QUESTION 1: DYNAMIC BRANCH PREDICTION

Consider the MIPS processor with 5-stage pipeline (IF, ID, EX, MEM, WB) with early branch resolution in the **ID-stage** and a dynamic **branch prediction unit (BPU)** in the **IF-stage** composed of:

- **1-entry 1-bit Branch History Table**
- **1-entry Branch Target Buffer**

- Disabling the BPU, each branch costs **1 cycle penalty** to fetch the correct instruction.

- Enabling the BPU, there are 4 cases for each conditional branch with the related branch penalty cycles:

Branch Outcome Prediction	Branch Outcome	Branch Penalty Cycles
Predicted Not Taken	Not Taken	0
Predicted Not Taken	Taken	1 (misprediction)
Predicted Taken	Not Taken	1 (misprediction)
Predicted Taken	Taken	0 with BTB hit 1 with BTB miss

Let's consider the following assembly loop:

```
INIT:  ADDUI $R1, $R0, 0
       ADDUI $R2, $R0, 40

LOOP:  LD $F0, 0 ($R1)
       FADD $F4, $F0, $F2
       SD $F4, 0 ($R1)
       ADDUI $R1, $R1, 4
       BNE $R1, $R2, LOOP
```

1. *How many loop iterations?*

   10 iterations _____

2. *Please complete the following table:*

	Explain the branch behavior in the loop.	***How many branch penalty cycles are needed to execute the loop?***	***Calculate the branch misprediction rate to execute the loop***
Assuming the BPU is enabled with BHT initialized as **Not Taken**.	In this case, at the first iteration we have a misprediction with PNT/T with 1 cycle penalty to update the BTB. Then there are 8 iterations predicted correctly as PT/T with 0 cycle penalty (BTB hit). The last iteration is mispredicted as PT/NT with 1 cycle penalty.	There are **(1 + 0 + 1) = 2** branch penalty cycles.	There are 2 mispredictions out of 10 predictions => **20%** misprediction rate.
Assuming the BPU is enabled with BHT initialized as **Taken** and BTB hit.	In this case, we have 9 iterations correctly predicted as PT/T with 0 cycle penalty (BTB hit). The last iteration is mispredicted as PT/NT with 1 cycle penalty.	There are: (0 + 1) = 1 branch penalty cycle.	There is 1 misprediction out of 10 predictions => 10% misprediction rate.
Assuming the BPU is disabled.	At each iteration, each branch costs 1 cycle penalty to fetch the correct instruction.	There are 10 branch penalty cycles to execute the loop.	

QUESTION 2: DYNAMIC BRANCH PREDICTION (5 points) from 22/01/2024

Assume a pipelined processor with a dynamic branch prediction unit in the **IF-stage** composed of:

- **1-entry 1-bit Branch History Table**
- **1-entry Branch Target Buffer**

Disabling the branch prediction unit, each branch costs **2 cycles penalty** to fetch the correct instruction.

Enabling the branch prediction unit, there are 4 cases for each conditional branch with the related **branch penalty cycles:**

Branch Outcome Prediction	Branch Outcome	Branch Penalty Cycles
Predicted Not Taken	Not Taken	0
Predicted Not Taken	Taken	2 (misprediction)
Predicted Taken	Not Taken	2 (misprediction)
Predicted Taken	Taken	1 with BTB hit 2 with BTB miss

Let's consider the following assembly loop:

```
INIT:  ADDUI $R1, $R0, 0
       ADDUI $R2, $R0, 40

LOOP:  LD $F0, 0 ($R1)
       FADD $F4, $F0, $F2
       SD $F4, 0 ($R1)
       ADDUI $R1, $R1, 4
       BNE $R1, $R2, LOOP
```

3. *How many loop iterations?*

   10 iterations _____

4. *Please complete the following table:*

	Explain the branch behavior in the loop.	***How many branch penalty cycles are needed to execute the loop?***	***Calculate the branch misprediction rate to execute the loop***
Assuming the BPU is enabled with BHT initialized as **Not Taken**	In this case, we have a first misprediction with PNT/T with 2 cycles penalty to update the BTB. Then there are 8 iterations predicted correctly as PT/T with 1 cycle penalty (BTB hit). The last iteration is mispredicted as PT/NT with 2 cycles penalty.	There are: (2 + 8 + 2) = 12 branch penalty cycles.	There are 2 mispredictions out of 10 predictions => 20% misprediction rate;
Assuming the BPU is enabled with BHT initialized as **Taken** and BTB hit.	In this case, we have 9 iterations correctly predicted as PT/T with 1 cycle penalty (BTB hit). The last iteration is mispredicted as PT/NT with 2 cycles penalty.	There are: (9 + 2) = 11 branch penalty cycles.	There is 1 misprediction out of 10 predictions => 10% misprediction rate.
Assuming the BPU is disabled.	At each iteration, each branch costs 2 cycles penalty to fetch the correct instruction.	There are 20 branch penalty cycles to execute the loop.	

QUESTION 3: DYNAMIC BRANCH PREDICTION (5 points)

Assume a pipelined processor with a dynamic branch prediction unit in the **IF-stage** composed of:

- **1-entry 1-bit Branch History Table**
- **2-entries Branch Target Buffer**

Disabling the branch prediction unit, each branch costs **2 cycle penalty** to fetch the correct instruction.

Enabling the branch prediction unit, there are 4 cases for each conditional branch with the related **branch penalty cycles:**

Branch Outcome Prediction	Branch Outcome	Branch Penalty Cycles
Predicted Not Taken	Not Taken	0
Predicted Not Taken	Taken	2 (misprediction)
Predicted Taken	Not Taken	2 (misprediction)
Predicted Taken	Taken	1 with BTB hit 2 with BTB miss

Let's consider the following assembly code:

```
INIT:  ADDUI $R1, $R0, 0
       ADDUI $R2, $R0, 40
       ADDUI $R4, $R0, 20

LOOP1: LD $F0, 0 ($R1)
       FADD $F4, $F0, $F2
       SD $F4, 0 ($R1)
       ADDUI $R3, $R0, 0

LOOP2: LD $F6, 0($R3)
       FADD $F8, $F6, $F2
       SD $F8, 0($R3)
       ADDUI $R3, $R3, 4
       BNE $R3, $R4, LOOP2

       ADDUI $R1, $R1, 4
       BNE $R1, $R2, LOOP1
```

5. *How many iterations for the outer loop **LOOP1?*** _____
   The outer loop LOOP1 is executed 10 times.

6. *How many iterations for the inner loop **LOOP2?*** _____
   The inner loop LOOP2 is executed 5 times for each iteration of LOOP1.
   => Globally LOOP2 is executed 50 times.
7. *How many branch predictions are in the code?* _____
   There are 50 for BNE-LOOP2 and 10 for BNE-LOOP1
   => Globally there are 60 branch predictions.

8. *Please complete the following table*

	Explain the branch behavior considering the inner LOOP2 in isolation.	***How many branch penalty cycles are needed to execute the LOOP2 in isolation?***	***Calculate the branch misprediction rate to execute the LOOP 2 in isolation?***
Assuming the BPU is enabled with BHT initialized as **Taken** and BTB hit.	Being the predictor initialized as PT, we have a misprediction only at the last iteration (exit) of the inner LOOP2 and the prediction bit is turned to PNT.	There are: (4 + 2) = 6 branch penalty cycles.	So, for LOOP 2 in isolation, we have 1 misprediction out of 5 branch predictions => misprediction rate 20% for LOOP2.

	Explain the branch behavior considering both loops.	***How many branch penalty cycles are needed to execute the both loops?***	***Calculate the global branch misprediction rate to execute both loops?***
Assuming the BPU is enabled with BHT initialized as **Taken** and BTB hit for both entries. Being 1-entry 1-BHT, notice that the 2 branch instructions **collide.** There are 2 entries in the BTB assigned to each branch instructions, so they do not collide.	Being the predictor initialized as PT, we have a misprediction only at the last iteration (exit) of the inner LOOP2 and the predictor is turned to PNT. Exiting from the inner LOOP2 with the PNT, this generates a misprediction on the BNE-LOOP1 for 9 iterations (except for the last iteration where we have PNT/NT with no cycle penalty). When re-entering in LOOP1, the prediction bit was turned to PT when re-entering in the inner LOOP2 as before.	There are: (4 + 2) = 6 BP cycles to execute LOOP2 for 10 iterations of the outer LOOP1 => 60 BP cycles. For the outer LOOP1, we have 9 mispredictions PNT/T for BNE-LOOP1 (except for the last iteration): (18 +0) = 18 BP cycles to execute LOOP1. Globally there are 78 BP cycles.	We have 1 misprediction for the BNE-LOOP2 only at the exit of LOOP2 times 10 iterations of the outer LOOP1 => globally 10 mispredictions. For the outer LOOP1, we have 9 mispredictions for BNE-LOOP1 (except for the last iteration). Globally (10 + 9) = 19 mispredictions, while there are 60 predictions (50 for BNE-LOOP2 and 10 for BNE-LOOP1) => 19 mispredictions out of 60 predictions => 31.67% misprediction rate.
Assuming the BPU is disabled.	At each branch instruction, we must pay 2 cycles penalty to fetch the correct instruction.	Globally we have executed 60 branch instructions (50 for BNE-LOOP2 and 10 for BNE-LOOP1) causing 2 cycles penalty => globally there are (60 x 2) = 120 BP cycles to execute the code.	