JDEP 284H
Foundations of Computer Systems

Processor Architecture III: Sequential Implementation

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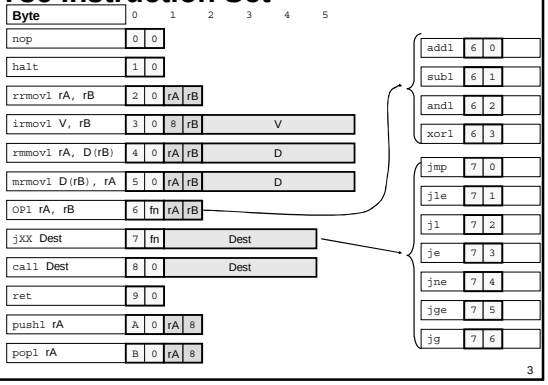
Giving credit where credit is due

- Most of slides for this lecture are based on slides created by Dr. Bryant, Carnegie Mellon University.
- I have modified them and added new slides.

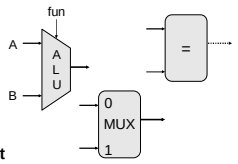
Y86 Instruction Set



Building Blocks

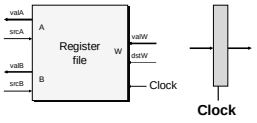
Combinational Logic

- 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

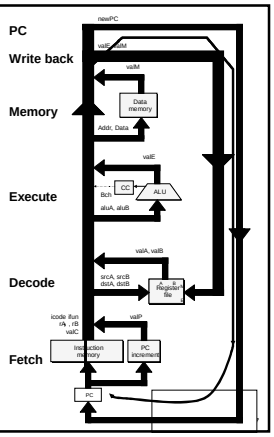
SEQ Hardware Structure

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

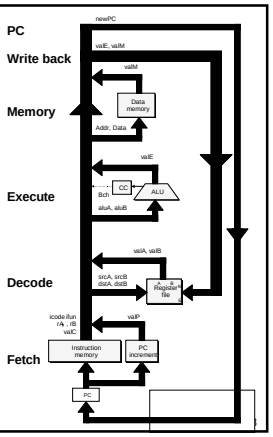
Decode
- Read program registers

Execute
- Compute value or address

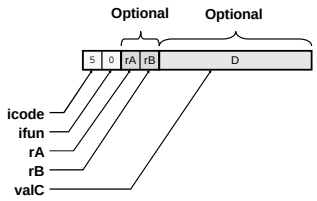
Memory
- Read or write data

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

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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

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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

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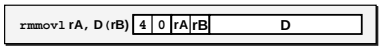
Executing `rmmovl`



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

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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`

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

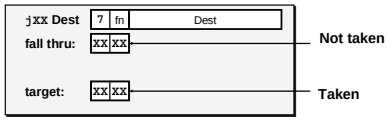
PC Update
- Increment PC by 2

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

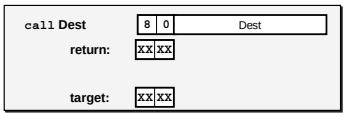
PC Update
- Set PC to Dest if branch taken or to incremented PC if not branch

Stage Computation: Jumps

	jXX Dest	
Fetch	icode:ifun ← M_1[PC]	Read instruction byte
	valC ← M_4[PC+1]	Read destination address
	valP ← PC+5	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

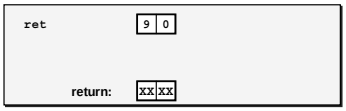
PC Update
- Set PC to Dest

Stage Computation: `call`

	`call` Dest	
Fetch	icode:ifun ← M_1[PC]	Read instruction byte
	valC ← M_4[PC+1]	Read destination address
	valP ← PC+5	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`]	Read operand stack pointer
	valB ← R[`%esp`]	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

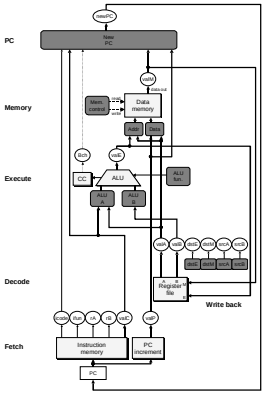
Execute
- valE ALU result
- Bch Branch flag

Memory
- valM Value from memory

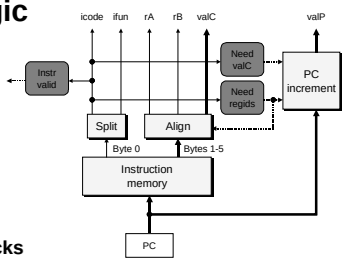
SEQ Hardware

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**



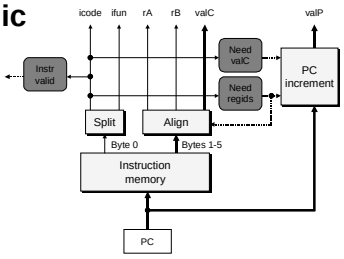
Fetch Logic



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**

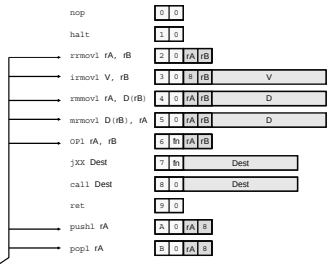
Fetch Logic



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



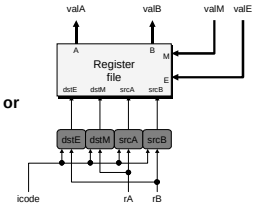

```
bool need_regids =
      icode in { IRRMOVL, IOPL, IPUSHL, IPOPL,
                 IIRMOVL, IRMMOVL, IMRMOVL };

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[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

	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
];
```

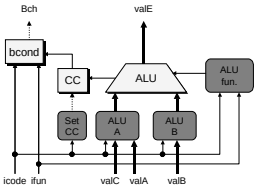

Execute Logic

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;
];
```

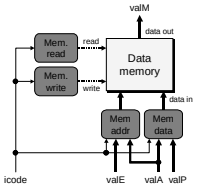

Memory Logic

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]

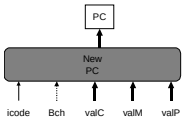
Read return address

```
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

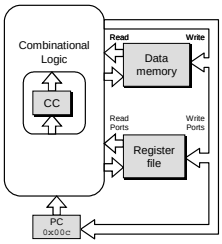
Set PC to destination

	`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

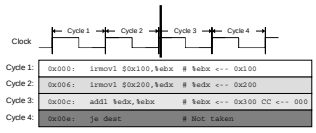
- PC register
- Cond. Code register
- Data memory
- Register file

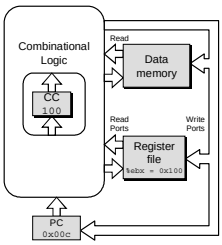
All updated as clock rises

Combinational Logic

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

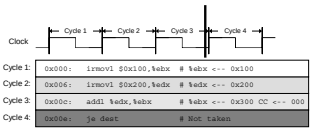
SEQ Operation #2

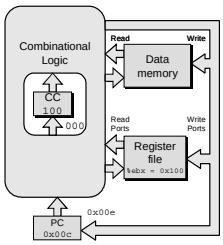




- state set according to second `irmovl` instruction
- combinational logic starting to react to state changes

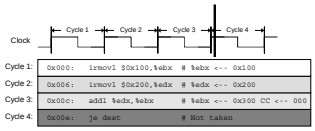
SEQ Operation #3

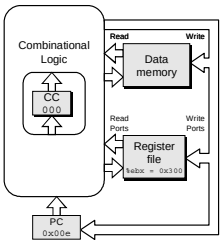




- state set according to second `irmovl` instruction
- combinational logic generates results for `addl` instruction

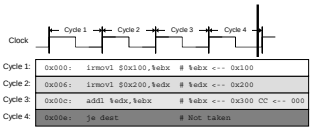
SEQ Operation #4

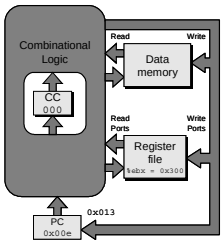




- **state set according to `addl` instruction**
- **combinational logic starting to react to state changes**

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**