Options for dealing with data and control hazards: stall, bypass, speculate

5-stage Pipelined Beta
Problem 1.

The program shown on the right is executed on a 5-stage pipelined Beta with full bypassing and annulment of instructions following taken branches.

The program has been running for a while and execution is halted at the end of cycle 108.

The pipeline diagram shown below shows the history of execution at the time the program was halted.

\[ . = \emptyset \]

\[ \text{outer_loop:} \]
\[ \text{CMOVE(16,R0)} \quad // \text{initialize loop index J} \]
\[ \text{CMOVE(0,R1)} \]

\[ \text{loop:} \quad // \text{add up elements in array} \]
\[ \text{SUBC(R0,1,R0)} \quad // \text{decrement index} \]
\[ \text{MULC(R0,4,R2)} \quad // \text{convert to byte offset} \]
\[ \text{LD(R2,0x310,R3)} // \text{load value from A[3]} \]
\[ \text{ADD(R3,R1,R1)} \quad // \text{add to sum} \]
\[ \text{BNE(R0,loop)} \quad // \text{loop until all words are summed} \]

\[ \text{BR(outer_loop)} \quad // \text{perform test again!} \]

<table>
<thead>
<tr>
<th>cycle</th>
<th>100</th>
<th>101</th>
<th>102</th>
<th>103</th>
<th>104</th>
<th>105</th>
<th>106</th>
<th>107</th>
<th>108</th>
</tr>
</thead>
<tbody>
<tr>
<td>IF</td>
<td>MULC</td>
<td>LD</td>
<td>ADD</td>
<td>BNE</td>
<td>BNE</td>
<td>BNE</td>
<td>BR</td>
<td>SUBC</td>
<td>MULC</td>
</tr>
<tr>
<td>RF</td>
<td>SUBC</td>
<td>MULC</td>
<td>LD</td>
<td>ADD</td>
<td>ADD</td>
<td>ADD</td>
<td>BNE</td>
<td>NOP</td>
<td>SUBC</td>
</tr>
<tr>
<td>ALU</td>
<td>NOP</td>
<td>SUBC</td>
<td>MULC</td>
<td>LD</td>
<td>NOP</td>
<td>NOP</td>
<td>ADD</td>
<td>BNE</td>
<td>NOP</td>
</tr>
<tr>
<td>MEM</td>
<td>BNE</td>
<td>NOP</td>
<td>SUBC</td>
<td>MULC</td>
<td>LD</td>
<td>NOP</td>
<td>NOP</td>
<td>ADD</td>
<td>BNE</td>
</tr>
<tr>
<td>WB</td>
<td>ADDC</td>
<td>BNE</td>
<td>NOP</td>
<td>SUBC</td>
<td>MULC</td>
<td>LD</td>
<td>NOP</td>
<td>NOP</td>
<td>ADD</td>
</tr>
</tbody>
</table>

Please indicate on which cycle(s), 100 through 108, each of the following actions occurred. If the action did not occur in any cycle, write “NONE”. You may wish to refer to the signal names in the 5-stage Pipelined Beta Diagram included in the reference material.

Register value used from Register File: 100,105,106,108

Register value bypassed from ALU stage to RF stage: 101,102

Register value bypassed from MEM stage to RF stage: none

Register value bypassed from WB stage to RF stage: 105

IRSrc\text{IF} was 1: 106

IRSrc\text{IF} was 2: none

STALL was 1: 103,104

PCSEL was 1: 106

WDSEL was 2: 105
Problem 2.

The following program fragments are being executed on the 5-stage pipelined Beta described in lecture with full bypassing, stall logic to deal with LD data hazards, and speculation for JMPs and taken branches (i.e., IF-stage instruction is replaced with a NOP if necessary). The execution pipeline diagram is shown for cycle 1000 of execution. Please fill in the diagram for cycle 1001; use “?” if you cannot tell what opcode to write into a stage. Then for both cycles use arrows to indicate any bypassing from the ALU/MEM/WB stages back to the RF stage (see example for cycle 1000 in part A).

(A) (2 points)  Assume BNE is taken.

```
  ...  
  ADDC(R1, 5, R1)  
  L: SUBC(R1, 1, R1)  
  SHR(R0, 1, R0)  
  BNE(R1, L)  
  ST(R1, data)  
  ...  
```

```
<table>
<thead>
<tr>
<th>Cycle</th>
<th>1000</th>
<th>1001</th>
</tr>
</thead>
<tbody>
<tr>
<td>IF</td>
<td>ST</td>
<td>SUBC</td>
</tr>
<tr>
<td>RF</td>
<td>BNE</td>
<td>NOP</td>
</tr>
<tr>
<td>ALU</td>
<td>SHR</td>
<td>BNE</td>
</tr>
<tr>
<td>MEM</td>
<td>SUB</td>
<td>SHR</td>
</tr>
<tr>
<td>WB</td>
<td>NOP</td>
<td>SUBC</td>
</tr>
</tbody>
</table>
```

(B) (2 points)

```
  ...  
  ST(R31, 0, BP)  
  LD(BP, -12, R17)  
  ADDC(SP, 4, SP)  
  SHLC(R17, 2, R1)  
  ST(R1, -4, SP)  
  BEQ(R31, fact, LP)  
  ...  
```

```
<table>
<thead>
<tr>
<th>Cycle</th>
<th>1000</th>
<th>1001</th>
</tr>
</thead>
<tbody>
<tr>
<td>IF</td>
<td>ST</td>
<td>ST</td>
</tr>
<tr>
<td>RF</td>
<td>SHLC</td>
<td>SHLC</td>
</tr>
<tr>
<td>ALU</td>
<td>ADDC</td>
<td>NOP</td>
</tr>
<tr>
<td>MEM</td>
<td>LD</td>
<td>ADDC</td>
</tr>
<tr>
<td>WB</td>
<td>ST</td>
<td>LD</td>
</tr>
</tbody>
</table>
```

(C) (2 points)

```
  ...  
  XOR(R1, R2, R1)  
  MULC(R2, 3, R2)  
  SUB(R2, R1, R3)  
  AND(R3, R1, R2)  
  ADD(R3, R2, R3)  
  ST(R3, x)  
  ...  
```

```
<table>
<thead>
<tr>
<th>Cycle</th>
<th>1000</th>
<th>1001</th>
</tr>
</thead>
<tbody>
<tr>
<td>IF</td>
<td>ADD</td>
<td>ST</td>
</tr>
<tr>
<td>RF</td>
<td>AND</td>
<td>ADD</td>
</tr>
<tr>
<td>ALU</td>
<td>SUB</td>
<td>ADD</td>
</tr>
<tr>
<td>MEM</td>
<td>MULC</td>
<td>SUB</td>
</tr>
<tr>
<td>WB</td>
<td>XOR</td>
<td>MULC</td>
</tr>
</tbody>
</table>
```

(D) (2 points) Assume during cycle 1000 the DIV instruction in the RF stage triggers an ILLEGAL OPCODE (ILLOP) exception.

```
  ...  
  LD(x, R1)  
  LD(y, R2)  
  SHLC(R1, 3, R1)  
  DIV(R2, R1, R3)  
  ADDC(R3, 17, R3)  
  ST(R3, z)  
  ...  
```

```
<table>
<thead>
<tr>
<th>Cycle</th>
<th>1000</th>
<th>1001</th>
</tr>
</thead>
<tbody>
<tr>
<td>IF</td>
<td>ADDC</td>
<td>?</td>
</tr>
<tr>
<td>RF</td>
<td>DIV</td>
<td>NOP</td>
</tr>
<tr>
<td>ALU</td>
<td>SHLC</td>
<td>BNE(R3, x, ... , xP)</td>
</tr>
<tr>
<td>MEM</td>
<td>NOP</td>
<td>SHLC</td>
</tr>
<tr>
<td>WB</td>
<td>LD</td>
<td>NOP</td>
</tr>
</tbody>
</table>
```

6.004 Worksheet - 3 of 8 - L17/L18 – Pipelining the Beta
Problem 3.

In answering this question, you may wish to refer to the diagram of the 5-stage pipelined Beta provided with the reference material.

The loop on the right has been executing for a while on our standard 5-stage pipelined Beta with branch annulment and full bypassing. The pipeline diagram below shows the opcode of the instruction in each pipeline stage during 10 consecutive cycles of execution.

<table>
<thead>
<tr>
<th>Cycle #</th>
<th>300</th>
<th>301</th>
<th>302</th>
<th>303</th>
<th>304</th>
<th>305</th>
<th>306</th>
<th>307</th>
<th>308</th>
<th>309</th>
</tr>
</thead>
<tbody>
<tr>
<td>IF</td>
<td>SUBC</td>
<td>CMPLTC</td>
<td>BF</td>
<td>LD</td>
<td>LD</td>
<td>ST</td>
<td>BNE</td>
<td>BNE</td>
<td>BNE</td>
<td>ADDC</td>
</tr>
<tr>
<td>RF</td>
<td>NOP</td>
<td>SUBC</td>
<td>CMPLTC</td>
<td>BF</td>
<td>NOP</td>
<td>LD</td>
<td>ST</td>
<td>ST</td>
<td>ST</td>
<td>BNE</td>
</tr>
<tr>
<td>ALU</td>
<td>BNE</td>
<td>SUBC</td>
<td>CMPLTC</td>
<td>BF</td>
<td>NOP</td>
<td>LD</td>
<td>NOP</td>
<td>NOP</td>
<td>NOP</td>
<td>ST</td>
</tr>
<tr>
<td>MEM</td>
<td>ST</td>
<td>SUBC</td>
<td>CMPLTC</td>
<td>BF</td>
<td>NOP</td>
<td>LD</td>
<td>NOP</td>
<td>NOP</td>
<td>NOP</td>
<td></td>
</tr>
<tr>
<td>WB</td>
<td>NOP</td>
<td>SUBC</td>
<td>CMPLTC</td>
<td>BF</td>
<td>NOP</td>
<td>LD</td>
<td>NOP</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(A) (4 Points) Indicate which bypass/forwarding paths are active in each cycle by drawing a vertical arrow in the pipeline diagram from pipeline stage X in a column to the RF stage in the same column if an operand would be bypassed from stage X back to the RF stage that cycle. Note that there may be more than one vertical arrow in a column.

**Draw bypass arrows in pipeline diagram above**

(B) (2 Points) Assume that the previous iteration of the loop executed the same instructions as the iteration show here. Please complete the pipeline diagram for cycle 300 by filling in the OPCODEs for the instructions in the RF, ALU, MEM, and WB stages.

**Fill in OPCODEs for Cycle 300**

For the following questions think carefully about when a signal would be asserted in order to produce the effect you see in the pipeline diagram.

(C) (2 Points) During which cycle(s), if any, would the IRSrcIF signal be 1?

\[
\text{IRSrcIF} = 1 \text{ when taken branches are in RF stage.}
\]

**Cycle number(s) or NONE:** 303, 309

(D) (2 Points) During which cycle(s), if any, would the IRSrcRF signal be 1?

\[
\text{IRSrcRF} = 1 \text{ when register operand not available in the data path.}
\]

**Cycle number(s) or NONE:** 306, 307

(E) (2 Points) During which cycle(s), if any, would the STALL signal be 1, i.e., cycle(s) when the IF and RF stages would be stalled?

\[
\text{STALL is 1 when IRSrcRF is 1.}
\]

**Cycle number(s) or NONE:** 306, 307
Problem 4.

You’ve discovered a secret room in the basement of the Stata center full of discarded 5-stage pipelined Betas. Unfortunately, many have certain defects. You discover that they fall into four categories:

C1: Completely functional 5-stage Betas with working bypass paths, annulment, and other components.
C2: Betas with a bad register file: all data read from the register file is zero.
C3: Betas without bypass paths: all source operands come from the register file.
C4: Betas without annulment of instructions following branches.

To help sort the Beta chips into the above classes, you write the following small test program:

```
= 0x0
// Start at 0x0, with ZERO in all registers...
ADDC(R31, 4, R0)  Rb<4
BEQ(R31, X, R2)   R2<8
MULC(R2, 2, R2)   --
X:  SUBC(R2, 4, R2) R2<4
    ADD(R0, R2, R3) R3<8
    JMP(R3) R3<16

A R3 loads 0x10
```

Your plan is to single-step through the program using each Beta chip, carefully noting the address the final JMP loads into the PC. Your goal is to determine which of the above four classes a chip falls into by this JMP address.

For each class of Beta processor described above, specify the value that will be loaded into the PC by the final JMP instruction.

Pipeline diagram showing first 7 cycles of test program executing on C1:

<table>
<thead>
<tr>
<th>cycle</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IF</td>
<td>ADD</td>
<td>BEQ</td>
<td>MUL</td>
<td>SUB</td>
<td>ADD</td>
<td>JMP</td>
</tr>
<tr>
<td></td>
<td>RF</td>
<td>ADD</td>
<td>BEQ</td>
<td>NOP</td>
<td>SUB</td>
<td>ADD</td>
<td>JMP</td>
</tr>
<tr>
<td></td>
<td>ALU</td>
<td>ADD</td>
<td>BEQ</td>
<td>NOP</td>
<td>SUB</td>
<td>ADD</td>
<td></td>
</tr>
<tr>
<td></td>
<td>MEM</td>
<td>ADD</td>
<td>BEQ</td>
<td>NOP</td>
<td>SUB</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>WB</td>
<td>ADD</td>
<td>BEQ</td>
<td>NOP</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

C1: JMP goes to address: 8
C2: JMP goes to address: 4
C3: JMP goes to address: 0
C4: JMP goes to address: 16
Problem 5.

Recall the code for gcd that we saw in lecture, and the assembly code for the while loop:

```
C code
int gcd(int x, int y) {
  while (x != y) {
    if (x > y) {
      x = x - y;
    } else {
      y = y - x;
    }
  }
  return x;
}
```

```
Corresponding Beta assembly for while loop
// x in R0, y in R1
CMPEQ(R0, R1, R2) // R2 ← (x == y)
BT(R2, end)
loop: CMPLT(R1, R0, R2) // R2 ← (x > y)
BF(R2, else)
SUB(R0, R1, R0) // x ← x - y
BR(cond)
else: SUB(R1, R0, R1) // y ← y - x
cond: CMPEQ(R1, R0, R2) // R2 ← (x == y)
BF(R2, loop)
end: ...
```

Assume a 5-stage pipelined Beta as presented in lecture, with full bypass paths, and which predicts branches by assuming they are not taken to resolve control (i.e., the instruction following the branch is fetched in the IF stage on the cycle after the branch is in the IF stage).

First, find the number of cycles per iteration in steady state (do not worry about the first or last iterations). Note that the BF(R2, else) branch is not taken if x > y and taken if x < y, so you should consider these two cases separately.

(A) Fill in the following table:

<table>
<thead>
<tr>
<th>Instructions per iteration</th>
<th>Iterations where x &gt; y</th>
<th>Iterations where x &lt; y</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ Cycles lost to data hazards</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>+ Cycles lost to annulments</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>= Total cycles per iteration</td>
<td>8</td>
<td>7</td>
</tr>
</tbody>
</table>

```

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```
To make this code faster, we modify the Beta ISA and pipeline to implement a technique called **predication** to reduce the number of branches.

First, all the compare instructions (CMPEQ, CMPLT, CMPLE, and their C variants) write their result into a special 1-bit register, called the **predicate register**, in addition to their normal destination register.

Second, we change the format of ALU instructions with two register source operands to use their lower two bits, which were previously unused:

```
| 31 | 26 | 25 | 24 | 23 | 22 | 21 | 20 | 19 | 18 | 17 | 16 | 15 | 14 | 13 | 12 | 11 | 10 | 9  | 8  | 7  | 6  | 5  | 4  | 3  |
|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| 10xxxx | Rc | Ra | Rb | unused |
```

- If PredBits == 10, the instruction only executes if the predicate register is false (0)
- If PredBits == 11, the instruction only executes if the predicate register is true (1)
- If PredBits == 0X, the instruction always executes and writes its result, as before

We say that instructions that depend on the predicate register are predicated. We denote predicated instructions in assembly as follows:

- If PredBits == 10, OP(Ra, Rb, Rc) [predFalse]
- If PredBits == 11, OP(Ra, Rb, Rc) [predTrue]
- If PredBits == 0X, OP(Ra, Rb, Rc), as before

For example, consider the following instruction sequence:

```
CMPLT(R1, R2, R3)
MUL(R3, R4, R5)
ADD(R4, R5, R6) [predTrue]
SUB(R5, R6, R7)
```

If the CMPLT instruction evaluates to true (i.e., writes 1 to R3), this sequence is equivalent to:

```
CMPLT(R1, R2, R3)
MUL(R3, R4, R5)
ADD(R4, R5, R6)
SUB(R5, R6, R7)
```

If the CMPLT instruction evaluates to false (i.e., writes 0 to R3), this sequence is equivalent to:

```
CMPLT(R1, R2, R3)
MUL(R3, R4, R5)
SUB(R5, R6, R7)
```

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(B) Modify the code to use predication, minimizing the number of instructions per loop iteration.

<table>
<thead>
<tr>
<th>Original code</th>
<th>Code with predication</th>
</tr>
</thead>
<tbody>
<tr>
<td>// x in R0, y in R1</td>
<td>// x in R0, y in R1</td>
</tr>
<tr>
<td>CMPEQ(R0, R1, R2)</td>
<td>CMPEQ(R0, R1, R2)</td>
</tr>
<tr>
<td>BT(R2, end)</td>
<td>BT(R2, end)</td>
</tr>
<tr>
<td>loop: CMPLT(R1, R0, R2)</td>
<td>loop: CMPLT(R1, R0, R2)</td>
</tr>
<tr>
<td>BF(R2, else)</td>
<td>SUB(R1, R0, R2) [predTrue]</td>
</tr>
<tr>
<td>SUB(R0, R1, R0)</td>
<td>SUB(R0, R1, R2) [predFalse]</td>
</tr>
<tr>
<td>BR(cond)</td>
<td>CMPEQ(R1, R0, R2)</td>
</tr>
<tr>
<td>else: SUB(R1, R0, R1)</td>
<td>BF(R2, loop)</td>
</tr>
<tr>
<td>cond: CMPEQ(R1, R0, R2)</td>
<td></td>
</tr>
<tr>
<td>end: ...</td>
<td>end: ...</td>
</tr>
</tbody>
</table>

We implement predication in the pipelined Beta with minor changes to the ALU stage:

Comparison instructions write the 1-bit predicate register (the PredWr control signal ensures that only comparison instructions update the register). The PredSel mux annuls ALU instructions if they are predicated and should not execute according to the value of the predicate register.

(C) Write the Boolean expression for the PredSel control signal. You can use AND, OR, NOT, Predicate, and comparisons with PredBits (e.g., PredBits == 0b10).

\[
\text{PredSel} = (\text{IR}_{\text{ALU}}[31:30] == \text{0b10}) \text{ AND } \text{PredBit}[3] = 1 \text{ and PredBit}[0] \neq \text{Predicate}
\]

(D) How fast is this modified code? Fill in the following table:

<table>
<thead>
<tr>
<th>Iterations where x &gt; y</th>
<th>Iterations where x &lt; y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Instructions per iteration</td>
<td>4</td>
</tr>
<tr>
<td>+ Cycles lost to data hazards</td>
<td>0</td>
</tr>
<tr>
<td>+ Cycles lost to annulments</td>
<td>2</td>
</tr>
<tr>
<td>= Total cycles per iteration</td>
<td>6</td>
</tr>
</tbody>
</table>

no cycles lost due to annulments after taken branches except for final BF.