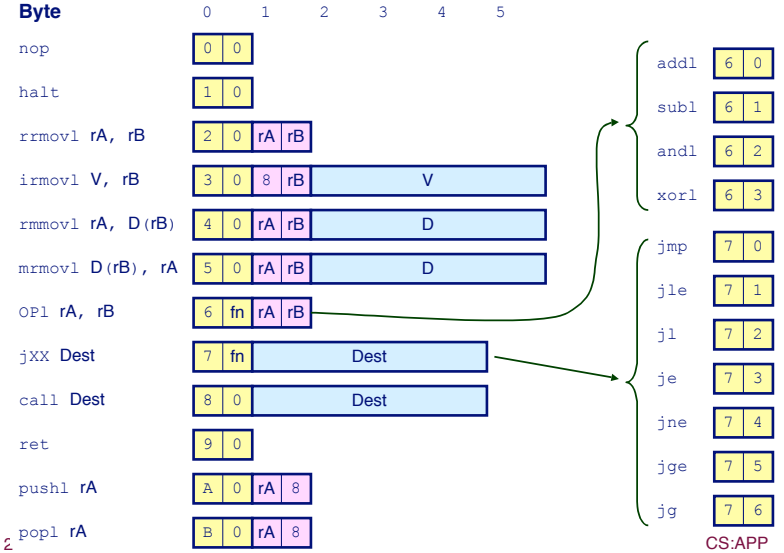
CS:APP Chapter 4
Computer Architecture
Sequential Implementation

Randal E. Bryant

Carnegie Mellon University

`http://csapp.cs.cmu.edu`

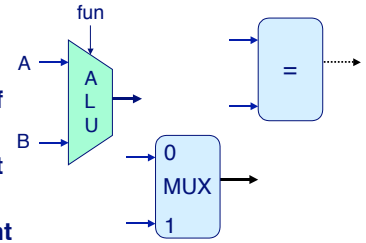
Y86 Instruction Set



Building Blocks

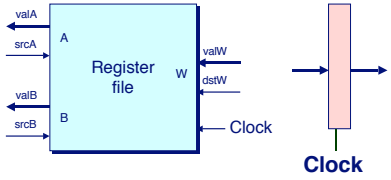
Combinational Logic

- 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

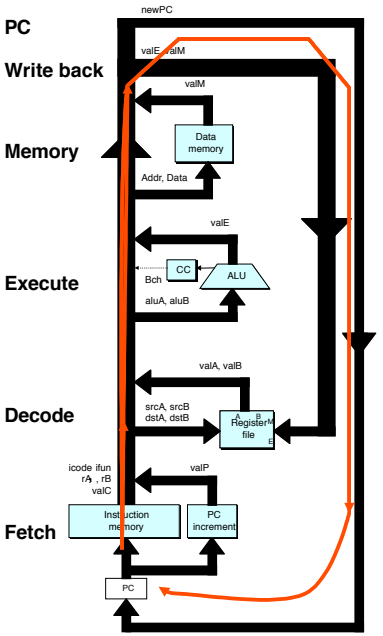
SEQ Hardware Structure

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

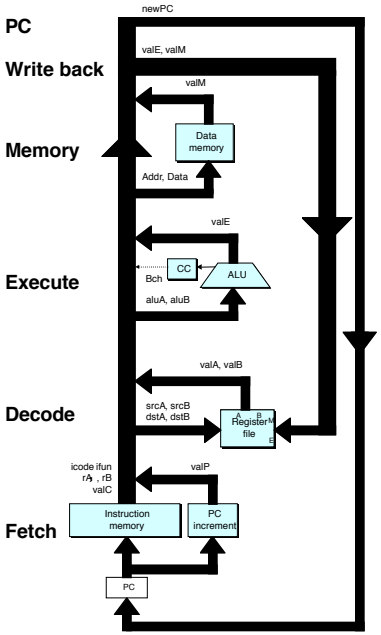
- Read or write data

Write Back

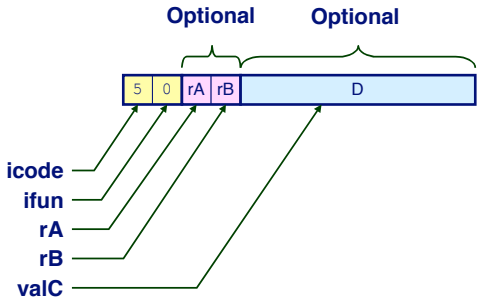
- Write program registers

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

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] rA:rB ← M_1[PC+1] valP ← PC+2	Read instruction byte Read register byte Compute next PC
Decode	valA ← R[rA] valB ← R[rB]	Read operand A Read operand B
Execute	valE ← valB OP valA Set CC	Perform ALU operation 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`

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] rA:rB ← M_1[PC+1] valC ← M_4[PC+2] valP ← PC+6	Read instruction byte Read register byte Read displacement D Compute next PC
Decode	valA ← R[rA] valB ← R[rB]	Read operand A 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`

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

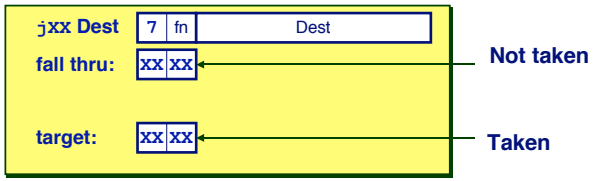
PC Update
- Increment PC by 2

Stage Computation: `popl`

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

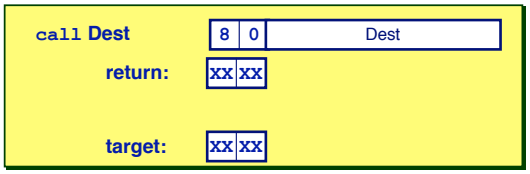
PC Update
- Set PC to Dest if branch taken or to incremented PC if not branch

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	Bch ← Cond(CC,ifun)	Take branch?
Memory		
Write back		
PC update	PC ← Bch ? 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

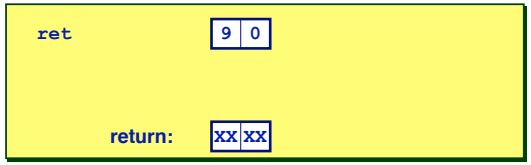
PC Update
- Set PC to Dest

Stage Computation: `call`

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

- Use ALU to decrement stack pointer
- Store incremented PC

Executing `ret`



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`

	`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
- Bch Branch flag

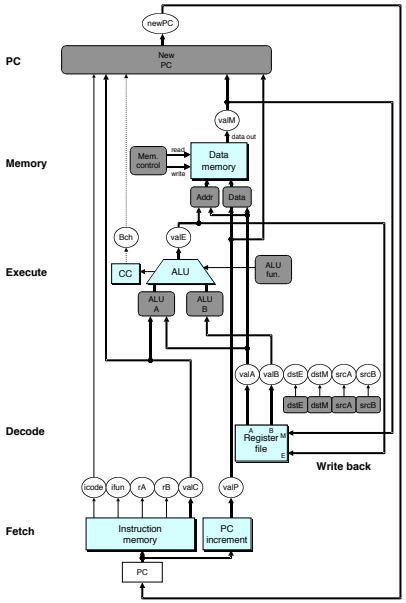
Memory

- valM Value from memory

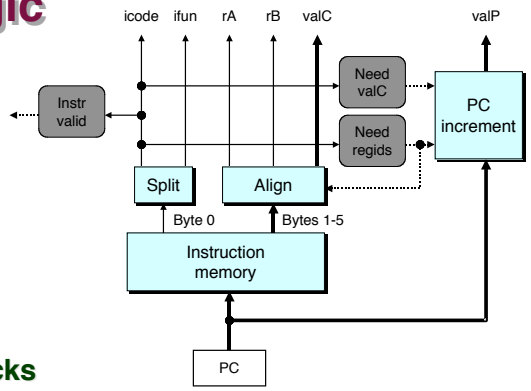
SEQ Hardware

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



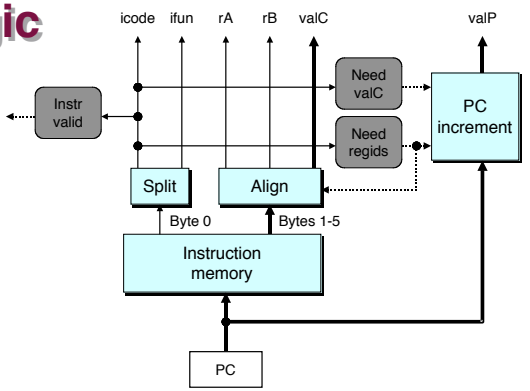
Fetch Logic



Predefined Blocks

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

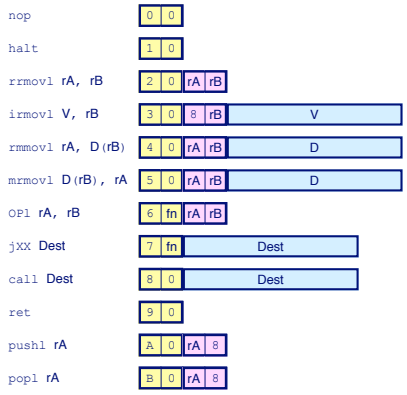
Fetch Logic



Control Logic

- Instr. Valid: Is this instruction valid?
- Need regids: Does this instruction have a register bytes?
- Need valC: Does this instruction have a constant word?

Fetch Control Logic



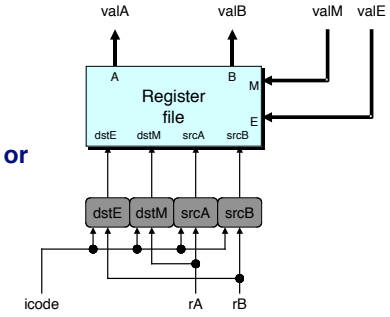

```
bool need_regids =
    icode in { IRRMOVL, IOPL, IPUSHL, IPOPL,
               IIRMOVL, IRMMOVL, IMRMOVL };

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 8 (no access)



Control Logic

- srcA, srcB: read port addresses
- dstA, dstB: write port addresses

A Source

	OPl rA, rB	
Decode	valA ← R[rA]	Read operand A
	`rmmovl` rA, D(rB)	
Decode	valA ← R[`%esp`]	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
	`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, IIRMOVL, IOPL} : rB;
        icode in { IPUSHL, IPOPL, ICALL, IRET } : RESP;
        1 : RNONE;  # Don't need register
];
```

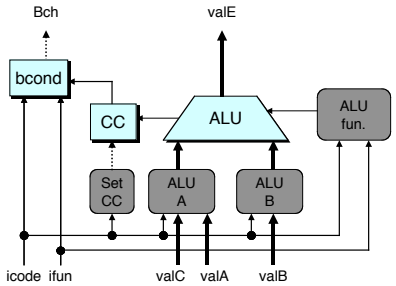

Execute Logic

Units

- ALU
  - Implements 4 required functions
  - Generates condition code values
- CC
  - Register with 3 condition code bits
- bcond
  - Computes branch 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

	OPl rA, rB	
Execute	valE ← valB OP valA	Perform ALU operation
	`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

	OPl rA, rB
Execute	valE ← valB OP valA

Perform ALU operation

	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;
];
```

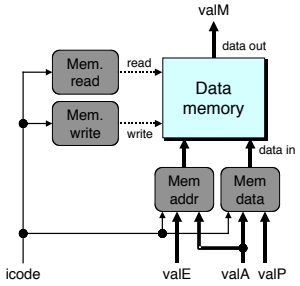

Memory Logic

Memory

- Reads or writes memory word

Control Logic

- Mem. read: should word be read?
- Mem. write: should word be written?
- Mem. addr.: Select address
- Mem. data.: Select data



Memory Address

	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

```
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]

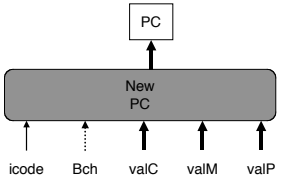
Read return address

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

PC Update Logic

New PC

- Select next value of PC

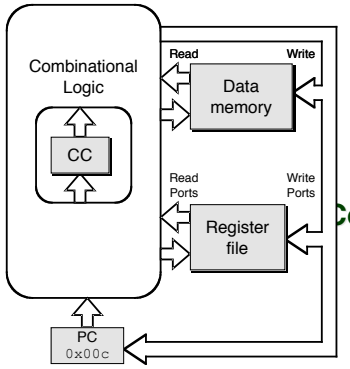


PC Update

	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 ← Bch ? 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 && Bch : valC;
        icode == IRET : valM;
        1 : valP;
];
```


SEQ Operation



State

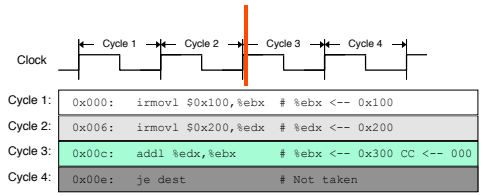
- PC register
- Cond. Code register
- Data memory
- Register file

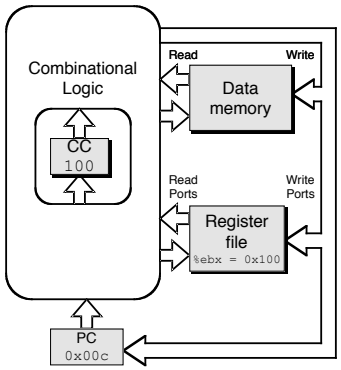
All updated as clock rises

Combinational Logic

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

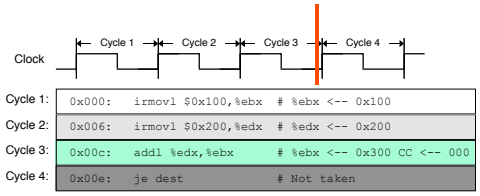
SEQ Operation #2

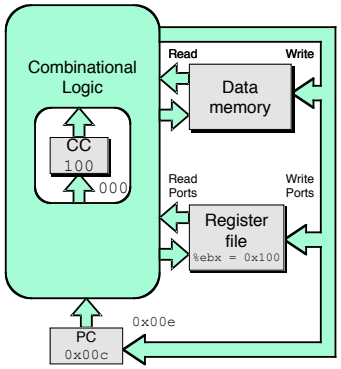




- state set according to second `irmovl` instruction
- combinational logic starting to react to state changes

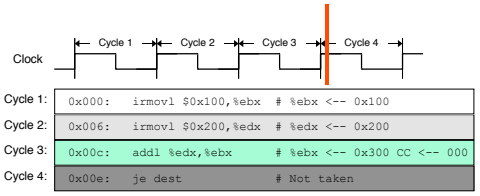
SEQ Operation #3

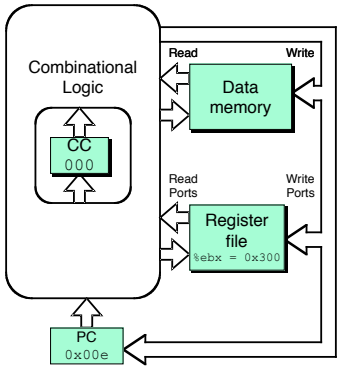




- state set according to second `irmovl` instruction
- combinational logic generates results for `addl` instruction

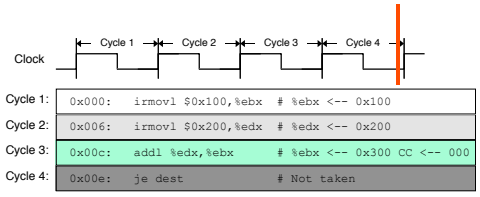
SEQ Operation #4

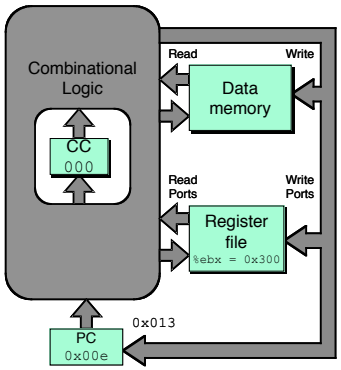




- state set according to `addl` instruction
- combinational logic starting to react to state changes

SEQ Operation #5





- 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