **Branch** insts don't require any changes.

12

- a) FF
- b) FT
- c) TF
- d) TT
- e) dunno

In conclusion

- MIPS Machine Language Instruction:
32 bits representing a single instruction

R	opcode	rs	rt	rd	shamt	funct
I	opcode	rs	rt		immediate	
J	opcode		target	address		

- Branches use PC-relative addressing,
Jumps use absolute addressing.
- Disassembly is simple and starts by
decoding opcode field. (more in a week)

0.10 Float Point

Computer Architecture (计算机体系结构)

Lecture 10 Floating Point 1

2020-09-21

Lecturer Yuanqing Cheng
www.cadetlab.cn/teaching



Quote of the day

“95% of the
folks out there are
completely clueless
about floating-point.”

James Gosling
Sun Fellow
Java Inventor
1998-02-28



Review of Numbers

- Computers are made to deal with numbers
- What can we represent in N bits?
 - 2^N things, and no more! They could be...
 - Unsigned integers:

0 to $2^N - 1$

(for N=32, $2^{32} - 1 = 4,294,967,295$)

- Signed Integers (Two's Complement)

$-2^{(N-1)}$ to $2^{(N-1)} - 1$

(for N=32, $2^{31} = 2,147,483,648$)

What about other numbers?

1. Very large numbers? (seconds/millennium)
⇒ $31,556,926,000_{10}$ ($3.1556926_{10} \times 10^{10}$)
2. Very small numbers? (Bohr radius)
⇒ $0.000000000529177_{10}\text{m}$ ($5.29177_{10} \times 10^{-11}$)
3. Numbers with both integer & fractional parts?
⇒ 1.5

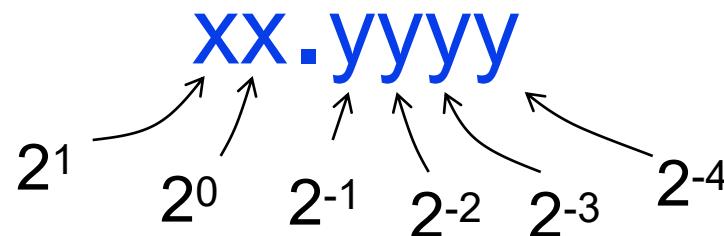
First consider #3.

...our solution will also help with 1 and 2.

Representation of Fractions

“Binary Point” like decimal point signifies boundary between integer and fractional parts:

Example 6-bit representation:



$$10.1010_2 = 1 \times 2^1 + 1 \times 2^{-1} + 1 \times 2^{-3} = 2.625_{10}$$

If we assume “fixed binary point”, range of 6-bit representations with this format:

0 to 3.9375 (almost 4)

Fractional Powers of 2

i	2^{-i}	
0	1.0	1
1	0.5	$1/2$
2	0.25	$1/4$
3	0.125	$1/8$
4	0.0625	$1/16$
5	0.03125	$1/32$
6	0.015625	
7	0.0078125	
8	0.00390625	
9	0.001953125	
10	0.0009765625	
11	0.00048828125	
12	0.000244140625	
13	0.0001220703125	
14	0.00006103515625	
15	0.000030517578125	

Representation of Fractions with Fixed Pt.

What about addition and multiplication?

Addition is
straightforward:

$$\begin{array}{r} 01.100 \\ + 00.100 \\ \hline 10.000 \end{array} \quad \begin{array}{r} 1.5_{10} \\ 0.5_{10} \\ 2.0_{10} \end{array}$$

Multiplication a bit more complex:

$$\begin{array}{r} 01.100 \\ \times 00.100 \\ \hline 0000110000 \end{array}$$

HI LOW

Where's the answer, 0.11? (need to remember where point is)

Representation of Fractions

So far, in our examples we used a “fixed” binary point what we really want is to “float” the binary point. Why?

Floating binary point most effective use of our limited bits (and thus more accuracy in our number representation):

example: put 0.1640625 into binary. Represent as in 5-bits choosing where to put the binary point.

... 00000.00101010000...



Store these bits and keep track of the binary point 2 places to the left of the MSB

Any other solution would lose accuracy!

With floating point rep., each numeral carries a exponent field recording the whereabouts of its binary point.

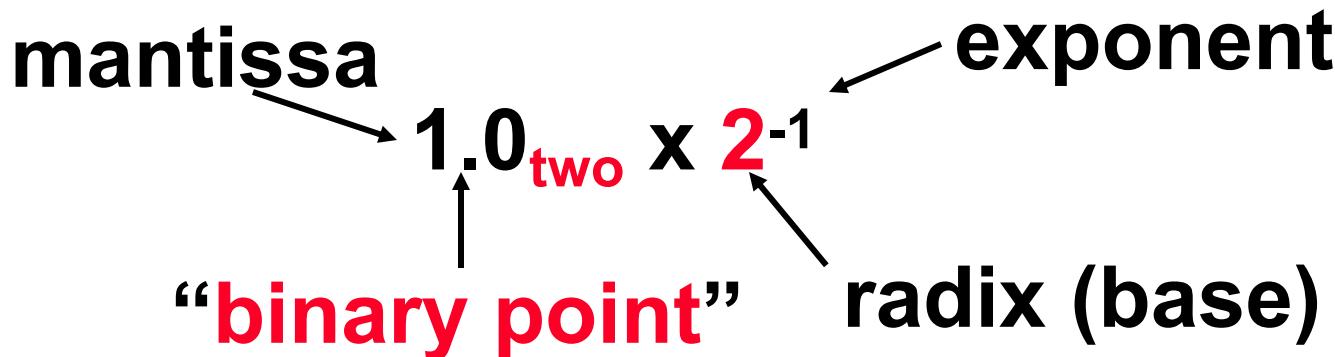
The binary point can be outside the stored bits, so very large and small numbers can be represented.

Scientific Notation (in Decimal)

mantissa → $6.02_{10} \times 10^{23}$ ← **exponent**
↑
decimal point **radix (base)**

- Normalized form: no leadings 0s
(exactly one digit to left of decimal point)
- Alternatives to representing 1/1,000,000,000
 - Normalized: 1.0×10^{-9}
 - Not normalized: $0.1 \times 10^{-8}, 10.0 \times 10^{-10}$

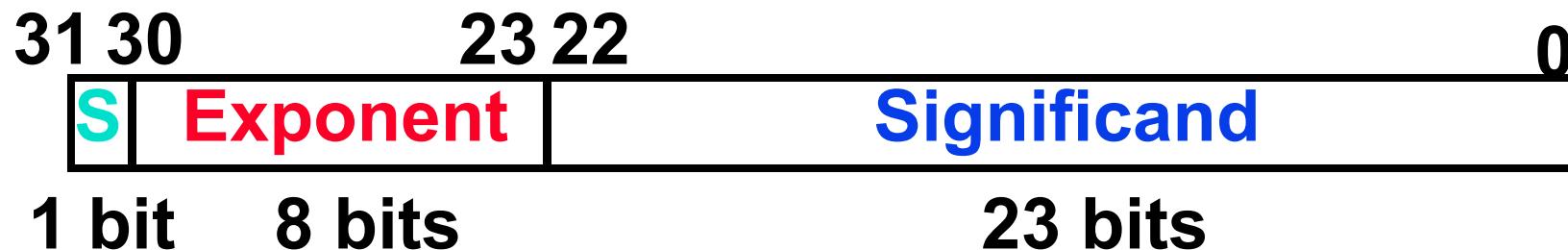
Scientific Notation (in Binary)



- Computer arithmetic that supports it called floating point, because it represents numbers where the binary point is not fixed, as it is for integers
 - Declare such variable in C as `float`

Floating Point Representation (1/2)

- Normal format: $+1.\text{xxx...x}_{\text{two}} * 2^{\text{yyy...y}_{\text{two}}}$
- Multiple of Word Size (32 bits)



- S represents Sign
Exponent represents y's
Significand represents x's

- Represent numbers as small as 2.0×10^{-38} to as large as 2.0×10^{38}

Floating Point Representation (2/2)

- What if result too large?

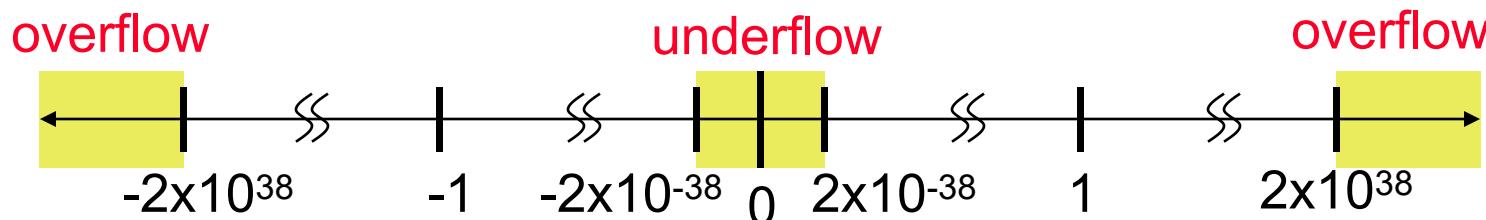
($> 2.0 \times 10^{38}$, $< -2.0 \times 10^{38}$)

- **Overflow!** \Rightarrow Exponent larger than represented in 8-bit Exponent field

- What if result too small?

(> 0 & $< 2.0 \times 10^{-38}$, < 0 & $> -2.0 \times 10^{-38}$)

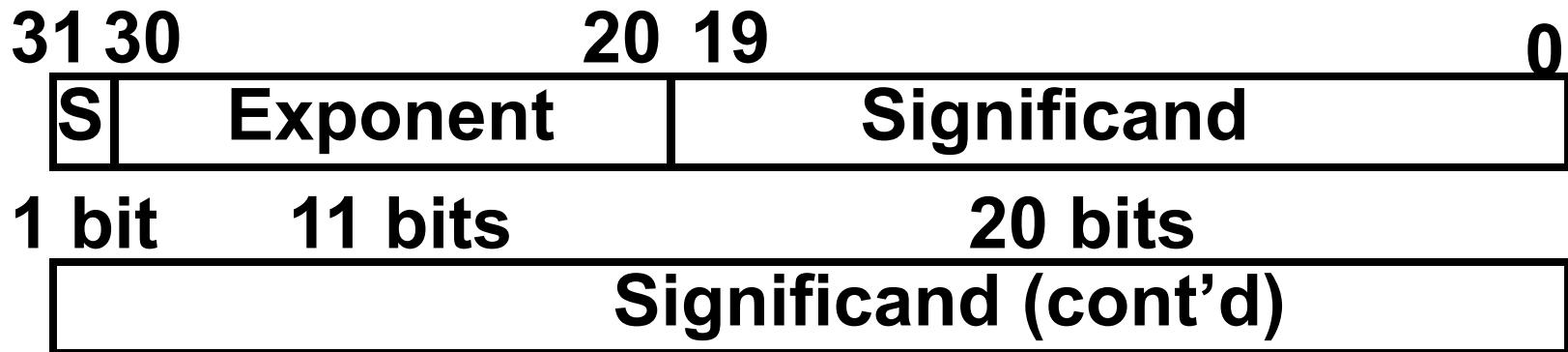
- **Underflow!** \Rightarrow Negative exponent larger than represented in 8-bit Exponent field



- What would help reduce chances of overflow and/or underflow?

Double Precision Fl. Pt. Representation

- Next Multiple of Word Size (64 bits)



32 bits

- Double Precision (vs. Single Precision)

- C variable declared as `double`
- Represent numbers almost as small as 2.0×10^{-308} to almost as large as 2.0×10^{308}
- But primary advantage is greater accuracy due to larger significand

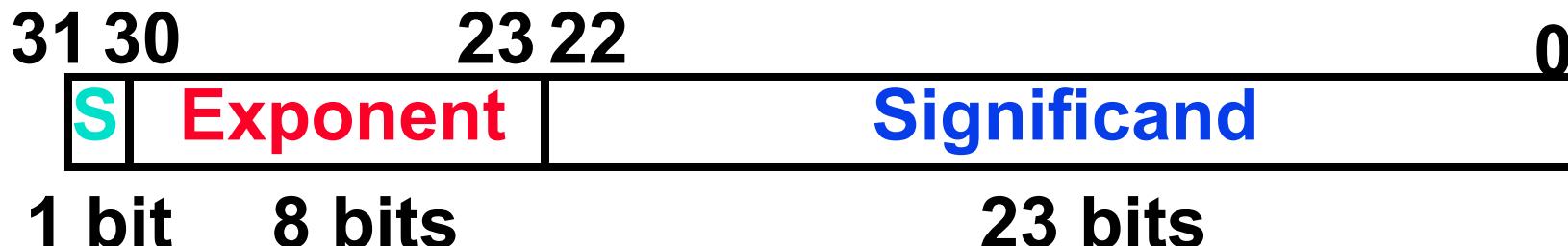
QUAD Precision Fl. Pt. Representation

- Next Multiple of Word Size (128 bits)
 - Unbelievable range of numbers
 - Unbelievable precision (accuracy)
- IEEE 754-2008 “binary128” standard
 - Has 15 exponent bits and 112 significand bits (113 precision bits)
- Oct-Precision?
 - Some have tried, no real traction so far
- Half-Precision?
 - Yep, “binary16”: 1/5/10

en.wikipedia.org/wiki/Floating_point

IEEE 754 Floating Point Standard (1/3)

Single Precision (DP similar):



- **Sign bit:** 1 means negative
0 means positive
- **Significand:**
 - To pack more bits, leading 1 implicit for normalized numbers
 - 1 + 23 bits single, 1 + 52 bits double
 - always true: $0 < \text{Significand} < 1$ (for normalized numbers)
- Note: 0 has no leading 1, so reserve exponent value 0 just for number 0

IEEE 754 Floating Point Standard (2/3)

- IEEE 754 uses “biased exponent” representation.
 - Designers wanted FP numbers to be used even if no FP hardware; e.g., sort records with FP numbers using integer compares
 - Wanted bigger (integer) exponent field to represent bigger numbers.
 - 2's complement poses a problem (because negative numbers look bigger)
 - We're going to see that the numbers are ordered EXACTLY as in sign-magnitude
 - I.e., counting from binary odometer 00...00 up to 11...11 goes from 0 to +MAX to -0 to -MAX to 0

IEEE 754 Floating Point Standard (3/3)

- Called **Biased Notation**, where bias is number subtracted to get real number
 - IEEE 754 uses bias of 127 for single prec.
 - Subtract 127 from Exponent field to get actual value for exponent
 - 1023 is bias for double precision

- Summary (single precision):

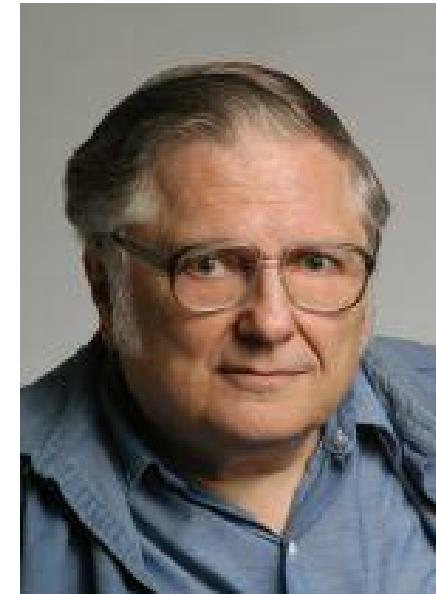
31	30	23	22	0
S	Exponent		Significand	
1 bit	8 bits		23 bits	

$$\bullet (-1)^S \times (1 + \text{Significand}) \times 2^{(\text{Exponent}-127)}$$

- Double precision identical, except with exponent bias of 1023 (half, quad similar)

“Father” of the Floating point standard

IEEE Standard 754
for Binary Floating-
Point Arithmetic.



Prof. Kahan

www.cs.berkeley.edu/~wkahan/ieee754status/754story.html

Example: Converting Binary FP to Decimal

0	0110 1000	101 0101 0100 0011 0100 0010
---	-----------	------------------------------

- Sign: 0 → positive

- Exponent:

- $0110\ 1000_{\text{two}} = 104_{\text{ten}}$

- Bias adjustment: $104 - 127 = -23$

- Significand:

$$\begin{aligned} & 1 + 1x2^{-1} + 0x2^{-2} + 1x2^{-3} + 0x2^{-4} + 1x2^{-5} + \dots \\ & = 1 + 2^{-1} + 2^{-3} + 2^{-5} + 2^{-7} + 2^{-9} + 2^{-14} + 2^{-15} + 2^{-17} + 2^{-22} \\ & = 1.0 + 0.666115 \end{aligned}$$

- Represents: $1.666115_{\text{ten}} * 2^{-23} \sim 1.986 * 10^{-7}$
(about 2/10,000,000)

Example: Converting Decimal to FP

-2.340625 x 10¹

1. Denormalize: -23.40625

2. Convert integer part:

$$23 = 16 + (7 = 4 + (3 = 2 + (1))) = 10111_2$$

3. Convert fractional part:

$$.40625 = .25 + (.15625 = .125 + (.03125)) = .01101_2$$

4. Put parts together and normalize:

$$10111.01101 = 1.011101101 \times 2^4$$

5. Convert exponent: $127 + 4 = 10000011_2$

1	1000 0011	011 1011 0100 0000 0000 0000
---	-----------	------------------------------

Peer Instruction

1 1000 0001 | 111 0000 0000 0000 0000 0000

What is the decimal equivalent of the floating pt # above?

- a) -7 * 2^{129}
- b) -3.5
- c) -3.75
- d) -7
- e) -7.5

Peer Instruction Answer

What is the decimal equivalent of:

1	1000 0001	111 0000 0000 0000 0000 0000
S	Exponent	Significand

$(-1)^S \times (1 + \text{Significand}) \times 2^{(\text{Exponent}-127)}$

$$(-1)^1 \times (1 + .111) \times 2^{(129-127)}$$

$$-1 \times (1.111) \times 2^{(2)}$$

-111.1

-7.5

- a) -7 * 2^{129}
 - b) -3.5
 - c) -3.75
 - d) -7
 - e) -7.5

“And in conclusion...”

- Floating Point lets us:
 - Represent numbers containing both integer and fractional parts; makes efficient use of available bits.
 - Store approximate values for very large and very small #s.
- IEEE 754 Floating Point Standard is most widely accepted attempt to standardize interpretation of such numbers (Every desktop or server computer sold since ~1997 follows these conventions)

- Summary (single precision):

31	30	23	22	0
S	Exponent	Significand		
1 bit	8 bits	23 bits		
$\bullet (-1)^S \times (1 + \text{Significand}) \times 2^{(\text{Exponent}-127)}$				

- Double precision identical, except with exponent bias of 1023 (half, quad similar)

Understanding the Significand (1/2)

- Method 1 (Fractions):

- In decimal: 0.340_{10} $\Rightarrow 340_{10}/1000_{10}$
 $\Rightarrow 34_{10}/100_{10}$

- In binary: $0.110_2 \Rightarrow 110_2/1000_2 = 6_{10}/8_{10}$
 $\Rightarrow 11_2/100_2 = 3_{10}/4_{10}$

- Advantage: less purely numerical, more thought oriented; this method usually helps people understand the meaning of the significand better

Understanding the Significand (2/2)

- Method 2 (Place Values):
 - Convert from scientific notation
 - In decimal: $1.6732 = (1 \times 10^0) + (6 \times 10^{-1}) + (7 \times 10^{-2}) + (3 \times 10^{-3}) + (2 \times 10^{-4})$
 - In binary: $1.1001 = (1 \times 2^0) + (1 \times 2^{-1}) + (0 \times 2^{-2}) + (0 \times 2^{-3}) + (1 \times 2^{-4})$
 - Interpretation of value in each position extends beyond the decimal/binary point
 - Advantage: good for quickly calculating significand value; use this method for translating FP numbers

Computer Architecture (计算机体系结构)

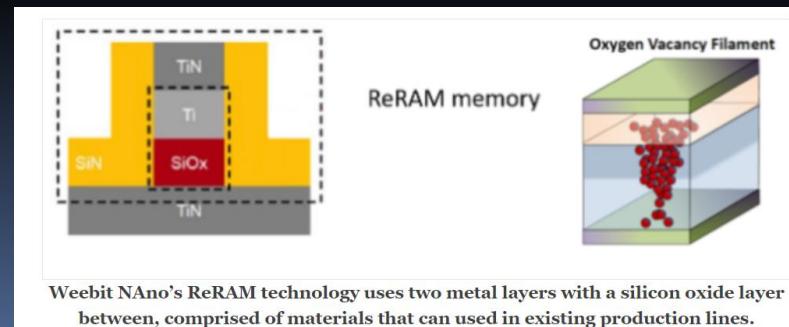
Lecture 11 Floating Point II

2020-09-25



Lecturer Yuanqing Cheng
www.cadetlab.cn/teaching

Emerging Memories May Never Go
Beyond Niche Applications



Review

Exponent tells Significand how much (2^i) to count by (... , $1/4$, $1/2$, 1 , 2 , ...)

- Floating Point lets us:
 - Represent numbers containing both integer and fractional parts; makes efficient use of available bits.
 - Store approximate values for very large and very small #s.
- IEEE 754 Floating Point Standard is most widely accepted attempt to standardize interpretation of such numbers (Every desktop or server computer sold since ~1997 follows these conventions)

Summary (single precision):



$$(-1)^S \times (1 + \text{Significand}) \times 2^{(\text{Exponent}-127)}$$

Double precision identical, except with exponent bias of 1023 (half, quad similar)

“Father” of the Floating point standard

IEEE Standard
754 for Binary
Floating-Point
Arithmetic.



1989 ACM Turing
Award Winner!

Prof. Kahan

[www.cs.berkeley.edu/~wkahan/
.../ieee754status/754story.html](http://www.cs.berkeley.edu/~wkahan/.../ieee754status/754story.html)

Precision and Accuracy

Don't confuse these two terms!

Precision is a count of the number bits in a computer word used to represent a value.

Accuracy is a measure of the difference between the actual value of a number and its computer representation.

High precision permits high accuracy but doesn't guarantee it. It is possible to have high precision but low accuracy.

Example: `float pi = 3.14;`

pi will be represented using all 24 bits of the significant (highly precise), but is only an approximation (not accurate).

Representation for $\pm \infty$

- In FP, divide by 0 should produce $\pm \infty$, not overflow.
- Why?
 - OK to do further computations with ∞ E.g., $X/0 > Y$ may be a valid comparison
 - Ask math majors
- IEEE 754 represents $\pm \infty$
 - Most positive exponent reserved for ∞
 - Significands all zeroes

Representation for 0

- Represent 0?
 - **exponent all zeroes**
 - **significand all zeroes**
 - **What about sign? Both cases valid.**
- +0: 0 00000000 00000000000000000000000000000000
- 0: 1 00000000 00000000000000000000000000000000

Special Numbers

- What have we defined so far? (Single Precision)

Exponent	Significand	Object
0	0	0
0	<u>nonzero</u>	???
1-254	anything	+/- fl. pt. #
255	0	+/- ∞
255	<u>nonzero</u>	???

- Professor Kahan had clever ideas;
“Waste not, want not”
 - We'll talk about $\text{Exp}=0, 255$ & $\text{Sig}!=0$ later

Representation for Not a Number

- What do I get if I calculate
 $\sqrt{-4.0}$ or $0/0$?
 - If ∞ not an error, these shouldn't be either
 - Called Not a Number (NaN)
 - Exponent = 255, Significand nonzero
- Why is this useful?
 - Hope NaNs help with debugging?
 - They contaminate: $op(\text{NaN}, X) = \text{NaN}$

Representation for Denorms (1 / 2)

- Problem: There's a gap among representable FP numbers around 0

- Smallest representable pos num:

$$a = 1.0\ldots_2 \cdot 2^{-126} = 2^{-126}$$

- Second smallest representable pos num:

$$b = 1.000\ldots1_2 \cdot 2^{-126}$$

$$= (1 + 0.00\ldots1_2) \cdot 2^{-126}$$

$$= (1 + 2^{-23}) \cdot 2^{-126}$$

$$= 2^{-126} + 2^{-149}$$

$$a - 0 = 2^{-126}$$

$$b - a = 2^{-149}$$



Normalization and
implicit 1
is to blame!

Representation for Denorm (2/2)

- Solution:
 - We still haven't used Exponent=0, Significand nonzero
 - Denormalized number: no (implied) leading 1, implicit exponent = -126
 - Smallest representable pos num:
 - $A = 2^{-149}$
 - Second smallest representable pos num:
 - $b = 2^{-148}$



Special Numbers Summary

- Reserve exponents, significands:

Exponent	Significand	Object
0	0	0
0	<u>nonzero</u>	<u>Denorm</u>
1-254	Anything	+/- fl. Pt #
255	<u>0</u>	<u>+/- ∞</u>
255	<u>nonzero</u>	<u>NaN</u>

Rounding

- When we perform math on real numbers, we have to worry about rounding to fit the result in the significant field.
- The FP hardware carries two extra bits of precision, and then round to get the proper value
- Rounding also occurs when converting:
double to a single precision value, or floating point number to an integer

IEEE FP Rounding Modes

- Halfway between two floating point values (rounding bits read 10)? Choose from the following:
 - Round towards $+\infty$
 - Round “up”: $1.01\ \underline{10} \rightarrow 1.10$, $-1.01\ \underline{10} \rightarrow -1.01$
 - Round towards $-\infty$
 - Round “down”: $1.01\ \underline{10} \rightarrow 1.01$, $-1.01\ \underline{10} \rightarrow -1.10$
 - Truncate
 - Just drop the extra bits (round towards 0)
- Unbiased (default mode). Round to nearest EVEN number
 - Half the time we round up on tie, the other half time we round down. Tends to balance out inaccuracies.
 - In binary, even means least significant bit is 0.
- Otherwise, not halfway (00, 01, 11)! Just round to the nearest float.

Peer Instruction

1. Converting float -> int -> float produces same float number
2. Converting int -> float -> int produces same int number
3. FP add is associative:
 $(x+y)+z = x+(y+z)$

ABC

1 : FFF

2 : FFT

3 : FTF

4 : FTT

5 : TFF

Peer Instruction Answer

1. Converting float > int > float produces same float number

FALSE

2. Converting int -> float > int produces same int number

FALSE

3. FP addition associative.

$(x+y) + z = x + (y+z)$

FALSE

1. $3.14 \rightarrow 3 \rightarrow 3$

2. 32 bits for signed int,
but 24 for FP mantissa?

3. $x = \text{biggest pos \#},$
 $y = -x, z = 1 (x \neq \text{inf})$

ABC

1: **FFF**

2: **FFT**

3: **FTF**

4: **FTT**

5: **TFF**

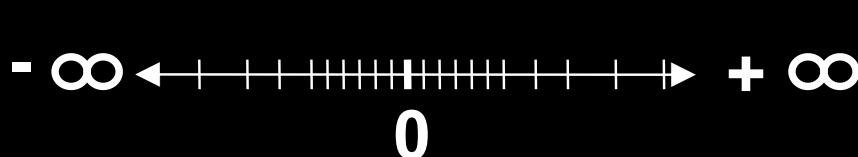
Peer Instruction

- Let $f(1, 2) = \# \text{ of floats between } 1 \text{ and } 2$
- Let $f(2, 3) = \# \text{ of floats between } 2 \text{ and } 3$

1: $f(1, 2) < f(2, 3)$
2: $f(1, 2) = f(2, 3)$
3: $f(1, 2) > f(2, 3)$

Peer Instruction Answer

- Let $f(1, 2) = \# \text{ of floats between } 1 \text{ and } 2$
- Let $f(2, 3) = \# \text{ of floats between } 2 \text{ and } 3$



1: $f(1, 2) < f(2, 3)$
2: $f(1, 2) = f(2, 3)$
3: $f(1, 2) > f(2, 3)$

“And in conclusion...”

- Reserve exponents, significands:

Exponent	Significand	Object
0	0	0
0	<u>nonzero</u>	<u>Denorm</u>
1-254	Anything	+/- fl. Pt #
255	0	+/- ∞
255	<u>nonzero</u>	<u>NaN</u>

- 4 Rounding modes (default: unbiased)
- MIPS Fl ops complicated, expensive

Bonus slides

- These are extra slides that used to be included in lecture notes, but have been moved to this, the “bonus” area to serve as a supplement.
- The slides will appear in the order they would have in the normal presentation

Bonus

FP Addition

- More difficult than with integers
- Can't just add significands
- How do we do it?
 - De-normalize to match exponents
 - Add significands to get resulting one
 - Keep the same exponent
 - Normalize (possibly changing exponent)
- Note: If signs differ, just perform a subtract instead.

MIPS Floating Point Architecture

(1/4)

- MIPS has special instructions for floating point operations:
 - **Single Precision:**
add.s, sub.s, mul.s, div.s
 - **Double Precision:**
add.d, sub.d, mul.d, div.d
- These instructions are far more complicated than their integer counterparts. They require special hardware and usually they can take much longer to compute.

MIPS Floating Point Architecture

(2 / 4)

• Problems:

- It's inefficient to have different instructions take vastly differing amounts of time.
- Generally, a particular piece of data will not change from FP to int, or vice versa, within a program. So only one type of instruction will be used on it.
- Some programs do no floating point calculations
- It takes lots of hardware relative to integers to do Floating Point fast

MIPS Floating Point Architecture

(3/4)

- 1990 Solution: Make a completely separate chip that handles only FP.
 - **Coprocessor 1: FP chip**
 - **contains 32 32-bit registers:** \$f0, \$f1, ...
 - **most registers specified in .s and .d instruction refer to this set**
 - **separate load and store:** lwcl and swcl (“load word coprocessor 1”, “store ...”)
 - **Double Precision: by convention, even/odd pair contain one DP FP number:** \$f0/\$f1, \$f2/\$f3, ... , \$f30/\$f31

MIPS Floating Point Architecture

(4/4) Computer actually contains multiple separate chips:

- Processor: handles all the normal stuff
- Coprocessor 1: handles FP and only FP;
- more coprocessors?... Yes, later
- Today, cheap chips may leave out FP HW
- Instructions to move data between main processor and coprocessors:
 - mfc0, mtc0, mfc1, mtc1, etc.
- Appendix pages A-70 to A-74 contain many, many more FP operations.

Example: Representing 1/3 in

MIPS
1/3

$$= 0.33333\dots_{10}$$

$$= 0.25 + 0.0625 + 0.015625 + 0.00390625 + \dots$$

$$= 1/4 + 1/16 + 1/64 + 1/256 + \dots$$

$$= 2^{-2} + 2^{-4} + 2^{-6} + 2^{-8} + \dots$$

$$= 0.0101010101\dots_2 * 2^0$$

$$= 1.0101010101\dots_2 * 2^{-2}$$

- **Sign:** 0
- **Exponent = -2 + 127 = 125 = 01111101**
- **Significand = 0101010101...**

0	0111 1101	0101 0101 0101 0101 0101 010
---	-----------	------------------------------

Casting floats to ints and vice

versa

(int) *floating_point_expression*

Coerces and converts it to the nearest integer (C uses truncation)

```
i = (int) (3.14159 * f);
```

(float) *integer_expression*

converts integer to nearest floating point

```
f = f + (float) i;
```

int → float → int

```
if (i == (int)((float) i)) {  
    printf("true");  
}
```

- Will not always print “true”
- Most large values of integers don’t have exact floating point representations!
- What about double?

float → int → float

```
if (f == (float)((int) f)) {  
    printf("true");  
}
```

- Will not always print “true”
- Small floating point numbers (<1) don’t have integer representations
- For other numbers, rounding errors

Floating Point Fallacy

- FP add associative: FALSE!
 - $x = -1.5 \times 10^{38}$, $y = 1.5 \times 10^{38}$, and $z = 1.0$
 - $x + (y + z) = -1.5 \times 10^{38} + (1.5 \times 10^{38} + 1.0)$
 $= -1.5 \times 10^{38} + (1.5 \times 10^{38}) = \underline{0.0}$
 - $(x + y) + z = (-1.5 \times 10^{38} + 1.5 \times 10^{38}) + 1.0$
 $= (0.0) + 1.0 = \underline{1.0}$
- Therefore, Floating Point add is not associative!
 - Why? FP result approximates real result!
 - This example: 1.5×10^{38} is so much larger than 1.0 that $1.5 \times 10^{38} + 1.0$ in floating point representation is still 1.5×10^{38}

0.11 Instruction Represation

Computer Architecture (计算机体系结构)

Lecture 12 Instruction Representation III



2020-09-25

Lecturer Yuanqing Cheng

www.cadetlab.cn/~courses

Review

- **MIPS Machine Language Instruction:**
32 bits representing a single instruction

R	opcode	rs	rt	rd	shamt	funct
I	opcode	rs	rt		immediate	
J	opcode		target	address		

- Branches use PC-relative addressing,
Jumps use absolute addressing.

Outline

- Disassembly
- Pseudoinstructions
- “True” Assembly Language (TAL) vs.
“MIPS” Assembly Language (MAL)

Decoding Machine Language

- How do we convert 1s and 0s to assembly language and to C code?
Machine language \Rightarrow assembly \Rightarrow C?
- For each 32 bits:
 1. Look at opcode to distinguish between R-Format, J-Format, and I-Format.
 2. Use instruction format to determine which fields exist.
 3. Write out MIPS assembly code, converting each field to name, register number/name, or decimal/hex number.
 4. Logically convert this MIPS code into valid C code. Always possible? Unique?

Decoding Example (1/7)

- Here are six machine language instructions in hexadecimal:

00001025_{hex}

0005402A_{hex}

11000003_{hex}

00441020_{hex}

20A5FFFF_{hex}

08100001_{hex}

- Let the first instruction be at address 4,194,304_{ten} (0x00400000_{hex}).
- Next step: convert hex to binary

Decoding Example (2/7)

- The six machine language instructions in binary:

```
0000000000000000000000001000000100101  
00000000000000001010100000000101010  
000100010000000000000000000000000011  
000000000010001000001000000100000  
00100000101001011111111111111111  
0000100000010000000000000000000001
```

- Next step: identify opcode and format

R	0	rs	rt	rd	shamt	funct
I	1, 4-62	rs	rt		immediate	
J	2 or 3		target	address		

Decoding Example (3/7)

- Select the opcode (first 6 bits) to determine the format:

Format:

R	000000	000000	000000	00010	00000	100101
R	000000	000000	000101	01000	00000	101010
I	000100	01000	000000	000000000000000011		
R	000000	000100	0100000010	000000	100000	
I	001000	00101	00101111111111111111			
J	000010	000001000000000000000001				

- Look at opcode:
0 means R-Format,
2 or 3 mean J-Format,
otherwise I-Format.
- Next step: separation of fields

Decoding Example (4/7)

- Fields separated based on format/opcode:

Format:

R	0	0	0	2	0	37
R	0	0	5	8	0	42
I	4	8	0		+3	
R	0	2	4	2	0	32
I	8	5	5		-1	
J	2			1,048,577		

- Next step: translate (“disassemble”) to MIPS assembly instructions

Decoding Example (5/7)

- MIPS Assembly (Part 1):

Address:	Assembly instructions:
----------	------------------------

0x00400000	or	\$2, \$0, \$0
0x00400004	slt	\$8, \$0, \$5
0x00400008	beq	\$8, \$0, 3
0x0040000c	add	\$2, \$2, \$4
0x00400010	addi	\$5, \$5, -1
0x00400014	j	0x100001

- Better solution: translate to more meaningful MIPS instructions (fix the branch/jump and add labels, registers)

Decoding Example (6/7)

- MIPS Assembly (Part 2):

	or	\$v0, \$0, \$0
Loop:	slt	\$t0, \$0, \$a1
	beq	\$t0, \$0, Exit
	add	\$v0, \$v0, \$a0
	addi	\$a1, \$a1, -1
	j	Loop

Exit:

- Next step: translate to C code
(must be creative!)

Decoding Example (7/7)

Before Hex: • After C code (Mapping below)

00001025_{hex}
0005402A_{hex}
11000003_{hex}
00441020_{hex}
20A5FFFF_{hex}
08100001_{hex}

\$v0: product
\$a0: multiplicand
\$a1: multiplier

```
product = 0;  
while (multiplier > 0) {  
    product += multiplicand;  
    multiplier -= 1;  
}
```

or \$v0,\$0,\$0
Loop: slt \$t0,\$0,\$a1
 beq \$t0,\$0,Exit
 add \$v0,\$v0,\$a0
 addi \$a1,\$a1,-1
 j Loop

Exit:

Demonstrated Big Idea: Instructions are just numbers, code is treated like data

Review from before: lui

- So how does lui help us?

- Example:

addi \$t0,\$t0, 0xABABCD

becomes:

lui	\$at, 0xABAB
ori	\$at, \$at, 0xCD
add	\$t0,\$t0,\$at

- Now each I-format instruction has only a 16-bit immediate.
 - Wouldn't it be nice if the assembler would do this for us automatically?
 - If number too big, then just automatically replace addi with lui, ori, add

True Assembly Language (1/3)

- **Pseudoinstruction:** A MIPS instruction that doesn't turn directly into a machine language instruction, but into other MIPS instructions
- What happens with pseudo-instructions?
 - They're broken up by the assembler into several “real” MIPS instructions.
 - Some examples follow

Example Pseudoinstructions

- **Register Move**

move reg2,reg1

Expands to:

add reg2,\$zero,reg1

- **Load Immediate**

li reg,value

If value fits in 16 bits:

addi reg,\$zero,value

else:

lui reg,upper 16 bits of value

ori reg,reg,lower 16 bits

Example Pseudoinstructions

- **Load Address:** How do we get the address of an instruction or global variable into a register?

`la reg, label`

Again if value fits in 16 bits:

`addi reg, $zero, label_value`

else:

`lui reg, upper 16 bits of value`

`ori reg, reg, lower 16 bits`

True Assembly Language (2/3)

- **Problem:**
 - When breaking up a pseudo-instruction, the assembler may need to use an extra register
 - If it uses any regular register, it'll overwrite whatever the program has put into it.
- **Solution:**
 - Reserve a register (\$1, called \$at for “assembler temporary”) that assembler will use to break up pseudo-instructions.
 - Since the assembler may use this at any time, it's not safe to code with it.

Example Pseudoinstructions

- Rotate Right Instruction

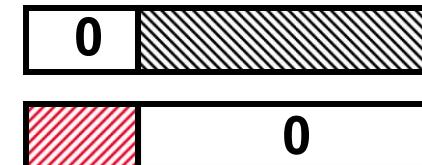
ror reg, value

Expands to:

srl \$at, reg, value



sll reg, reg, 32-value



or reg, reg, \$at



- “No OPeration” instruction

nop

Expands to instruction = 0_{ten},

sll \$0, \$0, 0

Example Pseudoinstructions

- Wrong operation for operand

`addu reg,reg,value # should be addiu`

If value fits in 16 bits, addu is changed to:

`addiu reg,reg,value`

`else:`

`lui $at,upper 16 bits of value`

`ori $at,$at,lower 16 bits`

`addu reg,reg,$at`

- How do we avoid confusion about whether we are talking about MIPS assembler with or without pseudoinstructions?

True Assembly Language (3/3)

- **MAL** (MIPS Assembly Language): the set of instructions that a programmer may use to code in MIPS; this includes pseudoinstructions
- **TAL** (True Assembly Language): set of instructions that can actually get translated into a single machine language instruction (32-bit binary string)
- A program must be converted from MAL into TAL before translation into 1s & 0s.

Questions on Pseudoinstructions

- **Question:**
 - How does MIPS assembler / SPIM recognize pseudo-instructions?
- **Answer:**
 - It looks for officially defined pseudo-instructions, such as `nor` and `move`
 - It looks for special cases where the operand is incorrect for the operation and tries to handle it gracefully

Rewrite TAL as MAL

- TAL:

	or	\$v0,\$0,\$0
Loop:	slt	\$t0,\$0,\$a1
	beq	\$t0,\$0,Exit
	add	\$v0,\$v0,\$a0
	addi	\$a1,\$a1,-1
	j	Loop

Exit:

- This time convert to MAL
- It's OK for this exercise to make up MAL instructions

Rewrite TAL as MAL (Answer)

- **TAL:**

Loop:

or	\$v0,\$0,\$0
slt	\$t0,\$0,\$a1
beq	\$t0,\$0,Exit
add	\$v0,\$v0,\$a0
addi	\$a1,\$a1,-1
j	Loop

Exit:

- **MAL:**

Loop:

li	\$v0,0
ble	\$a1,\$zero,Exit
add	\$v0,\$v0,\$a0
sub	\$a1,\$a1,1
j	Loop

Exit:

Peer Instruction

- Which of the instructions below are **MAL** and which are **TAL**?

1. addi \$t0, \$t1, 40000
2. beq \$s0, 10, Exit

	12
a)	MM
b)	MT
c)	TM
d)	TT

Peer Instruction Answer

- Which of the instructions below are **MAL** and which are **TAL**?

1. addi \$t0, \$t1, **40000** $40,000 > +32,767 \Rightarrow \text{lui,ori}$
2. beq \$s0, **10, Exit** Beq: both must be registers
Exit: if $> 2^{15}$, then MAL

12
a) MM
b) MT
c) TM
d) TT

In Conclusion

- Disassembly is simple and starts by decoding opcode field.
 - Be creative, efficient when authoring C
- Assembler expands real instruction set (TAL) with pseudoinstructions (MAL)
 - Only TAL can be converted to raw binary
 - Assembler's job to do conversion
 - Assembler uses reserved register \$at
 - MAL makes it much easier to write MIPS

0.12 Running a Program

Computer Architecture (计算机体系结构)

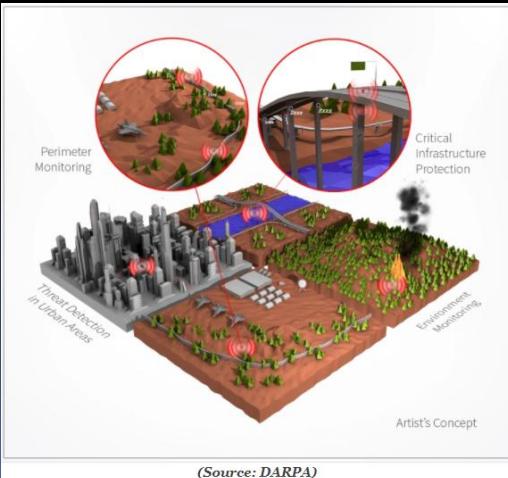


Lecturer
Yuanqing

Lecture 13 – Running a Program I (Compiling, Assembling, Linking, Loading)

2020.09.28

DARPA: Research Advances for Near-Zero-Power Sensors



Review

- Disassembly is simple and starts by decoding opcode field.
 - Be creative, efficient when authoring C
- Assembler expands real instruction set (TAL) with pseudoinstructions (MAL)
 - Only TAL can be converted to raw binary
 - Assembler's job to do conversion
 - Assembler uses reserved register \$at
 - MAL makes it much easier to write MIPS

Overview

- Interpretation vs Translation
- Translating C Programs
 - Compiler
 - Assembler
 - Linker (next time)
 - Loader (next time)
- An Example (next time)

Language Execution Continuum

- An Interpreter is a program that executes other programs.



- Language **translation** gives us another option.
- In general, we **interpret** a high level language when efficiency is not critical and **translate** to a lower level language

Interpretation vs Translation

- How do we run a program written in a source language?
 - **Interpreter**: Directly executes a program in the source language
 - **Translator**: Converts a program from the source language to an equivalent program in another language
- For example, consider a Scheme program `foo.scm`

Interpretation

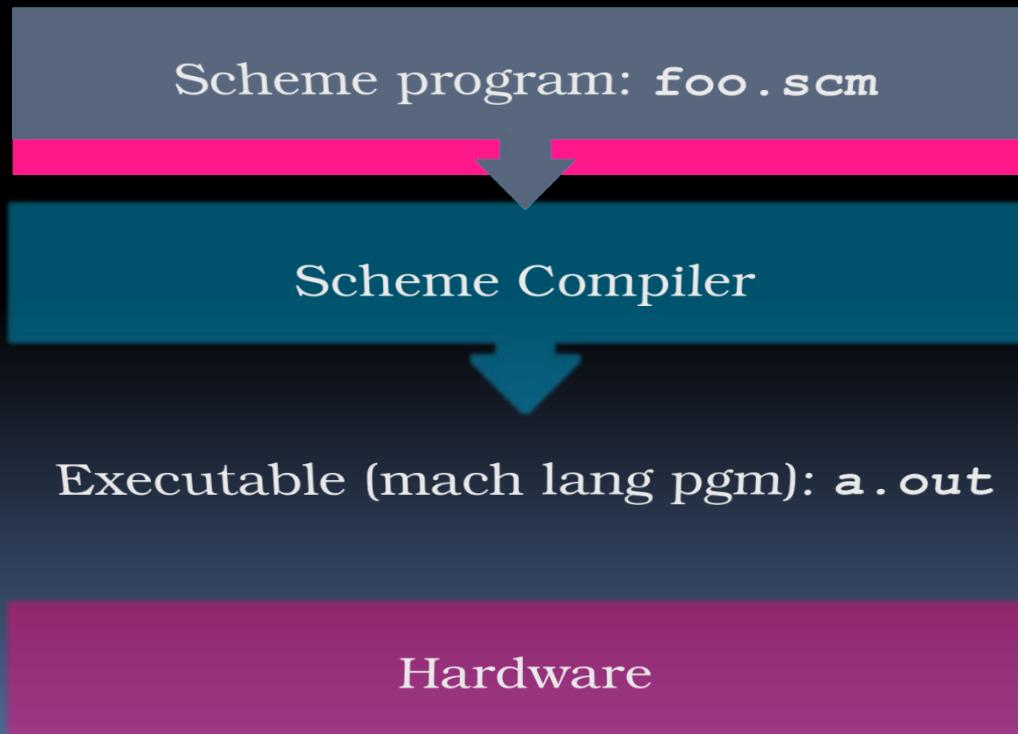
Scheme program: `foo.scm`

Scheme interpreter

- Scheme Interpreter is just a program that reads a scheme program and performs the functions of that scheme program.

Translation

- Scheme Compiler is a translator from Scheme to machine language.
- The processor is a hardware interpreter of machine language.



Interpretation

- Any good reason to interpret machine language in software?
- SPIM – useful for learning / debugging
- Apple Macintosh conversion
 - Switched from Motorola 680x0 instruction architecture to PowerPC.
 - Similar issue with switch to x86.
 - Could require all programs to be re-translated from high level language
 - Instead, let executables contain old and/or new machine code, interpret old code in software if necessary (emulation)

Interpretation vs. Translation?

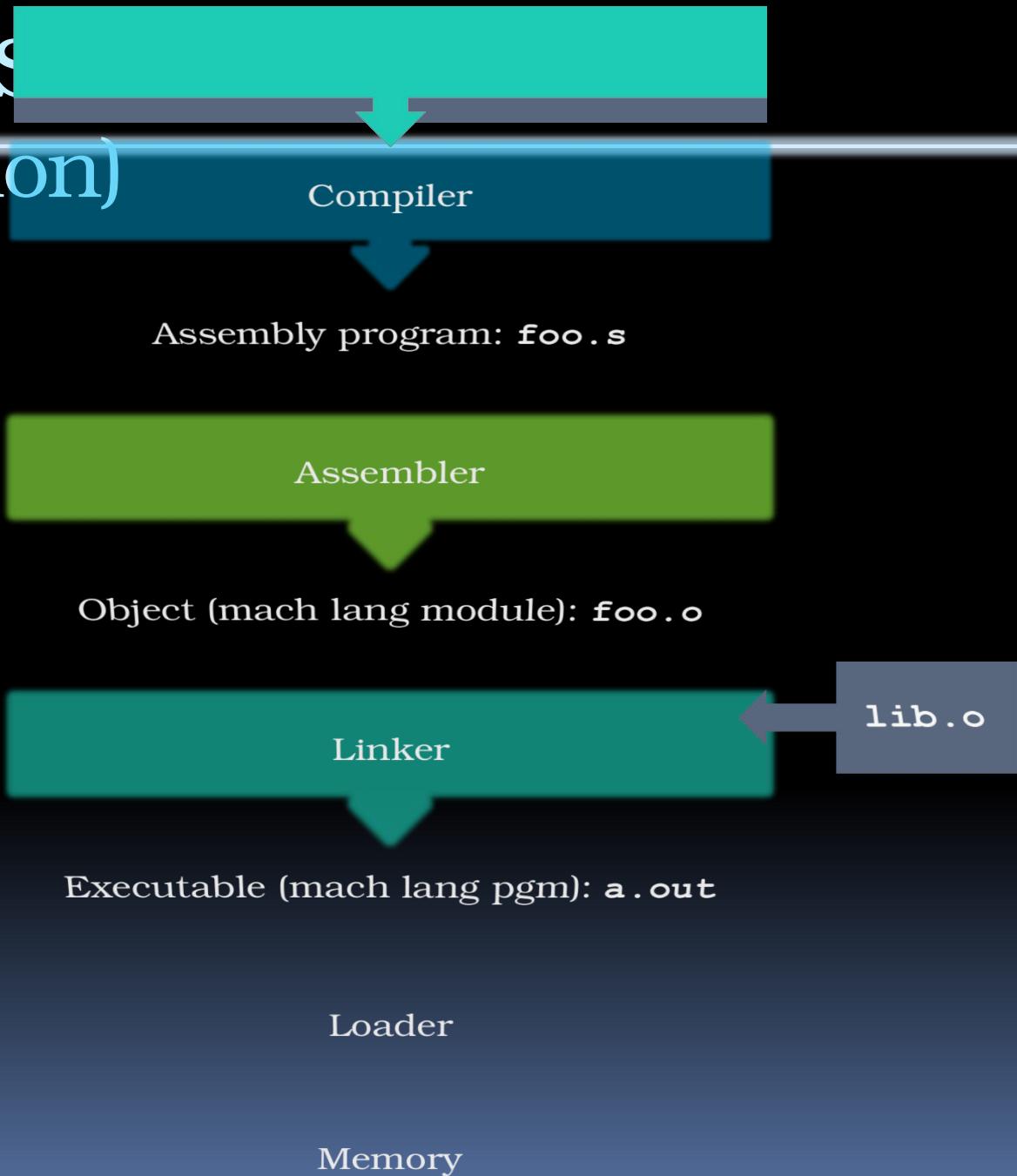
- Generally easier to write interpreter
 - Interpreter closer to high-level, so can give better error messages (e.g., MARS, stk)
 - Translator reaction: add extra information to help debugging (line numbers, names)
 - Interpreter slower (10x?), code smaller (2x?)
 - Interpreter provides instruction set independence: run on any machine

Interpretation vs. Translation?

Translated/compiled code almost always more efficient and therefore higher performance:

- Important for many applications, particularly operating systems.
- Translation/compilation helps “hide” the program “source” from the users:
 - One model for creating value in the marketplace (eg. Microsoft keeps all their source code secret)
 - Alternative model, “open source”, creates value by publishing the source code and fostering a community of developers.

Steps to S (translation)



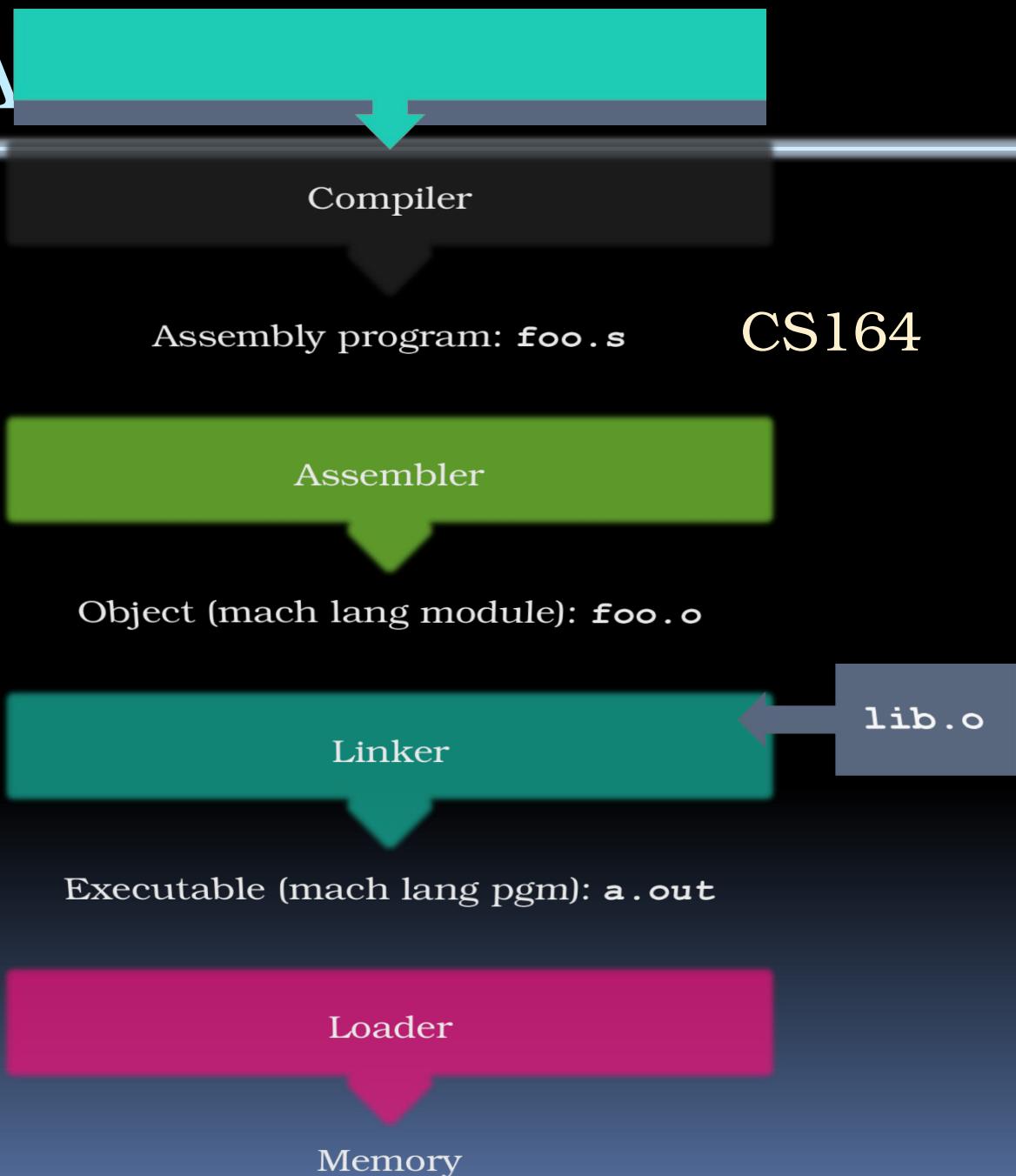
Compiler

- Input: High-Level Language Code (e.g., C, Java such as `foo.c`)
- Output: Assembly Language Code (e.g., `foo.s` for MIPS)
- Note: Output *may* contain pseudoinstructions
- Pseudoinstructions: instructions that assembler understands but not in machine (last lecture)
For example:
 - `mov $s1,$s2` ⇒ `or $s1,$s2,$zero`

Administrivia...

- Deadline of assignment: 10.9
- Deadline of lab 1 & lab 2: 10.9

Where Are We?



Assembler

- Input: Assembly Language Code
(e.g., `foo.s` for MIPS)
- Output: Object Code, information tables
(e.g., `foo.o` for MIPS)
- Reads and Uses Directives
- Replace Pseudoinstructions
- Produce Machine Language
- Creates Object File

Assembler Directives (p. A-51 to

A-53)

■ Give directions to assembler, but do not produce machine instructions

.text: Subsequent items put in user text segment (machine code)

.data: Subsequent items put in user data segment (binary rep of data in source file)

.globl sym: declares sym global and can be referenced from other files

.asciiz str: Store the string str in memory and null-terminate it

.word w1...wn: Store the n 32-bit quantities in successive memory words

Pseudoinstruction Replacement

subu \$sp,\$sp,32

sd \$a0, 32(\$sp)

mul \$t7,\$t6,\$t5

addu \$t0,\$t6,1

ble \$t0,100,loop

la \$a0, str

Real:

addiu \$sp,\$sp,-32

sw \$a0, 32(\$sp)

sw \$a1, 36(\$sp)

mul \$t6,\$t5

mflo \$t7

addiu \$t0,\$t6,1

slti \$at,\$t0,101

bne \$at,\$0,loop

lui \$at, left(str)

ori \$a0,\$at,right(str)

Producing Machine Language

■ 1 Simple Case

- Arithmetic, Logical, Shifts, and so on.
- All necessary info is within the instruction already.
- What about Branches?
 - PC-Relative
 - So once pseudo-instructions are replaced by real ones, we know by how many instructions to branch.
- So these can be handled.

Producing Machine Language

(2“/3)forward Reference” problem

- Branch instructions can refer to labels that are “forward” in the program:

```
        or    $v0, $0, $0
L1: slt   $t0, $0, $a1
     beq   $t0, $0, L2
     addi  $a1, $a1, -1
     j     L1
L2: add   $t1, $a0, $a1
```

- Solved by taking 2 passes over the program.
 - First pass remembers position of labels
 - Second pass uses label positions to generate code

Producing Machine Language

(3/3)

■ What about jumps (`j` and `jal`)?

- Jumps require **absolute address**.
- So, forward or not, still can't generate machine instruction without knowing the position of instructions in memory.
- What about references to data?
 - `la` gets broken up into `lui` and `ori`
 - These will require the full 32-bit address of the data.
- These can't be determined yet, so we create two tables...

Symbol Table

- List of “items” in this file that may be used by other files.
- What are they?
 - Labels: function calling
 - Data: anything in the **.data** section; variables which may be accessed across files

Relocation Table

- List of “items” this file needs the address later.
- What are they?
 - Any label jumped to: `j` or `jal`
 - internal
 - external (including lib files)
 - Any piece of data
 - such as the `la` instruction

Object File Format

- object file header: size and position of the other pieces of the object file
- text segment: the machine code
- data segment: binary representation of the data in the source file
- relocation information: identifies lines of code that need to be “handled”
- symbol table: list of this file’s labels and data that can be referenced
- debugging information
- A standard format is ELF (except MS)

http://www.skyfree.org/linux/references/ELF_Format.pdf

Peer Instruction

- 1) Assembler will **ignore** the instruction **Loop:nop** because it does nothing.
- 2) Java designers used a translater AND interpreter (rather than just a translater) **mainly** because of (at least 1 of): ease of writing, better error msgs, smaller object code.

	12
a)	FF
b)	FT
c)	TF
d)	TT

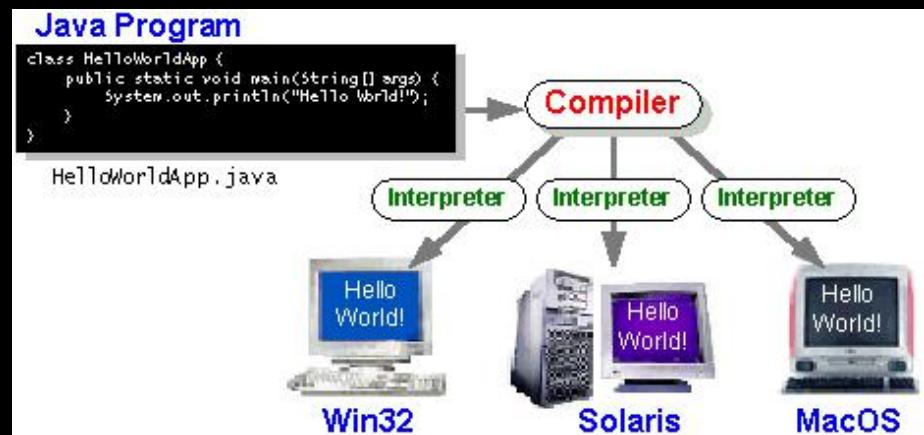
Peer Instruction Answer

1) Assembler keeps track of all labels in symbol table...F!

2) Java designers used both mainly because of code portability...F!

1) Assembler will **ignore** the instruction **Loop:nop** because it does nothing.

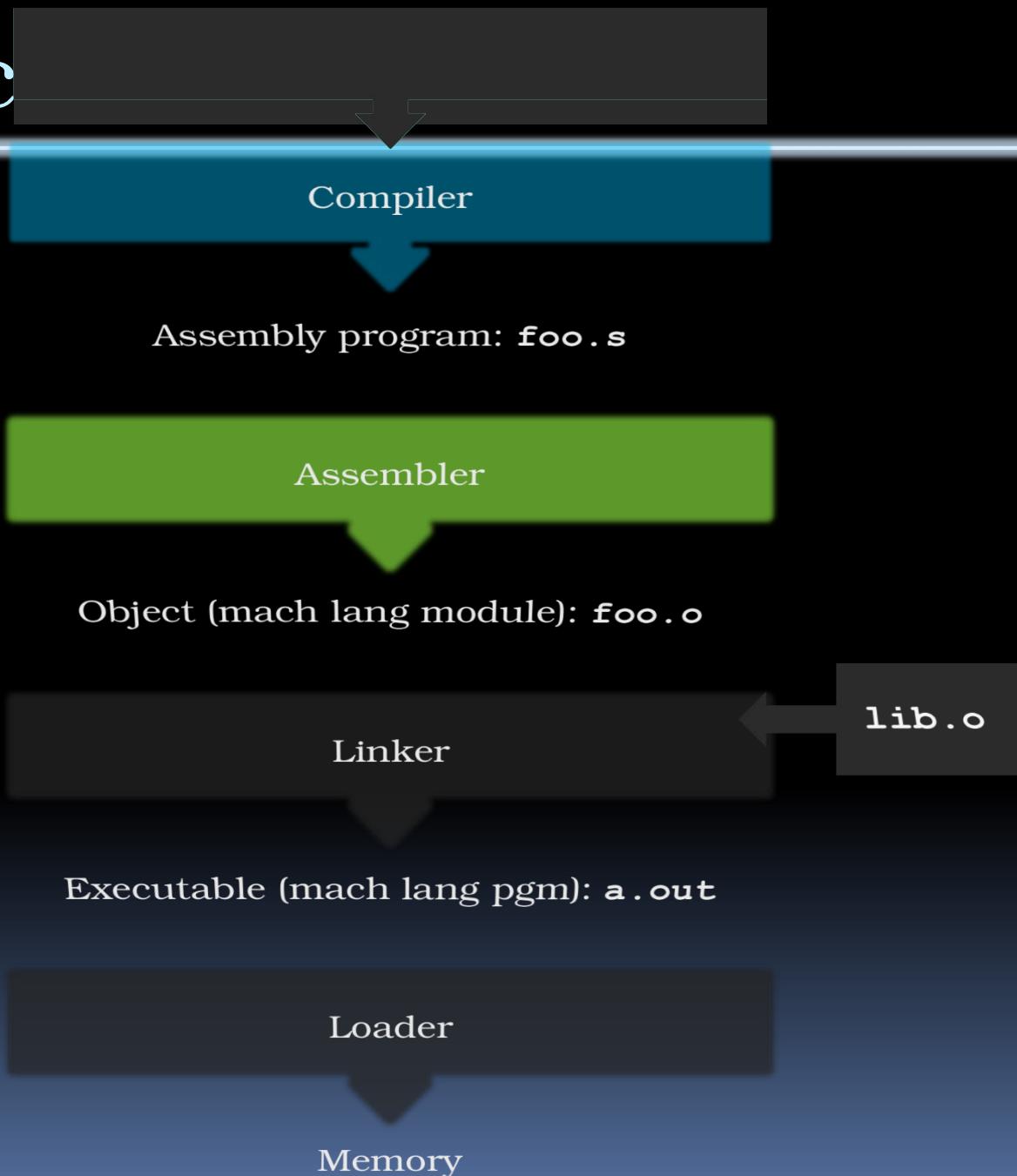
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12

- a) FF
- b) FT
- c) TF
- d) TT

And in c



Bonus slides

- These are extra slides that used to be included in lecture notes, but have been moved to this, the “bonus” area to serve as a supplement.
- The slides will appear in the order they would have in the normal presentation

Bonus

Integer Multiplication

- (1/3) Paper and pencil example (unsigned):

Multiplicand	1000	8
Multiplier	$\begin{array}{r} \times 1001 \\ \hline \end{array}$	9
	1000	
	0000	
	0000	
	$+1000$	
	\hline	
	01001000	

- $m \text{ bits} \times n \text{ bits} = m + n \text{ bit product}$

Integer Multiplication (2 / 3)

- In MIPS, we multiply registers, so:
 - 32-bit value \times 32-bit value = 64-bit value
- Syntax of Multiplication (signed):
 - `mult register1, register2`
 - Multiplies 32-bit values in those registers & puts 64-bit product in special result regs:
 - puts product **upper half in hi, lower half in lo**
 - **hi** and **lo** are 2 registers separate from the 32 general purpose registers
 - Use **mfhi** register & **mflo** register to move **from hi, lo** to another register

Integer Multiplication (3/3)

- Example:
 - in C: $a = b * c;$
 - in MIPS:
 - let b be $\$s2$; let c be $\$s3$; and let a be $\$s0$ and $\$s1$ (since it may be up to 64 bits)

```
mult $s2,$s3      # b*c
mfhi $s0          # upper half of
                  # product into $s0
mflo $s1          # lower half of
                  # product into $s1
```

- Note: Often, we only care about the lower half of the product.

Integer Division (1 / 2)

- Paper and pencil example (unsigned):

$$\begin{array}{r} & \underline{1001} & \text{Quotient} \\ \text{Divisor } 1000 | & 1001010 & \text{Dividend} \\ & \underline{-1000} \\ & 10 \\ & 101 \\ & 1010 \\ & \underline{-1000} \\ & 10 & \text{Remainder} \\ & & (\text{or Modulo result}) \end{array}$$

- $\text{Dividend} = \text{Quotient} \times \text{Divisor} + \text{Remainder}$

Integer Division (2/2)

- Syntax of Division (signed):
 - `div register1, register2`
 - Divides 32-bit register 1 by 32-bit register 2:
 - puts remainder of division in `hi`, quotient in `lo`
- Implements C division (`/`) and modulo (`%`)
- Example in C:
$$a = c / d; \quad b = c \% d;$$
- in MIPS:
$$a \leftrightarrow \$s0; b \leftrightarrow \$s1; c \leftrightarrow \$s2; d \leftrightarrow \$s3$$

```
div $s2,$s3      # lo=c/d, hi=c%d  
mflo $s0          # get quotient
```



Computer Architecture

(计算机体系结构)

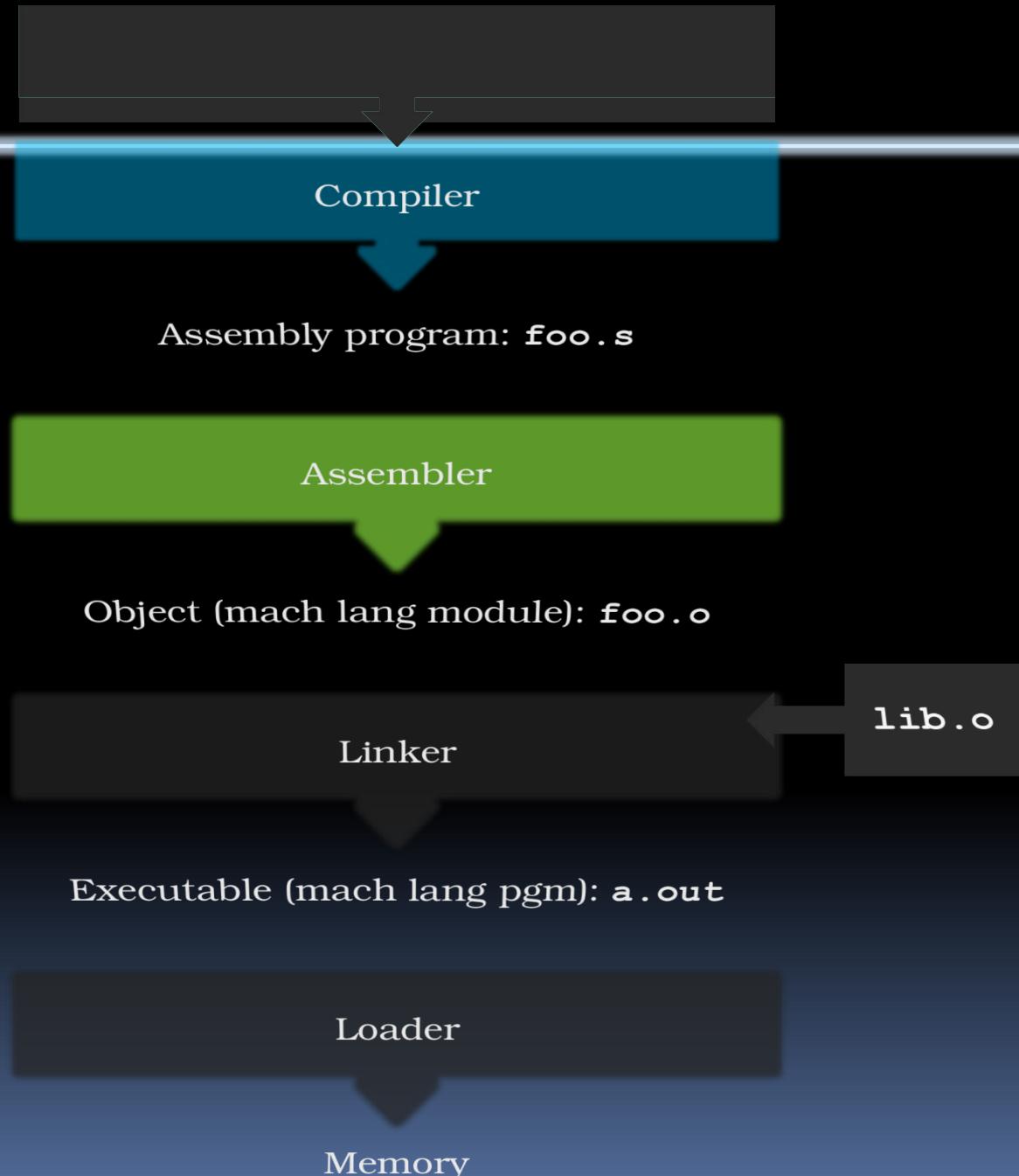
Lecture 14 – Running a Program II

**(Compiling, Assembling, Linking,
Loading)**

**Lecturer
Yuanqing
Cheng**

2020-09-27

Review



Symbol Table

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- What are they?
 - Labels: function calling
 - Data: anything in the .data section; variables which may be accessed across files

Relocation Table

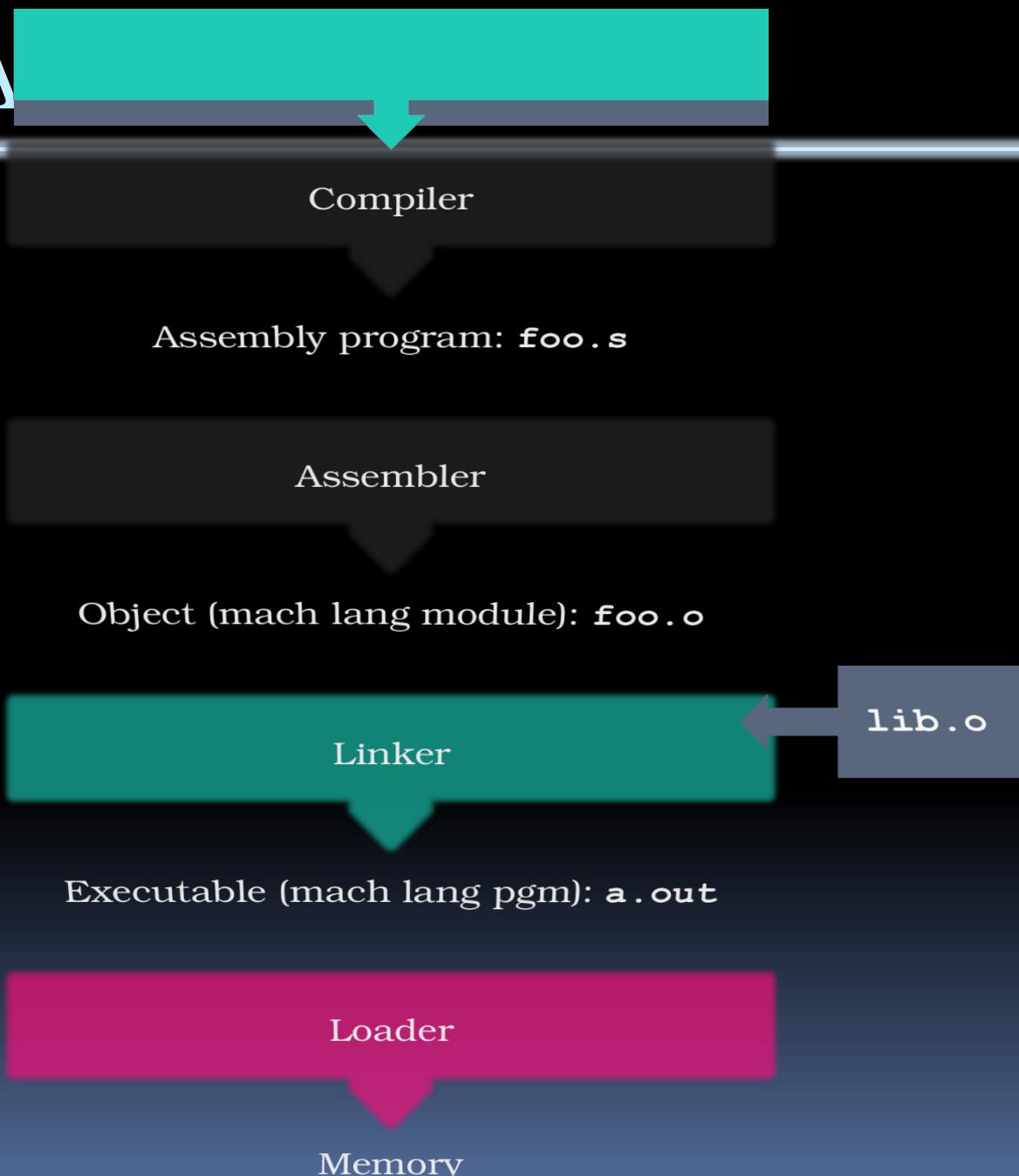
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http://www.skyfree.org/linux/references/ELF_Format.pdf

Where A



Linker (1 / 3)

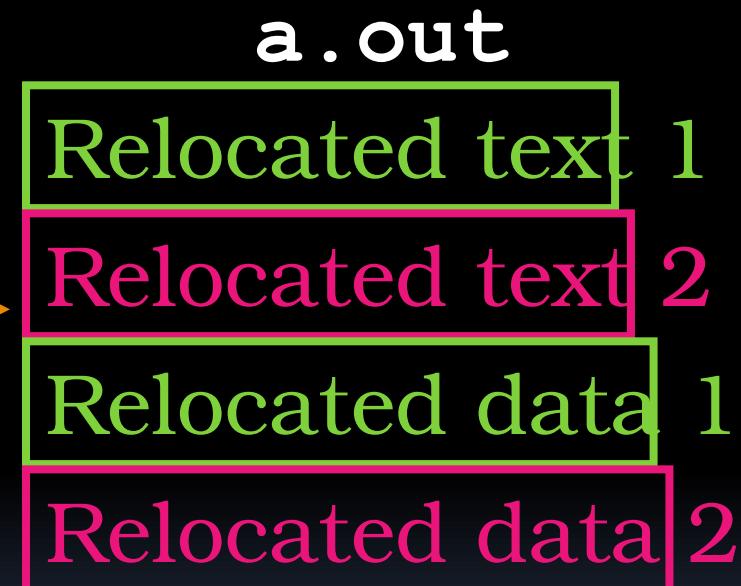
- Input: Object Code files, information tables (e.g., `foo.o`, `libc.o` for MIPS)
- Output: Executable Code (e.g., `a.out` for MIPS)
- Combines several object (`.o`) files into a single executable (“linking”)
- Enable Separate Compilation of files
 - Changes to one file do not require recompilation of whole program
 - Windows NT source was > 40 M lines of code!
 - Old name “Link Editor” from editing the “links” in jump and link instructions

Linker (2/3)

.o file 1



.o file 2



Linker (3/3)

- Step 1: Take text segment from each .o file and put them together.
- Step 2: Take data segment from each .o file, put them together, and concatenate this onto end of text segments.
- Step 3: Resolve References
 - Go through Relocation Table; handle each entry
 - That is, fill in all **absolute addresses**

Four Types of Addresses we'll discuss

- PC-Relative Addressing (beq, bne)

- never relocate
- Absolute Address (j, jal)
 - always relocate
- External Reference (usually jal)
 - always relocate
- Data Reference (often lui and ori)
 - always relocate

Absolute Addresses in MIPS

- Which instructions need relocation editing?

j[□] / jal[□] format: jump, jump_{xxxxx} and link

- Loads and stores to variables in static area,

lw/sw^{relative} \$gp^{to global pointer} \$x^{address}

beq/bne^{What about} \$rs^{conditional branches?} \$rt^{address}

- PC-relative addressing preserved even if code moves

Resolving References (1 / 2)

- Linker **assumes** first word of first text segment is at address **0x00000000**.
 - (More later when we study “virtual memory”)
- Linker knows:
 - length of each text and data segment
 - ordering of text and data segments
- Linker calculates:
 - absolute address of each label to be jumped to (internal or external) and each piece of data being referenced

Resolving References (2/2)

- To resolve references:
 - search for reference (data or label) in all “user” symbol tables
 - if not found, search library files (for example, for `printf`)
 - once absolute address is determined, fill in the machine code appropriately
- Output of linker: executable file containing text and data (plus header)

Static vs Dynamically linked

~~libraries~~, what we've described is the traditional way: **statically-linked** approach

- The library is now part of the executable, so if the library updates, we don't get the fix (have to recompile if we have source)
- It includes the entire library even if not all of it will be used.
- Executable is self-contained.
- An alternative is **dynamically linked libraries** (DLL), common on Windows & UNIX platforms

Dynamically linked libraries

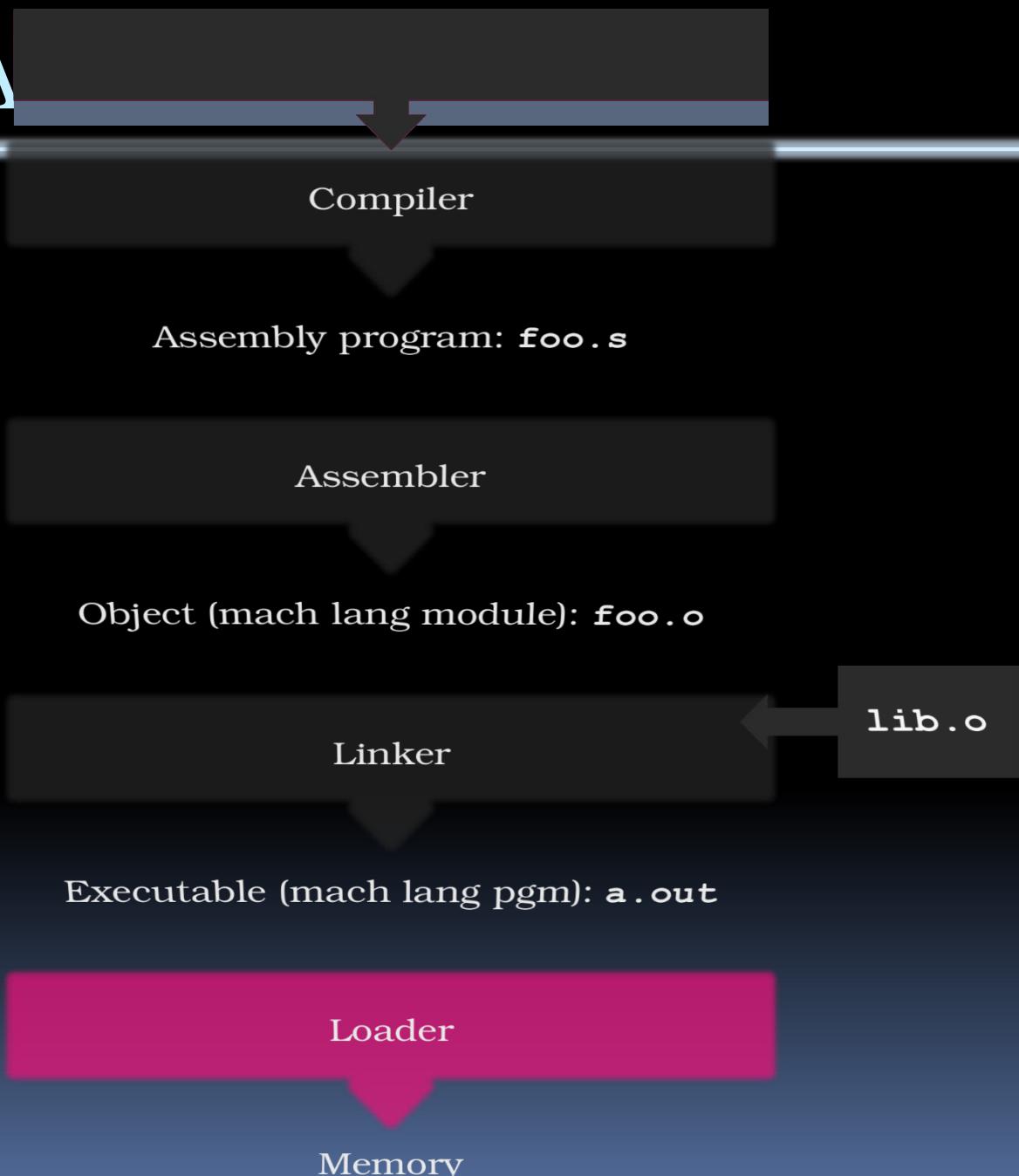
- Space/time issues
 - + Storing a program requires less disk space
 - + Sending a program requires less time
 - + Executing two programs requires less memory (if they share a library)
 - – At runtime, there's time overhead to do link
- Upgrades
 - + Replacing one file (`libXYZ.so`) upgrades every program that uses library “XYZ”

Overall, having the executable on the compiler, linker, and operating system. However, it provides many benefits that often outweigh these.
any more

Dynamically linked libraries

- The prevailing approach to dynamic linking uses machine code as the “lowest common denominator”
 - The linker does not use information about how the program or library was compiled (i.e., what compiler or language)
 - This can be described as “linking at the machine code level”
 - This isn’t the only way to do it...

Where A



Loader (1 / 3)

- Input: Executable Code
(e.g., a.out for MIPS)
- Output: (program is run)
- Executable files are stored on disk.
- When one is run, loader's job is to load it into memory and start it running.
- In reality, loader is the operating system (OS)
 - loading is one of the OS tasks

Loader (2/3)

- So what does a loader do?
 - Reads executable file's header to determine size of text and data segments
 - Creates new address space for program large enough to hold text and data segments, along with a stack segment
 - Copies instructions and data from executable file into the new address space

Loader (3/3)

- Copies arguments passed to the program onto the stack
- Initializes machine registers
 - Most registers cleared, but stack pointer assigned address of 1st free stack location
- Jumps to start-up routine that copies program's arguments from stack to registers & sets the PC
 - If main routine returns, start-up routine terminates program with the exit system call

Peer Instruction

Which of the following instr. may need to be edited during link phase?

Loop: lui \$at, 0xABCD }# 1

ori \$a0,\$at, 0xFEDC

bne \$a0,\$v0, Loop # 2

- | |
|-------|
| 12 |
| a) FF |
| b) FT |
| c) TF |
| d) TT |

Peer Instruction Answer

Which of the following instr. may need to be edited during link phase?

data reference; relocate

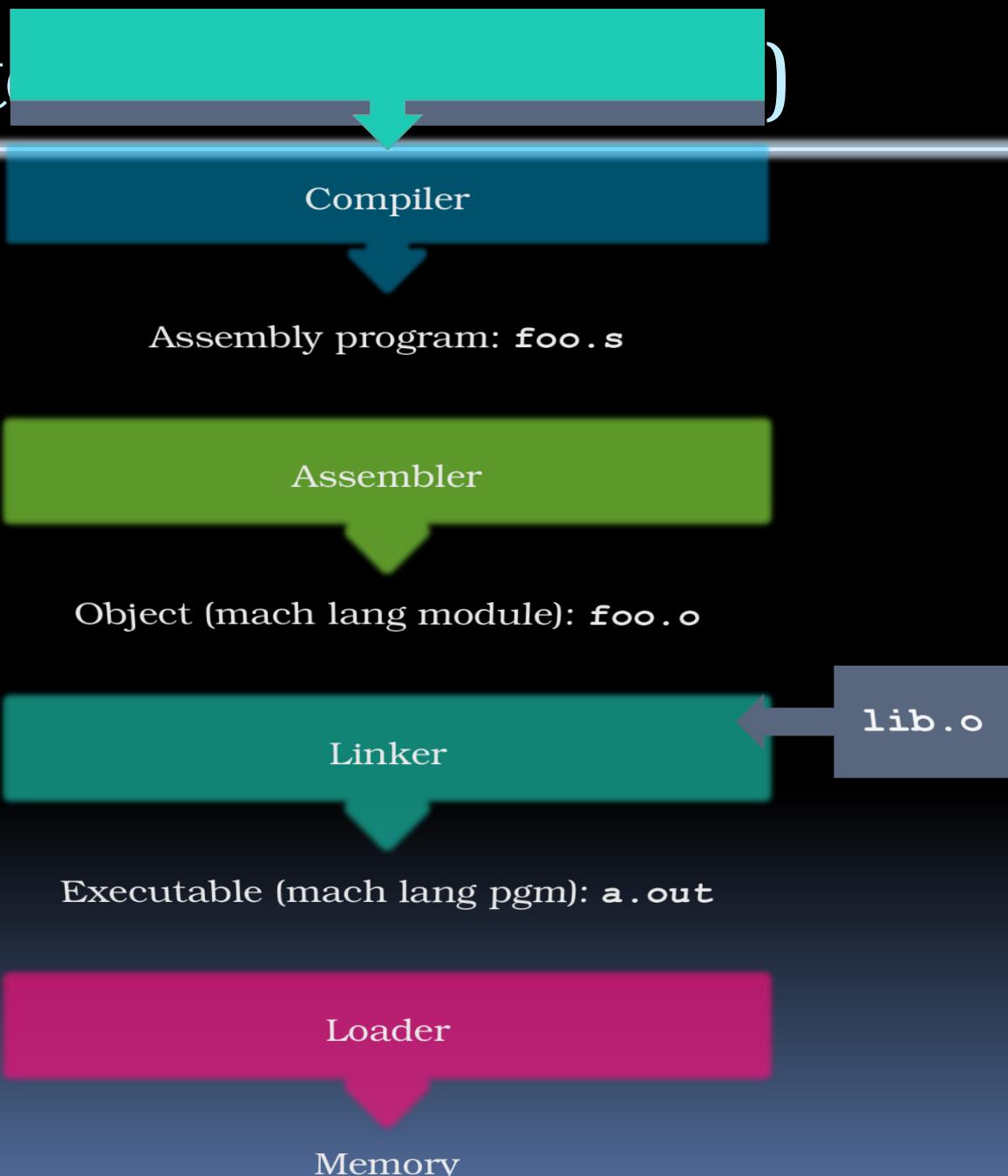
Loop: lui \$at, 0xABCD }# 1

ori \$a0,\$at, 0xFEDC PC-relative branch; OK

bne \$a0,\$v0, Loop # 2

- | |
|-------|
| 12 |
| a) FF |
| b) FT |
| c) TF |
| d) TT |

Things to know about the build process



Things to Remember (2/3)

- Compiler converts a single HLL file into a single assembly language file.
- Assembler removes pseudoinstructions, converts what it can to machine language, and creates a checklist for the linker (relocation table). A .s file becomes a .o file.
 - Does 2 passes to resolve addresses, handling internal forward references
- Linker combines several .o files and resolves absolute addresses.
 - Enables separate compilation, libraries that need not be compiled, and resolves remaining addresses
- Loader loads executable into memory and begins execution.

Things to Remember 3/3

- Stored Program concept is very powerful. It means that instructions sometimes act just like data. Therefore we can use programs to manipulate other programs!
 - Compiler Assembler Linker (Loader)

Bonus slides

- These are extra slides that used to be included in lecture notes, but have been moved to this, the “bonus” area to serve as a supplement.
- The slides will appear in the order they would have in the normal presentation

Bonus

Big Endian vs. Little

Endian

Big-endian and little-endian derive from Jonathan Swift's *Gulliver's Travels* in which the Big Endians were a political faction that broke their eggs at the large end ("the primitive way") and rebelled against the Lilliputian King who required his subjects (the Little Endians) to break their eggs at the small end.

- **The order in which BYTES are stored in memory**
- Bits always stored as usual. (E.g., **0xC2=0b 1100 0010**)

Consider the number 1025 as we normally write it:

BYTE3	BYTE2	BYTE1	BYTE0
00000000	00000000	00000100	00000001

Big Endian

- ADDR3 ADDR2 ADDR1 ADDR0
BYTE0 BYTE1 BYTE2 BYTE3
00000001 00000100 00000000 00000000
- ADDR0 ADDR1 ADDR2 ADDR3
BYTE3 BYTE2 BYTE1 BYTE0
00000000 00000000 00000100 00000001

Little Endian

- ADDR3 ADDR2 ADDR1 ADDR0
BYTE3 BYTE2 BYTE1 BYTE0
00000000 00000000 00000100 00000001
- ADDR0 ADDR1 ADDR2 ADDR3
BYTE0 BYTE1 BYTE2 BYTE3
00000001 00000100 00000000 00000000

www.webopedia.com/TERM/b/big_endian.html

searchnetworking.techtarget.com/sDefinition/0,,sid7_gci211659,00.html

www.noveltheory.com/TechPapers/endian.asp

en.wikipedia.org/wiki/Big_endian

Example: C \Rightarrow Asm \Rightarrow Obj \Rightarrow Exe \Rightarrow

Run

C Program Source Code: *prog.c*

```
#include <stdio.h>

int main (int argc, char *argv[] ) {
    int i, sum = 0;
    for (i = 0; i <= 100; i++)
        sum = sum + i * i;
    printf ("The sum of sq from 0 .. 100 is
            %d\n",
            sum);
}
```

“printf” lives in “libc”

Compilation: MAL

```
___.text
.align 2
.globl main
main:
    subu $sp,$sp,32
    sw $ra, 20($sp)
    sd $a0, 32($sp)
    sw $0, 24($sp)
    sw $0, 28($sp)
loop:
    lw $t6, 28($sp)
    mul $t7, $t6,$t6
    lw $t8, 24($sp)
    addu $t9,$t8,$t7
    sw $t9, 24($sp)
```

```
addu $t0, $t6, 1
sw $t0, 28($sp)
ble $t0,100, loop
la $a0, str
lw $a1, 24($sp)
jal printf
move $v0, $0
lw $ra, 20($sp)
addiu $sp,$sp,32
jr $ra
.data
.align 0
str:
.asciiiz "The sum
of sq from 0 ..
100 is %d\n"
```

**Where are
7 pseudo-
instructions?**

Compilation: MAL

```
___.text
.align 2
.globl main
main:
    subu $sp,$sp,32
    sw $ra, 20($sp)
    sd $a0, 32($sp)
    sw $0, 24($sp)
    sw $0, 28($sp)
loop:
    lw $t6, 28($sp)
    mul $t7, $t6,$t6
    lw $t8, 24($sp)
    addu $t9,$t8,$t7
    sw $t9, 24($sp)
```

```
addu $t0, $t6, 1
sw $t0, 28($sp)
ble $t0,100, loop
la $a0, str
lw $a1, 24($sp)
jal printf
move $v0, $0
lw $ra, 20($sp)
addiu $sp,$sp,32
jr $ra
.data
.align 0
str:
.asciiiz "The sum
of sq from 0 ..
100 is %d\n"
```

7 pseudo-instructions underlined

Assembly step 1:

Remove pseudoinstructions, assign addresses

00	addiu	\$29, \$29, -32
04	sw	\$31, 20(\$29)
08	sw	\$4, 32(\$29)
0c	sw	\$5, 36(\$29)
10	sw	\$0, 24(\$29)
14	sw	\$0, 28(\$29)
18	lw	\$14, 28(\$29)
1c	multu	\$14, \$14
20	mflo	\$15
24	lw	\$24, 24(\$29)
28	addu	\$25, \$24, \$15
2c	sw	\$25, 24(\$29)

30	addiu	\$8, \$14, 1
34	sw	\$8, 28(\$29)
38	slti	\$1, \$8, 101
3c	bne	\$1, \$0, loop
40	lui	\$4, l.str
44	ori	\$4, \$4, r.str
48	lw	\$5, 24(\$29)
4c	jal	printf
50	add	\$2, \$0, \$0
54	lw	\$31, 20(\$29)
58	addiu	\$29, \$29, 32
5c	jr	\$31

Assembly step 2

Create relocation table and symbol table

- Symbol Table

Label	address (in module)	type
main:	0x00000000	global text
loop:	0x00000018	local text
str:	0x00000000	local data

- Relocation Information

Address	Instr.	type
Dependency	0x00000040	lui
	l.str	
0x00000044	ori	r.str
0x0000004c	jal	printf

Assembly step 3

Resolve local PC-relative labels

00	addiu	\$29, \$29, -32
04	sw	\$31, 20(\$29)
08	sw	\$4, 32(\$29)
0C	sw	\$5, 36(\$29)
10	sw	\$0, 24(\$29)
14	sw	\$0, 28(\$29)
18	lw	\$14, 28(\$29)
1C	multu	\$14, \$14
20	mflo	\$15
24	lw	\$24, 24(\$29)
28	addu	\$25, \$24, \$15
2C	sw	\$25, 24(\$29)

30	addiu	\$8, \$14, 1
34	sw	\$8, 28(\$29)
38	slti	\$1, \$8, 101
3C	bne	\$1, \$0, -10
40	lui	\$4, <u>l.str</u>
44	ori	\$4, \$4, <u>r.str</u>
48	lw	\$5, 24(\$29)
4C	jal	<u>printf</u>
50	add	\$2, \$0, \$0
54	lw	\$31, 20(\$29)
58	addiu	\$29, \$29, 32
5C	jr	\$31

Assembly step 4

- Generate object (.o) file:
 - Output binary representation for
 - text segment (instructions),
 - data segment (data),
 - symbol and relocation tables.
 - Using dummy “placeholders” for unresolved absolute and external references.

Text segment in object

file

0x000000	001001110111101111111111111100000
0x000004	101011110111110000000000010100
0x000008	1010111101001000000000000100000
0x00000c	1010111101001010000000000100100
0x000010	1010111101000000000000000110000
0x000014	1010111101000000000000000111000
0x000018	1000111110101100000000000111000
0x00001c	1000111110111000000000000110000
0x000020	0000000111001110000000000110001
0x000024	0010010111001000000000000000001
0x000028	0010100100000010000000001100101
0x00002c	1010111110101000000000000111000
0x000030	00000000000000000111100000010010
0x000034	0000011000011111100100000100001
0x000038	000101000010000011111111110111
0x00003c	1010111110111001000000000011000
0x000040	0011110000000100000000000000000
0x000044	1000111110100101000000000000000
0x000048	000011000001000000000000011101100
0x00004c	0010010000000000000000000000000
0x000050	10001111101111110000000000010100
0x000054	001001111011110100000000000100000
0x000058	00000011111000000000000000000001000
0x00005c	0000000000000000000000000000000100001

Link step 1: combine `prog.o`,

`.libc.o`

- Merge text/data segments
- Create absolute memory addresses
- Modify & merge symbol and relocation tables
- Symbol Table
 - Label Address

Label	Address
main:	0x00000000
loop:	0x00000018
str:	0x10000430
printf:	0x000003b0
	...

- Relocation Information

Address	Instr.	Type	Dependency
0x00000040	lui		l.str
0x00000044	ori		r.str
0x0000004c	jal		printf

Link step 2:

- Edit Addresses in relocation table
 - (shown in TAL for clarity, but done in binary)

00	addiu	\$29, \$29, -32	30	addiu	\$8, \$14, 1
04	sw	\$31, 20 (\$29)	34	sw	\$8, 28 (\$29)
08	sw	\$4, 32 (\$29)	38	slti	\$1, \$8, 101
0c	sw	\$5, 36 (\$29)	3c	bne	\$1, \$0, -10
10	sw	\$0, 24 (\$29)	40	lui	\$4, <u>4096</u>
14	sw	\$0, 28 (\$29)	44	ori	\$4, \$4, <u>1072</u>
18	lw	\$14, 28 (\$29)	48	lw	\$5, 24 (\$29)
1c	multu	\$14, \$14	4c	jal	<u>812</u>
20	mflo	\$15	50	add	\$2, \$0, \$0
24	lw	\$24, 24 (\$29)	54	lw	\$31, 20 (\$29)
28	addu	\$25, \$24, \$15	58	addiu	\$29, \$29, 32
2c	sw	\$25, 24 (\$29)	5c	jr	\$31

Link step 3:

- Output executable of merged modules.
 - Single text (instruction) segment
 - Single data segment
 - Header detailing size of each segment
- NOTE:
 - The preceding example was a much simplified version of how ELF and other standard formats work, meant only to demonstrate the basic principles.

0.13 Intro to Synchronous Digital Systems

Computer Architecture (计算机体系结构)

Lecture 14 Introduction to Synchronous Digital Systems



2020-10-09

Lecturer Yuanqing Cheng

www.cadetlab.cn/~courses

Don't Let Your Power Rail Become a
Fusible Link

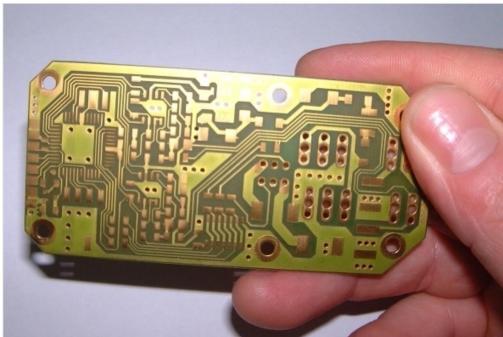


Figure 1: A small PC board similar to this one had a short, super-thin trace which acted like a fuse when hit with a 10-A surge, despite insignificant IR voltage drop. (Image Source: IBFriedrich/TARGET 3001!)

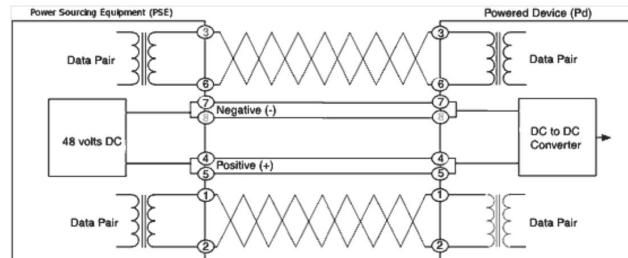
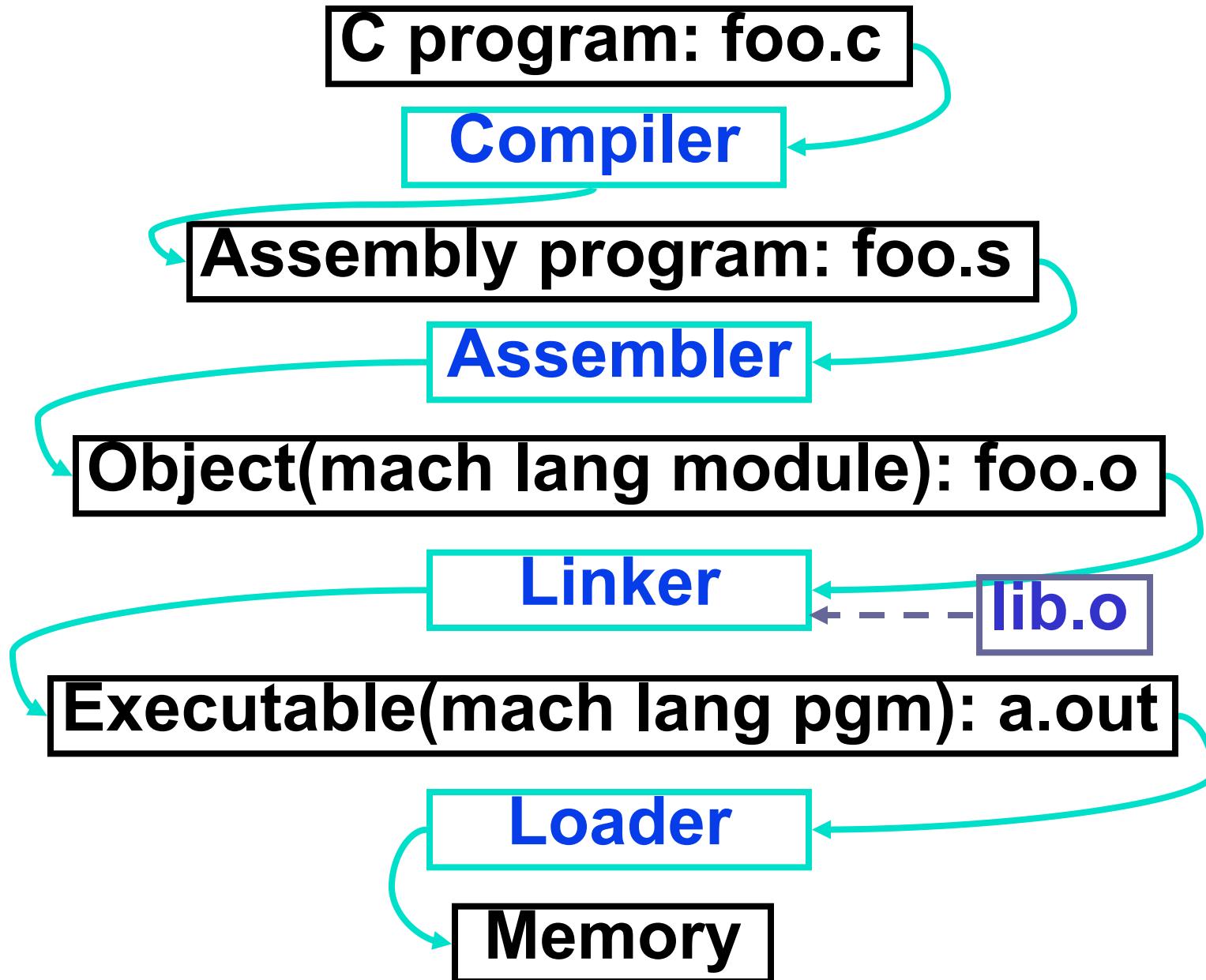
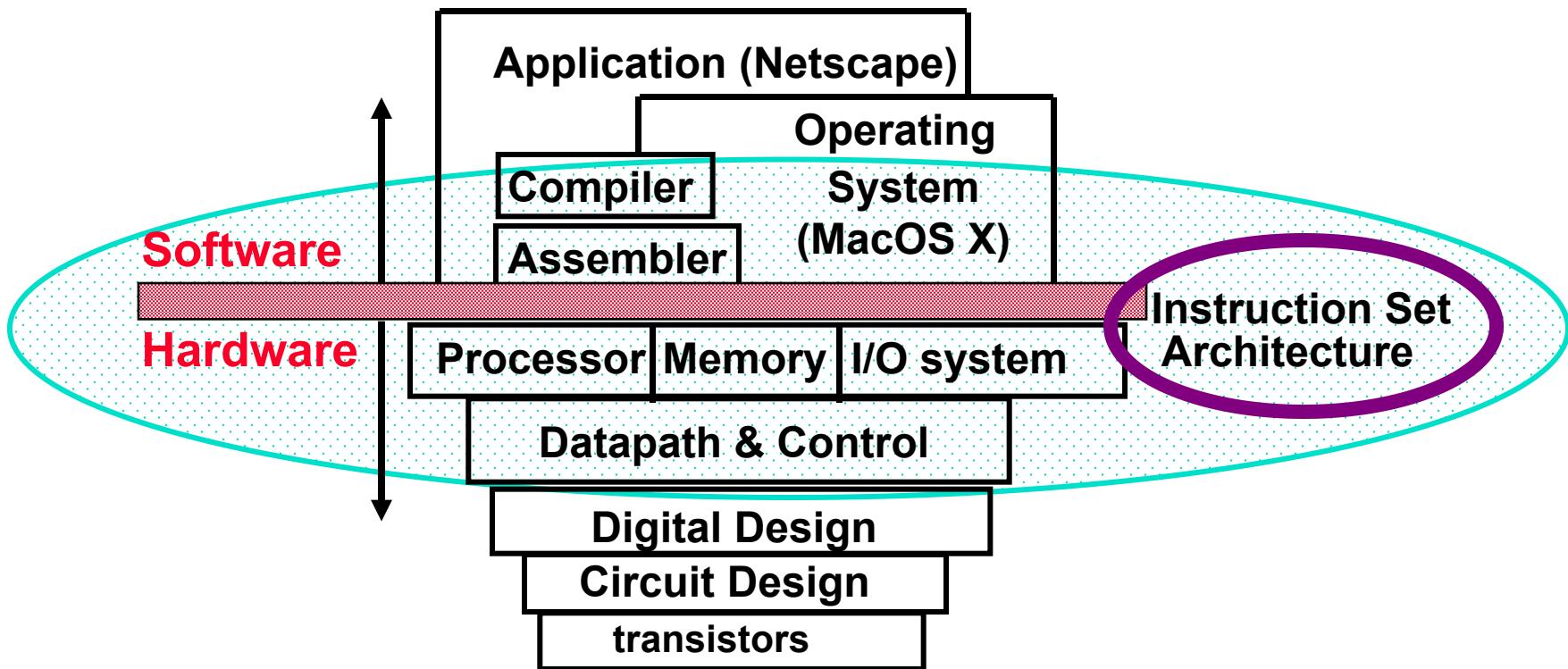


Figure 2: The recently approved third version of the Power-over-Ethernet allows for substantial power in the thin wires, which can result in excessive self-heating and performance degradation, especially in constrained installations. (Image Source: [Advantech B+B SmartWorx](#))

Review



What are “Machine Structures”?



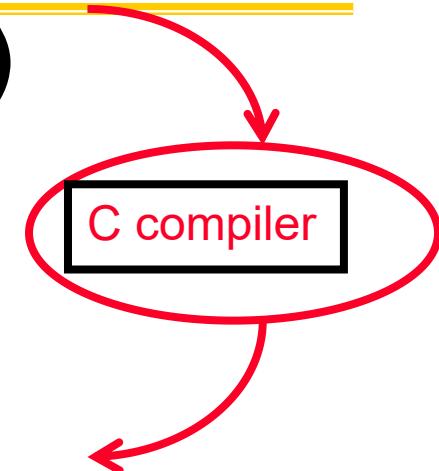
Coordination of many *levels of abstraction*

ISA is an important abstraction level:
contract between HW & SW

Below the Program

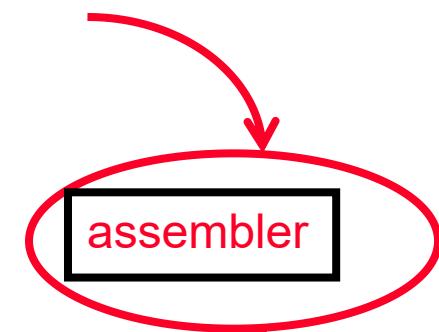
- High-level language program (in C)

```
swap int v[], int k){  
    int temp;  
    temp = v[k];  
    v[k] = v[k+1];  
    v[k+1] = temp;  
}
```



- Assembly language program (for MIPS)

```
swap: sll $2, $5, 2  
       add $2, $4,$2  
       lw $15, 0($2)  
       lw $16, 4($2)  
       sw $16, 0($2)  
       sw $15, 4($2)  
       jr $31
```



- Machine (object) code (for MIPS)

```
000000 00000 00101 0001000010000000  
000000 00100 00010 0001000000100000 . . .
```



Synchronous Digital Systems

The hardware of a processor, such as the MIPS, is an example of a Synchronous Digital System

Synchronous:

- Means all operations are coordinated by a central **clock**.
 - It keeps the “heartbeat” of the system!

Digital:

- Mean all values are represented by discrete values
- Electrical signals are treated as 1's and 0's and grouped together to form words.

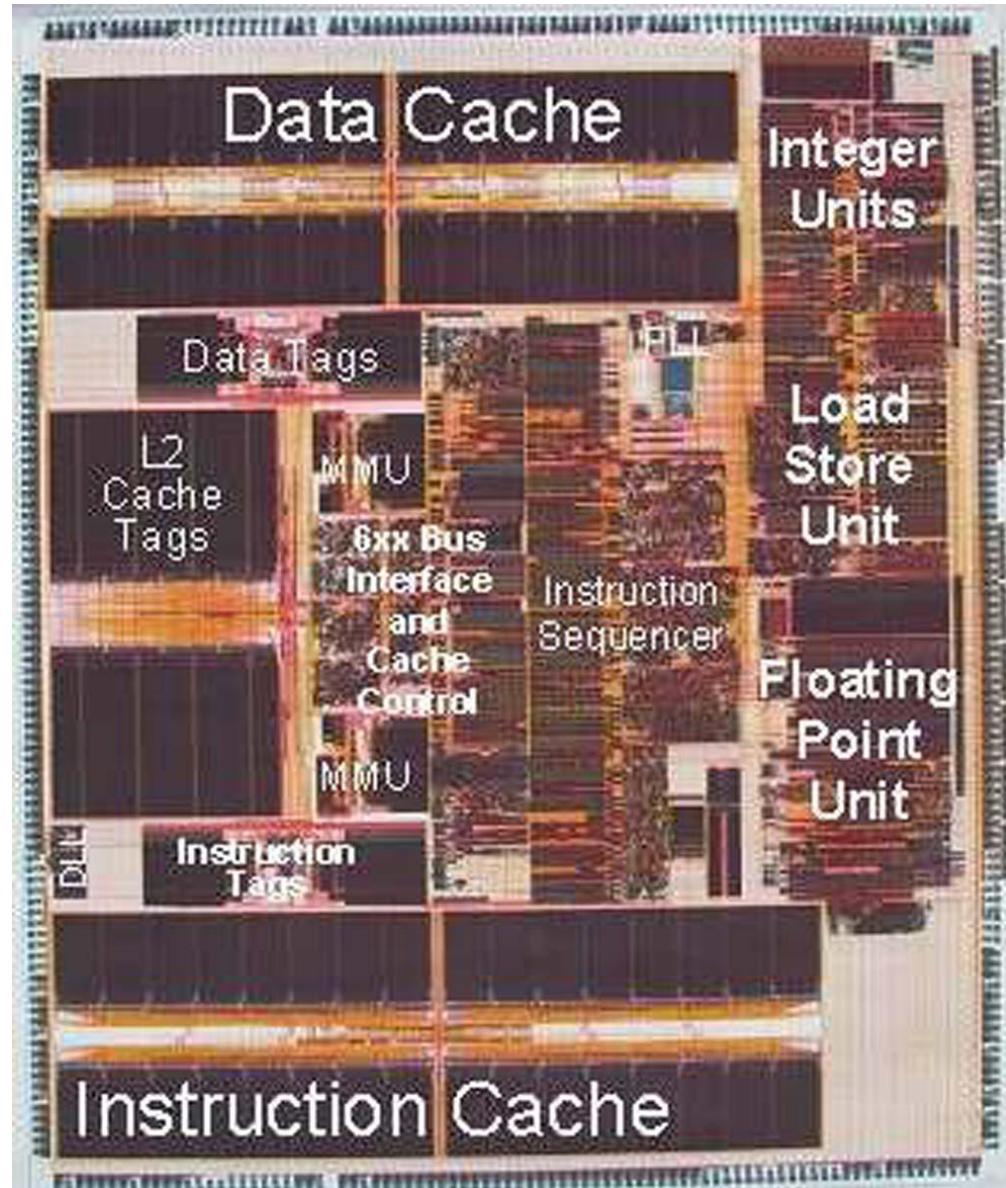
Logic Design

- Next 4 weeks: we'll study how a modern processor is built; starting with basic elements as building blocks.
- Why study hardware design?
 - Understand capabilities and limitations of hardware in general and processors in particular.
 - What processors can do fast and what they can't do fast (avoid slow things if you want your code to run fast!)
 - Background for more detailed hardware courses
 - There is just so much you can do with processors. At some point you may need to design your own custom hardware.

PowerPC Die Photograph



Let's look
closer...



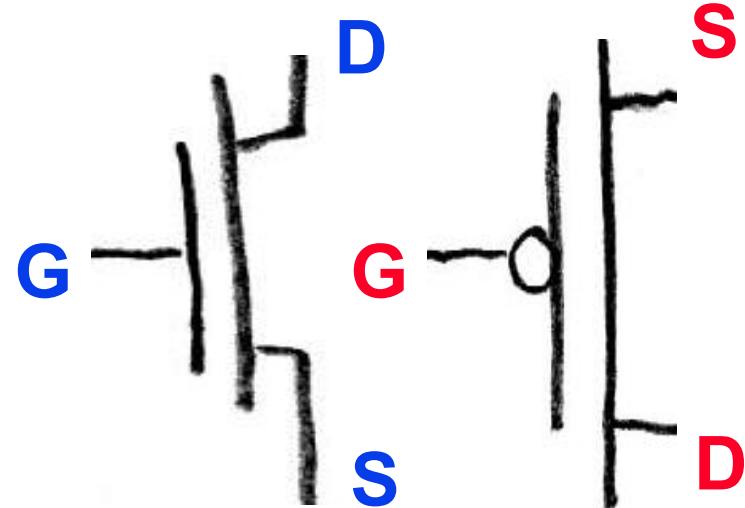
Transistors 101

- MOSFET

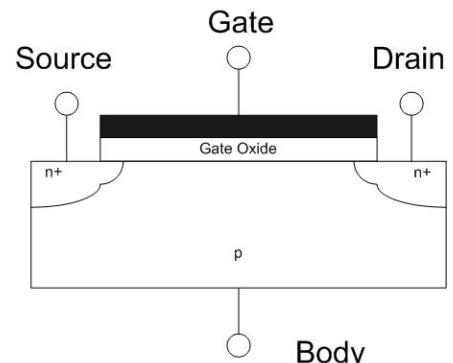
- Metal-Oxide-Semiconductor Field-Effect Transistor
- Come in two types:
 - n-type NMOSFET
 - p-type PMOSFET

- For n-type (p-type opposite)

- If voltage not enough between G & S, transistor turns “off” (cut-off) and Drain-Source NOT connected
- If the G & S voltage is high enough, transistor turns “on” (saturation) and Drain-Source ARE connected



n-type p-type

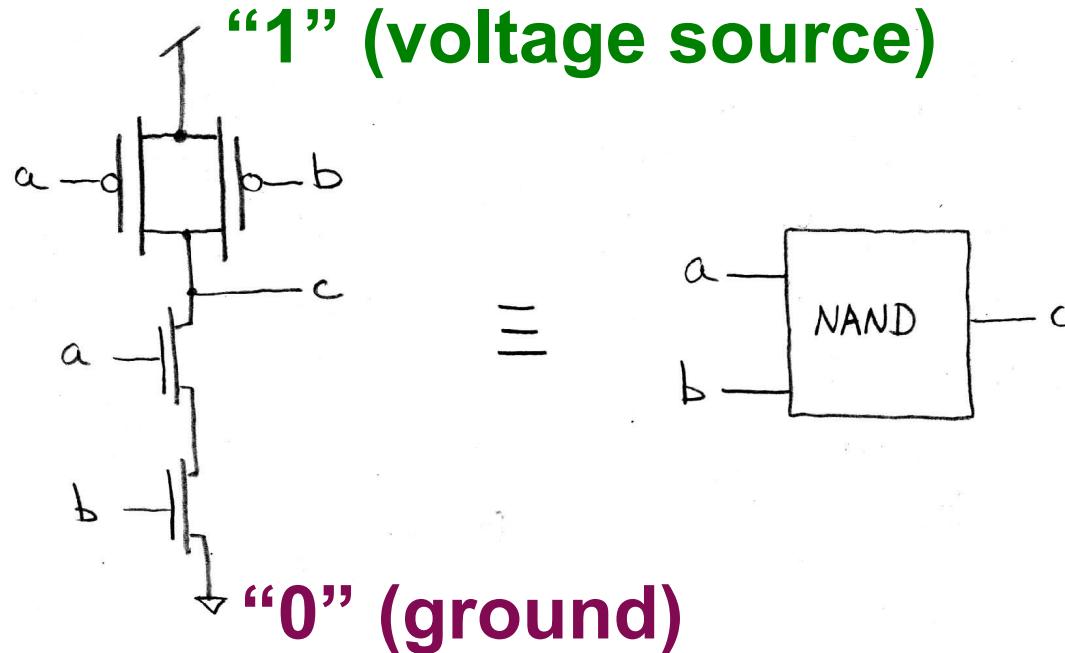


Side view

www.wikipedia.org/wiki/Mosfet

Transistor Circuit Rep. vs. Block diagram

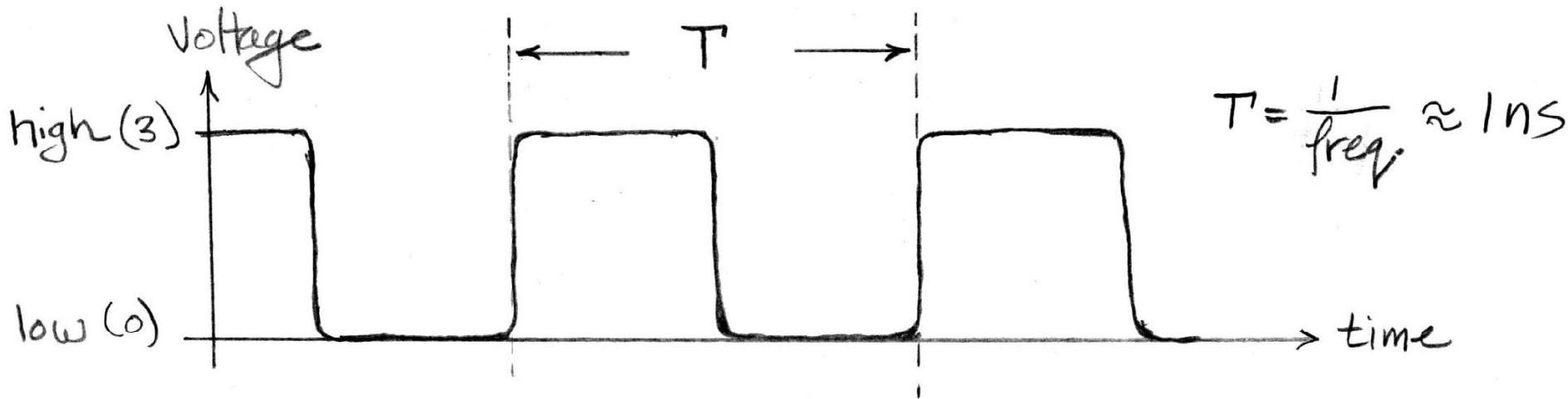
- Chips is composed of nothing but transistors and wires.
- Small groups of transistors form useful building blocks.



a	b	c
0	0	1
0	1	1
1	0	1
1	1	0

- Block are organized in a hierarchy to build higher-level blocks: ex: adders.

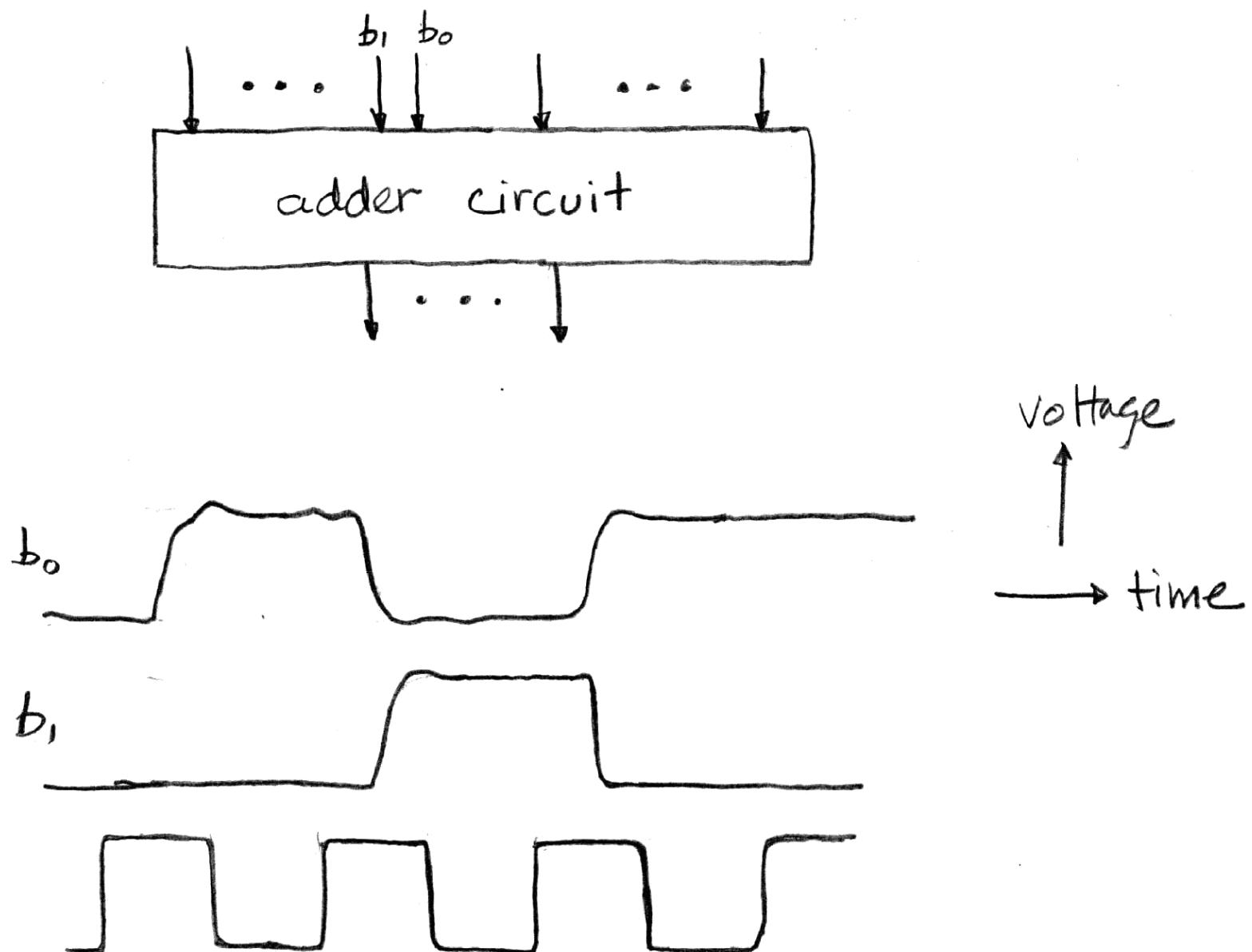
Signals and Waveforms: Clocks



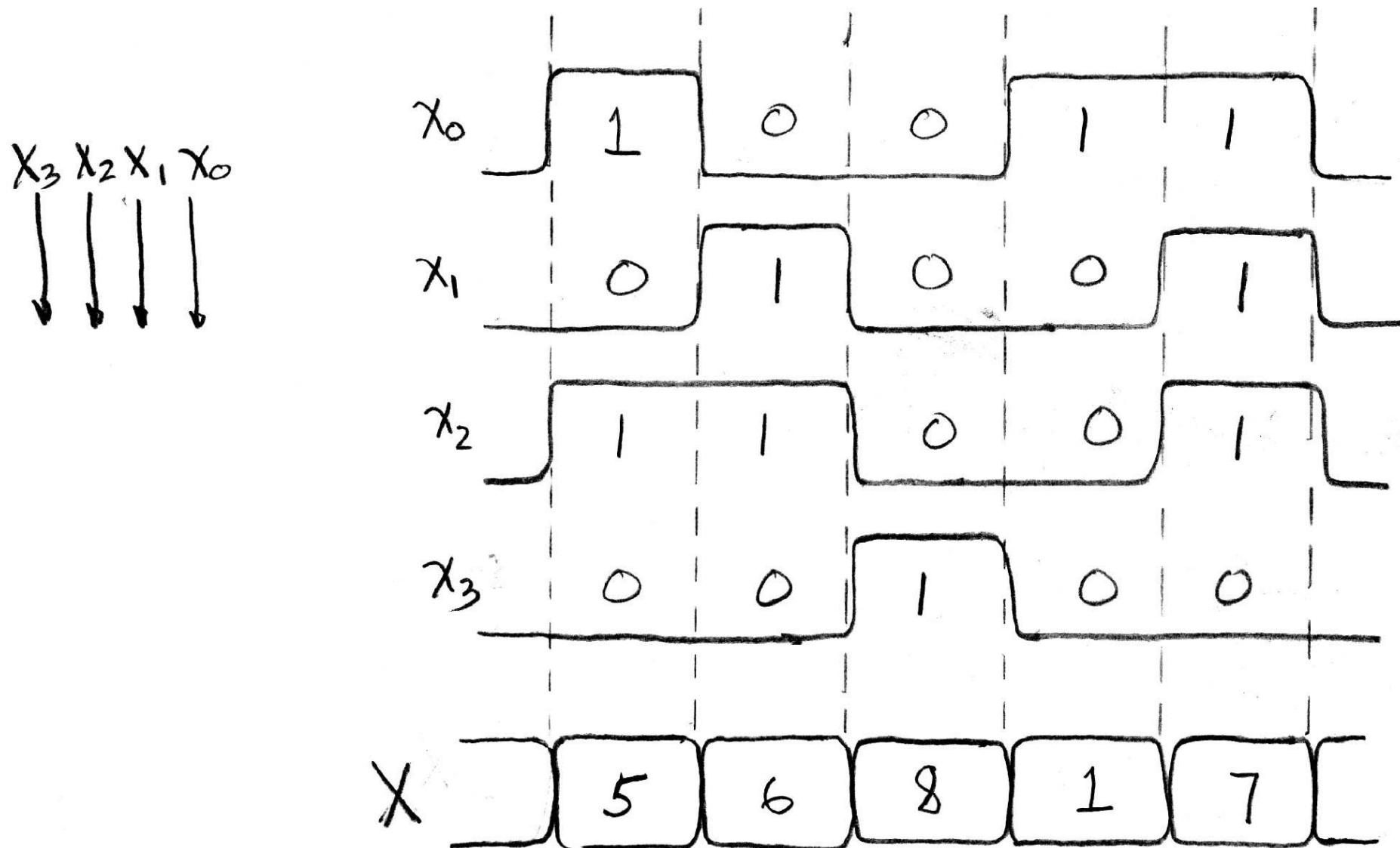
- **Signals**

- When **digital** is only treated as 1 or 0
- Is transmitted over wires continuously
- Transmission is effectively instant
 - Implies that any wire only contains 1 value at a time

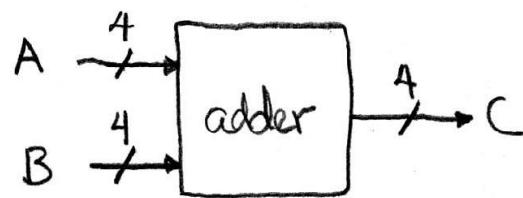
Signals and Waveforms



Signals and Waveforms: Grouping



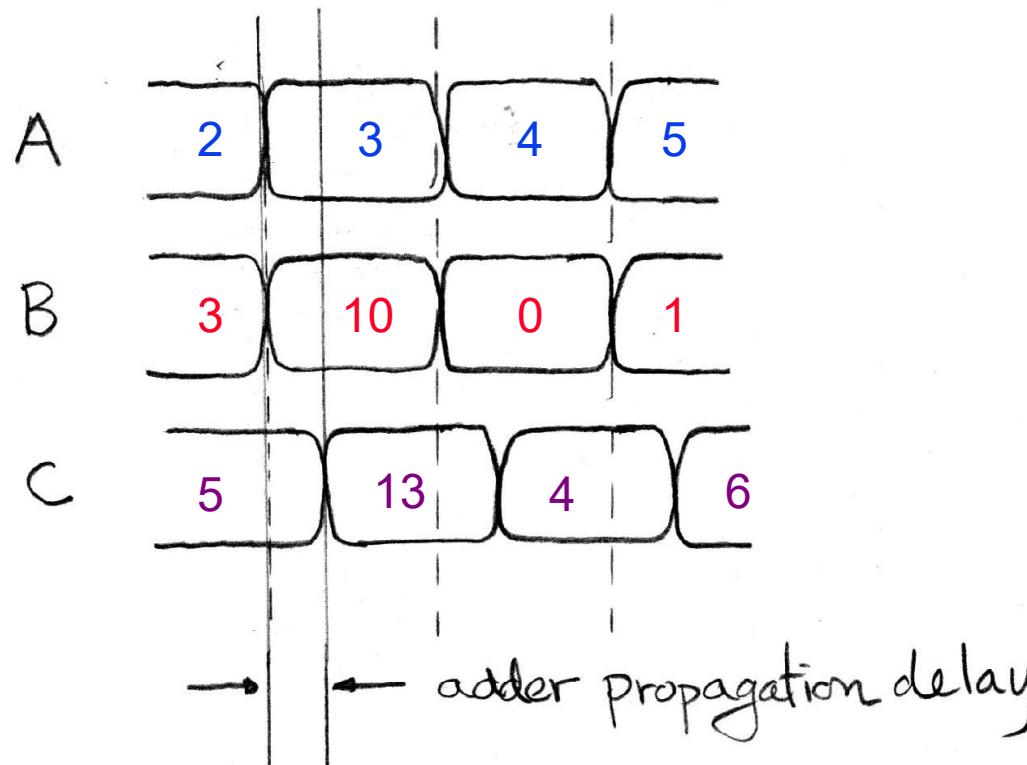
Signals and Waveforms: Circuit Delay



$$A = [a_3, a_2, a_1, a_0]$$

$$B = [b_3, b_2, b_1, b_0]$$

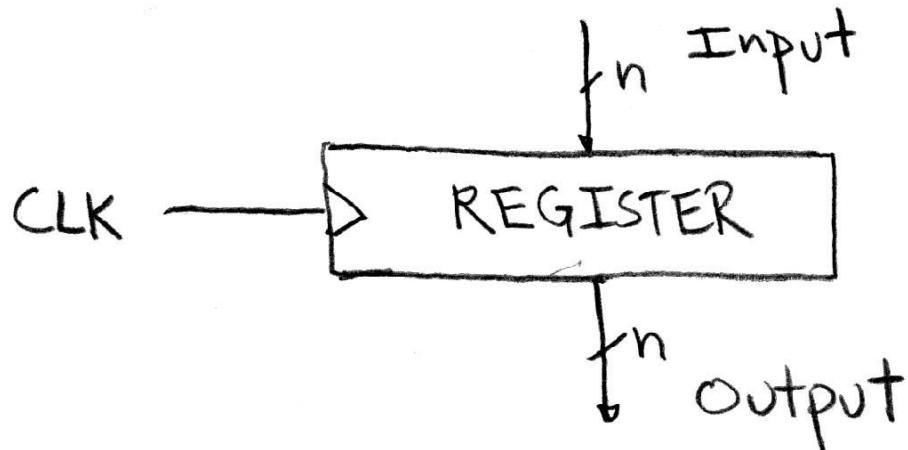
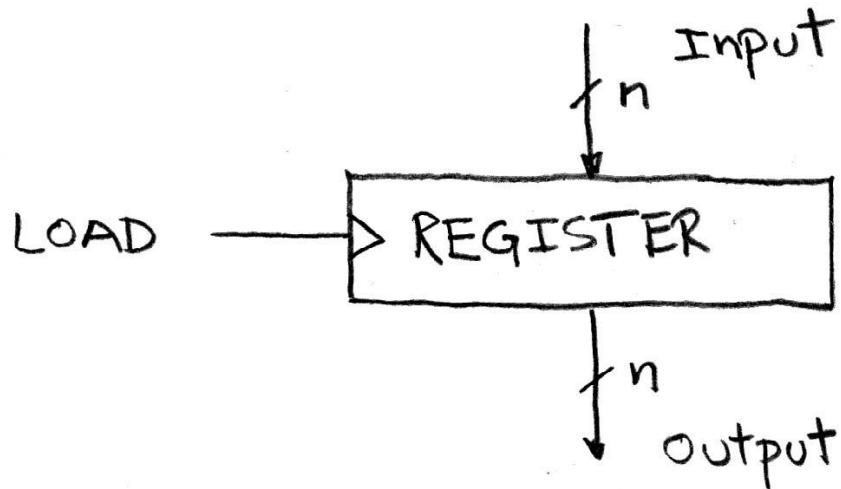
$$A \xrightarrow{4} = \begin{matrix} a_0 \longrightarrow \\ a_1 \longrightarrow \\ a_2 \longrightarrow \\ a_3 \longrightarrow \end{matrix}$$



Type of Circuits

- **Synchronous Digital Systems** are made up of two basic types of circuits:
- **Combinational Logic (CL) circuits**
 - Our previous adder circuit is an example.
 - Output is a function of the inputs only.
 - Similar to a pure function in mathematics, $y = f(x)$. (No way to store information from one invocation to the next. No side effects)
- **State Elements**: circuits that store information.

Circuits with STATE (e.g., register)



Peer Instruction

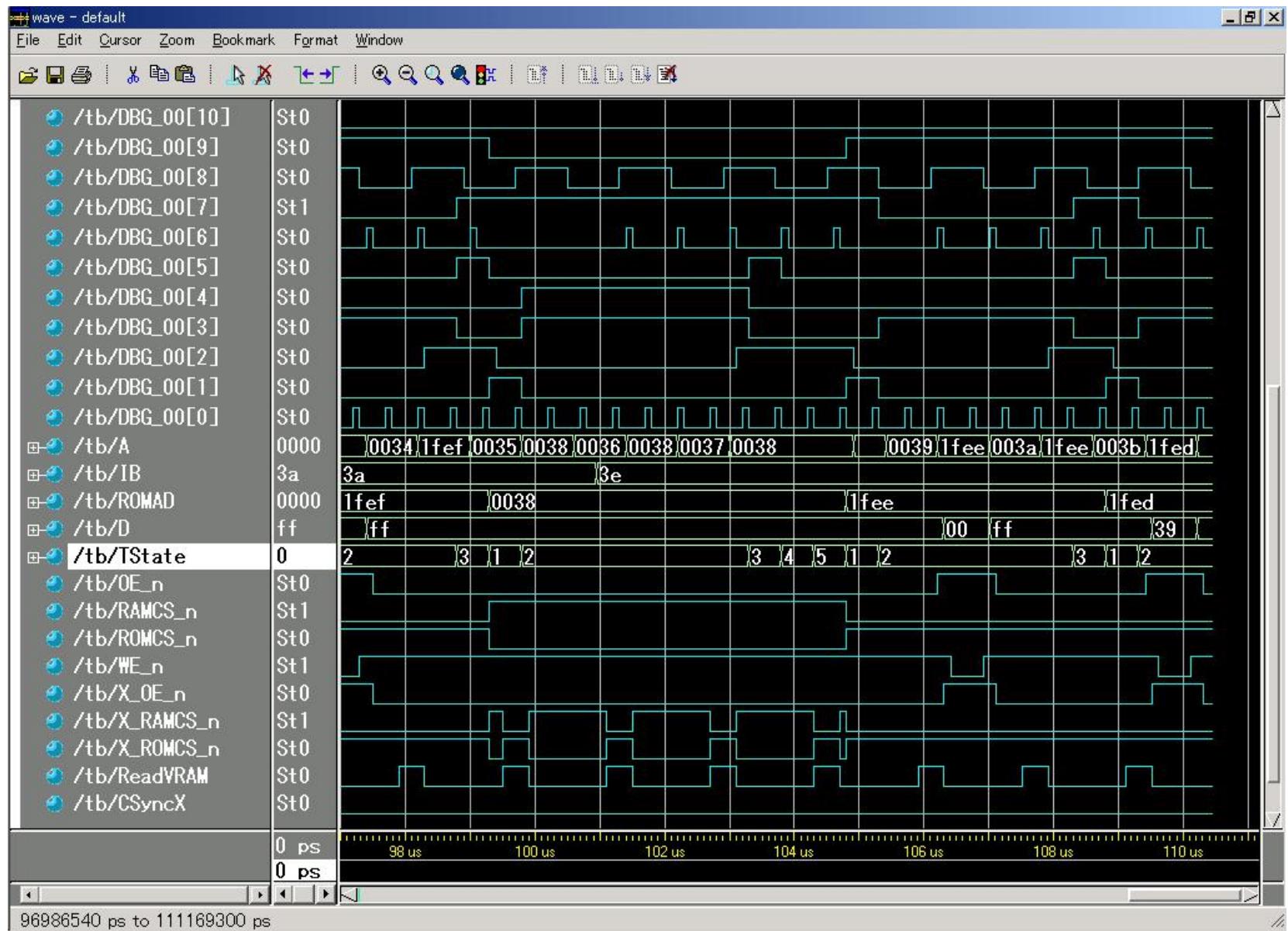
- 1) SW can peek at HW (past ISA abstraction boundary) for optimizations
- 2) SW can depend on particular HW implementation of ISA

	12
a)	FF
b)	FT
c)	TF
d)	TT

And in conclusion...

- ISA is very important abstraction layer
 - Contract between HW and SW
- Clocks control pulse of our circuits
- Voltages are analog, quantized to 0/1
- Circuit delays are fact of life
- Two types of circuits:
 - Stateless Combinational Logic ($\&$, $|$, \sim)
 - State circuits (e.g., registers)

Sample Debugging Waveform



0.14 Systems With Memory

Computer Architecture

(计算机体系结构)

Lecture #16

State Elements: Circuits that Remember

2020-10-09



Yuanqing Cheng
www.cadetlab.cn/~courses

Review

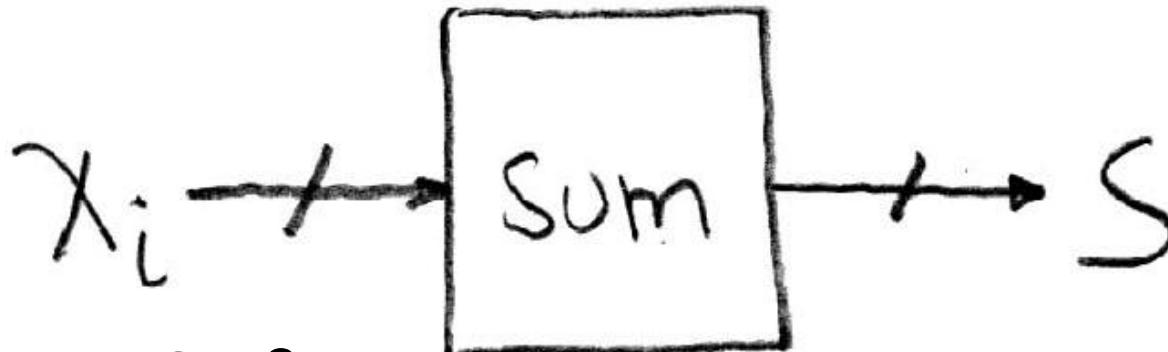
- ISA is very important abstraction layer
 - Contract between HW and SW
- Clocks control pulse of our circuits
- Voltages are analog, quantized to 0/1
- Circuit delays are fact of life
- Two types of circuits:
 - Stateless Combinational Logic ($\&$, $|$, \sim)
 - State circuits (e.g., registers)

Uses for State Elements

- 1. As a place to store values for some indeterminate amount of time:**
 - Register files (like \$1-\$31 on the MIPS)
 - Memory (caches, and main memory)
- 2. Help control the flow of information between combinational logic blocks.**
 - State elements are used to hold up the movement of information at the inputs to combinational logic blocks and allow for orderly passage.

Accumulator Example

Why do we need to control the flow of information?



Want: $S=0 ;$

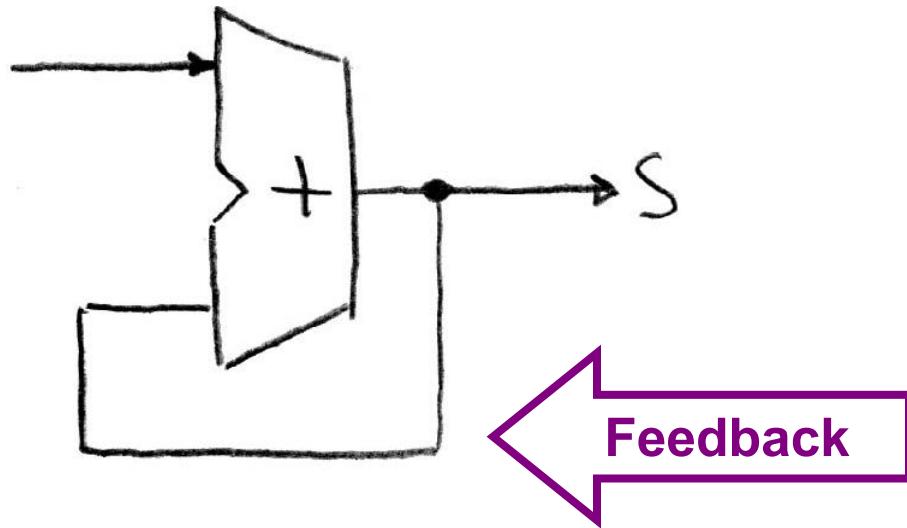
for ($i=0 ; i < n ; i++$)

$$S = S + X_i$$

Assume:

- **Each X value is applied in succession, one per cycle.**
- **After n cycles the sum is present on S .**

First try...Does this work?

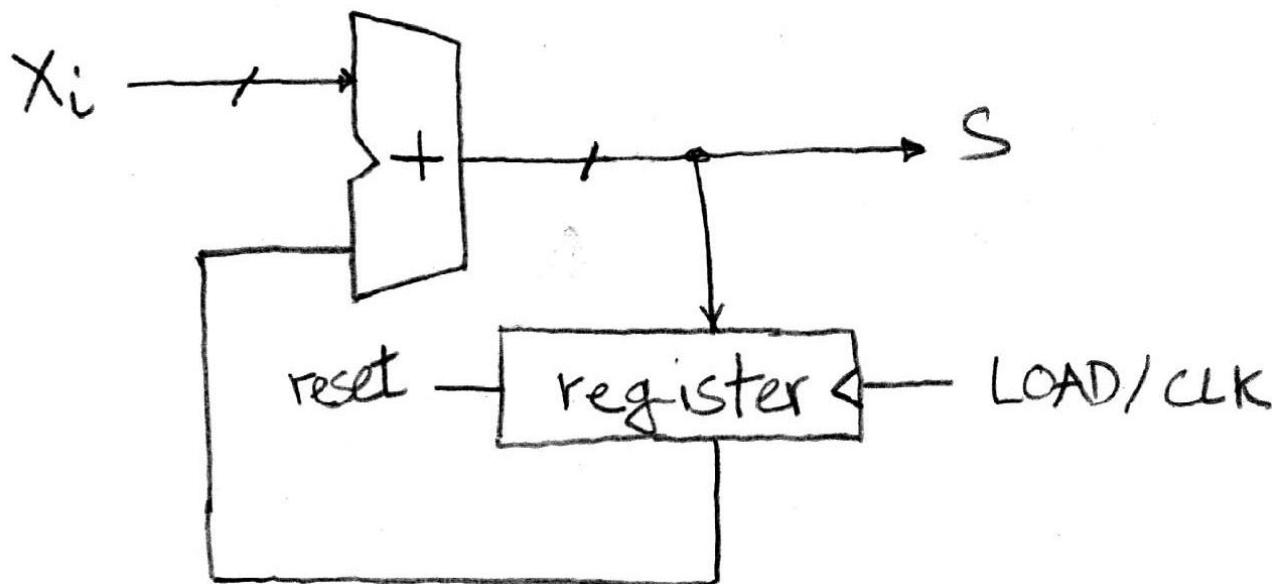


Nope!

Reason #1... What is there to control the next iteration of the 'for' loop?

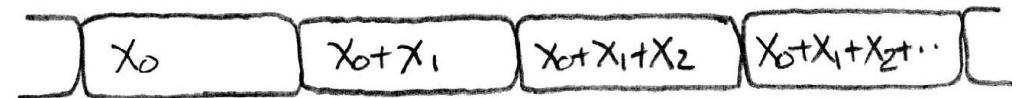
Reason #2... How do we say: 'S=0'?

Second try...How about this?



Rough
timing...

\$S

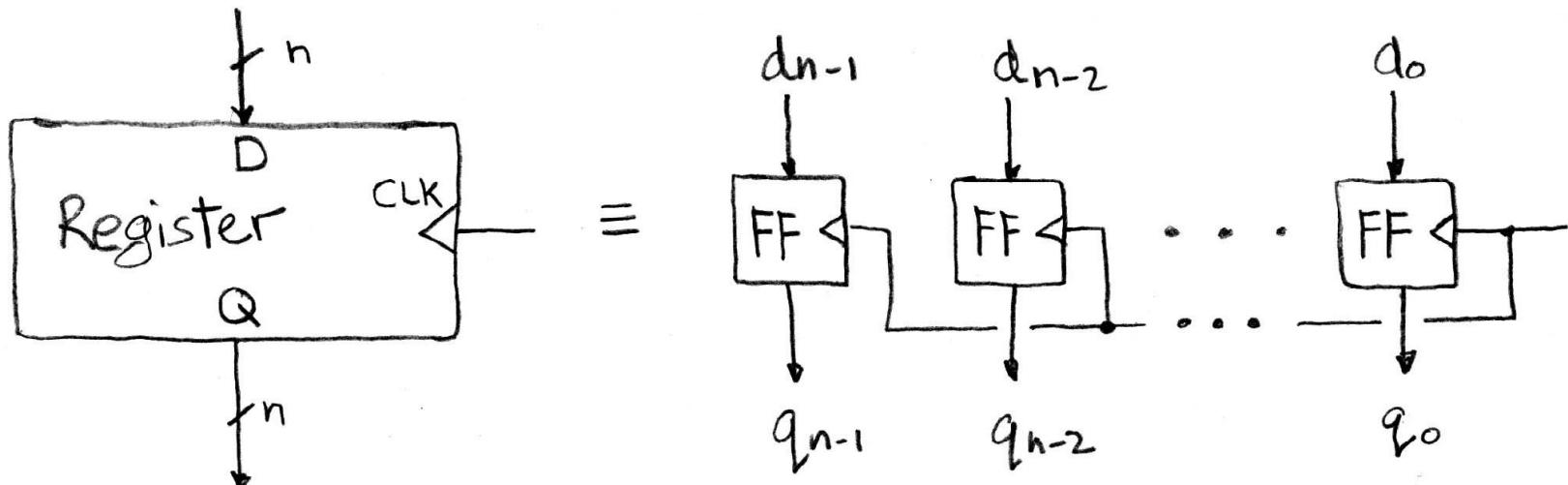


\$x\$



Register is used to hold up the transfer of data to adder.

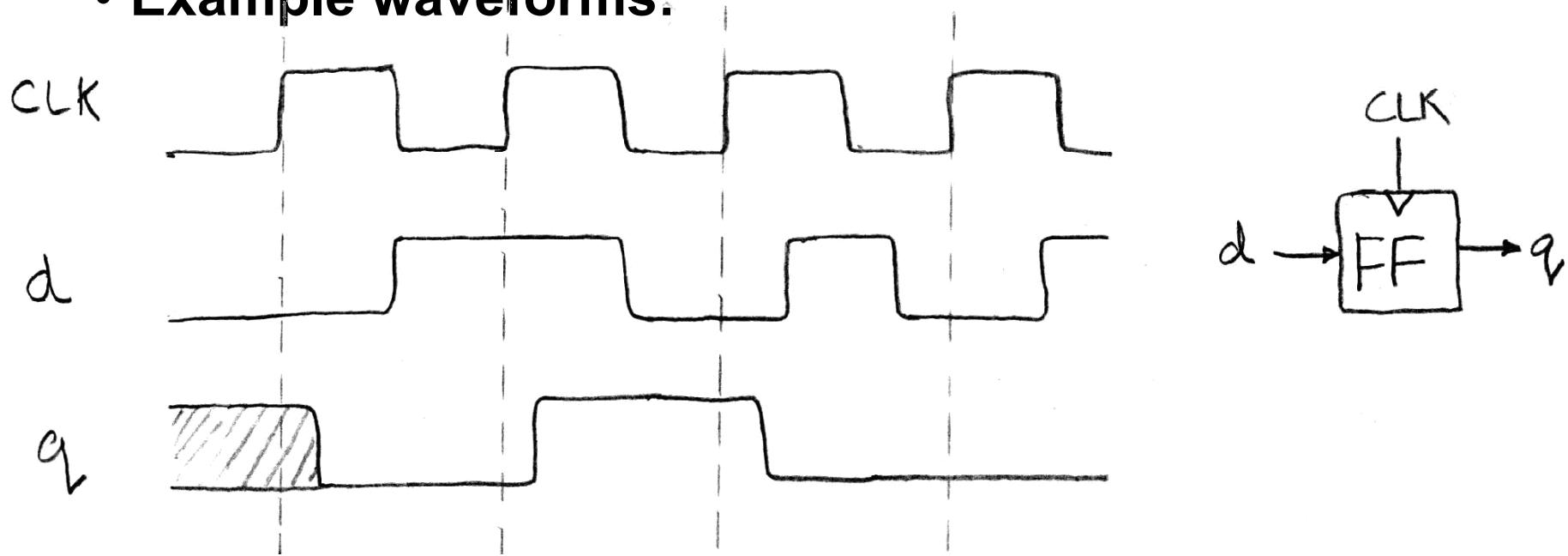
Register Details...What's inside?



- **n instances of a “Flip-Flop”**
- **Flip-flop name because the output flips and flops between and 0,1**
- D is “data”, Q is “output”
- **Also called “d-type Flip-Flop”**

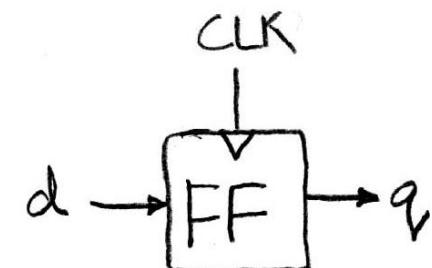
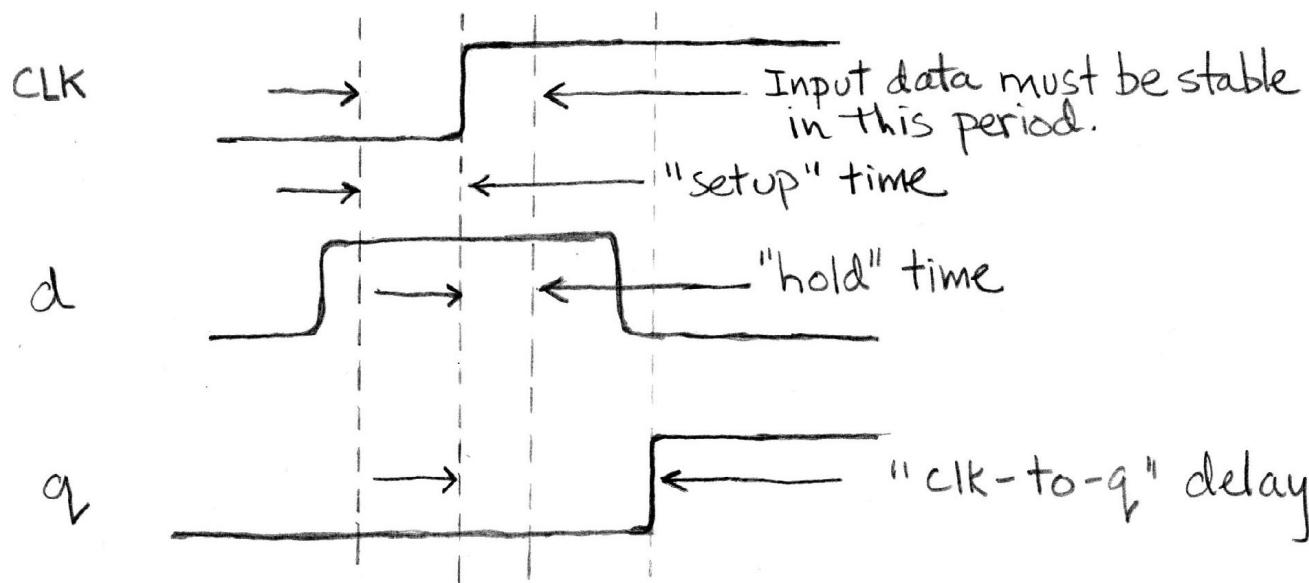
What's the timing of a Flip-flop? (1/2)

- Edge-triggered d-type flip-flop
 - This one is “positive edge-triggered”
- “On the rising edge of the clock, the input d is sampled and transferred to the output. At all other times, the input d is ignored.”
- Example waveforms:

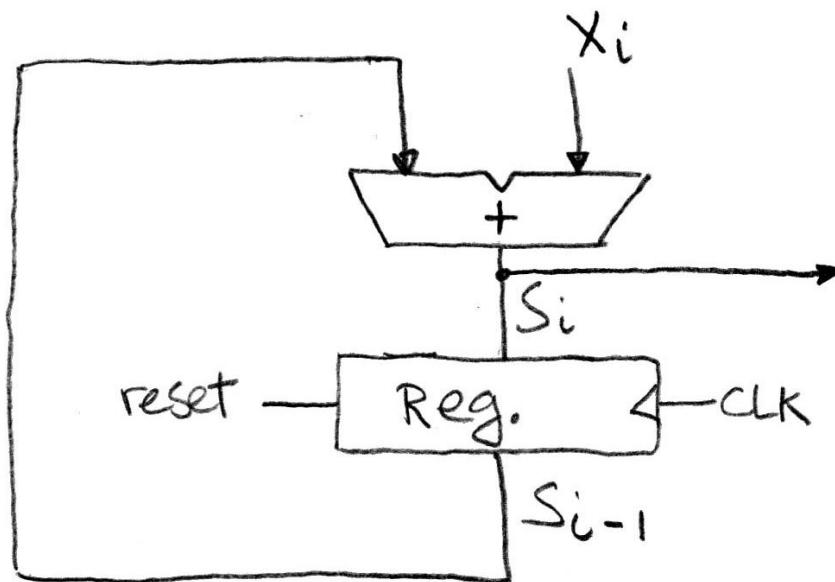


What's the timing of a Flip-flop? (2/2)

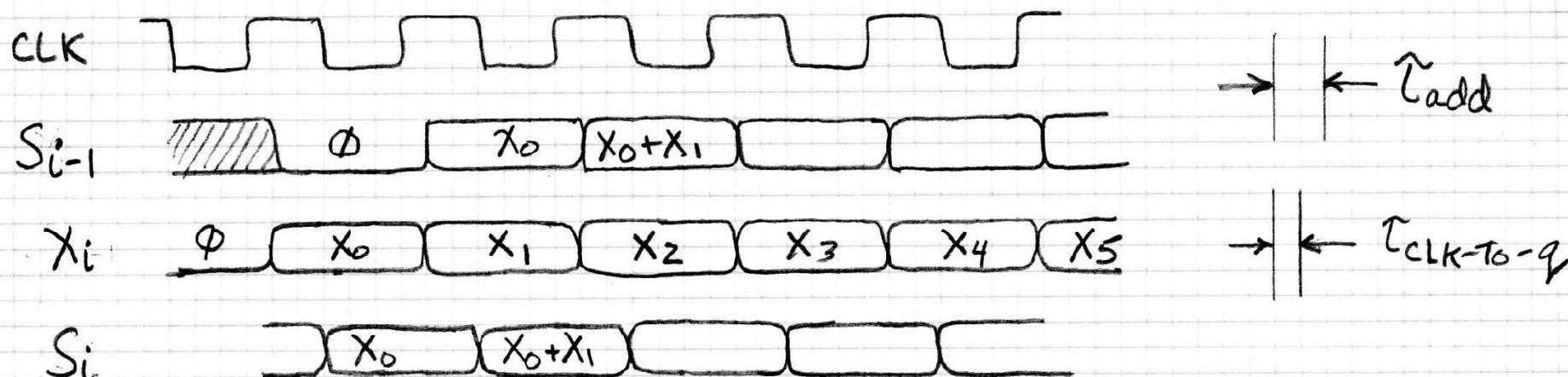
- Edge-triggered d-type flip-flop
 - This one is “positive edge-triggered”
- “On the rising edge of the clock, the input d is sampled and transferred to the output. At all other times, the input d is ignored.”
- Example waveforms (more detail):



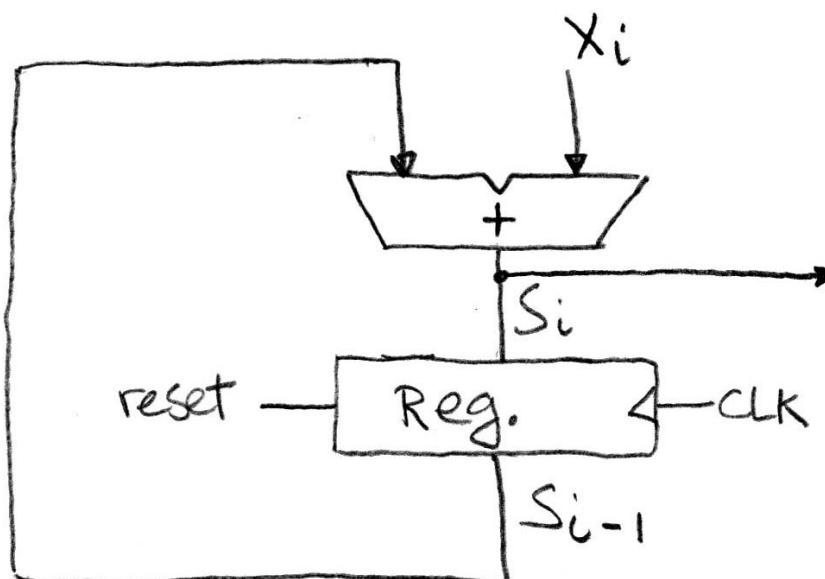
Accumulator Revisited (proper timing 1/2)



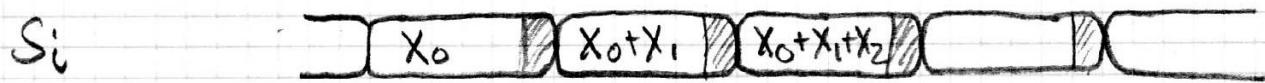
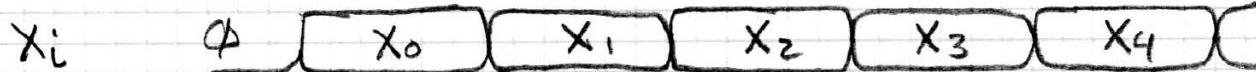
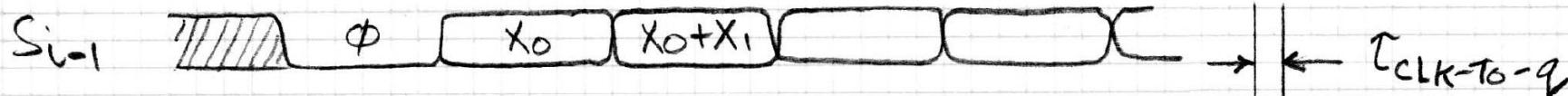
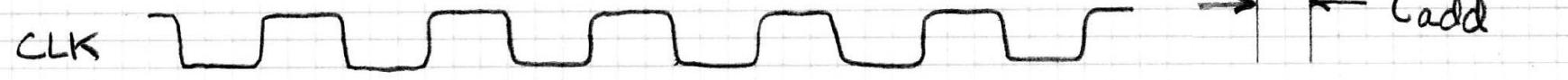
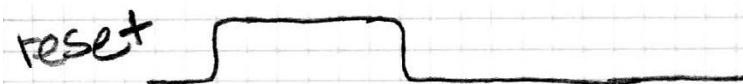
- Reset input to register is used to force it to all zeros (takes priority over D input).
- S_{i-1} holds the result of the $i^{\text{th}}\text{-}1$ iteration.
- Analyze circuit timing starting at the output of the register.



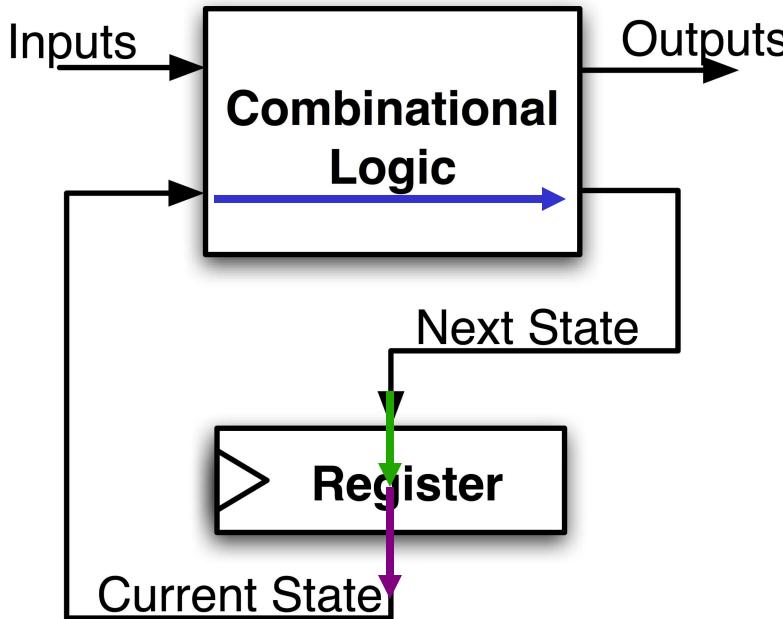
Accumulator Revisited (proper timing 2/2)



- reset signal shown.
- Also, in practice X might not arrive to the adder at the same time as S_{i-1}
- S_i temporarily is wrong, but register always captures correct value.
- In good circuits, instability never happens around rising edge of clk.



Maximum Clock Frequency



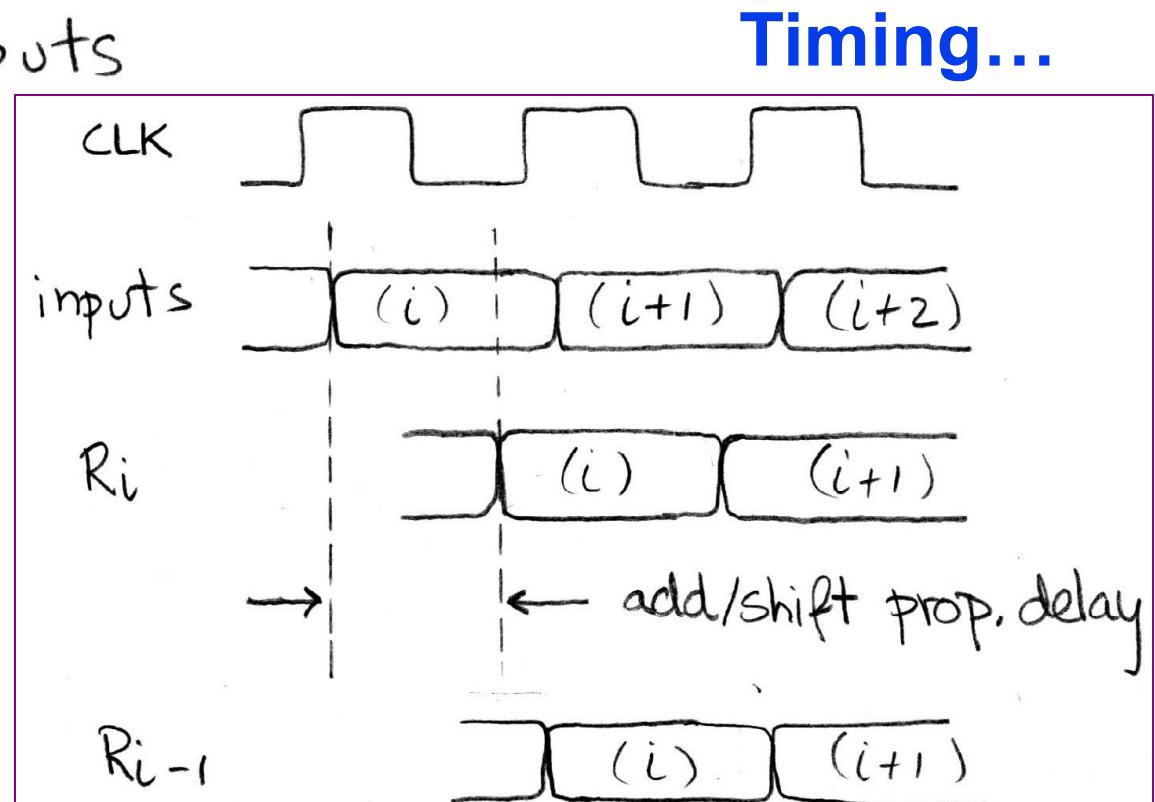
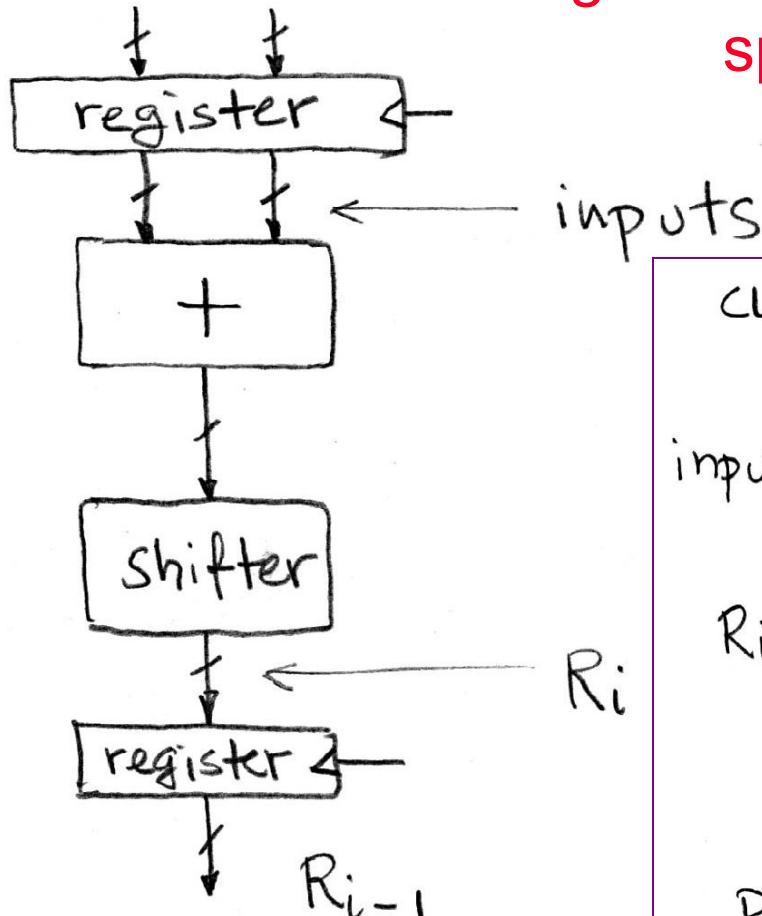
- What is the maximum frequency of this circuit?

**Max Delay = Setup Time + CLK-to-Q Delay
+ CL Delay**

Pipelining to improve performance

(1/2)

Extra Register are often added to help speed up the clock rate.

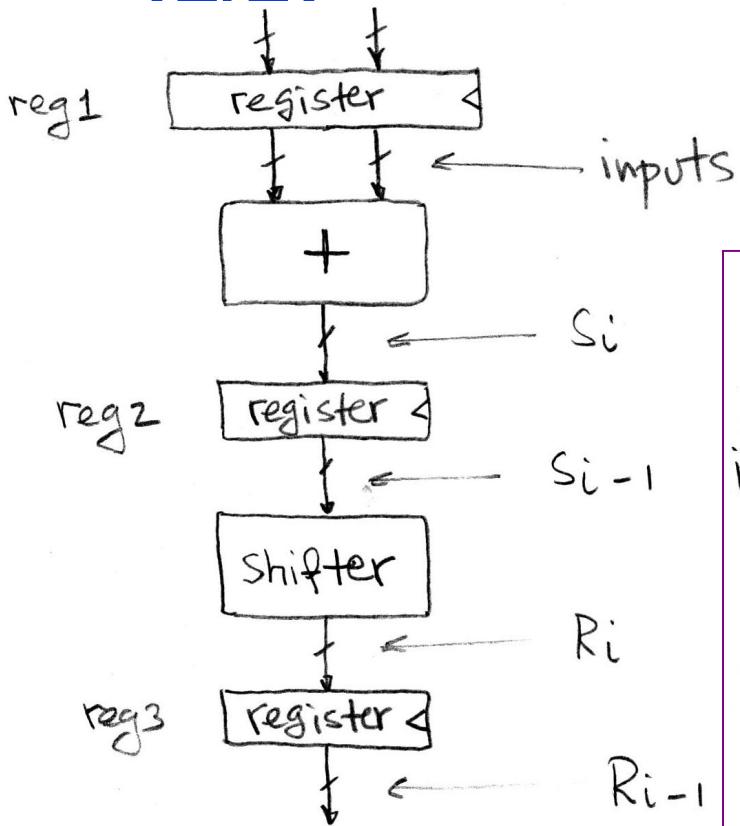


Note: delay of 1 clock cycle from input to output.

Clock period limited by propagation delay of adder/shifter.

Pipelining to improve performance

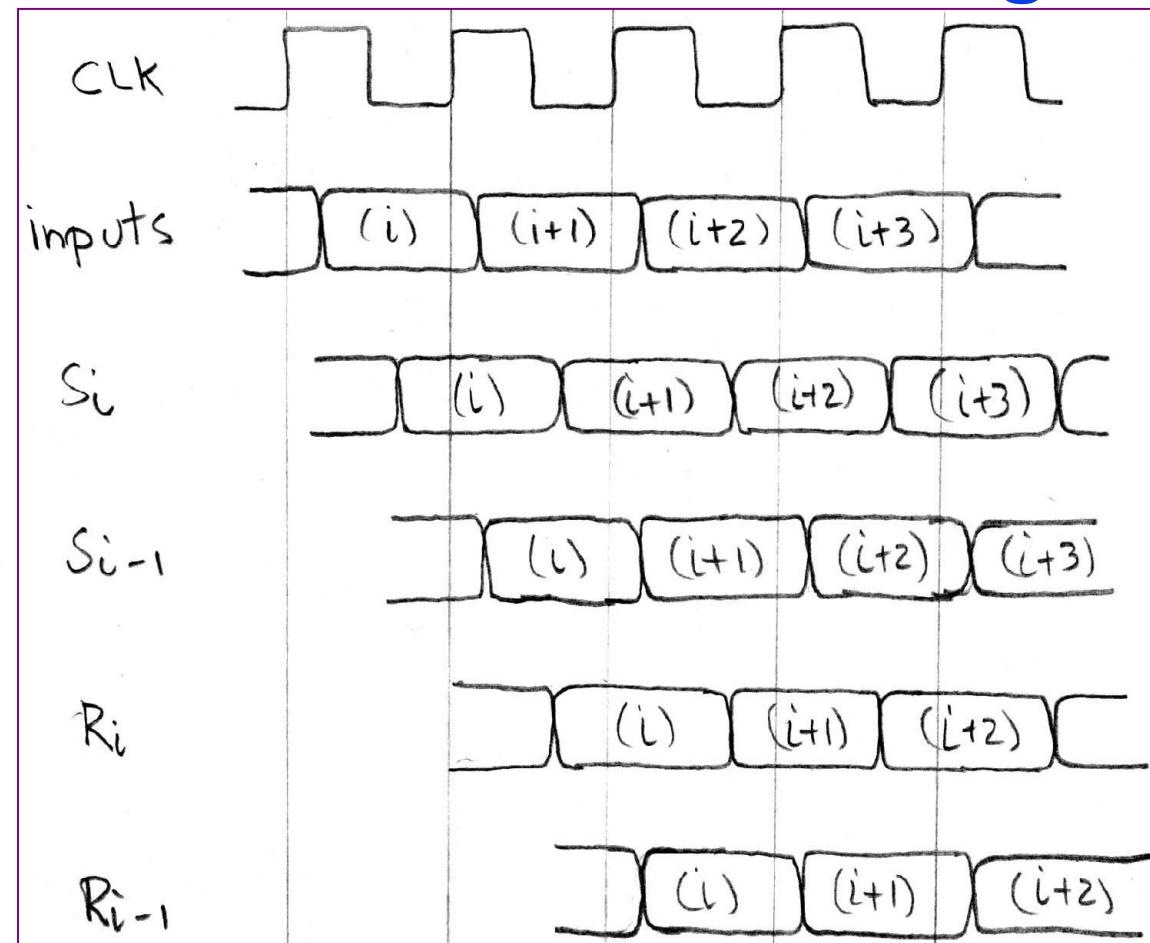
(2/2)



- Insertion of register allows higher clock frequency.

- More outputs per second.

Timing...

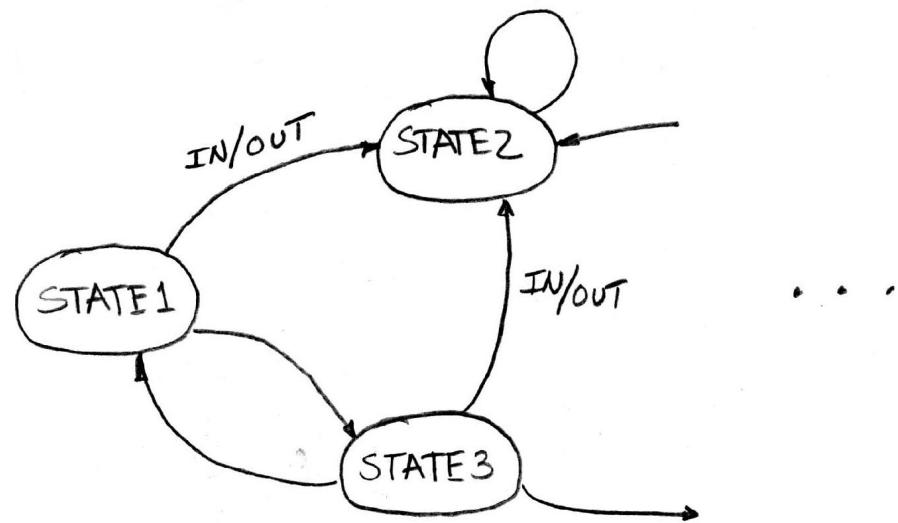


Recap of Timing Terms

- **Clock (CLK)** - steady square wave that synchronizes system
- **Setup Time** - when the input must be stable before the rising edge of the CLK
- **Hold Time** - when the input must be stable after the rising edge of the CLK
- **“CLK-to-Q” Delay** - how long it takes the output to change, measured from the rising edge
- **Flip-flop** - one bit of state that samples every rising edge of the CLK
- **Register** - several bits of state that samples on rising edge of CLK or on LOAD

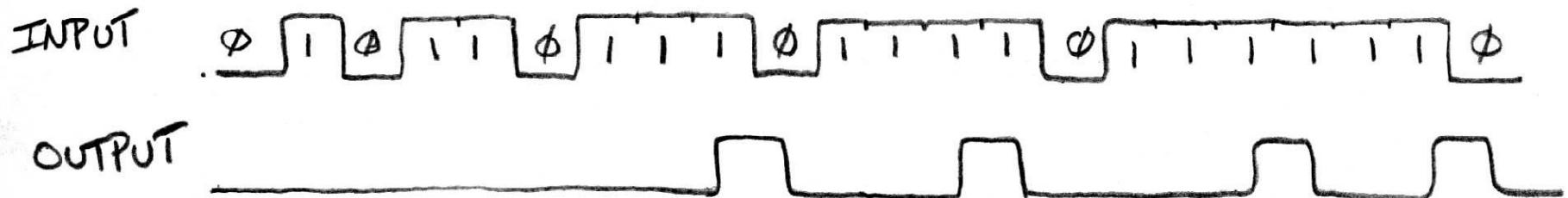
Finite State Machines (FSM) Introduction

- You have seen FSMs in other classes.
- Same basic idea.
- The function can be represented with a “state transition diagram”.
- With combinational logic and registers, any FSM can be implemented in hardware.

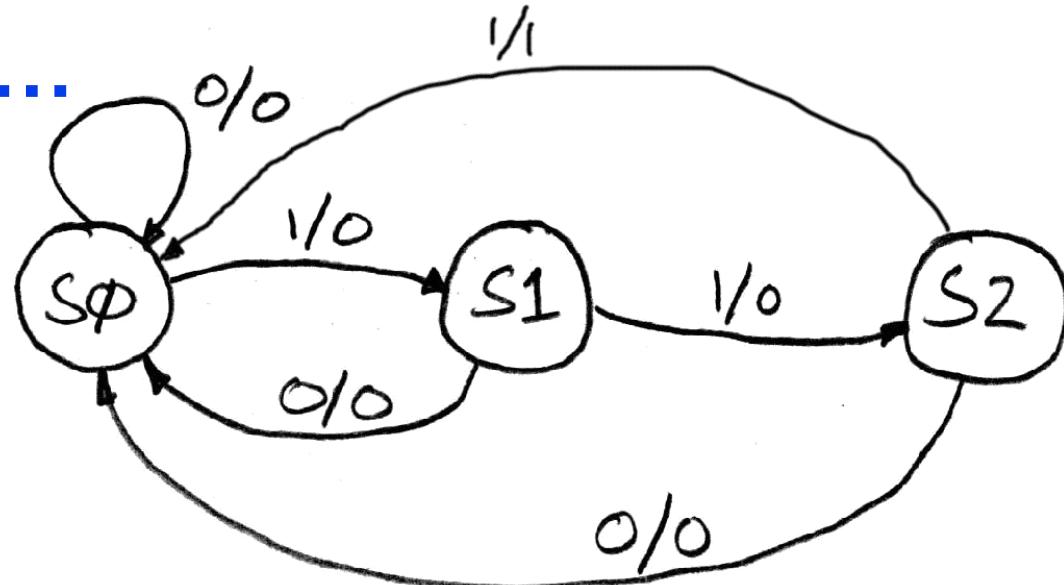


Finite State Machine Example: 3 ones...

FSM to detect the occurrence of 3 consecutive 1's in the input.



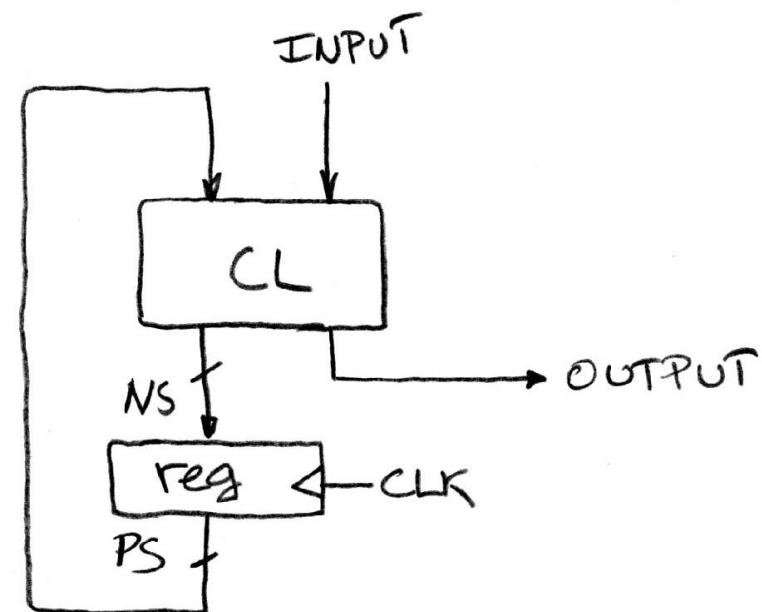
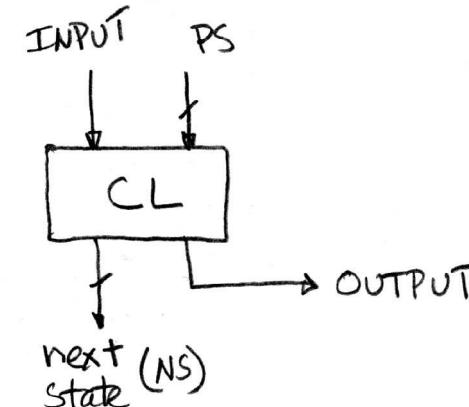
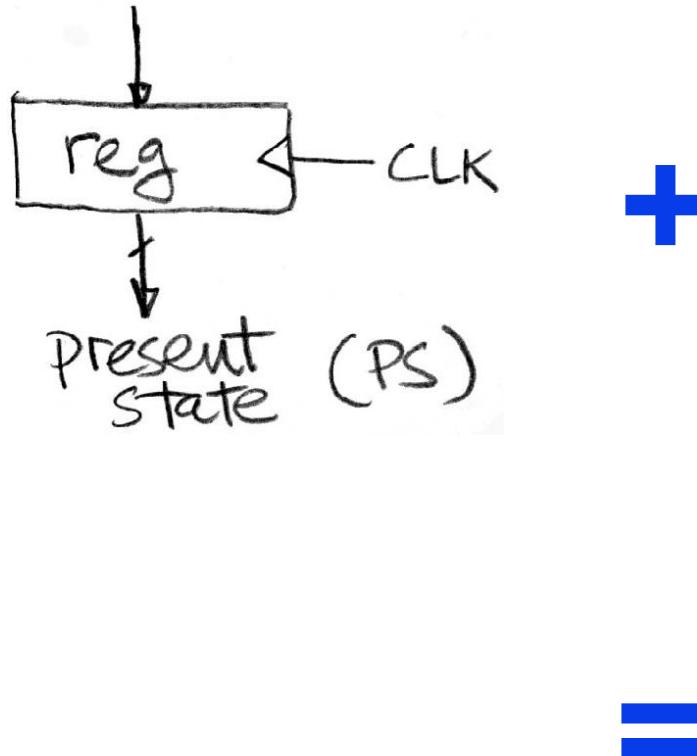
Draw the FSM...



Assume state transitions are controlled by the clock:
on each clock cycle the machine checks the inputs and moves
to a new state and produces a new output...

Hardware Implementation of FSM

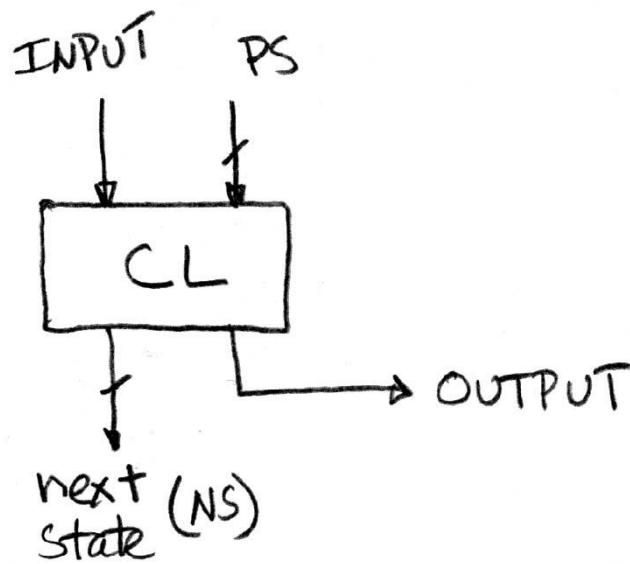
... Therefore a register is needed to hold the a representation of which state the machine is in. Use a unique bit pattern for each state.



Combinational logic circuit is used to implement a function maps from *present state and input* to *next state and output*.

Hardware for FSM: Combinational Logic

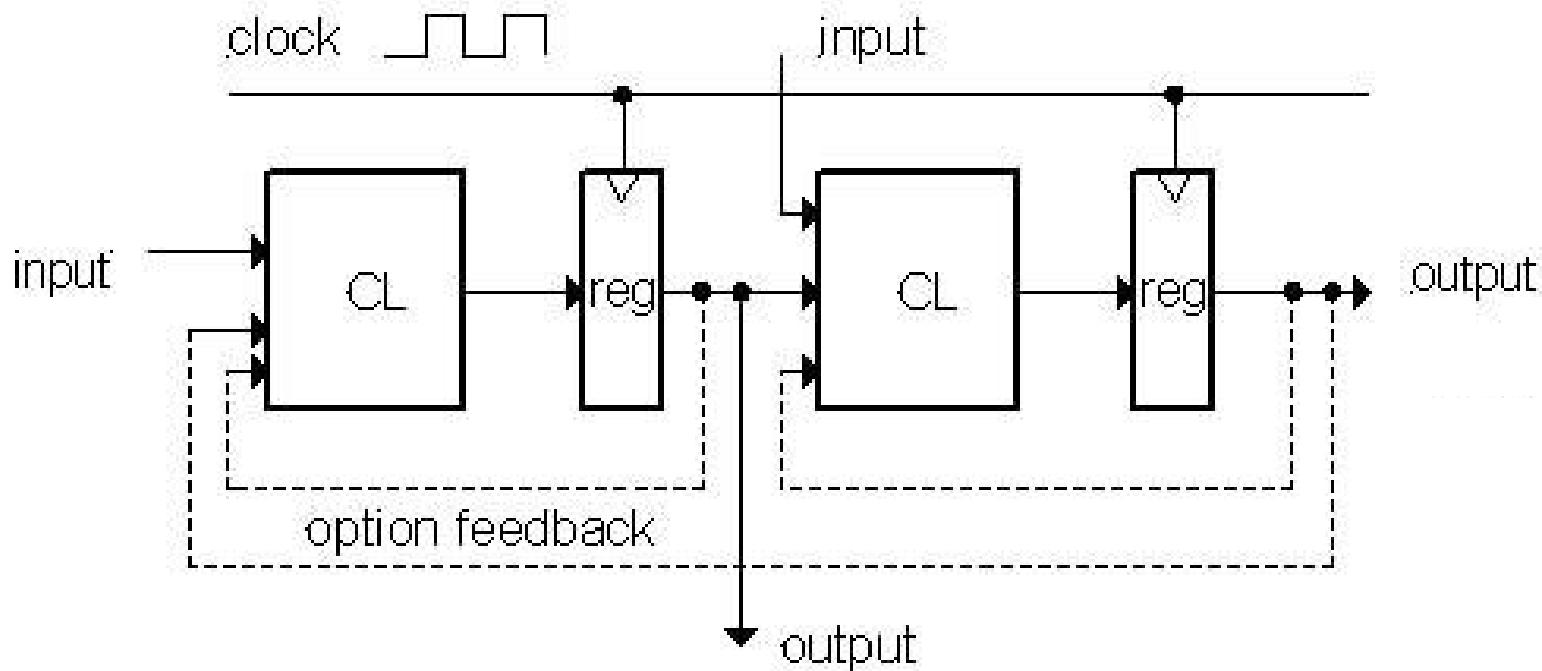
Next lecture we will discuss the detailed implementation, but for now can look at its functional specification, truth table form.



Truth table...

PS	Input	NS	Output
00	0	00	0
00	1	01	0
01	0	00	0
01	1	10	0
10	0	00	0
10	1	00	1

General Model for Synchronous Systems



- Collection of CL blocks separated by registers.
- Registers may be back-to-back and CL blocks may be back-to-back.
- Feedback is optional.
- Clock signal(s) connects only to clock input of registers.

Peer Instruction

- A. HW feedback akin to SW recursion
- B. The period of a **usable synchronous circuit** is greater than the CLK-to-Q delay
- C. You can build a FSM to signal when an equal number of 0s and 1s has appeared in the input.

	ABC
A:	FFF
B:	FTF
C:	TFF
D:	TTF
E:	TTT

Peer Instruction

- A. It needs ‘base case’ (req reset), way to step from i to $i+1$ (use register + clock). **True!**
- B. If not, will loose data! **True!**
- C. How many states would it have? Say it’s n . How does it know when $n+1$ bits have been seen?
False!

- A. HW feedback akin to SW recursion
- B. The period of a **usable synchronous circuit** is greater than the CLK-to-Q delay
- C. You can build a FSM to signal when an equal number of 0s and 1s has appeared in the input.

	ABC
A:	FFF
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C:	TFF
D:	TTF
E:	TTT

“And In conclusion...”

- State elements are used to:
 - Build memories
 - Control the flow of information between other state elements and combinational logic
- D-flip-flops used to build registers
- Clocks tell us when D-flip-flops change
 - Setup and Hold times important
- We pipeline long-delay CL for faster clock
- Finite State Machines extremely useful
 - You'll see them again...

0.15 Combinational Logic Circuit

Computer Architecture (计算机体系结构)

Lecture 17 – Representations of Combinatorial Logic Circuits

2020-10-12



Lecturer: Yuanqing Cheng



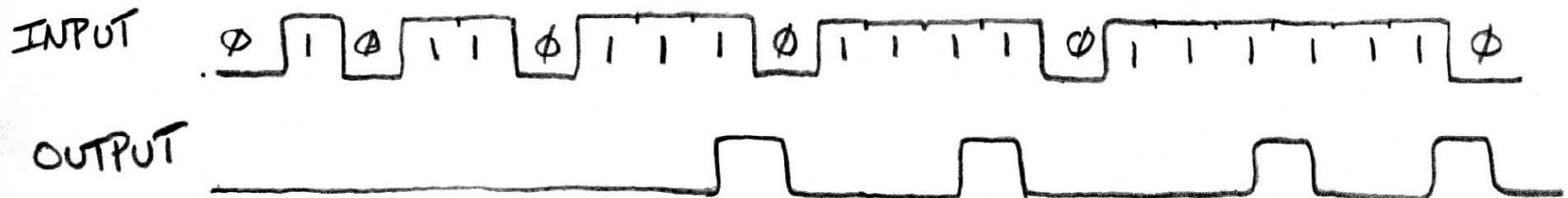
5G Rollout on a Steady Ramp
Toward Big Growth

Mobile network operators have done a decent job rolling out 5G technology and are beginning to reap needed returns on their huge investments.

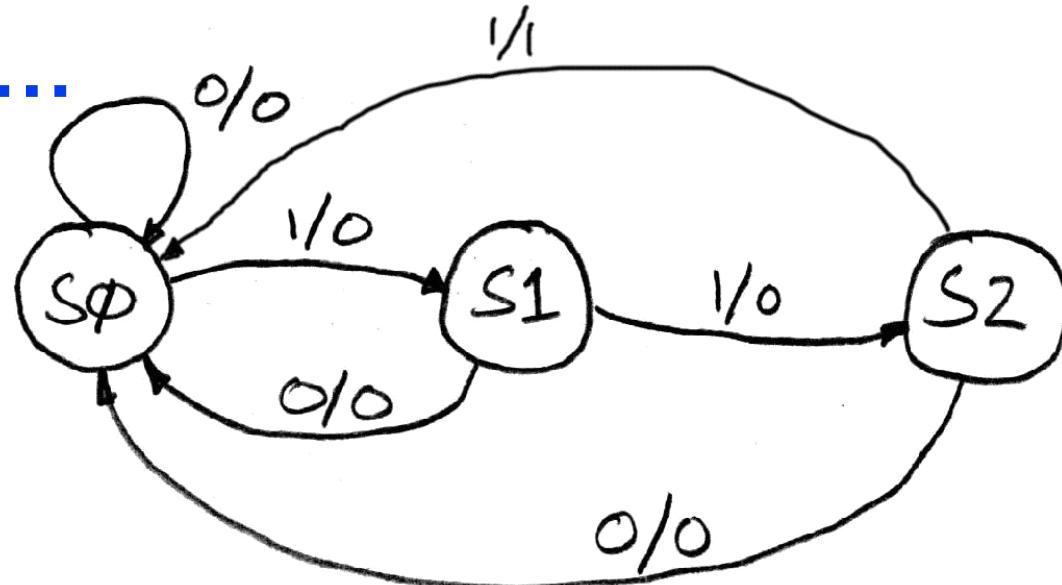
By John Walko Oct 09, 2020

Finite State Machine Example: 3 ones...

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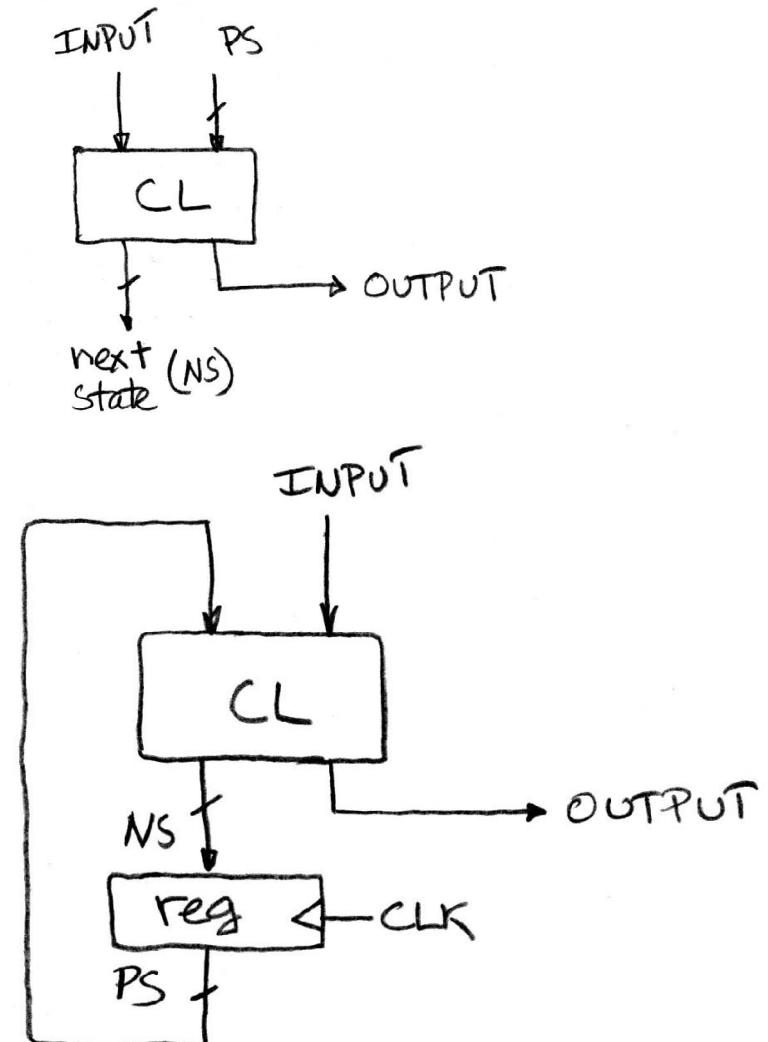
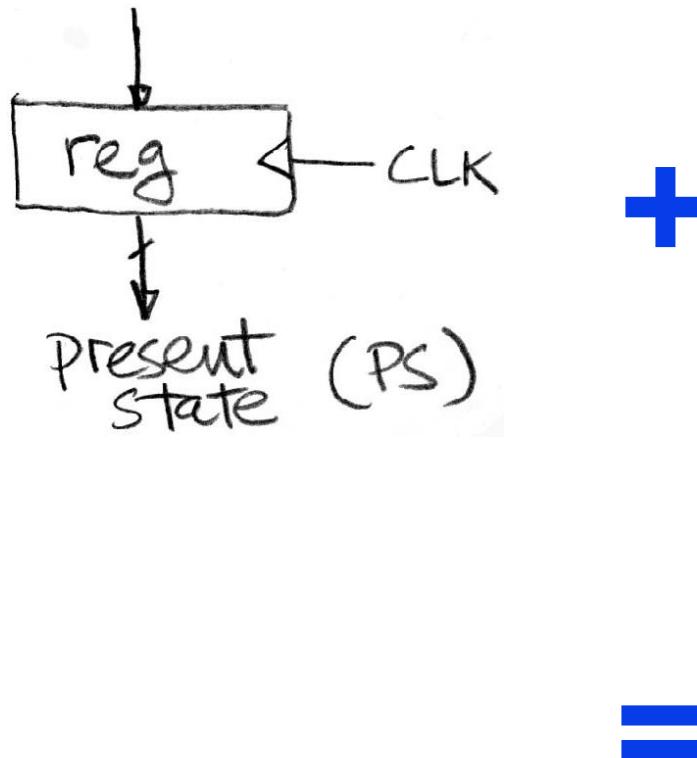
Draw the FSM...



Assume state transitions are controlled by the clock:
on each clock cycle the machine checks the inputs and moves
to a new state and produces a new output...

Hardware Implementation of FSM

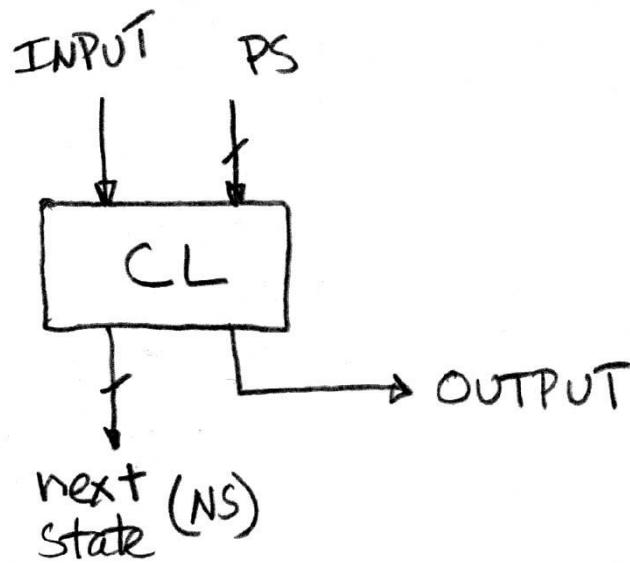
... Therefore a register is needed to hold the a representation of which state the machine is in. Use a unique bit pattern for each state.



Combinational logic circuit is used to implement a function maps from *present state and input* to *next state and output*.

Hardware for FSM: Combinational Logic

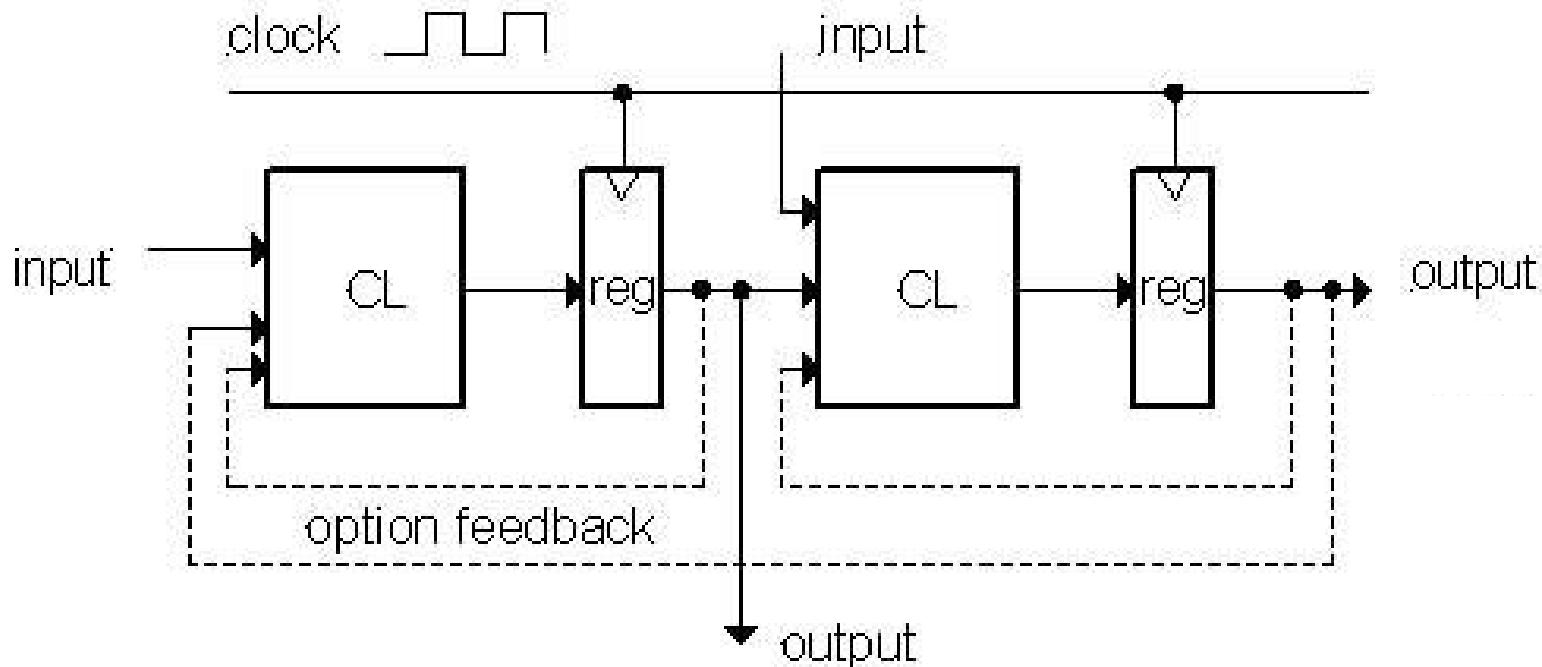
This lecture we will discuss the detailed implementation, but for now can look at its functional specification, truth table form.



Truth table...

PS	Input	NS	Output
00	0	00	0
00	1	01	0
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01	1	10	0
10	0	00	0
10	1	00	1

General Model for Synchronous Systems



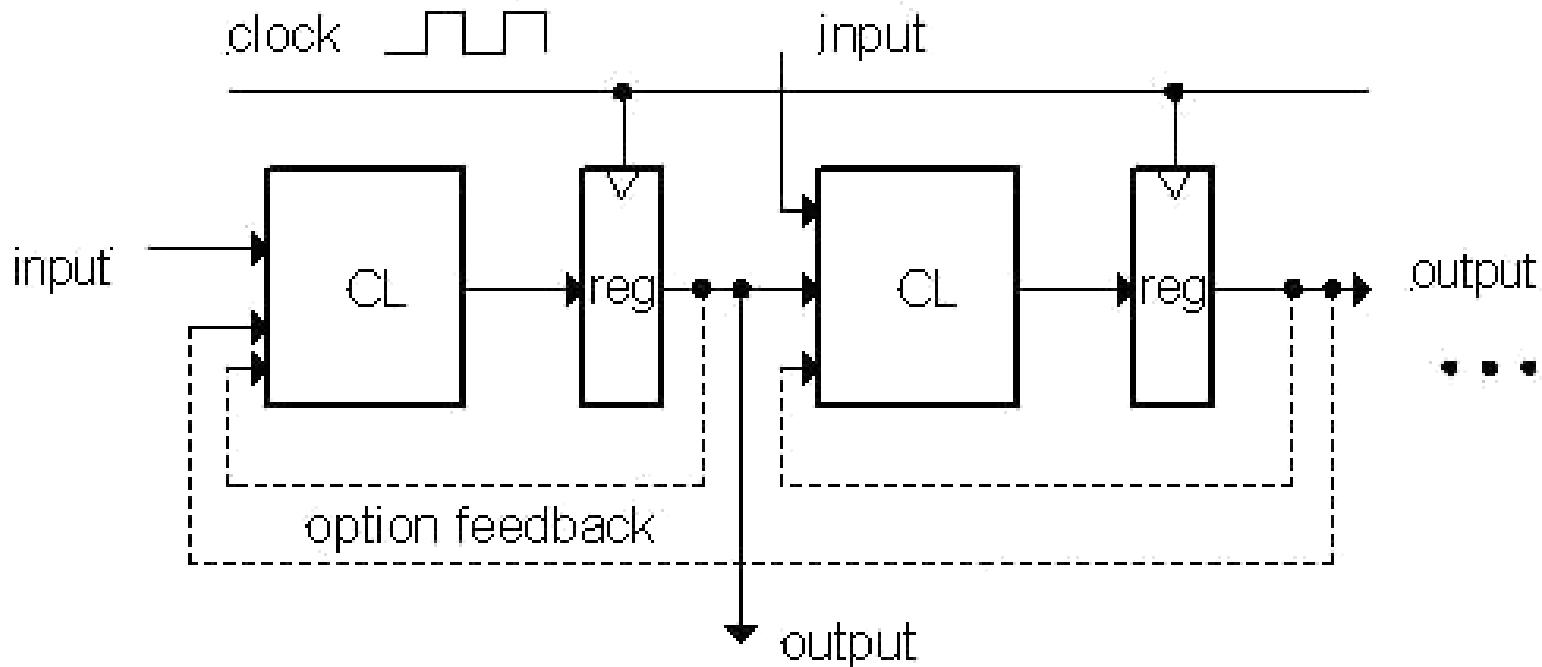
- Collection of CL blocks separated by registers.
- Registers may be back-to-back and CL blocks may be back-to-back.
- Feedback is optional.
- Clock signal(s) connects only to clock input of registers.

Review

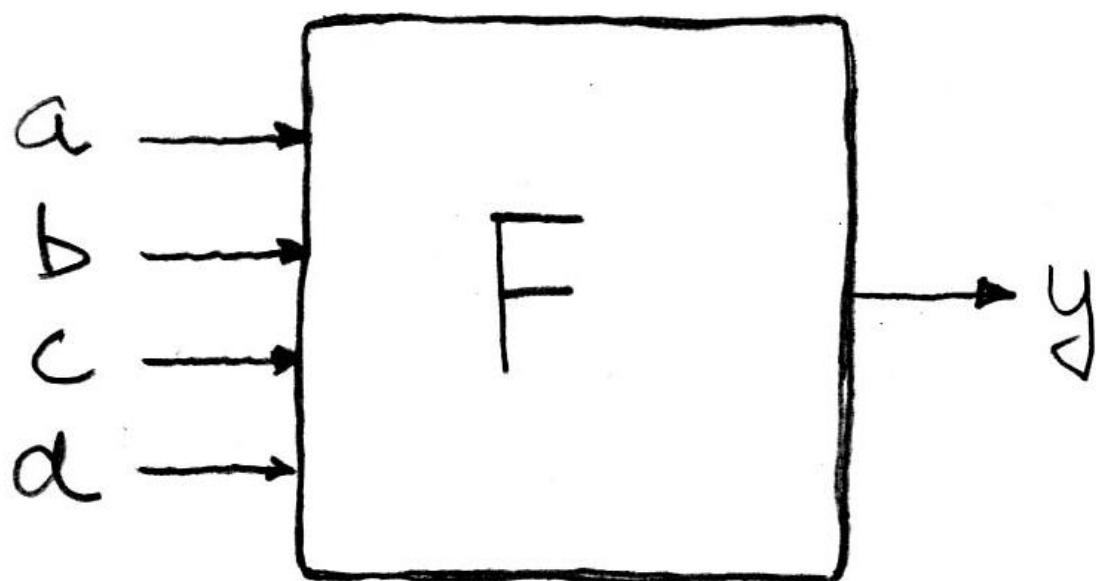
- State elements are used to:
 - Build memories
 - Control the flow of information between other state elements and combinational logic
- D-flip-flops used to build registers
- Clocks tell us when D-flip-flops change
 - Setup and Hold times important
- We pipeline long-delay CL for faster clock
- Finite State Machines extremely useful
 - Represent states and transitions

Combinational Logic

- FSMs had states and transitions
- How do we get from one state to the next?
- Answer: Combinational Logic



Truth Tables

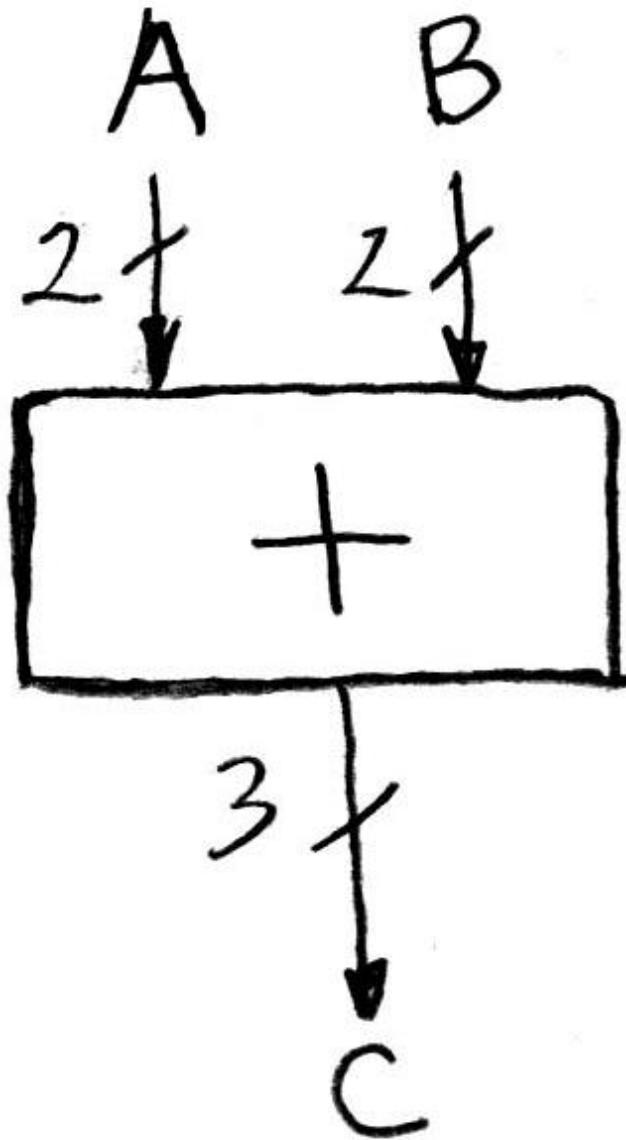


a	b	c	d	y
0	0	0	0	$F(0,0,0,0)$
0	0	0	1	$F(0,0,0,1)$
0	0	1	0	$F(0,0,1,0)$
0	0	1	1	$F(0,0,1,1)$
0	1	0	0	$F(0,1,0,0)$
0	1	0	1	$F(0,1,0,1)$
0	1	1	0	$F(0,1,1,0)$
0	1	1	1	$F(0,1,1,1)$
1	0	0	0	$F(1,0,0,0)$
1	0	0	1	$F(1,0,0,1)$
1	0	1	0	$F(1,0,1,0)$
1	0	1	1	$F(1,0,1,1)$
1	1	0	0	$F(1,1,0,0)$
1	1	0	1	$F(1,1,0,1)$
1	1	1	0	$F(1,1,1,0)$
1	1	1	1	$F(1,1,1,1)$

TT Example #1: 1 iff one (not both) a,b=1

a	b	y
0	0	0
0	1	1
1	0	1
1	1	0

TT Example #2: 2-bit adder



A a_1a_0	B b_1b_0	C $c_2c_1c_0$
00	00	000
00	01	001
00	10	010
00	11	011
01	00	001
01	01	010
01	10	011
01	11	100
10	00	010
10	01	011
10	10	100
10	11	101
11	00	011
11	01	100
11	10	101
11	11	110

How
Many
Rows?

TT Example #3: 32-bit unsigned adder

A	B	C
000 ... 0	000 ... 0	000 ... 00
000 ... 0	000 ... 1	000 ... 01
.	.	.
.	.	.
.	.	.
111 ... 1	111 ... 1	111 ... 10

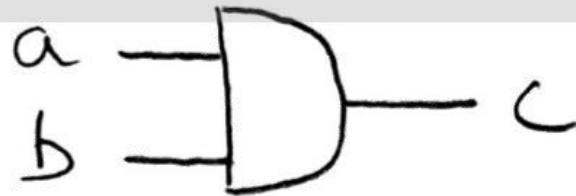
How
Many
Rows?

TT Example #4: 3-input majority circuit

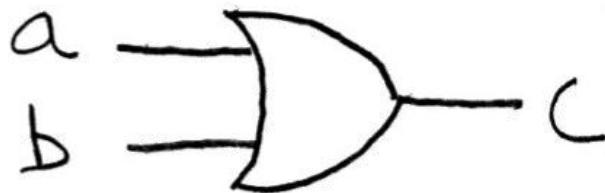
a	b	c	y
0	0	0	0
0	0	1	0
0	1	0	0
0	1	1	1
1	0	0	0
1	0	1	1
1	1	0	1
1	1	1	1

Logic Gates (1/2)

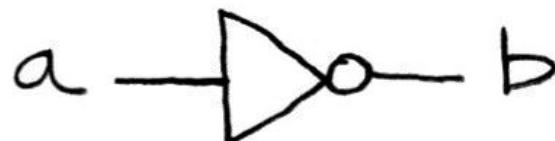
AND



OR



NOT



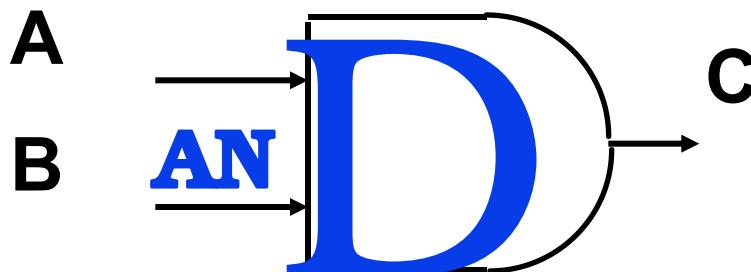
ab	c
00	0
01	0
10	0
11	1

a	b
0	1
1	0

And vs. Or review – Dan's mnemonic

AND Gate

Symbol

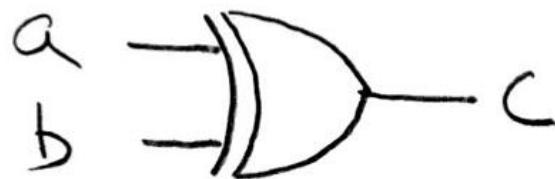


Definition

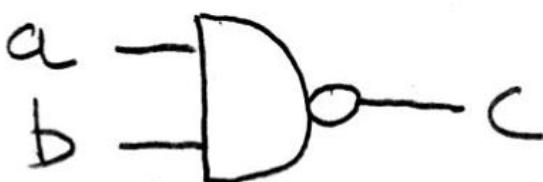
A	B	C
0	0	0
0	1	0
1	0	0
1	1	1

Logic Gates (2/2)

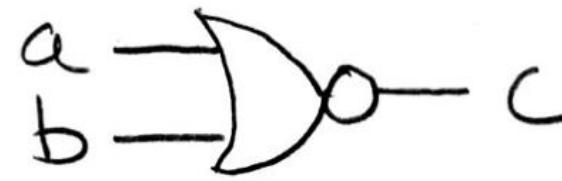
XOR



NAND



NOR



ab	c
00	0
01	1
10	1
11	0

ab	c
00	1
01	1
10	1
11	0

ab	c
00	1
01	0
10	0
11	0

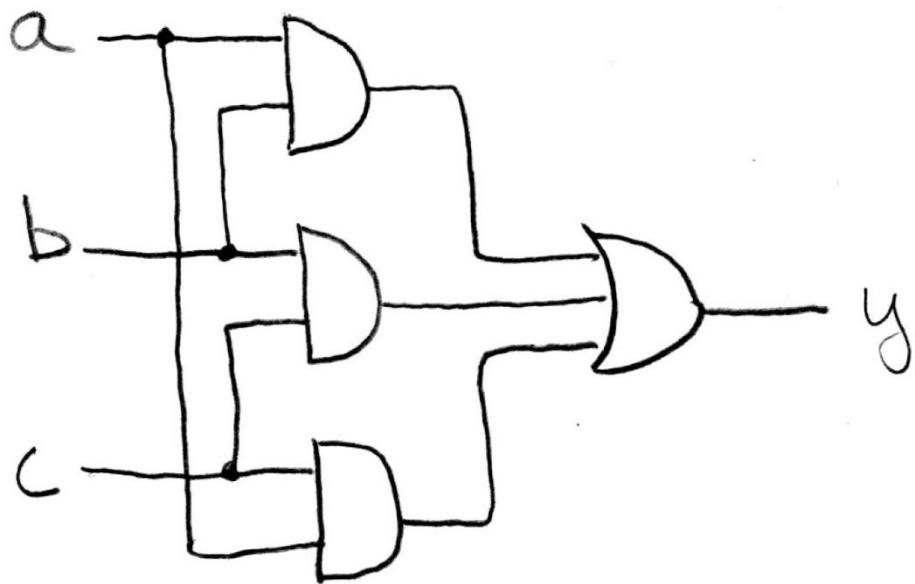
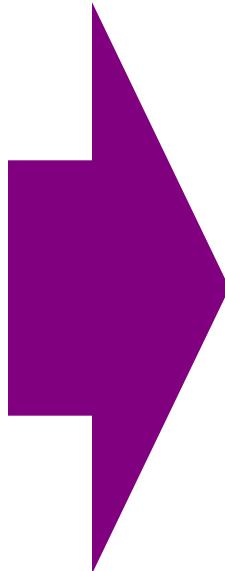
2-input gates extend to n-inputs

- N-input XOR is the only one which isn't so obvious
- It's simple: XOR is a 1 iff the # of 1s at its input is odd \Rightarrow

a	b	c	y
0	0	0	0
0	0	1	1
0	1	0	1
0	1	1	0
1	0	0	1
1	0	1	0
1	1	0	0
1	1	1	1

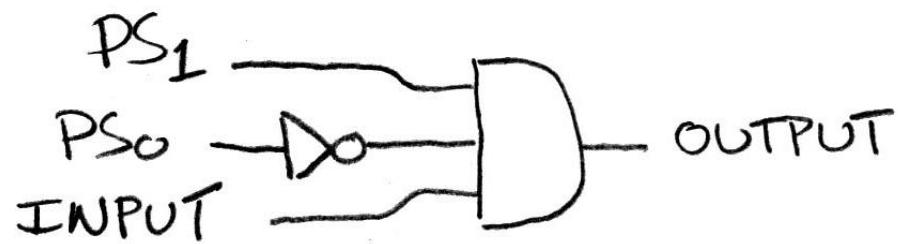
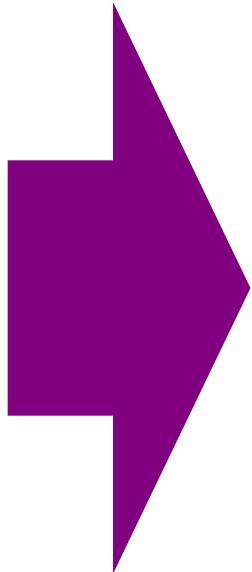
Truth Table \Rightarrow Gates (e.g., majority circ.)

a	b	c	y
0	0	0	0
0	0	1	0
0	1	0	0
0	1	1	1
1	0	0	0
1	0	1	1
1	1	0	1
1	1	1	1

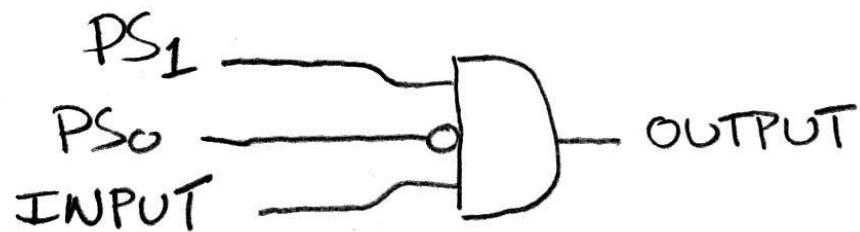


Truth Table \Rightarrow Gates (e.g., FSM circ.)

PS	Input	NS	Output
00	0	00	0
00	1	01	0
01	0	00	0
01	1	10	0
10	0	00	0
10	1	00	1

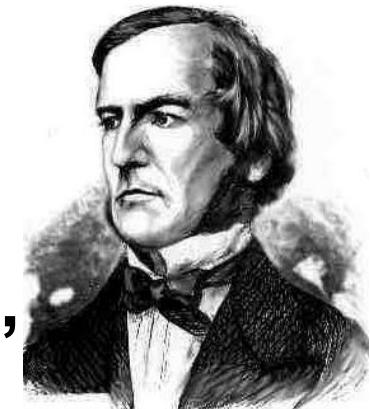


or equivalently...

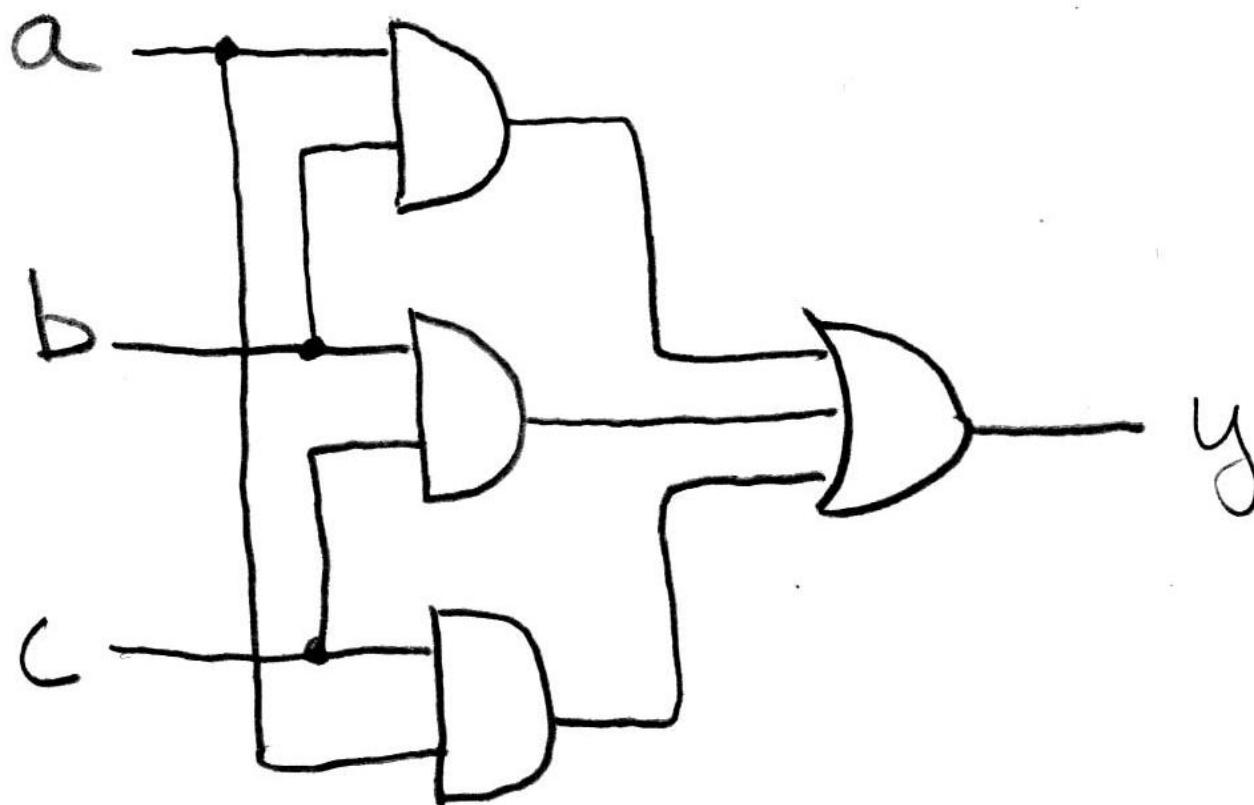


Boolean Algebra

- George Boole, 19th Century mathematician
- Developed a mathematical system (algebra) involving logic
 - later known as “Boolean Algebra”
- Primitive functions: AND, OR and NOT
- The power of BA is there's a one-to-one correspondence between circuits made up of AND, OR and NOT gates and equations in BA
 - + means OR, • means AND, \bar{x} means NOT



Boolean Algebra (e.g., for majority fun.)

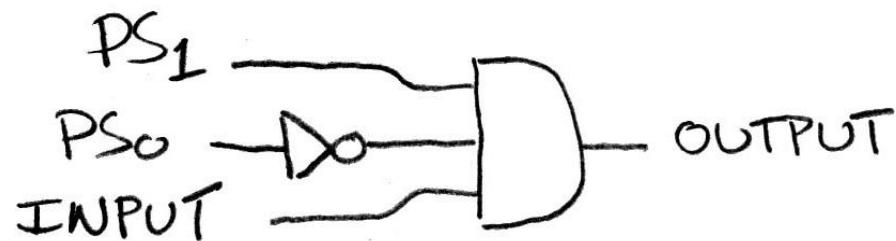
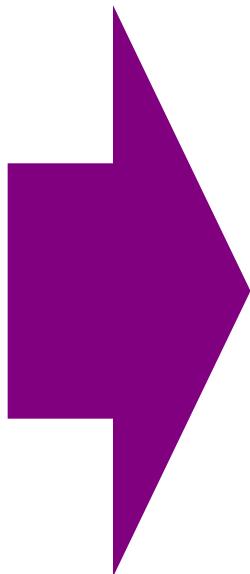


$$y = a \cdot b + a \cdot c + b \cdot c$$

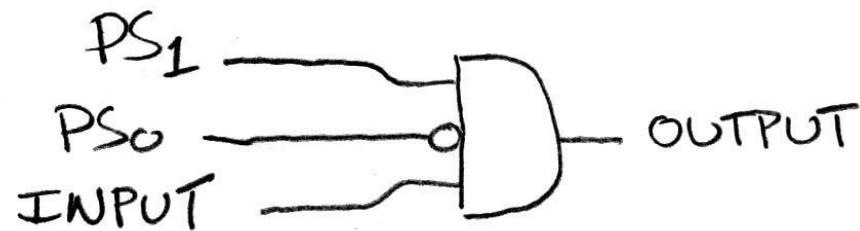
$$y = ab + ac + bc$$

Boolean Algebra (e.g., for FSM)

PS	Input	NS	Output
00	0	00	0
00	1	01	0
01	0	00	0
01	1	10	0
10	0	00	0
10	1	00	1

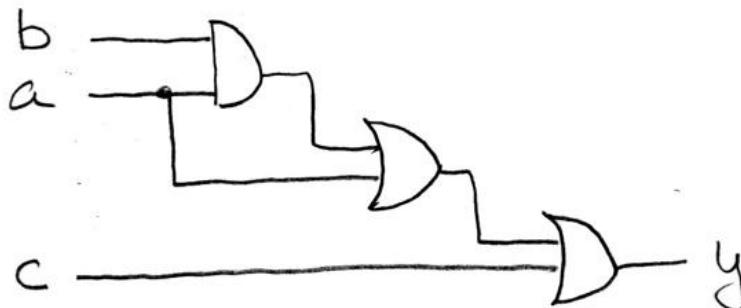


or equivalently...



$$y = \overline{PS_1} \cdot PS_0 \cdot INPUT$$

BA: Circuit & Algebraic Simplification



original circuit

$$y = ((ab) + a) + c$$

$$= ab + a + c$$

$$= a(b + 1) + c$$

$$= a(1) + c$$

$$= a + c$$



equation derived from original circuit

algebraic simplification

**BA also great for
circuit verification**
**Circ X = Circ Y?
use BA to prove!**

simplified circuit

Laws of Boolean Algebra

$$x \cdot \bar{x} = 0$$

$$x \cdot 0 = 0$$

$$x \cdot 1 = x$$

$$x \cdot x = x$$

$$x \cdot y = y \cdot x$$

$$(xy)z = x(yz)$$

$$x(y + z) = xy + xz$$

$$xy + x = x$$

$$\bar{xy} + x = x + y$$

$$\overline{x \cdot y} = \bar{x} + \bar{y}$$

$$x + \bar{x} = 1$$

$$x + 1 = 1$$

$$x + 0 = x$$

$$x + x = x$$

$$x + y = y + x$$

$$(x + y) + z = x + (y + z)$$

$$x + yz = (x + y)(x + z)$$

$$(x + y)x = x$$

$$(\bar{x} + y)x = xy$$

$$\overline{x + y} = \bar{x} \cdot \bar{y}$$

complementarity
laws of 0's and 1's
identities

 idempotent law

commutativity

associativity

distribution

uniting theorem

uniting theorem v.2

DeMorgan's Law

Boolean Algebraic Simplification Example

$$\begin{aligned}y &= ab + a + c \\&= a(b + 1) + c \quad \textit{distribution, identity} \\&= a(1) + c \quad \textit{law of 1's} \\&= a + c \quad \textit{identity}\end{aligned}$$

Canonical forms (1/2)

	abc	y
$\bar{a} \cdot \bar{b} \cdot \bar{c}$	000	1
$\bar{a} \cdot \bar{b} \cdot c$	001	1
	010	0
	011	0
$a \cdot \bar{b} \cdot \bar{c}$	100	1
	101	0
$a \cdot b \cdot \bar{c}$	110	1
	111	0

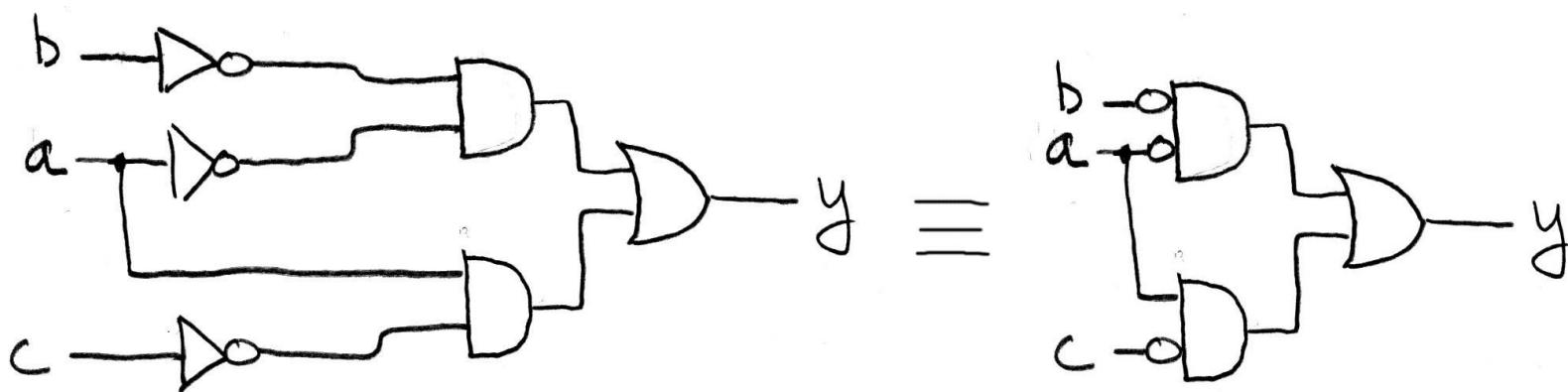
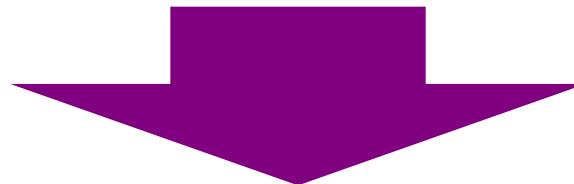
**Sum-of-products
(ORs of ANDs)**



Canonical forms (2/2)

$$\begin{aligned}y &= \bar{a}\bar{b}\bar{c} + \bar{a}\bar{b}c + a\bar{b}\bar{c} + ab\bar{c} \\&= \bar{a}\bar{b}(\bar{c} + c) + a\bar{c}(\bar{b} + b) \\&= \bar{a}\bar{b}(1) + a\bar{c}(1) \\&= \bar{a}\bar{b} + a\bar{c}\end{aligned}$$

distribution
complementarity
identity



Peer Instruction

- A. $(a+b) \cdot (\bar{a}+b) = b$
- B. N-input gates can be thought of cascaded 2-input gates. I.e.,
 $(a \Delta bc \Delta d \Delta e) = a \Delta (bc \Delta (d \Delta e))$
where Δ is one of AND, OR, XOR, NAND
- C. You can use NOR(s) with clever wiring to simulate AND, OR, & NOT

	ABC
1:	FFF
2:	FFT
3:	FTF
4:	FTT
5:	TFF
6:	TFT
7:	TTF
8:	TTT

Peer Instruction Answer (B)

- B. N-input gates can be thought of cascaded 2-input gates. I.e.,
 $(a \Delta bc \Delta d \Delta e) = a \Delta (bc \Delta (d \Delta e))$
where Δ is one of AND, OR, XOR, NAND...**FALSE**

Let's confirm!

CORRECT 3-input

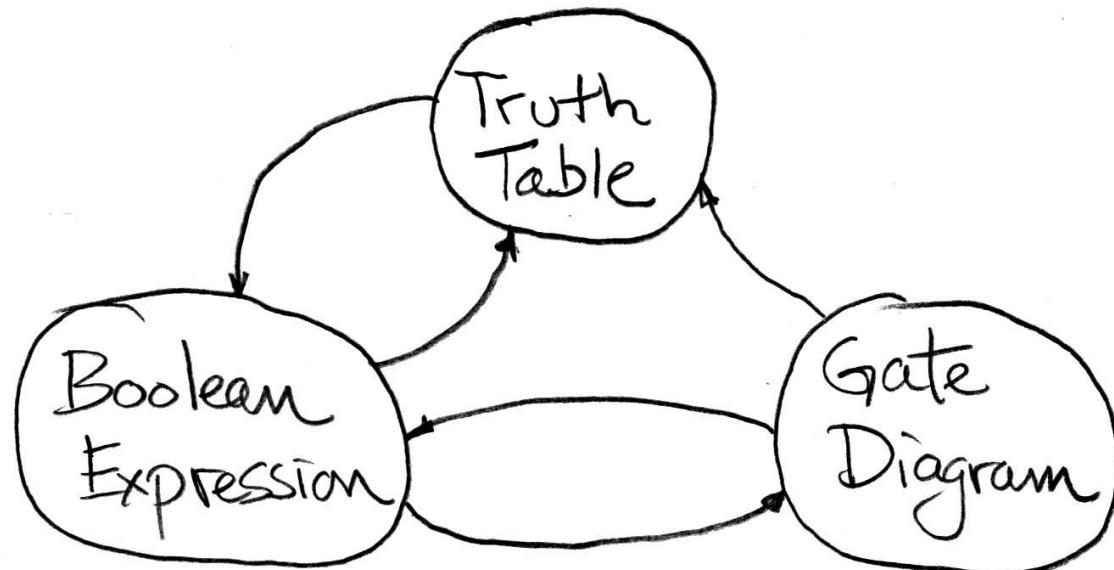
XYZ	AND	OR	XOR	NAND
000	0	0	0	1
001	0	1	1	1
010	0	1	1	1
011	0	1	0	1
100	0	1	1	1
101	0	1	0	1
110	0	1	0	1
111	1	1	1	0

CORRECT 2-input

YZ	AND	OR	XOR	NAND
00	0	0	0	1
01	0	1	1	1
10	0	1	1	1
11	1	1	0	0

“And In conclusion...”

- Pipeline big-delay CL for faster clock
- Finite State Machines extremely useful
 - You'll see them again in 150, 152 & 164
- Use this table and techniques we learned to transform from 1 to another



Computer Architecture (计算机体系结构)

Lecture 23 – Combinational Logic Blocks

2020-10-12

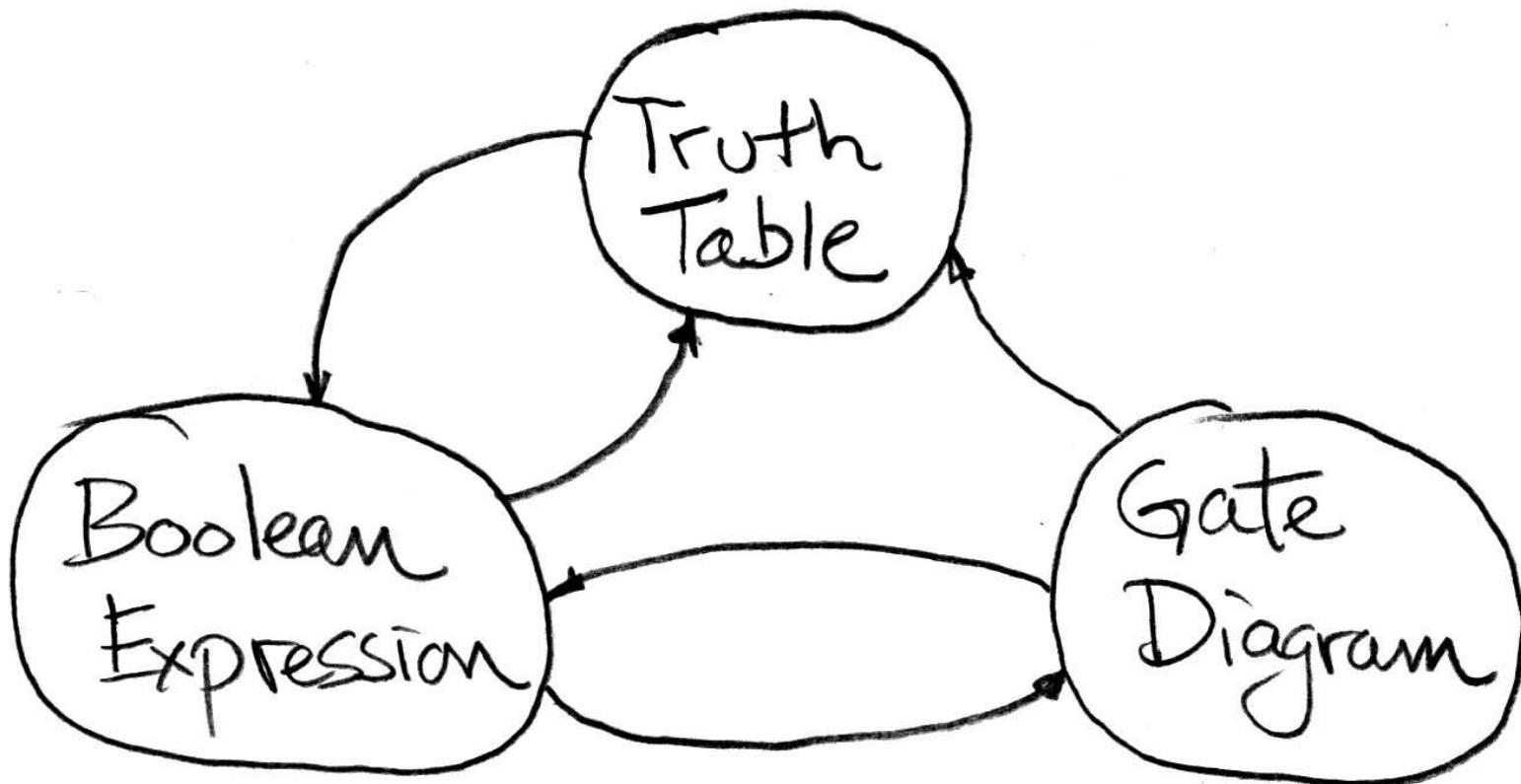


Lecturer Yuanqing Cheng

www.cadetlab.cn/~course

Review

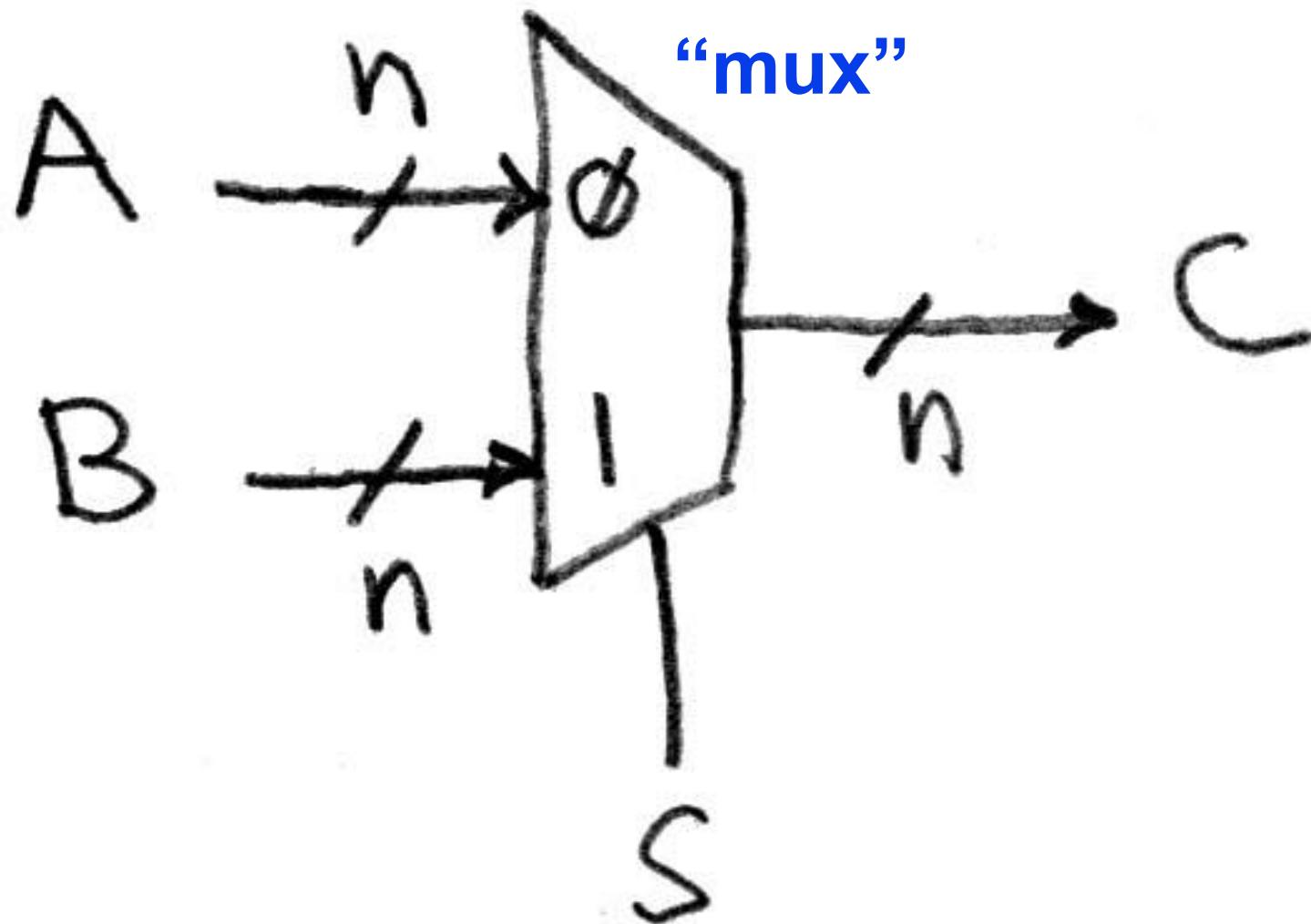
- Use this table and techniques we learned to transform from 1 to another



Today

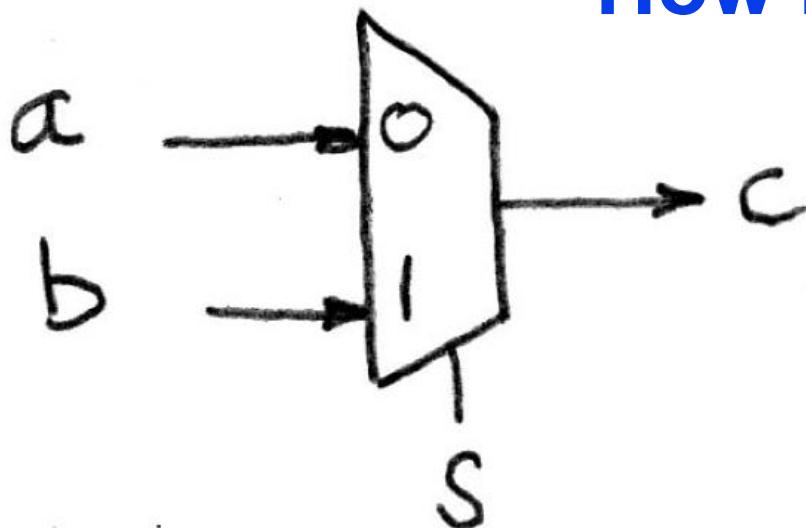
- Data Multiplexors
- Arithmetic and Logic Unit
- Adder/Subtractor

Data Multiplexor (here 2-to-1, n-bit-wide)



N instances of 1-bit-wide mux

How many rows in TT?

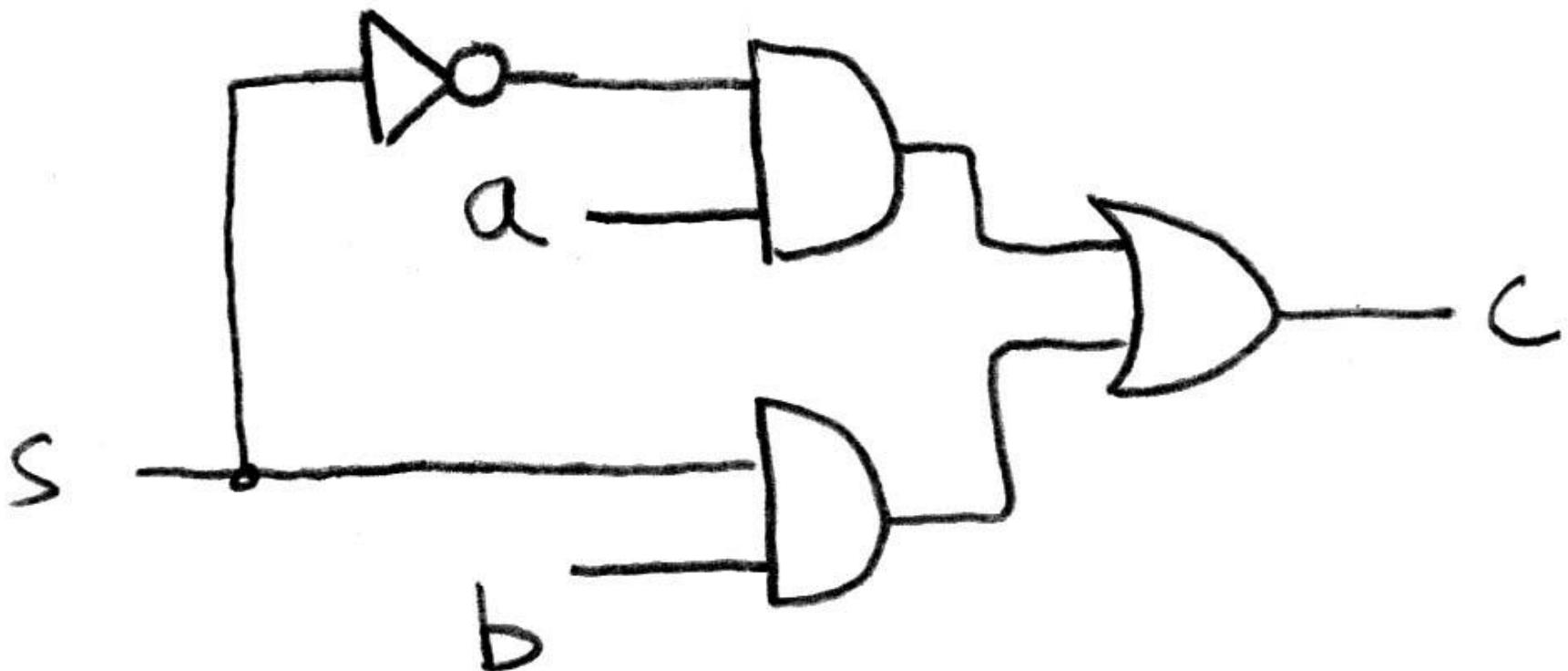


$$\begin{aligned} c &= \bar{s}ab + \bar{s}ab + s\bar{a}b + sab \\ &= \bar{s}(a\bar{b} + ab) + s(\bar{a}b + ab) \\ &= \bar{s}(a(\bar{b} + b)) + s((\bar{a} + a)b) \\ &= \bar{s}(a(1) + s((1)b) \\ &= \bar{s}a + sb \end{aligned}$$



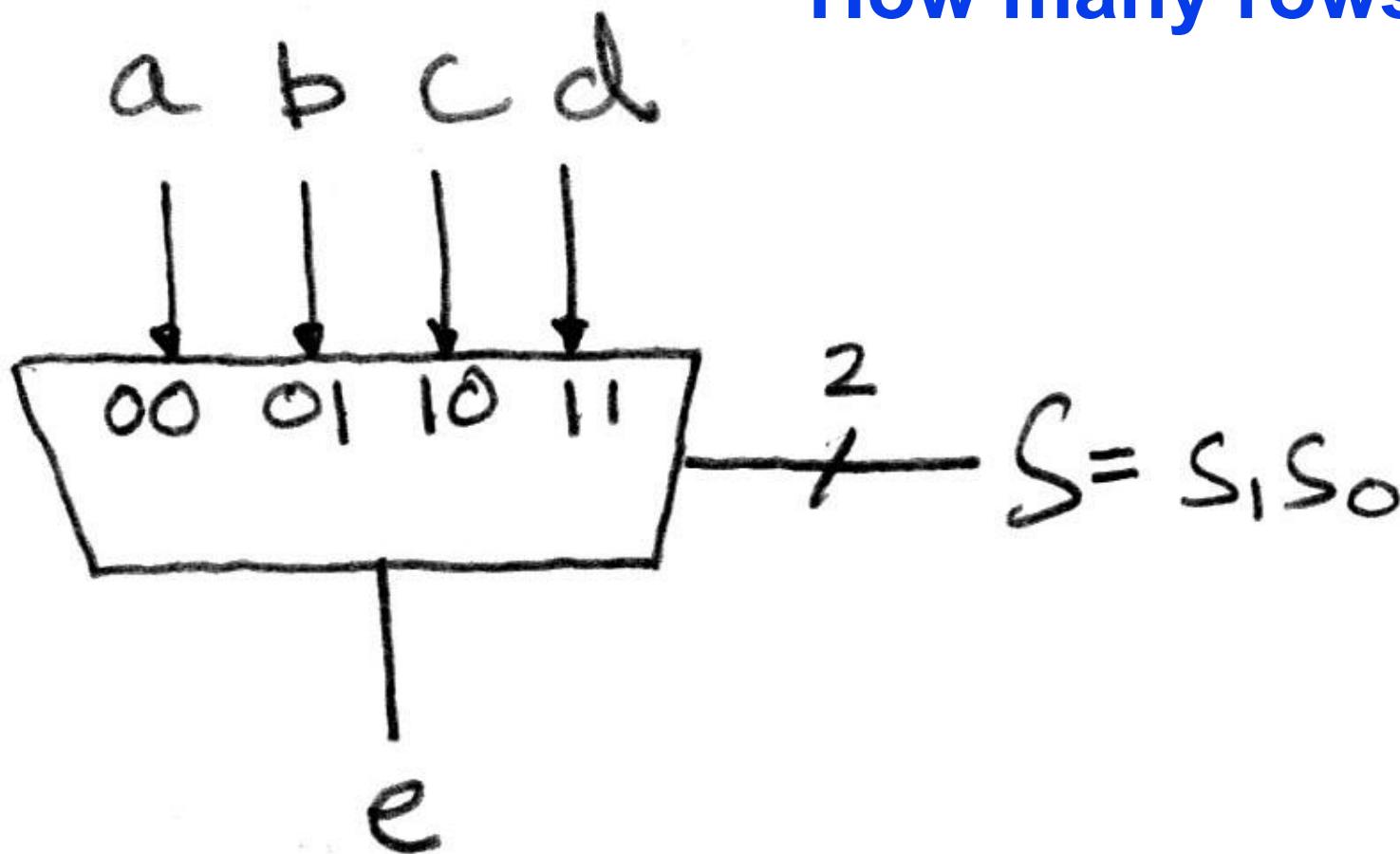
How do we build a 1-bit-wide mux?

$$\bar{s}a + sb$$



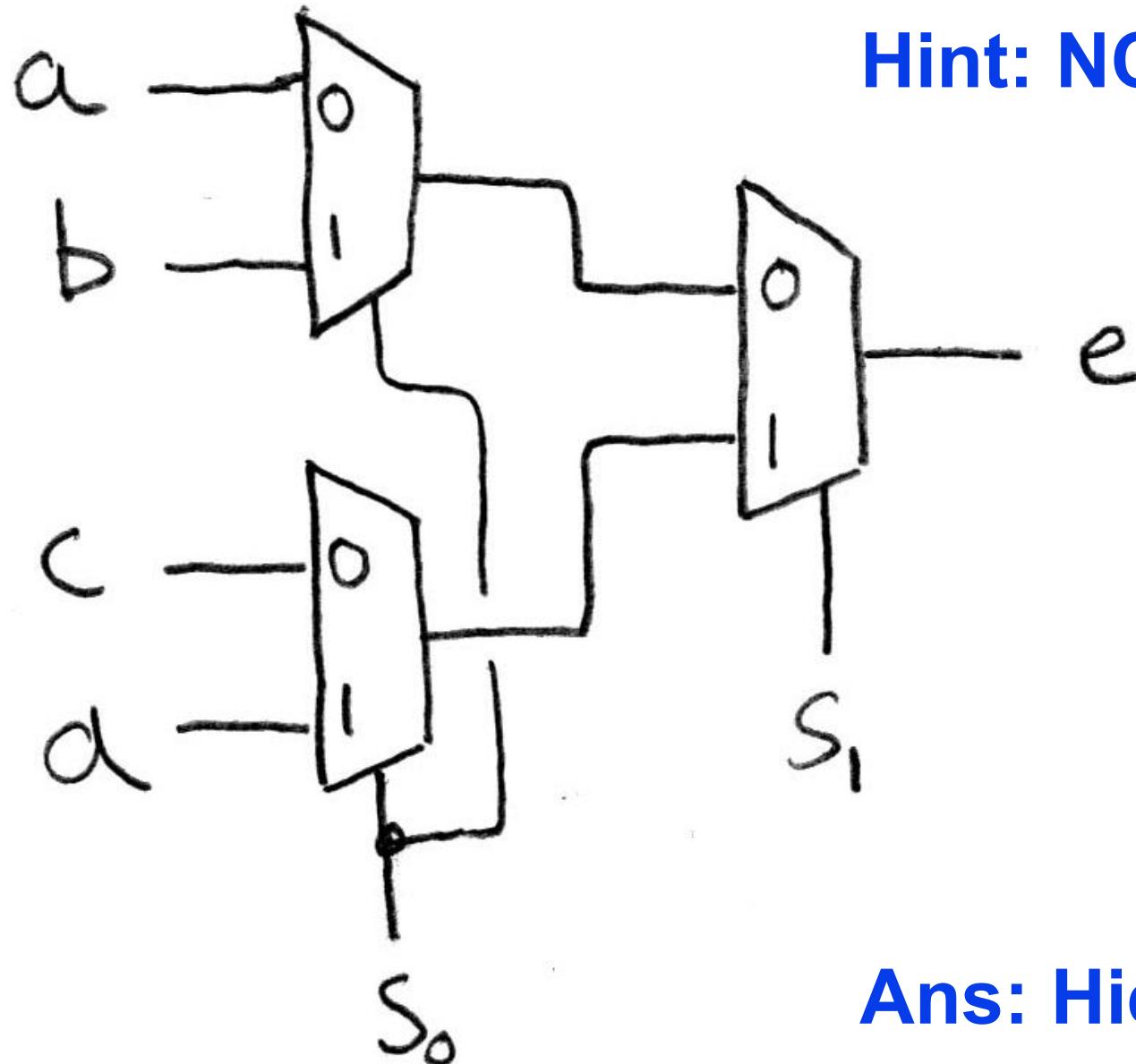
4-to-1 Multiplexor?

How many rows in TT?



$$e = \overline{s_1} \overline{s_0} a + \overline{s_1} s_0 b + s_1 \overline{s_0} c + s_1 s_0 d$$

Is there any other way to do it?

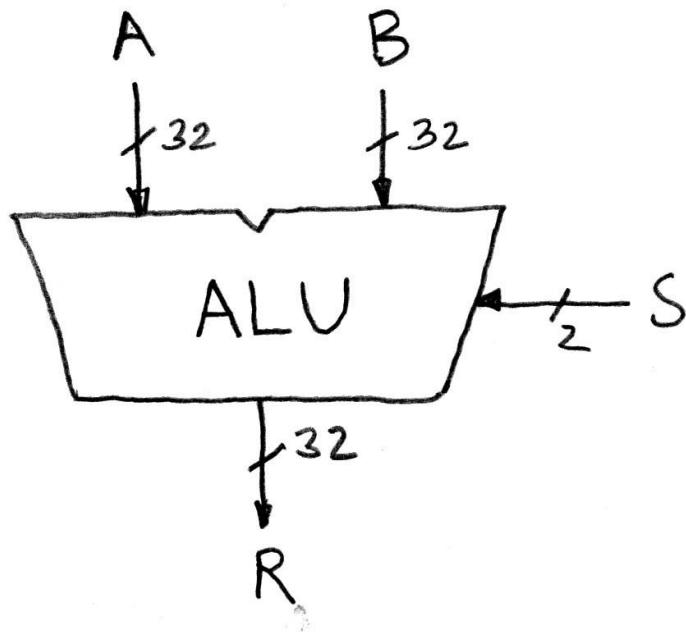


Hint: NCAA tourney!

Ans: Hierarchically!

Arithmetic and Logic Unit

- Most processors contain a special logic block called “Arithmetic and Logic Unit” (ALU)
- We’ll show you an easy one that does ADD, SUB, bitwise AND, bitwise OR



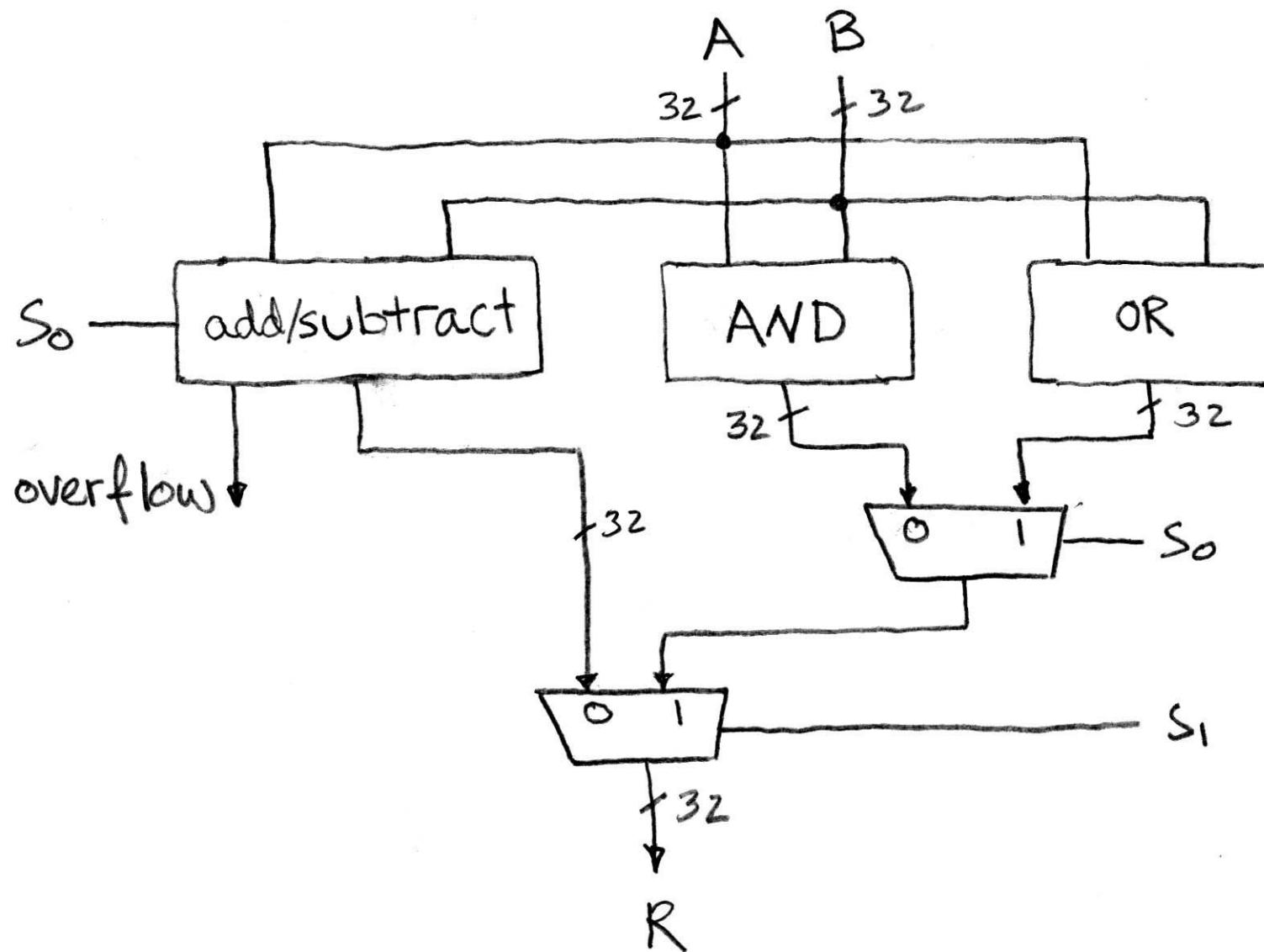
when $S=00$, $R=A+B$

when $S=01$, $R=A-B$

when $S=10$, $R=A \text{ AND } B$

when $S=11$, $R=A \text{ OR } B$

Our simple ALU



Adder/Subtractor Design -- how?

- **Truth-table, then determine canonical form, then minimize and implement as we've seen before**
- **Look at breaking the problem down into smaller pieces that we can cascade or hierarchically layer**

Adder/Subtractor – One-bit adder LSB...

$$\begin{array}{r} \text{a}_3 \quad \text{a}_2 \quad \text{a}_1 \quad \boxed{\text{a}_0} \\ + \quad \text{b}_3 \quad \text{b}_2 \quad \text{b}_1 \quad \boxed{\text{b}_0} \\ \hline \text{s}_3 \quad \text{s}_2 \quad \text{s}_1 \quad \boxed{\text{s}_0} \end{array}$$

a ₀	b ₀	s ₀	c ₁
0	0	0	0
0	1	1	0
1	0	1	0
1	1	0	1

$$s_0 =$$

$$c_1 =$$

Adder/Subtractor – One-bit adder (1/2)...

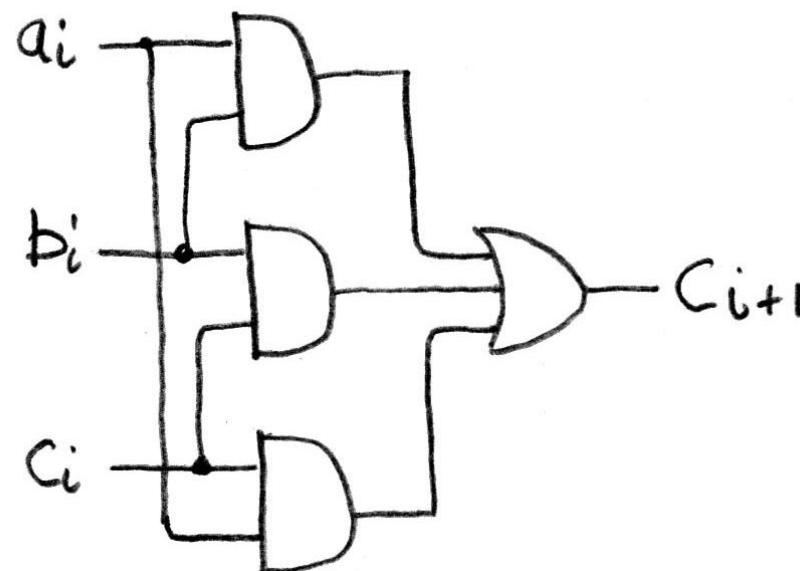
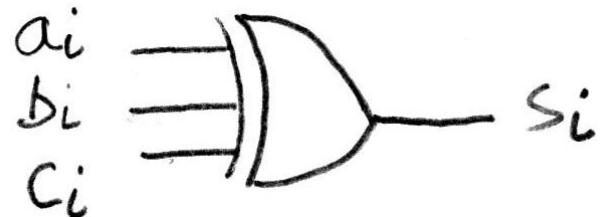
$$\begin{array}{r} \text{a}_3 \quad \text{a}_2 \quad \boxed{\text{a}_1} \quad \text{a}_0 \\ + \quad \text{b}_3 \quad \text{b}_2 \quad \boxed{\text{b}_1} \quad \text{b}_0 \\ \hline \text{s}_3 \quad \text{s}_2 \quad \boxed{\text{s}_1} \quad \text{s}_0 \end{array}$$

a_i	b_i	c_i	s_i	c_{i+1}
0	0	0	0	0
0	0	1	1	0
0	1	0	1	0
0	1	1	0	1
1	0	0	1	0
1	0	1	0	1
1	1	0	0	1
1	1	1	1	1

$$s_i =$$

$$c_{i+1} =$$

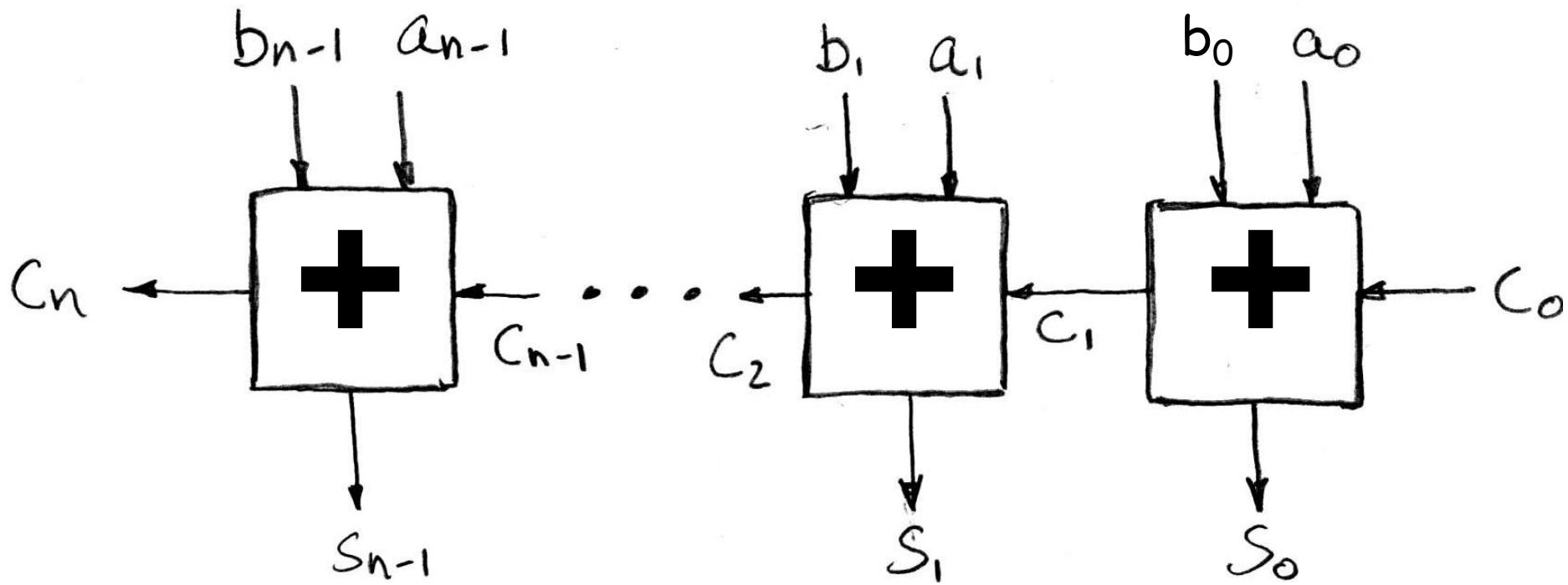
Adder/Subtractor – One-bit adder (2/2)...



$$s_i = \text{XOR}(a_i, b_i, c_i)$$

$$c_{i+1} = \text{MAJ}(a_i, b_i, c_i) = a_i b_i + a_i c_i + b_i c_i$$

N 1-bit adders \Rightarrow 1 N -bit adder

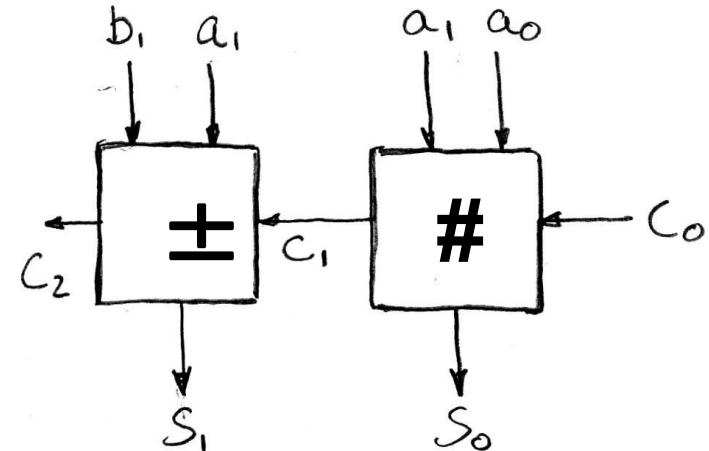


**What about overflow?
Overflow = c_n ?**

What about overflow?

- Consider a 2-bit signed # & overflow:

- $10 = -2 + -2$ or -1
- $11 = -1 + -2$ only
- $00 = 0$ NOTHING!
- $01 = 1 + 1$ only



- Highest adder

- $C_1 = \text{Carry-in} = C_{\text{in}}$, $C_2 = \text{Carry-out} = C_{\text{out}}$
- $\text{No } C_{\text{out}} \text{ or } C_{\text{in}} \Rightarrow \text{NO overflow!}$

What • C_{in} , and $C_{\text{out}} \Rightarrow \text{NO overflow!}$

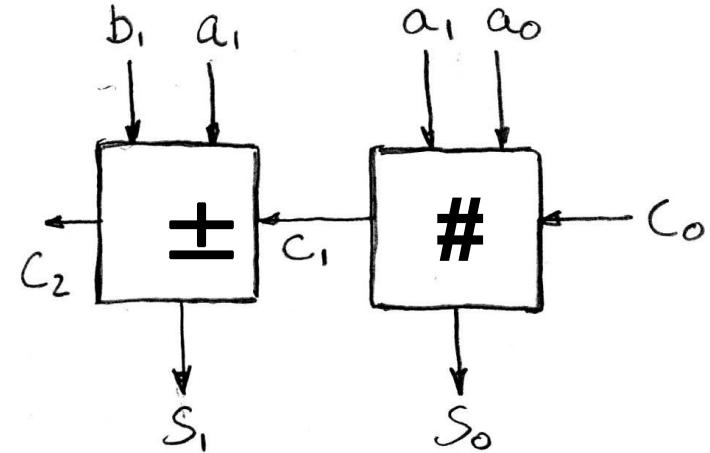
op?

- C_{in} , but no $C_{\text{out}} \Rightarrow A, B \text{ both } > 0, \text{ overflow!}$
- C_{out} , but no $C_{\text{in}} \Rightarrow A, B \text{ both } < 0, \text{ overflow!}$

What about overflow?

- Consider a 2-bit signed # & overflow:

$$\begin{array}{rcl} 10 & = & -2 \\ 11 & = & -1 \\ 00 & = & 0 \\ 01 & = & 1 \end{array}$$

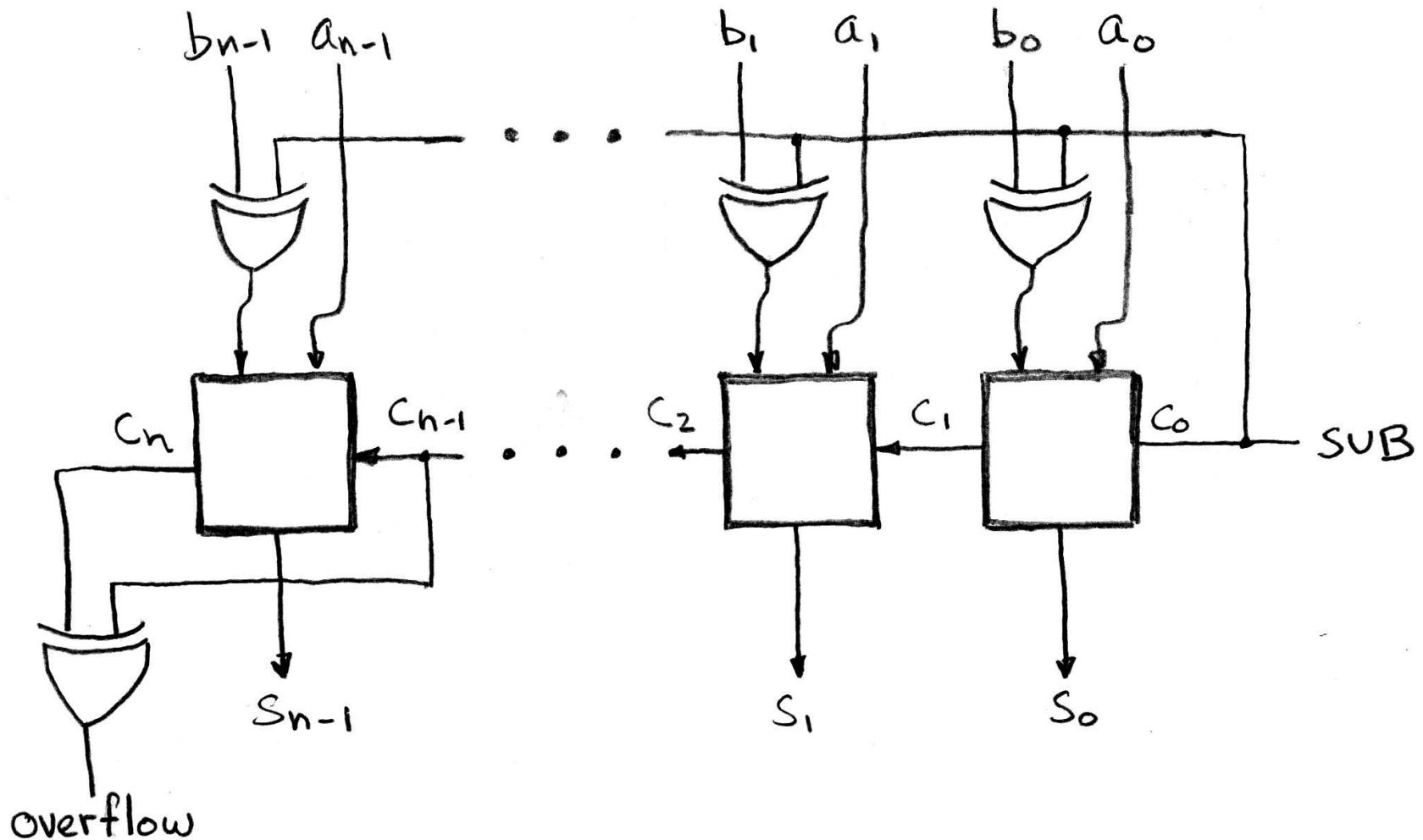


- Overflows when...

- C_{in} , but no $C_{out} \Rightarrow A, B$ both > 0 , overflow!
- C_{out} , but no $C_{in} \Rightarrow A, B$ both < 0 , overflow!

$$\text{overflow} = c_n \text{ XOR } c_{n-1}$$

Extremely Clever Subtractor



Peer Instruction

- 1) Truth table for mux with 4-bits of signals has 2^4 rows
- 2) We could cascade N 1-bit shifters to make 1 N-bit shifter for sll, srl

	12
a)	FF
b)	FT
c)	TF
d)	TT

Peer Instruction Answer

- 1) Truth table for mux with 4-bits of signals controls 16 inputs, for a total of 20 inputs, so truth table is 2^{20} rows... **FALSE**
- 2) We could cascade N 1-bit shifters to make 1 N-bit shifter for sll, srl ... **TRUE**

- 1) Truth table for mux with 4-bits of signals is 2^4 rows long
- 2) We could cascade N 1-bit shifters to make 1 N-bit shifter for sll, srl

	12
a)	FF
b)	FT
c)	TF
d)	TT

“And In conclusion...”

- Use muxes to select among input
 - S input bits selects 2^S inputs
 - Each input can be n-bits wide, indep of S
- Can implement muxes hierarchically
- ALU can be implemented using a mux
 - Coupled with basic block elements
- N-bit adder-subtractor done using N 1-bit adders with XOR gates on input
 - XOR serves as conditional inverter

0.16 Intro to CPU

Computer Architecture (计算机体系结构)



Lecturer
Yuanqing
Cheng

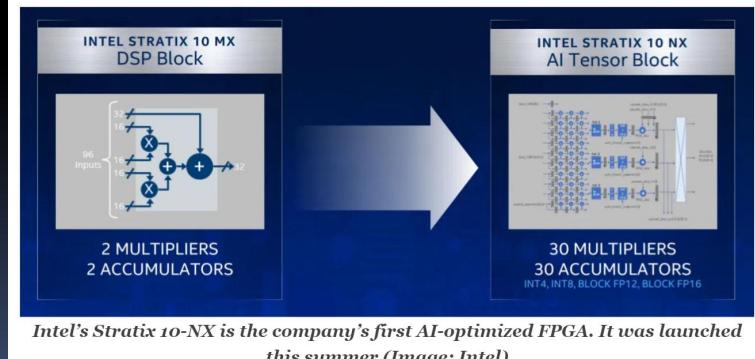
Lecture 24 Introduction to CPU design

2020-10-16

AMD-Xilinx Deal: Bringing The Fight
To The Data Center



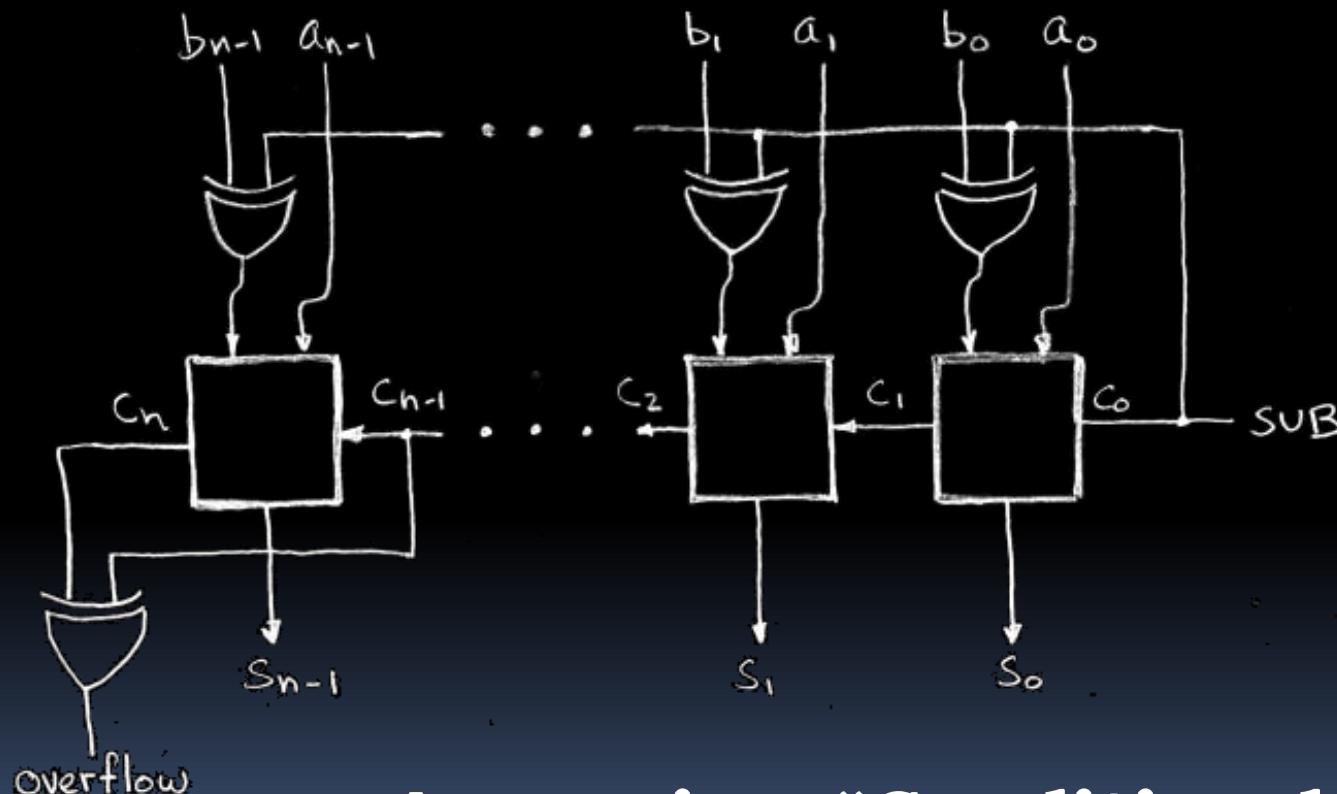
Xilinx Versal AI Core includes both programmable logic and an AI accelerator ASIC block (Image: Xilinx)



Intel's Stratix 10-NX is the company's first AI-optimized FPGA. It was launched this summer (Image: Intel)

Clever Signed Adder/Subtractor

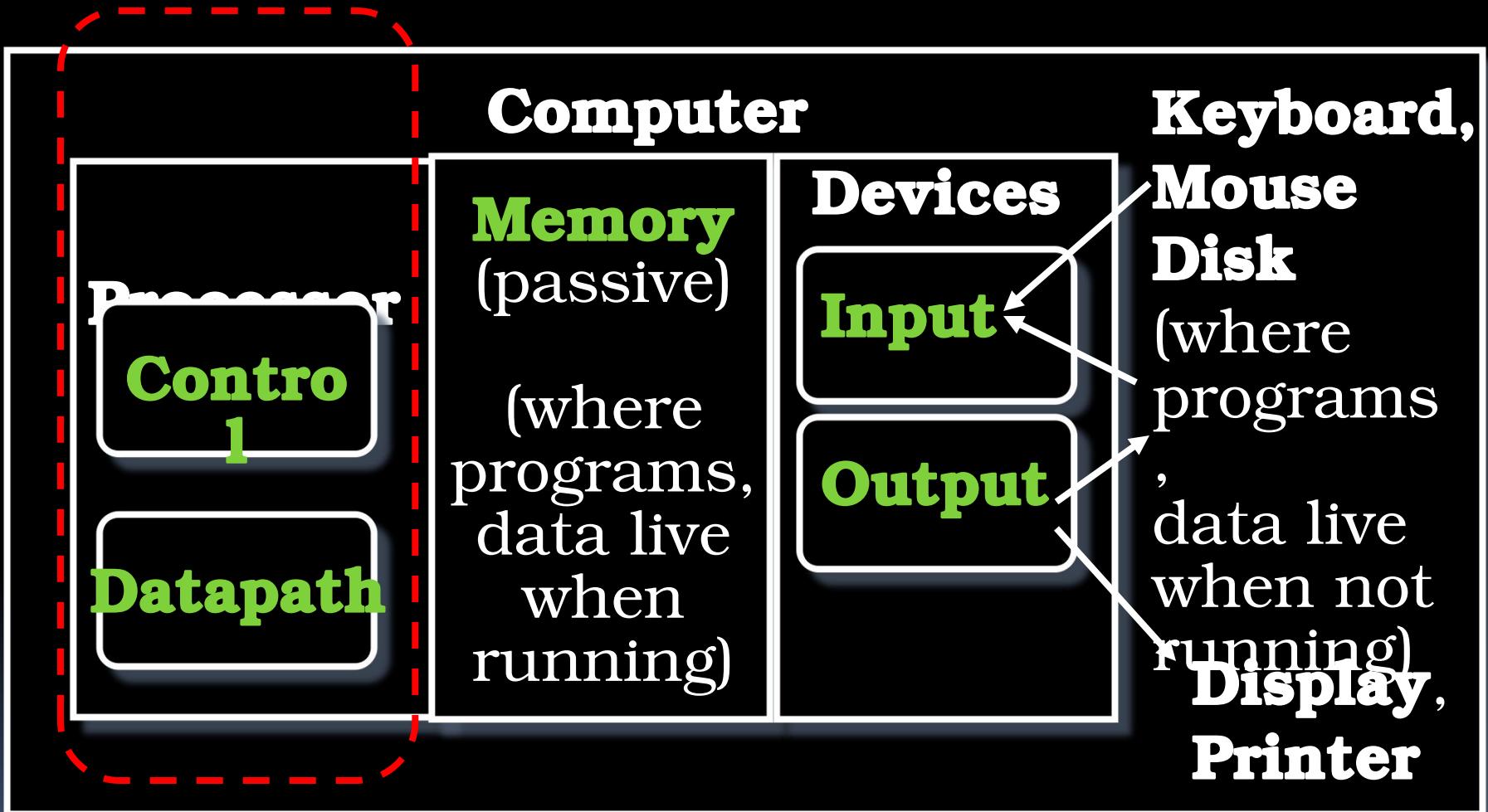
$A - B = A + (-B)$; how do we make “ $-B$ ”?



x	y	xo	r
0	0	0	
0	1	1	
1	0	1	
1	1	0	

An **xor** is a “Conditional Inverter!”

Five Components of a Computer



The CPU

- **Processor (CPU):** the active part of the computer, which does all the work (data manipulation and decision-making)
- **Datapath:** portion of the processor which contains hardware necessary to perform operations required by the processor (the brawn)
- **Control:** portion of the processor (also in hardware) which tells the datapath what needs to be done (the brain)

Stages of the Datapath : Overview

- **Problem:** a single, atomic block which “executes an instruction” (performs all necessary operations beginning with fetching the instruction) would be too bulky and inefficient
- **Solution:** break up the process of “executing an instruction” into **stages**, and then connect the stages to create the whole datapath
 - smaller stages are easier to design
 - easy to optimize (change) one stage without touching the others

Stages of the Datapath (1 / 5)

- There is a wide variety of MIPS instructions: so what general steps do they have in common?
- Stage 1: Instruction Fetch
 - no matter what the instruction, the 32-bit instruction word must first be fetched from memory (the cache-memory hierarchy)
 - also, this is where we Increment PC (that is, $PC = PC + 4$, to point to the next instruction: byte addressing so + 4)

Stages of the Datapath (2/5)

- **Stage 2: Instruction Decode**
 - upon fetching the instruction, we next gather data from the fields (decode all necessary instruction data)
 - first, read the opcode to determine instruction type and field lengths
 - second, read in data from all necessary registers
 - for add, read two registers
 - for addi, read one register
 - for jal, no reads necessary

Stages of the Datapath (3/5)

- **Stage 3: ALU (Arithmetic-Logic Unit)**
 - the real work of most instructions is done here: arithmetic (+, -, *, /), shifting, logic (&, |), comparisons (slt)
 - what about loads and stores?
 - `lw $t0, 40($t1)`
 - the address we are accessing in memory = the value in `$t1` PLUS the value 40
 - so we do this addition in this stage

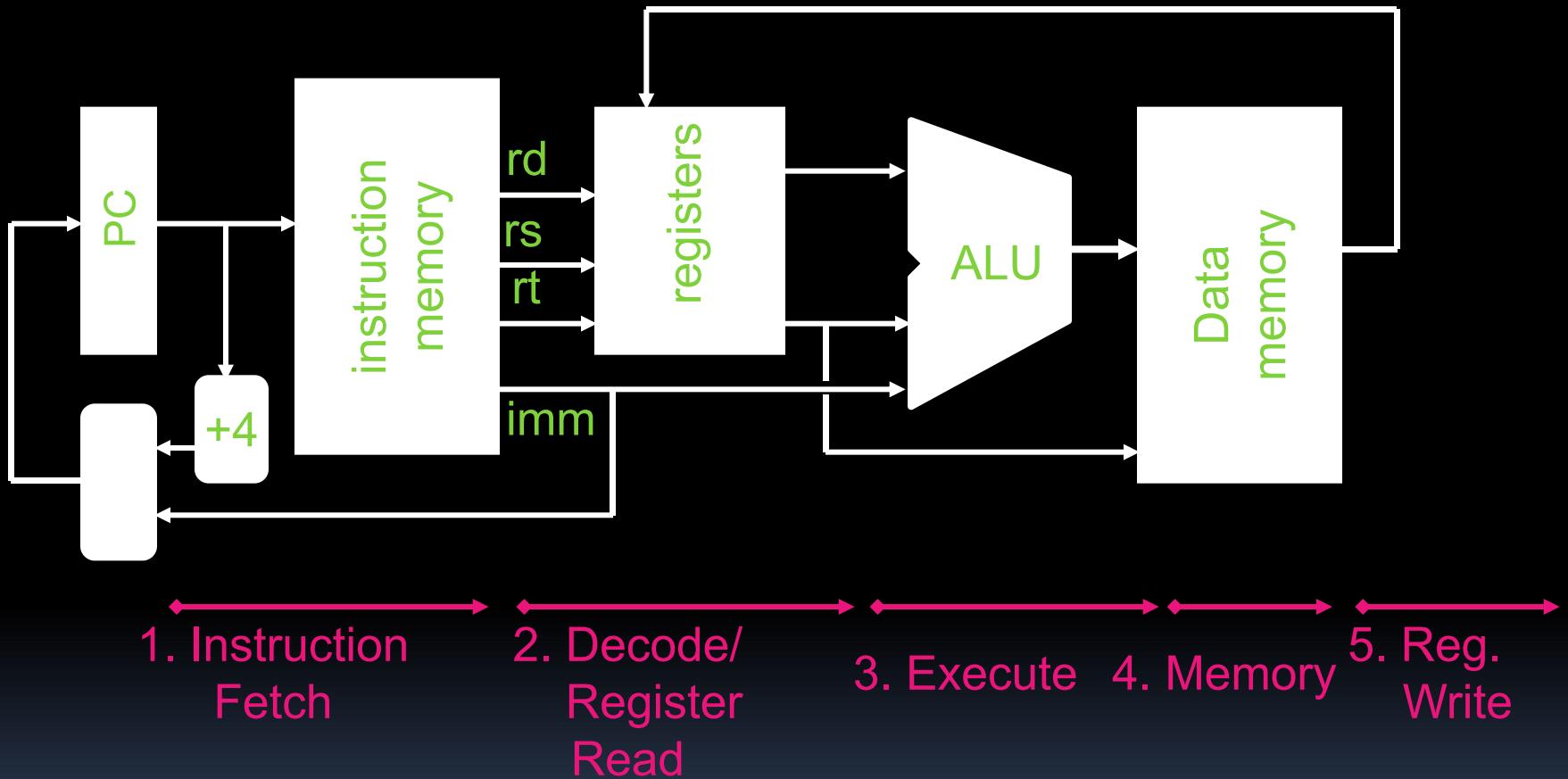
Stages of the Datapath (4/5)

- **Stage 4: Memory Access**
 - actually only the load and store instructions do anything during this stage; the others remain idle during this stage or skip it all together
 - since these instructions have a unique step, we need this extra stage to account for them
 - as a result of the cache system, this stage is expected to be fast

Stages of the Datapath (5/5)

- **Stage 5: Register Write**
 - most instructions write the result of some computation into a register
 - examples: arithmetic, logical, shifts, loads, slt
 - what about stores, branches, jumps?
 - don't write anything into a register at the end
 - these remain idle during this fifth stage or skip it all together

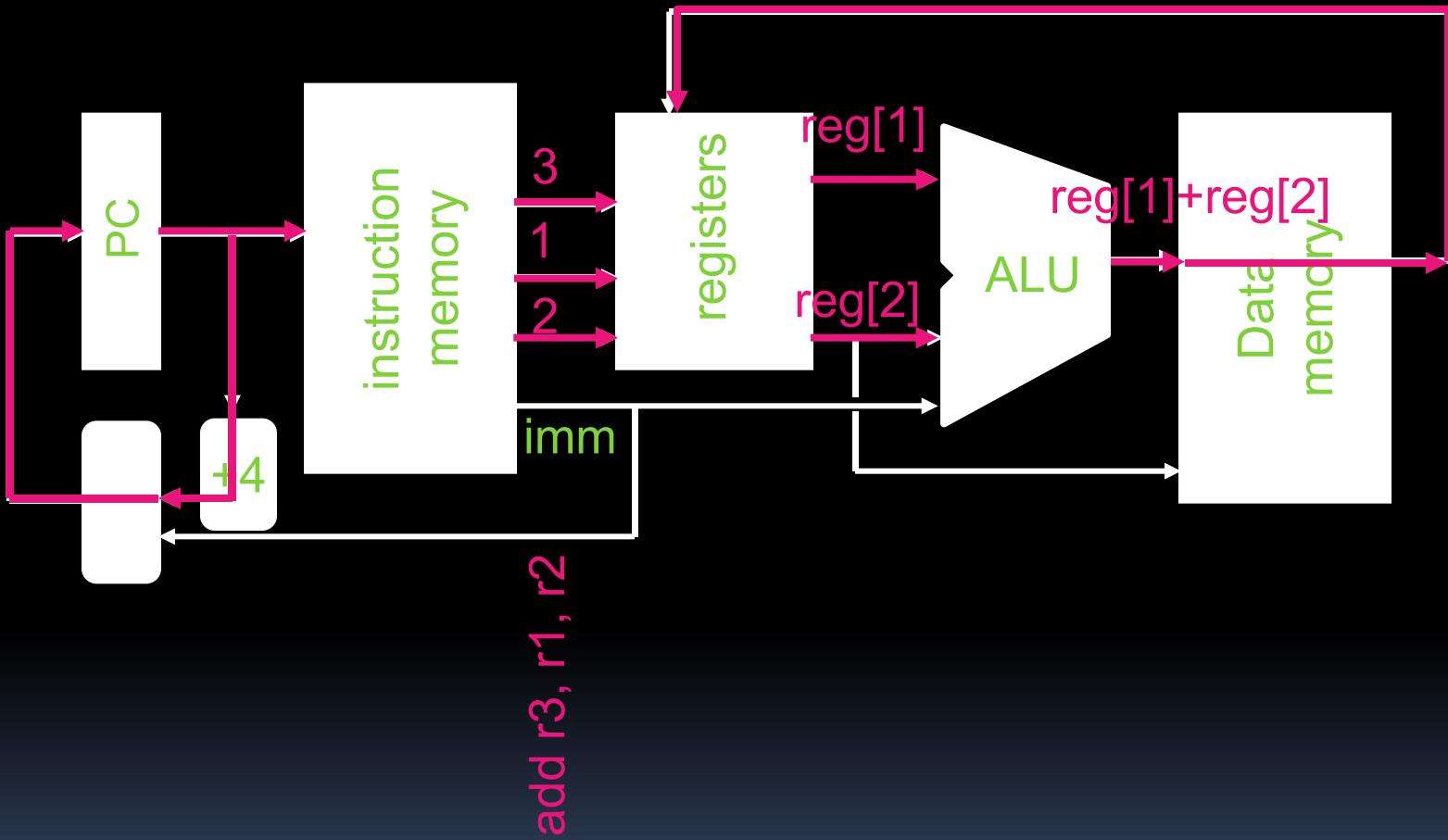
Generic Steps of Datapath



Datapath Walkthroughs (1 / 3)

- **add \$r3,\$r1,\$r2 # r3 = r1+r2**
 - **Stage 1: fetch this instruction, inc. PC**
 - **Stage 2: decode to find it's an add, then read registers \$r1 and \$r2**
 - **Stage 3: add the two values retrieved in Stage 2**
 - **Stage 4: idle (nothing to write to memory)**
 - **Stage 5: write result of Stage 3 into register \$r3**

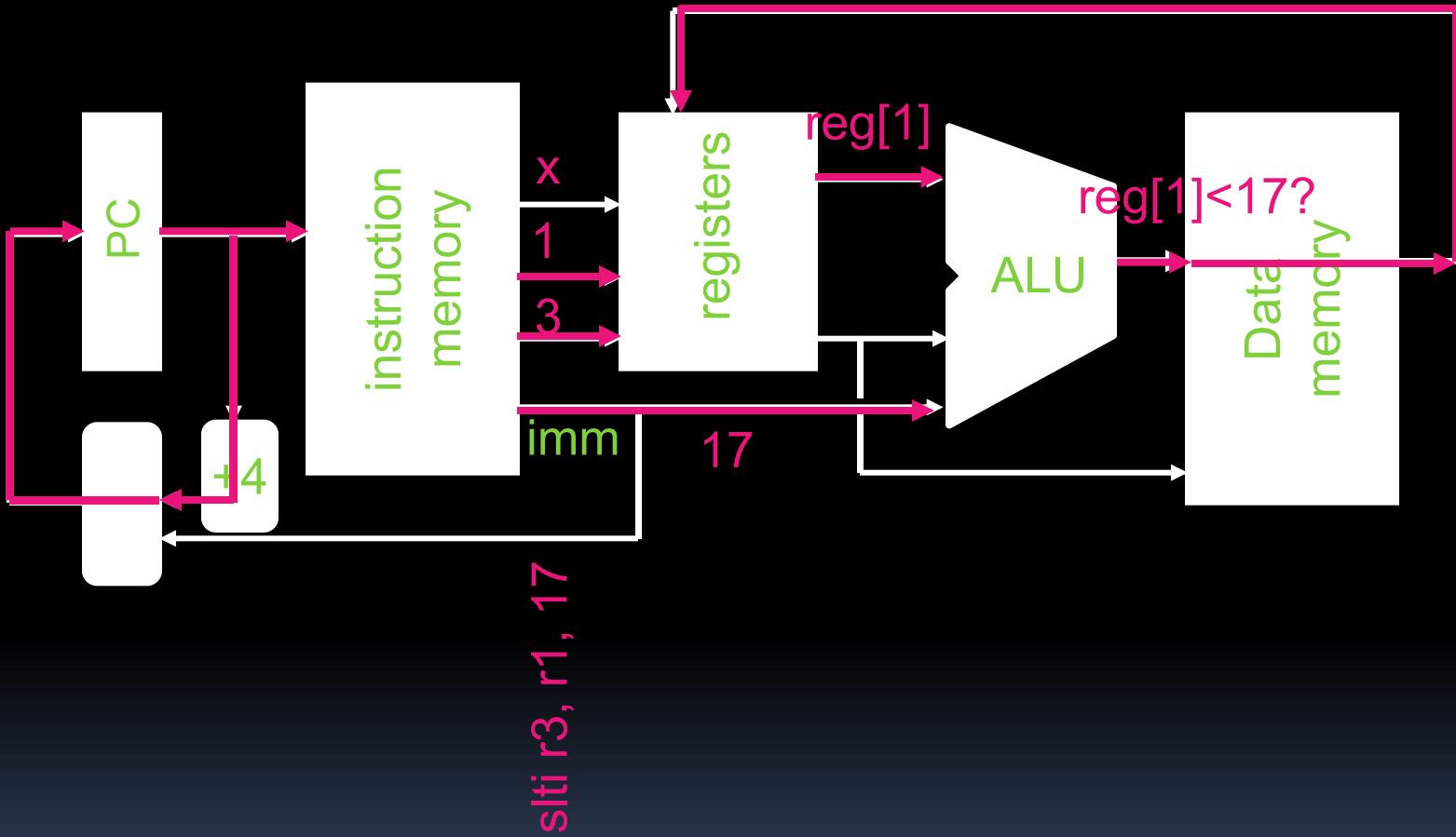
Example: add Instruction



Datapath Walkthroughs (2/3)

- **slti \$r3,\$r1,17**
 - **Stage 1: fetch this instruction, inc. PC**
 - **Stage 2: decode to find it's an slti, then read register \$r1**
 - **Stage 3: compare value retrieved in Stage 2 with the integer 17**
 - **Stage 4: idle**
 - **Stage 5: write the result of Stage 3 in register \$r3**

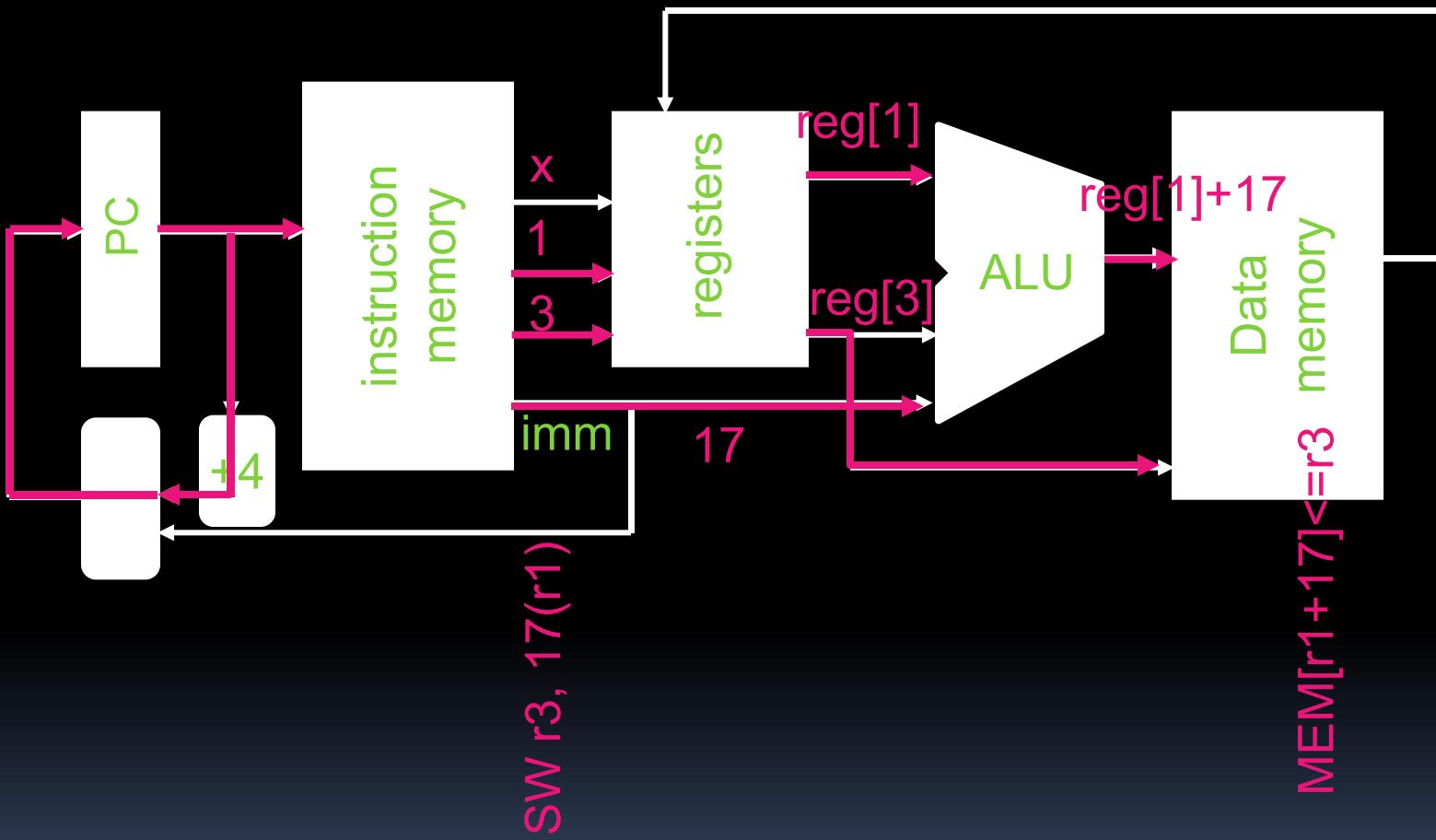
Example: slti Instruction



Datapath Walkthroughs (3/3)

- **sw \$r3, 17(\$r1)**
 - **Stage 1: fetch this instruction, inc. PC**
 - **Stage 2: decode to find it's a sw, then read registers \$r1 and \$r3**
 - **Stage 3: add 17 to value in register \$r1 (retrieved in Stage 2)**
 - **Stage 4: write value in register \$r3 (retrieved in Stage 2) into memory address computed in Stage 3**
 - **Stage 5: idle (nothing to write into a register)**

Example: sw Instruction



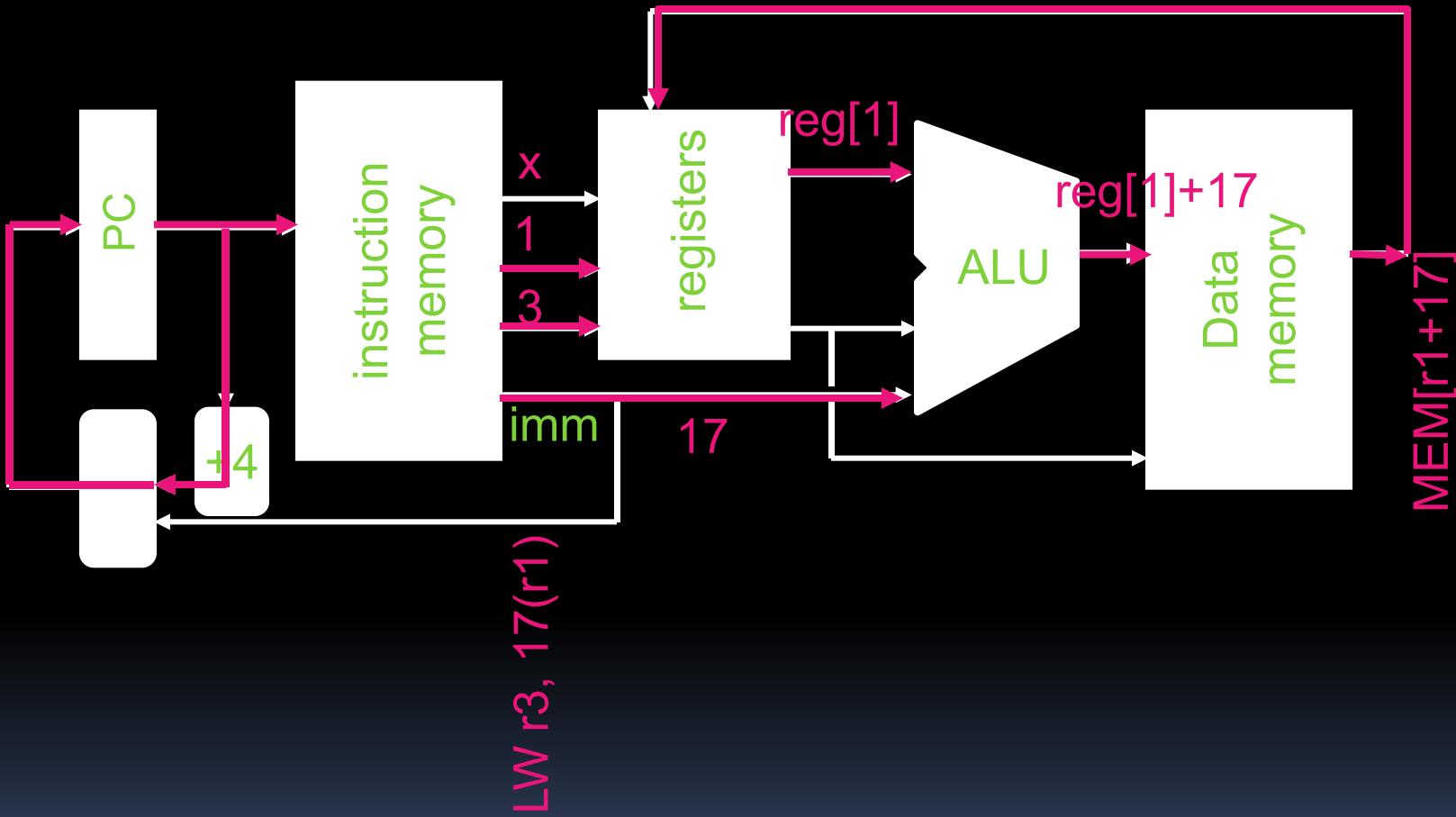
Why Five Stages? (1/2)

- Could we have a different number of stages?
 - Yes, and other architectures do
- So why does MIPS have five if instructions tend to idle for at least one stage?
 - The five stages are the union of all the operations needed by all the instructions.
 - There is one instruction that uses all five stages: the load

Why Five Stages? (2/2)

- `lw $r3, 17($r1)`
 - **Stage 1: fetch this instruction, inc. PC**
 - **Stage 2: decode to find it's a lw, then read register \$r1**
 - **Stage 3: add 17 to value in register \$r1 (retrieved in Stage 2)**
 - **Stage 4: read value from memory address compute in Stage 3**
 - **Stage 5: write value found in Stage 4 into register \$r3**

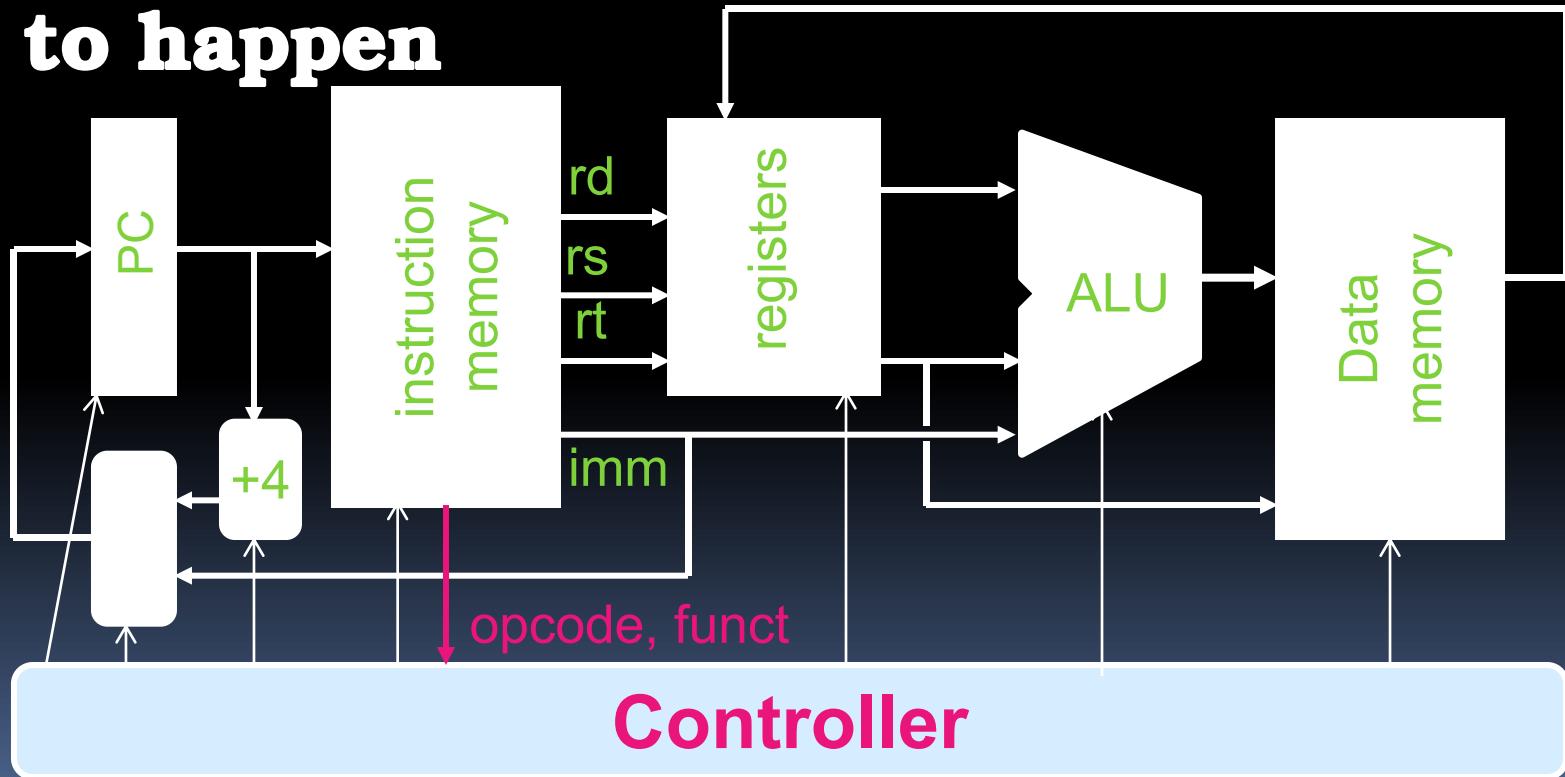
Example: lw Instruction



`LW r3, 17(r1)`

Datapath Summary

- The datapath based on data transfers required to perform instructions
- A controller causes the right transfers to happen



What Hardware Is Needed? (1 / 2)

- **PC: a register which keeps track of memory addr of the next instruction**
- **General Purpose Registers**
 - **used in Stages 2 (Read) and 5 (Write)**
 - **MIPS has 32 of these**
- **Memory**
 - **used in Stages 1 (Fetch) and 4 (R/W)**
 - **cache system makes these two stages as fast as the others, on average**

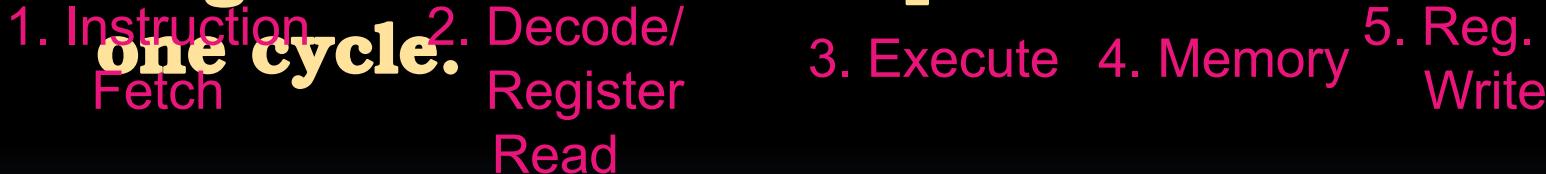
What Hardware Is Needed? (2/2)

- **ALU**
 - **used in Stage 3**
 - **something that performs all necessary functions: arithmetic, logicals, etc.**
 - **we'll design details later**
- **Miscellaneous Registers**
 - **In implementations with only one stage per clock cycle, registers are inserted between stages to hold intermediate data and control signals as they travels from stage to stage.**
 - **Note: Register is a general purpose term meaning something that stores bits. Not all registers are in the “register file”.**

CPU clocking (1/2)

For each instruction, how do we control the flow of information through the datapath?

- **Single Cycle CPU:** All stages of an instruction are completed within one long clock cycle.
 - The clock cycle is made sufficient long to allow each instruction to complete all stages without interruption and within one cycle.



For each instruction, how do we control the flow of information through the datapath?

CPU clocking (2/2)

- **Multiple-cycle CPU: Only one stage of instruction per clock cycle.**

- **The clock is made as long as the slowest stage.**



- **Several significant advantages over single cycle execution:** Unused stages in a particular instruction can be skipped OR instructions can be pipelined (overlapped).

Peer Instruction

- A. If the destination reg is the same as the source reg, we could compute the incorrect value!
- B. We're going to be able to read 2 registers and write a 3rd in 1 cycle

	ABC
0:	FFF
1:	FFT
2:	FTF
3:	FTT
4:	TFF
5:	TFT
6:	TTF
7:	TTT

Peer Instruction

- A. Truth table for mux with 4-bits of signals has 2^4 rows**
- B. We could cascade N 1-bit shifters to make 1 N-bit shifter for sll, srl**
- C. If 1-bit adder delay is T, the N-bit adder delay would also be T**

	ABC
1 :	FFF
2 :	FFT
3 :	FTF
4 :	FTT
5 :	TFF
6 :	TFT
7 :	TTF
8 :	TTT

Peer Instruction Answer

“And In conclusion...”

- **N-bit adder-subtractor done using N 1-bit adders with XOR gates on input**
 - **XOR serves as conditional inverter**
- **CPU design involves Datapath, Control**
 - **Datapath in MIPS involves 5 CPU stages**
 1. **Instruction Fetch**
 2. **Instruction Decode & Register Read**
 3. **ALU (Execute)**
 4. **Memory**
 5. **Register Write**

0.17 Single Cycle CPU



Lecturer
Yuanqing
Cheng

Lecture 20 CPU design (of a single-cycle CPU)

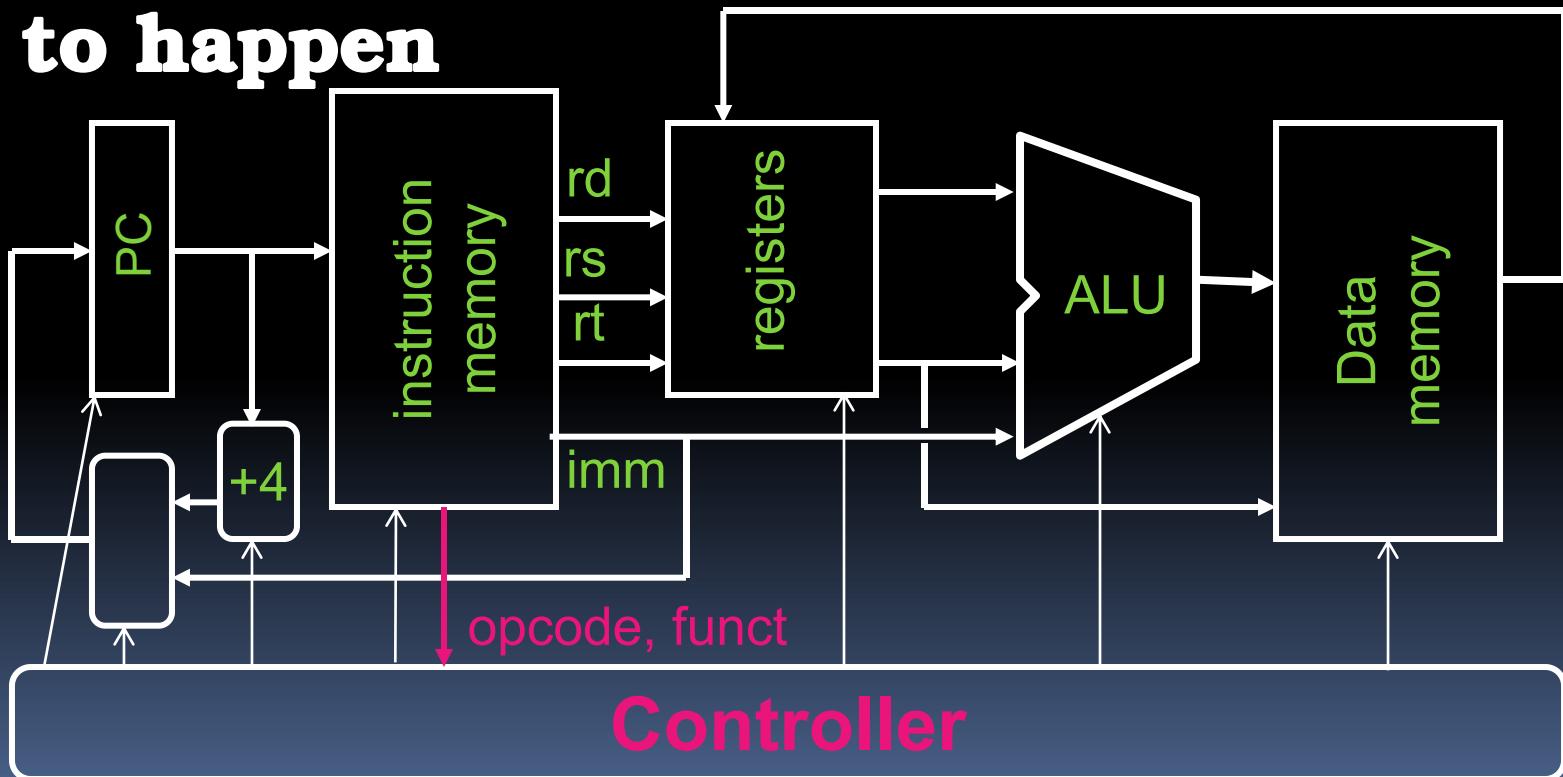
2020-10-16

Review

- CPU design involves Datapath, Control
 - Datapath in MIPS involves 5 CPU stages
 1. Instruction Fetch
 2. Instruction Decode & Register Read
 3. ALU (Execute)
 4. Memory
 5. Register Write

Datapath Summary

- The datapath based on data transfers required to perform instructions
- A controller causes the right transfers to happen



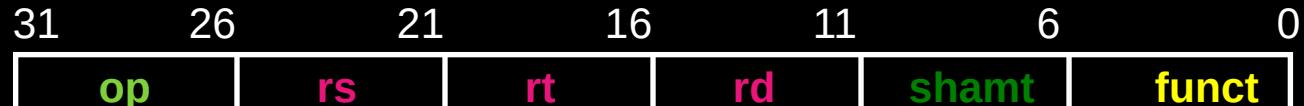
How to Design a Processor: step-by-step

- 1. Analyze instruction set architecture (ISA)
⇒ datapath requirements**
 - 1. meaning of each instruction is given by the register transfers**
 - 2. datapath must include storage element for ISA registers**
 - 3. datapath must support each register transfer**
- 2. Select set of datapath components and establish clocking methodology**
- 3. Assemble datapath meeting requirements**
- 4. Analyze implementation of each instruction to determine setting of control points that effects the register transfer.**
- 5. Assemble the control logic**

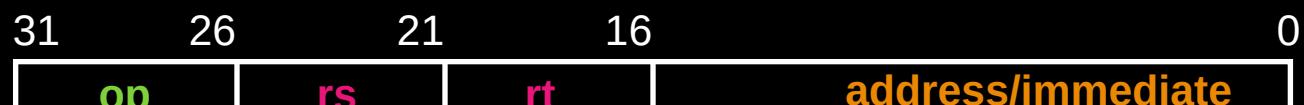
Review: The MIPS Instruction

~~All~~ MIPS instructions are 32 bits long. 3 formats:

- **R-type**



- **I-type**



- **J-type**



- The different fields are:

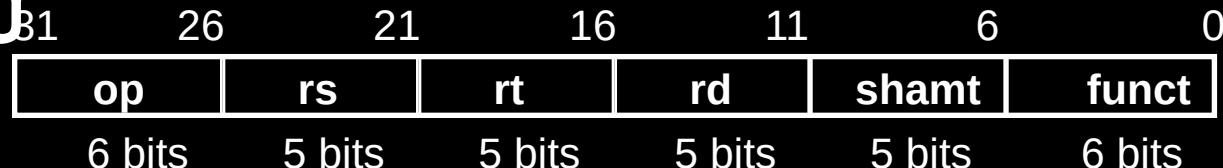
- **op**: operation (“opcode”) of the instruction
- **rs, rt, rd**: the source and destination register specifiers
- **shamt**: shift amount
- **funct**: selects the variant of the operation in the “op” field
- **address / immediate**: address offset or immediate value
- **target address**: target address of jump instruction

Step 1a: The MIPS-lite Subset for

today

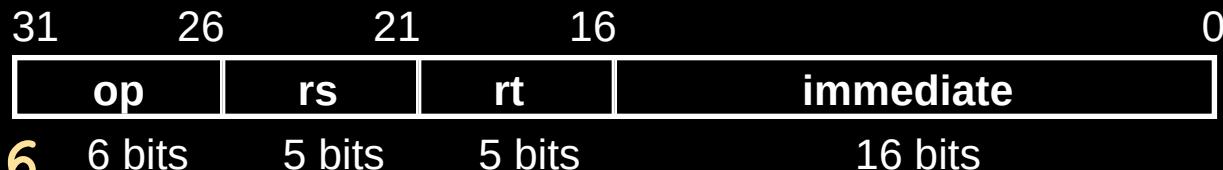
■ ADDU and SUBU

- addu rd,rs,rt
- subu rd,rs,rt



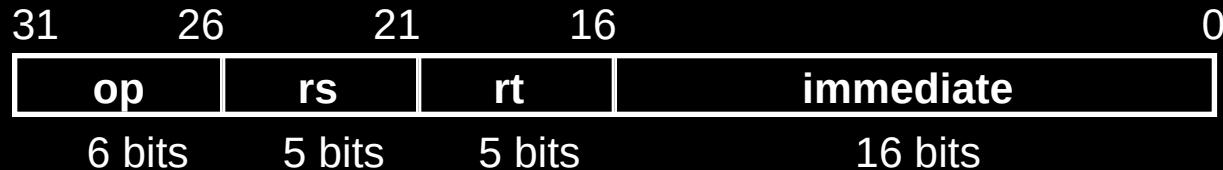
■ OR Immediate:

- ori rt,rs,imm16



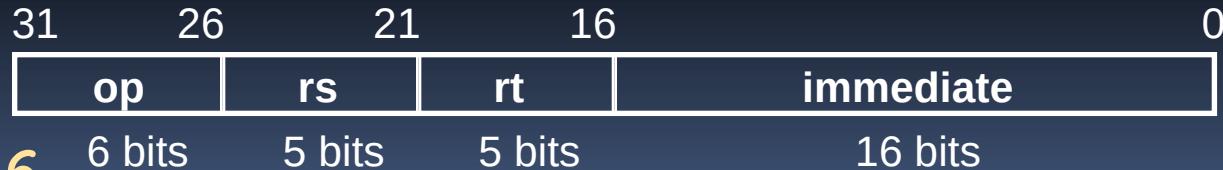
■ LOAD and STORE Word

- lw rt,rs,imm16
- sw rt,rs,imm16



■ BRANCH:

- beq rs,rt,imm16



Register Transfer Language (RTL)

- RTL gives the meaning of the instructions

{op , rs , rt , rd , shamt , funct} ← MEM[PC]

{op , rs , rt , Imm16} ← MEM[PC]

- All start by fetching the instruction
inst Register Transfers

ORI $R[rt] \leftarrow R[rs] \mid zero \ ext(Imm16); \quad PC \leftarrow PC + 4$

LOAD $R[rt] \leftarrow MEM[R[rs] + sign\ ext(Imm16)]; PC \leftarrow PC + 4$

STORE $\text{MEM}[R[rs] + \text{sign ext(Imm16)}] \leftarrow R[rt]; \text{PC} \leftarrow \text{PC} + 4$

BEQ if (R[rs] == R[rt]) then

$\text{PC} \leftarrow \text{PC} + 4 + (\text{sign_ext}(\text{Imm16}) \parallel 00)$

else PC \leftarrow PC + 4

Step 1: Requirements of the Instruction Set

- **Memory (MEM)**
 - instructions & data (will use one for each)
- **Registers (R: 32 x 32)**
 - **read RS**
 - **read RT**
 - **Write RT or RD**
- **PC**
- **Extender (sign/zero extend)**
- **Add/Sub/OR unit for operation on register(s) or extended immediate**
- **Add 4 (+ maybe extended immediate) to PC**
- **Compare registers?**

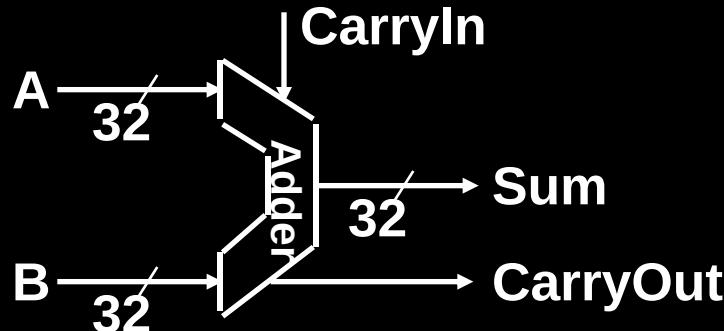
Step 2: Components of the

~~Datapath~~

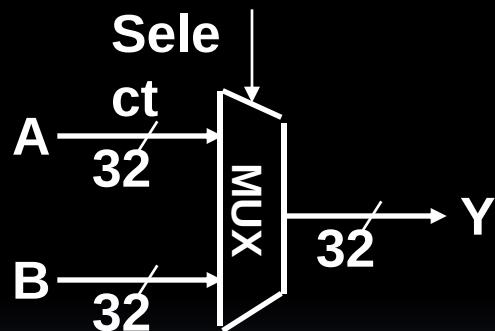
- **Combinational Elements**
- **Storage Elements**
 - **Clocking methodology**

Combinational Logic Elements (Building Blocks)

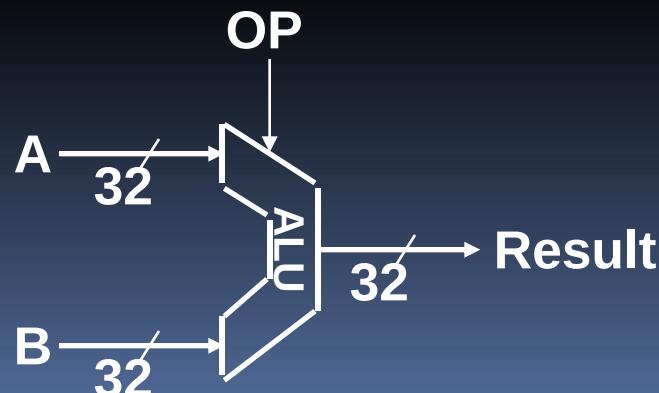
- **Adder**



- **MUX**



- **ALU**



ALU Needs for MIPS-lite + Rest of MIPS

- **Addition, subtraction, logical OR, ==:**

ADDU $R[rd] = R[rs] + R[rt]; \dots$

SUBU $R[rd] = R[rs] - R[rt]; \dots$

ORI $R[rt] = R[rs] |$

zero_ext(Imm16) ...

BEQ if ($R[rs] == R[rt]$) ...

- **Test to see if output == 0 for any ALU operation gives == test. How?**
- **P&H also adds AND, Set Less Than (1 if A < B, 0 otherwise)**
- **ALU follows chap 5**

Administrivia

- **Administrivia?**

What Hardware Is Needed? (1 / 2)

- **PC: a register which keeps track of memory addr of the next instruction**
- **General Purpose Registers**
 - **used in Stages 2 (Read) and 5 (Write)**
 - **MIPS has 32 of these**
- **Memory**
 - **used in Stages 1 (Fetch) and 4 (R/W)**
 - **cache system makes these two stages as fast as the others, on average**

What Hardware Is Needed? (2/2)

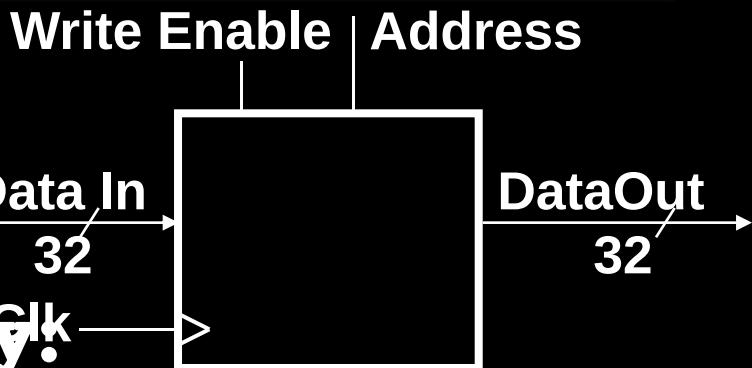
- **ALU**
 - **used in Stage 3**
 - **something that performs all necessary functions: arithmetic, logicals, etc.**
 - **we'll design details later**
- **Miscellaneous Registers**
 - **In implementations with only one stage per clock cycle, registers are inserted between stages to hold intermediate data and control signals as they travels from stage to stage.**
 - **Note: Register is a general purpose term meaning something that stores bits. Not all registers are in the “register file”.**

Storage Element: Idealized

Memory

- **Memory (idealized)**

- One input bus: Data In
 - One output bus: Data Out



- **Memory word is found by:**

- Address selects the word to put on Data Out
 - Write Enable = 1: address selects the memory word to be written via the Data In bus

- **Clock input (CLK)**

- The CLK input is a factor ONLY during write operation
 - During read operation, behaves as a combinational logic block:

- **Address valid \Rightarrow Data Out valid after “access”**

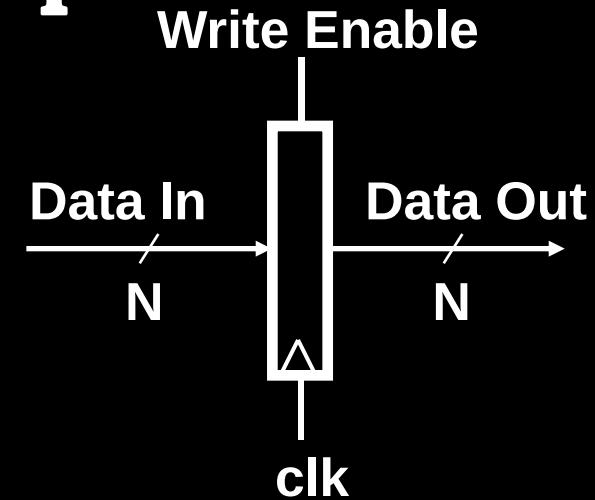
Storage Element: Register (Building Block)

- **Similar to D Flip Flop except**

- **N-bit input and output**
 - **Write Enable input**

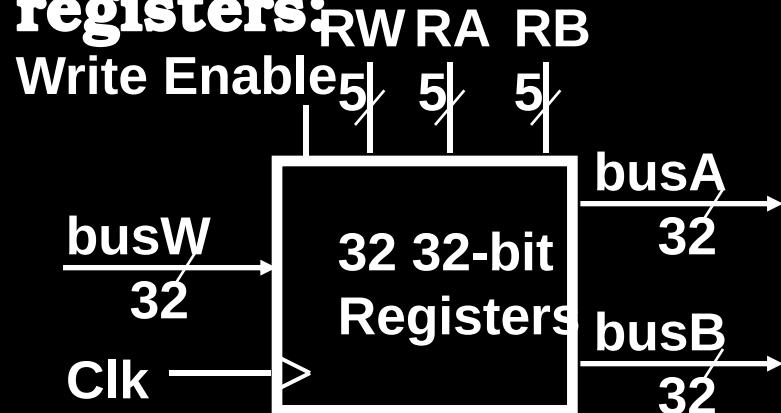
- **Write Enable:**

- **negated (or deasserted) (0): Data Out will not change**
 - **asserted (1): Data Out will become Data In on positive edge of clock**



Storage Element: Register File

- **Register File consists of 32 registers:**
 - Two 32-bit output busses: busA and busB
 - One 32-bit input bus: busW
- **Register is selected by:**
 - RA (number) selects the register to put on busA (data)
 - RB (number) selects the register to put on busB (data)
 - RW (number) selects the register to be written via busW (data) when Write Enable is 1
- **Clock input (clk)**
 - The clk input is a factor ONLY during write operation
 - During read operation, behaves as a combinational logic block:
 - RA or RB valid \Rightarrow busA or busB valid after “access time.”



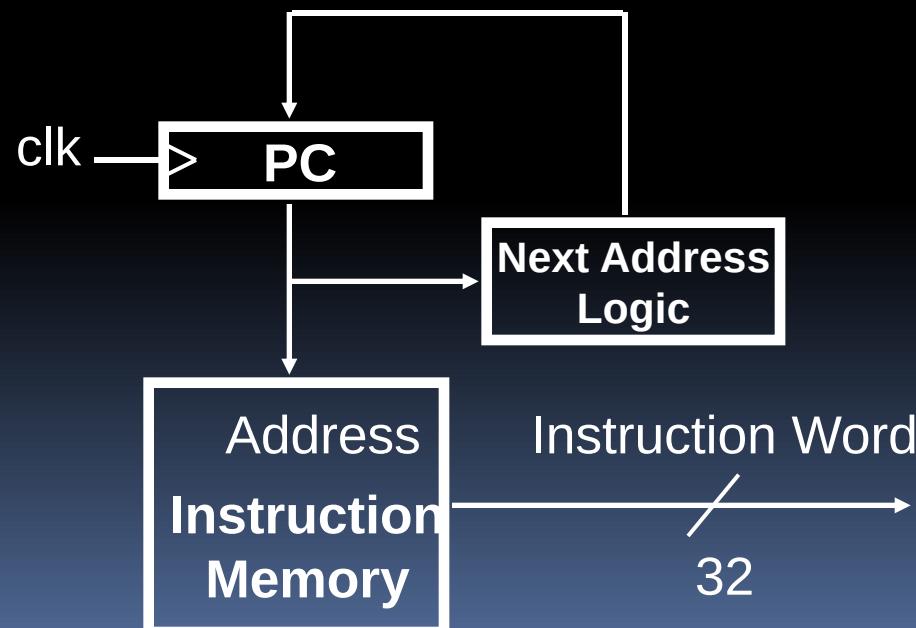
Step 3: Assemble DataPath meeting requirements

- **Register Transfer Requirements**
 ⇒ **Datapath Assembly**
- **Instruction Fetch**
- **Read Operands and Execute Operation**

3a: Overview of the Instruction Fetch Unit

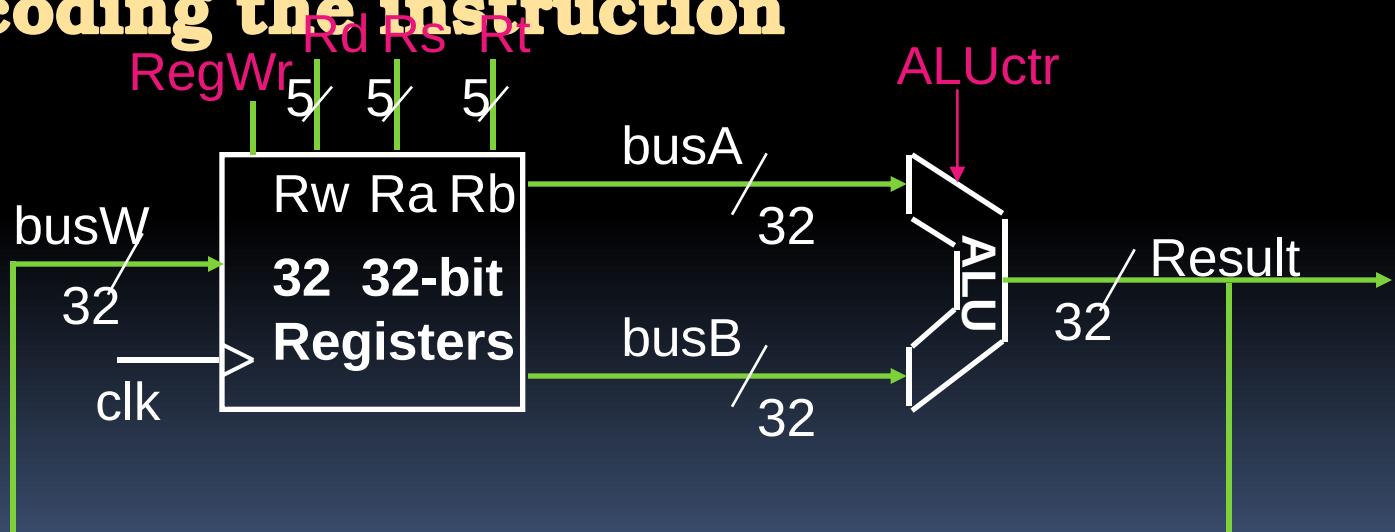
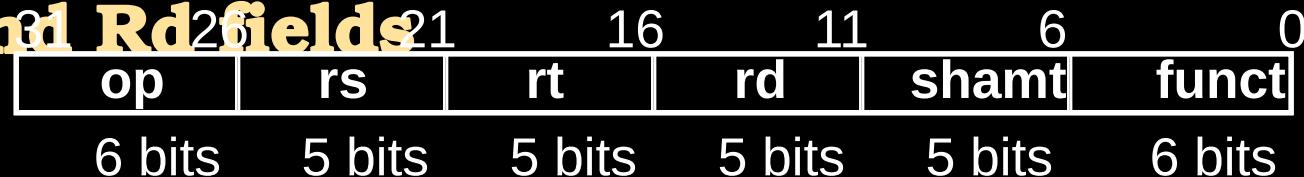
- **The common RTL operations**

- **Fetch the Instruction:** $\text{mem}[\text{PC}]$
- **Update the program counter:**
 - **Sequential Code:** $\text{PC} \leftarrow \text{PC} + 4$
 - **Branch and Jump:** $\text{PC} \leftarrow \text{"something else"}$



3b: Add & Subtract

- $R[rd] = R[rs] \text{ op } R[rt]$ (addu rd, rs, rt)
 - Ra, Rb, and Rw come from instruction's Rs, Rt, and Rd fields
 - ALUctr and RegWr: control logic after decoding the instruction



- ... Already defined the register file & ALU

Peer Instruction

- 1) We should use the main ALU to compute $PC=PC+4$
- 2) The ALU is inactive for memory reads or writes.

	12
a)	FF
b)	FT
c)	TF
d)	TT

How to Design a Processor: step-by-step

- 1. Analyze instruction set architecture (ISA)
⇒ datapath **requirements**
 - meaning of each instruction is given by the *register transfers*
 - datapath must include storage element for ISA registers
 - datapath must support each register transfer
- 2. Select set of datapath components and establish clocking methodology
- 3. Assemble datapath meeting requirements
- 4. Analyze implementation of each instruction to determine setting of control points that effects the register transfer.
- 5. Assemble the control logic (hard part!)

0.18 Pipeline



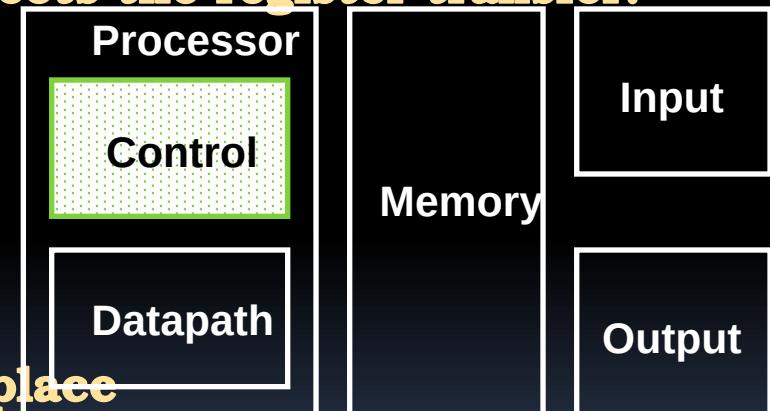
Lecture 23- CPU Design : Pipelining to Improve Performance

2020-10-23

Lecturer
Yuanqing
Cheng

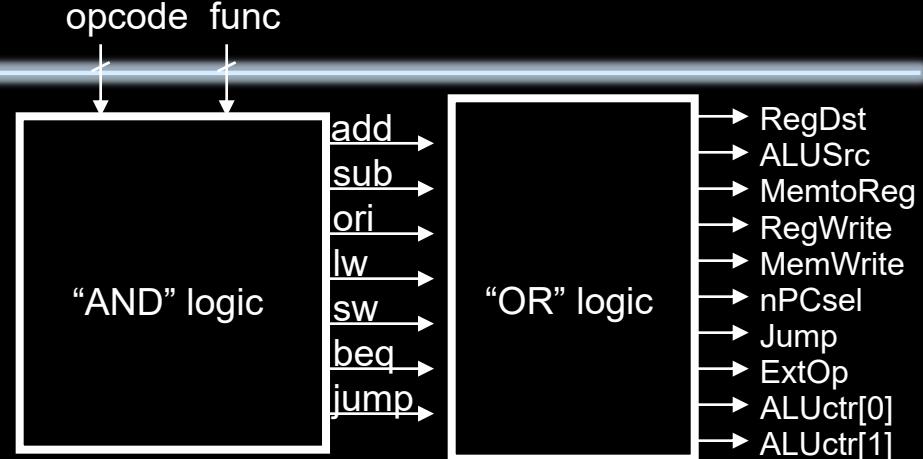
Review: Single cycle datapath

- **5 steps to design a processor**
 1. Analyze instruction set datapath **requirements**
 2. Select set of datapath components & establish clock methodology
 3. Assemble datapath meeting the requirements
 4. Analyze implementation of each instruction to determine setting of control points that effects the register transfer.
 5. Assemble the control logic
- **Control is the hard part**
- **MIPS makes that easier**
 - Instructions same size
 - Source registers always in same place
 - Immediates same size, location
 - Operations always on registers/immediates



How We Build The Controller

RegDst = add + sub
ALUSrc = ori + lw + sw
MemtoReg = lw
RegWrite = add + sub + ori + lw
MemWrite = sw
nPCsel = beq
Jump = jump
ExtOp = lw + sw
ALUctr[0] = sub + beq (assume ALUctr is 0 ADD, 01: SUB, 10: OR)
ALUctr[1] = or



where,

$$rtype = \neg op_5 \bullet \neg op_4 \bullet \neg op_3 \bullet \neg op_2 \bullet \neg op_1 \bullet \neg op_0,$$

$$ori = \neg op_5 \bullet \neg op_4 \bullet op_3 \bullet op_2 \bullet \neg op_1 \bullet op_0$$

$$lw = op_5 \bullet \neg op_4 \bullet \neg op_3 \bullet \neg op_2 \bullet op_1 \bullet op_0$$

$$sw = op_5 \bullet \neg op_4 \bullet op_3 \bullet \neg op_2 \bullet op_1 \bullet op_0$$

$$beq = \neg op_5 \bullet \neg op_4 \bullet \neg op_3 \bullet op_2 \bullet \neg op_1 \bullet \neg op_0$$

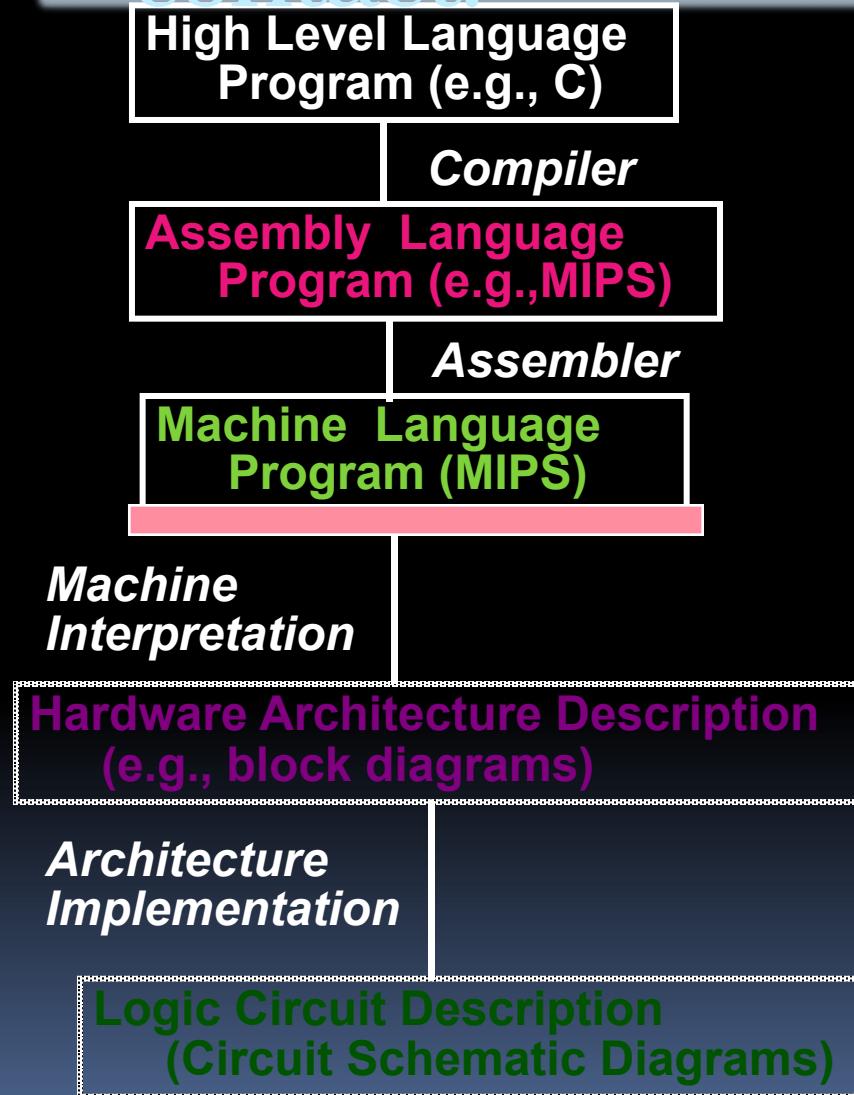
$$jump = \neg op_5 \bullet \neg op_4 \bullet \neg op_3 \bullet \neg op_2 \bullet op_1 \bullet \neg op_0$$

$$add = rtype \bullet func_5 \bullet \neg func_4 \bullet \neg func_3 \bullet \neg func_2 \bullet \neg func_1 \bullet \neg func_0$$

$$sub = rtype \bullet func_5 \bullet \neg func_4 \bullet \neg func_3 \bullet \neg func_2 \bullet func_1 \bullet \neg func_0$$

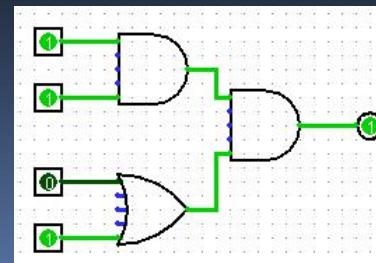
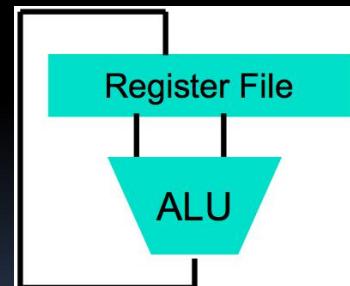
Omigosh
omigosh,
do you know
what this
means?

Call home, we've made HW/SW contact!



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)

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



Processor Performance

- **Can we estimate the clock rate (frequency) of our single-cycle processor? We know:**
 - **1 cycle per instruction**
 - **lw is the most demanding instruction.**
 - **Assume these delays for major pieces of the datapath:**
 - **Instr. Mem, ALU, Data Mem : 2ns each, regfile 1ns**
 - **Instruction execution requires: $2 + 1 + 2 + 2 + 1 = 8\text{ns}$**
 - **⇒ 125 MHz**
- **What can we do to improve clock rate?**
- **Will this improve performance as well?**

Gotta Do Laundry

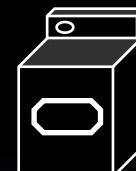
- **Ann, Brian, Cathy, Dave each have one load of clothes to wash, dry, fold, and put away**



- **Washer takes 30 minutes**



- **Dryer takes 30 minutes**



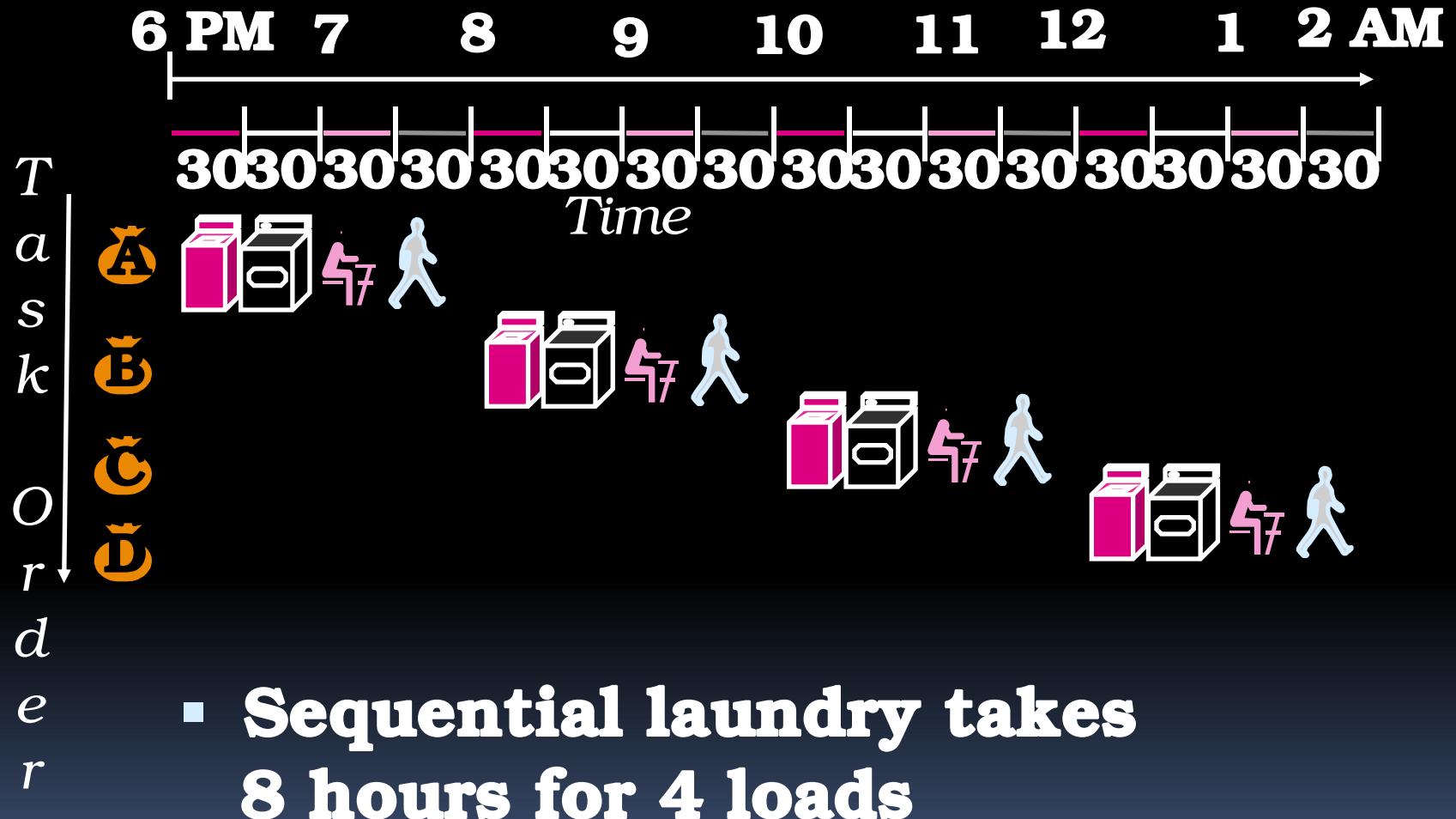
- **“Folder” takes 30 minutes**



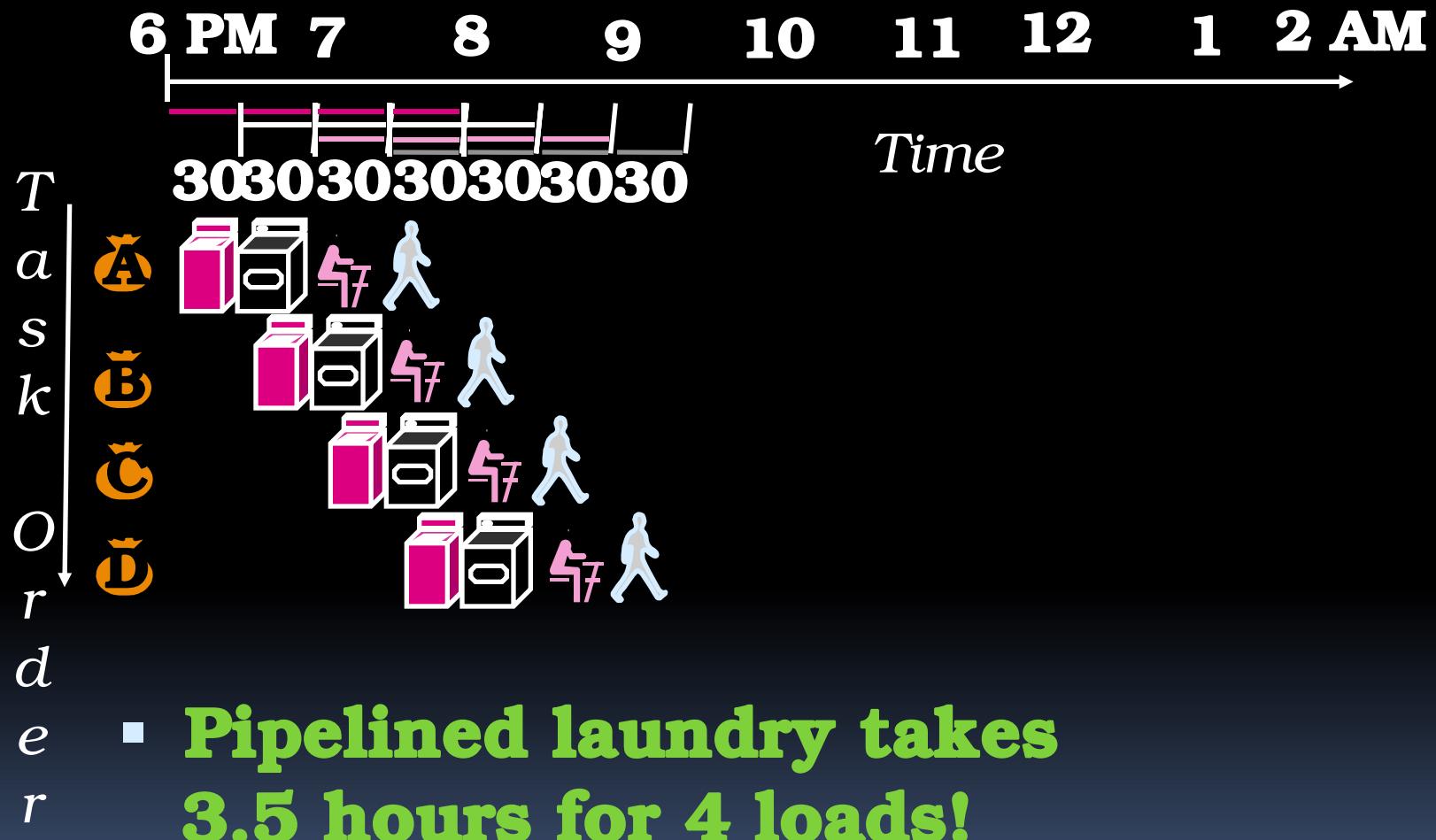
- **“Stasher” takes 30 minutes to put clothes into drawers**



Sequential Laundry



Pipelined Laundry

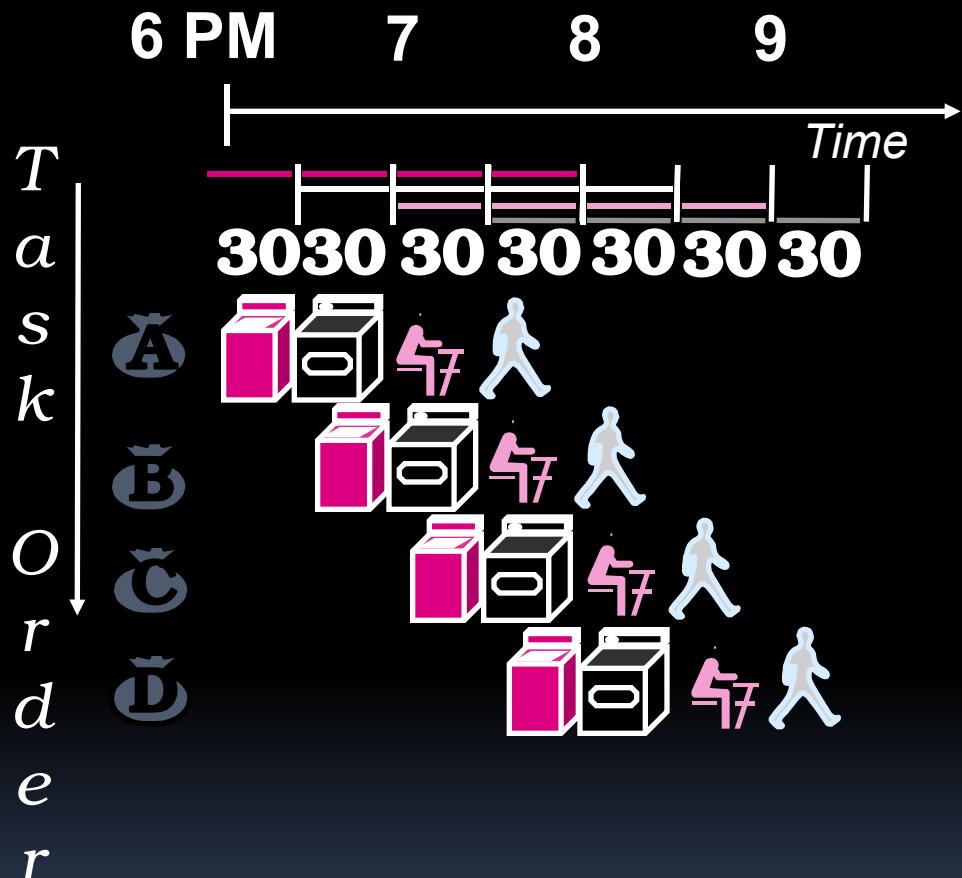


- **Pipelined laundry takes 3.5 hours for 4 loads!**

General Definitions

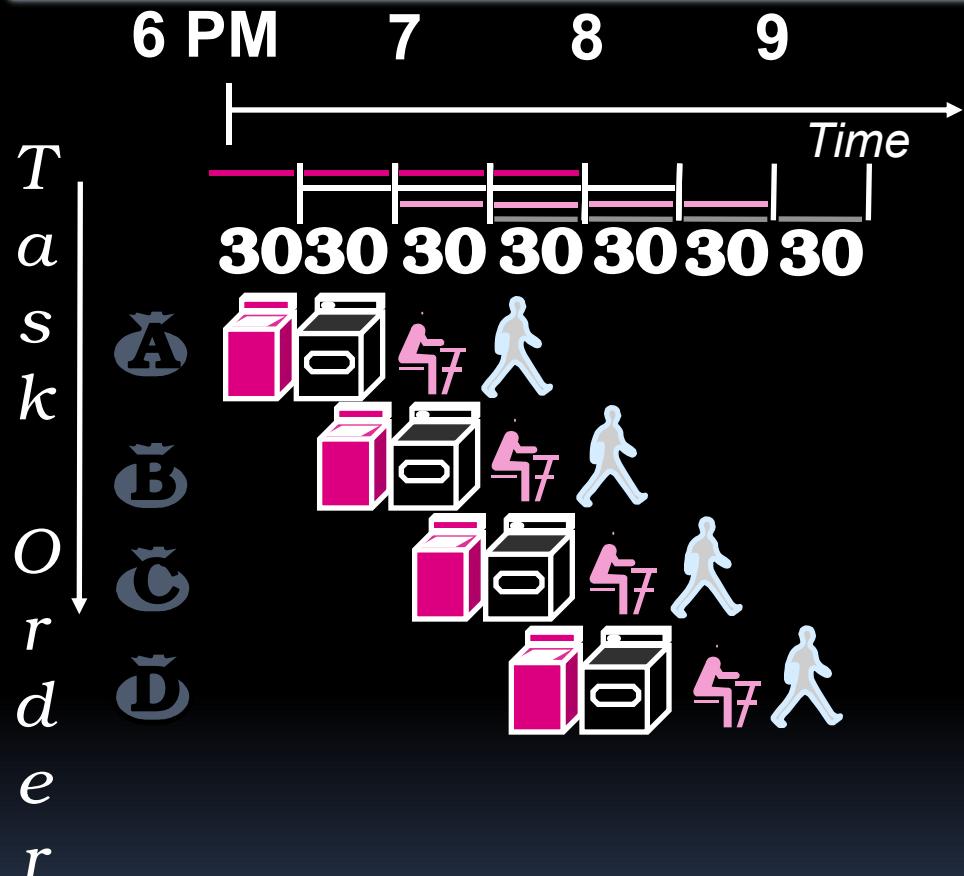
- **Latency:** time to completely execute a certain task
 - for example, time to read a sector from disk is disk access time or disk latency
- **Throughput:** amount of work that can be done over a period of time

Pipelining Lessons (1 / 2)



- Pipelining doesn't help latency of single task, it helps throughput of entire workload
- Multiple tasks operating simultaneously using different resources
- Potential speedup = Number pipe stages
- Time to “fill” pipeline and time to “drain” it reduces speedup:
2.3X v. 4X in this example

Pipelining Lessons (2/2)



- Suppose new Washer takes 20 minutes, new Stasher takes 20 minutes. How much faster is pipeline?
- Pipeline rate limited by **slowest** pipeline stage
- Unbalanced lengths of pipe

Steps in Executing MIPS

- 1) **IFtch: Instruction Fetch, Increment PC**
- 2) **Dcd: Instruction Decode, Read Registers**
- 3) **Exec:**
Mem-ref: Calculate Address
Arith-log: Perform Operation
- 4) **Mem:**
Load: Read Data from Memory
Store: Write Data to Memory
- 5) **WB: Write Data Back to Register**

Pipelined Execution

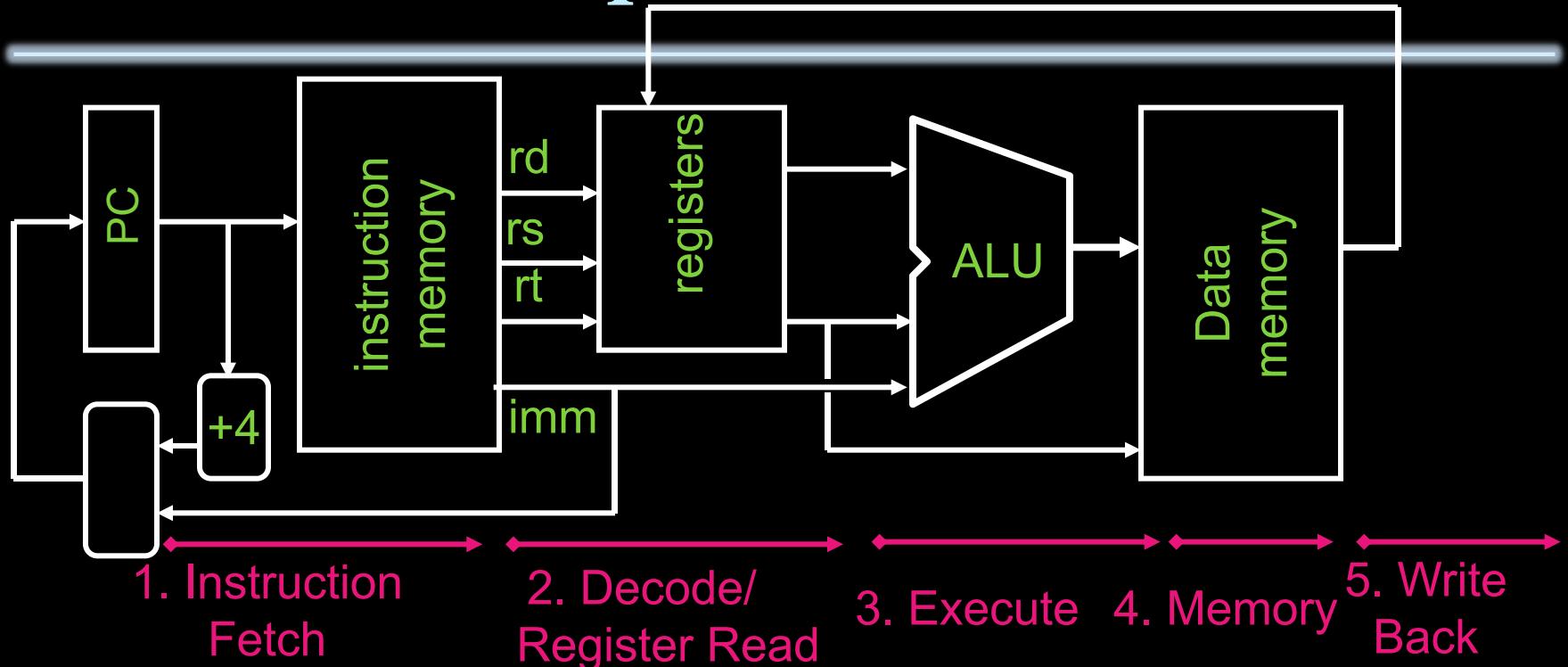
Representation

Time

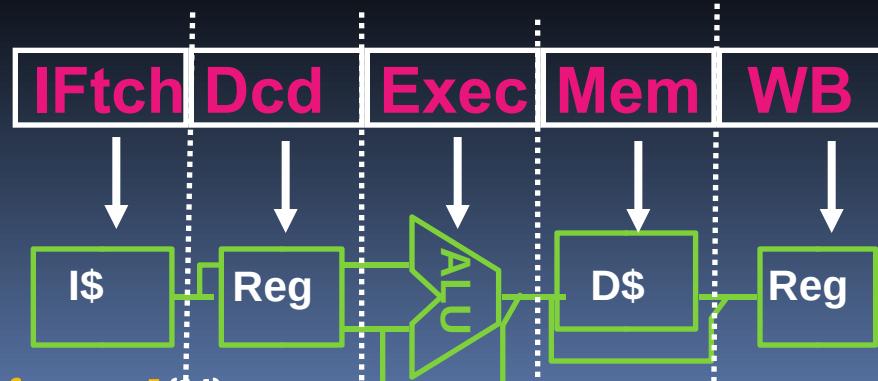


- Every instruction must take same number of steps, also called pipeline “stages”, so some will go idle sometimes

Review: Datapath for MIPS

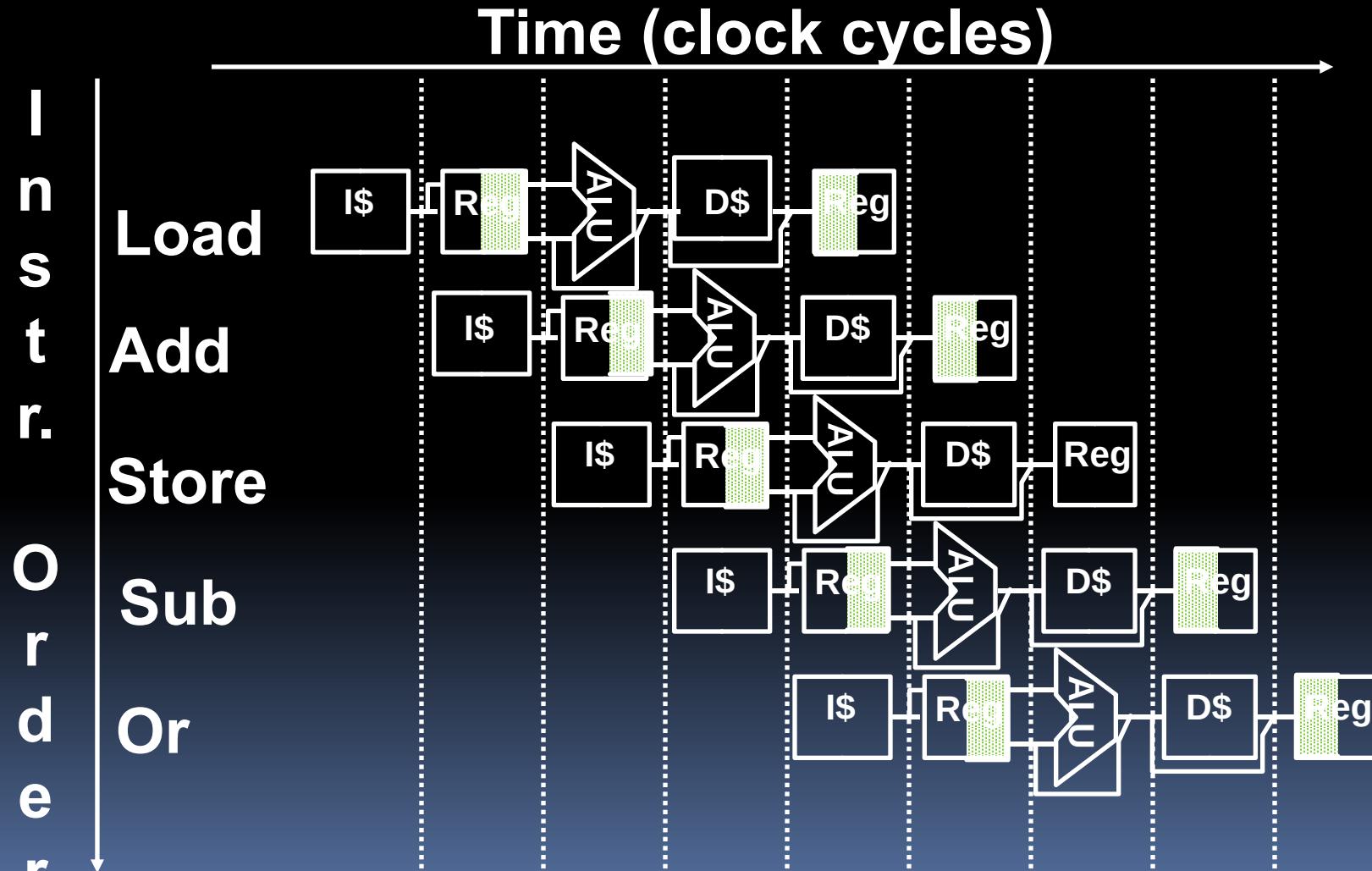


- **Use datapath figure to represent pipeline**



Graphical Pipeline Representation

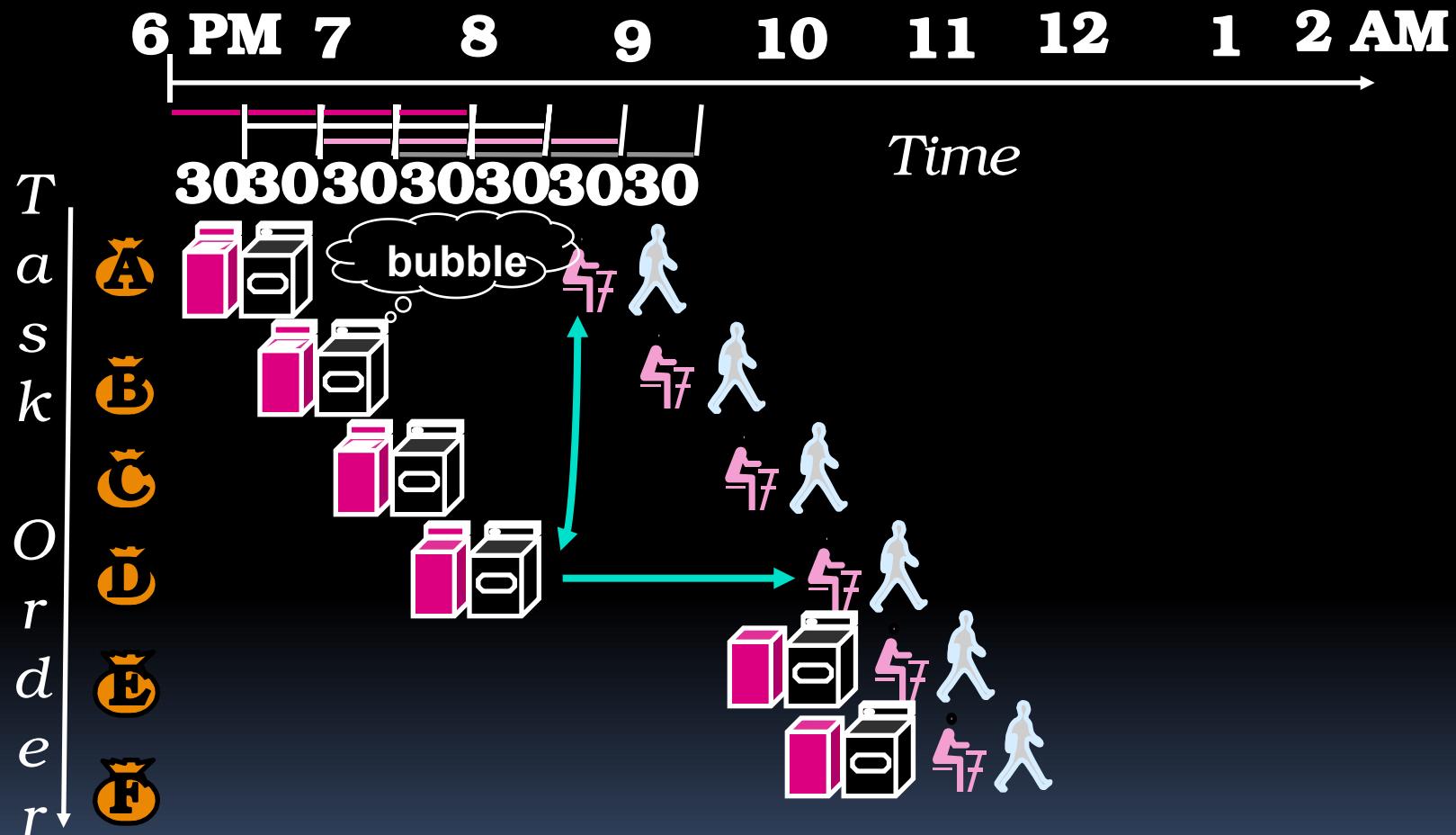
(In Reg, right half highlight read, left half write)



Example

- Suppose 2 ns for memory access, 2 ns for ALU operation, and 1 ns for register file read or write; compute instruction rate
- Nonpipelined Execution:
 - $lw : \text{IF} + \text{Read Reg} + \text{ALU} + \text{Memory} + \text{Write Reg} = 2 + 1 + 2 + 2 + 1 = 8 \text{ ns}$
 - $add: \text{IF} + \text{Read Reg} + \text{ALU} + \text{Write Reg} = 2 + 1 + 2 + 1 = 6 \text{ ns}$
(recall 8ns for single-cycle processor)
- Pipelined Execution:
 - $\text{Max(IF, Read Reg, ALU, Memory, Write Reg)} =$

Pipeline Hazard: Matching socks in later load

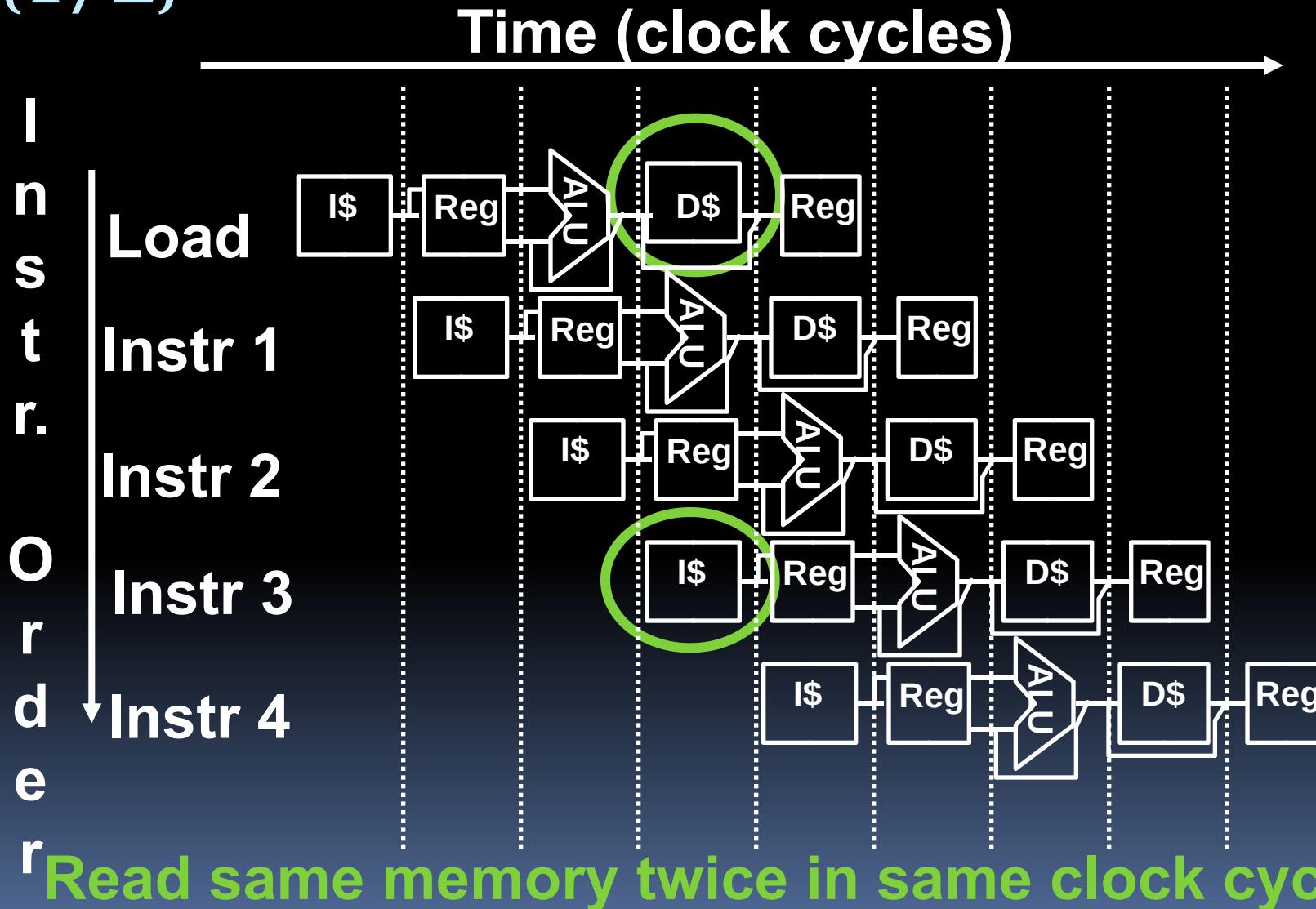


- A depends on D; **stall since folder tied**

Problems for Pipelining CPUs

- **Limits to pipelining:** **Hazards** prevent next instruction from executing during its designated clock cycle
 - **Structural hazards:** HW cannot support some combination of instructions (single person to fold and put clothes away)
 - **Control hazards:** Pipelining of branches causes later instruction fetches to wait for the result of the branch
 - **Data hazards:** Instruction depends on result of prior instruction still in the pipeline (missing sock)
- These might result in pipeline **stalls** or “**bubbles**” in the pipeline.

Structural Hazard #1: Single Memory (1/2)



Structural Hazard #1: Single Memory (2/2)

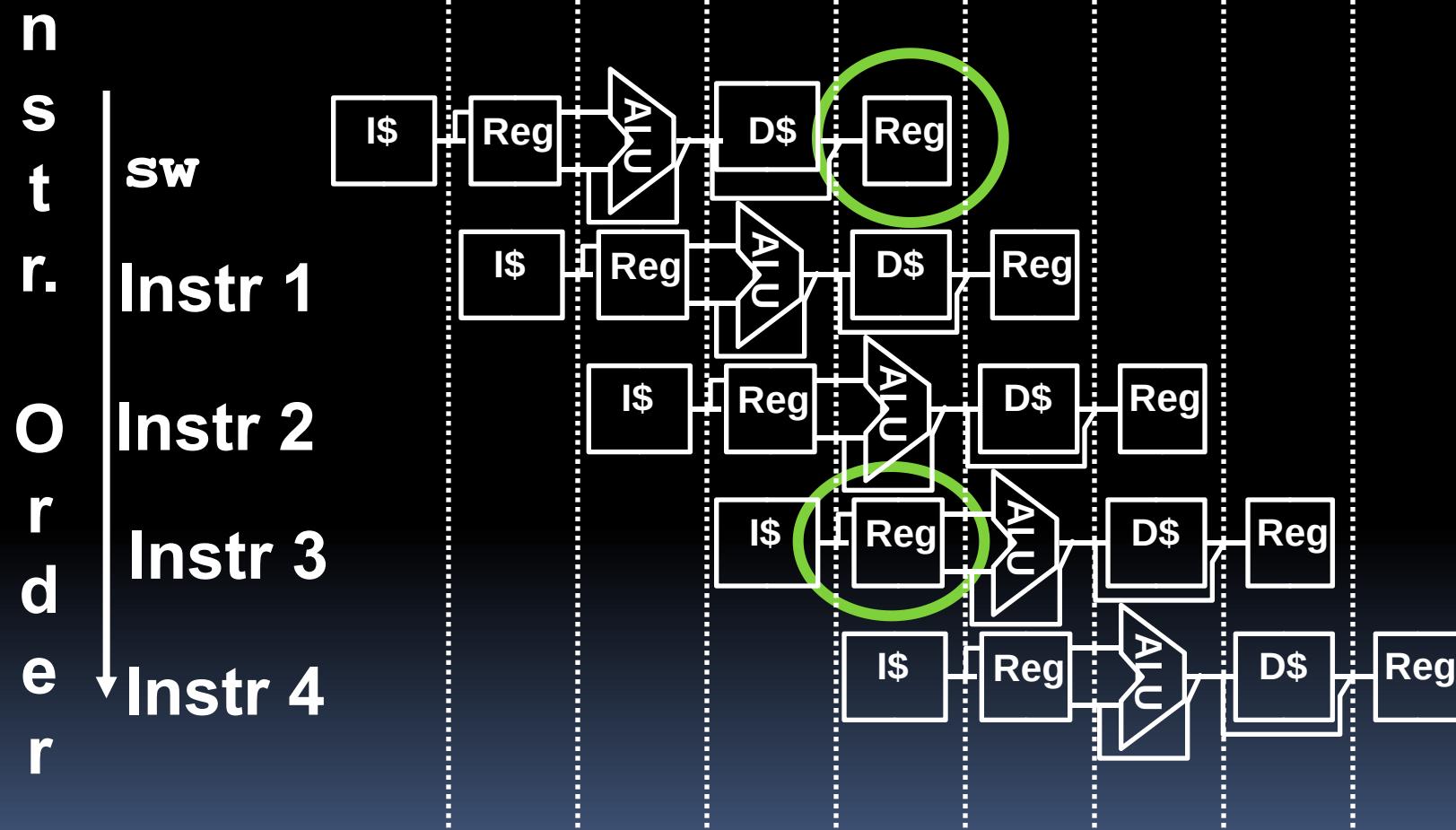
- **Solution:**

- **infeasible and inefficient to create second memory**
- (We'll learn about this more next week)
- **so simulate this by having two Level 1 Caches (a temporary smaller [of usually most recently used] copy of memory)**
- **have both an L1 Instruction Cache and an L1 Data Cache**
- **need more complex hardware to control when both caches miss**

Structural Hazard #2: Registers

(1/2)

Time (clock cycles)



Can we read and write to registers simultaneously?

Structural Hazard #2: Registers

(2/2)

- Two different solutions have been used:
 - 1) RegFile access is **VERY fast: takes less than half the time of ALU stage**
 - Write to Registers during first half of each clock cycle
 - Read from Registers during second half of each clock cycle
 - 2) Build RegFile with independent read and write ports
- **Result: can perform Read and Write during same clock cycle**

Peer Instruction

- 1) Thanks to pipelining, I have reduced the time it took me to wash my one shirt.

- 2) Longer pipelines are always a win (since less work per stage & a faster clock).

	12
a)	FF
b)	FT
c)	TF
d)	TT

Peer Instruction Answer

- 1) Throughput better, not execution time
- 2) “...longer pipelines do usually mean faster clock, but branches cause problems!”

- 1) Thanks to pipelining, I have reduced the time it took me to wash my one shirt.
- 2) Longer pipelines are always a win (since less work per stage & a faster clock).

	12
a)	FF
b)	FT
c)	TF
d)	TT

Things to Remember

- **Optimal Pipeline**
 - **Each stage is executing part of an instruction each clock cycle.**
 - **One instruction finishes during each clock cycle.**
 - **On average, execute far more quickly.**
- **What makes this work?**
 - **Similarities between instructions allow us to use same stages for all instructions (generally).**
 - **Each stage takes about the same amount of time as all others: little wasted time.**

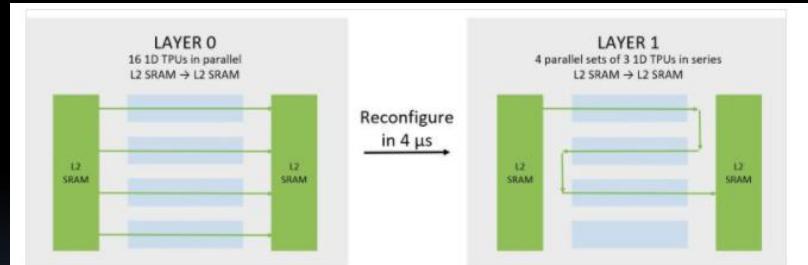


Lecturer
Yuanqing
Cheng

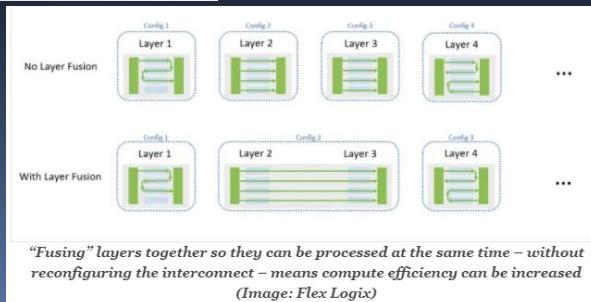
Lecture 25 – CPU Design : Pipelining to Improve Performance II

2020-10-26

Flex Logix' Edge AI Accelerator
Battles Nvidia on Price-Performance



One of the ingredients in Flex Logix' secret sauce is its configurable interconnect technology (Image: Flex Logix)



"Fusing" layers together so they can be processed at the same time – without reconfiguring the interconnect – means compute efficiency can be increased (Image: Flex Logix)

Review

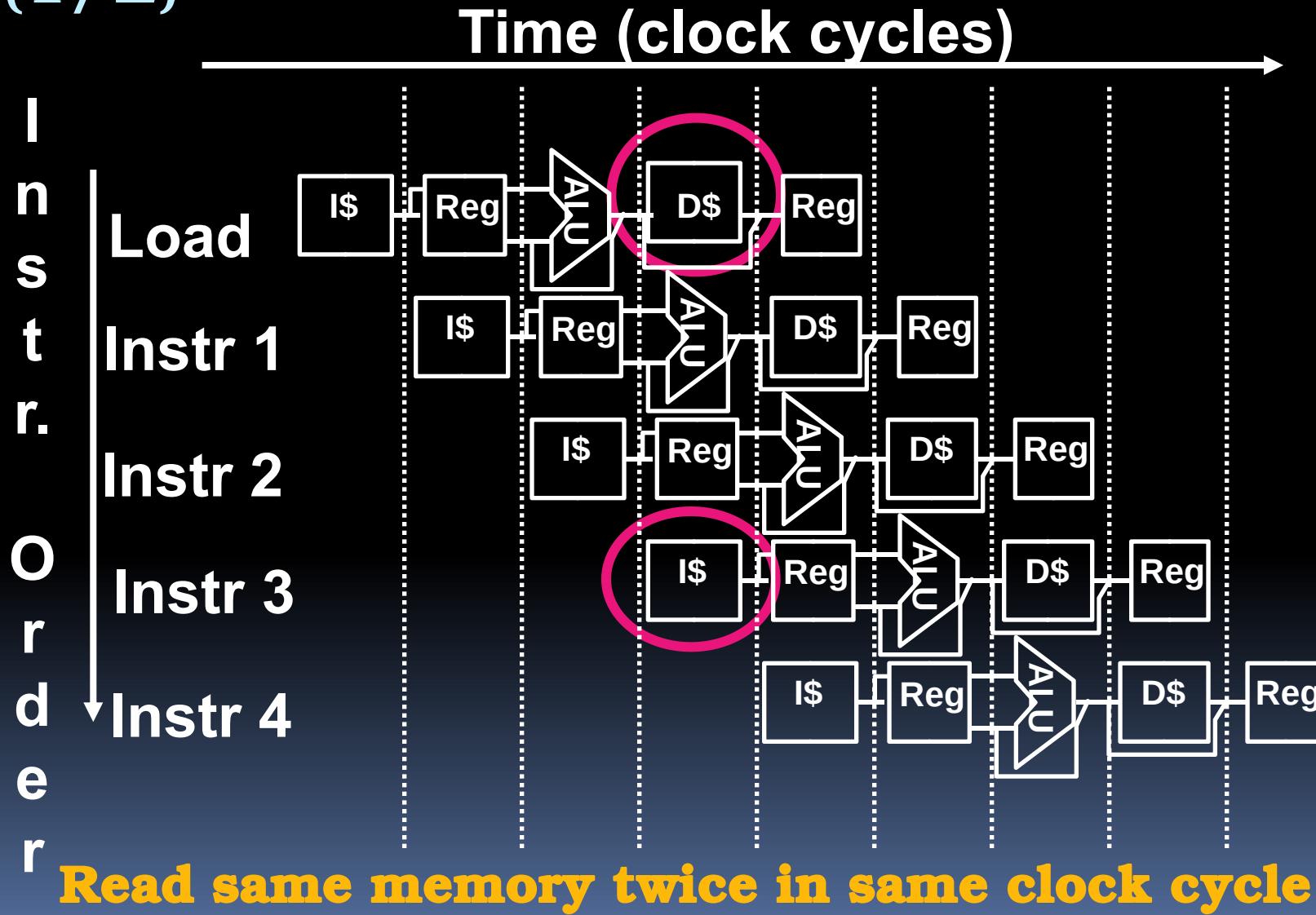
- Pipelining is a BIG idea
- Optimal Pipeline
 - Each stage is executing part of an instruction each clock cycle.
 - One instruction finishes during each clock cycle.
 - On average, execute far more quickly.
- What makes this work?
 - Similarities between instructions allow us to use same stages for all instructions (generally).
 - Each stage takes about the same amount

Problems for Pipelining CPUs

- **Limits to pipelining:** **Hazards** prevent next instruction from executing during its designated clock cycle
 - **Structural hazards:** HW cannot support some combination of instructions (single person to fold and put clothes away)
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Structural Hazard #1: Single Memory

(1/2)



Structural Hazard #1: Single Memory (2/2)

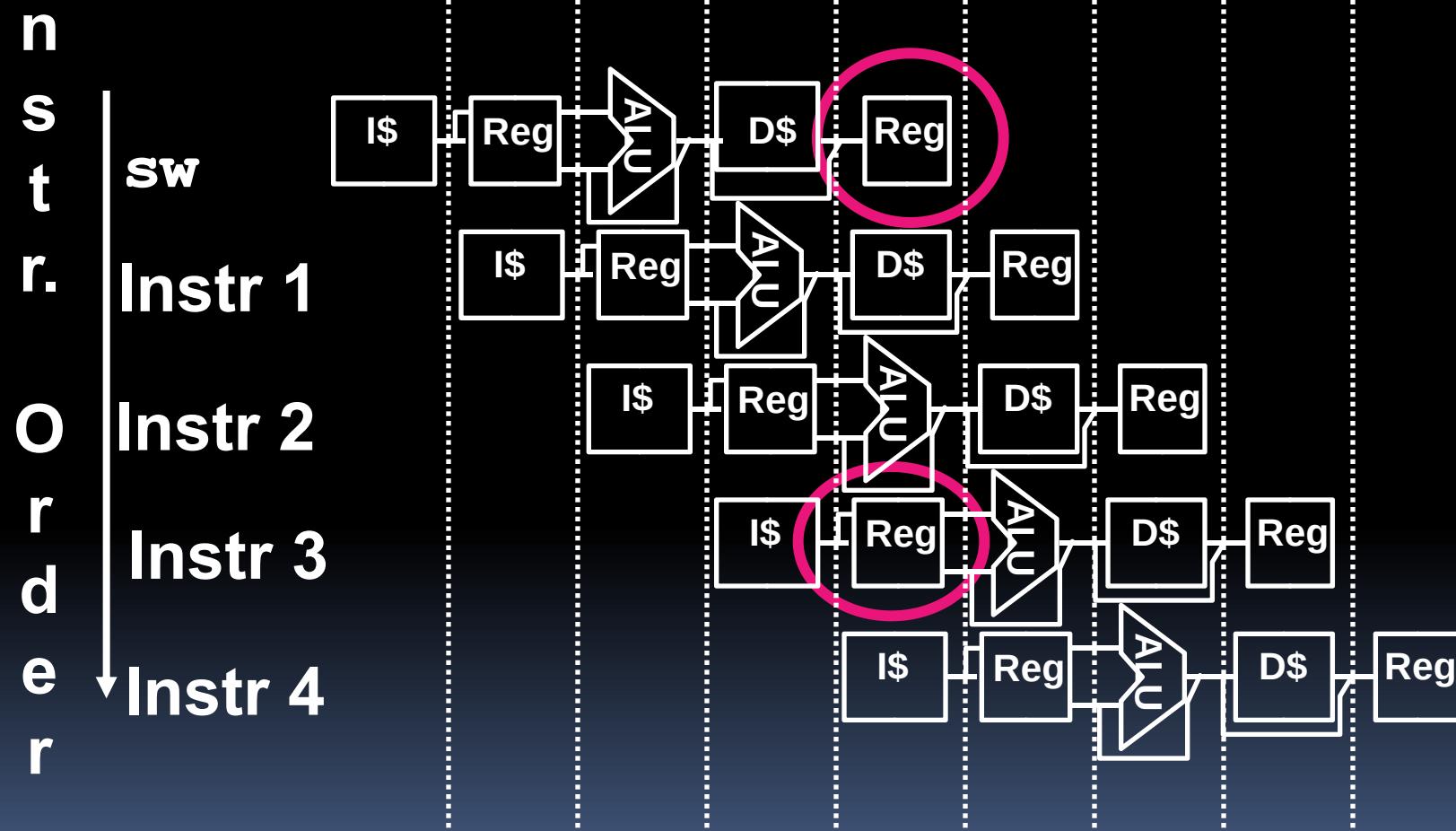
- **Solution:**

- **infeasible and inefficient to create second memory**
- (We'll learn about this shortly)
- ...so simulate this by having **two Level 1 Caches**
 - (a temporary smaller [of usually most recently used] copy of memory)
- have both an **L1 Instruction Cache** and an **L1 Data Cache**
- need more complex hardware to control when both caches miss

Structural Hazard #2: Registers

(1/2)

Time (clock cycles)



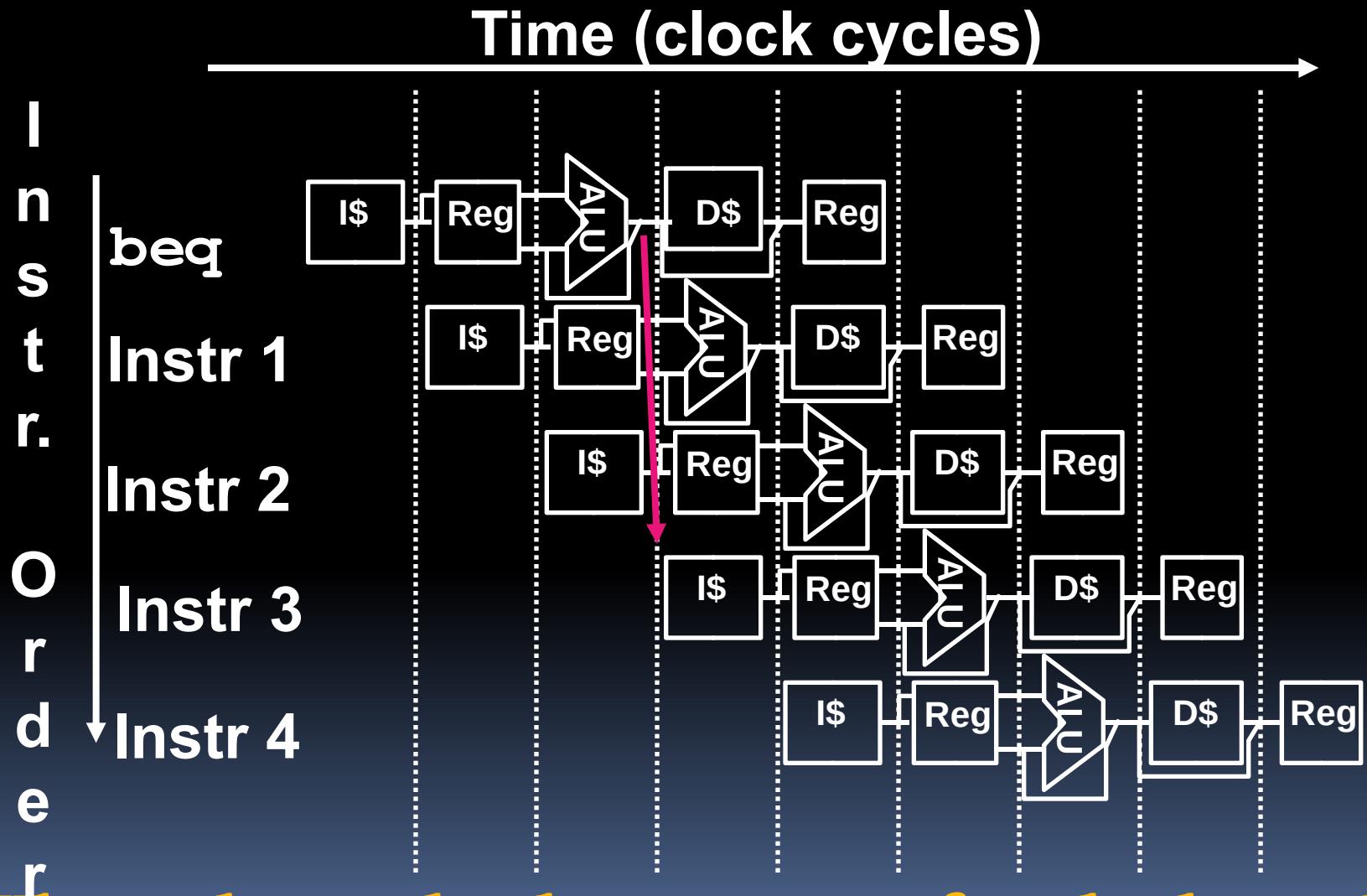
Can we read and write to registers simultaneously?

Structural Hazard #2: Registers

(2/2)

- Two different solutions have been used:
 - 1) RegFile access is **VERY fast: takes less than half the time of ALU stage**
 - Write to Registers during first half of each clock cycle
 - Read from Registers during second half of each clock cycle
 - 2) Build RegFile with independent read and write ports
- **Result: can perform Read and Write during same clock cycle**

Control Hazard: Branching (1 / 9)



Where do we do the compare for the branch?

Control Hazard: Branching (2/9)

- We had put branch decision-making hardware in ALU stage
 - therefore two more instructions after the branch will always be fetched, whether or not the branch is taken
- Desired functionality of a branch
 - if we do not take the branch, don't waste any time and continue executing normally
 - if we take the branch, don't execute any instructions after the branch, just go to the desired label

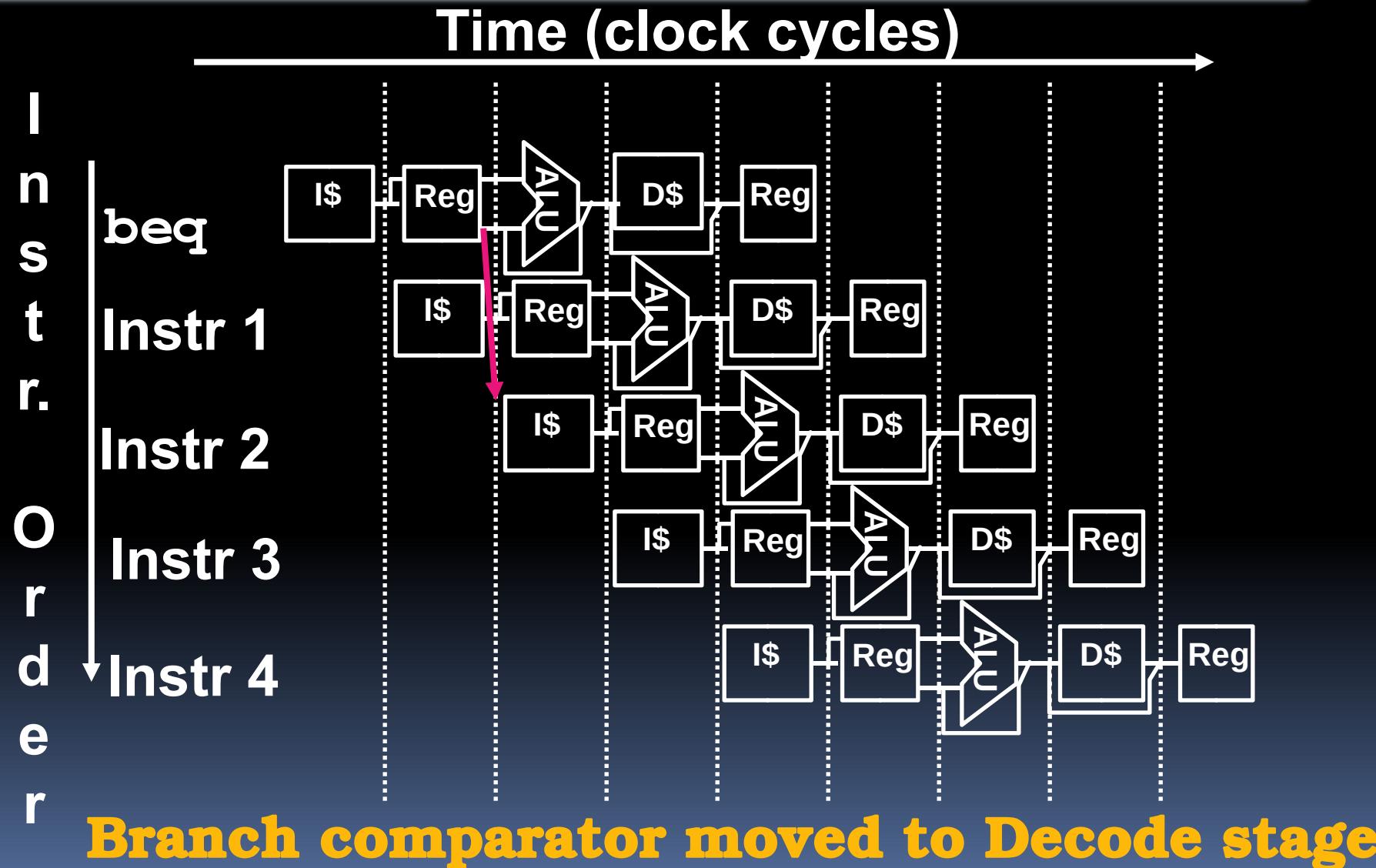
Control Hazard: Branching (3/9)

- **Initial Solution: Stall until decision is made**
 - **insert “no-op” instructions (those that accomplish nothing, just take time) or hold up the fetch of the next instruction (for 2 cycles).**
 - **Drawback: branches take 3 clock cycles each (assuming comparator is put in ALU stage)**

Control Hazard: Branching (4 / 9)

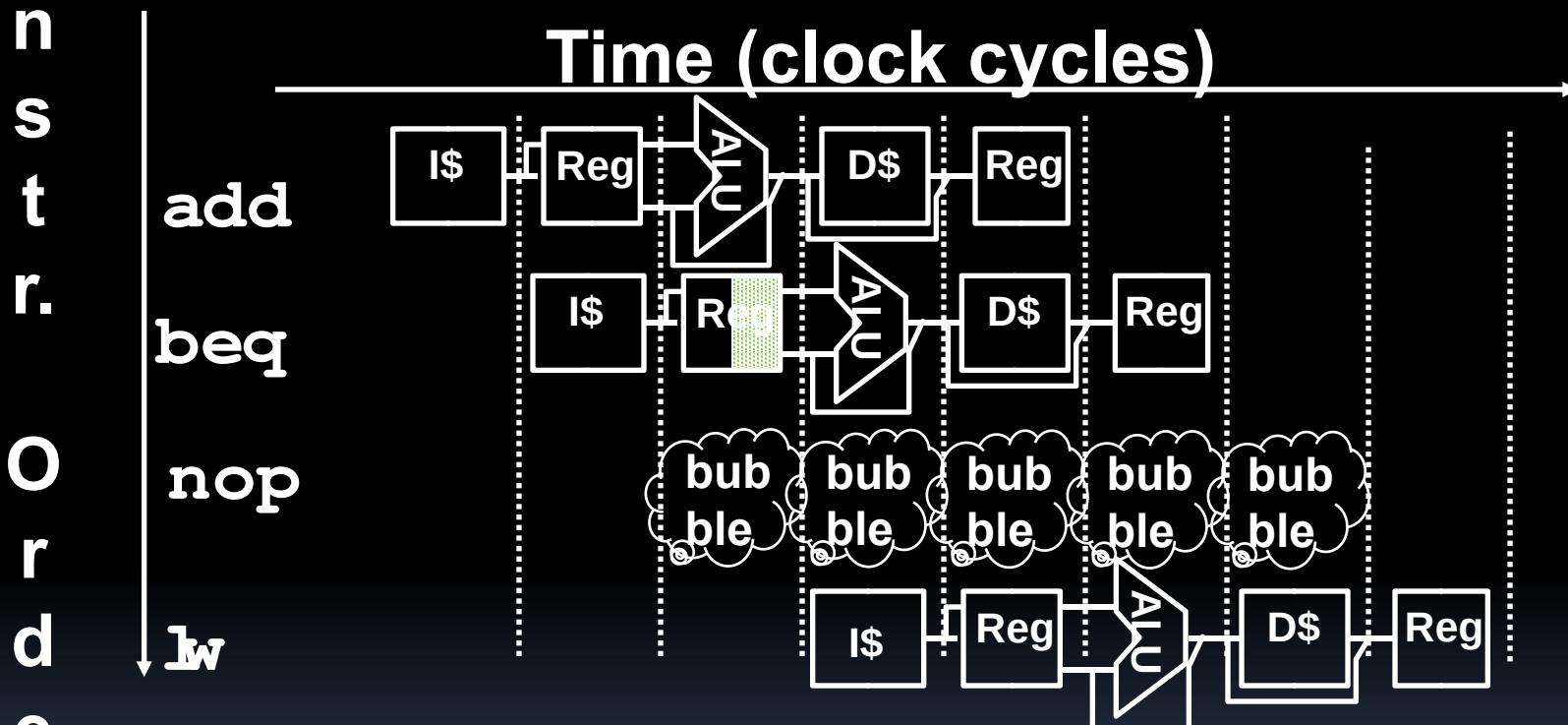
- **Optimization #1:**
 - **insert special branch comparator in Stage 2**
 - **as soon as instruction is decoded (Opcode identifies it as a branch), immediately make a decision and set the new value of the PC**
 - **Benefit: since branch is complete in Stage 2, only one unnecessary instruction is fetched, so only one no-op is needed**
 - **Side Note: This means that branches are idle in Stages 3, 4 and 5.**

Control Hazard: Branching (5 / 9)



Control Hazard: Branching (6/9)

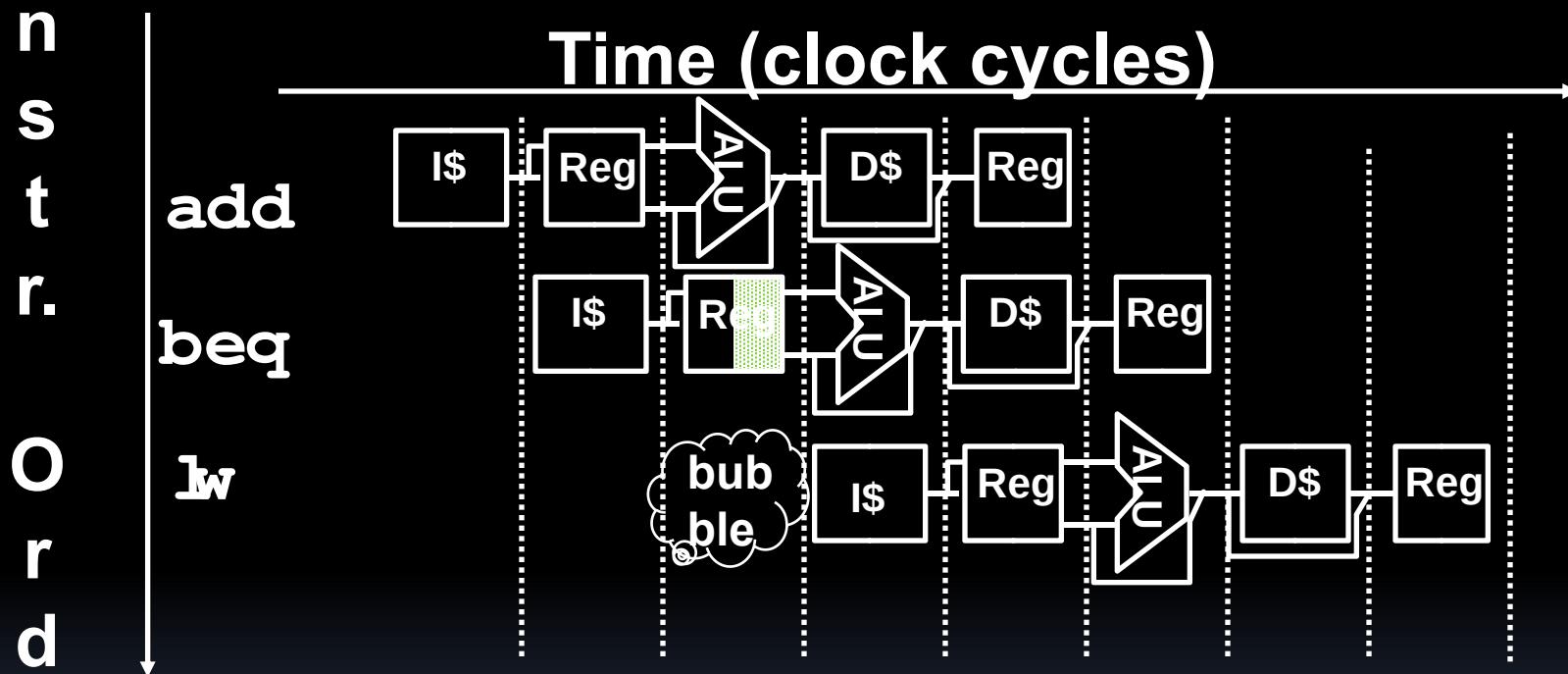
I ▪ User inserting no-op instruction



Impact: 2 clock cycles per branch instruction slow

Control Hazard: Branching (7 / 9)

I ▪ Controller inserting a single bubble



Impact: 2 clock cycles per branch instruction slow

...story about engineer, physicist, mathematician asked to build a fence around a flock of sheep

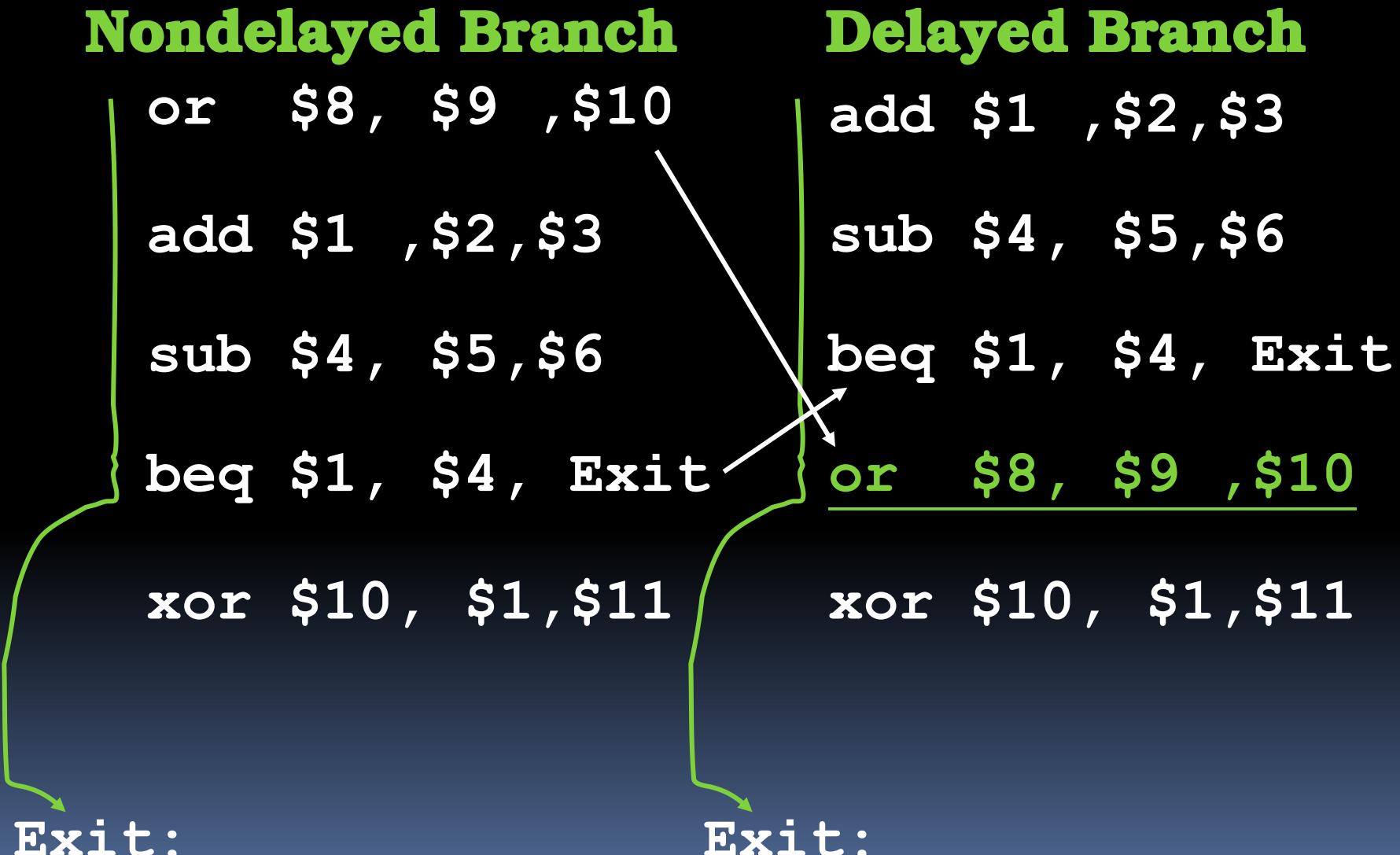
Control Hazard: Branching (8/9)

- **Optimization #2: Redefine branches**
 - Old definition: if we take the branch, none of the instructions after the branch get executed by accident
 - New definition: whether or not we take the branch, the single instruction immediately following the branch gets executed (called the **branch-delay slot**)
- The term “**Delayed Branch**” means we always execute inst after branch
- This optimization is used with MIPS

Control Hazard: Branching (9/9)

- **Notes on Branch-Delay Slot**
 - **Worst-Case Scenario:** can always put a no-op in the branch-delay slot
 - **Better Case:** can find an instruction preceding the branch which can be placed in the branch-delay slot without affecting flow of the program
 - re-ordering instructions is a common method of speeding up programs
 - compiler must be very smart in order to find instructions to do this
 - usually can find such an instruction at least 50% of the time

Example: Nondelayed vs. Delayed Branch



Data Hazards (1 / 2)

- Consider the following sequence of instructions

add \$t0, \$t1, \$t2

sub \$t4, \$t0 , \$t3

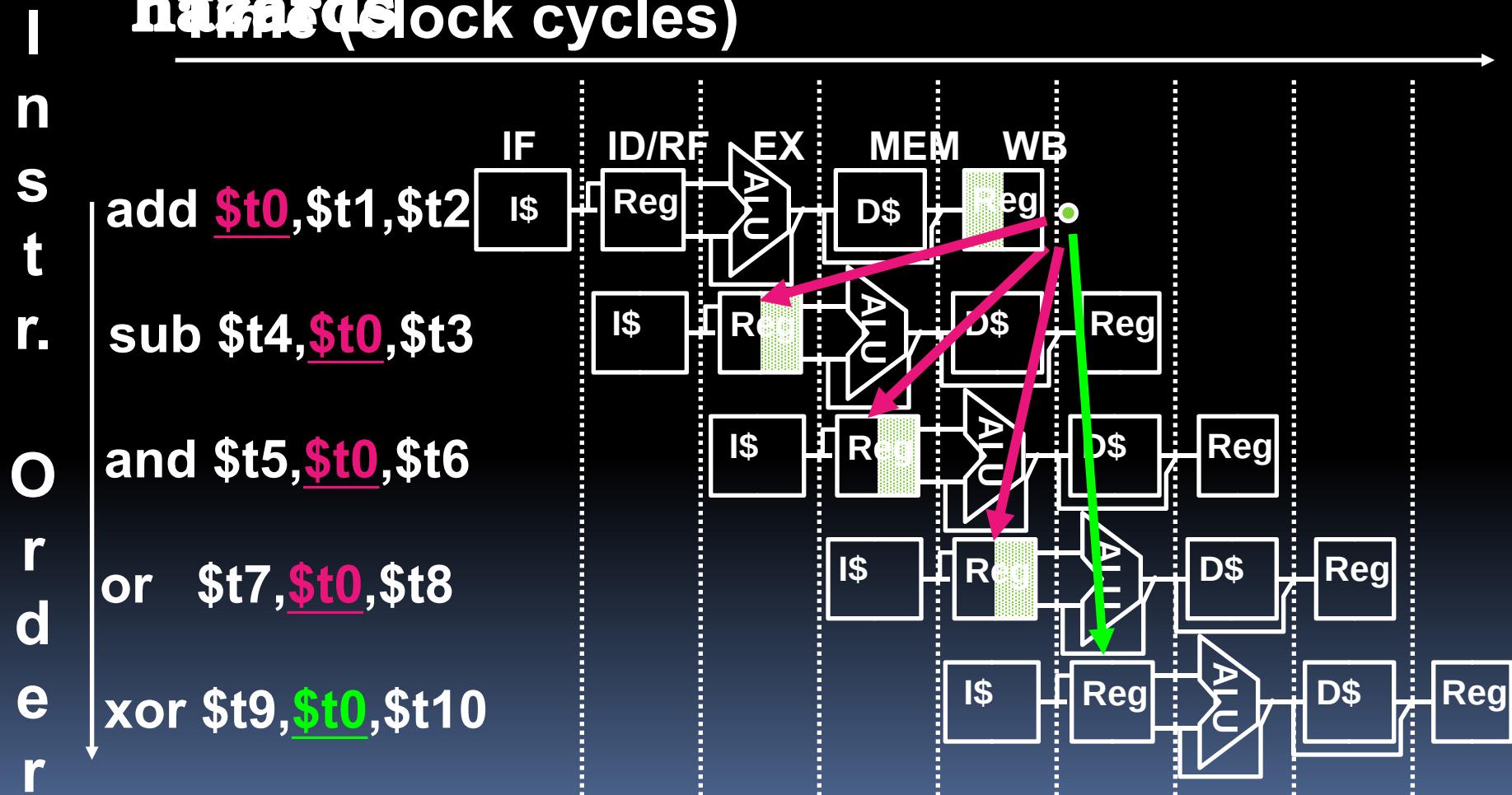
and \$t5, \$t0 , \$t6

or \$t7, \$t0 , \$t8

xor \$t9, \$t0 , \$t10

Data Hazards (2/2)

- Data-flow backward in time are hazards (lock cycles)



Data Hazard Solution:

Forwarding

Forward result from one stage to another

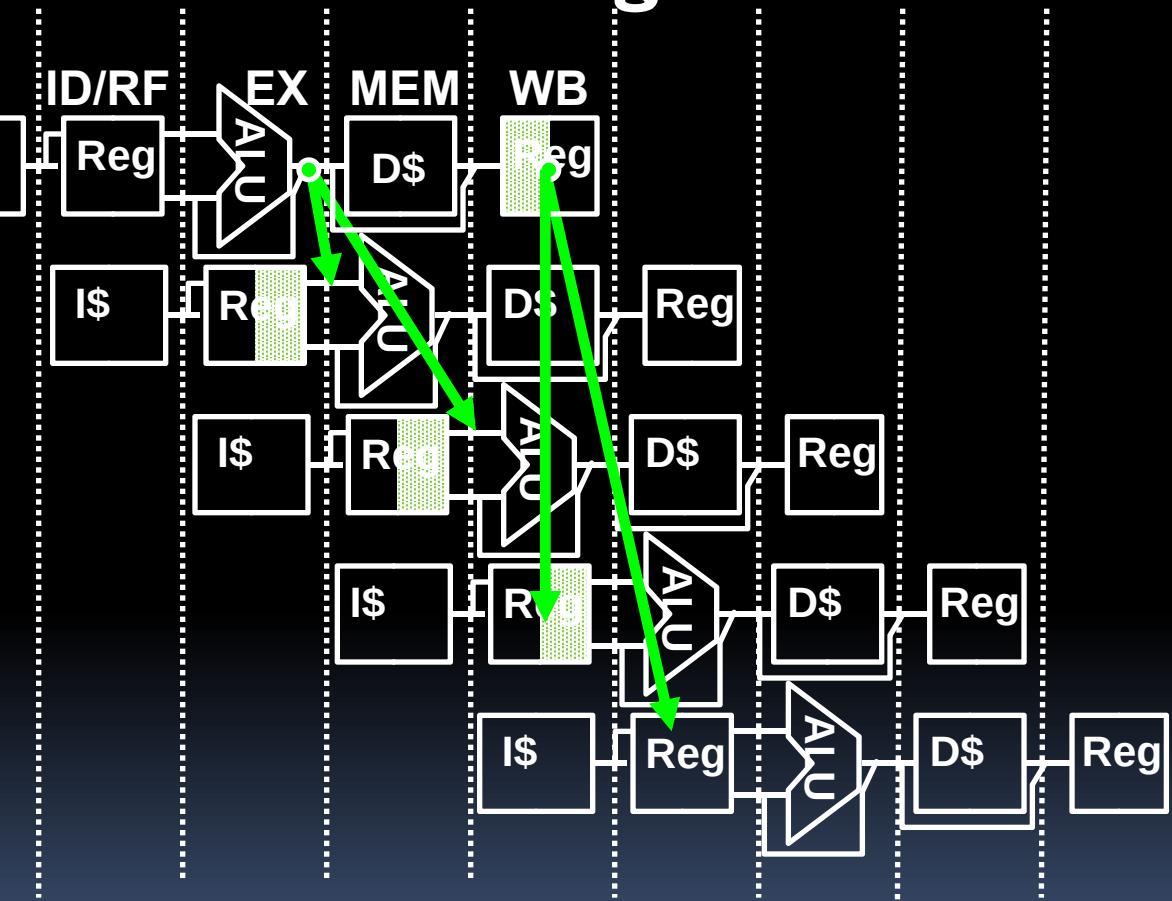
add \$t0,\$t1,\$t2

sub \$t4,\$t0,\$t3

and \$t5,\$t0,\$t6

or \$t7,\$t0,\$t8

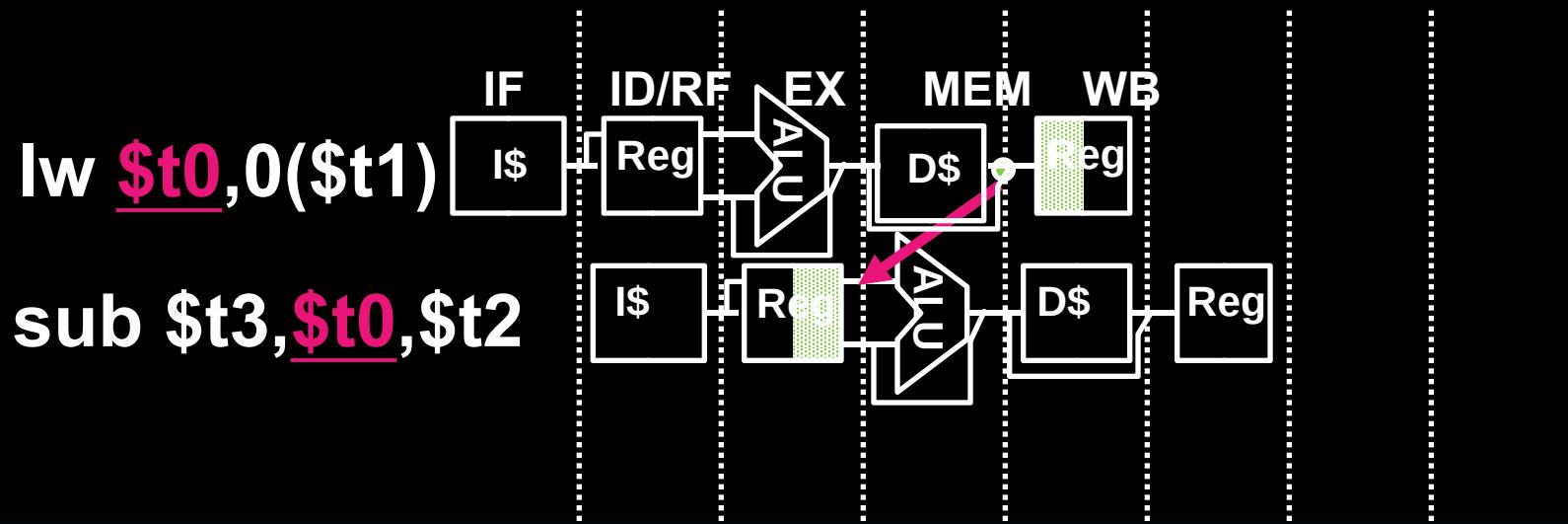
xor \$t9,\$t0,\$t10



“or” hazard solved by register hardware

Data Hazard: Loads (1 / 4)

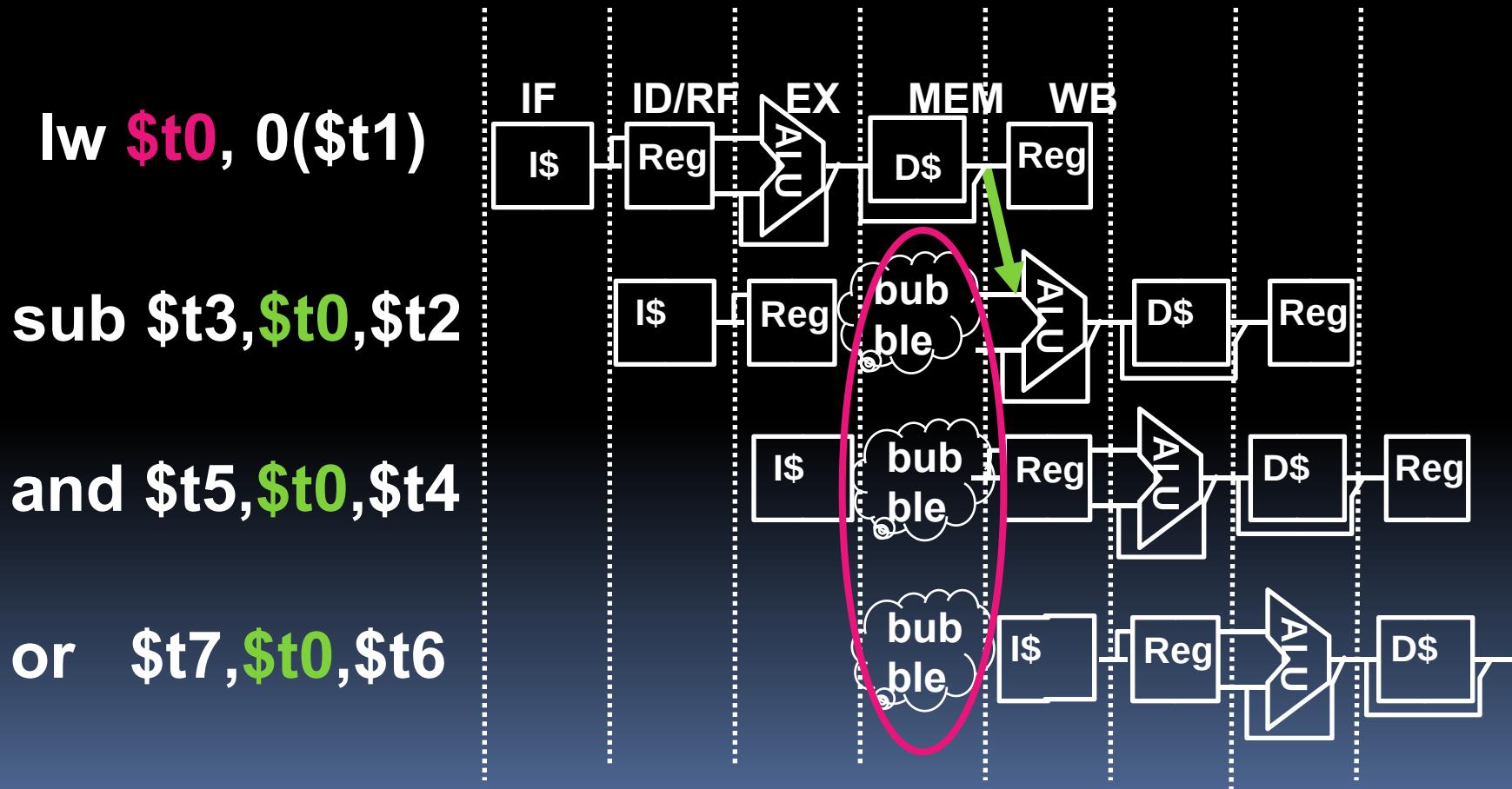
- Dataflow backwards in time are hazards



- Can't solve all cases with forwarding
- Must stall instruction dependent on load, then forward (more hardware)

Data Hazard: Loads (2 / 4)

- **Hardware stalls pipeline**
 - Called “interlock”



Data Hazard: Loads (3/4)

- **Instruction slot after a load is called “load delay slot”**
- **If that instruction uses the result of the load, then the hardware interlock will stall it for one cycle.**
- **If the compiler puts an unrelated instruction in that slot, then no stall**
- **Letting the hardware stall the instruction in the delay slot is equivalent to putting a nop in the slot (except the latter uses more code space)**

Data Hazard: Loads (4/4)

- Stall is equivalent to nop

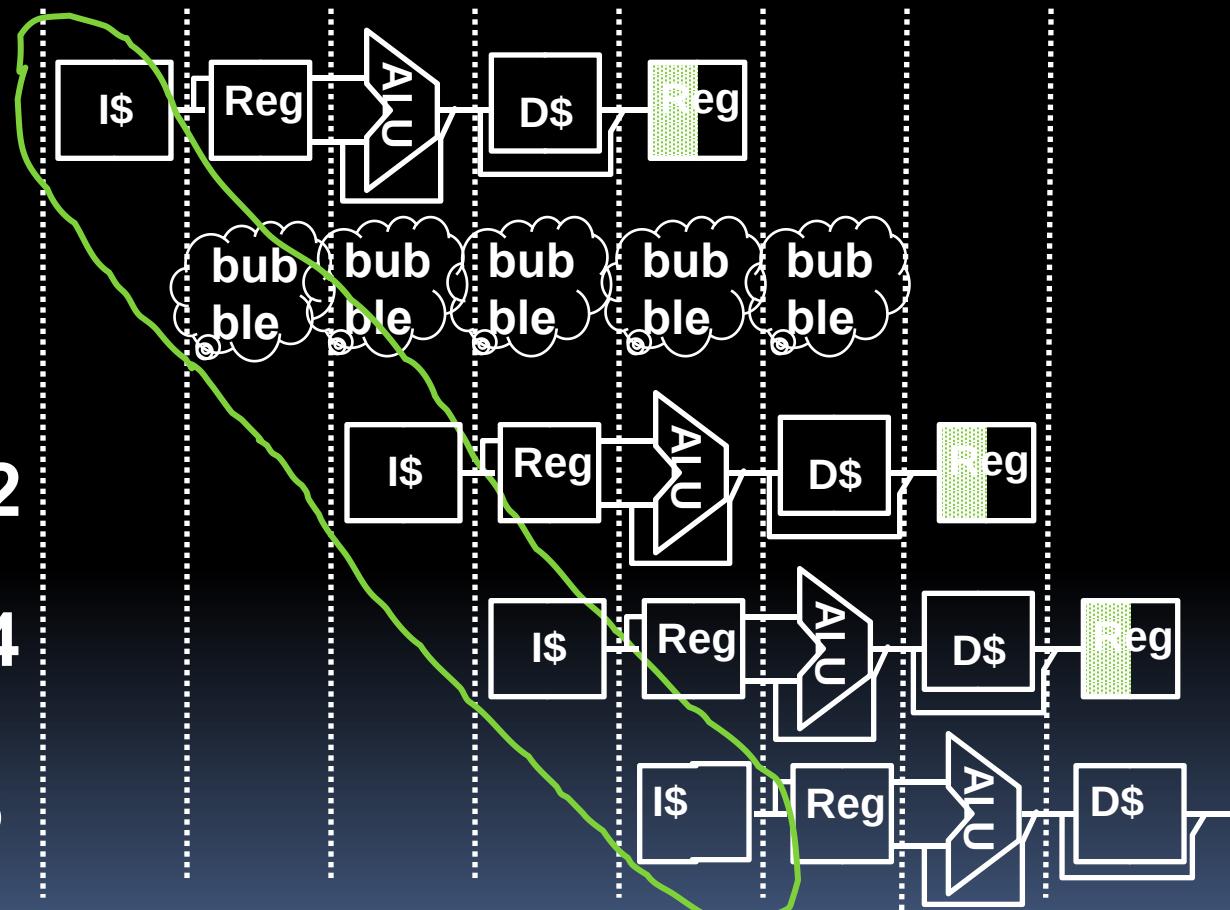
lw \$t0, 0(\$t1)

nop

sub \$t3,\$t0,\$t2

and \$t5,\$t0,\$t4

or \$t7,\$t0,\$t6



Peer Instruction

- 1) Thanks to pipelining, I have reduced the time it took me to wash my one shirt.

- 2) Longer pipelines are always a win (since less work per stage & a faster clock).

	12
a)	FF
b)	FT
c)	TF
d)	TT

“And in Conclusion..”

- **Pipeline challenge is hazards**
 - Forwarding helps w/many data hazards
 - Delayed branch helps with control hazard in 5 stage pipeline
 - Load delay slot / interlock necessary
- **More aggressive performance:**
 - Superscalar
 - Out-of-order execution

Bonus slides

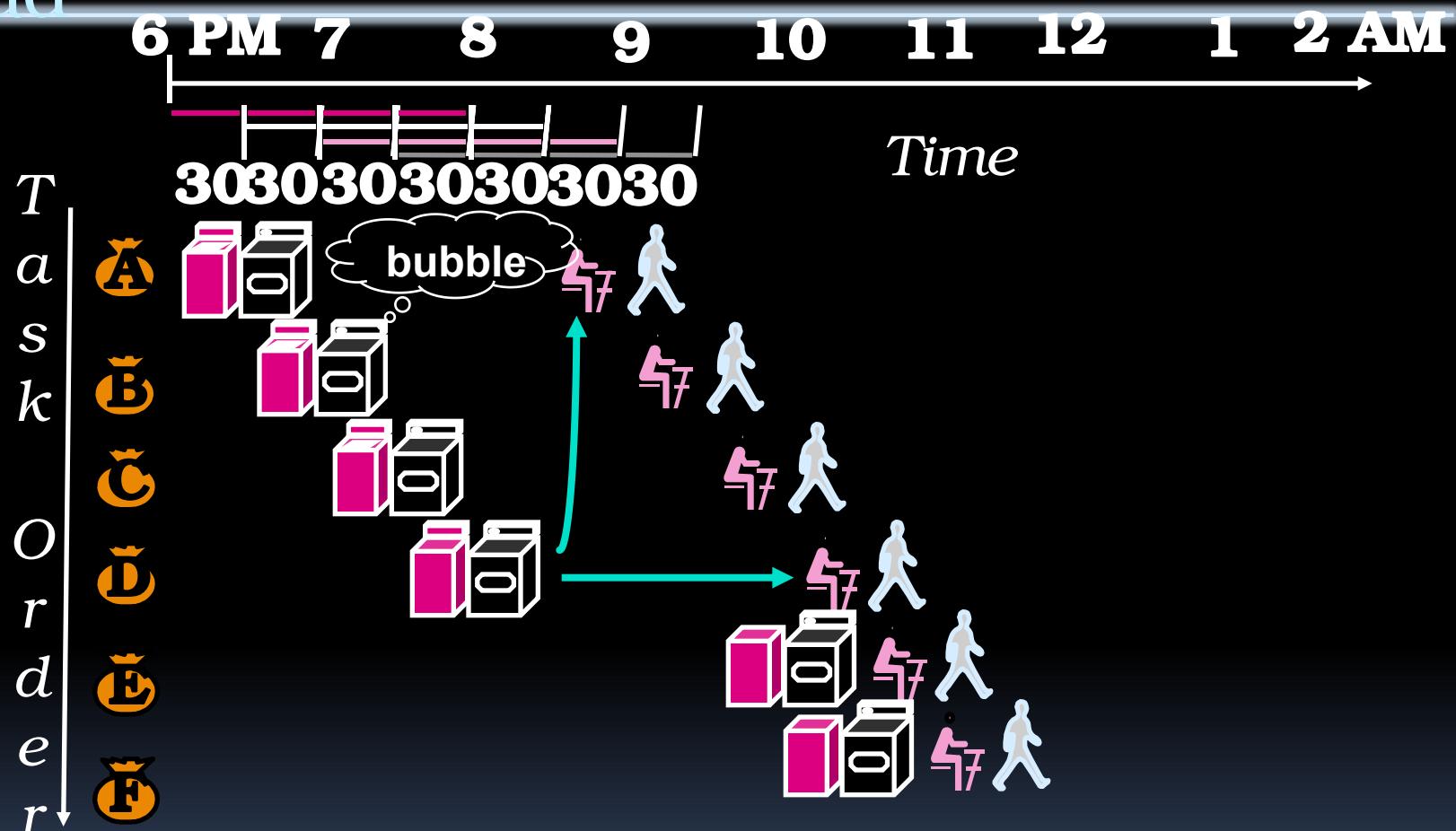
- These are extra slides that used to be included in lecture notes, but have been moved to this, the “bonus” area to serve as a supplement.
- The slides will appear in the order they would have in the normal presentation

Bonus

Historical Trivia

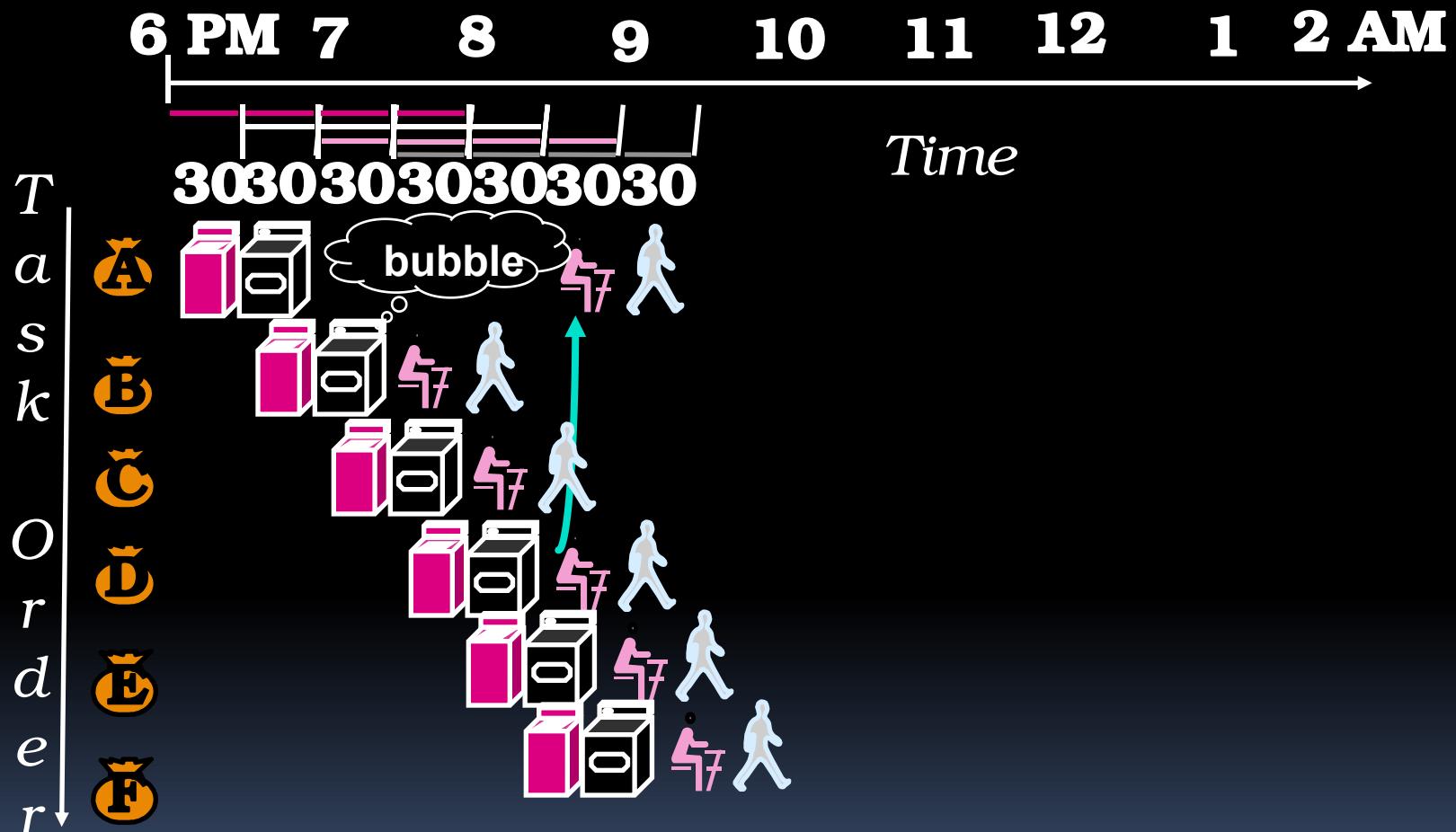
- **First MIPS design did not interlock and stall on load-use data hazard**
- **Real reason for name behind MIPS:**
**Microprocessor without
Interlocked
Pipeline
Stages**
 - **Word Play on acronym for Millions of Instructions Per Second, also called MIPS**

Pipeline Hazard: Matching socks in later load



- A depends on D; stall since folder tied up; Note this is much different from processor cases so far. We have not had a earlier instruction depend on a later one.

Out-of-Order Laundry: Don't Wait



- A depends on D; rest continue; need more resources to allow out-of-order

Superscalar Laundry: Parallel per stage



- More resources, HW to match mix of parallel tasks?

Superscalar Laundry: Mismatch



- Task mix underutilizes extra resources

Peer Instruction (1/2)

Assume 1 instr/clock, delayed branch, 5 stage pipeline, forwarding, interlock on unresolved load hazards (after 10^3 loops, so pipeline full)

Loop:

lw	\$t0, 0(\$s1)
addu	\$t0, \$t0, \$s2
sw	\$t0, 0(\$s1)
addiu	\$s1, \$s1, -4
bne	\$s1, \$zero, Loop
nop	

1
2
3
4
5
6
7
8
9
10

- How many pipeline stages (clock cycles) per loop iteration to execute this code?

Peer Instruction Answer (1 / 2)

- Assume 1 instr/clock, delayed branch, 5 stage pipeline, forwarding, interlock on unresolved load hazards. 10³ iterations, so pipe2in(data hazard so stall)

Loop:

1.	lw	\$t0, 0(\$\$s1)
3.	addu	\$t0, \$t0, \$\$s2
4.	sw	\$t0, 0(\$\$s1)
5.	addiu	\$s1, \$\$s1, -4
6.	bne	\$s1, \$zero, Loop
7.	nop	(delayed branch so exec. nop)

- How many pipeline stages (clock cycles) per loop iteration to execute this code?

1 2 3 4 5 6 7 8 9 10

Peer Instruction (2/2)

**Assume 1 instr/clock, delayed branch, 5 stage pipeline, forwarding, interlock on unresolved load hazards (after 10^3 loops, so pipeline full).
Rewrite this code to reduce pipeline stages (clock cycles) per loop to as few as possible.**

Loop:

lw	\$t0, 0(\$s1)
addu	\$t0, \$t0, \$s2
sw	\$t0, 0(\$s1)
addiu	\$s1, \$s1, -4
bne	\$s1, \$zero, Loop
nop	

1
2
3
4
5
6
7
8
9
10

- How many pipeline stages (clock cycles) per loop iteration to execute this code?

Peer Instruction (2/2) How long to execute?

- Rewrite this code to reduce clock cycles per loop to as few as possible:

Loop:

1.	lw	\$t0	0 (\$s1)
2.	addiu	\$s1,	\$s1, -4
3.	addu	\$t0,	\$t0 \$s2
4.	bne	\$s1,	\$zero, Loop
5.	sw	\$t0,	+4 (\$s1)

(no hazard since extra cycle)

(modified sw to put past addiu)

- How many pipeline stages (clock cycles) per loop iteration to execute your revised code? (assume pipeline is full)

1 2 3 4 5 6 7 8 9 10

0.19 Cache



Computer Architecture (计算机体系结构)

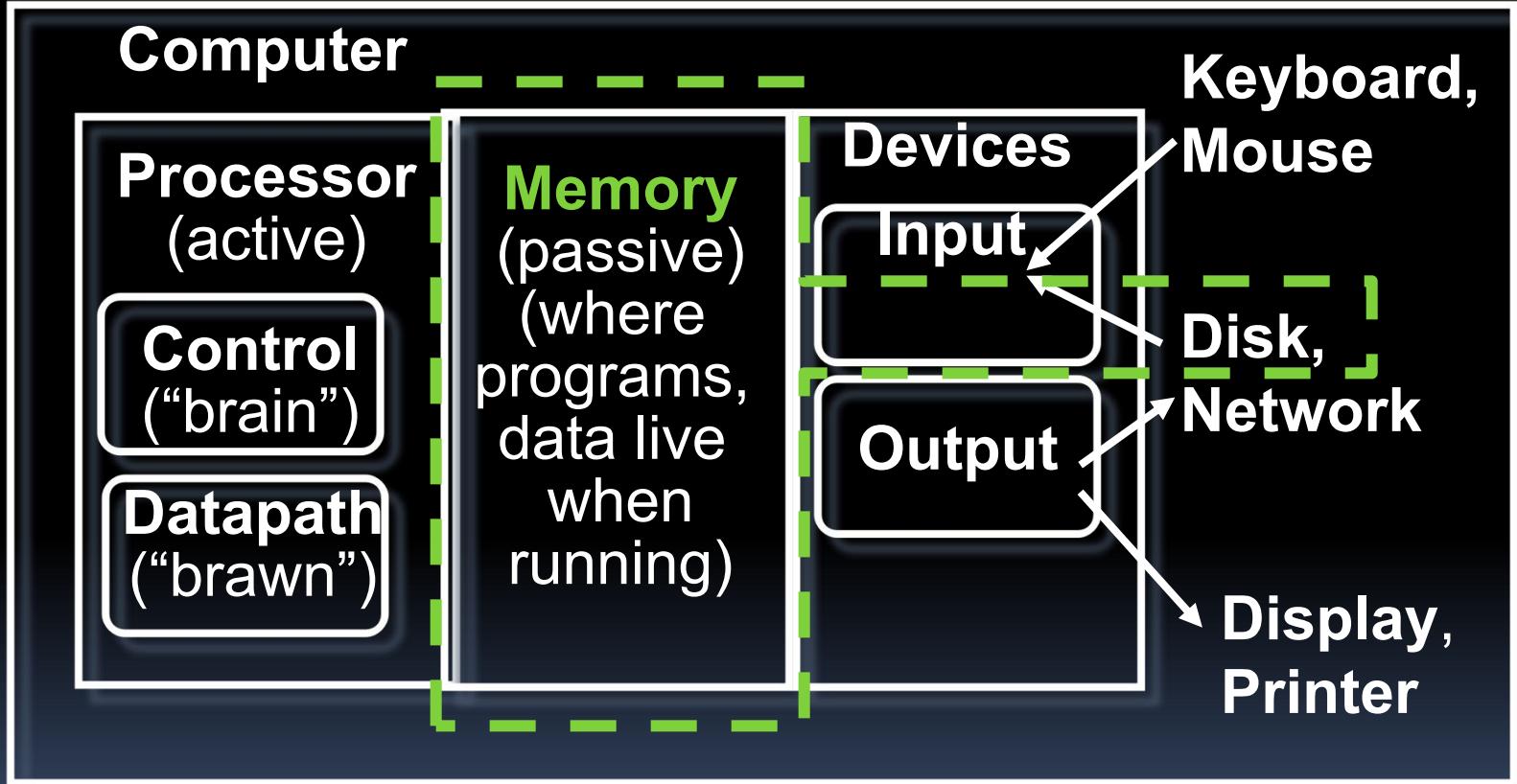
Lecture 25 – Caches I 2020-10-26

Lecturer:
Yuanqing
Cheng

Review : Pipelining

- **Pipeline challenge is hazards**
 - Forwarding helps w/many data hazards
 - Delayed branch helps with control hazard in our 5 stage pipeline
 - Data hazards w/Loads → Load Delay Slot
 - Interlock → “smart” CPU has HW to detect if conflict with inst following load, if so it stalls
- **More aggressive performance
(discussed in section next week)**
 - Superscalar (parallelism)
 - Out-of-order execution

The Big Picture



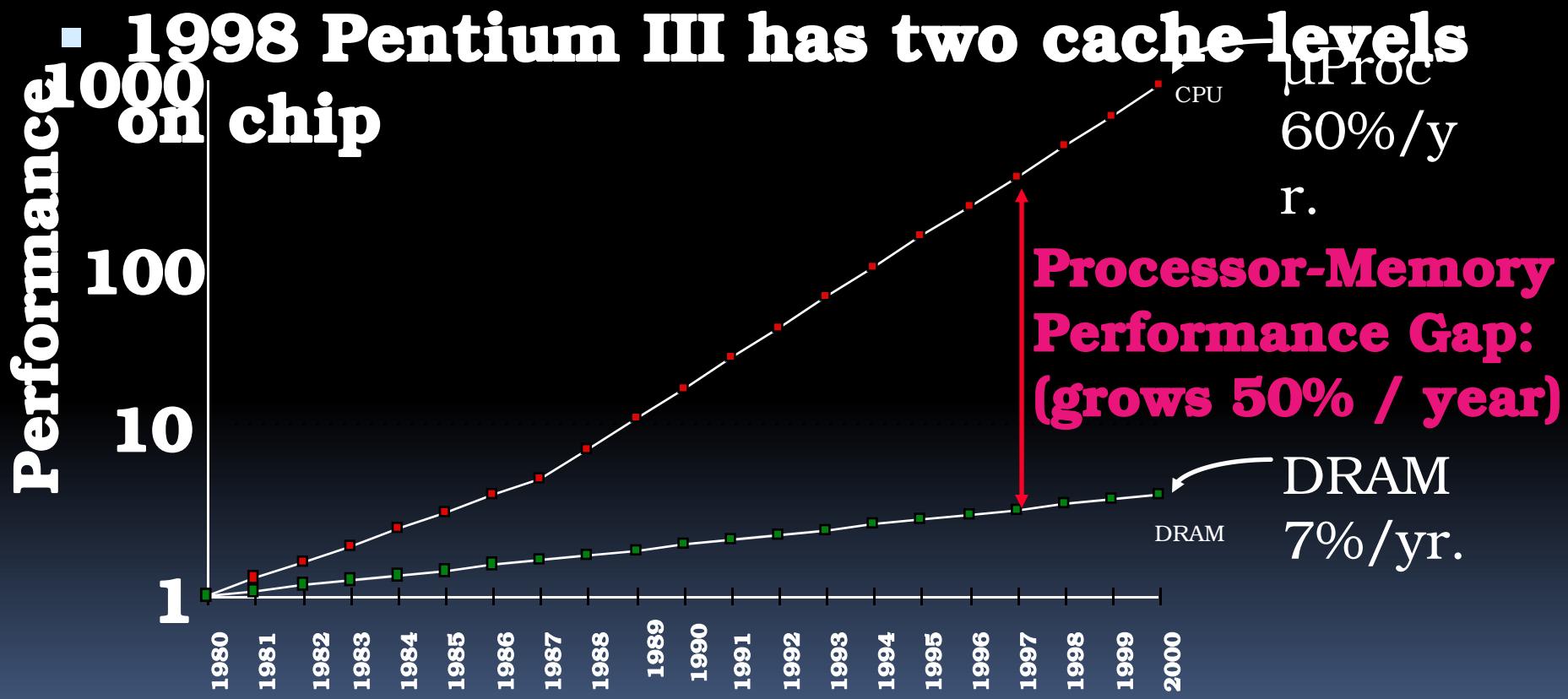
Memory Hierarchy

I.e., storage in computer systems

- **Processor**
 - **holds data in register file (~100 Bytes)**
 - **Registers accessed on nanosecond timescale**
- **Memory (we'll call “main memory”)**
 - **More capacity than registers (~Gbytes)**
 - **Access time ~50-100 ns**
 - **Hundreds of clock cycles per memory access?!**
- **Disk**
 - **HUGE capacity (virtually limitless)**
 - **VERY slow: runs ~milliseconds**

Motivation: Why We Use Caches (written \$)

- **1989 first Intel CPU with cache on chip**
- **1998 Pentium III has two cache levels on chip**



**Processor-Memory
Performance Gap:
(grows 50% / year)**

DRAM
7%/yr.

Memory Caching

- **Mismatch between processor and memory speeds leads us to add a new level: a memory cache**
- **Implemented with same IC processing technology as the CPU (usually integrated on same chip): faster but more expensive than DRAM memory.**
- **Cache is a copy of a subset of main memory.**
- **Most processors have separate caches for instructions and data.**

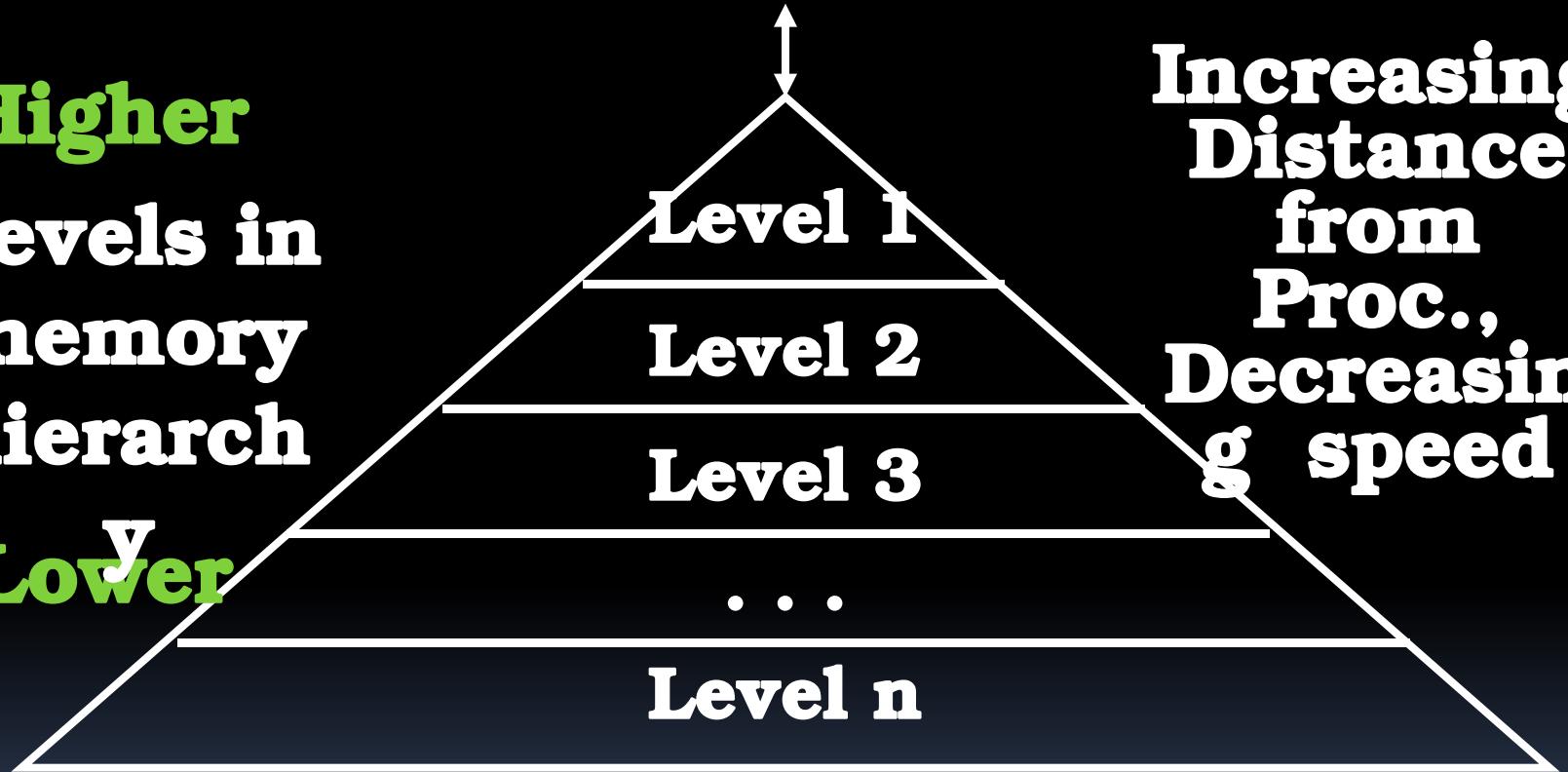
Memory Hierarchy

Higher
Levels in
memory
hierarch

Lower

Processor

Increasing
Distance
from
Proc.,
Decreasin
g speed



Size of memory at each level
As we move to deeper levels the latency goes up and price per bit goes down.

Memory Hierarchy

- If level closer to Processor, it is:
 - Smaller
 - Faster
 - More expensive
 - subset of lower levels (contains most recently used data)
- Lowest Level (usually disk) contains all available data (does it go beyond the disk?)
- Memory Hierarchy presents the processor with the illusion of a very large & fast memory

Memory Hierarchy Analogy: Library (1 / 2)

- You're writing a term paper (Processor) at a **table** in **Doe**
- **Doe Library** is equivalent to **disk**
 - essentially limitless capacity
 - very slow to retrieve a book
- **Table** is **main memory**
 - smaller capacity: means you must return book when table fills up
 - easier and faster to find a book there once you've already retrieved it

Memory Hierarchy Analogy: Library (2/2)

- **Open books on table are cache**
 - **smaller capacity:** can have very few open books fit on table; again, when table fills up, you must close a book
 - **much, much faster to retrieve data**
- **Illusion created: whole library open on the tabletop**
 - **Keep as many recently used books open on table as possible since likely to use again**
 - **Also keep as many books on table as possible, since faster than going to library**

Memory Hierarchy Basis

- Cache contains copies of data in memory that are being used.
- Memory contains copies of data on disk that are being used.
- Caches work on the principles of temporal and spatial locality.
 - Temporal Locality: if we use it now, chances are we'll want to use it again soon.
 - Spatial Locality: if we use a piece of memory, chances are we'll use the neighboring pieces soon.

Cache Design

- **How do we organize cache?**
- **Where does each memory address map to?**
 - (Remember that cache is subset of memory, so multiple memory addresses map to the same cache location.)
- **How do we know which elements are in cache?**
- **How do we quickly locate them?**

Direct-Mapped Cache (1 / 4)

- In a **direct-mapped cache**, each memory address is associated with one possible **block** within the cache
 - Therefore, we only need to look in a single location in the cache for the data if it exists in the cache
 - Block is the unit of transfer between cache and memory

Direct-Mapped Cache

(2/4)

Memory

Address Memory



Cache 4 Byte Direct
Mapped Cache



Block size = 1 byte

Cache Location 0 can

be

occupied by data from:

- **Memory location 0, 4, 8, ...**
- **4 blocks \Rightarrow any memory**

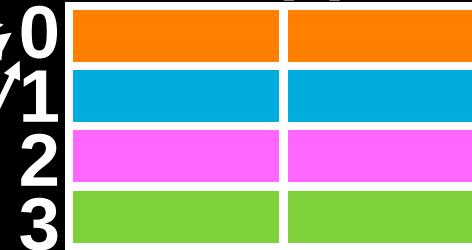
What if we wanted a block to be bigger than one byte?

Direct-Mapped Cache

(3/4)

Memory Address	Memory	
0	1	0
2	3	2
4	5	4
6	7	6
8	9	8
A	etc	
C		
E		
10		
12		
14		
16		
18		
1A		
1C		
1E		

Cache 8 Byte Direct
Mapped Cache



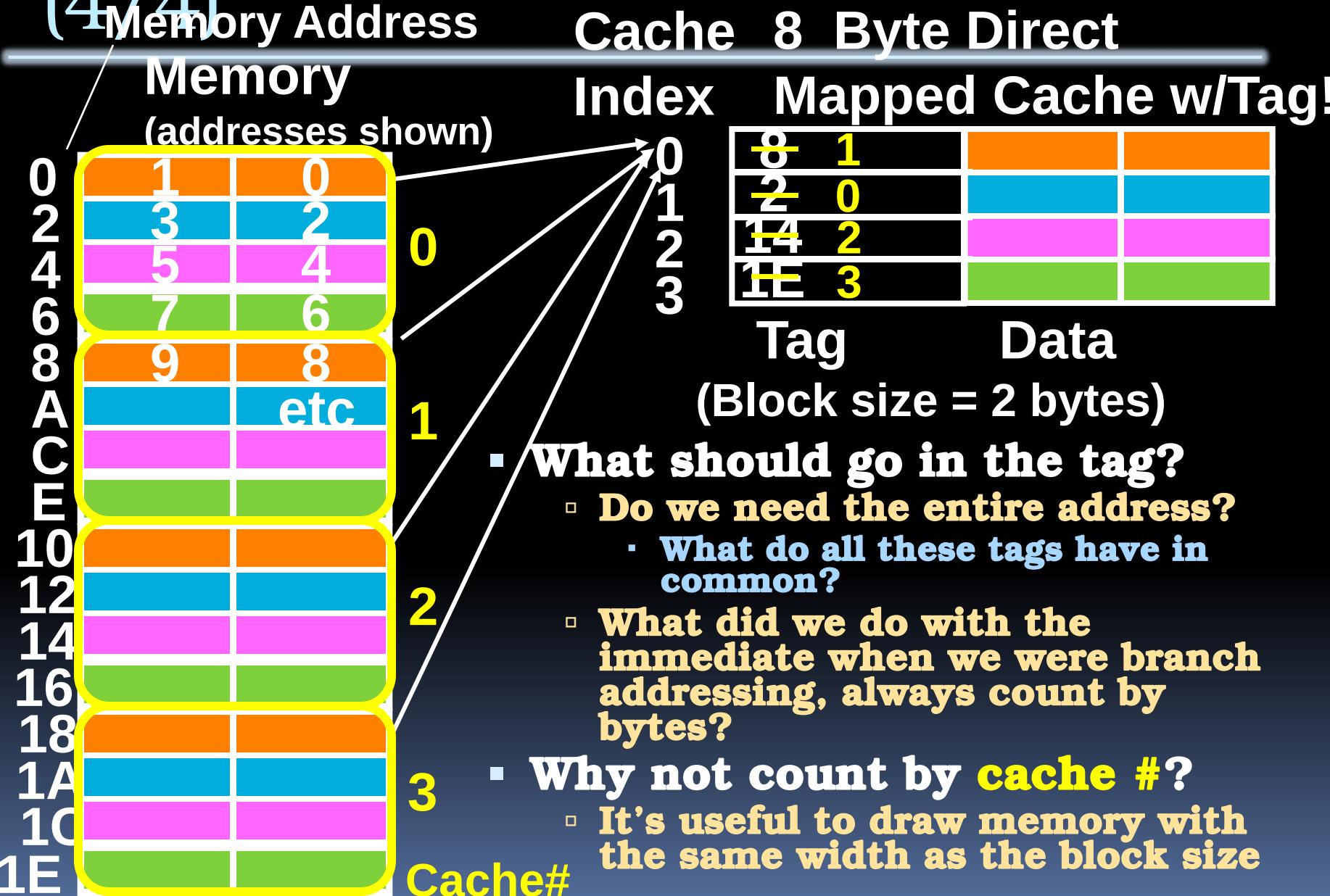
Block size = 2 bytes

When we ask for a byte, the system finds out the right block, and loads it all!

- How does it know right block?
- How do we select the byte?
- E.g., Mem address 11101?
- How does it know WHICH colored block it originated from?
 - What do you do at baggage claim?

Direct-Mapped Cache

(4/4)



Issues with Direct-Mapped

- Since multiple memory addresses map to same cache index, how do we tell which one is in there?
- What if we have a block size > 1 byte?
- Answer: divide memory address into three fields

tttttttttttttttt	iiiiiiiiii	oooo
------------------	------------	------

tag
to check
if have
correct block

index
to
select
block

byte
offset
within
block

Direct-Mapped Cache

Terminology

- All fields are read as unsigned integers.
- Index
 - specifies the cache index (which “row”/block of the cache we should look in)
- Offset
 - once we've found correct block, specifies which byte within the block we want
- Tag
 - the remaining bits after offset and index are determined; these are used to

TIO great cache mnemonic

AREA (cache size, B)

= **HEIGHT (# of blocks)**,

* **WIDTH (size of one block,**

B/block)

$$2^{(H+W)} = 2^H * 2^W$$

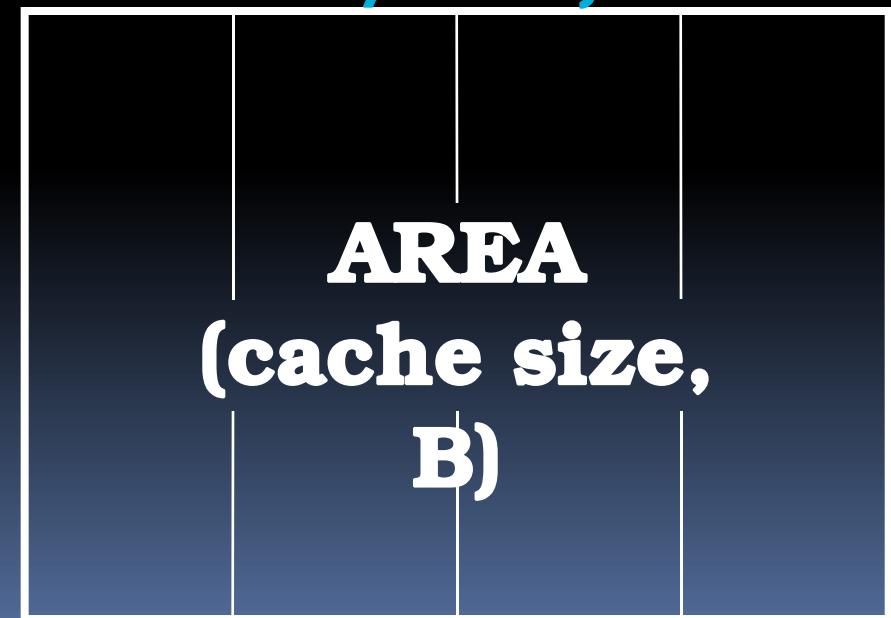
<u>Tag</u>	<u>Index</u>	<u>Offset</u>
------------	--------------	---------------

WIDTH

(size of one block,

B/block)

HEIGHT
(# of blocks)



Direct-Mapped Cache Example

(1 / 3)

- Suppose we have a 8B of data in a direct-mapped cache with 2 byte blocks
 - Sound familiar?
- Determine the size of the tag, index and offset fields if we're using a 32-bit architecture
- Offset
 - need to specify correct byte within a block
 - block contains 2 bytes
= 2^1 bytes

Direct-Mapped Cache Example

(2/3)

Index: (~index into an “array of blocks”)

- need to specify correct block in cache
- cache contains $8 \text{ B} = 2^3 \text{ bytes}$
- block contains $2 \text{ B} = 2^1 \text{ bytes}$
- # blocks/cache

$$= \frac{\text{bytes/cache}}{\text{bytes/block}}$$

$$= \frac{2^3 \text{ bytes/cache}}{2^1 \text{ bytes/block}}$$

$$= 2^2 \text{ blocks/cache}$$

- need 2 bits to specify this many blocks

Direct-Mapped Cache Example

(3/3)

- Tag: use remaining bits as tag
 - tag length = addr length - offset - index
 - = 32 - 1 - 2 bits
 - = 29 bits
 - so tag is leftmost 29 bits of memory address
- Why not full 32 bit address as tag?
 - All bytes within block need same address (4b)
 - Index must be same for every address within a block, so it's redundant in tag check, thus can leave off to save memory

And in Conclusion...

- We would like to have the capacity of disk at the speed of the processor: unfortunately this is not feasible.
- So we create a memory hierarchy:
 - each successively lower level contains “most used” data from next higher level
 - exploits temporal & spatial locality
 - do the common case fast, worry less about the exceptions
(design principle of MIPS)
- Locality of reference is a Big Idea

0.20 Comb Logic

Computer Architecture

(计算机体系结构)

Lecture 17 – Representations of Combinatorial Logic Circuits

2020-10-12



Lecturer: Yuanqing Cheng



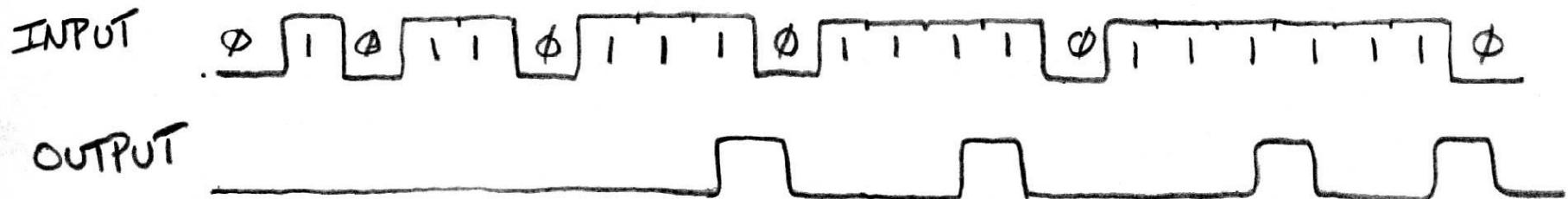
5G Rollout on a Steady Ramp
Toward Big Growth

Mobile network operators have done a decent job rolling out 5G technology and are beginning to reap needed returns on their huge investments.

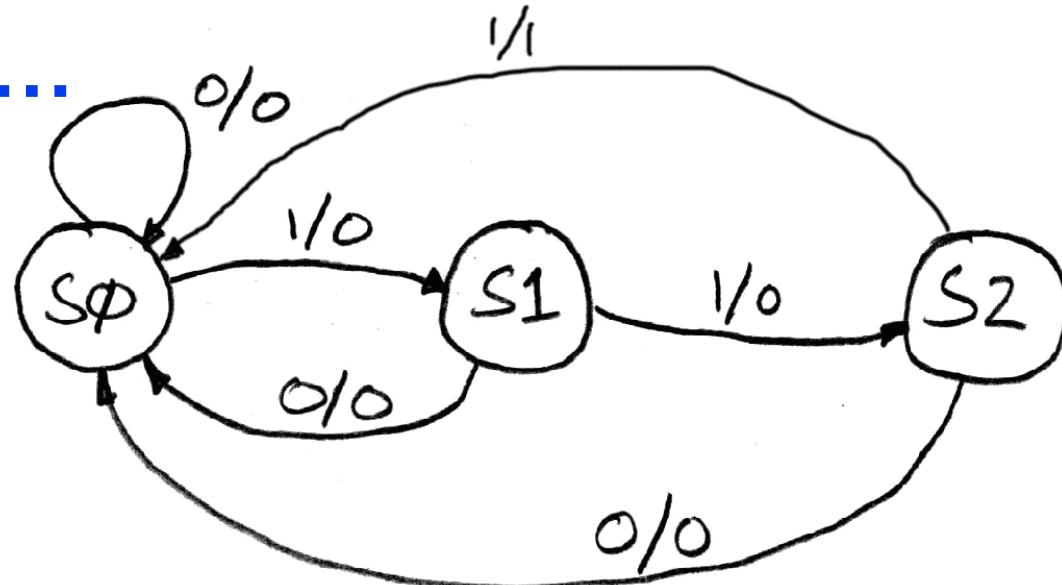
By John Walko Oct 09, 2020

Finite State Machine Example: 3 ones...

FSM to detect the occurrence of 3 consecutive 1's in the input.



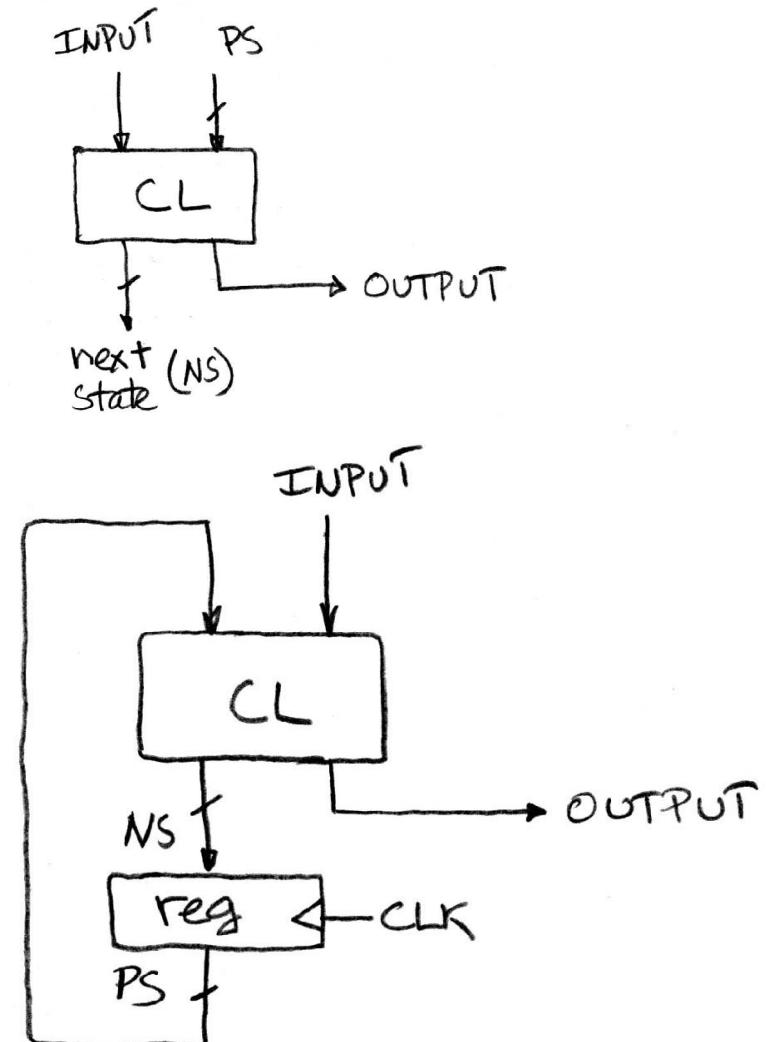
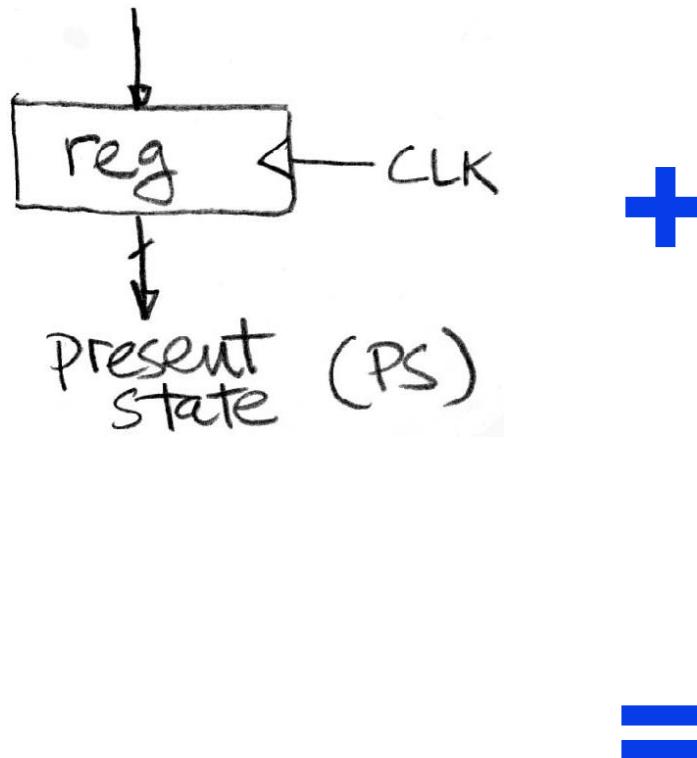
Draw the FSM...



Assume state transitions are controlled by the clock:
on each clock cycle the machine checks the inputs and moves
to a new state and produces a new output...

Hardware Implementation of FSM

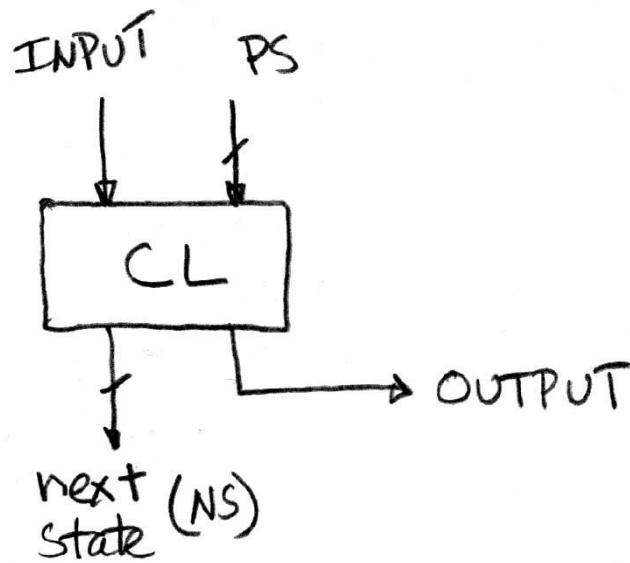
... Therefore a register is needed to hold the a representation of which state the machine is in. Use a unique bit pattern for each state.



Combinational logic circuit is used to implement a function maps from *present state and input* to *next state and output*.

Hardware for FSM: Combinational Logic

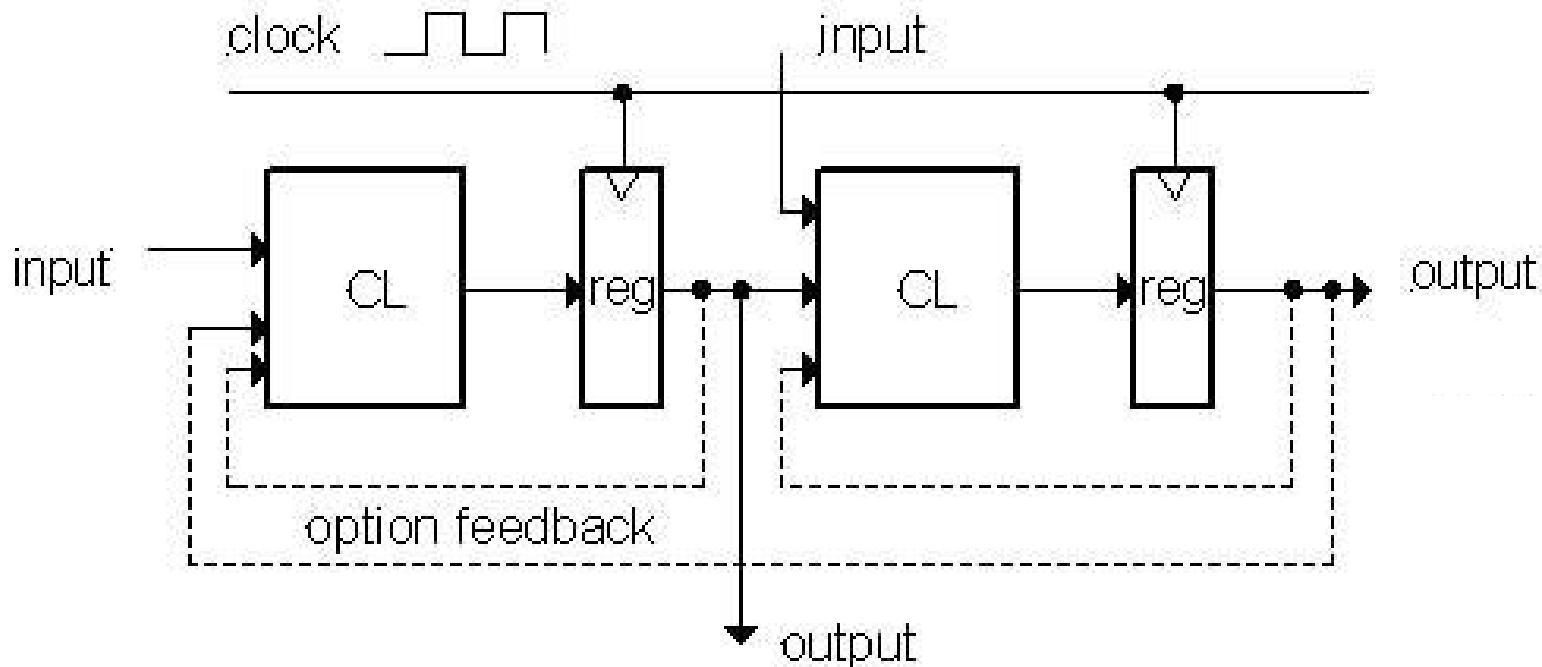
This lecture we will discuss the detailed implementation, but for now can look at its functional specification, truth table form.



Truth table...

PS	Input	NS	Output
00	0	00	0
00	1	01	0
01	0	00	0
01	1	10	0
10	0	00	0
10	1	00	1

General Model for Synchronous Systems



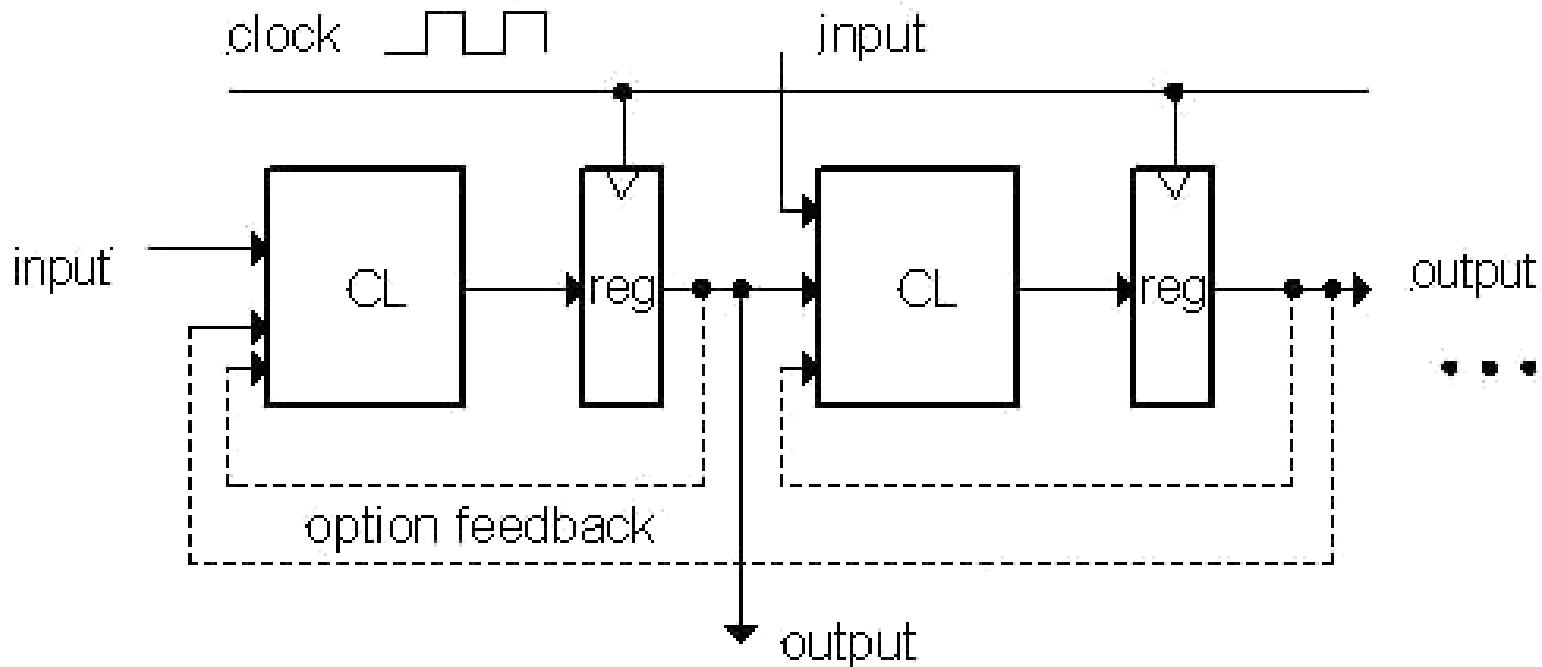
- Collection of CL blocks separated by registers.
- Registers may be back-to-back and CL blocks may be back-to-back.
- Feedback is optional.
- Clock signal(s) connects only to clock input of registers.

Review

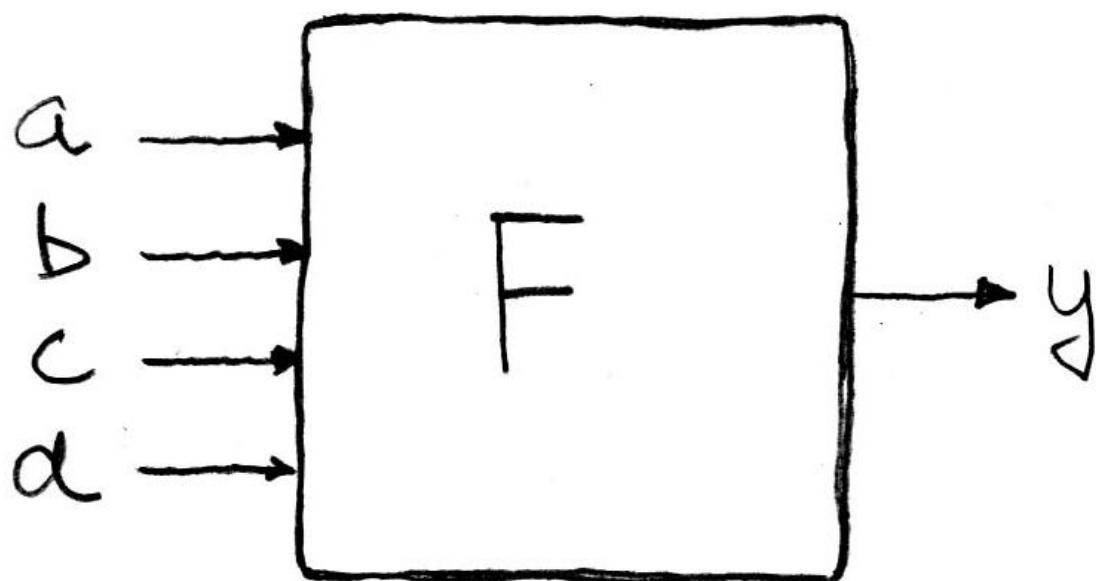
- State elements are used to:
 - Build memories
 - Control the flow of information between other state elements and combinational logic
- D-flip-flops used to build registers
- Clocks tell us when D-flip-flops change
 - Setup and Hold times important
- We pipeline long-delay CL for faster clock
- Finite State Machines extremely useful
 - Represent states and transitions

Combinational Logic

- FSMs had states and transitions
- How do we get from one state to the next?
- Answer: Combinational Logic



Truth Tables

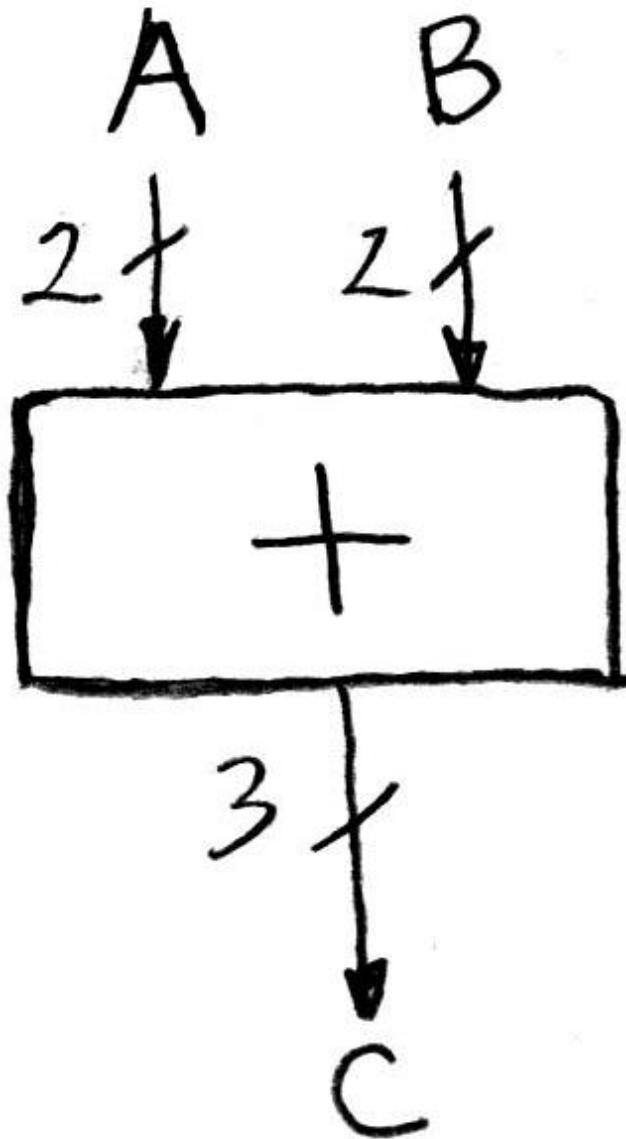


a	b	c	d	y
0	0	0	0	$F(0,0,0,0)$
0	0	0	1	$F(0,0,0,1)$
0	0	1	0	$F(0,0,1,0)$
0	0	1	1	$F(0,0,1,1)$
0	1	0	0	$F(0,1,0,0)$
0	1	0	1	$F(0,1,0,1)$
0	1	1	0	$F(0,1,1,0)$
0	1	1	1	$F(0,1,1,1)$
1	0	0	0	$F(1,0,0,0)$
1	0	0	1	$F(1,0,0,1)$
1	0	1	0	$F(1,0,1,0)$
1	0	1	1	$F(1,0,1,1)$
1	1	0	0	$F(1,1,0,0)$
1	1	0	1	$F(1,1,0,1)$
1	1	1	0	$F(1,1,1,0)$
1	1	1	1	$F(1,1,1,1)$

TT Example #1: 1 iff one (not both) a,b=1

a	b	y
0	0	0
0	1	1
1	0	1
1	1	0

TT Example #2: 2-bit adder



A a_1a_0	B b_1b_0	C $c_2c_1c_0$
00	00	000
00	01	001
00	10	010
00	11	011
01	00	001
01	01	010
01	10	011
01	11	100
10	00	010
10	01	011
10	10	100
10	11	101
11	00	011
11	01	100
11	10	101
11	11	110

How
Many
Rows?

TT Example #3: 32-bit unsigned adder

A	B	C
000 ... 0	000 ... 0	000 ... 00
000 ... 0	000 ... 1	000 ... 01
.	.	.
.	.	.
.	.	.
111 ... 1	111 ... 1	111 ... 10

How
Many
Rows?

TT Example #4: 3-input majority circuit

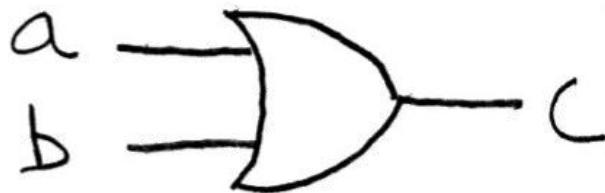
a	b	c	y
0	0	0	0
0	0	1	0
0	1	0	0
0	1	1	1
1	0	0	0
1	0	1	1
1	1	0	1
1	1	1	1

Logic Gates (1/2)

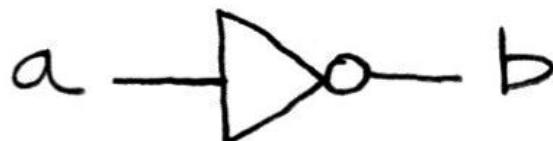
AND



OR



NOT



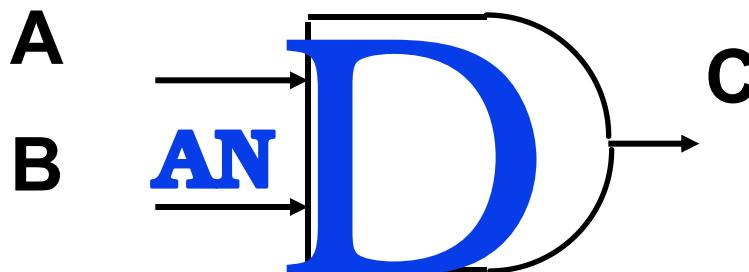
ab	c
00	0
01	0
10	0
11	1

a	b
0	1
1	0

And vs. Or review – Dan's mnemonic

AND Gate

Symbol

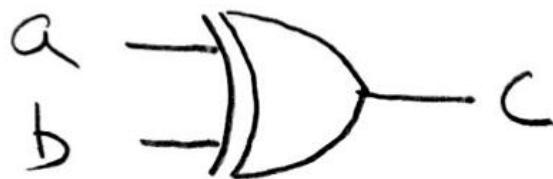


Definition

A	B	C
0	0	0
0	1	0
1	0	0
1	1	1

Logic Gates (2/2)

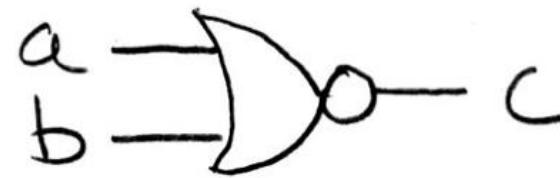
XOR



NAND



NOR



ab	c
00	0
01	1
10	1
11	0

ab	c
00	1
01	1
10	1
11	0

ab	c
00	1
01	0
10	0
11	0

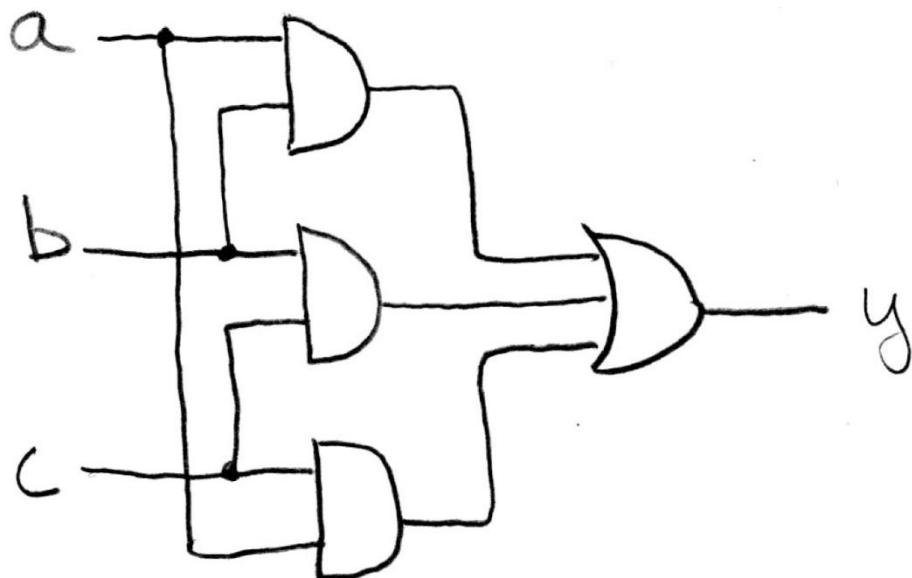
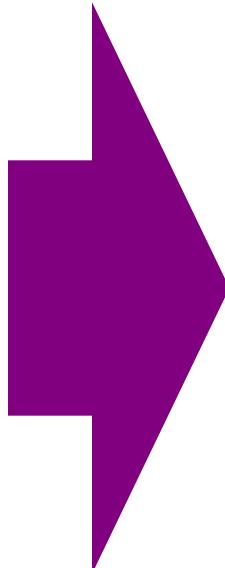
2-input gates extend to n-inputs

- N-input XOR is the only one which isn't so obvious
- It's simple: XOR is a 1 iff the # of 1s at its input is odd \Rightarrow

a	b	c	y
0	0	0	0
0	0	1	1
0	1	0	1
0	1	1	0
1	0	0	1
1	0	1	0
1	1	0	0
1	1	1	1

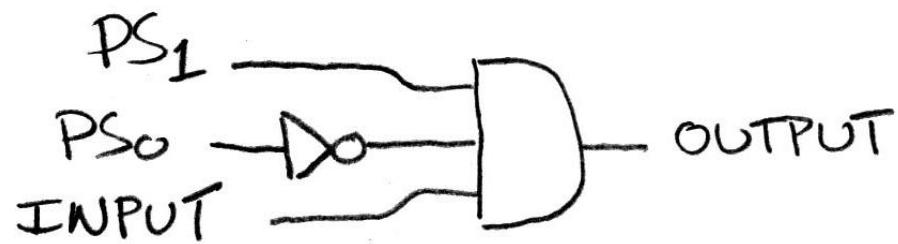
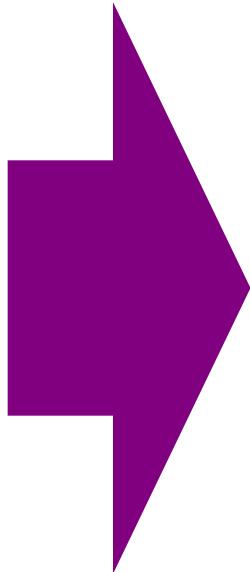
Truth Table \Rightarrow Gates (e.g., majority circ.)

a	b	c	y
0	0	0	0
0	0	1	0
0	1	0	0
0	1	1	1
1	0	0	0
1	0	1	1
1	1	0	1
1	1	1	1

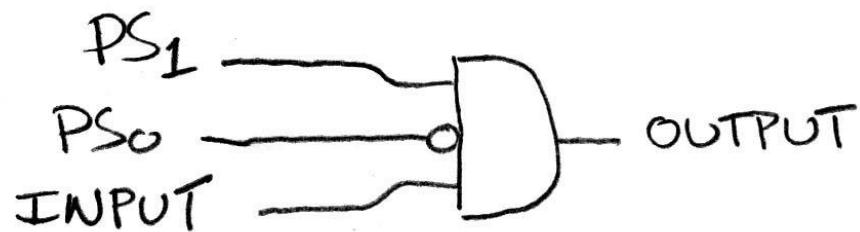


Truth Table \Rightarrow Gates (e.g., FSM circ.)

PS	Input	NS	Output
00	0	00	0
00	1	01	0
01	0	00	0
01	1	10	0
10	0	00	0
10	1	00	1

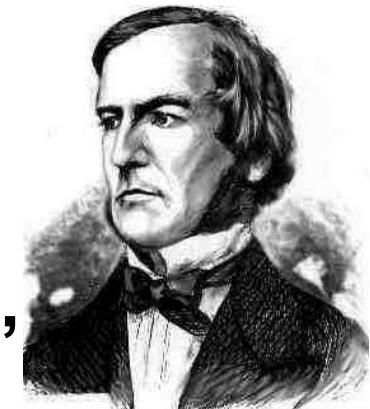


or equivalently...

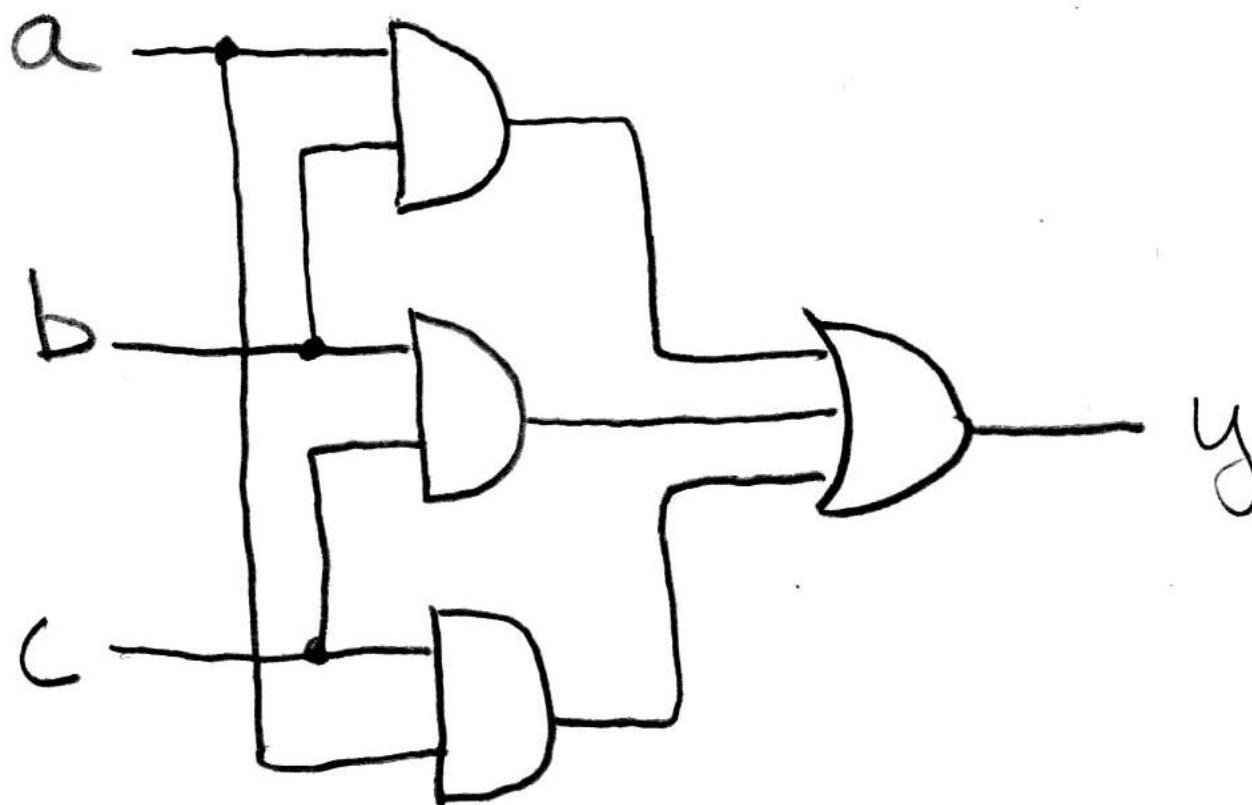


Boolean Algebra

- George Boole, 19th Century mathematician
- Developed a mathematical system (algebra) involving logic
 - later known as “Boolean Algebra”
- Primitive functions: AND, OR and NOT
- The power of BA is there's a one-to-one correspondence between circuits made up of AND, OR and NOT gates and equations in BA
 - + means OR, • means AND, \bar{x} means NOT



Boolean Algebra (e.g., for majority fun.)

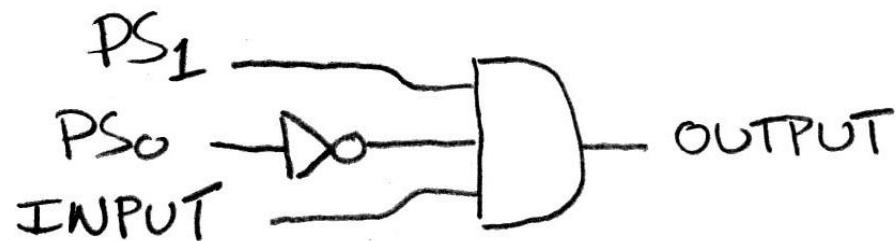
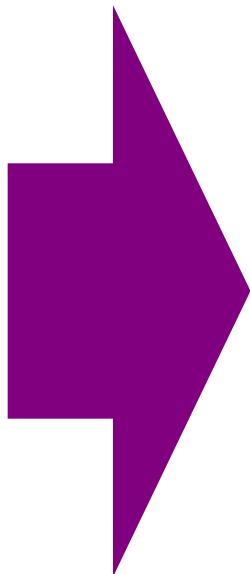


$$y = a \cdot b + a \cdot c + b \cdot c$$

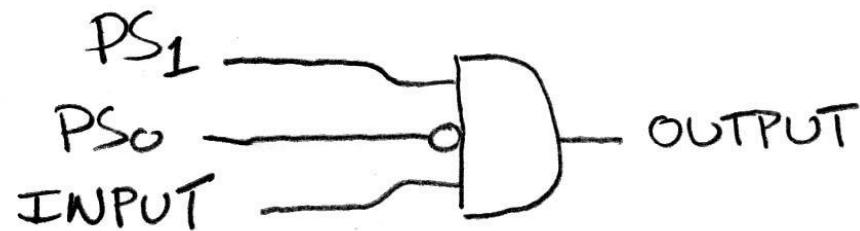
$$y = ab + ac + bc$$

Boolean Algebra (e.g., for FSM)

PS	Input	NS	Output
00	0	00	0
00	1	01	0
01	0	00	0
01	1	10	0
10	0	00	0
10	1	00	1

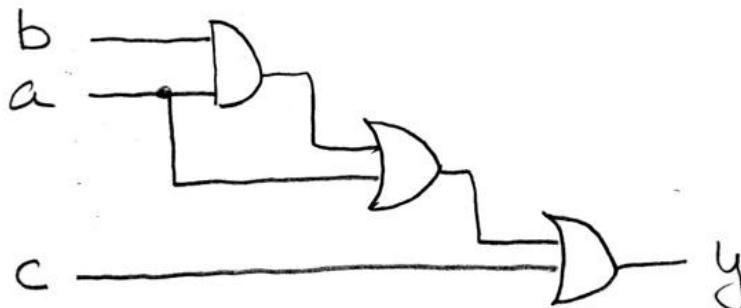


or equivalently...



$$y = \overline{PS_1} \cdot PS_0 \cdot INPUT$$

BA: Circuit & Algebraic Simplification



original circuit

$$y = ((ab) + a) + c$$

$$= ab + a + c$$

$$= a(b + 1) + c$$

$$= a(1) + c$$

$$= a + c$$



equation derived from original circuit

algebraic simplification

**BA also great for
circuit verification**
Circ X = Circ Y?
use BA to prove!

simplified circuit

Laws of Boolean Algebra

$$x \cdot \bar{x} = 0$$

$$x \cdot 0 = 0$$

$$x \cdot 1 = x$$

$$x \cdot x = x$$

$$x \cdot y = y \cdot x$$

$$(xy)z = x(yz)$$

$$x(y + z) = xy + xz$$

$$xy + x = x$$

$$\bar{xy} + x = x + y$$

$$\overline{x \cdot y} = \bar{x} + \bar{y}$$

$$x + \bar{x} = 1$$

$$x + 1 = 1$$

$$x + 0 = x$$

$$x + x = x$$

$$x + y = y + x$$

$$(x + y) + z = x + (y + z)$$

$$x + yz = (x + y)(x + z)$$

$$(x + y)x = x$$

$$(\bar{x} + y)x = xy$$

$$\overline{x + y} = \bar{x} \cdot \bar{y}$$

complementarity
laws of 0's and 1's
identities

 idempotent law

commutativity

associativity

distribution

uniting theorem

uniting theorem v.2

DeMorgan's Law

Boolean Algebraic Simplification Example

$$\begin{aligned}y &= ab + a + c \\&= a(b + 1) + c \quad \textit{distribution, identity} \\&= a(1) + c \quad \textit{law of 1's} \\&= a + c \quad \textit{identity}\end{aligned}$$

Canonical forms (1/2)

	abc	y
$\bar{a} \cdot \bar{b} \cdot \bar{c}$	000	1
$\bar{a} \cdot \bar{b} \cdot c$	001	1
	010	0
	011	0
$a \cdot \bar{b} \cdot \bar{c}$	100	1
	101	0
$a \cdot b \cdot \bar{c}$	110	1
	111	0

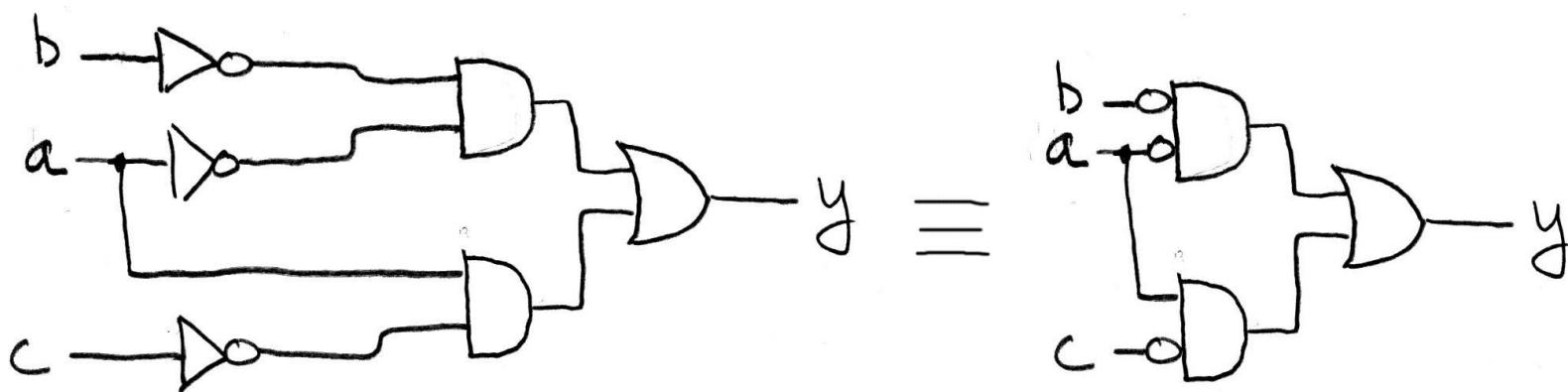
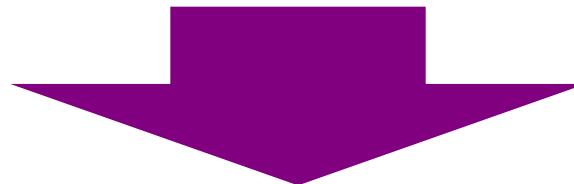
**Sum-of-products
(ORs of ANDs)**



Canonical forms (2/2)

$$\begin{aligned}y &= \bar{a}\bar{b}\bar{c} + \bar{a}\bar{b}c + a\bar{b}\bar{c} + ab\bar{c} \\&= \bar{a}\bar{b}(\bar{c} + c) + a\bar{c}(\bar{b} + b) \\&= \bar{a}\bar{b}(1) + a\bar{c}(1) \\&= \bar{a}\bar{b} + a\bar{c}\end{aligned}$$

distribution
complementarity
identity



Peer Instruction

- A. $(a+b) \cdot (\bar{a}+b) = b$
- B. N-input gates can be thought of cascaded 2-input gates. I.e.,
 $(a \Delta bc \Delta d \Delta e) = a \Delta (bc \Delta (d \Delta e))$
where Δ is one of AND, OR, XOR, NAND
- C. You can use NOR(s) with clever wiring to simulate AND, OR, & NOT

	ABC
1:	FFF
2:	FFT
3:	FTF
4:	FTT
5:	TFF
6:	TFT
7:	TTF
8:	TTT

Peer Instruction Answer (B)

- B. N-input gates can be thought of cascaded 2-input gates. I.e.,
 $(a \Delta bc \Delta d \Delta e) = a \Delta (bc \Delta (d \Delta e))$
where Δ is one of AND, OR, XOR, NAND...**FALSE**

Let's confirm!

CORRECT 3-input

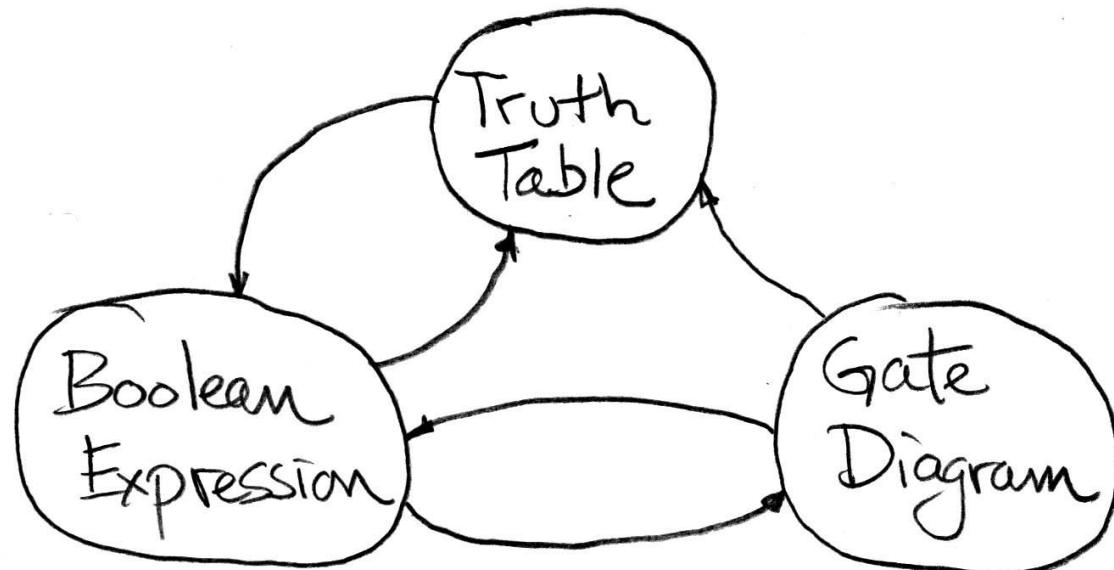
XYZ	AND	OR	XOR	NAND
000	0	0	0	1
001	0	1	1	1
010	0	1	1	1
011	0	1	0	1
100	0	1	1	1
101	0	1	0	1
110	0	1	0	1
111	1	1	1	0

CORRECT 2-input

YZ	AND	OR	XOR	NAND
00	0	0	0	1
01	0	1	1	1
10	0	1	1	1
11	1	1	0	0

“And In conclusion...”

- Pipeline big-delay CL for faster clock
- Finite State Machines extremely useful
 - You'll see them again in 150, 152 & 164
- Use this table and techniques we learned to transform from 1 to another



Computer Architecture (计算机体系结构)

Lecture 23 – Combinational Logic Blocks

2020-10-12

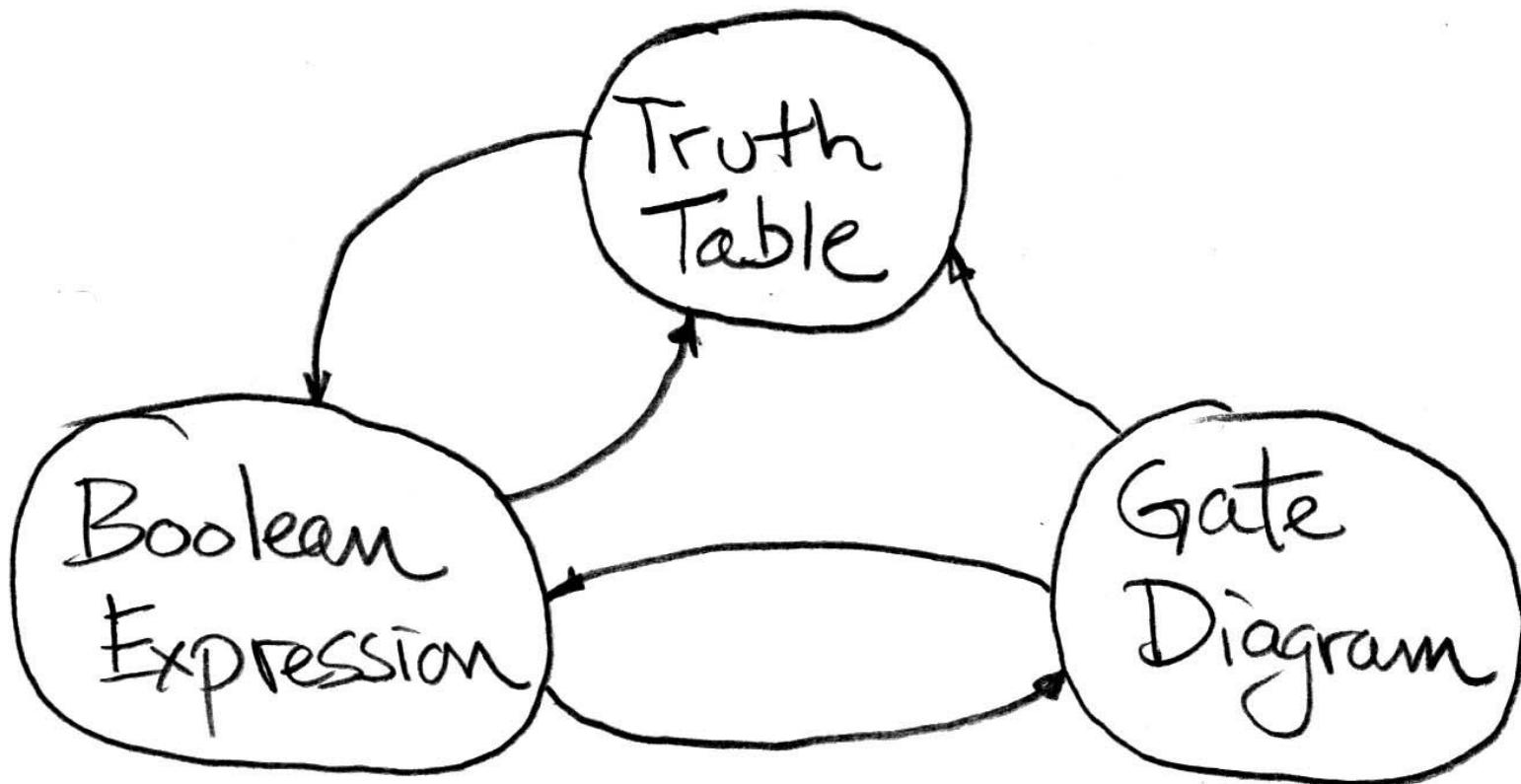


Lecturer Yuanqing Cheng

www.cadetlab.cn/~course

Review

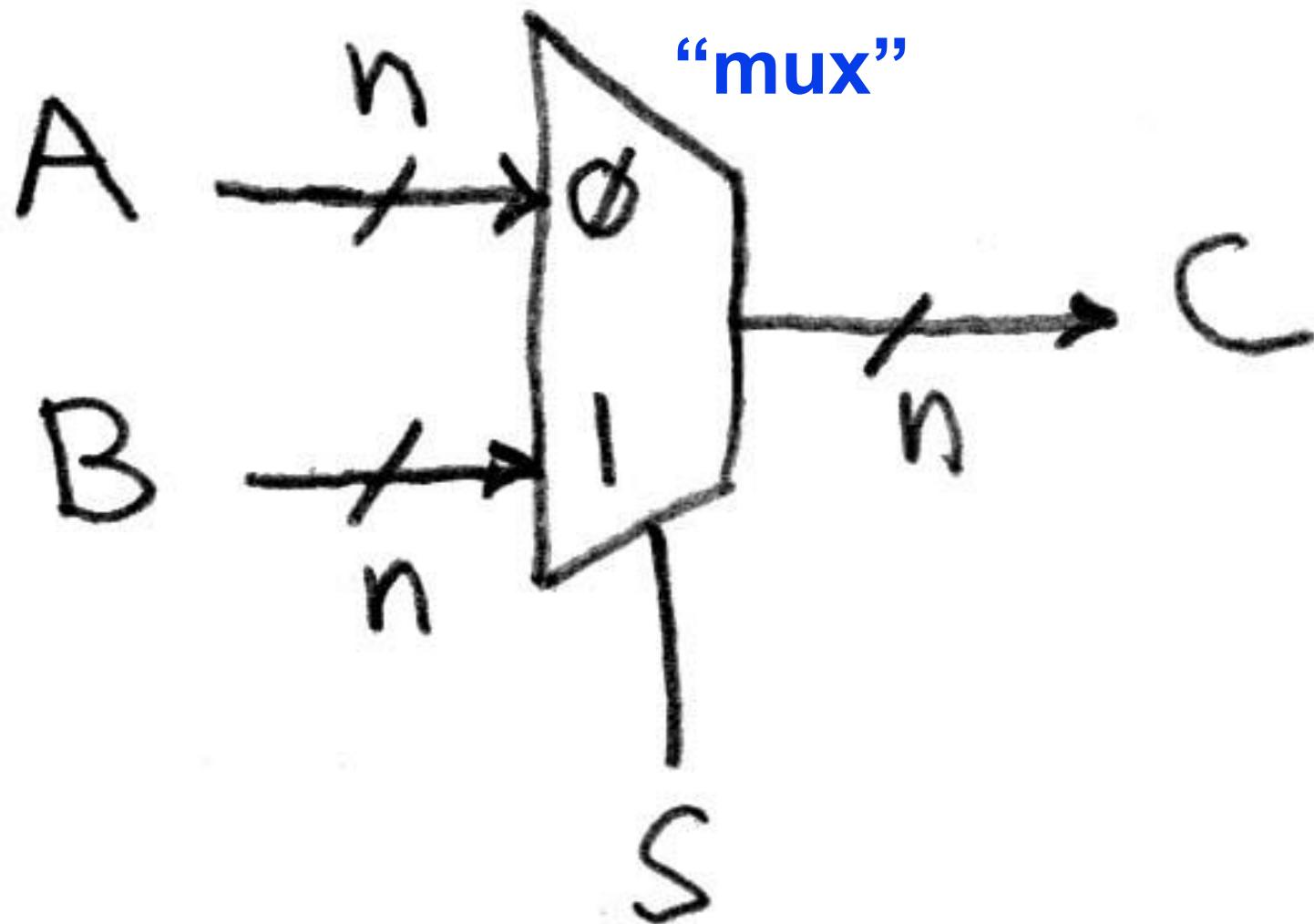
- Use this table and techniques we learned to transform from 1 to another



Today

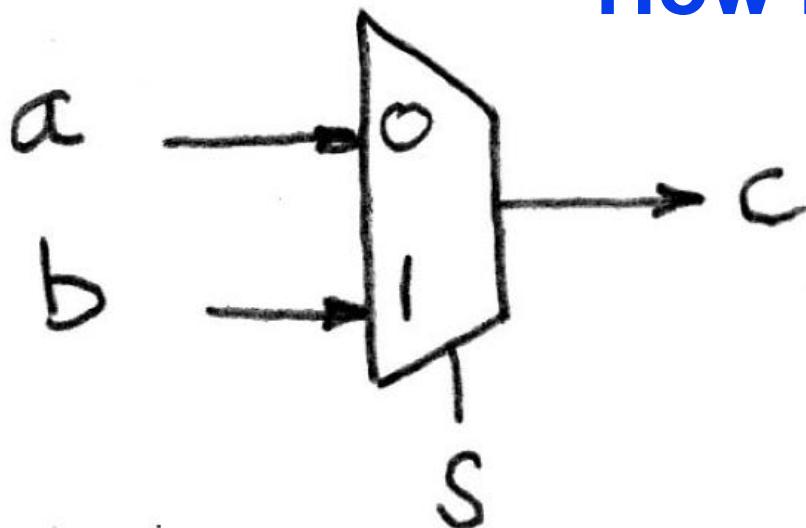
- Data Multiplexors
- Arithmetic and Logic Unit
- Adder/Subtractor

Data Multiplexor (here 2-to-1, n-bit-wide)



N instances of 1-bit-wide mux

How many rows in TT?

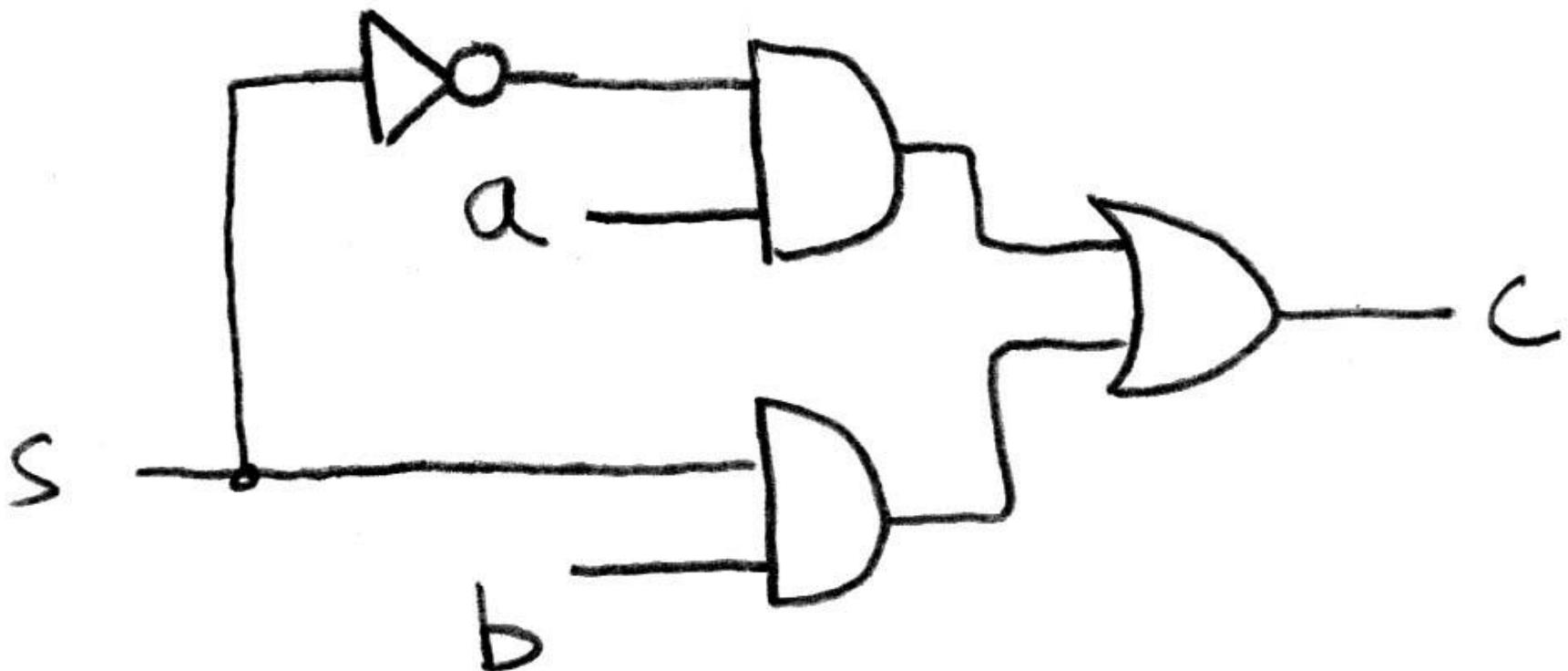


$$\begin{aligned} c &= \bar{s}ab + \bar{s}ab + s\bar{a}b + sab \\ &= \bar{s}(a\bar{b} + ab) + s(\bar{a}b + ab) \\ &= \bar{s}(a(\bar{b} + b)) + s((\bar{a} + a)b) \\ &= \bar{s}(a(1) + s((1)b) \\ &= \bar{s}a + sb \end{aligned}$$



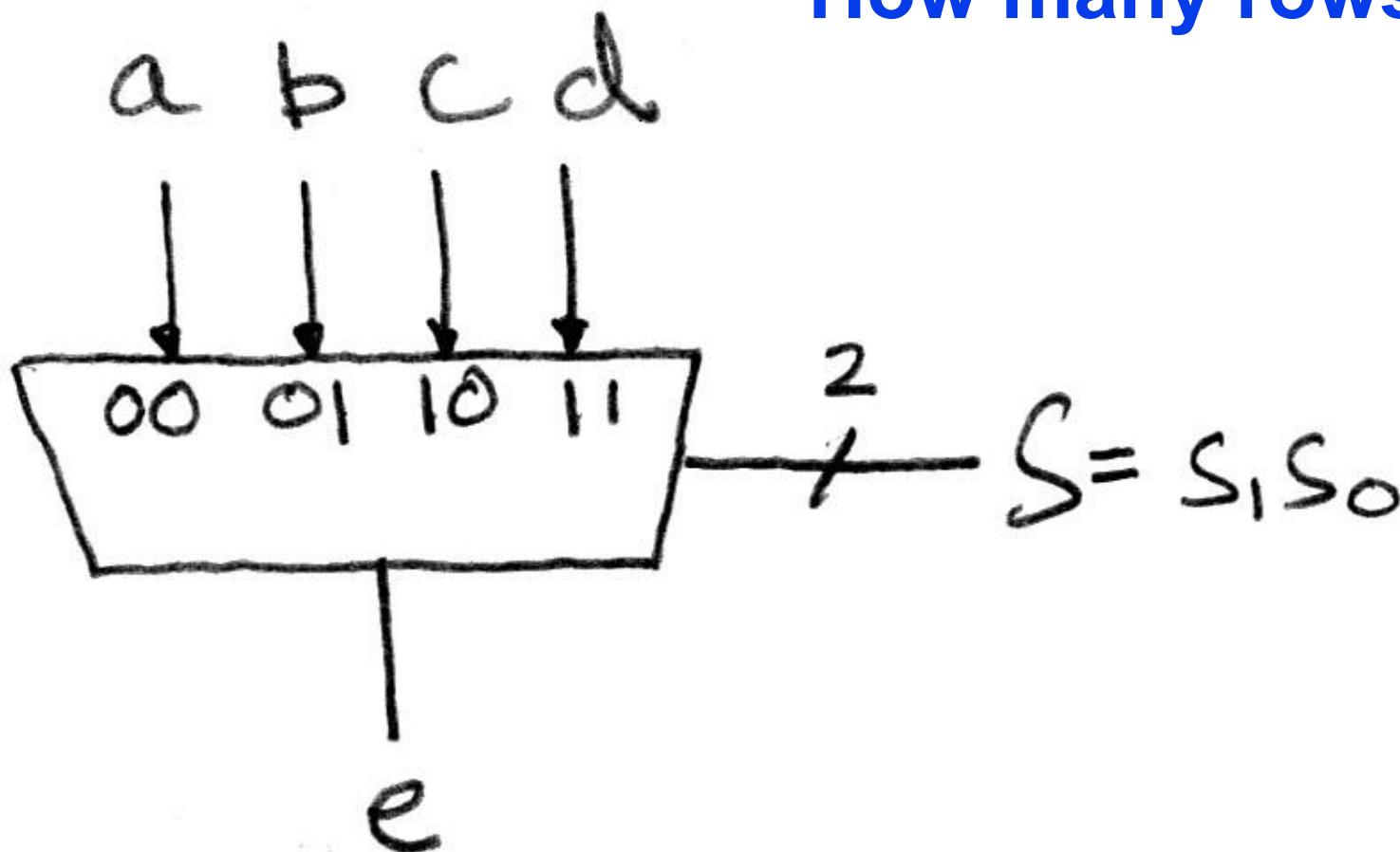
How do we build a 1-bit-wide mux?

$$\bar{s}a + sb$$



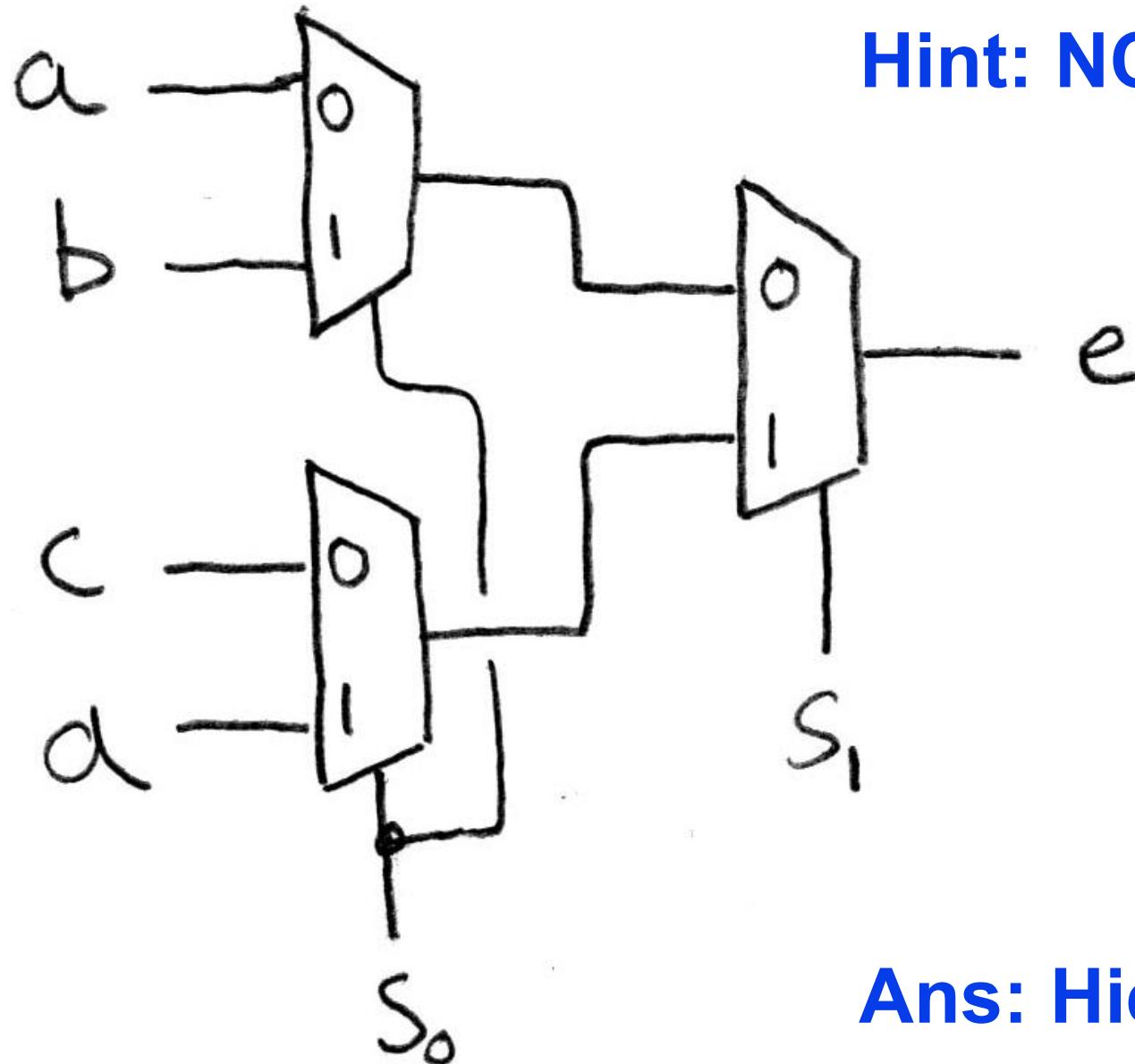
4-to-1 Multiplexor?

How many rows in TT?



$$e = \overline{s_1} \overline{s_0} a + \overline{s_1} s_0 b + s_1 \overline{s_0} c + s_1 s_0 d$$

Is there any other way to do it?

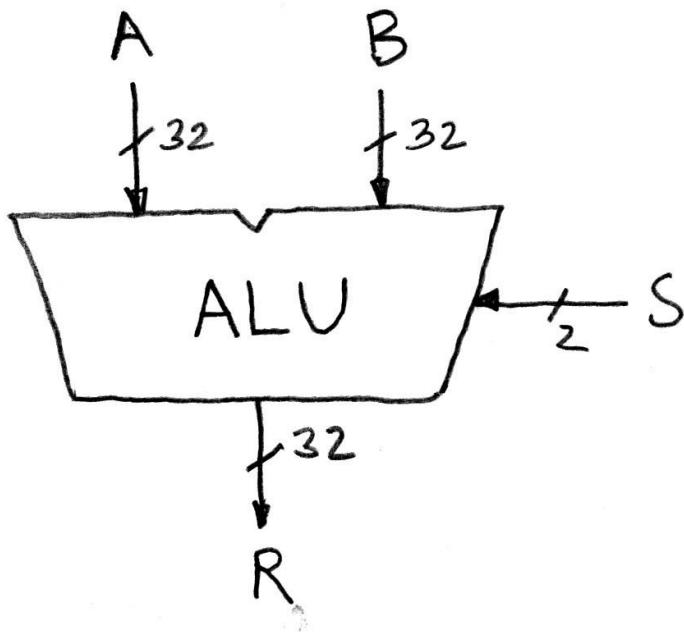


Hint: NCAA tourney!

Ans: Hierarchically!

Arithmetic and Logic Unit

- Most processors contain a special logic block called “Arithmetic and Logic Unit” (ALU)
- We’ll show you an easy one that does ADD, SUB, bitwise AND, bitwise OR



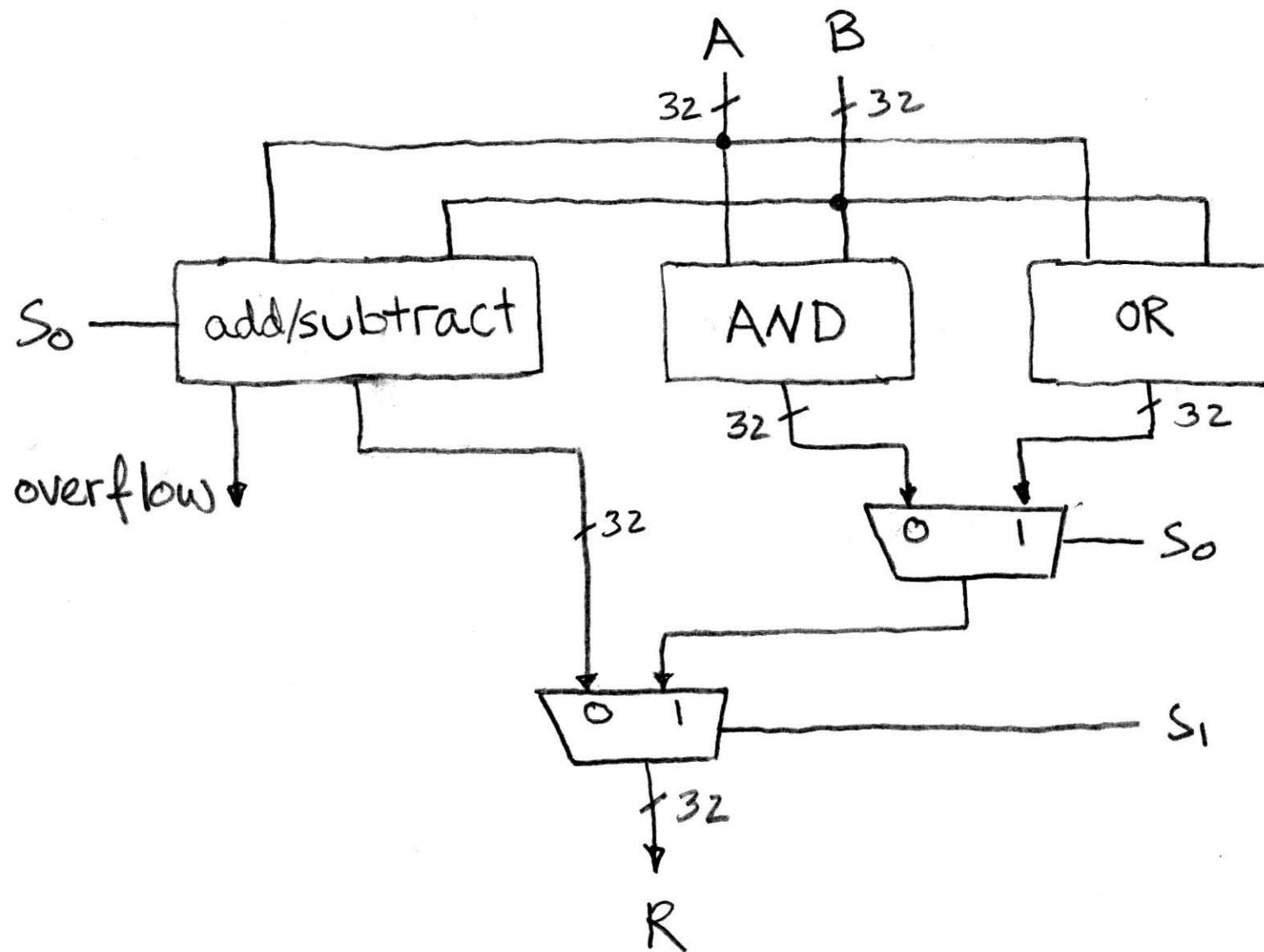
when $S=00$, $R=A+B$

when $S=01$, $R=A-B$

when $S=10$, $R=A \text{ AND } B$

when $S=11$, $R=A \text{ OR } B$

Our simple ALU



Adder/Subtractor Design -- how?

- **Truth-table, then determine canonical form, then minimize and implement as we've seen before**
- **Look at breaking the problem down into smaller pieces that we can cascade or hierarchically layer**

Adder/Subtractor – One-bit adder LSB...

$$\begin{array}{r} \text{a}_3 \quad \text{a}_2 \quad \text{a}_1 \quad \boxed{\text{a}_0} \\ + \quad \text{b}_3 \quad \text{b}_2 \quad \text{b}_1 \quad \boxed{\text{b}_0} \\ \hline \text{s}_3 \quad \text{s}_2 \quad \text{s}_1 \quad \boxed{\text{s}_0} \end{array}$$

a ₀	b ₀	s ₀	c ₁
0	0	0	0
0	1	1	0
1	0	1	0
1	1	0	1

$$s_0 =$$

$$c_1 =$$

Adder/Subtractor – One-bit adder (1/2)...

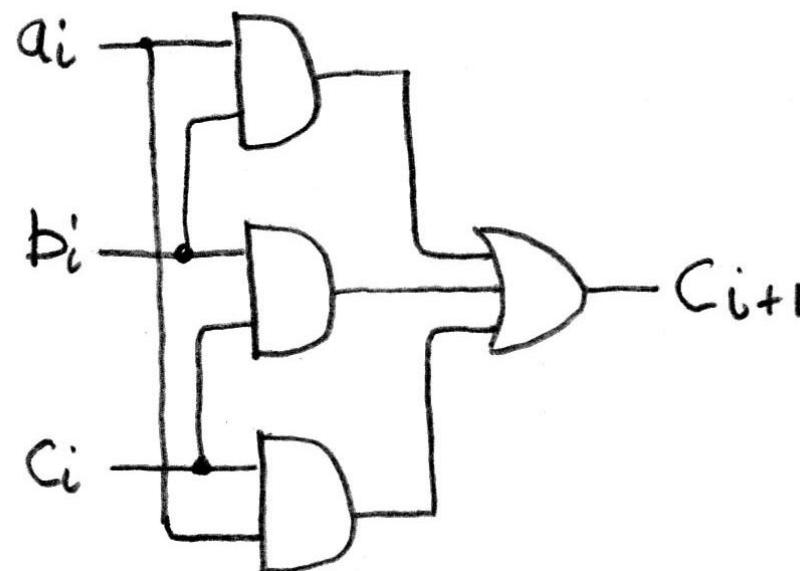
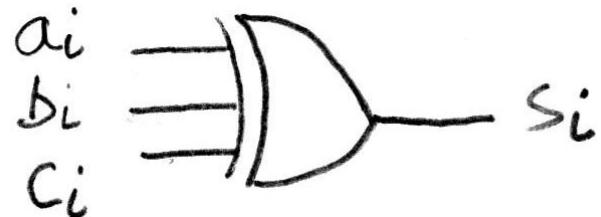
$$\begin{array}{r} \text{a}_3 \quad \text{a}_2 \quad \boxed{\text{a}_1} \quad \text{a}_0 \\ + \quad \text{b}_3 \quad \text{b}_2 \quad \boxed{\text{b}_1} \quad \text{b}_0 \\ \hline \text{s}_3 \quad \text{s}_2 \quad \boxed{\text{s}_1} \quad \text{s}_0 \end{array}$$

a_i	b_i	c_i	s_i	c_{i+1}
0	0	0	0	0
0	0	1	1	0
0	1	0	1	0
0	1	1	0	1
1	0	0	1	0
1	0	1	0	1
1	1	0	0	1
1	1	1	1	1

$$s_i =$$

$$c_{i+1} =$$

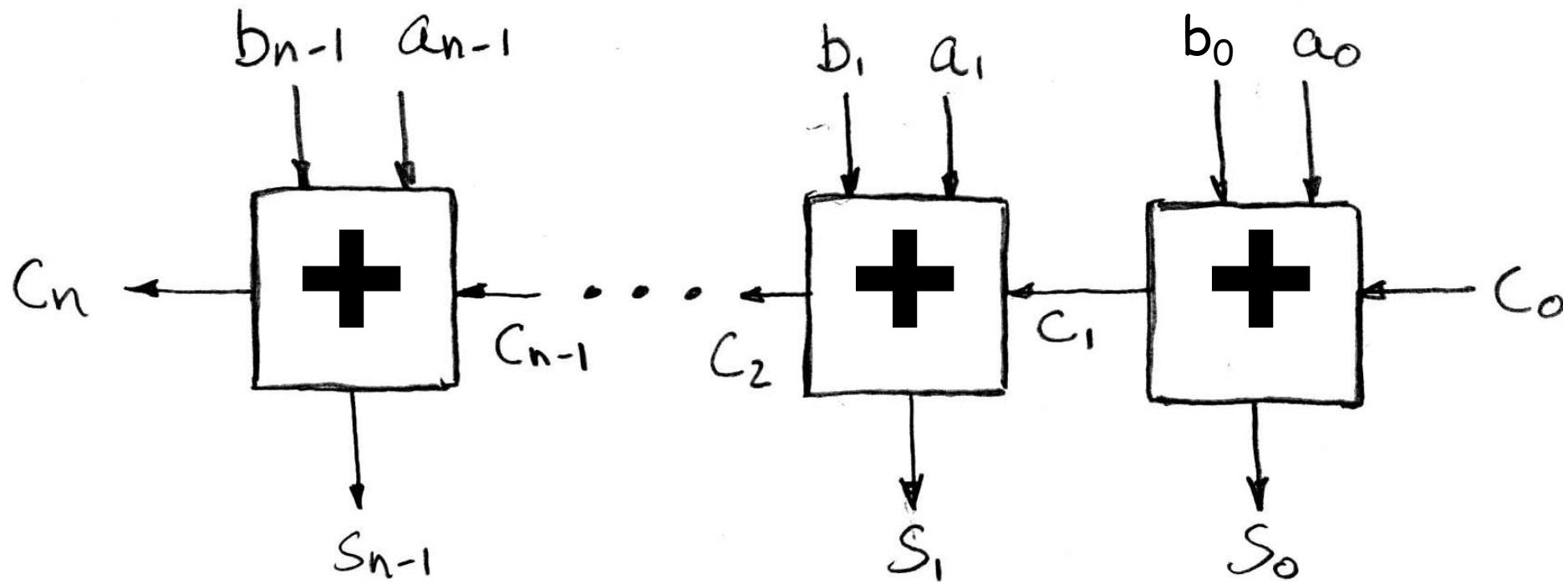
Adder/Subtractor – One-bit adder (2/2)...



$$s_i = \text{XOR}(a_i, b_i, c_i)$$

$$c_{i+1} = \text{MAJ}(a_i, b_i, c_i) = a_i b_i + a_i c_i + b_i c_i$$

N 1-bit adders \Rightarrow 1 N -bit adder

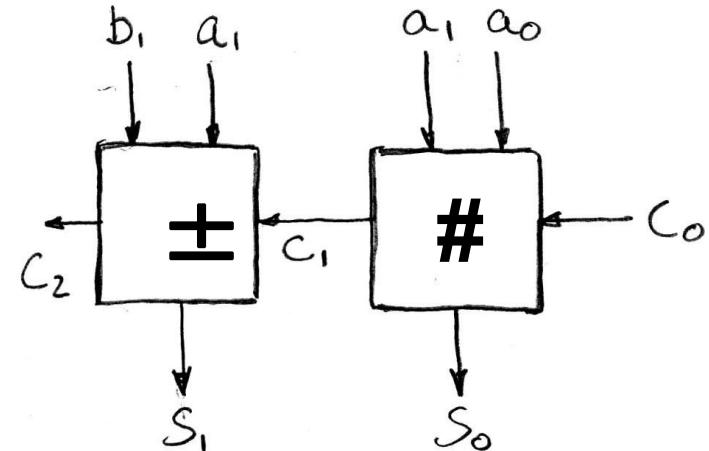


**What about overflow?
Overflow = c_n ?**

What about overflow?

- Consider a 2-bit signed # & overflow:

- $10 = -2 + -2$ or -1
- $11 = -1 + -2$ only
- $00 = 0$ NOTHING!
- $01 = 1 + 1$ only



- Highest adder

- $C_1 = \text{Carry-in} = C_{\text{in}}$, $C_2 = \text{Carry-out} = C_{\text{out}}$
- $\text{No } C_{\text{out}} \text{ or } C_{\text{in}} \Rightarrow \text{NO overflow!}$

What • C_{in} , and $C_{\text{out}} \Rightarrow \text{NO overflow!}$

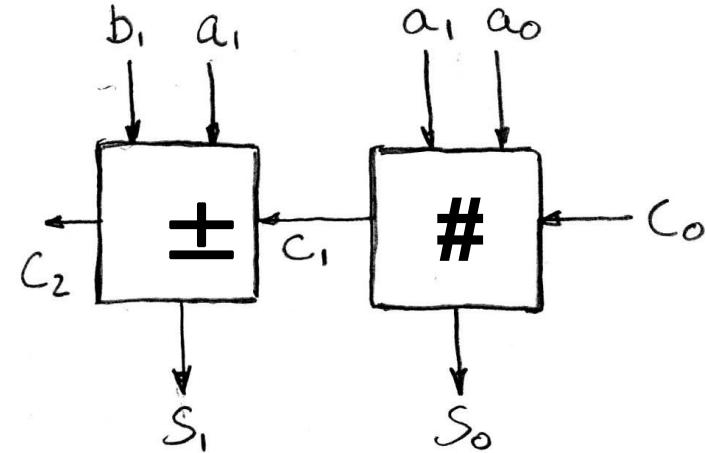
op?

- C_{in} , but no $C_{\text{out}} \Rightarrow A, B \text{ both } > 0, \text{ overflow!}$
- C_{out} , but no $C_{\text{in}} \Rightarrow A, B \text{ both } < 0, \text{ overflow!}$

What about overflow?

- Consider a 2-bit signed # & overflow:

$$\begin{array}{rcl} 10 & = & -2 \\ 11 & = & -1 \\ 00 & = & 0 \\ 01 & = & 1 \end{array}$$

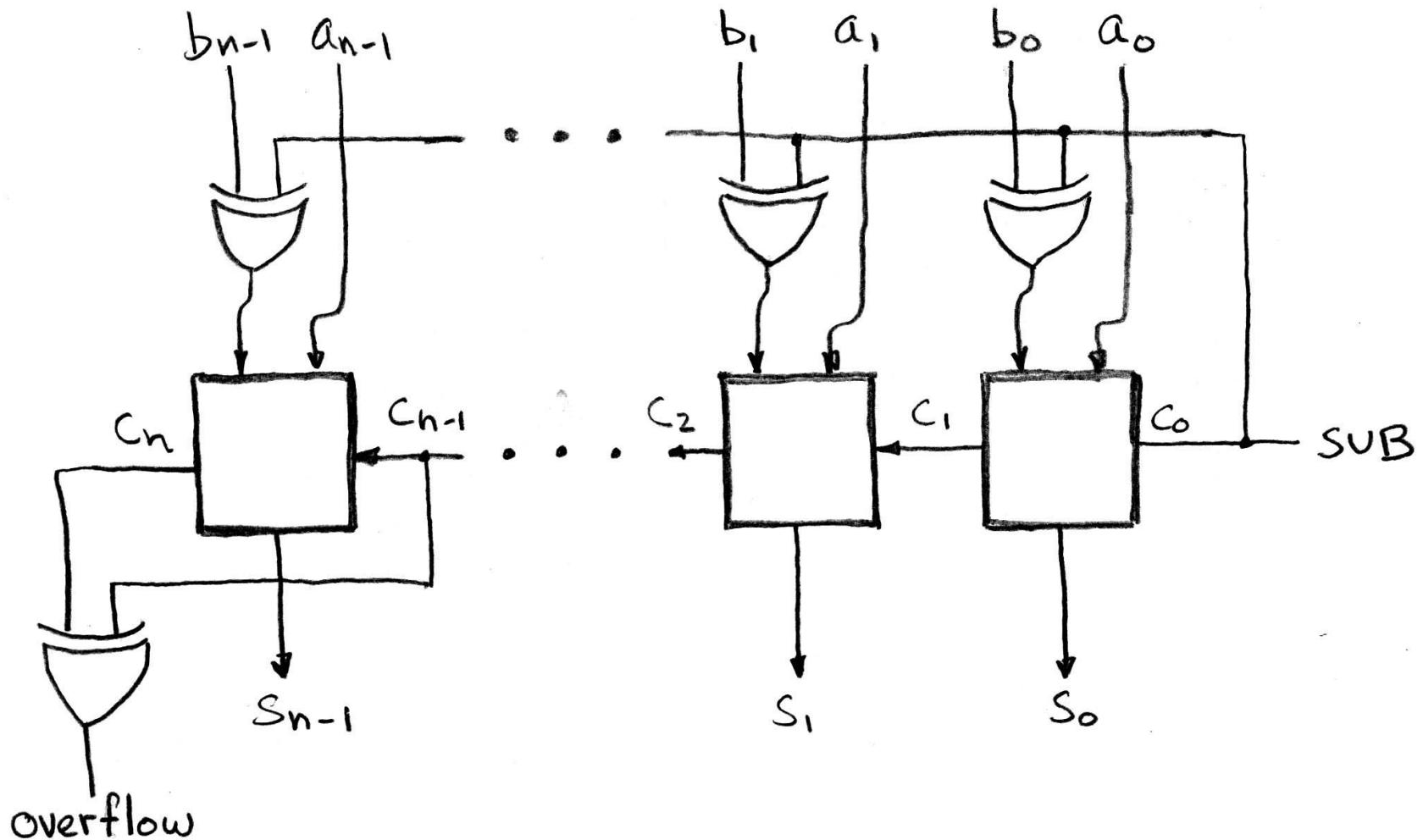


- Overflows when...

- C_{in} , but no $C_{out} \Rightarrow A, B$ both > 0 , overflow!
- C_{out} , but no $C_{in} \Rightarrow A, B$ both < 0 , overflow!

$$\text{overflow} = c_n \text{ XOR } c_{n-1}$$

Extremely Clever Subtractor



Peer Instruction

- 1) Truth table for mux with 4-bits of signals has 2^4 rows
- 2) We could cascade N 1-bit shifters to make 1 N-bit shifter for sll, srl

	12
a)	FF
b)	FT
c)	TF
d)	TT

Peer Instruction Answer

- 1) Truth table for mux with 4-bits of signals controls 16 inputs, for a total of 20 inputs, so truth table is 2^{20} rows... **FALSE**
- 2) We could cascade N 1-bit shifters to make 1 N-bit shifter for sll, srl ... **TRUE**

- 1) Truth table for mux with 4-bits of signals is 2^4 rows long
- 2) We could cascade N 1-bit shifters to make 1 N-bit shifter for sll, srl

	12
a)	FF
b)	FT
c)	TF
d)	TT

“And In conclusion...”

- Use muxes to select among input
 - S input bits selects 2^S inputs
 - Each input can be n-bits wide, indep of S
- Can implement muxes hierarchically
- ALU can be implemented using a mux
 - Coupled with basic block elements
- N-bit adder-subtractor done using N 1-bit adders with XOR gates on input
 - XOR serves as conditional inverter

0.21 Intro to CPU Design

Computer Architecture (计算机体系结构)



Lecturer
Yuanqing
Cheng

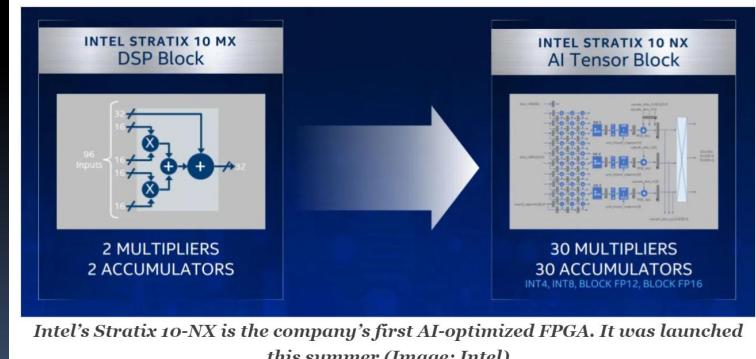
Lecture 24 Introduction to CPU design

2020-10-16

AMD-Xilinx Deal: Bringing The Fight
To The Data Center



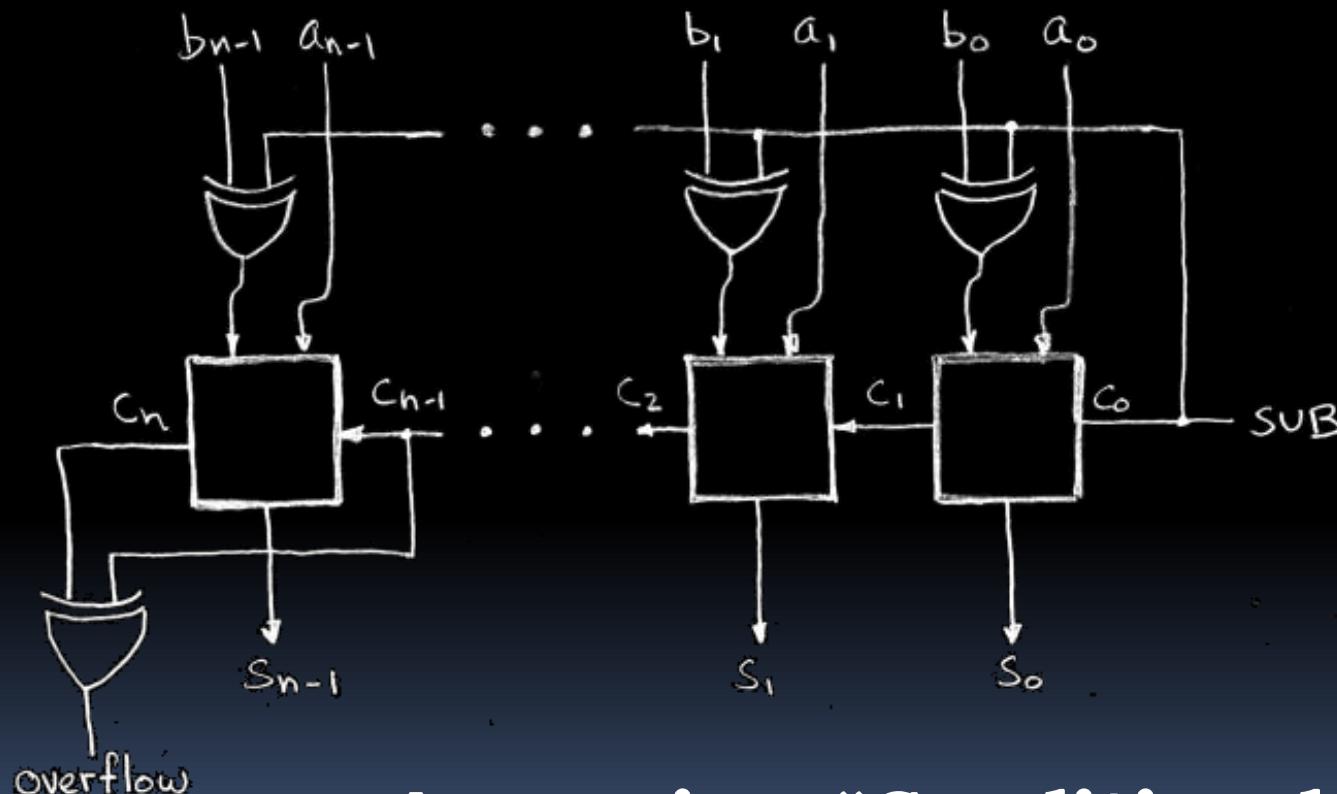
Xilinx Versal AI Core includes both programmable logic and an AI accelerator ASIC block (Image: Xilinx)



Intel's Stratix 10-NX is the company's first AI-optimized FPGA. It was launched this summer (Image: Intel)

Clever Signed Adder/Subtractor

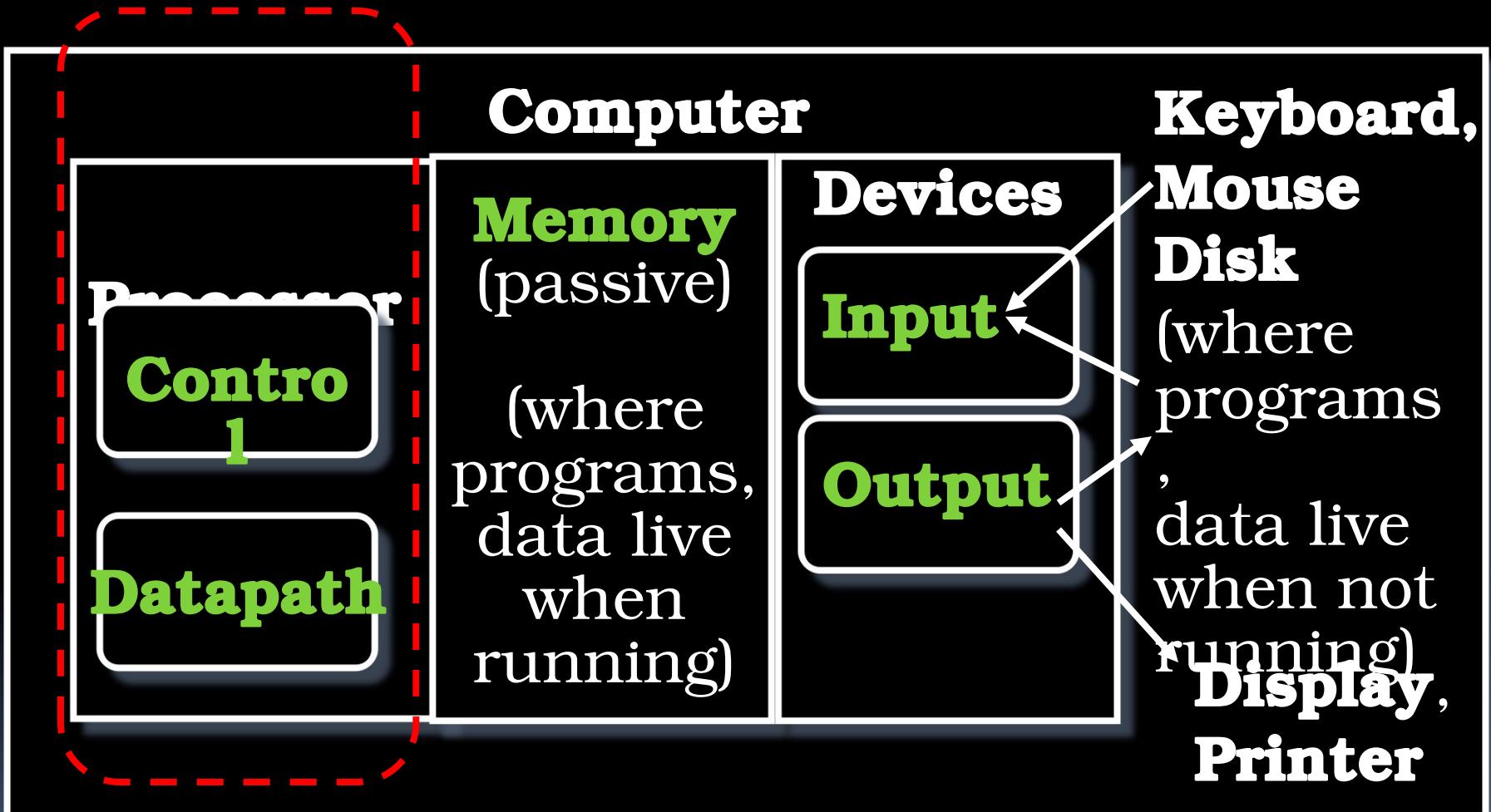
$A - B = A + (-B)$; how do we make “ $-B$ ”?



x	y	xo	r
0	0	0	
0	1	1	
1	0	1	
1	1	0	

An **xor** is a “Conditional Inverter!”

Five Components of a Computer



The CPU

- **Processor (CPU):** the active part of the computer, which does all the work (data manipulation and decision-making)
- **Datapath:** portion of the processor which contains hardware necessary to perform operations required by the processor (the brawn)
- **Control:** portion of the processor (also in hardware) which tells the datapath what needs to be done (the brain)

Stages of the Datapath : Overview

- **Problem:** a single, atomic block which “executes an instruction” (performs all necessary operations beginning with fetching the instruction) would be too bulky and inefficient
- **Solution:** break up the process of “executing an instruction” into **stages**, and then connect the stages to create the whole datapath
 - smaller stages are easier to design
 - easy to optimize (change) one stage without touching the others

Stages of the Datapath (1 / 5)

- There is a wide variety of MIPS instructions: so what general steps do they have in common?
- Stage 1: Instruction Fetch
 - no matter what the instruction, the 32-bit instruction word must first be fetched from memory (the cache-memory hierarchy)
 - also, this is where we Increment PC (that is, $PC = PC + 4$, to point to the next instruction: byte addressing so + 4)

Stages of the Datapath (2/5)

- **Stage 2: Instruction Decode**
 - upon fetching the instruction, we next gather data from the fields (decode all necessary instruction data)
 - first, read the opcode to determine instruction type and field lengths
 - second, read in data from all necessary registers
 - for add, read two registers
 - for addi, read one register
 - for jal, no reads necessary

Stages of the Datapath (3/5)

- **Stage 3: ALU (Arithmetic-Logic Unit)**
 - the real work of most instructions is done here: arithmetic (+, -, *, /), shifting, logic (&, |), comparisons (slt)
 - what about loads and stores?
 - `lw $t0, 40($t1)`
 - the address we are accessing in memory = the value in `$t1` PLUS the value 40
 - so we do this addition in this stage

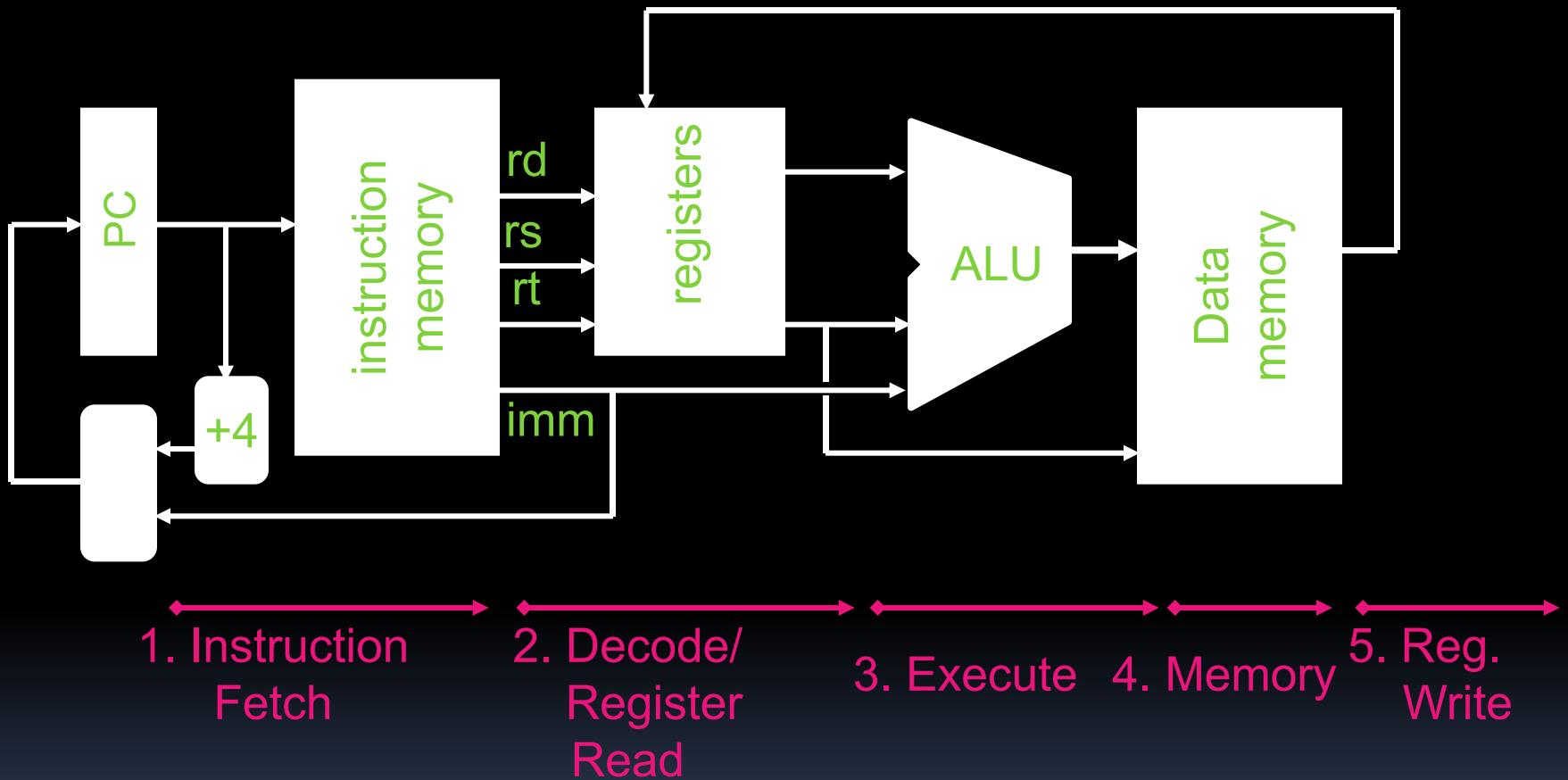
Stages of the Datapath (4/5)

- **Stage 4: Memory Access**
 - actually only the load and store instructions do anything during this stage; the others remain idle during this stage or skip it all together
 - since these instructions have a unique step, we need this extra stage to account for them
 - as a result of the cache system, this stage is expected to be fast

Stages of the Datapath (5/5)

- **Stage 5: Register Write**
 - most instructions write the result of some computation into a register
 - examples: arithmetic, logical, shifts, loads, slt
 - what about stores, branches, jumps?
 - don't write anything into a register at the end
 - these remain idle during this fifth stage or skip it all together

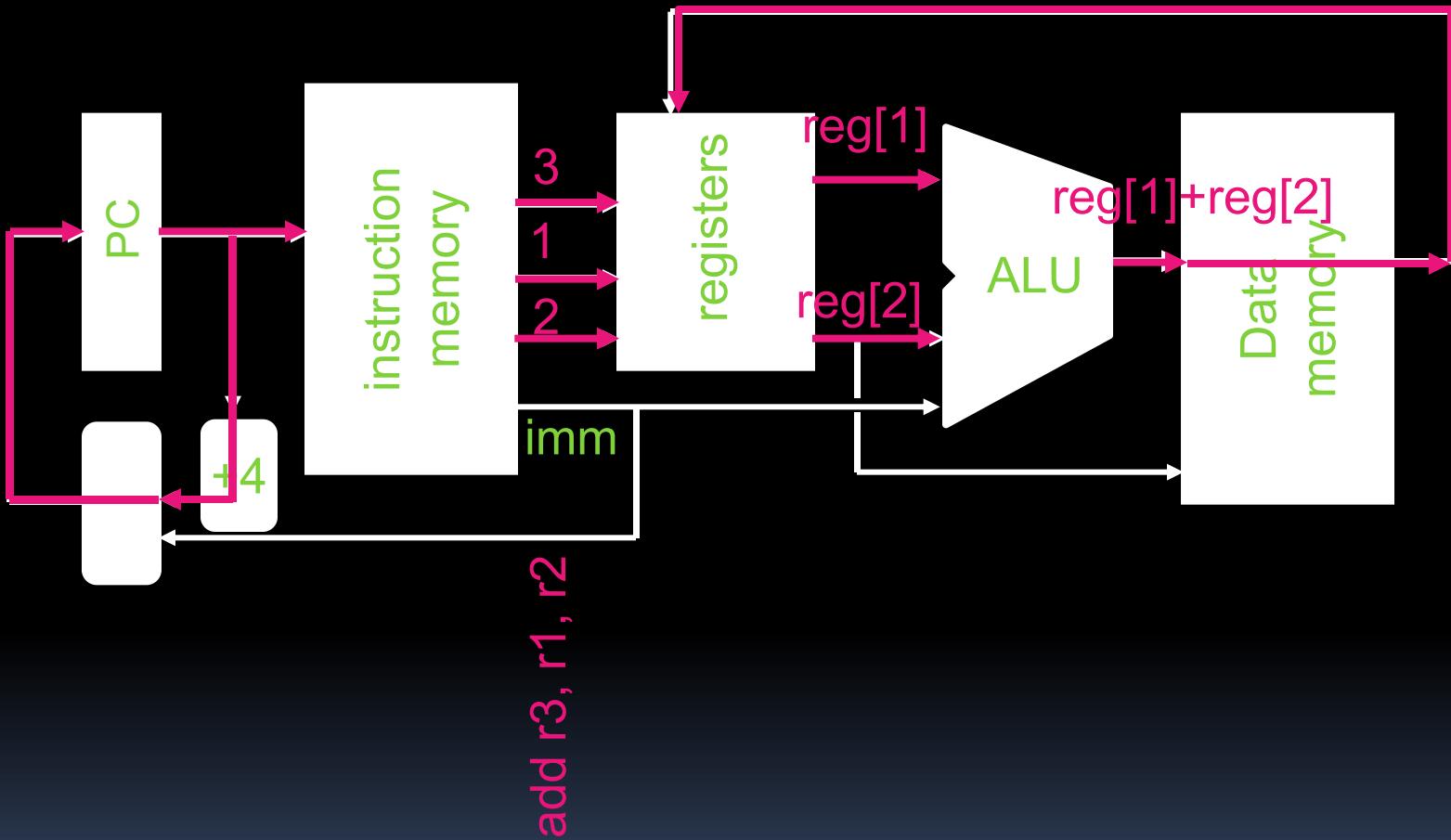
Generic Steps of Datapath



Datapath Walkthroughs (1 / 3)

- **add \$r3,\$r1,\$r2 # r3 = r1+r2**
 - **Stage 1: fetch this instruction, inc. PC**
 - **Stage 2: decode to find it's an add, then read registers \$r1 and \$r2**
 - **Stage 3: add the two values retrieved in Stage 2**
 - **Stage 4: idle (nothing to write to memory)**
 - **Stage 5: write result of Stage 3 into register \$r3**

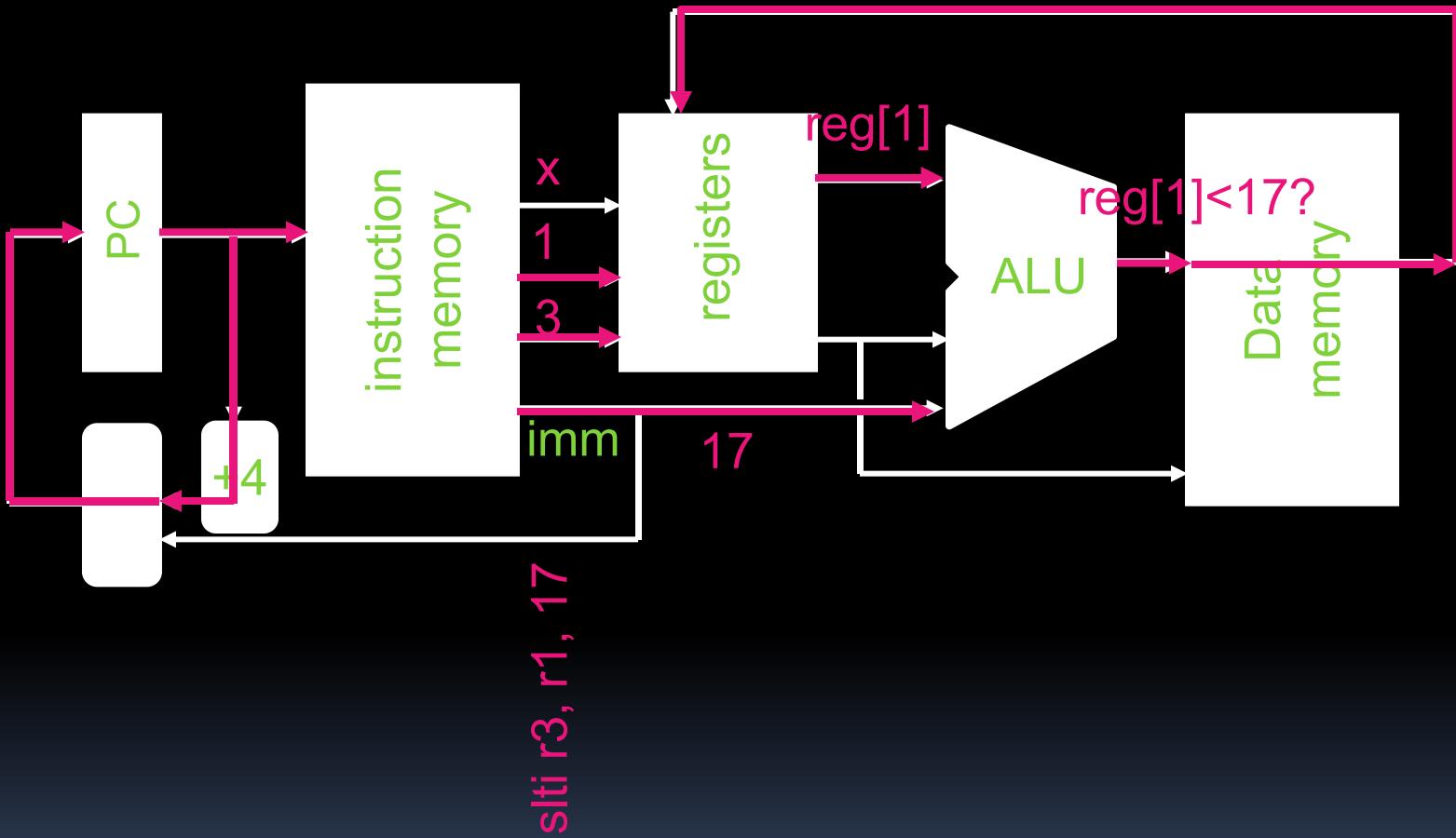
Example: add Instruction



Datapath Walkthroughs (2/3)

- **slti \$r3,\$r1,17**
 - **Stage 1: fetch this instruction, inc. PC**
 - **Stage 2: decode to find it's an slti, then read register \$r1**
 - **Stage 3: compare value retrieved in Stage 2 with the integer 17**
 - **Stage 4: idle**
 - **Stage 5: write the result of Stage 3 in register \$r3**

Example: slti Instruction

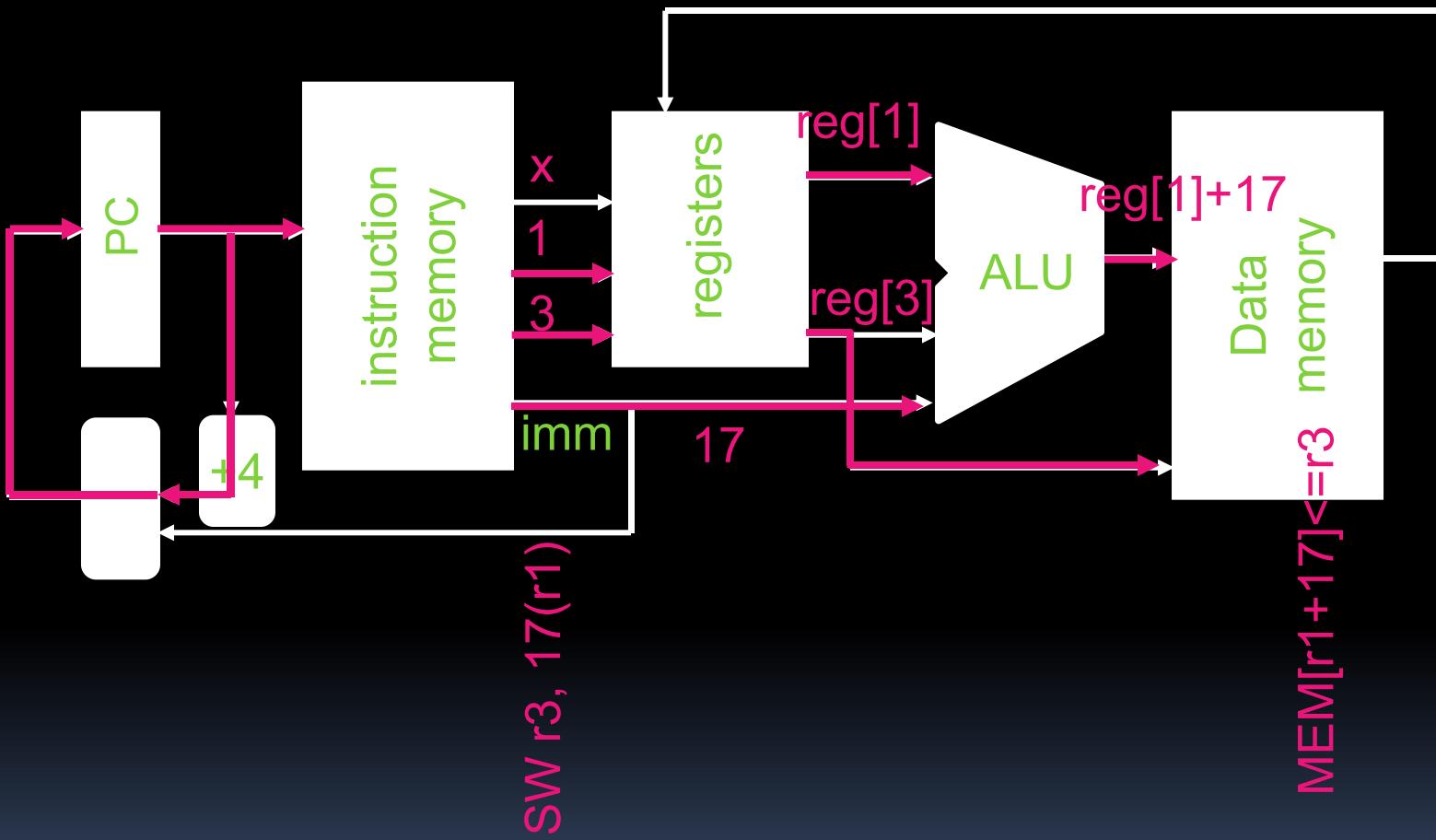


slt r3, r1, 17

Datapath Walkthroughs (3/3)

- **sw \$r3, 17(\$r1)**
 - **Stage 1: fetch this instruction, inc. PC**
 - **Stage 2: decode to find it's a sw, then read registers \$r1 and \$r3**
 - **Stage 3: add 17 to value in register \$r1 (retrieved in Stage 2)**
 - **Stage 4: write value in register \$r3 (retrieved in Stage 2) into memory address computed in Stage 3**
 - **Stage 5: idle (nothing to write into a register)**

Example: sw Instruction



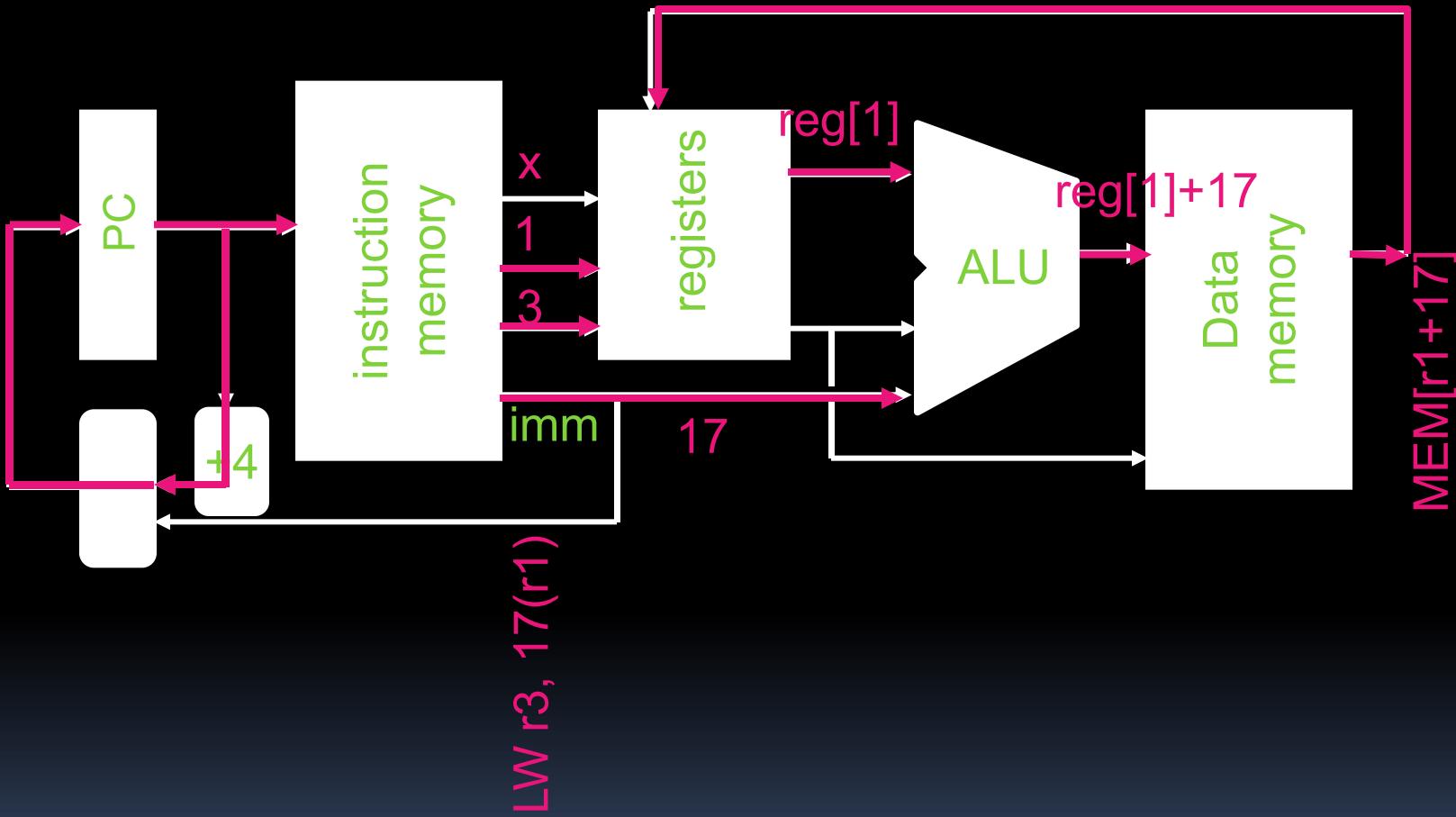
Why Five Stages? (1/2)

- Could we have a different number of stages?
 - Yes, and other architectures do
- So why does MIPS have five if instructions tend to idle for at least one stage?
 - The five stages are the union of all the operations needed by all the instructions.
 - There is one instruction that uses all five stages: the load

Why Five Stages? (2/2)

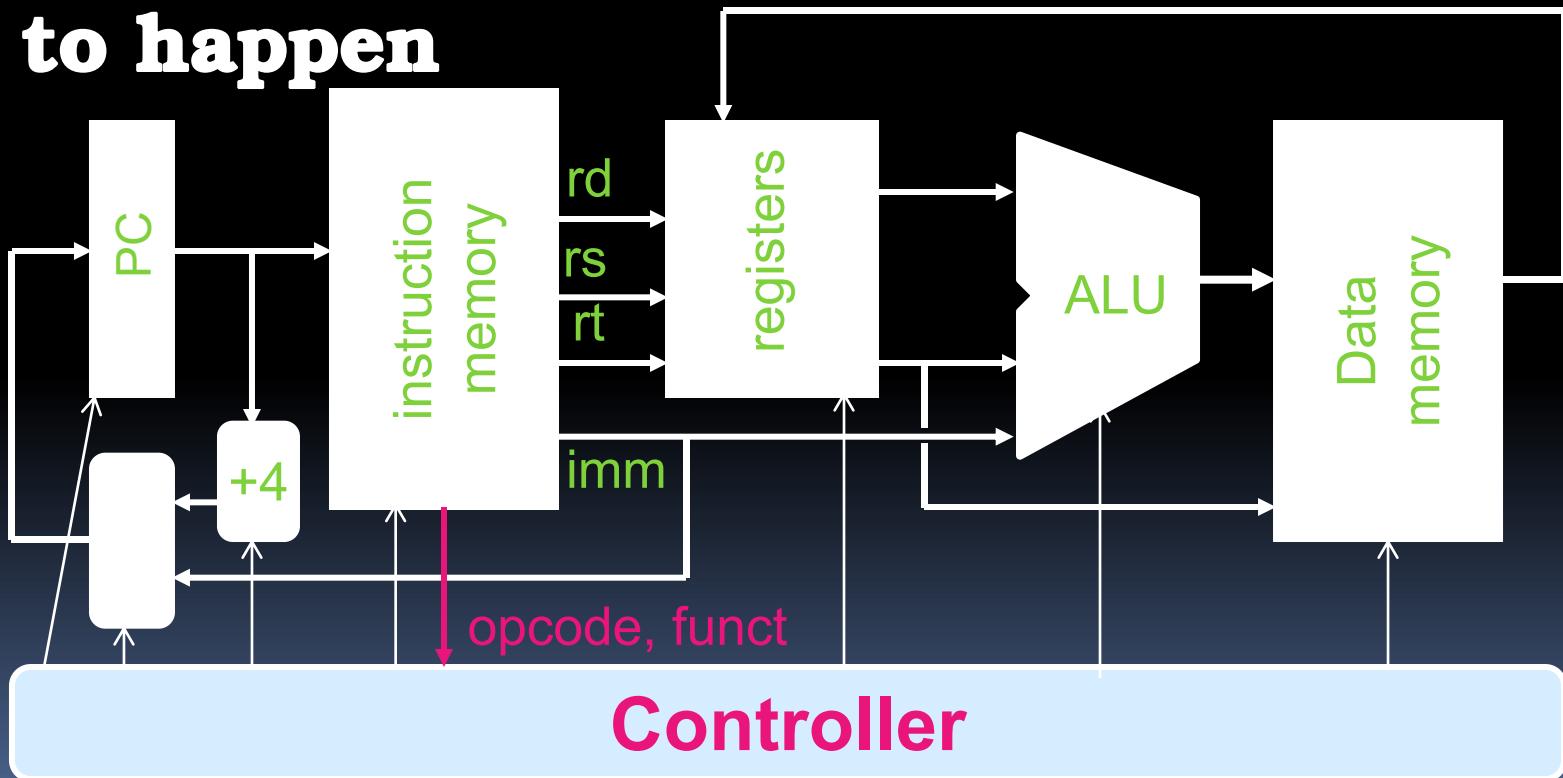
- `lw $r3, 17($r1)`
 - **Stage 1: fetch this instruction, inc. PC**
 - **Stage 2: decode to find it's a lw, then read register \$r1**
 - **Stage 3: add 17 to value in register \$r1 (retrieved in Stage 2)**
 - **Stage 4: read value from memory address compute in Stage 3**
 - **Stage 5: write value found in Stage 4 into register \$r3**

Example: lw Instruction



Datapath Summary

- The datapath based on data transfers required to perform instructions
- A controller causes the right transfers to happen



What Hardware Is Needed? (1 / 2)

- **PC: a register which keeps track of memory addr of the next instruction**
- **General Purpose Registers**
 - **used in Stages 2 (Read) and 5 (Write)**
 - **MIPS has 32 of these**
- **Memory**
 - **used in Stages 1 (Fetch) and 4 (R/W)**
 - **cache system makes these two stages as fast as the others, on average**

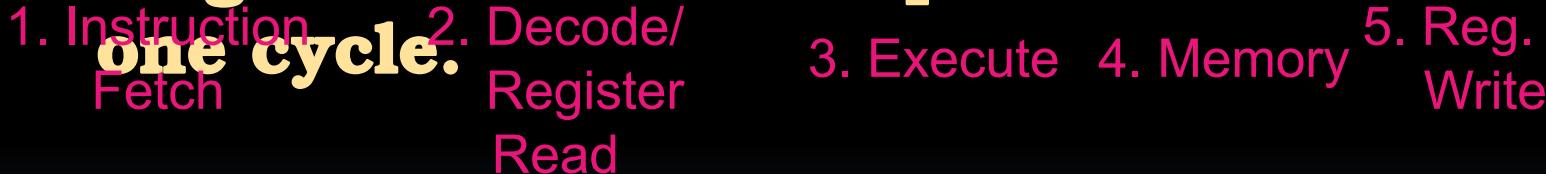
What Hardware Is Needed? (2/2)

- **ALU**
 - **used in Stage 3**
 - **something that performs all necessary functions: arithmetic, logicals, etc.**
 - **we'll design details later**
- **Miscellaneous Registers**
 - **In implementations with only one stage per clock cycle, registers are inserted between stages to hold intermediate data and control signals as they travels from stage to stage.**
 - **Note: Register is a general purpose term meaning something that stores bits. Not all registers are in the “register file”.**

CPU clocking (1/2)

For each instruction, how do we control the flow of information through the datapath?

- **Single Cycle CPU:** All stages of an instruction are completed within one long clock cycle.
 - The clock cycle is made sufficient long to allow each instruction to complete all stages without interruption and within one cycle.



For each instruction, how do we control the flow of information through the datapath?

CPU clocking (2/2)

- **Multiple-cycle CPU: Only one stage of instruction per clock cycle.**

- **The clock is made as long as the slowest stage.**



- **Several significant advantages over single cycle execution:** Unused stages in a particular instruction can be skipped OR instructions can be pipelined (overlapped).

Peer Instruction

- A. If the destination reg is the same as the source reg, we could compute the incorrect value!
- B. We're going to be able to read 2 registers and write a 3rd in 1 cycle

	ABC
0:	FFF
1:	FFT
2:	FTF
3:	FTT
4:	TFF
5:	TFT
6:	TTF
7:	TTT

Peer Instruction

- A. Truth table for mux with 4-bits of signals has 2^4 rows**
- B. We could cascade N 1-bit shifters to make 1 N-bit shifter for sll, srl**
- C. If 1-bit adder delay is T, the N-bit adder delay would also be T**

	ABC
1 :	FFF
2 :	FFT
3 :	FTF
4 :	FTT
5 :	TFF
6 :	TFT
7 :	TTF
8 :	TTT

Peer Instruction Answer

“And In conclusion...”

- **N-bit adder-subtractor done using N 1-bit adders with XOR gates on input**
 - **XOR serves as conditional inverter**
- **CPU design involves Datapath, Control**
 - **Datapath in MIPS involves 5 CPU stages**
 1. **Instruction Fetch**
 2. **Instruction Decode & Register Read**
 3. **ALU (Execute)**
 4. **Memory**
 5. **Register Write**

0.22 Intro to CPU Design: Single Cycle



Lecturer
Yuanqing
Cheng

Lecture 20 CPU design (of a single-cycle CPU)

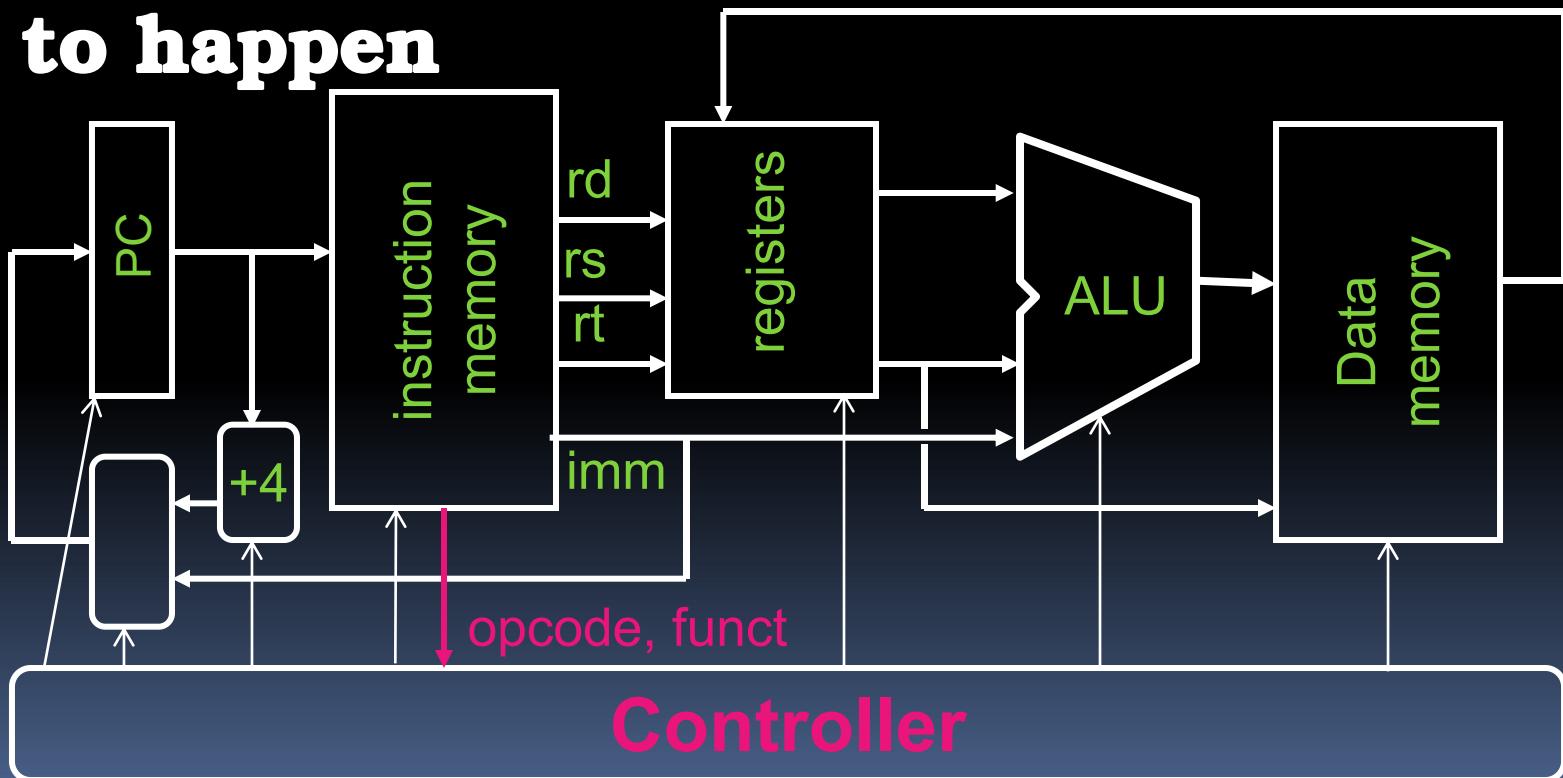
2020-10-16

Review

- CPU design involves Datapath, Control
 - Datapath in MIPS involves 5 CPU stages
 1. Instruction Fetch
 2. Instruction Decode & Register Read
 3. ALU (Execute)
 4. Memory
 5. Register Write

Datapath Summary

- The datapath based on data transfers required to perform instructions
- A controller causes the right transfers to happen



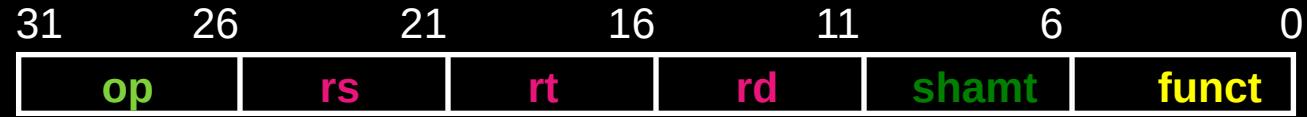
How to Design a Processor: step-by-step

- 1. Analyze instruction set architecture (ISA)
⇒ datapath requirements**
 - 1. meaning of each instruction is given by the register transfers**
 - 2. datapath must include storage element for ISA registers**
 - 3. datapath must support each register transfer**
- 2. Select set of datapath components and establish clocking methodology**
- 3. Assemble datapath meeting requirements**
- 4. Analyze implementation of each instruction to determine setting of control points that effects the register transfer.**
- 5. Assemble the control logic**

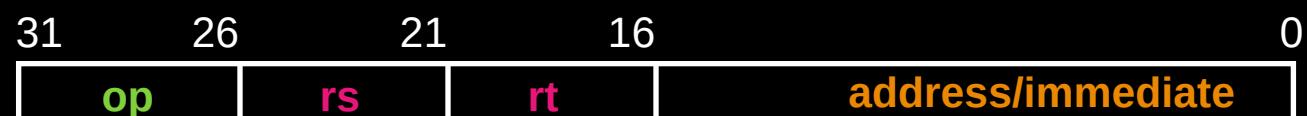
Review: The MIPS Instruction

~~All~~ MIPS instructions are 32 bits long. 3 formats:

- **R-type**



- **I-type**



- **J-type**



- The different fields are:

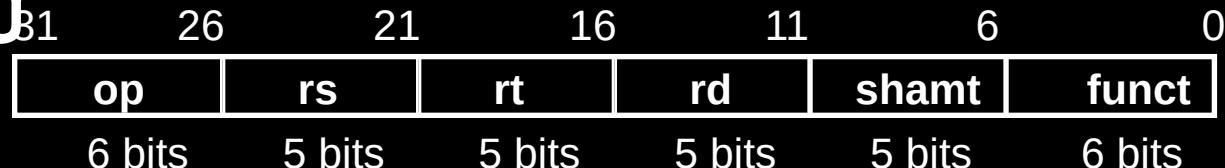
- **op**: operation (“opcode”) of the instruction
- **rs, rt, rd**: the source and destination register specifiers
- **shamt**: shift amount
- **funct**: selects the variant of the operation in the “op” field
- **address / immediate**: address offset or immediate value
- **target address**: target address of jump instruction

Step 1a: The MIPS-lite Subset for

today

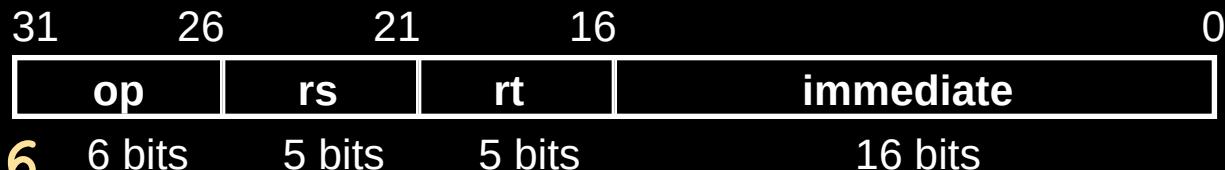
■ ADDU and SUBU

- addu rd,rs,rt
- subu rd,rs,rt



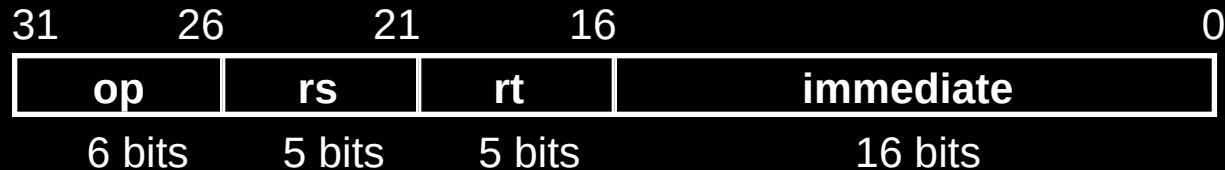
■ OR Immediate:

- ori rt,rs,imm16



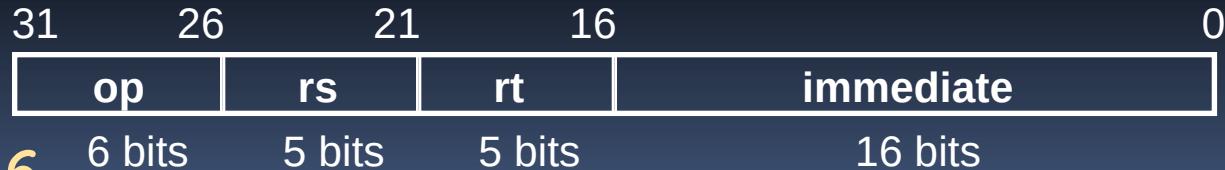
■ LOAD and STORE Word

- lw rt,rs,imm16
- sw rt,rs,imm16



■ BRANCH:

- beq rs,rt,imm16



Register Transfer Language (RTL)

- RTL gives the meaning of the instructions

{op , rs , rt , rd , shamt , funct} ← MEM[PC]

{op , rs , rt , Imm16} ← MEM[PC]

- All start by fetching the instruction
inst Register Transfers

ORI $R[rt] \leftarrow R[rs] \mid zero \ ext(Imm16); \quad PC \leftarrow PC + 4$

LOAD $R[rt] \leftarrow MEM[R[rs] + sign\ ext(Imm16)]; PC \leftarrow PC + 4$

STORE $\text{MEM}[R[rs] + \text{sign ext(Imm16)}] \leftarrow R[rt]; \text{PC} \leftarrow \text{PC} + 4$

BEQ if (R[rs] == R[rt]) then

$\text{PC} \leftarrow \text{PC} + 4 + (\text{sign_ext}(\text{Imm16}) \parallel 00)$

else PC \leftarrow PC + 4

Step 1: Requirements of the Instruction Set

- **Memory (MEM)**
 - instructions & data (will use one for each)
- **Registers (R: 32 x 32)**
 - **read RS**
 - **read RT**
 - **Write RT or RD**
- **PC**
- **Extender (sign/zero extend)**
- **Add/Sub/OR unit for operation on register(s) or extended immediate**
- **Add 4 (+ maybe extended immediate) to PC**
- **Compare registers?**

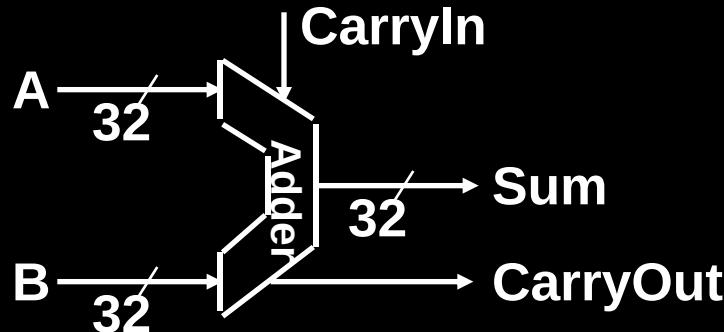
Step 2: Components of the

~~Datapath~~

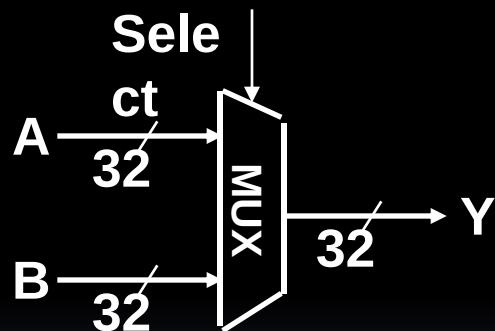
- **Combinational Elements**
- **Storage Elements**
 - **Clocking methodology**

Combinational Logic Elements (Building Blocks)

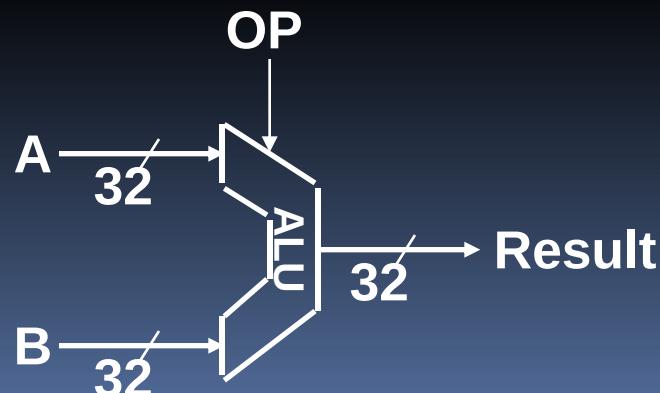
- **Adder**



- **MUX**



- **ALU**



ALU Needs for MIPS-lite + Rest of MIPS

- **Addition, subtraction, logical OR, ==:**

ADDU $R[rd] = R[rs] + R[rt]; \dots$

SUBU $R[rd] = R[rs] - R[rt]; \dots$

ORI $R[rt] = R[rs] |$

zero_ext(Imm16) ...

BEQ if ($R[rs] == R[rt]$) ...

- **Test to see if output == 0 for any ALU operation gives == test. How?**
- **P&H also adds AND, Set Less Than (1 if A < B, 0 otherwise)**
- **ALU follows chap 5**

Administrivia

- **Administrivia?**

What Hardware Is Needed? (1 / 2)

- **PC: a register which keeps track of memory addr of the next instruction**
- **General Purpose Registers**
 - **used in Stages 2 (Read) and 5 (Write)**
 - **MIPS has 32 of these**
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 - **cache system makes these two stages as fast as the others, on average**

What Hardware Is Needed? (2/2)

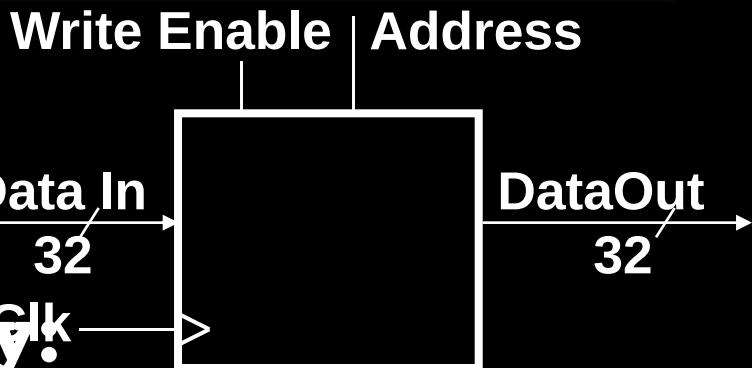
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 - **used in Stage 3**
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- **Miscellaneous Registers**
 - **In implementations with only one stage per clock cycle, registers are inserted between stages to hold intermediate data and control signals as they travels from stage to stage.**
 - **Note: Register is a general purpose term meaning something that stores bits. Not all registers are in the “register file”.**

Storage Element: Idealized

Memory

- **Memory (idealized)**

- One input bus: Data In
 - One output bus: Data Out



- **Memory word is found by:**

- Address selects the word to put on Data Out
 - Write Enable = 1: address selects the memory word to be written via the Data In bus

- **Clock input (CLK)**

- The CLK input is a factor ONLY during write operation
 - During read operation, behaves as a combinational logic block:

- **Address valid \Rightarrow Data Out valid after “access”**

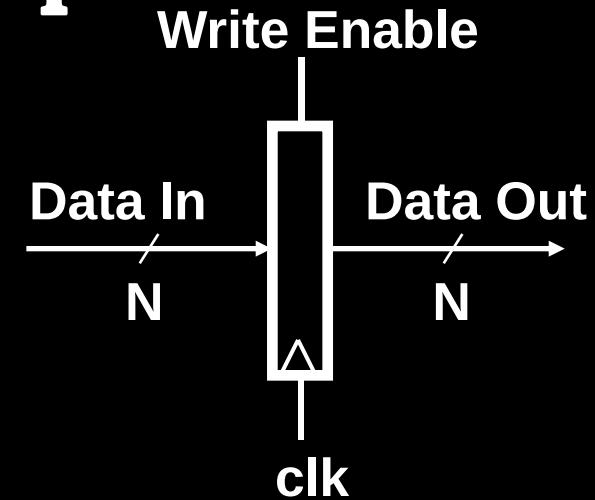
Storage Element: Register (Building Block)

- **Similar to D Flip Flop except**

- **N-bit input and output**
 - **Write Enable input**

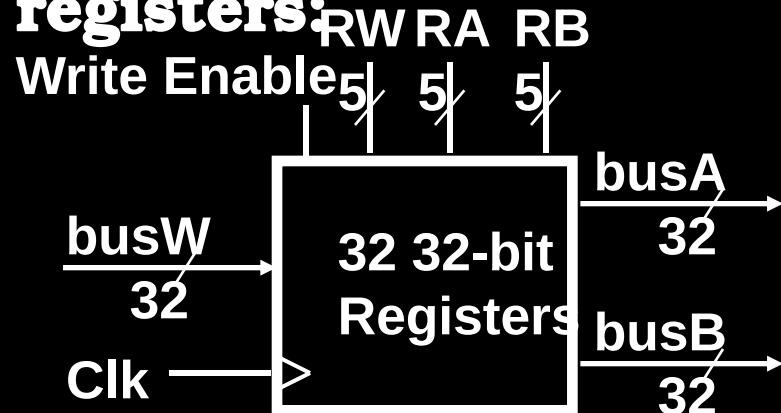
- **Write Enable:**

- **negated (or deasserted) (0): Data Out will not change**
 - **asserted (1): Data Out will become Data In on positive edge of clock**



Storage Element: Register File

- **Register File consists of 32 registers:**
 - Two 32-bit output busses: busA and busB
 - One 32-bit input bus: busW
- **Register is selected by:**
 - RA (number) selects the register to put on busA (data)
 - RB (number) selects the register to put on busB (data)
 - RW (number) selects the register to be written via busW (data) when Write Enable is 1
- **Clock input (clk)**
 - The clk input is a factor ONLY during write operation
 - During read operation, behaves as a combinational logic block:
 - RA or RB valid \Rightarrow busA or busB valid after “access time.”



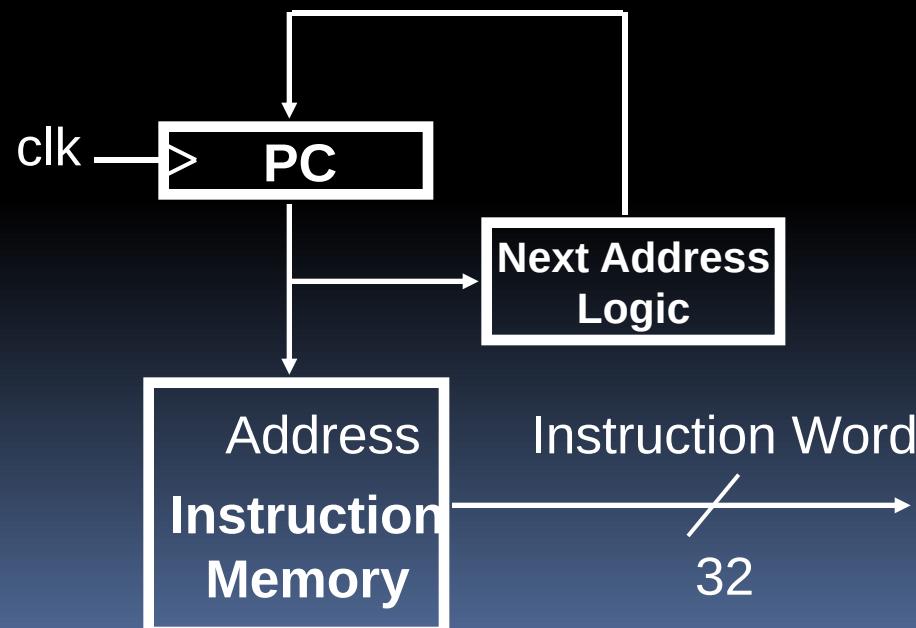
Step 3: Assemble DataPath meeting requirements

- **Register Transfer Requirements**
 ⇒ **Datapath Assembly**
- **Instruction Fetch**
- **Read Operands and Execute Operation**

3a: Overview of the Instruction Fetch Unit

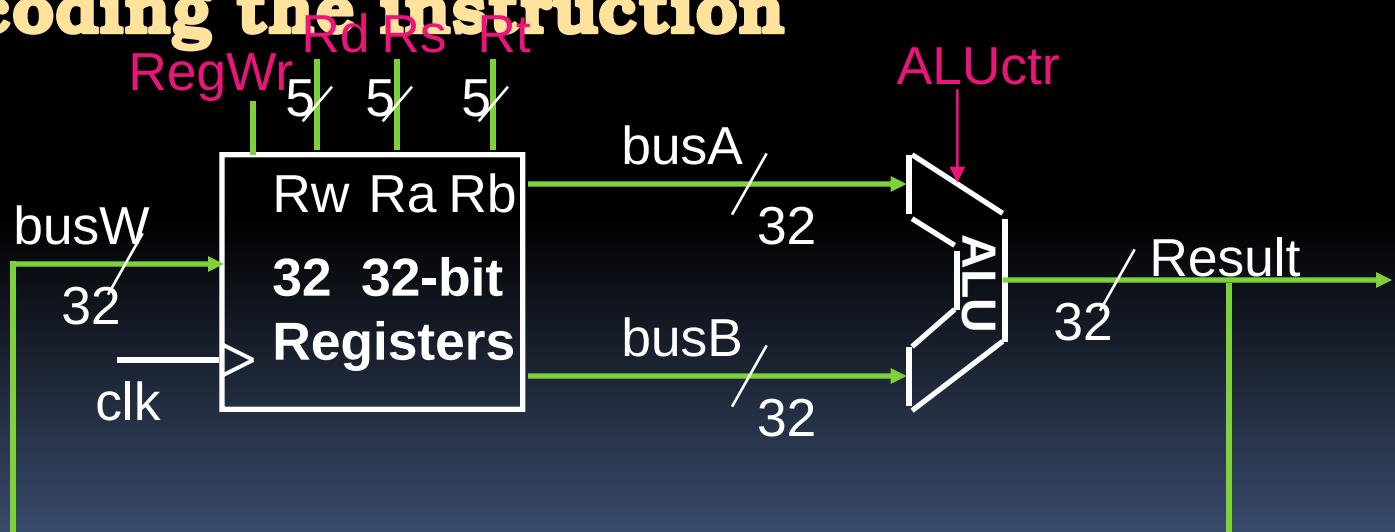
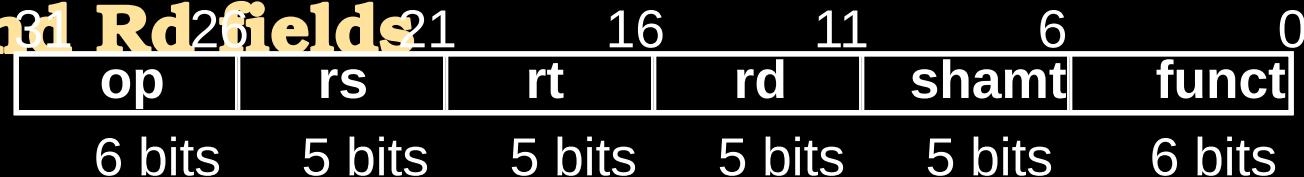
- **The common RTL operations**

- **Fetch the Instruction:** $\text{mem}[\text{PC}]$
- **Update the program counter:**
 - **Sequential Code:** $\text{PC} \leftarrow \text{PC} + 4$
 - **Branch and Jump:** $\text{PC} \leftarrow \text{"something else"}$



3b: Add & Subtract

- $R[rd] = R[rs] \text{ op } R[rt]$ (addu rd, rs, rt)
 - **Ra, Rb, and Rw come from instruction's Rs, Rt, and Rd fields**
 - **ALUctr and RegWr: control logic after decoding the instruction**



- ... Already defined the register file & ALU

Peer Instruction

- 1) We should use the main ALU to compute $PC=PC+4$
- 2) The ALU is inactive for memory reads or writes.

	12
a)	FF
b)	FT
c)	TF
d)	TT

How to Design a Processor: step-by-step

- 1. Analyze instruction set architecture (ISA)
⇒ datapath **requirements**
 - meaning of each instruction is given by the **register transfers**
 - datapath must include storage element for ISA registers
 - datapath must support each register transfer
- 2. Select set of datapath components and establish clocking methodology
- 3. Assemble datapath meeting requirements
- 4. Analyze implementation of each instruction to determine setting of control points that effects the register transfer.
- 5. Assemble the control logic (hard part!)

Lecture 21

CPU Design: Designing a Single-cycle CPU, pt 2



2020-10-19

How to Design a Processor: step-by-step

1. Analyze instruction set architecture (ISA) => datapath requirements

- meaning of each instruction is given by the *register transfers*
- datapath must include storage element for ISA registers
- datapath must support each register transfer

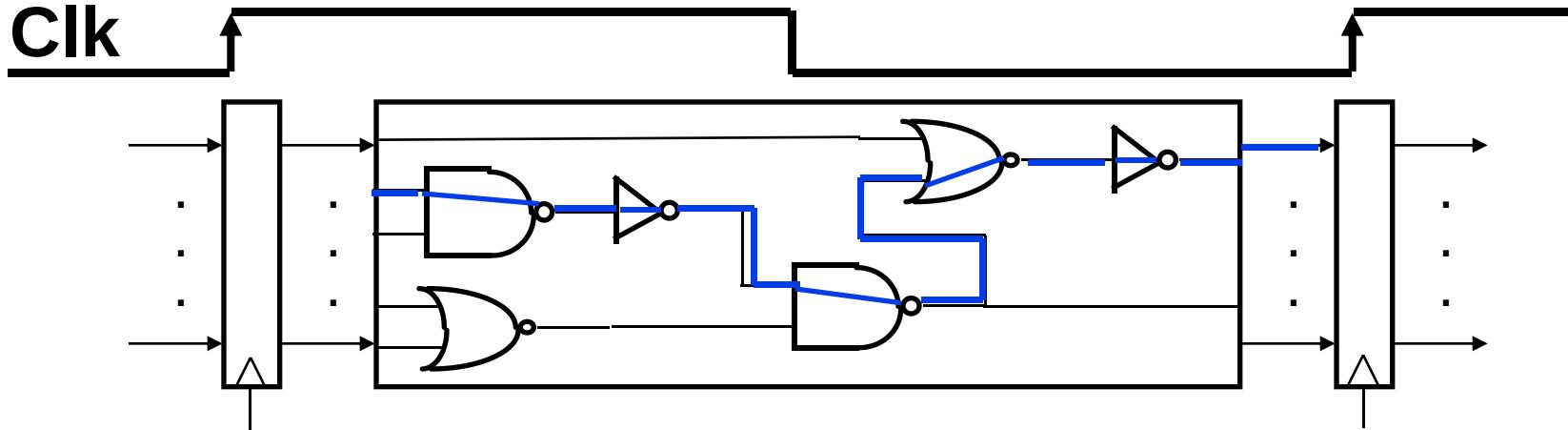
2. Select set of datapath components and establish clocking methodology

3. Assemble datapath meeting requirements

4. Analyze implementation of each instruction to determine setting of control points that effects the register transfer.

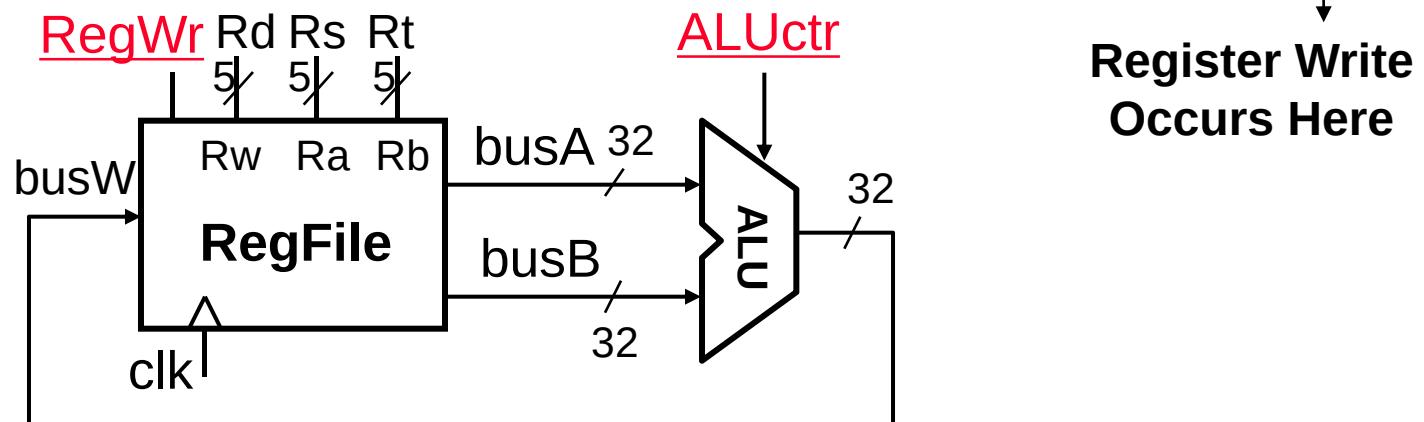
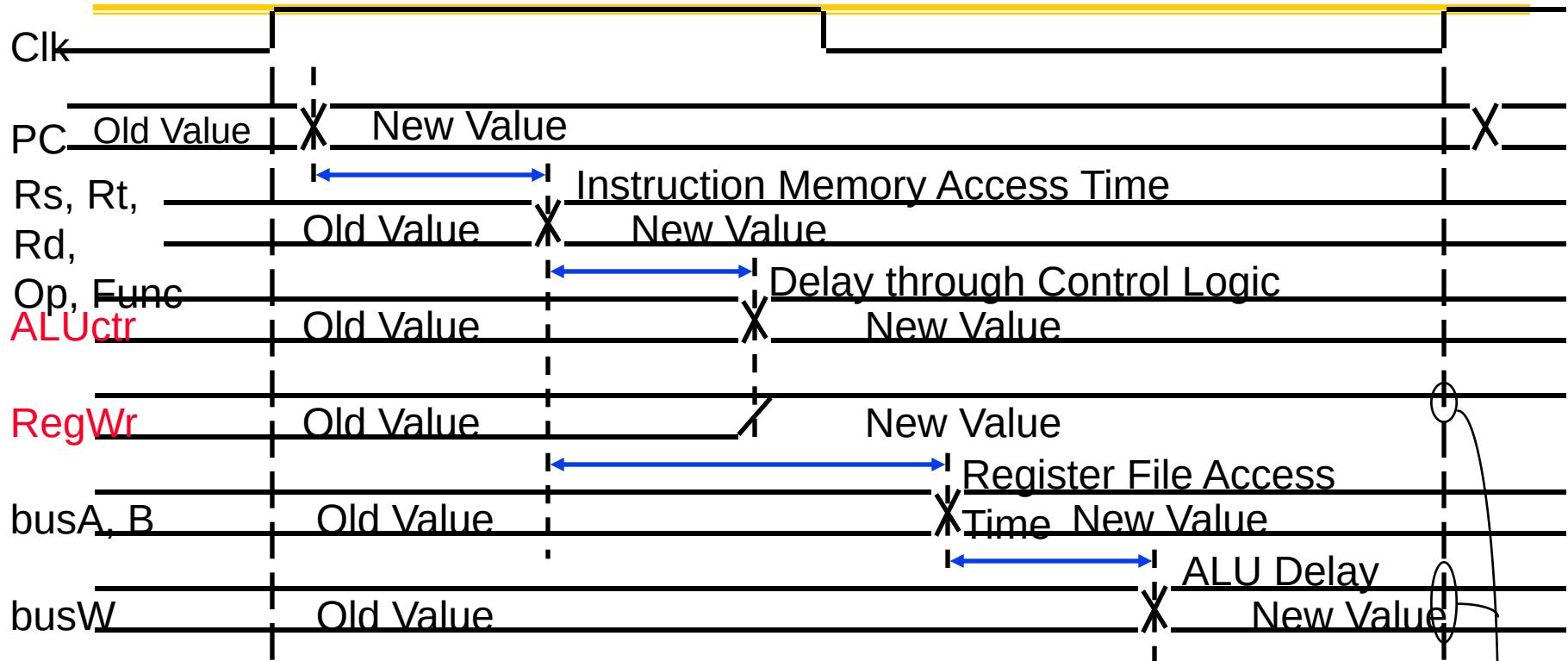
5. Assemble the control logic

Clocking Methodology



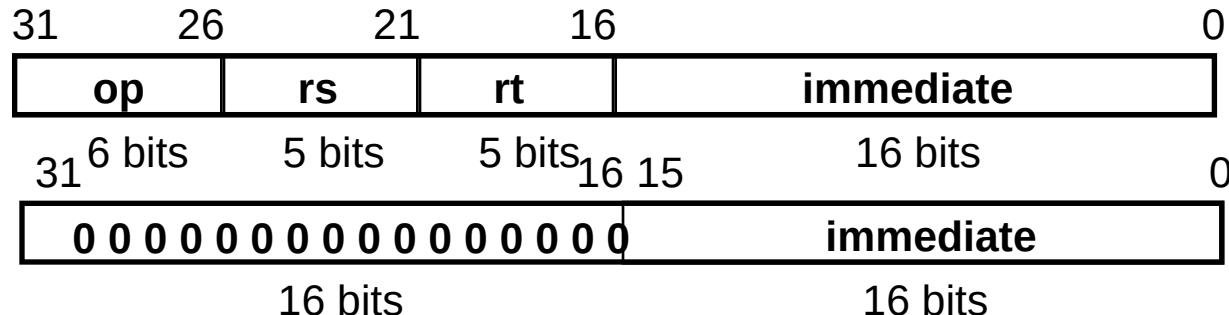
- Storage elements clocked by same edge
- Being physical devices, flip-flops (FF) and combinational logic have some delays
 - Gates: delay from input change to output change
 - Signals at FF D input must be stable before active clock edge to allow signal to travel within the FF (set-up time), and we have the usual clock-to-Q delay
- “Critical path” (longest path through logic) determines length of clock period

Register-Register Timing: One complete cycle

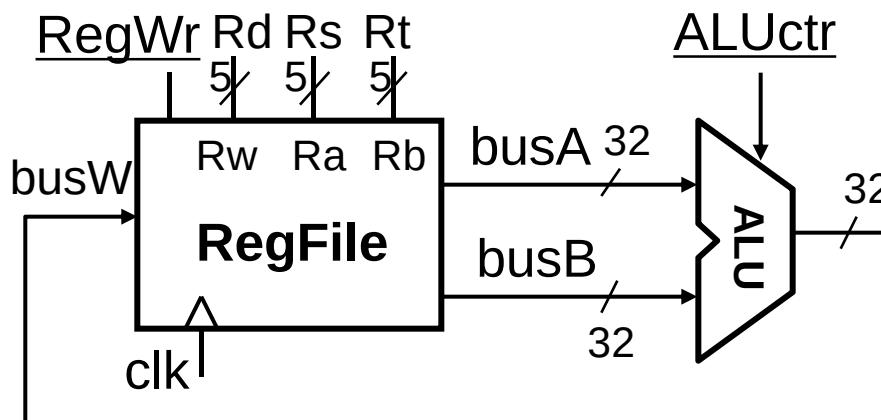


3c: Logical Operations with Immediate

- $R[\underline{rt}] = R[rs] \text{ op ZeroExt}[imm16]$

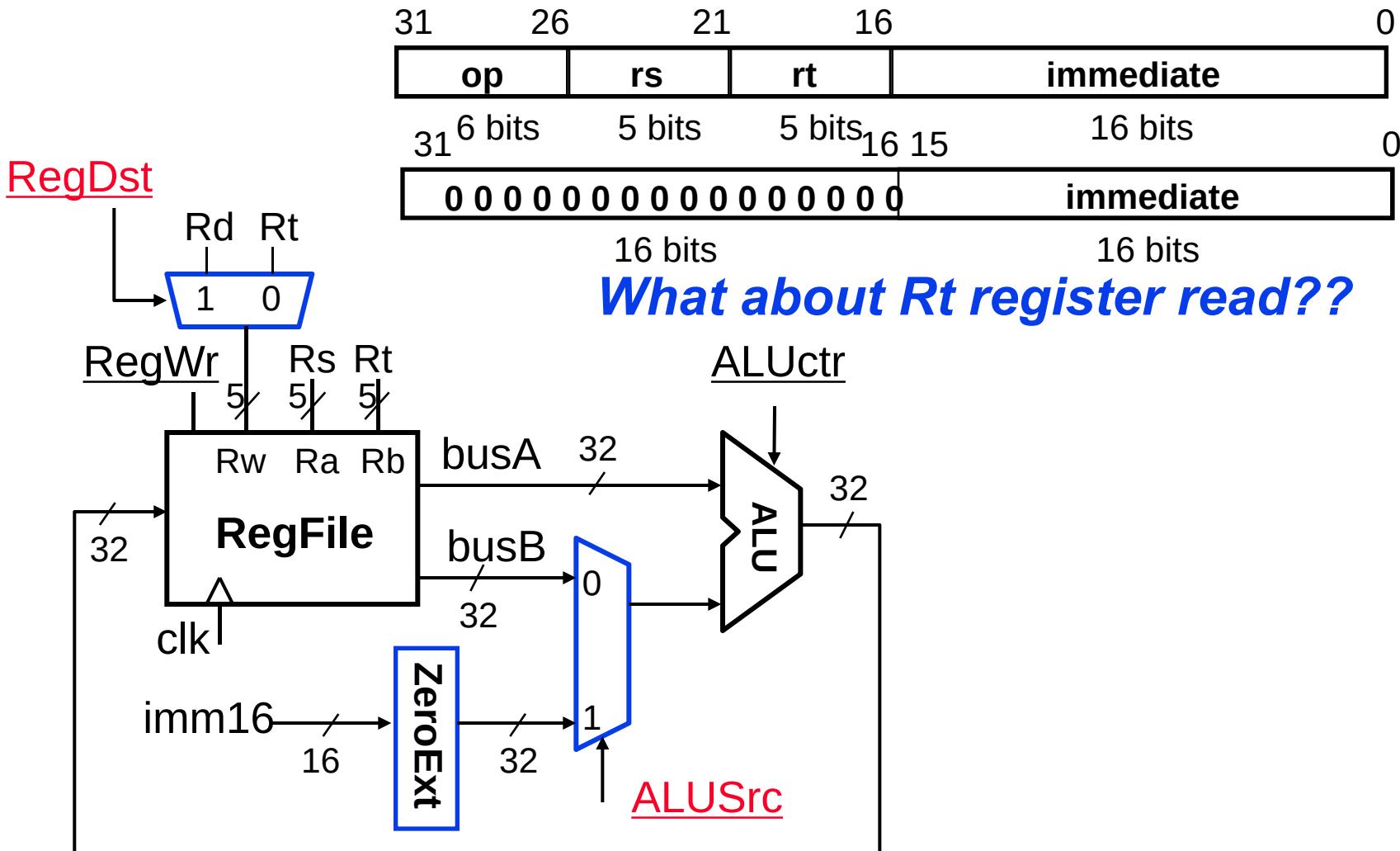


But we're writing to Rt register??



3c: Logical Operations with Immediate

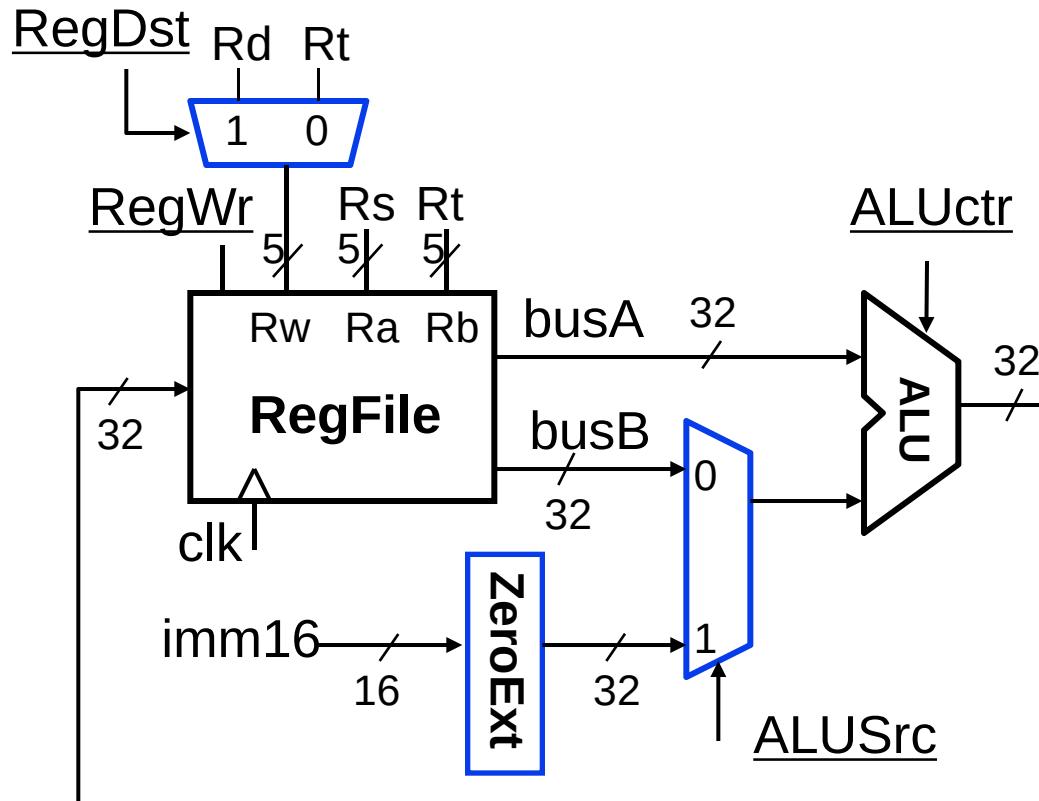
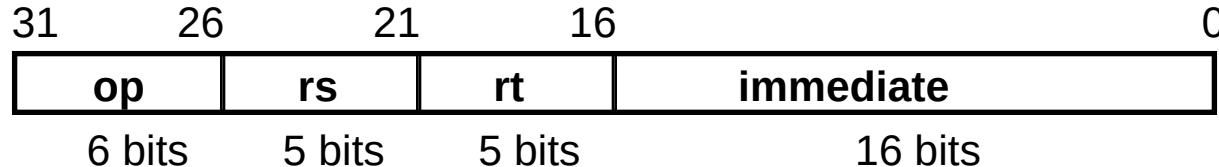
- $R[rt] = R[rs]$ op $\text{ZeroExt}[imm16]$



- Already defined 32-bit MUX; Zero Ext?

3d: Load Operations

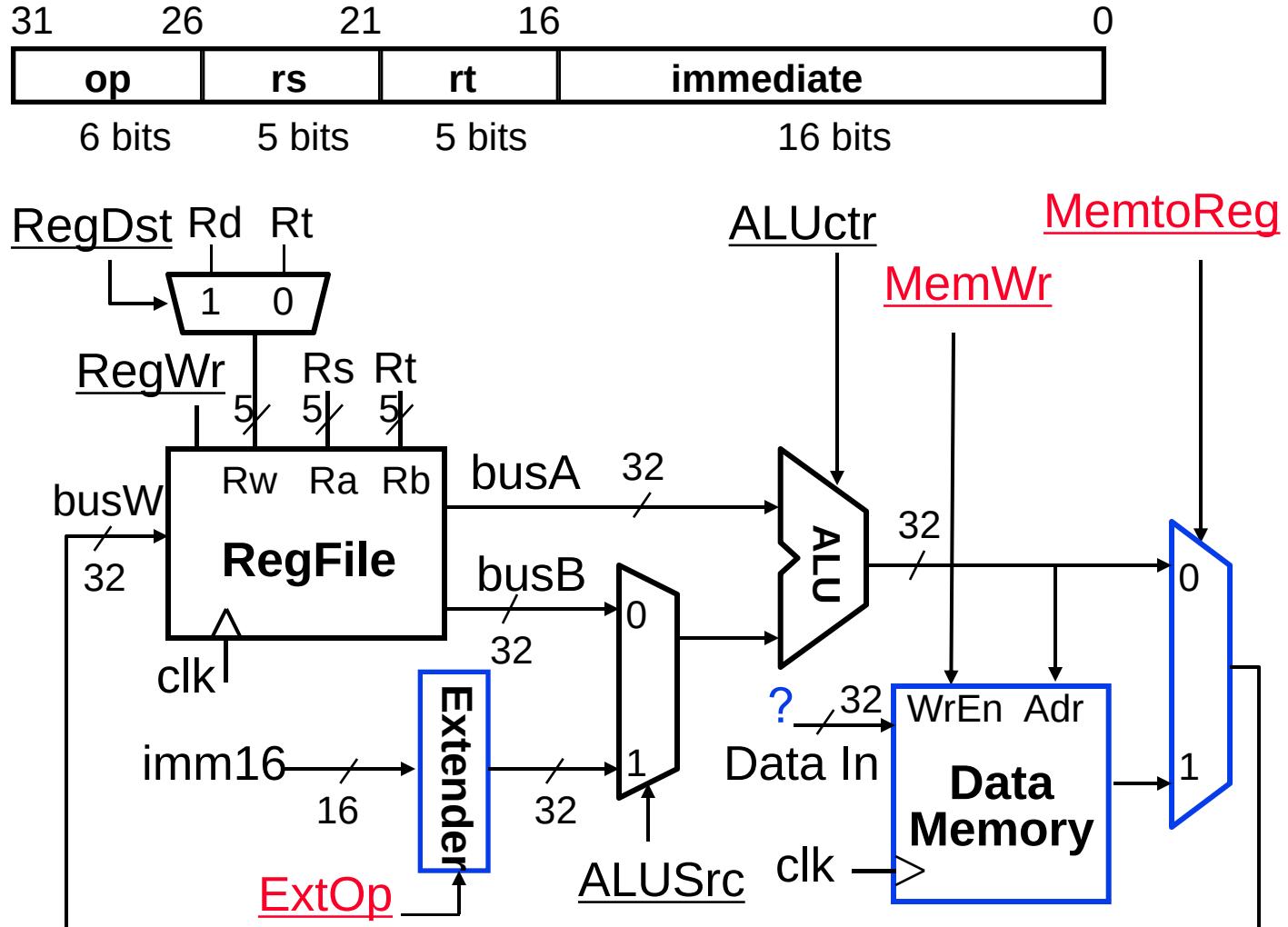
- $R[\underline{rt}] = \text{Mem}[R[rs] + \text{SignExt}[imm16]]$
- Example: `lw rt, rs, imm16`



3d: Load Operations

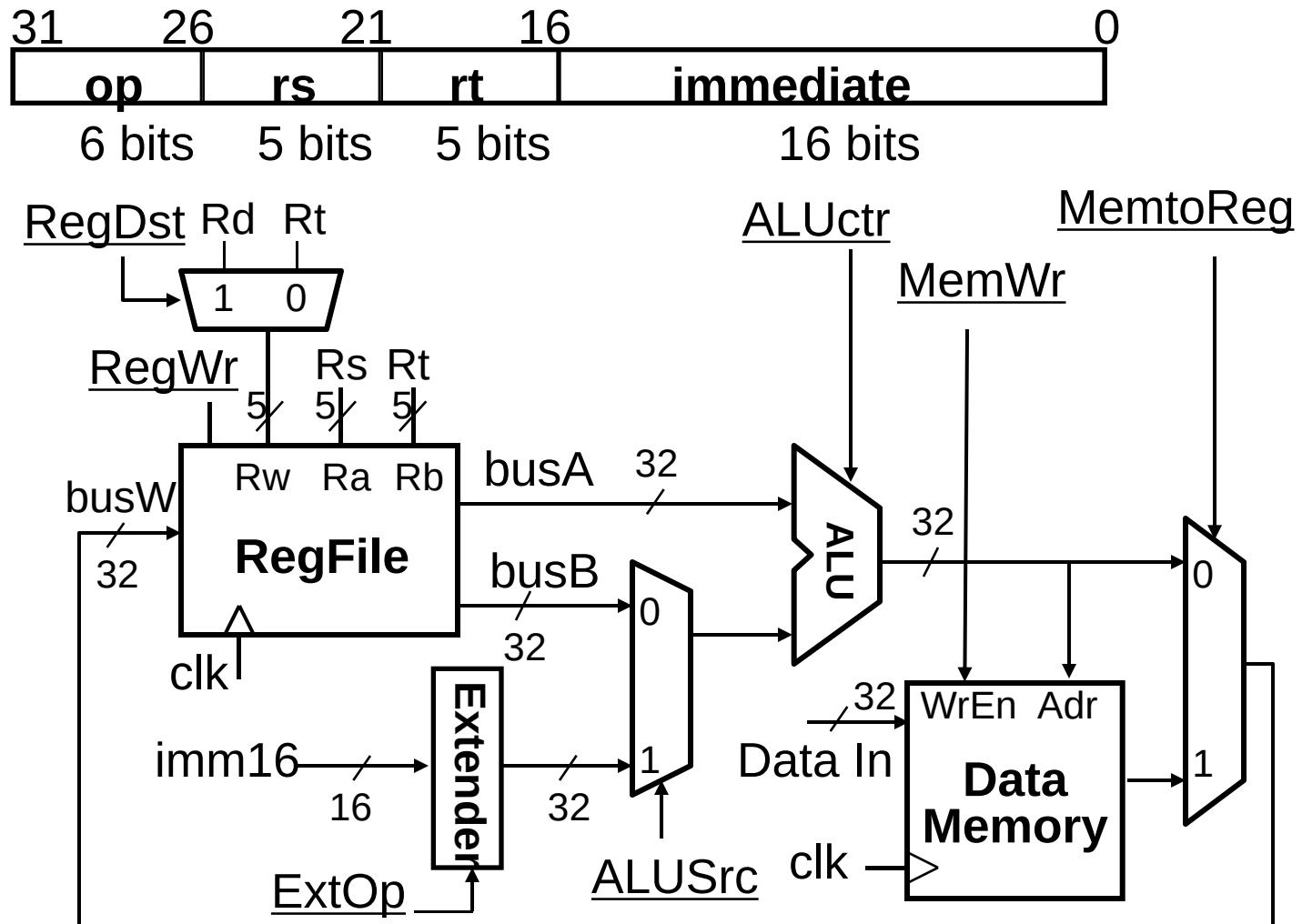
- $R[rt] = \text{Mem}[R[rs]] + \text{SignExt}[imm16]$

Example: `lw rt, rs, imm16`



3e: Store Operations

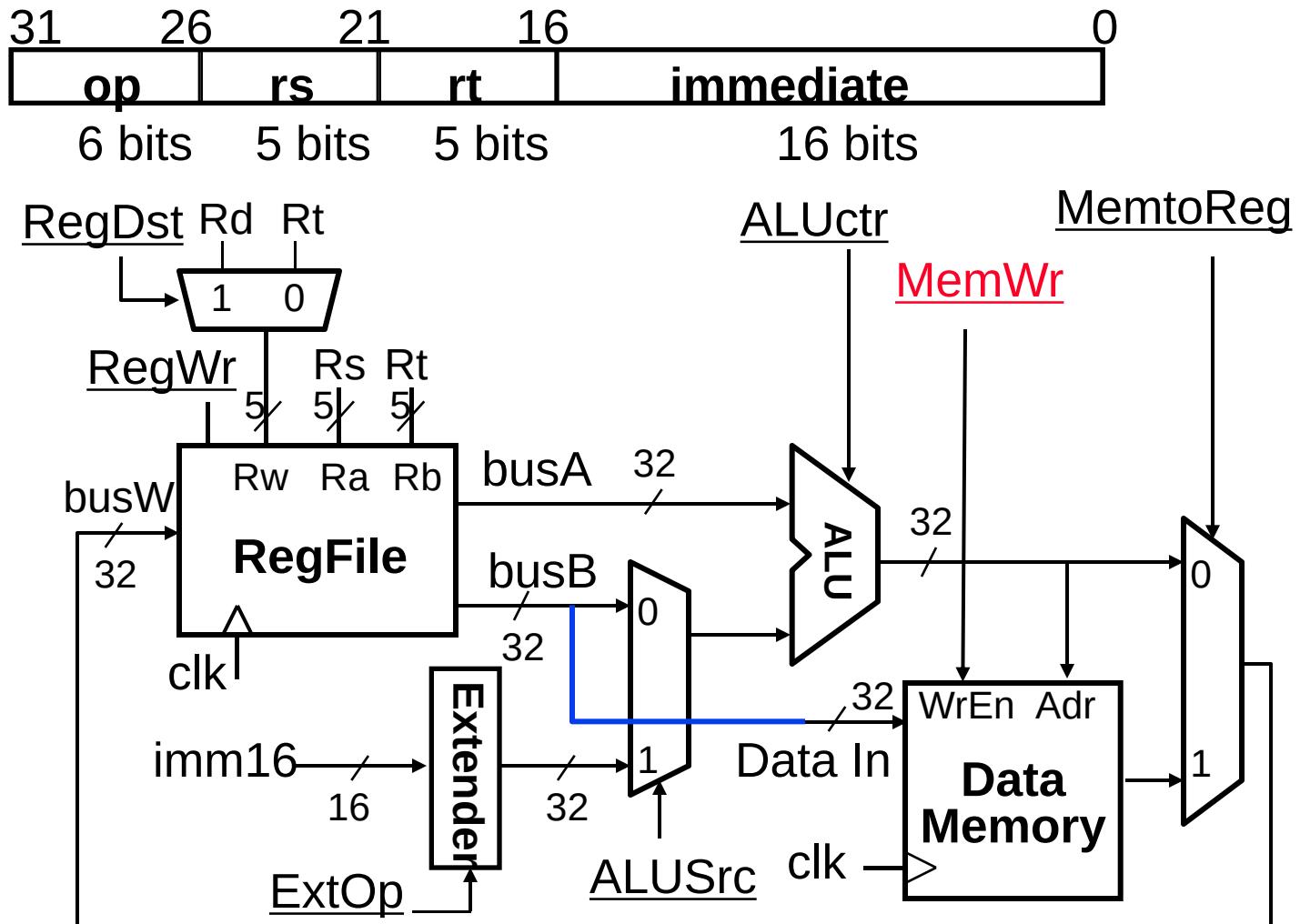
- **Mem[R[rs] + SignExt[imm16]] = R[rt]**
Ex.: sw rt, rs, imm16



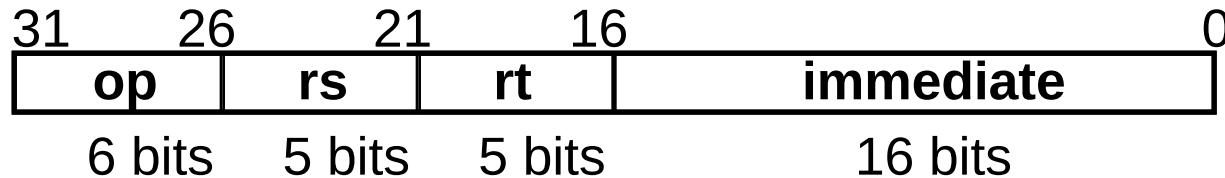
3e: Store Operations

- $\text{Mem}[R[\text{rs}] + \text{SignExt}[\text{imm16}]] = R[\text{rt}]$

Ex.: sw rt, rs, imm16



3f: The Branch Instruction



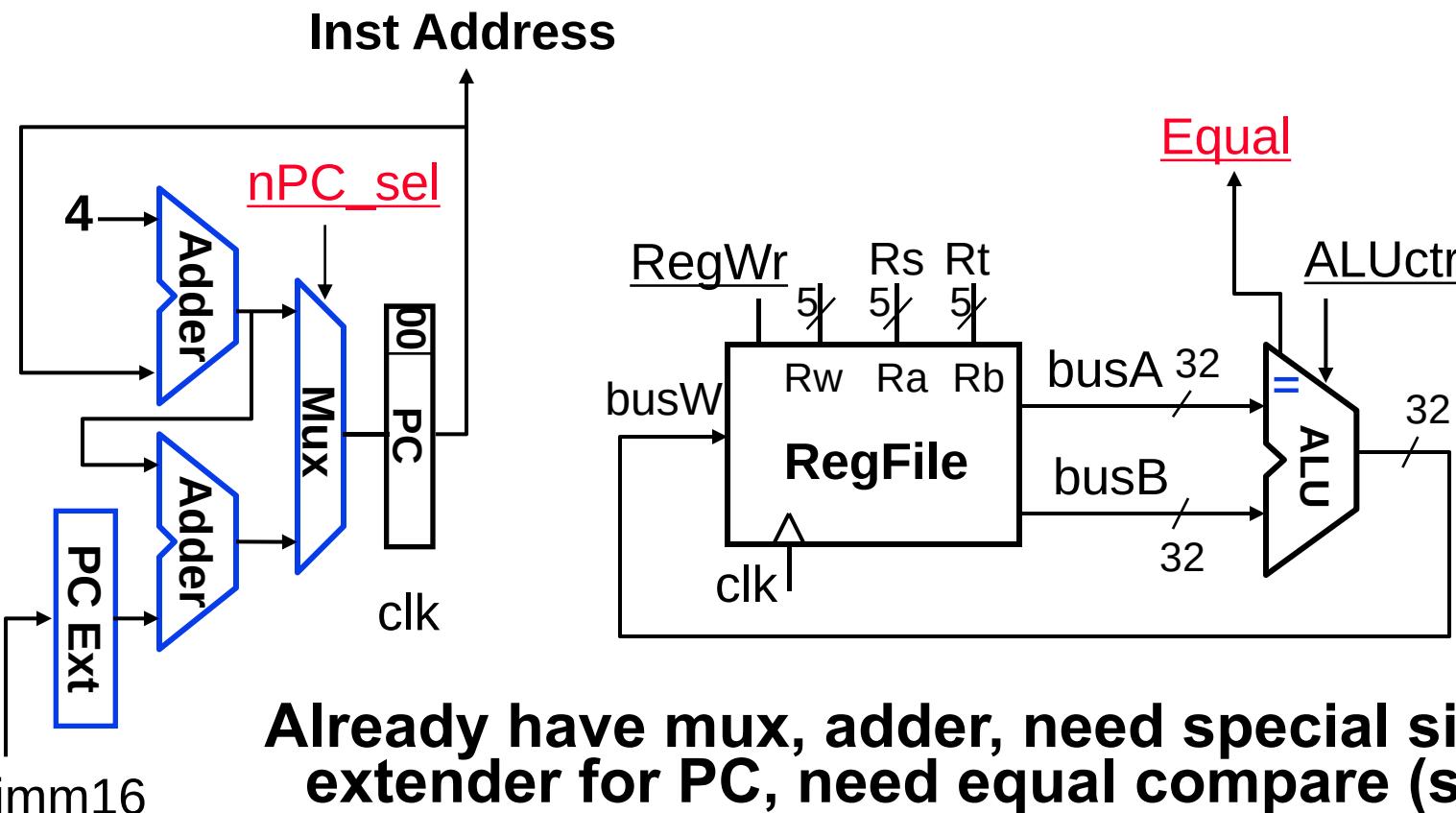
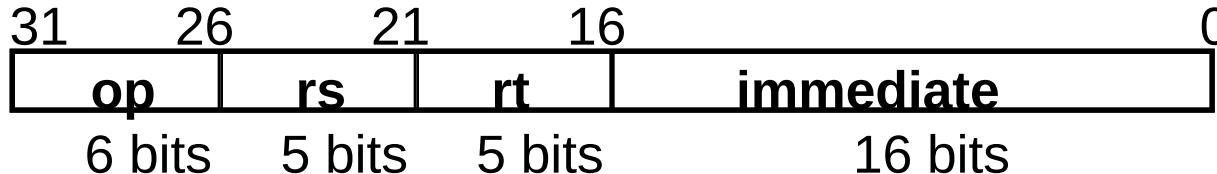
beq rs, rt, imm16

- **mem[PC]** Fetch the instruction from memory
- **Equal = R[rs] == R[rt]** Calculate branch condition
- **if (Equal)** Calculate the next instruction's address
 - $\text{PC} = \text{PC} + 4 + (\text{SignExt}(\text{imm16}) \times 4)$
- **else**
 - $\text{PC} = \text{PC} + 4$

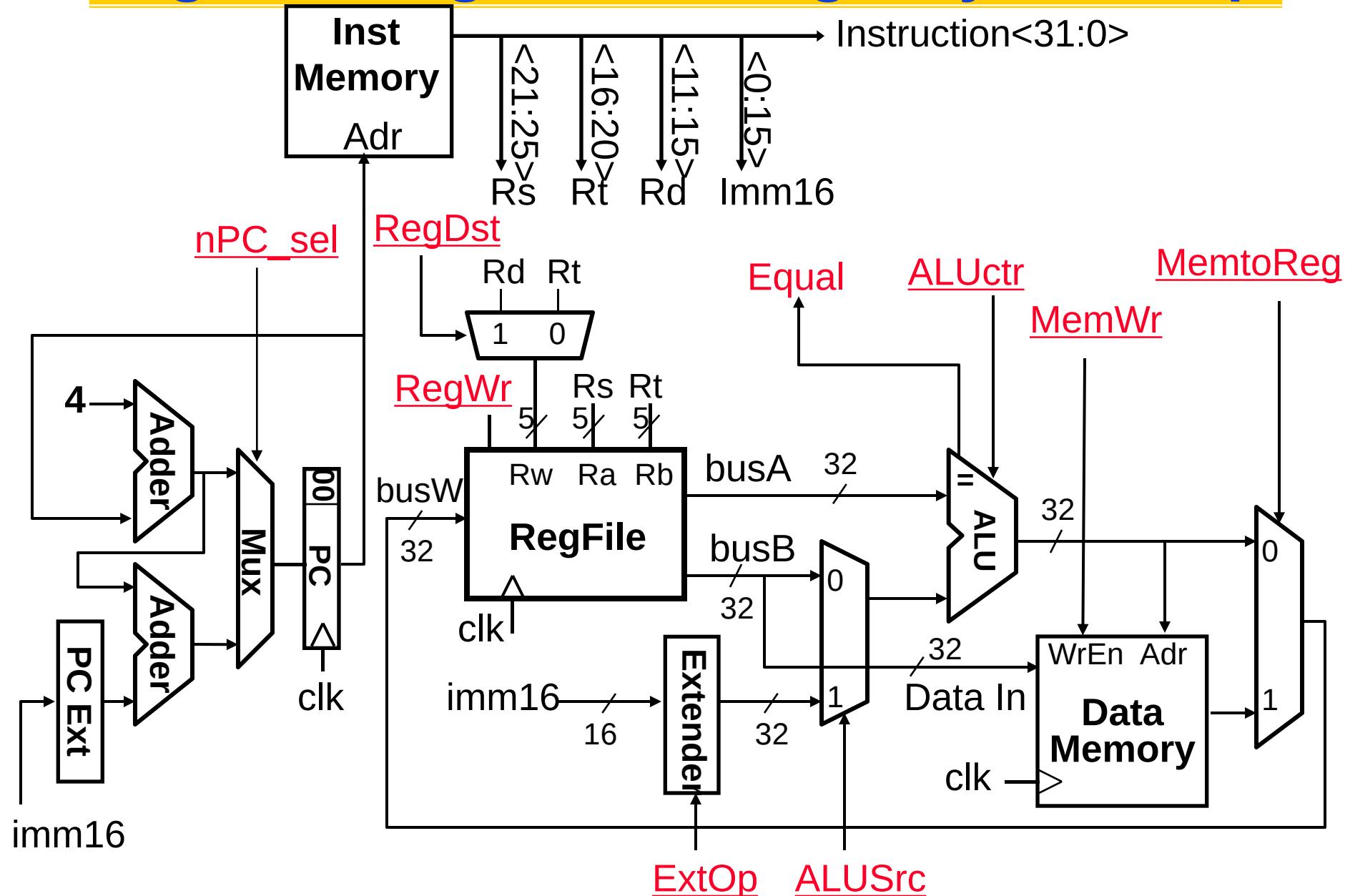
Datapath for Branch Operations

- **beq rs, rt, imm16**

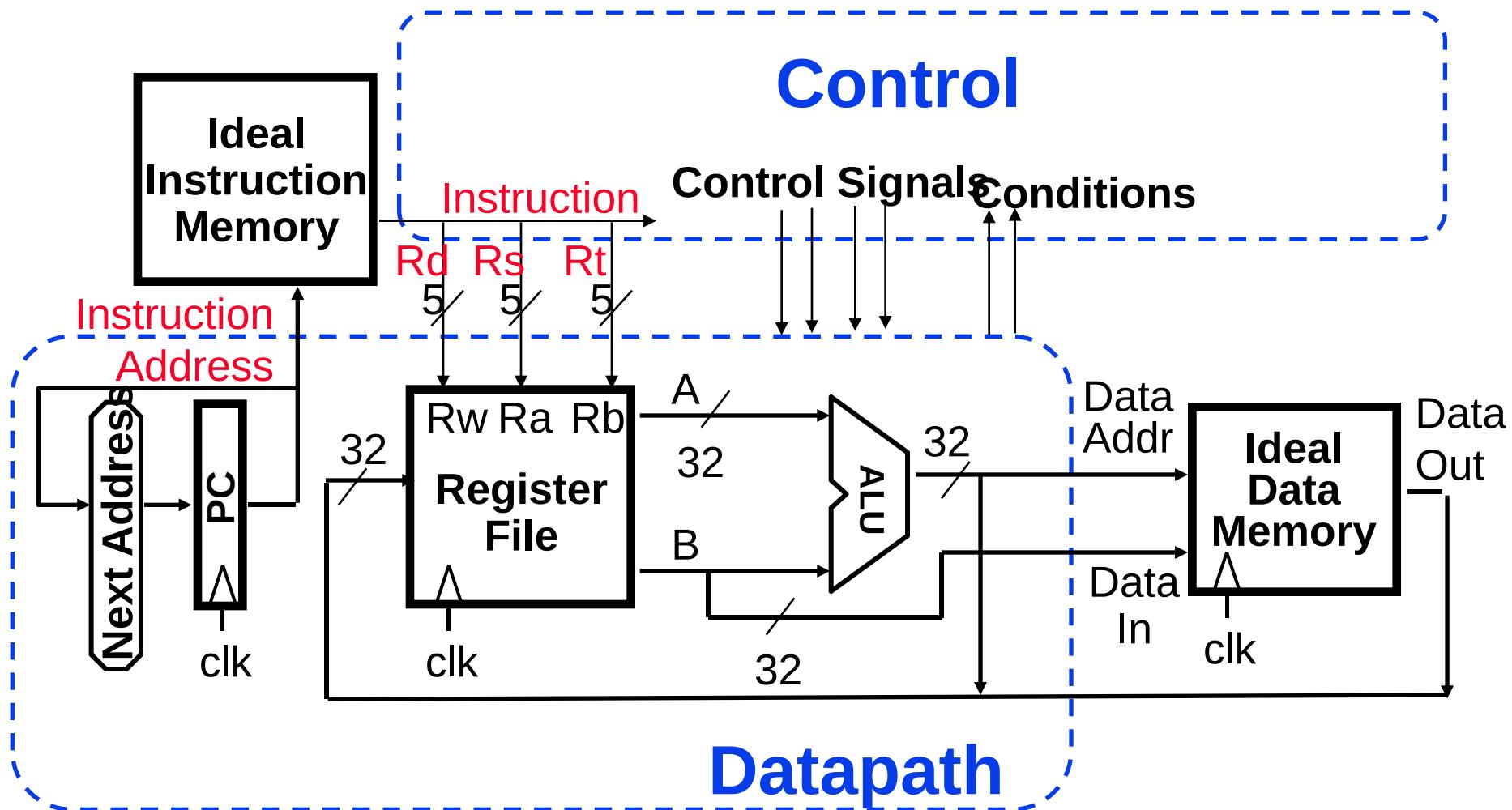
Datapath generates condition (equal)



Putting it All Together: A Single Cycle Datapath

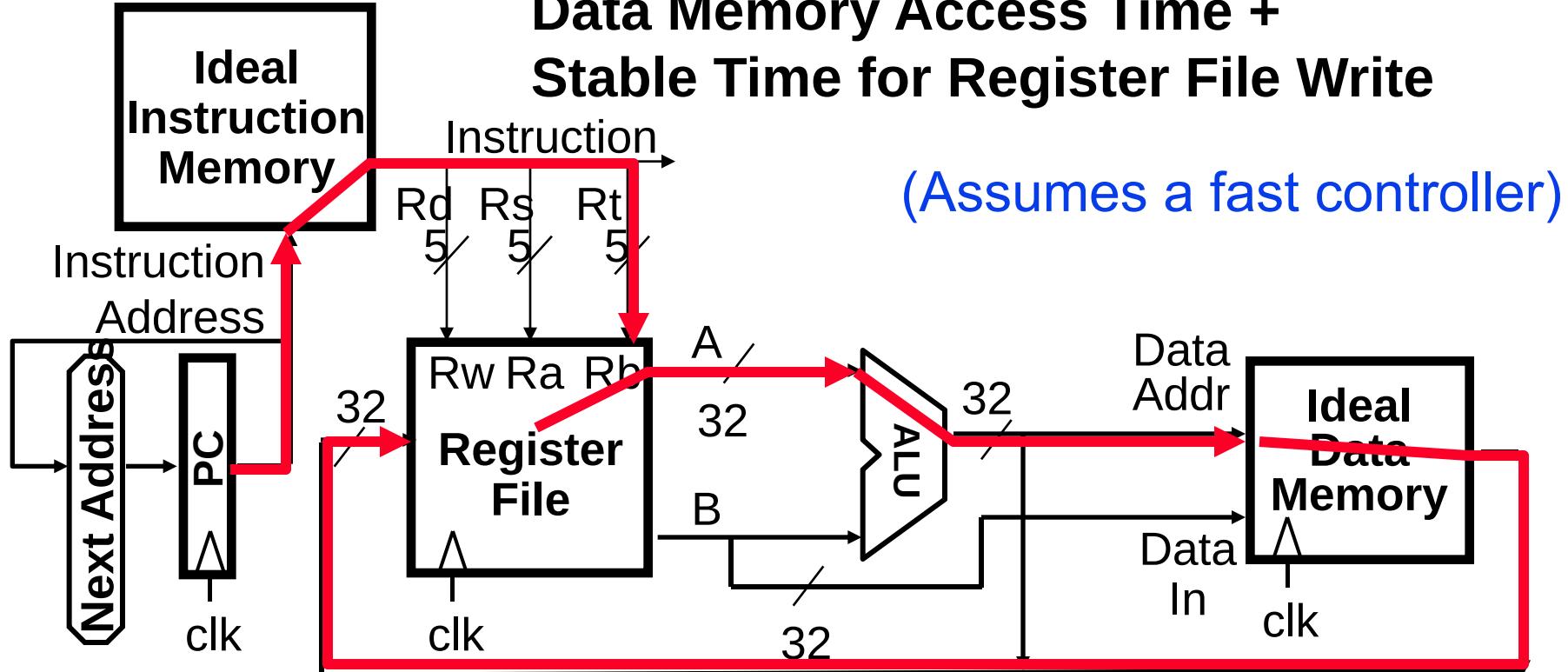


An Abstract View of the Implementation



An Abstract View of the Critical Path

Critical Path (Load Instruction) =
Delay clock through PC (FFs) +
Instruction Memory's Access Time +
Register File's Access Time, +
ALU to Perform a 32-bit Add +
Data Memory Access Time +
Stable Time for Register File Write



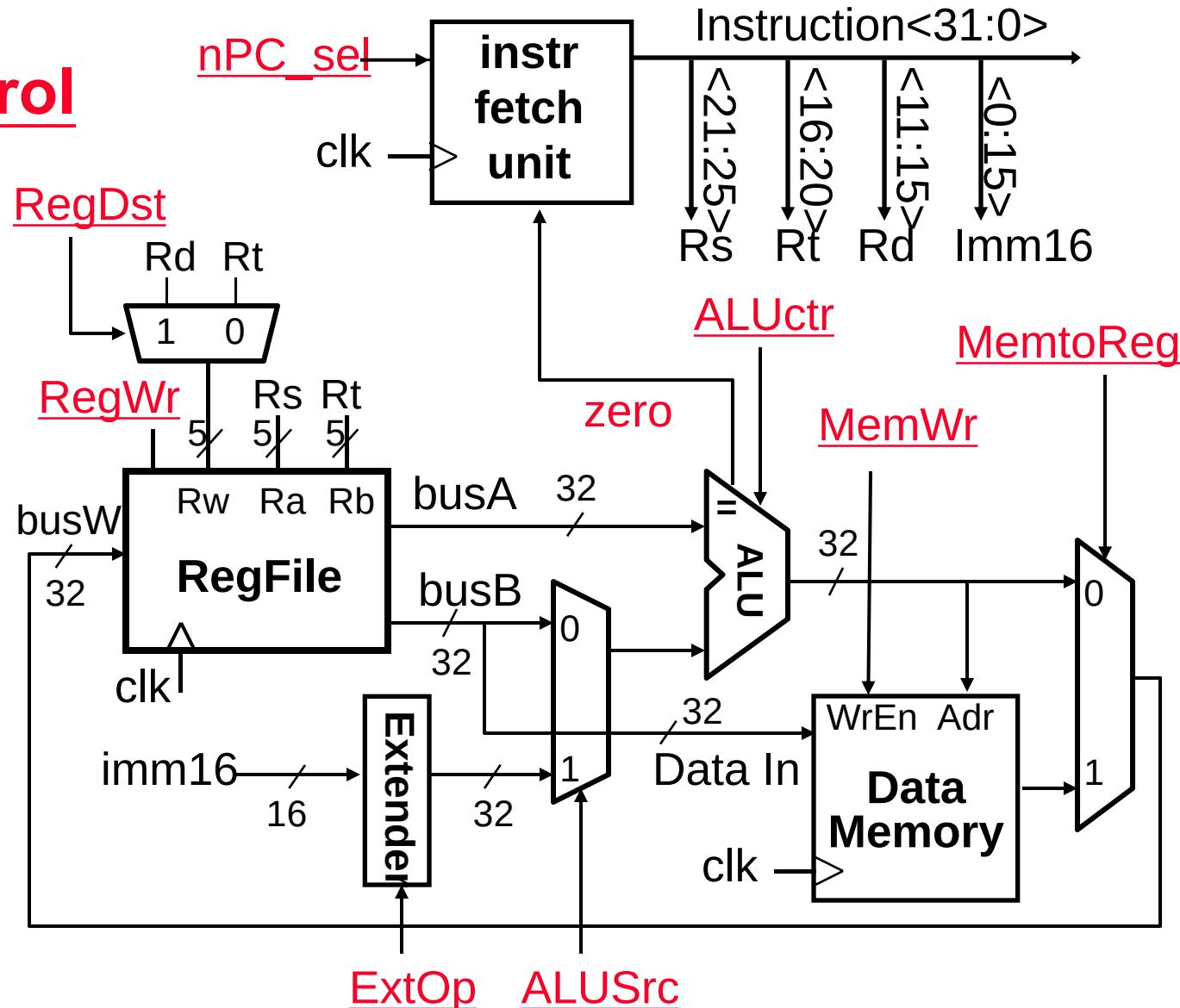
Peer Instruction

- 1) In the worst case, the delay is the memory access time**
- 2) With only changes to control, our datapath could write to memory and registers in one cycle.**

	12
a)	FF
b)	FT
c)	TF
d)	TT

Summary: A Single Cycle Datapath

- We have everything except control signals



0.23 Single Cycle CPU Control

Computer Architecture (计算机体系结构)

Lecture 22 Single-cycle CPU Control



2020-10-23

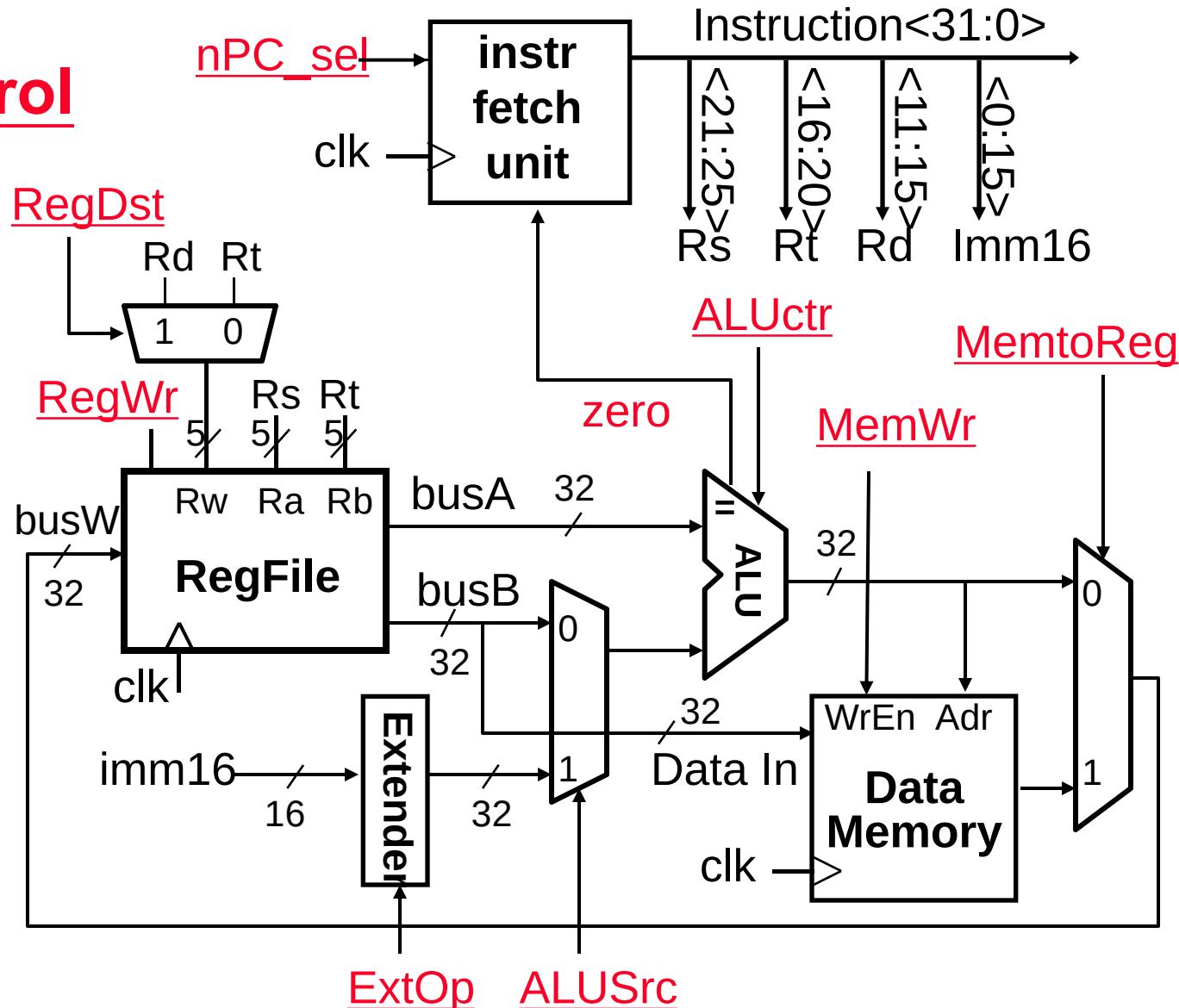
Lecturer Yuanqing Cheng
www.cadetlab.cn/~course

TSMC Sees HPC As Next Inflection Point



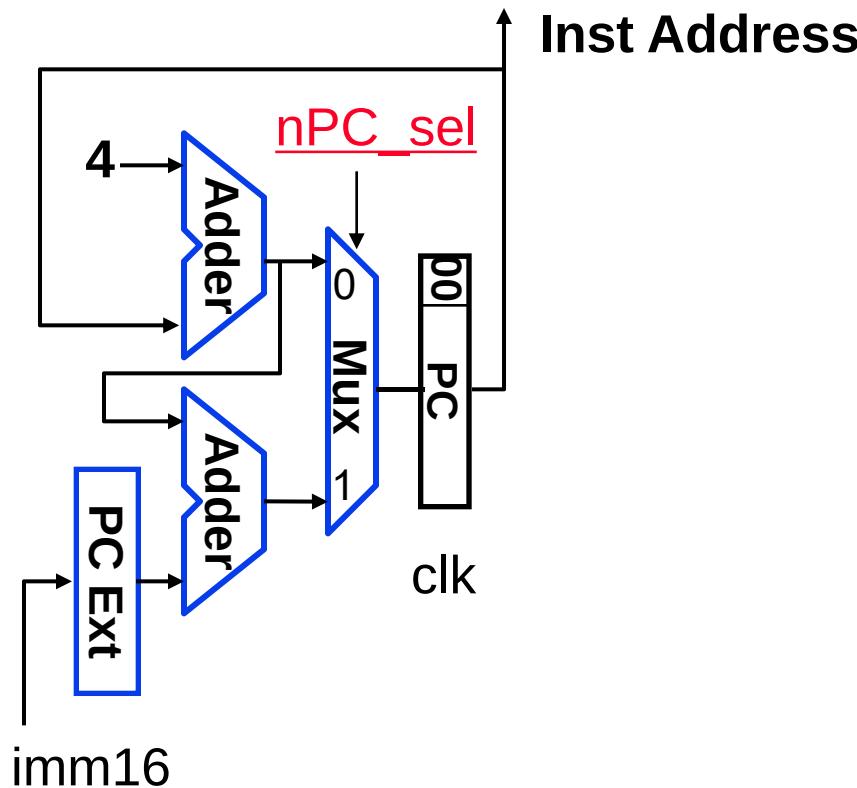
Review: A Single Cycle Datapath

- We have everything except control signals



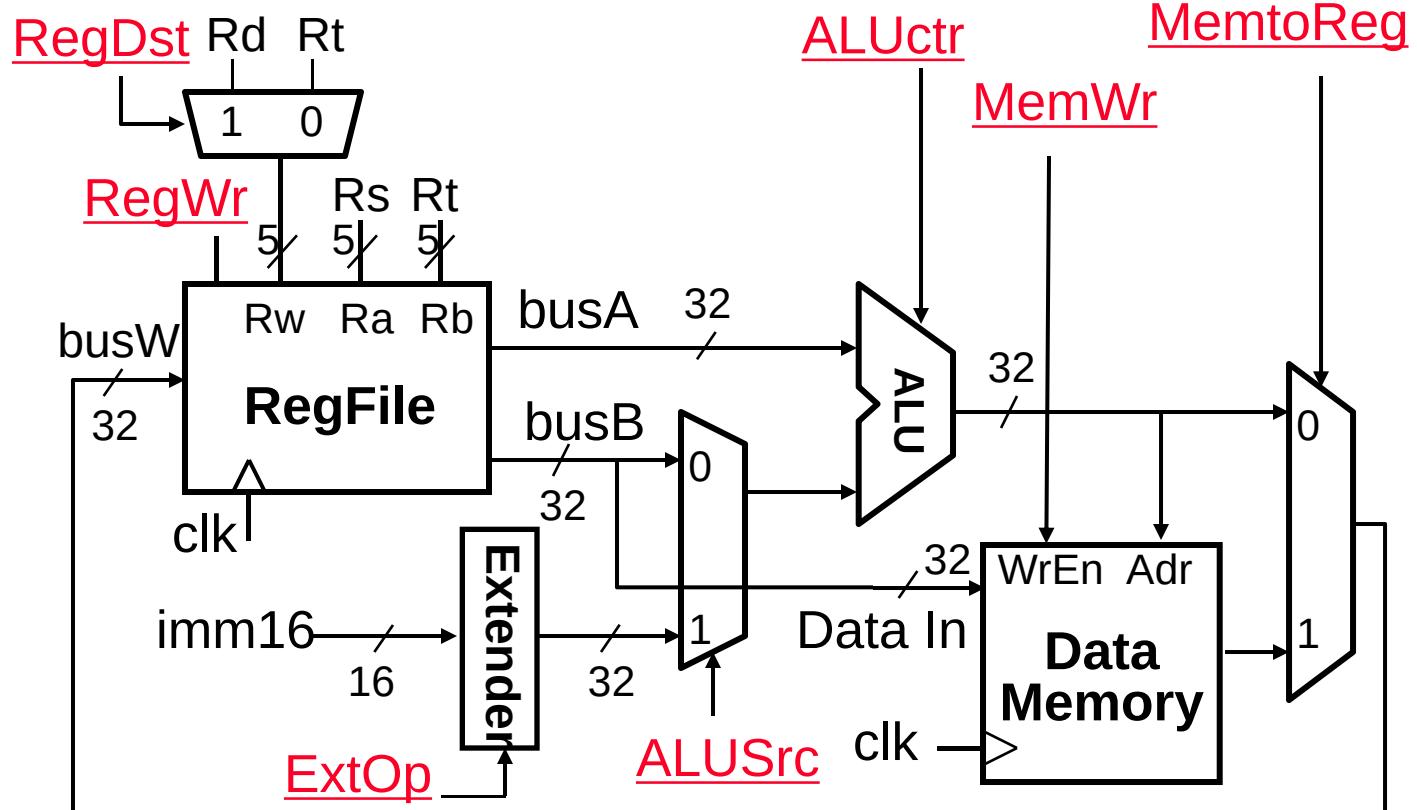
Recap: Meaning of the Control Signals

- **nPC_sel:**
“+4” 0 \Rightarrow PC \leftarrow PC + 4
“br” 1 \Rightarrow PC \leftarrow PC + 4 +
{SignExt(Im16) , 00 }
“n”=next
- Later in lecture: higher-level connection between mux and branch condition

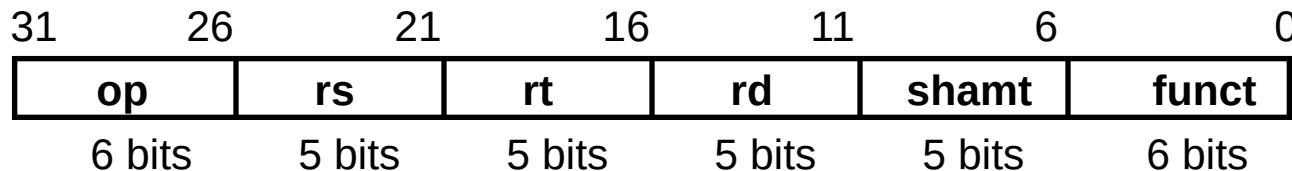


Recap: Meaning of the Control Signals

- **ExtOp:** “zero”, “sign”
 - **ALUsrc:** $0 \Rightarrow \text{regB}$; $1 \Rightarrow \text{immed}$
 - **ALUctr:** “ADD”, “SUB”, “OR”
- **MemWr:** $1 \Rightarrow \text{write memory}$
 - **MemtoReg:** $0 \Rightarrow \text{ALU}$; $1 \Rightarrow \text{Mem}$
 - **RegDst:** $0 \Rightarrow \text{"rt"}$; $1 \Rightarrow \text{"rd"}$
 - **RegWr:** $1 \Rightarrow \text{write register}$



RTL: The Add Instruction

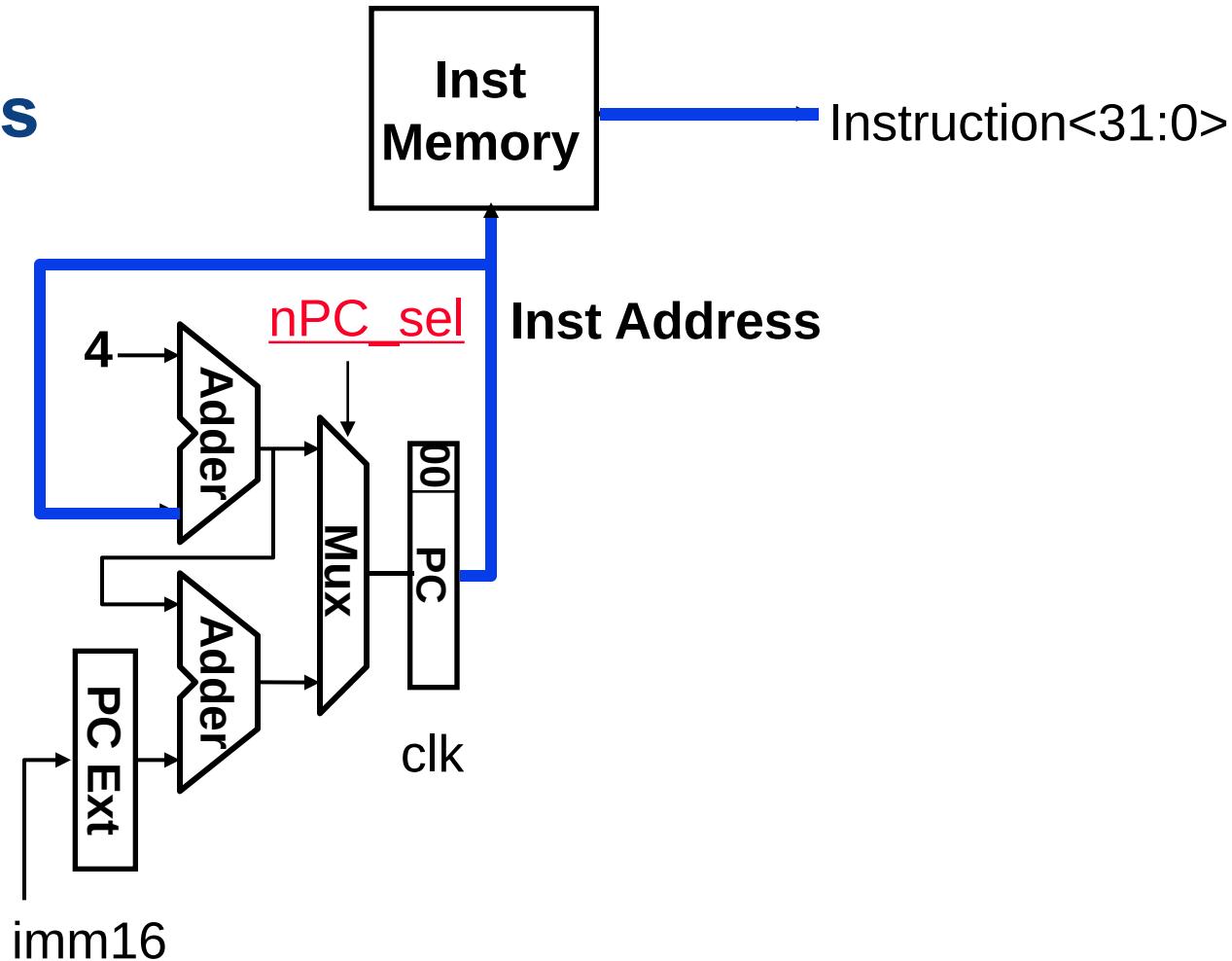


add rd, rs, rt

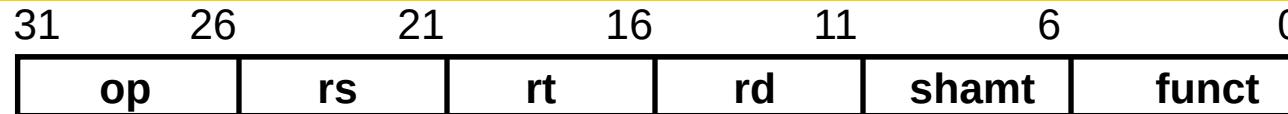
- **MEM[PC]** Fetch the instruction from memory
- **R[rd] = R[rs] + R[rt]** The actual operation
- **PC = PC + 4** Calculate the next instruction's address

Instruction Fetch Unit at the Beginning of Add

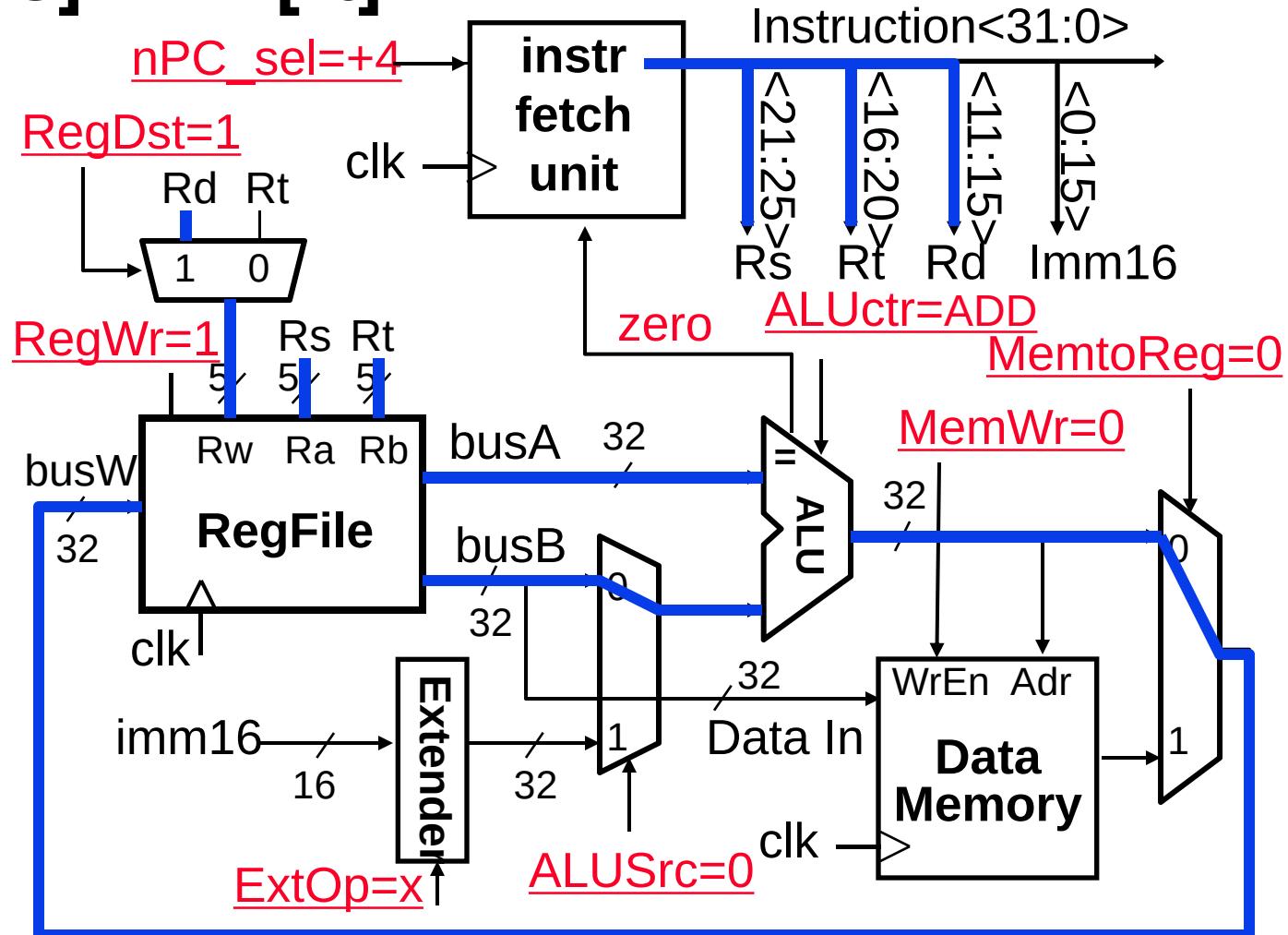
- Fetch the instruction from Instruction memory: $\text{Instruction} = \text{MEM}[\text{PC}]$
 - same for all instructions



The Single Cycle Datapath during Add



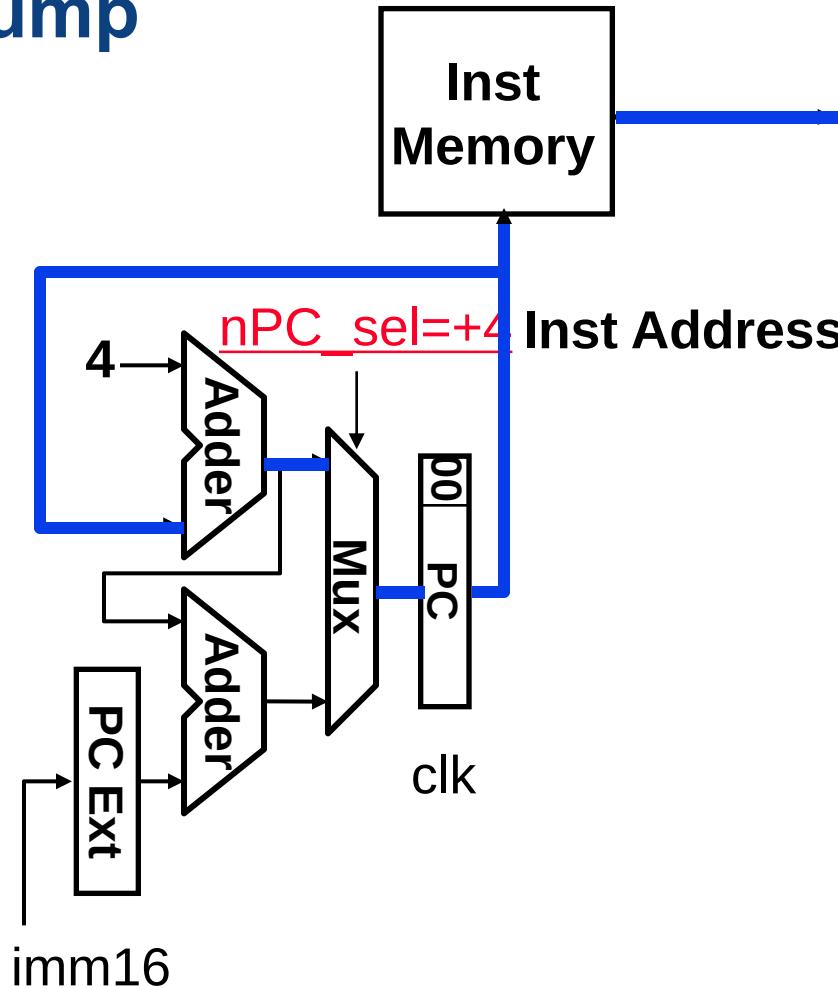
$$R[rd] = R[rs] + R[rt]$$



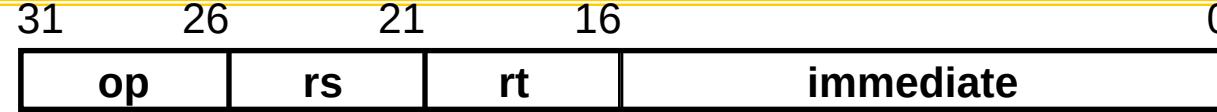
Instruction Fetch Unit at the End of Add

- $PC = PC + 4$

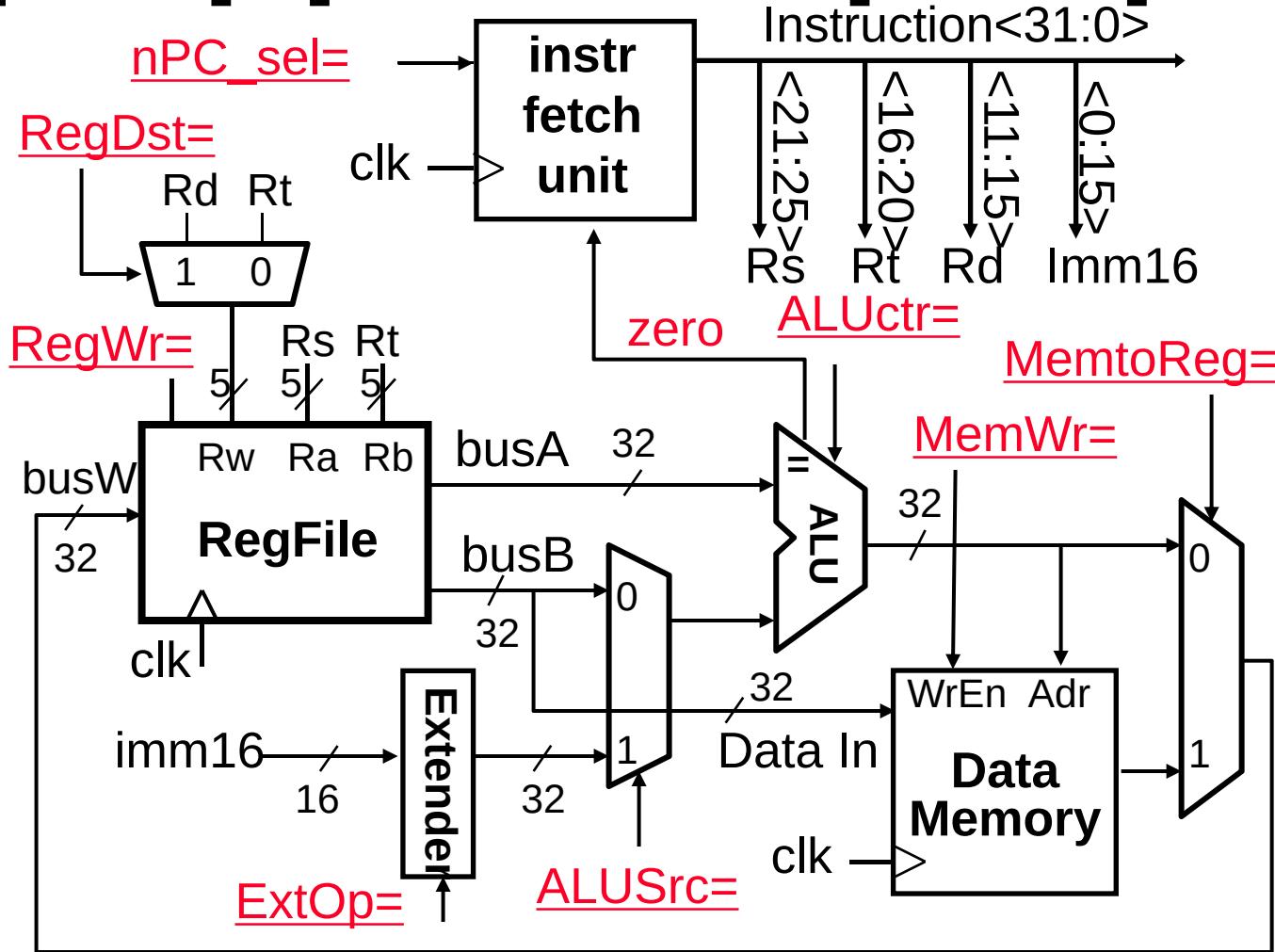
- This is the same for all instructions except:
Branch and Jump



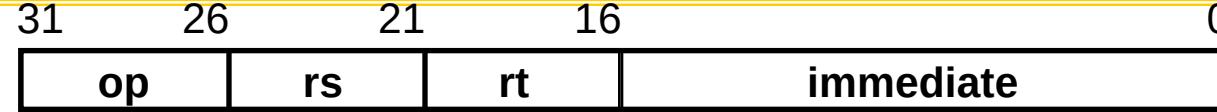
Single Cycle Datapath during Or Immediate?



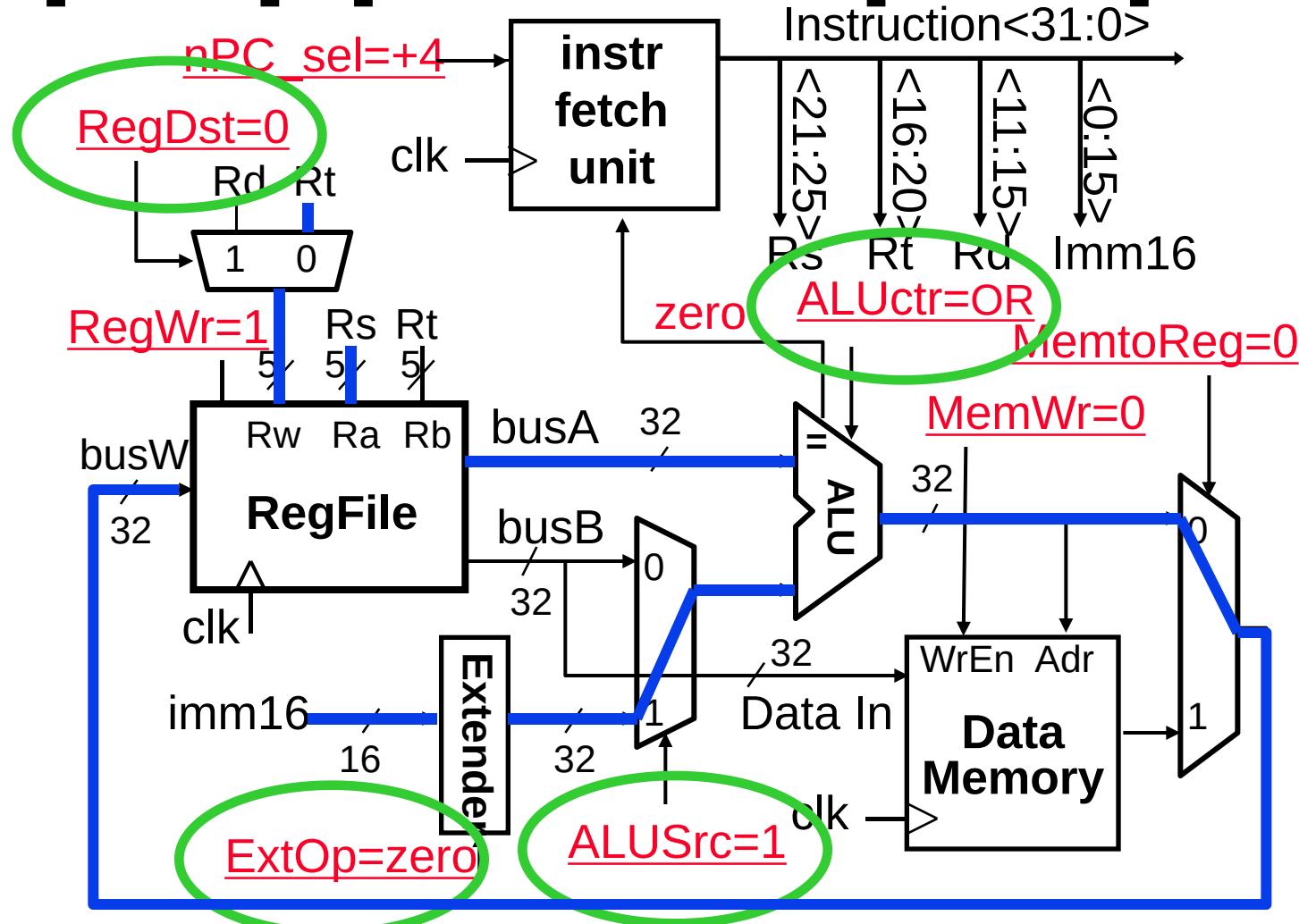
- $R[rt] = R[rs] \text{ OR } \text{ZeroExt}[Imm16]$



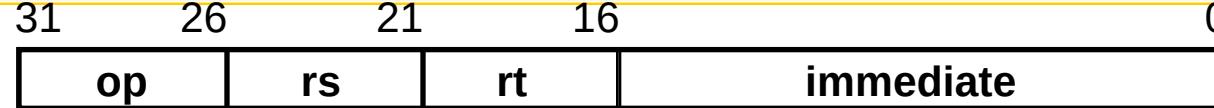
Single Cycle Datapath during Or Immediate?



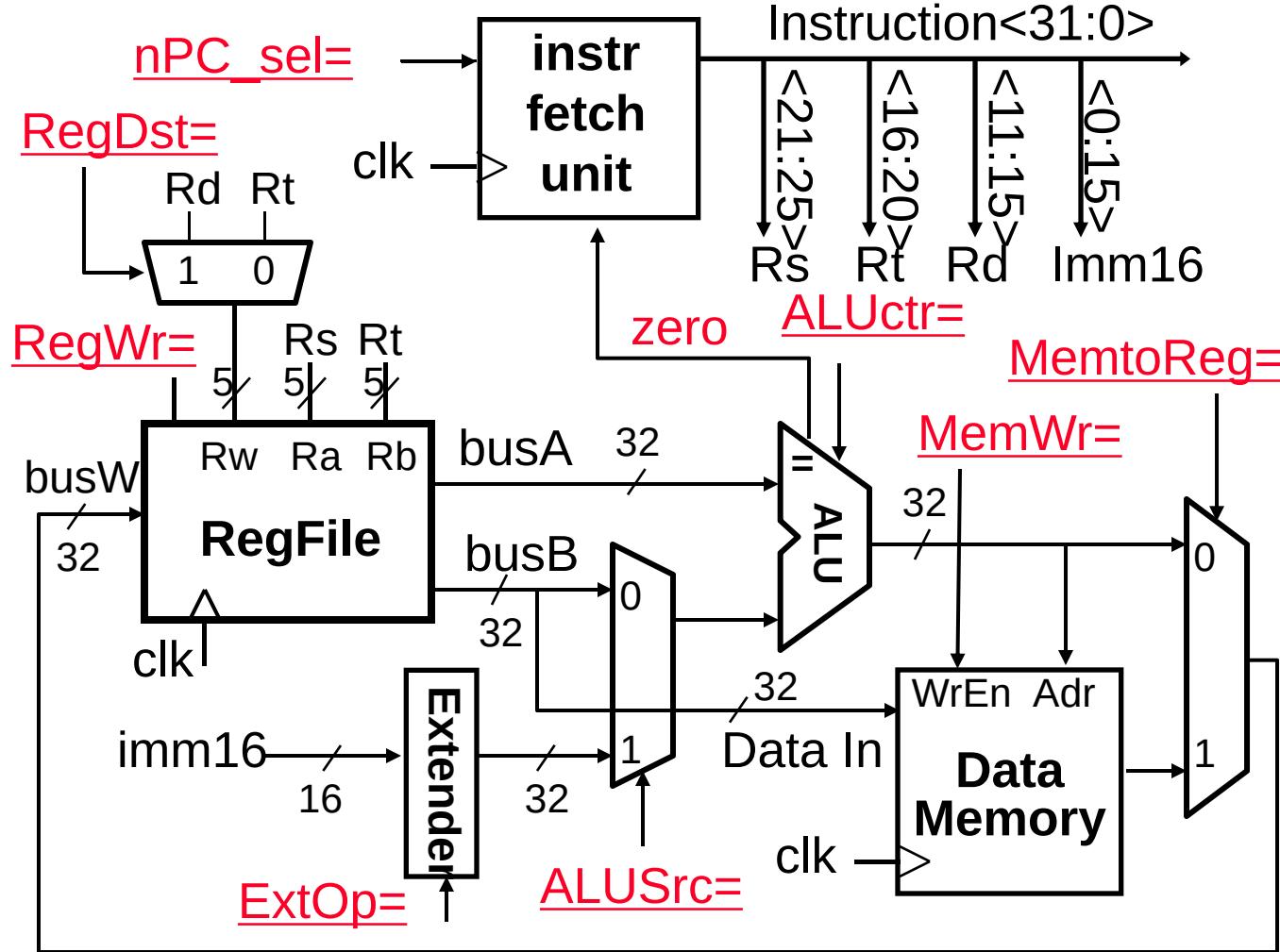
- $R[rt] = R[rs] \text{ OR } \text{ZeroExt}[Imm16]$



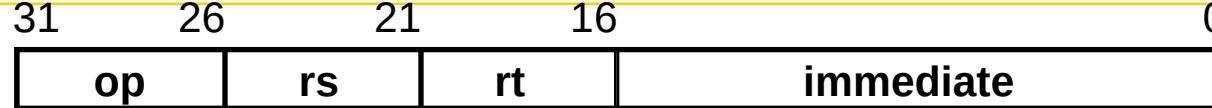
The Single Cycle Datapath during Load?



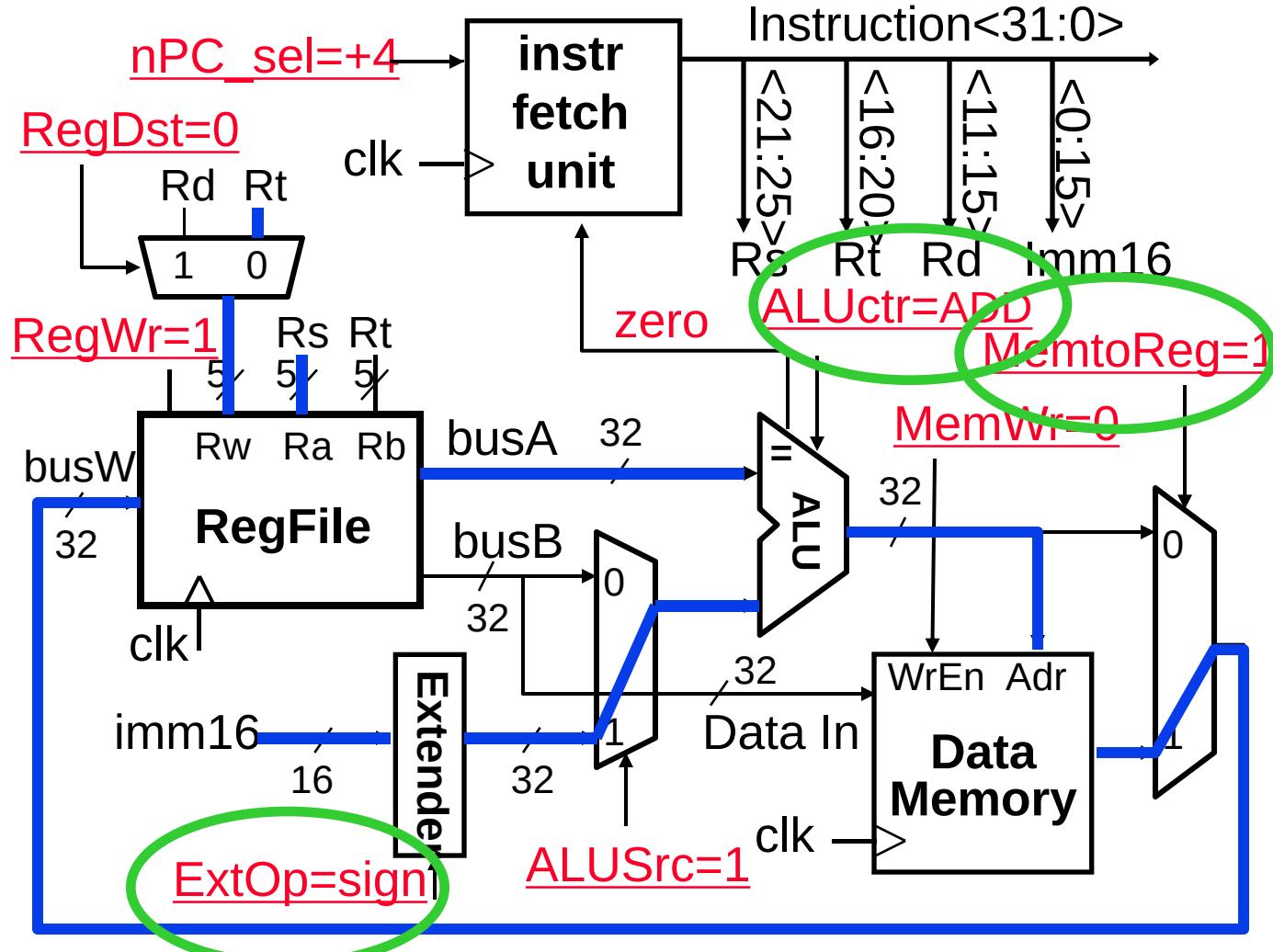
- $R[rt] = \text{Data Memory } \{R[rs] + \text{SignExt}[imm16]\}$



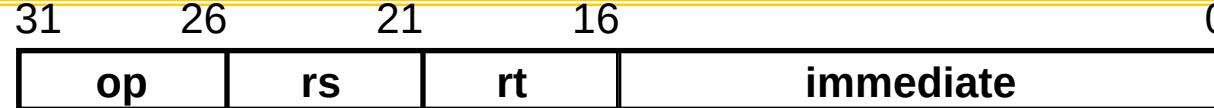
The Single Cycle Datapath during Load



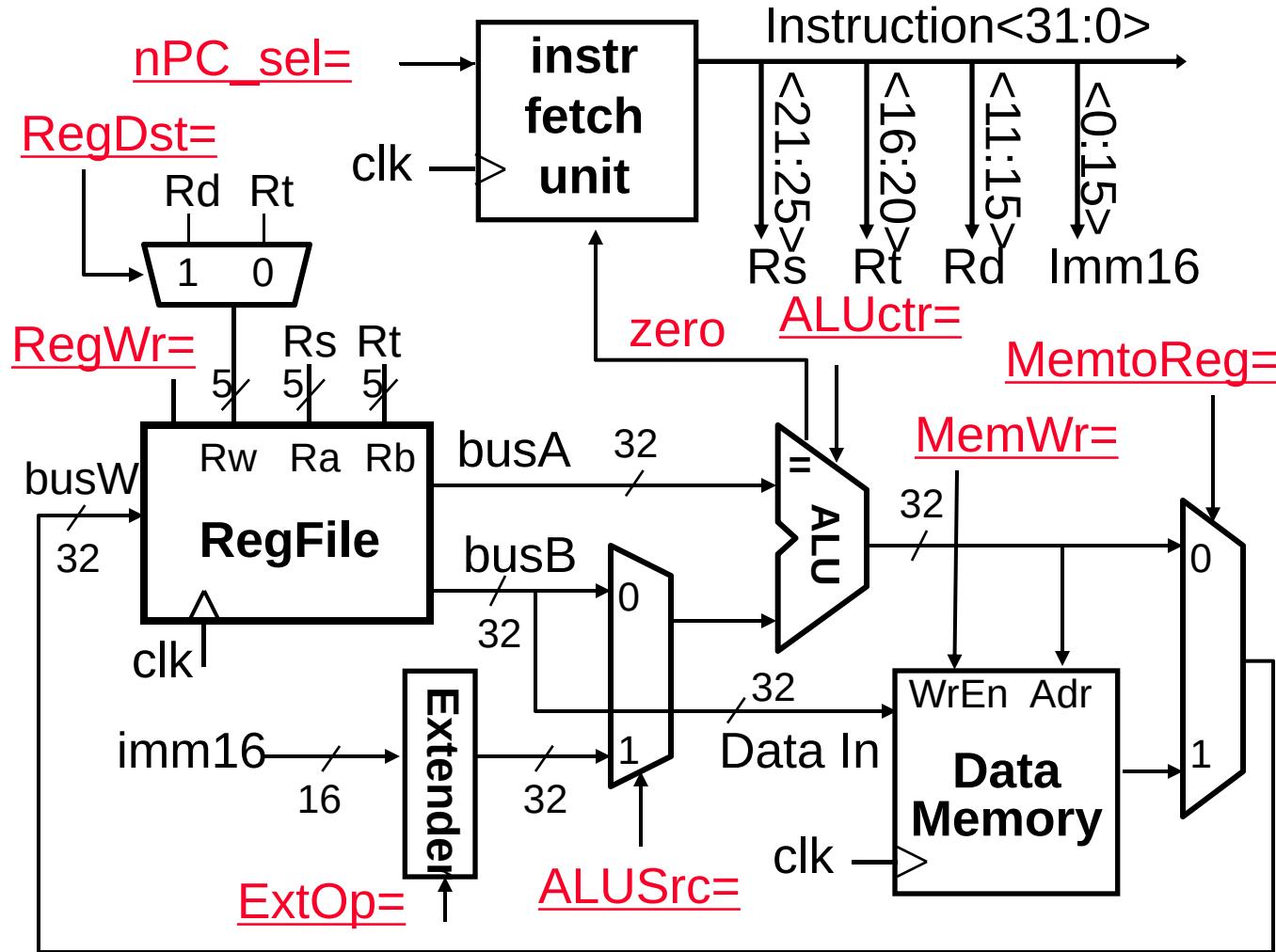
- $R[rt] = \text{Data Memory } \{R[rs] + \text{SignExt}[imm16]\}$



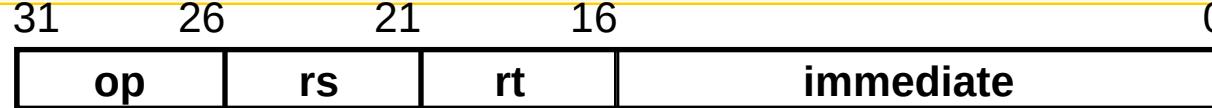
The Single Cycle Datapath during Store?



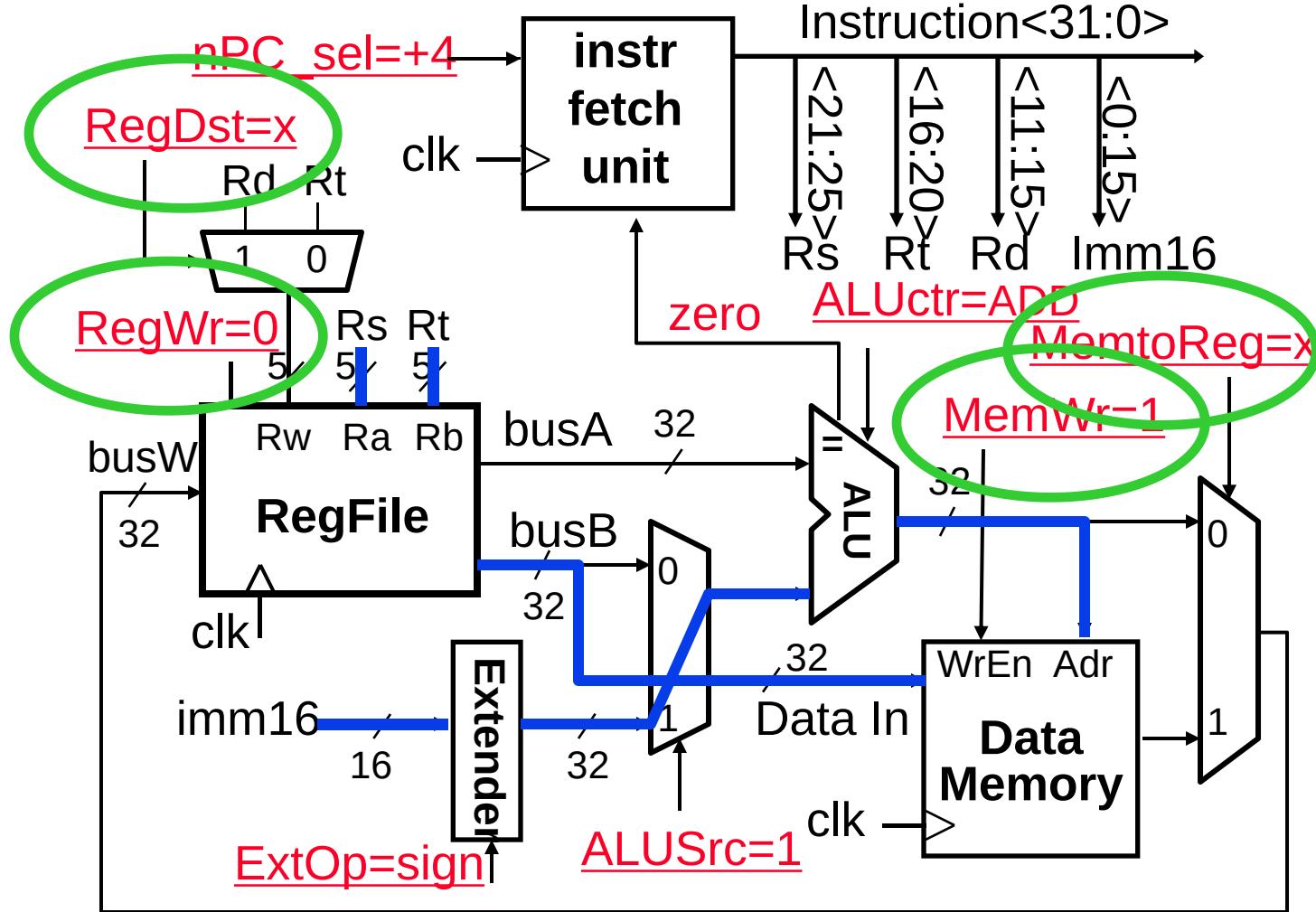
- Data Memory {R[rs] + SignExt[imm16]} = R[rt]**



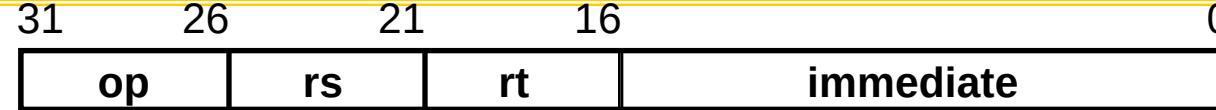
The Single Cycle Datapath during Store



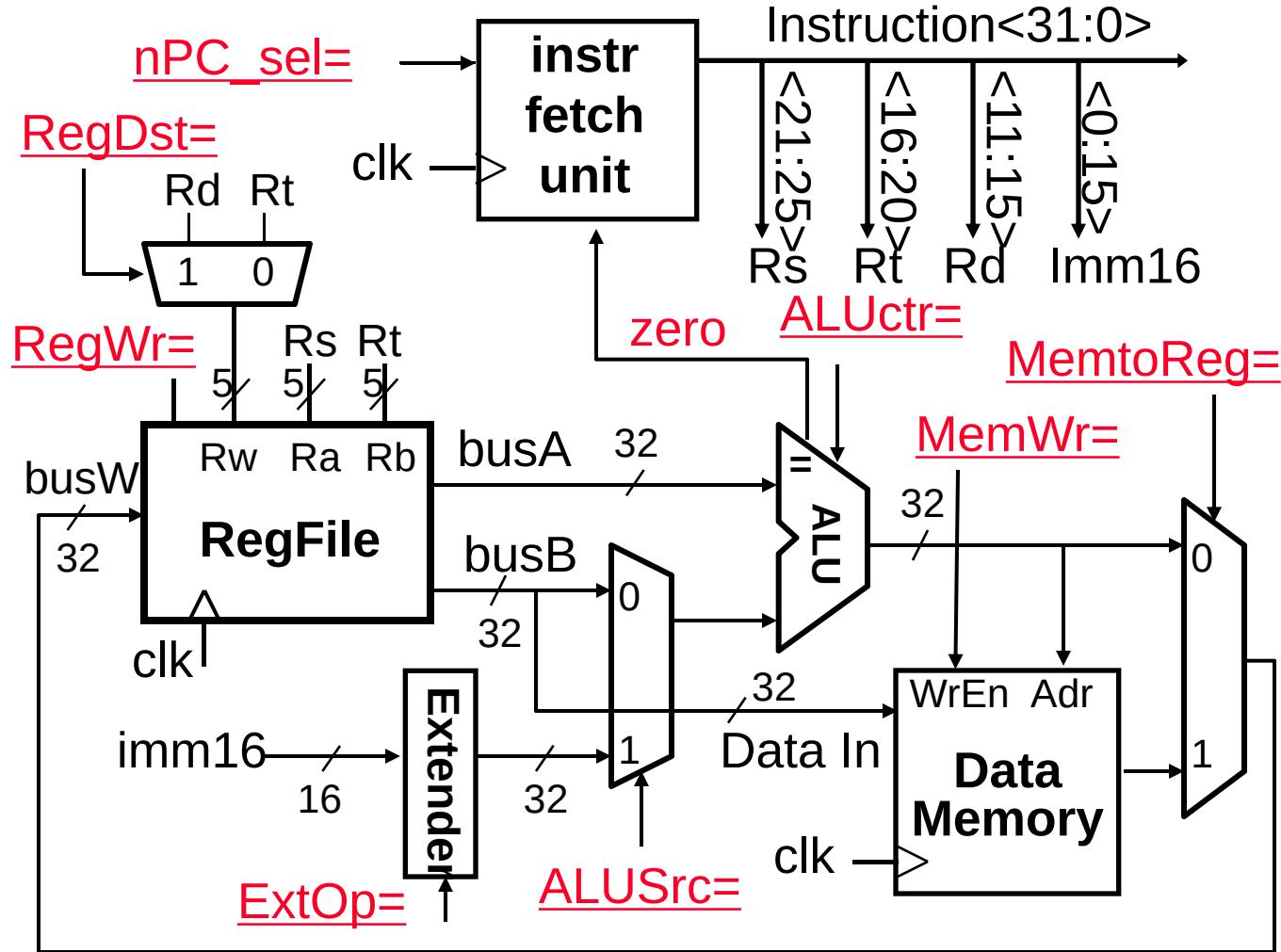
- Data Memory {R[rs] + SignExt[imm16]} = R[rt]**



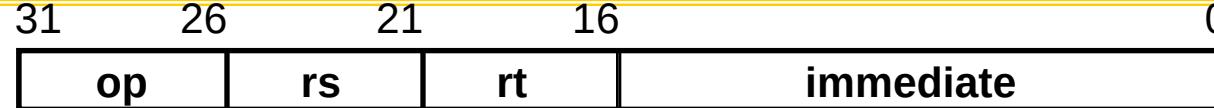
The Single Cycle Datapath during Branch?



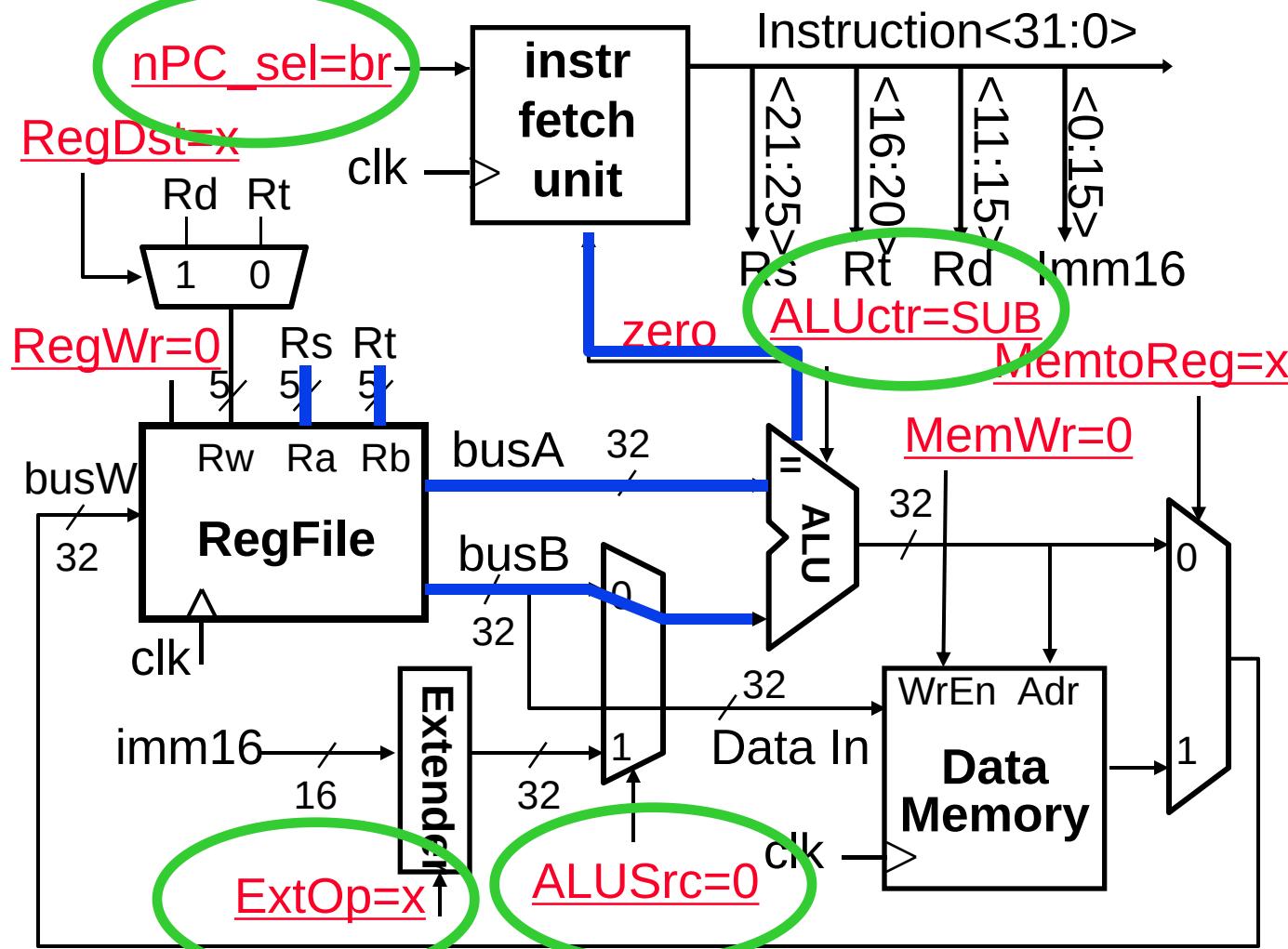
- if $(R[rs] - R[rt] == 0)$ then Zero = 1 ; else Zero = 0



The Single Cycle Datapath during Branch



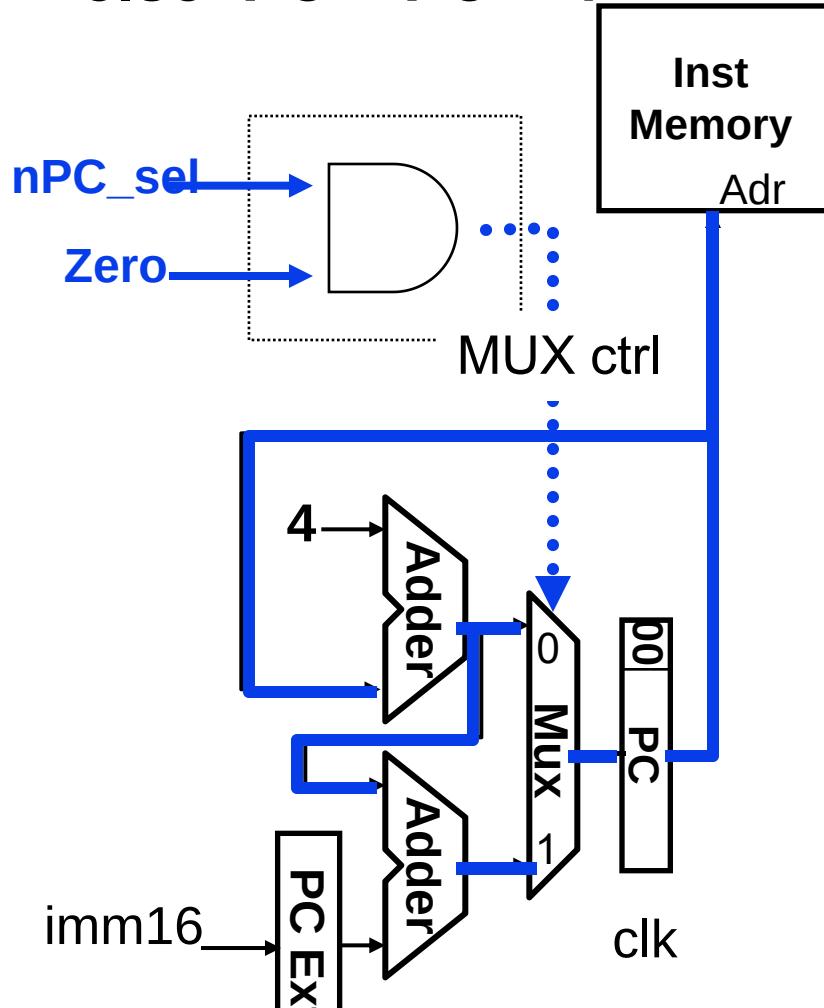
- if $(R[rs] - R[rt] == 0)$ then Zero = 1 ; else Zero = 0



Instruction Fetch Unit at the End of Branch



- if (Zero == 1) then $PC = PC + 4 + \text{SignExt}[\text{imm16}] * 4$;
else $PC = PC + 4$

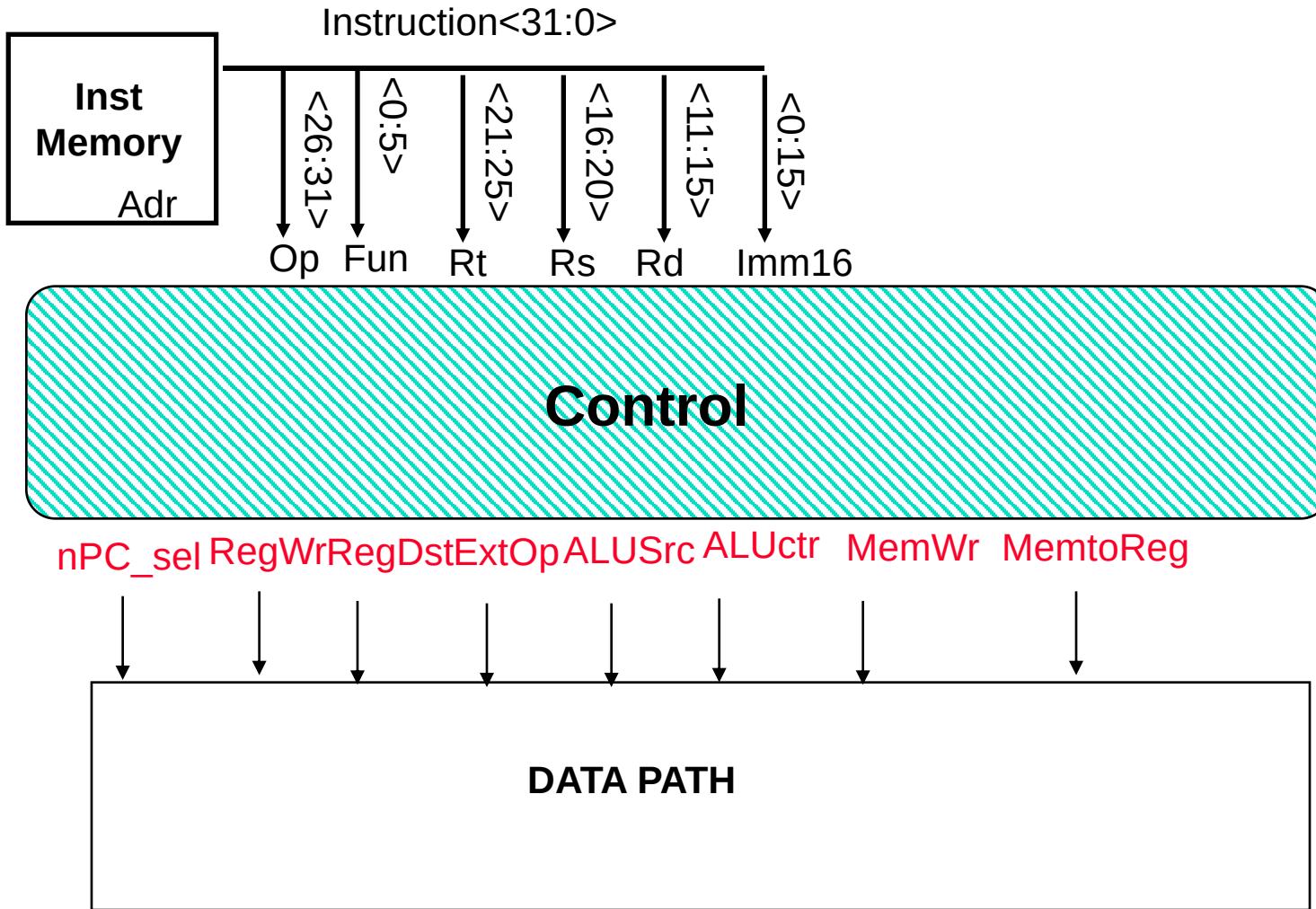


- What is encoding of **nPC_sel**?
 - Direct MUX select?
 - Branch inst. / not branch
- Let's pick 2nd option

Q: What logic gate?



Step 4: Given Datapath: RTL → Control



A Summary of the Control Signals (1/2)

inst Register Transfer

add	$R[rd] \leftarrow R[rs] + R[rt];$	$PC \leftarrow PC + 4$
	ALUsrc = RegB, ALUctr = "ADD", RegDst = rd, RegWr, nPC_sel = "+4"	
sub	$R[rd] \leftarrow R[rs] - R[rt];$	$PC \leftarrow PC + 4$
	ALUsrc = RegB, ALUctr = "SUB", RegDst = rd, RegWr, nPC_sel = "+4"	
ori	$R[rt] \leftarrow R[rs] + \text{zero_ext(Imm16)};$	$PC \leftarrow PC + 4$
	ALUsrc = Im, Extop = "Z", ALUctr = "OR", RegDst = rt, RegWr, nPC_sel = "+4"	
lw	$R[rt] \leftarrow \text{MEM}[R[rs] + \text{sign_ext(Imm16)}];$	$PC \leftarrow PC + 4$
	ALUsrc = Im, Extop = "sn", ALUctr = "ADD", MemtoReg, RegDst = rt, RegWr, nPC_sel = "+4"	
sw	$\text{MEM}[R[rs] + \text{sign_ext(Imm16)}] \leftarrow R[rs];$	$PC \leftarrow PC + 4$
	ALUsrc = Im, Extop = "sn", ALUctr = "ADD", MemWr, nPC_sel = "+4"	
beq	if (R[rs] == R[rt]) then $PC \leftarrow PC + \text{sign_ext(Imm16)}$] 00 else $PC \leftarrow PC + 4$	

A Summary of the Control Signals (2/2)

See Appendix A

	add	sub	ori	lw	sw	beq	jump
RegDst	1	1	0	0	x	x	x
ALUSrc	0	0	1	1	1	0	x
MemtoReg	0	0	0	1	x	x	x
RegWrite	1	1	1	1	0	0	0
MemWrite	0	0	0	0	1	0	0
nPCsel	0	0	0	0	0	1	?
Jump	0	0	0	0	0	0	1
ExtOp	x	x	0	1	1	x	x
ALUctr<2:0>	Add	Subtract	Or	Add	Add	Subtract	x

31 26 21 16 11 6 0

R-type

op	rs	rt	rd	shamt	funct
----	----	----	----	-------	-------

 add, sub

I-type

op	rs	rt	immediate		
----	----	----	-----------	--	--

 ori, lw, sw, beq

J-type

op	target address				
----	----------------	--	--	--	--

 jump

Boolean Expressions for Controller

RegDst = add + sub

ALUSrc = ori + lw + sw

MemtoReg = lw

RegWrite = add + sub + ori + lw

MemWrite = sw

nPCsel = beq

Jump = jump

ExtOp = lw + sw

ALUctr[0] = sub + beq (assume ALUctr is 00 ADD, 01: SUB, 10: OR)

ALUctr[1] = or

where,

rtype = $\sim op_5 \bullet \sim op_4 \bullet \sim op_3 \bullet \sim op_2 \bullet \sim op_1 \bullet \sim op_0$,

ori = $\sim op_5 \bullet \sim op_4 \bullet op_3 \bullet op_2 \bullet \sim op_1 \bullet op_0$

lw = $op_5 \bullet \sim op_4 \bullet \sim op_3 \bullet \sim op_2 \bullet op_1 \bullet op_0$

sw = $op_5 \bullet \sim op_4 \bullet op_3 \bullet \sim op_2 \bullet op_1 \bullet op_0$

beq = $\sim op_5 \bullet \sim op_4 \bullet \sim op_3 \bullet op_2 \bullet \sim op_1 \bullet \sim op_0$

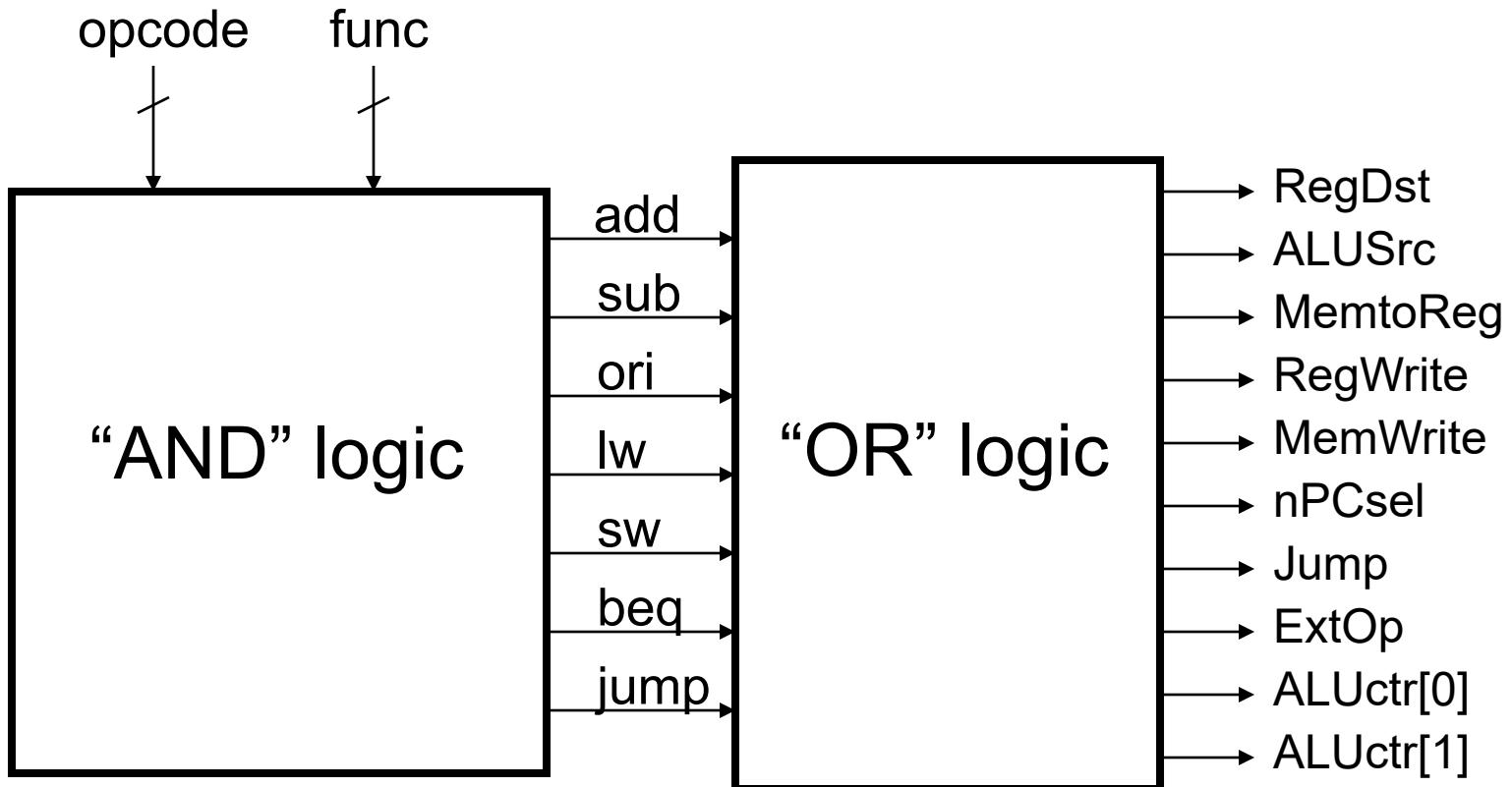
jump = $\sim op_5 \bullet \sim op_4 \bullet \sim op_3 \bullet \sim op_2 \bullet op_1 \bullet \sim op_0$

add = rtype • func₅ • \sim func₄ • \sim func₃ • \sim func₂ • \sim func₁ • \sim func₀

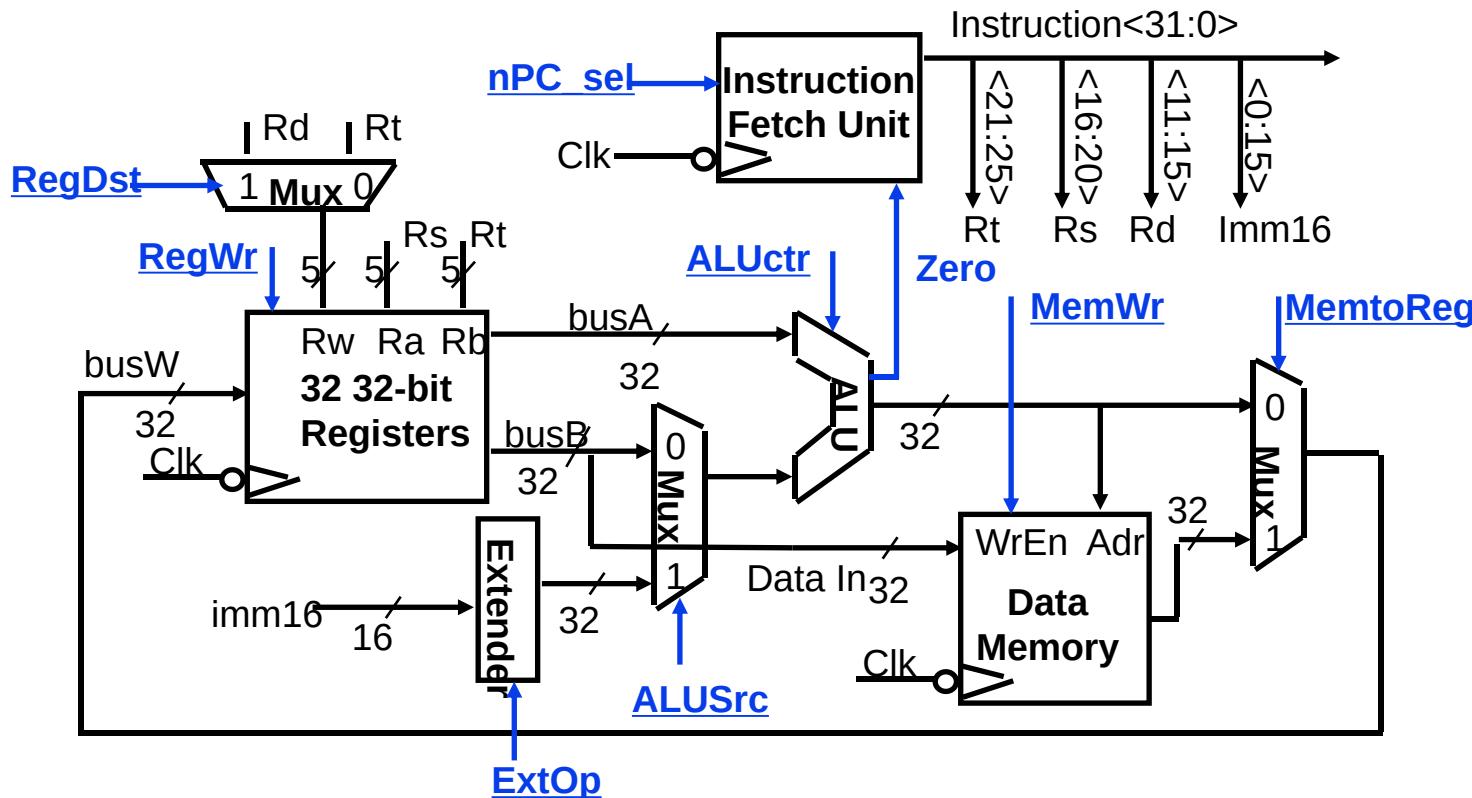
sub = rtype • func₅ • \sim func₄ • \sim func₃ • \sim func₂ • func₁ • \sim func₀

How do we
implement this in
gates?

Controller Implementation



Peer Instruction

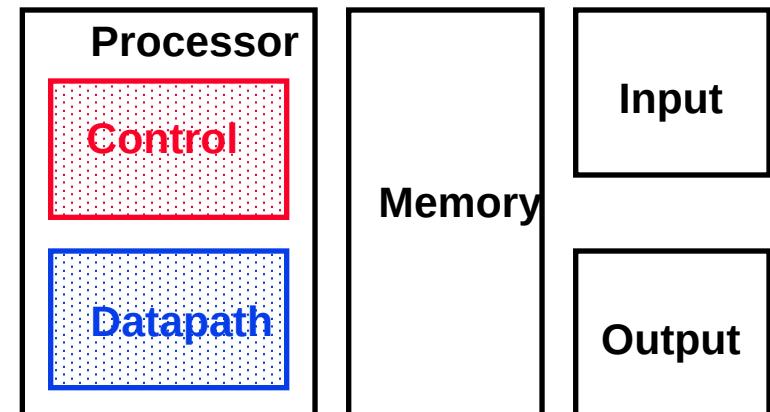


- 1) **MemToReg='x' & ALUctr='sub'.**
SUB or BEQ?
- 2) **ALUctr='add'.** Which 1 signal is different for all 3 of: ADD, LW, & SW?
RegDst or ExtOp?

	12
a)	SR
b)	SE
c)	BR
d)	BE

Summary: Single-cycle Processor

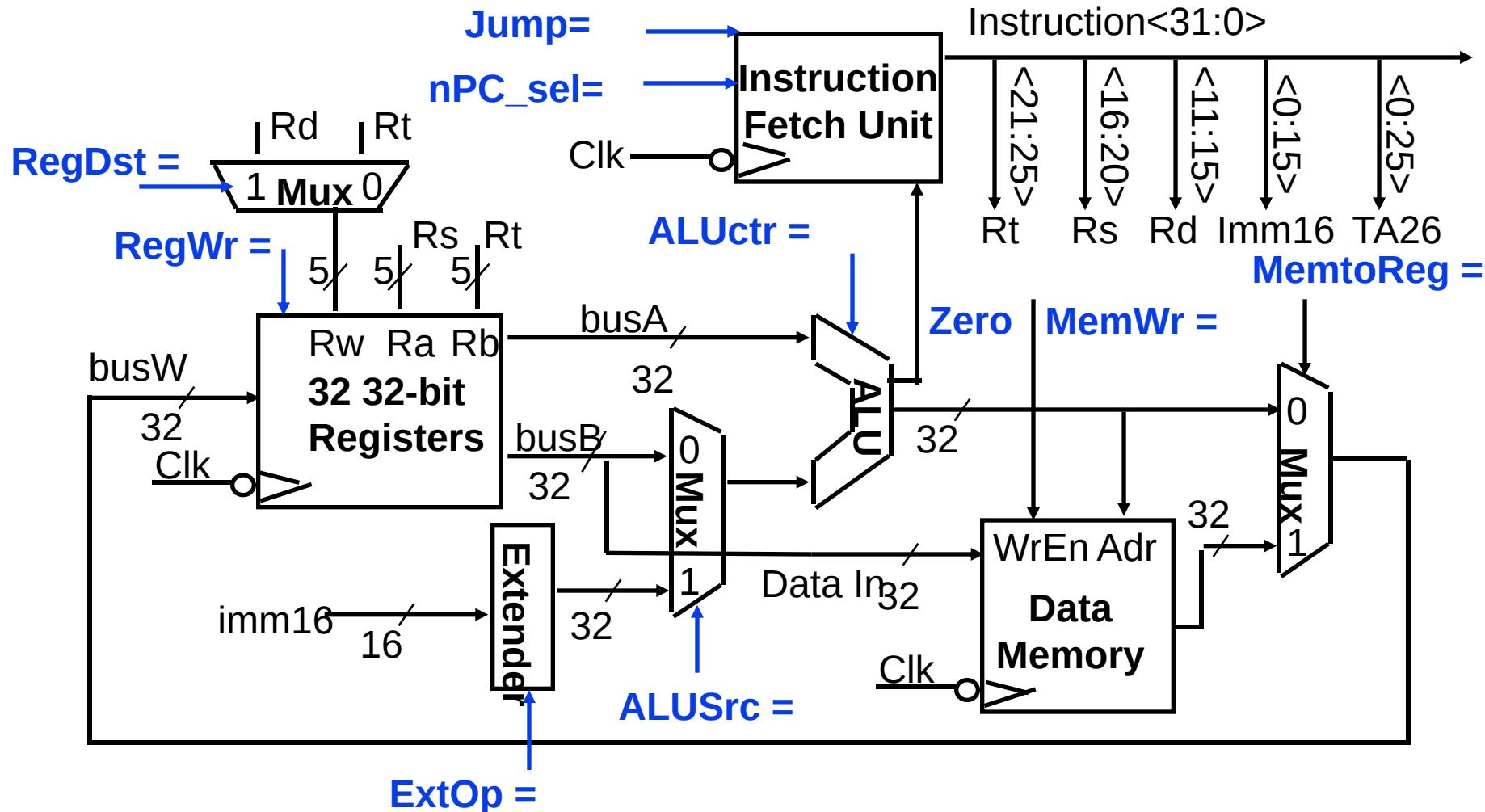
- **5 steps to design a processor**
 - 1. Analyze instruction set → datapath requirements
 - 2. Select set of datapath components & establish clock methodology
 - 3. Assemble datapath meeting the requirements
 - 4. Analyze implementation of each instruction to determine setting of control points that effects the register transfer.
 - 5. Assemble the control logic
 - Formulate Logic Equations
 - Design Circuits



The Single Cycle Datapath during Jump



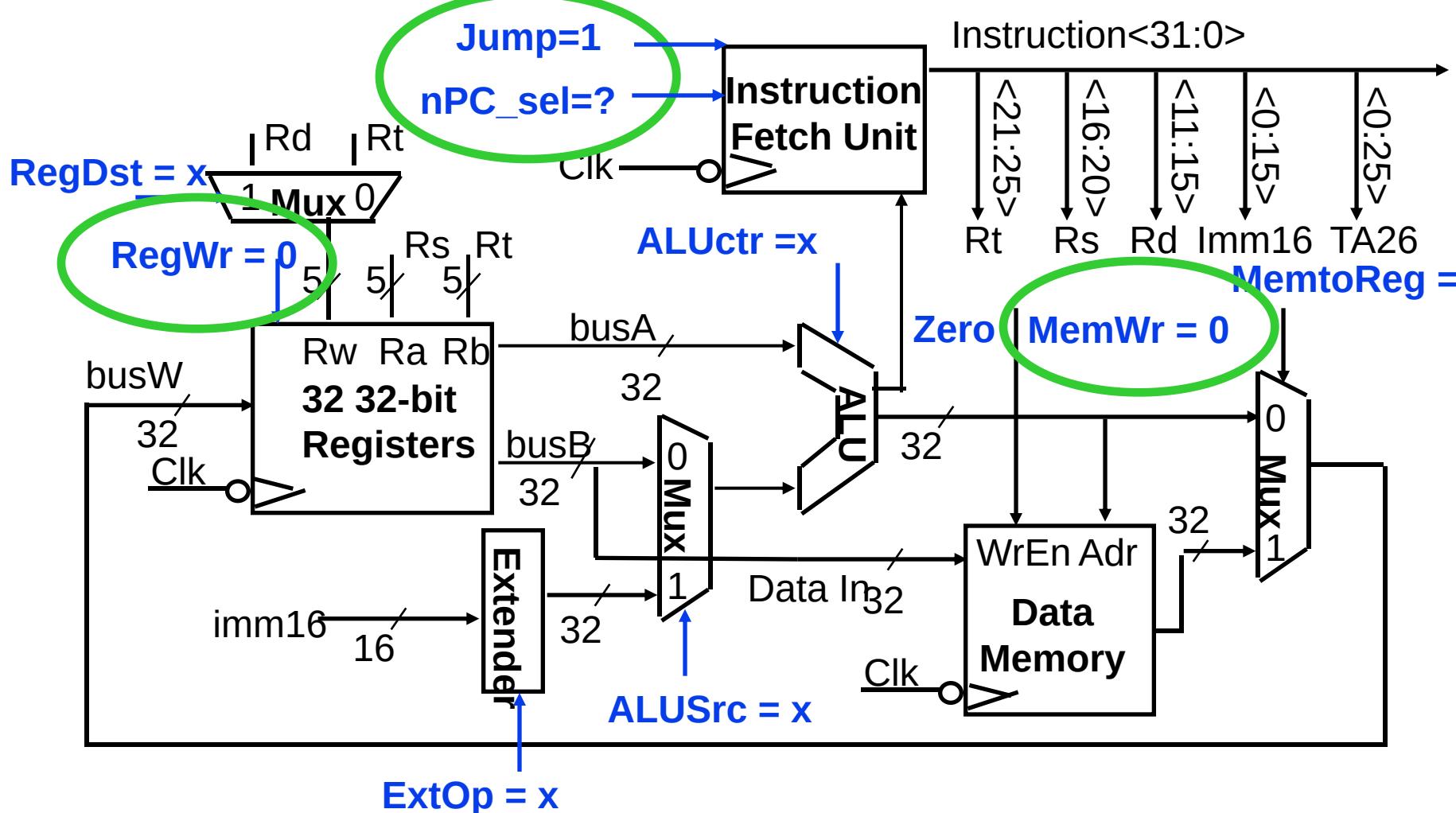
- New PC = { PC[31..28], target address, 00 }



The Single Cycle Datapath during Jump



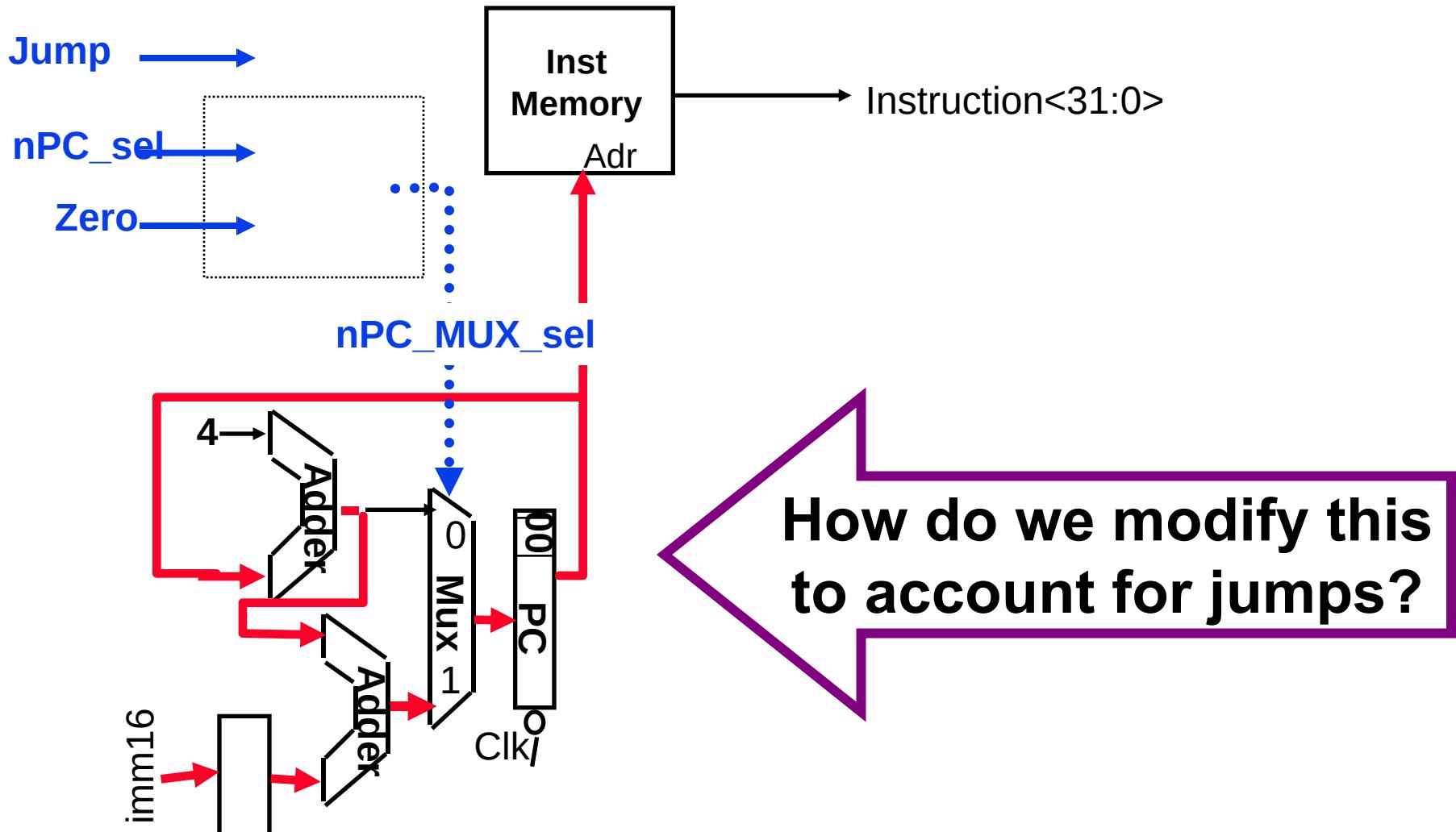
- New PC = { PC[31..28], target address, 00 }



Instruction Fetch Unit at the End of Jump



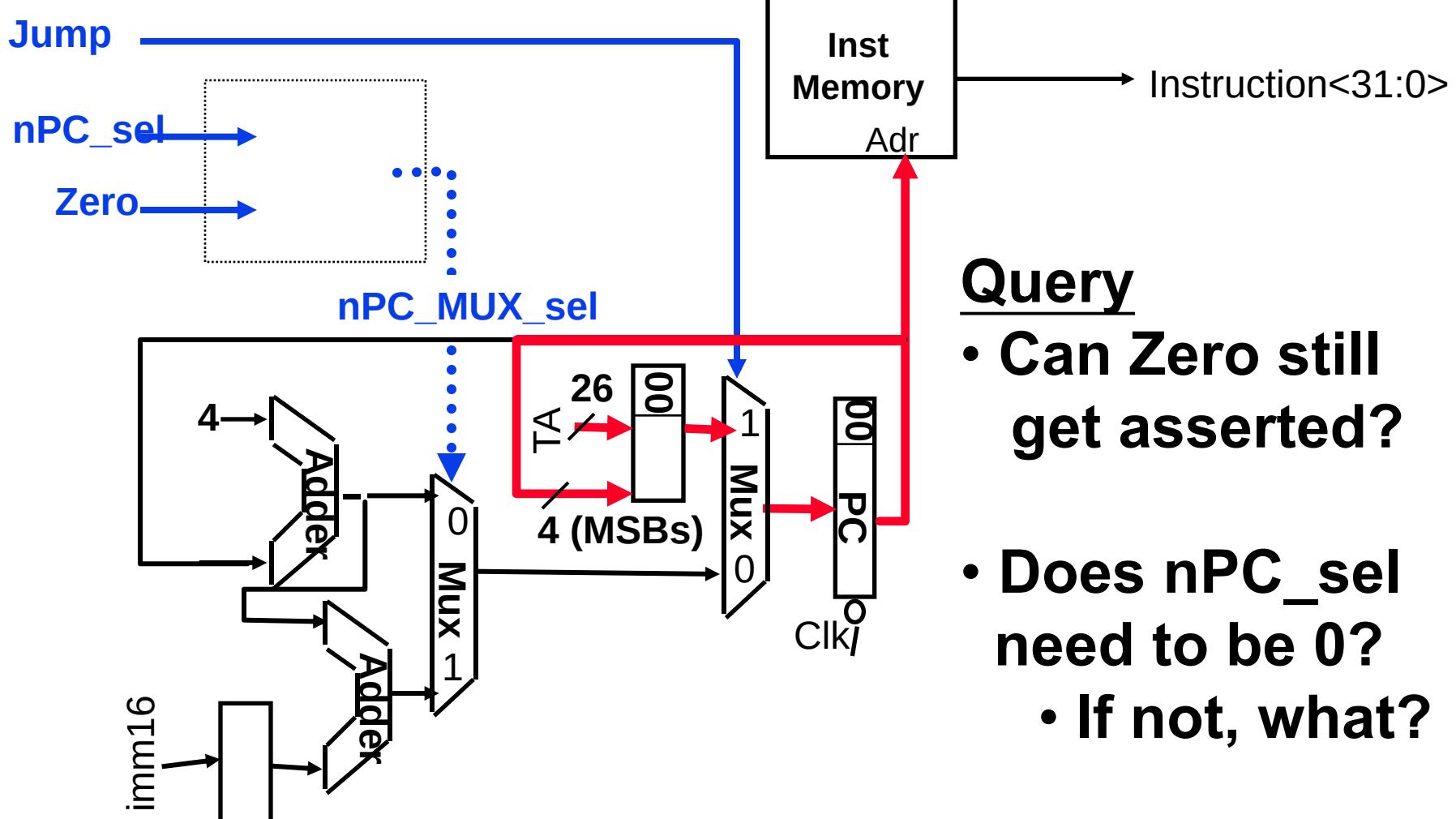
- **New PC = { PC[31..28], target address, 00 }**



Instruction Fetch Unit at the End of Jump



- New PC = { PC[31..28], target address, 00 }



0.24 Pipeline



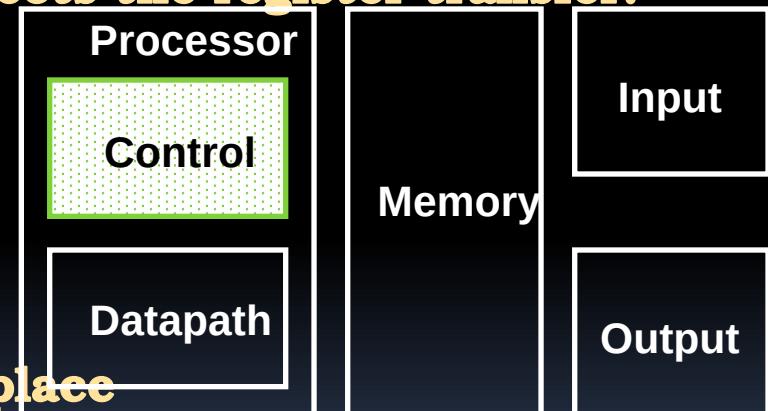
Lecture 23- CPU Design : Pipelining to Improve Performance

2020-10-23

Lecturer
Yuanqing
Cheng

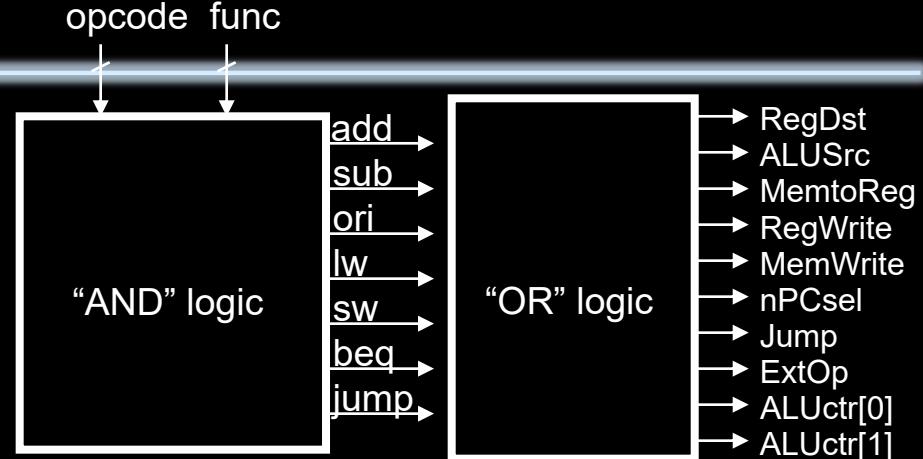
Review: Single cycle datapath

- **5 steps to design a processor**
 1. Analyze instruction set datapath **requirements**
 2. Select set of datapath components & establish clock methodology
 3. Assemble datapath meeting the requirements
 4. Analyze implementation of each instruction to determine setting of control points that effects the register transfer.
 5. Assemble the control logic
- **Control is the hard part**
- **MIPS makes that easier**
 - Instructions same size
 - Source registers always in same place
 - Immediates same size, location
 - Operations always on registers/immediates



How We Build The Controller

RegDst = add + sub
ALUSrc = ori + lw + sw
MemtoReg = lw
RegWrite = add + sub + ori + lw
MemWrite = sw
nPCsel = beq
Jump = jump
ExtOp = lw + sw
ALUctr[0] = sub + beq (assume ALUctr is 0 ADD, 01: SUB, 10: OR)
ALUctr[1] = or



where,

$$\text{rtype} = \neg op_5 \bullet \neg op_4 \bullet \neg op_3 \bullet \neg op_2 \bullet \neg op_1 \bullet \neg op_0,$$

$$\text{ori} = \neg op_5 \bullet \neg op_4 \bullet op_3 \bullet op_2 \bullet \neg op_1 \bullet op_0$$

$$\text{lw} = op_5 \bullet \neg op_4 \bullet \neg op_3 \bullet \neg op_2 \bullet op_1 \bullet op_0$$

$$\text{sw} = op_5 \bullet \neg op_4 \bullet op_3 \bullet \neg op_2 \bullet op_1 \bullet op_0$$

$$\text{beq} = \neg op_5 \bullet \neg op_4 \bullet \neg op_3 \bullet op_2 \bullet \neg op_1 \bullet \neg op_0$$

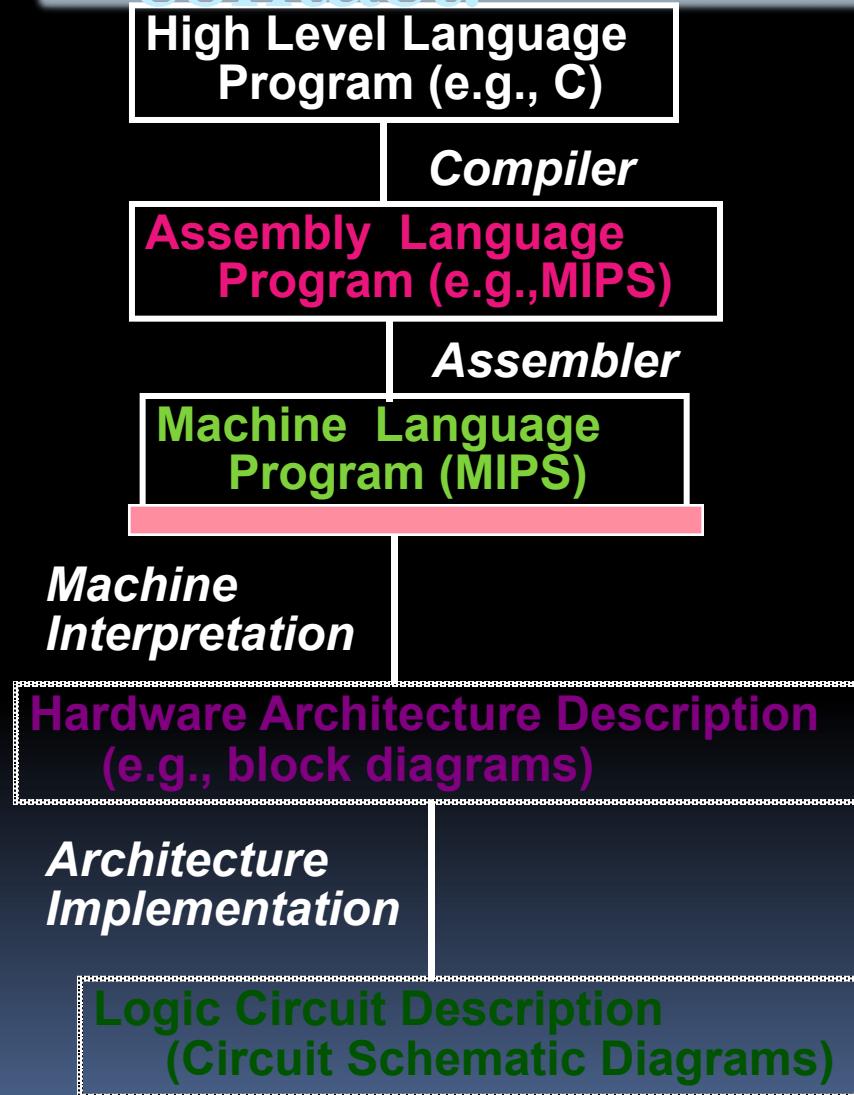
$$\text{jump} = \neg op_5 \bullet \neg op_4 \bullet \neg op_3 \bullet \neg op_2 \bullet op_1 \bullet \neg op_0$$

$$\text{add} = \text{rtype} \bullet \text{func}_5 \bullet \neg \text{func}_4 \bullet \neg \text{func}_3 \bullet \neg \text{func}_2 \bullet \neg \text{func}_1 \bullet \neg \text{func}_0$$

$$\text{sub} = \text{rtype} \bullet \text{func}_5 \bullet \neg \text{func}_4 \bullet \neg \text{func}_3 \bullet \neg \text{func}_2 \bullet \text{func}_1 \bullet \neg \text{func}_0$$

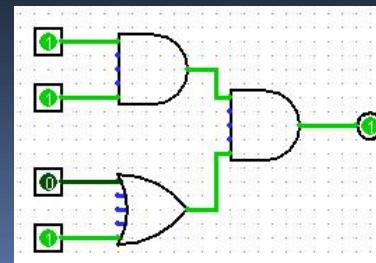
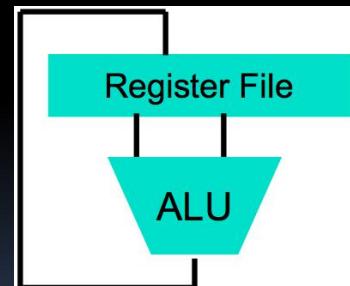
Omigosh
omigosh,
do you know
what this
means?

Call home, we've made HW/SW contact!



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)

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



Processor Performance

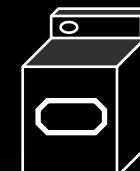
- **Can we estimate the clock rate (frequency) of our single-cycle processor? We know:**
 - **1 cycle per instruction**
 - **lw is the most demanding instruction.**
 - **Assume these delays for major pieces of the datapath:**
 - Instr. Mem, ALU, Data Mem : 2ns each, regfile 1ns
 - **Instruction execution requires: $2 + 1 + 2 + 2 + 1 = 8\text{ns}$**
 - **⇒ 125 MHz**
- **What can we do to improve clock rate?**
- **Will this improve performance as well?**

Gotta Do Laundry

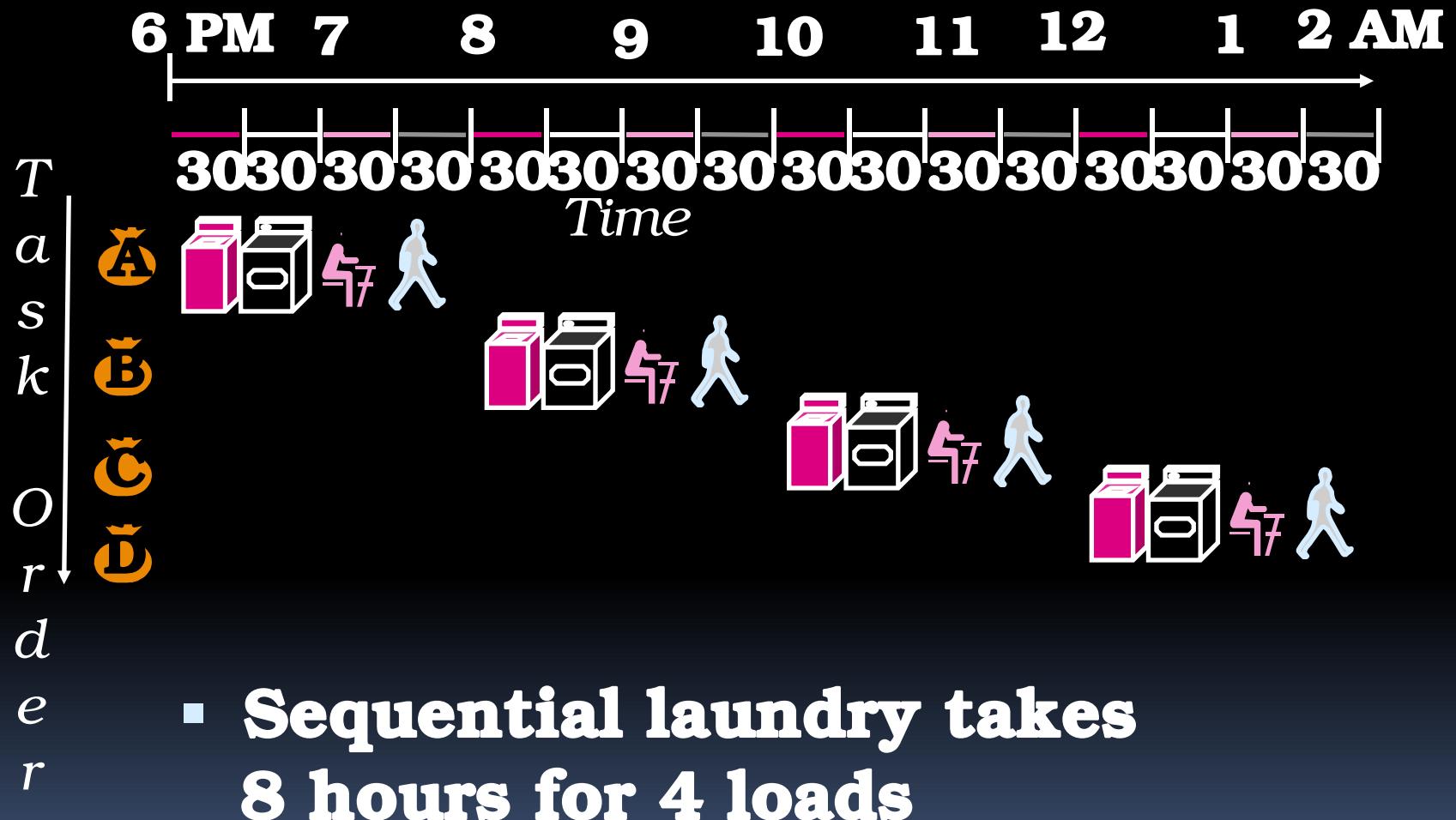
- **Ann, Brian, Cathy, Dave each have one load of clothes to wash, dry, fold, and put away**



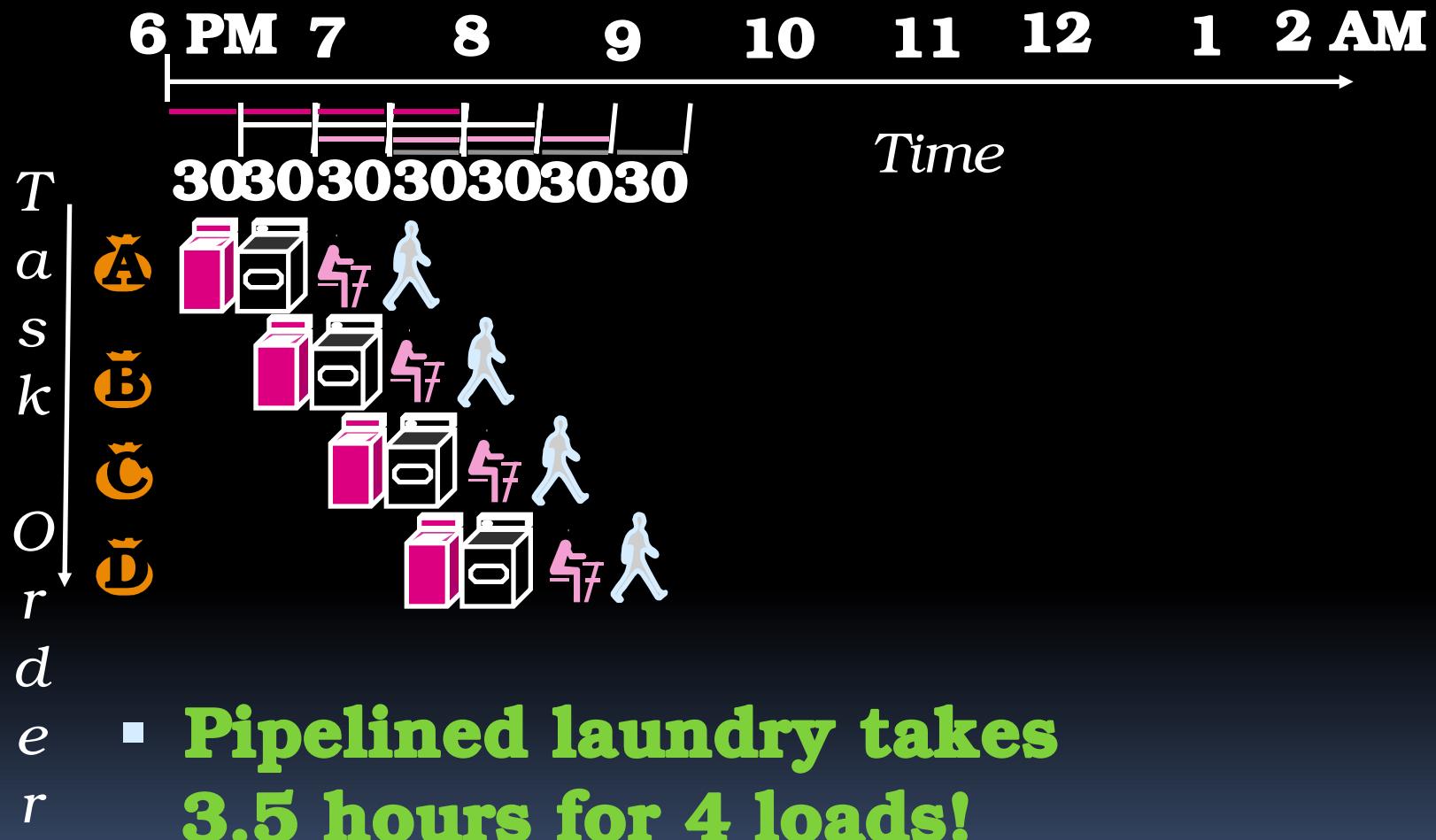
- **Washer takes 30 minutes**
- **Dryer takes 30 minutes**
- **“Folder” takes 30 minutes**
- **“Stasher” takes 30 minutes to put clothes into drawers**



Sequential Laundry



Pipelined Laundry

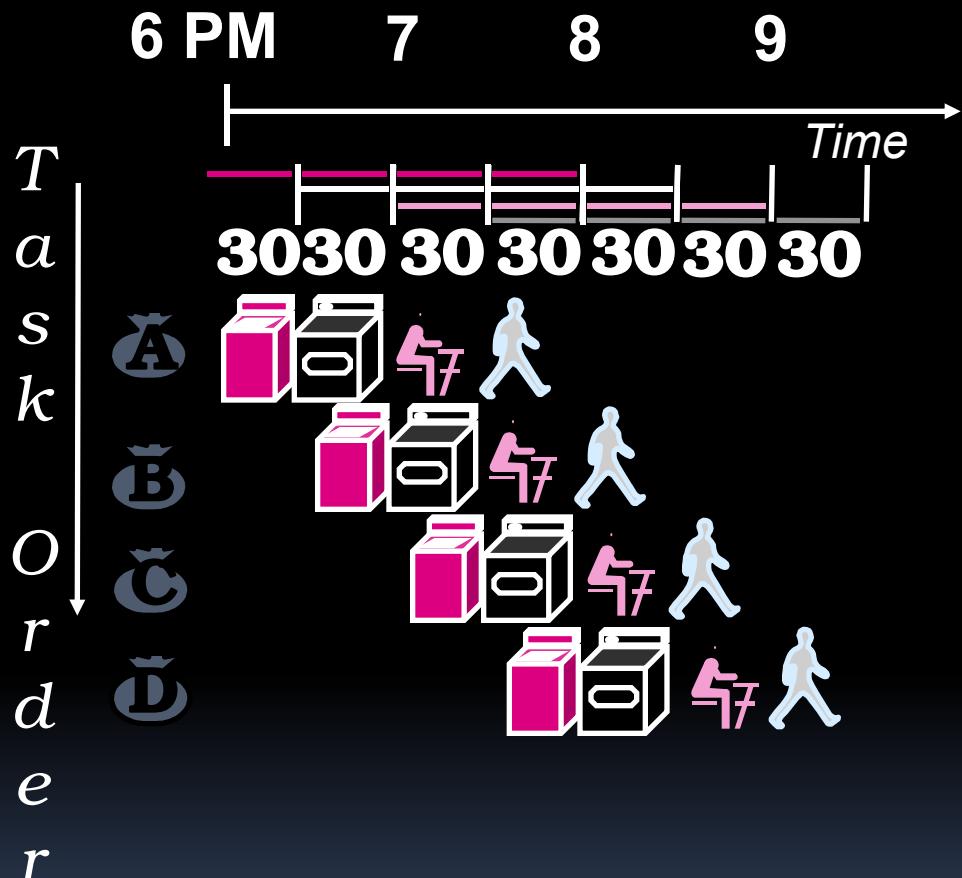


- **Pipelined laundry takes 3.5 hours for 4 loads!**

General Definitions

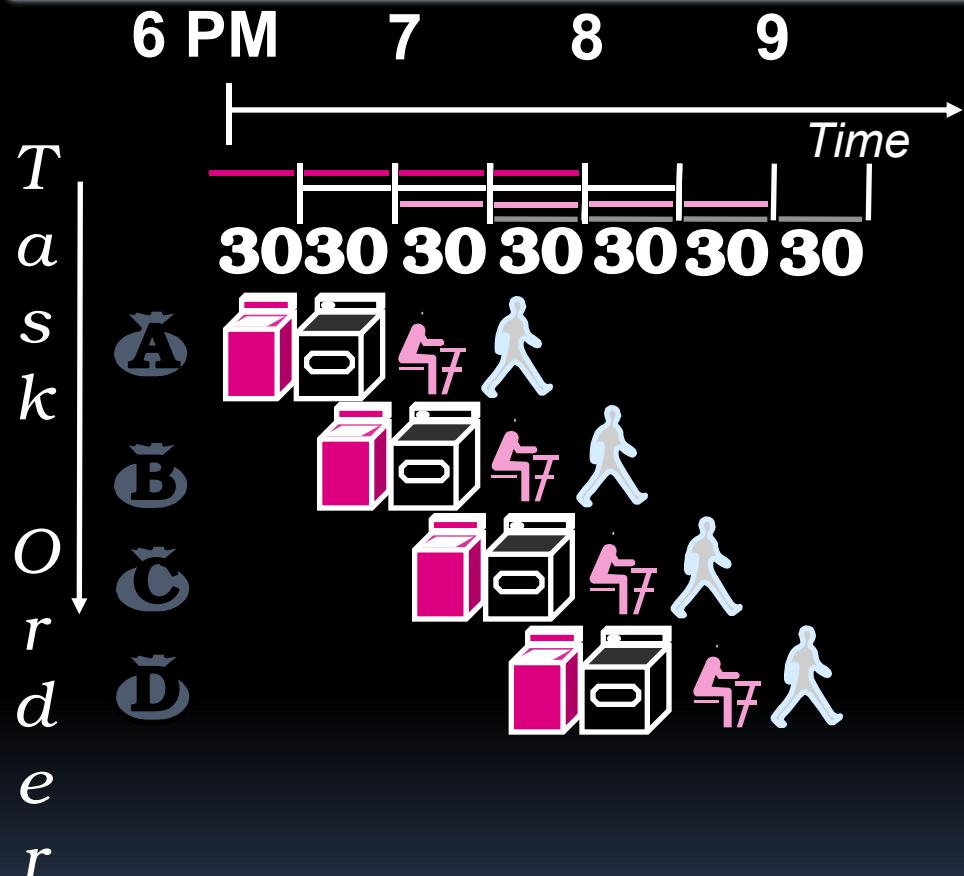
- **Latency:** time to completely execute a certain task
 - for example, time to read a sector from disk is disk access time or disk latency
- **Throughput:** amount of work that can be done over a period of time

Pipelining Lessons (1 / 2)



- Pipelining doesn't help latency of single task, it helps throughput of entire workload
- Multiple tasks operating simultaneously using different resources
- Potential speedup = Number pipe stages
- Time to “fill” pipeline and time to “drain” it reduces speedup:
2.3X v. 4X in this example

Pipelining Lessons (2/2)



- Suppose new Washer takes 20 minutes, new Stasher takes 20 minutes. How much faster is pipeline?
- Pipeline rate limited by **slowest** pipeline stage
- Unbalanced lengths of pipe

Steps in Executing MIPS

- 1) **IFtch: Instruction Fetch, Increment PC**
- 2) **Dcd: Instruction Decode, Read Registers**
- 3) **Exec:**
Mem-ref: Calculate Address
Arith-log: Perform Operation
- 4) **Mem:**
Load: Read Data from Memory
Store: Write Data to Memory
- 5) **WB: Write Data Back to Register**

Pipelined Execution

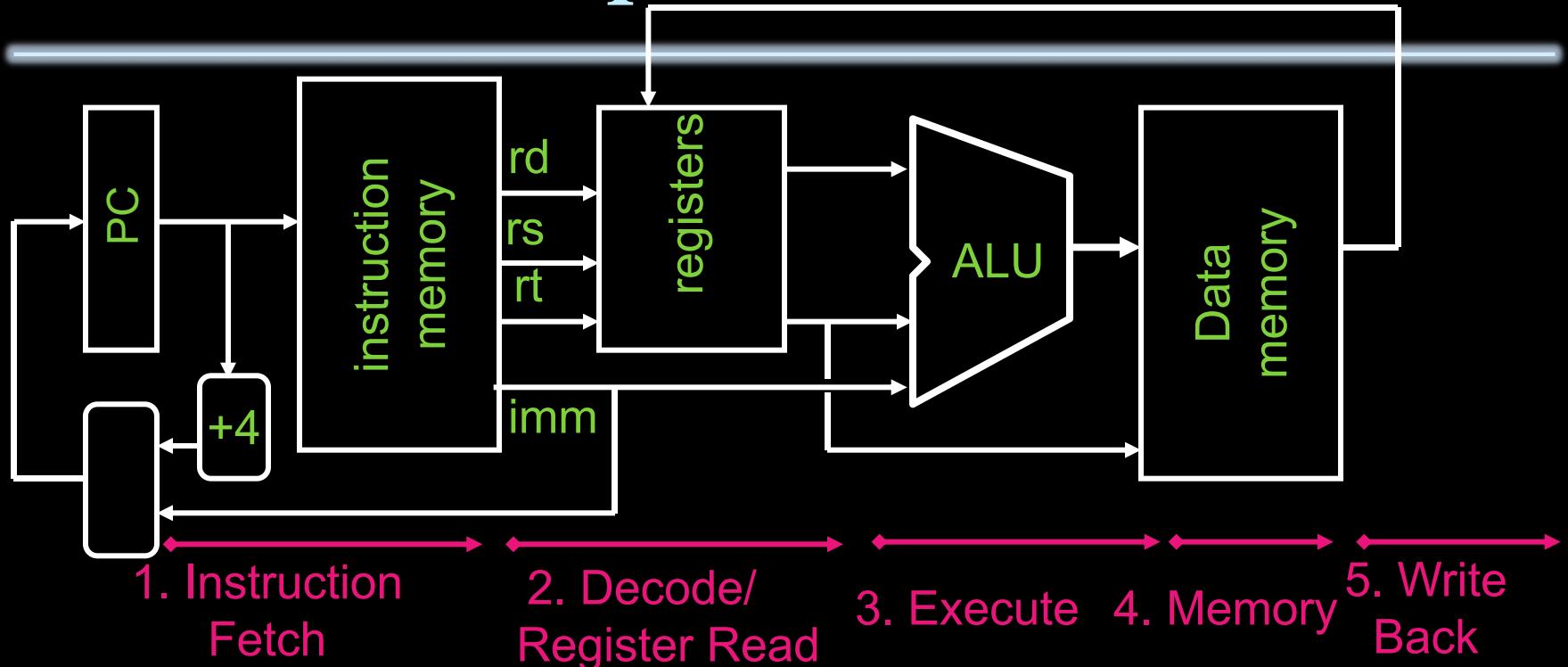
Representation

Time

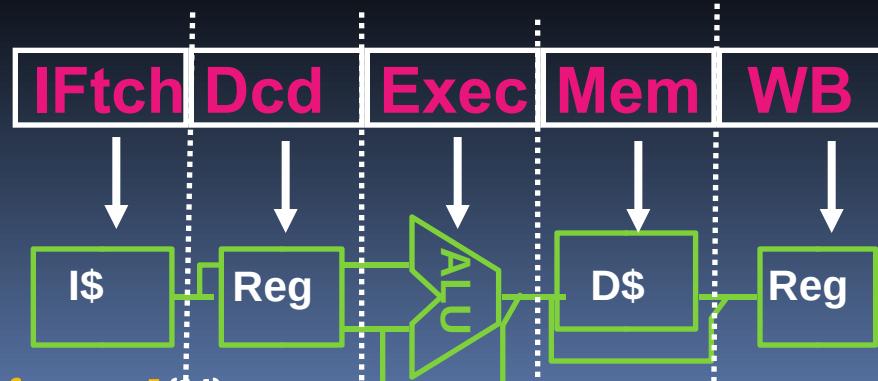


- Every instruction must take same number of steps, also called pipeline “stages”, so some will go idle sometimes

Review: Datapath for MIPS

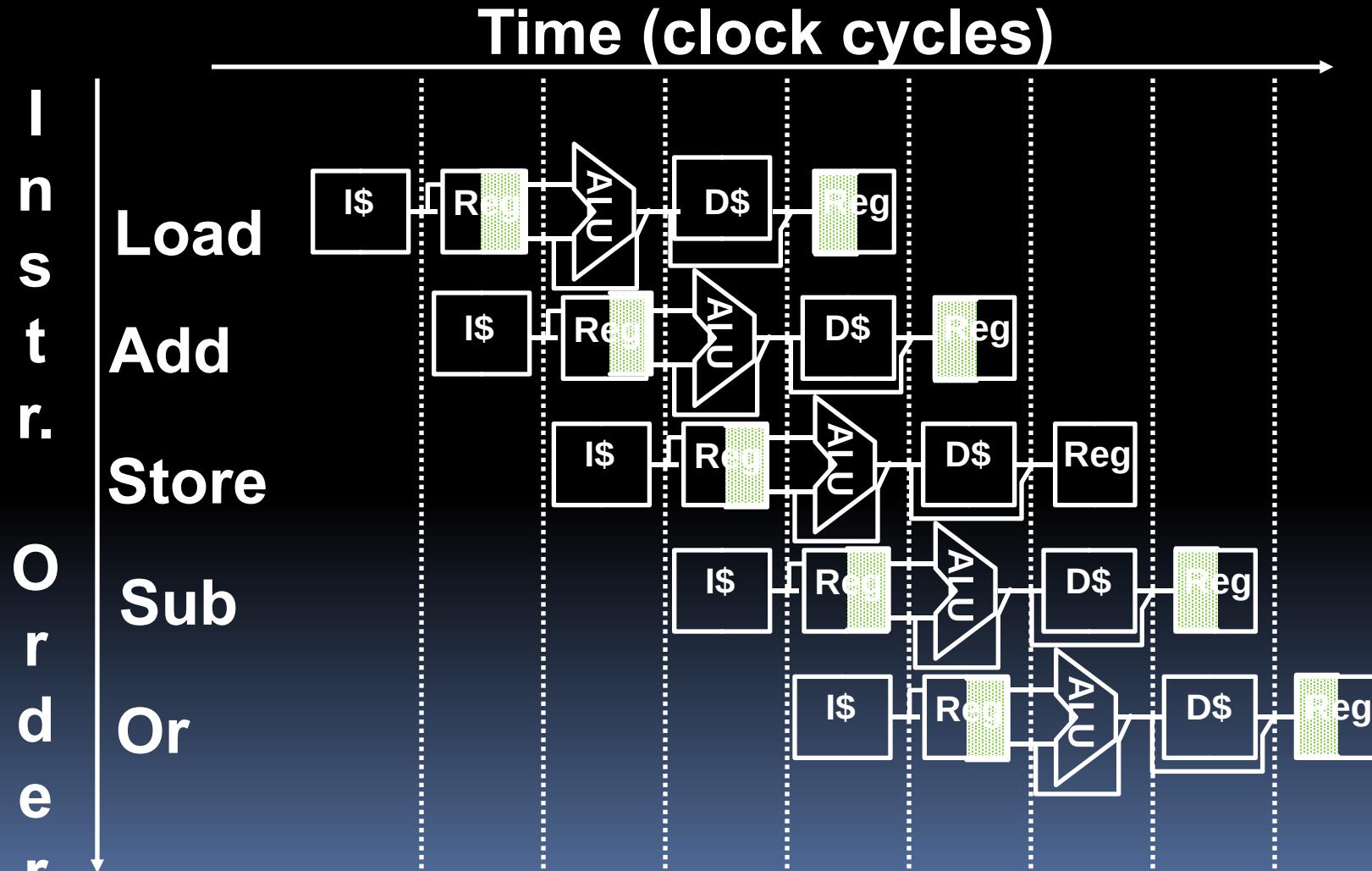


- **Use datapath figure to represent pipeline**



Graphical Pipeline Representation

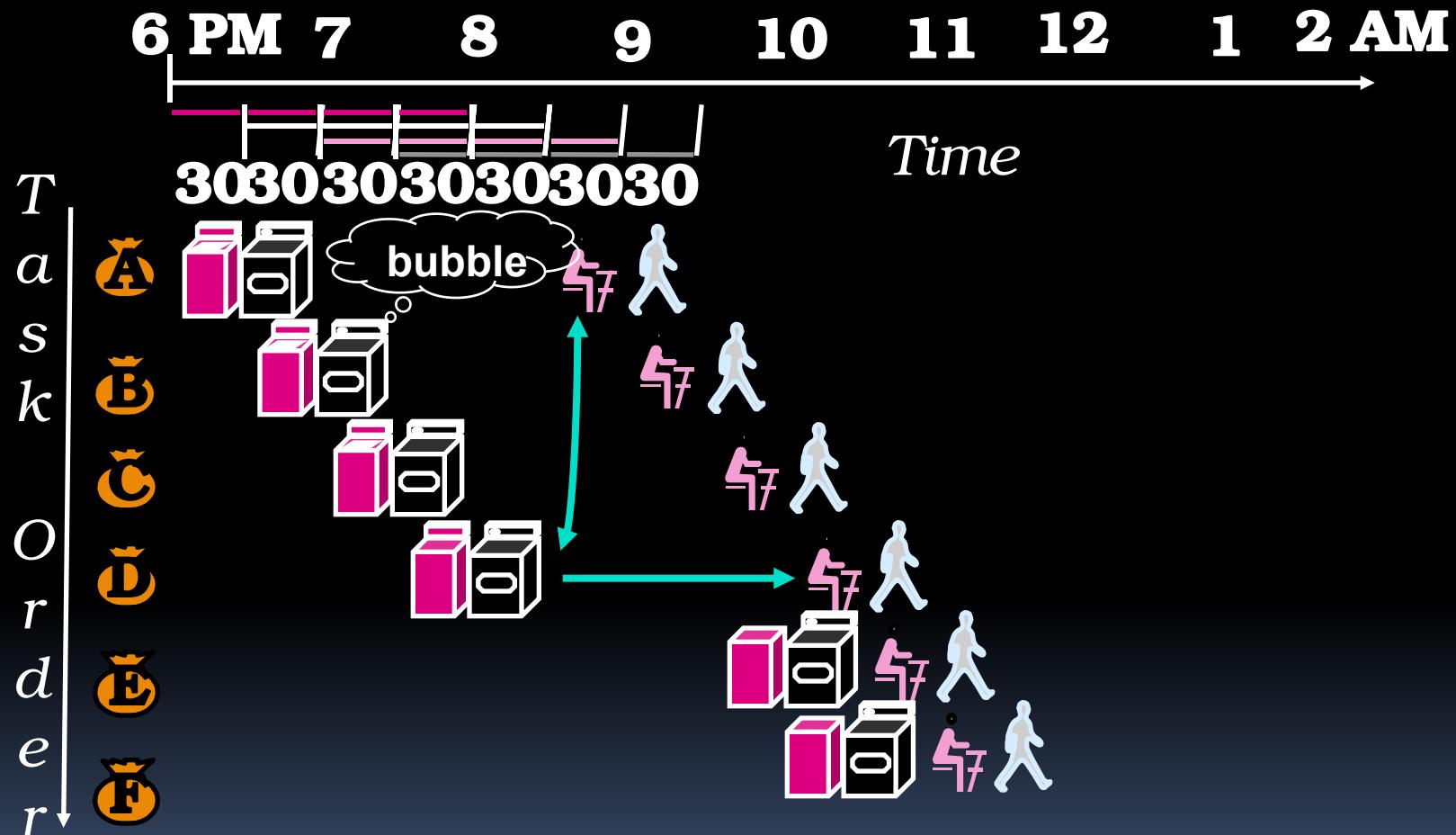
(In Reg, right half highlight read, left half write)



Example

- Suppose 2 ns for memory access, 2 ns for ALU operation, and 1 ns for register file read or write; compute instruction rate
- Nonpipelined Execution:
 - $lw : \text{IF} + \text{Read Reg} + \text{ALU} + \text{Memory} + \text{Write Reg} = 2 + 1 + 2 + 2 + 1 = 8 \text{ ns}$
 - $add: \text{IF} + \text{Read Reg} + \text{ALU} + \text{Write Reg} = 2 + 1 + 2 + 1 = 6 \text{ ns}$
(recall 8ns for single-cycle processor)
- Pipelined Execution:
 - $\text{Max(IF, Read Reg, ALU, Memory, Write Reg)} =$

Pipeline Hazard: Matching socks in later load

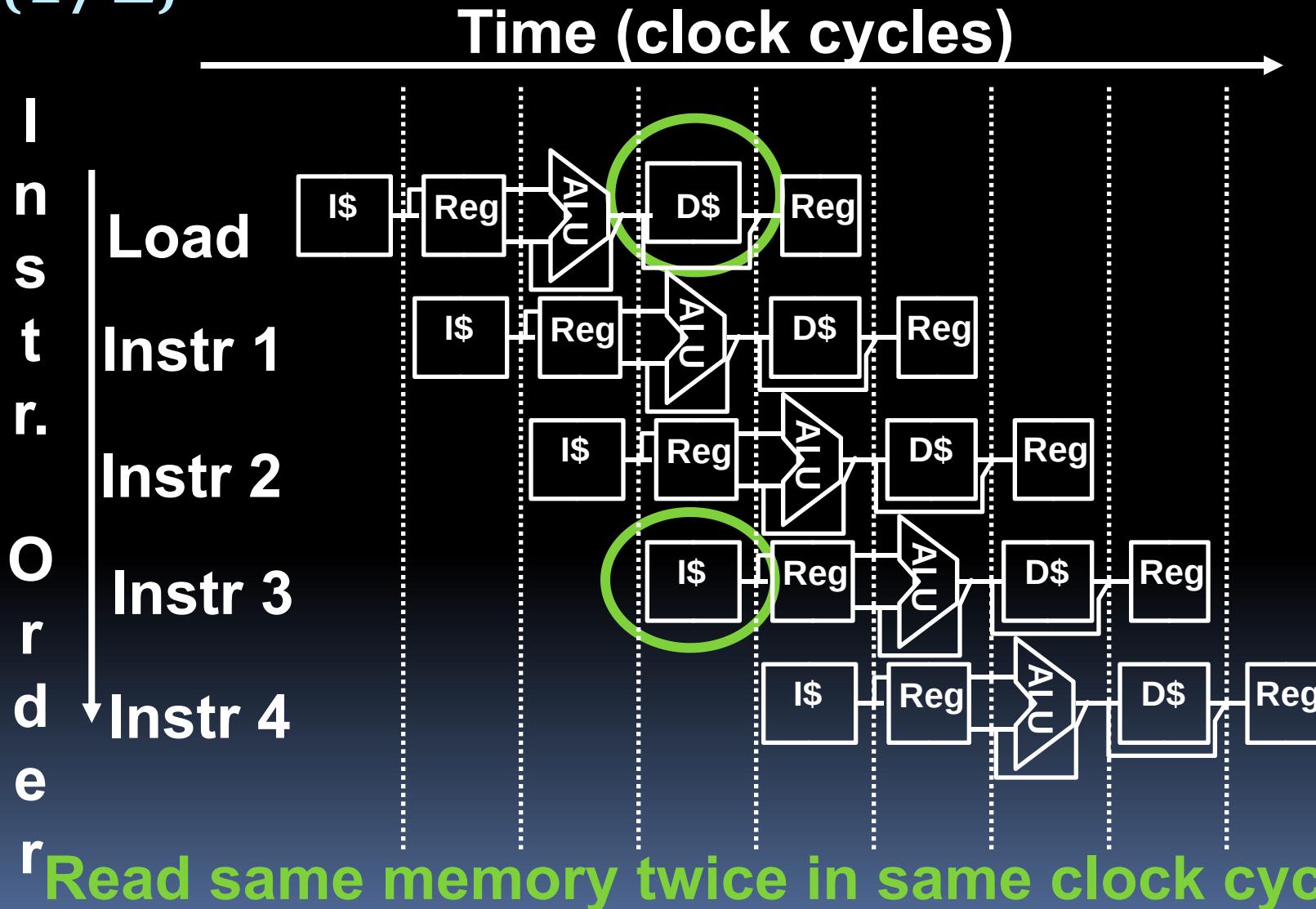


- A depends on D; **stall since folder tied**

Problems for Pipelining CPUs

- **Limits to pipelining:** **Hazards** prevent next instruction from executing during its designated clock cycle
 - **Structural hazards:** HW cannot support some combination of instructions (single person to fold and put clothes away)
 - **Control hazards:** Pipelining of branches causes later instruction fetches to wait for the result of the branch
 - **Data hazards:** Instruction depends on result of prior instruction still in the pipeline (missing sock)
- These might result in pipeline **stalls** or “**bubbles**” in the pipeline.

Structural Hazard #1: Single Memory (1/2)



Structural Hazard #1: Single Memory (2/2)

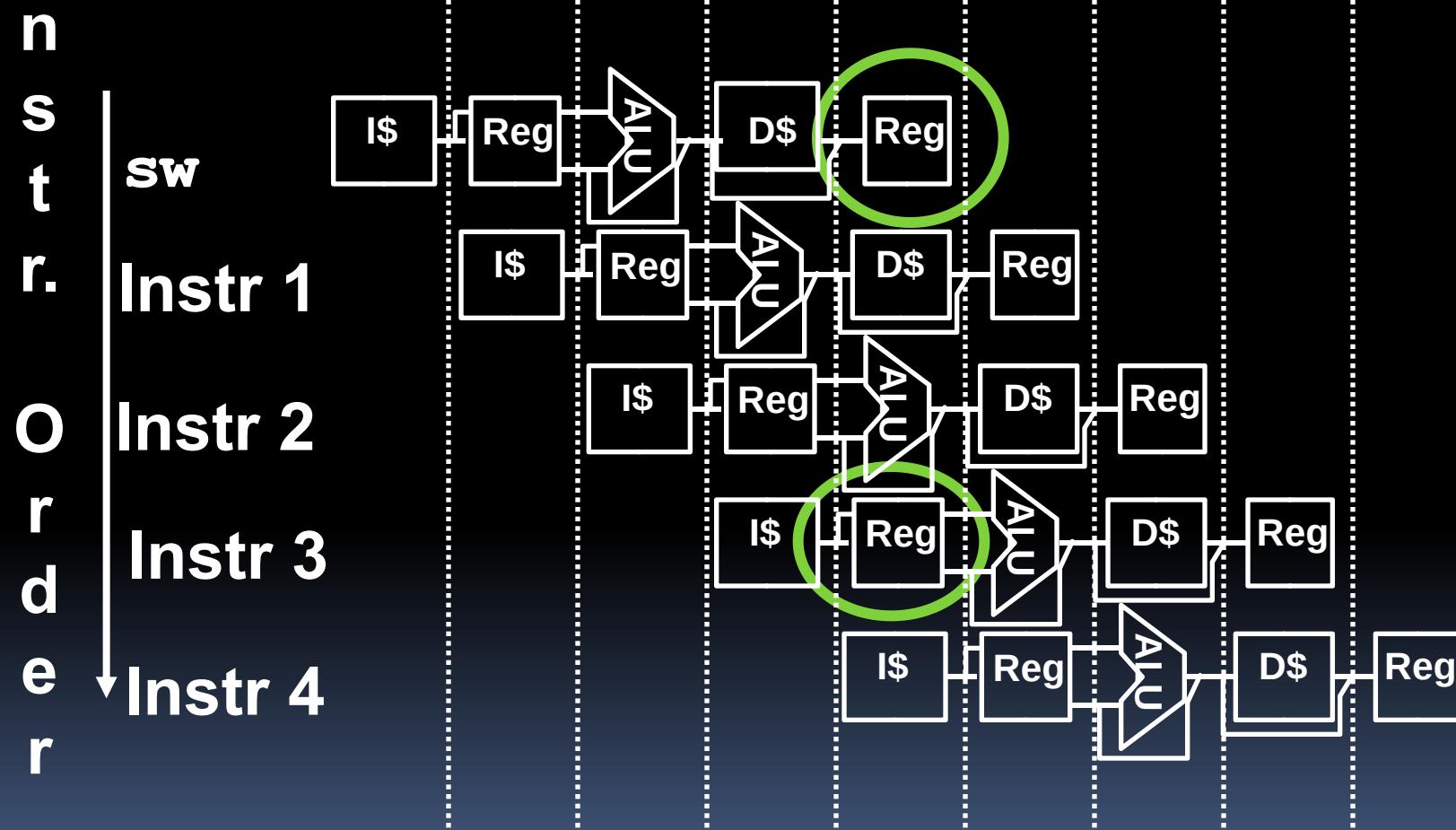
- **Solution:**

- **infeasible and inefficient to create second memory**
- (We'll learn about this more next week)
- **so simulate this by having two Level 1 Caches (a temporary smaller [of usually most recently used] copy of memory)**
- **have both an L1 Instruction Cache and an L1 Data Cache**
- **need more complex hardware to control when both caches miss**

Structural Hazard #2: Registers

(1/2)

Time (clock cycles)



Can we read and write to registers simultaneously?

Structural Hazard #2: Registers

(2/2)

- Two different solutions have been used:
 - 1) RegFile access is **VERY fast: takes less than half the time of ALU stage**
 - Write to Registers during first half of each clock cycle
 - Read from Registers during second half of each clock cycle
 - 2) Build RegFile with independent read and write ports
- **Result: can perform Read and Write during same clock cycle**

Peer Instruction

- 1) Thanks to pipelining, I have reduced the time it took me to wash my one shirt.

- 2) Longer pipelines are always a win (since less work per stage & a faster clock).

	12
a)	FF
b)	FT
c)	TF
d)	TT

Peer Instruction Answer

- 1) Throughput better, not execution time
- 2) “...longer pipelines do usually mean faster clock, but branches cause problems!”

- 1) Thanks to pipelining, I have reduced the time it took me to wash my one shirt.
- 2) Longer pipelines are always a win (since less work per stage & a faster clock).

	12
a)	FF
b)	FT
c)	TF
d)	TT

Things to Remember

- **Optimal Pipeline**
 - **Each stage is executing part of an instruction each clock cycle.**
 - **One instruction finishes during each clock cycle.**
 - **On average, execute far more quickly.**
- **What makes this work?**
 - **Similarities between instructions allow us to use same stages for all instructions (generally).**
 - **Each stage takes about the same amount of time as all others: little wasted time.**

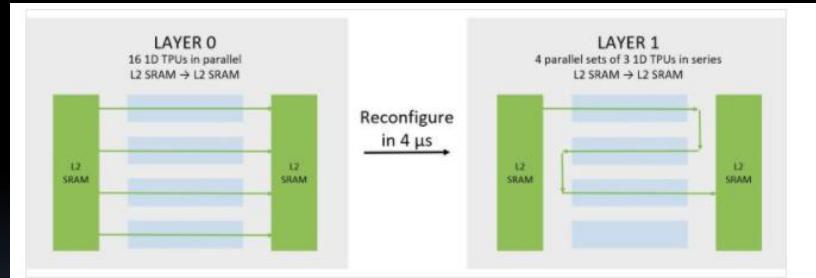


Lecturer
Yuanqing
Cheng

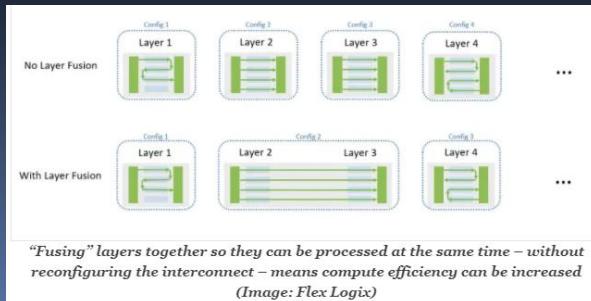
Lecture 25 – CPU Design : Pipelining to Improve Performance II

2020-10-26

Flex Logix' Edge AI Accelerator
Battles Nvidia on Price-Performance



One of the ingredients in Flex Logix' secret sauce is its configurable interconnect technology (Image: Flex Logix)



"Fusing" layers together so they can be processed at the same time – without reconfiguring the interconnect – means compute efficiency can be increased (Image: Flex Logix)

Review

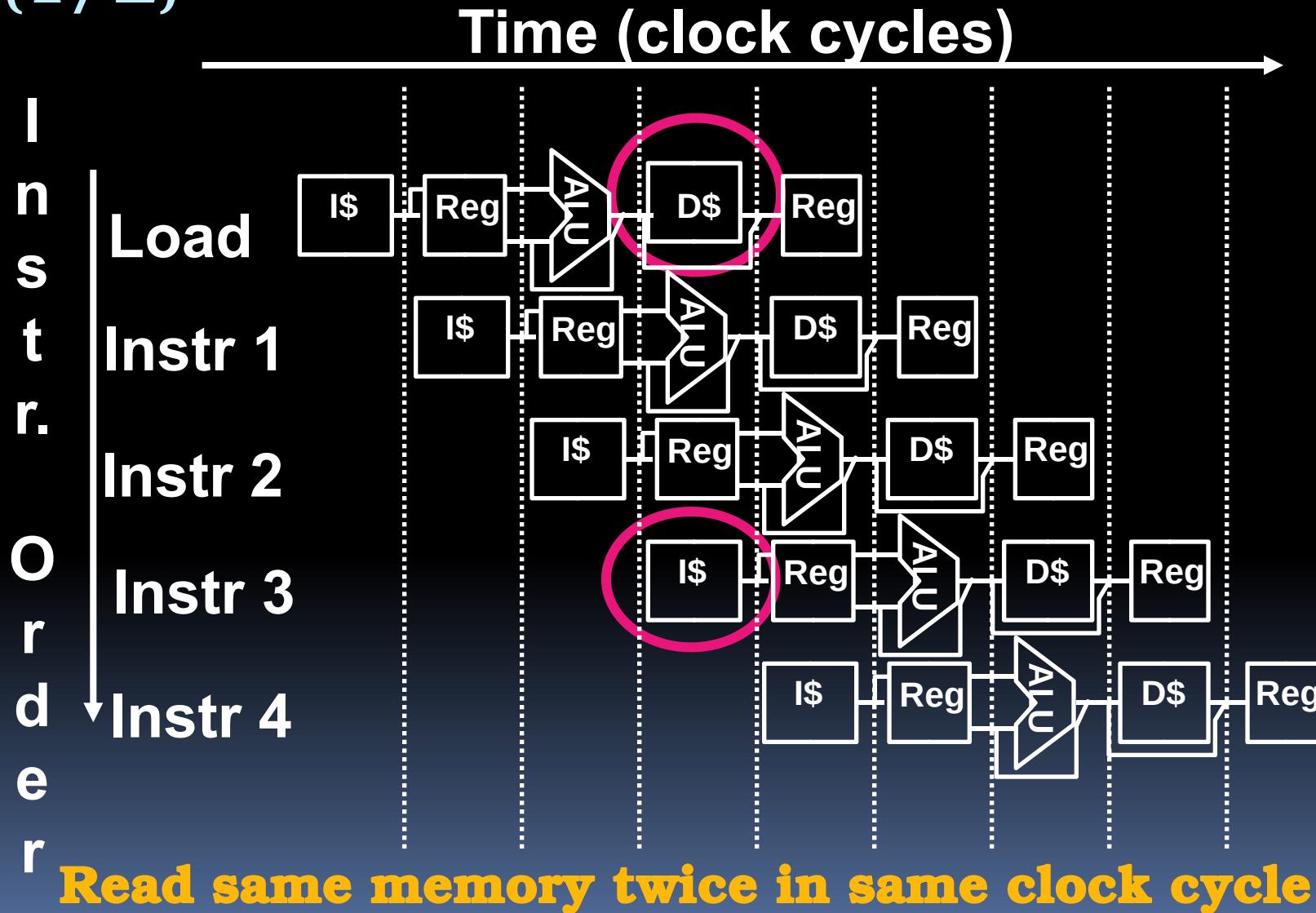
- Pipelining is a BIG idea
- Optimal Pipeline
 - Each stage is executing part of an instruction each clock cycle.
 - One instruction finishes during each clock cycle.
 - On average, execute far more quickly.
- What makes this work?
 - Similarities between instructions allow us to use same stages for all instructions (generally).
 - Each stage takes about the same amount

Problems for Pipelining CPUs

- **Limits to pipelining:** **Hazards** prevent next instruction from executing during its designated clock cycle
 - **Structural hazards:** HW cannot support some combination of instructions (single person to fold and put clothes away)
 - **Control hazards:** Pipelining of branches causes later instruction fetches to wait for the result of the branch
 - **Data hazards:** Instruction depends on result of prior instruction still in the pipeline (missing sock)
- These might result in pipeline **stalls** or “**bubbles**” in the pipeline.

Structural Hazard #1: Single Memory

(1/2)



Structural Hazard #1: Single Memory (2/2)

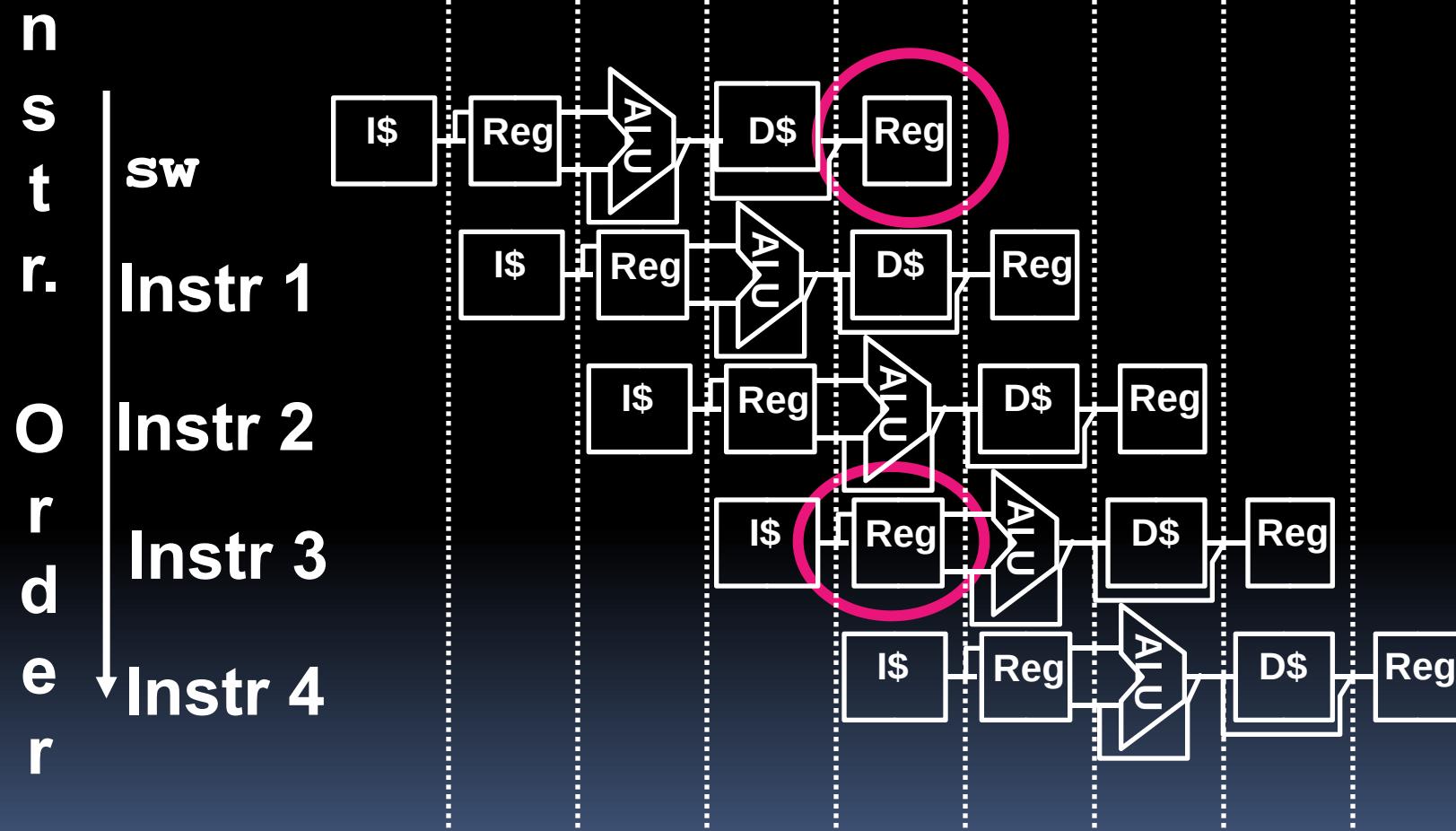
- **Solution:**

- **infeasible and inefficient to create second memory**
- (We'll learn about this shortly)
- ...so simulate this by having **two Level 1 Caches**
 - (a temporary smaller [of usually most recently used] copy of memory)
- have both an **L1 Instruction Cache** and an **L1 Data Cache**
- need more complex hardware to control when both caches miss

Structural Hazard #2: Registers

(1/2)

Time (clock cycles)



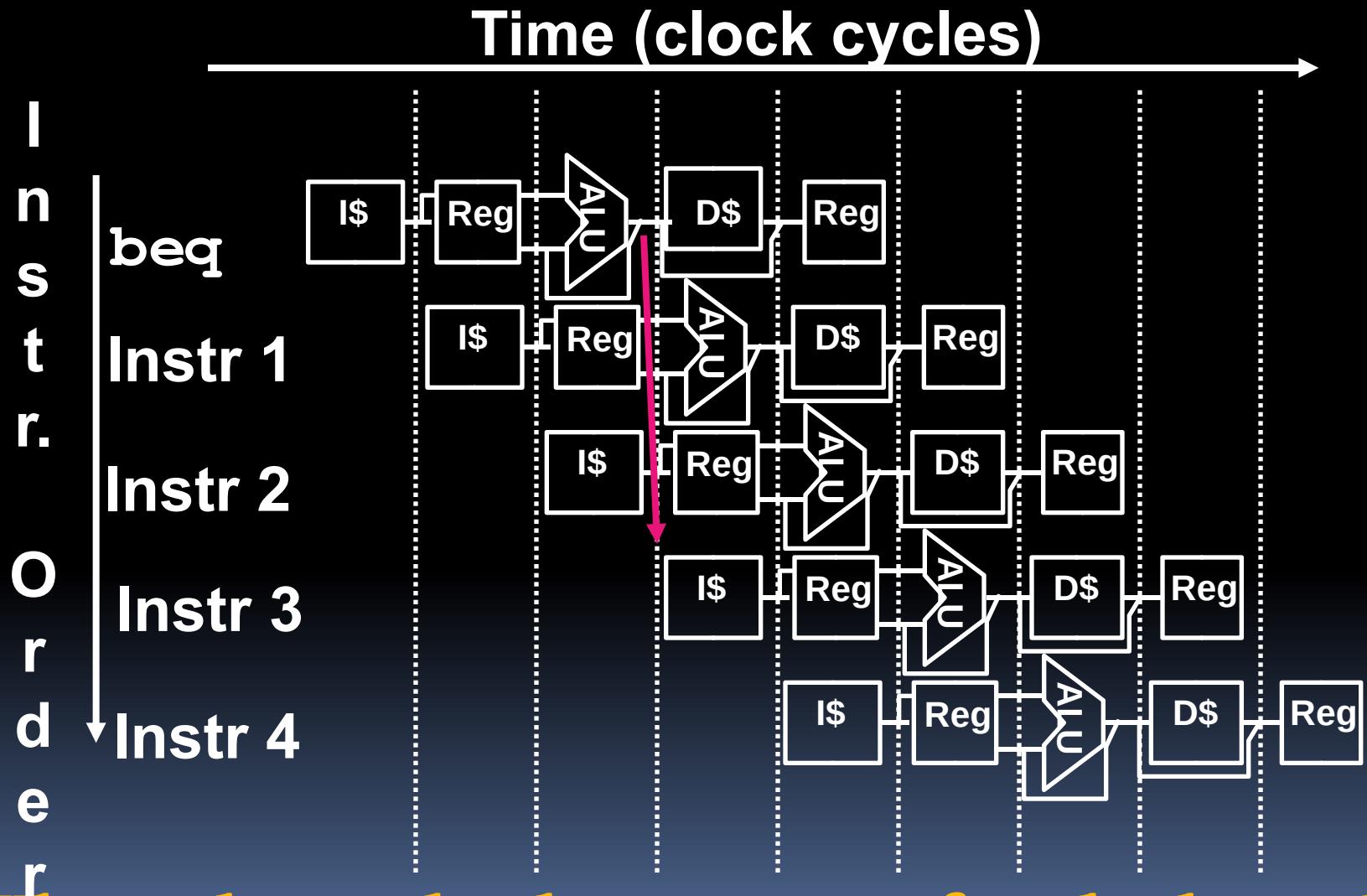
Can we read and write to registers simultaneously?

Structural Hazard #2: Registers

(2/2)

- Two different solutions have been used:
 - 1) RegFile access is **VERY fast: takes less than half the time of ALU stage**
 - Write to Registers during first half of each clock cycle
 - Read from Registers during second half of each clock cycle
 - 2) Build RegFile with independent read and write ports
- **Result: can perform Read and Write during same clock cycle**

Control Hazard: Branching (1 / 9)



Where do we do the compare for the branch?

Control Hazard: Branching (2/9)

- We had put branch decision-making hardware in ALU stage
 - therefore two more instructions after the branch will always be fetched, whether or not the branch is taken
- Desired functionality of a branch
 - if we do not take the branch, don't waste any time and continue executing normally
 - if we take the branch, don't execute any instructions after the branch, just go to the desired label

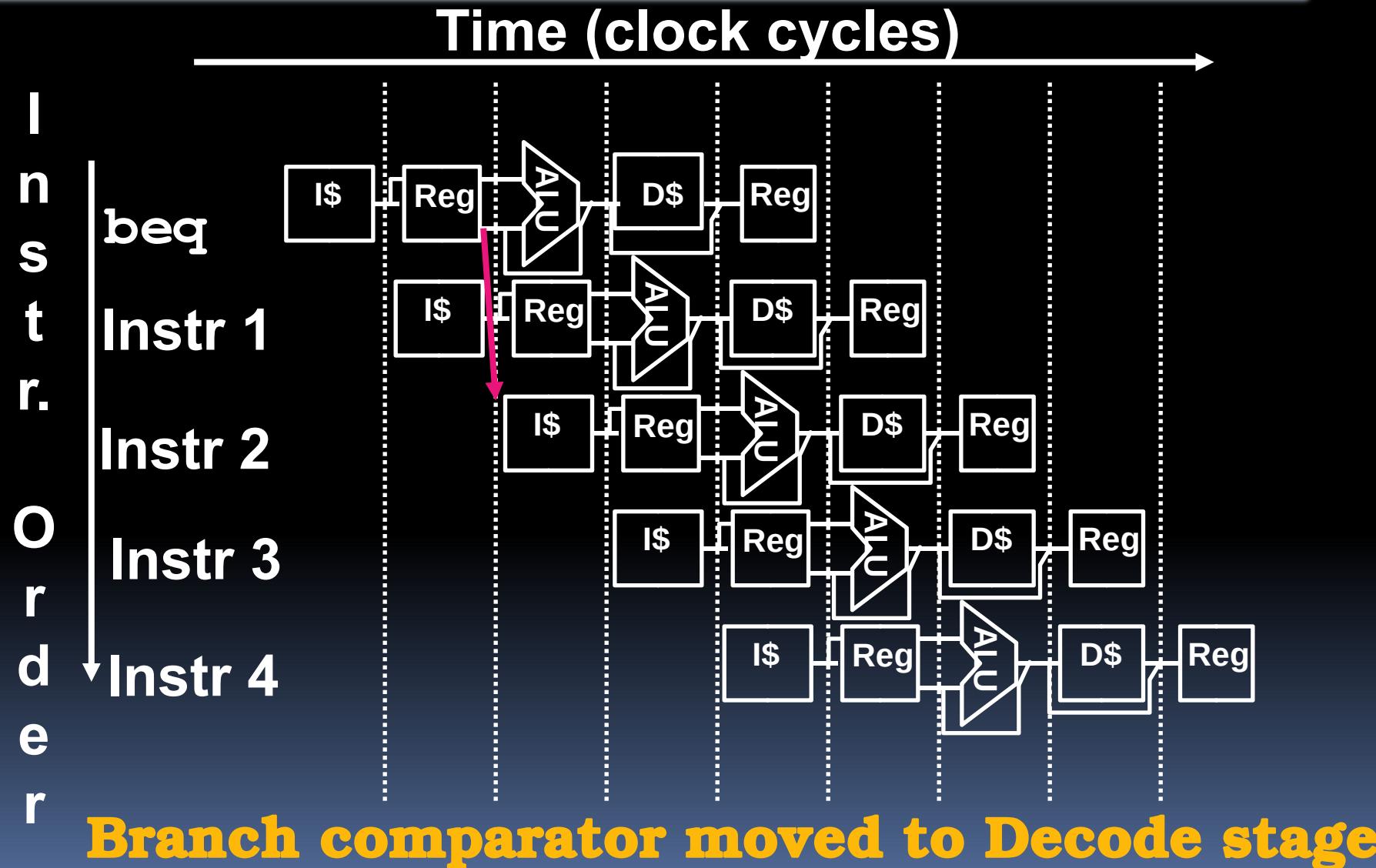
Control Hazard: Branching (3/9)

- **Initial Solution: Stall until decision is made**
 - **insert “no-op” instructions (those that accomplish nothing, just take time) or hold up the fetch of the next instruction (for 2 cycles).**
 - **Drawback: branches take 3 clock cycles each (assuming comparator is put in ALU stage)**

Control Hazard: Branching (4 / 9)

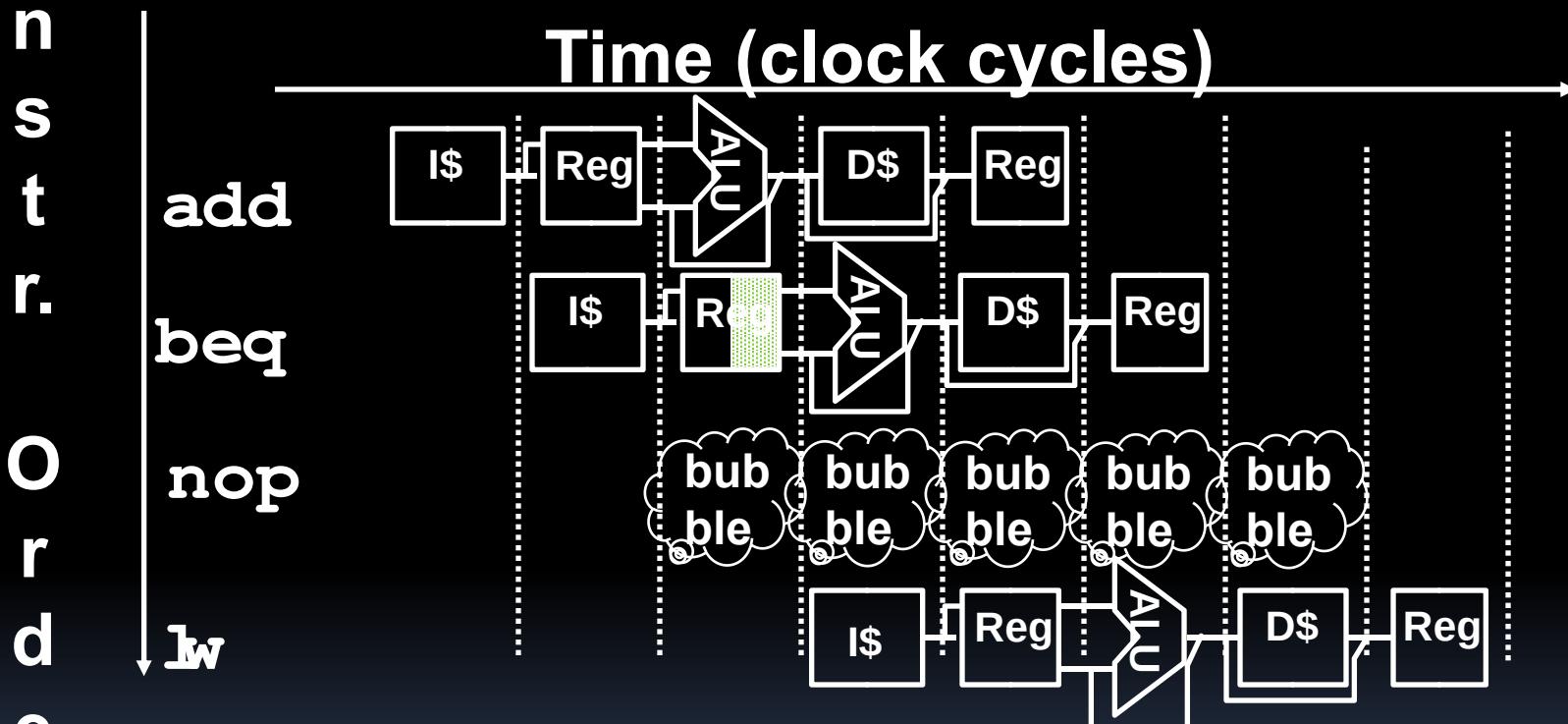
- **Optimization #1:**
 - **insert special branch comparator in Stage 2**
 - **as soon as instruction is decoded (Opcode identifies it as a branch), immediately make a decision and set the new value of the PC**
 - **Benefit: since branch is complete in Stage 2, only one unnecessary instruction is fetched, so only one no-op is needed**
 - **Side Note: This means that branches are idle in Stages 3, 4 and 5.**

Control Hazard: Branching (5 / 9)



Control Hazard: Branching (6/9)

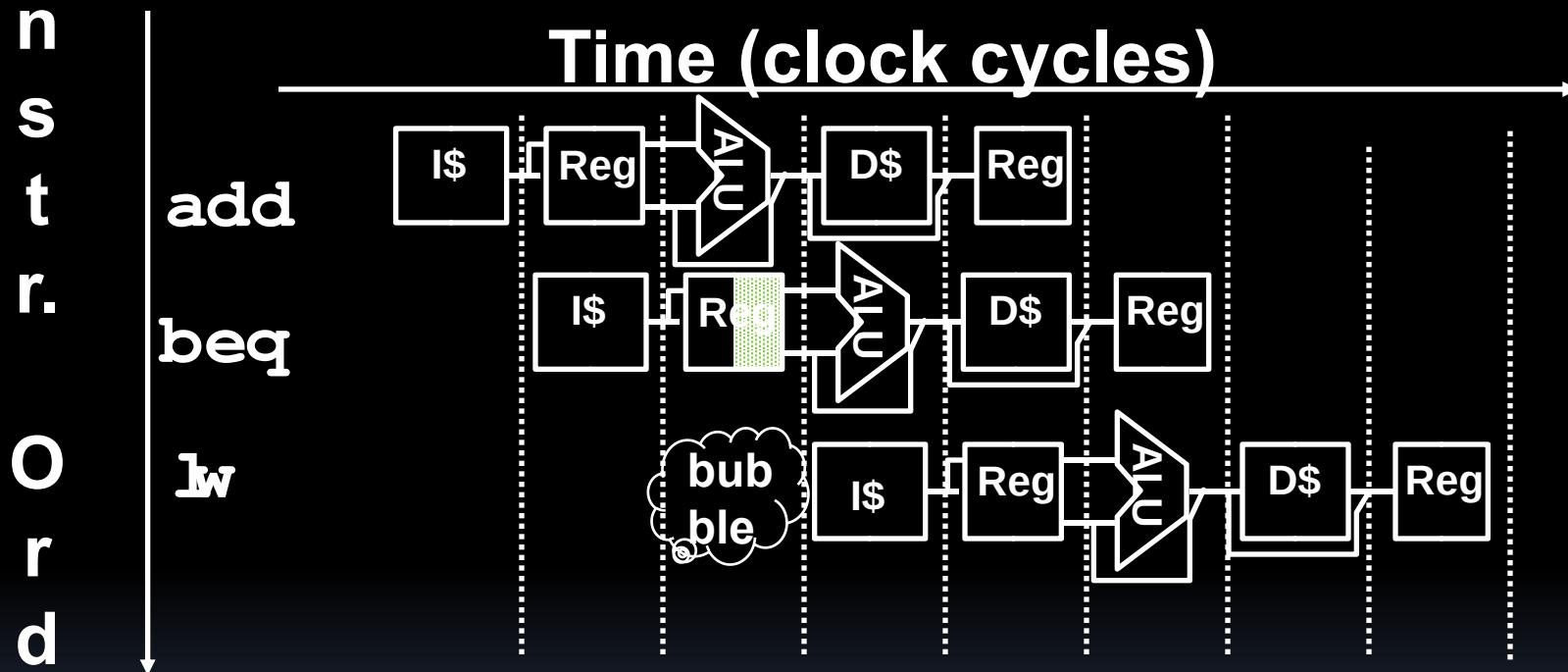
I ▪ User inserting no-op instruction



Impact: 2 clock cycles per branch instruction slow

Control Hazard: Branching (7 / 9)

I ▪ Controller inserting a single bubble



Impact: 2 clock cycles per branch instruction slow

...story about engineer, physicist, mathematician asked to build a fence around a flock of sheep

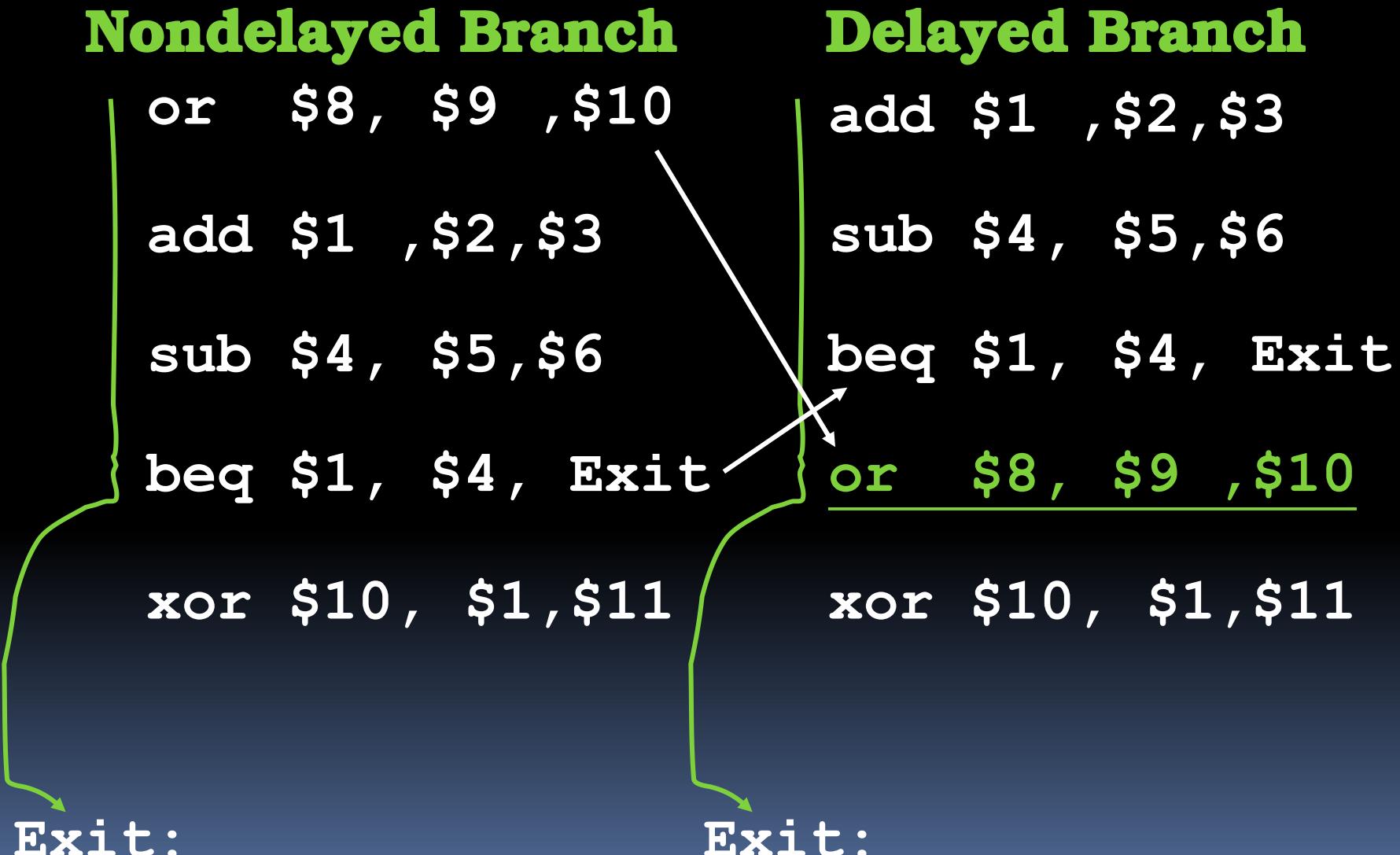
Control Hazard: Branching (8/9)

- **Optimization #2: Redefine branches**
 - Old definition: if we take the branch, none of the instructions after the branch get executed by accident
 - New definition: whether or not we take the branch, the single instruction immediately following the branch gets executed (called the **branch-delay slot**)
- The term “**Delayed Branch**” means we always execute inst after branch
- This optimization is used with MIPS

Control Hazard: Branching (9/9)

- **Notes on Branch-Delay Slot**
 - **Worst-Case Scenario:** can always put a no-op in the branch-delay slot
 - **Better Case:** can find an instruction preceding the branch which can be placed in the branch-delay slot without affecting flow of the program
 - re-ordering instructions is a common method of speeding up programs
 - compiler must be very smart in order to find instructions to do this
 - usually can find such an instruction at least 50% of the time

Example: Nondelayed vs. Delayed Branch



Data Hazards (1 / 2)

- Consider the following sequence of instructions

add \$t0, \$t1, \$t2

sub \$t4, \$t0 , \$t3

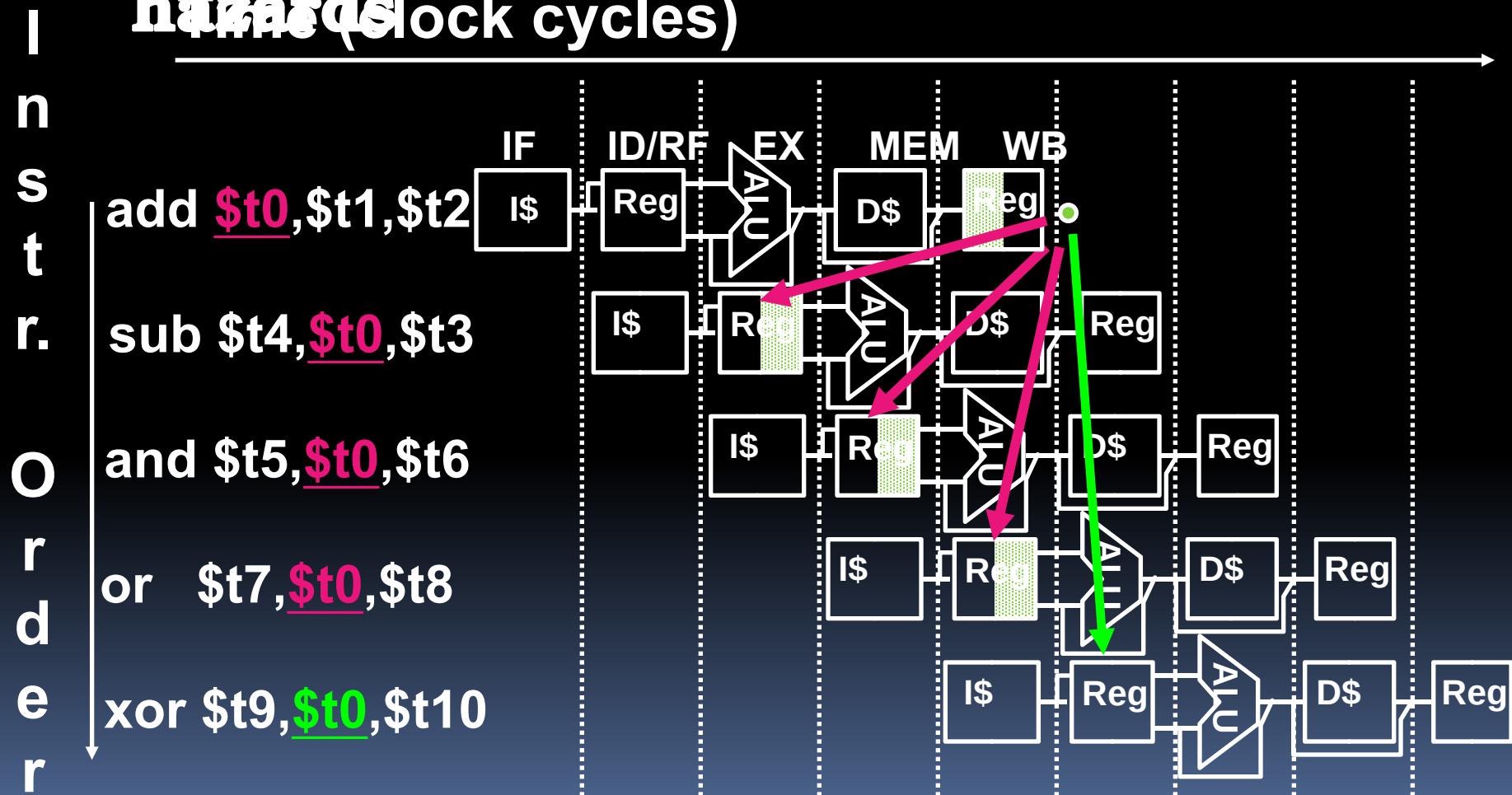
and \$t5, \$t0 , \$t6

or \$t7, \$t0 , \$t8

xor \$t9, \$t0 , \$t10

Data Hazards (2/2)

- Data-flow backward in time are hazards (lock cycles)



Data Hazard Solution:

Forwarding

Forward result from one stage to another

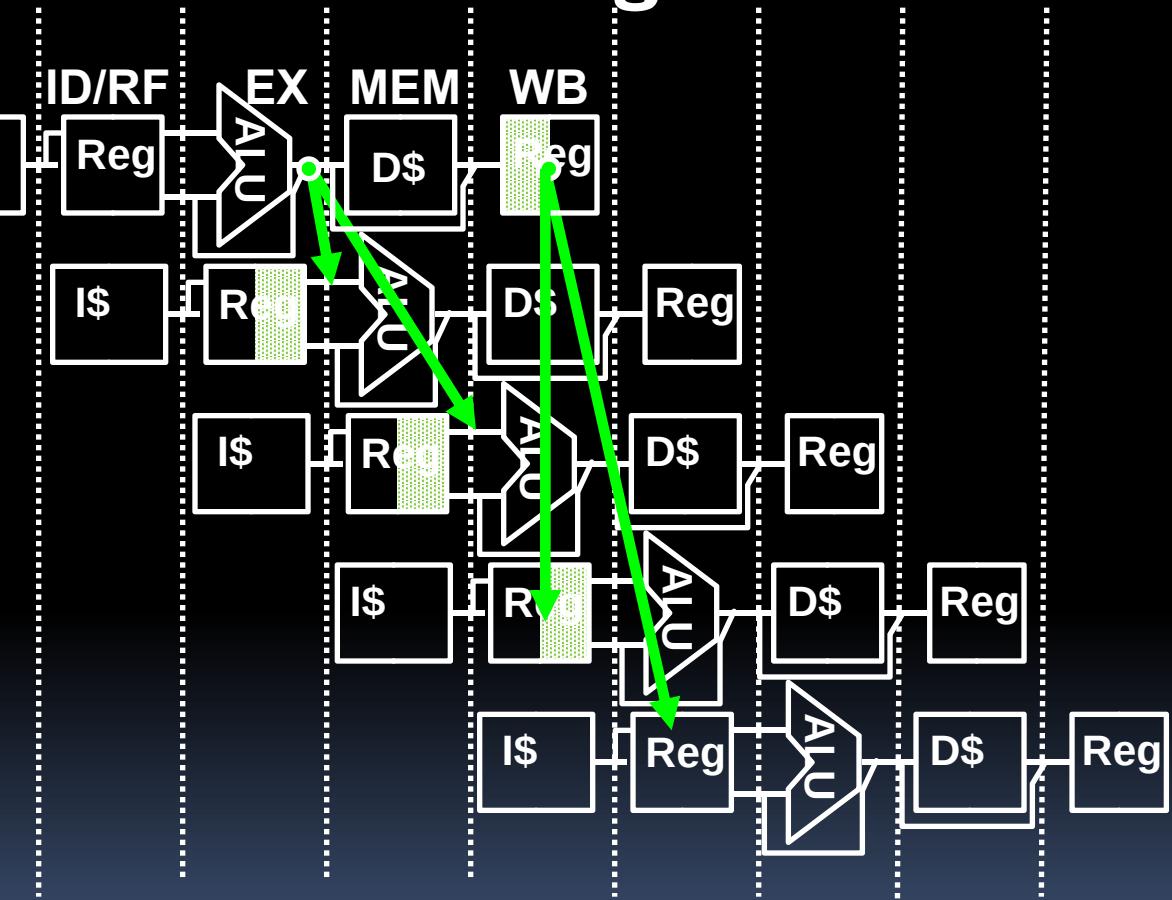
add \$t0,\$t1,\$t2

sub \$t4,\$t0,\$t3

and \$t5,\$t0,\$t6

or \$t7,\$t0,\$t8

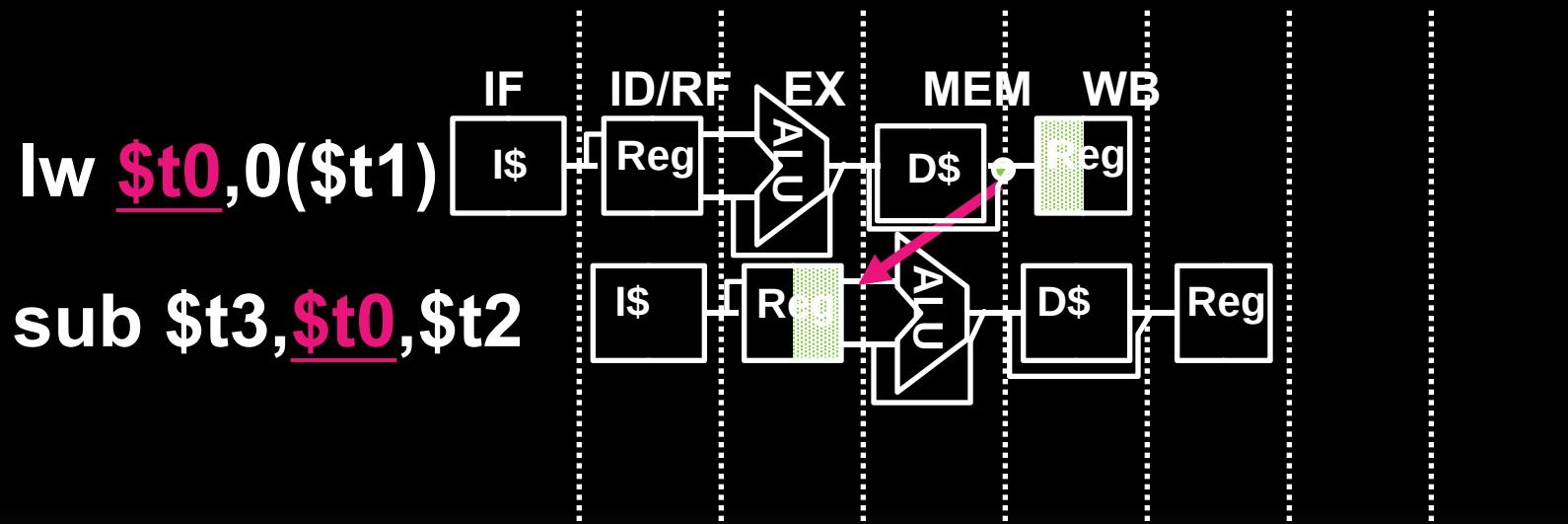
xor \$t9,\$t0,\$t10



“or” hazard solved by register hardware

Data Hazard: Loads (1 / 4)

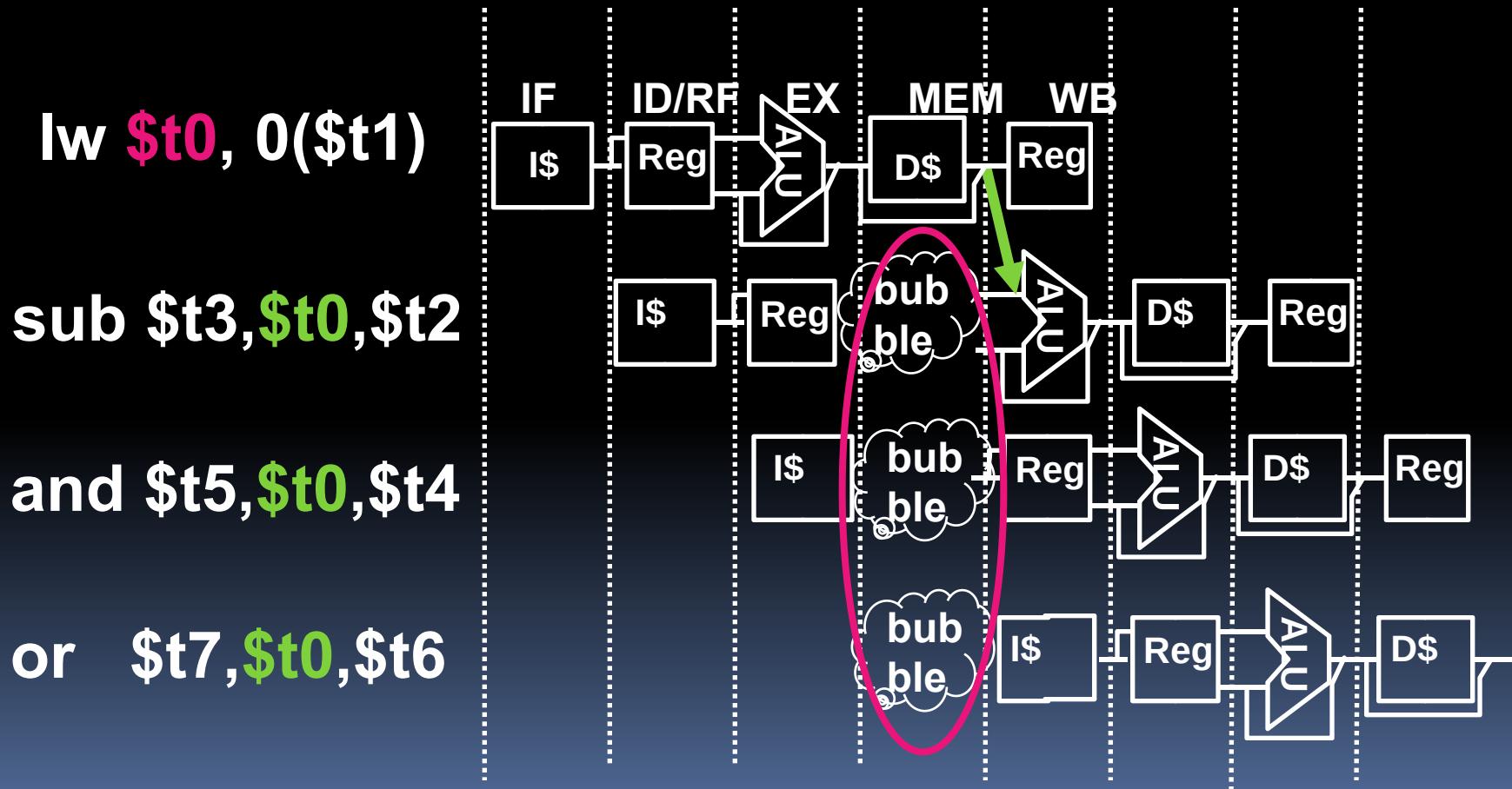
- Dataflow backwards in time are hazards



- Can't solve all cases with forwarding
- Must stall instruction dependent on load, then forward (more hardware)

Data Hazard: Loads (2 / 4)

- **Hardware stalls pipeline**
 - Called “interlock”



Data Hazard: Loads (3/4)

- **Instruction slot after a load is called “load delay slot”**
- **If that instruction uses the result of the load, then the hardware interlock will stall it for one cycle.**
- **If the compiler puts an unrelated instruction in that slot, then no stall**
- **Letting the hardware stall the instruction in the delay slot is equivalent to putting a nop in the slot (except the latter uses more code space)**

Data Hazard: Loads (4/4)

- Stall is equivalent to nop

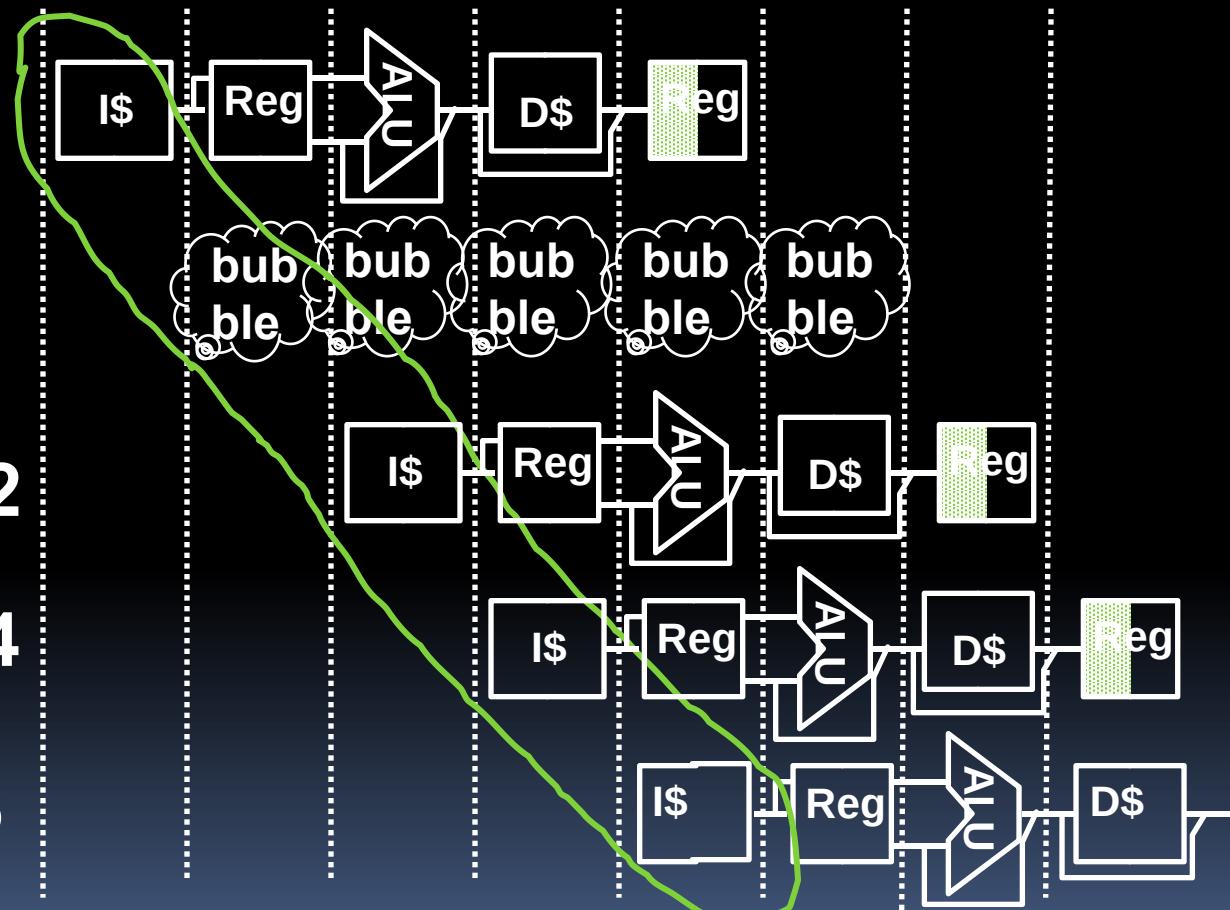
lw \$t0, 0(\$t1)

nop

sub \$t3,\$t0,\$t2

and \$t5,\$t0,\$t4

or \$t7,\$t0,\$t6



Peer Instruction

- 1) Thanks to pipelining, I have reduced the time it took me to wash my one shirt.

- 2) Longer pipelines are always a win (since less work per stage & a faster clock).

	12
a)	FF
b)	FT
c)	TF
d)	TT

“And in Conclusion..”

- **Pipeline challenge is hazards**
 - Forwarding helps w/many data hazards
 - Delayed branch helps with control hazard in 5 stage pipeline
 - Load delay slot / interlock necessary
- **More aggressive performance:**
 - Superscalar
 - Out-of-order execution

Bonus slides

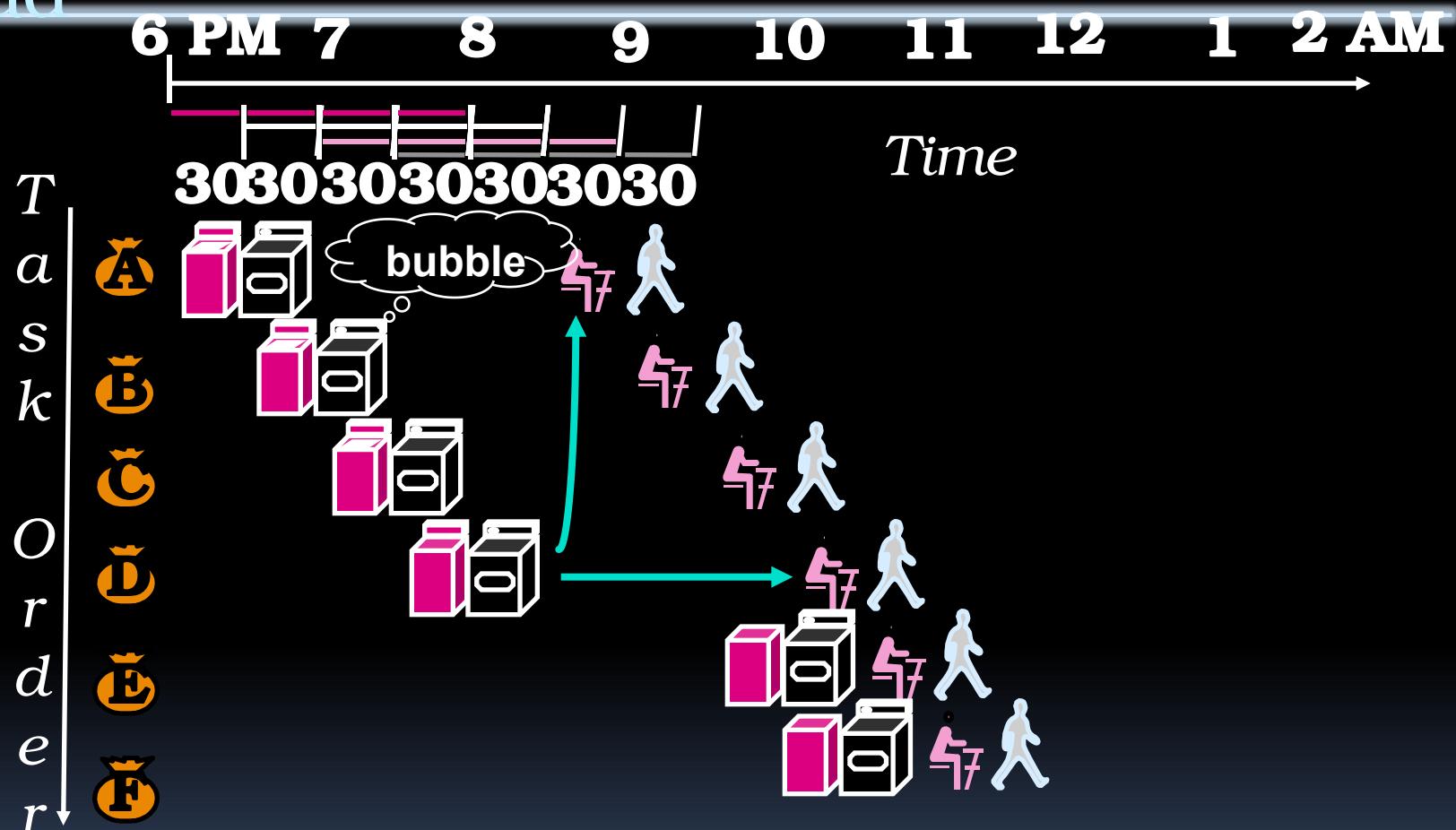
- These are extra slides that used to be included in lecture notes, but have been moved to this, the “bonus” area to serve as a supplement.
- The slides will appear in the order they would have in the normal presentation

Bonus

Historical Trivia

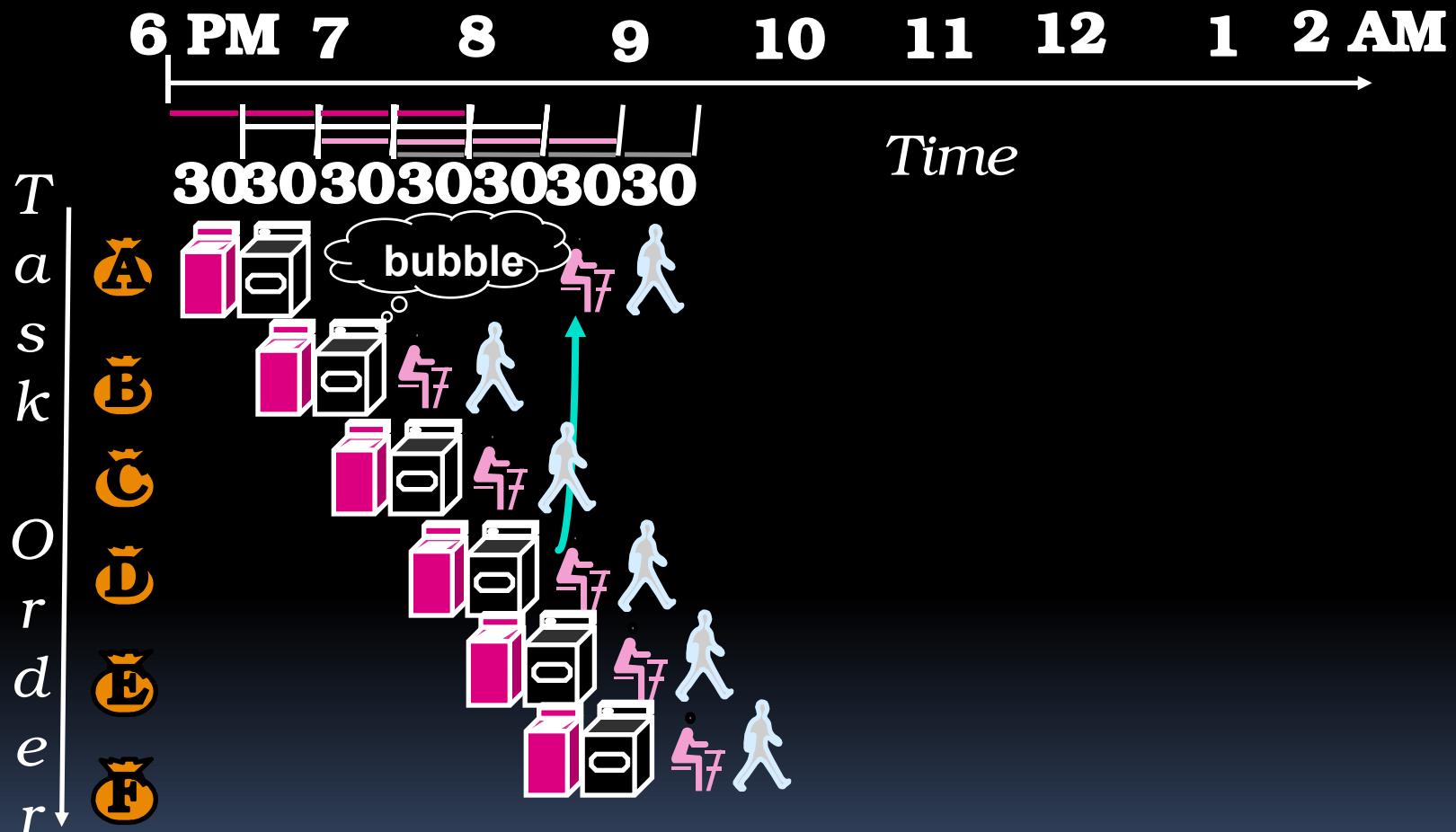
- **First MIPS design did not interlock and stall on load-use data hazard**
- **Real reason for name behind MIPS:**
**Microprocessor without
Interlocked
Pipeline
Stages**
 - **Word Play on acronym for Millions of Instructions Per Second, also called MIPS**

Pipeline Hazard: Matching socks in later load



- A depends on D; stall since folder tied up; Note this is much different from processor cases so far. We have not had a earlier instruction depend on a later one.

Out-of-Order Laundry: Don't Wait



- A depends on D; rest continue; need more resources to allow out-of-order

Superscalar Laundry: Parallel per stage



- More resources, HW to match mix of parallel tasks?

Superscalar Laundry: Mismatch



- Task mix underutilizes extra resources

Peer Instruction (1/2)

Assume 1 instr/clock, delayed branch, 5 stage pipeline, forwarding, interlock on unresolved load hazards (after 10^3 loops, so pipeline full)

Loop:

lw	\$t0, 0(\$s1)
addu	\$t0, \$t0, \$s2
sw	\$t0, 0(\$s1)
addiu	\$s1, \$s1, -4
bne	\$s1, \$zero, Loop
nop	

1
2
3
4
5
6
7
8
9
10

- How many pipeline stages (clock cycles) per loop iteration to execute this code?

Peer Instruction Answer (1 / 2)

- Assume 1 instr/clock, delayed branch, 5 stage pipeline, forwarding, interlock on unresolved load hazards. 10³ iterations, so pipe2in(data hazard so stall)

Loop:

1.	lw	\$t0, 0(\$\$s1)
3.	addu	\$t0, \$t0, \$\$s2
4.	sw	\$t0, 0(\$\$s1)
5.	addiu	\$s1, \$\$s1, -4
6.	bne	\$s1, \$zero, Loop
7.	nop	(delayed branch so exec. nop)

- How many pipeline stages (clock cycles) per loop iteration to execute this code?

1 2 3 4 5 6 7 8 9 10

Peer Instruction (2/2)

**Assume 1 instr/clock, delayed branch, 5 stage pipeline, forwarding, interlock on unresolved load hazards (after 10^3 loops, so pipeline full).
Rewrite this code to reduce pipeline stages (clock cycles) per loop to as few as possible.**

Loop:

lw	\$t0, 0(\$s1)
addu	\$t0, \$t0, \$s2
sw	\$t0, 0(\$s1)
addiu	\$s1, \$s1, -4
bne	\$s1, \$zero, Loop
nop	

1
2
3
4
5
6
7
8
9
10

- How many pipeline stages (clock cycles) per loop iteration to execute this code?

Peer Instruction (2/2) How long to execute?

- Rewrite this code to reduce clock cycles per loop to as few as possible:

Loop:

1.	lw	\$t0	0 (\$s1)
2.	addiu	\$s1,	\$s1, -4
3.	addu	\$t0,	\$t0 \$s2
4.	bne	\$s1,	\$zero, Loop
5.	sw	\$t0,	+4 (\$s1)

(no hazard since extra cycle)

(modified sw to put past addiu)

- How many pipeline stages (clock cycles) per loop iteration to execute your revised code? (assume pipeline is full)

1 2 3 4 5 6 7 8 9 10

0.25 Cache



Computer Architecture (计算机体系结构)

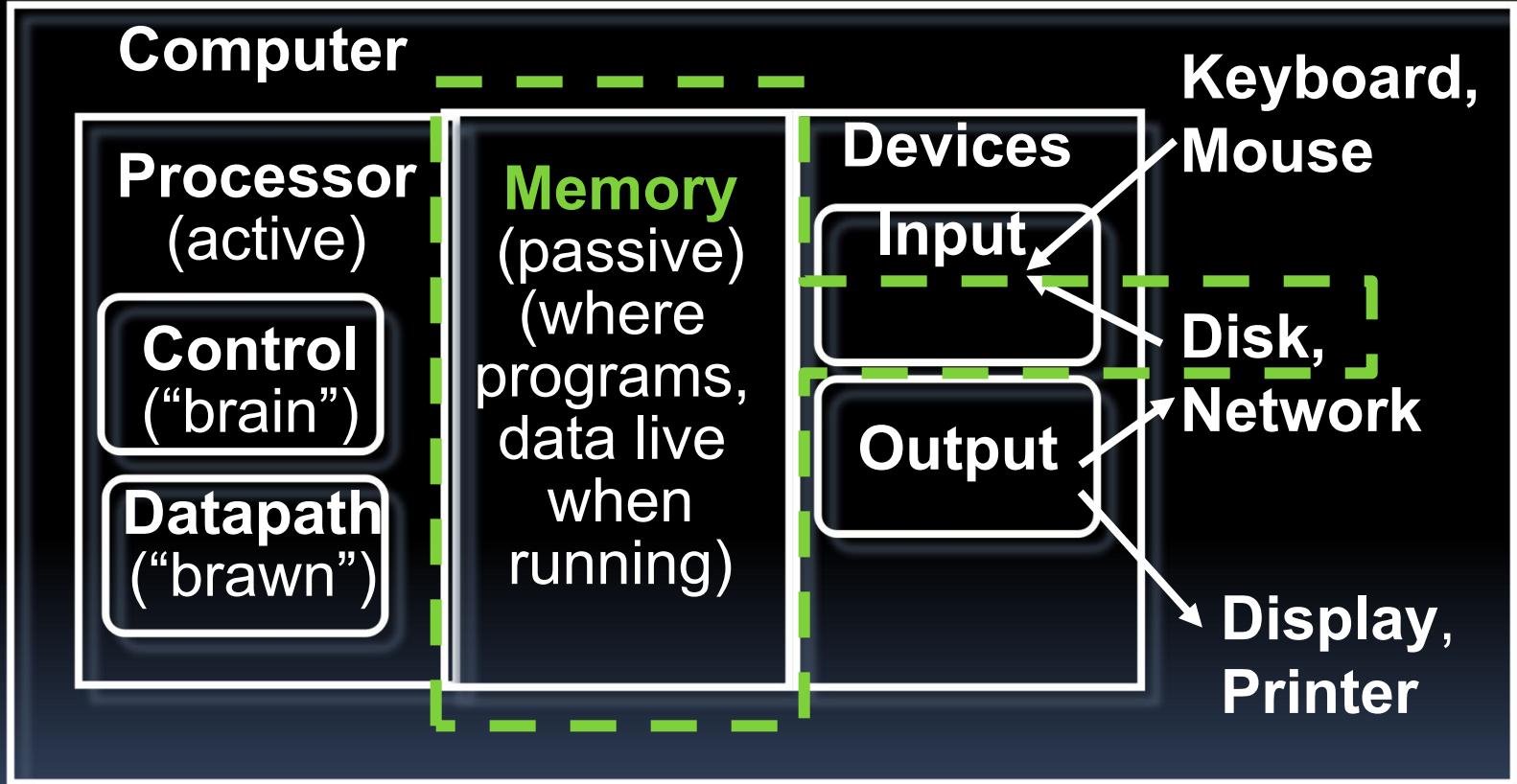
Lecture 25 – Caches I 2020-10-26

Lecturer:
Yuanqing
Cheng

Review : Pipelining

- **Pipeline challenge is hazards**
 - Forwarding helps w/many data hazards
 - Delayed branch helps with control hazard in our 5 stage pipeline
 - Data hazards w/Loads → Load Delay Slot
 - Interlock → “smart” CPU has HW to detect if conflict with inst following load, if so it stalls
- **More aggressive performance
(discussed in section next week)**
 - Superscalar (parallelism)
 - Out-of-order execution

The Big Picture



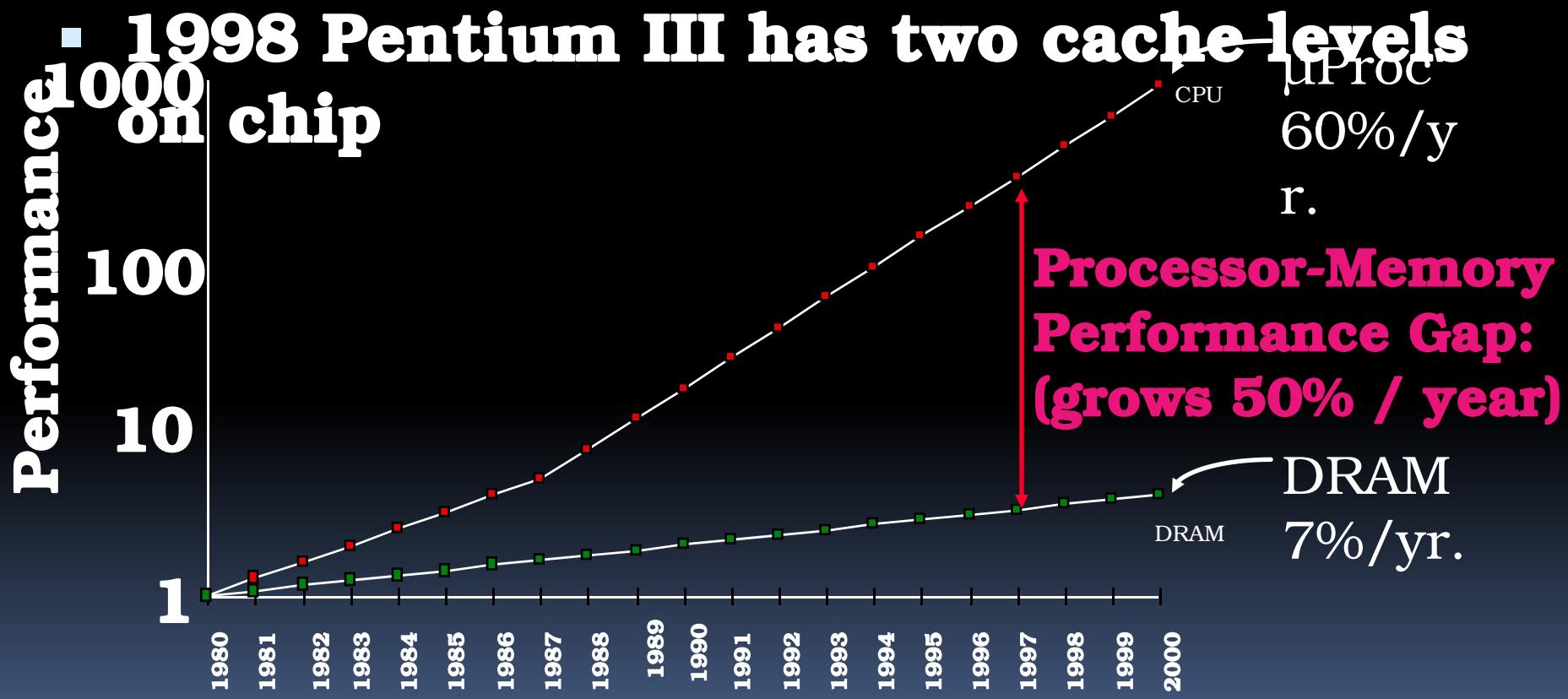
Memory Hierarchy

I.e., storage in computer systems

- **Processor**
 - **holds data in register file (~100 Bytes)**
 - **Registers accessed on nanosecond timescale**
- **Memory (we'll call “main memory”)**
 - **More capacity than registers (~Gbytes)**
 - **Access time ~50-100 ns**
 - **Hundreds of clock cycles per memory access?!**
- **Disk**
 - **HUGE capacity (virtually limitless)**
 - **VERY slow: runs ~milliseconds**

Motivation: Why We Use Caches (written \$)

- **1989 first Intel CPU with cache on chip**
- **1998 Pentium III has two cache levels on chip**



**Processor-Memory
Performance Gap:
(grows 50% / year)**

DRAM
7%/yr.

Memory Caching

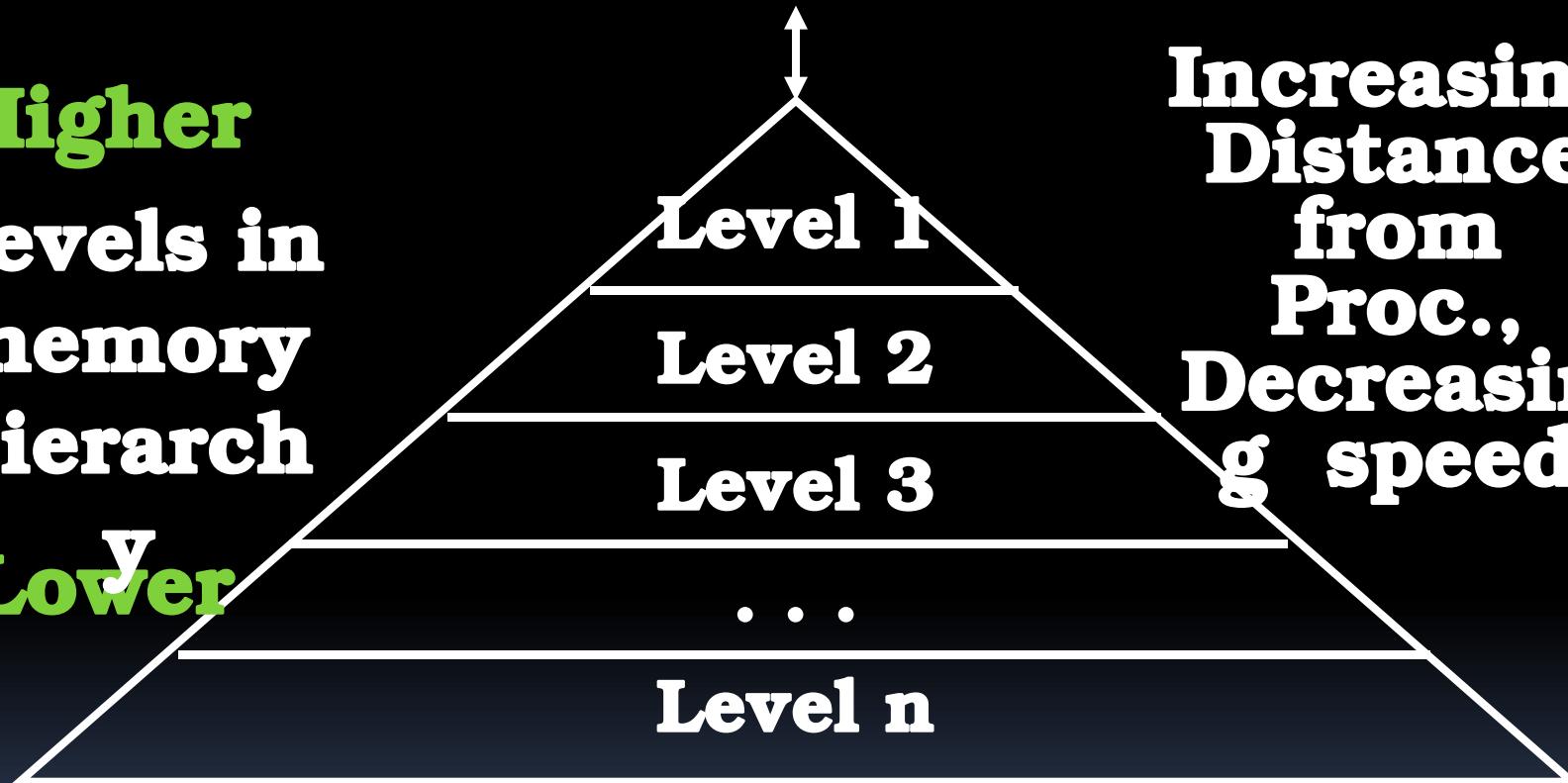
- **Mismatch between processor and memory speeds leads us to add a new level: a memory cache**
- **Implemented with same IC processing technology as the CPU (usually integrated on same chip): faster but more expensive than DRAM memory.**
- **Cache is a copy of a subset of main memory.**
- **Most processors have separate caches for instructions and data.**

Memory Hierarchy

Higher
Levels in
memory
hierarch

Lower

Processor



Size of memory at each level
As we move to deeper levels the latency goes up and price per bit goes down.

Memory Hierarchy

- If level closer to Processor, it is:
 - Smaller
 - Faster
 - More expensive
 - subset of lower levels (contains most recently used data)
- Lowest Level (usually disk) contains all available data (does it go beyond the disk?)
- Memory Hierarchy presents the processor with the illusion of a very large & fast memory

Memory Hierarchy Analogy: Library (1 / 2)

- You're writing a term paper (Processor) at a **table** in **Doe**
- **Doe Library** is equivalent to **disk**
 - essentially limitless capacity
 - very slow to retrieve a book
- **Table** is **main memory**
 - smaller capacity: means you must return book when table fills up
 - easier and faster to find a book there once you've already retrieved it

Memory Hierarchy Analogy: Library (2/2)

- **Open books on table are cache**
 - **smaller capacity:** can have very few open books fit on table; again, when table fills up, you must close a book
 - **much, much faster to retrieve data**
- **Illusion created: whole library open on the tabletop**
 - **Keep as many recently used books open on table as possible since likely to use again**
 - **Also keep as many books on table as possible, since faster than going to library**

Memory Hierarchy Basis

- Cache contains copies of data in memory that are being used.
- Memory contains copies of data on disk that are being used.
- Caches work on the principles of temporal and spatial locality.
 - Temporal Locality: if we use it now, chances are we'll want to use it again soon.
 - Spatial Locality: if we use a piece of memory, chances are we'll use the neighboring pieces soon.

Cache Design

- **How do we organize cache?**
- **Where does each memory address map to?**
 - (Remember that cache is subset of memory, so multiple memory addresses map to the same cache location.)
- **How do we know which elements are in cache?**
- **How do we quickly locate them?**

Direct-Mapped Cache (1 / 4)

- In a **direct-mapped cache**, each memory address is associated with one possible **block** within the cache
 - Therefore, we only need to look in a single location in the cache for the data if it exists in the cache
 - Block is the unit of transfer between cache and memory

Direct-Mapped Cache

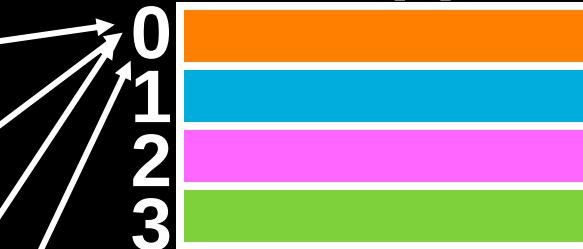
(2/4)

Memory

Address Memory



Cache 4 Byte Direct
Mapped Cache



Block size = 1 byte

**Cache Location 0 can
be
occupied by data from:**

- **Memory location 0, 4, 8, ...**
- **4 blocks \Rightarrow any memory**

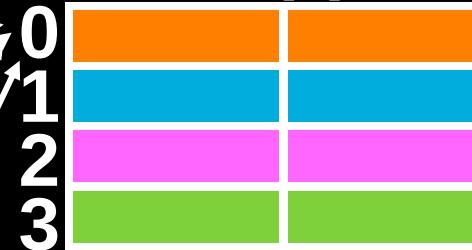
**What if we wanted a block
to be bigger than one byte?**

Direct-Mapped Cache

(3/4)

Memory Address	Memory	
0	1	0
2	3	2
4	5	4
6	7	6
8	9	8
A	etc	
C		
E		
10		
12		
14		
16		
18		
1A		
1C		
1E		

Cache 8 Byte Direct
Mapped Cache



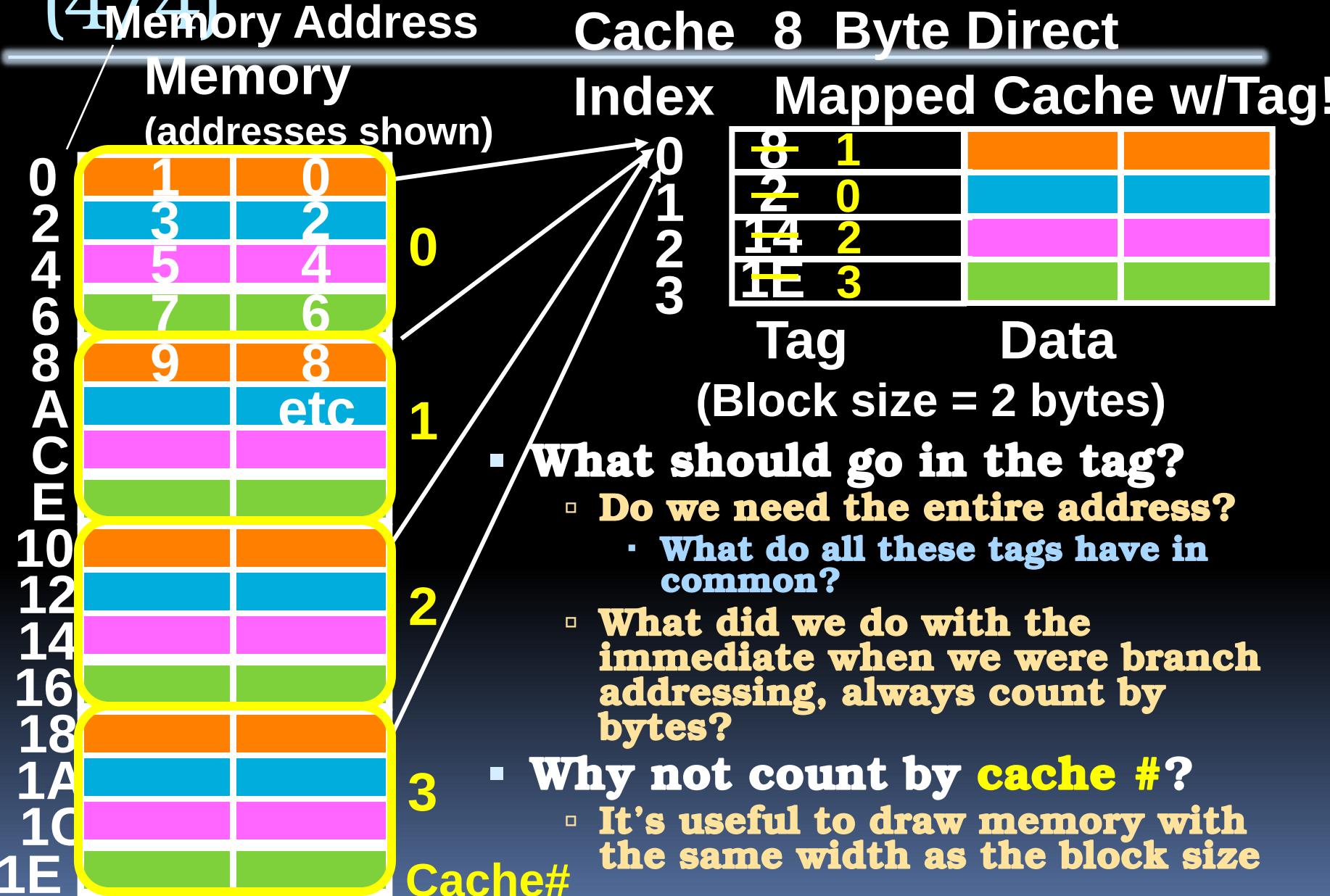
Block size = 2 bytes

When we ask for a byte, the system finds out the right block, and loads it all!

- How does it know right block?
- How do we select the byte?
- E.g., Mem address 11101?
- How does it know WHICH colored block it originated from?
 - What do you do at baggage claim?

Direct-Mapped Cache

(4/4)



Issues with Direct-Mapped

- Since multiple memory addresses map to same cache index, how do we tell which one is in there?
- What if we have a block size > 1 byte?
- Answer: divide memory address into three fields

tttttttttttttttt	iiiiiiiiii	oooo
------------------	------------	------

tag
to check
if have
correct block

index
to
select
block

byte
offset
within
block

Direct-Mapped Cache

Terminology

- All fields are read as unsigned integers.
- Index
 - specifies the cache index (which “row”/block of the cache we should look in)
- Offset
 - once we've found correct block, specifies which byte within the block we want
- Tag
 - the remaining bits after offset and index are determined; these are used to

TIO great cache mnemonic

AREA (cache size, B)

= **HEIGHT (# of blocks)**,

* **WIDTH (size of one block,**

B/block)

$$2^{(H+W)} = 2^H * 2^W$$

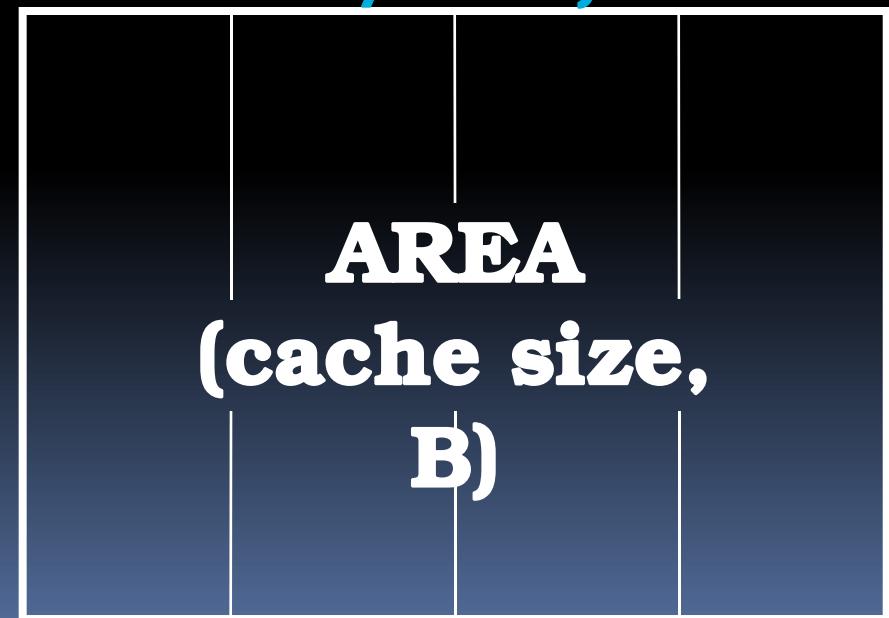
<u>Tag</u>	<u>Index</u>	<u>Offset</u>
------------	--------------	---------------

WIDTH

(size of one block,

B/block)

HEIGHT
(# of blocks)



Direct-Mapped Cache Example

(1 / 3)

- Suppose we have a 8B of data in a direct-mapped cache with 2 byte blocks
 - Sound familiar?
- Determine the size of the tag, index and offset fields if we're using a 32-bit architecture
- Offset
 - need to specify correct byte within a block
 - block contains 2 bytes
= 2^1 bytes

Direct-Mapped Cache Example

(2/3)

Index: (~index into an “array of blocks”)

- need to specify correct block in cache
- cache contains $8 \text{ B} = 2^3 \text{ bytes}$
- block contains $2 \text{ B} = 2^1 \text{ bytes}$
- # blocks/cache

$$= \frac{\text{bytes/cache}}{\text{bytes/block}}$$

$$= \frac{2^3 \text{ bytes/cache}}{2^1 \text{ bytes/block}}$$

$$= 2^2 \text{ blocks/cache}$$

- need 2 bits to specify this many blocks

Direct-Mapped Cache Example

(3/3)

- Tag: use remaining bits as tag
 - tag length = addr length - offset - index
 - = 32 - 1 - 2 bits
 - = 29 bits
 - so tag is leftmost 29 bits of memory address
- Why not full 32 bit address as tag?
 - All bytes within block need same address (4b)
 - Index must be same for every address within a block, so it's redundant in tag check, thus can leave off to save memory

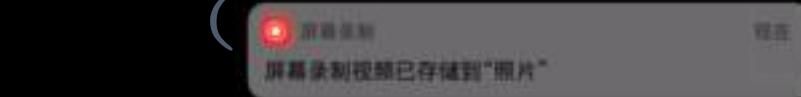
And in Conclusion...

- We would like to have the capacity of disk at the speed of the processor: unfortunately this is not feasible.
- So we create a memory hierarchy:
 - each successively lower level contains “most used” data from next higher level
 - exploits temporal & spatial locality
 - do the common case fast, worry less about the exceptions
(design principle of MIPS)
- Locality of reference is a Big Idea



Lecturer
Yuanqing
Cheng

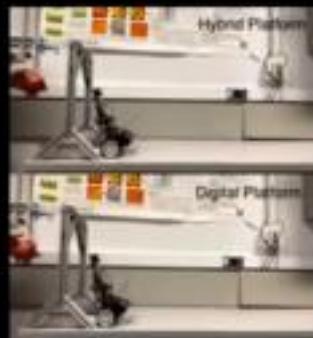
Computer Architecture



Lectures II

Brain-Inspired
Uses Memristors

Memristor-based



Controller
Efficient
Performance



Direct-Mapped Cache

Terminology

All fields are read as unsigned integers.

- **Index**
 - specifies the cache index (or “row”/block)
- **Tag**
 - distinguishes betw the addresses that map to the same location
- **Offset**
 - specifies which byte within the block we want



tag
to check
if have
within
correct block

index
to
select
block

byte
offset
block

TIO Dan's great cache mnemonic

AREA (cache size, B)

= **HEIGHT (# of blocks)**,

* **WIDTH (size of one block,**

B/block)

$$2^{(H+W)} = 2^H * 2^W$$



WIDTH
(size of one block,
B/block)

Addr size
(usu 32 bits)

HEIGHT
(# of blocks)

AREA
(cache size,
B)

Caching Terminology

- When reading memory, 3 things can happen:
 - **cache hit:** cache block is valid and contains proper address, so read desired word
 - **cache miss:** nothing in cache in appropriate block, so fetch from memory
 - **cache miss, block replacement:** wrong data is in cache at appropriate block, so discard it and fetch desired data from memory (cache always copy)

Accessing data in a direct mapped cache

- **Ex.: 16KB of data, direct-mapped, 4 word blocks**
 - Can you work out height, width, area?
- **Read 4 addresses**
 1. 0x00000014
 2. 0x0000001C
 3. 0x00000034
 4. 0x00008014

Memory Address (hexValue of Word)	...
00000010	a
00000014	b
00000018	c
0000001C	d
...	...
00000030	e
00000034	f
00000038	g
0000003C	h
...	...
00008010	j
00008014	j
00008018	k
0000801C	l
...	...

Accessing data in a direct mapped cache

- **4 Addresses:**

- 0x00000014 , 0x0000001C ,
0x00000034 , 0x00008014

- **4 Addresses divided (for convenience) into Tag, Index, Byte Offset fields**

0000000000000000 000000000001 0100

00000000000000000000000000 000000000001 1100

00000000000000000000000000 000000000011 0100

0000000000000000000000000010 000000000001 0100

Offset

Tag

Index

16 KB Direct Mapped Cache, 16B

- ~~blocks~~ **Valid bit:** determines whether anything is stored in that row (when computer initially turned on, all entries invalid)

Valid

Index	Tag	0xc-f	0x8-b	0x4-7	0x0-3
0	0				
1	0				
2	0				
3	0				
4	0				
5	0				
6	0				
7	0				
...		...			
1022	0				
1023	0				

1. Read 0x000000014

- 000000000000000000000001 0100
Tag field Index field Offset

Valid

Index	Tag	0xc-f	0x8-b	0x4-7	0x0-3
0	0				
1	0				
2	0				
3	0				
4	0				
5	0				
6	0				
7	0				

...

...

1022	0				
1023	0				

So we read block 1 (00000000001)

- 00000000000000000000 **0000000001** ~~0000000001~~ 0100
Tag field Index field Offset

Valid	Index	Tag	0xc-f	0x8-b	0x4-7	0x0-3
0	0					
1	0					
2	0					
3	0					
4	0					
5	0					
6	0					
7	0					
...			...			
1022	0					
1023	0					

1022	0					
1023	0					

No valid data

- 00000000000000000000 **0000000001** ~~0000000001~~ 0100
Tag field Index field Offset

Index	Tag	0xc-f	0x8-b	0x4-7	0x0-3
0	0				
1	1				
2	0				
3	0				
4	0				
5	0				
6	0				
7	0				
...		...			
1022	0				
1023	0				

So load that data into cache, setting tag,

valid

~~00000000000000000000~~ 0000000001 0100
Tag field Index field Offset

Valid

Index Tag

0xc-f

0x8-b

0x4-7

0x0-3

0	0	d	c	b	a
1	1				
2	0				
3	0				
4	0				
5	0				
6	0				
7	0				

...

...

1022 0

1023 0

Read from cache at offset, return word

b 00000000000000000000 0000000001 0100
Tag field Index field Offset

Valid

Index	Tag	0xc-f	0x8-b	0x4-7	0x0-3
0	0				
1	0	d	c	b	a
2	0				
3	0				
4	0				
5	0				
6	0				
7	0				

...

...

1022	0				
1023	0				

2. Read 0x00000001C = 0...00 0..001

- p₁₀₀ 0000000000000000 00000000001 1100
Valid Tag field Index field Offset

Index	Tag	0xc-f	0x8-b	0x4-7	0x0-3
0	0				
1	0	d	c	b	a
2	0				
3	0				
4	0				
5	0				
6	0				
7	0				

...

...

1022	0				
1023	0				

Index is Valid

- 00000000000000000000000000000001 1100
Tag field Index field Offset

Valid

Index Tag

0	0				
1	1	0	d	c	b
2	0				
3	0				
4	0				
5	0				
6	0				
7	0				

...

...

1022	0			
1023	0			

Index valid, Tag Matches

-  00000000000000000000000000000000 000000000001 1100
Tag field Index field Offset

Valid

Index Tag

	0	0xc-f	0x8-b	0x4-7	0x0-3
0	0				
1	0	d	c	b	a
2	0				
3	0				
4	0				
5	0				
6	0				
7	0				

...

...

1022	0				
1023	0				

Index Valid, Tag Matches, return d

- 00000000000000000000000000000000 00000000001 1100
 - Tag field
 - Index field
 - Offset

Valid	Index	Tag	0xc-f	0x8-b	0x4-7	0x0-3
0	0					
1	1	0	d	c	b	a
2	0					
3	0					
4	0					
5	0					
6	0					
7	0					

...

...

1022	0				
1023	0				

3. Read 0x000000034 = 0...00 0..011

01000000000000000000000000000000 00000000011 0100
Valid Tag field Index field Offset

Index	Tag	0xc-f	0x8-b	0x4-7	0x0-3
0	0				
1	0	d	c	b	a
2	0				
3	0				
4	0				
5	0				
6	0				
7	0				

...

...

1022	0				
1023	0				

So read block 3

- 00000000000000000000 **0000000011** 0100
Valid Tag field Index field Offset

Index	Tag	0xc-f	0x8-b	0x4-7	0x0-3
0	0				
1	0	d	c	b	a
2	0				
3	0				
4	0				
5	0				
6	0				
7	0				

...

...

1022	0				
1023	0				

No valid data

- 00000000000000000000 **Index field** 0000000011 **Offset** 0100
Valid Tag 0xc-f 0x8-b 0x4-7 0x0-3

Index	Tag	0xc-f	0x8-b	0x4-7	0x0-3
0	0				
1	0	d	c	b	a
2	0				
3	0				
4	0				
5	0				
6	0				
7	0				

...

...

1022	0				
1023	0				

Load that cache block, return word

- $\text{f}000000000000000000000000000000$ **Tag field** 0000000011 **Index field** 0100 **Offset**
Valid

Index	Tag	0xc-f	0x8-b	0x4-7	0x0-3
0	0				
1	0	d	c	b	a
2	0				
3	1	0	h	g	f
4	0				
5	0				
6	0				
7	0				e

...

...

1022	0				
1023	0				

4. Read $0x00008014 = 0...10\ 0..001$

▪ ~~0100~~0000000000000010 ~~0000000001~~ 0100
Valid Tag field Index field Offset

Index	Tag	0xc-f	0x8-b	0x4-7	0x0-3
0	0				
1	0	d	c	b	a
2	0				
3	0	h	g	f	e
4	0				
5	0				
6	0				
7	0				

...

...

1022	0				
1023	0				

So read Cache Block 1, Data is

- Valid 0000000000000010 0000000001 0100
Valid Tag field Index field Offset

Index	Tag	0xc-f	0x8-b	0x4-7	0x0-3
0	0				
1	1	0	d	c	b
2	0				
3	1	0	h	g	f
4	0				
5	0				
6	0				
7	0				

...

...

1022	0				
1023	0				

Cache Block 1 Tag does not match (0

!-000000000000000010 0000000001 0100
Tag field Index field Offset

Valid Index Tag

0					
1	0	d	c	b	a
2	0				
3	1	0	h	g	f
4	0				
5	0				
6	0				
7	0				

...

...

1022	0				
1023	0				

Miss, so replace block 1 with new data

& tag
000000000000000010 0000000001 0100
Valid Tag field Index field Offset

Index	Tag	0xc-f	0x8-b	0x4-7	0x0-3
0	0				
1	2	I	k	j	i
2	0				
3	1 0	h	g	f	e
4	0				
5	0				
6	0				
7	0				

...

...

1022	0				
1023	0				

And return word J

- 00000000000000000010 00000000001 **0100**
Valid Tag field Index field Offset
Index Tag 0xc-f 0x8-b 0x4-7 0x0-3

Index	Tag	0xc-f	0x8-b	0x4-7	0x0-3
0	0				
1	2	I	k	j	i
2	0				
3	1	0	h	g	f
4	0				
5	0				
6	0				
7	0				

...

...

1022	0				
1023	0				

Do an example yourself. What

- Choose from: Cache: Hit, Miss, Miss w. replace
happens? Values returned: a ,b, c, d, e, ..., k, l

- Read address **0x000000030** ?

00000000000000000000 0000000011 0000

- Read address **0x00000001c** ?

00000000000000000000 0000000001 1100

Cache

Index	Valid	Tag	0xc-f	0x8-b	0x4-7	0x0-3
0	0					
1	1	2	I	k	j	i
2	0					
3	1	0	h	g	f	e
4	0					
5	0					
6	0					
7	0					

...

Answers

- 0x00000030 a hit
Index = 3, Tag matches,
Offset = 0, value = e
- 0x0000001c a miss
Index = 1, Tag mismatch, so replace from memory,
Offset = 0xc, value = d
- Since reads, values must = memory values whether or not cached:

Memory Address (hexValue of Word)

00000010
00000014
00000018
0000001C

a
b
c
d

00000030
00000034
00000038
0000003C

e
f
g
h

00008010
00008014
00008018
0000801C

j
j
k
l

Peer Instruction

- 1) Mem hierarchies were invented before 1950. (UNIVAC I wasn't delivered 'til 1951)
- 2) If you know your computer's cache size, you can often make your code run faster.

	12
a)	FF
b)	FT
c)	TF
d)	TT

Peer Instruction Answer

- 1) “We are...forced to recognize the possibility of constructing a hierarchy of memories, each of which has greater capacity than the preceding but which is less accessible.” – von Neumann, 1946
 - 2) Certainly! That’s call “tuning”
- 1) Mem hierarchies were invented before 1950. (UNIVAC I wasn’t delivered ‘til 1951)
 - 2) If you know your computer’s cache size, you can often make your code run faster.

12
a) FF
b) FT
c) TF
d) TT

Peer Instruction

1. All caches take advantage of spatial locality.

2. All caches take advantage of temporal locality.

- | | |
|----|----|
| | 12 |
| a) | FF |
| b) | FT |
| c) | TF |
| d) | TT |

Peer Instruction Answer

1. All caches take advantage of spatial locality. **FALSE**
 1. Block size = 1, no spatial!
2. All caches take advantage of temporal locality. **TRUE**
 2. That's the idea of caches;
We'll need it again soon.

1. All caches take advantage of spatial locality.

2. All caches take advantage of

	12
a)	FF
b)	FT
c)	TF
d)	TT

And in Conclusion...

- **Mechanism for transparent movement of data among levels of a storage hierarchy**

- set of address/value bindings
- address \Rightarrow index to set of candidates
- compare desired address with tag
- service hit or miss

address: **load new tag** block and binding **index** miss
off

00000000000000000000000000000000 000000000001 1100

Valid

Tag 0xc-f

0x8-b

0x4-7

0x0-3

0
1
2
3
...

	0	1	d	c	b	a
0	1	0				
1						
2						
3						
...						

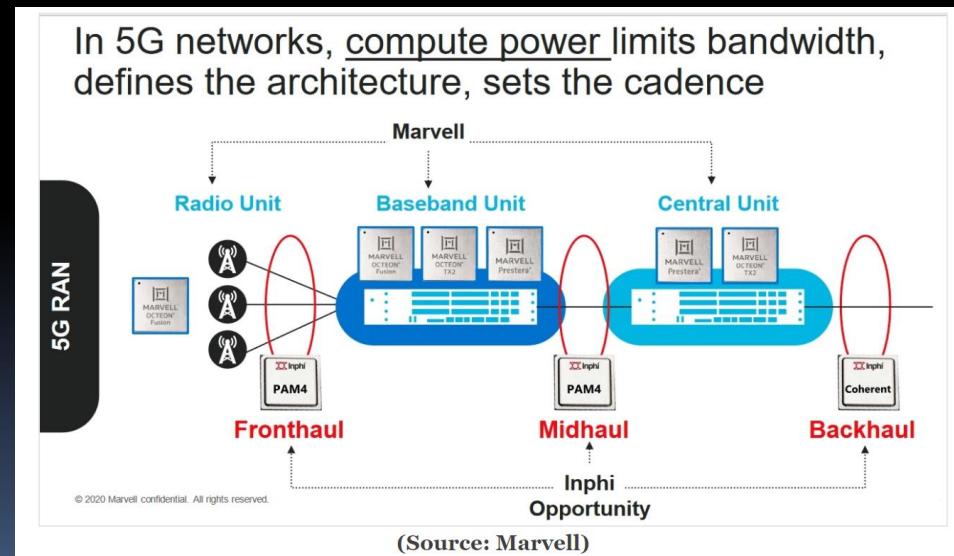
Computer Architecture (计算机体系结构)



Lecturer
Yuanqing
Cheng

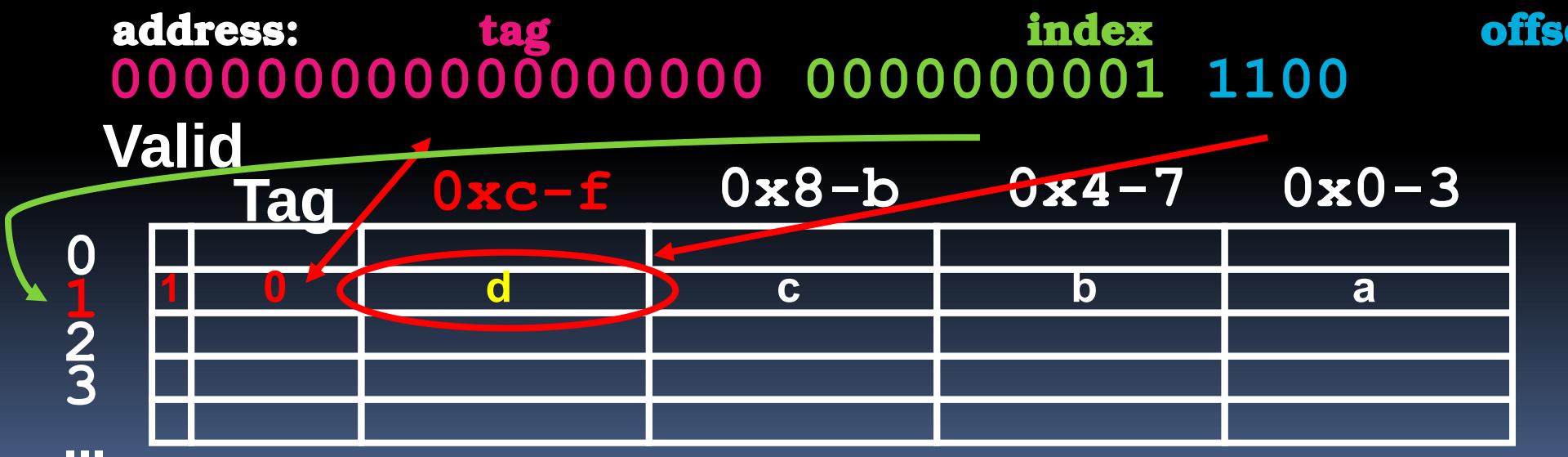
Lecture 29 – Caches III 2010-04-14

Inphi Acquisition: Marvell Bets Growth on Cloud, 5G



Review

- Mechanism for transparent movement of data among levels of a storage hierarchy
 - set of address/value bindings
 - address \Rightarrow index to set of candidates
 - compare desired address with tag
 - service hit or miss
 - load new block and binding on miss



What to do on a write hit?

- Write-through
 - update the word in cache block and corresponding word in memory
- Write-back
 - update word in cache block
 - allow memory word to be “stale”
 - add ‘**dirty**’ bit to each block indicating that memory needs to be updated when block is replaced
 - OS flushes cache before I/O...
- Performance trade-offs?

Block Size Tradeoff (1 / 3)

- Benefits of Larger Block Size
 - Spatial Locality: if we access a given word, we're likely to access other nearby words soon
 - Very applicable with Stored-Program Concept: if we execute a given instruction, it's likely that we'll execute the next few as well
 - Works nicely in sequential array accesses too

Block Size Tradeoff (2/3)

- Drawbacks of Larger Block Size
 - Larger block size means larger miss penalty
 - on a miss, takes longer time to load a new block from next level
 - If block size is too big relative to cache size, then there are too few blocks
 - Result: miss rate goes up
- In general, minimize
Average Memory Access Time (AMAT)
 - = Hit Time
 - + Miss Penalty x Miss Rate

Block Size Tradeoff (3/3)

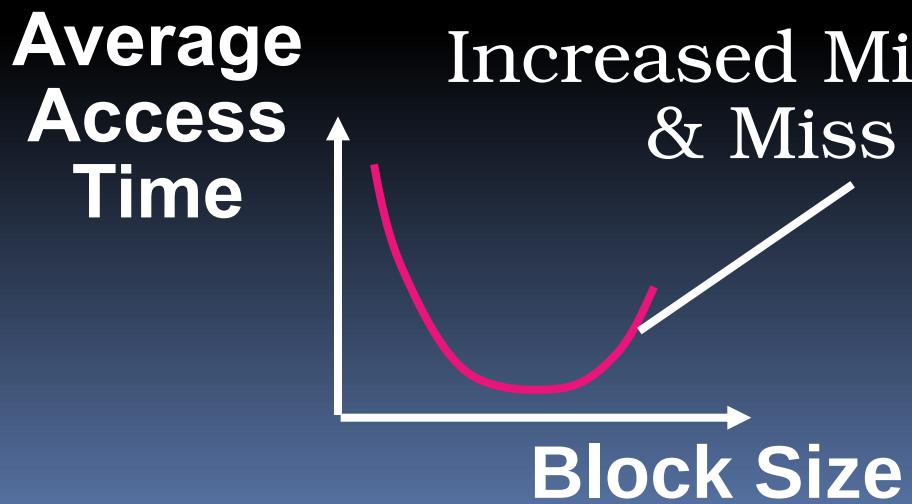
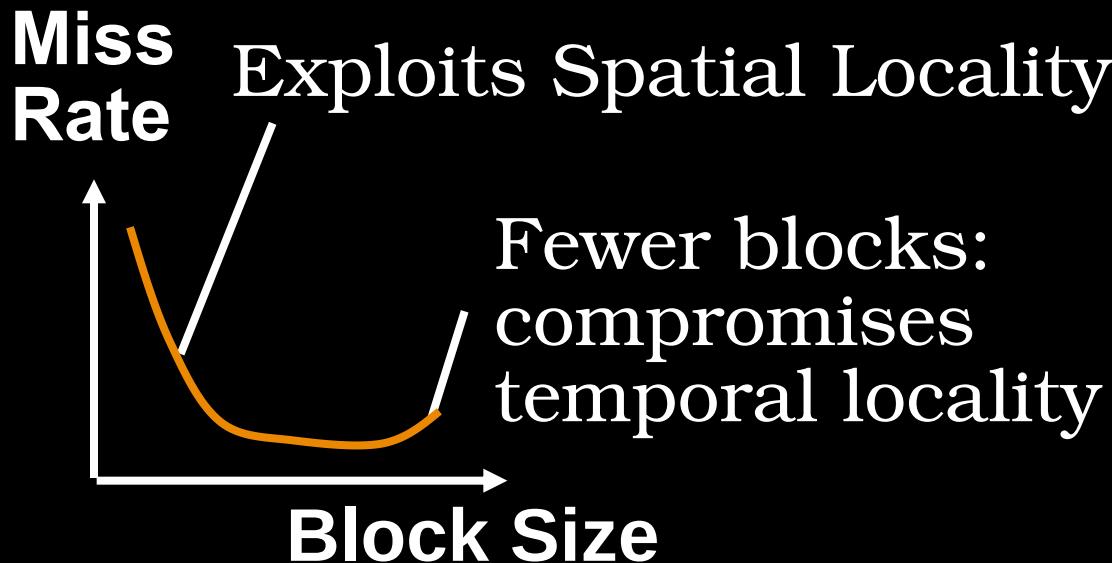
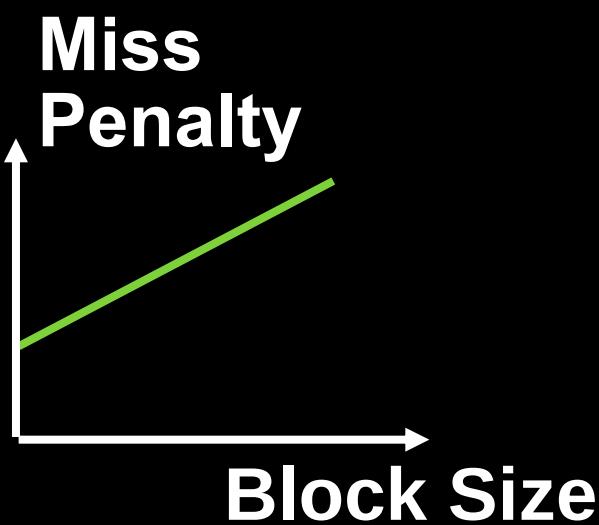
- Hit Time
 - time to find and retrieve data from current level cache
- Miss Penalty
 - average time to retrieve data on a current level miss (includes the possibility of misses on successive levels of memory hierarchy)
- Hit Rate
 - % of requests that are found in current level cache
- Miss Rate
 - $1 - \text{Hit Rate}$

Extreme Example: One Big Block

Valid Bit	Tag	Cache Data
<input type="checkbox"/>	<input type="text"/>	[B 3] [B 2] [B 1] [B 0]

- Cache Size = 4 bytes Block Size = 4 bytes
 - Only ONE entry (row) in the cache!
- If item accessed, likely accessed again soon
 - But unlikely will be accessed again immediately!
- The next access will likely to be a miss again

Block Size Tradeoff Conclusions



Types of Cache Misses (1 / 2)

- “Three Cs” Model of Misses
- 1st C: Compulsory Misses
 - occur when a program is first started
 - cache does not contain any of that program’s data yet, so misses are bound to occur
 - can’t be avoided easily, so won’t focus on these in this course

Types of Cache Misses (2/2)

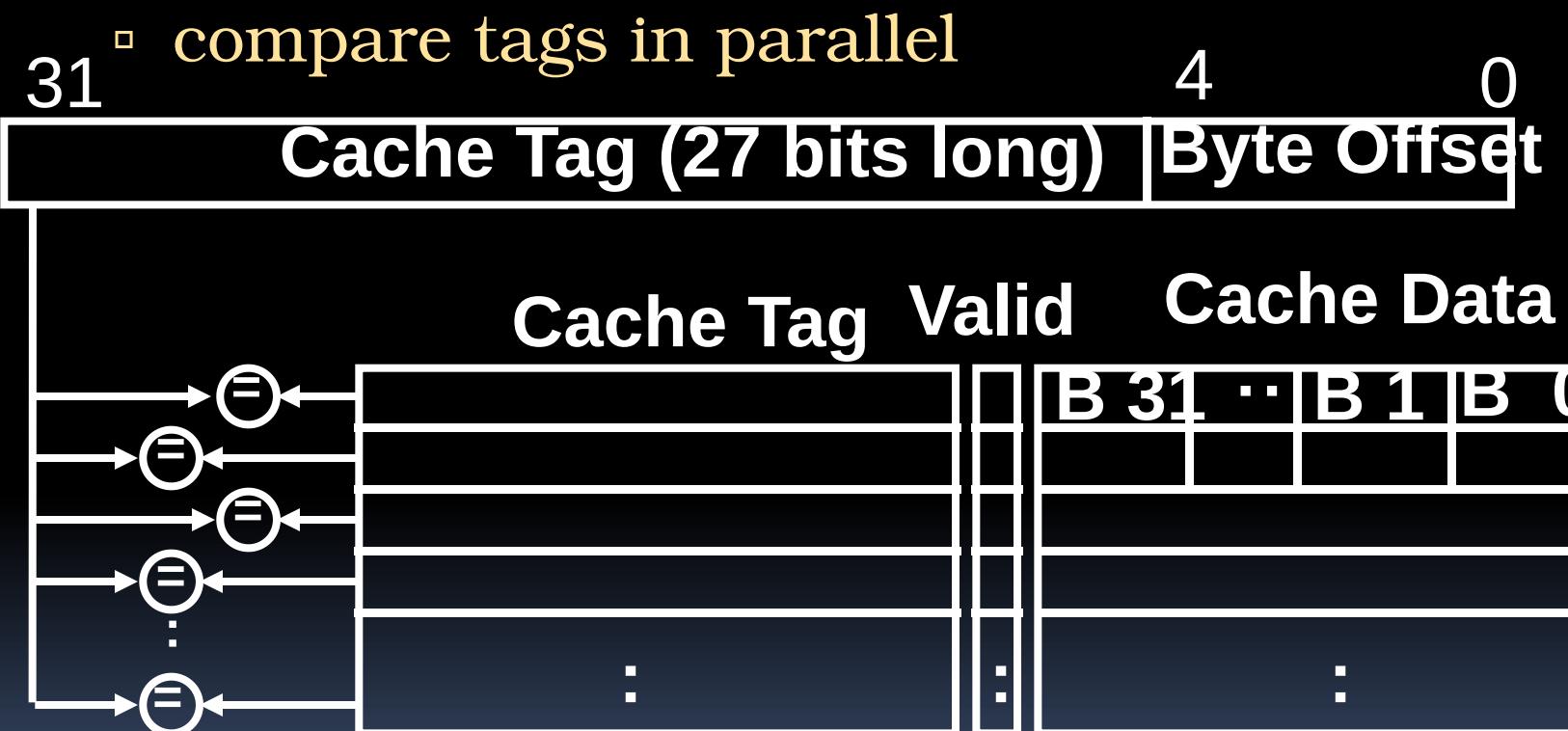
- 2nd C: Conflict Misses
 - miss that occurs because two distinct memory addresses map to the same cache location
 - two blocks (which happen to map to the same location) can keep overwriting each other
 - big problem in direct-mapped caches
 - how do we lessen the effect of these?
- Dealing with Conflict Misses
 - Solution 1: Make the cache size bigger
 - Fails at some point

Fully Associative Cache (1 / 3)

- Memory address fields:
 - Tag: same as before
 - Offset: same as before
 - Index: non-existent
- What does this mean?
 - no “rows”: any block can go anywhere in the cache
 - must compare with all tags in entire cache to see if data is there

Fully Associative Cache (2/3)

- Fully Associative Cache (e.g., 32 B block)



Fully Associative Cache (3/3)

- Benefit of Fully Assoc Cache
 - No Conflict Misses (since data can go anywhere)
- Drawbacks of Fully Assoc Cache
 - Need hardware comparator for every single entry: if we have a 64KB of data in cache with 4B entries, we need 16K comparators: infeasible

Final Type of Cache Miss

- 3rd C: Capacity Misses
 - miss that occurs because the cache has a limited size
 - miss that would not occur if we increase the size of the cache
 - sketchy definition, so just get the general idea
- This is the primary type of miss for Fully Associative caches.

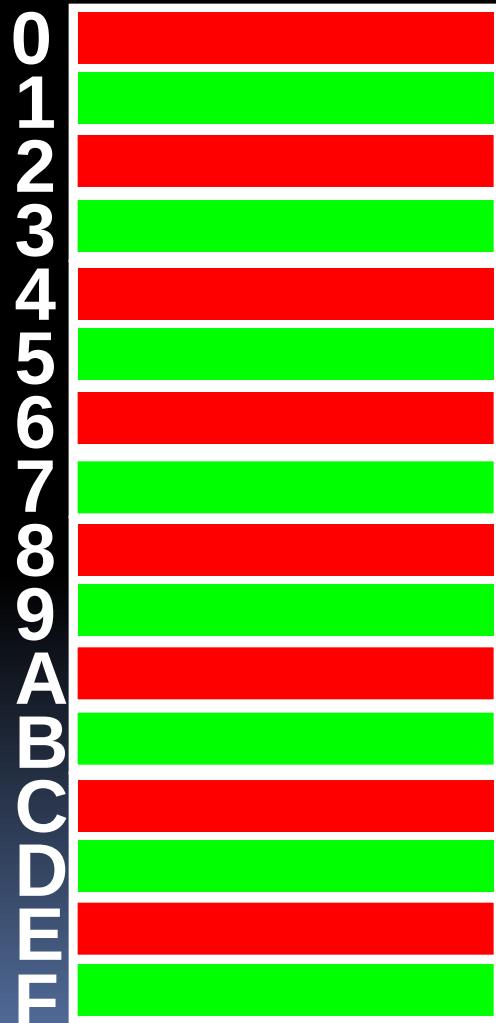
N-Way Set Associative Cache

Memory address fields:

- Tag: same as before
- Offset: same as before
- Index: points us to the correct “row” (called a set in this case)
- So what's the difference?
 - each set contains multiple blocks
 - once we've found correct set, must compare with all tags in that set to find our data

Associative Cache Example

Memory
Address Memory



Cache
Index



- Here's a simple 2-way set associative cache.

N-Way Set Associative Cache

Basic Idea

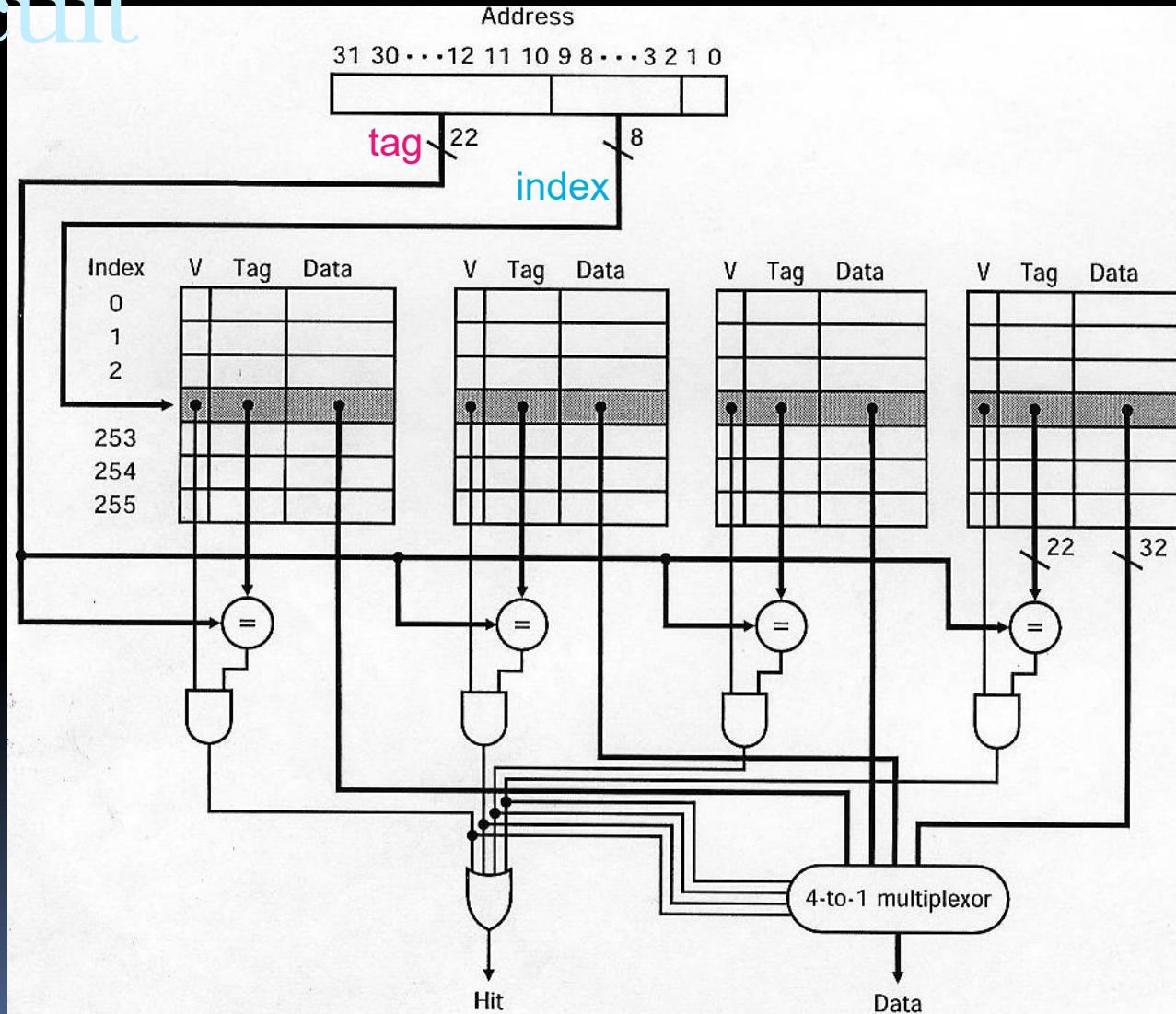
- cache is direct-mapped w/respect to sets
- each set is fully associative with N blocks in it
- Given memory address:
 - Find correct set using Index value.
 - Compare Tag with all Tag values in the determined set.
 - If a match occurs, hit!, otherwise a miss.
 - Finally, use the offset field as usual to find the desired data within the block.

N-Way Set Associative Cache

What's so great about this?

- even a 2-way set assoc cache avoids a lot of conflict misses
- hardware cost isn't that bad: only need N comparators
- In fact, for a cache with M blocks,
 - it's Direct-Mapped if it's 1-way set assoc
 - it's Fully Assoc if it's M -way set assoc
 - so these two are just special cases of the more general set associative design

4-Way Set Associative Cache Circuit



Block Replacement Policy

- Direct-Mapped Cache
 - index completely specifies position which position a block can go in on a miss
- N-Way Set Assoc
 - index specifies a set, but block can occupy any position within the set on a miss
- Fully Associative
 - block can be written into any position
- Question: if we have the choice, where should we write an incoming block?
 - If there are any locations with valid bit off (empty), then usually write the new block into the first one.
 - If all possible locations already have a valid block, we must pick a **replacement policy**: rule by which we determine which block gets “cached out” on a miss.

Block Replacement Policy: LRU

- LRU (Least Recently Used)
 - Idea: cache out block which has been accessed (read or write) least recently
 - Pro: **temporal locality** recent past use implies likely future use: in fact, this is a very effective policy
 - Con: with 2-way set assoc, easy to keep track (one LRU bit); with 4-way or greater, requires complicated hardware and much time to keep track of this

Block Replacement Example

- We have a 2-way set associative cache with a four word total capacity and one word blocks. We perform the following word accesses (ignore bytes for this problem):
 $0, 2, 0, 1, 4, 0, 2, 3, 5, 4$
- How many hits and how many misses will there be for the LRU block replacement policy?

Block Replacement Example: LRU

0: miss, bring into set 0 (loc 0)

	loc 0	loc 1
set 0	0	lru
set 1		

2: miss, bring into set 0 (loc 1)

set 0	lru	0	2
set 1			

0: hit

set 0	0	lru	2
set 1			

1: miss, bring into set 1 (loc 0)

set 0	0	lru	2
set 1	1	lru	

4: miss, bring into set 0 (loc 1, replace 2)

set 0	lru	0	4
set 1	1	lru	

Addresses 0, 2, 0, 1, 4, 0, ... 0: hit

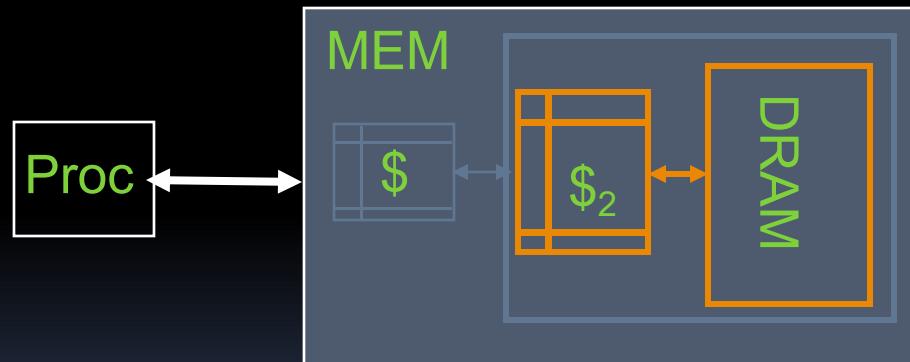
set 0	0	lru	4
set 1	1	lru	

Big Idea

- How to choose between associativity, block size, replacement & write policy?
- Design against a performance model
 - Minimize: **Average Memory Access Time**
= Hit Time
+ Miss Penalty x Miss Rate
 - influenced by technology & program behavior
- Create the illusion of a memory that is large, cheap, and fast - on average
- How can we improve miss penalty?

Improving Miss Penalty

- When caches first became popular, Miss Penalty ~ 10 processor clock cycles
- Today 2400 MHz Processor (0.4 ns per clock cycle) and 80 ns to go to DRAM
200 processor clock cycles!



Solution: another cache between memory and the processor cache: Second Level (L2) Cache

Peer Instruction

1. A 2-way set-associative cache can be outperformed by a direct-mapped cache.
2. Larger block size lower miss rate

	12
a)	FF
b)	FT
c)	TF
d)	TT

And in Conclusion...

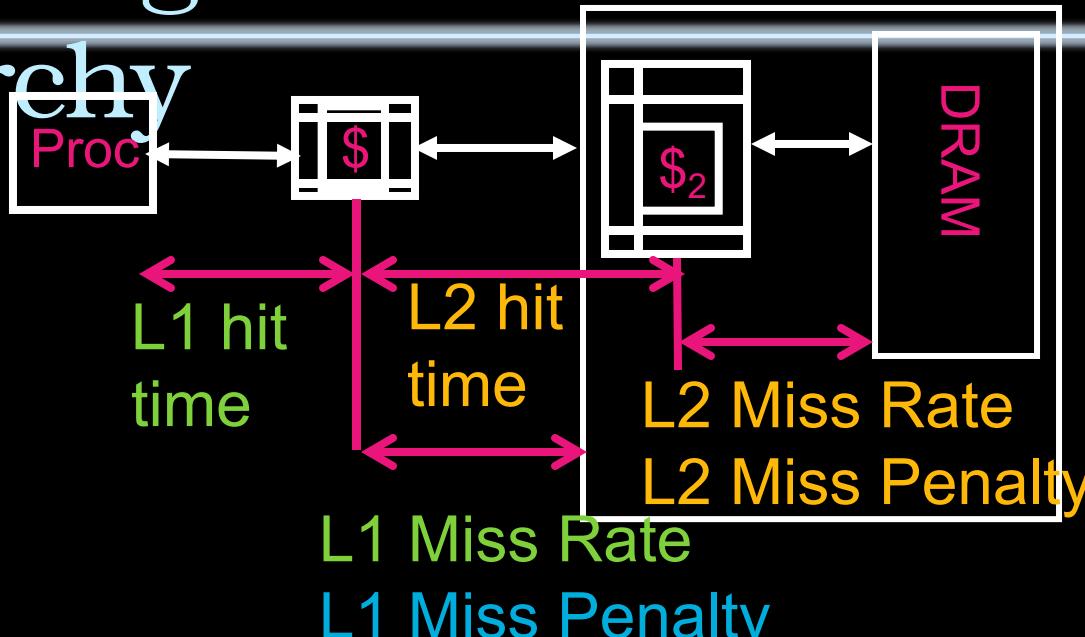
- We've discussed memory caching in detail. Caching in general shows up over and over in computer systems
 - Filesystem cache, Web page cache, Game databases / tablebases, Software memoization, Others?
- Big idea: if something is expensive but we want to do it repeatedly, do it once and cache the result.
- Cache design choices:
 - Size of cache: speed v. capacity
 - Block size (i.e., cache aspect ratio)
 - Write Policy (Write through v. write back)
 - Associativity choice of N (direct-mapped v. set v. fully associative)
 - Block replacement policy
 - 2nd level cache?
 - 3rd level cache?
- Use performance model to pick between choices, depending on programs, technology, budget, ...

Bonus slides

- These are extra slides that used to be included in lecture notes, but have been moved to this, the “bonus” area to serve as a supplement.
- The slides will appear in the order they would have in the normal presentation

Bonus

Analyzing Multi-level cache hierarchy



$$\text{Avg Mem Access Time} = \text{L1 Hit Time} + \text{L1 Miss Rate} * \text{L1 Miss Penalty}$$

$$\text{L1 Miss Penalty} = \text{L2 Hit Time} + \text{L2 Miss Rate} * \text{L2 Miss Penalty}$$

$$\begin{aligned} \text{Avg Mem Access Time} = & \\ & \text{L1 Hit Time} + \text{L1 Miss Rate} * \\ & (\text{L2 Hit Time} + \text{L2 Miss Rate} * \text{L2 Miss Penalty}) \end{aligned}$$

Example

- Assume
 - Hit Time = 1 cycle
 - Miss rate = 5%
 - Miss penalty = 20 cycles
 - Calculate AMAT...
- Avg mem access time
 - = $1 + 0.05 \times 20$
 - = $1 + 1$ cycles
 - = 2 cycles

Ways to reduce miss rate

- Larger cache
 - limited by cost and technology
 - hit time of first level cache < cycle time
(bigger caches are slower)
- More places in the cache to put each block of memory – associativity
 - fully-associative
 - any block any line
 - N-way set associated
 - N places for each block
 - direct map: N=1

Typical Scale

- L1
 - size: tens of KB
 - hit time: complete in one clock cycle
 - miss rates: 1-5%
- L2:
 - size: hundreds of KB
 - hit time: few clock cycles
 - miss rates: 10-20%
- L2 miss rate is fraction of L1 misses that also miss in L2
 - why so high?

Example: with L2 cache

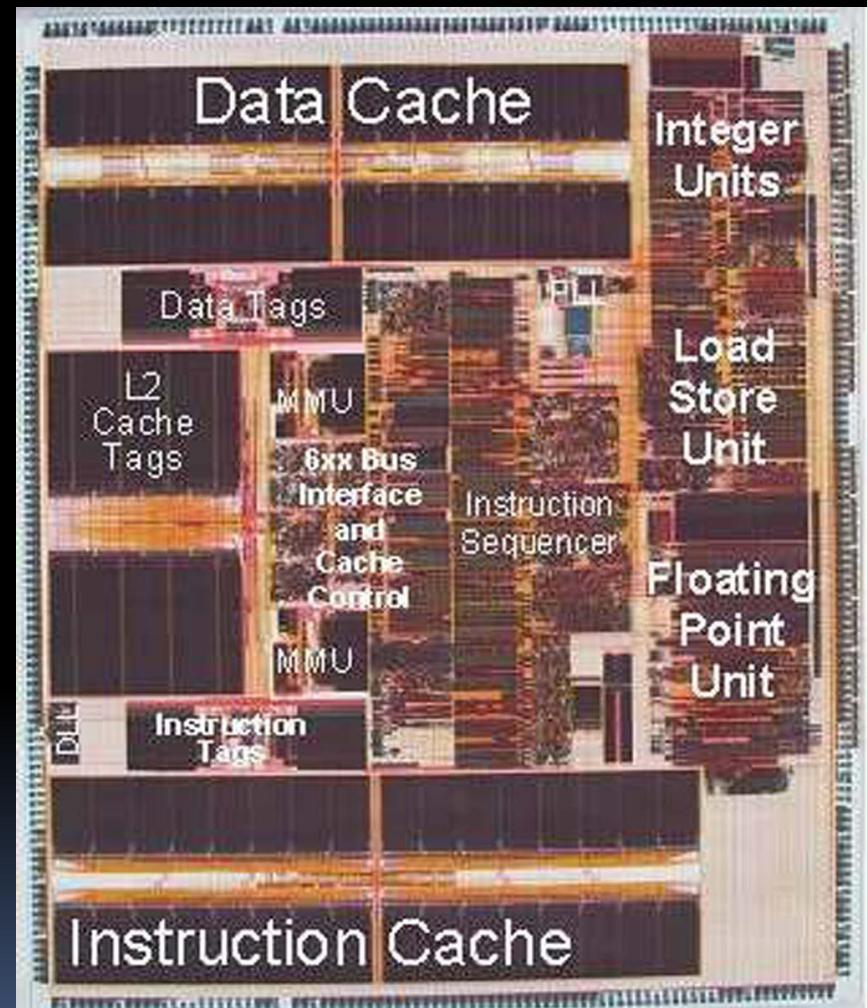
- Assume
 - L1 Hit Time = 1 cycle
 - L1 Miss rate = 5%
 - L2 Hit Time = 5 cycles
 - L2 Miss rate = 15% (% L1 misses that miss)
 - L2 Miss Penalty = **200 cycles**
- L1 miss penalty = $5 + 0.15 * 200 = 35$
- Avg mem access time = $1 + 0.05 \times 35$
= **2.75 cycles**

Example: without L2 cache

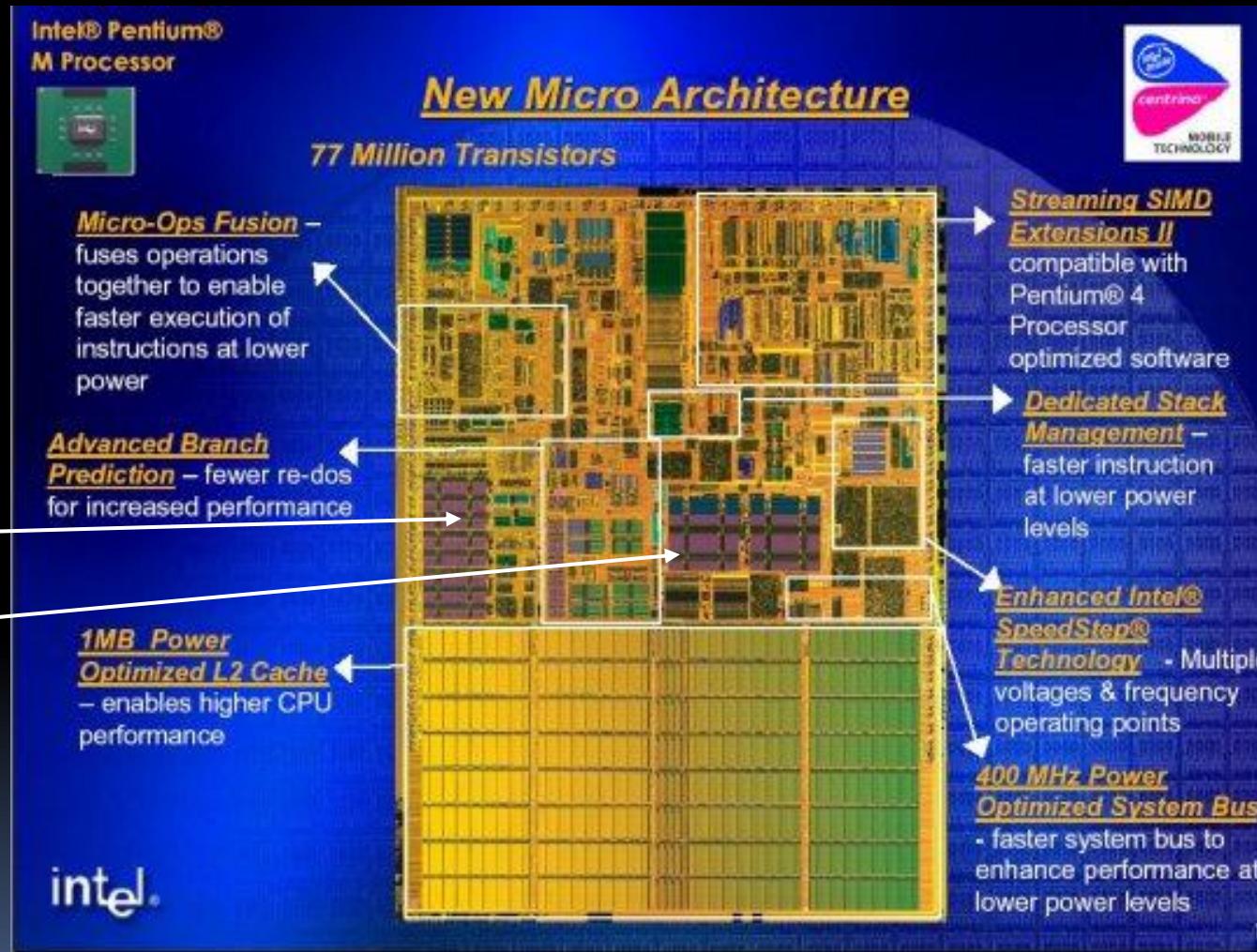
- Assume
 - L1 Hit Time = 1 cycle
 - L1 Miss rate = 5%
 - L1 Miss Penalty = 200 cycles
- Avg mem access time = $1 + 0.05 \times 200$
= 11 cycles
- 4x faster with L2 cache! (2.75 vs. 11)

An actual CPU – Early PowerPC

- Cache
 - 32 KB Instructions and 32 KB Data L1 caches
 - External L2 Cache interface with integrated controller and cache tags, supports up to 1 MByte external L2 cache
 - Dual Memory Management Units (MMU) with Translation Lookaside Buffers (TLB)
- Pipelining
 - Superscalar (3 inst/cycle)
 - 6 execution units (2 integer and 1 double precision IEEE floating point)



An Actual CPU – Pentium M



0.26 Virtual Memory



Computer Architecture (计算机体系结构)

Lecture 30 – Virtual Memory I

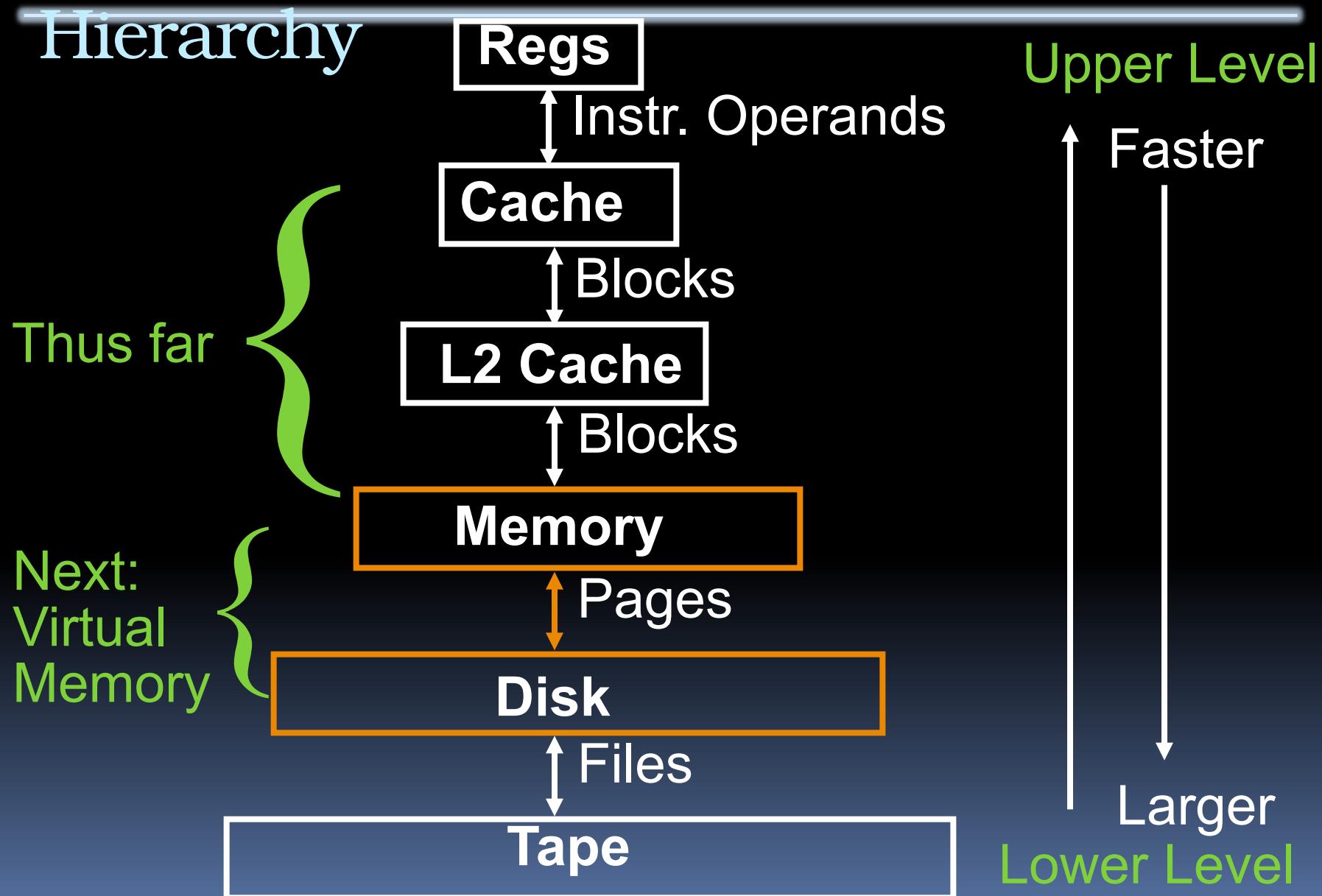
2020-11-2

Lecturer
Yuanqing
Cheng

Review

- Cache design choices:
 - Size of cache: speed v. capacity
 - Block size (i.e., cache aspect ratio)
 - Write Policy (Write through v. write back)
 - Associativity choice of N (direct-mapped v. set v. fully associative)
 - Block replacement policy
 - 2nd level cache?
 - 3rd level cache?
- Use performance model to pick between choices, depending on programs, technology, budget, ...

Another View of the Memory



Memory Hierarchy Requirements

- If Principle of Locality allows caches to offer (close to) speed of cache memory with size of DRAM memory, then recursively why not use at next level to give speed of DRAM memory, size of Disk memory?
- While we're at it, what other things do we need from our memory system?

Memory Hierarchy Requirements

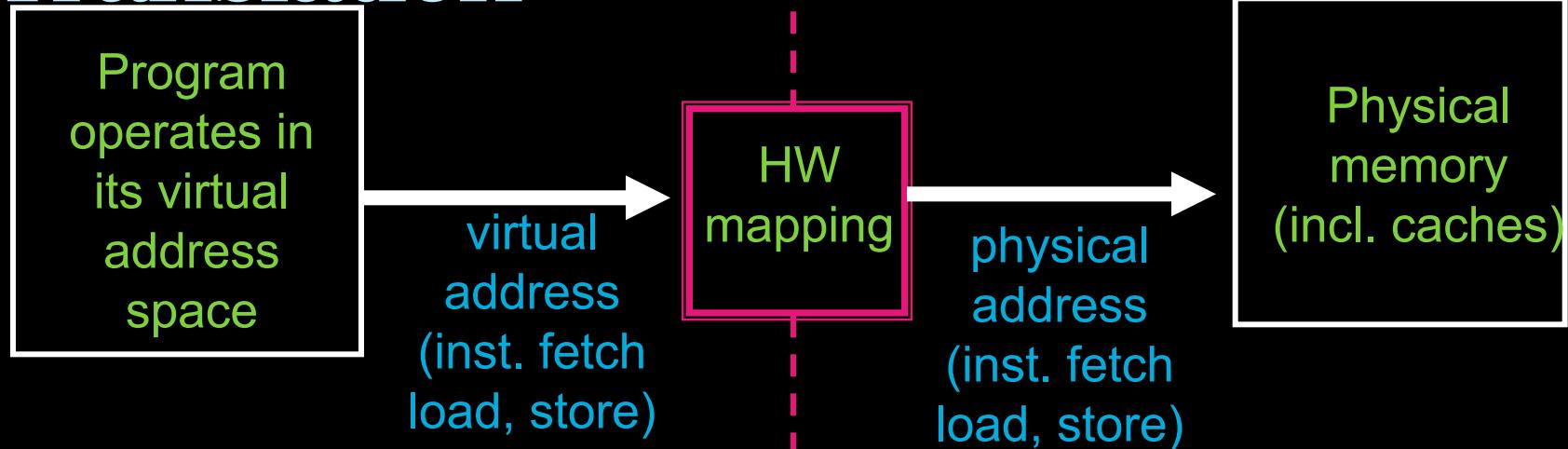
- Allow multiple **processes** to simultaneously occupy memory and provide protection – don't let one program read/write memory from another
- Address space – give each program the **illusion** that it has its own private memory
 - Suppose code starts at address 0x40000000. But different processes have different code, both residing at the same address. So each program has a different view of memory

Virtual Memory

- Next level in the memory hierarchy:
 - Provides program with illusion of a very large main memory:
 - Working set of “pages” reside in main memory - others reside on disk.
- Also allows OS to share memory, protect programs from each other
- Today, more important for **protection** vs. just another level of memory hierarchy
- Each process thinks it has all the memory to itself
- (Historically, it predates caches)

Virtual to Physical Address

Translation



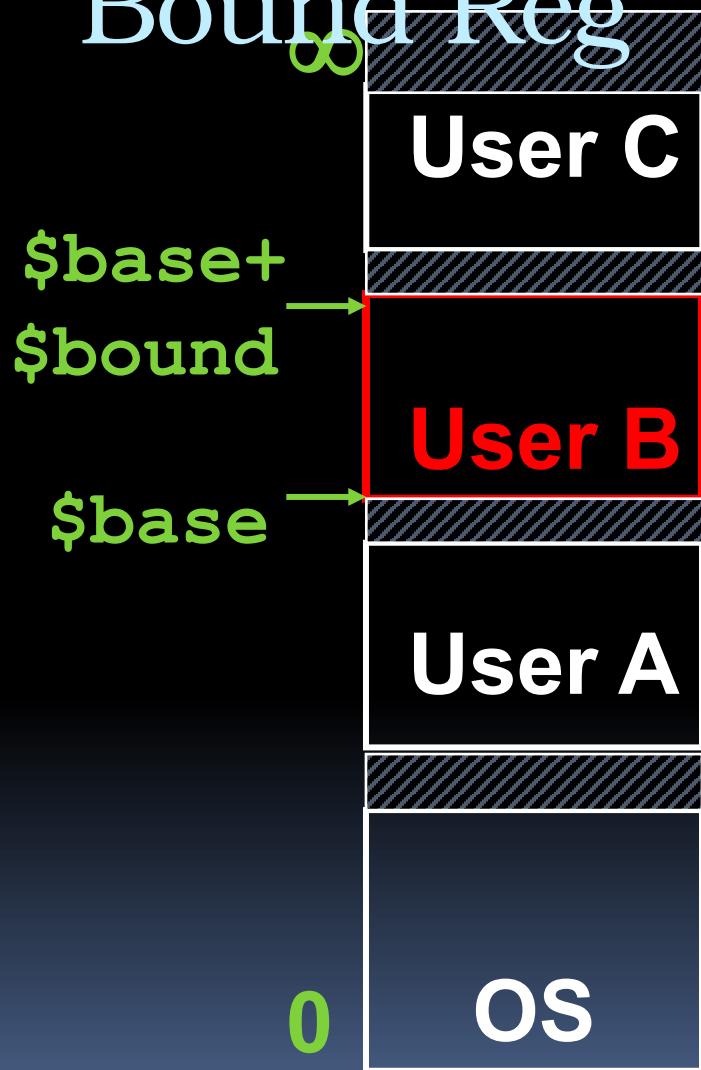
- Each program operates in its own virtual address space; ~only program running
- Each is protected from the other
- OS can decide where each goes in memory

Analogy

- Book title like **virtual address**
- Library of Congress call number like **physical address**
- Card catalogue like **page table**, mapping from book title to call #
- On card for book, in local library vs. in another branch like **valid bit** indicating in main memory vs. on disk
- On card, available for 2-hour in library use (vs. 2-week checkout) like **access rights**

Simple Example: Base and

Bound Reg



Enough space for User D,
but discontinuous
("fragmentation problem")
• Want:

- discontinuous mapping
- Process size $>>$ mem
- Addition not enough!

use Indirection!

Mapping Virtual Memory to Physical Memory

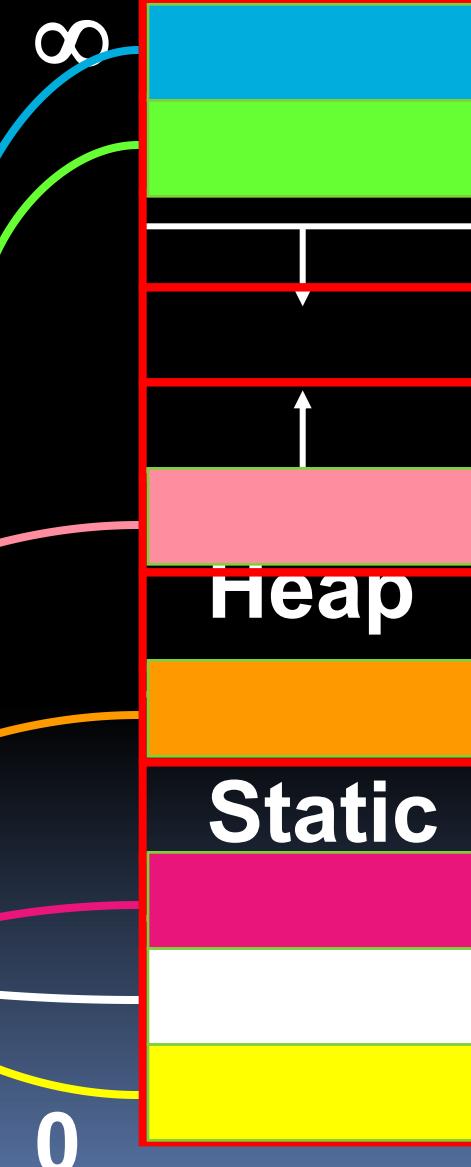
- Divide into equal sized chunks (about 4 KB - 8 KB)
- Any chunk of Virtual Memory assigned to any chunk of Physical Memory (“page”)

64 MB **Physical Memory**

0



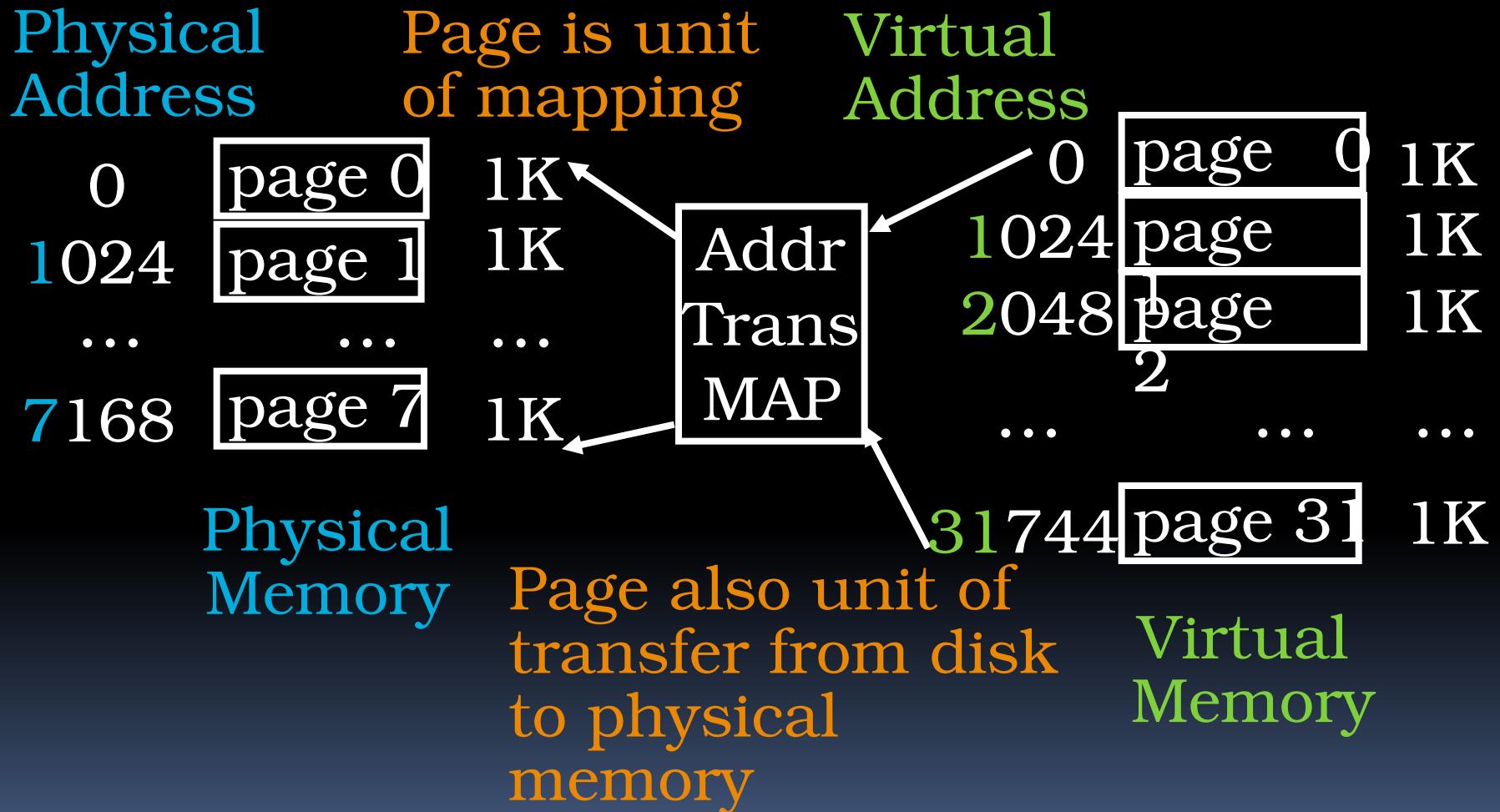
Virtual Memory



Heap

Static

Paging Organization (assume 1 KB pages)



Virtual Memory Mapping

Function cannot have simple function to predict arbitrary mapping

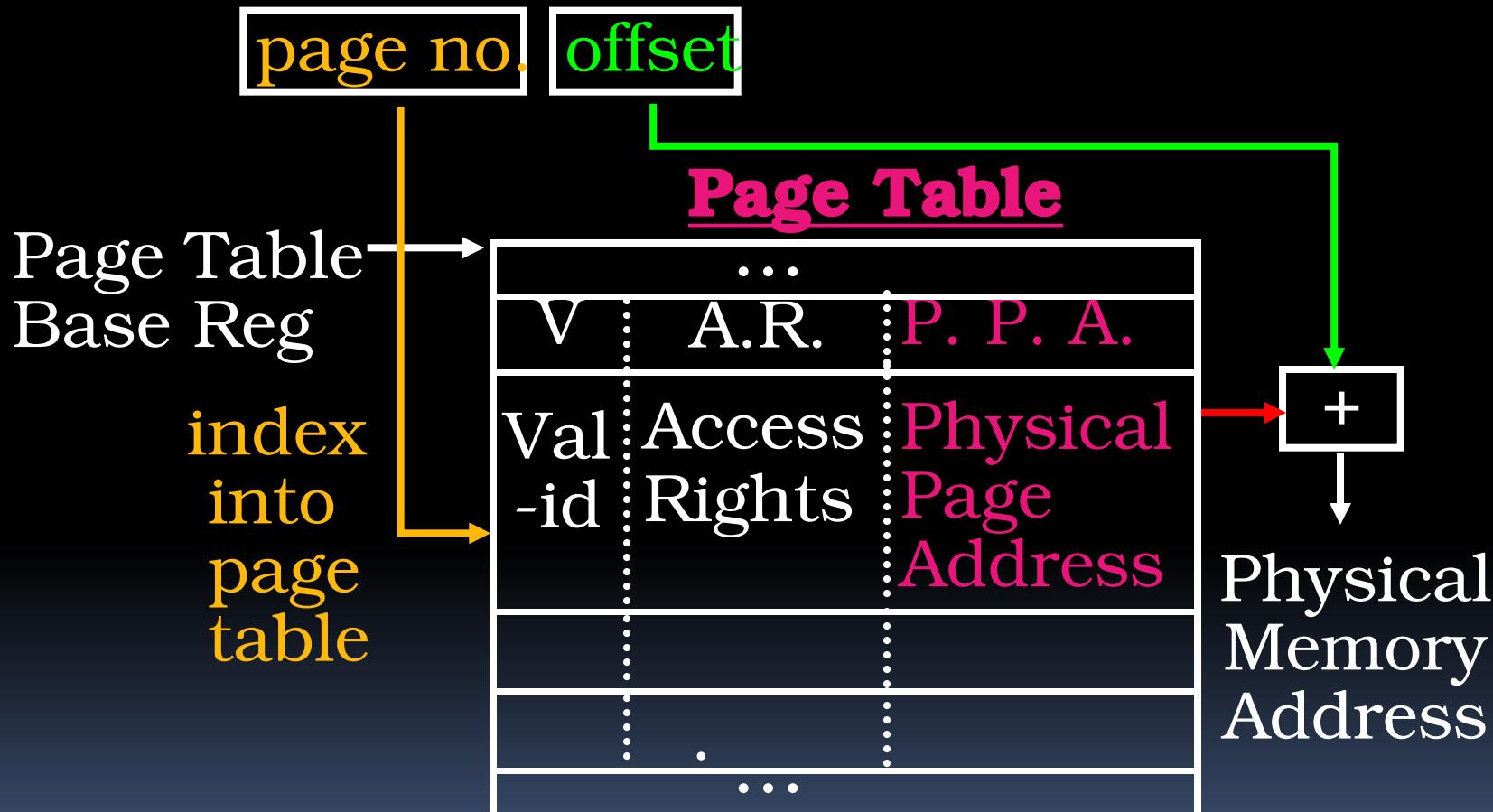
- Use table lookup of mappings

Page Number	Offset
-------------	--------

- Use table lookup (“Page Table”) for mappings: Page number is index
- Virtual Memory Mapping Function
 - Physical Offset = Virtual Offset
 - Physical Page Number
= PageTable[Virtual Page Number]
(P.P.N. also called “Page Frame”)

Address Mapping: Page Table

Virtual Address:



Page Table located in physical memory

Page Table

- A page table is an operating system structure which contains the mapping of virtual addresses to physical locations
 - There are several different ways, all up to the operating system, to keep this data around
- Each process running in the operating system has its own page table
 - “**State**” of process is PC, all registers, plus page table
 - OS changes page tables by changing contents of **Page Table Base Register**

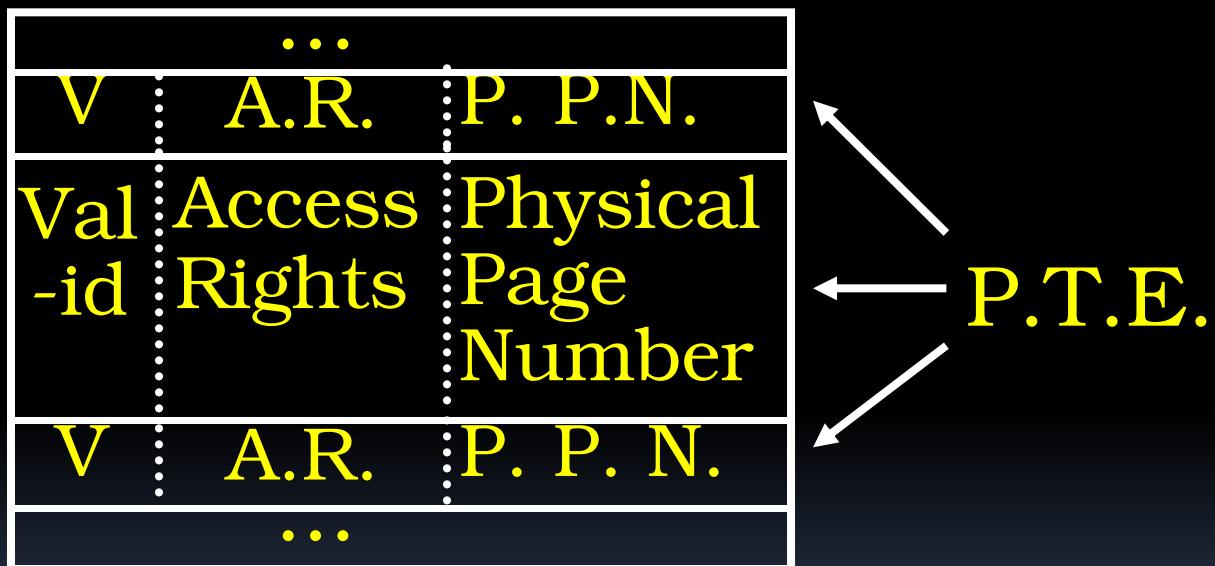
Requirements revisited

- Remember the motivation for VM:
- **Sharing memory with protection**
 - Different physical pages can be allocated to different processes (sharing)
 - A process can only touch pages in its own page table (protection)
- **Separate address spaces**
 - Since programs work only with virtual addresses, different programs can have different data/code at the same address!
- What about the memory hierarchy?

Page Table Entry (PTE) Format

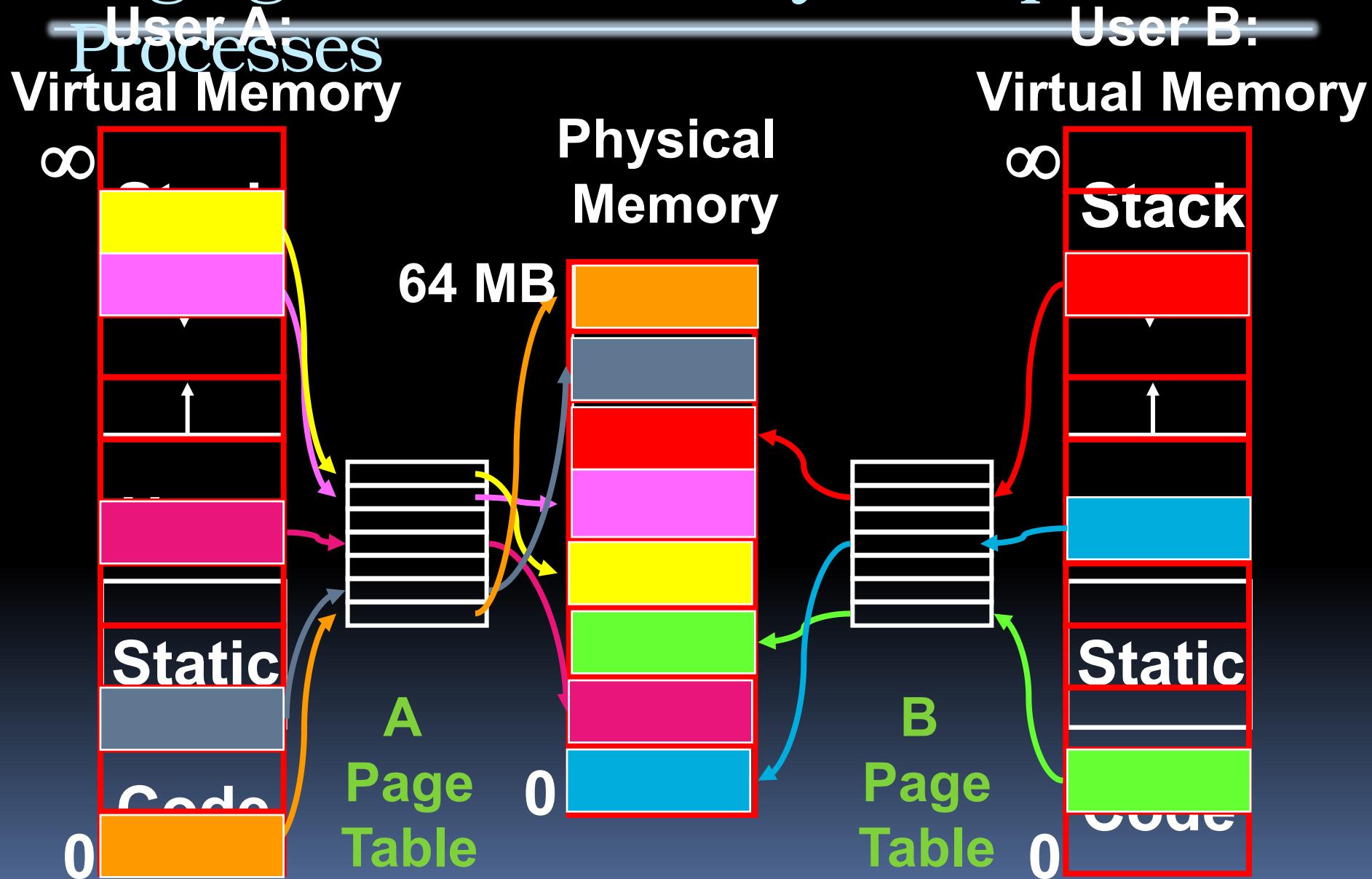
- Contains either Physical Page Number or indication not in Main Memory
- OS maps to disk if Not Valid ($V = 0$)

Page Table



- If valid, also check if have permission to use page: **Access Rights** (A.R.) may be Read Only, Read/Write, Executable

Paging/Virtual Memory Multiple



Comparing the 2 levels of

hierarchy vers.

Virtual Memory

Block or Line

Page

Miss

Page Fault

Block Size: 32-64B

Page Size: 4K-8KB

Placement:

Fully Associative

Direct Mapped,
N-way Set Associative

Replacement:

Least Recently

Used

LRU or Random (LRU)

Write Thru or Back Write Back

Notes on Page Table

- Solves Fragmentation problem: all chunks same size, so all holes can be used
- OS must reserve “Swap Space” on disk for each process
- To grow a process, ask Operating System
 - If unused pages, OS uses them first
 - If not, OS swaps some old pages to disk
 - (Least Recently Used to pick pages to swap)
- Each process has own Page Table

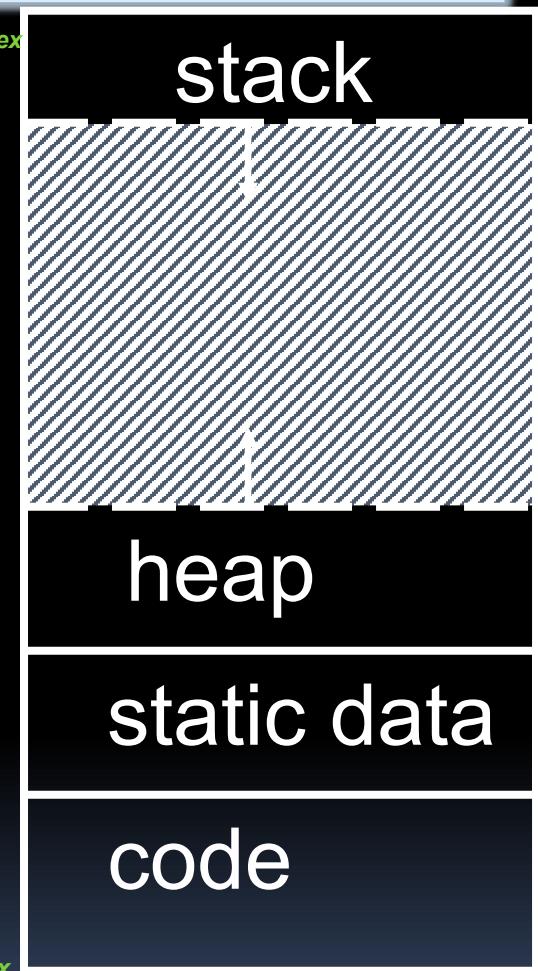
Why would a process need to

“grow” program’s *address space*

$\sim FFFF\ FFFF_{hex}$

space contains 4 regions:

- **stack**: local variables, grows downward
- **heap**: space requested for pointers via `malloc()` ; resizes dynamically, grows upward
- **static data**: variables declared outside main, does not grow or shrink
- **code**: loaded when program starts, does not change



For now, OS somehow prevents accesses between stack and heap (gray hash)

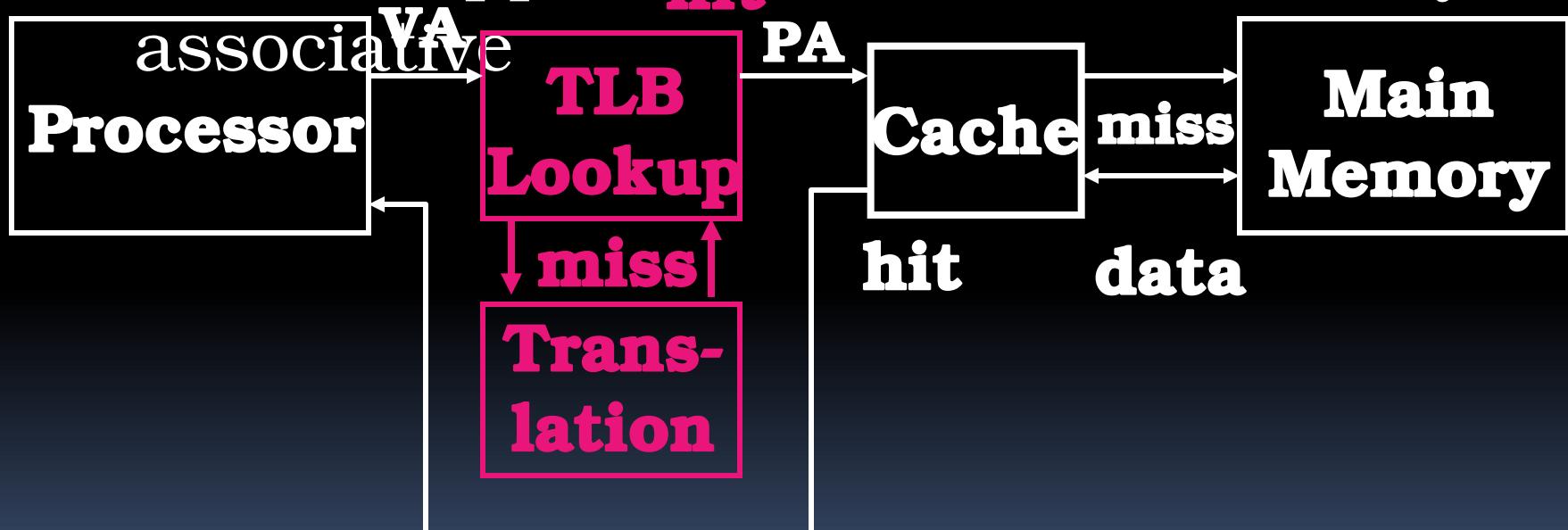
Virtual Memory Problem #1

- Map every address 1 indirection via Page Table in memory per virtual address 1 virtual memory accesses = 2 physical memory accesses SLOW!
- Observation: since locality in pages of data, there must be locality in **virtual address translations** of those pages
- Since small is fast, why not use a small cache of virtual to physical address translations to make translation fast?
- For historical reasons, cache is called a **Translation Lookaside Buffer**, or **TLB**

Translation Look-Aside Buffers

(TLBs) usually small, typically 128 - 256 entries

- Like any other cache, the TLB can be direct mapped, set associative, or fully associative



On TLB miss, get page table entry from main memory

Peer Instruction

- 1) Locality is important yet different for cache and virtual memory (VM): temporal locality for caches but spatial locality for VM
- 2) VM helps both with security and cost

	12
a)	FF
b)	FT
c)	TF
d)	TT

Peer Instruction Answer

- 1) Locality is important yet different for cache and Virtual memory (VM). Item 1: temporal locality for caches but spatial locality for VM
- FALSE**
- 2) VM helps to deal with security and cost
- TRUE**
1. No. Both for VM and cache
 2. Yes. Protection and a bit smaller memory

12
a) FF
b) FT
c) TF
d) TT

And in conclusion...

- Manage memory to disk? Treat as cache
 - Included protection as bonus, now critical
 - Use Page Table of mappings for each user vs. tag/data in cache
 - TLB is **cache** of Virtual Physical addr trans
- Virtual Memory allows protected sharing of memory between processes
- Spatial Locality means Working Set of Pages is all that must be in memory for process to run fairly well

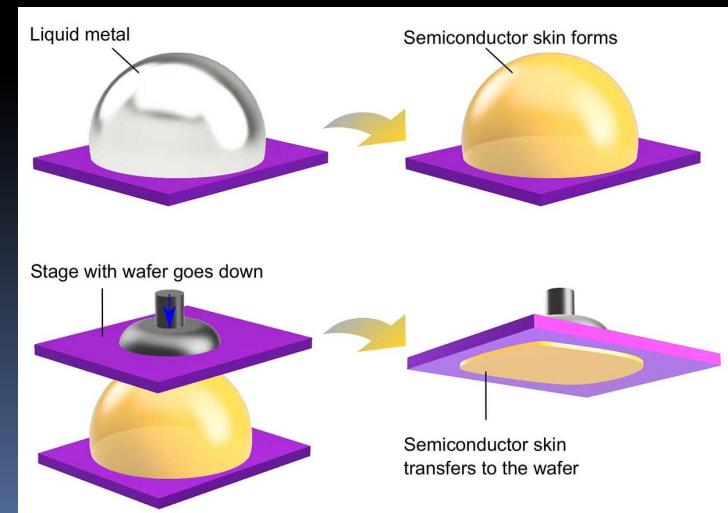
Computer Architecture (计算机体系结构)



Lecturer
Yuanqing
Cheng

Lecture 31 – Virtual Memory II 2020-11-06

Can Two-dimensional
Semiconductors Created Using
Liquid Metals Forestall Moore's
Law's Demise?



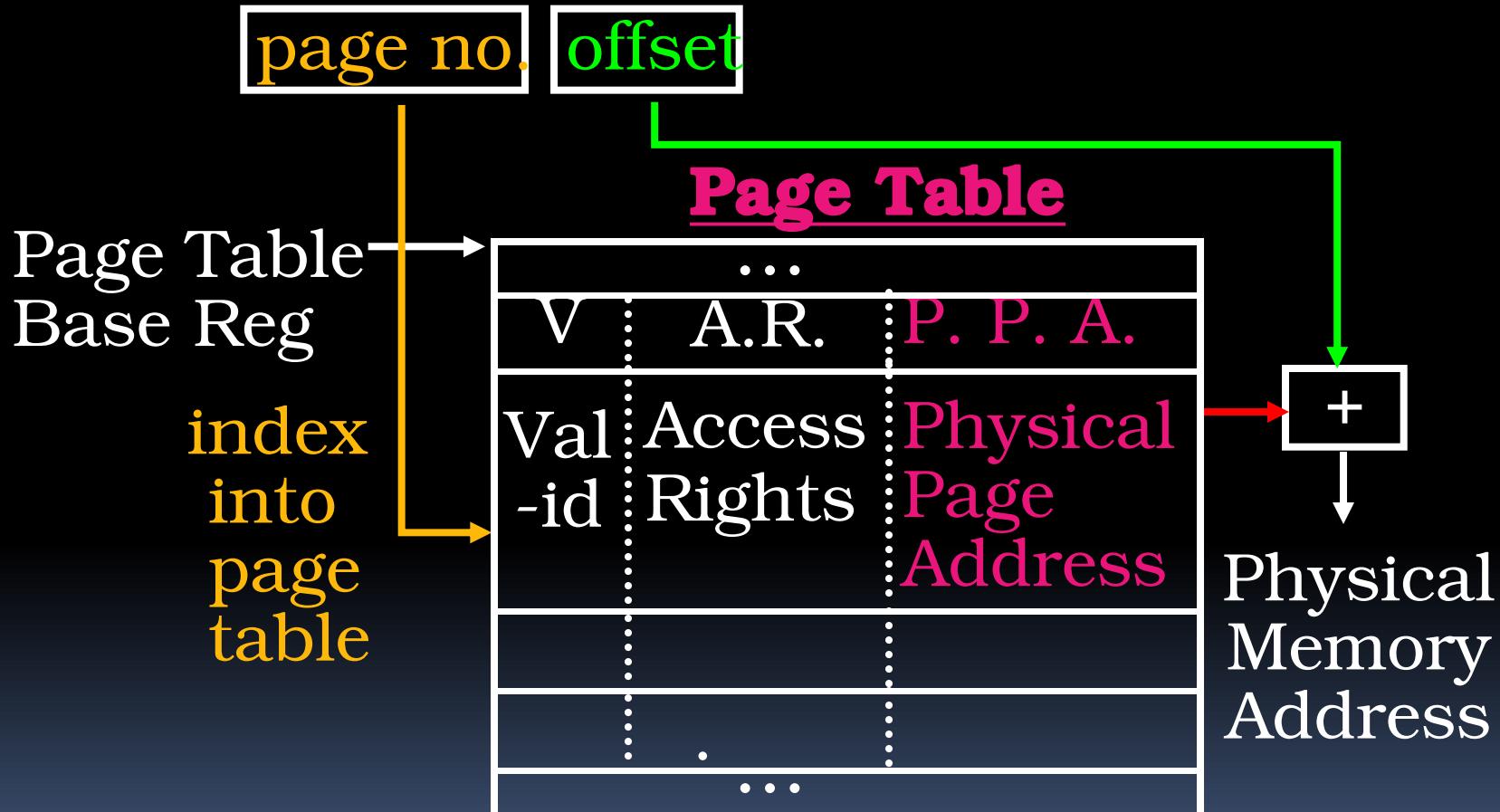
Review

- Manage memory to disk? Treat as cache
 - Included protection as bonus, now critical
 - Use Page Table of mappings for each user vs. tag/data in cache
 - TLB is **cache** of Virtual & Physical addr trans
- Virtual Memory allows protected sharing of memory between processes
- Spatial Locality means Working Set of Pages is all that must be in memory for process to run fairly well

Review Address Mapping: Page

Table

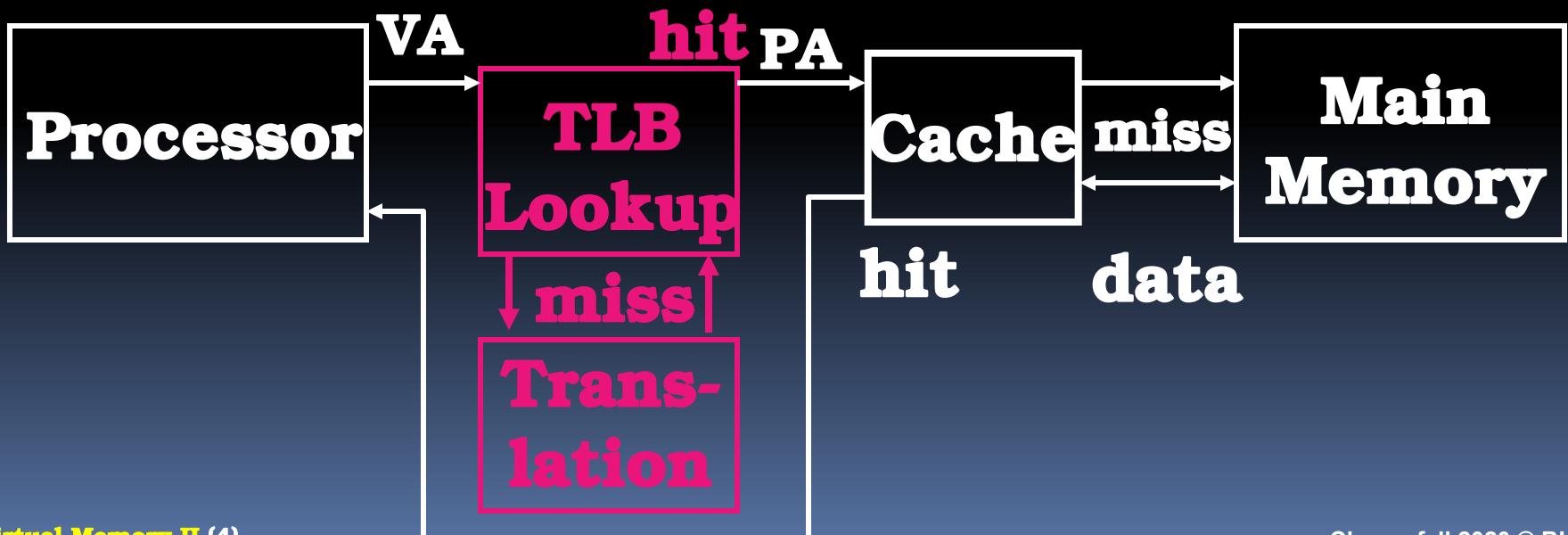
Virtual Address:



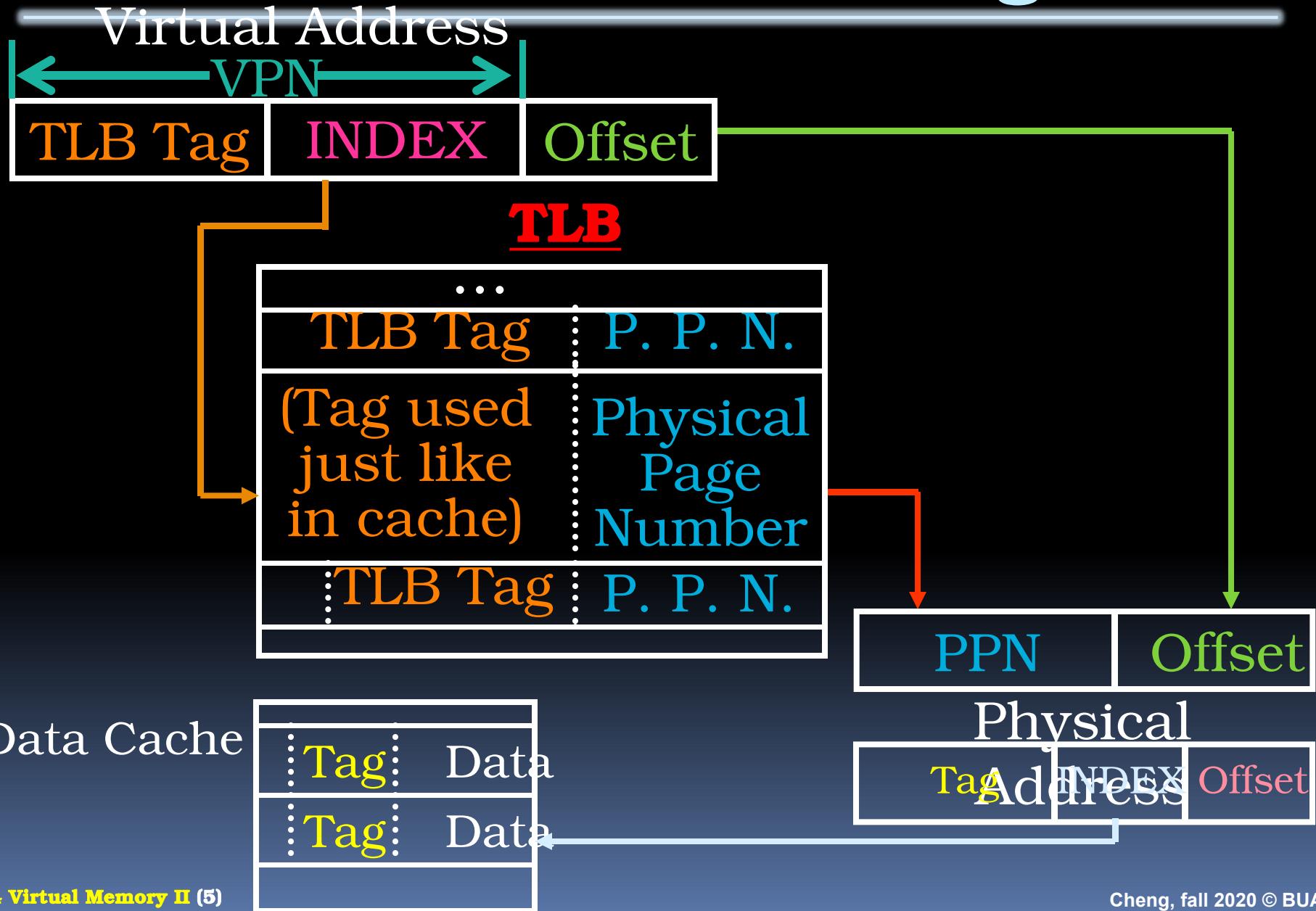
Page Table located in physical memory

Fetching data on a memory read

- Check TLB (input: VPN, output: PPN)
 - hit: fetch translation
 - miss: check page table (in memory)
 - Page table hit: fetch translation
 - Page table miss: page fault, fetch page from disk to memory, return translation to TLB
- Check cache (input: PPN, output: data)
 - hit: return value
 - miss: fetch value from memory, remember it in cache, return value



Address Translation using TLB



Typical TLB Format

Tag	Physical Page #	Dirty	Ref	Valid	Access Rights

- TLB just a cache on the page table mappings
- TLB access time comparable to cache
(much less than main memory access time)
- Dirty: since use write back, need to know whether or not to write page to disk when replaced
- Ref: Used to help calculate LRU on replacement
 - Cleared by OS periodically, then checked to see if page was referenced

What if not in TLB?

- Option 1: Hardware checks page table and loads new Page Table Entry into TLB
- Option 2: Hardware **traps** to OS, up to OS to decide what to do
 - MIPS follows Option 2: Hardware knows nothing about page table
 - A trap is a synchronous exception in a user process, often resulting in the OS taking over and performing some action before returning to the program.
 - More about exceptions next lecture

What if the data is on disk?

- We load the page off the disk into a free block of memory, using a **DMA transfer** (Direct Memory Access – special hardware support to avoid processor)
 - Meantime we switch to some other process waiting to be run
- When the DMA is complete, we get an interrupt and update the process's page table
 - So when we switch back to the task, the desired data will be in memory

What if we don't have enough

memory?

- We choose some other page belonging to a program and transfer it onto the disk if it is dirty
 - If clean (disk copy is up-to-date), just overwrite that data in memory
 - We chose the page to evict based on replacement policy (e.g., LRU)
- And update that program's page table to reflect the fact that its memory moved somewhere else
- If continuously swap between disk and memory, called **Thrashing**

**WE'RE DONE WITH NEW
MATERIAL**

Let's now review w/Questions

Question (1 / 3)

- 40-bit virtual address, 16 KB page

Virtual Page Number (? bits)	Page Offset (? bits)
------------------------------	----------------------

- 36-bit physical address

Physical Page Number (? bits)	Page Offset (? bits)
-------------------------------	----------------------

- Number of bits in
Virtual Page Number/Page offset,
Physical Page Number/Page offset?

1: **22/18 (VPN/PO), 22/14 (PPN/PO)**

2: **24/16, 20/16**

3: **26/14, 22/14**

4: **26/14, 26/10**

5: **28/12, 24/12**

(1 / 3) Answer

- 40-bit virtual address, 16 KB page

Virtual Page Number (26 bits)	Page Offset (14 bits)
--------------------------------------	------------------------------

- 36-bit physical address

Physical Page Number (22 bits)	Page Offset (14 bits)
---------------------------------------	------------------------------

- Number of bits in
Virtual Page Number/Page offset,
Physical Page Number/Page offset?

1: **22/18 (VPN/PO), 22/14 (PPN/PO)**

2: **24/16, 20/16**

3: 26/14, 22/14

4: **26/14, 26/10**

5: **28/12, 24/12**

Question (2/3): 40b VA, 36b PA

- 2-way set-assoc. TLB, 512 entries, 40b



- TLB Entry: Valid bit, Dirty bit, Access Control (say 2 bits),



- 1: 12 / 14 / 38 (TLB Tag / Index / Entry)
- Number of bits in TLB Tag / Index / Entry: 14 / 12 / 40
3: 18 / 8 / 44
4: 8 / 8 / 58

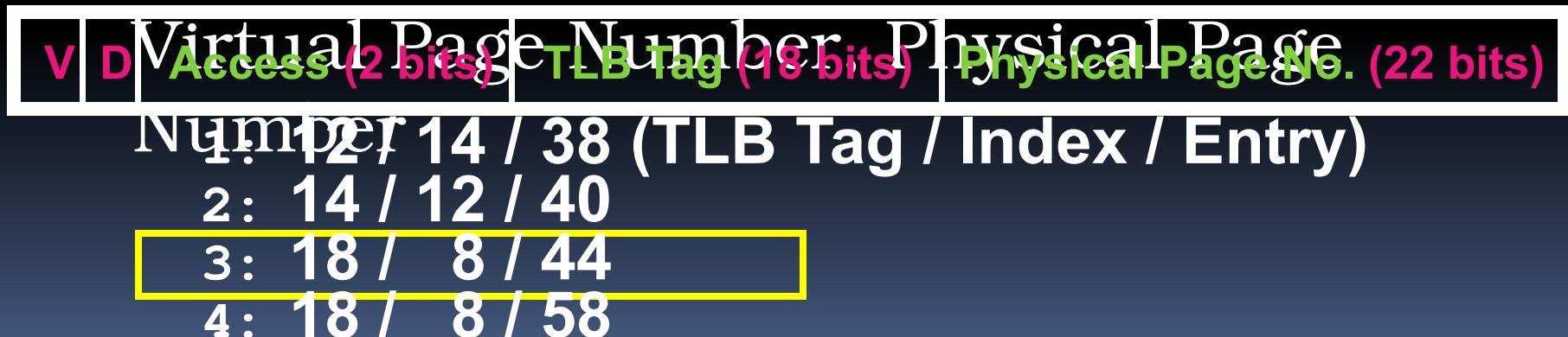
(2/3) Answer

- 2-way set-assoc data cache, 256 (2^8) “sets”, 2 TLB entries per set => 8 bit



Virtual Page Number (26 bits)

- TLB Entry: Valid bit, Dirty bit, Access Control (2 bits),



Question (3/3)

- 2-way set-assoc, 64KB data cache, 64B block



- Data Cache Entry: Valid bit, Dirty bit,



- Number of bits in Data cache Tag /
1: 12 / 9 / 14 / 87 (Tag/Index/Offset/Entry)
2: 20 / 10 / 6 / 86
3: 20 / 10 / 6 / 534
4: 21 / 9 / 6 / 87
5: 21 / 9 / 6 / 535

(3/3) Answer

- 2-way set-assoc data cache, 64K/1K
 (2^{10}) “sets”, 2 entries per sets => 9 bit



- Data Cache Entry: Valid bit, Dirty bit,



1: 12 / 9 / 14 / 87 (Tag/Index/Offset/Entry)

2: 20 / 10 / 6 / 86

3: 20 / 10 / 6 / 534

4: 21 / 9 / 6 / 87

5: 21 / 9 / 6 / 535

And in Conclusion...

- Virtual memory to Physical Memory Translation too slow?
 - Add a cache of Virtual to Physical Address Translations, called a **TLB**
- Spatial Locality means Working Set of Pages is all that must be in memory for process to run fairly well
- Virtual Memory allows protected sharing of memory between processes with less swapping to disk

Bonus slides

- These are extra slides that used to be included in lecture notes, but have been moved to this, the “bonus” area to serve as a supplement.
- The slides will appear in the order they would have in the normal presentation

Bonus

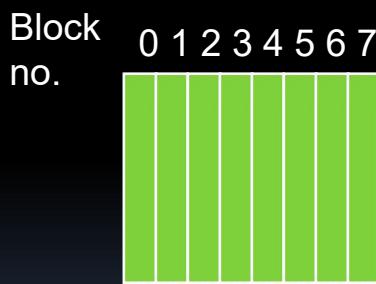
4 Qs for any Memory Hierarchy

- Q1: Where can a block be placed?
 - One place (direct mapped)
 - A few places (set associative)
 - Any place (fully associative)
- Q2: How is a block found?
 - Indexing (as in a direct-mapped cache)
 - Limited search (as in a set-associative cache)
 - Full search (as in a fully associative cache)
 - Separate lookup table (as in a page table)
- Q3: Which block is replaced on a miss?
 - Least recently used (LRU)
 - Random
- Q4: How are writes handled?
 - Write through (Level never inconsistent w/lower)
 - Write back (Could be “dirty”, must have dirty bit)

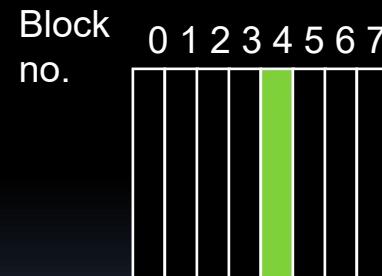
Q1: Where block placed in upper level?

Block #12 placed in 8 block cache:

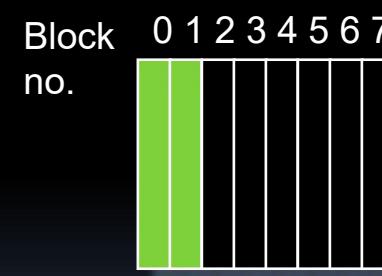
- Fully associative
- Direct mapped
- 2-way set associative
 - Set Associative Mapping = Block # Mod # of Sets



Fully associative:
block 12 can go
anywhere



Direct mapped:
block 12 can go
only into block 4
(12 mod 8)



Set Set Set Set
0 1 2 3
Set associative:
block 12 can go
anywhere in set 0
(12 mod 4)

Q2: How is a block found in upper level?



- Direct indexing (using index and block offset), tag compares, or combination
- Increasing associativity shrinks index, expands tag

Q3: Which block replaced on a miss? for Direct Mapped

- Set Associative or Fully Associative:
 - Random
 - LRU (Least Recently Used)

Miss Rates

Associativity: 2-way 4-way
8-way

Size	LRU	Ran	LRU	Ran	LRU	Ran
16 KB	5.2%	5.7%	4.7%	5.3%	4.4%	5.0%
64 KB	1.9%	2.0%	1.5%		1.7%	1.4%
	1.5%					

Q4: What to do on a write hit?

- Write-through
 - update the word in cache block and corresponding word in memory
- Write-back
 - update word in cache block
 - allow memory word to be “stale”
 - => add ‘dirty’ bit to each line indicating that memory be updated when block is replaced
 - => OS flushes cache before I/O !!!
- Performance trade-offs?
 - WT: read misses cannot result in writes
 - WB: no writes of repeated writes

Three Advantages of Virtual

Memory Translation:

- Program can be given consistent view of memory, even though physical memory is scrambled
- Makes multiple processes reasonable
- Only the most important part of program (“Working Set”) must be in physical memory
- Contiguous structures (like stacks) use only as much physical memory as necessary yet still grow later

Three Advantages of Virtual

Memory:

- Different processes protected from each other
- Different pages can be given special behavior
 - (Read Only, Invisible to user programs, etc).
- Kernel data protected from User programs
- Very important for protection from malicious programs Far more “viruses” under Microsoft Windows
- Special Mode in processor (“Kernel mode”) allows processor to change page table/TLB
- 3) Sharing:
 - Can map same physical page to multiple users (“Shared memory”)

Why Translation Lookaside Buffer

TLB?

- Paging is most popular implementation of virtual memory (vs. base/bounds)
- Every paged virtual memory access must be checked against Entry of Page Table in memory to provide protection / indirection
- Cache of Page Table Entries (TLB) makes address translation possible without memory access in common case to make fast

Bonus slide: Virtual Memory

Overview (1/3)

- User program view of memory:
 - Contiguous
 - Start from some set address
 - Infinitely large
 - Is the only running program
- Reality:
 - Non-contiguous
 - Start wherever available memory is
 - Finite size
 - Many programs running at a time

Bonus slide: Virtual Memory Overview

~~(2/3)~~

- Virtual memory provides:

- illusion of contiguous memory
- all programs starting at same set address
- illusion of ~ infinite memory
(2^{32} or 2^{64} bytes)
- protection

Bonus slide: Virtual Memory Overview

(3/3)

■ Implementation:

- Divide memory into “chunks” (pages)
- Operating system controls page table that maps virtual addresses into physical addresses
- Think of memory as a cache for disk
- TLB is a cache for the page table

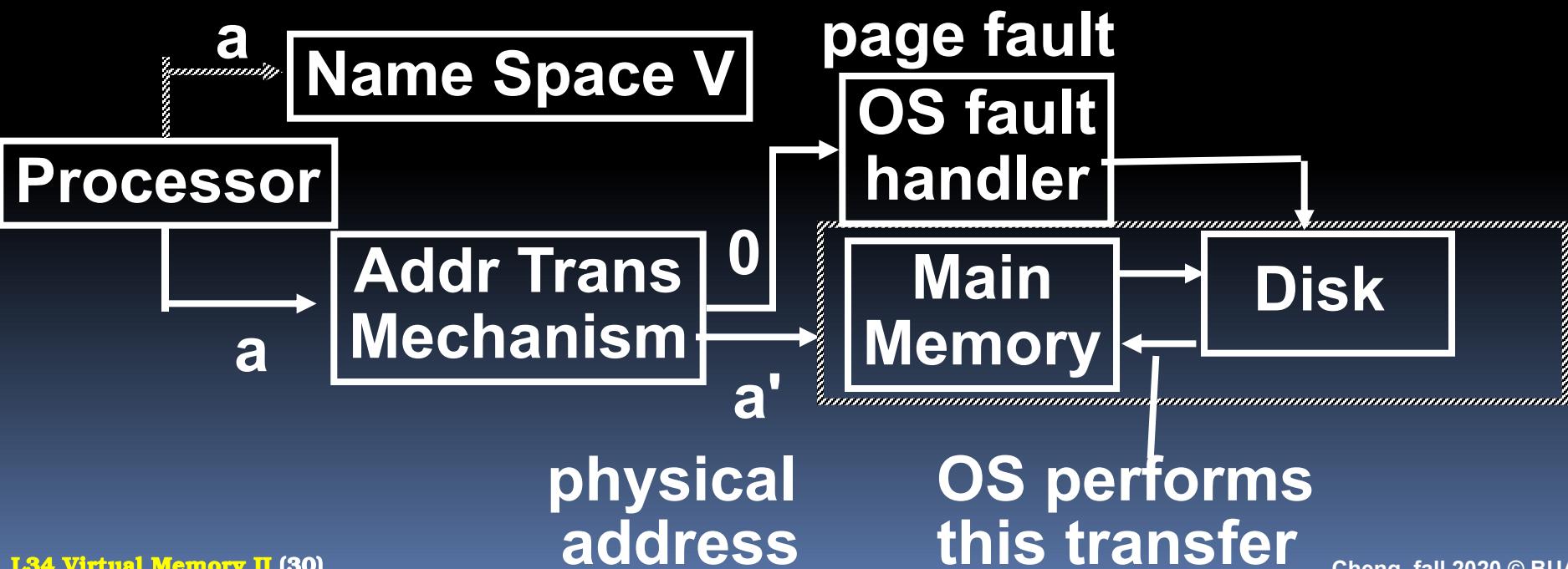
Address Map, Mathematically

$V = \{0, 1, \dots, n - 1\}$ virtual address space ($n > m$)

$M = \{0, 1, \dots, m - 1\}$ physical address space

MAP: $V \rightarrow M \cup \{\theta\}$ address mapping function

$\text{MAP}(a) = a'$ if data at virtual address a is present in physical address $\underline{a'}$ and $\underline{a'}$ in M
 $= \theta$ if data at virtual address a is not present in M



0.27 IO



Computer Architecture (计算机体系结构)

Lecture 32 – Input / Output 2020-11-06

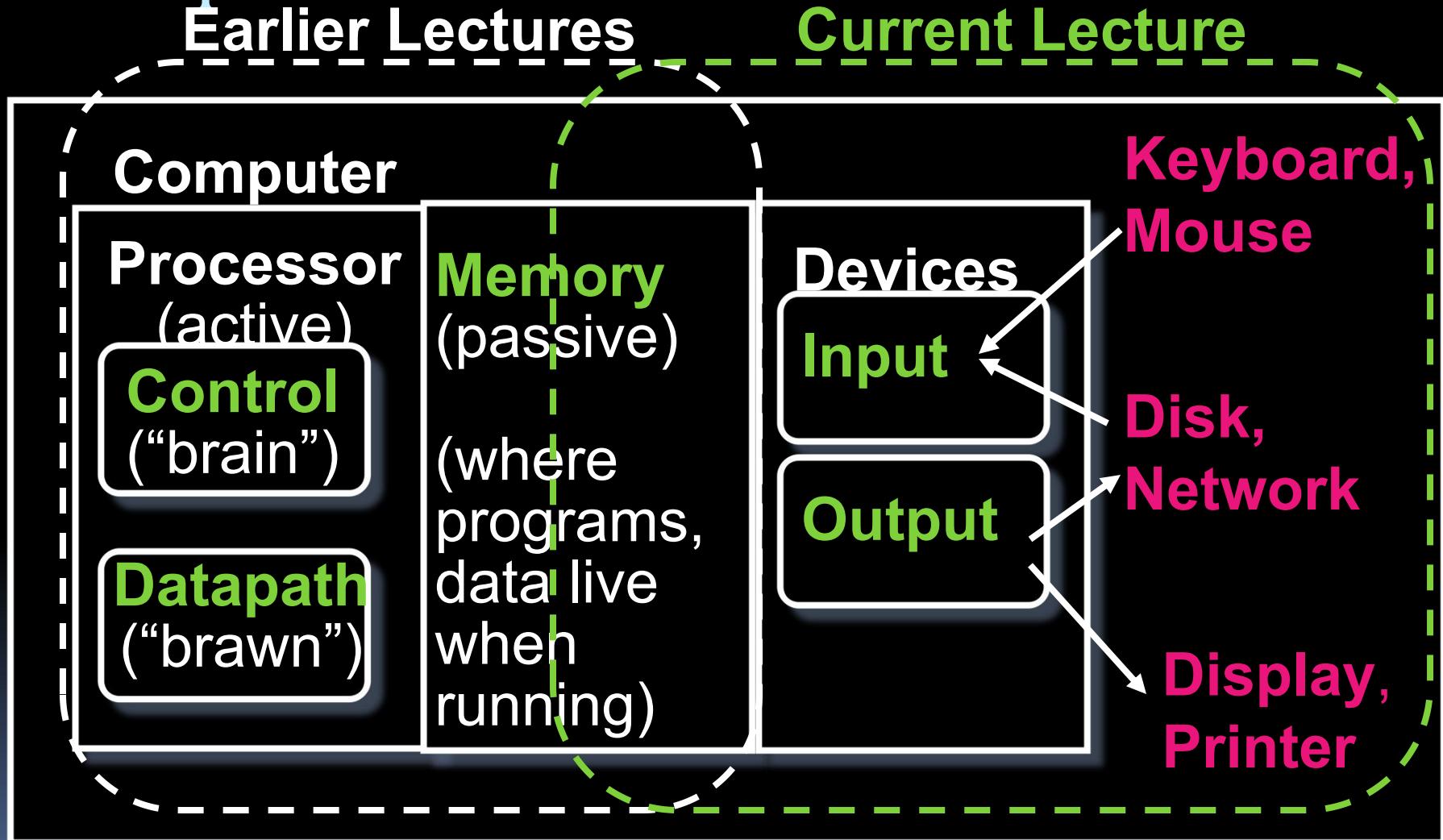
We've merged 3 lectures into 1...

Lecturer
Yuanqing
Cheng

I/O BASICS

Recall : 5 components of any

Computer



Motivation for Input/Output

- I/O is how humans interact with computers
- I/O gives computers long-term memory.



I/O lets computers do amazing things:



Read pressure of synthetic hand and control synthetic arm and hand of fireman

Control propellers, fins, communicate in BOB (Breathable Observable Bubble)

- Computer without I/O like a car w/no wheels; great technology, but gets you nowhere

I/O Device Examples and Speeds

- I/O Speed: bytes transferred per second
(from mouse to Gigabit LAN: 7 orders of mag!)

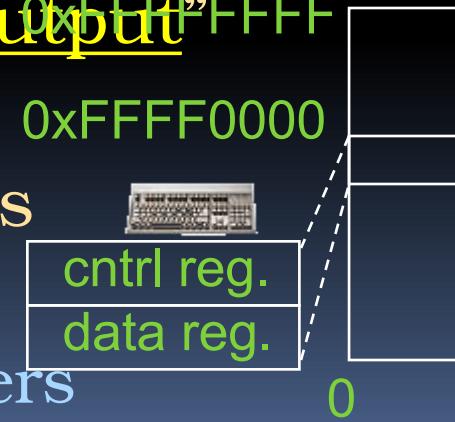
Device (KB/s)	Behavior	Partner	Data Rate
Keyboard	Input	Human	0.01
Mouse	Input	Human	0.02
Voice output	Output	Human	5.00
Floppy disk	Storage	Machine	50.00
Laser Printer	Output	Human	100.00
Magnetic Disk	Storage	Machine	10,000.00
Wireless Network	I or O	Machine	10,000.00
Graphics Display	Output	Human	30,000.00
Wired LAN Network	I or O	Machine	125,000.00

When discussing transfer rates, use 10^x

Instruction Set Architecture for

I/O What must the processor do for I/O?

- Input: reads a sequence of bytes
- Output: writes a sequence of bytes
- Some processors have special input and output instructions
- Alternative model (used by MIPS):
 - Use loads for input, stores for output address
 - Called “Memory Mapped Input/Output”
 - A portion of the address space 0xFFFF0000 dedicated to communication paths to I/O devices (no mem there)
 - Instead, they correspond to registers in I/O devices



Processor-I/O Speed Mismatch

- 1GHz microprocessor can execute 1 billion load or store instructions per second, or 4,000,000 KB/s data rate
 - I/O devices data rates range from 0.01 KB/s to 125,000 KB/s
- Input: device may not be ready to send data as fast as the processor loads it
 - Also, might be waiting for human to act
- Output: device not be ready to accept data as fast as processor stores it
- What to do?

Processor Checks Status before Acting

■ A ~~Reading~~ device generally has 2 registers:

- Control Register, says it's OK to read/write (I/O ready) [think of a flagman on a road]
- Data Register, contains data
- Processor reads from Control Register in loop, spins while waiting for device to set Ready bit in Control reg ($0 \Rightarrow 1$) to say its OK
- Processor then loads from (input) or writes to (output) data register
 - Load from or Store into Data Register resets Ready bit ($1 \Rightarrow 0$) of Control Register
- This is called “**Polling**”

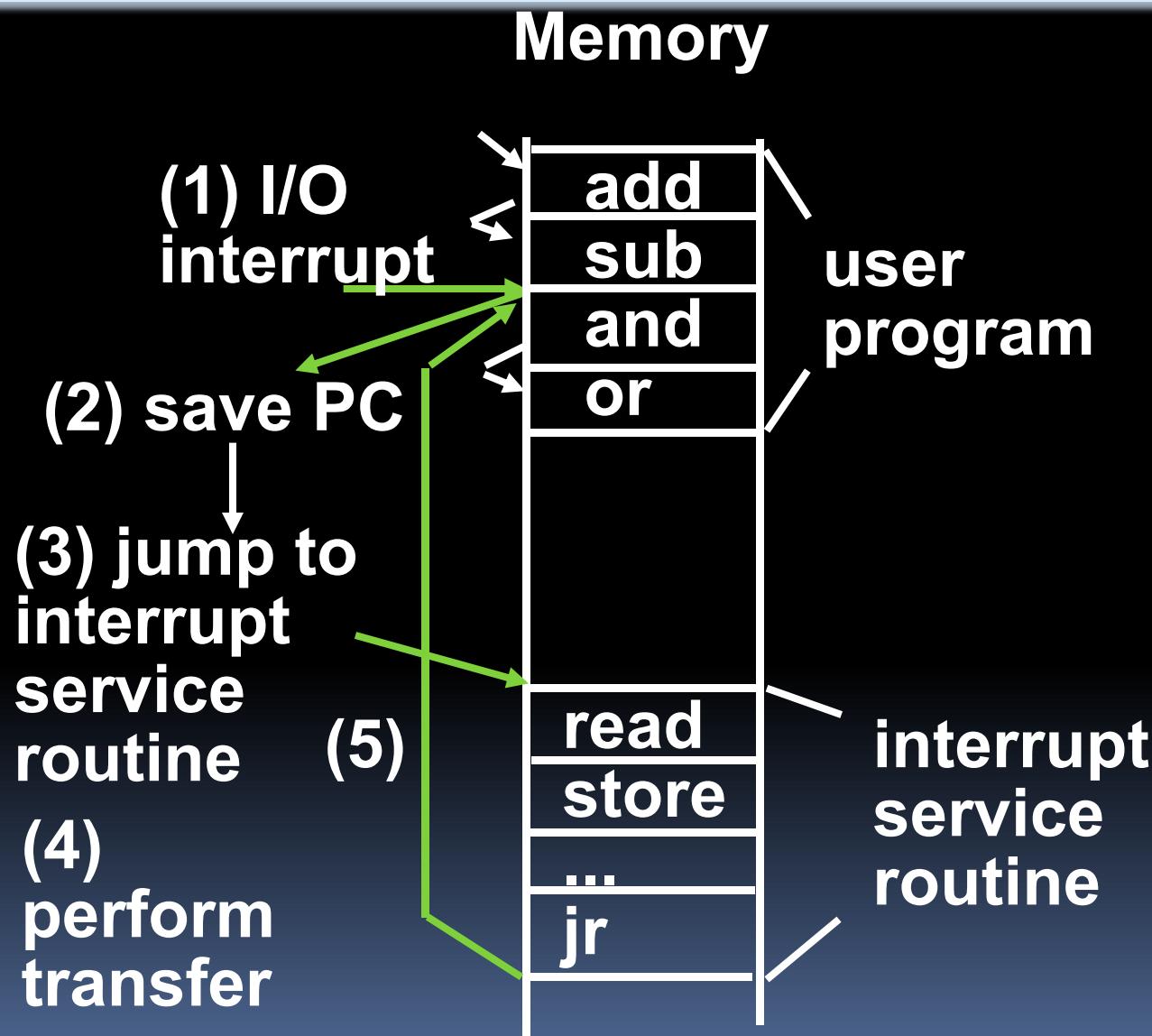
What is the alternative to polling?

- Wasteful to have processor spend most of its time “spin-waiting” for I/O to be ready
- Would like an unplanned procedure call that would be invoked only when I/O device is ready
- Solution: use **exception mechanism** to help I/O. **Interrupt** program when I/O ready, return when done with data transfer

I/O Interrupt

- An I/O interrupt is like overflow exceptions except:
 - An I/O interrupt is “asynchronous”
 - More information needs to be conveyed
- An I/O interrupt is asynchronous with respect to instruction execution:
 - I/O interrupt is not associated with any instruction, but it can happen in the middle of any given instruction
 - I/O interrupt does not prevent any instruction from completion

Interrupt-Driven Data Transfer



Administrivia

- Project 2 graded face-to-face,
check web page for scheduling
- Project 3 (Cache simulator) out
 - You may work in pairs for this project
- Try the performance competition!
 - You may work in pairs for this too
 - Do it for fun!
 - Do it to shine!
 - Do it to test your mettle!
 - Do it for EPA!

Upcoming Calendar

Week #	Mon	Wed	Thu Lab	Fri
#13 This week		I/O P3 out	VM	Performance
#14 Last week o' classes	Inter-machine Parallelism	Summary, Review, Evaluation	Parallel	Intra-machine Parallelism(Scott) P3 due
#15 RRR Week				Perf comp due 11:59pm
#16 Finals Week Review Sun May 9 3-6pm 10 Evans				Final Exam 8-11am in Hearst Gym

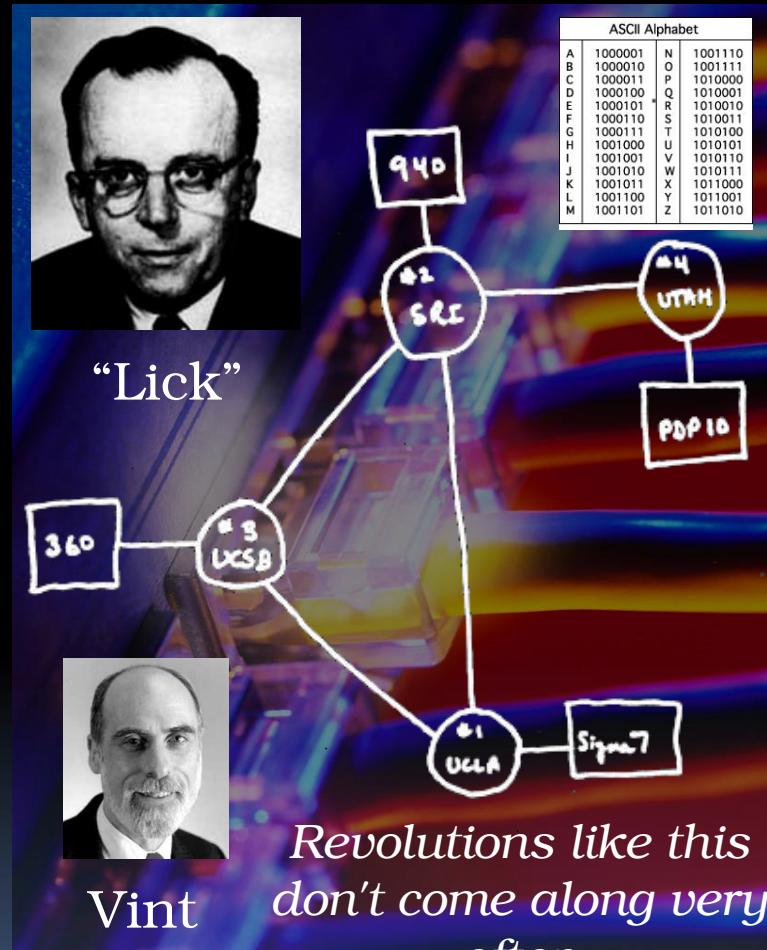
NETWORKS



The Internet (1962)

■ Founders

- JCR Licklider, as head of ARPA, writes on “intergalactic network”
- 1963 : ASCII becomes first universal computer standard
- 1969 : Defense Advanced Research Projects Agency (DARPA) deploys 4 “nodes” @ UCLA, SRI, Utah, & UCSB
- 1973 Robert Kahn & Vint Cerf invent TCP, now part of the Internet Protocol Suite www.greatachievements.org/?id=3736



■ Internet growth rates

Why Networks?

- Originally sharing I/O devices between computers
 - E.g., printers
- Then communicating between computers
 - E.g., file transfer protocol
- Then communicating between people
 - E.g., e-mail
- Then communicating between networks of computers
 - E.g., file sharing, www, ...

The World Wide Web (1989)

- “System of interlinked hypertext documents on the Internet”
- History
 - 1945: Vannevar Bush describes hypertext system called “memex” in article
 - 1989: Tim Berners-Lee proposes, gets system up '90
 - ~2000 Dot-com entrepreneurs rushed in, 2001 bubble burst
- Wayback Machine
 - Snapshots of web over time



Tim Berners-Lee

World's First
web server in
1990

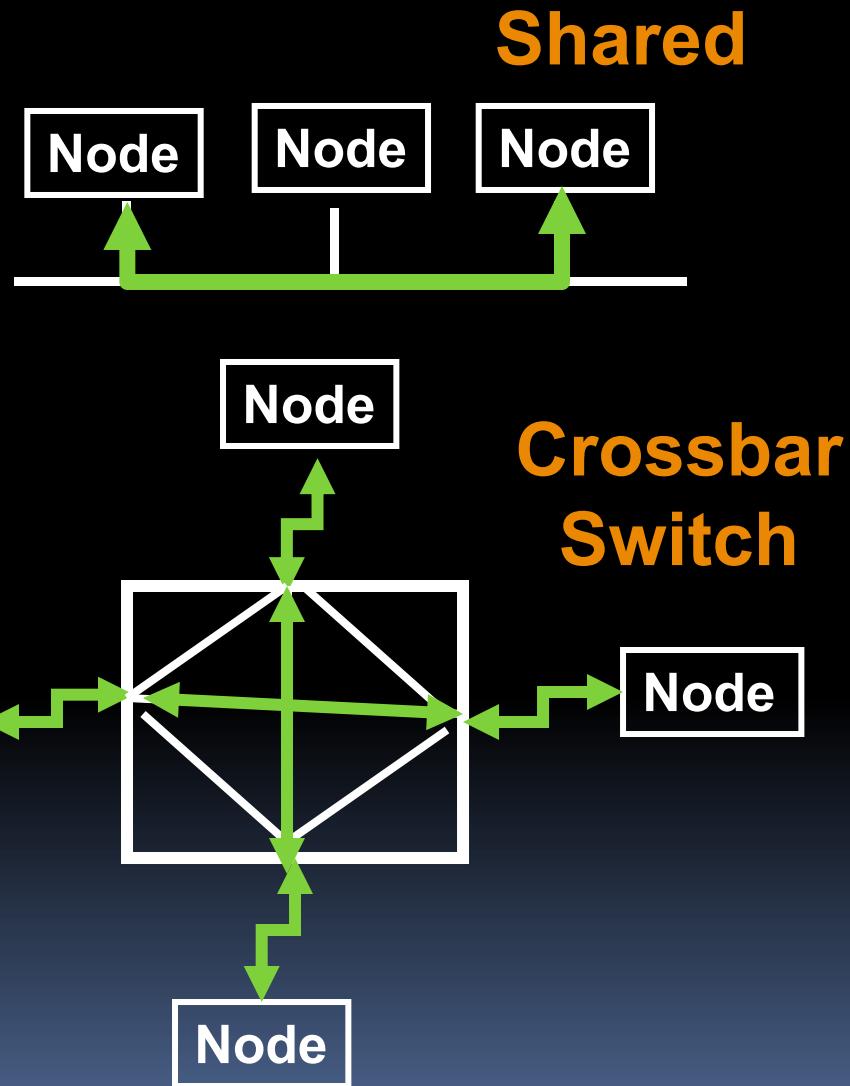


Shared vs. Switched Based Networks

- Shared vs. Switched:

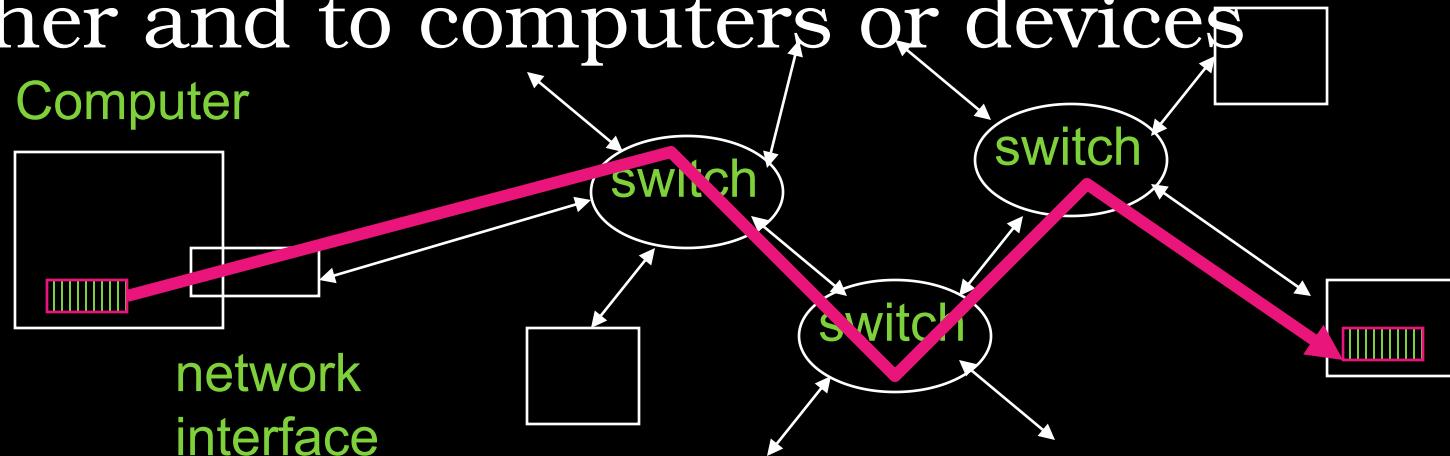
- **Switched:** pairs (“point-to-point” connections) communicate at same time
 - **Shared:** 1 at a time (CSMA/CD)

- Aggregate bandwidth (BW) in switched network is many times shared:
 - point-to-point faster since no arbitration, simpler



What makes networks work?

- links connecting switches to each other and to computers or devices



- ability to name the components and to route packets of information - messages - from a source to a destination

- Layering, redundancy, protocols, and encapsulation as means of abstraction (61C big idea)



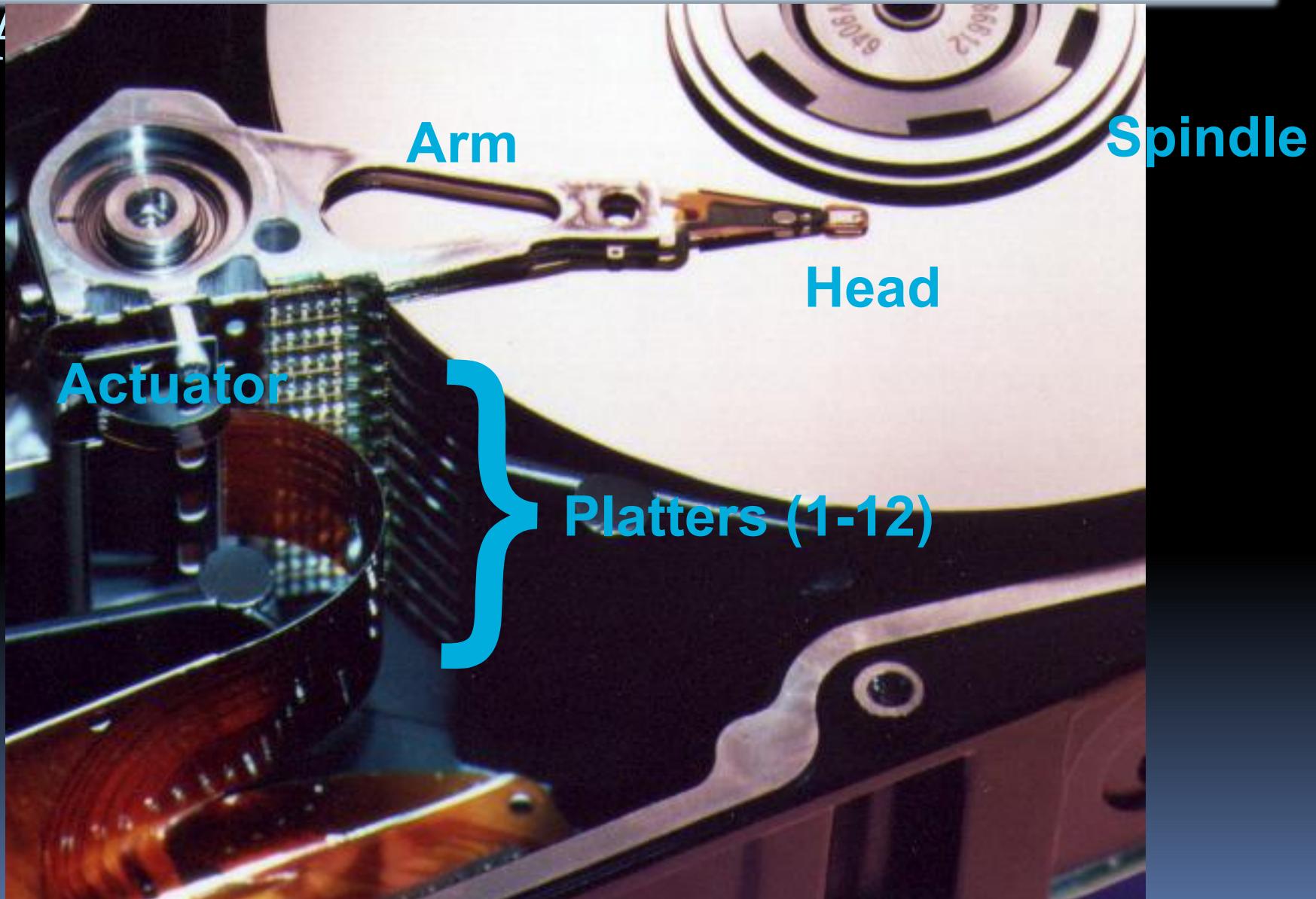
DISKS

Magnetic Disk – common I/O

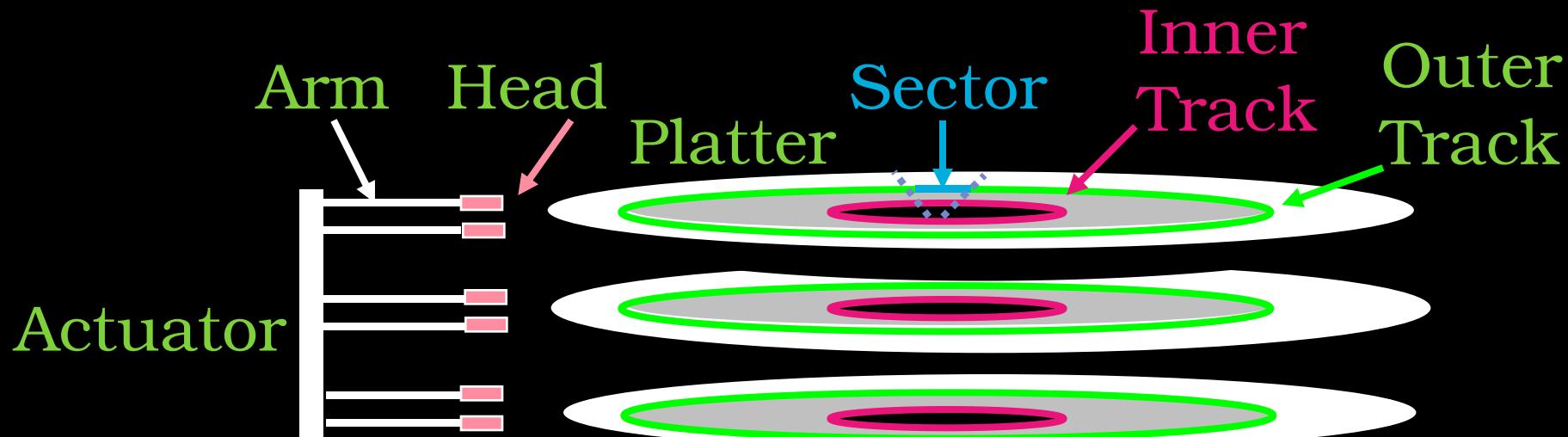
device of computer memory

- Akin to device of computer memory
- Information stored by magnetizing ferrite material on surface of rotating disk
 - similar to tape recorder except digital rather than analog data
- Nonvolatile storage
 - retains its value without applying power to disk.
- Two Types
 - Floppy disks – slower, less dense, removable.
 - Hard Disk Drives (HDD) – faster, more dense, non-removable.
- Purpose in computer systems (Hard Drive):
 - Long-term, inexpensive storage for files
 - “Backup” for main-memory. Large, inexpensive, slow level in the memory hierarchy (virtual memory)

Photo of Disk Head, Arm,

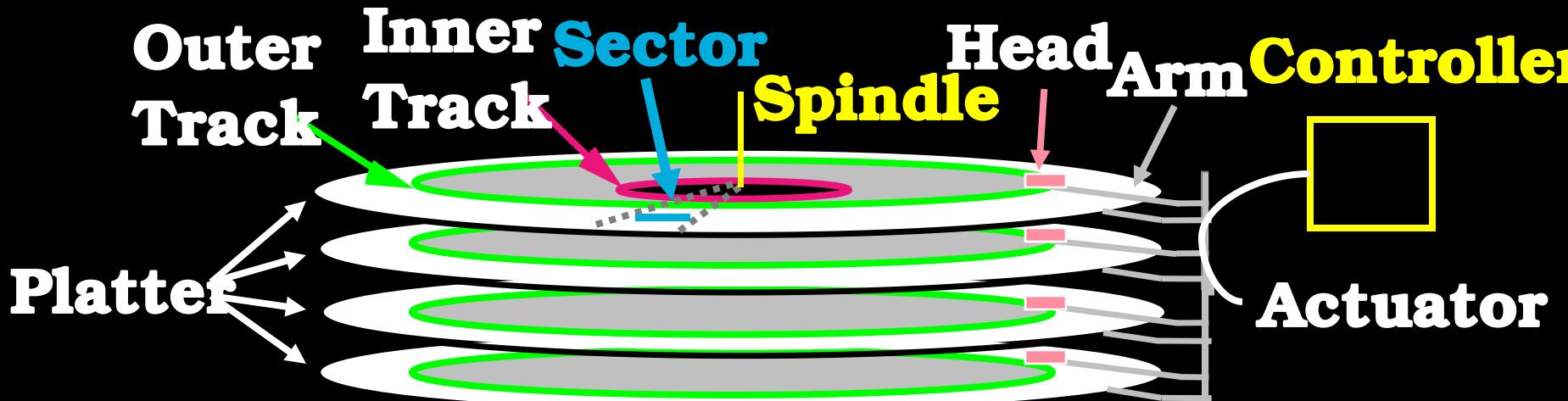


Disk Device Terminology



- Several platters, with information recorded magnetically on both surfaces (usually)
- **Bits recorded in tracks, which in turn divided into sectors** (e.g., 512 Bytes)
- **Actuator moves head (end of arm) over track (“seek”), wait for sector rotate under head, then read or write**

Disk Device Performance (1 / 2)



- **Disk Latency = Seek Time + Rotation Time + Transfer Time + Controller Overhead**
 - Seek Time? depends on no. tracks to move arm, speed of actuator
 - Rotation Time? depends on speed disk rotates, how far sector is from head
 - Transfer Time? depends on data rate (bandwidth) of disk ($f(\text{bit density}, \text{rpm})$), size of request

Disk Device Performance (2/2)

- Average distance of sector from head?
- 1/2 time of a rotation
 - 7200 Revolutions Per Minute \Rightarrow 120 Rev/sec
 - 1 revolution = $1/120$ sec \Rightarrow 8.33 milliseconds
 - 1/2 rotation (revolution) \Rightarrow 4.17 ms
- Average no. tracks to move arm?
 - Disk industry standard benchmark:
 - Sum all time for all possible seek distances from all possible tracks / # possible
 - Assumes average seek distance is random
- Size of Disk cache can strongly affect perf!
 - Cache built into disk system, OS knows nothing

Where does Flash memory come

in Microdrives and Flash memory (e.g., CompactFlash) are going head-to-head

- Both non-volatile (no power, data ok)
- Flash benefits: durable & lower power (no moving parts, need to spin µdrives up/down)
- Flash limitations: finite number of write cycles (wear on the insulating oxide layer around the charge storage mechanism). Most $\geq 100K$, some $\geq 1M$ W/erase cycles.
- How does Flash memory work?
 - NMOS transistor with an additional conductor between gate and source/drain which “traps” electrons. The presence/absence is a 1 or 0.



en.wikipedia.org/wiki/Flash_memory

What does Apple put in its iPods?

Toshiba flash 1, 2GB	Samsung flash 4, 8GB	Toshiba 1.8-inch HDD 80, 160GB	Toshiba flash 8, 16, 32GB
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shuffle,



nano,



classic,

RAID : Redundant Array of Inexpensive Disks

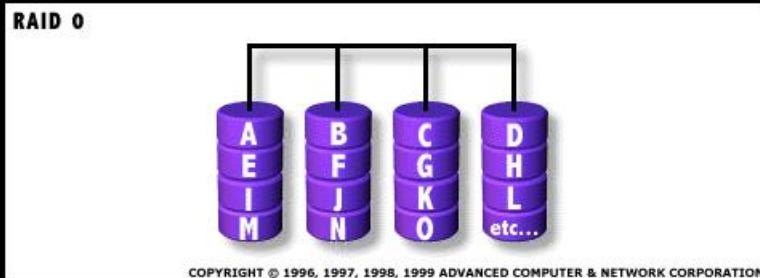
- Invented @ Berkeley (1989)
- A multi-billion industry
80% non-PC disks sold in RAID
- Idea:
 - Files are “striped” across multiple
 - Redundancy yields high data avail
 - Disks will still fail
 - Contents reconstructed from data redundantly stored in the array
 - Capacity penalty to store redundant info
 - Bandwidth penalty to update redundant info



Common RAID configurations

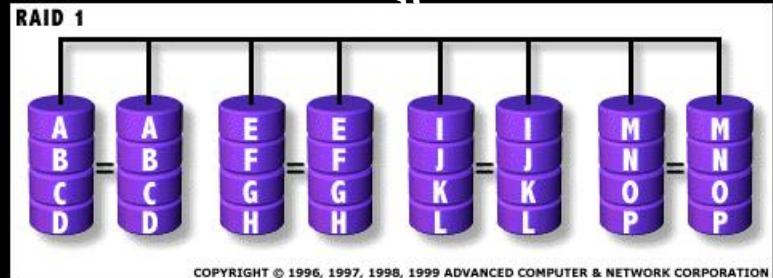
RAID 0

No redundancy, Fast access



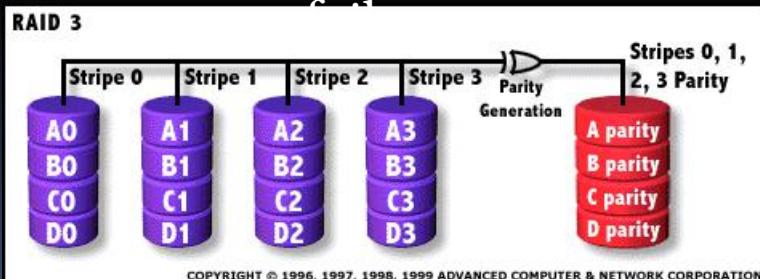
RAID 1

Mirror Data, most expensive



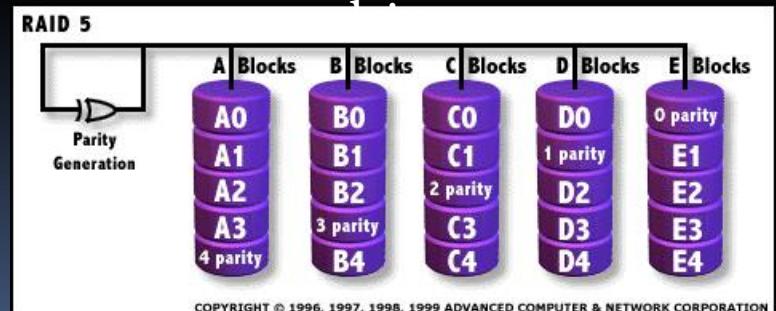
RAID 3

Parity drive protects against 1 failure



RAID 5

Rotated parity across all drives



“And in conclusion...”

- I/O gives computers their 5 senses
- I/O speed range is 100-million to one
- Processor speed means must synchronize with I/O devices before use
- Polling works, but expensive
 - processor repeatedly queries devices
- Interrupts works, more complex
 - devices causes an exception, causing OS to run and deal with the device
- I/O control leads to Operating Systems