Designing a Calculator Using MIPS in MARS

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***Abstract*—This report goes over the steps to implement the basic operations of a calculator; addition, subtraction, multiplication and division. The program will be written MIPS normal and logical operations in MARS.**

I. Introduction

We will be using MIPS to implement our code in MARS which is also known as MIPS Assembler and Runtime Simulator. Then using MIPS assembly language and the MARS platform we will design a code to run addition, subtraction, multiplication, and division problems; both using normal and logical operations. Throughout the process of this project we will complete the following:

1) Install MARS and learn the basic functionalities of the assmebler

2) Implement the basic caluclator functions using normal operations

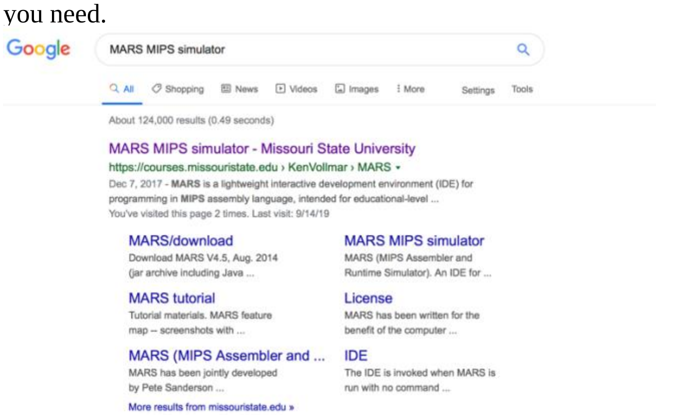
3) Implement the basic caluclator functions using logical operations

4) Test the code we designed to confirm our program performs as expected

II. Installing MARS And The Basics

A. Installation

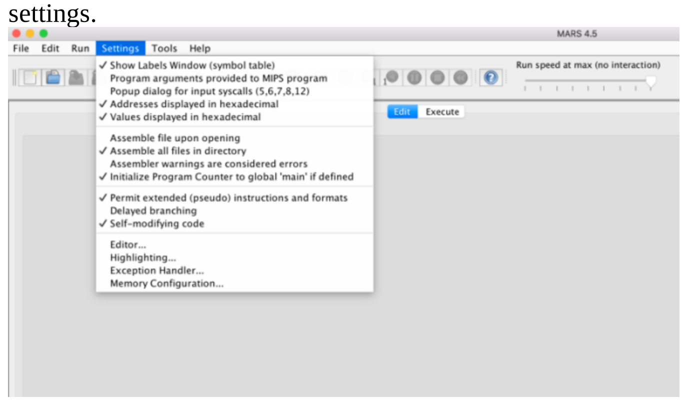
To install MARS, begin by doing a simple Google search for "MARS MIPS Simulator. The first link should be the one you need.



However, if this does not show up for you please visit https://courses.missouristate.edu/KenVollmar/MARS/. On the left-hand side of the website you will find a button that says "download." Click that button and then click the option that says, "Download MARS."

B. The Setup

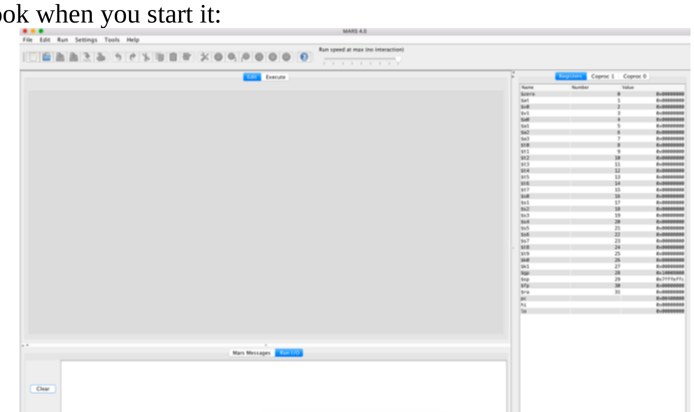
Once MARS is installed you will be able to launch the jar file to begin programming. However, before you begin programming you should make sure that you have the correct settings.



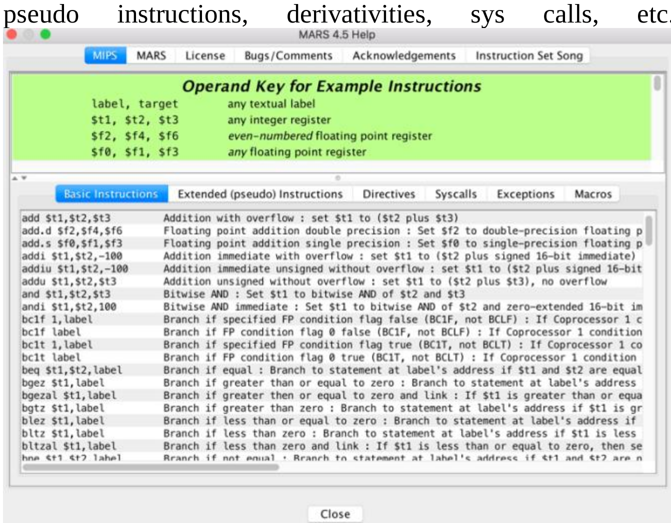
Make sure to have the following settings checked; show labels window (symbol table), addresses displayed in hexadecimal, values displayed in hexadecimal, assemble all files in directory, initialize program counter to global 'main' if defined, permit extended (pseudo) instructions and formats, and self-modifying code.

C. The Basics of MARS

In order to program a calculator on the MARS assembler we just downloaded we must go over the basics of how to use and navigate MARS. To begin with, this is how the assembler will look when you start it:



Going across the top you have your basics, easy to navigate buttons: File, Edit, Settings, Tools, and Help. Help is a very useful and important button that we will get back to. Right below this set of buttons you have another row. From left to right the buttons are used to; create a new file for editing, open a file for editing, save the current file, save the current file with a different name, dump machine code or data in available format, print current file, undo last edit, redo last edit, cut, copy, past, find/replace, run the current program, run one step at a time, undo the last step, pause the currently running program, stop the currently running program, reset MIPS memory and registers, and lastly, help once again. Below these buttons you have an edit view and an execution view which are used as needed (for editing and execution). On the bottom of the assembler, there is a rectangular box which gives your any messages from MARS, run time errors, and the run time output. Lastly, on the right side there is an option which allows you to view the values in your registers and coprocessors. An important feature of MARS that you must know before you begin your project is the "Help" button. Clicking this button will bring up all the basic instructions used in MIPS, as well as pseudo instructions, derivativities, sys calls, etc.



III. INSTALLING/OPENING STARTER FILES AND UNDERSTANDING PROJECT INSTRUCTIONS

Now that we know the basics of MARS, we can begin programming the calculator. To start, visit the "Project 1" assignment on canvas and download the zip file. If you cannot find the assignment use the following link: https://sjsu.instructure.com/courses/1324477/assignments/5056985?module_item_id=10137487. However, this link will only work if the project is open to you. After installing the zip file make sure to extract it. Doing so should give you an extracted file including: cs47_common_macro.asm, CS47_proj_alu_logical.asm, CS47_proj_alu_normal.asm, cs47_proj_macro .asm, cs47_proj_procs.asm, proj-auto-test.asm.

Now that we got the starter files installed, we should go over the instructions of what exactly needs to be done. The only files that need to be (or should be) edited during the process of writing this program are CS47_proj_alu_logical.asm, CS47_proj_alu_normal.asm, and cs47_proj_macro .asm. The other files are important to testing and running your code, however you must make sure that you do not edit or change these files. The

A. *Instructions for Normal*

You must edit CS47_proj_alu_normal.asm which takes three arguments $a0 first operand, $a1 second operand, and $a2 the operation code. This part of the program should use normal math operations in MIPS (add, sub, mul and div). to make the basic functions of the calculator. The result of operation will be stored into register $v0 for addition and subtraction. For multiplication, the result of HI will be stored into $v1 and LO will be stored into $v0. Lastly, for division, the quotient will be stored into $v0 and the remainder will be stored into $v1.

B. *Instrcutions for Logical*

For this step you must edit CS47_proj_alu_logical.asm which also take the same three arguments as the normal implementation. The outputs should also be the same as the normal implementation. However, the difference between alu_normal and alu_logical is the implementation itself. In alu_logical you may not use MIPS mathematical operations, but instead use only MIPS logic. Alu_logical may use regular math operations for uses such as incrementing and initializing.

- Complete the following two procedures in **CS47_proj_alu_normal.asm** and **CS47_proj_alu_logical.asm**. You may include your required macros (those you write) in the **cs47_proj_macro.asm**. Do not update proj-auto-test.asm or cs47_proj_procs.asm or cs47_common_macro.asm.
  - **au_normal (in CS47_proj_alu_normal.asm):** It takes three arguments as $a0 (First operand), $a1 (Second operand), $a2 (Operation code '+', '-', '*', '/' - ASCII code). It returns result in $v0 and $v1 (for multiplication $v1 it will contain HI, for division $v1 will contain remainder). This procedure uses normal math operations of MIPS to compute the result (add, sub, mul and div).
  - **au_logical (in CS47_proj_alu_logical.asm):** It takes three arguments as $a0 (First operand), $a1 (Second operand), $a2 (Operation code '+', '-', '*', '/' - ASCII code). It returns result in $v0 and $v1 (for multiplication $v1 it will contain HI, for division $v1 will contain remainder). The evaluation of mathematical operations should use MIPS logic operations only (**result should not be generated directly using MIPS mathematical operations**). The implementation needs to follow the digital algorithm implemented in hardware to implement the mathematical operations.

Before writing the code, you will get a 0/40 on the test cases and after the code is written correctly, you should receive a 40/40.

C. *Opening Starter Files*

Since we know the instructions and know what we have to do, let's begin with opening the starter files. To open the files, begin with starting up MARS. Once you are there, choose the button which is used to "Open a file for editing".

After this, navigate to the unzipped folder and open each asm file one by one. After opening each file in MARS, you should have something which looks like this above your edit view:

IV. Implementation of The Normal Procedure

In this part we will cover how to implement the alu_normal part of this project.

A. *Creating the differnet operation symbols*

Begin with creating a frame and then an if statement which will do the following: "if $a2 (operation symbol) = '+' then jump to add". Do this for all operation symbols (+,-,*, and /).

- '+' represents additions
- '-' represents subtractions
- '*' represents multiplication
- '/' represents division

```
au_normal:

        # TBD: Complete it
        #create frame
        addi    $sp, $sp, -24
        sw      $fp, 24($sp)
        sw      $ra, 20($sp)
        sw      $a0, 16($sp)
        sw      $a1, 12($sp)
        sw      $a2,  8($sp)
        addi    $fp, $sp, 24

        #body
        beq $a2, '+' , add #if operation is + jump to add
        beq $a2, '-' , subtract #if operation is - jump to subtract
        beq $a2, '*' , multiply #if operation is * jump to multiply
        beq $a2, '/' , divide #if operation is / jump to divide
```

B. *Add*

For the addition, simply use the MIPS instruction 'add' and store the addition into $v0.

C. *Subtract*

For the subtraction, use the MIPS instruction 'sub' and store the subtraction into $v0.

D. *Multiply*

For multiplication, multiply the operands together using 'mult' which will automatically store the HI value into HI and the LO value into LO. The 'mflo' (move from lo) and 'mfhi' (move from hi) to be the values into $v0 and $v1 as instructed.

E. *Divide*

For division, divide the operands using 'div' which will automatically move the quotient to LO and the remainder to HI. Then, as you did in multiply, use 'mflo' and mfhi' to move the values into $v0 and $v1.

```
add:
        add $v0, $a0, $a1 #$v0=$a0+$a1
        j end #jump to end where program restores frame

subtract:
        sub $v0, $a0, $a1 #v0=$a0-$a1
        j end #jump to end where program restores frame

multiply:
        mult  $a0, $a1 #multiply $a0 and $a1
        mflo $v0 #v0 = LO
        mfhi $v1 #v1 = HI
        j end #jump to end where program restores frame

divide:
        div $a0, $a1 #divide $a0 by $a1 where LO is quotient and HI is remainder
        mflo $v0 #quotient
        mfhi $v1 #remainder
        j end #jump to end where program restores frame
end:
        #restore frame
        lw      $fp, 24($sp)
        lw      $ra, 20($sp)
        lw      $a0, 16($sp)
        lw      $a1, 12($sp)
        lw      $a2,  8($sp)
        addi    $sp, $sp, 24
        jr $ra
```

Once you have completed the implementation of alu_normal you should be able to get 1/40 on the test case.

V. Implementation of The Logical Procedure

In this part we will go over the implementation of alu_logical.

A. *Macros*

To make the process a little simpler we will create some macros: extract_nth_bit($regD,$regS,$regT) and insert_to_nth _bit($regD,$regS,$regT,$maskReg).

Extract_nth_bit($regD,$regS,$regT) should be able to extract the bit at the $regT position (0-31) from $regS (the source bit pattern) and this should result into $regD being 0x1 or 0x0. To implement this macro use 'srlv' to shift right on $regS by $regT and store that value into $regD. Then you AND that value with 0x1 to get the value of the bit. This macro should look something like this:

```
.macro extract_nth_bit($regD, $regS, $regT) #as described in video
        srlv  $regD, $regS, $regT
        and $regD, $regD, 1
        .end_macro
```

Insert_to_nth_bit($regD,$regS,$regT,$maskReg) should insert the value from $regT (register containing the bit to insert, 0 or 1) into $regD at $regS (the nth position). $regMask is used to hold a temporary mask. Begin by initializing the $regMask to 1. Then, left shifting mask by n bits. After you have done that, invert $maskReg. Next, do an AND operation with your new $maskReg and $regD. After this, you shift $regT n times and then perform an OR operation with $regD.

```
                1
                V
    1 1 1 1 0 1 1 0 <--- D; n=3; b=1

 ---------------------------------------------
   0 0 0 0 0 0 0 1 <---- M == Mask

   0 0 0 0 1 0 0 0 <---- M = M << n

   1 1 1 1 0 1 1 1 <--- M = !M
 & 1 1 1 1 0 1 1 0 <--- D
 -------------------------
   1 1 1 1 0 1 1 0
 | 0 0 0 0 1 0 0 0 <--- b = b << n
 ----------------------
   1 1 1 1 1 1 1 0
```

After following these steps, you should get a macro looking like this:

```
.macro  insert_to_nth_bit ($regD, $regS, $regT, $maskReg) #as described in video
        li $maskReg, 1
        sllv $maskReg, $maskReg, $regS
        not $maskReg, $maskReg
        and $regD, $regD, $maskReg
        sllv $regT, $regT, $regS
        or $regD, $regD, $regT
        .end_macro
```

B. *Creating the differnet operation symbols*

Similar to the way we created if then statements using beq in the alu_normal, we will do the same here.

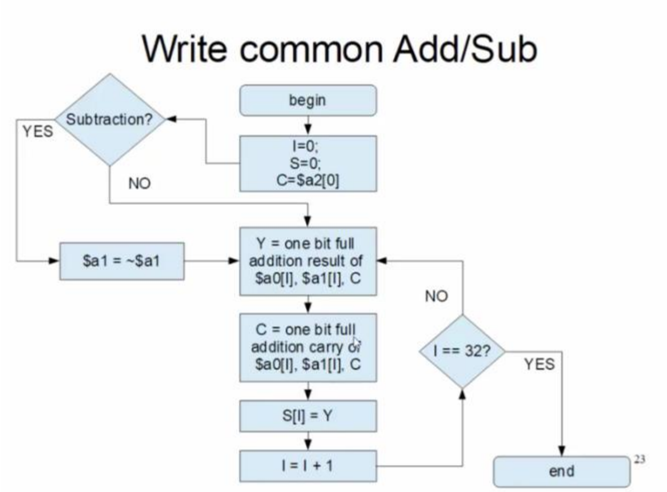
```
au_logical:
# TBD: Complete it
        #body
        beq     $a2, '+' , addition #if operation is + jump to add_sub
        beq     $a2, '-' , subtract #if operation is - jump to add_sub
        beq     $a2, '*' , multiply #if operation is * jump to multiply
        beq     $a2, '/' , divide #if operation is / jump to divide
  .....
```

C. Addition and Subtraction

The process for addition and subtraction is very similar, so we will attempt to combine some parts of the process for these two operations.

$a0 is the first operand, $a1 is the second operand and $a2 is a “mode” where it is set to 0x00000000 if the operation is addition and 0xFFFFFFFF if the operation is subtraction. To begin with, the if statement should branch to a label called addition or subtraction depending on the operation which should alter the value in $a2 register as needed. These two should come back together by branching to a label, ‘add_sub’ which initializes the counter, summation, and C (the first bit of $a2). Check to see what the value of C is. If C is 0 then the procedure addition, so jump to ‘add_sub_process’. On the other hand, if C is 1 then the procedure is subtraction, so invert the second operand and then jump to ‘add_sub_process’.

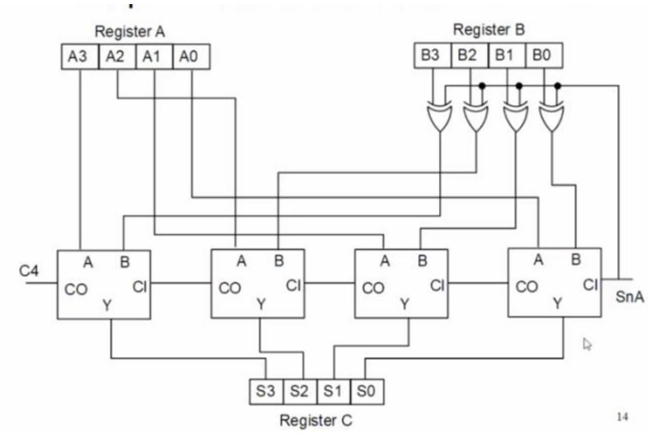
Inside of the ‘add_sub_process’ you perform one-bit full addition. One-bit full addition is where you pick up one bit at a time from each operand and from C and then XOR between them. C is the carry bit of the XOR between the previous one-bit addition. Since you are doing one bit at a time for the entire number you should have a loop going from 0 to 31. Use the macros created to extract one bit at a time, add them and then insert each bit where it belongs inside of $v0, which should include your final answer. Repeat this process by incrementing I until you finish with the MSB (Incrementor = 31). Once I = 31 branch to ‘add_sub_end’ where you restore the frame. The algorithm of this process is visualized as the following:



Once completed, your implementation should look similar to the one shown below. However, it may or may not differ depending on if you followed this algorithm or not. Also, it may differ depending on the instructions and pseudo instructions you used and in what order you performed your operations.

```
addition:
        li      $a2,0x00000000

        j       add_sub

subtract:
        li      $a2,0xFFFFFFFF

        j       add_sub

add_sub:
        #create frame
        addi    $sp, $sp, -32
        sw      $fp, 32($sp)
        sw      $ra, 28($sp)
        sw      $t0, 24($sp)
        sw      $t1, 20($sp)
        sw      $t2, 16($sp)
        sw      $t3, 12($sp)
        sw      $t4, 8($sp)
        addi    $fp, $sp, 32

        li      $t0, 0x0 #index=0
        li      $v0, 0x0 #summation = 0

        extract_nth_bit($t1,$a2,$t0) #c=$a2[0]

        beq     $a2, 0x0, add_sub_process

        j       invert

invert:
        nor     $a1, $a1, $zero

        j       add_sub_process

add_sub_process:
        extract_nth_bit($t2,$a0,$t0)
        extract_nth_bit($t3,$a1,$t0)

        xor     $t4, $t2, $t3 #op 1 xor op 2
        and     $t5, $t2,$t3
        xor     $t6, $t4, $t1 #c xor (op1 xor op 2)
        and     $t1,$t1,$t4

        or      $t1, $t1, $t5

        insert_to_nth_bit($v0,$t0,$t6,$t3)

        addi    $t0, $t0, 0x1 #increment index
        beq     $t0, 32, add_sub_end #if index = 32 then break loop

        j       add_sub_process #loop

add_sub_end:
        #restore frame
        lw      $fp, 32($sp)
        lw      $ra, 28($sp)
        lw      $t0, 24($sp)
        lw      $t1, 20($sp)
        lw      $t2, 16($sp)
        lw      $t3, 12($sp)
        lw      $t4, 8($sp)
        addi    $sp, $sp, 32

        jr      $ra
```

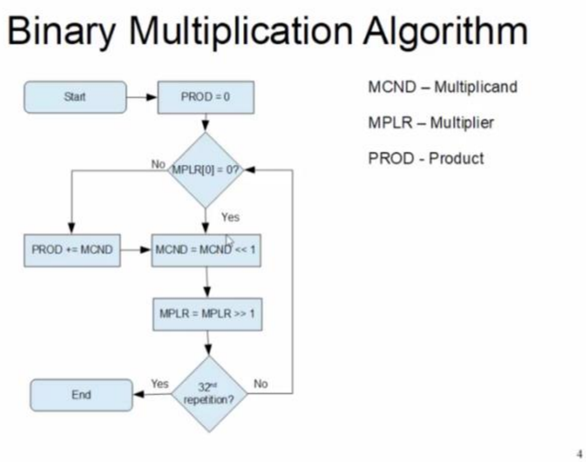
The multi bit addition and subtraction diagram/flow chart looks as shown below:



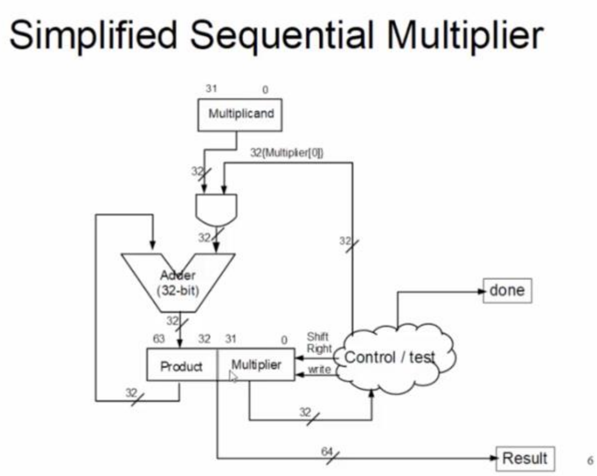
Once you have completed the implementation of the alu_normal and the alu_logical addition and subtraction part you should be able to get a 20/40 on the test cases. You should be halfway done with the project (P.S this was the easier half, the next part gets crazy).

D. Multiplication

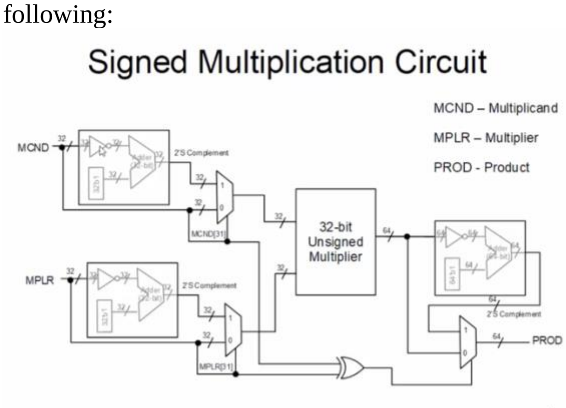
The algorithm of the multiplication processes goes as follows. You start and assign product (a 64-bit output) as 0. Then, you look at the LSB of the multiplier and test if it is 0 or not. If the multiplier is 1, add the product with the multiplicand, so product = product + multiplicand and then left shift multiplicand by one bit. If the multiplier is 0 then skip straight to shifting the multiplicand by one bit. Next, you shift the multiplier to the right by one bit. You do this on a loop, with an incrementor. Once, you hit 31 you stop. The visual representation of the algorithm looks like this:



A 32-bit unsigned multiplier has a diagram which make it a lot easier to visualize what the multiplier is actually doing.



However, this is only for a 32-bit unsigned multiplier. We also want to construct signed multiplication. Unsigned multiplication will ignore the signs of the operands and only give you a positive answer, thus having a signed multiplier in our program is essential. A signed multiplier visual looks like the following:



To implement this in MARS we must create a few procedures:

1) Twos_complement- This procedure should return the twos complement of the argument ($a0). In this procedure you use 'NOT' and your previously designed addition procedure to compute ~$a0+1.

```
twos_complement:
        not     $a0, $a0
        li      $a1, 1
        j       addition #~$a0 + 1

```

2) Twos_complement_if_negative- Depending on if the bit pattern is negative use this procedure. It should return the twos complement of $a0 if $a0 is negative. If the incoming bit pattern is negative then do twos_complement otherwise do not. This procedure should simply call twos_complement if necessary.

```
twos_complement_if_negative:
        bltz    $a0, twos_complement
        jr      $ra

```

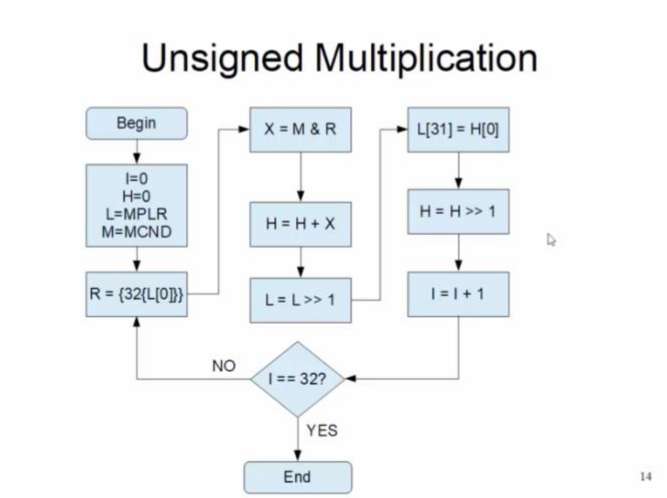
3) Twos_comp_64bit- the argument $a0 is the lower half of the adress and the argument $a1 is the hi of the number. It should return $v0, the lo part of the 2s complement 64 bit and $v1, the hi part of the the 2s complement 64 bit. First invert both $a0 and $a1. Then, use your previously created addition procedure to add 1 to $a0. Lastly, add carry from previous step to $a1 (also using the addition procedure you created). Make sure to not just take the complement of the upper and lower half because this will not work.

```
twos_comp_64bit:
        #create frame
        addi    $sp, $sp, -16
        sw      $fp, 16($sp)
        sw      $ra, 12($sp)
        sw      $t0,  8($sp)
        addi    $fp, $sp, 16

        nor     $t0, $a1, $zero
        nor     $a0, $a0, $zero
        add     $a1, $zero, 1

        jal     addition

        move    $a0, $t0
        move    $t0, $v0
        move    $a1, $v1

        jal     addition

        move    $v1, $v0
        move    $v0, $t0

        #restore frame
        lw      $fp, 16($sp)
        lw      $ra, 12($sp)
        lw      $t0,  8($sp)
        addi    $sp, $sp, 16

        jr      $ra

```

4) Bit_replicator- replicates a given bit value to 32 times. This takes an argument of $a0 which is 0x0 or 0x1 and sets $v0 to 0x00000000 if $a0 is 0x0 or 0xFFFFFFFF if $a0 is 0x1.

```
bit_replicator:
        beq     $a0, 0x0, replicate_0
        li      $v0, 0xFFFFFFFF
        jr      $ra

replicate_0:
        li      $v0, 0
        jr      $ra

```

5) Multiply_unsigned- this should take $a0 (the multiplicand) and $a1 (the multiplier) as arguments. Its should return lo through $v0 and high through $v1. The algorithm looks like this:



The code for unsigned multiply should look like the following:

```
multiply_unsigned:
        #create frame
        addi    $sp, $sp, -48
        sw      $fp,  48($sp)
        sw      $ra,  44($sp)
        sw      $s0,  40($sp)
        sw      $s1,  36($sp)
        sw      $s2,  32($sp)
        sw      $s3,  28($sp)
        sw      $s4,  24($sp)
        sw      $s5,  20($sp)
        sw      $t0,  16($sp)
        sw      $t1,  12($sp)
        sw      $t2,  8($sp)
        addi    $fp, $sp, 48

        add     $s0, $zero, $zero #I
        add     $s1, $zero, $zero #H
        move    $s2, $a0 #$a0 is multiplicand = M
        move    $s3, $a1 #$a1 is multiplier = L

        j       multiply_process

```

6) Signed Multiplication: Set n1 to $a0 and n2 to $a1. Make n1 and n2 twos complemenet if they are negative.Then, call unsigned multiplication using n1 and n2. Then determine the sign of the bit by extracting the MSB of $a0 and $a and xor between them. The xor result is S. If S is 1 then use twos_comp_64bit to determine the twos complement of the number.

Following the algorithms and diagrams above your code for multiplication should appear as this:

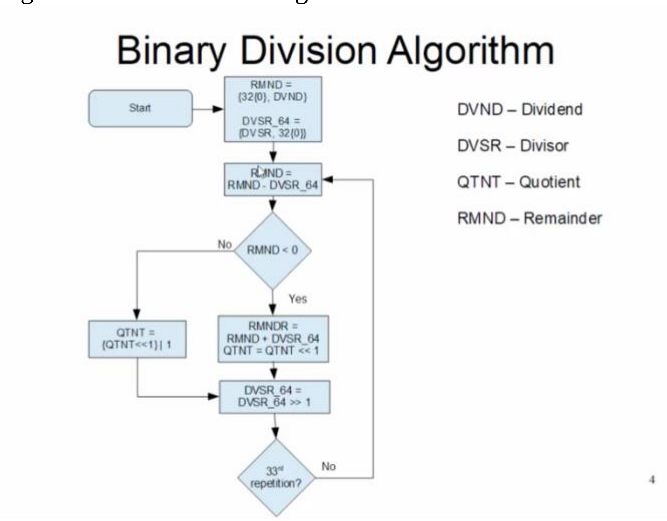
```
multiply:
        #create frame
        addi    $sp, $sp, -28
        sw      $fp, 28($sp)
        sw      $ra, 24($sp)
        sw      $s2, 20($sp)
        sw      $s1, 16($sp)
        sw      $s0, 12($sp)
        sw      $t0, 8($sp)
        addi    $fp, $sp, 28

        move    $s0, $a0 #n1
        move    $s1, $a1 #n2
        move    $v0, $a0

        jal     twos_complement_if_negative     #if negative returns in $v0

        move    $s2, $v0 #n1 is stored in s2
        move    $a0, $s1
        move    $v0, $s1

        jal     twos_complement_if_negative

        move    $a1, $v0 #n2 = a1
        move    $a0, $s2

        jal     multiply_unsigned #calls unsigned multiplication with $a1 and $a0

        move    $a0, $v0 #quotent
        move    $a1, $v1 #remainder
        add     $t0, $zero, 31

        extract_nth_bit($s0, $s0, $t0) #sign of a0 in s0
        extract_nth_bit($s1, $s1, $t0) #sign of a1 in s1

        xor     $s0, $s0, $s1 #s in s0
        beq     $s0, 1, twos_comp_64bit #get complement if s is 1

        #restore frame
        lw      $fp, 28($sp)
        lw      $ra, 24($sp)
        lw      $s2, 20($sp)
        lw      $s1, 16($sp)
        lw      $s0, 12($sp)
        lw      $t0, 8($sp)
        addi    $sp, $sp, 28
        jr      $ra

```

```
multiply_process:
        extract_nth_bit($s4, $s3, $zero)

        move    $a0, $s4

        jal     bit_replicator #replicate the value in R 32 times, returns in $v0

        move    $s4, $v0
        and     $s5, $s2, $s4 #X = M & R
        add     $s1, $s1, $s5 #H = H + X
        srl     $s3, $s3, 1 #L = L >> 1

        extract_nth_bit($t0, $s1, $zero) #extract 0th bit from H

        add     $t1, $zero, 31

        insert_to_nth_bit($s3,$t1,$t0,$t2) #L[31] = H[0]

        srl     $s1, $s1, 1 #H = H >> 1
        add     $s0, $s0, 1 #increment counter
        beq     $s0, 32, multiply_end #if index = 32 then break loop

        j       multiply_process #loop

multiply_end:
        move    $v0, $s3 #lo
        move    $v1, $s1 #hi

        #restore frame
        lw      $fp,  48($sp)
        lw      $ra,  44($sp)
        lw      $s0,  40($sp)
        lw      $s1,  36($sp)
        lw      $s2,  32($sp)
        lw      $s3,  28($sp)
        lw      $s4,  24($sp)
        lw      $s5,  20($sp)
        lw      $t0,  16($sp)
        lw      $t1,  12($sp)
        lw      $t2,  8($sp)
        addi    $sp, $sp, 48
        jr      $ra

```

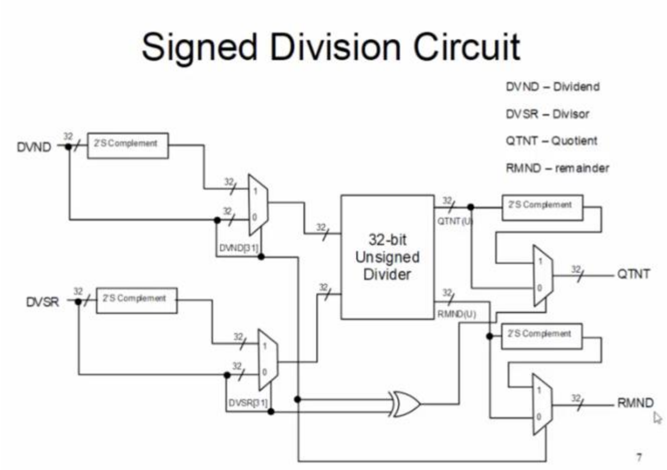
This code above should be accompanied with the procedures we went over.

E. Division

The algorithm should begin by loading the remainder register (64 bits) with the dividend in the lower half and 32 0's in the upper half and loading the divisor register (64 bits) with the divisor in the upper half and 32 0's in the lower half. Next, you do remainder = remainder – divisor (64) using a 64-bit subtractor. Next, if the remainder is not less than 0 then left shift quotient by one and then OR with 1. On the other hand, if the remainder is less than one after doing remainder = remainder – divisor, then you do remainder = remainder + divisor and then left shift quotient by 1. Then, we right shift divisor by 1. You do this until 33rd repetition. The visual representation of the algorithm looks as following:

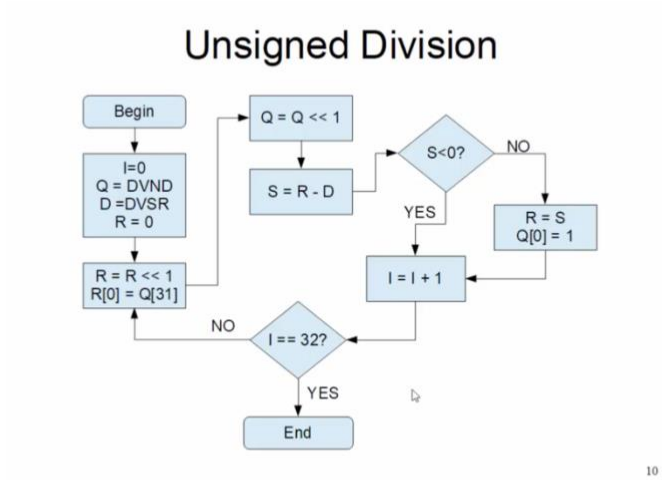


A visual representation of a signed division circuit looks like this:

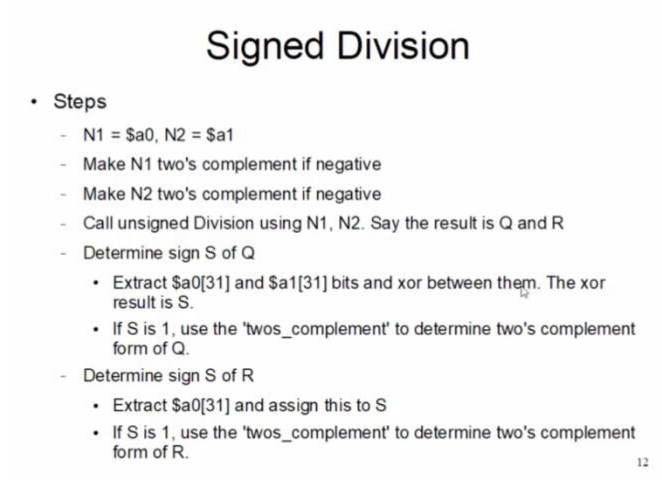


Your code for alu_divide should include the following procedures:

1) Divide_unassigned- this takes the aruguments $a0 (dividend) and $a1 (divisor) and returns $vo (quotient) and $v1 (remainder). The approach to writing the algorithm for divide_unassigned is as follows:



The steps of signed division are as follows:



Once completed, your code for divide should look like this:

```
divide:
        #create frame
        addi    $sp, $sp, -28
        sw      $fp, 28($sp)
        sw      $ra, 24($sp)
        sw      $s2, 20($sp)
        sw      $s1, 16($sp)
        sw      $s0, 12($sp)
        sw      $t0, 8($sp)
        addi    $fp, $sp, 28

        la      $s0, ($a0) #N1
        la      $s1, ($a1) #N2
        move    $v0, $a0

        jal     twos_complement_if_negative #if negative then take complement

        move    $s2, $v0 #N1 = s2
        move    $a0, $s1
        move    $v0, $s1

        jal     twos_complement_if_negative #if negative then take complement

        move    $a1, $v0 #N2 = a1 divisor
        move    $a0, $s2 #N1 = a0 dividend

        jal      divide_unsigned #returns $v0 quotent and $v1 remainder

        move     $a0, $v0 #Q
        move    $a1, $v1 #R

        #determine sign
        add     $t0, $zero, 31

        extract_nth_bit($s0, $s0, $t0) #sign of a0 in t2
        extract_nth_bit($s1, $s1, $t0) #sign of a1 in s1

        xor     $t6, $s0, $s1 #S in t2
        and     $t7, $t6, $s0
        beq     $t7, 1, complement2 #if both are 1 then negate both
        beq     $t6, 1 , twos_complement
        beq     $s0, 1, complement

        #restore frame
        lw      $fp, 28($sp)
        lw      $ra, 24($sp)
        lw      $s2, 20($sp)
        lw      $s1, 16($sp)
```

```
        lw      $s1, 16($sp)
        lw      $s0, 12($sp)
        lw      $t0, 8($sp)
        addi    $sp, $sp, 28
        jr $ra

divide_unsigned:
        addi    $sp, $sp, -48
        sw      $fp,  48($sp)
        sw      $ra,  44($sp)
        sw      $s0,  40($sp)
        sw      $s1,  36($sp)
        sw      $s2,  32($sp)
        sw      $s3,  28($sp)
        sw      $s4,  24($sp)
        sw      $s5,  20($sp)
        sw      $t0,  16($sp)
        sw      $t1,  12($sp)
        sw      $t2,  8($sp)
        addi    $fp, $sp, 48

        add     $s0, $zero, $zero# I  (counter)
        add     $s1, $zero, $zero# R Remaninder
        move    $s2, $a0# Q
        move    $s3, $a1# D

        j        divide_process

divide_process:
        sll     $s1, $s1, 1 #R = R << 1
        li      $t0, 31

        extract_nth_bit($s4, $s2, $t0) #extract 31st bit from Q
        insert_to_nth_bit ($s1, $zero, $s4, $t9) #insert at R[0]

        sll     $s2, $s2, 1 #Q = Q << 1
        move    $a0, $s1 #move R into $a0
        move    $a1, $s3 #move D into $a1

        jal     subtract

        move    $s5, $v0 #solution stored in $s5 after subtracting S
        la      $a0, ($s2)
        bltz    $s5, check_loop
        move    $s1, $s5
        li      $t1, 1

        insert_to_nth_bit ($s2, $zero, $t1, $t9)


        j       check_loop

check_loop:
        addi    $s0, $s0, 1
        li      $t2, 32
        beq     $s0, $t2, divide_process_end #if index = 32 then break loop
        j       divide_process #loop

divide_process_end:
        move    $v1, $s1 #remainder
        move    $v0, $s2 #quotent

        #restore frame
        lw      $fp,  48($sp)
        lw      $ra,  44($sp)
        lw      $s0,  40($sp)
        lw      $s1,  36($sp)
        lw      $s2,  32($sp)
        lw      $s3,  28($sp)
        lw      $s4,  24($sp)
        lw      $s5,  20($sp)
        lw      $t0,  16($sp)
        lw      $t1,  12($sp)
        lw      $t2,  8($sp)
        addi    $sp, $sp, 48
        jr      $ra
```

F. Testing

Now you should be finished with implementing alu_normal and alu_logical so we could test if our code works as expected. To test the code, make sure all files are saved as the latest version and then run the code. To run the code, go to the project auto-test.asm file (on MARS) and hit the 'assemble the current file and clear breakpoints' button. Then, hit the 'run the current program' button. Assuming you did everything correct, your output should be:

```
(4 + 2)         normal => 6     logical => 6    [matched]
(4 - 2)         normal => 2     logical => 2    [matched]
(4 * 2)         normal => HI:0 LO:8     logical => HI:0 LO:8    [matched]
(4 / 2)         normal => R:0 Q:2       logical => R:0 Q:2      [matched]
(16 + -3)       normal => 13    logical => 13   [matched]
(16 - -3)       normal => 19    logical => 19   [matched]
(16 * -3)       normal => HI:-1 LO:-48          logical => HI:-1 LO:-48         [matched]
(16 / -3)       normal => R:1 Q:-5      logical => R:1 Q:-5     [matched]
(-13 + 5)       normal => -8    logical => -8   [matched]
(-13 - 5)       normal => -18   logical => -18          [matched]
(-13 * 5)       normal => HI:-1 LO:-65          logical => HI:-1 LO:-65         [matched]
(-13 / 5)       normal => R:-3 Q:-2     logical => R:-3 Q:-2    [matched]
(-2 + -8)       normal => -10   logical => -10          [matched]
(-2 - -8)       normal => 6     logical => 6    [matched]
(-2 * -8)       normal => HI:0 LO:16    logical => HI:0 LO:16   [matched]
(-2 / -8)       normal => R:-2 Q:0      logical => R:-2 Q:0     [matched]
(-6 + -6)       normal => -12   logical => -12          [matched]
(-6 - -6)       normal => 0     logical => 0    [matched]
(-6 * -6)       normal => HI:0 LO:36    logical => HI:0 LO:36   [matched]
(-6 / -6)       normal => R:0 Q:1       logical => R:0 Q:1      [matched]
(-18 + 18)      normal => 0     logical => 0    [matched]
(-18 - 18)      normal => -36   logical => -36          [matched]
(-18 * 18)      normal => HI:-1 LO:-324         logical => HI:-1 LO:-324        [matched]
(-18 / 18)      normal => R:0 Q:-1      logical => R:0 Q:-1     [matched]
(5 + -8)        normal => -3    logical => -3   [matched]
(5 - -8)        normal => 13    logical => 13   [matched]
(5 * -8)        normal => HI:-1 LO:-40          logical => HI:-1 LO:-40         [matched]
(5 / -8)        normal => R:5 Q:0       logical => R:5 Q:0      [matched]
(-19 + 3)       normal => -16   logical => -16          [matched]
(-19 - 3)       normal => -22   logical => -22          [matched]
(-19 * 3)       normal => HI:-1 LO:-57          logical => HI:-1 LO:-57         [matched]
(-19 / 3)       normal => R:-1 Q:-6     logical => R:-1 Q:-6    [matched]
(4 + 3)         normal => 7     logical => 7    [matched]
(4 - 3)         normal => 1     logical => 1    [matched]
(4 * 3)         normal => HI:0 LO:12    logical => HI:0 LO:12   [matched]
(4 / 3)         normal => R:1 Q:1       logical => R:1 Q:1      [matched]
(-26 + -64)     normal => -90   logical => -90          [matched]
(-26 - -64)     normal => 38    logical => 38   [matched]
(-26 * -64)     normal => HI:0 LO:1664          logical => HI:0 LO:1664         [matched]
(-26 / -64)     normal => R:-26 Q:0     logical => R:-26 Q:0    [matched]


Total passed 40 / 40
*** OVERALL RESULT PASS ***

-- program is finished running --
```