

COMP 273: Intro to Computer Systems Review

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Adapted from Joseph Vybihal's Winter 2017 COMP273 slides.
Some things taken from Allan Wang's website.

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1 Basics

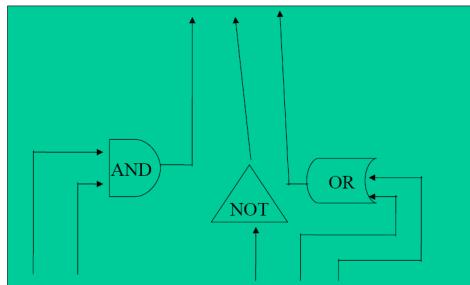
1.1 Bytes

A **byte** consists of 8 bits, 8 inputs and outputs. The main thing we will be working with in this course.



5v signifies T/1, whereas 2v signifies F/0.

Bytes consist solely of 3 gates (AND, OR, NOT), other gates can be made from these.

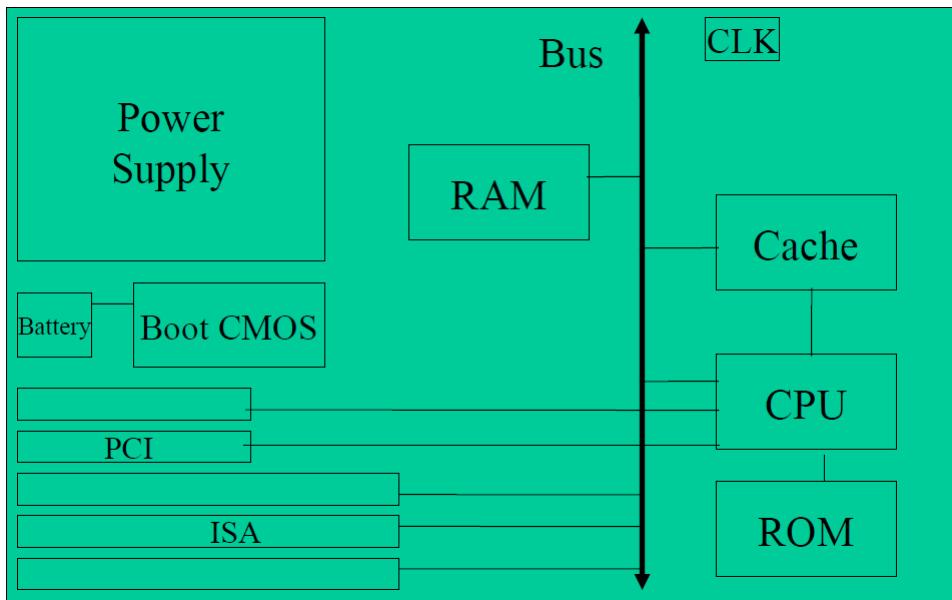


1.2 Electricity Flow

Electricity flows like water on a flat surface, will go in all directions. In order to control electricity flow, we will use **gates**.

If electricity flows the opposite way it's supposed to (in where it's out), the computer will freeze.

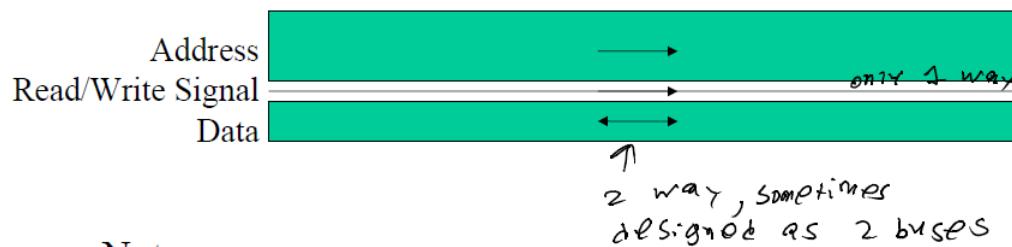
2 System Board



The system board consists of data paths, such that everything is connected.
Many definitions on Lecture 1, are they needed?

2.1 Bus

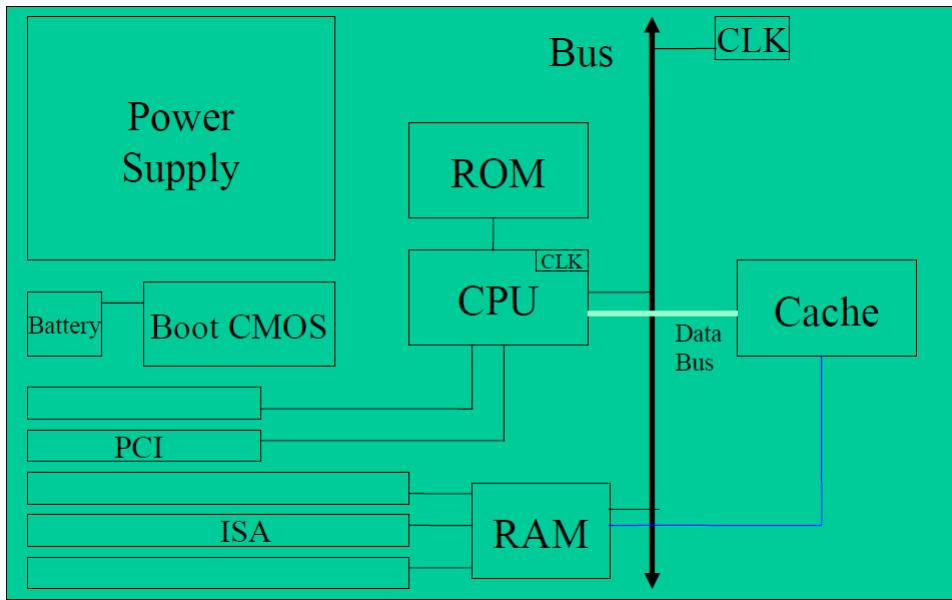
The **bus** links everything together on the system board. A conduit for bytes to travel from one location to another location (pathway). On the classical CPUs, there is only 1 bus, so only 1 thing can use the bus at once.



Here's an optimized schematic that uses the bus less. It provides several direct/private data lines:

- From the CPU to the cache (cache can operate at CPU clock speed)
- Cache to RAM
- CPU to PCI
- All of these make things faster

- Great use of speediness of CPU



Can multi-thread with multiple buses, but multiplies the cost of the computer

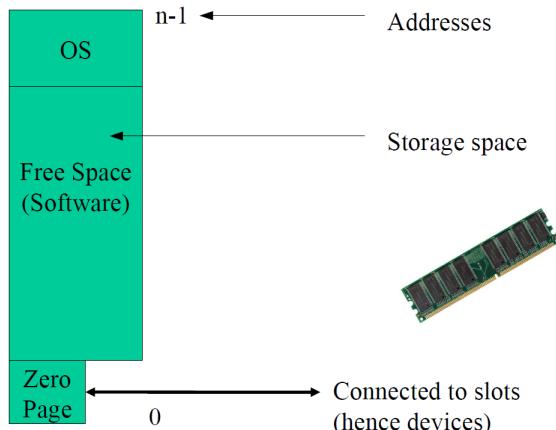
2.2 Pathways

There are many other **pathways**, such as system buses (ISA, PCI), data bus, CPU bus, wires. These pathways are to **interconnect** components. Pathways are composed of multiple parallel wires (to be executed independently), one wire per bit. One byte goes through a bus per tick.

Shorthand for multiple wires 8 wires

2.3 RAM

Volatile (live data) general purpose main memory bank, large & slow, **RAM** consists of addresses, storage space and the zero page, which connects to slots. Comparable to an array.

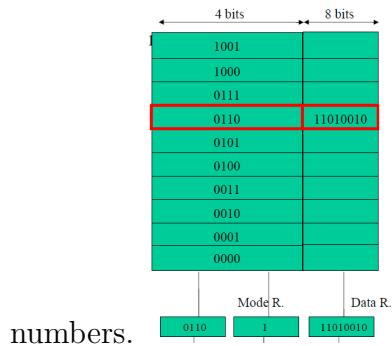


In comparison to cache, RAM costs pennies and

cache costs dollars. Cache is much faster, but RAM is used as an illusion to make the computer work as if all the memory was cache.

RAM separated into 2 sections, addresses and data. RAM is actually mostly addresses. **Data** is typically 8 bits, whereas the size of addresses varies. Typically 32 or 64 bit right now, soon to be 128. Once RAM is built with some size, you can't change it (so you must decide wisely). Need 1 wire per bit (i.e. 8 wires going to data part and however many for addresses). In order to r/w to RAM, we need a few things. **Address register** to select address/row, mode register for r/w and data register. For large values/things, like strings, store in consecutive memory areas.

Video and RAM 1:1 correspondence with RAM and pixels. Pixels represented by integer



2.4 Clock

There are always at least 2 **clocks**. One for the bus (much slower) and one for the CPU (much faster). The bus clock is 1 or 2 orders of magnitude slower than the CPU clock.

Bus Clock

- Mainly for gating access to bus.

- Also regulates data movement on system board.

CPU Clock

- Responsible for instruction execution inside CPU.
- Moves data using CPU bus or moves code from IP → sequencer
- Doesn't affect things outside CPU.
- The clock will determine order of instruction execution (they have to take turns).

2.5 PCI & ISA

Connect outside of the computer, to other peripherals like monitors. PCI can run at higher clock speeds than ISA.

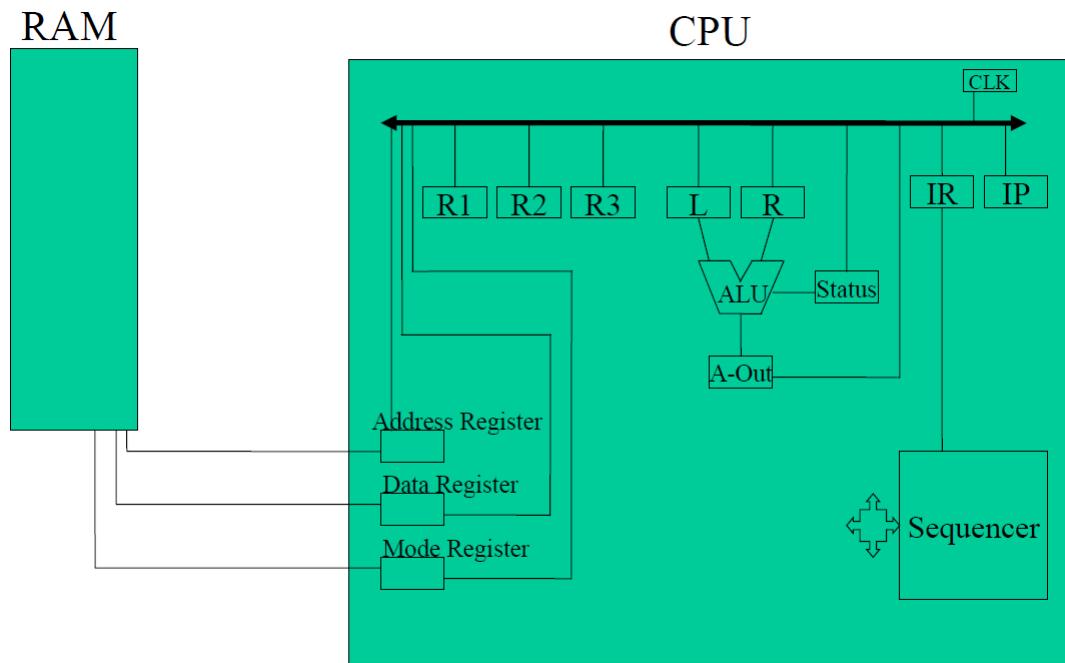
2.6 Addressing

All components of system board have a unique integer number identifying them. Needed, so that we can block electricity from going to certain peripherals.

2.7 CPU

Central Processing Unit, used for math, logic, data, movement & loops. The **CPU** is pretty simple/basic, even though it's the “brain” of the computer. It's main capabilities consist of adding, subtracting, multiplying, knows about the 3 gates.

Classical CPU Scheme Without Cache



Here, RAM

reads the address from the address register, writes to the data register and the mode register differentiates read/write. The sequencer opens and closes gates.

Registers Like temp variables for the CPU. Store single value.

ALU: Arithmetic Logic Unit The ALU takes 2 inputs, L and R to get it's output, A-Out. The Status register takes input (for type of operation) and output to report errors, like overflow, dividing by zero.

ALU consists of a bunch of adders, 2s complement circuit for L and for R (need something that inverts bits and then use an adder to increment by 1).

IP(Instruction Pointer) or IC (Instruction Counter)

- Next instruction/address to execute
- Address Register points to it when needed

IR (Instruction Register)

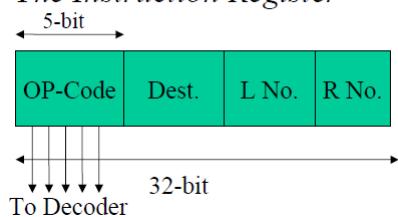
- Current instruction being executed
- From data register
- First part is op-code, goes to control unit

- Parts after are arguments
- Usually 3 args, 3rd is usually optional?

Example Instructions

- lw \$2, (\$3) (indirect)
 - Loads word into reg 2 from address in reg 3
- lw \$2, #1A2F
 - Goes directly to address, no need to check register (direct)

The Instruction Register



- L → L register
- R → R register
- A-Out → Dest
- OP-Code is used by sequencer to trigger circuit that will do this action.

We can't distinguish variables, addresses and operations.

RAM Access Register System

- Communicates CPU ↔ RAM
- Address register (r/w this address)
- Data register (data received or sending)
- Mode register (r/w)

CPU Boundary Register Keeps track of addresses used, addresses requested shouldn't pass boundary address.

Sequencer/Decoder

- Table, codes with circuits
- Circuits have gated triggers, allowing data to go in a specific order
- Sequencer and ROM have circuitry to react to machine lang, allow computer to execute instr. Sequencer: built-in instr. ROM: extended instr.

CPU Clock See 2.4.

CPU Loop (Execution)

1. Get instruction: $IR \leftarrow RAM$ (or cache), slow bus
2. Sequencer $\leftarrow IR[\text{op-code}]$
3. Selected gates open
4. Clock ticks (if this is outside CPU, have to respect other clocks too)
5. All gates close
6. Increment \rightarrow next instruction (fast). Back to step 1.

Shorthand:

1. $AR \leftarrow PC$
2. $PC \leftarrow PC+1$
3. $DR \leftarrow RAM[AR]$
4. $IR \leftarrow DR$
5. Re-loop

Constant switch from slow to fast clock means we are never really fast, which is why we need things like a cache.

Memory Different types of memory. See specific sections for more info.

- RAM (primary storage). DRAM: Dynamic, must refresh. SRAM: Static, no refresh.
- ROM, read only memory (advanced instructions). ROM is hardwired. PROM programmable once (fuses). EPROM, erasable by heat. EEPROM electrically erasable. PAL, PLA.
- Cache. Very fast memory, usually on CPU. Store frequently accessed info. Doesn't use system bus. 1 direction, cache1 → CPU and CPU → cache2.
- Pipeline. Use assembly line to process instructions. Partially parallel. Series of instruction registers.

3 Data/Data Encoding

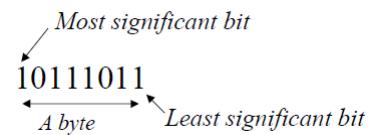
Data is information stored in RAM or secondary storage. Can be instructions or information. There are built-in types CPU can understand (int, real, char), since there are circuits made to interpret them. Language types must be simulated. The **bit** is the fundamental unit of the computer. Using bits and gates, we will group things in order to store data.

Bit Grouping Two forms: numerical binary representation and tabulated binary encoding (ASCII, UNICODE, instructions, etc.). Can count, add, subtract, multiply and divide with

Name	Bits per Symbol	Total Symbols	Comments
BCD	6	64	A-Z; 0-9, \$... (only capitals)
ASCII	7	128	a-z; A-Z; 0-9; Bel, Tab, \$, ...
USASCII	8	256	Even parity bit for transmit
EBCDIC	8	256	Odd parity bit (only IBM)
UNICODE	16	65,536	Many languages

binary numbers.

How to represent data? How many bits do we need? What medium to use? (lights, sound,



signals) Lightbulbs originally used, either on or off.

Nibble	4 bits
Byte	8 bits
Word	16 bits
Long Word/Word	32 bits
Quad Word/Word	64 bits

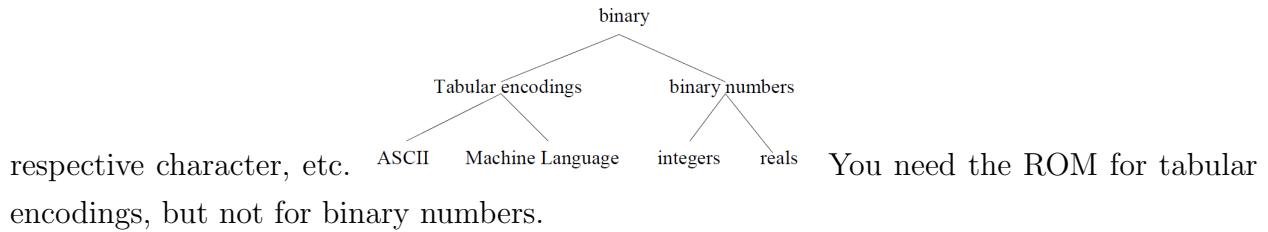
There are

standards for data types/storage established by IEEE and ISO. 3 basic things to encode: chars, numbers and instructions. For **characters**, we use a predetermined table (ASCII, unicode), **numbers** use binary arithmetic and **instructions** use a table, gate sequence code-number.

Word Word is the common size of a register of CPU(best for design of CPU). CPUs often have multiple register sizes. Word sizes differ between CPUs. Nowadays, register size is usually the same as address size.

3.1 Data Types & Encoding

How does the machine know that a byte is a character? The ROM (Read Only Memory), has predefined instructions to deal with it. Compiler will look at ASCII table and display the



3.1.1 Number Representations

Binary

- Used for flags, numbers, strings, encodings
- Longhand addition in binary is the same as elementary grade addition with decimals
 - But we have a fixed size
 - If we carry past size → **Arithmetic Overflow**
 - Signed overflow expected for 2's complement subtraction

Hexadecimal Easier to read for humans, better correspondence with binary. Base 16, with 10-15 being A, B, C, D, E, F. Decimal to Binary conversion is slow. Computers often convert binary to hex for errors to make it easier to read.

Octal

- Barely used anymore
- Except for Unix permissions and C, Perl escape codes

3.1.2 Conversion

Decimal → Binary Keep dividing by 2 until you get 0, read the remainders from bottom

$$123_{10} = N_2 = 1111011_2$$

↑
 123 /2 = 61 R 1
 61/2 = 30 R 1
 30/2 = 15 R 0
 15/2 = 7 R 1
 7/2 = 3 R 1
 3/2 = 1 R 1
 1/2 = 0 R 1
 Read
 to top → left to right.

Decimal → Hex Divide by 16 until 0, read remainders in same way.

$$53241_{10} = N_{16} = \text{CFF9}_{16}$$

↑
 53241/16 = 3327 R 9
 3327/16 = 207 R F
 207/16 = 12 R F
 12/16 = 0 R C

Binary → Decimal Depending on position of number, multiply value by $2^{n^{\text{th}} \text{position}}$

$$1011_2 = N_{10} = 11_{10} = 1 \times 2^3 + 0 \times 2^2 + 1 \times 2^1 + 1 \times 2^0$$

Hex → Decimal Same principle with base 16.

$$1AB_{16} = N_{10} = 427_{10} = 1 \times 16^2 + A \times 16^1 + B \times 16^0$$

Binary ↔ Hex 1 nibble = 1 hex digit

$$\begin{array}{cccc} 1 & 1 & 1 & 1 \\ \hline 0 & 0 & 1 & 1 \\ \hline 0 & 0 & 0 & 1 \\ \hline 0 & 0 & 0 & 0 \end{array} = F310_{16}$$

Binary ↔ Octal 3 bits = 1 octal, same as Hex strategy.

3.1.3 Binary Encodings

ASCII 2^7 values, but wasn't enough for special characters like accents.

0	0011 0000	o	0100 1111	m	0110 1101
1	0011 0001	p	0101 0000	n	0110 1110
2	0011 0010	Q	0101 0001	o	0110 1111
3	0011 0011	R	0101 0010	p	0111 0000
4	0011 0100	S	0101 0011	q	0111 0001
5	0011 0101	T	0101 0100	r	0111 0010
6	0011 0110	U	0101 0101	s	0111 0011
7	0011 0111	v	0101 0110	t	0111 0100
8	0011 1000	w	0101 0111	u	0111 0101
9	0011 1001	x	0101 1000	v	0111 0110
A	0100 0001	y	0101 1001	w	0111 0111
B	0100 0010	z	0101 1010	x	0111 1000
C	0100 0011	a	0110 0001	y	0111 1001
D	0100 0100	b	0110 0010	z	0111 1010
E	0100 0101	c	0110 0011	.	0010 1110
F	0100 0110	d	0110 0100	,	0010 0111
G	0100 0111	e	0110 0101	:	0011 1010
H	0100 1000	f	0110 0110	,	0011 1011
I	0100 1001	g	0110 0111	?	0011 1111
J	0100 1010	h	0110 1000	!	0010 0001
K	0100 1011	i	0110 1001	'	0010 1100
L	0100 1100	j	0110 1010	"	0010 0010
M	0100 1101	k	0110 1011	(0010 1000
N	0100 1110	l	0110 1100)	0010 1001
				space	0010 0000

3.1.4 Data Representation

Representing data consists of a choice, that comes at a cost. Pros/cons to each choice.
Specify the base when writing numbers in this class. 3 representations:

- Logical description (how it truly looks & behaves)
- Physical construction
- Circuit

We need legal operators, abstraction of what is being recorded (chars don't exist) and want to know how we want to represent information in binary (size, addressing).

Integers Usually 16,32 or 64 bits. How do we differentiate sign? We can have a **signed** bit (use most significant bit as sign) or use "2's complement". With signed bits, there exists a negative 0, but with 2's comp, only one 0 and most significant bit is still a sign bit. We don't need a null at the end of an int, it's matched with x bit instructions made for its size.

Two's Complement Easier to build computers if they subtract using:

$$X - Y = X + (-Y) = X + (\text{2's complement of } Y)$$

How to convert?

- Take Y
- Flip bits
- Add 1

Uses a signed overflow in order to get expected result.

Example

00111	+11011
- 00101	-----
-----	Overflow (Expected)
? Add 1:	11011 00010 ₂ Flip bits: (Ignored)

Base 10 Two's Complement

$$\begin{aligned} -N &= \text{Base}^{\text{size}} - N \\ -12_{10} &= 10^2 - 12 = 88_{10} \\ 15 - 12 = 15 + 88 &= 103 \implies \text{Drop carry, get 3} \end{aligned}$$

Signed vs 2's Comp

- Signed
 - Easy to read
 - No conversion
- 2's
 - Unique 0
 - Auto subtracts when adding

Characters Encoded using ASCII or UNICODE or something similar (standard). Type not stored in computer, there are no types.

Strings Each char stored in 1 byte in RAM (consecutive). Either a null at the end signifying the end of the String, or the most significant bit describes length.

Floating Point/Real Numbers Scientific notation approximation, store decimal and exponent.

Sign	Exponent	Mantissa	31 30 29 28 27 26 25 24 23 22 21 20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1 0												
0	4	100025	s exponent fraction												
			1 bit	8 bits	23 bits										
In general, floating-point numbers are of the form $(-1)^s \times F \times 2^E$															

IEEE format Uses bias for exponent, i.e. for 32 bit, 127=0, 126=-1, 128=1. This way

		Single	Double	Quad
Number of bits taken by:				
Sign	1	1	1	1
Exponent	8	11	15	
Fractional mantissa	23	52	111	
Total	32	64	128	
Exponent:				
Bias	127	1023	16383	
Range of (biased) exponent:	0..255	0..2047	0..32767	

we don't need a signed bit.

Mantissa stores a fraction(raw digits after decimal) for approximation. Normalize your fraction such that you get 1.something and ignore the 1.

Example

$$\begin{aligned}
 -0.75_{10} &= -3/4_{10} = -3/2^2 \\
 \implies -11_2/2^2 &= -0.11_2 = -0.11_2 \times 2^0 = -1.1_2 \times 2^{-1} \\
 \implies (-1)^1 \times (\underbrace{1}_{\text{ignored}} + .100\dots00_2) \times 2^{126-217}
 \end{aligned}$$

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
1	0	1	1	1	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

1 bit 8 bits 23 bits

Notice that the leading 1 before the decimal is ignored. The 22nd bit is 2⁻¹, the 23rd is 2⁻², etc. Since we had 1.1₂, we look at the numbers after the decimal and just copy those.

Logical Single bit, 0=false, 1=true

Packed Decimal One nibble per digit of a number in base 10. Can be used to store decimal numbers. Addition is strange. Add 2 nibbles together, if you get over 10, subtract 10 and carry and add 1 over to next nibble. (i.e, if you do 3+9, you'll get 12 (5 bits), subtract 10 and represent 2 in binary)

$$5372_{10} = 0101\ 0011\ 0111\ 0010$$

Very user friendly, but wastes space and complicates hardware.

3.2 Mathematical Operation Algorithms for Floating Points

Addition

- Normalize (floating point)
- Round if required
- Put numbers to same exponent (shift smaller to right until it's the same as larger)
- Add significands
- Normalize (check for over/underflow)
- Round
- Sign?

Ex Add 0.5_{10} and -0.4375_{10}

$$\begin{aligned} 0.5_{\text{ten}} &= 1/2_{\text{ten}} & = 1/2^1_{\text{ten}} \\ &= 0.1_{\text{two}} & = 0.1_{\text{two}} \times 2^0 & = 1.000_{\text{two}} \times 2^{-1} \\ -0.4375_{\text{ten}} &= -7/16_{\text{ten}} & = -7/2^4_{\text{ten}} \\ &= -0.0111_{\text{two}} & = -0.0111_{\text{two}} \times 2^0 & = -1.110_{\text{two}} \times 2^{-2} \end{aligned}$$

Now we follow the algorithm:

Step 1. The significand of the number with the lesser exponent ($-1.11_{\text{two}} \times 2^{-2}$) is shifted right until its exponent matches the larger number:

$$-1.110_{\text{two}} \times 2^{-2} = -0.111_{\text{two}} \times 2^{-1}$$

Step 2. Add the significands:

$$1.000_{\text{two}} \times 2^{-1} + (-0.111_{\text{two}} \times 2^{-1}) = 0.001_{\text{two}} \times 2^{-1}$$

Step 3. Normalize the sum, checking for overflow or underflow:

$$\begin{aligned} 0.001_{\text{two}} \times 2^{-1} &= 0.010_{\text{two}} \times 2^{-2} = 0.100_{\text{two}} \times 2^{-3} \\ &= 1.000_{\text{two}} \times 2^{-4} \end{aligned}$$

Since $127 \geq +4 \geq -126$, there is no overflow or underflow. (The biased exponent would be $-4 + 127$, or 123, which is between 1 and 254, the smallest and largest unreserved biased exponents.)

Step 4. Round the sum:

$$1.000_{\text{two}} \times 2^{-4}$$

The sum already fits exactly in 4 bits, so there is no change to the bits due to rounding.

This sum is then

$$\begin{aligned} 1.000_{\text{two}} \times 2^{-4} &= 0.0001000_{\text{two}} = 0.0001_{\text{two}} \\ &= 1/2^4_{\text{ten}} & = 1/16_{\text{ten}} & = 0.0625_{\text{ten}} \end{aligned}$$

This sum is what we would expect from adding 0.5_{ten} to -0.4375_{ten} .

Multiplication

- Remove exponent bias
- Match exp
- Multiply significands
- Normalize & round
- Sign

Ex Multiply 0.5_{10} and -0.4375_{10}

In binary, the task is multiplying $1.000_{\text{two}} \times 2^{-1}$ by $-1.110_{\text{two}} \times 2^{-2}$.

Step 1. Adding the exponents without bias:

$$-1 + (-2) = -3$$

or, using the biased representation:

$$\begin{aligned} (-1 + 127) + (-2 + 127) - 127 &= (-1 - 2) + (127 + 127 - 127) \\ &= -3 + 127 = 124 \end{aligned}$$

Step 2. Multiplying the significands:

$$\begin{array}{r} & 1.000_{\text{two}} \\ \times & 1.110_{\text{two}} \\ \hline & 0000 \\ & 1000 \\ & 1000 \\ & \hline 1110000_{\text{two}} \end{array}$$

The product is $1.110000_{\text{two}} \times 2^{-3}$, but we need to keep it to 4 bits, so it is $1.110_{\text{two}} \times 2^{-3}$.

Step 3. Now we check the product to make sure it is normalized, and then check the exponent for overflow or underflow. The product is already normalized and, since $127 \geq -3 \geq -126$, there is no overflow or underflow. (Using the biased representation, $254 \geq 124 \geq 1$, so the exponent fits.)

Step 4. Rounding the product makes no change:

$$1.110_{\text{two}} \times 2^{-3}$$

Step 5. Since the signs of the original operands differ, make the sign of the product negative. Hence, the product is

$$-1.110_{\text{two}} \times 2^{-3}$$

Converting to decimal to check our results:

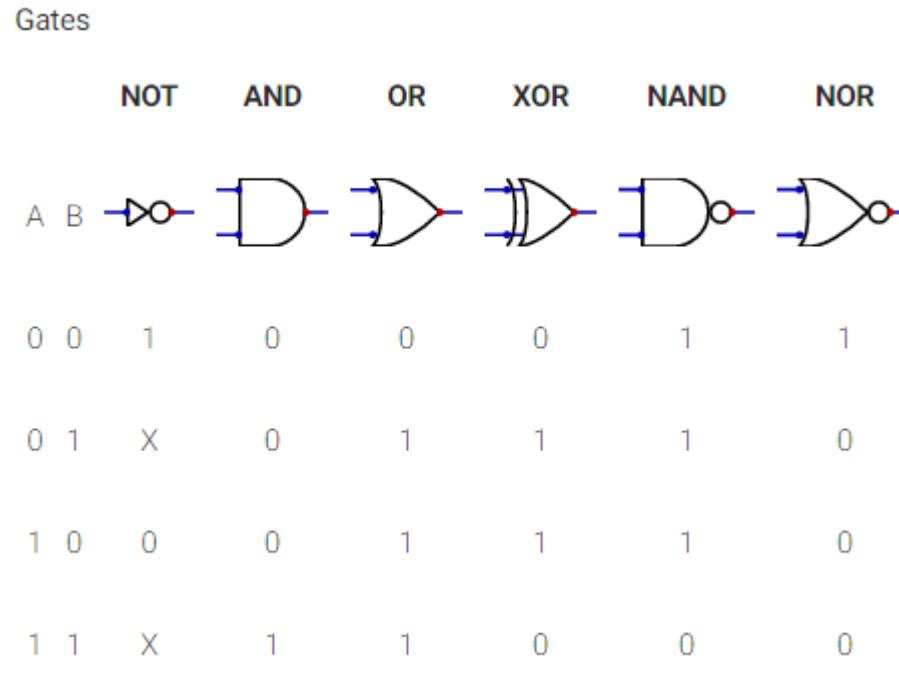
$$\begin{aligned} -1.110_{\text{two}} \times 2^{-3} &= -0.001110_{\text{two}} = -0.00111_{\text{two}} \\ &= -7/2^5_{\text{ten}} = -7/32_{\text{ten}} = -0.21875_{\text{ten}} \end{aligned}$$

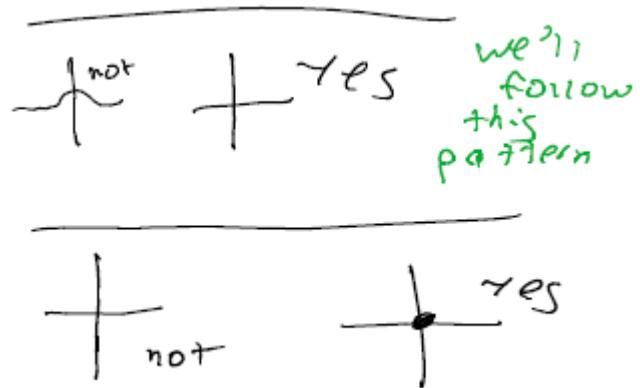
The product of 0.5_{ten} and -0.4375_{ten} is indeed -0.21875_{ten} .

4 Logic & Gates

- Circle \Rightarrow not
- Extra line \Rightarrow exclusive

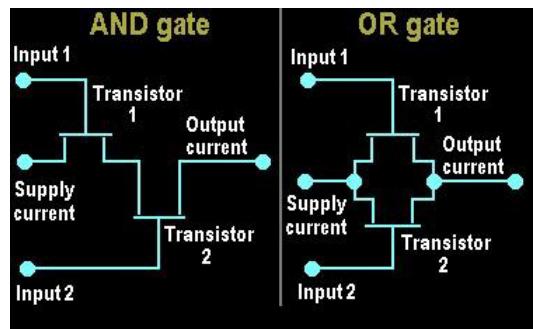
Figure 1: Taken from Allan Wang's website



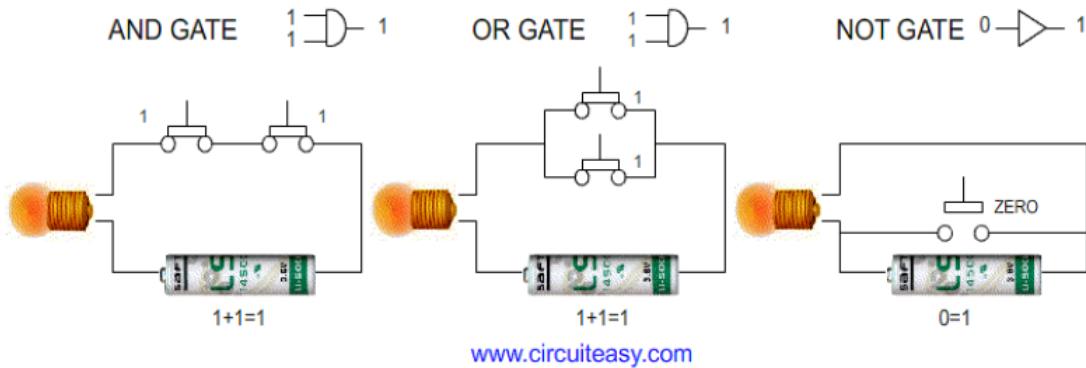


Wire crosses, i.e. when are two wires connected:

Low-level Construction



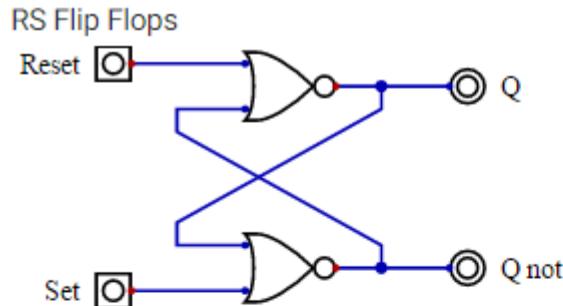
SIMPLE LOGIC GATE PROCESSOR



4.1 Basic Flip Flop Circuits

Flip Flops are bits!

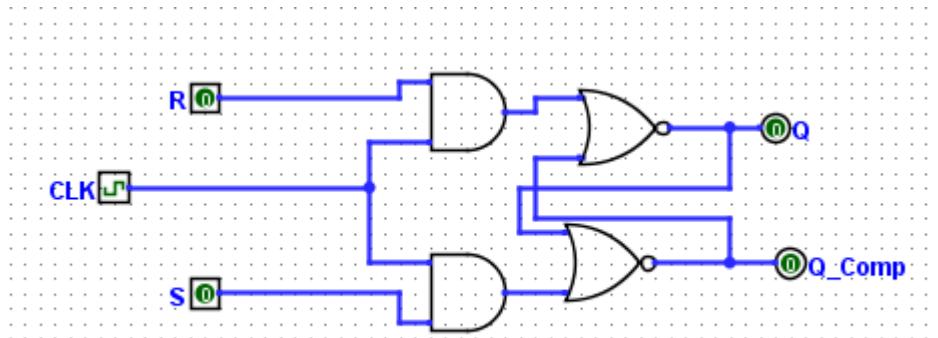
Figure 2: RS Flip Flops, Allan Wang



Basic reset set flip flop to save bit data; a clock can be connected to the inputs of both nor gates for synchronization

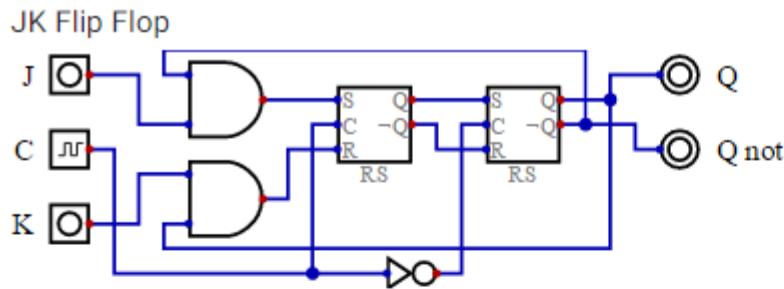
R	S	Q	Q'	Result
0	0	Q	Q'	No Change
0	1	1	0	Set
1	0	0	1	Reset
1	1	1	1	Avoid

Sending 1 to reset(R) and set(S) is an invalid input. They must be opposites, or both 0. Sending a 1 through set, sets the bit's output, Q to 1, and it's complement Q' to 0. Sending 1 through reset does the opposite. If both are 0, keep current value (clocked). Can test **steady state** of the circuit. Give a 1 to R and follow the circuit, realize nothing conflicts. The flip flops don't actually store anything, they just have data going through them → live data, lost when unplugged.



Clocked RS: Like an RS Flip-Flop, except only let's things through when clock ticks.

Figure 3: JK Flip Flop, Allan Wang

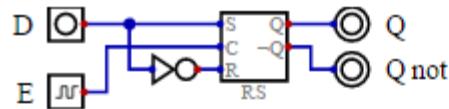


JK flip flops cycle at half the speed of its input, as only one SR flip flop is enabled at a time and it takes two clicks to pass data to the output.

J	K	Q	Q'	Result
0	0	Q	Q'	Unchanged
0	1	0	1	Reset
1	0	1	0	Set
1	1	Q'	Q	Toggle

2 SR flip flops, adds a delay.

Figure 4: D Flip Flop/D Latch, Allan Wang

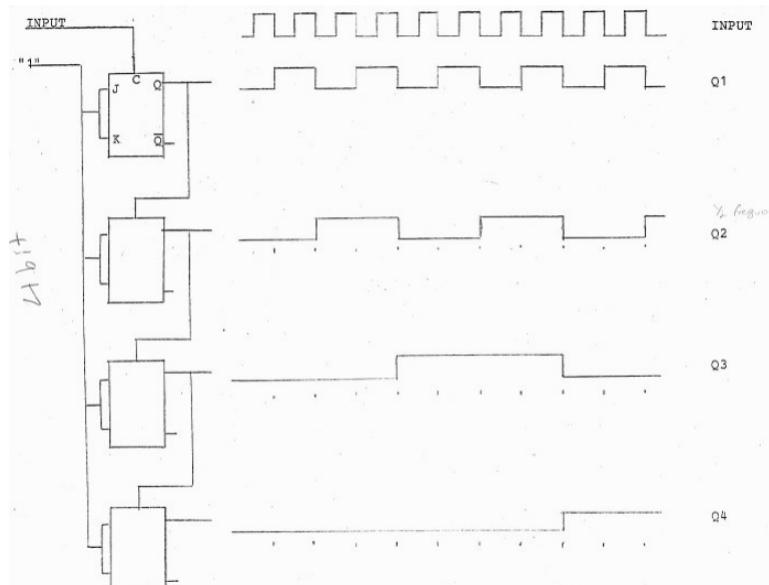


An addition to the RS flip flop to accept a single input. Together with the clock (E), the input (D) directly changes the output of the latch. This also eliminates the Reset = 1 & Set = 1 issue.

E	D	Q	Q'	Result
0	0	Q	Q'	Latch
0	1	Q	Q'	Latch
1	0	0	1	Reset
1	1	1	1	Set

Used for registers/data.

Chaining flip flops and their clock input stretches out inputs even more, how we use



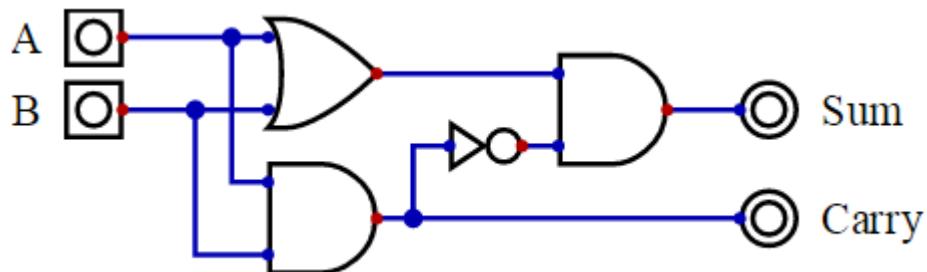
counters.

4.2 Adders

How do we do grade school addition in binary at the hardware level? When adding 2 numbers together, we need a half adder for least significant bit (no carry) and full adders for all the other bits. Be careful of overflows and signed bits!

Half-Adder 2 bits in, sum & carry out

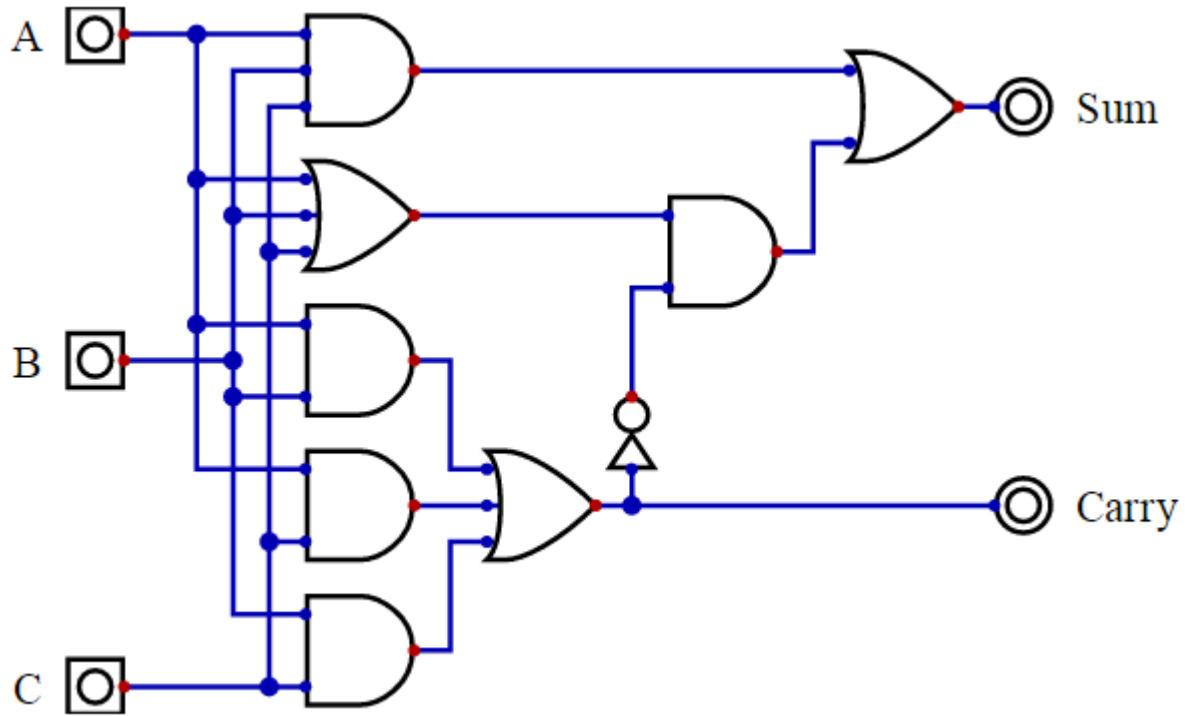
Figure 5: Half Adder, Allan Wang



If A & B are both 1, then we will give 1 to carry and negate adding to sum.

Full Adder 3 bits in (3^{rd} is carry), sum & carry out

Figure 6: Full Adder, Allan Wang



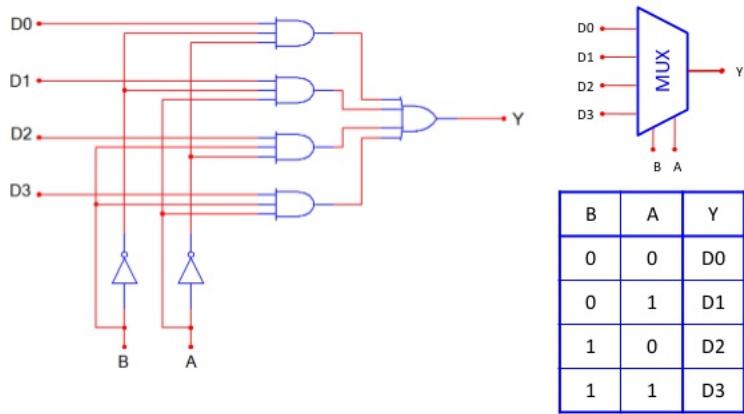
Above is the more optimized version. Can just have 2 half adders and an or. Include simpler version with half-adders?

4.3 Combinatorial Networks

Premade circuits for specific purposes, readily available.

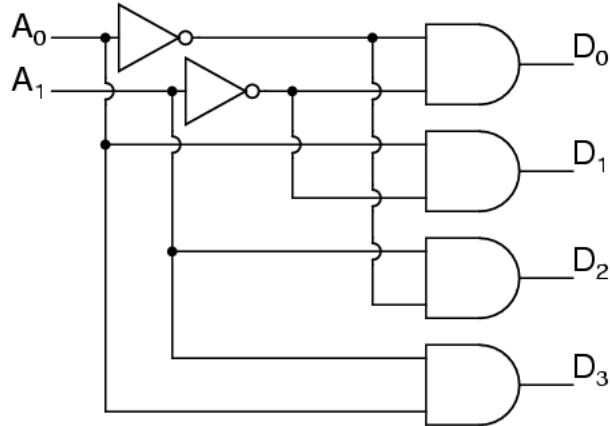
Multiplexers $2^a \rightarrow 1$ mux, 2^a inputs x_0, \dots, x_{n-1} and a single output z. Selector address a, with input signals y_0, \dots, y_{a-1} , selects which x_i to pass through z. Useful for when you have multiple signals but can only let one through at a time. Addressing, but with 1 output, z.

4-to-1 Multiplexer (MUX)



6

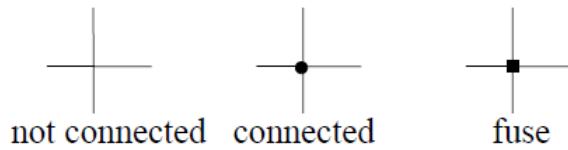
Decoders $a \rightarrow 2^a$ decoder, gives out one of its 2^a outputs. Once again, like addressing, but selecting which you want to turn on. Like controlling switches. CPU sequencer is a



decoder.

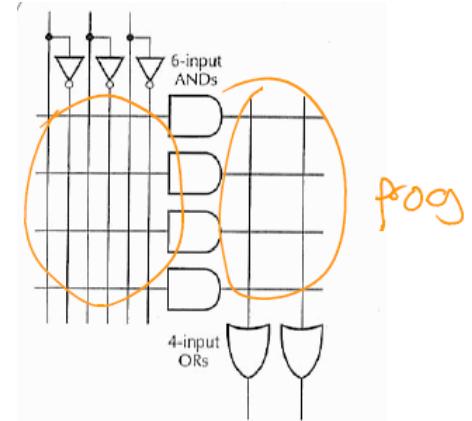
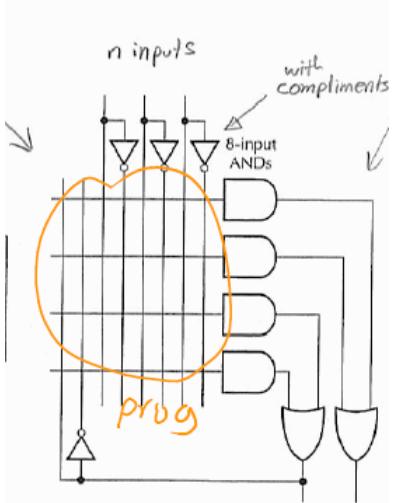
Encoders Outputs a-bit binary number, y_i equal to index of single 1 signal on among 2^a inputs x_0, \dots, x_{a-1} . All of the xs are connected to an or gate, so if they're all off but x_0 is on, will show 0.

Programmable Combinatorial Parts VIA Fuses that can be blown (disconnected) from enough current or VIA anti-fuses that are set (connected) from enough current.



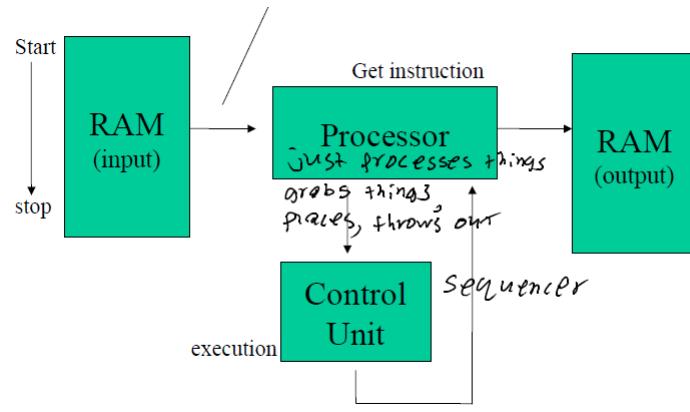
PROM Programmable read only memory, has anti-fuses that can be set, linked to decoder.

PAL Programmable Array Logic, input wires are programmable, but output isn't.

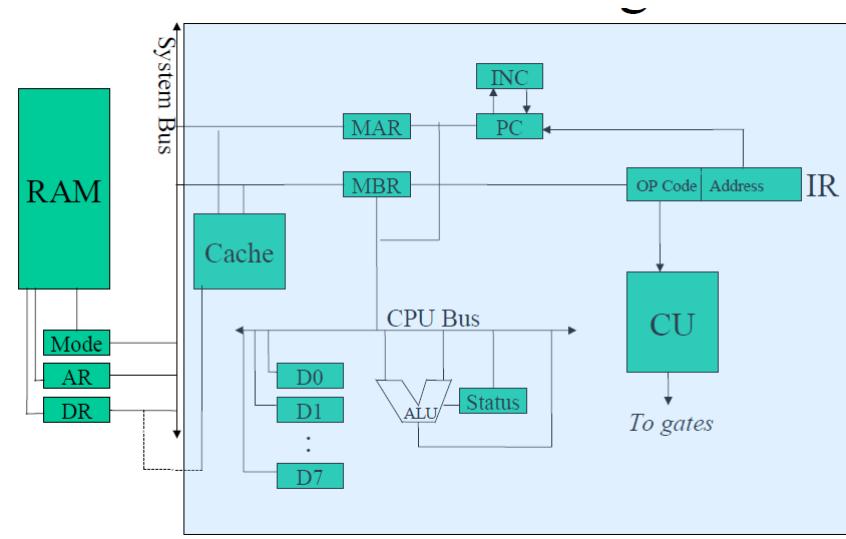


PLA Programmable Logic Array, input & output programmable.

5 In-Depth Classical CPU Analysis



Von Neumann Machine



Classical CPU Design

PC = Program Counter or Instruction Pointer. **MAR**, memory address register, downloads instructions from PC, sends to AR. AR and MAR work a lot together, both address registers. **MBR**, memory buffer register, can contain many things (reason why it's called a buffer), like address, data from data registers. AR, DR and MAR, MBR work well together. INC is incrementer (override data in address), CU is control unit. Can add onto this diagram by adding peripherals on bus.

CPU does one instruction at a time in however x ticks it takes, then increments to next address to do next operation. Making things parallel & local to avoid ticks and make it faster.

5.1 Instructions

Group of assembler instructions CPU supports. Standard size is usually the word size. Command that is formatted string of binary. Stored in RAM. Makes programs/algorithms.

Program running (Classical CPU)

- OS sleeps (no multithreading)
- 1. $\text{MAR} \leftarrow \text{PC}$
- $\text{PC} \leftarrow \text{PC} + 1$
- 2. $\text{AR} \leftarrow \text{MAR}$
- $\text{DR} \leftarrow \text{RAM}[\text{AR}]$
- 3. $\text{MBR} \leftarrow \text{DR}$
- $\text{IR} \leftarrow \text{MBR}$
- $\text{CU} \leftarrow \text{IR}(\text{OP-CODE})$

See instruction register for more info.

Register vs RAM Can give type to instructions, such that it goes through CPU registers or RAM. Through IR it does addition in 1 tick, but with RAM it has to go through several things, AR, MBR, IR in order to get what's at the RAM.

When program is done running, it tells the OS it can wake up now and stops program.

5.2 CPU Execution Cycle

Fetch

1. $\text{PC} \rightarrow \text{MAR}, \text{PC}++$
2. $\text{MAR} \rightarrow \text{RAM AR}$
3. Read signal
4. $\text{RAM DR} \rightarrow \text{MBR} \rightarrow \text{IR} (\text{or other register})$

Decode

1. Do we need operands?
 - (a) Get operands, using address in instruction to fetch each parameter, but last step goes to CPU register instead of IR and no incrementing of $\text{PC}++$
2. $\text{OP-CODE} \rightarrow \text{CU}$

Execute CU triggers gates to perform instruction

Store

1. Register with address → MAR
2. Register with data → MBR
3. Write signal sent to RAM AR and DR

5.3 Micro Instructions

Express operation of CPU, step by step. Syntax to follow.

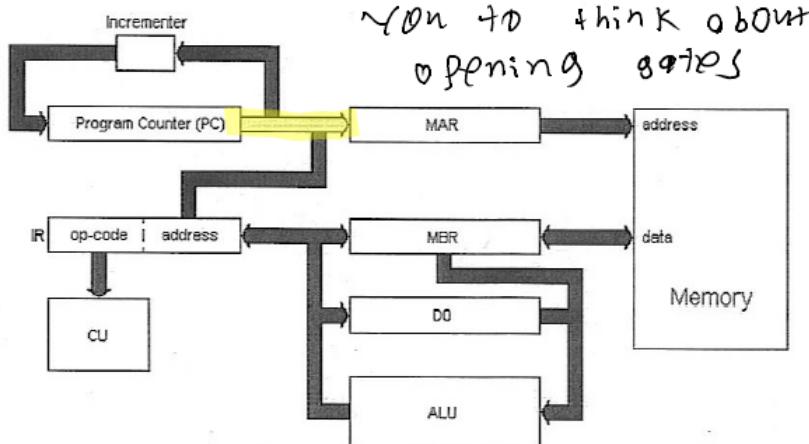
CHANGE_STATE ← OPERATION

- MACHINE(addr)

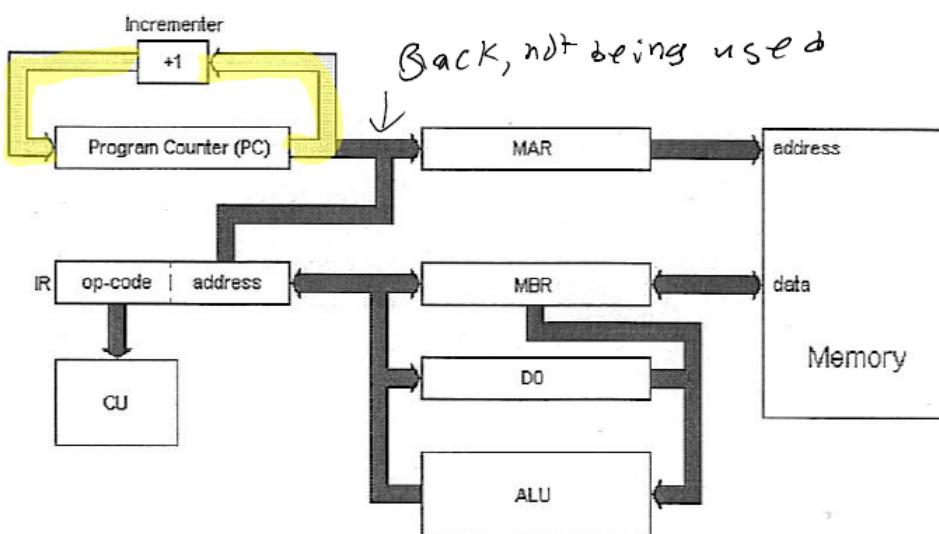
FETCH $[MAR] \leftarrow [PC]$
 $[PC] \leftarrow [PC] + 1$ eg
 $[MBR] \leftarrow [M([MAR])]$ ADD D0,D0,X
 $[IR] \leftarrow [MBR]$

EXECUTE $[MAR] \leftarrow [IR(\text{Address_Field})]$
 $[MBR] \leftarrow [M([MAR])]$
 $[D0] \leftarrow [D0] + [MBR]$

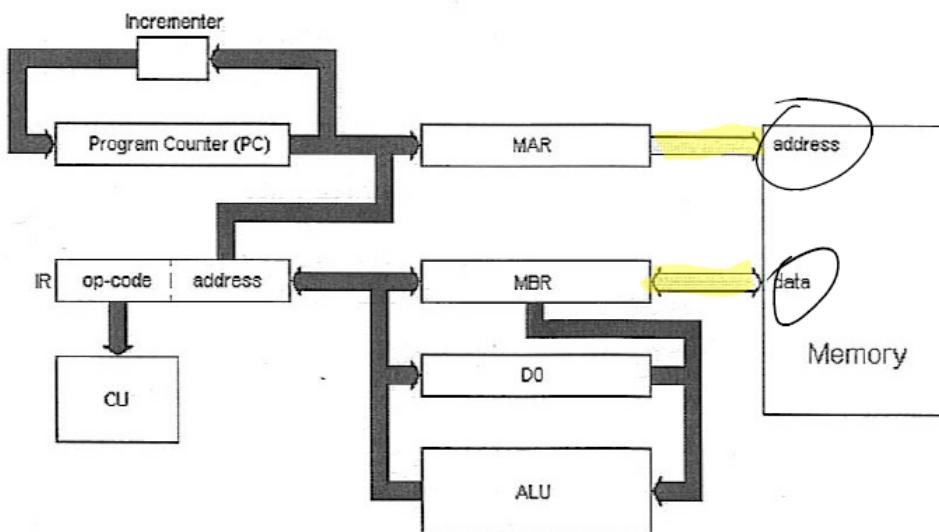
1) $[MAR] \leftarrow [PC]$



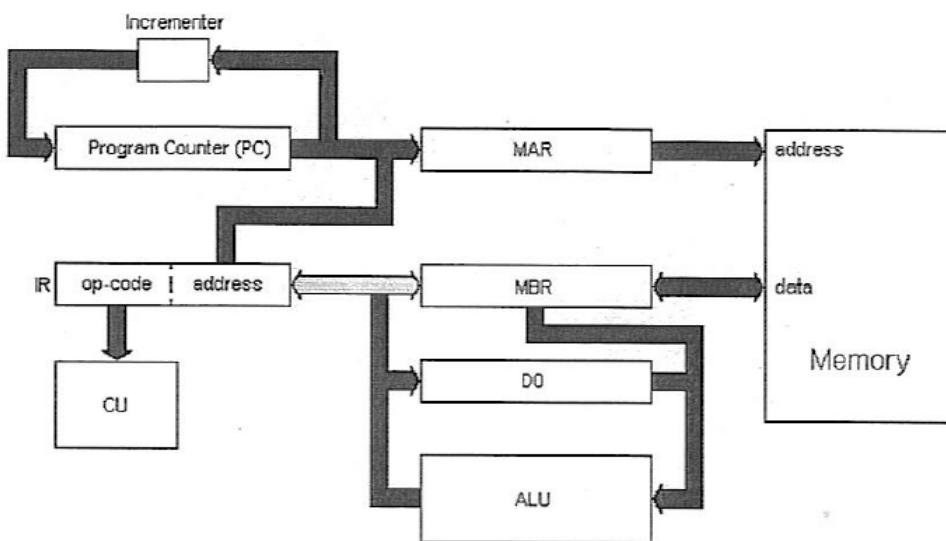
2) $[PC] \leftarrow [PC] + 1$



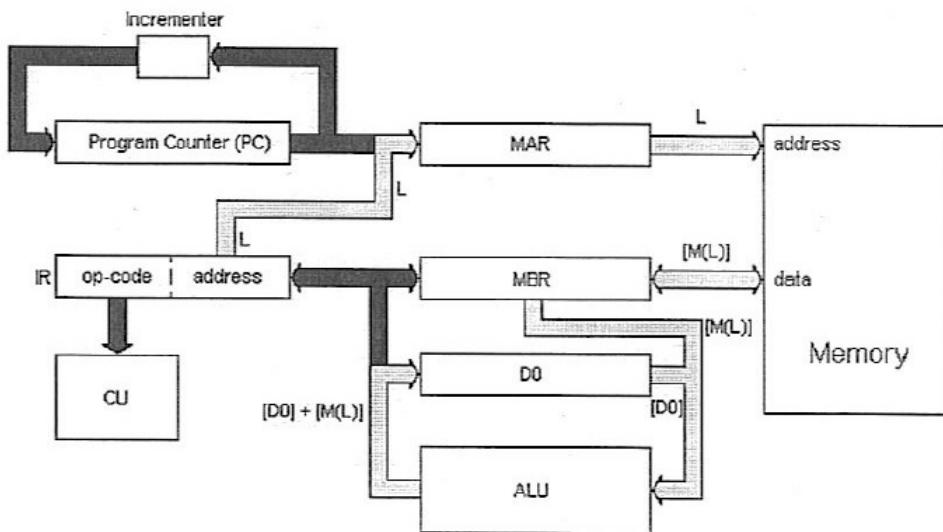
3) $[MBR] \leftarrow [M([MAR])]$



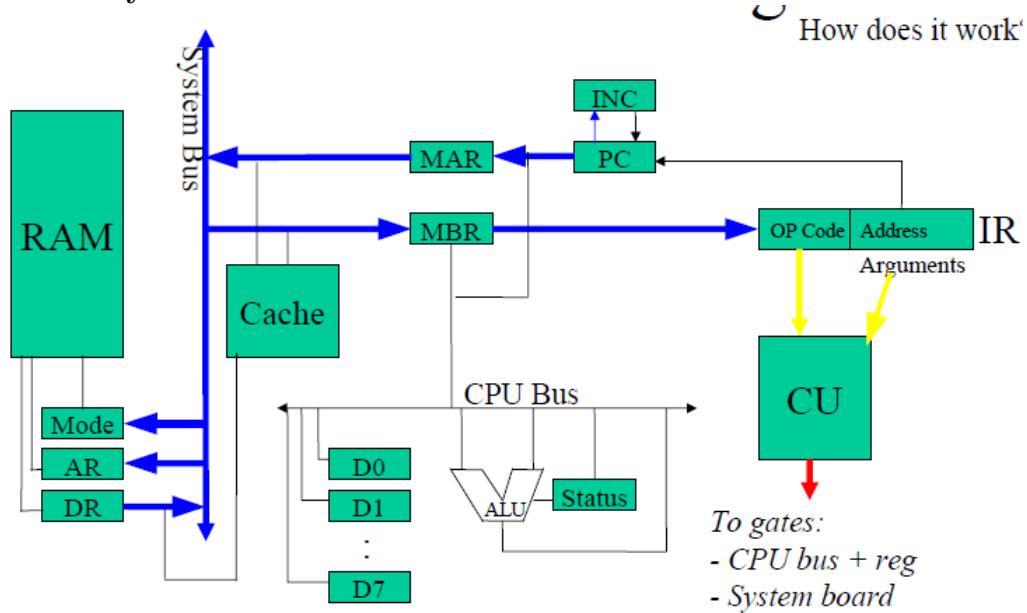
4) $[IR] \leftarrow [MBR]$



5) The execution phase:

$$\begin{aligned} [\text{MAR}] &\leftarrow [\text{IR}(\text{Address_Field})] \\ [\text{MBR}] &\leftarrow [M([\text{MAR}])] \\ [\text{D0}] &\leftarrow [\text{D0}] + [\text{MBR}] \end{aligned}$$


Summary



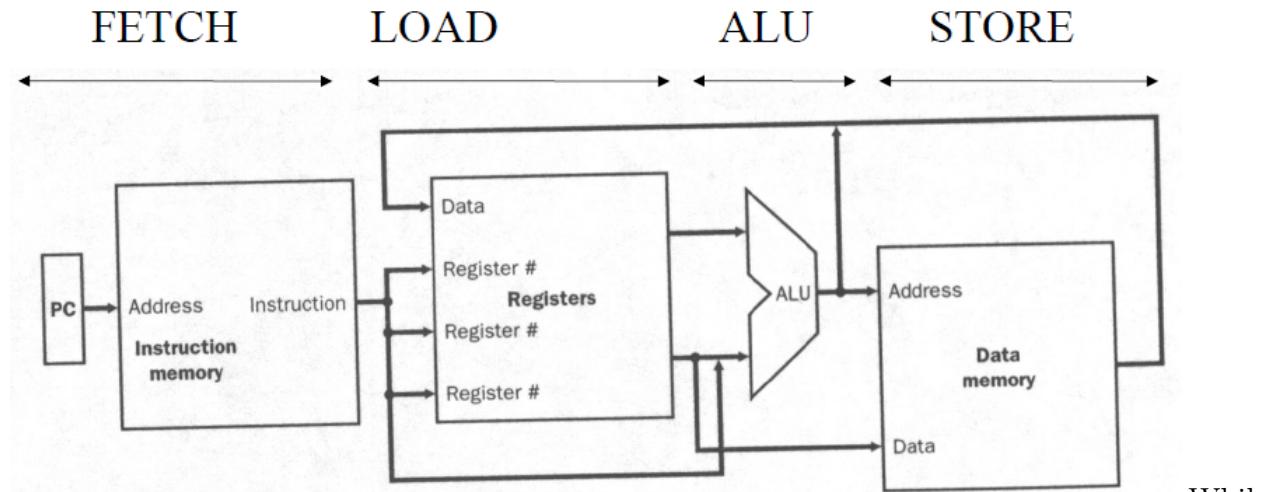
1. Fetch 2. Decode 3. Execute

McGill (5 cs) (1 cs) Vybihal (c) 2013 (1 cs per step = 3 – 5 steps)

6 Pipeline CPU Structure

When we look at the classical CPU architecture, we see that it is easy to build/cheaper and the bus allows flexibility of data movement. But, there are unused circuits and everyone has to share the same clock tick.

What about the pipeline CPU? The CPU **is** the bus. Only goes in one direction. Each instruction does a separate part at once, so you can have multiple instructions flowing through the pipeline at once (not executing simultaneously, more like doing different steps simultaneously). Pipeline instead of CPU loop.

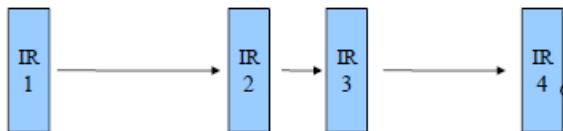


While

fetching next instruction, can load current instruction. Can do 4 instructions at different phases at the “same time”. Need a lot of instruction registers, one at each stage (4). Two caches. Code/Load prediction has dumb(blind dump of code) vs smart(look ahead for go-to/jump). The linearity/one way of the bus imposes restrictions on the language. All instructions go through the pipeline, need a wide 32 bit+ size bus.

Effects on IR and CU

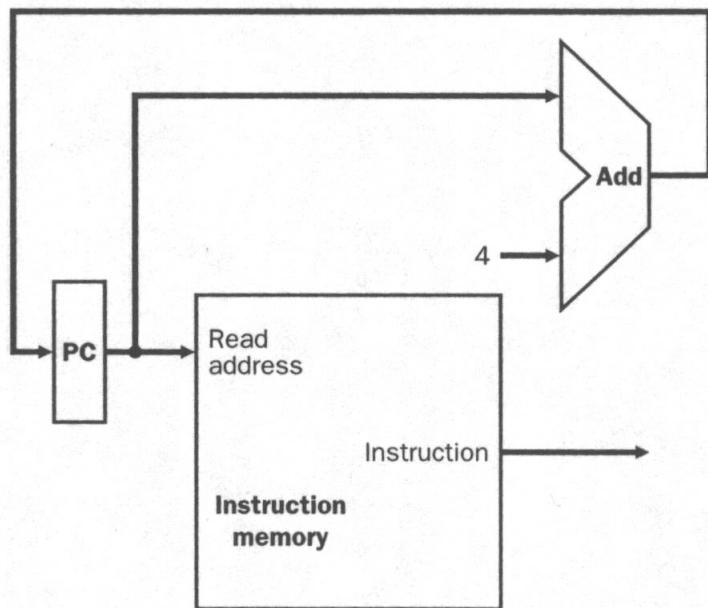
- No longer 1:1 IR and PC
- Either one long CU or many small CUs
- 1 IR for every silo (data lock/gates), i.e. every step



- Pipeline has to be gated

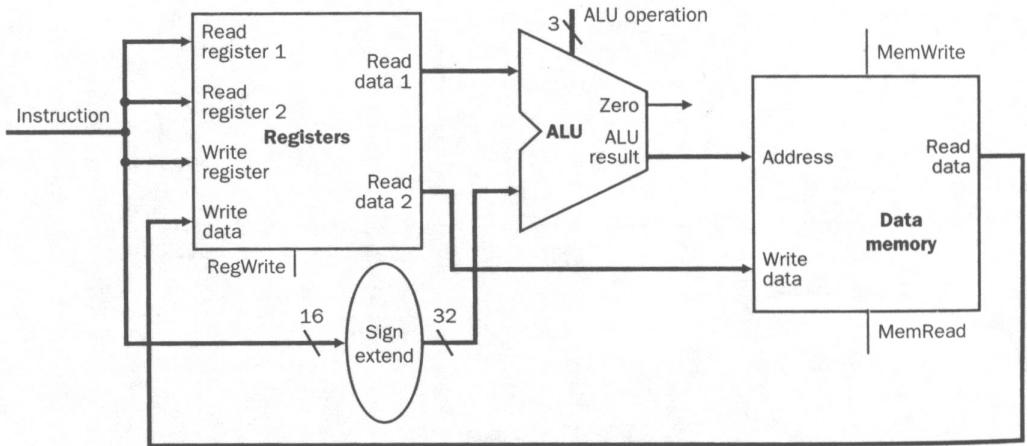
Fetch

- Read address from PC, get instruction and send it out.
- Increment by 4 since 32-bit instructions.



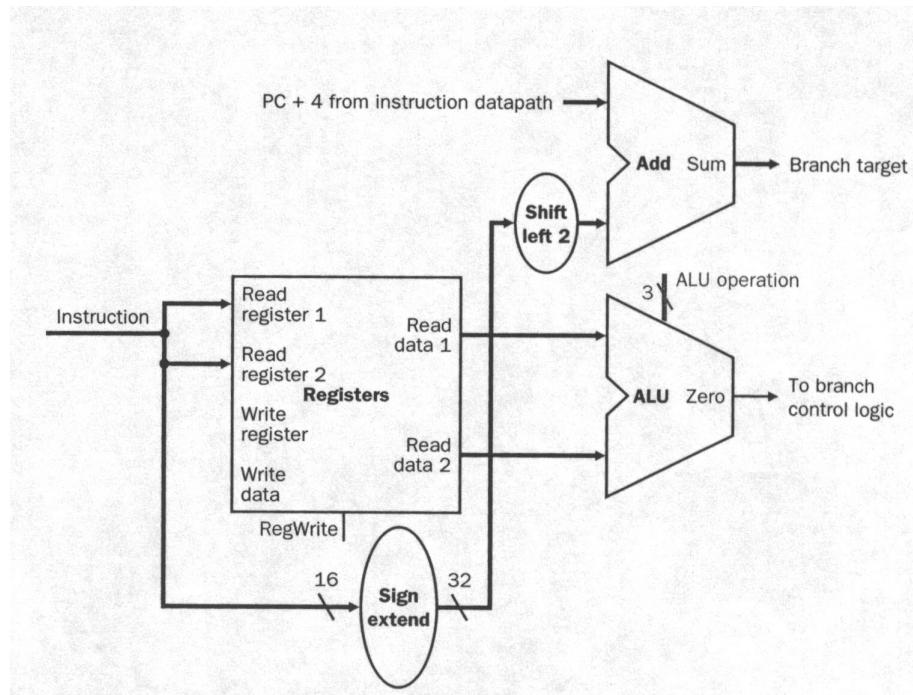
Load & ALU

- Instruction goes to registers
- After op code and registers that are arguments, have 16 bits leftover, have to sign extend, add 0s in front
 - This is for short constants, like offset of a LW instruction
 - Some instructions don't require ALU, like $x = 5$. Look at read data 2, skips ALU



Delayed Branching ALU

- For things like BEQ, bottom ALU checks conditions like $X > Y$
- If true, will send op to upper ALU, new address with offset specified
- Will have to dump everything loaded after branch if we branch

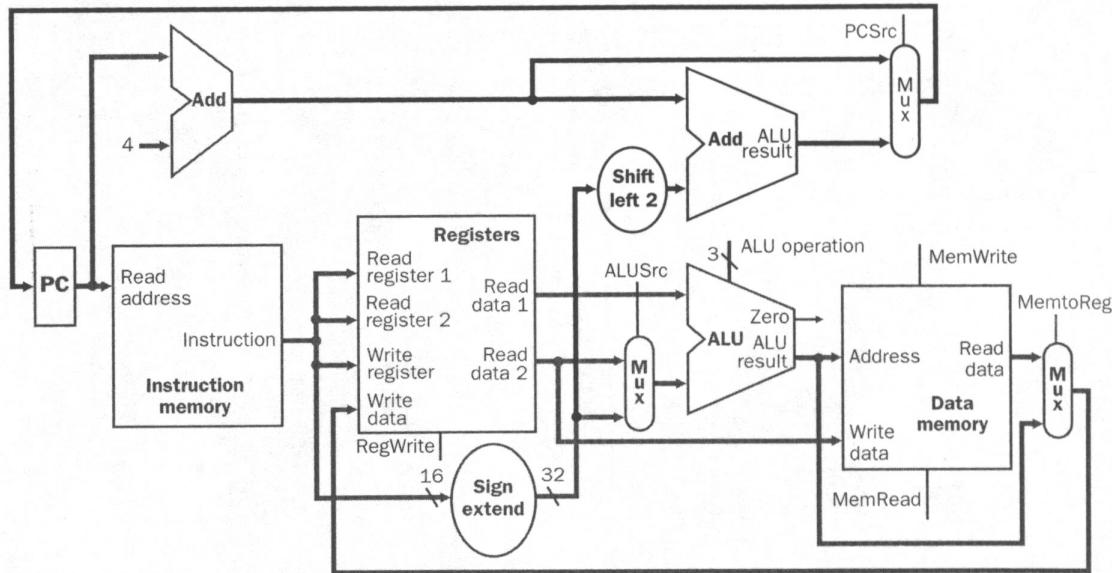


Multi-Purpose ALU ALU does different things depending on instruction, diff control codes.

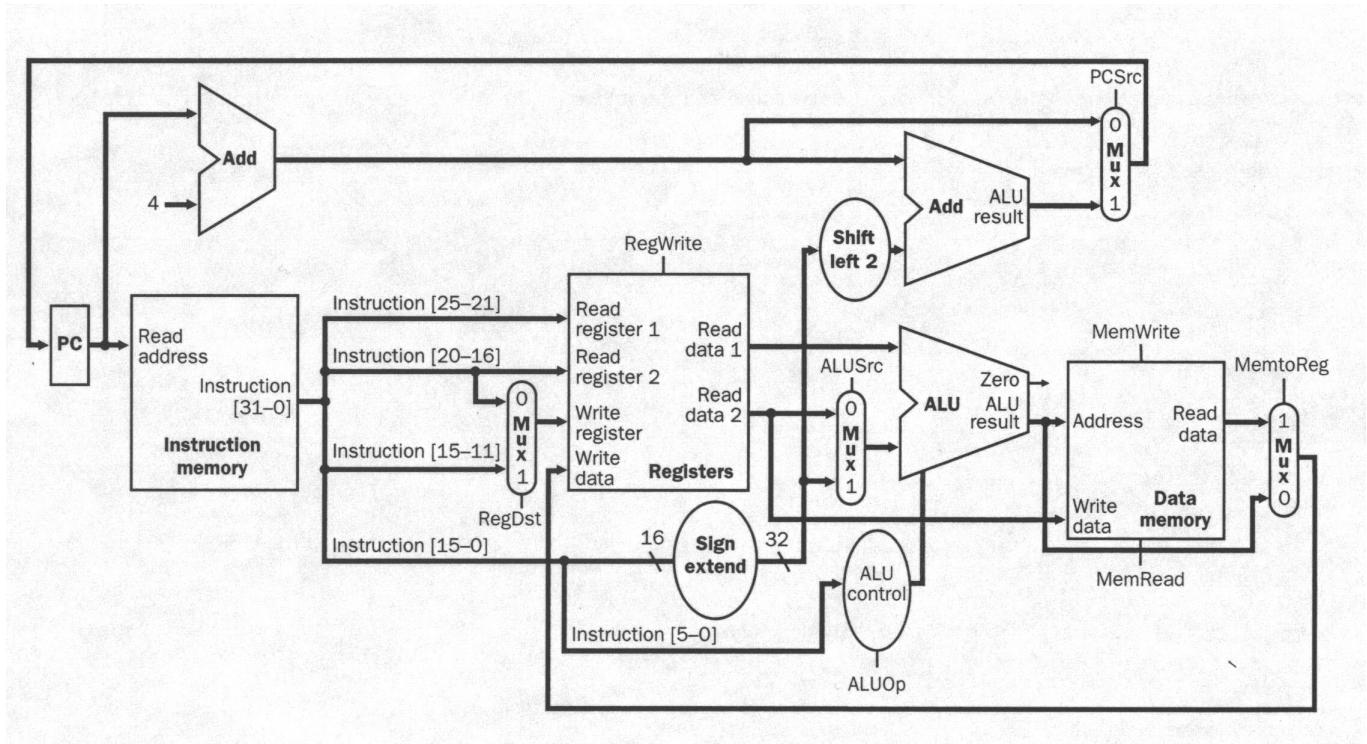
Instruction opcode	ALUOp	Instruction operation	Funct field	Desired ALU action	ALU control input
LW	00	load word	XXXXXX	add	010
SW	00	store word	XXXXXX	add	010
Branch equal	01	branch equal	XXXXXX	subtract	110
R-type	10	add	100000	add	010
R-type	10	subtract	100010	subtract	110
R-type	10	AND	100100	and	000
R-type	10	OR	100101	or	001
R-type	10	set on less than	101010	set on less than	111

6.1 Summary Layouts

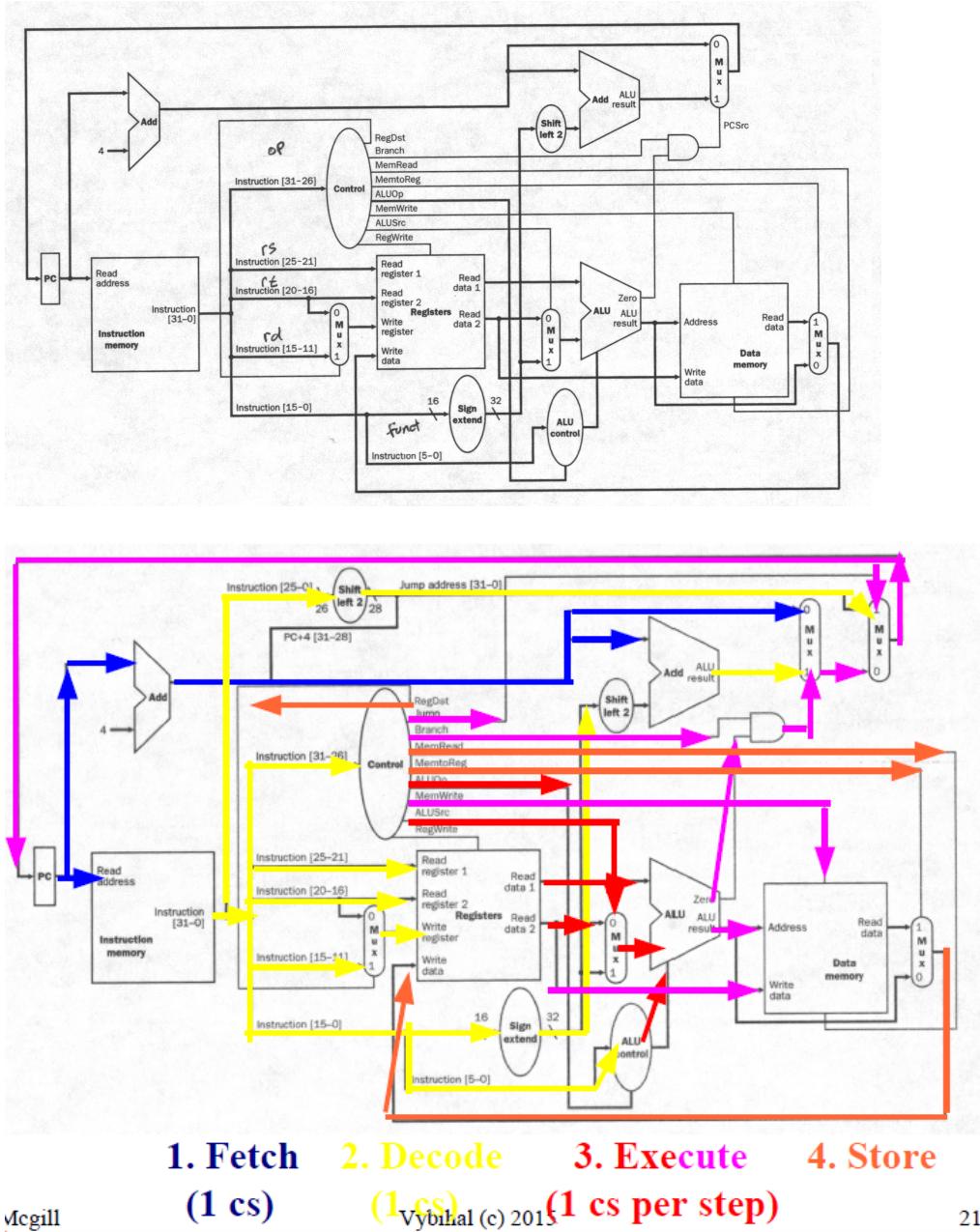
- Can see that there are 4 silos here
- Mux → multiplexer, decides which input to take in



- Bit Layouts



- 2 control units



7 Control Unit/Sequencer

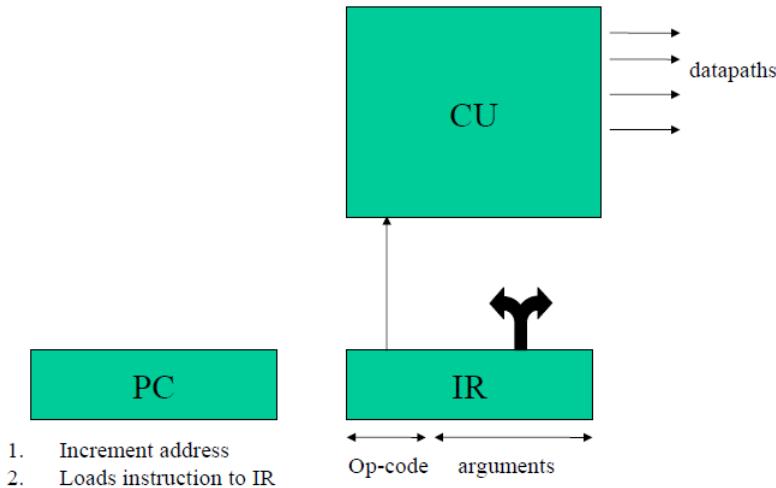
CU is the portion of the CPU responsible for timing and triggering of data paths.

Datapaths Wires of CPU needed for particular tick/instruction.

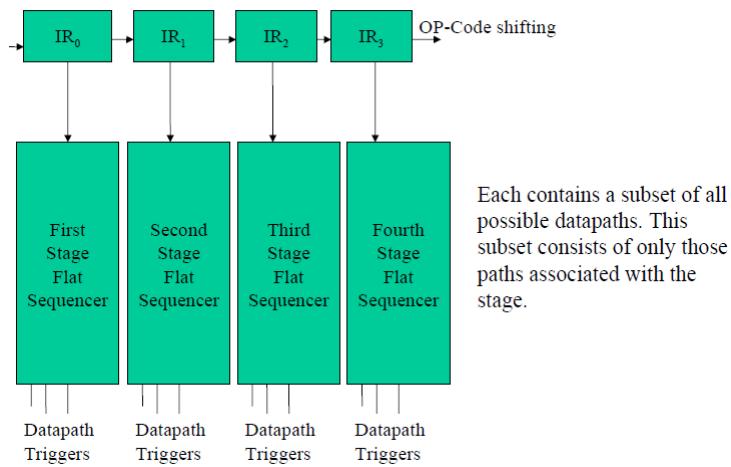
Instruction Format Organization of bits in IR

Micro-programming

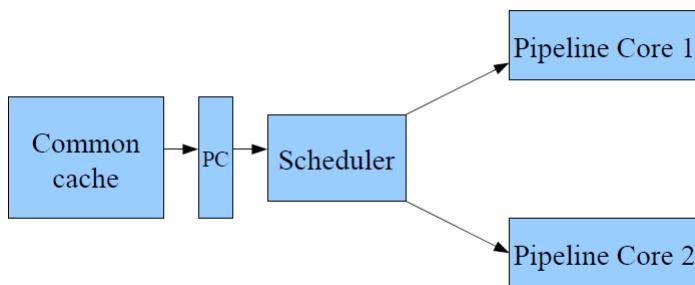
- Flat: one instr at a time



- Pipeline: Assembly execution of multiple



- Cores: Parallel exec



- Takes in an op-code register, associate numbers to instructions, like addressing. Open needed gates for specific instructions, mux
- The CU is like a decoder
- All commands belong to a certain family (see MIPS instructions)
- CU has a counter to tick the microinstructions of one instruction, op-code implemented via multiple sub-steps, works well if we make all instructions the same tick length
 - When it overflows (gets to 0), resets itself for next instruction
- Pipeline has IR at each silo and 2 CUs, with 0-1 count

Buffers Multiple IR registers (buffers) for each instruction in pipeline.

8 Performance

8.1 Hazards & Faults

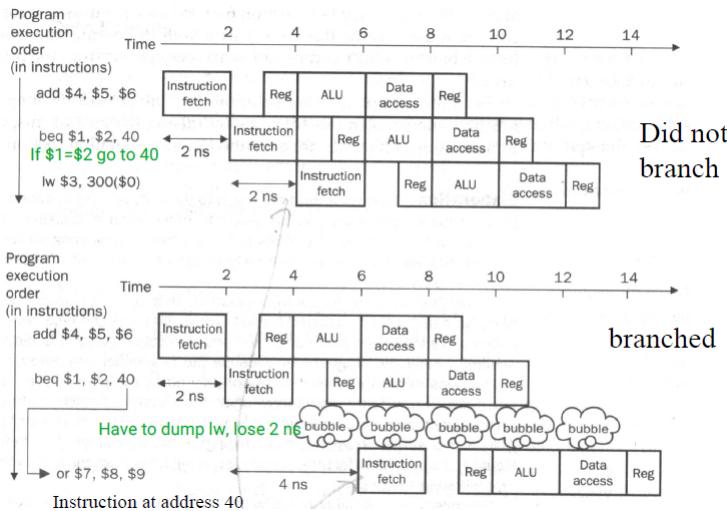
- Hazard: danger to keep watch for
 - Not being able to control what user can divide by, hazard
- Fault: error has occurred
 - Dividing by 0, fault
- Stall: Normal CPU exec cycle lengthens
 - Cache smaller than RAM
 - Small loops, try to fit it all in cache to run quickly
 - Otherwise it slows down to get parts in RAM
 - Stall might happen if CPU is running faster than code → stop pipelining and do classical or no-op
 - Instructions going from CPU to RAM, slower clock speed, stalls
- Dump: Instructions after fault dumped from pipeline, re-loaded after fault handled
- No-op: Extra instruction that doesn't do anything, between fault and next instruction, allows CPU to exec problematic instruction without many side-effects

hazard → fault → stall → dump or no-op

ALU has a status register. If CU is in a certain operation (ex. div) and ALU gives an error, it'll stop program. Go back to PC or OS register, stop incrementor, OS looks at error.

Types of Hazards

- Structural Hazards
 - Bad combination of instructions, store/load in 1 Instructions
 - Illegal instruction or result
- Control Hazards
 - Branching (pipeline), making previous half executed instructions useless, comparison only happens at ALU



• Data Hazards

- Instruction depends on result of previous instruction, save only happens at 4th stage for pipeline
 - * Make CU check if instructions use same arguments
- Use NOP or buffer to fix, can also reorder

Loss Calculate loss. At what stage did the fault happen? How many no-ops? How many things need to be reloaded after dump? How many instructions don't have faults (full speed)? The performance loss experienced → $E[Loss] = p(Loss) * cost$, stalls happen 17% of the time, still worth it to use pipeline.

Solutions

- Insert no-ops or reorder instructions (reordering branch or instructions that conflict)
- Assume branch will always fail (bad, not used)
- Assume branch success based on type
 - Function calls good
 - Backwards jumps, probably loops, good
 - If statements, no

8.2 Performance Issues

- Clock ticks: Number of clock ticks required to perform activity, only reliable measure
- Cycles: count of number of micro instructions to perform an activity
- CPU execution time = n instructions in prog $\times Y$ ticks per instr $\times Z$ seconds per tick
 - Classical CPU, different ticks for different instructions
 - Pipeline, all the same

8.3 CPU Exception Handling

Why?

- Bad machine language Binary
- Bad arithmetic
- Incorrect address

Supporting registers:

- Exception Program Counter register (EPC), stores addr of bad instr
- Cause, has error code
- Jump to reserved cache mem for exception assembler code

Assembler implementations

- Jump to OS exception handler

- Jump to code in user program to handle it

What ends up happening: Exception handling hardware built into CPU, has default PC address locations (hardwired) to interrupt. Error happens, PC stored into EPC, PC gets default address relating to type of error. OS or programmer has code at that address to handle.

9 CPU & Chipsets

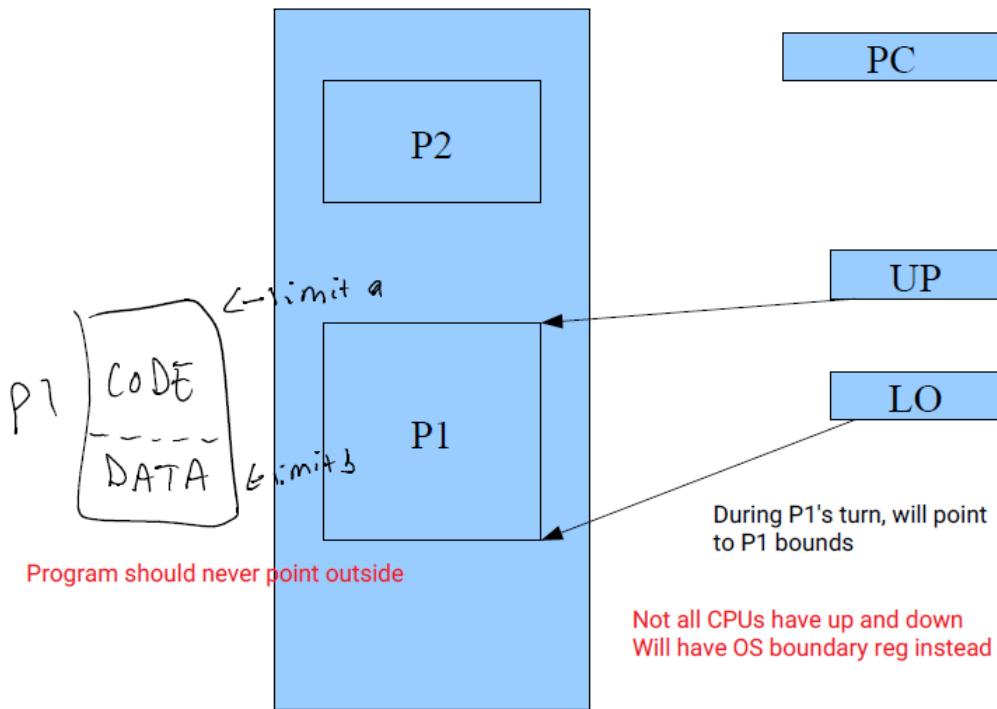
9.1 CPU

What does the CPU system consist of?

- General purpose registers
- ALU
- Cache
- OS registers
- System-Board registers
- Supporting chipsets

Supporting CPU Registers Running 2 programs on a computer, shouldn't interfere with each other.

- Process Boundary Register: has upper bound and lower bound for jump/branch statements compare PC with illegal situations. Protect processes, OS and zero page. OS' job to load registers.



Some don't have upper and lower boundary registers, have OS boundary register instead, prevents processes from addressing into OS space, programs can damage each other, but not OS. For special instructions, we can use assembler instructions (like syscall).

9.2 Chipsets

Chips & circuitry to support CPU, your CPU needs a team.

- On Die chip sets: circuitry on CPU die, same Board
- On Board chip sets: circuitry on system board, usually close to CPU, different bus

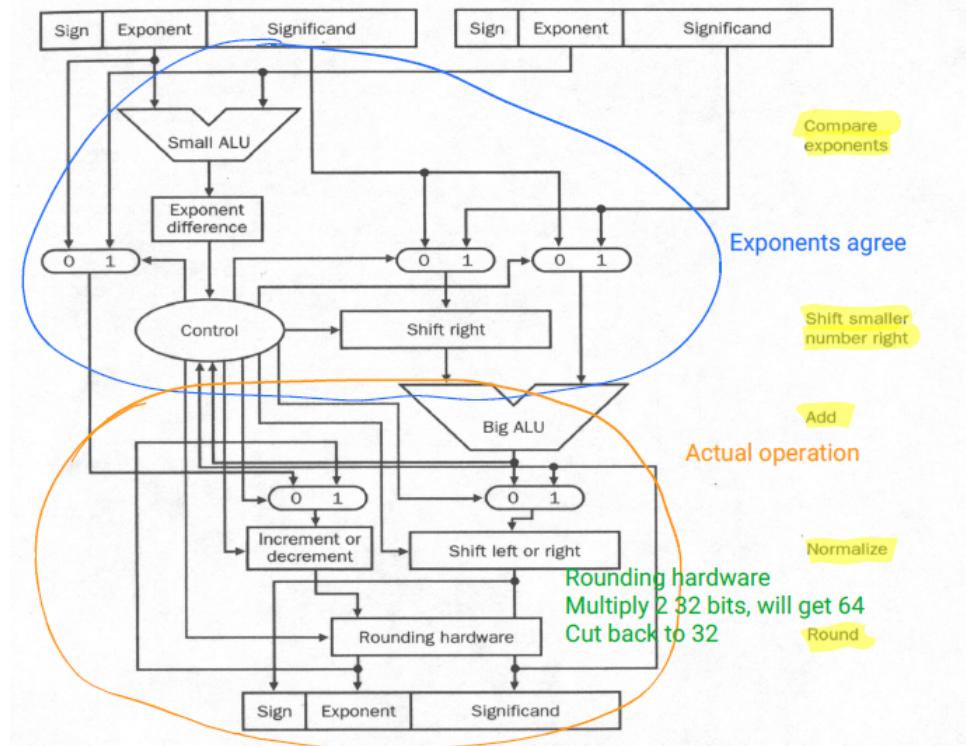
Some chipsets

- Co-processors
 - Math, matrix, graphics GPUs
 - MIPS only has an integer ALU, has a co-processor to do floating point arithmetic
- ROMS
 - Support for video, basic graphics

- ASCII
- Ports to communicate, peripherals

9.3 Co-Processors

Like CPU, but CPU has everything, co-processor only has the things it needs to do what it was made for, i.e. math. Floating point numbers are stored very differently from integers, need a co-processor to do arithmetic.

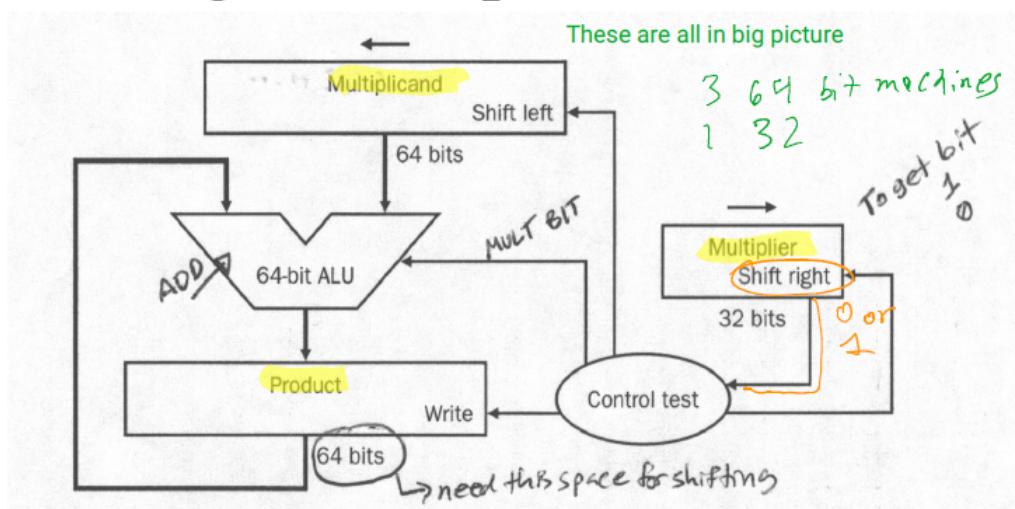


Grade School Multiplication Works the same way as decimal multiplication:

1. Right most digit of multiplier multiplies multiplicand
2. Write answer below digit
3. Next digit of multiplier, go to step 1 (writing underneath next digit implies shifting)
4. Sum

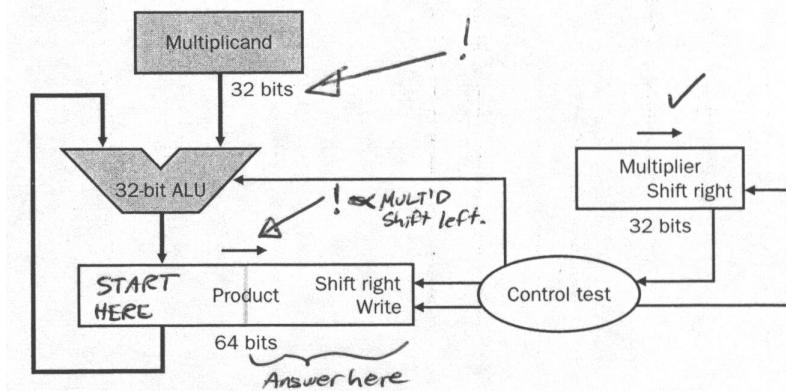
Really just need to AND everything, $1 \times 1 = 1, 0 \times 1 = 0$. Floating point numbers are 32 bits, will take 32 ticks per floating multiplication, convert to integer when possible as this is a huge stall.

Integer Multiplier Circuit Note that we have 3 64 bit registers here!

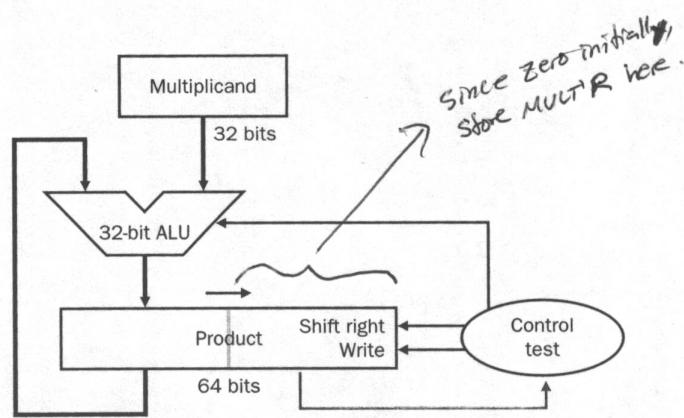


Improvement I Change multiplicand & multiplier to 32, right shift product register instead, Will constantly have a line splitting the 64 bit product register, because right most bits are only added a few times, least significant is not added, 2nd least is added once, etc.

~~0000~~
~~0000~~
 ↓
 only
 added once

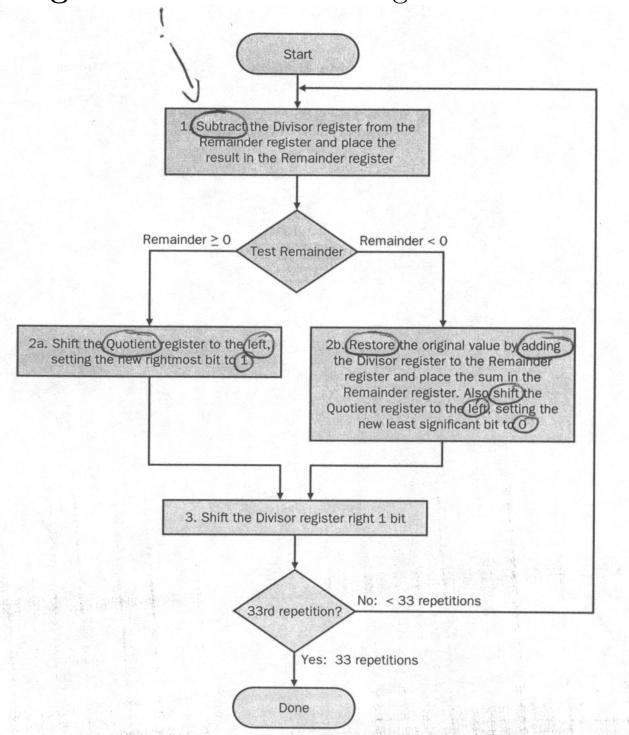


Improvement II No more multiplier register, placed in answer part of product instead.

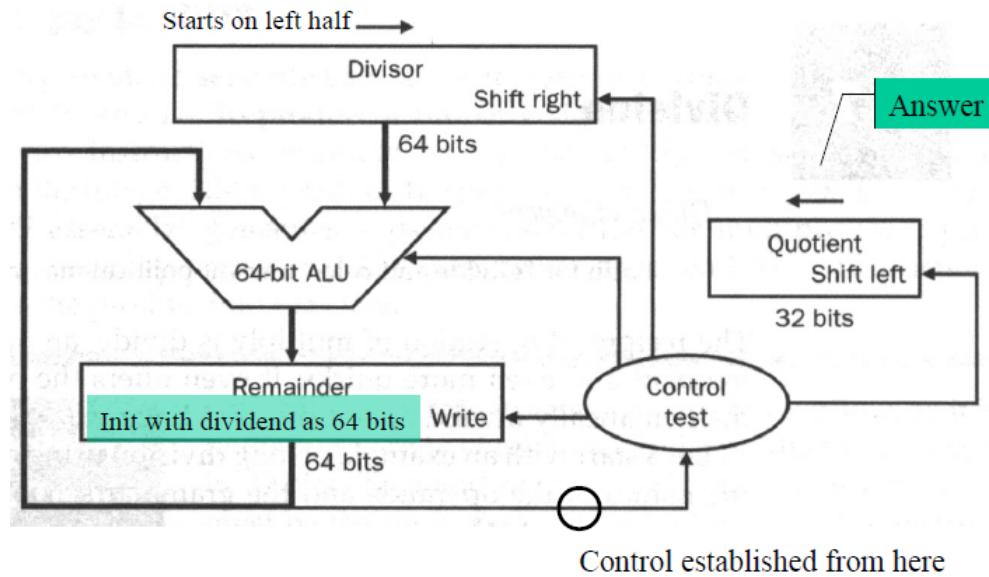


To do negative multiplication, convert to a positive value and check signs at the end
 Multiplication by 2^i does not require multiplication (much faster), just shift left i times

Integer Division Same as grade school division

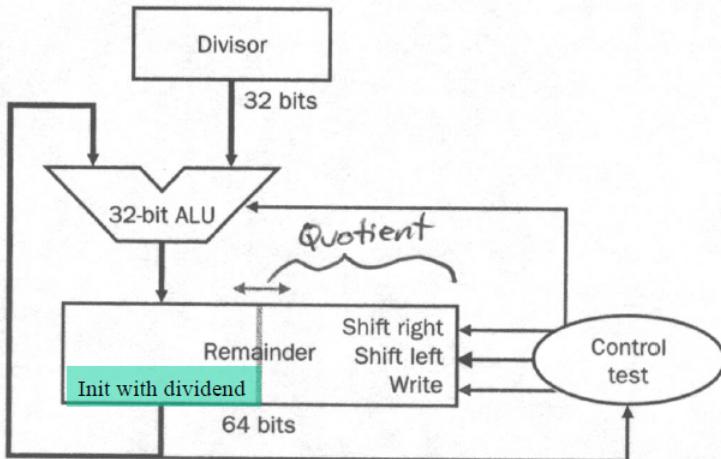


Iteration	Step	Quotient	Divisor	Remainder
0	Initial values	0000	0010 0000	0000 0111
1	1: Rem = Rem - Div	0000	0010 0000	①110 0111
	2b: Rem < 0 \Rightarrow +Div, sll Q, Q0 = 0	0000	0010 0000	0000 0111
	3: Shift Div right	0000	0001 0000	0000 0111
2	1: Rem = Rem - Div	0000	0001 0000	①111 0111
	2b: Rem < 0 \Rightarrow +Div, sll Q, Q0 = 0	0000	0001 0000	0000 0111
	3: Shift Div right	0000	0000 1000	0000 0111
3	1: Rem = Rem - Div	0000	0000 1000	①111 1111
	2b: Rem < 0 \Rightarrow +Div, sll Q, Q0 = 0	0000	0000 1000	0000 0111
	3: Shift Div right	0000	0000 0100	0000 0111
4	1: Rem = Rem - Div	0000	0000 0100	①000 0011
	2a: Rem \geq 0 \Rightarrow sll Q, Q0 = 1	0001	0000 0100	0000 0011
	3: Shift Div right	0001	0000 0010	0000 0011
5	1: Rem = Rem - Div	0001	0000 0010	①000 0001
	2a: Rem \geq 0 \Rightarrow sll Q, Q0 = 1	0011	0000 0010	0000 0001
	3: Shift Div right	0011	0000 0001	0000 0001



Optimization

- Shift remainder left instead of divisor right, make divisor reg 32 bits
- Remove quotient register, put in right half of remainder
- 1 cannot be first bit in quotient, shift remainder left by 1 to do one less iteration

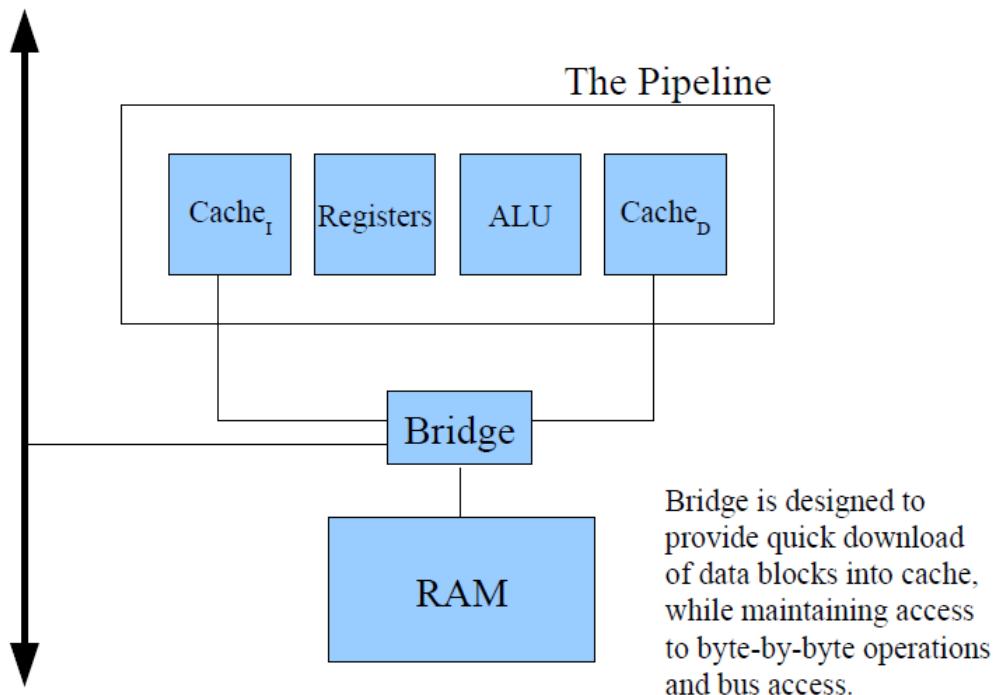


Iteration	Step	Divisor	Remainder
0	Initial values	0010	0000 0111
	Shift Rem left 1	0010	0000 1110
1	2: Rem = Rem - Div	0010	0110 1110
	3b: Rem < 0 \Rightarrow + Div, sll R, R0 = 0	0010	0001 1100
2	2: Rem = Rem - Div	0010	0111 1100
	3b: Rem < 0 \Rightarrow + Div, sll R, R0 = 0	0010	0011 1000
3	2: Rem = Rem - Div	0010	0001 1000
	3a: Rem \geq 0 \Rightarrow sll R, R0 = 1	0010	0011 0001
4	2: Rem = Rem - Div	0010	0001 0001
	3a: Rem \geq 0 \Rightarrow sll R, R0 = 1	0010	0010 0011
	Shift left half of Rem right 1	0010	0001 0011

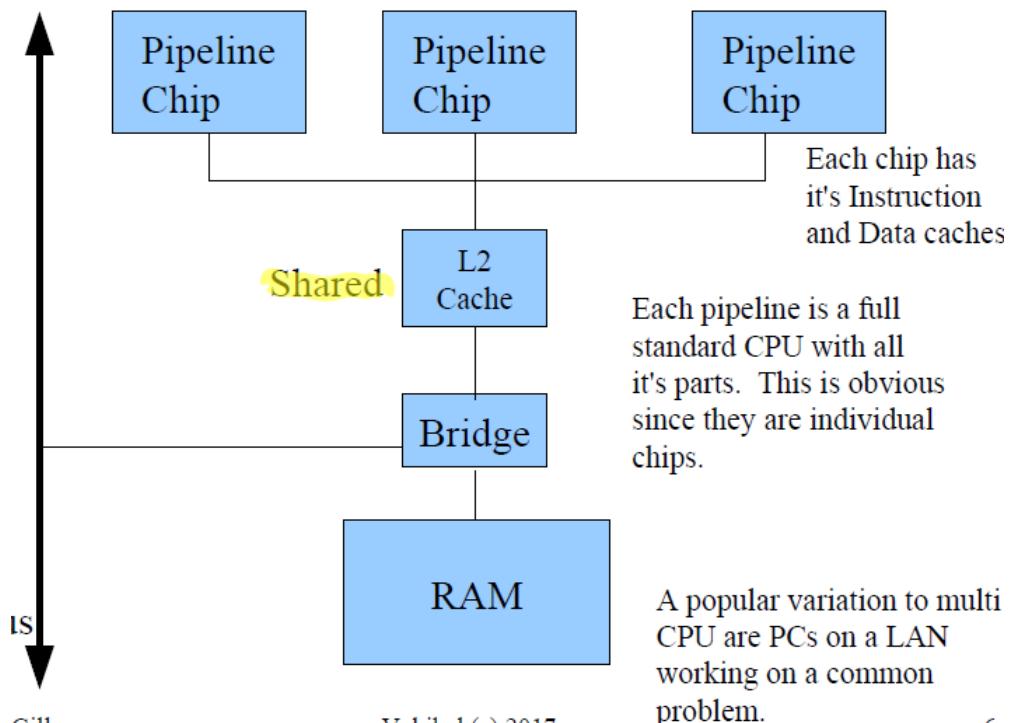
9.4 Multiprocessing

Types of computers

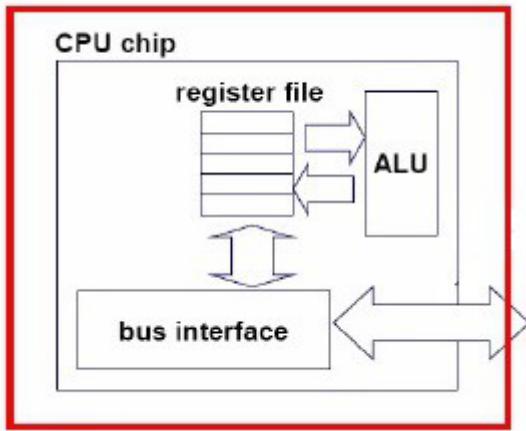
- Single CPU, one CPU chip, any type (flat, pipeline, hyper threaded)



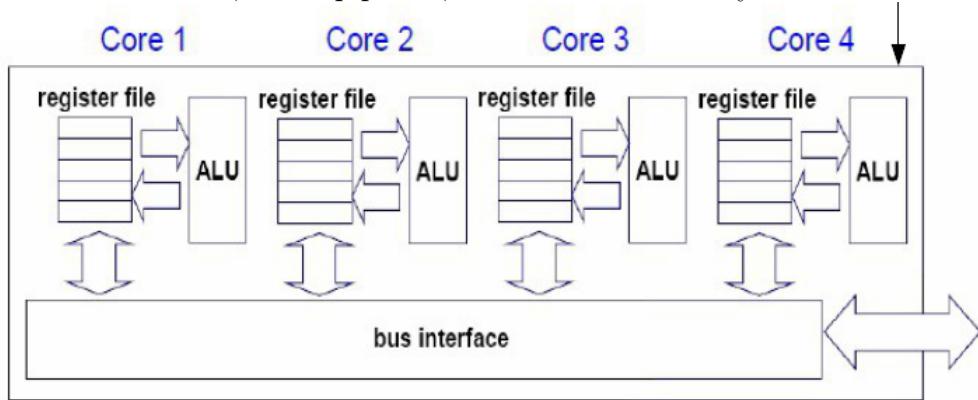
- Multi-CPU, more than one CPU chip, any type



- Single Core, like single CPU chip, but optimized. Has a bridge (connected to buses) to connect core with rest of system board



- Multi-Core, single cpu chip with multiple processors, aka Chip Multi-Processor (CMP).
Bus interface shared (unlike Multi-CPU), to have same data
Cache instructions, like a pipeline, but faults more likely



Programs

- Program is a compiled algorithm stored on disk, static
- Process is executing version of program in RAM, static & dynamic
- Thread are instructions currently being run
 - * Process can have many threads
 - * Thread is an instance of process

For multi-core, threads run in parallel, one for each core. Can have hyperthreading and have queues in each core. Fork a program to split across multiple cores. The more cores, the more the advantages get smaller since they all need to communicate with each other. Multicore because we can't make things go faster than speed of light, so we need more of them.

OS Core Management OS treats each core as a unique processor. OS schedules processes and threads to diff cores

- Special purpose core assignment: OS reserves cores for types of apps
- Dedicated application assignment: Application attached to core, always done on that core. Shareable with other processes
- Core pooled assignment: Queue manages all processes, process at front gets any available core
- Simple Management
 - Queue of processes to execute
 - Each core assigned to waiting process
 - After n microsec, release core and loop
- Complex Management
 - One process has multiple threads in queue
 - Need to share data, put on a core that can share
 - Hardware for data access conflicts

Problem

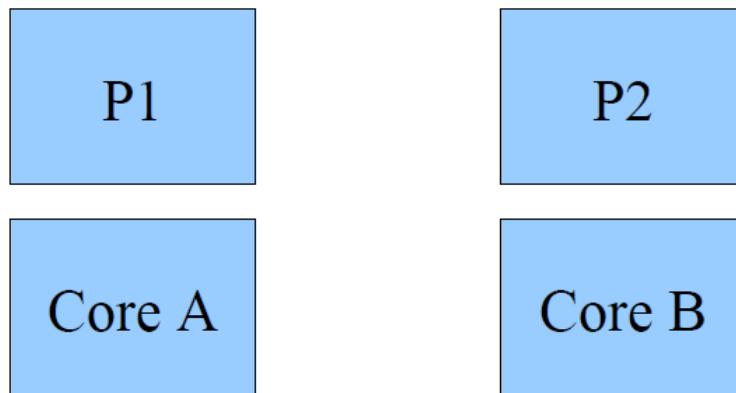
- Uniqueness of threads
 - 1 thread per program? Programs all execute at the same time
 - N threads per program? (like a browser with multiple windows)
 - * They have to coordinate with each other, overhead to manage
 - * $N > 6$, overhead starts to be more than speed improvement

Parallelism

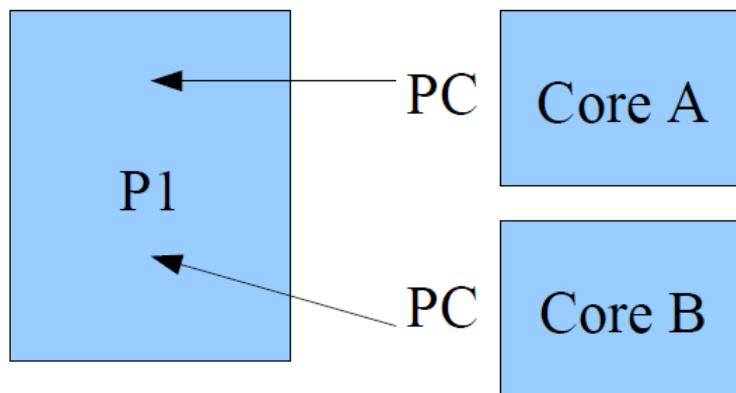
- Single core, instruction level parallelism → pipeline
- Thread-level parallelism (TLP), multi-core
 - Each core gets a part of program to execute

- Single cores cannot take advantage of TLP, future will involve multi-cores exploiting TLP

Multiple Programs



Multiple threads



Single Instruction Multiple Data (SIMD)

- Ex. Modern GPU
- Matrix of data
- 1 instruction executed on all cells at same time
- One cell is a core

Multiple Instruction Multiple Data (MIMD)

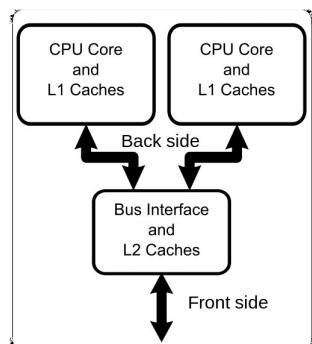
- Multi pipeline CPU
- 1 pipeline per core
- Shared RAM
- Each core has own caches
- Core itself is SIMD
- Chip as a whole is MIMD

Simultaneous multi-threading (SMT)

- Multiple independent threads executing at same time on same core
- Can do integer operation on one thread and floating point on another (2 ALUs)
- Not really parallel, 30% threading, virtual processor, does not have resources for each core like Multi-core
- Can have multi-cores with SMT
- Intel calls SMT hyper-threads

Memory Types

- Shared memory, shared between all processors
- Distributed memory, each processor has own memory



- Lots of computers have both

Private vs Shared Cache

- Private is closer to core, faster access, less contention
- Shared, different cores can access the same thing, more space for big stuff

Problems

- Contention: More than one core needs access to same cache, one has to wait, need circuitry to handle
- Cache coherence: Private caches, need data to be consistent, each core should perceive memory as shared
 - Core 1 changes a value, core 2 reads the old value
 - Solution: Inter-core bus, looks at MAR, addresses being used, issues faults (invalidation + snooping)
 - * Core writes to cache, then all other copies → invalid
 - * All cores snoop the bus connecting cores for write ops

Memory Hierarchy

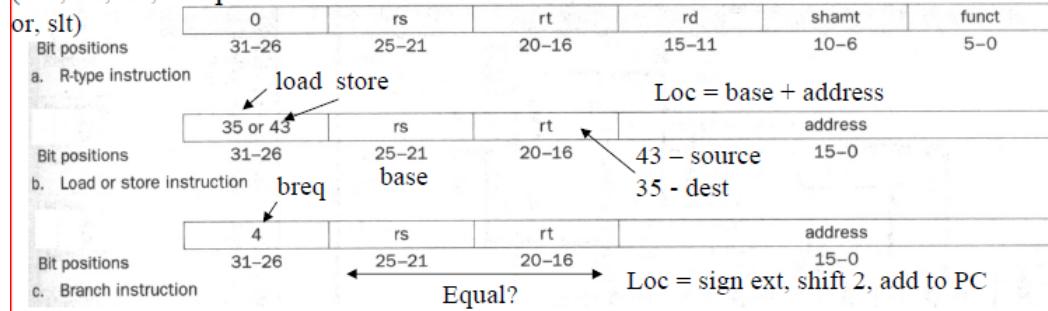
- Not shared: Pipeline, L1 private
- Shared: L2 (sometimes private), L3, RAM
- Special: SMT, all caches shared

10 MIPS

10.1 Instructions

4 instruction classes:

(add,sub,and, Op-Code)

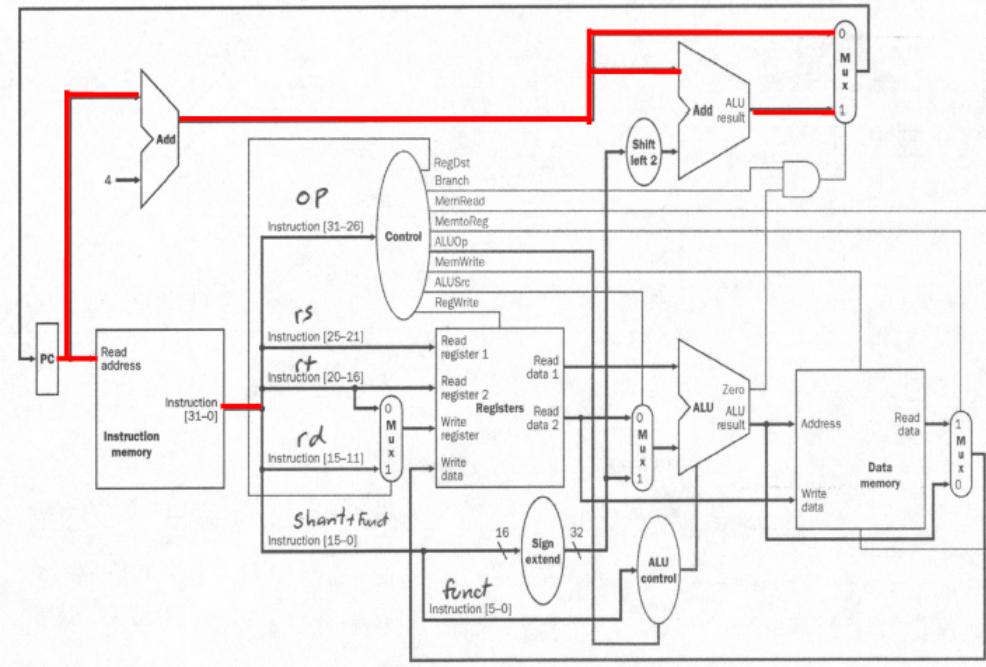


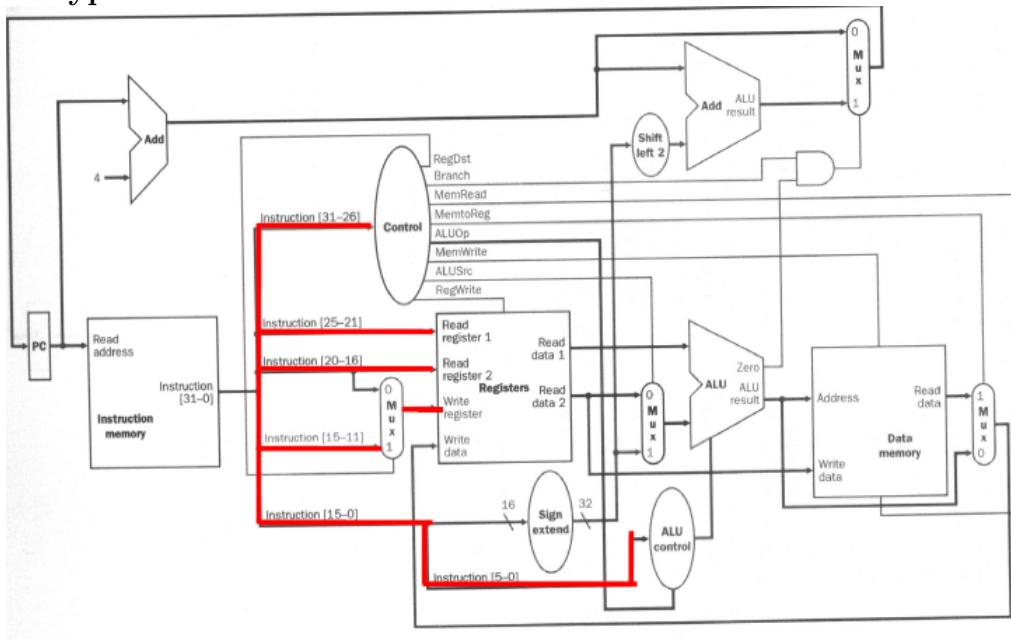
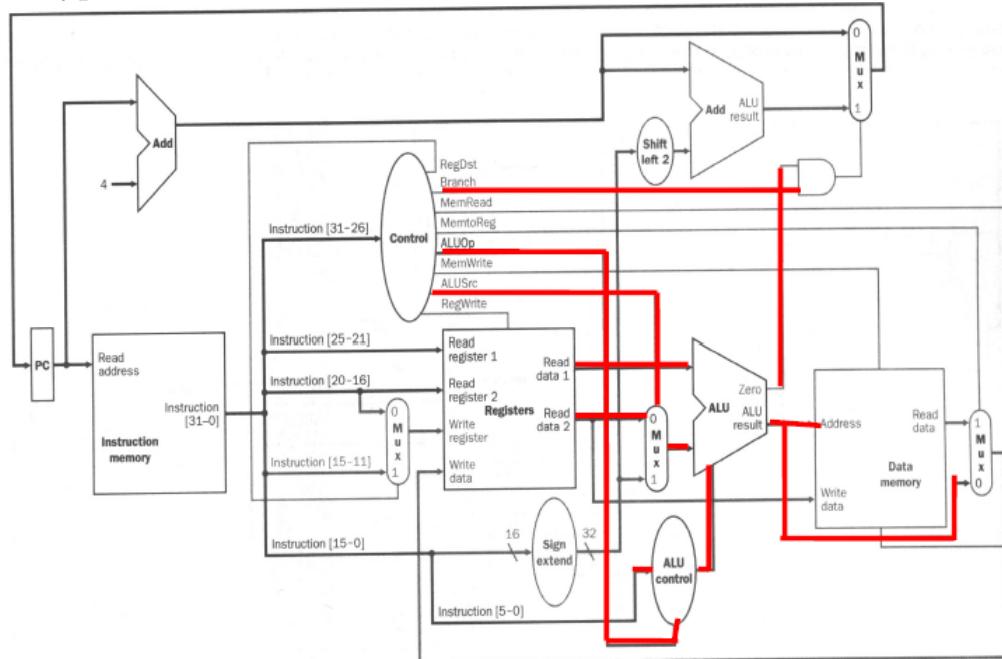
Effects on CU

Instruction	RegDst	ALUSrc	MemtoReg	RegWrite	MemRead	MemWrite	Branch	ALUOp1	ALUOp0
R-format	1	0	0	1	0	0	0	1	0
lw	0	1	1	1	1	0	0	0	0
sw	X	1	X	0	0	1	0	0	0
beq	X	0	X	0	0	0	1	0	1

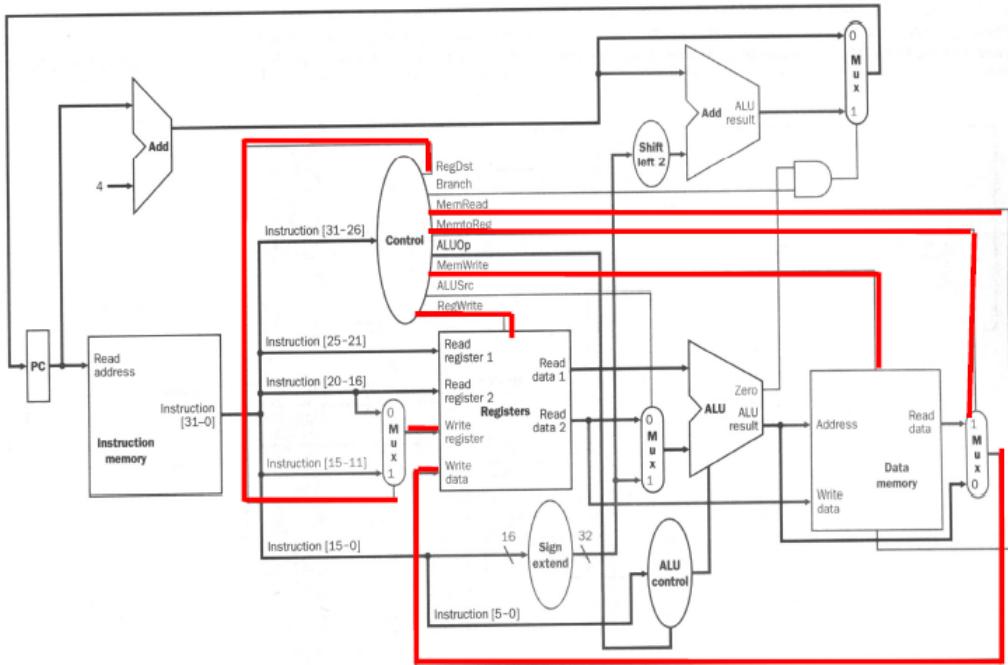
Different pathways for different types of instructions.

R-Type Fetch



R-Type Load**R-Type ALU**

R-Type Store



10.2 Assembler Code

Scope All peripherals and system components accessible by instructions. Can access hardware through RAM (zero page), but you need to know address, binary format, command, status & data registers. Access to hardware requires privileged instructions.

- Privileged mode allows all registers protecting OS to be accessible (like boundary registers)
- Non-privileged is the opposite, used in this class

Compiling High Level Languages Code \rightarrow Compiler \rightarrow Assembler \rightarrow linker (with library and loader) \rightarrow executable

- Compiler checks syntax, converts to assembly
- Assembler checks for syntax, converts to machine code
- Linker verifies library calls exist, merges library into program, adds special OS functions, determines memory locations that code will occupy, resolves references, ensures no undefined labels
- Loader & Loading

- Loading: Puts program into RAM, notifies OS
- OS responsible to pass CPU to program later
- Loader: subroutine, knows how to put program into RAM and notify OS
 - * Three types of OS
 - * Loader function to be inserted as first instruction of program, done by linker
 - * Built-in function, require program to call it
 - * Require data record for parameters and do the whole process internally, no loader

We need the outputs and versions to match each other for the program to execute/work.
 Assembly program consists of the above, without a compiler, going directly from source code to assembler

Assembler Converts assembler text file into .o file, has instructions and directives

Directives

- Comments indicated by #
- .text indicates code is after this
- .globl name of LABEL → where is main program
- .data indicates things stored and whatnot
- LABELS: define label's location, LABEL references its location

Two-Pass Assembly Building to linker:

- Pass 1: builds symbol table, identifies labels, determines offset addresses of identifiers
 - Scans source, top to bottom
 - Count number of bytes in instructions passed to see how many bytes long the program is
 - Find a label, add to symbol table with offset from beginning of program
 - First instruction/label receives a base address in the symbol table, all others are just offsets from that address

LABEL	OFFSET
main	x
int a	+3 (offset from x)

- Pass 2: builds machine language program, 1-to-1 map
 - Scan source, top to bot again
 - One line of assembly is one line of machine, convert op-code & args
 - Assembly Template, just like Symbol Table, but has addresses (with offsets) and instructions in binary

Unix Loading Algorithm

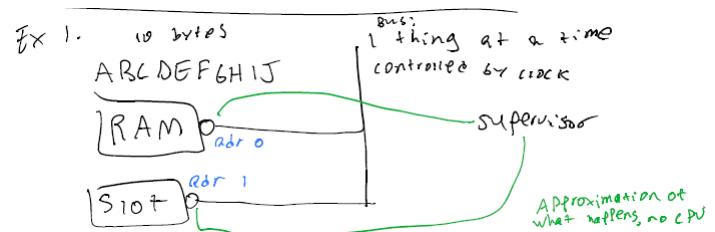
- Read file header, determine CODE and DATA size req
- Find space in RAM for prog, set BASE addr
- Copy instructions and data into RAM
- Copy args onto run-time stack
- Assign SP to next free stack position, IP to first instr
- Clear registers

11 Examples

An example of Copying from RAM to a Slot

In this example, we'd like to copy 10 letters from RAM to an arbitrary slot on a traditional system board. We must loop through as follows:

1. Open gate 0 & 1, close all other gates.
2. Wait for tick.
3. 1 character passes.
4. Go back to step 2.
5. Once all 10 characters are written, “supervisor” (later, central unit?) closes all gates and the operation is done.



Can a single byte in RAM and a single CPU instruction in RAM both exit RAM at once?

No, not possible with traditional system board. You can do each one very quickly, but not simultaneously.

What does the circuit of a full 2-byte r/w memory look like? Size of RAM is 2-byte, need 16 flip flops. Need a r/w register, data register and some sort of addressing system (many gates, only opening access to 1 bit at a time). Clock controls it all.

ALU Questions

What do we need to assume about our data to build an ALU Size of inputs & outputs.

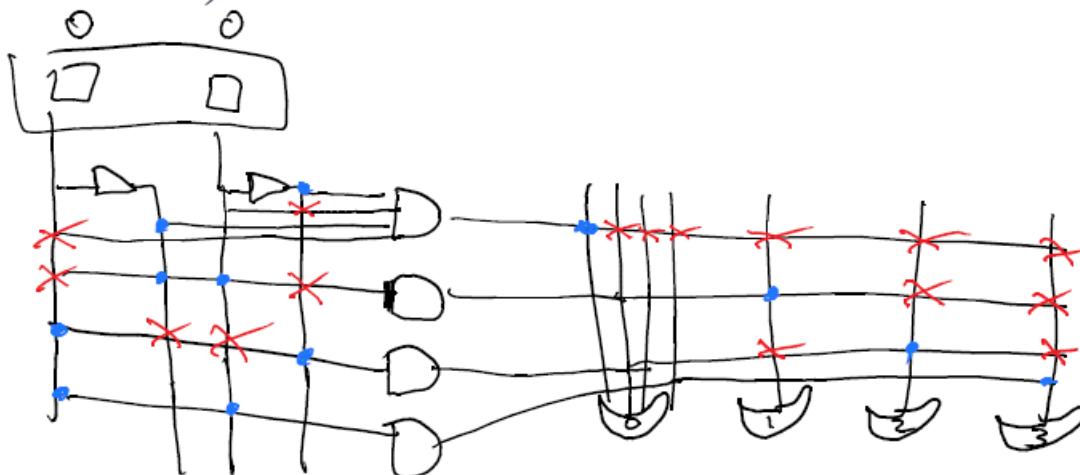
How would the assumptions impact the design of the ALU? Limit capacity to do arithmetic, depending on size of data.

4-bit integer ALU with addition and subtraction? 2 Half-adders.

Upgrading size? Add more half adders, bigger output.

Binary Code Decimal 7 segments (calculator LED), depending on which bits are on, display that number. Uses addressing.

Given 2 bit binary number, use PLA to send out single bit value for each binary value. (Like a decoder)



Temperature stored in a register as a binary number, set off alarm when temp is ≥ 500 Do all the situations 5+, then put them all into an or.

2 GHz computer CPU that executes 1 instruction/20 ticks

How long to run linear program of 1000 lines of code?

$$T = 1000 \times 20/2 \times 10^9 = 0.00001 \text{ sec}$$

Comparing Pipeline & Classical Given ratio of program instructions (how much % is loads, stores, etc.) and how long each step takes. Use: $time = \frac{\text{instructions} \times \text{ticks}}{\text{instr} \times \text{clock}}$

Instruction class	Functional units used by the instruction class					
	JALU type	Instruction fetch	Register access	ALU	Register access	
Load word					Memory access	
Store word					Memory access	
Branch				ALU		
Jump						

Instruction class	Instruction memory	Register read	ALU operation	Data memory	Register write	Total
ALU type	2	1	2	0	1	6 ns
Load word	2	1	2	2	1	8 ns
Store word	2	1	2	2		7 ns
Branch	2	1	2			5 ns
Jump	2					2 ns

Even here, where it's 2 for classical, still 2 for pipeline

Times for Classical

Variable vs. fixed cycle lengths?

secs/ticks ill

Vybihal (c) 2015

Pipeline needs slowest, 8 ns
But only first guy needs 8
2 for remaining

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12 Exercises

12.1 Circuits

- Make a circuit with a truth table
- Simple 3 bit increment with 1 circuit, no adder
- 2's complement circuit
- Circuit picking 1 bit out of 2 bits, given a 1 bit number