Assignment 5 Solutions
Branch Prediction and Intro to Caches

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1 Data Hazards

```
Sequence of instructions:
lw  $s2, 0($s1)     //1
lw  $s1, 40($s3)    //2
sub $s3, $s1, $s2   //3
add $s3, $s2, $s2   //4
or  $s4, $s3, $zero //5
sw  $s3, 50($s1)    //6
```

1.1

List the Read-After-Write data dependencies.

```
3 on 1 ($s2)
3 on 2 ($s1)
4 on 1 ($s2)
5 on 4 ($s3)
6 on 2 ($s1)
6 on 4 ($s3)
```

1.2

Assume the 5-stage MIPS pipeline with no forwarding, and each stage takes 1 cycle. Instead of inserting nops, you let the processor stall on hazards. How many times does the processor stall? How long is each stall (in cycles)? What is the execution time (in cycles) for the whole program?

```
----------------------------------------------------------
  | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10| 11| 12| 13| 14|
--|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
1 | F | D | E | M | W |   |   |   |   |   |   |   |   |   |
2 |   | F | D | E | M | W |   |   |   |   |   |   |   |   |
3 |   |   | F | - | - | D | E | M | W |   |   |   |   |   |
4 |   |   |   |   |   | F | D | E | M | W |   |   |   |   |
5 |   |   |   |   |   |   | F | - | - | D | E | M | W |   |
6 |   |   |   |   |   |   |   |   |   | F | D | E | M | W |
----------------------------------------------------------
```

The processor stalls twice for instructions 3 and 5.

```
Each stall is two cycles.
The total execution time is 14 cycles.
```

1.3

Assume the 5-stage MIPS pipeline with full forwarding. Write the program with nops to eliminate the hazards. (Hint: time travel is not possible!)

```
Place a NOP after the 2nd instruction so that the value of $s1 can be directly forwarded
from the MEM stage of instruction 2 to the EXE stage of instruction 3.

-----------------------------------------------
   | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10| 11|
---|---|---|---|---|---|---|---|---|---|---|---|
1  | F | D | E | M | W |   |   |   |   |   |   |
2  |   | F | D | E | M | W |   |   |   |   |   |
nop|   |   |   |   |   |   |   |   |   |   |   |
3  |   |   |   | F | D | E | M | W |   |   |   |
4  |   |   |   |   | F | D | E | M | W |   |   |
5  |   |   |   |   |   | F | D | E | M | W |   |
6  |   |   |   |   |   |   | F | D | E | M | W |
-----------------------------------------------
```

2 Measuring branch prediction speedup

You'd like to add a branch predictor to your Baseline processor, and you're considering two options: PikaChooser and CharWizard. Evaluate the speedup of each relative to your Baseline if branches are 15% of all instructions. Assume normal CPI is 1, but the branch mispredict penalty is 2 extra stall cycles.

```
PikaChooser:
10% misprediction rate
Will increase the cycle time by 15%

CharWizard:
12% misprediction rate
Will increase the cycle time by 20%
```

2.1

Which predictor would you choose?

$\text{CT}_{PikaChooser} = 1.15$
$\text{CPI}_{PikaChooser} = 0.15 * (0.1 * 3 + 0.9) + (1 - 0.15) = 0.15 * 1.2 + 0.85 = 1.03$
$\text{ET}_{PikaChooser} = \text{CT}_{PikaChooser} * \text{CPI}_{PikaChooser} = 1.15 * 1.03 = 1.185$

$\text{CT}_{CharWizard} = 1.2$
$\text{CPI}_{CharWizard} = 0.15 * (0.12 * 3 + 0.88) + (1 - 0.15) = 0.15 * 1.24 + 0.85 = 1.036$
$\text{ET}_{CharWizard} = \text{CT}_{CharWizard} * \text{CPI}_{CharWizard} = 1.2 * 1.036 = 1.243$

```
PikaChooser is the better branch predictor.
```

2.2

If branches are instead 25% of all instructions, which predictor would you choose?

$$\mathrm{CT}_{PikaChooser} = 1.15$$
$$\mathrm{CPI}_{PikaChooser} = 0.25 * (0.1 * 3 + 0.9) + (1 - 0.25) = 0.25 * 1.2 + 0.75 = 1.05$$
$$\mathrm{ET}_{PikaChooser} = \mathrm{CT}_{PikaChooser} * \mathrm{CPI}_{PikaChooser} = 1.15 * 1.05 = 1.2075$$

$$\mathrm{CT}_{CharWizard} = 1.2$$
$$\mathrm{CPI}_{CharWizard} = 0.25 * (0.12 * 3 + 0.88) + (1 - 0.25) = 0.25 * 1.24 + 0.75 = 1.06$$
$$\mathrm{ET}_{CharWizard} = \mathrm{CT}_{CharWizard} * \mathrm{CPI}_{CharWizard} = 1.2 * 1.06 = 1.272$$

```
PikaChooser is the better branch predictor.
```

3 Measuring branch predictor accuracy

This exercise examines the accuracy of various branch predictors for the following repeating patterns (e.g., in a loop) of branch outcomes. Accuracy is defined as the percentage of guesses that are correct.

3.1

```
(a) T, NT, NT, NT, T
```

3.1.1

What is the accuracy of always-taken and always-not-taken predictors for this sequence of branch outcomes?

```
Always-Taken Predictor
  Actual   T NT NT NT T
  Predict  T T  T  T  T

  Accuracy = 2/5 = 0.4

Always-not-taken Predictor
  Actual   T  NT NT NT T
  Predict  NT NT NT NT NT

  Accuracy = 3/5 = 0.6
```

3.1.2

What is the accuracy of a predict-last-taken predictor for the first 5 branches in this sequence? Assume this predictor starts in the "Predict not taken" state.

```
Actual   T  NT NT NT T
Predict  NT T  NT NT NT

Accuracy = 2/5 = 0.4
```

3.1.3

What is the accuracy of a 2-bit predictor for the first 5 branches in this sequence? Using the diagram in slide 115 ("ImplementingMIPS-e" PDF page 196), assume this predictor starts in the "Strongly not taken" state.

```
Actual     T  NT NT NT T
Predictor  0  1  0  0  0
Predict    NT NT NT NT NT

Accuracy = 3/5 = 0.6
```

3.1.4

What is the accuracy of a 2-bit predictor if this pattern is repeated forever? Using the diagram in slide 115 ("ImplementingMIPS-e" PDF page 196), assume this predictor starts in the "Strongly not taken" state.

```
Actual     T  NT NT NT T  | T  NT NT NT T  | T  NT NT NT T  |
Predictor  0  1  0  0  0  | 1  2  1  0  0  | 1  2  1  0  0  |
Predict    NT NT NT NT NT | NT T  NT NT NT | NT T  NT NT NT |

Steady-state Accuracy = 2/5 = 0.4
```

3.2

```
(b) T, NT, T, NT, T
```

3.2.1

What is the accuracy of always-taken and always-not-taken predictors for this sequence of branch outcomes?

```
Always-Taken Predictor
  Actual   T NT T NT T
  Predict  T T  T  T  T

  Accuracy = 3/5 = 0.6

Always-not-taken Predictor
  Actual   T  NT T NT T
  Predict  NT NT NT NT NT

  Accuracy = 2/5 = 0.4
```

3.2.2

What is the accuracy of a predict-last-taken predictor for the first 5 branches in this sequence? Assume this predictor starts in the "Predict not taken" state.

```
Actual   T  NT T  NT T
Predict  NT T  NT T  NT

Accuracy = 0/5 = 0
```

3.2.3

What is the accuracy of a 2-bit predictor for the first 5 branches in this sequence? Using the diagram in slide 115 ("ImplementingMIPS-e" PDF page 196), assume this predictor starts in the "Strongly not taken" state.

```
Actual    T  NT T  NT T
Predictor 0  1  0  1  0
Predict   NT NT NT NT NT

Accuracy = 2/5 = 0.4
```

3.2.4

What is the accuracy of a 2-bit predictor if this pattern is repeated forever? Using the diagram in slide 115 ("ImplementingMIPS-e" PDF page 196), assume this predictor starts in the "Strongly not taken" state.

```
Actual    T  NT T  NT T | T  NT T  NT T | T  NT T  NT T | T  NT T  NT T | T  NT T  NT T |
Predictor 0  1  0  1  0 | 1  2  1  2  1 | 2  1  2  1  2 | 3  2  3  2  3 | 3  2  3  2  3 |
Predict   NT NT NT NT NT| NT T  NT T  NT| T  NT T  NT T | T  T  T  T  T | T  T  T  T  T |

Steady-state Accuracy = 3/5 = 0.6
```