Modern Processor Design (2): I guess I just feel like...

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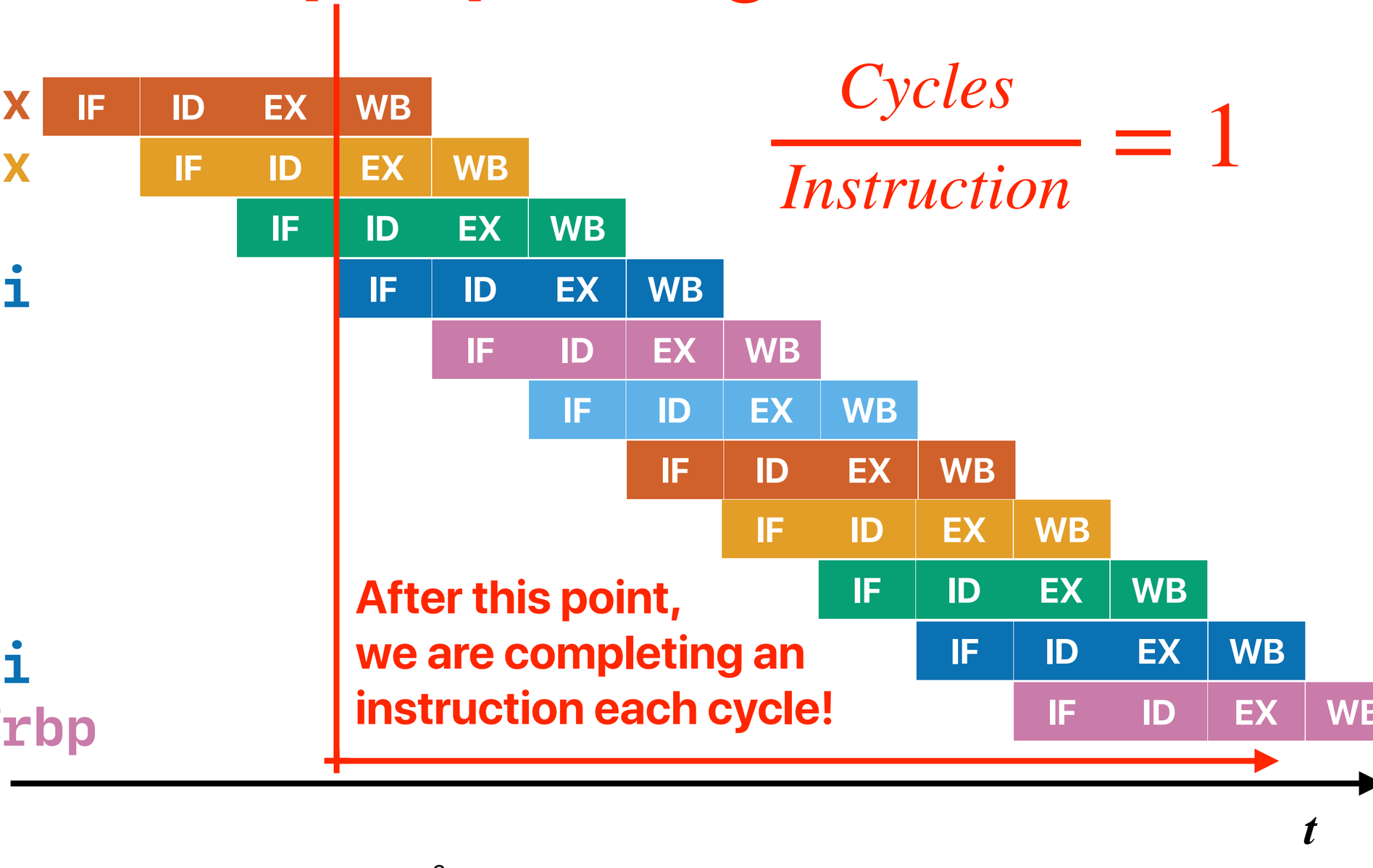
Recap: Pipelining

```
addl   %eax, %eax
addl   %rdi, %ecx
addq   $4, %r11
testl %esi, %esi
movl   $10, %edx
pushq %r12
pushq %rbp
pushq %rbx
subq   $8, %rsp
addl   %rsi, %rdi
movslq  %eax, %rbp
```



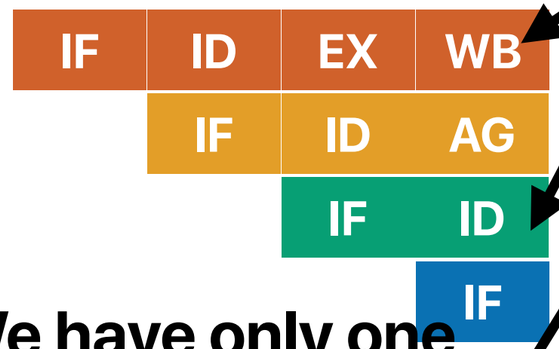
$$\frac{Cycles}{Instruction} = 1$$

Pipeline Hazards

```
① xorl %eax, %eax
② movl (%rdi), %ecx
③ addl %ecx, %eax
④ addq $4, %rdi
⑤ cmpq %rdx, %rdi
⑥ jne  .L3
⑦ ret
```

- How many of the "hazards" are data hazards?

A. 0
B. 1
C. 2
D. 3
E. 4



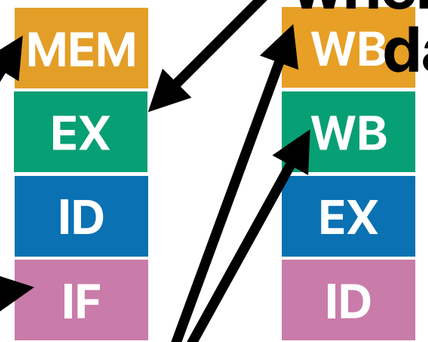
Structural Hazard

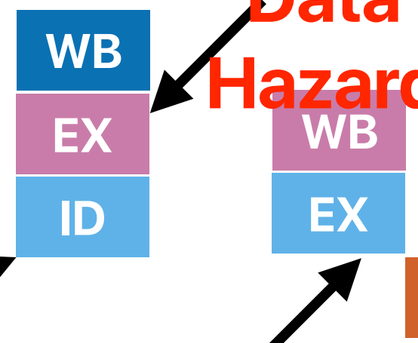
Data Hazard

Both (1) and (3) are attempting to access %eax

data is not in %ecx when we start EX

data is not in %rdi when we start EX





Data Hazard

We have only one memory unit, but two access requests!

Structural Hazard

Structural Hazard

Two instructions at the same stage?

We cannot know if we should fetch (7) or (2) before the EX is done

(6) may not have the outcome from (5)

Control Hazard

Recap: Structural Hazards

- Force later instructions to stall
- Improve the pipeline unit design to allow parallel execution
  - Write-first, read later register files
  - Split L1-Cache
  - Non-blocking, multi-banked cache/memory

3:00

When and how will you make a guess?

Outline

- Why branch prediction for control hazards
- Dynamic branch predictions
  - Local predictor — 2 bit
  - Global predictor — 2-level
  - Hybrid predictors
    - Tournament
    - Perceptron

Control Hazards

How does the code look like?

```
for (unsigned i = 0; i < size; ++i) {
    if (data[i] < threshold)
        call_when_true(&a[i]);
    else
        call_when_false(&a[i]);
}
```

// taken when true

// taken when false

Branch taken simply means we are using branch target address as the next address

```
.L12:
    movl  -32(%rbp), %eax
    cltq
    leaq  0(,%rax,8), %rdx
    movq  -8(%rbp), %rax
    addq  %rdx, %rax
    movq  (%rax), %rax
    andl  $1, %eax
    testq %rax, %rax
    je .L10
    movl  -32(%rbp), %eax
    cltq
    leaq  0(,%rax,8), %rdx
    movq  -8(%rbp), %rax
    addq  %rdx, %rax
    movq  %rax, %rdi
    call  call_when_true
```

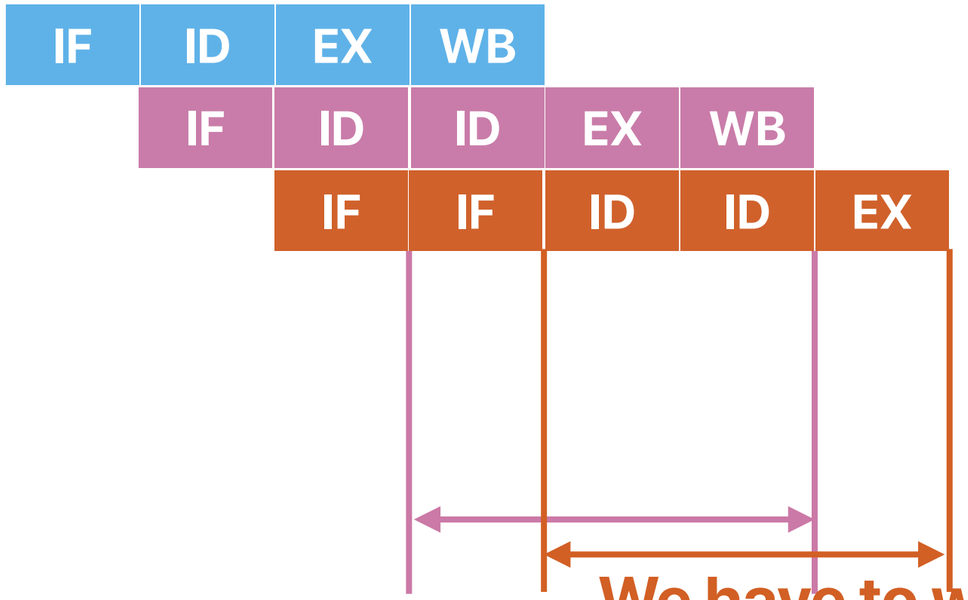
Branch taken

Branch taken

```
    jmp   .L11
.L10:
    movl  -32(%rbp), %eax
    cltq
    leaq  0(,%rax,8), %rdx
    movq  -8(%rbp), %rax
    addq  %rdx, %rax
    movq  %rax, %rdi
    call  call_when_false
.L11:
    addl  $1, -32(%rbp)
.L9:
    movl  -32(%rbp), %eax
    cmpl  -28(%rbp), %eax
    jl .L12
```

Why is “branch” problematic in performance?

```
① addq $8, %rbx
② cmpq %r12, %rbx
③ jne  .L5
```



The latency of executing the cmpq instruction

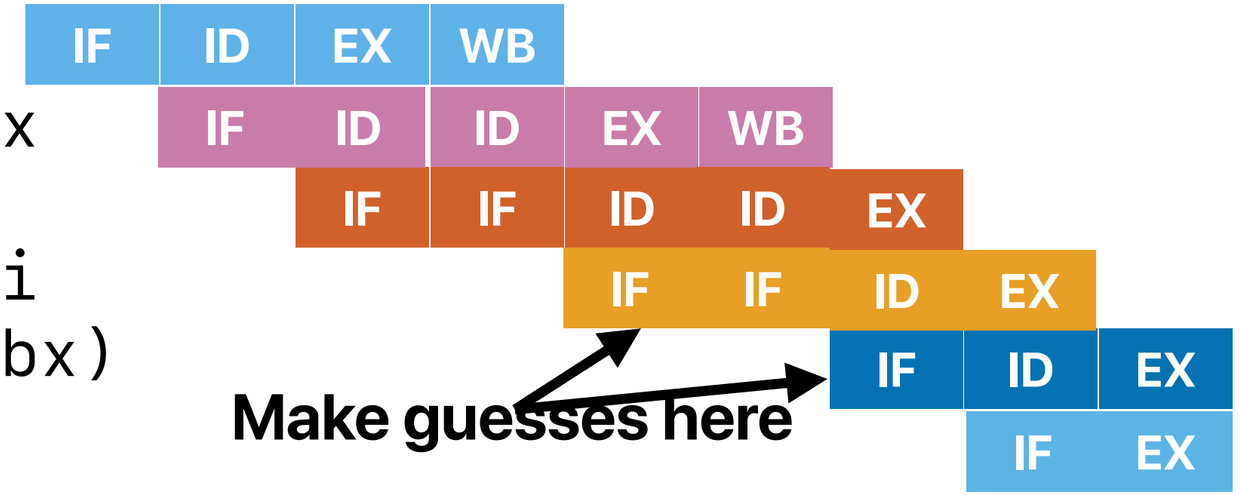
We have to wait almost as long as the latency of the previous instruction to make a decision — we cannot fetch anything before that

Takeaways: branch predictions

- The cost of not to predict a branch is to stall until the data dependency is resolved

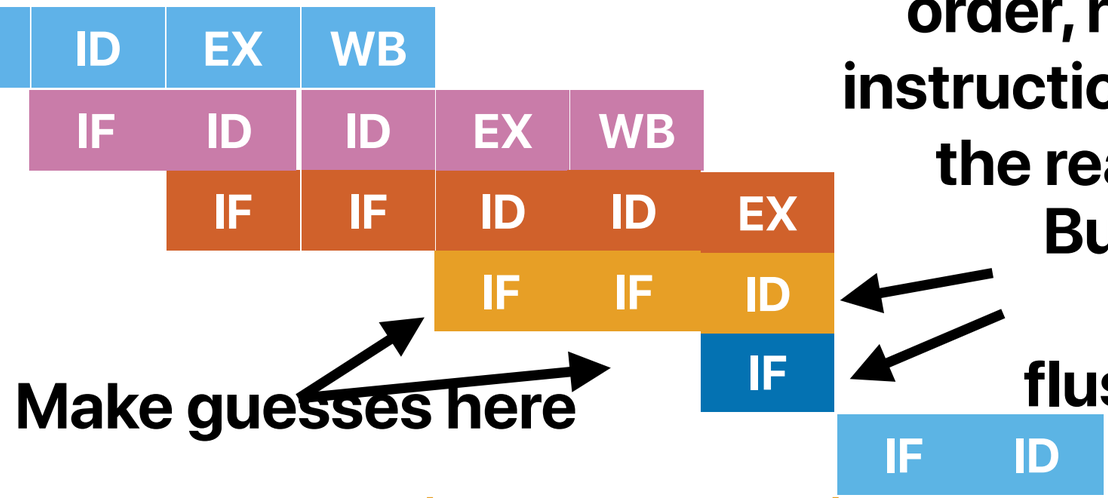
Prediction: What if we guessed right?

```
①         addq  $8, %rbx
②         cmpq  %r12, %rbx
③         jne   .L5
④ .L5:    movq  %rbx, %rdi
⑤         cmpq  %rbp, (%rbx)
```



Prediction: What if we are wrong?

```
①         addq  $8, %rbx
②         cmpq  %r12, %rbx
③         jne   .L5
④ .L5:    movq  %rbx, %rdi
⑤         cmpq  %rbp, (%rbx)
⑥ .L14:   popq  %rbx
```



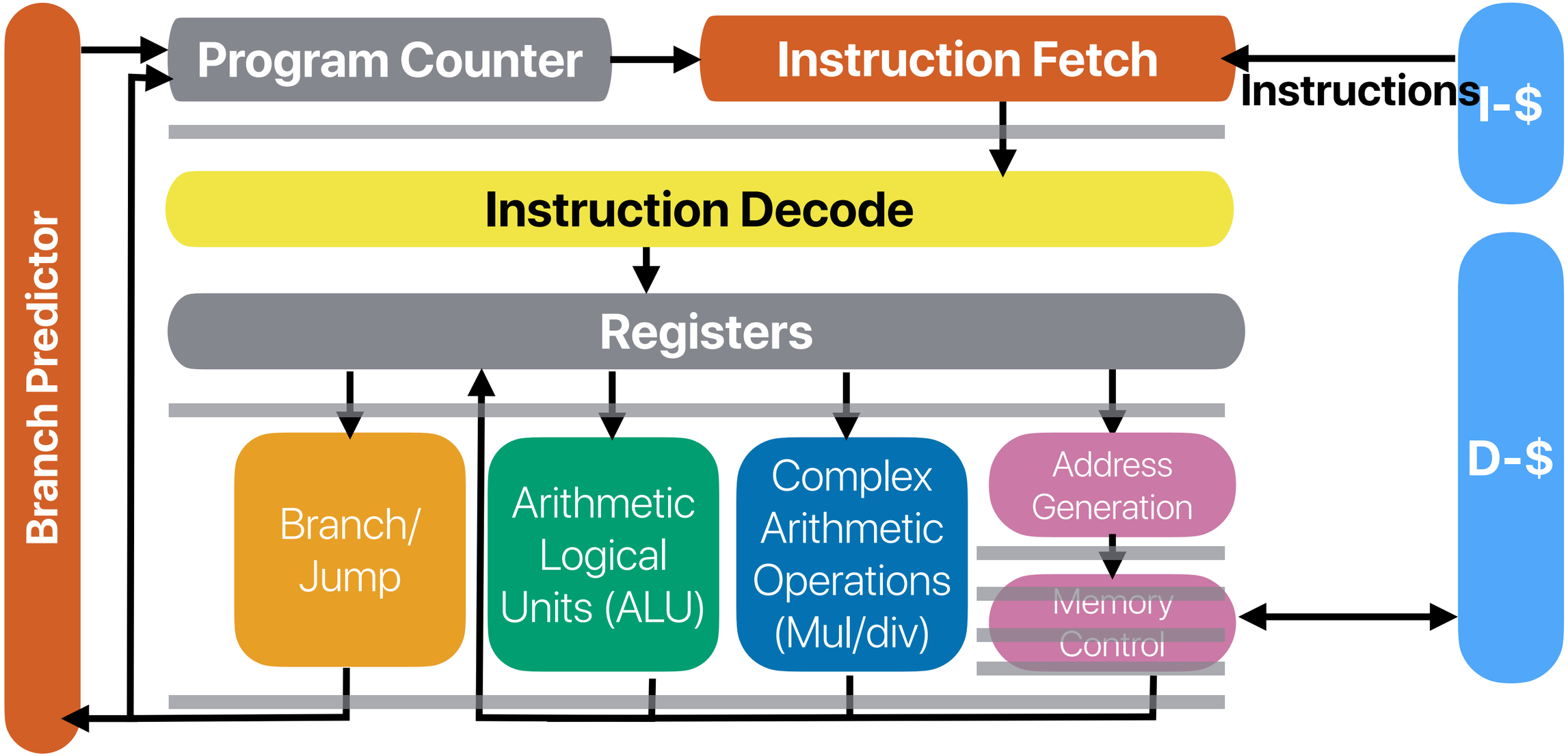
Make guesses here

Since we execute in-order, no predicted instructions will modify the real registers

Bubble the rest stages by flushing pipeline registers

We still only wasted three cycles — same as not doing anything

Microprocessor with a “branch predictor”



Takeaways: branch predictions

- The cost of not to predict a branch is to stall until the data dependency is resolved
- Branch predictions allow the processor to at least make some progress and hide the stalls if we guessed correctly!

https://www.pollev.com/hungweitseng close in 1:30

What should branch prediction "predict"

- How many of the following statements are true regarding the why is branch can lead to serious performance issues
  - ① The result value of the previous instruction generating the input to the branch
  - ② The direction of the branch (i.e., taken or not-taken)
  - ③ The target address of the branch
  - ④ The forth-through address of the branch
  - A. 0
  - B. 1
  - C. 2
  - D. 3
  - E. 4

What should branch prediction "predict"

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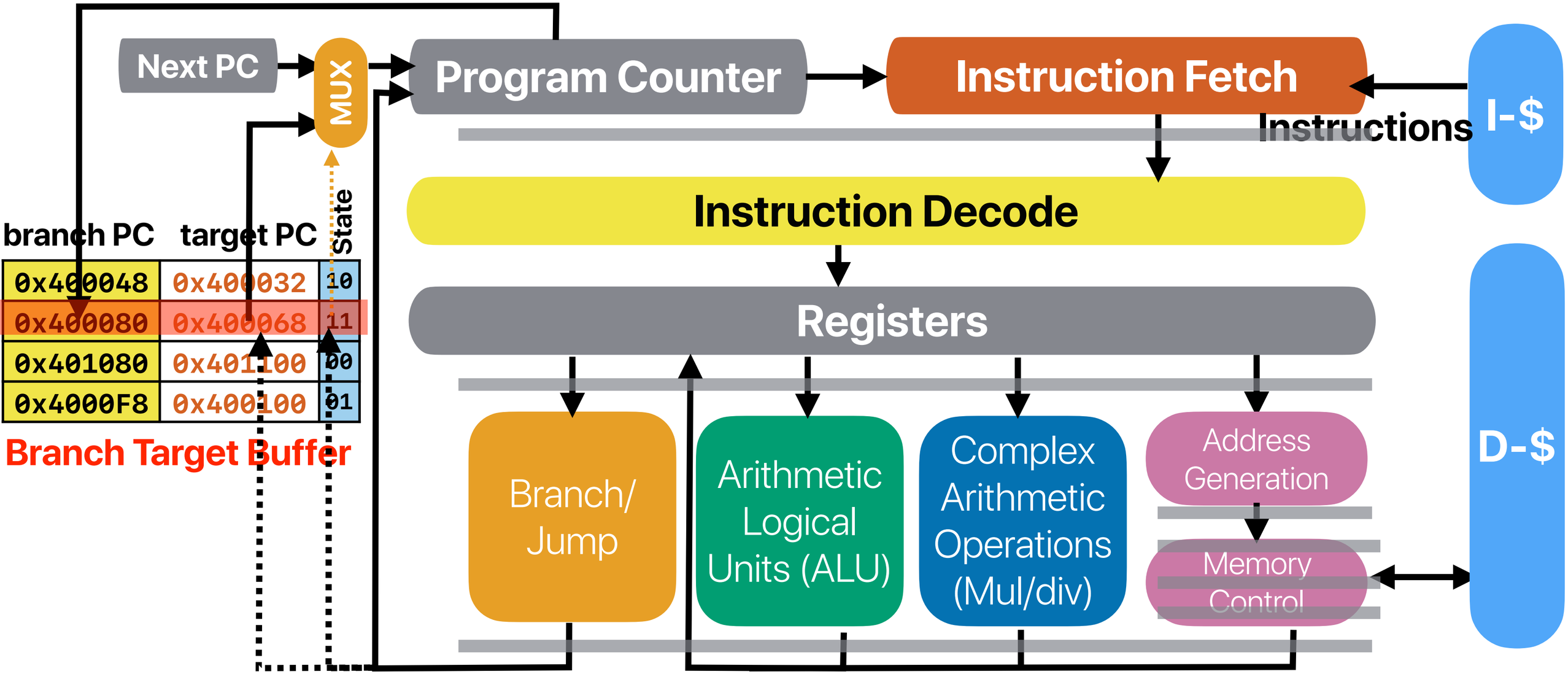
What are the "outcome" of the branch?

- **Taken, not-take You need to predict that — history/states**
- **Target address, if taken**

You need a cheatsheet for that — branch target buffer

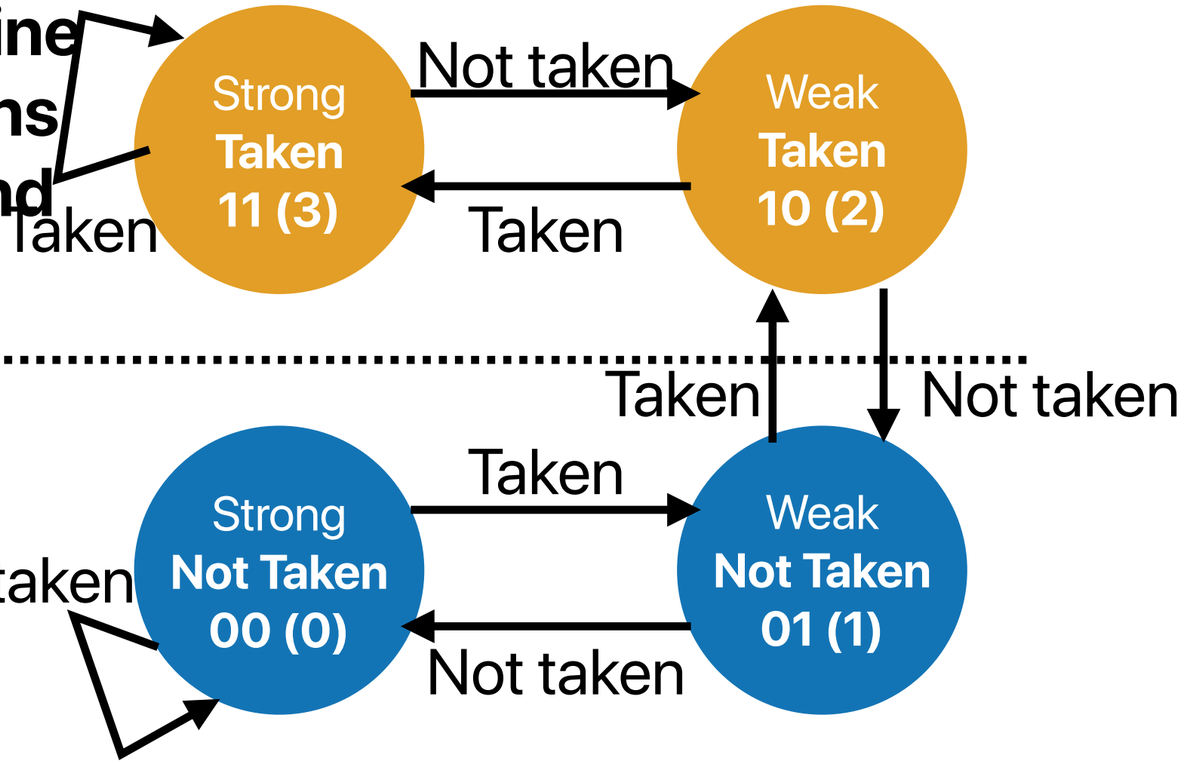
Detail of a basic dynamic branch predictor



2-bit/Bimodal local predictor

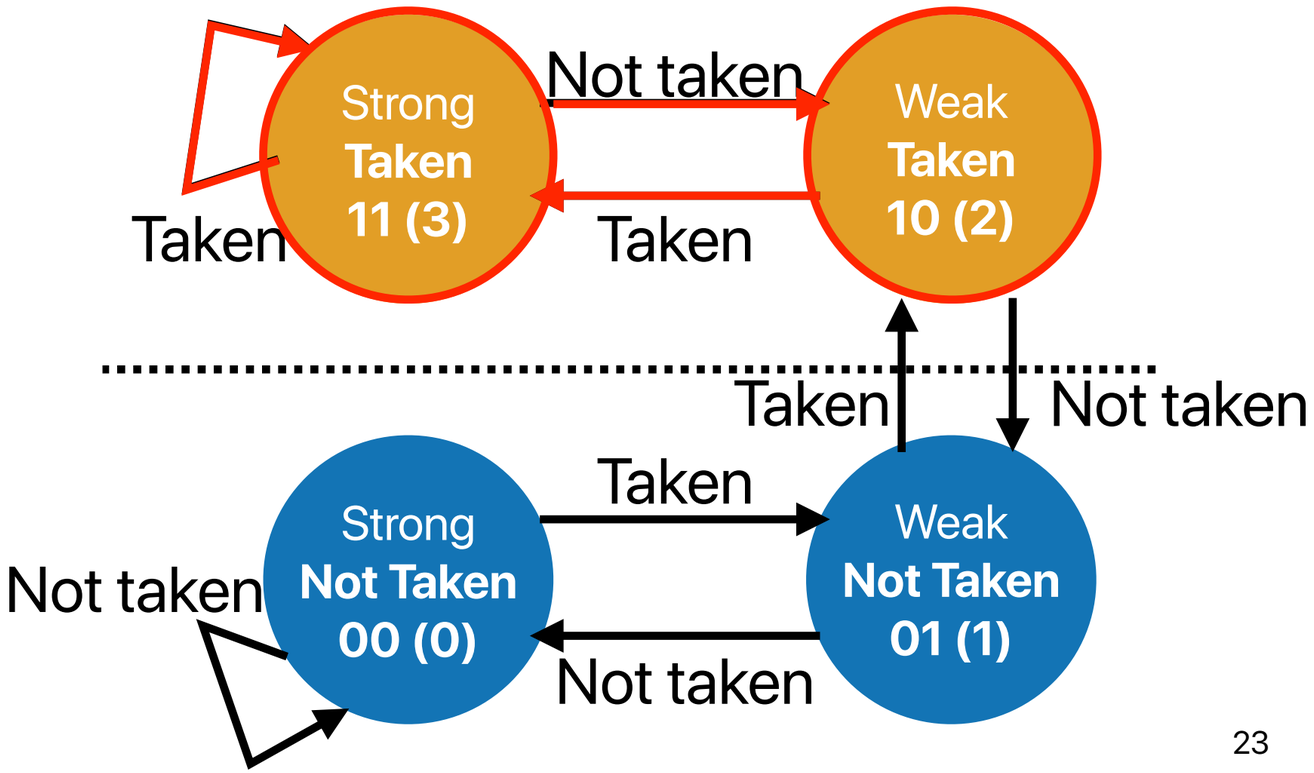
- Local predictor — every branch instruction has its own state
- 2-bit — each state is described using 2 bits
- Change the state based on **actual** outcome
- If we guess right — no penalty
- **If we guess wrong — flush (clear pipeline registers) for mis-predicted instructions that are currently in IF and ID stages and reset the PC**

	branch PC	target PC	State
	0x400048	0x400032	10
Predict Taken	0x400080	0x400068	11
	0x401080	0x401100	00
	0x4000F8	0x400100	01



2-bit local predictor

```
i = 0;
do {
     sum += a[i];
} while(++i < 10);
```



i	state	predict	actual
1	10	T	T
2	11	T	T
3	11	T	T
4-9	11	T	T
10	11	T	NT

90% accuracy!

Demo revisited

- Assume that we have a 2-bit local predictor and the values in data is randomly distributed in the number space, what's the branch prediction accuracy of branch X when option is "0" and "1". You may also assume the predictors' states start with 0s.

	Without sorting	After sorting
A	100%	0%
B	50%	0%
C	50%	50%
D	50%	100%
E	0%	100%

```
if(option)
    std::sort(data, data + arraySize);

for (unsigned i = 0; i < 100000; ++i) {
    int threshold = std::rand();
    for (unsigned i = 0; i < arraySize; ++i) {
        if (data[i] >= threshold)  // Branch X
            sum ++;
    }
}
```

Demo revisited

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        if (data[i] >= threshold)  // Branch X
```

	Without sorting	With sorting
The prediction accuracy of X before threshold	50%	100%
The prediction accuracy of X after threshold	50%	100%

Demo revisited

If there is no branch predictor on the processor, the code w/ sorting will be slower — but every processor has branch predictors now

	Without sorting	After sorting
A	100%	0%
B	50%	0%
C	50%	50%
D	50%	100%
E	0%	100%

```
if(option)
    std::sort(data, data + arraySize);

for (unsigned i = 0; i < 100000; ++i) {
    int threshold = std::rand();
    for (unsigned i = 0; i < arraySize; ++i) {
        if (data[i] >= threshold)  // Branch X
```

	Without sorting	With sorting
The prediction accuracy of X before threshold	50%	100%
The prediction accuracy of X after threshold	50%	100%

How can we evaluate the cost of mis-predicted branches?

- Compare the number of mis-predictions
- Calculate the difference of cycles
- We can get the “average CPI” of a mis-prediction!

Demo revisited: evaluating the cost of mis-predicted branches

- Compare the number of mis-predictions
- Calculate the difference of cycles
- We can get the “average CPI” of a mis-prediction!

34 cycles on Intel Alder Lake

23 cycles on AMD Zen 3

Could be more expensive than cache misses

2-bit local predictor

- What's the overall branch prediction (include both branches) accuracy for this nested for loop?

```
i = 0;
do {
    if( i % 2 != 0) // Branch X, taken if i % 2 == 0
       a[i] *= 2;
    a[i] += i;
} while ( ++i < 100)// Branch Y
```

(assume all states started with 00)

A. ~25%
B. ~33%
C. ~50%
D. ~67%
E. ~75%

2-bit local predictor

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} while ( ++i < 100)// Branch Y
```

(assume all states started with 00)

A. ~25%
B. ~33%
C. ~50%
D. ~67%
E. ~75%

Can we do a better job?

For branch Y, almost 100%,
For branch X, only 50%

i	branch?	state	prediction	actual
0	X	00	NT	T
1	Y	00	NT	T
1	X	01	NT	NT
2	Y	01	NT	T
2	X	00	NT	T
3	Y	10	T	T
3	X	01	NT	NT
4	Y	11	T	T
4	X	00	NT	T
5	Y	11	T	T
5	X	01	NT	NT
6	Y	11	T	T
6	X	00	NT	T
7	Y	11	T	T

Takeaways: branch predictions

- The cost of not to predict a branch is to stall until the data dependency is resolved — 34 cycles on modern intel processors and 23 on AMD processors
- Branch predictions allow the processor to at least make some progress and hide the stalls if we guessed correctly!
- Dynamic branch prediction — predict based on prior history
  - Local predictor — make prediction based on the state of each branch instruction

Two-level global predictor

Marius Evers, Sanjay J. Patel, Robert S. Chappell, and Yale N. Patt. 1998. An analysis of correlation and predictability: what makes two-level branch predictors work. In Proceedings of the 25th annual international symposium on Computer architecture (ISCA '98).

2-bit local predictor

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       a[i] *= 2;
    a[i] += i;
} while ( ++i < 100)// Branch Y
```

(assume all states started with 00)

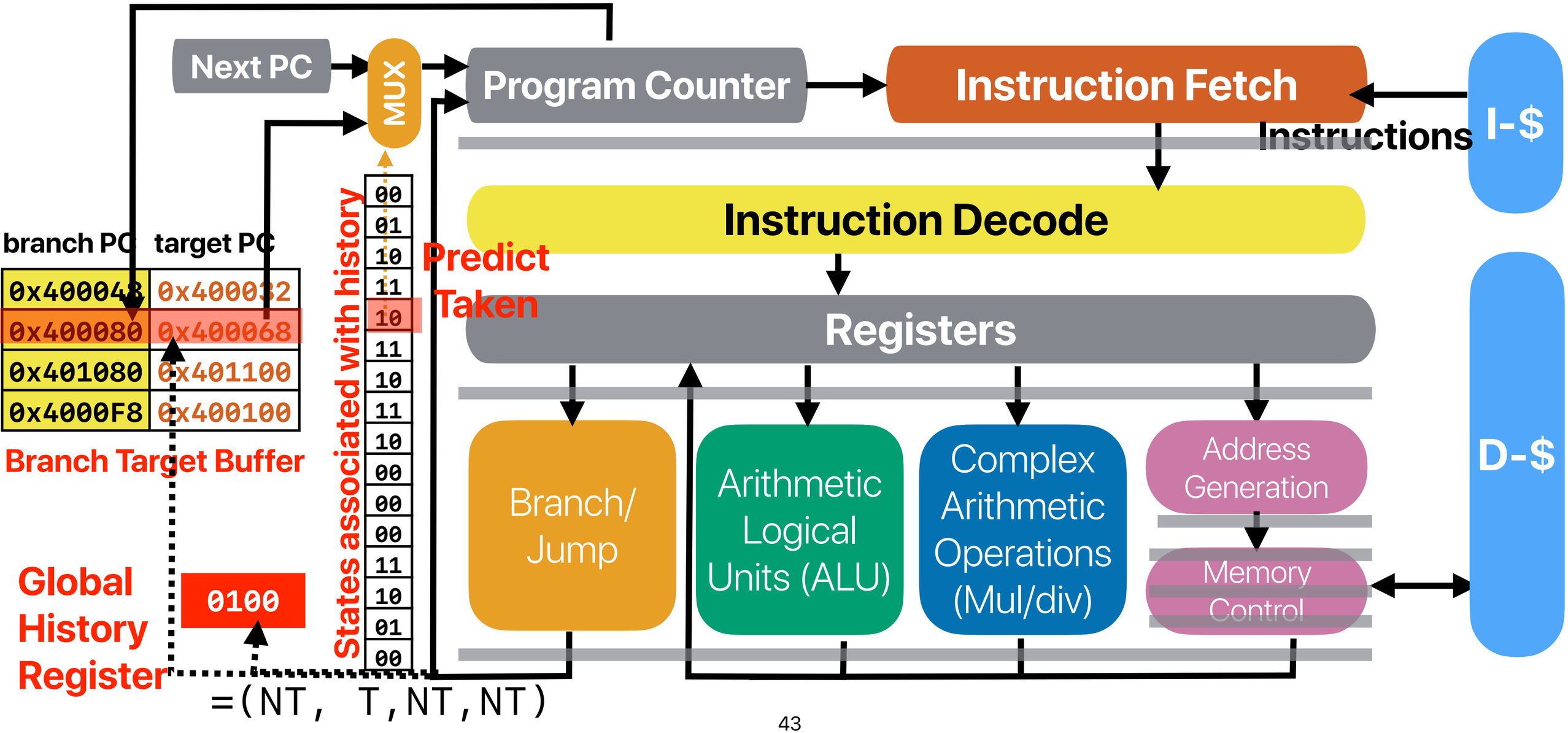
A. ~25%
B. ~33%
C. ~50%
D. ~67%
E. ~75%

This pattern repeats all the time!

For branch Y, almost 100%,
For branch X, only 50%

i	branch?	state	prediction	actual
0	X	00	NT	T
1	Y	00	NT	T
1	X	01	NT	NT
2	Y	01	NT	T
2	X	00	NT	T
3	Y	10	T	T
3	X	01	NT	NT
4	Y	11	T	T
4	X	00	NT	T
5	Y	11	T	T
5	X	01	NT	NT
6	Y	11	T	T
6	X	00	NT	T
7	Y	11	T	T

Detail of a basic dynamic branch predictor



Performance of GH predictor

```
i = 0;
do {
    if( i % 2 != 0) // Branch X, taken if i % 2 == 0
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    a[i] += i;
} while ( ++i < 100)// Branch Y
```

i	branch?	GHR	state	prediction	actual
0	X	000	00	NT	T
1	Y	001	00	NT	T
1	X	011	00	NT	NT
2	Y	110	00	NT	T
2	X	101	00	NT	T
3	Y	011	00	NT	T
3	X	111	00	NT	NT
4	Y	110	01	NT	T
4	X	101	01	NT	T
5	Y	011	01	NT	T
5	X	111	00	NT	NT
6	Y	110	10	T	T
6	X	101	10	T	T
7	Y	011	10	T	T
7	X	111	00	NT	NT
8	Y	110	11	T	T
8	X	101	11	T	T
9	Y	011	11	T	T
9	X	111	00	NT	NT
10	Y	110	11	T	T
10	X	101	11	T	T
11	Y	011	11	T	T

Near perfect after this

Better predictor?

- Consider two predictors — (L) 2-bit local predictor with unlimited BTB entries and (G) 4-bit global history with 2-bit predictors. How many of the following code snippet would allow (G) to outperform (L)?

I
```
i = 0;
do {
    if( i % 10 != 0)
       a[i] *= 2;
    a[i] += i;
} while ( ++i < 100);
```

II
```
i = 0;
do {
    a[i] += i;
} while ( ++i < 100);
```

III
```
i = 0;
do {
    j = 0;
    do {
      sum += A[i*2+j];
    }
    while( ++j < 2);
} while ( ++i < 100);
```

IV
```
i = 0;
do {
    if( rand() %2 == 0)
       a[i] *= 2;
    a[i] += i;
} while ( ++i < 100)
```

A. 0
B. 1
C. 2
D. 3
E. 4

Better predictor?

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about the same

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II

about the same

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i = 0;
do {
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i = 0;
do {
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    }
    while( ++j < 2);
} while ( ++i < 100);
```

IV

L could be better

```
i = 0;
do {
    if( rand() %2 == 0)
       a[i] *= 2;
    a[i] += i;
} while ( ++i < 100)
```

A. 0

B. 1

C. 2

D. 3

E. 4

Takeaways: branch predictions

- The cost of not to predict a branch is to stall until the data dependency is resolved — 34 cycles on modern intel processors and 23 on AMD processors
- Branch predictions allow the processor to at least make some progress and hide the stalls if we guessed correctly!
- Dynamic branch prediction — predict based on prior history
  - Local predictor — make predictions based on the state of each branch instruction
  - Global predictor — make predictions based on the state from all branches
  - Both are not perfect

Announcements

- Reading quiz #7 due next Tuesday
- Programming assignment #2 and assignment #3 due this Thursday

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