12 BONUS: Branch Prediction [40 points]

Assume a processor that implements an ISA with eight registers (R0-R7). In this ISA, the main memory is byte-addressable and each word contains 4 bytes. The processor employs a branch predictor. The ISA implements the instructions given in the following table:

Instructions	**Description**
la R_i, Address	load the *Address* into R_i
move R_i, R_j	$R_i \leftarrow R_j$
move R_i, (R_j)	$R_i \leftarrow$ Memory[R_j]
move (R_i), R_j	Memory[R_i] $\leftarrow R_j$
li R_i, Imm	$R_i \leftarrow$ Imm
add R_i, R_j, R_k	$R_i \leftarrow R_j + R_k$
addi R_i, R_j, Imm	$R_i \leftarrow R_j +$ Imm
cmp R_i, R_j	Compare: Set sign flag, if $R_i < R_j$; set zero flag, if $R_i = R_j$
cmp R_i, (R_j)	Compare: Set sign flag, if $R_i <$ Memory[R_j]; set zero flag, if $R_i =$ Memory[R_j]
cmpi R_i, Imm	Compare: Set sign flag, if $R_i <$ Imm; set zero flag, if $R_i =$ Imm.
jg label	Jump to the target address if **both** of sign and zero flags are zero.
jnz label	Jump to the target address if zero flag is zero.
halt	Stop executing instructions.

The processor executes the following program. Answer the questions below related to the accuracy of the branch predictors that the processor can potentially implement.

```
1         la R0, Array
2         move R6, R0
3         li R1, 4
4         move R5, R1
5         move R7, R1
6         move R2, R0
7         addi R2, R2, 4
8   Loop:
9         move R3, (R2)
10        cmp R3, (R0)
11        jg Next_Iteration
12        move R4, (R0)
13        move (R0), R3
14        move (R2), R4
15  Next_Iteration:
16        addi R0, R0, 4
17        addi R2, R2, 4
18        addi R1, R1, -1
19        cmpi R1, 0
20        jnz Loop
21        move R1, R7
22        addi R5, R5, -1
23        move R0, R6
24        move R2, R0
25        addi R2, R2, 4
26        cmpi R5, 0
27        jnz Loop
28        halt
29  .data
30  Array: word 5, 20, 1, -5, 34
```

(a) [15 points] What would be the prediction accuracy using a global one-bit-history (last-time) branch predictor shared between *all* the branches? The initial state of the predictor is "taken".

Answer: 19/36.

Note that initial values of both R_1 and R_5 are 4; and they change only before the branches in lines 20 and 27 respectively. Both branches follow the pattern of T-T-T-NT, which creates a nested loop.

At each iteration of the internal loop, adjacent elements (pointed by R_0 and R_2) are swapped, if $Memory[R_0] \leq Memory[R_2]$. Then, both R_0 and R_4 are incremented by 4. So they point to the next element in the next iteration.

Therefore, the code sorts the elements in *Array* in increasing order.

Table below shows the behavior of each branch through the code. Here T means that the corresponding branch is taken at specified turn, whereas N indicates that it is not taken.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Line11	T		N		N		T			N		N		T		T		
Line20		T		T		T		N			T		T		T		N	
Line27									T									T

	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
Line11	N		T		T		T			T		T		T		T		
Line20		T		T		T		N			T		T		T		N	
Line27									T									N

One-bit-history branch predictor suggests that the next branch's behavior will be the same with the last one. Table below shows the predictor states, hits, and misses through the execution.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Predictor State	T	T	T	N	T	N	T	T	N	T	N	T	N	T	T
Branch Behavior	T	T	N	T	N	T	T	N	T	N	T	N	T	T	T
Hit/Miss	H	H	M	M	M	M	H	M	M	M	M	M	M	H	H

	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Predictor State	T	T	N	T	N	T	T	T	T	T	T	N	T	T	T
Branch Behavior	T	N	T	N	T	T	T	T	T	T	N	T	T	T	T
Hit/Miss	H	M	M	M	M	H	H	H	H	H	M	M	H	H	H

	31	32	33	34	35	36
Predictor State	T	T	T	T	T	N
Branch Behavior	T	T	T	T	N	N
Hit/Miss	H	H	H	H	M	H

(b) [15 points] What would be the prediction accuracy using a global two-bit-history (two-bit counter) branch predictor shared between *all* the branches? Assume that the initial state of the two-bit counter is "weakly taken". The "weakly taken" state transitions to the "weakly not-taken" state on misprediction. Similarly, the "weakly not-taken" state transitions to the "weakly taken" state on misprediction. A correct prediction in one of the "weak" states transitions the state to the corresponding "strong" state.

Answer: 26/36.

Explanation:
Table below shows the predictor states, hits, and misses through the code. Used abbreviations are as follows: ST: Strongly Taken, WT: Weakly Taken, WN: Weakly Not-taken, SN: Strongly Not-taken.

Branch behavior is the same with question (a), since both of them are shared predictors.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Predictor State	WT	ST	ST	WT	ST	WT	ST	ST	WT	ST	WT	ST	WT	ST
Branch Behavior	T	T	N	T	N	T	T	N	T	N	T	N	T	T
Hit/Miss	H	H	M	H	M	H	H	M	H	M	H	M	H	H

	15	16	17	18	19	20	21	22	23	24	25	26	27	28
Predictor State	ST	ST	ST	WT	ST	WT	ST	ST	ST	ST	ST	ST	WT	ST
Branch Behavior	T	T	N	T	N	T	T	T	T	T	T	N	T	T
Hit/Miss	H	H	M	H	M	H	H	H	H	H	H	M	H	H

	29	30	31	32	33	34	35	36
Predictor State	ST	ST	ST	ST	ST	ST	ST	WT
Branch Behavior	T	T	T	T	T	T	N	N
Hit/Miss	H	H	H	H	H	H	M	M

(c) [10 points] What would be the prediction accuracy using a local two-bit-history (two-bit counter) branch predictor that is separate for *each* branch? The initial state is "weakly taken" and the state transitions are the same as in part (b).

Answer:

- L11: 8/16
- L20: 12/16
- L27: 3/4
- All Branches: 23/36

Explanation: Private predictors update their states only based on the behaviors of corresponding branches.

	1	2	3	4	5	6	7	8	9	10	11	12
L11 Predictor State	WT		ST		WT		WN			WT		WN
L11 Branch Behavior	T		N		N		T			N		N
L11 Hit/Miss	H		M		M		M			M		H
L20 Predictor State		WT		ST		ST		ST			WT	
L20 Branch Behavior		T		T		T		N			T	
L20 Hit/Miss		H		H		H		M			H	
L27 Predictor State									WT			
L27 Branch Behavior									T			
L27 Hit/Miss									H			

	13	14	15	16	17	18	19	20	21	22	23	24
L11 Predictor State		SN		WN			WT		WN		WT	
L11 Branch Behavior		T		T			N		T		T	
L11 Hit/Miss		M		M			M		M		H	
L20 Predictor State	ST		ST		ST			WT		ST		ST
L20 Branch Behavior	T		T		N			T		T		T
L20 Hit/Miss	H		H		M			H		H		H
L27 Predictor State						ST						
L27 Branch Behavior						T						
L27 Hit/Miss						H						

	25	26	27	28	29	30	31	32	33	34	35	36
L11 Predictor State	ST			ST		ST		ST		ST		
L11 Branch Behavior	T			T		T		T		T		
L11 Hit/Miss	H			H		H		H		H		
L20 Predictor State		ST			WT		ST		ST		ST	
L20 Branch Behavior		N			T		T		T		N	
L20 Hit/Miss		M			H		H		H		M	
L27 Predictor State			ST									ST
L27 Branch Behavior			T									N
L27 Hit/Miss			H									M