CSc 252: Computer Organization
Spring 2018 (Lewis)

HW 3
due at the beginning of lecture on test day

Policy Reminders

- Include your CS username on your page. You will lose a few points from your score if you do not include it.
- You are allowed to work with other students on this homework, as we will not be grading it for correctness. However, each student must turn in their own copy of the homework.
- Show your work for all problems. While we won’t be grading for correctness, you will not receive full credit unless you show your work.
  After all, showing your work is required on the test - and homeworks are intended to help you practice for the test!

Required Problems:

1(b), 2(c), 3(c), 4(c), 5(c), 6(c) Problem list fixed after due date!

Allowable Instructions

When writing MIPS assembly, the only instructions that you are allowed to use (so far) are:

- add, addi, sub, addu, addiu, subu
- beq, bne, j, jal, jr
- slt, slti
- and, andi, or, ori, nor, nori, xor, xori
- sll, srl, sra
- lw, lh, lb, sw, sh, sb
- la
- syscall

While MIPS has many other useful instructions (and the assembler recognizes many pseudo-instructions), do not use them! We want you to learn the fundamentals of how assembly language works - you can use fancy tricks after this class is over.
Problem 1 - Truth Tables and Sum of Products

For each part, convert the truth table into a sum-of-products expression for each of the outputs (W, X, Y, Z).

Then draw a logic network which calculates only the Z output from the inputs.

(a)

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<th>C</th>
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<th>X</th>
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(b) - Turn in this one

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Solution: $W = \overline{ABC} + \overline{ABC} + \overline{A}BC$

$X = \overline{AB}C + \overline{ABC} + ABC$

$Y = \overline{ABC} + \overline{ABC} + ABC + ABC$

$Z = ABC + \overline{A}BC + ABC + ABC$
Problem 2 - Loops in MIPS

Convert the following loops from C to assembly. Some variables have already been assigned to registers; for others, you will need to assign them registers yourself. Use sX registers for all variables that have names in the C program; use tX registers for any other temporaries that you create.

(a)
C code:
```c
int sum = 0; // s0
for (int i=-10; i<10; i++)
{
    sum += i;
}
```

(b)
C code:
```c
int val = ... ; // s2 - assume that some previous code has set it!
while (val > 0)
{
    // HINT: '0' is equal to 0x30 http://www.asciitable.com
    printf("%c", '0'+(val & 0x1));
    // REMINDER: 'div' is not allowed. Use a shift.
    val /= 2;
}
```

**Bonus Question (not required):** What does this program do? Why does it have a bug if $s2 < 0$?

(c) - Turn in this one
C code:
```c
int len = ... ; // s1 - this is set by previous code
int min = ... ; // s3 - this is set by previous code
for (int i=0; i<len; i++)
{
    if (i >= min)
        printf("%d", i);
}
```

Solution:
# remember: s1 contains len, s3 contains min
#
# s0 will contain i
# t0 will be used for various temporaries

addi $s0, $zero, 0  # i = 0

LOOP:
    slt $t0, $s0, $s1  # t0 = (i < len)
    beq $t0, $zero, AFTER  # if (i >= len) break
    slt $t0, $s0, $s3  # t0 = (i < min)
    beq $t0, $zero, SKIP  # if (i >= min) skip over
    addi $v0, $zero, 1  # print_int(i)
    add $a0, $s0, $zero
    syscall

SKIP:
    addi $s0, $s0, 1  # i++
    j LOOP

AFTER:
Problem 3 - ALUs

In this problem, you will simulate an ALU, following the designs we've seen in class. However, to make the work easier, you will only need to simulate a 4-bit ALU, not a 32-bit one. (Just like in the 32-bit ALU, the Less input for ALU Element 0 - the LSB - comes from the adder output from ALU Element 3 - the MSB.)

(a)
Give the proper control bits - that is, the bNegate and aluOp values - to configure the ALU to Add. Then, consider what would happen if the input values were as follows:

\[
\begin{align*}
a &= 1101 \\
b &= 0111
\end{align*}
\]

Give the following values as 4 bit numbers:

- The 4 AND bits
- The 4 OR bits
- The 4 Add results
- The 4 Out values (that is, the output from the various Result MUXes)

(b)
Repeat part (a), except that you must give the configuration to perform subtraction. This time, give the following information:

- The 4 Add results
- The 4 Less inputs
- The 4 Out values (that is, the output from the various Result MUXes)

For this problem, use the following input values:

\[
\begin{align*}
a &= 0011 \\
b &= 1001
\end{align*}
\]

(c) - Turn in this one
Repeat part (b), except that you must give the configuration bits to perform Set-Less-Than. Report the same output information as from part(b).

For this problem, use the following input values:

\[
\begin{align*}
a &= 1111 \\
b &= 0110
\end{align*}
\]
**Solution:** For set-less-than, we must set $b_{\text{Negate}}=1$ and $aluOp=3$.

The Add results are: $1001$

The MSB of the Add result wraps around, to be the LSB of the Less input. Therefore, the Less inputs are: $0001$. **Instructor's Note:** Since $a$ is negative (MSB=1) and $b$ is positive, it is reasonable that $\text{slt}$ would produce a 1 result.

Since $aluOp=3$, we will select the Less input in every ALU Element as our the desired Output. Therefore, the output will be $0001$. 
Problem 4 - Tracking a Stack

(a)

In this problem, foo() calls bar(). The first column shows the state of the stack while foo() is running, just before its startup code.

In the second column, show the state of the stack after the startup code in foo() has completed, but before the jal instruction. In the third column show the state of the stack after bar() has run its function prologue and it has saved any registers that are required.

Make sure to mark:
- The positions of $fp, $sp
- All values which have been written to stack
  Use arg1, arg2, etc. for the various parameters. Use arg1 for the first parameter - which is stored in $a0.

Notes:
- When this problem begins, foo() is using (and wants to preserve) the registers $t0, $t1, $t2, $s3, $s4, $s5.
- bar() takes 5 parameters. It will need to the 1st, 3rd, and 5th on the stack.
- bar() will be using the following registers somewhere in its code: $s0, $s1, $t2, $t3, $t4.
(b)

In this problem, foo() calls bar(). The first column shows the state of the stack while foo() is running, just before its startup code.

In the second column, show the state of the stack after the startup code in foo() has completed, but before the jal instruction. In the third column show the state of the stack after bar() has run its function prologue, but before it saved any other than the prologue (not even aX registers). In the third column show the state of the stack after bar() has saved all necessary registers.

Make sure to mark:

- The positions of $fp, $sp
- All values which have been written to stack

Use arg1, arg2, etc. for the various parameters. Use arg1 for the first parameter - which is stored in $a0.

Notes:

- When this problem begins, foo() is using (and wants to preserve) the registers $s3, $s4, $t0, $t6, $t7.
- bar() takes 2 parameters. It will need to store both on the stack.
- bar() will be using the following registers somewhere in its code: $s3, $s4, $t0, $t1.
(c) - Turn in this one

In this problem, foo() calls bar(). The first column shows the state of the stack while foo() is running, just before its startup code.

In the second column, show the state of the stack after the startup code in foo() has completed, but before the jal instruction. In the third column show the state of the stack after bar() has run its function prologue, but before it saved any other than the prologue (not even aX registers). In the fourth column show the state of the stack after bar() has saved all necessary registers.

Make sure to mark:

- The positions of $fp, $sp
- All values which have been written to stack

Use arg1, arg2, etc. for the various parameters. Use arg1 for the first parameter - which is stored in $a0.

Notes:

- When this problem begins, foo() is using (and wants to preserve) the registers $t2, $s0, $s1, $s2, $s3.
- bar() takes 8 parameters. It will need to store the first and fourth on the stack.
- bar() will be using the following registers somewhere in its code: $t0, $t1, $t3, $t4, $s4, $s5, $s6, $s7.

<table>
<thead>
<tr>
<th>$fp</th>
<th>stack at beginning</th>
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<tbody>
<tr>
<td>$sp</td>
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Problem 5 - Calling Functions

For each problem below, I have given a set of registers which are currently in use and which need to be saved, and then a function call with a certain set of parameters. Write the code that should run in the caller - including the startup and cleanup code. Save every register which might be destroyed by the called function, but do not save any register which would be saved by the called function.

(a)
Registers to save: $s0, $s1, $s3, $t0, $t1, $t2
Call to make: foo(1,2)

(b)
Registers to save: $s2, $s4, $s6, $t1, $t3, $t5
Call to make: bar(0, 0x1234, str)
   (Assume that str is a label of a string. Pass the address of the first character as the third parameter.)

(c) - Turn in this one
Registers to save: $t1, $t2, $t3, $t4, $s0, $s1
Call to make: fred(123, 456, 0xabc, 0xdef, 0, 10)
addiu $sp, $sp, -16  
sw $t1, 12($sp)  
sw $t2, 8($sp)  
sw $t3, 4($sp)  
sw $t4, 0($sp)  
addi $a0, $zero, 123  
addi $a1, $zero, 456  
addi $a2, $zero, 0xabc  
addi $a3, $zero, 0xdef  

# we don’t want to save t5, so it’s OK to use it as a  
# temporary in this code.  
sw $zero, -8($sp)  
addi $t5, $zero, 10  
sw $t5, -4($sp)  
jal fred  
lw $t4, 0($sp)  
lw $t3, 4($sp)  
lw $t2, 8($sp)  
lw $t1, 12($sp)  
addiu $sp, $sp, 16  

Problem 6 - Function Prologues and Epilogues

For each problem below, I have given a set of registers which will be modified by a certain function, along  
with the number of parameters it has; I will also list if any of the parameters need to be copied to the stack  
(so that they can be saved across a future function call). Write the appropriate prologue and epilogue plus  
the register save/restore code) for this function.

(a)
 Registers which will be modified: $s0, $s1, $s3, $t0, $t1, $t2  
Number of Parameters: 3  
Parameters to Save on Stack: $a2

(b)
 Registers which will be modified: $s2, $s4, $s6, $t1, $t3, $t5  
Number of Parameters: 3  
Parameters to Save on Stack: None

(c) - Turn in this one
 Registers which will be modified: $t1, $t2, $t3, $t4, $s0, $s1  
Number of Parameters: 6  
Parameters to Save on Stack: $a0, $a1, $a2, $a3
Solution:

```assembly
    addiu $sp, $sp, -32
    sw $ra, 4($sp)
    sw $fp, 0($sp)
    addiu $fp, $sp, 28

    # save the aX registers
    sw $a0, 8($sp)
    sw $a1, 12($sp)
    sw $a2, 16($sp)
    sw $a3, 20($sp)

    # save the sX registers that we’re going to use.
    addiu $sp, $sp, -8
    sw $s0, 4($sp)
    sw $s1, 0($sp)

    ... body ...

    lw $s1, 0($sp)
    lw $s0, 4($sp)
    addiu $sp, $sp, 8

    lw $fp, 0($sp)
    lw $ra, 4($sp)
    addiu $sp, $sp, 32
    jr $ra
```
EXAMPLES

Example: Problem 1(a)

\[ W = AB\overline{C} + ABC \]
\[ X = \overline{A}BC + ABC + AB\overline{C} \]
\[ Y = \overline{A}BC + ABC \]
\[ Z = \overline{A}BC + AB\overline{C} + ABC \]
Example: Problem 2(a)

# Remember: sum is in s0.
# We’ll decide to store i in t0, and other temporaries in t1.

addi $s0, $zero, 0  # sum = 0
addi $t0, $zero, -10 # i = -10

LOOP:
slti $t1, $t0, 10  # t1 = (i < 10)
beq $t1, $zero, AFTER  # if (i >= 10) break
add $s0, $s0, $t0  # sum += i
addi $t0, $t0, 1  # i++
  j LOOP

AFTER:

Example: Problem 2(b)

# Remember: val is in s2. It has been initialized to *some* value before
# this code runs.
# We’ll decide to use t1 for all temporaries.

LOOP:
slt $t1, $zero, $s2  # t1 = (0 < val)
beq $t1, $zero, AFTER  # if (val <= 0) break
andi $t1, $s2, 0x1  # t1 = (val & 0x1)
addi $a0, $t1, 0x30  # t1 = 0x30 + (val & 0x1)
addi $v0, $zero, 11  # print_char('0' + (val & 0x1))
syscall
sra $s2, $s2, 1  # s2 /= 2
  j LOOP

AFTER:

Bonus Question: This program prints out the bits of $s2, in reverse order (that is, from LSB to MSB). It has a bug if $s2 < 0 because it will loop forever at $s2 == -1, and print an infinite number of high bits.

Example: Problem 3(a)

For addition, we must set bNegate==0 and aluOp==2.

The AND bits are: 0101
The OR bits are: 1111
The Add results are: 0100 Instructors Note: You will notice that the value had a carry-out, but our 4-bit addeer simply discarded the extra bits in the result.
Since aluOp==2 we will select the Add result in every ALU Element as our the desired Output. Therefore, the output will be 0100
Example: Problem 3(b)

For subtraction, we must set $bNegate==1$ and $aluOp == 2$.

Since we are performing subtraction, we have a Carry-In to our first element - and the B input is negated. Thus, the adder result will be:

$1010$

The Less input #0 will be 1, of course, because the MSB of the Adder result is wired to the Less input of ALU Element 0. All three other Less inputs are zero; thus, the entire Less value is 0001.

Since $aluOp==2$ we will select the Add result in every ALU Element as our the desired Output. Therefore, the output will be 1010.

Example: Problem 4(a)

$fp$ $fp$
$sp$ prev stack $fp$ prev stack

$fp$ $fp$
$sp$ prev stack $fp$ prev stack

$fp$
$sp$

$fp$
$sp$

$fp$
$sp$

$fp$
$sp$

$fp$
$sp$

Instructor's Note: Notice the two empty slots in the last column. These are where the 2nd and 4th arguments ($a_1, a_3$) would be stored on the stack, if they need to be saved somewhere. But in this problem, it wasn’t required that they be saved.

Example: Problem 4(b)

$fp$ $fp$
$sp$ prev stack $fp$ prev stack $fp$ prev stack $sp$

$fp$
$sp$

$fp$
$sp$

$fp$
$sp$

Example: Problem 5(a)

```
addiu $sp, $sp, -12
sw  $t0, 8($sp)
sw  $t1, 4($sp)
sw  $t2, 0($sp)
```
addi $a0, $zero, 1
addi $a1, $zero, 2
jal foo
lw $t2, 0($sp)
lw $t1, 4($sp)
lw $t0, 8($sp)
addiu $sp, $sp, 12

Example: Problem 5(b)
addiu $sp, $sp, -12
sw $t1, 8($sp)
sw $t3, 4($sp)
sw $t5, 0($sp)
addi $a0, $zero, 0
addi $a1, $zero, 0x1234
la $a2, str
jal bar
lw $t5, 0($sp)
lw $t3, 4($sp)
lw $t1, 8($sp)
addiu $sp, $sp, 12

Example: Problem 6(a)
addiu $sp, $sp, -24
sw $ra, 4($sp)
sw $fp, 0($sp)
addiu $fp, $sp, 20
sw $a2, 16($sp)
addiu $sp, $sp, -12
sw $s0, 8($sp)
sw $s1, 4($sp)
sw $s3, 0($sp)
... body ...
lw $s3, 0($sp)
lw $s1, 4($sp)
lw $s0, 8($sp)
addiu $sp, $sp, 12
lw $fp, 0($sp)
lw $ra, 4($sp)
addiu $sp, $sp, 24
jr $ra

Example: Problem 6(b)

addiu $sp, $sp, -24
sw $ra, 4($sp)
sw $fp, 0($sp)
addiu $fp, $sp, 20

addiu $sp, $sp, -12
sw $s2, 8($sp)
sw $s4, 4($sp)
sw $s6, 0($sp)

... body ...

lw $s6, 0($sp)
lw $s4, 4($sp)
lw $s2, 8($sp)
addiu $sp, $sp, 12

lw $fp, 0($sp)
lw $ra, 4($sp)
addiu $sp, $sp, 24
jr $ra