CS:APP Chapter 4
Computer Architecture
Sequential Implementation

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Y86 Instruction Set #1

Byte	0	1	2	3	4	5
`halt`	0 0					
`nop`	1 0					
`cmovXX` rA, rB	2 fn	rA rB				
`irmovl` V, rB	3 0	8 rB	V			
`rmmovl` rA, D(rB)	4 0	rA rB	D			
`mrmovl` D(rB), rA	5 0	rA rB	D			
`OPl` rA, rB	6 fn	rA rB				
`jXX` Dest	7 fn	Dest				
`call` Dest	8 0	Dest				
`ret`	9 0					
`pushl` rA	A 0	rA 8				
`popl` rA	B 0	rA 8				

`rrmovl`	2 0
`cmovle`	2 1
`cmovl`	2 2
`cmove`	2 3
`cmovne`	2 4
`cmovge`	2 5
`cmovg`	2 6

Y86 Instruction Set #2

Byte	0		1		2	3	4	5
`halt`	0	0						
`nop`	1	0						
`cmovXX` rA, rB	2	fn	rA	rB				
`irmovl` V, rB	3	0	8	rB	V			
`rmmovl` rA, D(rB)	4	0	rA	rB	D			
`mrmovl` D(rB), rA	5	0	rA	rB	D			
`OPl` rA, rB	6	fn	rA	rB				
`jXX` Dest	7	fn	Dest					
`call` Dest	8	0	Dest					
`ret`	9	0						
`pushl` rA	A	0	rA	8				
`popl` rA	B	0	rA	8				

`addl`	6	0
`subl`	6	1
`andl`	6	2
`xorl`	6	3

Y86 Instruction Set #3

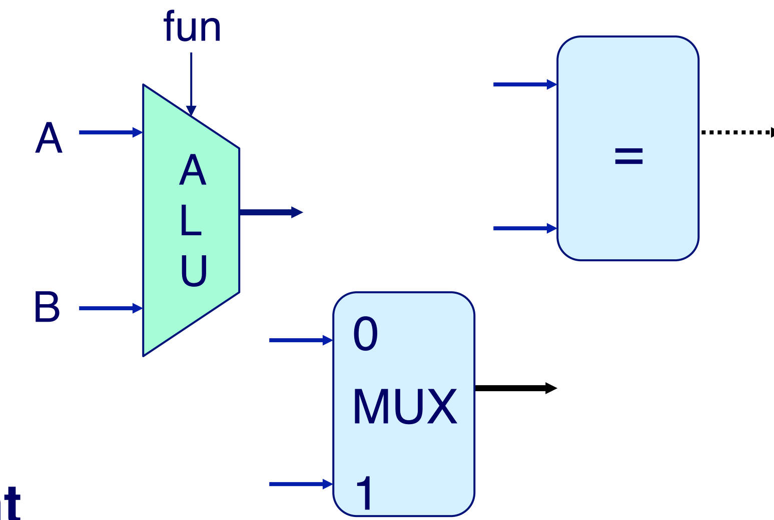
Byte	0	1	2	3	4	5
`halt`	0 0					
`nop`	1 0					
`rrmovl` rA, rB	2 fn	rA rB				
`irmovl` V, rB	3 0	8 rB	V			
`rmmovl` rA, D(rB)	4 0	rA rB	D			
`mrmovl` D(rB), rA	5 0	rA rB	D			
`OPl` rA, rB	6 fn	rA rB				
`jXX` Dest	7 fn	Dest				
`call` Dest	8 0	Dest				
`ret`	9 0					
`pushl` rA	A 0	rA 8				
`popl` rA	B 0	rA 8				

`jmp`	7 0
`jle`	7 1
`jl`	7 2
`je`	7 3
`jne`	7 4
`jge`	7 5
`jg`	7 6

Building Blocks

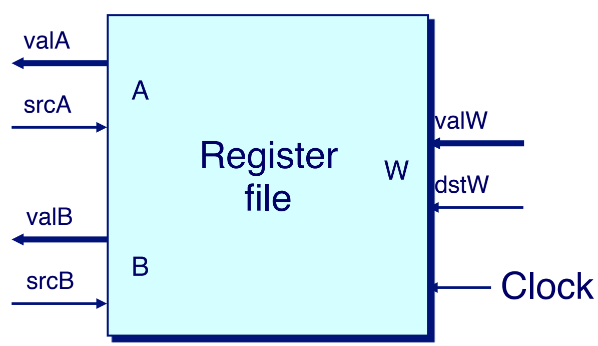
Combinational Logic

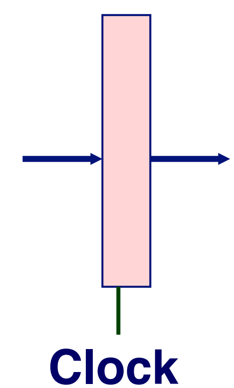
- Compute Boolean functions of inputs
- Continuously respond to input changes
- Operate on data and implement control



Storage Elements

- Store bits
- Addressable memories
- Non-addressable registers
- Loaded only as clock rises





Hardware Control Language

- Very simple hardware description language
- Can only express limited aspects of hardware operation
  - Parts we want to explore and modify

Data Types

- `bool`: Boolean
  - `a`, `b`, `c`, …
- `int`: words
  - `A`, `B`, `C`, …
  - Does not specify word size---bytes, 32-bit words, …

Statements

- `bool a =` ***`bool-expr ;`***
- `int A =` ***`int-expr ;`***

HCL Operations

- Classify by type of value returned

Boolean Expressions

- Logic Operations
  - `a && b, a || b, !a`
- Word Comparisons
  - `A == B, A != B, A < B, A <= B, A >= B, A > B`
- Set Membership
  - `A in { B, C, D }`
    - » Same as `A == B || A == C || A == D`

Word Expressions

- Case expressions
  - `[ a : A; b : B; c : C ]`
  - Evaluate test expressions `a`, `b`, `c`, … in sequence
  - Return word expression `A`, `B`, `C`, … for first successful test

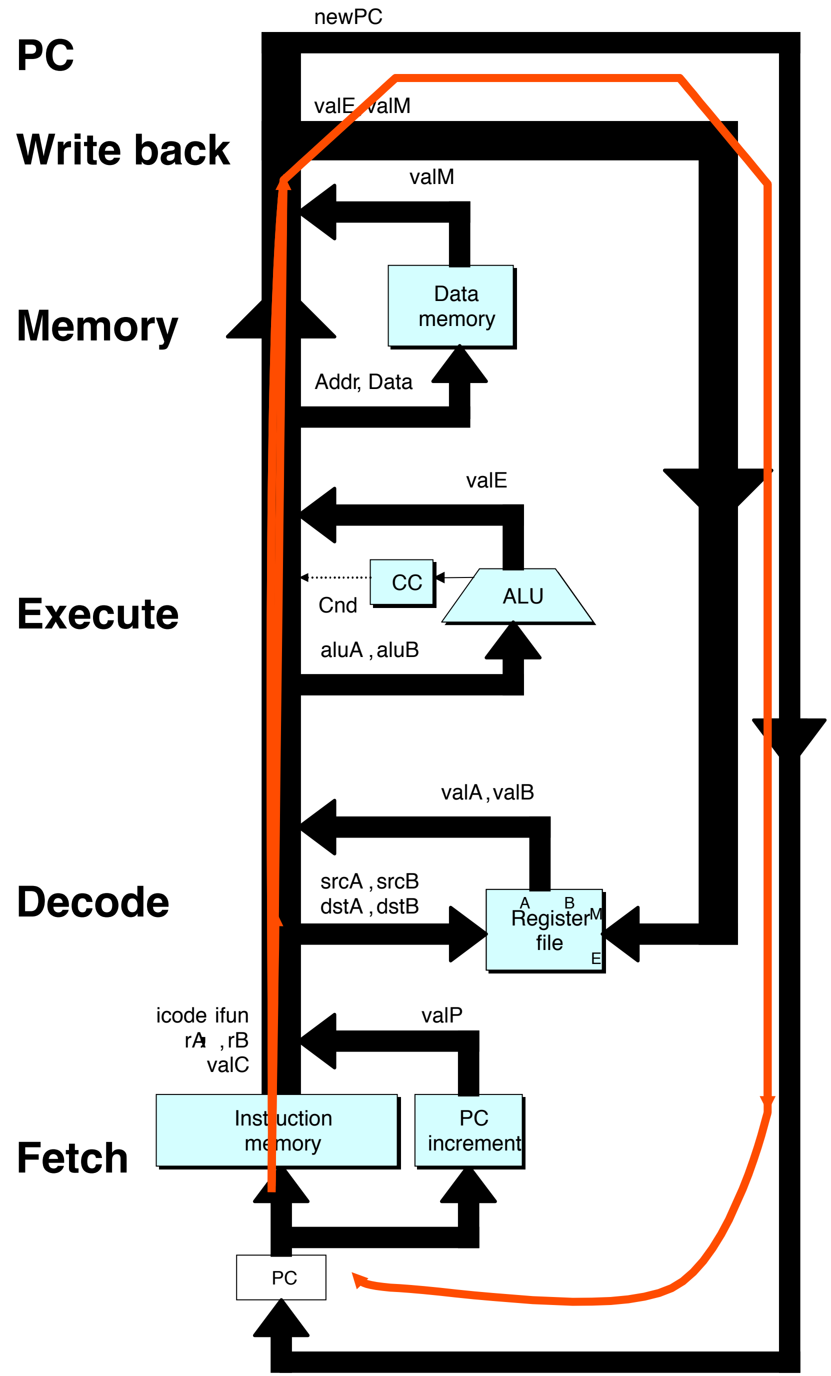
SEQ Hardware Structure

State

- Program counter register (PC)
- Condition code register (CC)
- Register File
- Memories
  - Access same memory space
  - Data: for reading/writing program data
  - Instruction: for reading instructions

Instruction Flow

- Read instruction at address specified by PC
- Process through stages
- Update program counter



SEQ Stages

Fetch

- Read instruction from instruction memory

Decode

- Read program registers

Execute

- Compute value or address

Memory

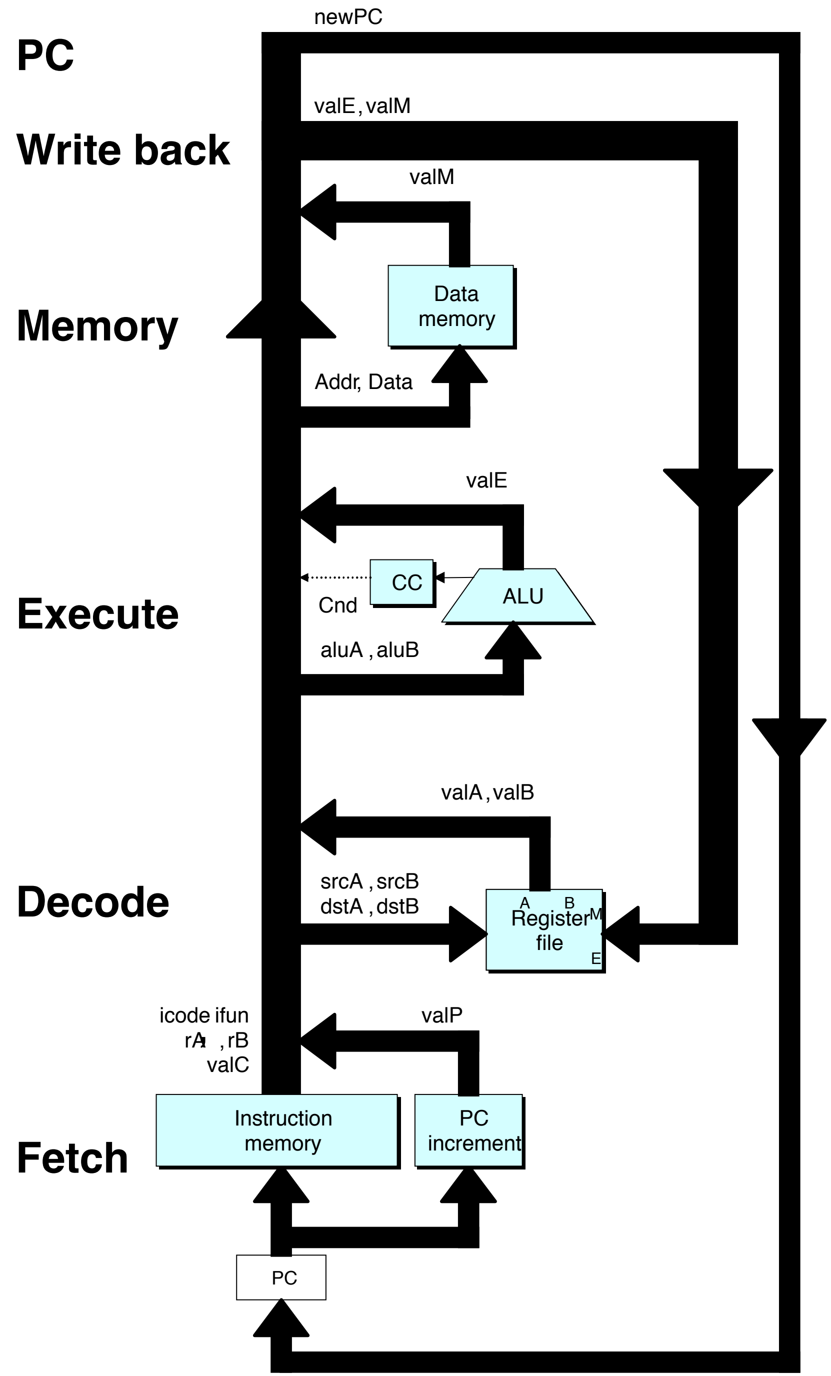
- Read or write data

Write Back

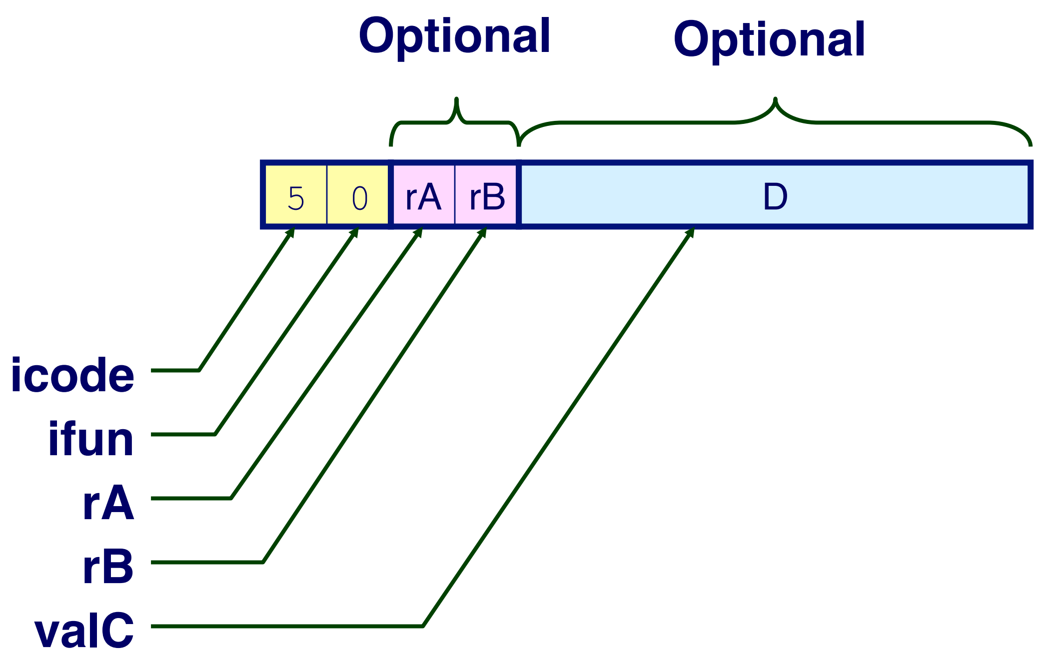
- Write program registers

PC

- Update program counter



Instruction Decoding



Instruction Format

- Instruction byte icode:ifun
- Optional register byte rA:rB
- Optional constant word valC

Executing Arith./Logical Operation

`OPl rA, rB`	6	fn	rA	rB

Fetch

- Read 2 bytes

Decode

- Read operand registers

Execute

- Perform operation
- Set condition codes

Memory

- Do nothing

Write back

- Update register

PC Update

- Increment PC by 2

Stage Computation: Arith/Log. Ops

	OPl rA, rB	
Fetch	icode:ifun ← M_1[PC]	Read instruction byte
	rA:rB ← M_1[PC+1]	Read register byte
	valP ← PC+2	Compute next PC
Decode	valA ← R[rA]	Read operand A
	valB ← R[rB]	Read operand B
Execute	valE ← valB OP valA	Perform ALU operation
	Set CC	Set condition code register
Memory		
Write back	R[rB] ← valE	Write back result
PC update	PC ← valP	Update PC

- Formulate instruction execution as sequence of simple steps
- Use same general form for all instructions

Executing `rmmovl`

`rmmovl rA, D(rB)`	4	0	rA	rB	D

Fetch

- Read 6 bytes

Decode

- Read operand registers

Execute

- Compute effective address

Memory

- Write to memory

Write back

- Do nothing

PC Update

- Increment PC by 6

Stage Computation: `rmmovl`

	`rmmovl` rA, D(rB)	
Fetch	icode:ifun ← M_1[PC]	Read instruction byte
	rA:rB ← M_1[PC+1]	Read register byte
	valC ← M_4[PC+2]	Read displacement D
	valP ← PC+6	Compute next PC
Decode	valA ← R[rA]	Read operand A
	valB ← R[rB]	Read operand B
Execute	valE ← valB + valC	Compute effective address
Memory	M_4[valE] ← valA	Write value to memory
Write back		
PC update	PC ← valP	Update PC

- Use ALU for address computation

Executing `popl`

`popl rA`	b	0	rA	8

Fetch

- Read 2 bytes

Decode

- Read stack pointer

Execute

- Increment stack pointer by 4

Memory

- Read from old stack pointer

Write back

- Update stack pointer
- Write result to register

PC Update

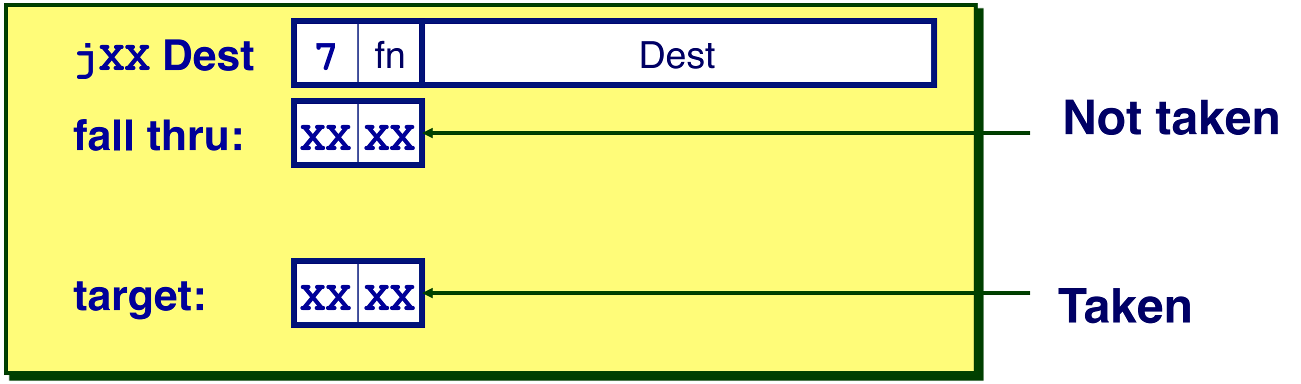
- Increment PC by 2

Stage Computation: `popl`

	`popl` rA	
Fetch	icode:ifun ← M_1[PC]	Read instruction byte
	rA:rB ← M_1[PC+1]	Read register byte
	valP ← PC+2	Compute next PC
Decode	valA ← R[`%esp`]	Read stack pointer
	valB ← R [`%esp`]	Read stack pointer
Execute	valE ← valB + 4	Increment stack pointer
Memory	valM ← M_4[valA]	Read from stack
Write back	R[`%esp`] ← valE	Update stack pointer
	R[rA] ← valM	Write back result
PC update	PC ← valP	Update PC

- Use ALU to increment stack pointer
- Must update two registers
  - Popped value
  - New stack pointer

Executing Jumps



Fetch

- Read 5 bytes
- Increment PC by 5

Decode

- Do nothing

Execute

- Determine whether to take branch based on jump condition and condition codes

Memory

- Do nothing

Write back

- Do nothing

PC Update

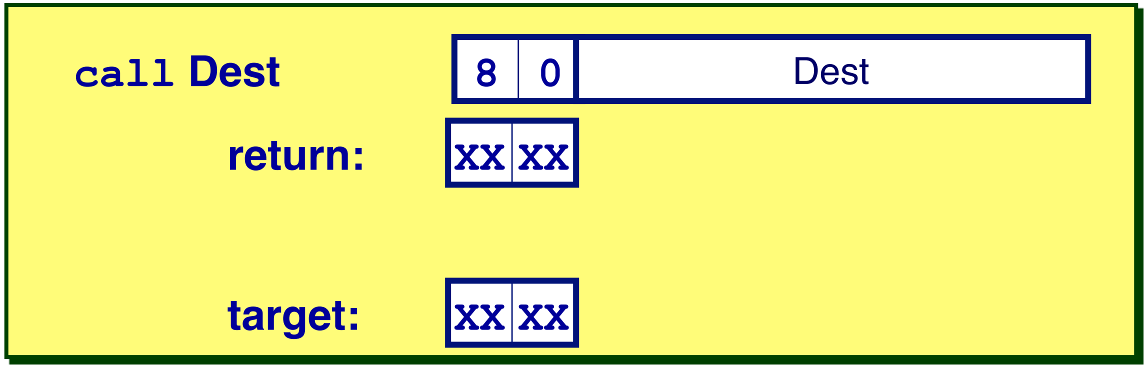
- Set PC to Dest if branch taken or to incremented PC if not branch

Stage Computation: Jumps

	jXX Dest	
Fetch	icode:ifun ← M_1[PC] valC ← M_4[PC+1] valP ← PC+5	Read instruction byte Read destination address Fall through address
Decode		
Execute	Cnd ← Cond(CC,ifun)	Take branch?
Memory		
Write back		
PC update	PC ← Cnd ? valC : valP	Update PC

- Compute both addresses
- Choose based on setting of condition codes and branch condition

Executing `call`



Fetch

- Read 5 bytes
- Increment PC by 5

Decode

- Read stack pointer

Execute

- Decrement stack pointer by 4

Memory

- Write incremented PC to new value of stack pointer

Write back

- Update stack pointer

PC Update

- Set PC to Dest

Stage Computation: `call`

	`call` Dest	
Fetch	icode:ifun $\leftarrow$ M_1[PC]	Read instruction byte
	valC $\leftarrow$ M_4[PC+1]	Read destination address
	valP $\leftarrow$ PC+5	Compute return point
Decode	valB $\leftarrow$ R[`%esp`]	Read stack pointer
Execute	valE $\leftarrow$ valB + –4	Decrement stack pointer
Memory	M_4[valE] $\leftarrow$ valP	Write return value on stack
Write back	R[`%esp`] $\leftarrow$ valE	Update stack pointer
PC update	PC $\leftarrow$ valC	Set PC to destination

- Use ALU to decrement stack pointer
- Store incremented PC

Executing `ret`

`ret`		9 | 0
	return:	xx | xx

Fetch

- Read 1 byte

Decode

- Read stack pointer

Execute

- Increment stack pointer by 4

Memory

- Read return address from old stack pointer

Write back

- Update stack pointer

PC Update

- Set PC to return address

Stage Computation: `ret`

Stage	`ret`	
Fetch	icode:ifun ← M_1[PC]	Read instruction byte
Decode	valA ← R[`%esp`] valB ← R[`%esp`]	Read operand stack pointer Read operand stack pointer
Execute	valE ← valB + 4	Increment stack pointer
Memory	valM ← M_4[valA]	Read return address
Write back	R[`%esp`] ← valE	Update stack pointer
PC update	PC ← valM	Set PC to return address

- Use ALU to increment stack pointer
- Read return address from memory

Computation Steps

		OPl rA, rB	
Fetch	icode,ifun	icode:ifun ← M_1[PC]	Read instruction byte
	rA,rB	rA:rB ← M_1[PC+1]	Read register byte
	valC		[Read constant word]
	valP	valP ← PC+2	Compute next PC
Decode	valA, srcA	valA ← R[rA]	Read operand A
	valB, srcB	valB ← R[rB]	Read operand B
Execute	valE	valE ← valB OP valA	Perform ALU operation
	Cond code	Set CC	Set condition code register
Memory	valM		[Memory read/write]
Write back	dstE	R[rB] ← valE	Write back ALU result
	dstM		[Write back memory result]
PC update	PC	PC ← valP	Update PC

- All instructions follow same general pattern
- Differ in what gets computed on each step

Computation Steps

		`call` Dest	
Fetch	icode,ifun	icode:ifun ← M_1[PC]	Read instruction byte
	rA,rB		[Read register byte]
	valC	valC ← M_4[PC+1]	Read constant word
	valP	valP ← PC+5	Compute next PC
Decode	valA, srcA		[Read operand A]
	valB, srcB	valB ← R[`%esp`]	Read operand B
Execute	valE	valE ← valB + –4	Perform ALU operation
	Cond code		[Set condition code reg.]
Memory	valM	M_4[valE] ← valP	[Memory read/write]
Write back	dstE	R[`%esp`] ← valE	[Write back ALU result]
	dstM		Write back memory result
PC update	PC	PC ← valC	Update PC

- All instructions follow same general pattern
- Differ in what gets computed on each step

Computed Values

Fetch

icode	Instruction code
ifun	Instruction function
rA	Instr. Register A
rB	Instr. Register B
valC	Instruction constant
valP	Incremented PC

Decode

srcA	Register ID A
srcB	Register ID B
dstE	Destination Register E
dstM	Destination Register M
valA	Register value A
valB	Register value B

Execute

- valE ALU result
- Cnd Branch/move flag

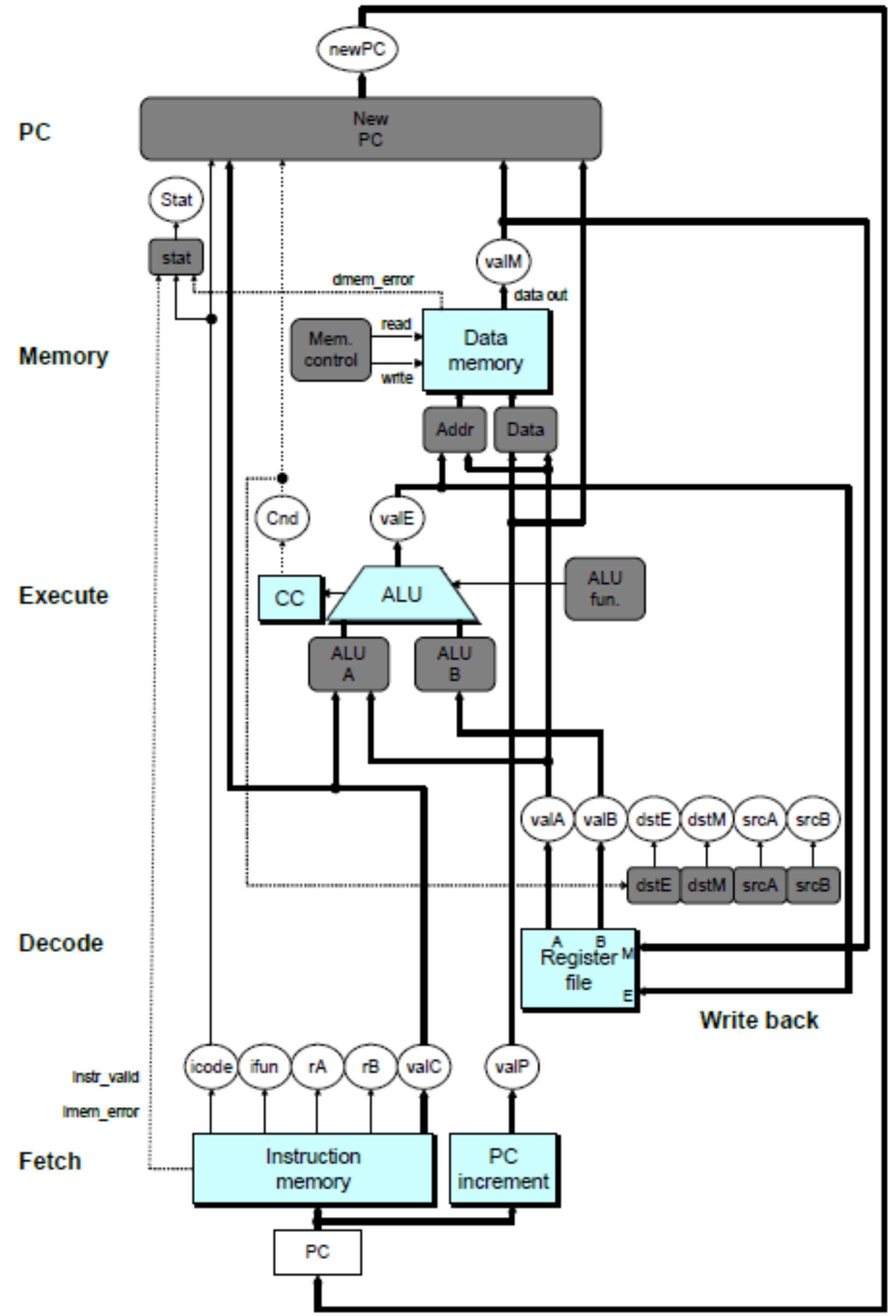
Memory

- valM Value from memory

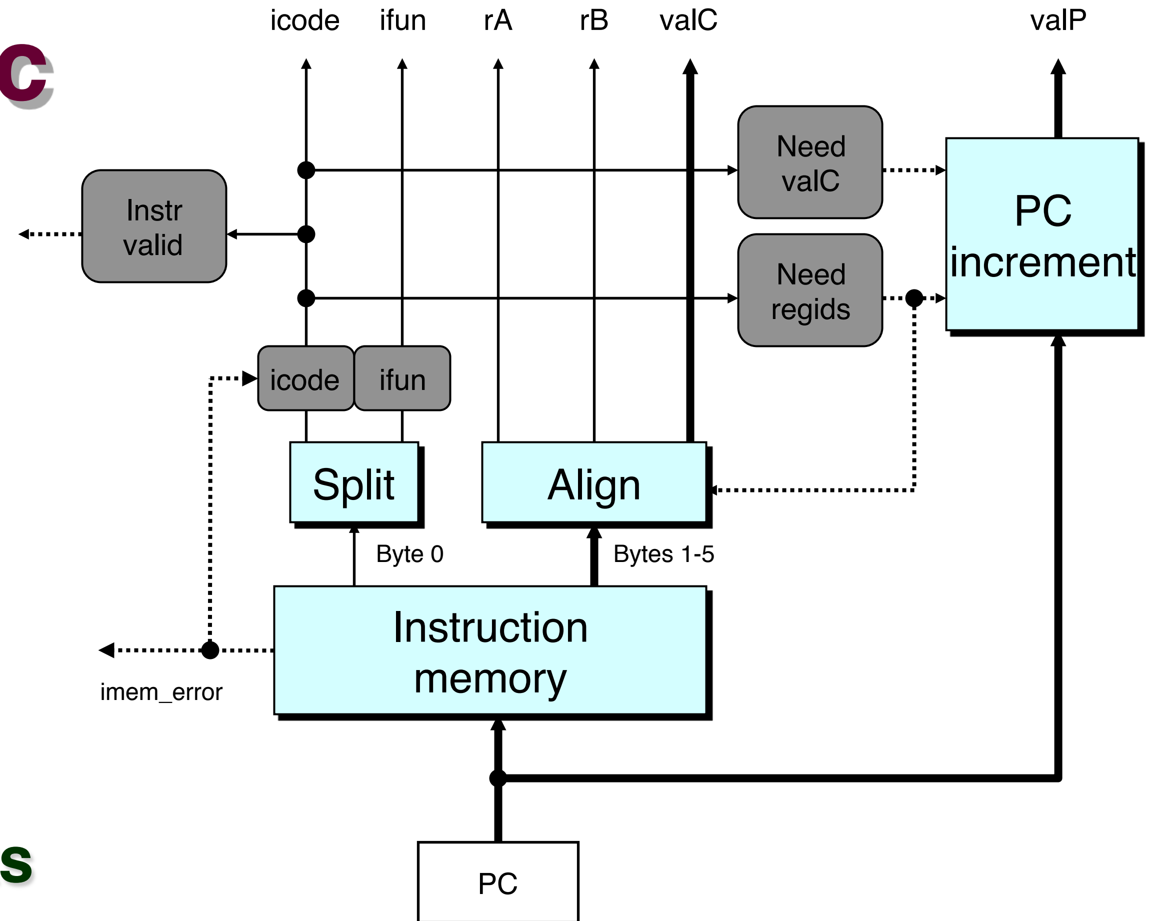
SEQ Hardware

Key

- Blue boxes: predesigned hardware blocks
  - E.g., memories, ALU
- Gray boxes: control logic
  - Describe in HCL
- White ovals: labels for signals
- Thick lines: 32-bit word values
- Thin lines: 4-8 bit values
- Dotted lines: 1-bit values



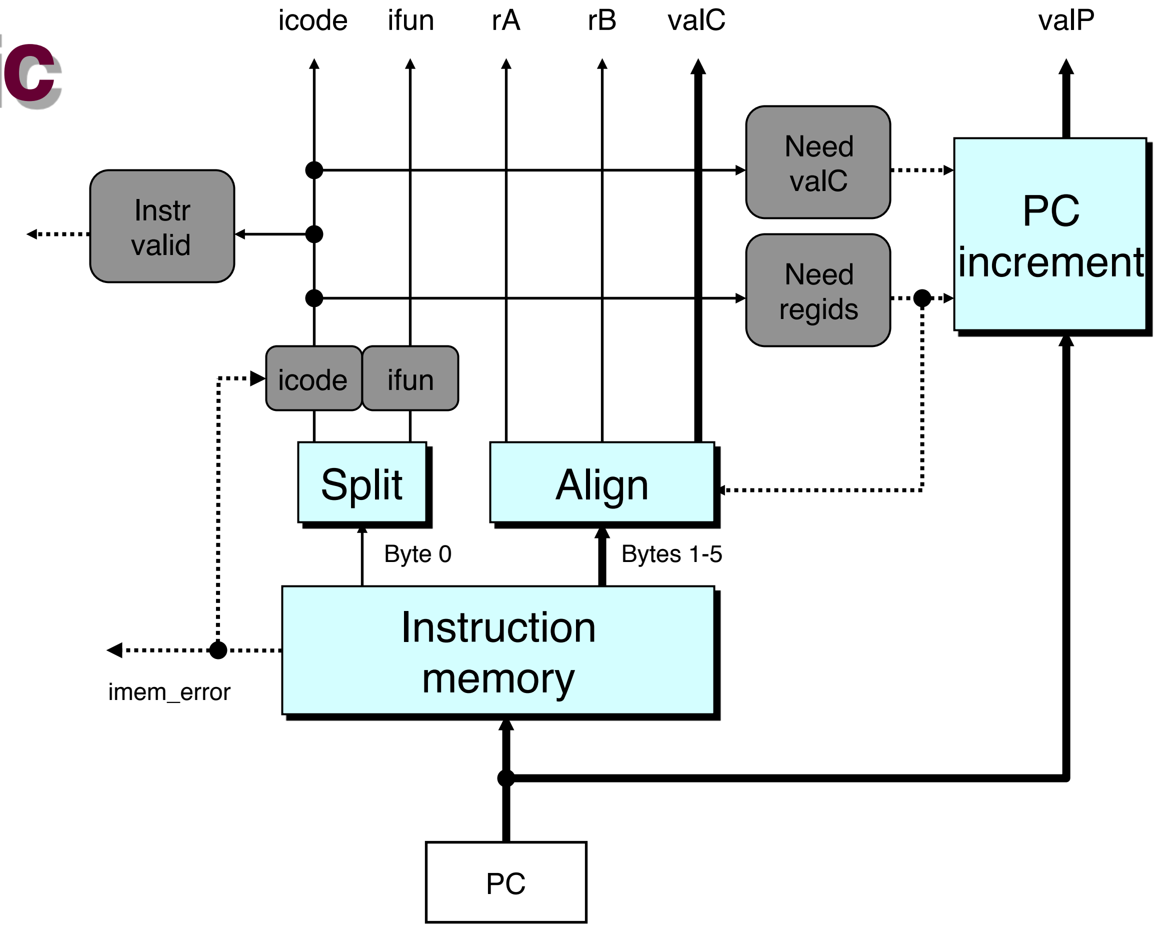
Fetch Logic



Predefined Blocks

- **PC: Register containing PC**
- **Instruction memory: Read 6 bytes (PC to PC+5)**
  - **Signal invalid address**
- **Split: Divide instruction byte into icode and ifun**
- **Align: Get fields for rA, rB, and valC**

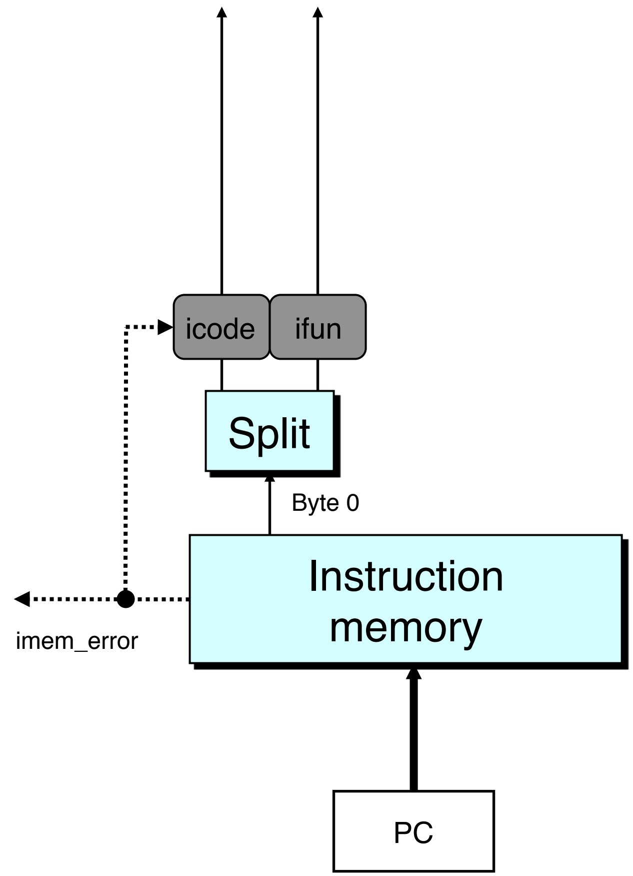
Fetch Logic



Control Logic

- Instr. Valid: Is this instruction valid?
- icode, ifun: Generate no-op if invalid address
- Need regids: Does this instruction have a register byte?
- Need valC: Does this instruction have a constant word?

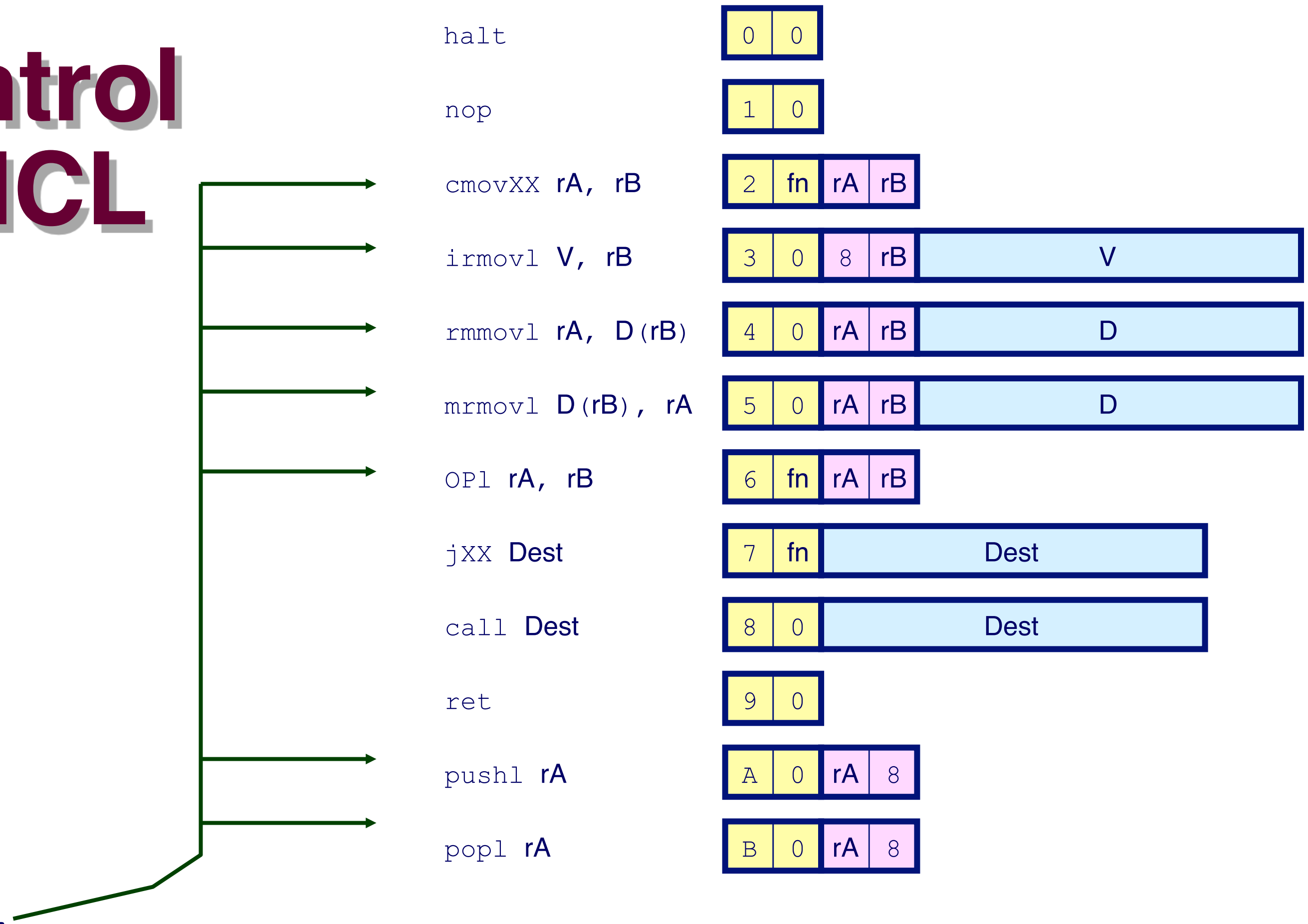
Fetch Control Logic in HCL




```
# Determine instruction code
int icode = [
        imem_error: INOP;
        1: imem_icode;
];

# Determine instruction function
int ifun = [
        imem_error: FNONE;
        1: imem_ifun;
];
```

Fetch Control Logic in HCL




```
bool need_regids =
        icode in { IRRMOVL, IOPL, IPUSHL, IPOPL,
                   IIRMOVL, IRMMOVL, IMRMOVL };

bool instr_valid = icode in
        { INOP, IHALT, IRRMOVL, IIRMOVL, IRMMOVL, IMRMOVL,
              IOPL, IJXX, ICALL, IRET, IPUSHL, IPOPL };
```

Decode Logic

Register File

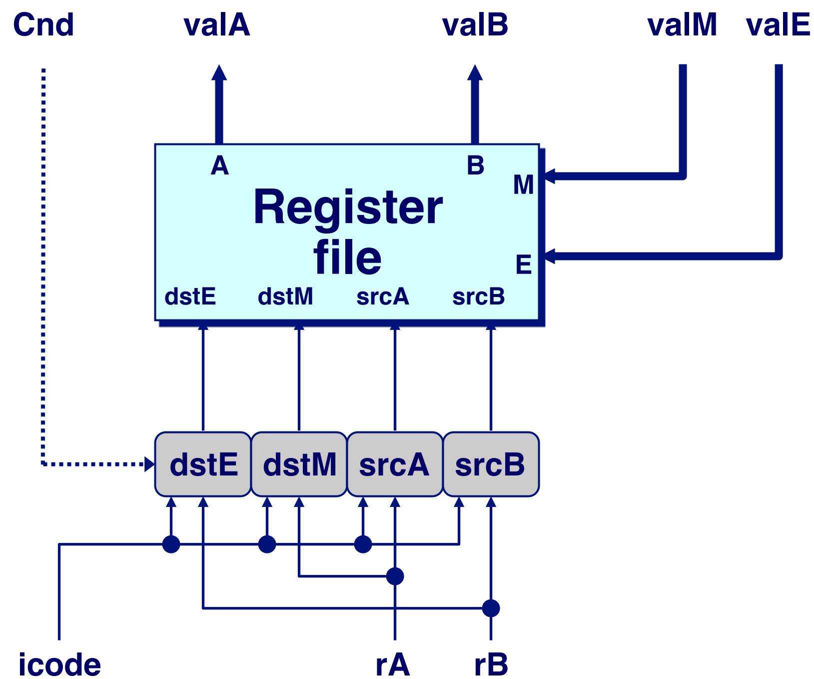
- Read ports A, B
- Write ports E, M
- Addresses are register IDs or 15 (0xF) (no access)

Control Logic

- srcA, srcB: read port addresses
- dstE, dstM: write port addresses

Signals

- Cnd: Indicate whether or not to perform conditional move
  - Computed in Execute stage



A Source

	OPl rA, rB	
Decode	valA ← R[rA]	Read operand A

	cmovXX rA, rB	
Decode	valA ← R[rA]	Read operand A

	`rmmovl` rA, D(rB)	
Decode	valA ← R[rA]	Read operand A

	`popl` rA	
Decode	valA ← R[`%esp`]	Read stack pointer

	jXX Dest	
Decode		No operand

	`call` Dest	
Decode		No operand

	`ret`	
Decode	valA ← R[`%esp`]	Read stack pointer

```
int srcA = [
        icode in { IRRMOVL, IRMMOVL, IOPL, IPUSHL  } : rA;
        icode in { IPOPL, IRET } : RESP;
        1 : RNONE; # Don't need register
];
```

E Destination

	OPl rA, rB	
Write-back	R[rB] ← valE	Write back result

	cmovXX rA, rB	
Write-back	R[rB] ← valE	Conditionally write back result

	`rmmovl` rA, D(rB)	
Write-back		None

	`popl` rA	
Write-back	R[`%esp`] ← valE	Update stack pointer

	jXX Dest	
Write-back		None

	`call` Dest	
Write-back	R[`%esp`] ← valE	Update stack pointer

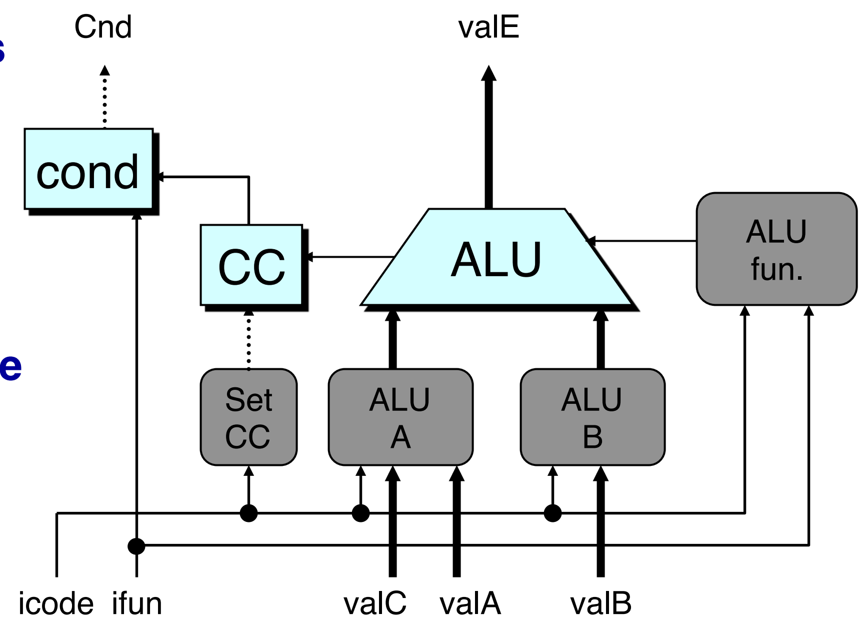
	`ret`	
Write-back	R[`%esp`] ← valE	Update stack pointer

```
int dstE = [
        icode in { IRRMOVL } && Cnd : rB;
        icode in { IIRMOVL, IOPL} : rB;
        icode in { IPUSHL, IPOPL, ICALL, IRET } : RESP;
        1 : RNONE;  # Don't write any register
];
```

Execute Logic

Units

- ALU
  - Implements 4 required functions
  - Generates condition code values
- CC
  - Register with 3 condition code bits
- cond
  - Computes conditional jump/move flag



Control Logic

- Set CC: Should condition code register be loaded?
- ALU A: Input A to ALU
- ALU B: Input B to ALU
- ALU fun: What function should ALU compute?

ALU A Input

Instruction	Stage	Computation	Purpose
OPl rA, rB	Execute	valE ← valB OP valA	Perform ALU operation
cmovXX rA, rB	Execute	valE ← 0 + valA	Pass valA through ALU
`rmmovl` rA, D(rB)	Execute	valE ← valB + valC	Compute effective address
`popl` rA	Execute	valE ← valB + 4	Increment stack pointer
jXX Dest	Execute		No operation
`call` Dest	Execute	valE ← valB + –4	Decrement stack pointer
`ret`	Execute	valE ← valB + 4	Increment stack pointer

```
int aluA = [
        icode in { IRRMOVL, IOPL } : valA;
        icode in { IIRMOVL, IRMMOVL, IMRMOVL } : valC;
        icode in { ICALL, IPUSHL } : -4;
        icode in { IRET, IPOPL } : 4;
        # Other instructions don't need ALU
];
```

ALU Operation

Instruction	Stage	Computation	Description
OPl rA, rB	Execute	valE ← valB OP valA	Perform ALU operation
cmovXX rA, rB	Execute	valE ← 0 + valA	Pass valA through ALU
`rmmovl` rA, D(rB)	Execute	valE ← valB + valC	Compute effective address
`popl` rA	Execute	valE ← valB + 4	Increment stack pointer
jXX Dest	Execute		No operation
`call` Dest	Execute	valE ← valB + –4	Decrement stack pointer
`ret`	Execute	valE ← valB + 4	Increment stack pointer

```
int alufun = [
        icode == IOPL : ifun;
        1 : ALUADD;
];
```

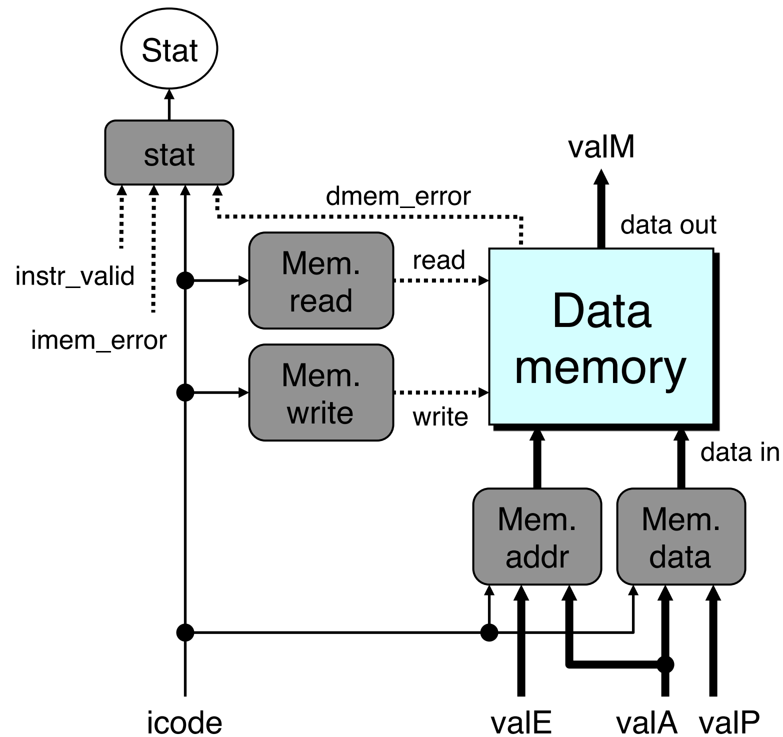
Memory Logic

Memory

- Reads or writes memory word

Control Logic

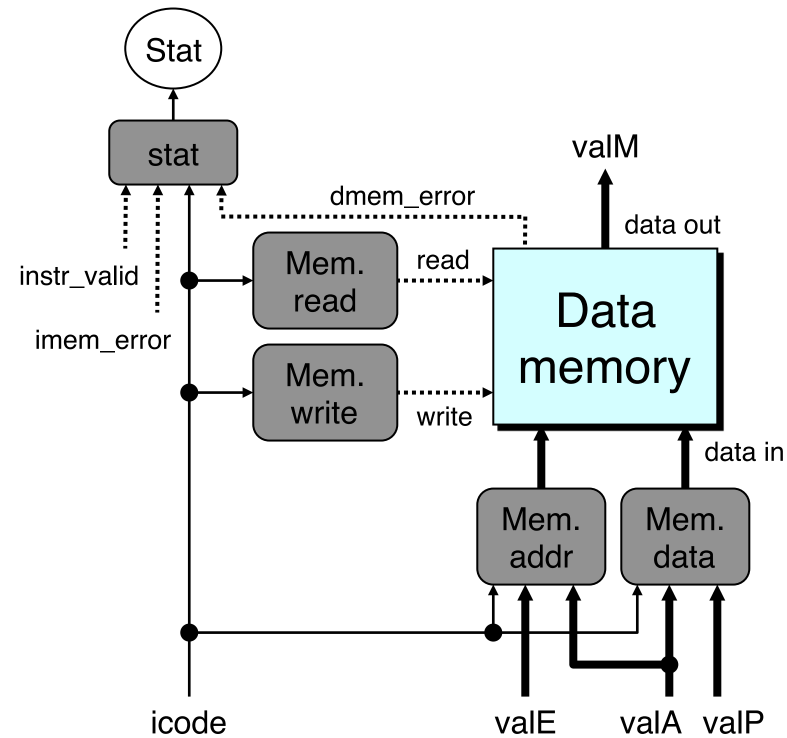
- stat: What is instruction status?
- Mem. read: should word be read?
- Mem. write: should word be written?
- Mem. addr.: Select address
- Mem. data.: Select data



Instruction Status

Control Logic

- **stat: What is instruction status?**




```
## Determine instruction status
int Stat = [
        imem_error || dmem_error : SADR;
        !instr_valid: SINS;
        icode == IHALT : SHLT;
        1 : SAOK;
];
```

Memory Address

OPl rA, rB	Memory		No operation
`rmmovl` rA, D(rB)	Memory	$M_4[valE] \leftarrow valA$	Write value to memory
`popl` rA	Memory	$valM \leftarrow M_4[valA]$	Read from stack
jXX Dest	Memory		No operation
`call` Dest	Memory	$M_4[valE] \leftarrow valP$	Write return value on stack
`ret`	Memory	$valM \leftarrow M_4[valA]$	Read return address

```
int mem_addr = [
        icode in { IRMMOVL, IPUSHL, ICALL, IMRMOVL } : valE;
        icode in { IPOPL, IRET } : valA;
        # Other instructions don't need address
];
```

Memory Read

	OPl rA, rB	
Memory		No operation

	`rmmovl` rA, D(rB)	
Memory	M_4[valE] ← valA	Write value to memory

	`popl` rA	
Memory	valM ← M_4[valA]	Read from stack

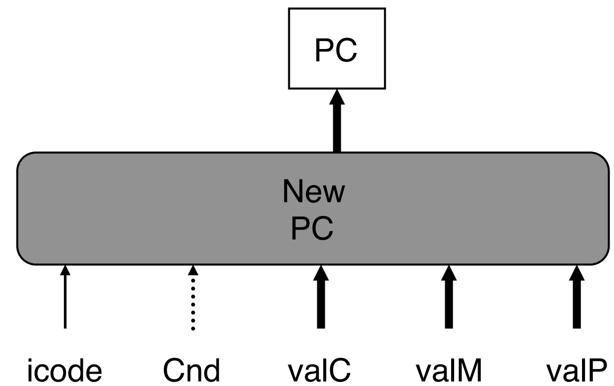
	jXX Dest	
Memory		No operation

	`call` Dest	
Memory	M_4[valE] ← valP	Write return value on stack

	`ret`	
Memory	valM ← M_4[valA]	Read return address

```
bool mem_read = icode in { IMRMOVL, IPOPL, IRET };
```

PC Update Logic



New PC

- Select next value of PC

PC Update

	OPl rA, rB	
PC update	PC ← valP	Update PC

	`rmmovl` rA, D(rB)	
PC update	PC ← valP	Update PC

	`popl` rA	
PC update	PC ← valP	Update PC

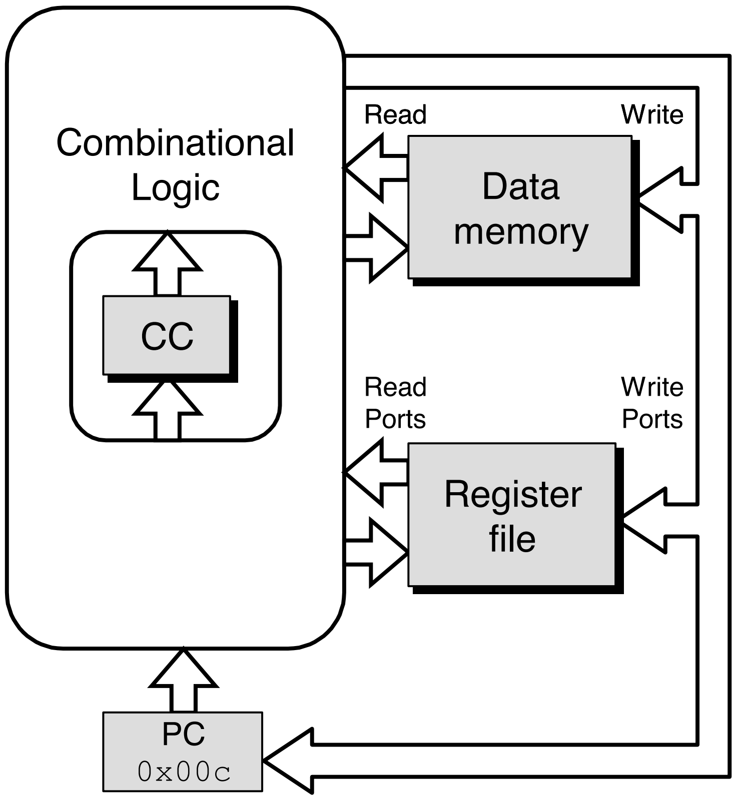
	jXX Dest	
PC update	PC ← Cnd ? valC : valP	Update PC

	`call` Dest	
PC update	PC ← valC	Set PC to destination

	`ret`	
PC update	PC ← valM	Set PC to return address

```
int new_pc = [
        icode == ICALL : valC;
        icode == IJXX && Cnd : valC;
        icode == IRET : valM;
        1 : valP;
];
```

SEQ Operation



State

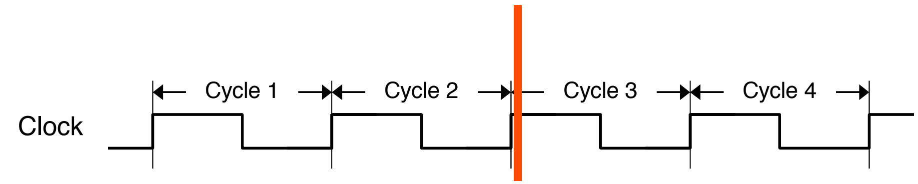
- PC register
- Cond. Code register
- Data memory
- Register file

All updated as clock rises

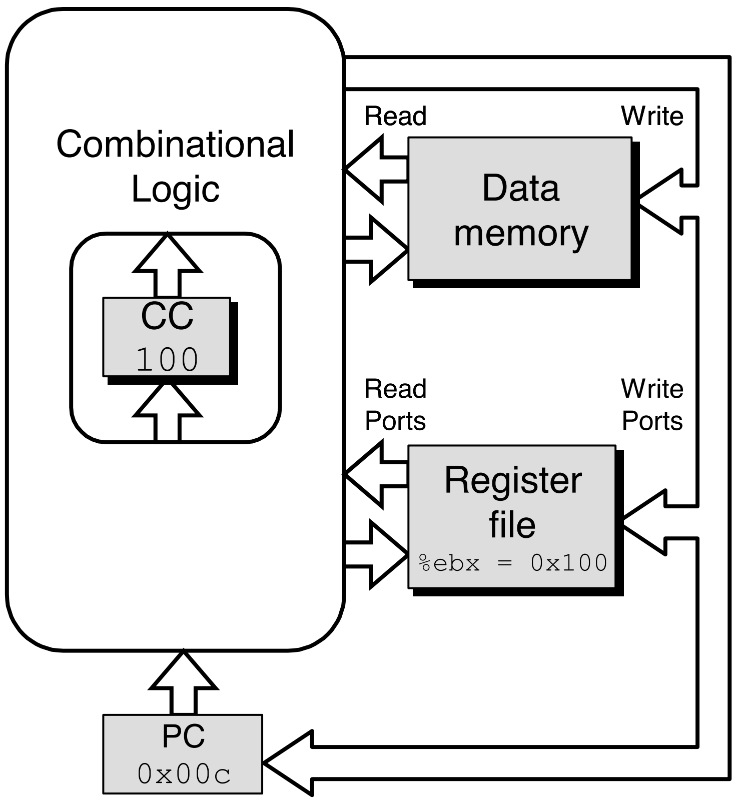
Combinational Logic

- ALU
- Control logic
- Memory reads
  - Instruction memory
  - Register file
  - Data memory

SEQ Operation #2

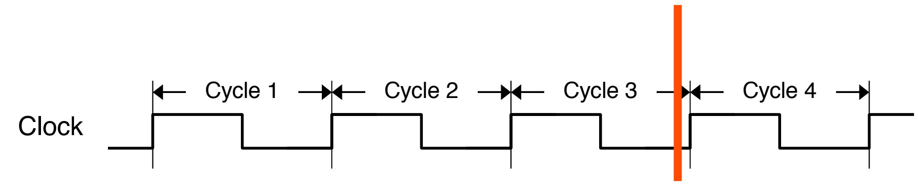


Cycle 1:	`0x000: irmovl $0x100,%ebx # %ebx <-- 0x100`
Cycle 2:	`0x006: irmovl $0x200,%edx # %edx <-- 0x200`
Cycle 3:	`0x00c: addl %edx,%ebx # %ebx <-- 0x300 CC <-- 000`
Cycle 4:	`0x00e: je dest # Not taken`

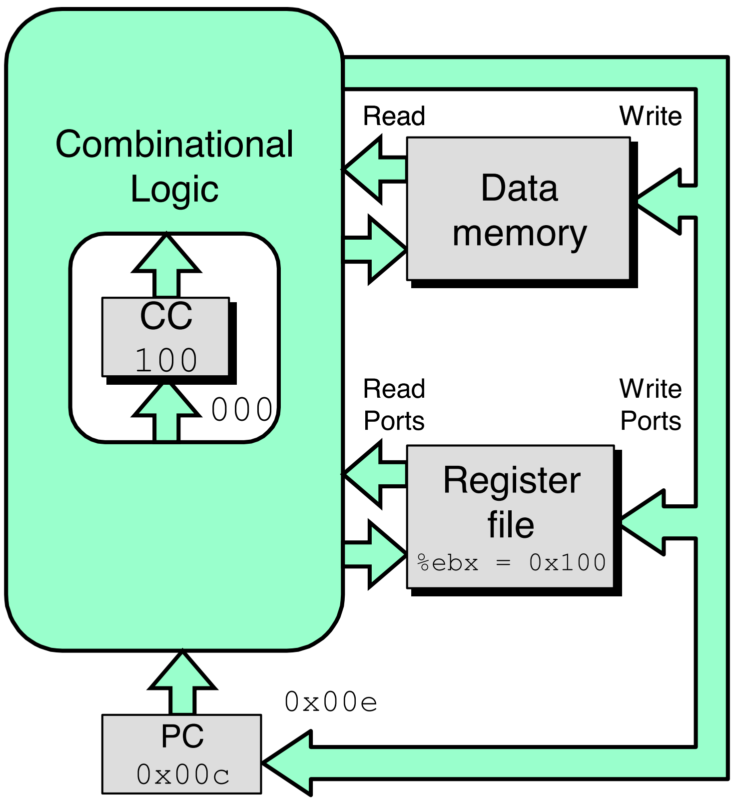


- state set according to second `irmovl` instruction
- combinational logic starting to react to state changes

SEQ Operation #3

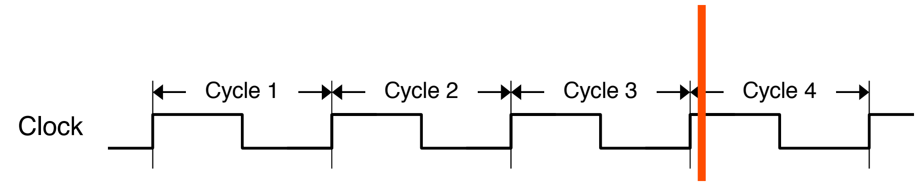


Cycle 1:	`0x000:`	`irmovl $0x100,%ebx`	`# %ebx <-- 0x100`
Cycle 2:	`0x006:`	`irmovl $0x200,%edx`	`# %edx <-- 0x200`
Cycle 3:	`0x00c:`	`addl %edx,%ebx`	`# %ebx <-- 0x300 CC <-- 000`
Cycle 4:	`0x00e:`	`je dest`	`# Not taken`

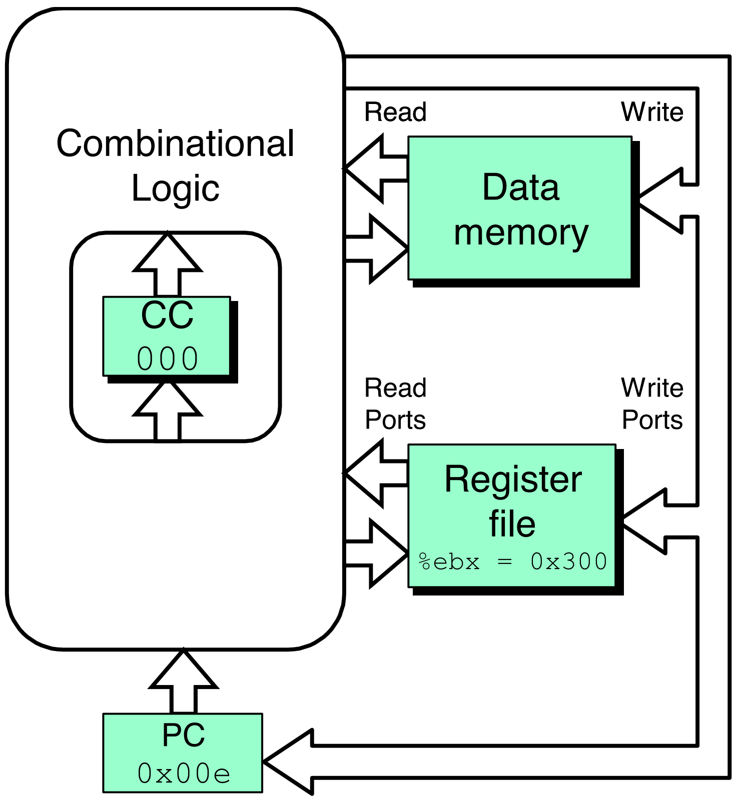


- **state set according to second `irmovl` instruction**
- **combinational logic generates results for `addl` instruction**

SEQ Operation #4

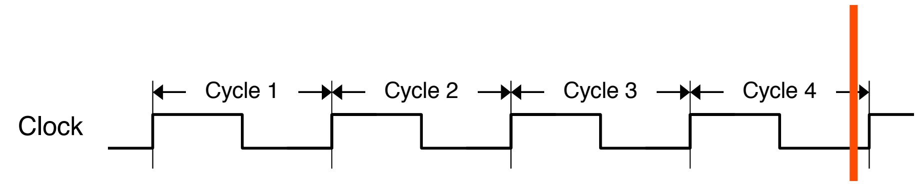


Cycle 1:	`0x000:   irmovl $0x100,%ebx   # %ebx <-- 0x100`
Cycle 2:	`0x006:   irmovl $0x200,%edx   # %edx <-- 0x200`
Cycle 3:	`0x00c:   addl %edx,%ebx       # %ebx <-- 0x300 CC <-- 000`
Cycle 4:	`0x00e:   je dest              # Not taken`

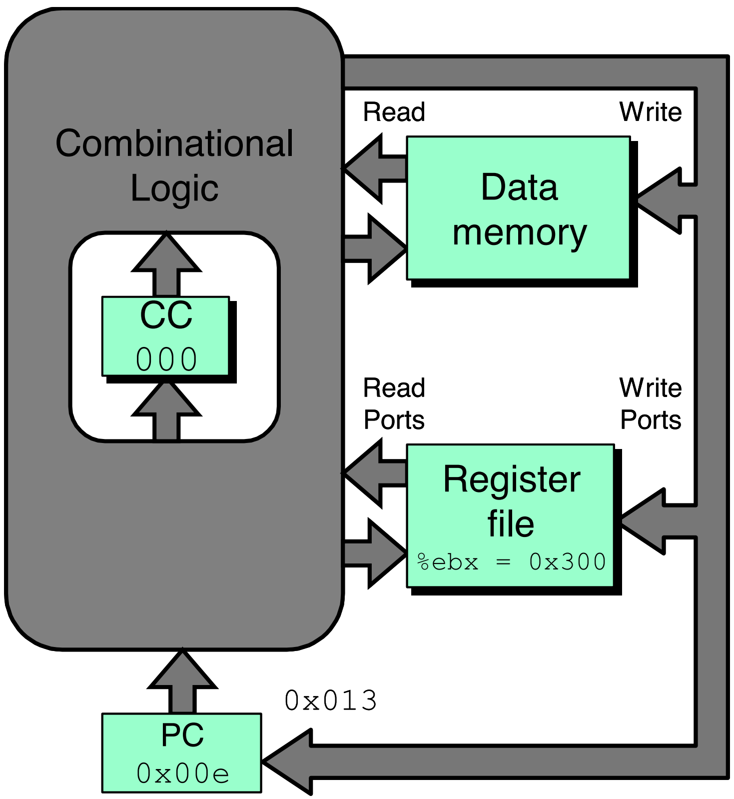


- **state set according to `addl` instruction**
- **combinational logic starting to react to state changes**

SEQ Operation #5



Cycle 1:	0x000:	irmovl $0x100,%ebx	# %ebx <-- 0x100
Cycle 2:	0x006:	irmovl $0x200,%edx	# %edx <-- 0x200
Cycle 3:	0x00c:	addl %edx,%ebx	# %ebx <-- 0x300 CC <-- 000
Cycle 4:	0x00e:	je dest	# Not taken



- **state set according to `addl` instruction**
- **combinational logic generates results for `je` instruction**

SEQ Summary

Implementation

- Express every instruction as series of simple steps
- Follow same general flow for each instruction type
- Assemble registers, memories, predesigned combinational blocks
- Connect with control logic

Limitations

- Too slow to be practical
- In one cycle, must propagate through instruction memory, register file, ALU, and data memory
- Would need to run clock very slowly
- Hardware units only active for fraction of clock cycle