Part A

In this part, you will implement a few math operations that will be used for classification later.

Before starting, please pull from the starter and update Venus.

```
$ git pull starter main
$ bash test.sh download_tools
```

Task 1: Absolute Value (Walkthrough)

To familiarize you with the workflow of this project, we will walk you through this task.

Running Tests

In this project, tests are written in Python and compiled into RISC-V assembly.

The Python source for the provided tests is located in `unittests.py`. **Look** over the contents of `unittests.py`. Although the tests are written for you in Tasks 1-4, it helps to be familiar with the unit testing framework to understand what the tests are doing.

To run the tests, on your **local machine**, start by **running** **`bash test.sh`** in the `61c-proj2` directory on your local machine. This gives you an overview of the commands you can run for testing. In particular, `bash test.sh part_a` compiles and runs all the tests for Part A. You can also provide the name of a specific function to compile and run all the tests for that particular function.

For this task, since we are implementing the `abs` function, on your **local machine**, **run** **`bash test.sh test_abs`**. This creates a `test-src` folder containing the Python tests compiled into RISC-V.

Since we haven't implemented the `abs` function yet, some of the tests are failing. Let's try implementing `abs`.

You can edit files in a text editor or directly in Venus. To edit files in Venus, switch to the Files tab. Here you can open and edit assembly files. Remember to save your files frequently with `control+S` (Windows) or `command+S` (Mac). Venus does not auto-save as you work.

Open `src/abs.s` (either in a text editor or Venus) and **copy-paste** the implementation below.

```
abs:
  # Load number from memory
  lw t0 0(a0)
```

```
  blt t0, zero, done

  # Negate a0
  sub t0, x0, t0

  # Store number back to memory
  sw t0 4(a0)

done:
  ret
```

Again on your **local machine**, **run** `bash test.sh test_abs`. The tests don't pass, so something is probably wrong with our implementation.

Using VDB to debug tests via Venus

First, **open up** Venus in your web browser and **mount** your files. (Refer back to [the setup section of the spec]() if you're having trouble.)

Let's start by setting a breakpoint. **Type** `ebreak` at the start of the `abs` function. This places a breakpoint just before the `blt t0, zero, done` instruction.

To start the debugger, in the **Venus terminal**, **run** `cd /vmfs/test-src` and **run** `ls`. This should list all the test files you can run. **Run** `vdb test_abs_one.s` to start the debugger for an absolute value test.

In the **Venus simulator tab**, **Click Run** to start running the program. The debugger will pause at the breakpoint we set. While paused, you can inspect the registers and memory. In particular, notice that register `a0` contains a large number here, because this test calls your function with argument `a0` as a memory address. You can look use this number in the "Memory" tab of Venus to see the data stored at this memory address. We would recommend changing the display settings to "Hex".

You can also step through code line-by-line in the debugger. **Click Step** to execute the next instruction, `blt t0, zero, done`. Step through the function and inspect the registers. See if you can spot the bug in our implementation.

▼ Click to reveal answer

In the first line, we're skipping the negation and branching to `done` if the number is less than 0. However, we actually want to skip the negation if the number is greater than and equal to 0, and perform the negation if the number is less than 0.

One way to fix this is to branch to `done` if the argument is greater than or equal to 0. Other ways to fix this are possible!

Change the implementation in `src/abs.s` to fix the bug. **Run** `bash test.sh test_abs` again, and you should see that 2 out of the 3 tests are passing now.

Using memcheck to debug tests via `test.sh`

In this project, you'll often run into situations where the logic of the code seems correct, but your tests are still failing. These errors are often caused by invalid memory accesses. This semester, we've introduced a new feature, memcheck, that should allow you to debug these errors easily, though please let course staff know on Ed if you run into any trouble using this feature!

Memcheck introduces two different flags you can add to your `test.sh` command: `-mc` for normal memcheck, and `-mcv` for a more verbose version. Let's try using memcheck to see what's wrong with our code.

Run `bash test.sh test_abs -mc`, and you should see something similar to the following error in addition to the error messages you saw at the end of the last section:

```
[memcheck] Invalid memory access of size 4. Address 0x10000004 is 0 bytes after a block o
        Program Counter: 0x00000044
        File: ../src/abs.s:23
        Instruction: sw t0 4(a0)
        Registers:
                              x1(ra)=0x0000000C   x2(sp)=0x7FFFFFF0   x3(gp)=0x10000000
          x4(tp)=0x00000000   x5(t0)=0x00000001   x6(t1)=0x00000000   x7(t2)=0x00000000
          x8(s0)=0x00000000   x9(s1)=0x00000000  x10(a0)=0x10000000  x11(a1)=0x00000000
         x12(a2)=0x00000000  x13(a3)=0x00000000  x14(a4)=0x00000000  x15(a5)=0x00000000
         x16(a6)=0x00000000  x17(a7)=0x00000000  x18(s2)=0x00000000  x19(s3)=0x00000000
         x20(s4)=0x00000000  x21(s5)=0x00000000  x22(s6)=0x00000000  x23(s7)=0x00000000
         x24(s8)=0x00000000  x25(s9)=0x00000000 x26(s10)=0x00000000 x27(s11)=0x00000000
         x28(t3)=0x00000000  x29(t4)=0x00000000  x30(t5)=0x00000000  x31(t6)=0x00000000
```

These errors are designed to be as similar to `valgrind` as possible. Try to use this error message to pinpoint where our illegal memory access is happening.

▼ Click to reveal answer

In the fourth line of the output, it shows that this is caused by the `sw t0 4(a0)` instruction. Instead of offset 4, we should be writing to offset 0 in this line.

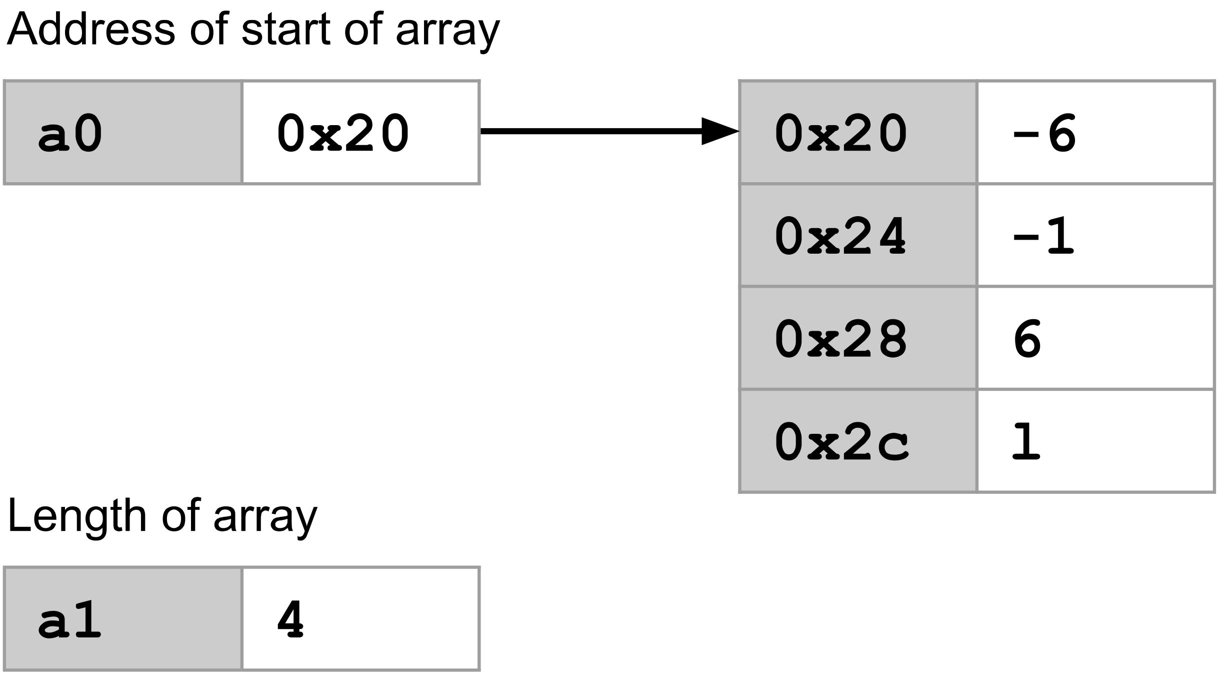
Change the implementation in `src/abs.s` to fix the bug. **Run** `bash test.sh test_abs` again, and you should be passing all of the test cases.

Task 2: ReLU

Conceptual Overview: Arrays

In this project, we will be working with integer arrays. Remember that the integers in an integer array are stored in a consecutive block of memory.

To pass an integer array as an argument, we will pass a pointer to the start of the integer array, and the number of elements in the array.

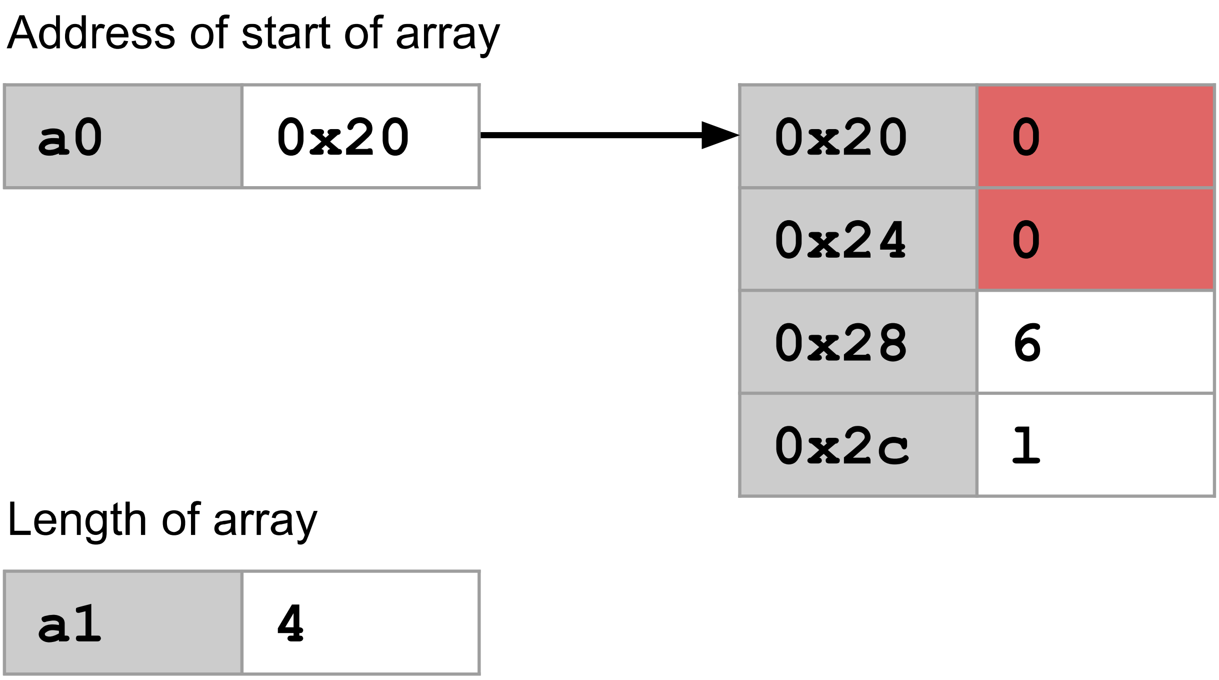


In this diagram, register `a0` stores the first argument (the address of the start of the array). Register `a1` stores the second argument (the number of integers in the array).

Conceptual Overview: ReLU

The ReLU function takes in an integer array and sets every negative value in the array to 0. Positive values in the array are unchanged. In other words, for each element `x` in the array, ReLU computes `max(x, 0)`.

ReLU should modify the array in place. For example, if the above integer array is passed into ReLU, the result would be stored in the same place in memory:



Note that the negative values in the array were set to 0 in memory.

Your Task

Fill in the `relu` function in `src/relu.s`.

`relu`: Task 2.			
Arguments	`a0`	`int *`	A pointer to the start of the integer array.
	`a1`	`int`	The number of integers in the array. You can assume that this argument matches the actual length of the integer array.
Return values	None		

If the input is malformed in the following ways, put the appropriate return code into `a0` and run `j exit` to quit the program. (For example, if the length of the array is less than 1, run `li a0 36` and `j exit`.)

Return code	**Exception**
36	The length of the array is less than 1.

Testing and debugging

To test your function, in your local terminal, run `bash test.sh test_relu`.

To debug your function, in your Venus terminal, run `cd /vmfs/test-src`, then run a VDB command to start the debugger:

```
vdb test_relu_standard.s
vdb test_relu_length_1.s
vdb test_relu_invalid_n.s
```

Here are some debugging tips that should apply to the entire project:

- If you see the error "You are attempting to edit the text of the program though the program is set to immutable at address 0x00000000!", this means that you are trying to write to memory address 0x00000000 (or whatever memory address you see in the error). This is probably happening because you're giving this address to a store instruction, which then tries to write to this address.
- If you see the error "label exit used but not defined" when starting the debugger, make sure that you're starting the debugger with the `vdb` commands above. Clicking "assemble and simulate from editor" will not work.
- Unfortunately the local tests don't check for out-of-bounds memory accesses. If you ever encounter a failing test on the autograder, try making sure that your code never writes to memory outside of an array.

If your ReLU works locally but not on Gradescope, here are some edge cases we've seen that the local cases don't check. You can modify `unittests.py` to write your own tests for these cases!

- The local tests don't perform ReLU on larger numbers.
- Watch the debugging videos.

Task 3: Argmax

Conceptual Overview: Argmax

The argmax function takes in an integer array and returns the *index* of the largest element in the array. If multiple elements are tied as the largest element, return the smallest index.

For example, if the integer array `[-6, -1, 6, 1]` is passed into the argmax function, the output should be 2, because the largest integer (6) is located at index 2 in the array. If the integer array were instead `[6, 1, 6, 1]`, then the output should be 0, because the largest integer (6) is first found at index 0.

Your Task

Fill in the `argmax` function in `src/argmax.s`.

`argmax`: Task 3.			
Arguments	`a0`	`int *`	A pointer to the start of the integer array.
	`a1`	`int`	The number of integers in the array. You can assume that this argument matches the actual length of the integer array.
Return values	`a0`	`int`	The index of the largest element. If the largest element appears multiple times, return the smallest index.

If the input is malformed in the following ways, put the appropriate return code into `a0` and run `j exit` to quit the program.

Return code	**Exception**
36	The length of the array is less than 1.

Testing and debugging

To test your function, in your local terminal, run `bash test.sh test_argmax`.

To debug your function, in your Venus terminal, run `cd /vmfs/test-src`, then run a VDB command to start the debugger:

```
vdb test_argmax_invalid_n.s
vdb test_argmax_length_1.s
vdb test_argmax_standard.s
```

If your argmax works locally but not on Gradescope, here are some edge cases we've seen that the local cases don't check. You can modify `unittests.py` to write your own tests for these cases!

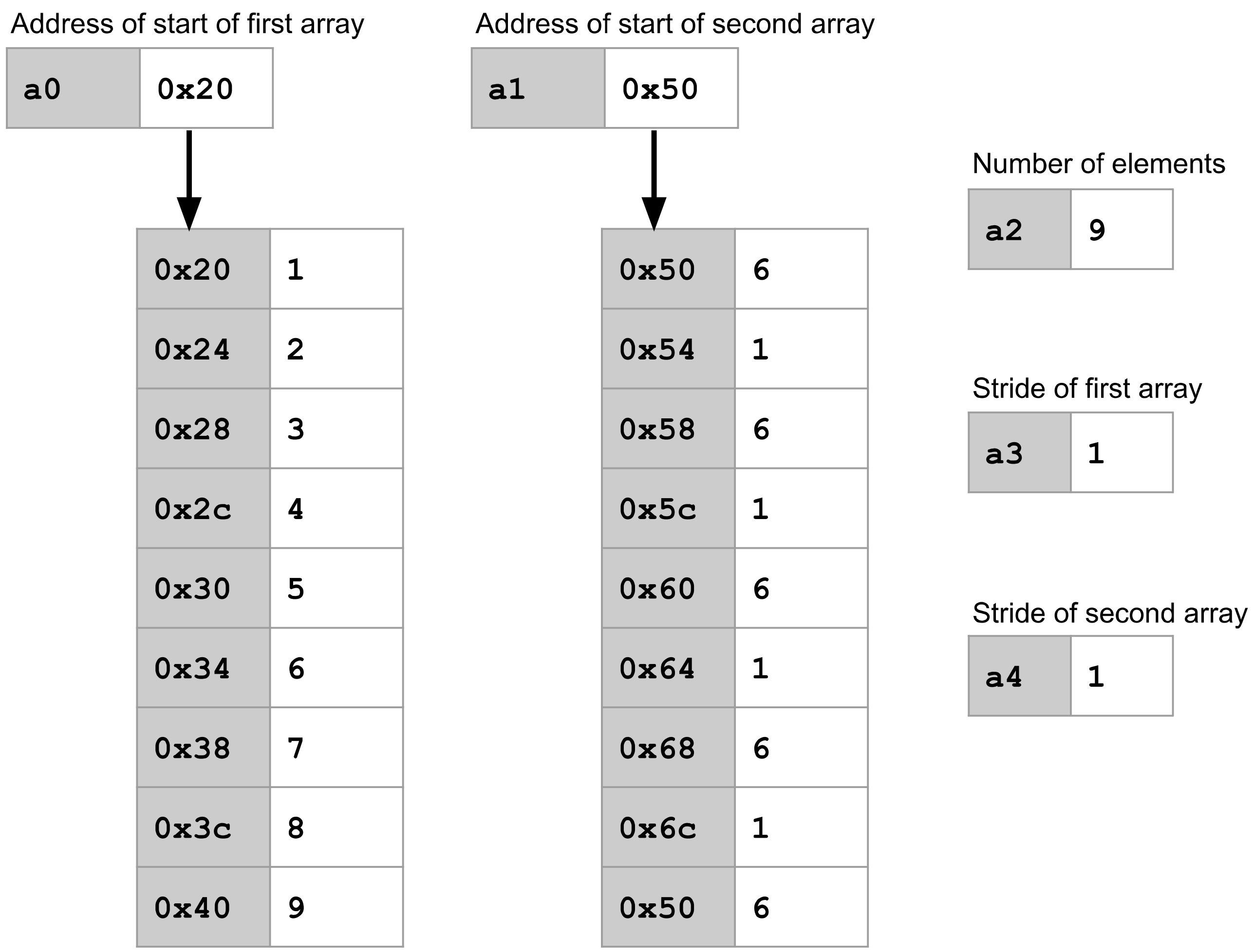
- The local tests don't check that your code works if the largest element in the array is the last element of the array.
- The local tests don't check that your code works if the largest element appears more than once.
- Watch the [debugging videos](#).

Task 4: Dot Product

Conceptual Overview: Dot Product

The dot product function takes in two integer arrays, multiplies the corresponding entries of the arrays together, and returns the sum of all the products.

For example, if these two integer arrays were passed into the dot product function, the function would return `(1*6) + (2*1) + (3*6) + (4*1) + (5*6) + (6*1) + (7*6) + (8*1) + (9*6) = 170`.

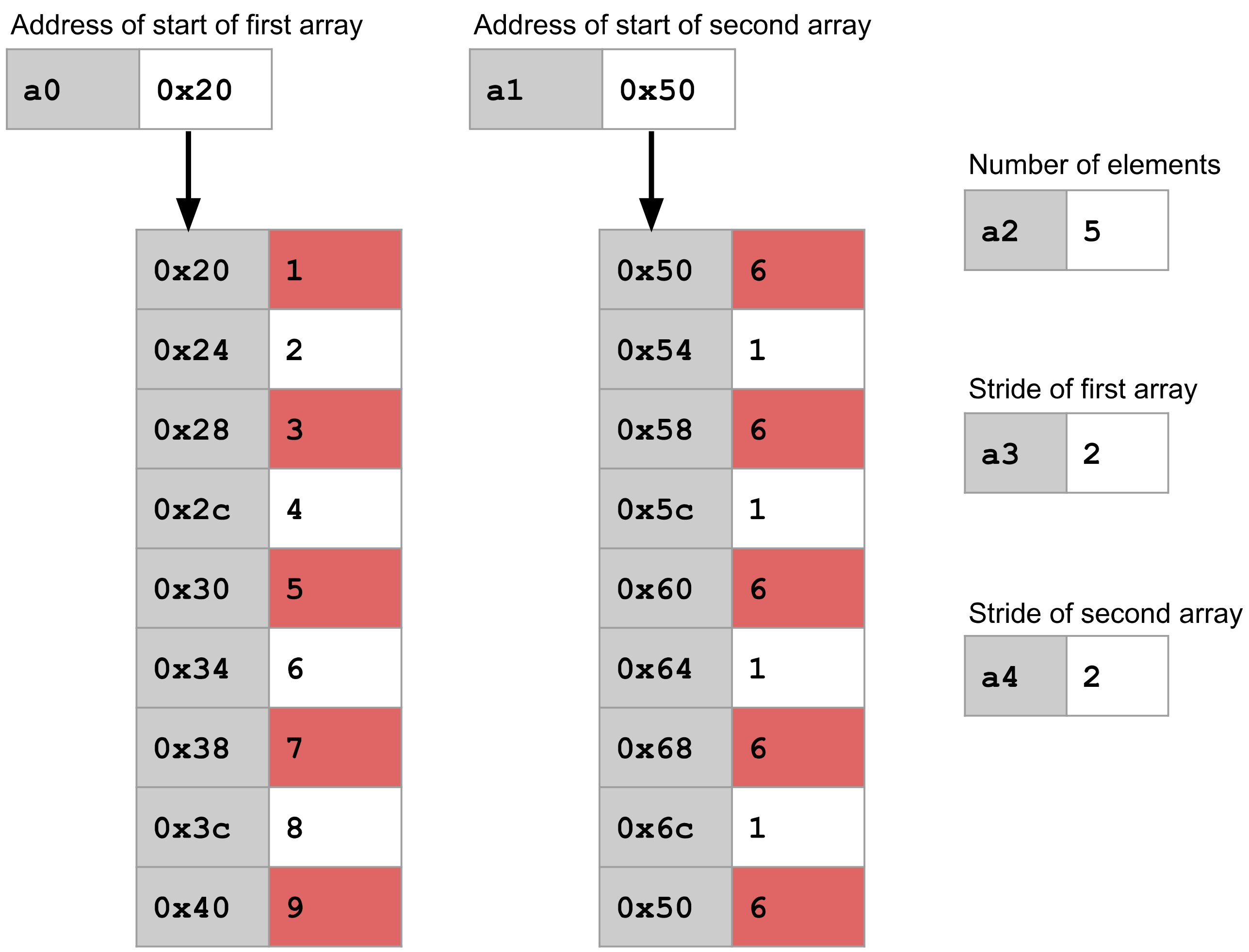


Conceptual Overview: Array Strides

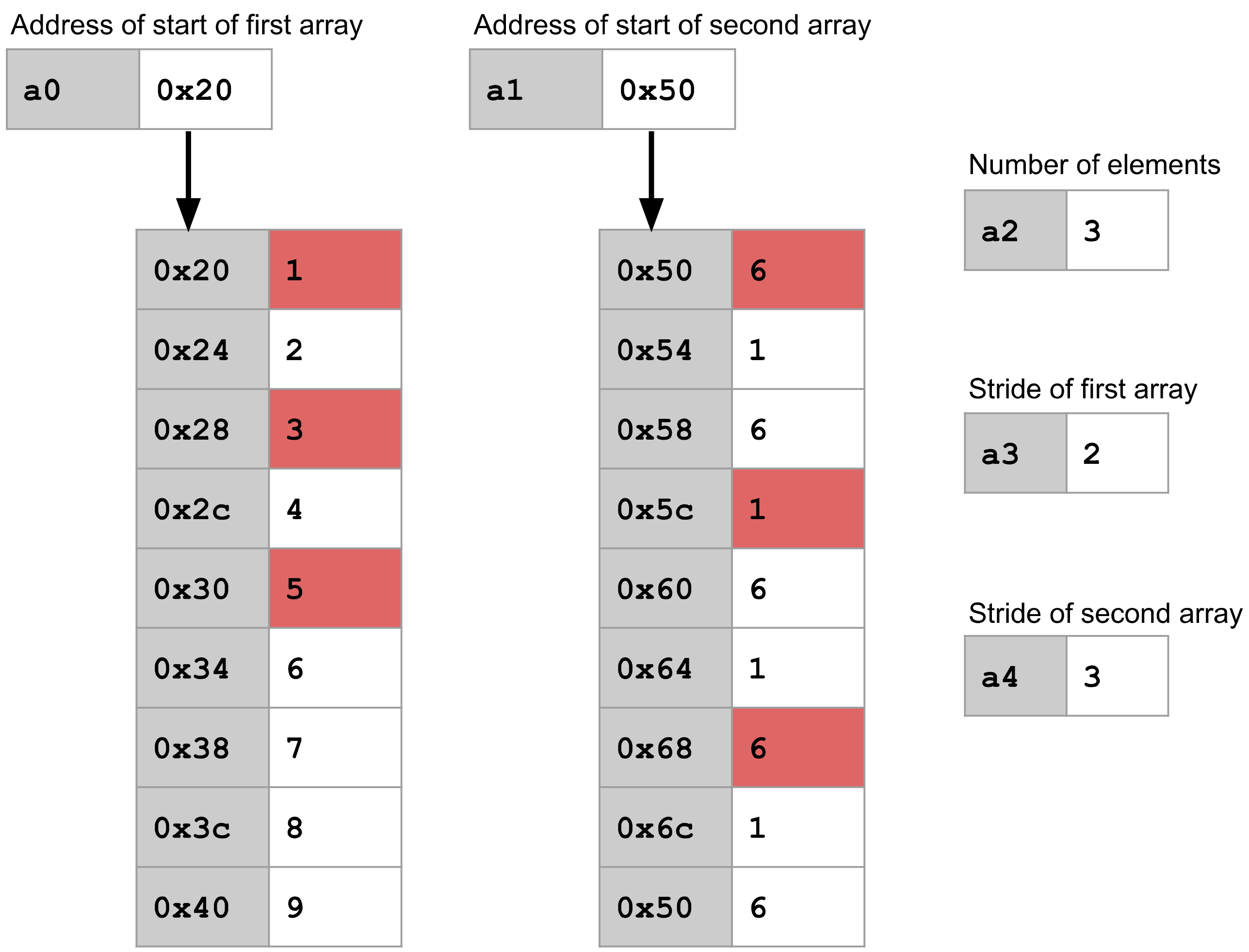
Instead of iterating through every element of the array, what if we want to iterate through every other element, or every third element? To do this, we will define the stride of an array.

To iterate through an array with stride *n*, start at the beginning of the array and only consider every *n*th element, skipping the elements in between.

Note that the stride is given in number of elements, not number of bytes. This means that iterating with stride 1 is equivalent to iterating through every element of the array.



For example, in the above diagram, both arrays are using stride 2, so we skip every other element in the array. 5 elements should be considered, so we stop after multiplying 5 pairs of elements together. The function would return `(1*6) + (3*6) + (5*6) + (7*6) + (9*6) = 150`.



In the above diagram, the first array is using stride 2, so we skip every other element in this array. The second array is using stride 3, so we use every third element in this array. 3 elements should be considered, so we stop after multiplying 3 pairs of elements together. The function would return `(1*6) + (3*1) + (5*6) = 39`.

Your Task

Fill in the `dot` function in `src/dot.s`.

The `dot` function may assume that the `a2` argument for the number of elements to use in the calculation will not cause an out-of-bounds array access. However, you will need to enforce this when calling `dot` from other functions later in this project.

`dot`: Task 4.			
Arguments	`a0`	`int *`	A pointer to the start of the first array.
	`a1`	`int *`	A pointer to the start of the second array.
	`a2`	`int`	The number of elements to use in the calculation.
	`a3`	`int`	The stride of the first array.

	`a4`	`int`	The stride of the second array.
Return values	`a0`	`int`	The dot product of the two arrays, using the given number of elements and the given strides.

If the input is malformed in the following ways, put the appropriate return code into `a0` and run `j exit` to quit the program.

Return code	**Exception**
36	The number of elements to use is less than 1.
37	The stride of either array is less than 1.

Testing and debugging

To test your function, in your local terminal, run `bash test.sh test_dot`.

To debug your function, in your Venus terminal, run `cd /vmfs/test-src`, then run a VDB command to start the debugger:

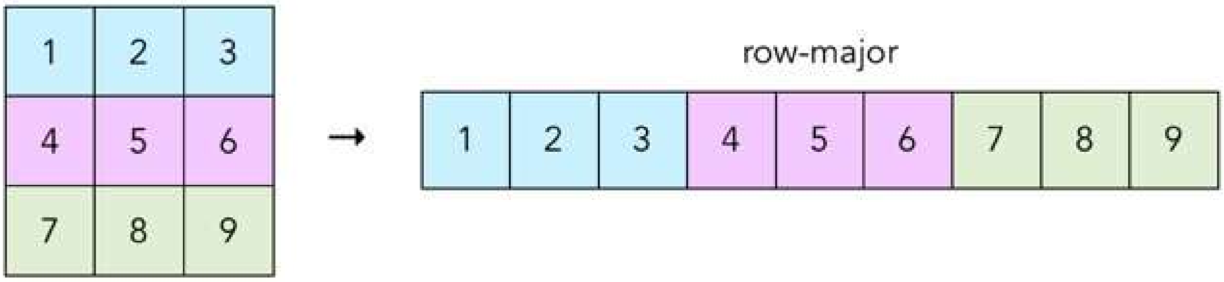
```
vdb test_dot_length_1.s
vdb test_dot_length_error.s
vdb test_dot_length_error2.s
vdb test_dot_standard.s
vdb test_dot_stride.s
vdb test_dot_stride_error1.s
vdb test_dot_stride_error2.s
```

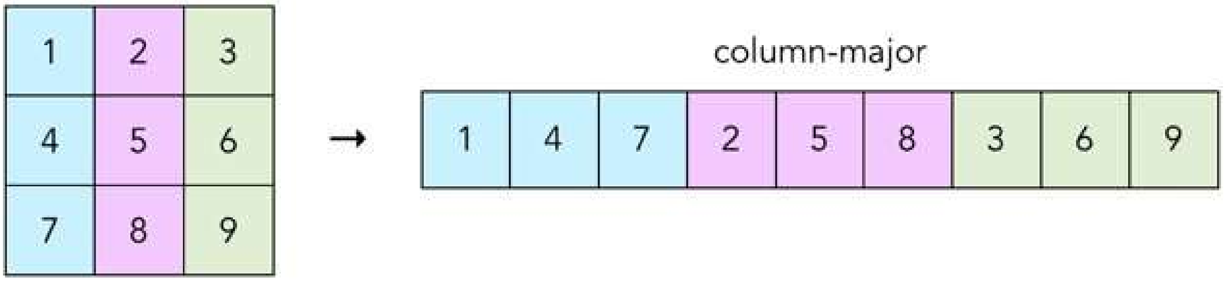
Also, check out the debugging videos!

Task 5: Matrix Multiplication

Conceptual Overview: Storing Matrices

A matrix is a 2-dimensional array of integers. In this project, matrices will be stored as an integer array in row-major order. Row-major order means we store each row of the matrix consecutively in memory as a 1-dimensional integer array.

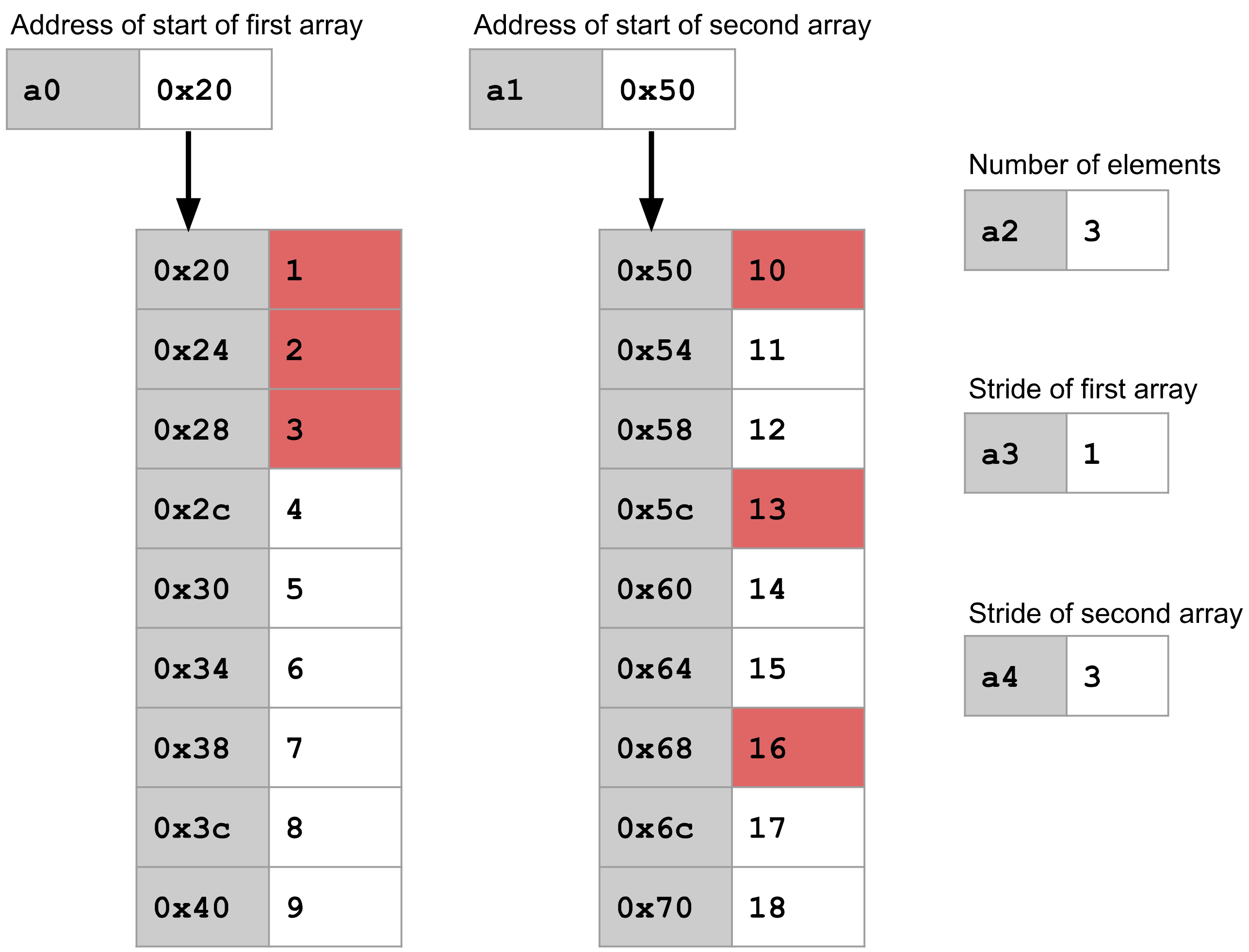




Conceptual Overview: Matrix Multiplication

The matrix multiplication function takes in two integer matrices A (dimension $n \times m$) and B (dimension $m \times k$) and outputs an integer matrix C (dimension $n \times k$).

To calculate the entry at row i, column j of C, take the dot product of the ith row of A and the jth column of B. Note that this can be done by calling the `dot` function with the proper strides.



For example, in the above diagram, we are computing the entry in row 1, column 1 of C by taking the dot product of the 1st row of A and the 1st row of B.

In the above diagram, we are computing the entry in row 2, column 2 of C. Note that we are changing the pointer to the start of the array in order to access later rows and columns.

Your Task

Fill in the `matmul` function in `src/matmul.s`.

`matmul`: Task 5.			
Arguments	`a0`	`int *`	A pointer to the start of the first matrix A (stored as an integer array in row-major order).
	`a1`	`int`	The number of rows (height) of the first matrix A.
	`a2`	`int`	The number of columns (width) of the first matrix A.
	`a3`	`int *`	A pointer to the start of the second matrix B (stored as an integer array in row-major order).
	`a4`	`int`	The number of rows (height) of the second matrix B.

	`a5`	`int`	The number of columns (width) of the second matrix B.
	`a6`	`int *`	A pointer to the start of an integer array where the result C should be stored. You can assume this memory has been allocated (but is uninitialized) and has enough space to store C.
Return values	None		

If the input is malformed in the following ways, put the appropriate return code into `a0` and run `j exit` to quit the program.

Return code	**Exception**
38	The height or width of either matrix is less than 1.
38	The number of columns (width) of the first matrix A is not equal to the number of rows (height) of the second matrix B.

Testing and debugging

To test your function, in your local terminal, run `bash test.sh test_matmul`.

To debug your function, in your Venus terminal, run `cd /vmfs/test-src`, then run a VDB command to start the debugger:

```
vdb test_matmul_length_1.s
vdb test_matmul_negative_dim_m0_x.s
vdb test_matmul_negative_dim_m0_y.s
vdb test_matmul_negative_dim_m1_x.s
vdb test_matmul_negative_dim_m1_y.s
vdb test_matmul_nonsquare_1.s
vdb test_matmul_nonsquare_2.s
vdb test_matmul_square.s
vdb test_matmul_unmatched_dims.s
vdb test_matmul_zero_dim_m0.s
vdb test_matmul_zero_dim_m1.s
```

Debugging advice:

- Since you'll need to call the `dot` function in `matmul`, make sure to follow calling convention! See the calling convention appendix for more details. In particular, as soon as you call `dot`, the `dot` function is allowed to change all the t0-t6 and a1-a7 registers, so when the `dot` function returns, you need to assume that those registers contain *garbage*.

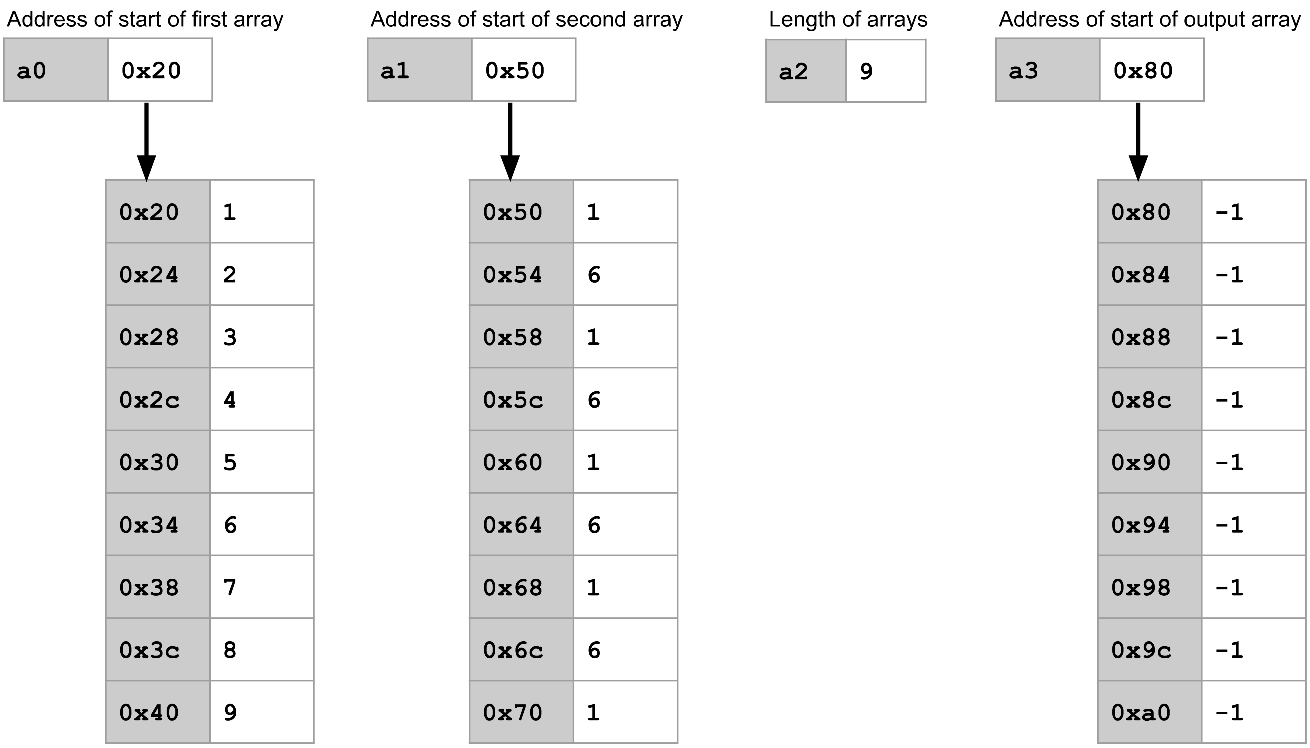
- You can use the functions described in the calling convention appendix to debug calling convention errors.
- Watch the debugging videos!

Task 6: Testing

In this task, you will be writing tests for some mathematical functions that have already been implemented for you.

Conceptual Overview: Loss Functions

A loss function takes in two integer arrays and outputs an integer array containing some measure of how different each pair of corresponding entries are. Some loss functions also output the sum of all the difference measurements. This project uses three different loss functions.



The absolute loss function computes and outputs the absolute difference between each pair of corresponding entries, and then outputs the sum of all the absolute differences.

Sum of elements in the output array

`a0`	`28`

Output array

`0x80`	0
`0x84`	4
`0x88`	2
`0x8c`	2
`0x90`	4
`0x94`	0
`0x98`	6
`0x9c`	2
`0xa0`	8

The squared loss function computes and outputs the square of the difference between each pair of corresponding entries, and then outputs the sum of all the squared differences.

Sum of elements in the output array

a0	144

Output array

0x80	0
0x84	16
0x88	4
0x8c	4
0x90	16
0x94	0
0x98	36
0x9c	4
0xa0	64

The zero-one loss function computes whether each pair of corresponding entries is equal, and does not output any sum.

Output array

0x80	1
0x84	0
0x88	0
0x8c	0
0x90	0
0x94	1
0x98	0
0x9c	0
0xa0	0

These loss functions use a helper function `initialize-zero`. It takes in the length of the array as input and outputs a newly-allocated array of the given length, filled with zeros.

Your Task

Fill in the tests for the three loss functions and the `initialize-zero` helper function in `studenttests.py`.

We recommend looking through `unittests.py` to understand how the Python framework for writing tests works.

To ensure that your tests are run by the unit testing framework, make sure that your function names start with `test_`! For example, the function `def test_length_0(self)` will run, but the function `def length_0(self)` will not run.

Loss functions: Task 6.			
Arguments	`a0`	`int *`	A pointer to the start of the first input array.
	`a1`	`int *`	A pointer to the start of the second input array.
	`a2`	`int`	The number of integers in the array.

	`a3`	`int *`	A pointer to the start of the output array, where the results will be stored.
Return values	`a0`	`int`	The sum of the elements in the output array. (No return value for zero-one loss.)

`initialize_zero`: Task 6.			
Arguments	`a0`	`int`	The size of the array to be created.
Return values	`a0`	`int *`	A pointer to the newly-allocated array of zeros.

The functions will return the following error codes if the input is malformed:

Return code	Exception
36	The length of the array is less than 1.
26	`malloc` returns an error.

To test your code coverage, run `bash test.sh coverage`. To get full credit on this part, make sure that your tests achieve 100% coverage. (In other words, your tests must cause every line of the implementation to be executed.)

Submission and Grading

Submit your code to the Project 2A assignment on Gradescope.

To ensure the autograder runs correctly, do not add any `.import` statements to the starter code. Also, make sure there are no `ecall` instructions in your code.