CSE 390B, Spring 2023

Building Academic Success Through Bottom-Up Computing

Annotation Strategies & Hack Assembly

Annotation Strategies, Hack Assembly Memory Representation, Multiplication Implementation Exercise

Lecture Outline

- **Strategies for Annotating Texts**
  - **Motivation and Techniques for Annotation**
- Hack Assembly Language Review
  - Registers, A-Instructions, Symbols, & C-Instructions
- Hack Assembly Memory Representation
  - I/O, Memory Mapping, External vs. Internal Memory
- Multiplication Implementation Exercise
  - Multiplying Two Numbers in Hack Assembly

Annotating Your Texts

- **WHAT**

  Intentionality of interacting with a text to enhance the reader's understanding of, recall of, and reaction to the text

Annotating Your Texts

- **WHAT**

  Intentionality of interacting with a text to enhance the reader's understanding of, recall of, and reaction to the text

- **HOW**
  - Highlighting, underlining or using [brackets] to note key points or ideas

Annotating Your Texts

- **WHAT**

  Intentionality of interacting with a text to enhance the reader's understanding of, recall of, and reaction to the text

- **HOW**
  - Highlighting, underlining or using [brackets] to note key points or ideas
  - Circling unfamiliar words or confusing parts of the text

Annotating Your Texts

- **WHAT**

  Intentionality of interacting with a text to enhance the reader's understanding of, recall of, and reaction to the text

- **HOW**
  - Highlighting, underlining or using [brackets] to note key points or ideas
  - Circling unfamiliar words or confusing parts of the text
  - *Paraphrasing or summarizing passages/chapters/sections*

Annotating Your Texts

- **WHAT**

  Intentionality of interacting with a text to enhance the reader's understanding of, recall of, and reaction to the text

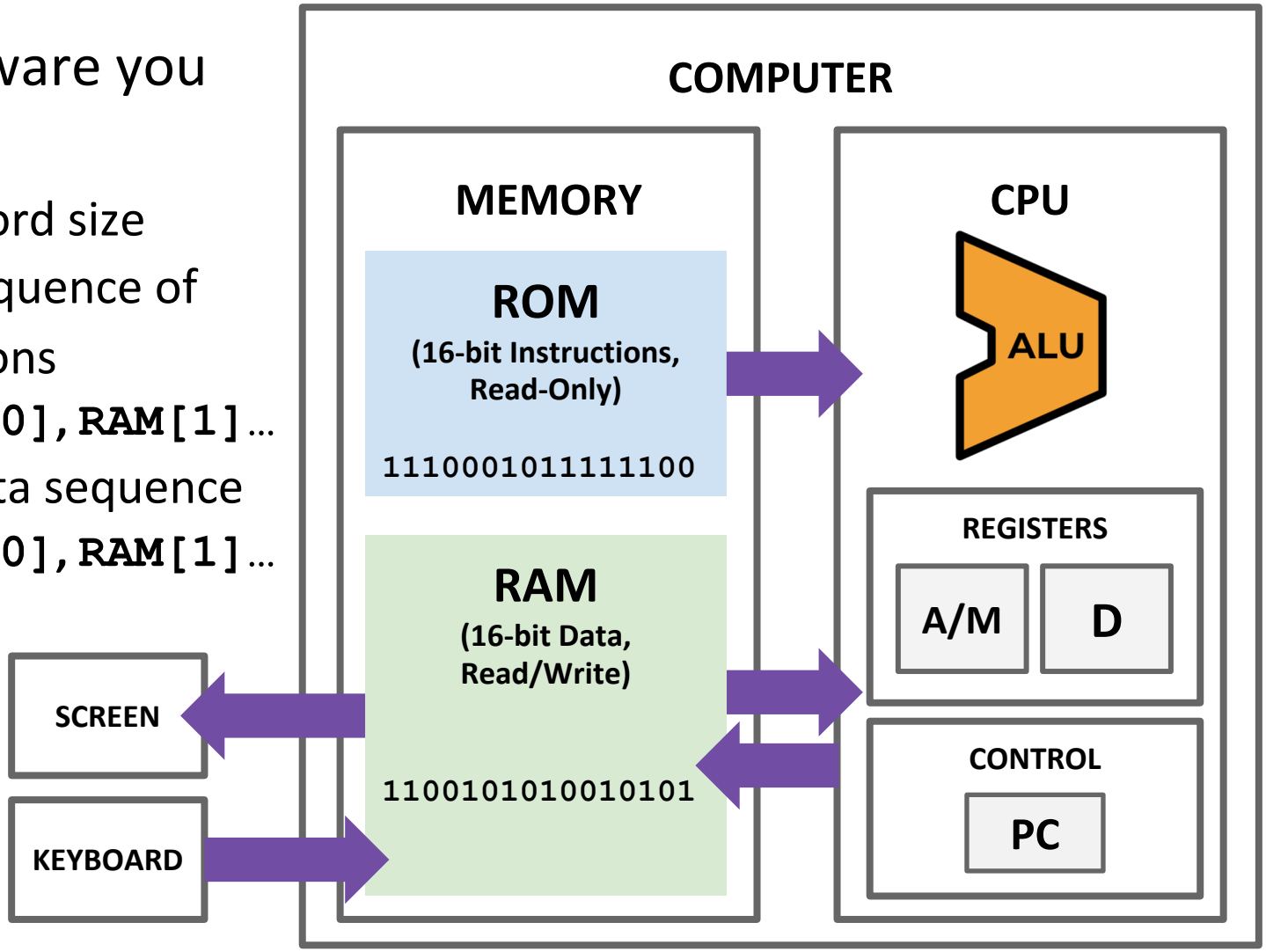
- **HOW**
  - Highlighting, underlining or using [brackets] to note key points or ideas
  - Circling unfamiliar words or confusing parts of the text
  - *Paraphrasing or summarizing passages/chapters/sections*
  - Commenting or reacting to the text 🤯

Lecture Outline

- Strategies for Annotating Texts
  - Motivation and Techniques for Annotation
- **Hack Assembly Language Review**
  - **Registers, A-Instructions, Symbols, & C-Instructions**
- Hack Assembly Memory Representation
  - I/O, Memory Mapping, External vs. Internal Memory
- Multiplication Implementation Exercise
  - Multiplying Two Numbers in Hack Assembly

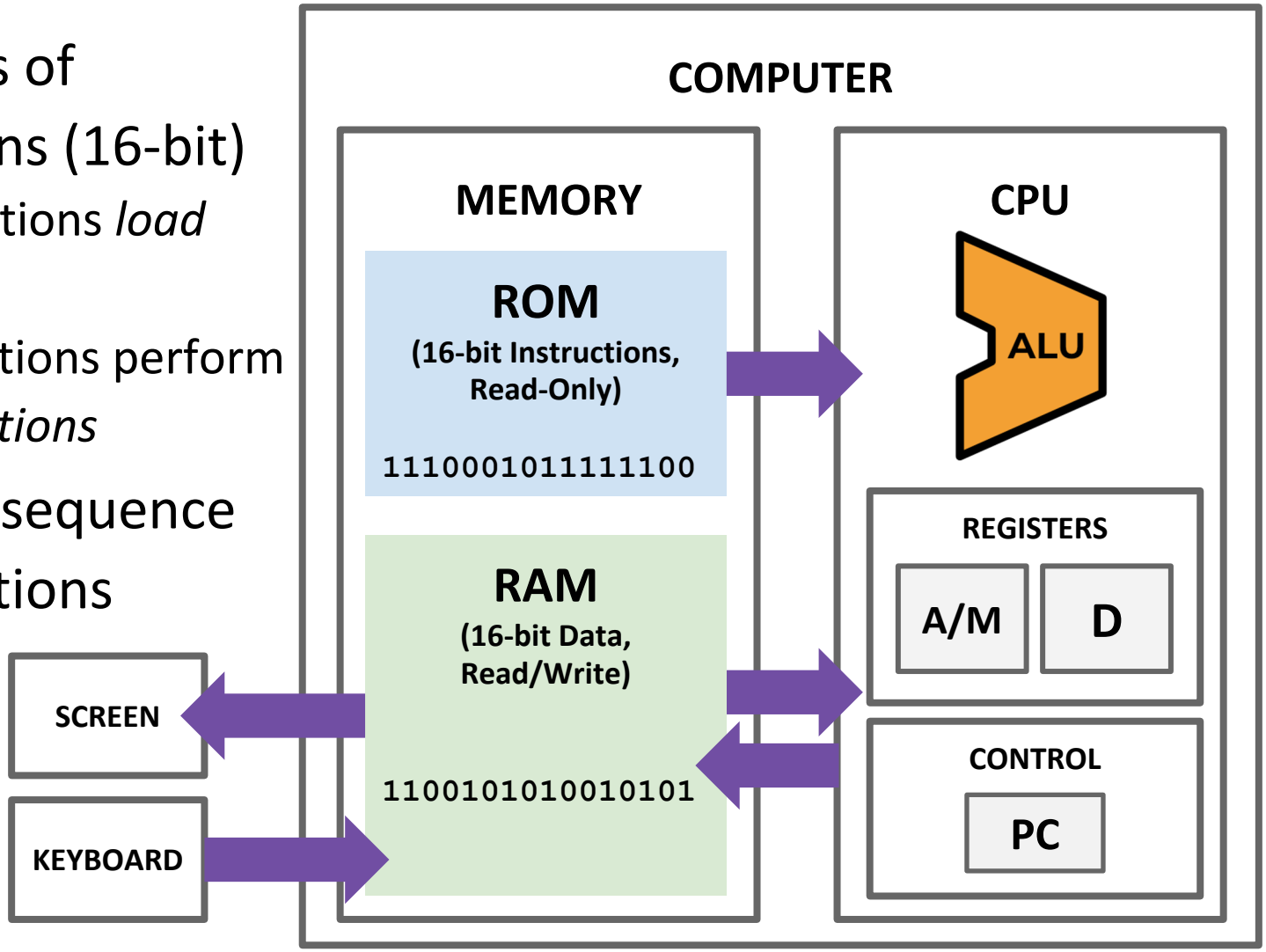
The Hack Computer

- The hardware you will build
  - 16-bit word size
  - ROM: sequence of instructions
    - `ROM[0], RAM[1]…`
  - RAM: data sequence
    - `RAM[0], RAM[1]…`



The Hack Machine Language

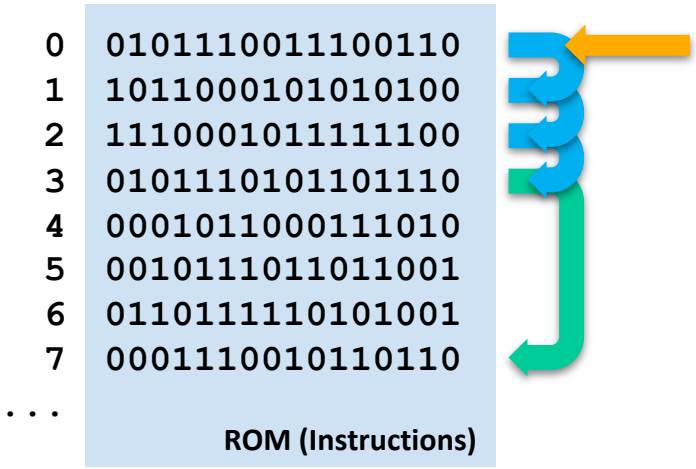
- Two types of instructions (16-bit)
  - A-instructions *load data*
  - C-instructions perform *computations*
- Program: sequence of instructions



Hack: Control Flow

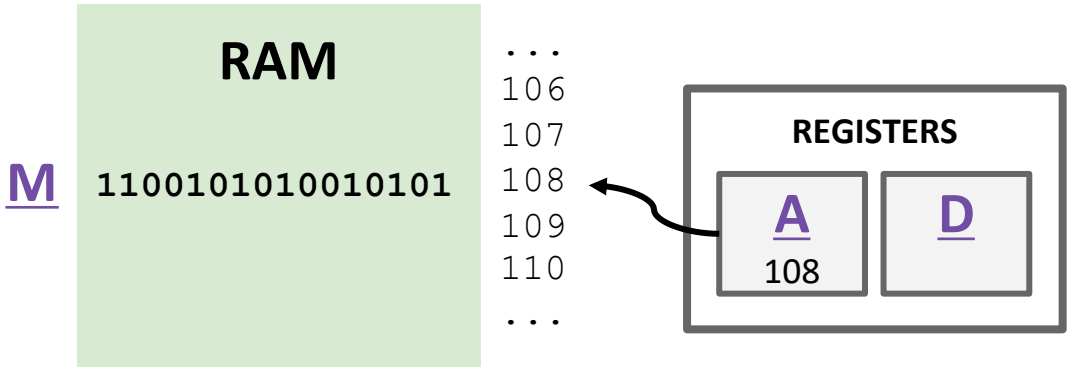
- Startup
  - Hack instructions loaded into ROM
  - Reset signal initializes computer state (instruction 0)

- Execution
  - Usually, advance to next instruction each cycle
  - On jump instruction, write a different address into the PC



Hack: Registers

- D Register: For storing Data
- A Register: For storing data *and* Addressing memory
- M "Register": The 16-bit word in Memory currently being referenced by the address in A



Hack: A-Instructions

- Syntax: `@value`

- **`value`** can either be:
  - A decimal constant
  - A symbol referring to a constant

- Semantics:
  - Stores **`value`** in the A register

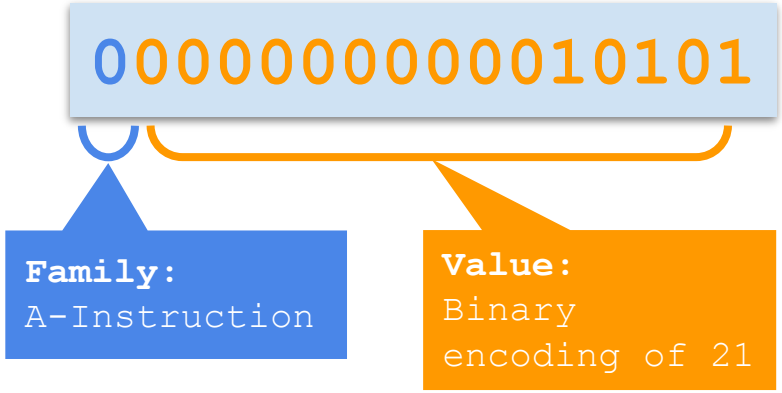
Hack: A-Instructions

- Symbolic Syntax

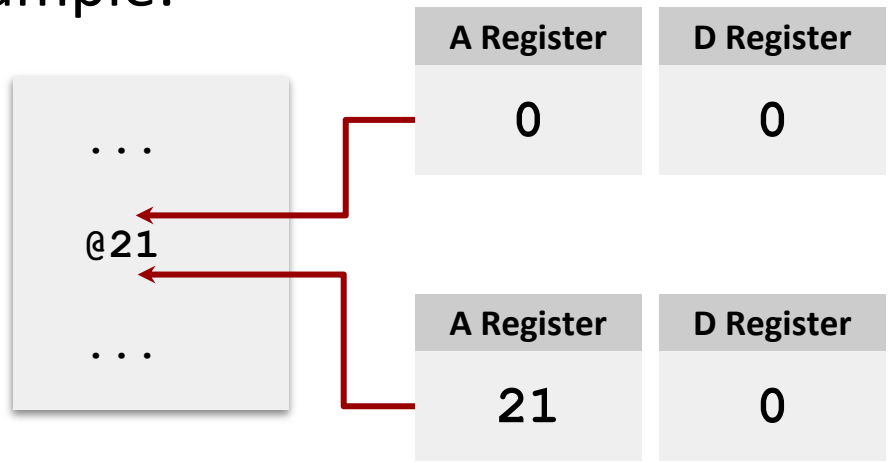
```
@value
```

  - Loads a value into the A register

- Binary Syntax



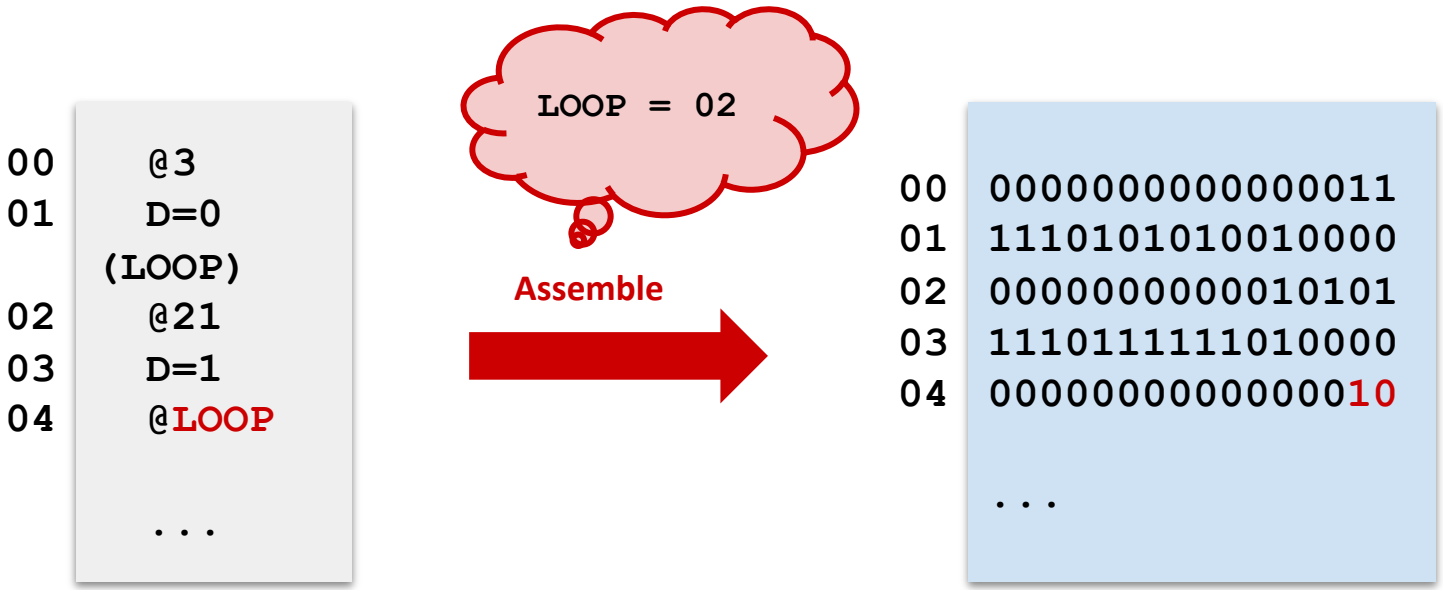
- Example:



Hack: Symbols

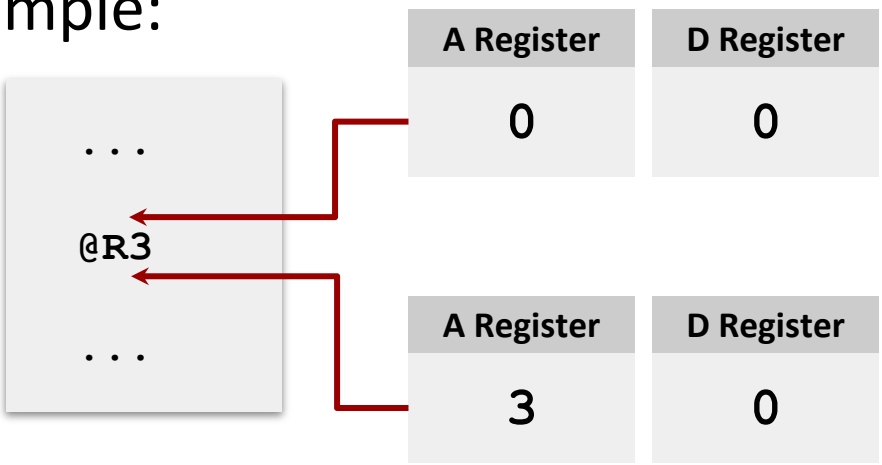
- Symbols are simply an alias for some address
  - Only in the symbolic code—don't turn into a binary instruction
  - Assembler converts use of that symbol to its value instead

- Example:



Hack: Built-In Symbols

- Using `(  )` defines a symbol in ROM / Instructions
- Assembler knows a few built-in symbols in RAM / Data
- **`R0, R1, ..., R15`**: Correspond to addresses at the very beginning of RAM (0, 1, …, 15)
  - "Virtual registers," Useful to store variables
- **`SCREEN, KBD`**: Base of I/O Memory Maps
- Example:



Hack: C-Instructions

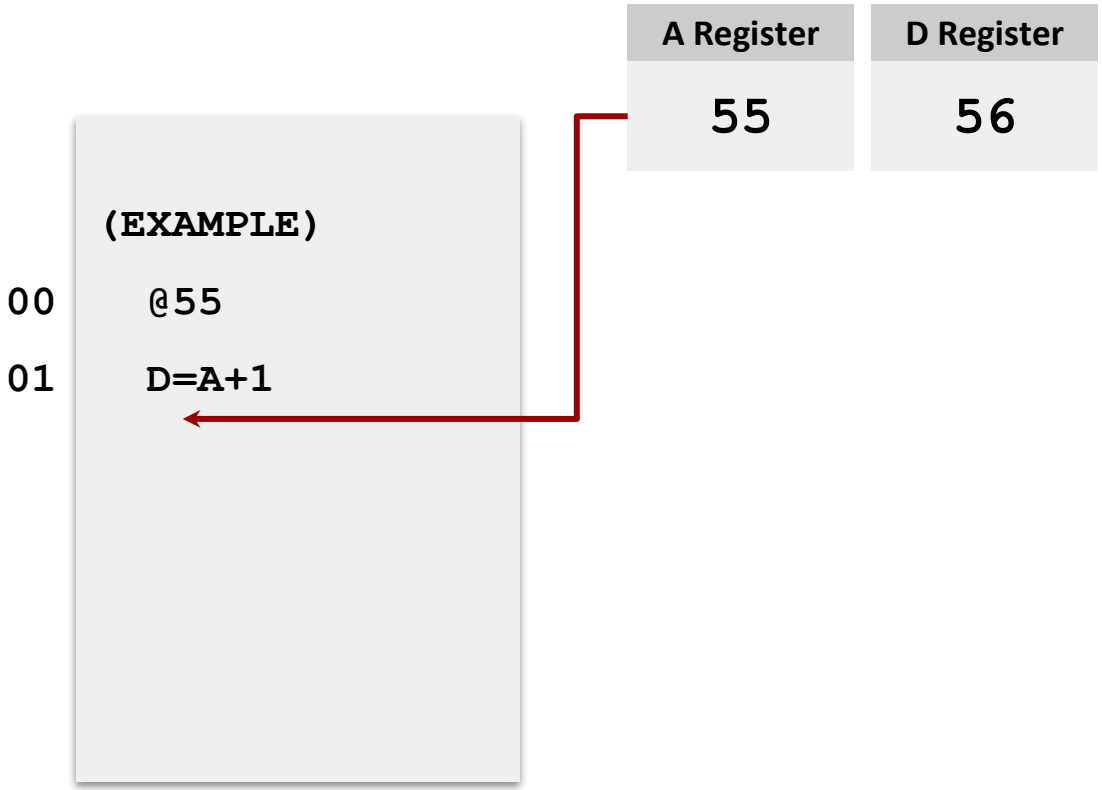
- Syntax: `dest = comp ; jump` (**`dest`** and **`jump`** optional)
  - **`dest`** is a combination of destination registers:

    `M, D, MD, A, AM, AD, AMD`
  - **`comp`** is a computation:

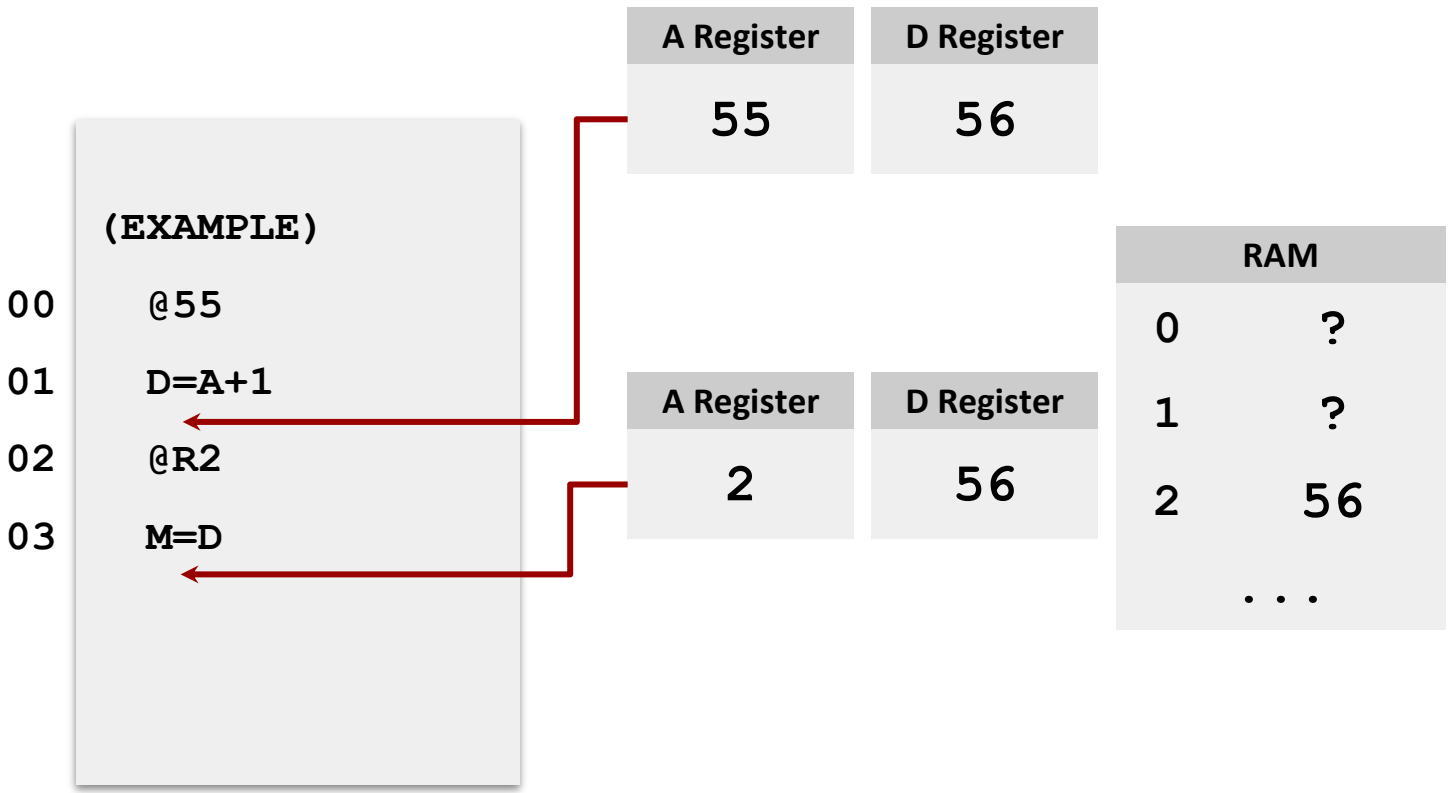
    `0, 1, -1, D, A, !D, !A, -D, -A, D+1, A+1, D-1, A-1, D+A, D-A, A-D, D&A, D|A, M, !M, -M, M+1, M-1, D+M, D-M, M-D, D&M, D|M`
  - **`jump`** is an unconditional or conditional jump:

    `JGT, JEQ, JGE, JLT, JNE, JLE, JMP`
- Semantics:
  - Computes value of **`comp`**
  - Stores results in **`dest`** (if specified)
  - If **`jump`** is specified and condition is true (by testing **`comp`** result), jump to instruction **`ROM[A]`**

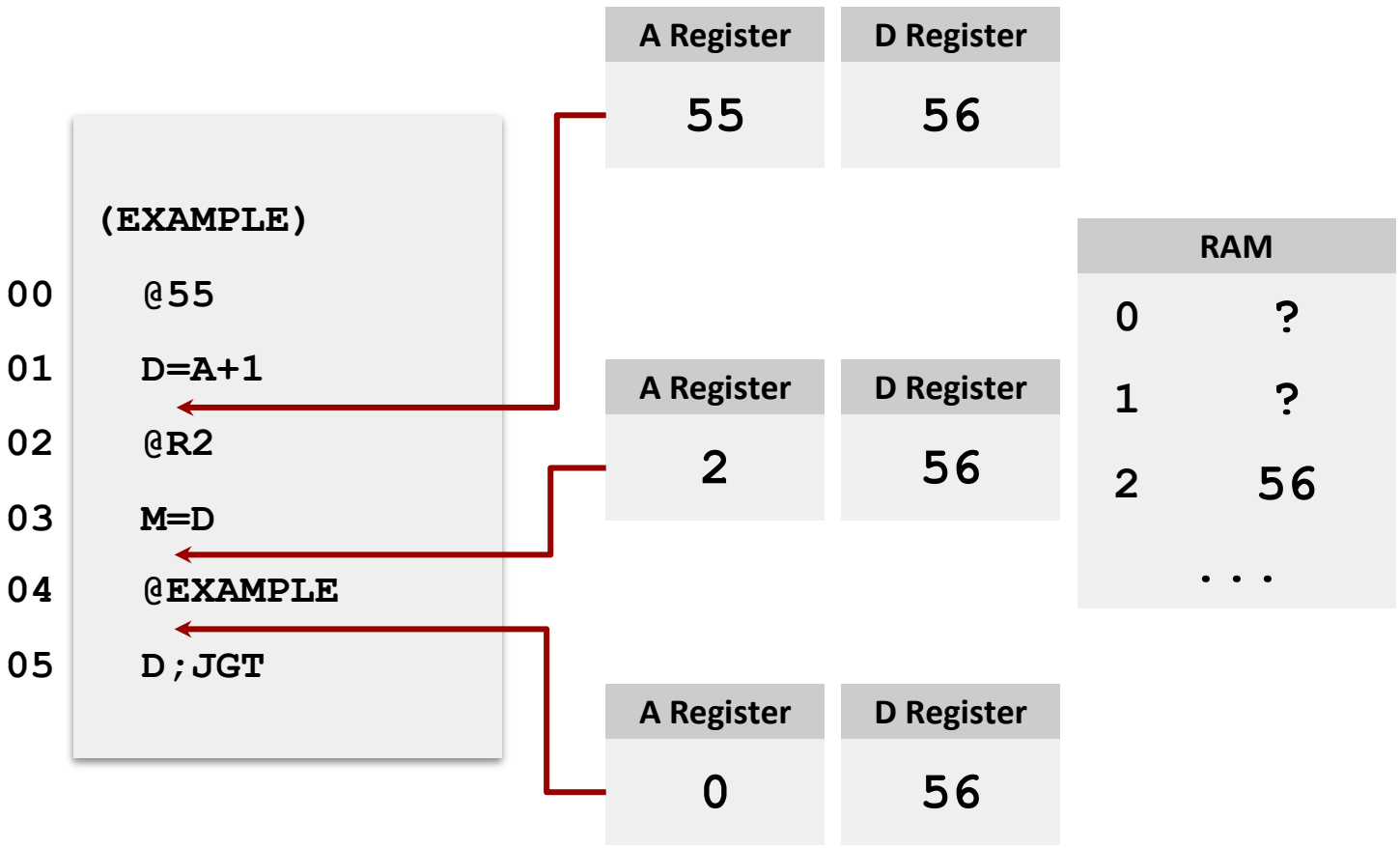
Hack: C-Instructions Example



Hack: C-Instructions Example



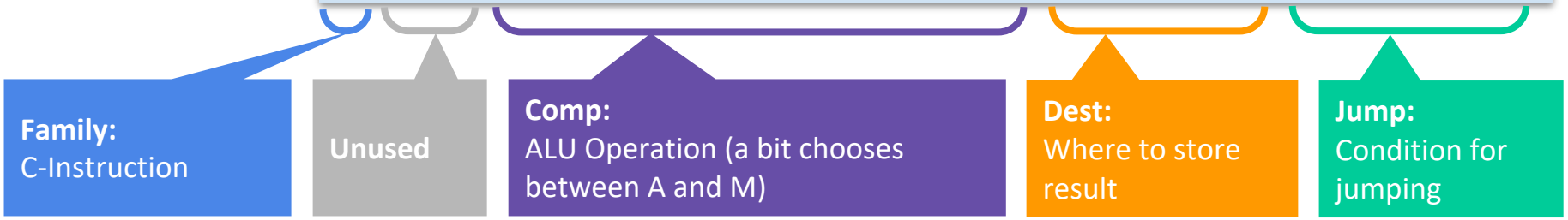
Hack: C-Instructions Example



(Will jump to instruction 0, since D > 0)

Hack: C-Instructions

- Symbolic: `dest = comp ; jump`
- Binary: `1 1 1 a c1 c2 c3 c4 c5 c6 d1 d2 d3 j1 j2 j3`



Hack: C-Instructions

- Symbolic: `dest = comp ; jump`
- Binary: `1 1 1 a c1 c2 c3 c4 c5 c6 d1 d2 d3 j1 j2 j3`

Jump: Condition for jumping

Chapter 4

j1 ($out < 0$)	j2 ($out = 0$)	j3 ($out > 0$)	Mnemonic	Effect
0	0	0	null	No jump
0	0	1	JGT	If $out > 0$ jump
0	1	0	JEQ	If $out = 0$ jump
0	1	1	JGE	If $out \geq 0$ jump
1	0	0	JLT	If $out < 0$ jump
1	0	1	JNE	If $out \neq 0$ jump
1	1	0	JLE	If $out \leq 0$ jump
1	1	1	JMP	Jump

Hack: C-Instructions

- Symbolic: `dest = comp ; jump`
- Binary: `1 1 1 a c1 c2 c3 c4 c5 c6 d1 d2 d3 j1 j2 j3`

Dest:
Where to store result

Chapter 4

d1	d2	d3	*Mnemonic*	*Destination (where to store the computed value)*
0	0	0	null	The value is not stored anywhere
0	0	1	M	Memory[A] (memory register addressed by A)
0	1	0	D	D register
0	1	1	MD	Memory[A] and D register
1	0	0	A	A register
1	0	1	AM	A register and Memory[A]
1	1	0	AD	A register and D register
1	1	1	AMD	A register, Memory[A], and D register

Hack: C-Instructions

- Symbolic: `dest = comp ; jump`
- Binary: `1 1 1 a c1 c2 c3 c4 c5 c6 d1 d2 d3 j1 j2 j3`

Comp:
ALU Operation (a bit chooses between A and M)

(when a=0) *comp mnemonic*	c1	c2	c3	c4	c5	c6	(when a=1) *comp mnemonic*
0	1	0	1	0	1	0	
1	1	1	1	1	1	1	
-1	1	1	1	0	1	0	
D	0	0	1	1	0	0	
A	1	1	0	0	0	0	M
!D	0	0	1	1	0	1	
!A	1	1	0	0	0	1	!M
-D	0	0	1	1	1	1	
-A	1	1	0	0	1	1	-M
D+1	0	1	1	1	1	1	
A+1	1	1	0	1	1	1	M+1
D-1	0	0	1	1	1	0	
A-1	1	1	0	0	1	0	M-1
D+A	0	0	0	0	1	0	D+M
D-A	0	1	0	0	1	1	D-M
A-D	0	0	0	1	1	1	M-D
D&A	0	0	0	0	0	0	D&M
D|A	0	1	0	1	0	1	D|M

Chapter 4

Important: just pattern matching text!

Cannot have "**1+M**"

Lecture 8: Annotation Strategies & Hack Assembly

When poll is active, respond at **PollEv.com/cse390b**

What is the C-instruction encoding for D;JGE?

- 1111100111001001
- 1110001100000011
- 1110100111010010
- 1111001100000011
- We're lost…

Total Results: 0

Powered by Poll Everywhere

Poll Everywhere

Vote at https://pollev.com/cse390b

What is the C-instruction encoding for `D ; JGE`?

j1 (*out* < 0)	j2 (*out* = 0)	j3 (*out* > 0)	Mnemonic	Effect
0	0	0	null	No jump
0	0	1	JGT	If *out* > 0 jump
0	1	0	JEQ	If *out* = 0 jump
0	1	1	JGE	If *out* ≥ 0 jump
1	0	0	JLT	If *out* < 0 jump
1	0	1	JNE	If *out* ≠ 0 jump
1	1	0	JLE	If *out* ≤ 0 jump
1	1	1	JMP	Jump

d1	d2	d3	*Mnemonic*	*Destination (where to store the computed value)*
0	0	0	null	The value is not stored anywhere
0	0	1	M	Memory[A] (memory register addressed by A)
0	1	0	D	D register
0	1	1	MD	Memory[A] and D register
1	0	0	A	A register
1	0	1	AM	A register and Memory[A]
1	1	0	AD	A register and D register
1	1	1	AMD	A register, Memory[A], and D register

(when a=0) *comp* mnemonic	c1	c2	c3	c4	c5	c6	(when a=1) *comp* mnemonic
0	1	0	1	0	1	0	
1	1	1	1	1	1	1	
-1	1	1	1	0	1	0	
D	0	0	1	1	0	0	
A	1	1	0	0	0	0	M
!D	0	0	1	1	0	1	
!A	1	1	0	0	0	1	!M
-D	0	0	1	1	1	1	
-A	1	1	0	0	1	1	-M
D+1	0	1	1	1	1	1	
A+1	1	1	0	1	1	1	M+1
D-1	0	0	1	1	1	0	
A-1	1	1	0	0	1	0	M-1
D+A	0	0	0	0	1	0	D+M
D-A	0	1	0	0	1	1	D-M
A-D	0	0	0	1	1	1	M-D
D&A	0	0	0	0	0	0	D&M
D|A	0	1	0	1	0	1	D|M

Lecture Outline

- Strategies for Annotating Texts
  - Motivation and Techniques for Annotation
- Hack Assembly Language Review
  - Registers, A-Instructions, Symbols, & C-Instructions
- **Hack Assembly Memory Representation**
  - **I/O, Memory Mapping, External vs. Internal Memory**
- Multiplication Implementation Exercise
  - Multiplying Two Numbers in Hack Assembly

Hack Assembly: Input / Output

- Two memory maps are created for you by underlying hardware
  - **SCREEN** is a huge map where each pixel is one bit
  - **KEYBOARD** is a single 16-bit word map with code of current key

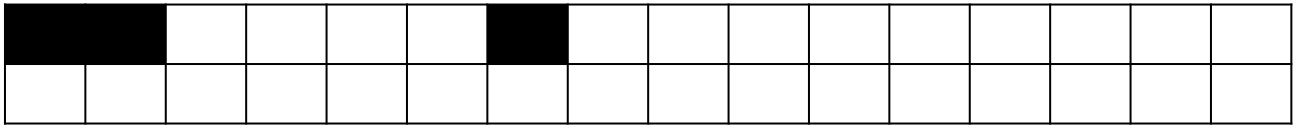
- Example:

```
@KBD
D=M

@SCREEN
M=D
```

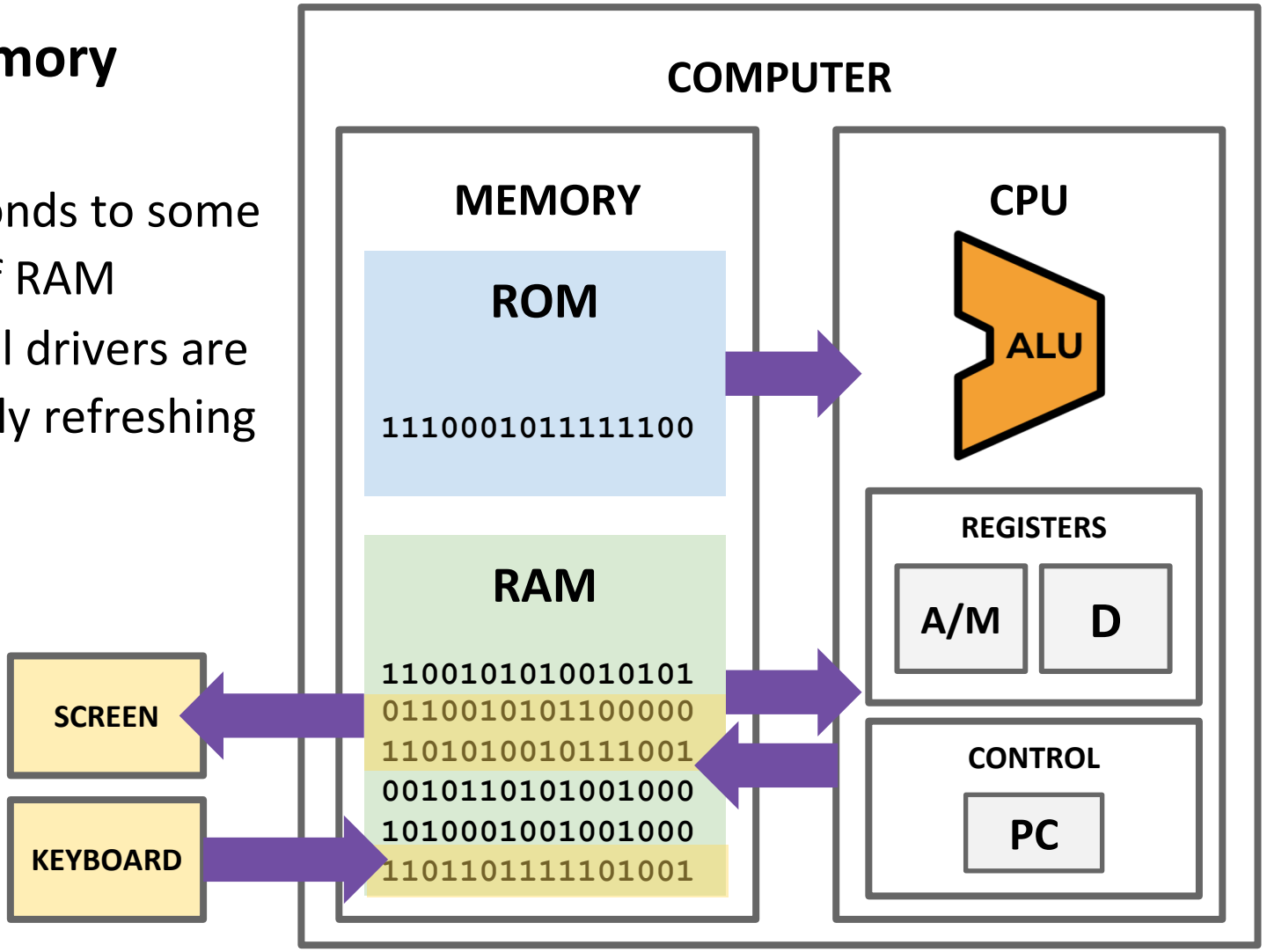
D contains code of current key (e.g., 67 for "C")

First 16 bits of screen (top left) show binary for 67



Hack: Input / Output

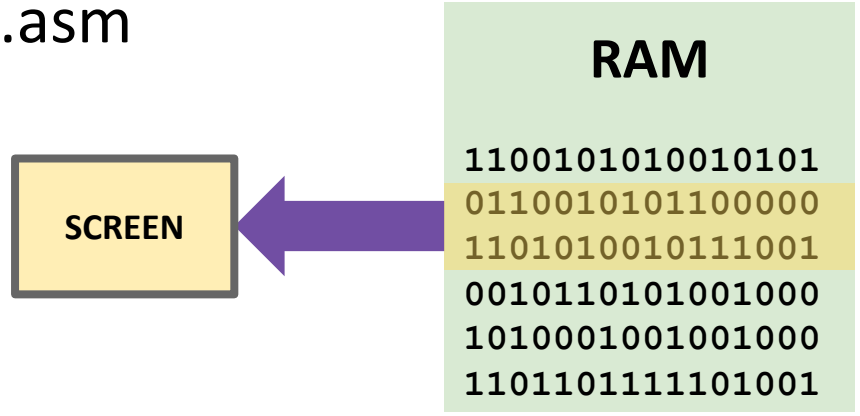
- I/O is **memory mapped**
  - Corresponds to some region of RAM
  - Low-level drivers are constantly refreshing

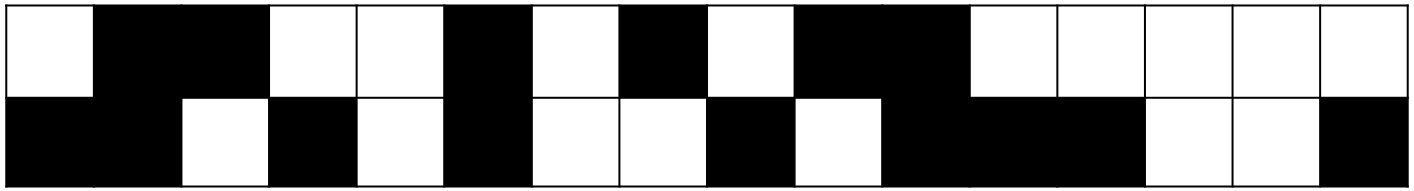


Hack: Memory Mapped Output

- Each bit of the screen memory map corresponds to one pixel (1 = black, 0 = white)

- The start of the memory map is accessible via the **`SCREEN`** symbol in Hack.asm





Hack: External Memory Abstraction

- Programmer sees one **`RAM32K`** memory region
  - Only 16K + 8K + 1 words are being used

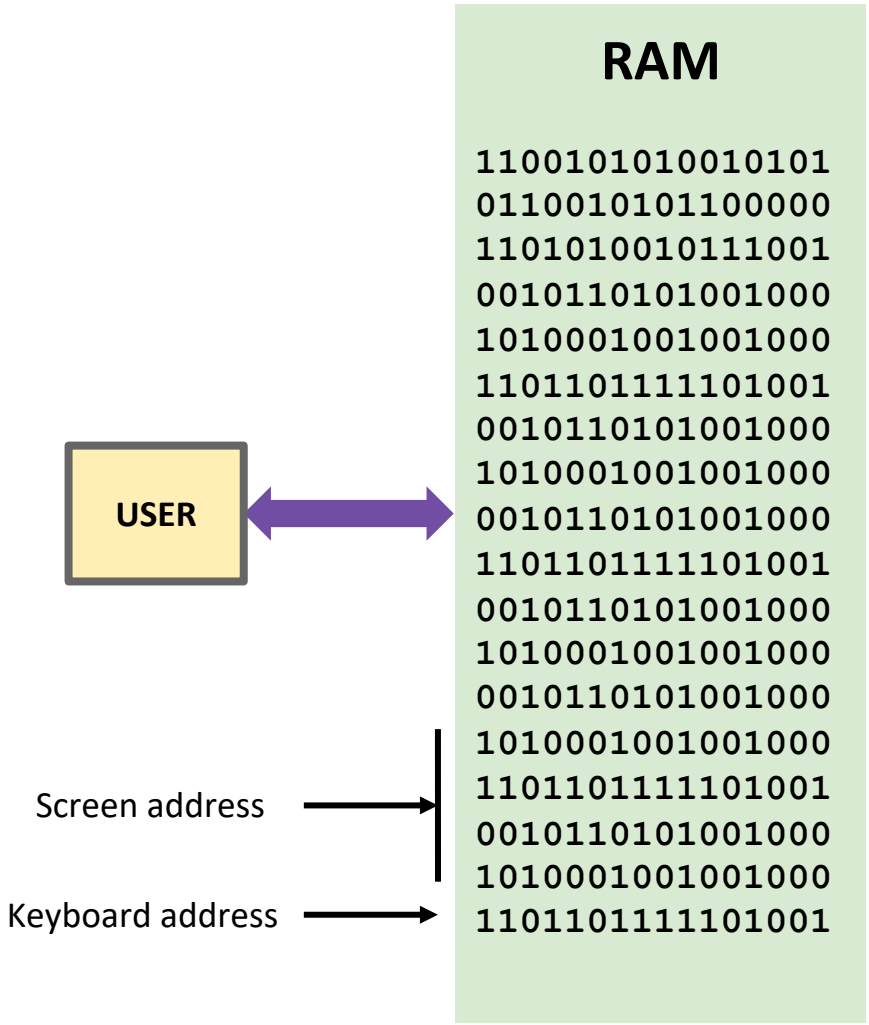
- Split into three parts: **`SCREEN`**, **`KEYBOARD`**, and the rest
  - Screen: 8K words
  - Keyboard: 1 words
  - The rest: 16K words (used for data and instructions)

- Programmer can use the same interface to interact with the **`SCREEN`**, **`KEYBOARD`**, or normal RAM
  - Just specify address, value, and other inputs
  - Address determines what part we are interacting with

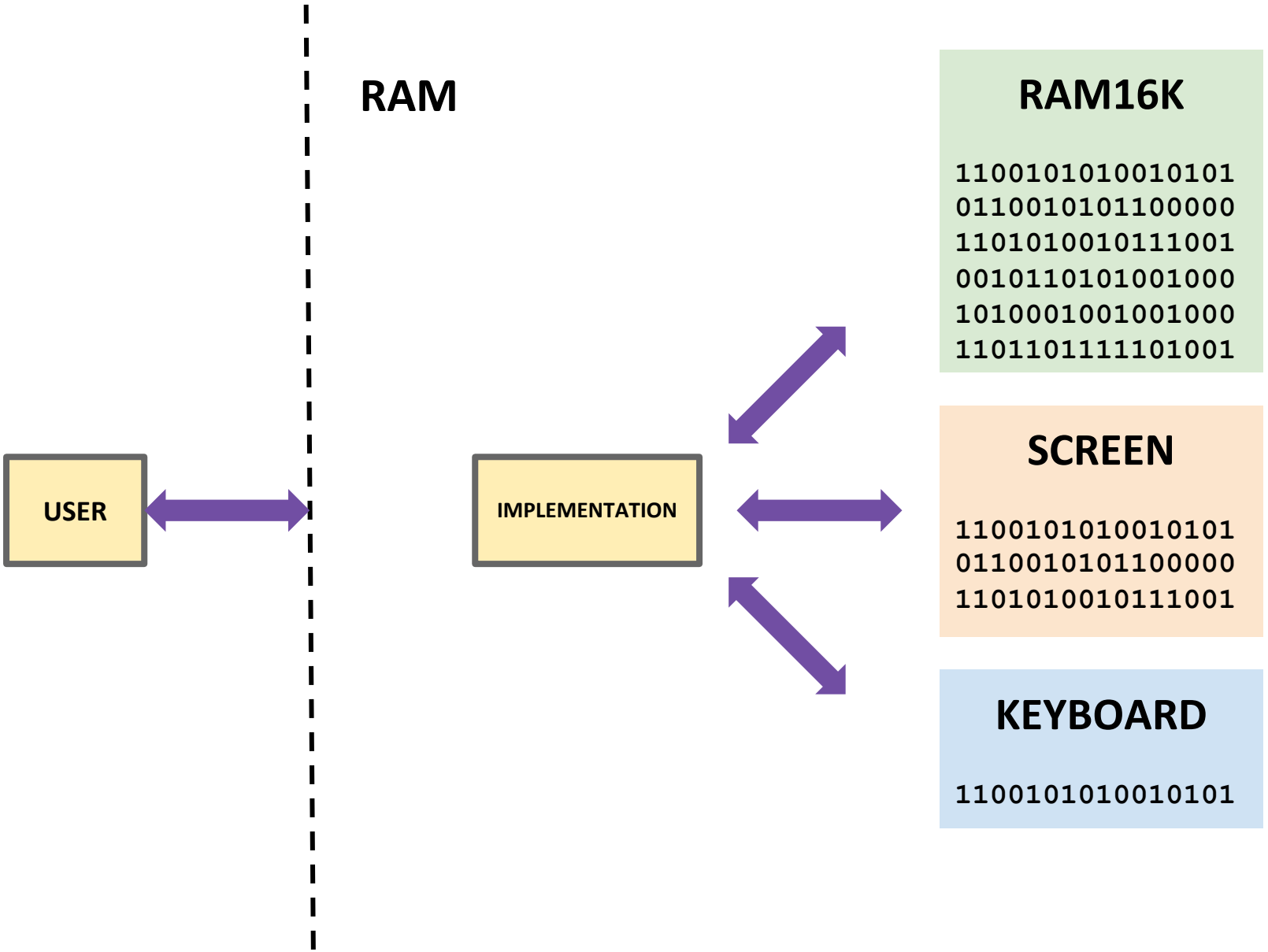
Hack: Internal Memory Implementation

- In reality, separate memory chips for memory devices is unnecessary
  - "Drivers" are code relaying changes in memory values to the device
- In Hack, it's not as simple as one **`RAM32K`** chip
  - Use internal **`SCREEN`** and **`KEYBOARD`** chips so our virtual computer can detect and show changes in the screen and keyboard
- Our memory chip has three subchips: **`SCREEN`**, **`KEYBOARD`**, and **`RAM16K`**
  - Process the address given by the programmer and relay the request to the appropriate subchip

Hack: Memory Abstraction User View



Hack: Memory Abstraction Internal View



Lecture 8: Annotation Strategies & Hack Assembly

When poll is active, respond at **PollEv.com/cse390b**

Which of the following statements is FALSE?

- Hexadecimal is useful because it's easier for humans to read while still being interpretable by a computer
- 0x390B in binary is 0b0011_1001_0000_1011
- 390 in hexadecimal is 0x186
- A programmer can only read from and write to the SCREEN and KEYBOARD parts of the Hack computer
- We're lost…

Total Results: 0

Powered by Poll Everywhere

Lecture Outline

- Strategies for Annotating Texts
  - Motivation and Techniques for Annotation
- Hack Assembly Language Review
  - Registers, A-Instructions, Symbols, & C-Instructions
- Hack Assembly Memory Representation
  - I/O, Memory Mapping, External vs. Internal Memory
- **Multiplication Implementation Exercise**
  - **Multiplying Two Numbers in Hack Assembly**

Exercise: Implementing Multiplication

- Write a program that multiplies **`R0`** and **`R1`** and stores the result in **`R2`**
  - Remember we don't have a multiply operation
  - We will have to use add and loops to get the job done

- Roadmap
  - Start with pseudocode using if statements, loops, etc.
  - Remove conditionals and loops by using jumps in pseudocode
  - Convert pseudocode to assembly

Exercise: Implementing Multiplication

- Goal: Implement $\mathrm{R0} \times \mathrm{R1} = \mathrm{R2}$

Pseudocode	Hack Assembly

Exercise: Implementing Multiplication

- Goal: Implement $\mathrm{R0} \times \mathrm{R1} = \mathrm{R2}$

Pseudocode	Hack Assembly
- Approach: add **`R0`** to the result **`R1`** times	

Exercise: Implementing Multiplication

- Goal: Implement $\mathrm{R0} \times \mathrm{R1} = \mathrm{R2}$

Pseudocode	Hack Assembly

- Approach: add **R0** to the result **R1** times
 	
`R2 = 0`
`while (R1 > 0) {`
`  R2 = R0 + R2`
`  R1 = R1 - 1`
`}`	

Exercise: Implementing Multiplication

- Remove loops from pseudocode
- Use labels to notate important sections of the code

```
R2 = 0
while (R1 > 0) {
    R2 = R0 + R2
    R1 = R1 - 1
}
```

```
START:
    R2 = 0
LOOP:
    R2 = R0 + R2
    R1 = R1 - 1
    IF R1 > 0 JMP LOOP
END:
    INFINITE LOOP
```

- Attempt 1: What happens when **R1** is 0? What should happen?

Exercise: Implementing Multiplication

- Remove loops from pseudocode
- Use labels to notate important sections of the code

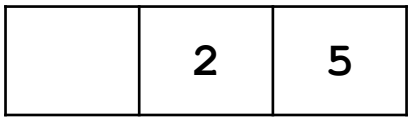
```
R2 = 0
while (R1 > 0) {
    R2 = R0 + R2
    R1 = R1 - 1
}
```

- Attempt 1: What happens when **R1** is 0? What should happen?

```
START:
  R2 = 0
LOOP:
    IF R1 <= 0
        JMP to END
    R2 = R0 + R2
    R1 = R1 - 1
    JMP LOOP
END:
    INFINITE LOOP
```

Exercise: Implementing Multiplication

- Convert to Hack Assembly

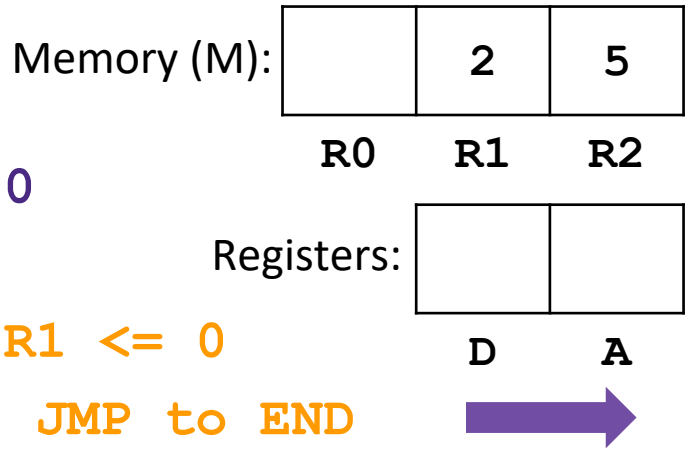



```
START:
   R2 = 0
LOOP:
      IF R1 <= 0
           JMP to END
      R2 = R0 + R2
      R1 = R1 - 1
      JMP LOOP
END:
      INFINITE LOOP
```

```
(START)
      @R2
      M = 0
(LOOP)
(END)
```

Exercise: Implementing Multiplication

- Convert to Hack Assembly

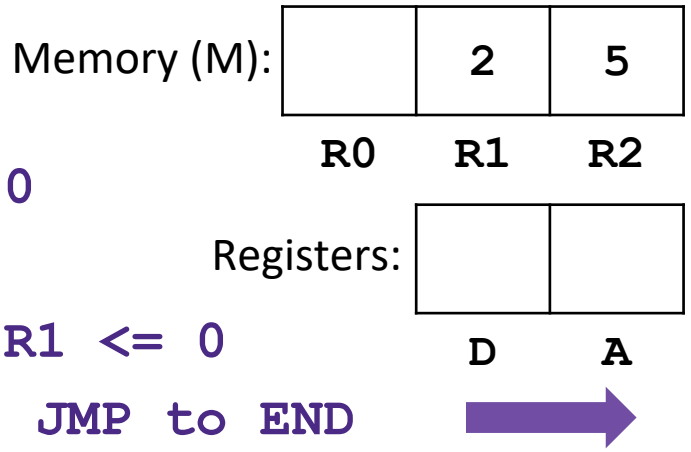



```
START:
   R2 = 0
LOOP:
     IF R1 <= 0
          JMP to END
     R2 = R0 + R2
     R1 = R1 - 1
     JMP LOOP
END:
     INFINITE LOOP
```

```
(START)
     @R2
     M = 0
(LOOP)
     @R1
     D = M
     @END
     D; JLE
(END)
```

Exercise: Implementing Multiplication

- Convert to Hack Assembly

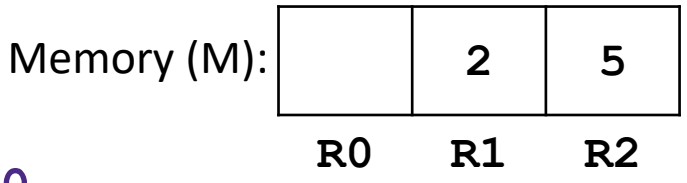



```
START:
  R2 = 0
LOOP:
     IF R1 <= 0
          JMP to END
     R2 = R0 + R2
     R1 = R1 - 1
     JMP LOOP
END:
     INFINITE LOOP
```

```
(START)
     @R2
     M = 0
(LOOP)
     @R1
     D = M
     @END
     D; JLE
     @R0
     D = M
     @R2
     M = M + D
(END)
```

Exercise: Implementing Multiplication

- Convert to Hack Assembly

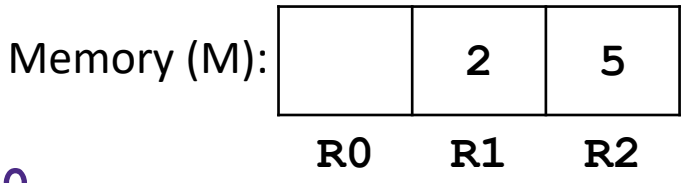



```
START:
   R2 = 0
LOOP:
      IF R1 <= 0
           JMP to END
      R2 = R0 + R2
      R1 = R1 - 1
      JMP LOOP
END:
      INFINITE LOOP
```

```
(START)
      @R2
      M = 0
(LOOP)
      @R1
      D = M
      @END
      D; JLE
      @R0
      D = M
      @R2
      M = M + D
      @R1
      M = M - 1
      @LOOP
      0; JMP
(END)
```

Exercise: Implementing Multiplication

- Convert to Hack Assembly

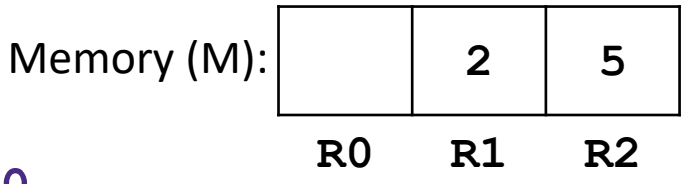



```
START:
  R2 = 0
LOOP:
     IF R1 <= 0
          JMP to END
     R2 = R0 + R2
     R1 = R1 - 1
     JMP LOOP
END:
     INFINITE LOOP
```

```
(START)
     @R2
     M = 0
(LOOP)
     @R1
     D = M
     @END
     D; JLE
     @R0
     D = M
     @R2
     M = M + D
     @R1
     M = M - 1
     @LOOP
     0; JMP
(END)
```

Exercise: Implementing Multiplication

- Convert to Hack Assembly




```
START:
   R2 = 0
LOOP:
      IF R1 <= 0
           JMP to END
      R2 = R0 + R2
      R1 = R1 - 1
      JMP LOOP
END:
      INFINITE LOOP
```

```
(START)
      @R2
      M = 0
(LOOP)
      @R1
      D = M
      @END
      D; JLE
      @R0
      D = M
      @R2
      M = M + D
      @R1
      M = M - 1
      @LOOP
      0; JMP
(END)
      @END
      0; JMP
```

Lecture Outline

- Hack Assembly Memory Representation
  - I/O, Memory Mapping, External vs. Internal Memory
- Hack Assembly Language Review
  - Registers, A-Instructions, Symbols, & C-Instructions
- Multiplication Implementation Exercise
  - Multiplying Two Numbers in Hack Assembly
- **Project 5 Overview**
  - **Specification Annotation, Machine Language, & Building Computer Memory**

Project 5 Overview

- Part I: Annotation
  - Come prepared to your upcoming Student-TA 1:1 meeting to work on Project 5 (e.g., specification reading and identifying annotation strategies you would want to use)
- Part II: Machine Language
  - Implement Max.asm in Hack Assembly
- Part III: Building Computer Memory
  - Implement Memory.hdl in HDL
- Part IV: Project 5 Reflection

Project 5, Part I: Annotation

- **Fill out the Assignment Timeline**
  - Divide up Project 5 into doable chunks for the days you plan to work on the assignment
  - Describe each day's task in as much detail as possible

- **Annotate the Project 5 Specification**
  - Identify five annotation strategies that you want to try
  - Practice these strategies on the Project 5 specification

- **Complete Annotation Reflection Questions**
  - Reflect on the strategies you used and why or why not they were effective

Annotate the Project 5 Specification

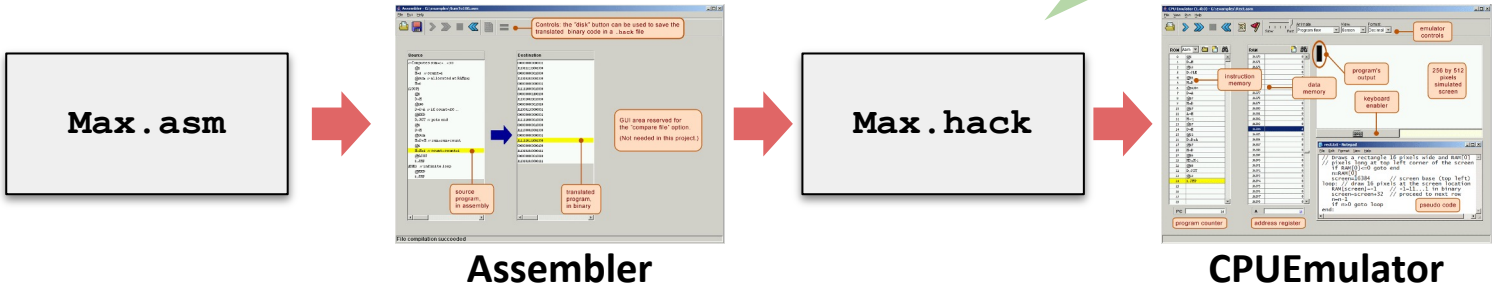
- We'll provide you with an opportunity to start annotating the Project 5 specification in class now

- Recall these annotation strategies:
  - Highlighting, underlining or using [brackets] to note key points or ideas
  - Circling unfamiliar words or confusing parts of the text
  - Paraphrasing or summarizing passages/chapters/sections
  - Commenting or reacting to the text 🤯

Project 5: Tools

- Running a Test Script (recommended flow):

The test scripts use the .hack files directly! Don't let your .asm and .hack get out of sync!



- Quickly Iterating or Experimenting:

Can still "run" the program, even without a script

Post-Lecture 8 Reminders

- **Project 4 due tonight (4/20) at 11:59pm**
- Project 5 (Annotation, Machine Language, & Building Computer Memory) released today, due next Thursday (4/27) at 11:59pm
- Today only: No office hours after class today (see Anam's announcement)
  - Please post any questions on the Ed board