Writing an Assembler: Part 2

Writing an Assembler with Labels

- For our first assembler, we made the simplifying assumption that **every line contains exactly one instruction or .word directive.**
- Let's remove this assumption, and also add support for labels.
- The general format of a MIPS line is *[labels] [instruction] [comment]*
  - **All three parts** are optional and can be omitted, but must appear **in order**.
    - A line can be completely blank.
    - A line can have only labels, only an instruction/directive, or only a comment.
    - A line can have labels+instruction, labels+comment, or instruction+comment.
    - A line can have all three parts (in the specified order only).

```
label: HELLO: meow241: beq $0, $0, meow241 ; three labels!
```

Extending Our Scanner

```
label: HELLO: meow241: beq $0, $0, meow241 ; three labels!
```

- This line illustrates the new syntax our scanner needs to support:
    - **Label definitions:** A sequence of *alphanumeric* characters (uppercase or lowercase) that *starts with an alphabet letter,* followed by a colon.
    - **Label uses:** Like a label definition, but without the colon.
    - **Comments:** A semicolon starts a comment. All characters up until the end of the line are part of the comment. (Discarded by the scanner)
- The changes to our DFA should be fairly straightforward…
- A minor issue: Instruction identifiers are also valid label names.

```
beq: beq $0, $0, beq
```

Extending Our Scanner

```
label: HELLO: meow241: beq $0, $0, meow241 ; three labels!
```

- Instruction identifiers are also valid label names, so to support labels, we will extend the definition of an identifier token:
  - An **Identifier** is a sequence of alphanumeric characters (uppercase or lowercase) that starts with an alphabet letter.
  - A **Label-Def** token is an **Identifier** followed by a colon.
  - Note this means that **label uses** are represented by **Identifier** tokens.
  - For consistency, **Dot-Identifiers** will follow the same rules as **Identifier** tokens except that they begin with a dot.
- A full MIPS scanning DFA is provided as a starter file for Project 1.

Extending our Parser

- Parsing MIPS instruction lines was fairly straightforward before.
  - Look up the required syntax based on the instruction name.
  - Match tokens against the required syntax to check for errors.
  - Extract important information for the synthesis phase.
- The scanner discards comments, but we do need to worry about blank lines and label definitions during parsing.
- If a line contains *zero tokens,* skip it.
- Otherwise, check if the first token is a *label definition.*
  - If so, process all labels on the line first. Then, check for an instruction or .word, and if one exists, process that as before.

Processing Labels

- Before we can explain what "processing labels" means, we need to back up and look at the big picture.

```
label: HELLO: meow241: beq $0, $0, meow241
```

- A line can have multiple label definitions before the instruction.
- Each label must have a **unique name**, not just within the line, but within the whole program. (No duplicate label definitions)
- Labels can be *used* in some instructions. For example, **beq $0, $0, meow241** uses the label called **meow241**.
    - Using a label that has no definition is an error! (No undefined label uses)

Labels and .word Directives

- Aside from beq and bne, labels can also be used as an argument to the .word directive.
- A line of the form ".word label" is equivalent to writing ".word i" where i is the memory address where the label is defined.
  - This address is computed assuming the program is loaded at address 0.
- What value does the program below place in $3?

```
lis $3
.word end
end: jr $31
```

- Answer: The address of the jr $31 instruction, which is 8 (because there are two 4-byte words preceding it).

Labels and Machine Language

- How do you encode a label in machine language?
- There is not enough space in our 32-bit instruction words to do something like encoding the name in ASCII.
- **All labels need to be converted to the appropriate integer values.**

```
loop: lis $7                        lis $7
      .word pool                    .word 0x0C
      beq $0, $0, loop              beq $0, $0, -3
pool: jr $31                        jr $31
```

- The program on the left and the program on the right get translated into the same machine code.

Summary of Label Problems

- We need to keep track of which labels have been defined.
- One reason is to check for **duplicate label definition errors.**
- Another is to check for **undefined label use errors.**
- We also need to keep track of *where* each label was defined to compute the corresponding numeric values for encoding.
- More precisely, assuming the program is loaded at address 0, for each label, we want to keep track of the memory address of the corresponding location in the program.
- We will create a **symbol table** that maps label names to addresses.

Symbol Table Example

```
main: lis $2
      .word beyond
      lis $1
      .word 2
      ; Hello, I'm a comment
      add $3, $0, $0


top: begin: ; Two labels on the same line
  add $3, $3, $2
  sub $2, $2, $1
  bne $2, $0, top ; Go to top
  jr $31
beyond: ; Label after last instruction
```

Symbol Table Example

Label definitions highlighted.

```
main: lis $2
      .word beyond
      lis $1
      .word 2
      ; Hello, I'm a comment
      add $3, $0, $0


top: begin: ; Two labels on the same line
  add $3, $3, $2
  sub $2, $2, $1
  bne $2, $0, top ; Go to top
  jr $31
beyond: ; Label after last instruction
```

Symbol Table Example

```
0x00    main: lis $2
0x04          .word beyond
0x08          lis $1
0x0c          .word 2
              ; Hello, I'm a comment
0x10          add $3, $0, $0


        top: begin: ; Two labels on the same line
0x14      add $3, $3, $2
0x18      sub $2, $2, $1
0x1c      bne $2, $0, top ; Go to top
0x20      jr $31
        beyond: ; Label after last instruction
```

Each line with an **instruction or .word** takes up 4 bytes (32 bits) in memory once assembled.

Other lines do not take up space in memory!!

Symbol Table Example

```
0x00    main: lis $2
0x04          .word beyond
0x08          lis $1
0x0c          .word 2
              ; Hello, I'm a comment
0x10          add $3, $0, $0


        top: begin: ; Two labels on the same line
0x14      add $3, $3, $2
0x18      sub $2, $2, $1
0x1c      bne $2, $0, top ; Go to top
0x20      jr $31
        beyond: ; Label after last instruction
```

Two views of label addresses:

- It's the address where the next instruction *after* the label is (or would be) located.
- Count the number of instruction lines *before* the definition and multiply by 4.

Symbol Table Example

```
0x00    main: lis $2
0x04          .word beyond
0x08          lis $1
0x0c          .word 2
              ; Hello, I'm a comment
0x10          add $3, $0, $0

        top: begin: ; Two labels on the same line
0x14      add $3, $3, $2
0x18      sub $2, $2, $1
0x1c      bne $2, $0, top ; Go to top
0x20      jr $31
        beyond: ; Label after last instruction
```

Two views of label addresses:

- It's the address where the next instruction *after* the label is (or would be) located.
- Count the number of instruction lines *before* the definition and multiply by 4.

Label	Address
main	0x00 (0 x 4 = 0)
top	0x14 (5 x 4 = 20)
begin	0x14 (5 x 4 = 20)
beyond	0x24 (9 x 4 = 36)

Symbol Table Implementation

- Keep track of a *counter* which you start at 0 and increment by 4 each time you encounter a line with an instruction or .word.
  - You can think of this as where **PC** will be when the instruction executes.
- When you encounter a label definition during parsing, add the pair (label name, PC counter) to the symbol table.
- Check first if the pair already exists in the table. If so, this is a *duplicate label definition error*.
- Although you catch this error while parsing lines, it is an example of a semantic error (an error in *meaning* rather than *syntax*).

Symbol Table Data Structures

- Use a data structure with efficient lookups.
- A vector or list of pairs will be slow.
    - Lookups are linear time, so the performance could be quadratic in the number of labels.
- A map (using a hash table or binary tree) is a good choice.
    - In C++, std::map (probably) uses a binary tree, and std::unordered_map uses a hash table.
    - In Racket, you can use (hash …) or (make-hash …)

Replacing Labels

- Assembling ".word label" is equivalent to assembling ".word i", where i is the location of the label.
- Assembling "beq $0, $0, label" is trickier because we need to convert the label to an *offset from PC*.
- Let's think about what happens when we branch.
- Desired effect: PC is set to the address of the label (PC = address).
- Branching does PC += offset * 4, so we want: PC + (offset * 4) = address.
- Basic algebra gives the formula: **offset = (address – PC) / 4**.
- Conveniently, when we read the branch instruction, the counter we use to determine label addresses will contain the required value of PC!

Synthesis with Labels

- Synthesis works just as before once labels have been translated into the appropriate numeric values.
- There are two issues:
    - What if we try to assemble an instruction that uses a label, and the label turns out to be undefined? (See the following slides.)
    - When assembling a branch instruction, what if the formula **(address – PC) / 4** gives a value that is *outside the 16-bit two's complement range?*
- The out-of-range issue requires a rather large program to occur, but it is possible! You need to check for this and report an error.

The Forward Reference Problem

- We still haven't seen how to deal with this very common situation:

```
bne $1, $2, notEqual
…
notEqual:
```

- Here the label definition appears **after** the branch, so it's not in our symbol table when we first encounter the branch instruction.
- In C/C++ this is solved by requiring "forward declarations" of symbols that are used before their definition.
- But MIPS assembly allows labels to be freely defined anywhere.

Two-Pass Assembly

- A simple way of dealing with forward references, i.e., references to names that are not yet defined, is to do *two passes* over the source.
- **Pass 1:** Build a complete symbol table.
- **Pass 2:** Resolve label references.
  - In Pass 1, parse the instructions and store the parsed lines in a data structure. Pass 2 is over the contents of this data structure.
- The two passes are *not* an "analysis pass" and a "synthesis pass".
  - Duplicate label are checked in Pass 1 while the symbol table is being built.
  - Undefined label errors and out-of-range branch offset errors must be checked in Pass 2 since this requires knowing label addresses.

Dealing with Labels: Summary

- Implement the assembler in **two passes**.
- The first pass builds a **symbol table** containing a mapping of label names to label locations.
- The second pass uses this table for error checking and synthesis.
- Duplicate label errors are caught in the first pass, undefined label errors and branch offset range errors are caught in the second pass.
- Analysis can otherwise be split across both passes as you see fit.
- For .word with labels, the label is replaced with its value in the symbol table. For branching with labels, use a formula to compute the offset.

Assembler Complete!

- We've covered enough to write a complete MIPS assembler that supports labels.
- In Project 2, you will implement such an assembler yourself.
- Now that we can write complex programs more conveniently, we'll dive even deeper into MIPS programming.
- We'll first discuss **arrays** in more detail, then learn how to implement **procedures** (not in this lecture).
- We will see how to manage the associated memory by using part of RAM as a **stack**.
- You will see how recursion actually works at a low level!

MIPS Assembly Language Programming: Part 2

Arrays Revisited

- An array like "int A[3] = {1,2,3};" would be stored as follows in memory.
- To access element A[i], you need to multiply i by 4 and add it to the starting address of the array A.
- The Load Word (lw) and Store Word (sw) instructions read or write entire words.

A[0]	MEM[address of A]	00000000
	MEM[address of A + 1]	00000000
	MEM[address of A + 2]	00000000
	MEM[address of A + 3]	00000001
A[1]	MEM[address of A + 4]	00000000
	MEM[address of A + 5]	00000000
	MEM[address of A + 6]	00000000
	MEM[address of A + 7]	00000010
A[2]	MEM[address of A + 8]	00000000
	MEM[address of A + 9]	00000000
	MEM[address of A + 10]	00000000
	MEM[address of A + 11]	00000011

Tracing an Array Loop

- The following program sets all elements of an array to 0.

```
   ; $1 contains the starting address of A
   ; $2 contains the size of A
   lis $11
   .word 1
   lis $4
   .word 4
   add $5, $0, $0        ; $5 holds i
PC for: slt $6, $5, $2   ; $6 is 1 if i < n, 0 otherwise
        beq $6, $0, end  ; Go to end if i < n is false
        mult $5, $4
        mflo $6          ; $6 = i * 4
        add $6, $1, $6   ; $6 = address of A[i]
        sw $0, 0($6)     ; A[i] = 0
        add $5, $5, $11  ; i += 1
        beq $0, $0, for  ; back to top of loop
   end: jr $31
```

A[0]	MEM[address of A]	00000000
	MEM[address of A + 1]	00000000
	MEM[address of A + 2]	00000000
	MEM[address of A + 3]	00000001
A[1]	MEM[address of A + 4]	00000000
	MEM[address of A + 5]	00000000
	MEM[address of A + 6]	00000000
	MEM[address of A + 7]	00000010
A[2]	MEM[address of A + 8]	00000000
	MEM[address of A + 9]	00000000
	MEM[address of A + 10]	00000000
	MEM[address of A + 11]	00000011

```
$1 = address of A[0]   $2 = 3
$6 = ?                 $5 = 0
```

Tracing an Array Loop

- The following program sets all elements of an array to 0.

```
    ; $1 contains the starting address of A
    ; $2 contains the size of A
    lis $11
    .word 1
    lis $4
    .word 4
    add $5, $0, $0       ; $5 holds i
    for: slt $6, $5, $2  ; $6 is 1 if i < n, 0 otherwise
PC       beq $6, $0, end ; Go to end if i < n is false
         mult $5, $4
         mflo $6         ; $6 = i * 4
         add $6, $1, $6  ; $6 = address of A[i]
         sw $0, 0($6)    ; A[i] = 0
         add $5, $5, $11 ; i += 1
         beq $0, $0, for ; back to top of loop
    end: jr $31
```

A[0]	MEM[address of A]	00000000
	MEM[address of A + 1]	00000000
	MEM[address of A + 2]	00000000
	MEM[address of A + 3]	00000001
A[1]	MEM[address of A + 4]	00000000
	MEM[address of A + 5]	00000000
	MEM[address of A + 6]	00000000
	MEM[address of A + 7]	00000010
A[2]	MEM[address of A + 8]	00000000
	MEM[address of A + 9]	00000000
	MEM[address of A + 10]	00000000
	MEM[address of A + 11]	00000011

`$1 = address of A[0]`   `$2 = 3`

`$6 = 1`   `$5 = 0`

Tracing an Array Loop

- The following program sets all elements of an array to 0.

```
   ; $1 contains the starting address of A
   ; $2 contains the size of A
   lis $11
   .word 1
   lis $4
   .word 4
   add $5, $0, $0       ; $5 holds i
   for: slt $6, $5, $2  ; $6 is 1 if i < n, 0 otherwise
        beq $6, $0, end ; Go to end if i < n is false
PC      mult $5, $4
        mflo $6         ; $6 = i * 4
        add $6, $1, $6  ; $6 = address of A[i]
        sw $0, 0($6)    ; A[i] = 0
        add $5, $5, $11 ; i += 1
        beq $0, $0, for ; back to top of loop
   end: jr $31
```

A[0]	MEM[address of A]	00000000
	MEM[address of A + 1]	00000000
	MEM[address of A + 2]	00000000
	MEM[address of A + 3]	00000001
A[1]	MEM[address of A + 4]	00000000
	MEM[address of A + 5]	00000000
	MEM[address of A + 6]	00000000
	MEM[address of A + 7]	00000010
A[2]	MEM[address of A + 8]	00000000
	MEM[address of A + 9]	00000000
	MEM[address of A + 10]	00000000
	MEM[address of A + 11]	00000011

`$1 = address of A[0]` `$2 = 3`
`$6 = 1` `$5 = 0`

Tracing an Array Loop

- The following program sets all elements of an array to 0.

```
    ; $1 contains the starting address of A
    ; $2 contains the size of A
    lis $11
    .word 1
    lis $4
    .word 4
    add $5, $0, $0       ; $5 holds i
    for: slt $6, $5, $2  ; $6 is 1 if i < n, 0 otherwise
         beq $6, $0, end ; Go to end if i < n is false
         mult $5, $4
PC       mflo $6         ; $6 = i * 4
         add $6, $1, $6  ; $6 = address of A[i]
         sw $0, 0($6)    ; A[i] = 0
         add $5, $5, $11 ; i += 1
         beq $0, $0, for ; back to top of loop
    end: jr $31
```

A[0]	MEM[address of A]	00000000
	MEM[address of A + 1]	00000000
	MEM[address of A + 2]	00000000
	MEM[address of A + 3]	00000001
A[1]	MEM[address of A + 4]	00000000
	MEM[address of A + 5]	00000000
	MEM[address of A + 6]	00000000
	MEM[address of A + 7]	00000010
A[2]	MEM[address of A + 8]	00000000
	MEM[address of A + 9]	00000000
	MEM[address of A + 10]	00000000
	MEM[address of A + 11]	00000011

$1 = address of A[0] $2 = 3

$6 = 1 **lo** = 0 $5 = 0

Tracing an Array Loop

- The following program sets all elements of an array to 0.

```
    ; $1 contains the starting address of A
    ; $2 contains the size of A
    lis $11
    .word 1
    lis $4
    .word 4
    add $5, $0, $0      ; $5 holds i
    for: slt $6, $5, $2 ; $6 is 1 if i < n, 0 otherwise
         beq $6, $0, end ; Go to end if i < n is false
         mult $5, $4
         mflo $6        ; $6 = i * 4
PC       add $6, $1, $6 ; $6 = address of A[i]
         sw $0, 0($6)   ; A[i] = 0
         add $5, $5, $11 ; i += 1
         beq $0, $0, for ; back to top of loop
    end: jr $31
```

A[0]	MEM[address of A]	00000000
	MEM[address of A + 1]	00000000
	MEM[address of A + 2]	00000000
	MEM[address of A + 3]	00000001
A[1]	MEM[address of A + 4]	00000000
	MEM[address of A + 5]	00000000
	MEM[address of A + 6]	00000000
	MEM[address of A + 7]	00000010
A[2]	MEM[address of A + 8]	00000000
	MEM[address of A + 9]	00000000
	MEM[address of A + 10]	00000000
	MEM[address of A + 11]	00000011

`$1 = address of A[0]` `$2 = 3`

`$6 = 0` `$5 = 0`

Tracing an Array Loop

- The following program sets all elements of an array to 0.

```
    ; $1 contains the starting address of A
    ; $2 contains the size of A
    lis $11
    .word 1
    lis $4
    .word 4
    add $5, $0, $0       ; $5 holds i
    for: slt $6, $5, $2  ; $6 is 1 if i < n, 0 otherwise
         beq $6, $0, end ; Go to end if i < n is false
         mult $5, $4
         mflo $6         ; $6 = i * 4
         add $6, $1, $6  ; $6 = address of A[i]
PC       sw $0, 0($6)    ; A[i] = 0
         add $5, $5, $11 ; i += 1
         beq $0, $0, for ; back to top of loop
    end: jr $31
```

A[0]	MEM[address of A]	00000000
	MEM[address of A + 1]	00000000
	MEM[address of A + 2]	00000000
	MEM[address of A + 3]	00000001
A[1]	MEM[address of A + 4]	00000000
	MEM[address of A + 5]	00000000
	MEM[address of A + 6]	00000000
	MEM[address of A + 7]	00000010
A[2]	MEM[address of A + 8]	00000000
	MEM[address of A + 9]	00000000
	MEM[address of A + 10]	00000000
	MEM[address of A + 11]	00000011

`$1 = address of A[0]   $2 = 3`

`$6 = address of A[0]   $5 = 0`

Tracing an Array Loop

- The following program sets all elements of an array to 0.

```
    ; $1 contains the starting address of A
    ; $2 contains the size of A
    lis $11
    .word 1
    lis $4
    .word 4
    add $5, $0, $0       ; $5 holds i
    for: slt $6, $5, $2  ; $6 is 1 if i < n, 0 otherwise
         beq $6, $0, end ; Go to end if i < n is false
         mult $5, $4
         mflo $6         ; $6 = i * 4
         add $6, $1, $6  ; $6 = address of A[i]
         sw $0, 0($6)    ; A[i] = 0
PC       add $5, $5, $11 ; i += 1
         beq $0, $0, for ; back to top of loop
    end: jr $31
```

A[0]	**MEM[address of A]**	**00000000**
	MEM[address of A + 1]	**00000000**
	MEM[address of A + 2]	**00000000**
	MEM[address of A + 3]	**00000000**
A[1]	MEM[address of A + 4]	00000000
	MEM[address of A + 5]	00000000
	MEM[address of A + 6]	00000000
	MEM[address of A + 7]	00000010
A[2]	MEM[address of A + 8]	00000000
	MEM[address of A + 9]	00000000
	MEM[address of A + 10]	00000000
	MEM[address of A + 11]	00000011

$1 = address of A[0] $2 = 3

$6 = address of A[0] $5 = 0

Tracing an Array Loop

- The following program sets all elements of an array to 0.

```
   ; $1 contains the starting address of A
   ; $2 contains the size of A
   lis $11
   .word 1
   lis $4
   .word 4
   add $5, $0, $0       ; $5 holds i
   for: slt $6, $5, $2  ; $6 is 1 if i < n, 0 otherwise
        beq $6, $0, end ; Go to end if i < n is false
        mult $5, $4
        mflo $6         ; $6 = i * 4
        add $6, $1, $6  ; $6 = address of A[i]
        sw $0, 0($6)    ; A[i] = 0
        add $5, $5, $11 ; i += 1
PC      beq $0, $0, for ; back to top of loop
   end: jr $31
```

A[0]	MEM[address of A]	00000000
	MEM[address of A + 1]	00000000
	MEM[address of A + 2]	00000000
	MEM[address of A + 3]	00000000
A[1]	MEM[address of A + 4]	00000000
	MEM[address of A + 5]	00000000
	MEM[address of A + 6]	00000000
	MEM[address of A + 7]	00000010
A[2]	MEM[address of A + 8]	00000000
	MEM[address of A + 9]	00000000
	MEM[address of A + 10]	00000000
	MEM[address of A + 11]	00000011

`$1 = address of A[0]`   `$2 = 3`

`$6 = address of A[0]`   **`$5 = 1`**

Tracing an Array Loop

- The following program sets all elements of an array to 0.

```
   ; $1 contains the starting address of A
   ; $2 contains the size of A
   lis $11
   .word 1
   lis $4
   .word 4
   add $5, $0, $0       ; $5 holds i
PC for: slt $6, $5, $2  ; $6 is 1 if i < n, 0 otherwise
        beq $6, $0, end ; Go to end if i < n is false
        mult $5, $4
        mflo $6         ; $6 = i * 4
        add $6, $1, $6  ; $6 = address of A[i]
        sw $0, 0($6)    ; A[i] = 0
        add $5, $5, $11 ; i += 1
        beq $0, $0, for ; back to top of loop
   end: jr $31
```

A[0]	MEM[address of A]	00000000
	MEM[address of A + 1]	00000000
	MEM[address of A + 2]	00000000
	MEM[address of A + 3]	00000000
A[1]	MEM[address of A + 4]	00000000
	MEM[address of A + 5]	00000000
	MEM[address of A + 6]	00000000
	MEM[address of A + 7]	00000010
A[2]	MEM[address of A + 8]	00000000
	MEM[address of A + 9]	00000000
	MEM[address of A + 10]	00000000
	MEM[address of A + 11]	00000011

$1 = address of A[0] $2 = 3
$6 = address of A[0] $5 = 1

Tracing an Array Loop

- The following program sets all elements of an array to 0.

```
    ; $1 contains the starting address of A
    ; $2 contains the size of A
    lis $11
    .word 1
    lis $4
    .word 4
    add $5, $0, $0       ; $5 holds i
    for: slt $6, $5, $2  ; $6 is 1 if i < n, 0 otherwise
PC       beq $6, $0, end ; Go to end if i < n is false
         mult $5, $4
         mflo $6         ; $6 = i * 4
         add $6, $1, $6  ; $6 = address of A[i]
         sw $0, 0($6)    ; A[i] = 0
         add $5, $5, $11 ; i += 1
         beq $0, $0, for ; back to top of loop
    end: jr $31
```

A[0]	MEM[address of A]	00000000
	MEM[address of A + 1]	00000000
	MEM[address of A + 2]	00000000
	MEM[address of A + 3]	00000000
A[1]	MEM[address of A + 4]	00000000
	MEM[address of A + 5]	00000000
	MEM[address of A + 6]	00000000
	MEM[address of A + 7]	00000010
A[2]	MEM[address of A + 8]	00000000
	MEM[address of A + 9]	00000000
	MEM[address of A + 10]	00000000
	MEM[address of A + 11]	00000011

```
$1 = address of A[0]   $2 = 3
$6 = 1                 $5 = 1
```

Tracing an Array Loop

- The following program sets all elements of an array to 0.

```
    ; $1 contains the starting address of A
    ; $2 contains the size of A
    lis $11
    .word 1
    lis $4
    .word 4
    add $5, $0, $0       ; $5 holds i
    for: slt $6, $5, $2  ; $6 is 1 if i < n, 0 otherwise
         beq $6, $0, end ; Go to end if i < n is false
PC       mult $5, $4
         mflo $6         ; $6 = i * 4
         add $6, $1, $6  ; $6 = address of A[i]
         sw $0, 0($6)    ; A[i] = 0
         add $5, $5, $11 ; i += 1
         beq $0, $0, for ; back to top of loop
    end: jr $31
```

A[0]	MEM[address of A]	00000000
	MEM[address of A + 1]	00000000
	MEM[address of A + 2]	00000000
	MEM[address of A + 3]	00000000
A[1]	MEM[address of A + 4]	00000000
	MEM[address of A + 5]	00000000
	MEM[address of A + 6]	00000000
	MEM[address of A + 7]	00000010
A[2]	MEM[address of A + 8]	00000000
	MEM[address of A + 9]	00000000
	MEM[address of A + 10]	00000000
	MEM[address of A + 11]	00000011

`$1 = address of A[0]` `$2 = 3`

`$6 = 1` `$5 = 1`

Tracing an Array Loop

- The following program sets all elements of an array to 0.

```
   ; $1 contains the starting address of A
   ; $2 contains the size of A
   lis $11
   .word 1
   lis $4
   .word 4
   add $5, $0, $0       ; $5 holds i
   for: slt $6, $5, $2  ; $6 is 1 if i < n, 0 otherwise
        beq $6, $0, end ; Go to end if i < n is false
        mult $5, $4
PC      mflo $6         ; $6 = i * 4
        add $6, $1, $6  ; $6 = address of A[i]
        sw $0, 0($6)    ; A[i] = 0
        add $5, $5, $11 ; i += 1
        beq $0, $0, for ; back to top of loop
   end: jr $31
```

A[0]	MEM[address of A]	00000000
	MEM[address of A + 1]	00000000
	MEM[address of A + 2]	00000000
	MEM[address of A + 3]	00000000
A[1]	MEM[address of A + 4]	00000000
	MEM[address of A + 5]	00000000
	MEM[address of A + 6]	00000000
	MEM[address of A + 7]	00000010
A[2]	MEM[address of A + 8]	00000000
	MEM[address of A + 9]	00000000
	MEM[address of A + 10]	00000000
	MEM[address of A + 11]	00000011

`$1 = address of A[0]` `$2 = 3`

`$6 = 1` **`lo = 4`** `$5 = 1`

Tracing an Array Loop

- The following program sets all elements of an array to 0.

```
   ; $1 contains the starting address of A
   ; $2 contains the size of A
   lis $11
   .word 1
   lis $4
   .word 4
   add $5, $0, $0       ; $5 holds i
   for: slt $6, $5, $2  ; $6 is 1 if i < n, 0 otherwise
        beq $6, $0, end ; Go to end if i < n is false
        mult $5, $4
        mflo $6         ; $6 = i * 4
PC      add $6, $1, $6  ; $6 = address of A[i]
        sw $0, 0($6)    ; A[i] = 0
        add $5, $5, $11 ; i += 1
        beq $0, $0, for ; back to top of loop
   end: jr $31
```

A[0]	MEM[address of A]	00000000
	MEM[address of A + 1]	00000000
	MEM[address of A + 2]	00000000
	MEM[address of A + 3]	00000000
A[1]	MEM[address of A + 4]	00000000
	MEM[address of A + 5]	00000000
	MEM[address of A + 6]	00000000
	MEM[address of A + 7]	00000010
A[2]	MEM[address of A + 8]	00000000
	MEM[address of A + 9]	00000000
	MEM[address of A + 10]	00000000
	MEM[address of A + 11]	00000011

`$1 = address of A[0]    $2 = 3`

`$6 = 4`   `$5 = 1`

Tracing an Array Loop

- The following program sets all elements of an array to 0.

```
    ; $1 contains the starting address of A
    ; $2 contains the size of A
    lis $11
    .word 1
    lis $4
    .word 4
    add $5, $0, $0       ; $5 holds i
    for: slt $6, $5, $2  ; $6 is 1 if i < n, 0 otherwise
         beq $6, $0, end ; Go to end if i < n is false
         mult $5, $4
         mflo $6         ; $6 = i * 4
         add $6, $1, $6  ; $6 = address of A[i]
PC       sw $0, 0($6)    ; A[i] = 0
         add $5, $5, $11 ; i += 1
         beq $0, $0, for ; back to top of loop
    end: jr $31
```

A[0]	MEM[address of A]	00000000
	MEM[address of A + 1]	00000000
	MEM[address of A + 2]	00000000
	MEM[address of A + 3]	00000000
A[1]	MEM[address of A + 4]	00000000
	MEM[address of A + 5]	00000000
	MEM[address of A + 6]	00000000
	MEM[address of A + 7]	00000010
A[2]	MEM[address of A + 8]	00000000
	MEM[address of A + 9]	00000000
	MEM[address of A + 10]	00000000
	MEM[address of A + 11]	00000011

$1 = address of A[0] $2 = 3

$6 = address of A[1] $5 = 1

Tracing an Array Loop

- The following program sets all elements of an array to 0.

```
    ; $1 contains the starting address of A
    ; $2 contains the size of A
    lis $11
    .word 1
    lis $4
    .word 4
    add $5, $0, $0       ; $5 holds i
    for: slt $6, $5, $2  ; $6 is 1 if i < n, 0 otherwise
         beq $6, $0, end ; Go to end if i < n is false
         mult $5, $4
         mflo $6         ; $6 = i * 4
         add $6, $1, $6  ; $6 = address of A[i]
         sw $0, 0($6)    ; A[i] = 0
PC       add $5, $5, $11 ; i += 1
         beq $0, $0, for ; back to top of loop
    end: jr $31
```

A[0]	MEM[address of A]	00000000
	MEM[address of A + 1]	00000000
	MEM[address of A + 2]	00000000
	MEM[address of A + 3]	00000000
A[1]	**MEM[address of A + 4]**	**00000000**
	MEM[address of A + 5]	**00000000**
	MEM[address of A + 6]	**00000000**
	MEM[address of A + 7]	**00000000**
A[2]	MEM[address of A + 8]	00000000
	MEM[address of A + 9]	00000000
	MEM[address of A + 10]	00000000
	MEM[address of A + 11]	00000011

```
$1 = address of A[0]   $2 = 3
$6 = address of A[1]   $5 = 1
```

Tracing an Array Loop

- The following program sets all elements of an array to 0.

```
   ; $1 contains the starting address of A
   ; $2 contains the size of A
   lis $11
   .word 1
   lis $4
   .word 4
   add $5, $0, $0       ; $5 holds i
   for: slt $6, $5, $2  ; $6 is 1 if i < n, 0 otherwise
        beq $6, $0, end ; Go to end if i < n is false
        mult $5, $4
        mflo $6         ; $6 = i * 4
        add $6, $1, $6  ; $6 = address of A[i]
        sw $0, 0($6)    ; A[i] = 0
        add $5, $5, $11 ; i += 1
PC      beq $0, $0, for ; back to top of loop
   end: jr $31
```

A[0]	MEM[address of A]	00000000
	MEM[address of A + 1]	00000000
	MEM[address of A + 2]	00000000
	MEM[address of A + 3]	00000000
A[1]	MEM[address of A + 4]	00000000
	MEM[address of A + 5]	00000000
	MEM[address of A + 6]	00000000
	MEM[address of A + 7]	00000000
A[2]	MEM[address of A + 8]	00000000
	MEM[address of A + 9]	00000000
	MEM[address of A + 10]	00000000
	MEM[address of A + 11]	00000011

`$1 = address of A[0]`   `$2 = 3`
`$6 = address of A[1]`   **`$5 = 2`**

Tracing an Array Loop

- The following program sets all elements of an array to 0.

```
   ; $1 contains the starting address of A
   ; $2 contains the size of A
   lis $11
   .word 1
   lis $4
   .word 4
   add $5, $0, $0       ; $5 holds i
PC for: slt $6, $5, $2  ; $6 is 1 if i < n, 0 otherwise
        beq $6, $0, end ; Go to end if i < n is false
        mult $5, $4
        mflo $6         ; $6 = i * 4
        add $6, $1, $6  ; $6 = address of A[i]
        sw $0, 0($6)    ; A[i] = 0
        add $5, $5, $11 ; i += 1
        beq $0, $0, for ; back to top of loop
   end: jr $31
```

A[0]	MEM[address of A]	00000000
	MEM[address of A + 1]	00000000
	MEM[address of A + 2]	00000000
	MEM[address of A + 3]	00000000
A[1]	MEM[address of A + 4]	00000000
	MEM[address of A + 5]	00000000
	MEM[address of A + 6]	00000000
	MEM[address of A + 7]	00000000
A[2]	MEM[address of A + 8]	00000000
	MEM[address of A + 9]	00000000
	MEM[address of A + 10]	00000000
	MEM[address of A + 11]	00000011

$1 = address of A[0] $2 = 3

$6 = address of A[1] $5 = 2

Tracing an Array Loop

- The following program sets all elements of an array to 0.

```
    ; $1 contains the starting address of A
    ; $2 contains the size of A
    lis $11
    .word 1
    lis $4
    .word 4
    add $5, $0, $0       ; $5 holds i
    for: slt $6, $5, $2  ; $6 is 1 if i < n, 0 otherwise
PC       beq $6, $0, end ; Go to end if i < n is false
         mult $5, $4
         mflo $6         ; $6 = i * 4
         add $6, $1, $6  ; $6 = address of A[i]
         sw $0, 0($6)    ; A[i] = 0
         add $5, $5, $11 ; i += 1
         beq $0, $0, for ; back to top of loop
    end: jr $31
```

A[0]	MEM[address of A]	00000000
	MEM[address of A + 1]	00000000
	MEM[address of A + 2]	00000000
	MEM[address of A + 3]	00000000
A[1]	MEM[address of A + 4]	00000000
	MEM[address of A + 5]	00000000
	MEM[address of A + 6]	00000000
	MEM[address of A + 7]	00000000
A[2]	MEM[address of A + 8]	00000000
	MEM[address of A + 9]	00000000
	MEM[address of A + 10]	00000000
	MEM[address of A + 11]	00000011

$1 = address of A[0] $2 = 3
$6 = 1 $5 = 2

Tracing an Array Loop

- The following program sets all elements of an array to 0.

```
   ; $1 contains the starting address of A
   ; $2 contains the size of A
   lis $11
   .word 1
   lis $4
   .word 4
   add $5, $0, $0       ; $5 holds i
   for: slt $6, $5, $2  ; $6 is 1 if i < n, 0 otherwise
        beq $6, $0, end ; Go to end if i < n is false
PC      mult $5, $4
        mflo $6         ; $6 = i * 4
        add $6, $1, $6  ; $6 = address of A[i]
        sw $0, 0($6)    ; A[i] = 0
        add $5, $5, $11 ; i += 1
        beq $0, $0, for ; back to top of loop
   end: jr $31
```

A[0]	MEM[address of A]	00000000
	MEM[address of A + 1]	00000000
	MEM[address of A + 2]	00000000
	MEM[address of A + 3]	00000000
A[1]	MEM[address of A + 4]	00000000
	MEM[address of A + 5]	00000000
	MEM[address of A + 6]	00000000
	MEM[address of A + 7]	00000000
A[2]	MEM[address of A + 8]	00000000
	MEM[address of A + 9]	00000000
	MEM[address of A + 10]	00000000
	MEM[address of A + 11]	00000011

$1 = address of A[0]

$2 = 3

$6 = 1

$5 = 2

Tracing an Array Loop

- The following program sets all elements of an array to 0.

```
    ; $1 contains the starting address of A
    ; $2 contains the size of A
    lis $11
    .word 1
    lis $4
    .word 4
    add $5, $0, $0       ; $5 holds i
    for: slt $6, $5, $2  ; $6 is 1 if i < n, 0 otherwise
         beq $6, $0, end ; Go to end if i < n is false
         mult $5, $4
PC       mflo $6         ; $6 = i * 4
         add $6, $1, $6  ; $6 = address of A[i]
         sw $0, 0($6)    ; A[i] = 0
         add $5, $5, $11 ; i += 1
         beq $0, $0, for ; back to top of loop
    end: jr $31
```

A[0]	MEM[address of A]	00000000
	MEM[address of A + 1]	00000000
	MEM[address of A + 2]	00000000
	MEM[address of A + 3]	00000000
A[1]	MEM[address of A + 4]	00000000
	MEM[address of A + 5]	00000000
	MEM[address of A + 6]	00000000
	MEM[address of A + 7]	00000000
A[2]	MEM[address of A + 8]	00000000
	MEM[address of A + 9]	00000000
	MEM[address of A + 10]	00000000
	MEM[address of A + 11]	00000011

```
$1 = address of A[0]   $2 = 3
$6 = 1  lo = 8         $5 = 2
```

Tracing an Array Loop

- The following program sets all elements of an array to 0.

```
    ; $1 contains the starting address of A
    ; $2 contains the size of A
    lis $11
    .word 1
    lis $4
    .word 4
    add $5, $0, $0       ; $5 holds i
    for: slt $6, $5, $2  ; $6 is 1 if i < n, 0 otherwise
         beq $6, $0, end ; Go to end if i < n is false
         mult $5, $4
         mflo $6         ; $6 = i * 4
PC       add $6, $1, $6  ; $6 = address of A[i]
         sw $0, 0($6)    ; A[i] = 0
         add $5, $5, $11 ; i += 1
         beq $0, $0, for ; back to top of loop
    end: jr $31
```

A[0]	MEM[address of A]	00000000
	MEM[address of A + 1]	00000000
	MEM[address of A + 2]	00000000
	MEM[address of A + 3]	00000000
A[1]	MEM[address of A + 4]	00000000
	MEM[address of A + 5]	00000000
	MEM[address of A + 6]	00000000
	MEM[address of A + 7]	00000000
A[2]	MEM[address of A + 8]	00000000
	MEM[address of A + 9]	00000000
	MEM[address of A + 10]	00000000
	MEM[address of A + 11]	00000011

$1 = address of A[0] $2 = 3
$6 = 8 $5 = 2

Tracing an Array Loop

- The following program sets all elements of an array to 0.

```
    ; $1 contains the starting address of A
    ; $2 contains the size of A
    lis $11
    .word 1
    lis $4
    .word 4
    add $5, $0, $0      ; $5 holds i
    for: slt $6, $5, $2  ; $6 is 1 if i < n, 0 otherwise
         beq $6, $0, end ; Go to end if i < n is false
         mult $5, $4
         mflo $6         ; $6 = i * 4
         add $6, $1, $6  ; $6 = address of A[i]
PC       sw $0, 0($6)    ; A[i] = 0
         add $5, $5, $11 ; i += 1
         beq $0, $0, for ; back to top of loop
    end: jr $31
```

A[0]	MEM[address of A]	00000000
	MEM[address of A + 1]	00000000
	MEM[address of A + 2]	00000000
	MEM[address of A + 3]	00000000
A[1]	MEM[address of A + 4]	00000000
	MEM[address of A + 5]	00000000
	MEM[address of A + 6]	00000000
	MEM[address of A + 7]	00000000
A[2]	MEM[address of A + 8]	00000000
	MEM[address of A + 9]	00000000
	MEM[address of A + 10]	00000000
	MEM[address of A + 11]	00000011

`$1 = address of A[0]` `$2 = 3`

`$6 = address of A[2]` `$5 = 2`

Tracing an Array Loop

- The following program sets all elements of an array to 0.

```
    ; $1 contains the starting address of A
    ; $2 contains the size of A
    lis $11
    .word 1
    lis $4
    .word 4
    add $5, $0, $0       ; $5 holds i
    for: slt $6, $5, $2  ; $6 is 1 if i < n, 0 otherwise
         beq $6, $0, end ; Go to end if i < n is false
         mult $5, $4
         mflo $6         ; $6 = i * 4
         add $6, $1, $6  ; $6 = address of A[i]
         sw $0, 0($6)    ; A[i] = 0
PC       add $5, $5, $11 ; i += 1
         beq $0, $0, for ; back to top of loop
    end: jr $31
```

A[0]	MEM[address of A]	00000000
	MEM[address of A + 1]	00000000
	MEM[address of A + 2]	00000000
	MEM[address of A + 3]	00000000
A[1]	MEM[address of A + 4]	00000000
	MEM[address of A + 5]	00000000
	MEM[address of A + 6]	00000000
	MEM[address of A + 7]	00000000
A[2]	**MEM[address of A + 8]**	**00000000**
	MEM[address of A + 9]	**00000000**
	MEM[address of A + 10]	**00000000**
	MEM[address of A + 11]	**00000000**

```
$1 = address of A[0]   $2 = 3
$6 = address of A[2]   $5 = 2
```

Tracing an Array Loop

- The following program sets all elements of an array to 0.

```
    ; $1 contains the starting address of A
    ; $2 contains the size of A
    lis $11
    .word 1
    lis $4
    .word 4
    add $5, $0, $0      ; $5 holds i
    for: slt $6, $5, $2  ; $6 is 1 if i < n, 0 otherwise
         beq $6, $0, end ; Go to end if i < n is false
         mult $5, $4
         mflo $6         ; $6 = i * 4
         add $6, $1, $6  ; $6 = address of A[i]
         sw $0, 0($6)    ; A[i] = 0
         add $5, $5, $11 ; i += 1
PC       beq $0, $0, for ; back to top of loop
    end: jr $31
```

A[0]	MEM[address of A]	00000000
	MEM[address of A + 1]	00000000
	MEM[address of A + 2]	00000000
	MEM[address of A + 3]	00000000
A[1]	MEM[address of A + 4]	00000000
	MEM[address of A + 5]	00000000
	MEM[address of A + 6]	00000000
	MEM[address of A + 7]	00000000
A[2]	MEM[address of A + 8]	00000000
	MEM[address of A + 9]	00000000
	MEM[address of A + 10]	00000000
	MEM[address of A + 11]	00000000

`$1 = address of A[0]` `$2 = 3`
`$6 = address of A[2]` **`$5 = 3`**

Tracing an Array Loop

- The following program sets all elements of an array to 0.

```
    ; $1 contains the starting address of A
    ; $2 contains the size of A
    lis $11
    .word 1
    lis $4
    .word 4
    add $5, $0, $0       ; $5 holds i
PC  for: slt $6, $5, $2  ; $6 is 1 if i < n, 0 otherwise
         beq $6, $0, end ; Go to end if i < n is false
         mult $5, $4
         mflo $6         ; $6 = i * 4
         add $6, $1, $6  ; $6 = address of A[i]
         sw $0, 0($6)    ; A[i] = 0
         add $5, $5, $11 ; i += 1
         beq $0, $0, for ; back to top of loop
    end: jr $31
```

A[0]	MEM[address of A]	00000000
	MEM[address of A + 1]	00000000
	MEM[address of A + 2]	00000000
	MEM[address of A + 3]	00000000
A[1]	MEM[address of A + 4]	00000000
	MEM[address of A + 5]	00000000
	MEM[address of A + 6]	00000000
	MEM[address of A + 7]	00000000
A[2]	MEM[address of A + 8]	00000000
	MEM[address of A + 9]	00000000
	MEM[address of A + 10]	00000000
	MEM[address of A + 11]	00000000

```
$1 = address of A[0]   $2 = 3
$6 = address of A[2]   $5 = 3
```

Tracing an Array Loop

- The following program sets all elements of an array to 0.

```
    ; $1 contains the starting address of A
    ; $2 contains the size of A
    lis $11
    .word 1
    lis $4
    .word 4
    add $5, $0, $0       ; $5 holds i
    for: slt $6, $5, $2  ; $6 is 1 if i < n, 0 otherwise
PC       beq $6, $0, end ; Go to end if i < n is false
         mult $5, $4
         mflo $6         ; $6 = i * 4
         add $6, $1, $6  ; $6 = address of A[i]
         sw $0, 0($6)    ; A[i] = 0
         add $5, $5, $11 ; i += 1
         beq $0, $0, for ; back to top of loop
    end: jr $31
```

A[0]	MEM[address of A]	00000000
	MEM[address of A + 1]	00000000
	MEM[address of A + 2]	00000000
	MEM[address of A + 3]	00000000
A[1]	MEM[address of A + 4]	00000000
	MEM[address of A + 5]	00000000
	MEM[address of A + 6]	00000000
	MEM[address of A + 7]	00000000
A[2]	MEM[address of A + 8]	00000000
	MEM[address of A + 9]	00000000
	MEM[address of A + 10]	00000000
	MEM[address of A + 11]	00000000

`$1 = address of A[0]` `$2 = 3`

`$6 = 0` `$5 = 3`

Tracing an Array Loop

- The following program sets all elements of an array to 0.

```
   ; $1 contains the starting address of A
   ; $2 contains the size of A
   lis $11
   .word 1
   lis $4
   .word 4
   add $5, $0, $0       ; $5 holds i
   for: slt $6, $5, $2  ; $6 is 1 if i < n, 0 otherwise
        beq $6, $0, end ; Go to end if i < n is false
        mult $5, $4
        mflo $6         ; $6 = i * 4
        add $6, $1, $6  ; $6 = address of A[i]
        sw $0, 0($6)    ; A[i] = 0
        add $5, $5, $11 ; i += 1
        beq $0, $0, for ; back to top of loop
PC end: jr $31
```

A[0]	MEM[address of A]	00000000
	MEM[address of A + 1]	00000000
	MEM[address of A + 2]	00000000
	MEM[address of A + 3]	00000000
A[1]	MEM[address of A + 4]	00000000
	MEM[address of A + 5]	00000000
	MEM[address of A + 6]	00000000
	MEM[address of A + 7]	00000000
A[2]	MEM[address of A + 8]	00000000
	MEM[address of A + 9]	00000000
	MEM[address of A + 10]	00000000
	MEM[address of A + 11]	00000000

```
$1 = address of A[0]    $2 = 3
$6 = 0                  $5 = 3
```

Tracing an Array Loop

- The following program sets all elements of an array to 0.

```
; $1 contains the starting address of A
; $2 contains the size of A
lis $11
.word 1
lis $4
.word 4
add $5, $0, $0       ; $5 holds i
for: slt $6, $5, $2  ; $6 is 1 if i < n, 0 otherwise
     beq $6, $0, end ; Go to end if i < n is false
     mult $5, $4
     mflo $6         ; $6 = i * 4
     add $6, $1, $6  ; $6 = address of A[i]
     sw $0, 0($6)    ; A[i] = 0
     add $5, $5, $11 ; i += 1
     beq $0, $0, for ; back to top of loop
end: jr $31
```

A[0]	MEM[address of A]	00000000
	MEM[address of A + 1]	00000000
	MEM[address of A + 2]	00000000
	MEM[address of A + 3]	00000000
A[1]	MEM[address of A + 4]	00000000
	MEM[address of A + 5]	00000000
	MEM[address of A + 6]	00000000
	MEM[address of A + 7]	00000000
A[2]	MEM[address of A + 8]	00000000
	MEM[address of A + 9]	00000000
	MEM[address of A + 10]	00000000
	MEM[address of A + 11]	00000000

```
$1 = address of A[0]   $2 = 3
$6 = 0                 $5 = 3
```

Allocating Arrays

- How do we actually get an array into memory so we can work with it?
- We can allocate it **statically**: the array is allocated before running the program at a fixed location.
- In C/C++, we can allocate arrays **dynamically** (at runtime) on either "the stack" or "the heap".
- We will learn how "the heap" works near the end of the course.
- We will learn about "the stack" today!
- But first, let's take a look at what static allocation looks like.

Example: A Statically Allocated Array

```
           ; returns 1 in $3 if $7 is in the courses array, returns 0 otherwise
PC 0x00    lis $4
   0x04    .word 4
   0x08    lis $1
   0x0c    .word courses  ; equivalent to .word 0x38
   0x10    lis $2
   0x14    .word endArray ; equivalent to .word 0x44
   0x18    add $3, $0, $0
   0x1c    loop: beq $1, $2, end  ; go to end if $1 == endArray
   0x20          lw $6, 0($1)     ; load A[i] into $6
   0x24          add $1, $1, $4   ; $1 = address of A[i+1]
   0x28          bne $6, $7, loop ; continue loop if $7 != A[i]
   0x2c          lis $3
   0x30          .word 1          ; return $3 = 1 if $7 == A[i]
   0x34     end: jr $31
   0x38 courses: .word 240        ; array A starts here
   0x3c          .word 241
   0x40          .word 251
   0x44 endArray:                 ; array A ends here
```

$1 = ?
$2 = ?
$3 = ?
$4 = ?
$6 = ?
$7 = 241

Example: A Statically Allocated Array

```
           ; returns 1 in $3 if $7 is in the courses array, returns 0 otherwise
   0x00    lis $4
   0x04    .word 4
PC 0x08    lis $1
   0x0c    .word courses  ; equivalent to .word 0x38
   0x10    lis $2
   0x14    .word endArray ; equivalent to .word 0x44
   0x18    add $3, $0, $0
   0x1c    loop: beq $1, $2, end  ; go to end if $1 == endArray
   0x20          lw $6, 0($1)     ; load A[i] into $6
   0x24          add $1, $1, $4   ; $1 = address of A[i+1]
   0x28          bne $6, $7, loop ; continue loop if $7 != A[i]
   0x2c          lis $3
   0x30          .word 1          ; return $3 = 1 if $7 == A[i]
   0x34     end: jr $31
   0x38 courses: .word 240        ; array A starts here
   0x3c          .word 241
   0x40          .word 251
   0x44 endArray:                 ; array A ends here
```

$1 = ?
$2 = ?
$3 = ?
$4 = 4
$6 = ?
$7 = 241

Example: A Statically Allocated Array

```
           ; returns 1 in $3 if $7 is in the courses array, returns 0 otherwise
   0x00    lis $4
   0x04    .word 4
   0x08    lis $1
   0x0c    .word courses  ; equivalent to .word 0x38
PC 0x10    lis $2
   0x14    .word endArray ; equivalent to .word 0x44
   0x18    add $3, $0, $0
   0x1c    loop: beq $1, $2, end  ; go to end if $1 == endArray
   0x20          lw $6, 0($1)     ; load A[i] into $6
   0x24          add $1, $1, $4   ; $1 = address of A[i+1]
   0x28          bne $6, $7, loop ; continue loop if $7 != A[i]
   0x2c          lis $3
   0x30          .word 1          ; return $3 = 1 if $7 == A[i]
   0x34     end: jr $31
$1 0x38 courses: .word 240        ; array A starts here
   0x3c          .word 241
   0x40          .word 251
   0x44 endArray:                 ; array A ends here
```

$1 = 0x38 (courses)
$2 = ?
$3 = ?
$4 = 4
$6 = ?
$7 = 241

Example: A Statically Allocated Array

```
           ; returns 1 in $3 if $7 is in the courses array, returns 0 otherwise
   0x00    lis $4
   0x04    .word 4
   0x08    lis $1
   0x0c    .word courses  ; equivalent to .word 0x38
   0x10    lis $2
   0x14    .word endArray ; equivalent to .word 0x44
PC 0x18    add $3, $0, $0
   0x1c    loop: beq $1, $2, end  ; go to end if $1 == endArray
   0x20          lw $6, 0($1)     ; load A[i] into $6
   0x24          add $1, $1, $4   ; $1 = address of A[i+1]
   0x28          bne $6, $7, loop ; continue loop if $7 != A[i]
   0x2c          lis $3
   0x30          .word 1          ; return $3 = 1 if $7 == A[i]
   0x34     end: jr $31
$1 0x38 courses: .word 240        ; array A starts here
   0x3c          .word 241
   0x40          .word 251
   0x44 endArray:                 ; array A ends here
```

```
$1 = 0x38 (courses)
$2 = 0x44 (endArray)
$3 = ?
$4 = 4
$6 = ?
$7 = 241
```

Example: A Statically Allocated Array

```
                ; returns 1 in $3 if $7 is in the courses array, returns 0 otherwise
    0x00        lis $4
    0x04        .word 4
    0x08        lis $1
    0x0c        .word courses  ; equivalent to .word 0x38
    0x10        lis $2
    0x14        .word endArray ; equivalent to .word 0x44
    0x18        add $3, $0, $0
PC  0x1c        loop: beq $1, $2, end  ; go to end if $1 == endArray
    0x20              lw $6, 0($1)     ; load A[i] into $6
    0x24              add $1, $1, $4   ; $1 = address of A[i+1]
    0x28              bne $6, $7, loop ; continue loop if $7 != A[i]
    0x2c              lis $3
    0x30              .word 1          ; return $3 = 1 if $7 == A[i]
    0x34         end: jr $31
$1  0x38 courses: .word 240            ; array A starts here
    0x3c              .word 241
    0x40              .word 251
    0x44 endArray:                     ; array A ends here
```

$1 = 0x38 (courses)
$2 = 0x44 (endArray)
$3 = 0
$4 = 4
$6 = ?
$7 = 241

Example: A Statically Allocated Array

```
                ; returns 1 in $3 if $7 is in the courses array, returns 0 otherwise
   0x00         lis $4
   0x04         .word 4
   0x08         lis $1
   0x0c         .word courses  ; equivalent to .word 0x38
   0x10         lis $2
   0x14         .word endArray ; equivalent to .word 0x44
   0x18         add $3, $0, $0
   0x1c         loop: beq $1, $2, end  ; go to end if $1 == endArray
PC 0x20               lw $6, 0($1)     ; load A[i] into $6
   0x24               add $1, $1, $4   ; $1 = address of A[i+1]
   0x28               bne $6, $7, loop ; continue loop if $7 != A[i]
   0x2c               lis $3
   0x30               .word 1          ; return $3 = 1 if $7 == A[i]
   0x34          end: jr $31
$1 0x38 courses:      .word 240        ; array A starts here
   0x3c               .word 241
   0x40               .word 251
   0x44 endArray:                      ; array A ends here
```

```
$1 = 0x38 (courses)
$2 = 0x44 (endArray)
$3 = 0
$4 = 4
$6 = ?
$7 = 241
```

Example: A Statically Allocated Array

```
           ; returns 1 in $3 if $7 is in the courses array, returns 0 otherwise
   0x00    lis $4
   0x04    .word 4
   0x08    lis $1
   0x0c    .word courses  ; equivalent to .word 0x38
   0x10    lis $2
   0x14    .word endArray ; equivalent to .word 0x44
   0x18    add $3, $0, $0
   0x1c    loop: beq $1, $2, end  ; go to end if $1 == endArray
   0x20          lw $6, 0($1)     ; load A[i] into $6
PC 0x24          add $1, $1, $4   ; $1 = address of A[i+1]
   0x28          bne $6, $7, loop ; continue loop if $7 != A[i]
   0x2c          lis $3
   0x30          .word 1          ; return $3 = 1 if $7 == A[i]
   0x34     end: jr $31
$1 0x38 courses: .word 240        ; array A starts here
   0x3c          .word 241
   0x40          .word 251
   0x44 endArray:                 ; array A ends here
```

```
$1 = 0x38 (courses)
$2 = 0x44 (endArray)
$3 = 0
$4 = 4
$6 = 240
$7 = 241
```

Example: A Statically Allocated Array

```
           ; returns 1 in $3 if $7 is in the courses array, returns 0 otherwise
   0x00    lis $4
   0x04    .word 4
   0x08    lis $1
   0x0c    .word courses  ; equivalent to .word 0x38
   0x10    lis $2
   0x14    .word endArray ; equivalent to .word 0x44
   0x18    add $3, $0, $0
   0x1c    loop: beq $1, $2, end  ; go to end if $1 == endArray
   0x20          lw $6, 0($1)     ; load A[i] into $6
   0x24          add $1, $1, $4   ; $1 = address of A[i+1]
PC 0x28          bne $6, $7, loop ; continue loop if $7 != A[i]
   0x2c          lis $3
   0x30          .word 1          ; return $3 = 1 if $7 == A[i]
   0x34     end: jr $31
   0x38 courses: .word 240        ; array A starts here
$1 0x3c          .word 241
   0x40          .word 251
   0x44 endArray:                 ; array A ends here
```

$1 = 0x3c (courses+4)

$2 = 0x44 (endArray)

$3 = 0

$4 = 4

$6 = 240

$7 = 241

Example: A Statically Allocated Array

```
                ; returns 1 in $3 if $7 is in the courses array, returns 0 otherwise
   0x00         lis $4
   0x04         .word 4
   0x08         lis $1
   0x0c         .word courses  ; equivalent to .word 0x38
   0x10         lis $2
   0x14         .word endArray ; equivalent to .word 0x44
   0x18         add $3, $0, $0
PC 0x1c         loop: beq $1, $2, end   ; go to end if $1 == endArray
   0x20               lw $6, 0($1)      ; load A[i] into $6
   0x24               add $1, $1, $4    ; $1 = address of A[i+1]
   0x28               bne $6, $7, loop  ; continue loop if $7 != A[i]
   0x2c               lis $3
   0x30               .word 1           ; return $3 = 1 if $7 == A[i]
   0x34          end: jr $31
   0x38 courses:      .word 240         ; array A starts here
$1 0x3c               .word 241
   0x40               .word 251
   0x44 endArray:                       ; array A ends here
```

```
$1 = 0x3c (courses+4)
$2 = 0x44 (endArray)
$3 = 0
$4 = 4
$6 = 240
$7 = 241
```

Example: A Statically Allocated Array

```
           ; returns 1 in $3 if $7 is in the courses array, returns 0 otherwise
   0x00    lis $4
   0x04    .word 4
   0x08    lis $1
   0x0c    .word courses  ; equivalent to .word 0x38
   0x10    lis $2
   0x14    .word endArray ; equivalent to .word 0x44
   0x18    add $3, $0, $0
   0x1c    loop: beq $1, $2, end  ; go to end if $1 == endArray
PC 0x20          lw $6, 0($1)     ; load A[i] into $6
   0x24          add $1, $1, $4   ; $1 = address of A[i+1]
   0x28          bne $6, $7, loop ; continue loop if $7 != A[i]
   0x2c          lis $3
   0x30          .word 1          ; return $3 = 1 if $7 == A[i]
   0x34     end: jr $31
   0x38 courses: .word 240        ; array A starts here
$1 0x3c          .word 241
   0x40          .word 251
   0x44 endArray:                 ; array A ends here
```

```
$1 = 0x3c (courses+4)
$2 = 0x44 (endArray)
$3 = 0
$4 = 4
$6 = 240
$7 = 241
```

Example: A Statically Allocated Array

```
             ; returns 1 in $3 if $7 is in the courses array, returns 0 otherwise
   0x00      lis $4
   0x04      .word 4
   0x08      lis $1
   0x0c      .word courses  ; equivalent to .word 0x38
   0x10      lis $2
   0x14      .word endArray ; equivalent to .word 0x44
   0x18      add $3, $0, $0
   0x1c      loop: beq $1, $2, end   ; go to end if $1 == endArray
   0x20            lw $6, 0($1)      ; load A[i] into $6
PC 0x24            add $1, $1, $4    ; $1 = address of A[i+1]
   0x28            bne $6, $7, loop  ; continue loop if $7 != A[i]
   0x2c            lis $3
   0x30            .word 1           ; return $3 = 1 if $7 == A[i]
   0x34       end: jr $31
   0x38 courses:   .word 240         ; array A starts here
$1 0x3c            .word 241
   0x40            .word 251
   0x44 endArray:                    ; array A ends here
```

$1 = 0x3c (courses+4)
$2 = 0x44 (endArray)
$3 = 0
$4 = 4
$6 = 241
$7 = 241

Example: A Statically Allocated Array

```
             ; returns 1 in $3 if $7 is in the courses array, returns 0 otherwise
    0x00     lis $4
    0x04     .word 4
    0x08     lis $1
    0x0c     .word courses  ; equivalent to .word 0x38
    0x10     lis $2
    0x14     .word endArray ; equivalent to .word 0x44
    0x18     add $3, $0, $0
    0x1c     loop: beq $1, $2, end  ; go to end if $1 == endArray
    0x20           lw $6, 0($1)     ; load A[i] into $6
    0x24           add $1, $1, $4   ; $1 = address of A[i+1]
PC  0x28           bne $6, $7, loop ; continue loop if $7 != A[i]
    0x2c           lis $3
    0x30           .word 1          ; return $3 = 1 if $7 == A[i]
    0x34      end: jr $31
    0x38 courses:  .word 240        ; array A starts here
    0x3c           .word 241
$1  0x40           .word 251
    0x44 endArray:                  ; array A ends here
```

$1 = 0x40 (courses+8)
$2 = 0x44 (endArray)
$3 = 0
$4 = 4
$6 = 241
$7 = 241

Example: A Statically Allocated Array

```
           ; returns 1 in $3 if $7 is in the courses array, returns 0 otherwise
   0x00    lis $4
   0x04    .word 4
   0x08    lis $1
   0x0c    .word courses  ; equivalent to .word 0x38
   0x10    lis $2
   0x14    .word endArray ; equivalent to .word 0x44
   0x18    add $3, $0, $0
   0x1c    loop: beq $1, $2, end  ; go to end if $1 == endArray
   0x20          lw $6, 0($1)     ; load A[i] into $6
   0x24          add $1, $1, $4   ; $1 = address of A[i+1]
   0x28          bne $6, $7, loop ; continue loop if $7 != A[i]
PC 0x2c          lis $3
   0x30          .word 1          ; return $3 = 1 if $7 == A[i]
   0x34     end: jr $31
   0x38 courses: .word 240        ; array A starts here
   0x3c          .word 241
$1 0x40          .word 251
   0x44 endArray:                 ; array A ends here
```

```
$1 = 0x40 (courses+8)
$2 = 0x44 (endArray)
$3 = 0
$4 = 4
$6 = 241
$7 = 241
```

Example: A Statically Allocated Array

```
           ; returns 1 in $3 if $7 is in the courses array, returns 0 otherwise
   0x00    lis $4
   0x04    .word 4
   0x08    lis $1
   0x0c    .word courses  ; equivalent to .word 0x38
   0x10    lis $2
   0x14    .word endArray ; equivalent to .word 0x44
   0x18    add $3, $0, $0
   0x1c    loop: beq $1, $2, end  ; go to end if $1 == endArray
   0x20          lw $6, 0($1)     ; load A[i] into $6
   0x24          add $1, $1, $4   ; $1 = address of A[i+1]
   0x28          bne $6, $7, loop ; continue loop if $7 != A[i]
   0x2c          lis $3
   0x30          .word 1          ; return $3 = 1 if $7 == A[i]
PC 0x34     end: jr $31
   0x38 courses: .word 240        ; array A starts here
   0x3c          .word 241
$1 0x40          .word 251
   0x44 endArray:                 ; array A ends here
```

$1 = 0x40 (courses+8)
$2 = 0x44 (endArray)
$3 = 1
$4 = 4
$6 = 241
$7 = 241

Example: A Statically Allocated Array

```
           ; returns 1 in $3 if $7 is in the courses array, returns 0 otherwise
   0x00    lis $4
   0x04    .word 4
   0x08    lis $1
   0x0c    .word courses  ; equivalent to .word 0x38
   0x10    lis $2
   0x14    .word endArray ; equivalent to .word 0x44
   0x18    add $3, $0, $0
   0x1c    loop: beq $1, $2, end  ; go to end if $1 == endArray
   0x20          lw $6, 0($1)     ; load A[i] into $6
   0x24          add $1, $1, $4   ; $1 = address of A[i+1]
   0x28          bne $6, $7, loop ; continue loop if $7 != A[i]
   0x2c          lis $3
   0x30          .word 1          ; return $3 = 1 if $7 == A[i]
   0x34     end: jr $31
   0x38 courses: .word 240        ; array A starts here
   0x3c          .word 241
$1 0x40          .word 251
   0x44 endArray:                 ; array A ends here
```

$1 = 0x40 (courses+8)
$2 = 0x44 (endArray)
$3 = 1
$4 = 4
$6 = 241
$7 = 241

Stack Allocation

- When you run a program, it does not take up all available memory. Instead, the program is allocated a specific chunk of memory.
- In our MIPS emulator, programs are always allocated the region of memory from 0x00000000 (inclusive) to 0x01000000 (exclusive).
  - Accessing addresses 0x01000000 or higher gives an "out of bounds" error.
- The program code itself is at address 0, the "lower end" of memory.
- We will use the opposite end of program memory as a **stack**.
- To facilitate this, $30 is initialized to 0x01000000, and we treat $30 as the **stack pointer**, the memory address of the top of the stack.

Using the Stack

- Note that the initial value of the stack pointer $30 is an out of bounds address. This represents the stack being *empty*.
- All addresses higher than 0x01000000 are out of bounds. So the stack actually grows "backwards" from high to low addresses.
    - It's a little confusing. When we push to the stack, we say the stack gets "higher", but the address of the top of the stack *decreases* numerically.
- To push something on the stack, there are two steps.
    - *Store* the word at the address 4 bytes before the stack pointer.
    - *Decrement* the stack pointer by 4, so it points to the new top of the stack.
- Popping from the stack is similar, but reversed: increment then load.

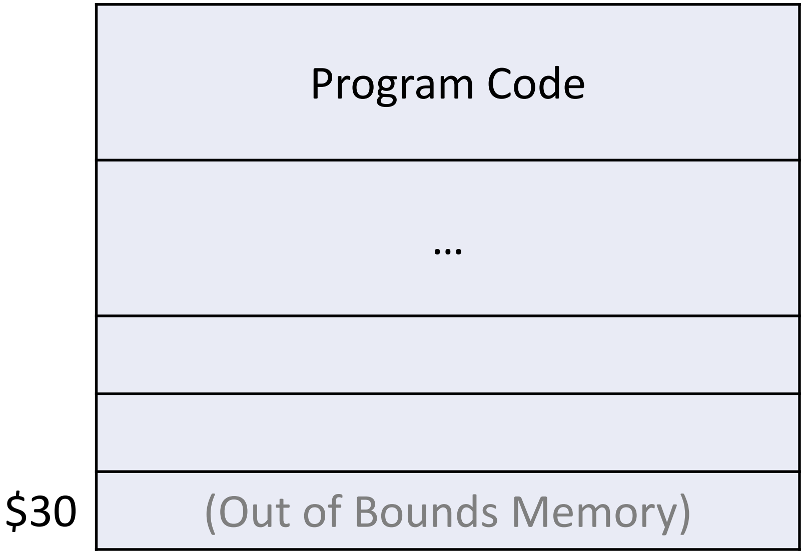
Pushing and Popping: Examples

- Push value in $3 onto the stack:

```
sw $3, -4($30)
lis $3
.word 4
sub $30, $30, $3
```

- Pop value from top of stack into $3:

```
lis $3
.word 4
add $30, $30, $3
lw $3, -4($30)
```



- **There are other ways of doing this, but the methods shown here are fairly safe and general.** Alternative approaches might require care.

Pushing and Popping: Examples

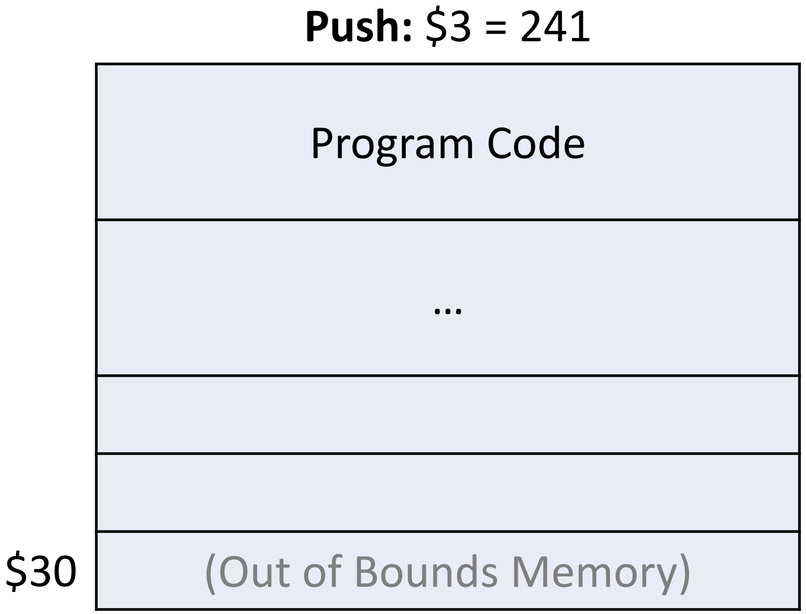
- Push value in $3 onto the stack:

```
sw $3, -4($30)
lis $3
.word 4
sub $30, $30, $3
```

- Pop value from top of stack into $3:

```
lis $3
.word 4
add $30, $30, $3
lw $3, -4($30)
```

- **There are other ways of doing this, but the methods shown here are fairly safe and general.** Alternative approaches might require care.



Pushing and Popping: Examples

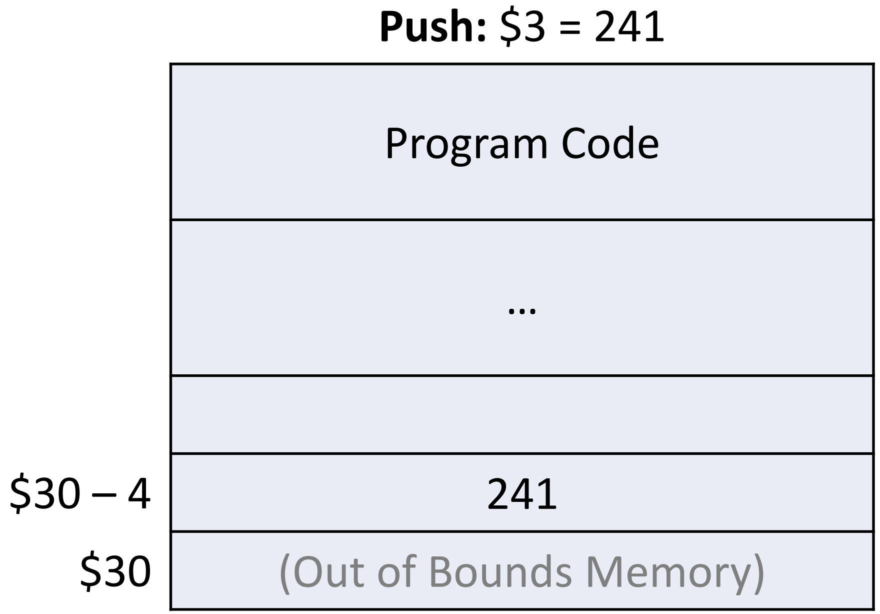
- Push value in $3 onto the stack:

```
sw $3, -4($30)
lis $3
.word 4
sub $30, $30, $3
```

- Pop value from top of stack into $3:

```
lis $3
.word 4
add $30, $30, $3
lw $3, -4($30)
```

- **There are other ways of doing this, but the methods shown here are fairly safe and general.** Alternative approaches might require care.



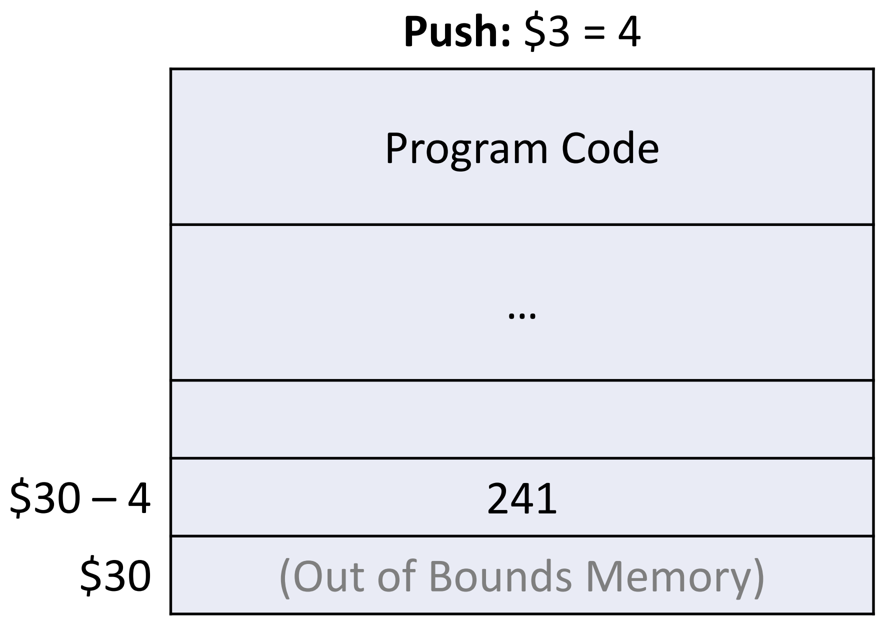
Pushing and Popping: Examples

- Push value in $3 onto the stack:

```
sw $3, -4($30)
lis $3
.word 4
sub $30, $30, $3
```

- Pop value from top of stack into $3:

```
lis $3
.word 4
add $30, $30, $3
lw $3, -4($30)
```



Push: $3 = 4

Program Code

…

$30 – 4 241

$30 (Out of Bounds Memory)

- **There are other ways of doing this, but the methods shown here are fairly safe and general.** Alternative approaches might require care.

Pushing and Popping: Examples

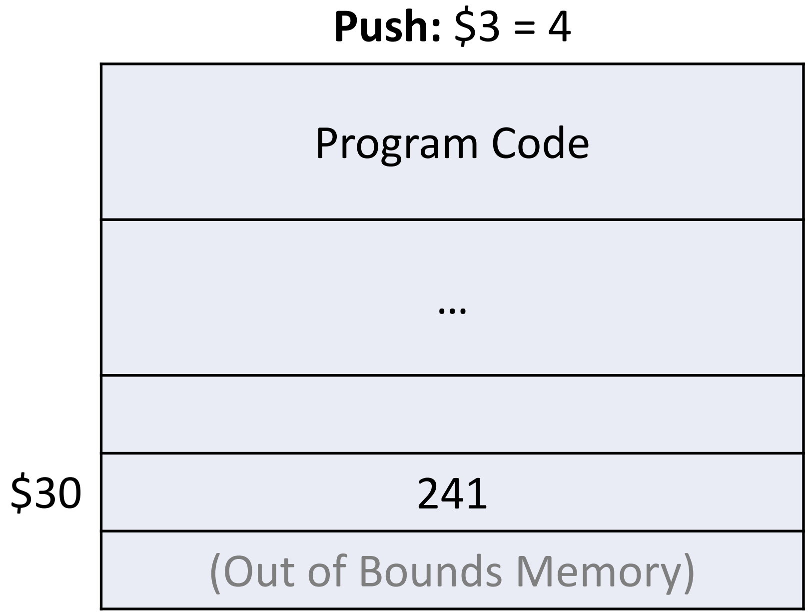
- Push value in $3 onto the stack:

```
sw $3, -4($30)
lis $3
.word 4
sub $30, $30, $3
```

- Pop value from top of stack into $3:

```
lis $3
.word 4
add $30, $30, $3
lw $3, -4($30)
```

- **There are other ways of doing this, but the methods shown here are fairly safe and general.** Alternative approaches might require care.



Push: $3 = 4

Program Code

…

$30

241

(Out of Bounds Memory)

Pushing and Popping: Examples

- Push value in $3 onto the stack:

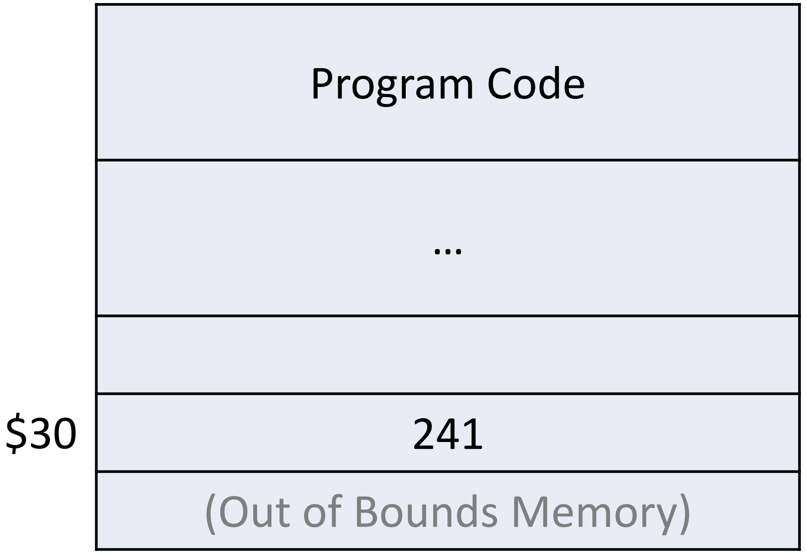
```
sw $3, -4($30)
lis $3
.word 4
sub $30, $30, $3
```

- Pop value from top of stack into $3:

```
lis $3
.word 4
add $30, $30, $3
lw $3, -4($30)
```

- **There are other ways of doing this, but the methods shown here are fairly safe and general.** Alternative approaches might require care.

Pop: $3 = 333



Pushing and Popping: Examples

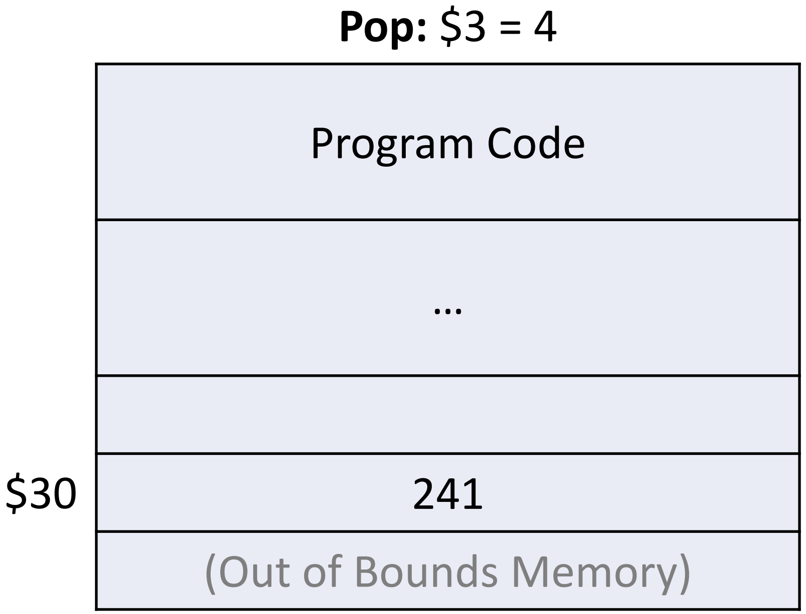
- Push value in $3 onto the stack:

```
sw $3, -4($30)
lis $3
.word 4
sub $30, $30, $3
```

- Pop value from top of stack into $3:

```
lis $3
.word 4
add $30, $30, $3
lw $3, -4($30)
```

- **There are other ways of doing this, but the methods shown here are fairly safe and general.** Alternative approaches might require care.



Pop: $3 = 4

Program Code

…

$30

241

(Out of Bounds Memory)

Pushing and Popping: Examples

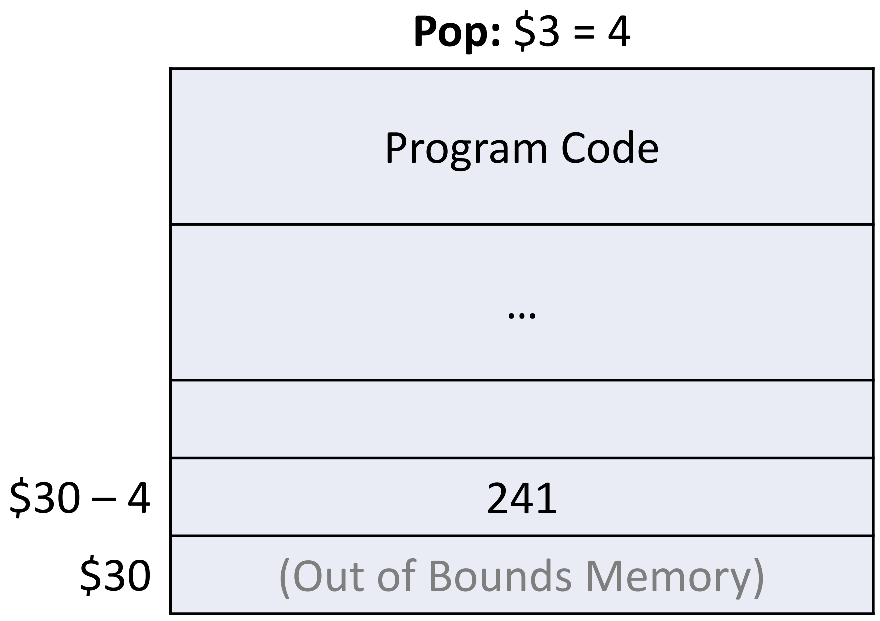
- Push value in $3 onto the stack:

```
sw $3, -4($30)
lis $3
.word 4
sub $30, $30, $3
```

- Pop value from top of stack into $3:

```
lis $3
.word 4
add $30, $30, $3
lw $3, -4($30)
```

- **There are other ways of doing this, but the methods shown here are fairly safe and general.** Alternative approaches might require care.



Pop: $3 = 4

Program Code

…

$30 – 4 241

$30 (Out of Bounds Memory)

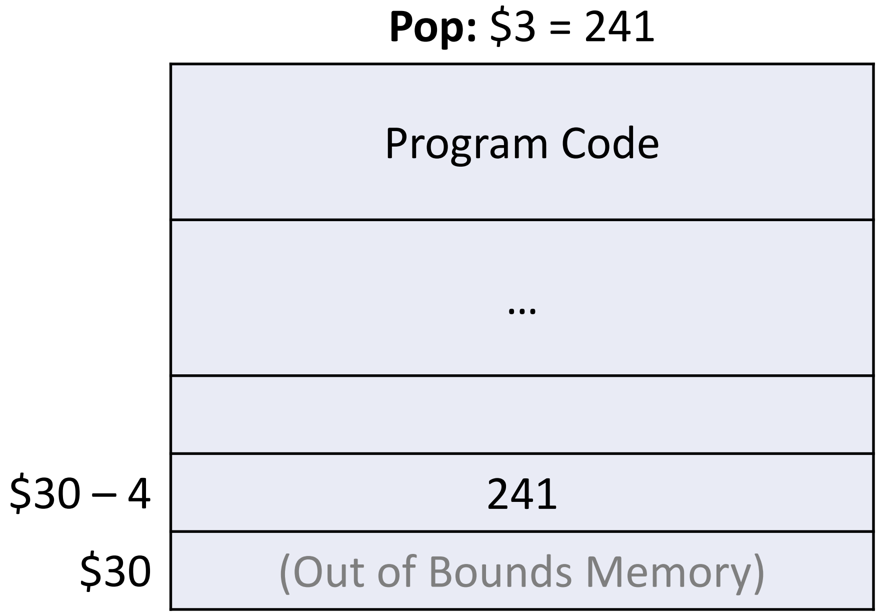
Pushing and Popping: Examples

- Push value in $3 onto the stack:

```
sw $3, -4($30)
lis $3
.word 4
sub $30, $30, $3
```

- Pop value from top of stack into $3:

```
lis $3
.word 4
add $30, $30, $3
lw $3, -4($30)
```


Pop: $3 = 241

- **There are other ways of doing this, but the methods shown here are fairly safe and general.** Alternative approaches might require care.

Pushing and Popping: Examples

- Push value in $3 onto the stack:

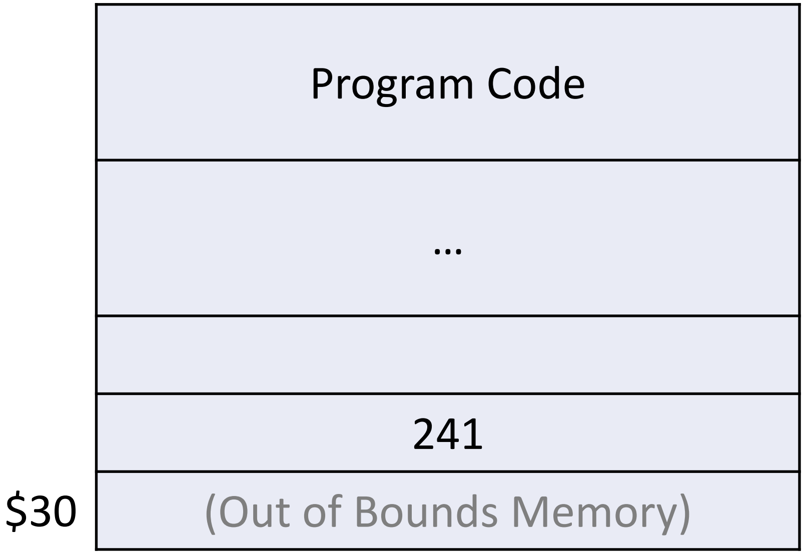
```
sw $3, -4($30)
lis $3
.word 4
sub $30, $30, $3
```

- Pop value from top of stack into $3:

```
lis $3
.word 4
add $30, $30, $3
lw $3, -4($30)
```

- **There are other ways of doing this, but the methods shown here are fairly safe and general.** Alternative approaches might require care.

Pop: $3 = 241



Examples of Pitfalls

- "I don't like the use of -4. Why not just use offset 0 instead?"

```
sw $3, 0($30)
lis $3
.word 4
sub $30, $30, $3
```

Examples of Pitfalls

- "I don't like the use of -4. Why not just use offset 0 instead?"

```
sw $3, 0($30)
lis $3
.word 4
sub $30, $30, $3
```

- Initially, $30 is an out-of-bounds address, so this will crash.

Examples of Pitfalls

- "I don't like the use of -4, so I will decrement first, then use offset 0."

```
lis $3
.word 4
sub $30, $30, $3
sw $3, 0($30)
```

Examples of Pitfalls

- "I don't like the use of -4, so I will decrement first, then use offset 0."

```
lis $3
.word 4
sub $30, $30, $3
sw $3, 0($30)
```

- $3 gets overwritten with 4, so you need to use a different register for the decrement, or you lose the value of $3.

Examples of Pitfalls

- "I don't like the use of -4, so I will decrement first, then use offset 0."

```
lis $4
.word 4
sub $30, $30, $4
sw $3, 0($30)
```

- This is fine, as long as you weren't using $4 for anything important. Being able to use the same register for increment/decrement and store/load is kind of nice.

Allocating an Array on the Stack

- To allocate an array of *n* words, simply decrement the stack pointer by *4n* rather than just 4.

```
; assume $2 contains n, the size of the array
lis $4
.word 4
mult $2, $4
mflo $5          ; $5 contains 4 * n
sub $30, $30, $5 ; decrement stack pointer
add $1, $30, $0
; now $1 contains the starting address of the array
```

- Notice that we didn't do anything to "initialize" the array! We just made space for it. You can initialize it using a loop as discussed earlier.
- To *deallocate*, increment the stack pointer by *4n*.

Coming Up Next

- Now that we understand how to use part of memory as a stack, we will use this to implement *procedures* in MIPS assembly.
- You may be familiar with the concept of the "call stack" that forms when procedures call each other.
- We will see the precise details of how this is implemented using our stack pointer in $30!
- We will learn about the final instruction in our version of MIPS, Jump and Link Register (jalr) which is used for procedure calls.
- We'll even be able to write recursive procedures!