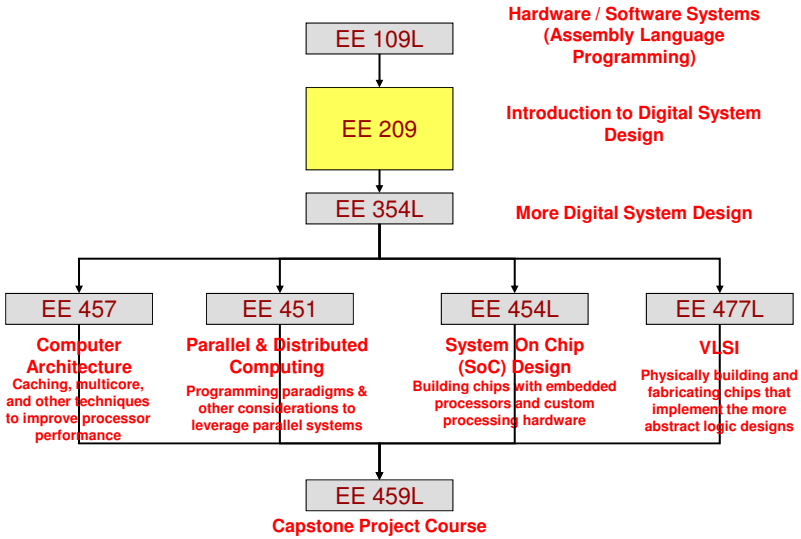
Spiral 0 – Review of EE 109L

Class Overview
Analog to Digital Conversion
Binary Representation
MIPS Assembly and CPU Organization

EE 209 in Context



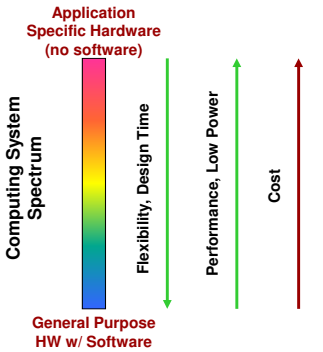
Where Does Digital Design Fit In

- Electrical, biomedical, or computer scientists/engineers develop algorithms for
  - Wireless and communication systems
  - Media and imaging systems
  - Biomedical devices

- Digital design engineers take these general algorithms and architect/design a HW/SW system to implement them dealing with constraints of size, speed, weight, power, etc.
- Other electrical engineers may help with the final fabrication of the chip

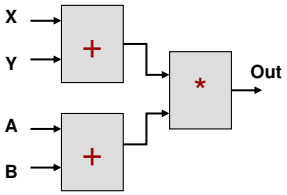
Digital System Spectrum

- Key idea: Any "algorithm" can be implemented in HW or SW or some mixture of both
- A digital systems can be located anywhere in a spectrum of:
  - ALL HW: (a.k.a. Application-Specific IC's)
  - ALL SW: An embedded computer system
- Advantages of application specific HW
  - Faster, less power
- Advantages of an embedded computer system (i.e. general purpose HW for executing SW)
  - Reprogrammable (i.e. make a mistake, fix it)
  - Less expensive than a dedicated hardware system (single computer system can be used for multiple designs)
- Phone: System-on-Chip (SoC) approach
  - Some dedicated HW for intensive camera/radio/etc. decoding operations
  - Programmable processor for UI & other simple tasks

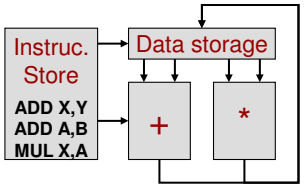


Processing Logic Approaches

- Custom Logic
  - Logic that directly implements a specific task
  - Example above may use separate adders and a multiplier unit
- General Purpose Processor
  - Logic designed to execute SW instructions
  - Provides basic processing resources that are reused by each instruction
- Design Decision: HW only or HW/SW
  - HW only = faster
  - HW/SW = much more flexible



Custom Logic Circuit Implementation



GPP Implementation of (X+Y)*(A+B)

HW/SW Design Example

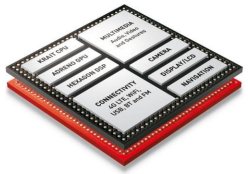
- Suppose you need to design a JPEG encoder (converts raw pixels to JPG format…consisting of a preprocessing stage + encoding stage) for the camera on your mobile phone
- Your design considerations requirements
  - 1 second max. latency (time)
  - 200 mW max power
  - Energy (Power * Time) as low as possible
  - Consider time to market (design time) and cost
- Options
  1. Software only running on microcontroller/processor
  2. Hardware preprocessor + Software encoder
  3. Hardware preprocessor + Fixed-point software encoder
  4. Hardware preprocessor + encoder

	Option 1	Option 2	Option 3	Option 4
Performance (sec.)	> 10	9.1	1.5	0.1
Power (milliwatt)	< 200	33	33	40
Size (gates)	N/A	98,000	90,000	128,000
Energy (Joules=sec*watt)		0.3	0.05	0.004
Time to Market	3 months	6 months	8 months	12 months

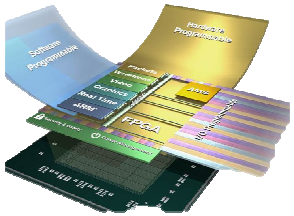
Taken from "Embedded System Design" by Vahid and Givargis, Wiley and Sons Publishing 2002.

Integrated Solutions: Systems-On-Chip

- Chips now combine general purpose processing, hardware accelerated engines for things like comm., video, security, etc., and integrated I/O peripherals
- Some contain customizable hardware resources (FPGAs) for custom hardware processing engines

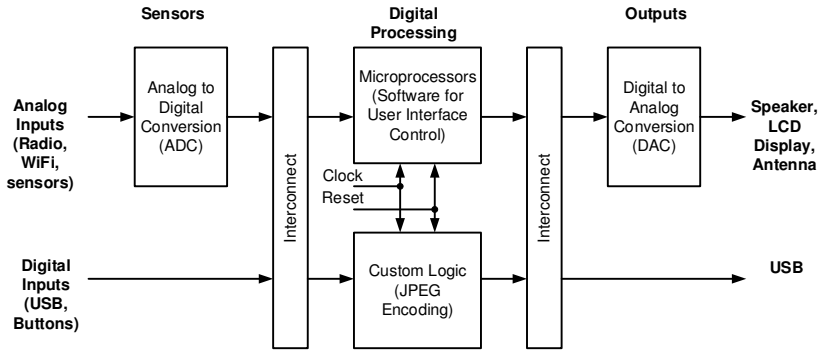


Qualcomm Snapdragon™

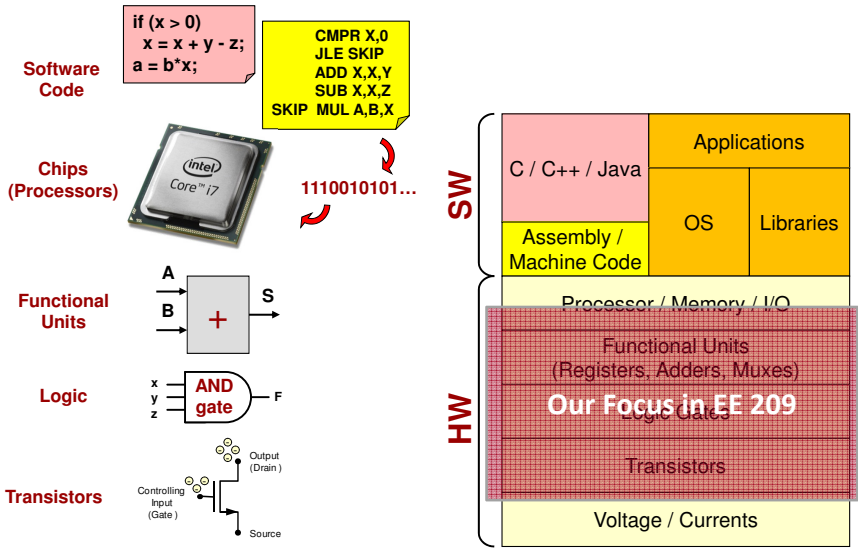


Xilinx Zynq MPSoC

Mobile Phone Block Diagram



Digital System Abstraction Levels



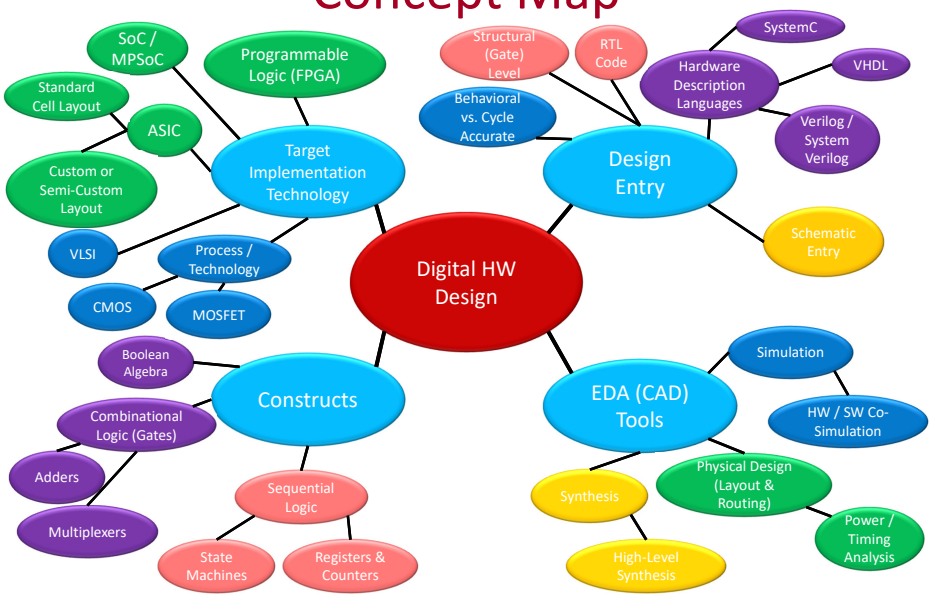
How are we going to go about this class

LEARNING

Reflecting on Learning

- Bjork's Presentation
- Spiral Model (Interleaving)
- We need to be a team?
  - I need you
  - You need me
- What do you want to learn?
  - I will be your guide and try to build experiences

Concept Map



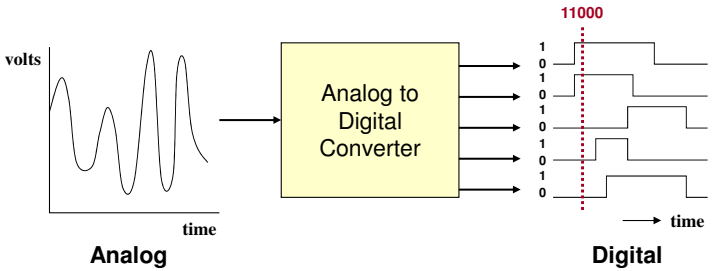
Spiral Content Mapping

Spiral	Theory	Combinational Design	Sequential Design	System Level Design	Implementation and Tools	Project
1	• Performance metrics (latency vs. throughput) • Boolean Algebra • Canonical Representations	• Decoders and muxes • Synthesis with min/maxterms • Synthesis with Karnaugh Maps	• Edge-triggered flip-flops • Registers (with enables)	• Encoded State machine design	• Structural Verilog HDL • CMOS gate implementation • Fabrication process	
2	• Shannon's Theorem	• Synthesis with muxes & memory • Adder and comparator design	• Bistables, latches, and Flip-flops • Counters • Memories	• One-hot state machine design • Control and datapath decomposition	• MOS Theory • Capacitance, delay and sizing • Memory constructs	
3				• HW/SW partitioning • Bus interfacing • Single-cycle CPU	• Power and other logic families • EDA design process	

REVIEW

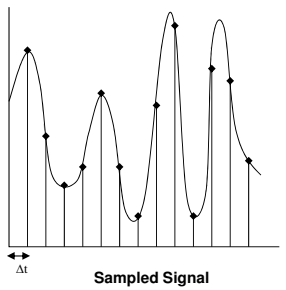
Analog to Digital Conversion

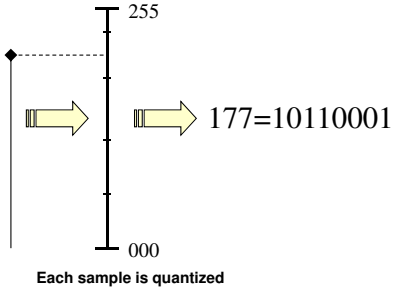
- 1 Analog signal can be converted to a *set* of digital signals (0's and 1's)
- 3 Step Process
  - Sample
  - Quantize (Measure)
  - Digitize



ADC Conversion

- Sampling converts continuous time scale to a discrete (finite) set of voltage samples
- Quantization converts continuous voltage scale to a discrete (finite) set of numbers
- Each number is then output as bits

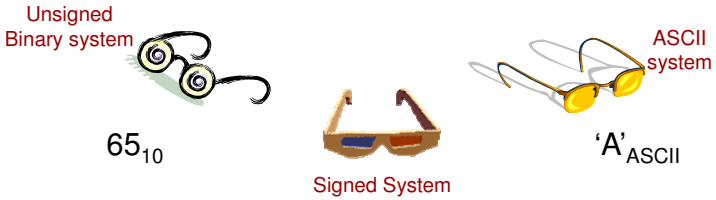




Interpreting Binary Strings

- Given a string of 1's and 0's, you need to know the *representation system* being used, before you can understand the value of those 1's and 0's.
- Information (value) = Bits + Context (System)

01000001 = ?



Unsigned and Signed Variables

- Unsigned variables use unsigned binary (normal power-of-2 place values) to represent numbers

1	0	0	1	0	0	1	1	= +147
128	64	32	16	8	4	2	1	

- Signed variables use the 2's complement system (Neg. MSB weight) to represent numbers

1	0	0	1	0	0	1	1	= -109
-128	64	32	16	8	4	2	1	

2's Complement System

- MSB has negative weight
- MSB determines sign of the number
  - 1 = negative
  - 0 = positive
- Positive numbers retain same representation as unsigned
  - 0110 = +6 in unsigned and in 2's complement
- To take the negative of a number requires taking the complement

```
 0111   x = +7                1001   x = -7

 1000   Bit flip (1's comp.)  0110   Bit flip (1's comp.)
+   1   Add 1                +   1   Add 1
 1001   -x = -(+7) = -7       0111   -x = -(-7) = +7
```


Zero and Sign Extension

- Extension is the process of increasing the number of bits used to represent a number without changing its value

Unsigned = Zero Extension (Always add leading 0's):

111011 = 00111011

Increase a 6-bit number to 8-bit number by zero extending

2's complement = Sign Extension (Replicate sign bit):

pos. 011010 = 00011010

neg. 110011 = 11110011

Sign bit is just repeated as many times as necessary

Zero and Sign Truncation

- Truncation is the process of decreasing the number of bits used to represent a number without changing its value

Unsigned = Zero Truncation (Remove leading 0's):

~~00~~111011 = 111011

Decrease an 8-bit number to 6-bit number by truncating 0's. Can't remove a '1' because value is changed

2's complement = Sign Truncation (Remove copies of sign bit):

pos. ~~000~~11010 = 011010

neg. ~~111~~10011 = 10011

Any copies of the MSB can be removed without changing the numbers value. Be careful not to change the sign by cutting off ALL the sign bits.

Representation Range

- Given an n-bit system we can represent 2^n unique numbers
  - In unsigned systems we use all combinations to represent positive numbers [0 to 2^n-1]
  - In 2's complement we use half for positive and half for negative [-2^{n-1} to $+2^{n-1}$-1]

n	2^n
1	2
2	4
3	8
4	16
5	32
6	64
7	128
8	256
9	512

Hexadecimal Representation

- Since values in modern computers are many bits, we use hexadecimal as a shorthand notation (4 bits = 1 hex digit)
  - 1101 0010 = D2 hex
  - 0111 0110 1100 1011 = 76CB hex

REVIEW OF MIPS ASSEMBLY

MIPS Instruction Set

- 32-bit data and address
  - Memory supports Byte, Halfword (2-bytes), and Word (4-bytes) access
- 32 General Purpose Registers ($0-$31)
  - $0 = Constant value of 0
- Fixed Size Instructions of 32-bits (4 bytes)
  - Three formats (ways to partition and interpret those 32-bits)
  - R-Type (Register Type) [ex. ADD $5, $10, $20]
  - I-Type (Immediate Type) [ex. LW $5, 0x230($6)]
  - J-Type (Jump Type) [ex. J Addr.]

MIPS Data Sizes

Integer

- 3 Sizes Defined
  - Byte (B)
    - 8-bits
  - Halfword (H)
    - 16-bits = 2 bytes
  - Word (W)
    - 32-bits = 4 bytes

Floating Point

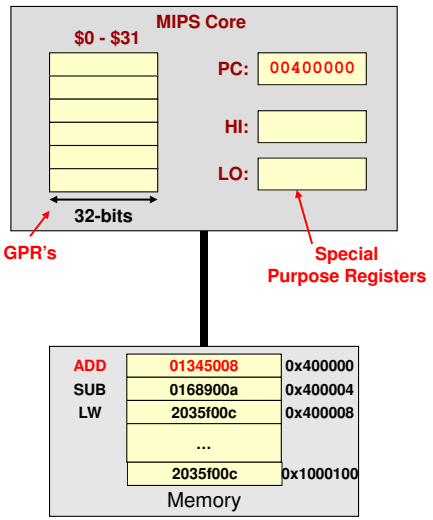
- 3 Sizes Defined
  - Single (S)
    - 32-bits = 4 bytes
  - Double (D)
    - 64-bits = 8 bytes
    - (For a 32-bit data bus, a double would be accessed from memory in 2 reads)

MIPS GPR's

Assembler Name	Reg. Number	Description
$zero	$0	Constant 0 value
$at	$1	Assembler temporary
$v0-$v1	$2-$3	Procedure return values or expression evaluation
$a0-$a3	$4-$7	Arguments/parameters
$t0-$t7	$8-$15	Temporaries
$s0-$s7	$16-$23	Saved Temporaries
$t8-$t9	$24-$25	Temporaries
$k0-$k1	$26-$27	Reserved for OS kernel
$gp	$28	Global Pointer (Global and static variables/data)
$sp	$29	Stack Pointer
$fp	$30	Frame Pointer
$ra	$31	Return address for current procedure

MIPS Programmer-Visible Registers

- General Purpose Registers (GPR's)
  - Hold data operands or addresses (pointers) to data stored in memory
- Special Purpose Registers
  - PC: Program Counter (32-bits)
    - Holds the address of the next instruction to be fetched from memory & executed
  - HI: Hi-Half Reg. (32-bits)
    - For MUL, holds 32 MSB's of result. For DIV, holds 32-bit remainder
  - LO: Lo-Half Reg. (32-bits)
    - For MUL, holds 32 LSB's of result. For DIV, holds 32-bit quotient
- Memory
  - Stores instructions and data



Instruction Format

- 32-bit Fixed Size Instructions
- R-Type
  - 3 register operands
- I-Type
  - 2 register + 16-bit const.
- J-Type
  - 26-bit jump address

	6-bits	5-bits	5-bits	5-bits	5-bits	6-bits
R-Type	opcode	rs (src1)	rt (src2)	rd (dest)	shamt	function
add $5,$7,$8	000000	00111	01000	00101	00000	100000

	6-bits	5-bits	5-bits	16-bits
I-Type	opcode	rs (src1)	rt (src/dst)	immediate
lw $18, -4($3)	100011	00011	10010	1111 1111 1111 1100

	6-bits	26-bits
J-Type	opcode	Jump address
j 0x0400018	000010	0000 0100 0000 0000 0000 0001 10

R-Type Instructions

- Format

6-bits	5-bits	5-bits	5-bits	5-bits	6-bits
opcode	rs (src1)	rt (src2)	rd (dest)	shamt	function

  - rs, rt, rd are 5-bit fields for register numbers
  - shamt = shift amount and is used for shift instructions indicating # of places to shift bits
  - opcode and func identify actual operation
- Example:
  - ADD $5, $24, $17

opcode	rs	rt	rd	shamt	func
000000	11000	10001	00101	00000	100000
Arith. Inst.	$24	$17	$5	unused	ADD

R-Type Arithmetic/Logic Instructions

C operator	Assembly	Notes
+	ADD Rd, Rs, Rt	
-	SUB Rd, Rs, Rt	Order: R[s] – R[t]. SUBU for unsigned
*	MULT Rs, Rt MULTU Rs, Rt	Result in HI/LO. Use mfhi and mflo instruction to move results
*	MUL Rd, Rs, Rt	If multiply won't overflow 32-bit result
/	DIV Rs, Rt DIVU Rs, Rt	R[s] / R[t]. Remainder in HI, quotient in LO
&	AND Rd, Rs, Rt	
|	OR Rd, Rs, Rt	
^	XOR Rd, Rs, Rt	
~(|)	NOR Rd, Rs, Rt	Can be used for bitwise-NOT (~)
<<	SLL Rd, Rs, shamt SLLV Rd, Rs, Rt	Shifts R[s] left by shamt (shift amount) or R[t] bits
>> (signed)	SRA Rd, Rs, shamt SRAV Rd, Rs, Rt	Shifts R[s] right by shamt or R[t] bits replicating sign bit to maintain sign
>> (unsigned)	SRL Rd, Rs, shamt SRLV Rd, Rs, Rt	Shifts R[s] left by shamt or R[t] bits shifting in 0's
<, >, <=, >=	SLT Rd, Rs, Rt SLTU Rd, Rs, Rt	Order: R[s] – R[t]. Sets R[d]=1 if R[s] < R[t], 0 otherwise

I-Type Instructions

- Format

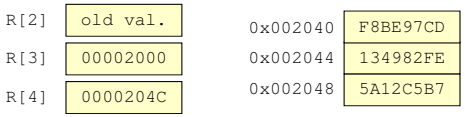
6-bits	5-bits	5-bits	16-bits
opcode	rs (src1)	rt (src/dst)	immediate

  - rs, rt are 5-bit fields for register numbers
  - immediate is a 16-bit constant
  - opcode identifies actual operation
- Example:
  - ADDI $5, $24, 1
  - LW $5, -8($3)

opcode	rs	rt	immediate
001000	11000	00101	0000 0000 0000 0001
ADDI	$24	$5	1
010011	00011	00101	1111 1111 1111 1000
LW	$3	$5	-8

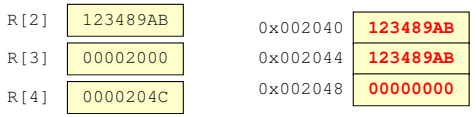
Load Format (LW)

- LW Rt, offset(Rs)
  - Rt = Destination register
  - offset(Rs) = Address of desired data
  - Shorthand: R[t] = M[offset + R[s]]
  - offset limited to 16-bit signed number
- Examples
  - LW $2, 0x40($3) // R[2] = 0xF8BE97CD
  - LW $2, 0xFFFC($4) // R[2] = 0x5A12C5B7



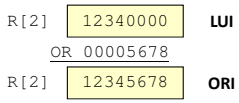
Store Format (SW)

- SW Rt, offset(Rs)
  - Rt = Source register
  - offset(Rs) = Address to store data
  - Shorthand: M[offset + R[s]] = R[t]
  - offset limited to 16-bit signed number
- Examples
  - SW $2, 0x40($3)
  - SW $2, 0xFFF8($4)



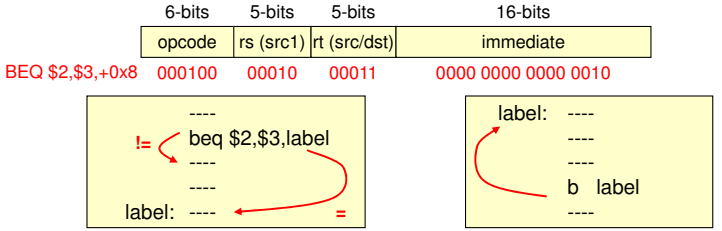
Loading an Immediate

- If immediate (constant) 16-bits or less
  - Use ORI or ADDI instruction with $0 register
  - Examples
    - ADDI $2, $0, 1 // R[2] = 0 + 1 = 1
    - ORI $2, $0, 0xF110 // R[2] = 0 | 0xF110 = 0xF110
- If immediate more than 16-bits
  - Immediates limited to 16-bits so we must load constant with a 2 instruction sequence using the special LUI (Load Upper Immediate) instruction
  - To load $2 with 0x12345678
    - LUI $2,0x1234
    - ORI $2,$2,0x5678



Branch Instructions

- Add a displacement to the PC (PC = PC + disp.)
- Conditional Branches
  - Branches only if a particular condition is true
  - Fundamental Instrucs.: BEQ (if equal), BNE (not equal)
  - Syntax: `BNE/BEQ Rs, Rt, label`
    - Compares Rs, Rt and if EQ/NE, branch to label, else continue
- Unconditional Branches
  - Always branches to a new location in the code
  - Instruction: `BEQ $0,$0,label`



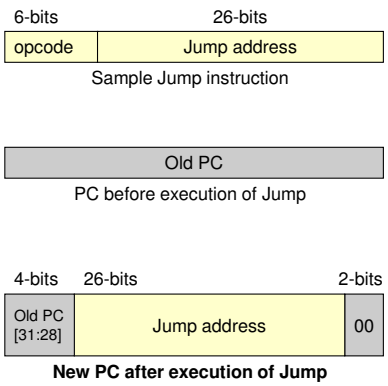
Two-Operand Compare & Branches

- Two-operand comparison is accomplished using the SLT/SLTI instruction
  - Syntax: SLT Rd,Rs,Rt or SLT Rd,Rs,imm
    - If Rs < Rt then Rd = 1, else Rd = 0
  - Use appropriate BNE/BEQ instruction to infer relationship

Branch if…	SLT	BNE/BEQ
$2 < $3	SLT $1,$2,$3	BNE $1,$0,label
$2 ≤ $3	SLT $1,$3,$2	BEQ $1,$0,label
$2 > $3	SLT $1,$3,$2	BNE $1,$0,label
$2 ≥ $3	SLT $1,$2,$3	BEQ $1,$0,label

Jump Instructions

- Jumps provide method of branching beyond range of 16-bit displacement
- Syntax: J *label/address*
  - Operation: PC = address
  - Address is appended with two 0's just like branch displacement yielding a 28-bit address with upper 4-bits of PC unaffected
- New instruction format: J-Type

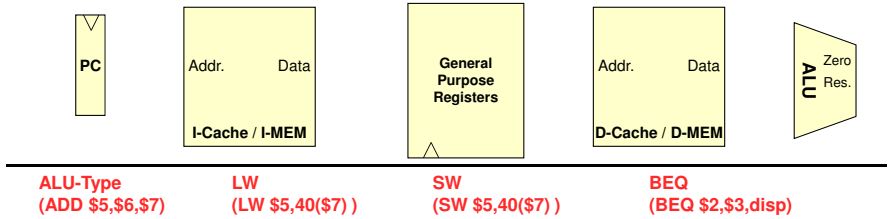


Jump Register

- 'jr' instruction can be used if a full 32-bit jump is needed or variable jump address is needed
- Syntax: JR rs
  - Operation: PC = R[s]
  - R-Type machine code format
- Usage:
  - Can load rs with an immediate address
  - Can calculate rs for a variable jump (class member functions, switch statements, etc.)

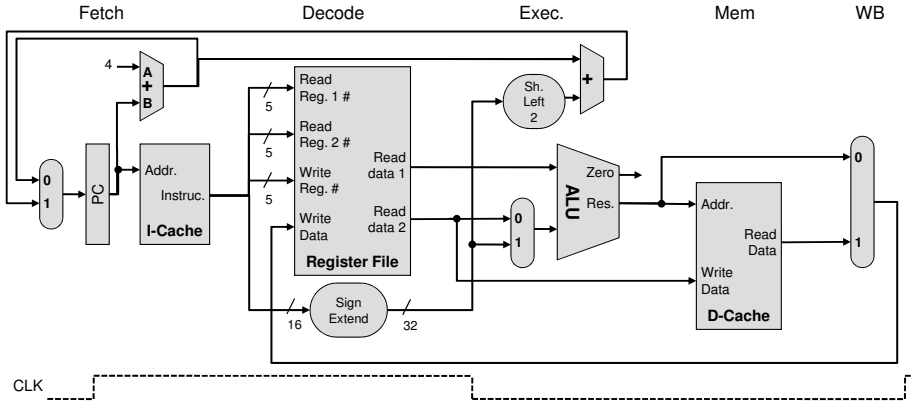
Instruction Ordering

- Identify which components each instruction type would use and in what order: ALU-Type, LW, SW, BEQ



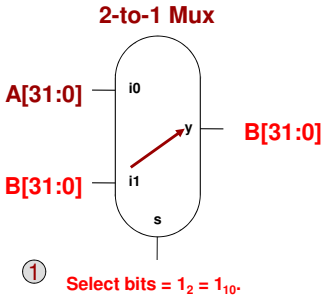
Single Cycle CPU Datapath

- Each instruction will execute in one LONG clock cycle
- To understand the whole datapath we'll walk through it in five phases (Fetch, Decode, Execute, Memory, Writeback)



Multiplexers

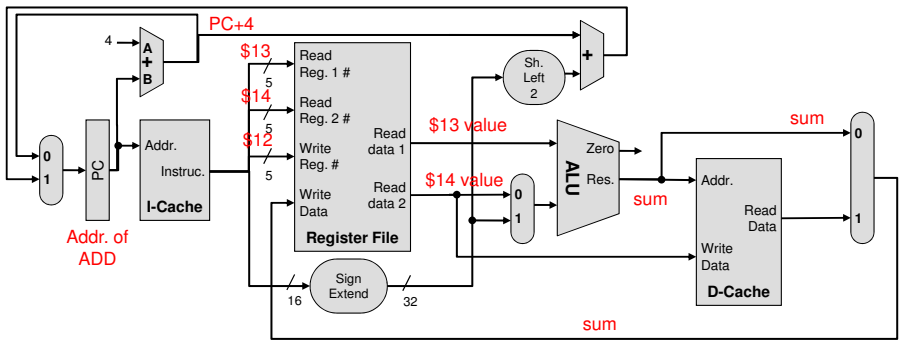
- Your first HW building block
- Traffic cop…Selects 1 data input and passes it to the output



② Thus, input 1 = B[31:0] is selected and passed to the output

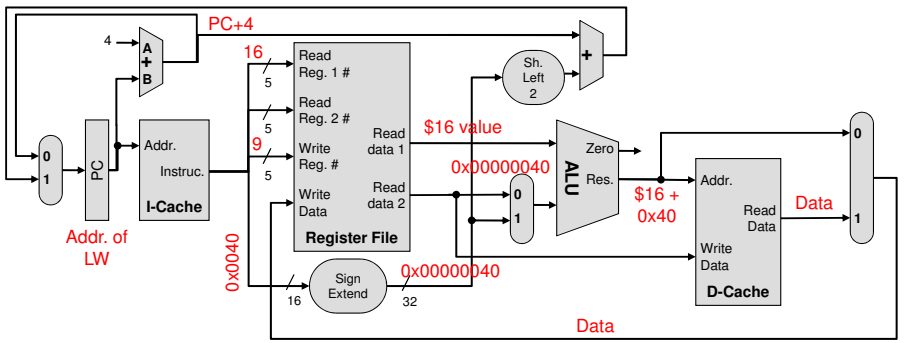
① Select bits = $1_2 = 1_{10}$.

ADD $12,$13,$14



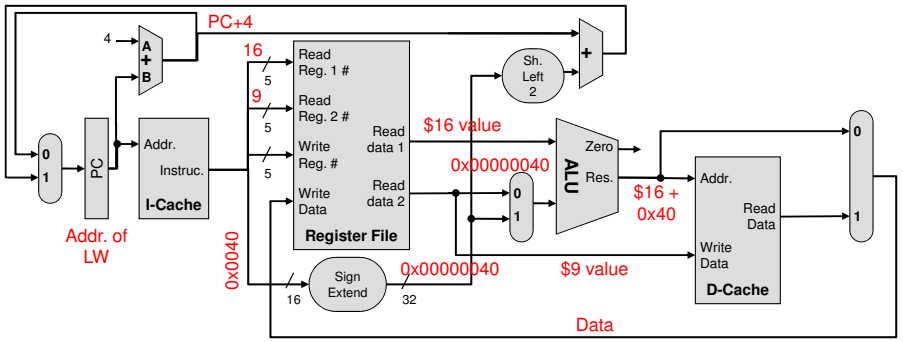
Fetch ADD | Decode instruction and fetch operands | Add $13 +$14 | Just pass sum through | Write sum to $t4

LW $9,0x40($16)



Fetch LW | Decode instruction and fetch operands | Add offset 0x40 to $16 | Read word from memory | Write word to $9

SW $9,0x40($16)



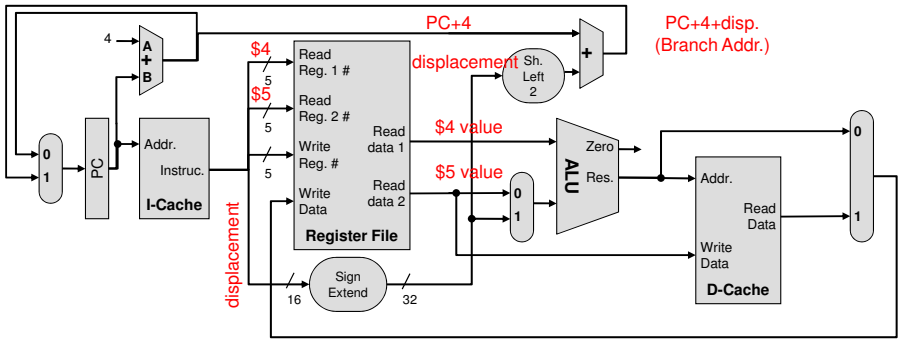
Fetch LW

Decode instruction and fetch operands

Add offset 0x40 to $16

Write word to memory

BEQ $4,$5,disp.



Fetch BEQ, increment PC, pass on PC+4

Decode instruction and fetch operands, pass on PC+4

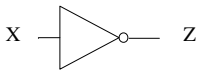
Do $4-$5 and check if result = 0 Calculate branch target address

Update PC

Do Nothing

SAMPLE PROBLEMS (IF TIME ALLOWS)

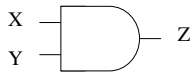
AND, OR, NOT Gates



NOT (Inverter)

$Z = X'$ or $\overline{X}$ or $\sim X$

X	Z
0	1
1	0

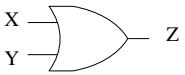


AND

$Z = X \cdot Y$

X	Y	Z
0	0	0
0	1	0
1	0	0
1	1	1

AND = 'ALL' (true when ALL inputs are true)



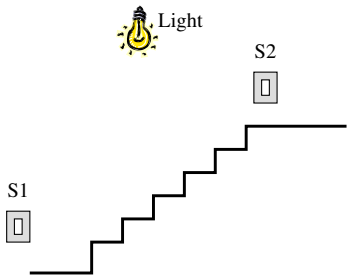
OR

$Z = X + Y$

X	Y	Z
0	0	0
0	1	1
1	0	1
1	1	1

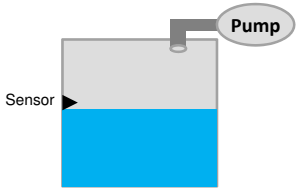
OR = 'ANY' (true when ANY input is true)

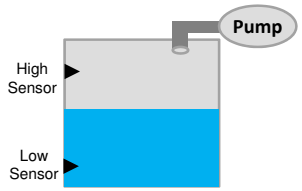
Staircase Light Switch Logic



Water Tank Problem

- Build a control system for a pump to keep the tank from going empty





Instruction Ordering Solutions

- Identify which components each instruction type would use and in what order: ALU-Type, LW, SW, BEQ

ALU-Type
(ADD $5,$6,$7)

1. PC
2. I-Memory
3. Registers
4. ALU
5. WB to Reg.

LW
(LW $5,40($7))

1. PC
2. I-Memory
3. Base. Reg.
4. ALU
5. Read Mem.
6. WB to Reg.

SW
(SW $5,40($7))

1. PC
2. I-Memory
3. Base. Reg.
4. ALU
5. Write Mem.

BEQ
(BEQ $2,$3,disp)

1. PC
2. I-Memory
3. Register Access
4. Compare
5. If Zero, Update PC=PC+d