

CS:APP Chapter 4 Computer Architecture Sequential Implementation

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<http://csapp.cs.cmu.edu>

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Y86 Instruction Set

Byte	0	1	2	3	4	5
nop	0	0				
halt	1	0				
rrmovl rA, rB	2	0	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		

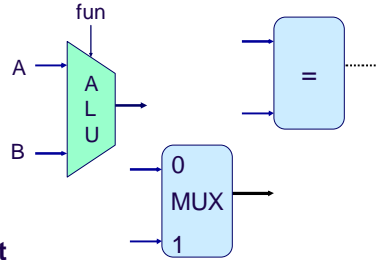
addl	6	0
subl	6	1
andl	6	2
xorl	6	3
jmp	7	0
jle	7	1
jl	7	2
je	7	3
jne	7	4
jge	7	5
jg	7	6

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Building Blocks

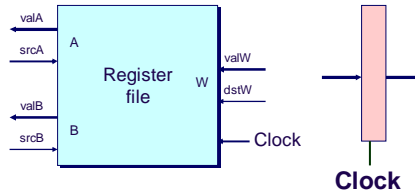
Combinational Logic

- 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



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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 ;`

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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
 - $A \ \text{in} \ \{ B, C, D \}$
 - » Same as $A == B \ || \ A == C \ || \ A == D$

Word Expressions

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

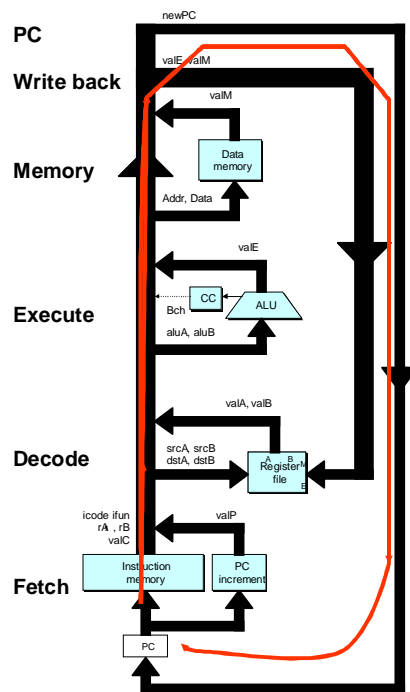
SEQ Hardware Structure

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

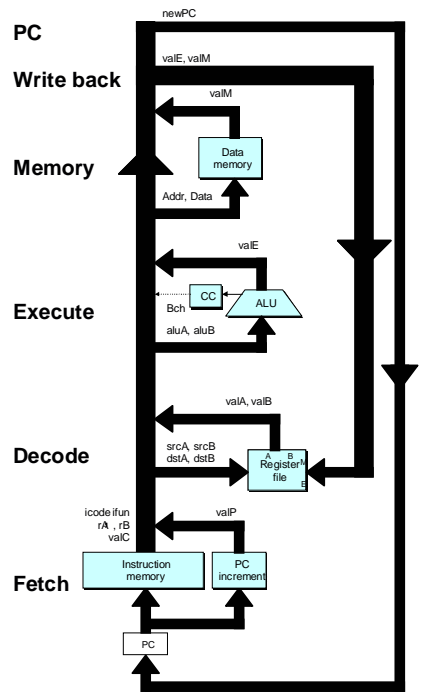
- Read or write data

Write Back

- Write program registers

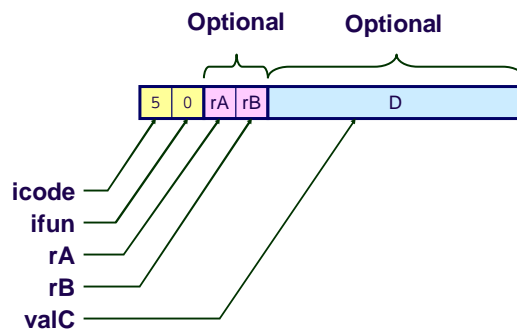
PC

- Update program counter



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Instruction Decoding



Instruction Format

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

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Executing Arith./Logical Operation

OPI 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

	OPI rA, rB	
Fetch	$icode:ifun \leftarrow M_1[PC]$ $rA:rB \leftarrow M_1[PC+1]$ $valP \leftarrow PC+2$	Read instruction byte Read register byte Compute next PC
Decode	$valA \leftarrow R[rA]$ $valB \leftarrow R[rB]$	Read operand A Read operand B
Execute	$valE \leftarrow valB \text{ OP } valA$ Set CC	Perform ALU operation Set condition code register
Memory		
Write back	$R[rB] \leftarrow valE$	Write back result
PC update	$PC \leftarrow valP$	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`

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

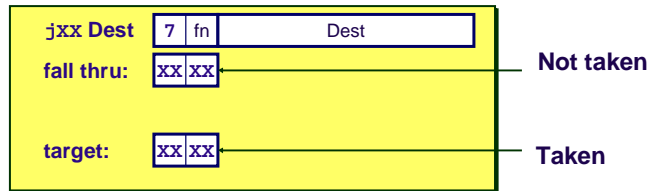
- Increment PC by 2

Stage Computation: `popl`

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

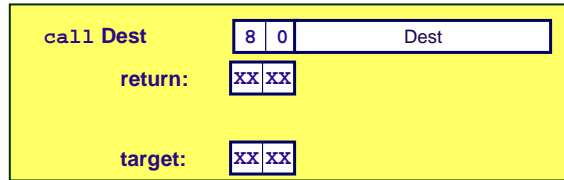
- Set PC to Dest if branch taken or to incremented PC if not branch

Stage Computation: Jumps

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

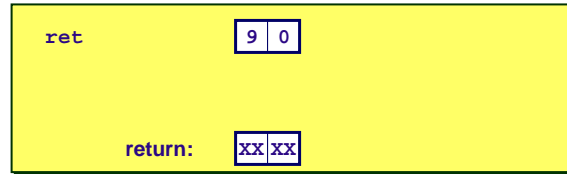
- Set PC to Dest

Stage Computation: call

	call Dest	
Fetch	$icode:ifun \leftarrow M_1[PC]$ $valC \leftarrow M_4[PC+1]$ $valP \leftarrow PC+5$	Read instruction byte Read destination address 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`



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

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

Computation Steps

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

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

Computation Steps

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

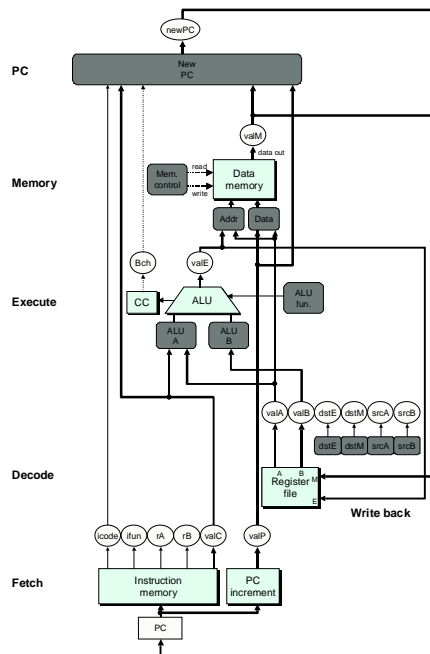
Memory

valM Value from memory

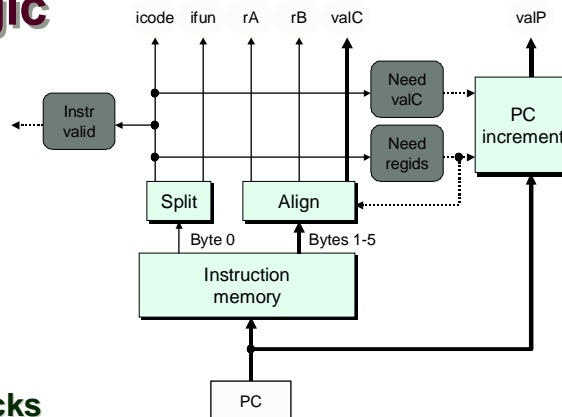
SEQ Hardware

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



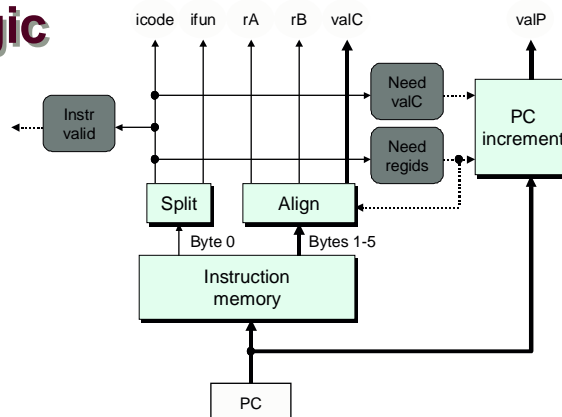
Fetch Logic



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

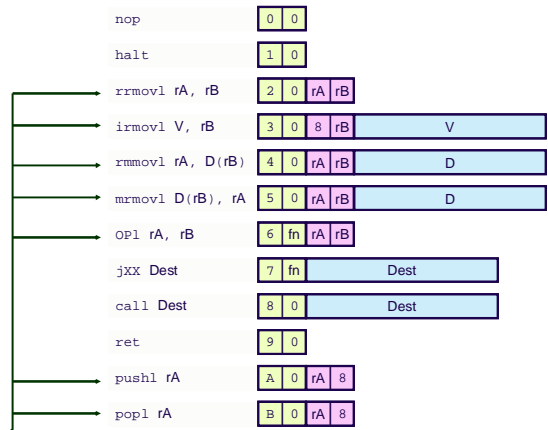
Fetch Logic



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 };
```

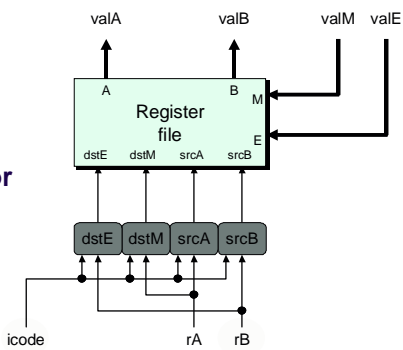
Decode Logic

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[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
];
```

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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, IRMMOVL, IOPL } : rB;
    icode in { IPUSHL, IPOPL, ICALL, IRET } : RESP;
    1 : RNONE; # Don't need register
];
```

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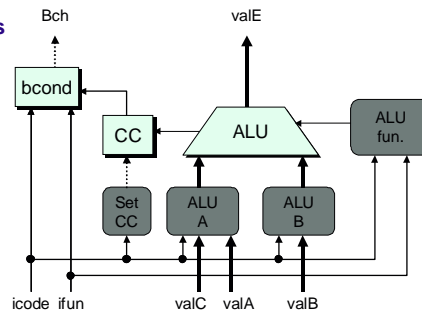
Execute Logic

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?



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ALU A Input

Execute	OPl rA, rB $valE \leftarrow valB \text{ OP } valA$	Perform ALU operation
Execute	rmmovl rA, D(rB) $valE \leftarrow valB + valC$	Compute effective address
Execute	popl rA $valE \leftarrow valB + 4$	Increment stack pointer
Execute	jXX Dest	No operation
Execute	call Dest $valE \leftarrow valB + -4$	Decrement stack pointer
Execute	ret $valE \leftarrow valB + 4$	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
];
```

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ALU Operation

	OPl rA, rB	
Execute	$valE \leftarrow valB \text{ OP } valA$	Perform ALU operation
	rmmovl rA, D(rB)	
Execute	$valE \leftarrow valB + valC$	Compute effective address
	popl rA	
Execute	$valE \leftarrow valB + 4$	Increment stack pointer
	jXX Dest	
Execute		No operation
	call Dest	
Execute	$valE \leftarrow valB + -4$	Decrement stack pointer
	ret	
Execute	$valE \leftarrow valB + 4$	Increment stack pointer

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

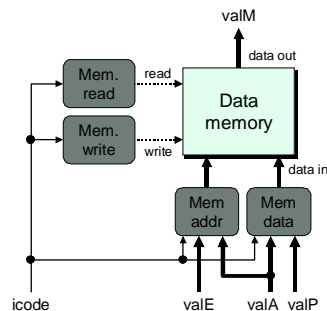
Memory Logic

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	$M_4[\text{valE}] \leftarrow \text{valA}$	Write value to memory
	popl rA	
Memory	$\text{valM} \leftarrow M_4[\text{valA}]$	Read from stack
	jXX Dest	
Memory		No operation
	call Dest	
Memory	$M_4[\text{valE}] \leftarrow \text{valP}$	Write return value on stack
	ret	
Memory	$\text{valM} \leftarrow M_4[\text{valA}]$	Read return address

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

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Memory Read

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

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

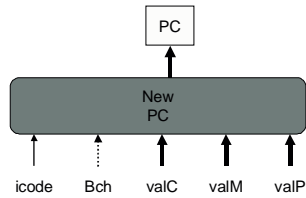
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PC Update Logic

New PC

- Select next value of PC

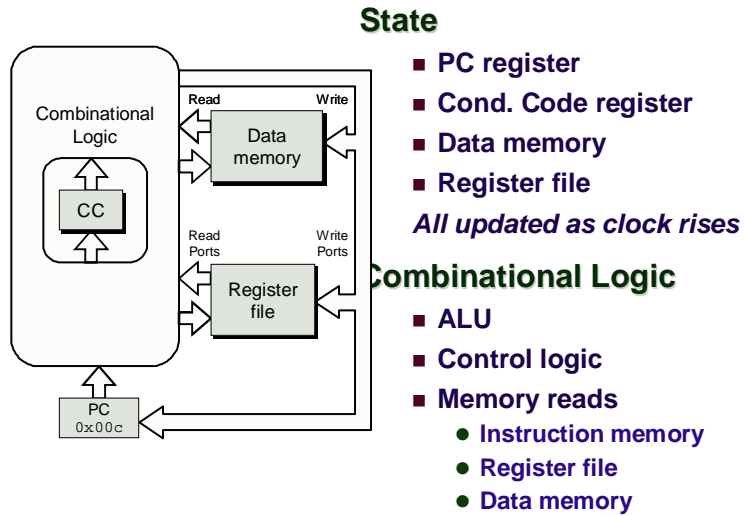


PC Update

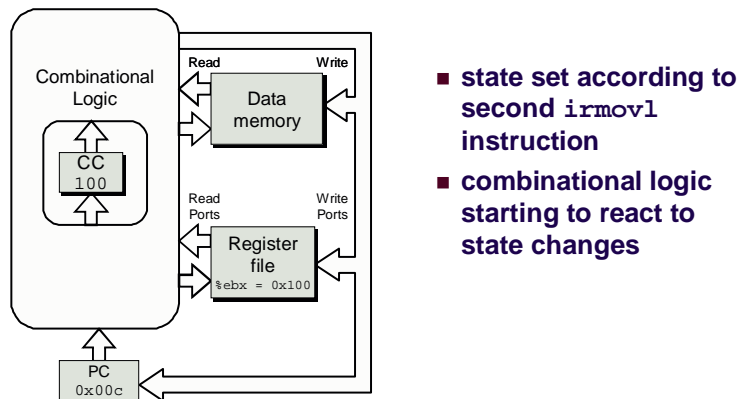
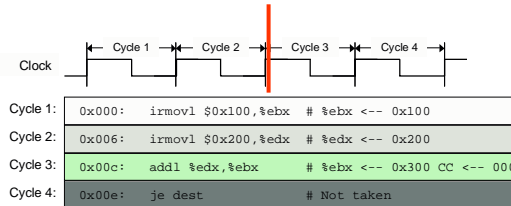
	OPl rA, rB	
PC update	PC ← valP	Update PC
	rmmovl rA, D(rB)	
PC update	PC ← valP	Update PC
	popl rA	
PC update	PC ← valP	Update PC
	jXX Dest	
PC update	PC ← Bch ? valC : valP	Update PC
	call Dest	
PC update	PC ← valC	Set PC to destination
	ret	
PC update	PC ← valM	Set PC to return address

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

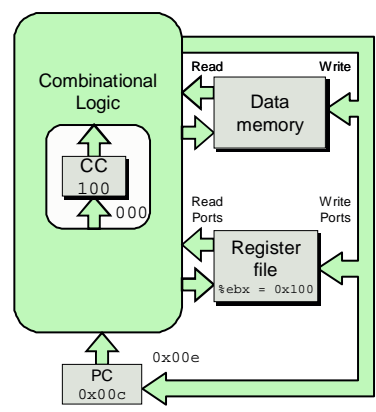
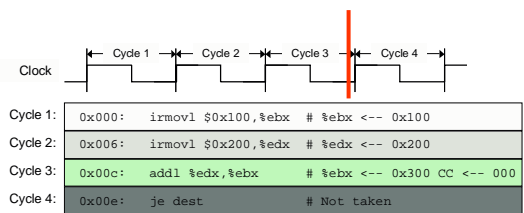
SEQ Operation



SEQ Operation #2

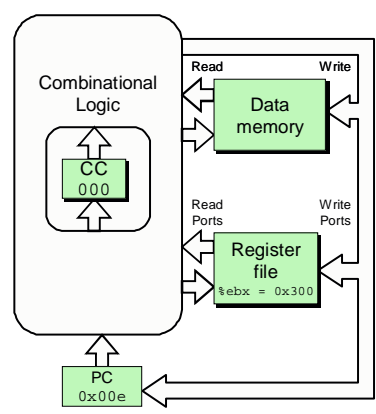
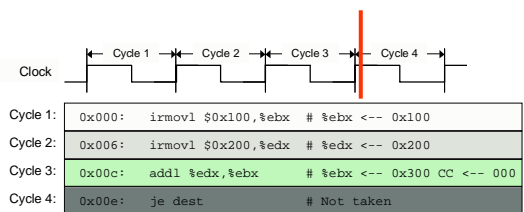


SEQ Operation #3



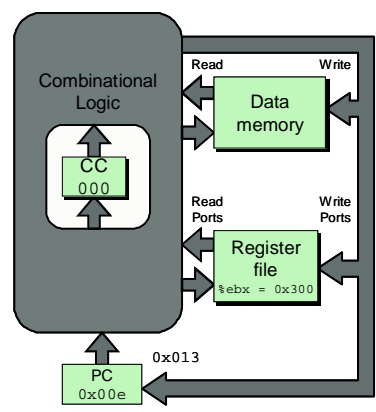
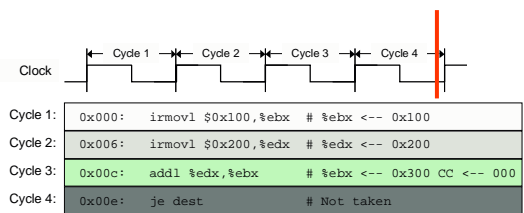
- state set according to second `irmovl` instruction
- combinational logic generates results for `addl` instruction

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