Problem M2.1: Execute Data Instructions (Spring 2014 Quiz 1, Part A)

Problem M2.1.A

One easy way to create an infinite loop is to load the EXD instruction from memory:

LD exd
exd: EXD

Problem M2.1.B

<table>
<thead>
<tr>
<th>Data Mem</th>
<th>Instr Mem</th>
</tr>
</thead>
<tbody>
<tr>
<td>Addr</td>
<td>Data</td>
</tr>
<tr>
<td>A:</td>
<td>120</td>
</tr>
<tr>
<td></td>
<td>107</td>
</tr>
<tr>
<td></td>
<td>122</td>
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<td></td>
<td>130</td>
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<td></td>
<td>151</td>
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<td>112</td>
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<td>132</td>
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<tr>
<td></td>
<td>109</td>
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<tr>
<td></td>
<td>140</td>
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<tr>
<td></td>
<td>117</td>
</tr>
<tr>
<td>s:</td>
<td>0</td>
</tr>
<tr>
<td>i:</td>
<td>10</td>
</tr>
<tr>
<td>107:</td>
<td>40</td>
</tr>
<tr>
<td>109:</td>
<td>10</td>
</tr>
<tr>
<td>112:</td>
<td>24</td>
</tr>
<tr>
<td>117:</td>
<td>50</td>
</tr>
<tr>
<td>120:</td>
<td>5</td>
</tr>
<tr>
<td>122:</td>
<td>10</td>
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<tr>
<td>130:</td>
<td>20</td>
</tr>
<tr>
<td>132:</td>
<td>29</td>
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<tr>
<td>140:</td>
<td>22</td>
</tr>
<tr>
<td>151:</td>
<td>12</td>
</tr>
<tr>
<td>one:</td>
<td>1</td>
</tr>
<tr>
<td>ldz:</td>
<td>LD 0 (0000 1000 0000 0000)</td>
</tr>
<tr>
<td>lda:</td>
<td>LD A (0000 1 + A)</td>
</tr>
</tbody>
</table>

Addr Data
Loop: LD i
    SUB one
    BLT Done
    STORE i
We should stall our instruction fetch since we are not consuming instructions from the instruction memory.

\[
stall' = \text{stall} \mid \text{Opcode(IRd)} == \text{EXD}
\]

\[
\text{EXDmux} = \text{Opcode(IRd)} == \text{EXD}
\]
**Problem M2.2: CISC, RISC, and Stack: Comparing ISAs**

**Problem M2.2.A**

**CISC**

How many bytes is the program? 19

How many bytes of instructions need to be fetched if \( b = 10 \)?

\[
(2+2) + 10 \times (13) + (6+2+2) = 144
\]

Assuming 32-bit data values, how many bytes of data memory need to be fetched? Stored?

Fetched: the compare instruction accesses memory, and brings in a 4 byte word \( b+1 \) times: \( 4 \times 11 = 44 \)

Stored: 0

**Problem M2.2.B**

**RISC**

Many translations will be appropriate, here’s one. We ignore MIPS32’s branch-delay slot in this solution since it hadn’t been discussed in lecture. Remember that you need to construct a 32-bit address from 16-bit immediate values.

<table>
<thead>
<tr>
<th>x86 instruction</th>
<th>label</th>
<th>MIPS32 instruction sequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>xor %edx,%edx</td>
<td></td>
<td>xor r4, r4, r4</td>
</tr>
<tr>
<td>xor %ecx,%ecx</td>
<td></td>
<td>xor r3, r3, r3</td>
</tr>
<tr>
<td>cmp 0x8047580,%ecx</td>
<td>loop</td>
<td>lui r6, 0x0804[360] lw r1, 0x7580 (r6) [360] slt r5, r3, r1</td>
</tr>
<tr>
<td>jl L1</td>
<td></td>
<td>bnez r5, L1</td>
</tr>
<tr>
<td>jmp done</td>
<td></td>
<td>j done</td>
</tr>
<tr>
<td>add %edx,%eax</td>
<td>L1</td>
<td>add r4, r4, r2</td>
</tr>
<tr>
<td>inc %ecx</td>
<td></td>
<td>addi r3, r3, #1</td>
</tr>
<tr>
<td>jmp loop</td>
<td></td>
<td>j loop</td>
</tr>
<tr>
<td>...</td>
<td>done:</td>
<td>...</td>
</tr>
</tbody>
</table>

How many bytes is the MIPS32 program using your direct translation?

\[ 10 \times 4 = 40 \]

How many bytes of MIPS32 instructions need to be fetched for \( b = 10 \) using your direct translation.

There are 2 instructions in the prelude and 7 that are part of the loop (we don’t need to fetch the ‘j done’ until the 11th iteration). There are 5 instructions in the 11th iteration. All instructions are 4 bytes. 4(2+10*7+5) = 308.
Note: You can also place the label ‘loop’ in two other locations assuming r6 and r1 hold the same values for the remaining of the program after being loaded. One location is in front of the lw instruction, and we reduce the number of fetched byte to 268. The other is in front of the slt instruction, and we further decrease the number of fetched bytes to 228.

**How many bytes of data memory need to be fetched? Stored?**

Fetched: 11 * 4 = 44 (or 4 if you place the label ‘loop’ in front of the slt instruction)
Stored: 0

<table>
<thead>
<tr>
<th>Problem M2.2.C</th>
<th>Optimization</th>
</tr>
</thead>
</table>

There are two ideas that we have for optimization.

1) We count down to zero instead of up for the number of iterations. By doing this, we can eliminate the slt instruction prior to the branch instruction.

2) Hold b value in a register if you haven’t done it already.

```assembly
xor r4, r4, r4
lui r6, 0x0804
lw r1, 0x9580(r6)
jmp dec

loop:    add r4, r4, r2
dec:     addiu r1, r1, #1
         bgez r1, loop
done:    
```

This modification brings the dynamic code size down to 144 bytes, the static code size down to 28 and memory traffic down to 4 bytes.
Problem M2.3: Addressing Modes on MIPS ISA

**Problem M2.3.A**

Displacement addressing mode

The answer is yes.

\[
\begin{align*}
\text{LW} & \; \text{R1, 16(R2)} & \Rightarrow & \; \text{ADDI} \; \text{R3, R2, #16} \\
& & & \text{LW} \; \text{R1, 0(R3)} \\
\end{align*}
\]

(R3 is a temporary register.)

**Problem M2.3.B**

Register indirect addressing

The answer is yes once again.

\[
\begin{align*}
\text{LW} & \; \text{R1, 16(R2)} & \Rightarrow & \; \\
\text{lw} & _\text{template:} \; \text{LW} \; \text{R1, 0} & ; & \text{it is placed in data} \\
& & & \text{region} \\
& & \ldots & \\
\text{lW}_ & _\text{start:} \; \text{LW} \; \text{R3, lw} _\text{template} \\
& & & \text{ADDI} \; \text{R4, R2, #16} \\
& & & \text{ADD} \; \text{R3, R3, R4} ; \; \text{R3} \leftarrow \; \text{“LW R1, addr”} \\
& & & \text{SW} \; \text{R3, _L1} ; \; \text{write the LW instruction} \\
& & & _\text{L1:} \; \text{NOP} ; \; \text{to be replaced by “LW ..”} \\
\end{align*}
\]

(R3 and R4 are temporary registers.)
Yes, you can rewrite the code as follows.

```assembly
Subroutine: lw   R6, ret_inst ; r6 = "j 0"
            add R6, R6, R31 ; R6 = "j return_addr"
            sw   R6, return ; replacing nop with "j return_addr"
            xor R4, R4, R4 ; result = 0
            xor R3, R3, R3 ; i = 0
loop:     slt R5, R3, R1
            bnez R5, L1 ; if (i < b) goto L1
return:   nop ; will be replaced by "j return_addr"
L1:       add R4, R4, R2 ; result += a
            addi R3, R3, #1 ; i++
            j   loop
ret_inst: j    0 ; jump instruction template
```
Problem M2.4: Write Effective Address Extensions (Spring 2014 Quiz 1, Part B)

You’ve noticed that many programs execute code similar to the following during loops:

\[
\begin{align*}
\text{LD} & \quad R1, 4(R2) \\
\text{ADD} & \quad R2, R2, 4
\end{align*}
\]

Or:

\[
\begin{align*}
\text{ST} & \quad R1, 4(R2) \\
\text{ADD} & \quad R2, R2, 4
\end{align*}
\]

You want to optimize your architecture for this common case. You are going to do so by adding “write effective address” variants of the load and store instructions, \texttt{LDWA} and \texttt{STWA}. The semantics of these instructions are that they will perform the normal memory operation (\texttt{LD} or \texttt{ST}) and then write the effective address in the register that indexed into memory \textit{(not} the register whose contents are read/written to memory). Specifically these instructions do the following:

\[
\begin{align*}
\text{LDWA } & \quad rs, rt, \text{ Imm}:
\quad rs \leftarrow \text{Memory}[\text{rt} + \text{Imm}] \\
\quad rt \leftarrow (\text{rt}) + \text{Imm}
\end{align*}
\]

\[
\begin{align*}
\text{STWA } & \quad rs, rt, \text{ Imm}:
\quad \text{Memory}[\text{rt} + \text{Imm}] \leftarrow (rs) \\
\quad rt \leftarrow (\text{rt}) + \text{Imm}
\end{align*}
\]

These extensions allow us to rewrite the previous examples as:

\[
\begin{align*}
\text{LDWA } & \quad R1, R2, 4
\end{align*}
\]

And:

\[
\begin{align*}
\text{STWA } & \quad R1, R2, 4
\end{align*}
\]
Problem M2.4.A

You start with implementing STWA. For the following sequence of instructions and the standard five-stage pipeline (shown above), indicate how each instruction will flow through the pipeline on the following page. Assume full bypassing and stall logic are implemented for your architecture. Use arrows to indicate forwarding and dashes for stalls, as illustrated.
Instructions cannot enter a pipeline stage that other instructions occupy. If an instruction is stalled in fetch, then no subsequent instruction can enter fetch until that instruction has moved to decode.

This solution assumes all forwarding is done during decode, as in lecture. Bypassing from memory to execute can avoid the second stall because R1 is available at that point. This solution is also acceptable if indicated (next page).
<table>
<thead>
<tr>
<th>Instruction</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>LD R1, 0(R2)</td>
<td>F</td>
<td>D</td>
<td>E</td>
<td>M</td>
<td>W</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADD R3, R1, 10</td>
<td>F</td>
<td>D</td>
<td>-</td>
<td>E</td>
<td>M</td>
<td>W</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LD R4, 0(R3)</td>
<td>F</td>
<td>-</td>
<td>D</td>
<td>E</td>
<td>M</td>
<td>W</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>STWA, R4, R1, 4</td>
<td>F</td>
<td>D</td>
<td>E</td>
<td>M</td>
<td>W</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>STWA R4, R1, 4</td>
<td>F</td>
<td>D</td>
<td>E</td>
<td>M</td>
<td>W</td>
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<td></td>
</tr>
<tr>
<td>ADD R2, R1, R3</td>
<td>F</td>
<td>D</td>
<td>E</td>
<td>M</td>
<td>W</td>
<td></td>
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</tbody>
</table>
You next want to implement LDWA, and quickly realize that LDWA runs into a structural hazard on the register file. You decide to fix this by adding an extra writeback stage (W2) to your pipelined design as shown above. In one or two sentences, explain what the hazard is and why the additional stage fixes it (assume correct stall logic).

The register file has a single write port, but LDWA writes two registers. Buffering the values to be written in an additional pipeline phase gives us two chances to write the register file per LDWA, but may force the pipeline to stall in writeback if there are multiple LDWAs.
Problem M2.4.C

Assume that the six-stage design above has full bypassing and correct stall logic. Fill in the pipeline for the instructions given below, using arrows and dashes as before.

<table>
<thead>
<tr>
<th>Instruction</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>LD R1, 0(R2)</td>
<td>F</td>
<td>D</td>
<td>E</td>
<td>M</td>
<td>W1</td>
<td>W2</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADD R3, R1, 10</td>
<td>F</td>
<td>D</td>
<td>-</td>
<td>E</td>
<td>M</td>
<td>W1</td>
<td>W2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LDWA R5, R3, 0</td>
<td>F</td>
<td>-</td>
<td>D</td>
<td>E</td>
<td>M</td>
<td>W1</td>
<td>W2</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADD R1, R3, R4</td>
<td>F</td>
<td>D</td>
<td>E</td>
<td>M</td>
<td>W1</td>
<td>W2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LDWA R5, R3, 0</td>
<td>F</td>
<td>D</td>
<td>E</td>
<td>M</td>
<td>-</td>
<td>W1</td>
<td>W2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADD R1, R5, R0</td>
<td>F</td>
<td>D</td>
<td>-</td>
<td>E</td>
<td>M</td>
<td>W1</td>
<td>W2</td>
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</tbody>
</table>

Structural hazard on register file causes stalls in writeback (even with extra stage) as LDWAs write their registers.
Adding a second writeback stage is only one way to fix this structural hazard. An alternative design is to add a second write port to the register file. Quickly sketch the datapath for this design in the diagram above. You do *not* need to write the stall logic. (Additional signals are: we2, ws2, wd2.)

IRw goes to we2 and ws2 via an independent path. Y is latched again in another register for writeback and written to wd2. Y can also be written directly to the register file, making stage four a combined Memory/ALU Writeback stage, but in this case we2 and ws2 must come from IRe.
In one or two sentences, explain the tradeoffs between adding an additional pipeline stage vs. adding a write port to the register file. What conditions might favor one or the other design?

Increasing the ports in the register file increases its size quadratically. If the register file is the critical path in the pipeline, this will slow down the processor, and no matter what it increases area and power overheads. On the other hand, if applications commonly stall on the structural hazard due to many LDWAs, it may be worth it to add a write port to the register file. An additional stage can also complicate bypassing and stalling logic, although this is likely to be less expensive than expanding the register file. (The latency of the additional pipeline stage, ignoring stalls, is not a major concern.)