CS51 MACHINE

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CS 51 – Spring 2026

Admin

Checkpoint 1

- Covers material up through this week (lighter coverage of this week's material)
- 1 double-side page of notes, hand-written
- will post a few practice problems

Assignment 4

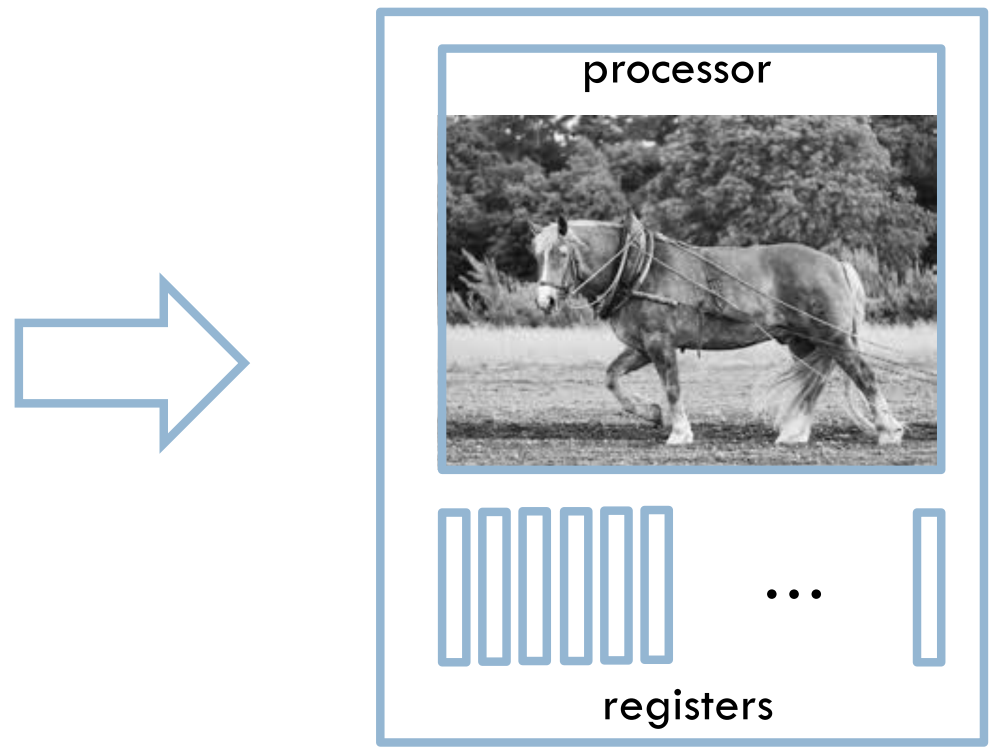
Assignment 5

Examples from this lecture

http://www.cs.pomona.edu/classes/cs51/cs51machine/

How does a program run on the CPU?

```python
def add(x, y):
    return x + y

def double(num):
    return 2 * num

def add_then_double(x, y):
    added = x + y
    doubled = double(added)
    return doubled

def absolute(x):
    if x < 0:
        x = -x

    return x
```



How do programs run/execute on a computer?

Assembly code

Python is a "high-level" programming language

high-level programming languages allow you to write code:

- without worrying about hardware-specific details of the computer (memory, registers, CPU specifics…)
- higher-level abstraction, e.g., 2**6 or print()

What actually runs on the processor is assembly code

Assembly code

```python
def add(x, y):
    return x + y

def double(num):
    return 2 * num

def add_then_double(x, y):
    added = x + y
    doubled = double(added)
    return doubled

def absolute(x):
    if x < 0:
        x = -x

    return x
```

```
add
    psh r2
    loa r2 r1 4
    add r3 r3 r2
    pop r2
    jmp r2

double
    psh r2
    add r3 r3 r3
    pop r2
    jmp r2

absolute
    psh r2
    bge r3 r0 else
    sub r3 r0 r3
else
    pop r2
    jmp r2

add_then_double
    psh r2
    loa r2 r1 4

    ; setup function call for add
    ; r3 already has parameter, push 2nd on stack
    psh r2
    lcw r2 add
    cal r2 r2
    pop r0

    ; answer is in r3, so no need to do anything
    lcw r2 double
    cal r2 r2

    pop r2
    jmp r2

    dat 100
stack
```

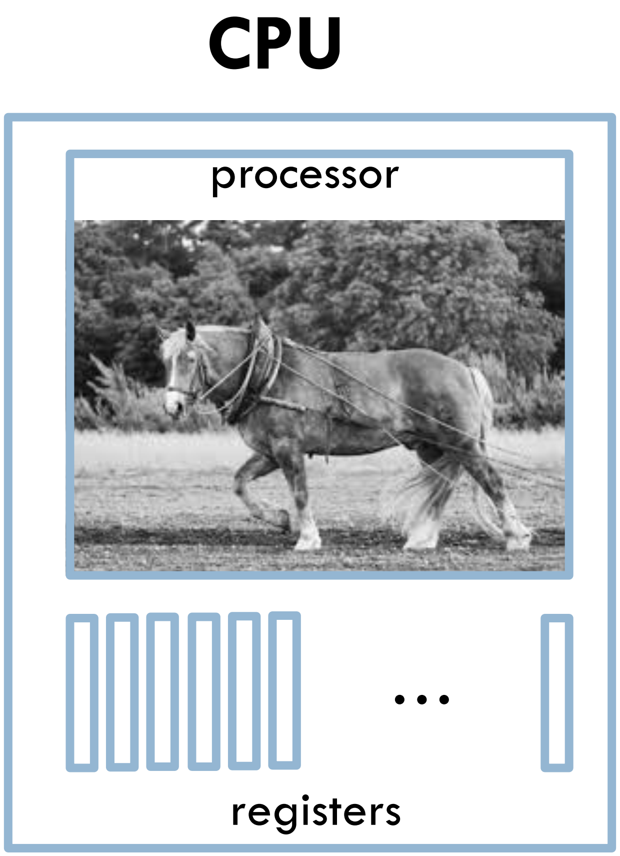
This week

Introduce the CS51 machine

This is a simplified version of an assembly language

It is a "simulator" that assumes a very simple CPU and memory setup

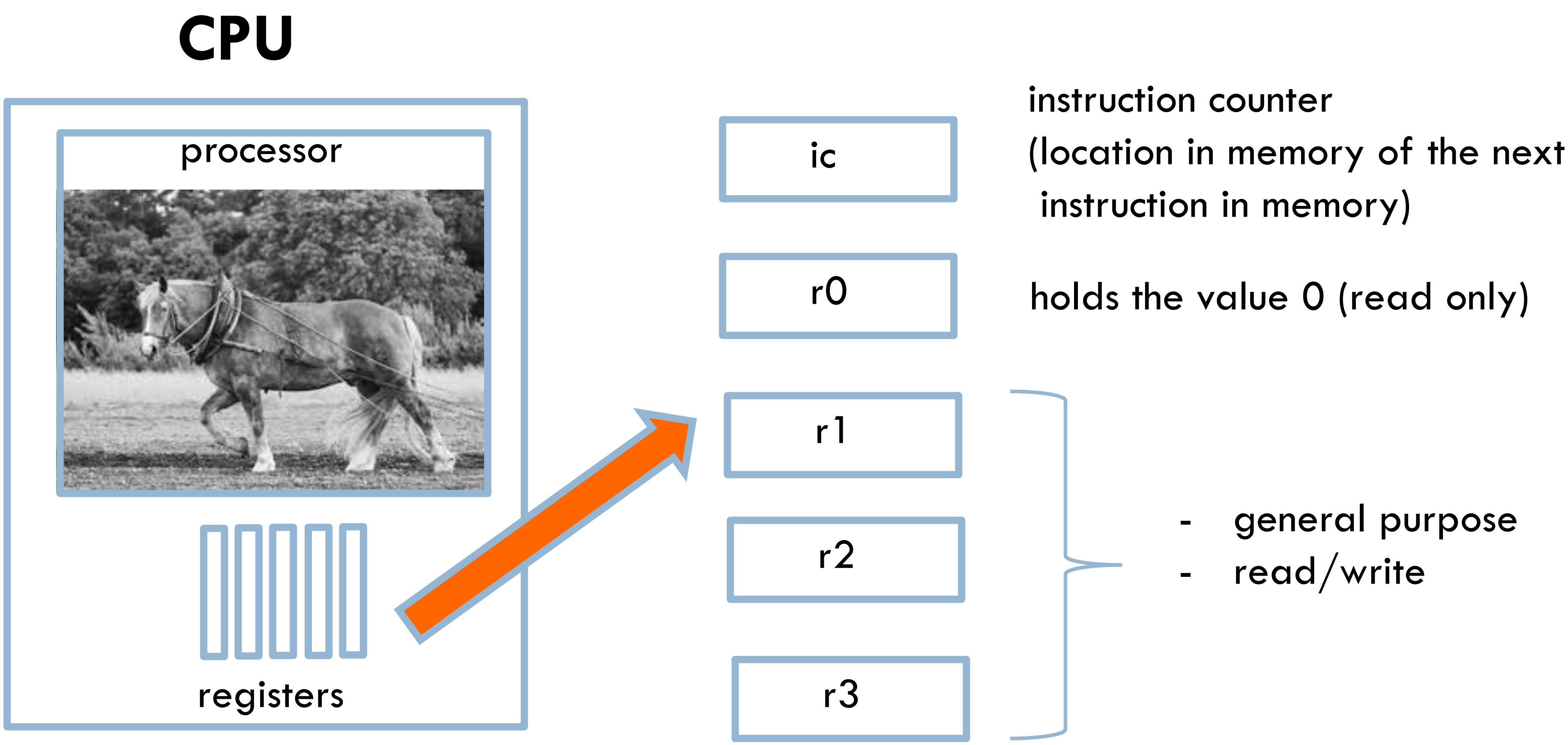
Inside the CPU



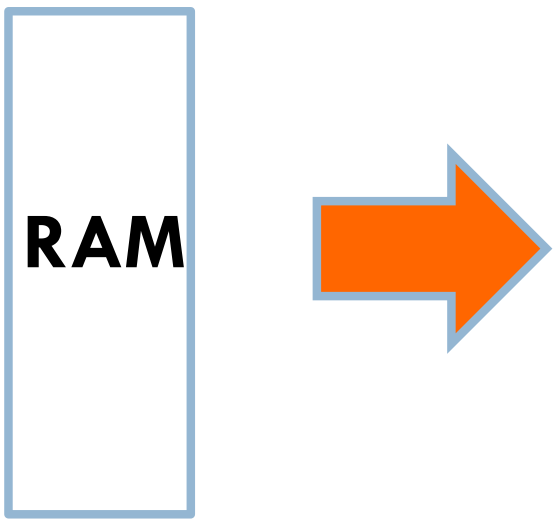
processor: does the work

registers: local, fast memory slots

CS51 machine (processor)



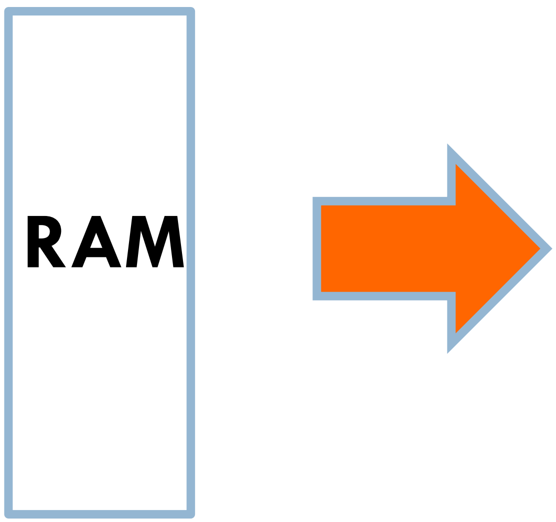
Memory



address	32-bit words
0	10101011 10001010 00010010 01011010
4	11001011 00001110 01010010 01010110
8	10111011 10010010 00000000 01110100
...	...

Most modern computers use 32-bit (4 byte) or 64-bit (8 byte) words

Memory in the CS51 Machine

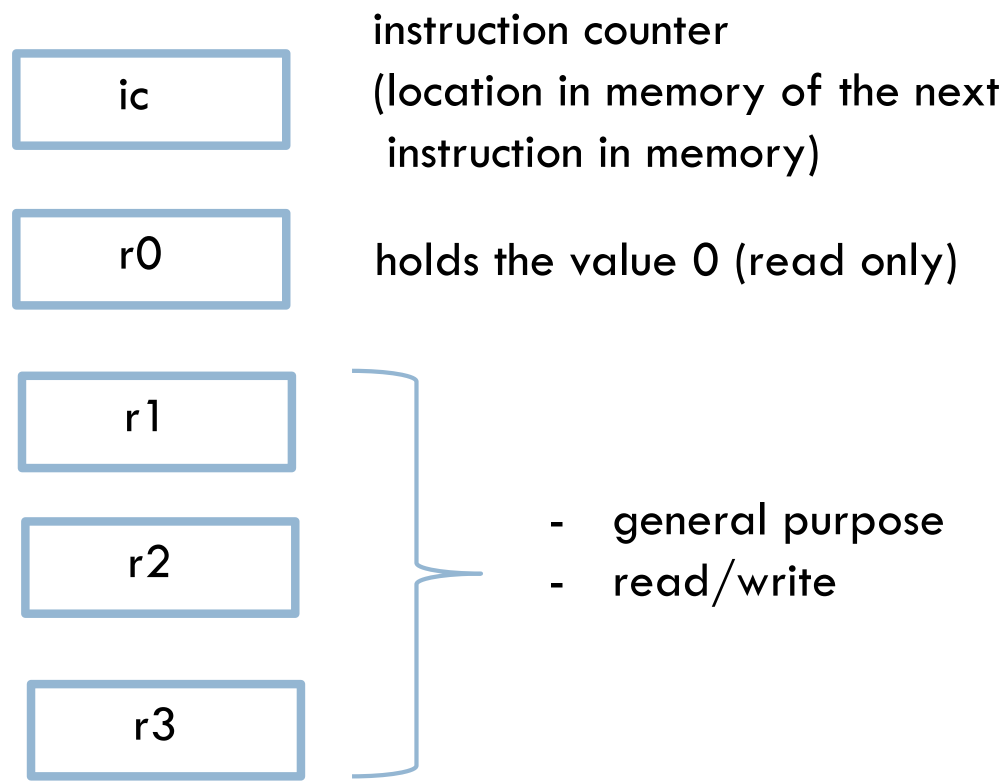


address	16-bit words
0	10101011 10001010
2	00010010 01011010
4	11001011 00001110
…	…

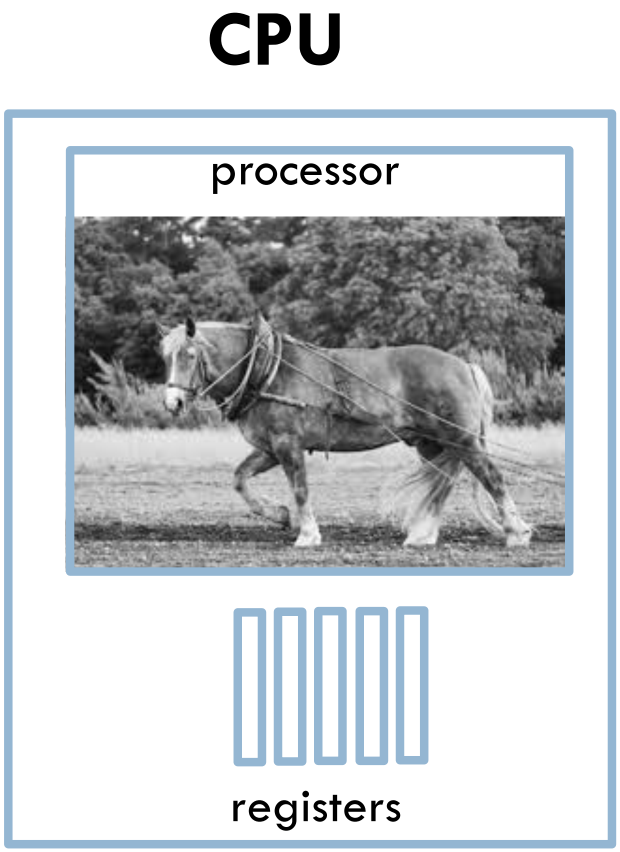
We'll use 16-bit words for our model (the CS51 machine)

When executing a program, the CS51 machine loops over the follow:

- Fetch the value from $\mathrm{mem[ic]}$ for use as an instruction
- Increment ic by 2
- Decode the instruction and then execute it



CS51 machine instructions



What types of operations might we want to do (think really basic)?

CS51 machine code

Four main types of instructions

1. math/logical
2. branch (conditionals, loops)
3. memory
4. control the machine (e.g., stop it)

Math/logical operations

instruction name   arguments

instruction name	arguments
add	RRR or RRS
sub	RRR or RRS
and	RRR or RRS
orr	RRR or RRS
xor	RRR or RRS

Math/logical operations

instruction name   arguments

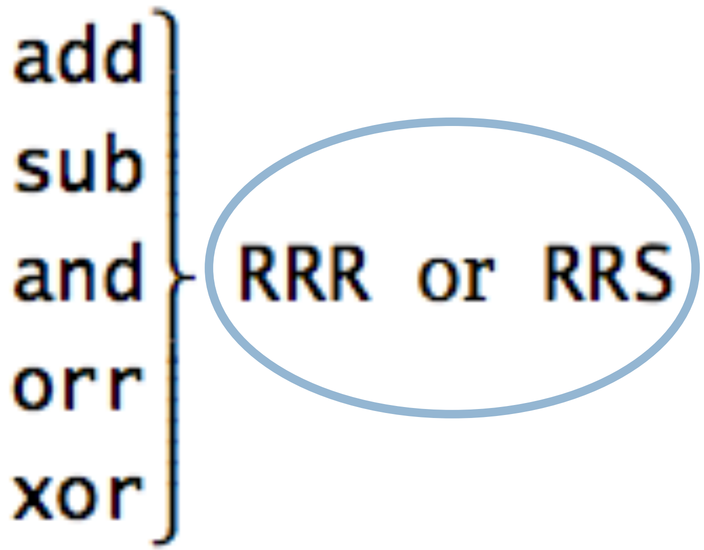
add
sub
and
orr
xor

} RRR or RRS

instruction/operation name
(always three characters)

Math/logical operations

instruction name arguments



operation arguments

R = register (e.g. r0)

S = signed number (byte)

Math/logical operations

instruction name	arguments
add	RRR or RRS
sub	RRR or RRS
and	RRR or RRS
orr	RRR or RRS
xor	RRR or RRS

1st R: register where the answer will go

2nd R: register of first operand

3rd S/R: register/value of second operand

operand = input to operator (think, parameters for functions) add r1 r2 r3

What does this do?

1st R:	register where the answer will go
2nd R:	register of first operand
3rd S/R:	register/value of second operand

add r1 r2 r3

$r1 = r2 + r3$

Add contents of registers r2 and r3 and store the result in r1

1st R:	register where the answer will go
2nd R:	register of first operand
3rd S/R:	register/value of second operand

add r2 r1 10

What does this do?

1st R:	register where the answer will go
2nd R:	register of first operand
3rd S/R:	register/value of second operand

add r2 r1 10

$r2 = r1 + 10$

Add 10 to the contents of register r1 and store in r2

1st R:	register where the answer will go
2nd R:	register of first operand
3rd S/R:	register/value of second operand

add r1 r0 8
sub r2 r0 r1
sub r2 r1 r2

Hint: r0 is always 0

What number is in r2?

1st R:	register where the answer will go
2nd R:	register of first operand
3rd S/R:	register/value of second operand

add r1 r0 8	r1 = 8
sub r2 r0 r1	r2 = -8, r1 = 8
sub r2 r1 r2	r2 = 16

1st R:	register where the answer will go
2nd R:	register of first operand
3rd S/R:	register/value of second operand

```
add r1 r0 6
and r2 r1 10
add r3 r1 r2
```

Hint: r0 is always 0

What number is in r3?

1st R:	register where the answer will go
2nd R:	register of first operand
3rd S/R:	register/value of second operand

add r1 r0 6 (00110) — r1 = 6 (0110)

and r2 r1 10 (01010) — r2 = 2, r1 = 6

add r3 r1 r2 — r3 = 8

1st R: register where the answer will go

2nd R: register of first operand

3rd S/R: register/value of second operand

Accessing memory

sto }
loa } RRS

sto = save data in register TO memory
loa = put data FROM memory into a register

sto r1 r2 ; store the contents of r1 to mem[r2]
loa r1 r2 ; get data from mem[r2] and put into r1

Accessing memory

```
sto }
loa } RRS
```

sto = save data in register TO memory

loa = put data FROM memory into a register

Special cases:

- saving TO (sto) address 0 (r0) prints
- reading from (loa) address 0 (r0) gets input from user

Basic structure of CS51 program

```
; great comments at the top!
;
        instruction1        ; comment
        instruction2        ; comment
        ...
        hlt
```

whitespace before operations/instructions

subtract.a51

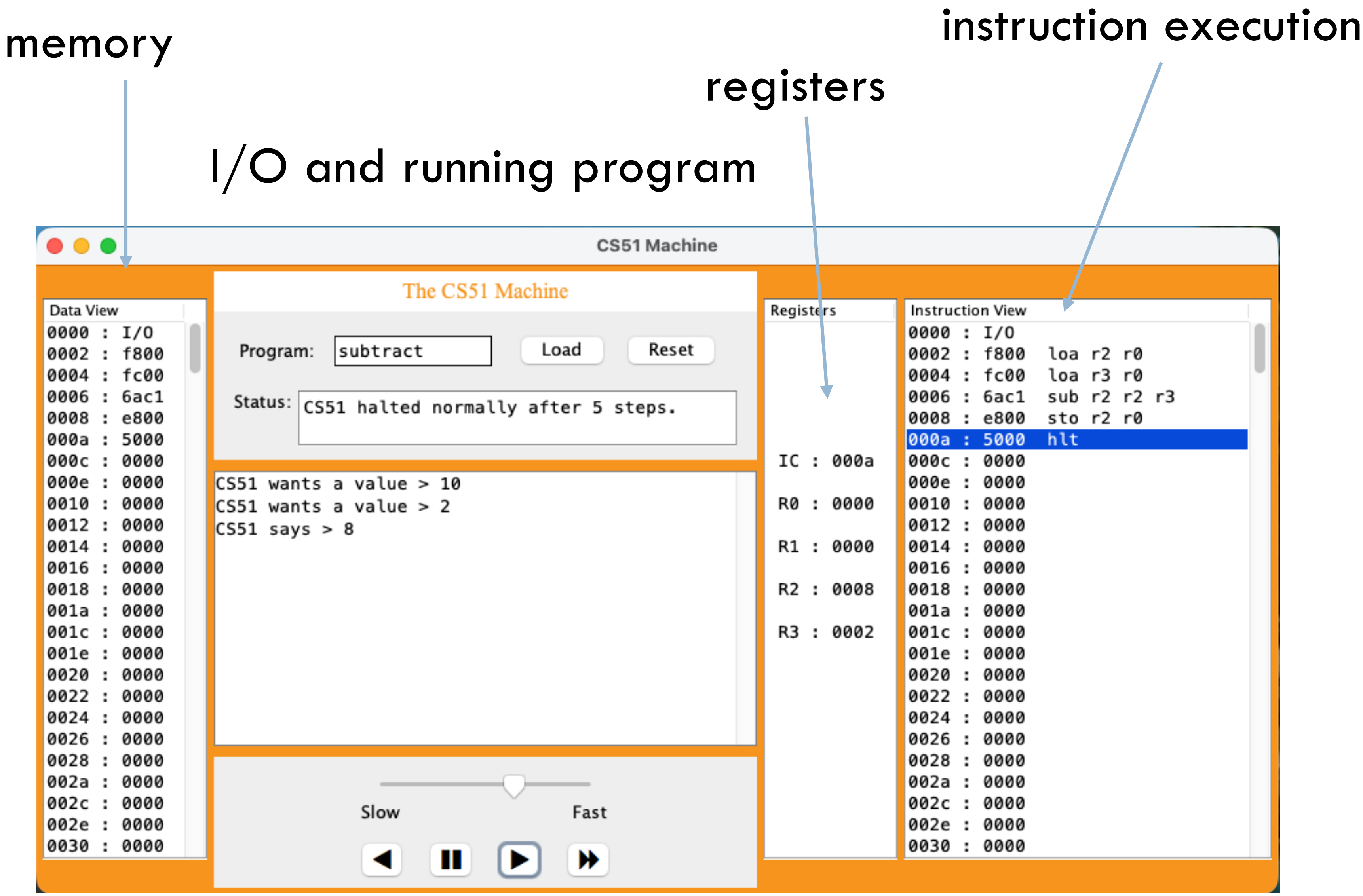
```
; A simple CS51 Machine program that subtracts
; two numbers.

        loa r2 r0          ; get first value
        loa r3 r0          ; get second value
        sub r2 r2 r3       ; subtract them
        sto r2 r0          ; print result
        hlt                ; quit
```

Running the CS51 machine

Look at subtract.a51

- load two numbers from the user
- subtract
- print the result

CS51 simulator



Branch instructions

branch (always)	brs	B
branch if ==	beq	RRB
branch if !=	bne	RRB
branch if <	blt	RRB
branch if >=	bge	RRB
branch if >	bgt	RRB
branch if <=	ble	RRB

1st R: first register for comparison

2nd R: second register in comparison

3rd B: label

Branch instructions

beq r3 r0 done

What does this do?

1st R:	first register for comparison
2nd R:	second register in comparison
3rd B:	label

Branch instructions

beq r3 r0 done

If r3 = 0, branch to the label "done"
if not (else) ic is incremented as normal to the next instruction

1^{st} R:	first register for comparison
2^{nd} R:	second register in comparison
3^{rd} B:	label

Branch instructions

ble r2 r3 done

What does this do?

1st R:	first register for comparison
2nd R:	second register in comparison
3rd B:	label

Branch instructions

ble r2 r3 done

If r2 <= r3, branch to the label done

1^{st} R:	first register for comparison
2^{nd} R:	second register in comparison
3^{rd} B:	label

Branch instructions

branch (always)	brs	B
branch if ==	beq	RRB
branch if !=	bne	RRB
branch if <	blt	RRB
branch if >=	bge	RRB
branch if >	bgt	RRB
branch if <=	ble	RRB

- Conditionals
- Loops
- Change the order that instructions are executed

CS51 machine execution

A *program* is a sequence of instructions stored in a memory. To execute a program, the CS51 machine follows a simple loop:

- Fetch the value from $\mathrm{mem}[\mathrm{ic}]$ for use as an instruction
- Increment ic by 2
- Decode the instruction and then execute it

Basic structure of CS51 program

```
; great comments at the top!
;
        instruction1         ; comment
        instruction2         ; comment
        ...
label1
        instruction          ; comment
        instruction          ; comment
label2
        ...
        hlt
```

- whitespace before operations/instructions
- labels go here

simple_max.a51

```
;
; simple program to compute the max of
; two numbers
;
        loa r2 r0       ; get the first value and put it in r2
        loa r3 r0       ; get the second value and put it in r3

        bge r3 r2 done  ; check if r3 >= r2, if so jump to done
        add r3 r2 0     ; r3 = r2, (r2 is larger so copy it)
done
        sto r3 r0
        hlt
```

More CS51 examples

Look at max_simple.a51

- Get two values from the user
- Compare them
- Use a branch to distinguish between the two cases
  - Goal is to get largest value in r3
- print largest value

if/else

if block

else block

```
    bxx _ _ else          ; not of if statement
    ...                   ; body of if
    ...
    brs end               ; jump to the end of if/else
else
    ...                   ; body of else
    ...
end
    ...                   ; instructions after if/else
```

- check the opposite of the if statement
  - if it is true, we'll jump down to else
  - if it is not true, we'll continue into the body of the if part
- At the end of the if block, need to jump to the end, otherwise, we'd continue onto else

if/else

```
    loa r3 r0

    and r2 r3 1
    beq r2 r0 else
    add r3 r0 47
    brs end
else
    add r3 r0 -47
end

    sto r3 r0
    hlt
```

What does this code do?

if/else

```
    loa r3 r0

    and r2 r3 1
    beq r2 r0 else
    add r3 r0 47        } if block
    brs end
else
    add r3 r0 -47       } else block
end

    sto r3 r0
    hlt
```

if/else (even_commented.a51)

```
    loa r3 r0               ; get a value from the user

    and r2 r3 1             ; get the low-order bit into r2
    beq r2 r0 else          ; branch to else if even
    add r3 r0 47            ; put 47 in r3
    brs end                 ; go to the end of the if/else
else
    add r3 r0 -47           ; put -47 in r3
end

    sto r3 r0               ; print out r3
    hlt
```

If/elif/else

if block

elif block

elif block

else block

```
    bxx _ _ nextif      ; not of if statement
    ...                 ; body of if
    ...
    brs end             ; jump to the end of if/elif/else
nextif
    bxx _ _ nextif2     ; not of elif statement
    ...                 ; body of elif
    ...
    brs end
nextif2
    bxx _ _ else        ; not of elif statement
    ...                 ; body of elif
    ...
    brs end
else
    ...                 ; body of else
    ...
end
    ...                 ; instructions after if/else
```

if/elif/else

```
    loa r3 r0

    bge r3 r0 nextif
    add r3 r0 -1
    brs end
nextif
    bgt r3 r0 else
    add r3 r0 0
    brs end
else
    add r3 r0 1
end

    sto r3 r0
    hlt
```

What does this code do?

if/elif/else (sign_commented.a51)

```
    loa r3 r0                  ; get a number from the user

    bge r3 r0 nextif           ; if r3 < 0
    add r3 r0 -1               ; r3 = -1
    brs end
nextif
    bgt r3 r0 else             ; if r3 == 0
    add r3 r0 0                ; r3 = 0
    brs end
else
    add r3 r0 1                ; r3 is positive: r3 = 1
end

    sto r3 r0                  ; print out r3
    hlt
```

while loop

while block

```
start
    bxx _ _ end         ; not of the while condition
    ...                 ; body of the while loop
    ...
    brs start
end
    ...                 ; after the while loop
```

while loop

```
    loa r3 r0

    add r2 r0 0
start
    ble r3 r0 end
    add r2 r2 r3
    sub r3 r3 1
    brs start
end

    sto r2 r0
    hlt
```

What does this code do?

while loop (sum_commented.a51)

```
    loa r3 r0             ; get a number from the user

    add r2 r0 0           ; r2 = 0
start
    ble r3 r0 end         ; while r3 > 0
    add r2 r2 r3          ; r2 += r3
    sub r3 r3 1           ; r3 -= 1
    brs start
end

    sto r2 r0             ; print out r2
    hlt
```

Instructions to binary

CS51 Machine uses 16-bit words

Data View

```
0000 : I/O
0002 : f800
0004 : fc00
0006 : 6ac1
0008 : e800
000a : 5000
```

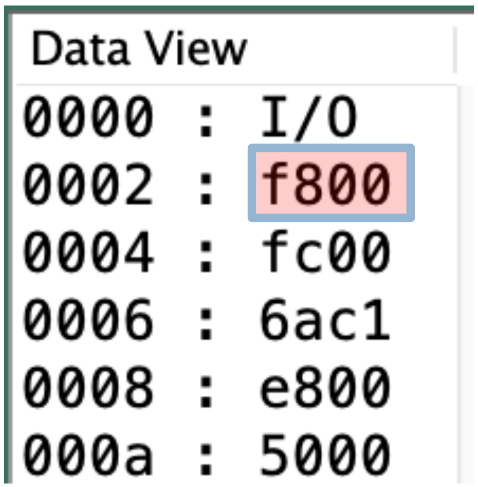
This is my assembly program

16-bit value
(displayed as hexadecimal number)

memory address

Instructions to binary

CS51 Machine uses 16-bit words



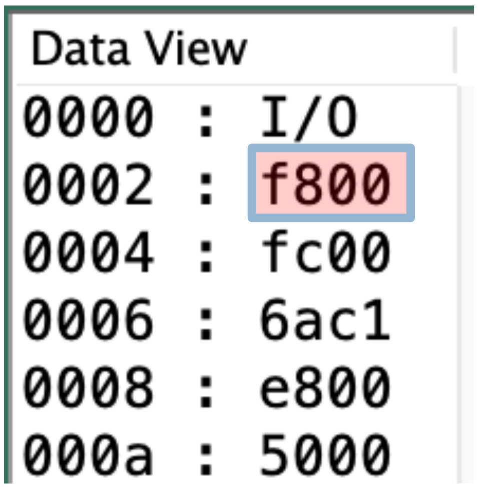
What binary number is this?

16-bit value
(displayed as hexadecimal number)

memory address

Instructions to binary

CS51 Machine uses 16-bit words



What binary number is this?

15 8 0 0

1111 1000 0000 0000

16 bits

16-bit value
(displayed as hexadecimal number)

memory address

Instructions to binary

CS51 Machine uses 16-bit words

Data View

```
0000 : I/O
0002 : f800
0004 : fc00
0006 : 6ac1
0008 : e800
000a : 5000
```

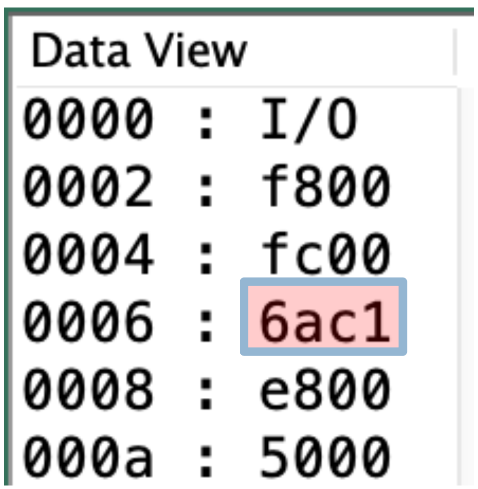
What binary number is this?

16-bit value
(displayed as hexadecimal number)

memory address

Instructions to binary

CS51 Machine uses 16-bit words



What binary number is this?

6 10 12 1

0110 1010 1100 0001

16-bit value
(displayed as hexadecimal number)

memory address

Encoding instructions

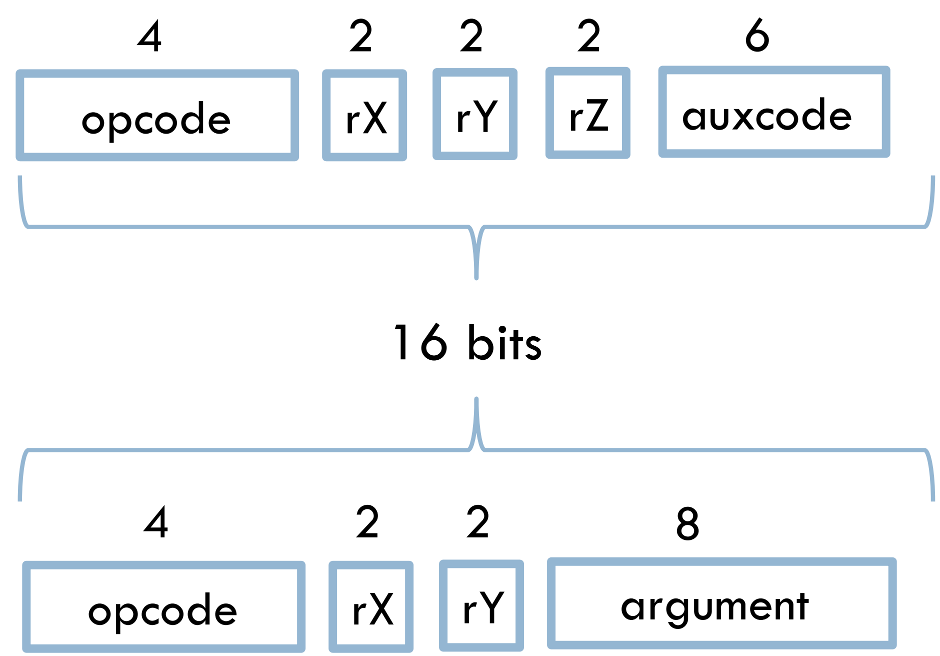
Two formats for instructions

opcode: specifies what operation (or category of operation)

r_: specifies a register

auxcode: specifies additional operations

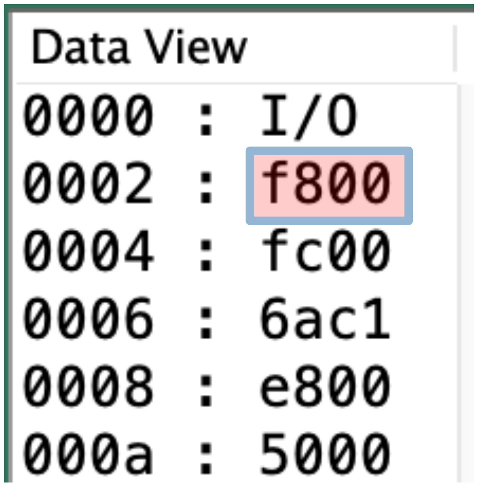
argument: a number



opcode

opcode	instruction
0x0	beq
0x1	bne
0x2	blt
0x3	bge
0x4	cal
0x5	hlt
0x6	arithmetic instruction
…	
0xe	sto
0xf	loa

Instructions to binary


Data View

```
0000 : I/O
0002 : f800
0004 : fc00
0006 : 6ac1
0008 : e800
000a : 5000
```

What is this instruction?

15 8 0 0

1111 1000 0000 0000

opcode	rX	rY	argument
4	2	2	8

Instructions to binary

Data View

```
0000 : I/O
0002 : f800
0004 : fc00
0006 : 6ac1
0008 : e800
000a : 5000
```

What is this instruction?

15 8 0 0

1111 1000 0000 0000

opcode	rX	rY	argument
4	2	2	8
loa	r2	r0	

Instructions to binary

Data View	
0000 :	I/O
0002 :	f800
0004 :	fc00
0006 :	6ac1
0008 :	e800
000a :	5000

What is this instruction?

6 10 12 1

0110 1010 1100 0001

4	2	2	2	6
opcode	rX	rY	rZ	auxcode

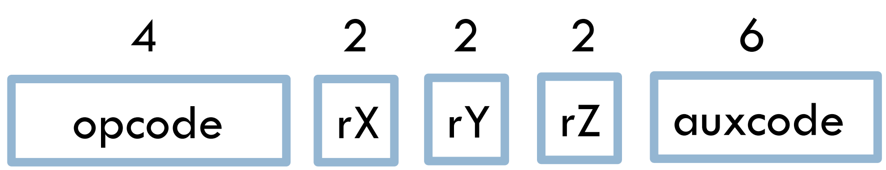
Instructions to binary

```
Data View
0000 : I/O
0002 : f800
0004 : fc00
0006 : 6ac1
0008 : e800
000a : 5000
```

What is this instruction?

6 10 12 1

0110 1010 1100 0001



arithmetic r2 r2 r3 0x1

arithmetic auxcode

opcode	instruction
0x0	add
0x1	sub
0x2	
0x3	
0x4	and
0x5	orr
0x6	
0x7	
0x8	logical shift left
0x9	logical shift right
…	

Instructions to binary

```
Data View
0000 : I/O
0002 : f800
0004 : fc00
0006 : 6ac1
0008 : e800
000a : 5000
```

What is this instruction?

6 10 12 1

0110 1010 1100 0001

4	2	2	2	6
opcode	rX	rY	rZ	auxcode

sub r2 r2 r3

instructions to binary

Data View

```
0000 : I/O
0002 : f800
0004 : fc00
0006 : 6ac1
0008 : e800
000a : 5000
```

Instruction View

```
0000 : I/O
0002 : f800   loa r2 r0
0004 : fc00   loa r3 r0
0006 : 6ac1   sub r2 r2 r3
0008 : e800   sto r2 r0
000a : 5000   hlt
```