static branch prediction

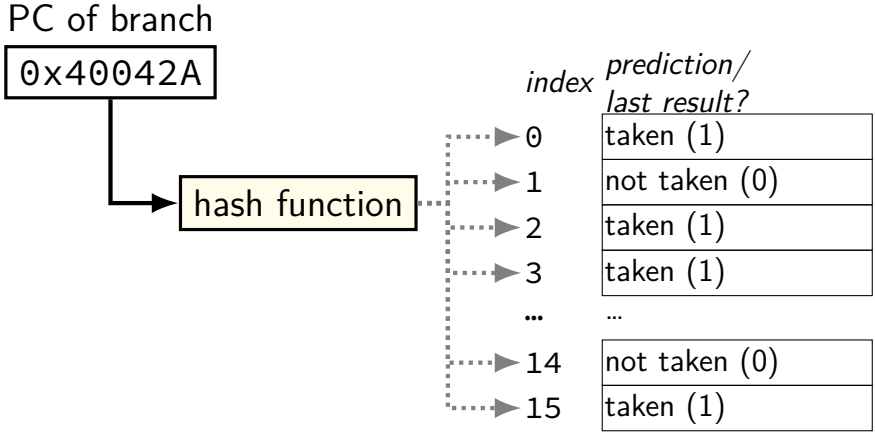
forward (target $>$ PC) not taken; backward taken

intuition: loops:

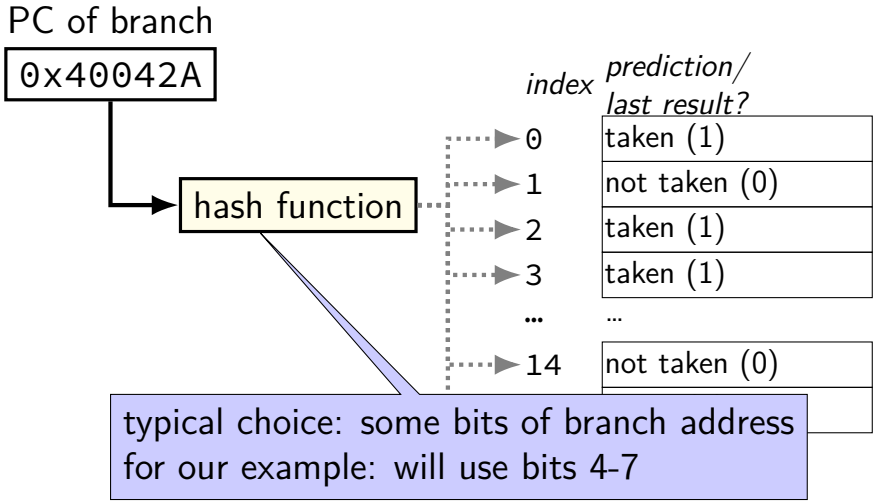
```
LOOP: ...
      ...
      je LOOP

LOOP: ...
      jne SKIP_LOOP
      ...
      jmp LOOP
SKIP_LOOP:
```

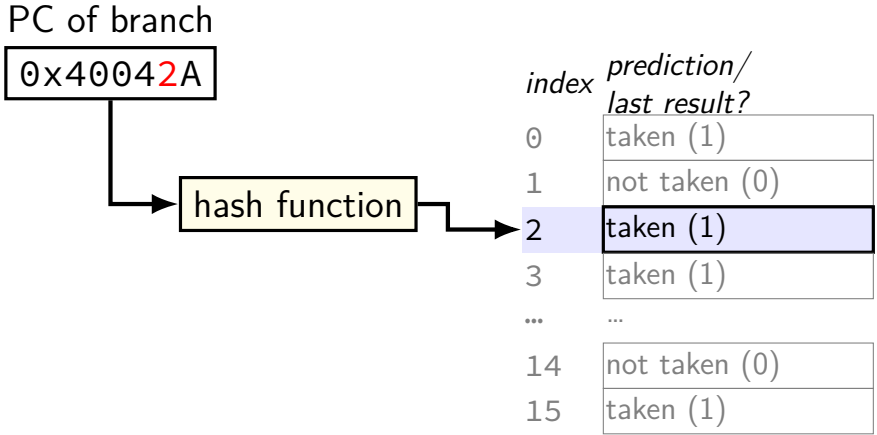
predict: repeat last



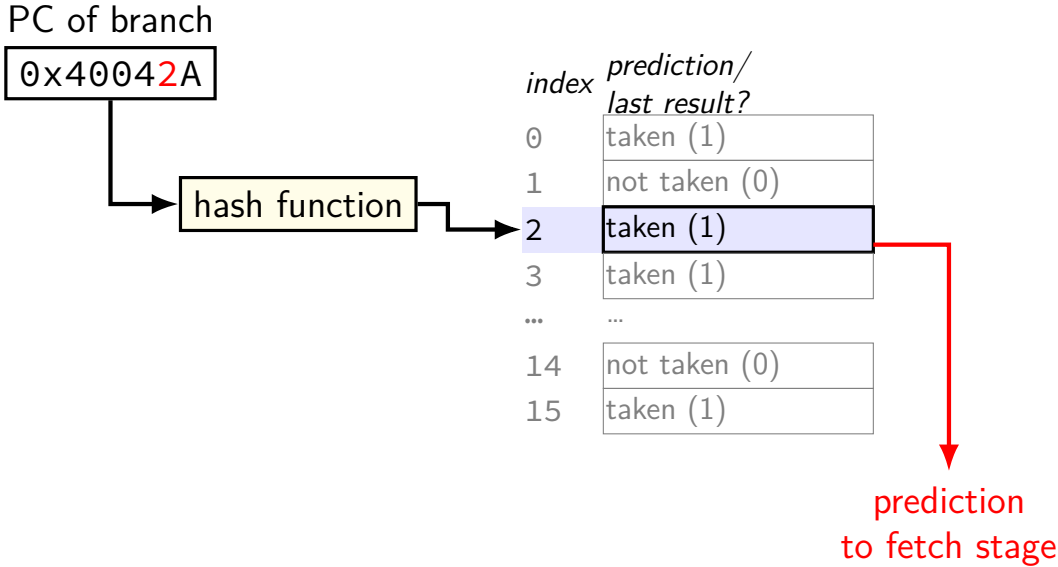
predict: repeat last



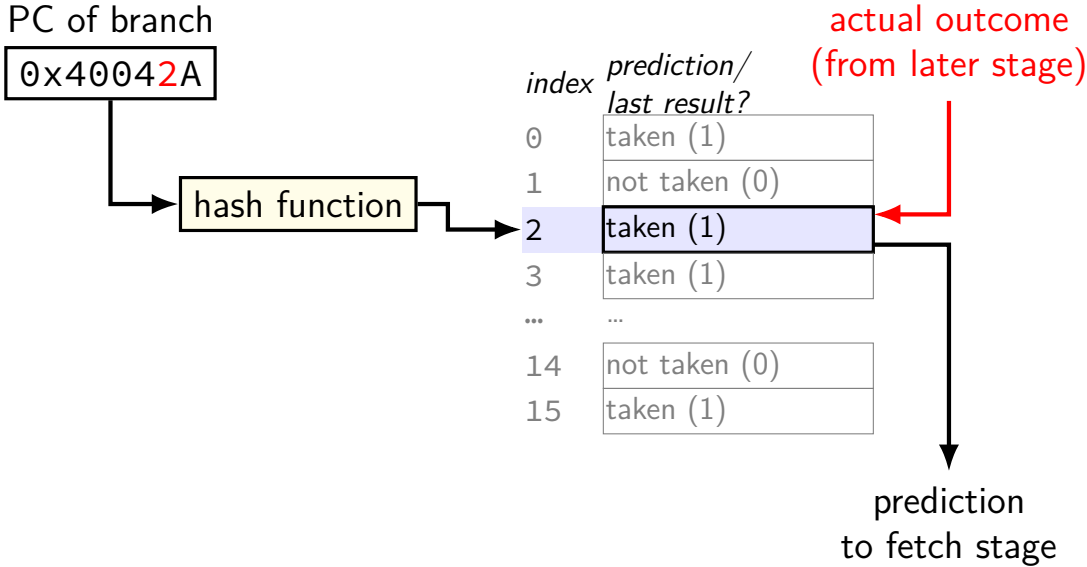
predict: repeat last



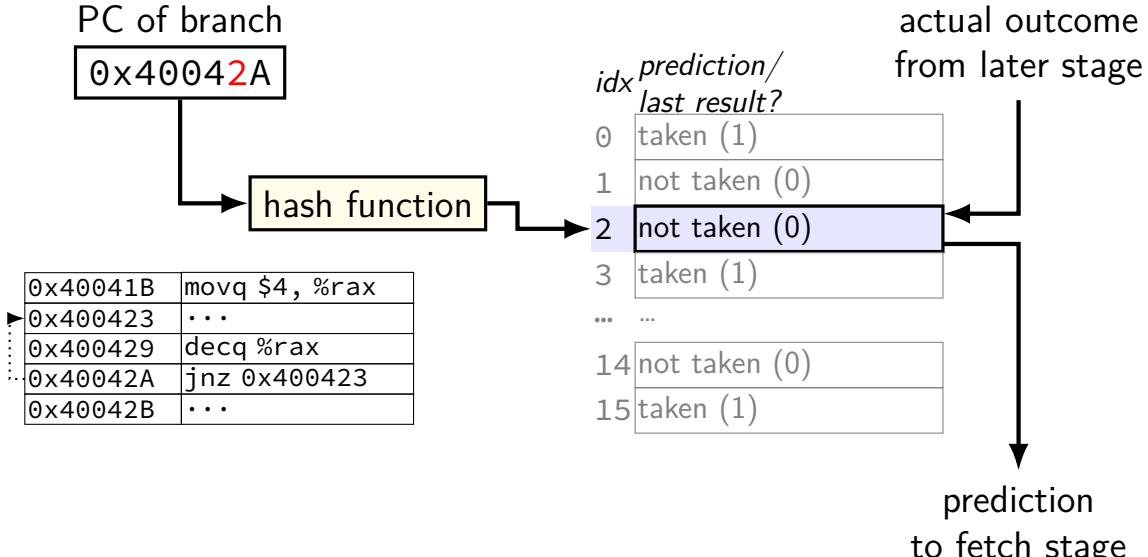
predict: repeat last



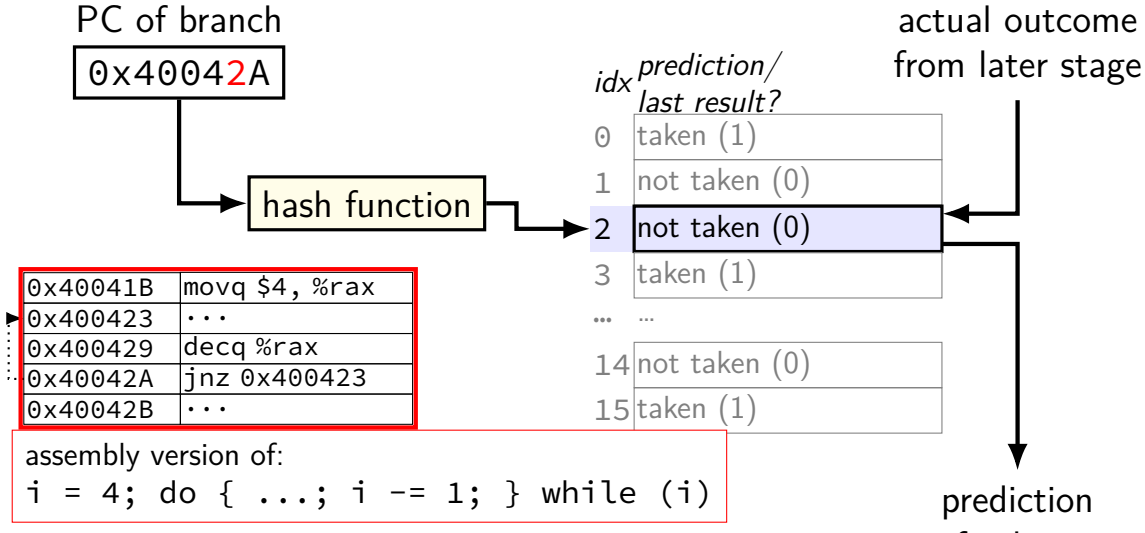
predict: repeat last



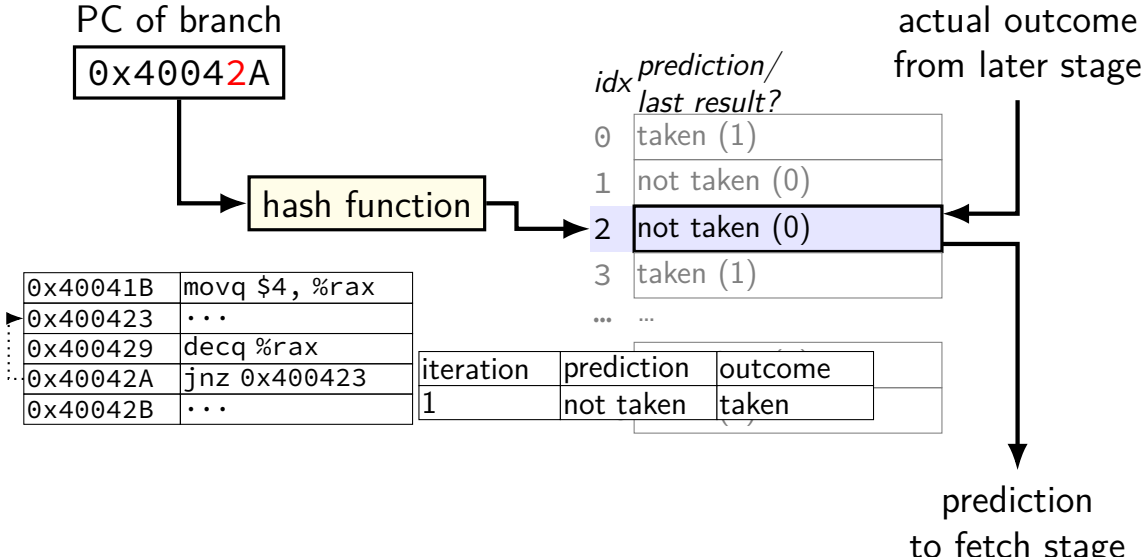
example


PC of branch
0x40042A
hash function
idx
prediction/
last result?
0 taken (1)
1 not taken (0)
2 not taken (0)
3 taken (1)
... ...
14 not taken (0)
15 taken (1)
actual outcome
from later stage
prediction
to fetch stage
0x40041B movq $4, %rax
0x400423 ...
0x400429 decq %rax
0x40042A jnz 0x400423
0x40042B ...

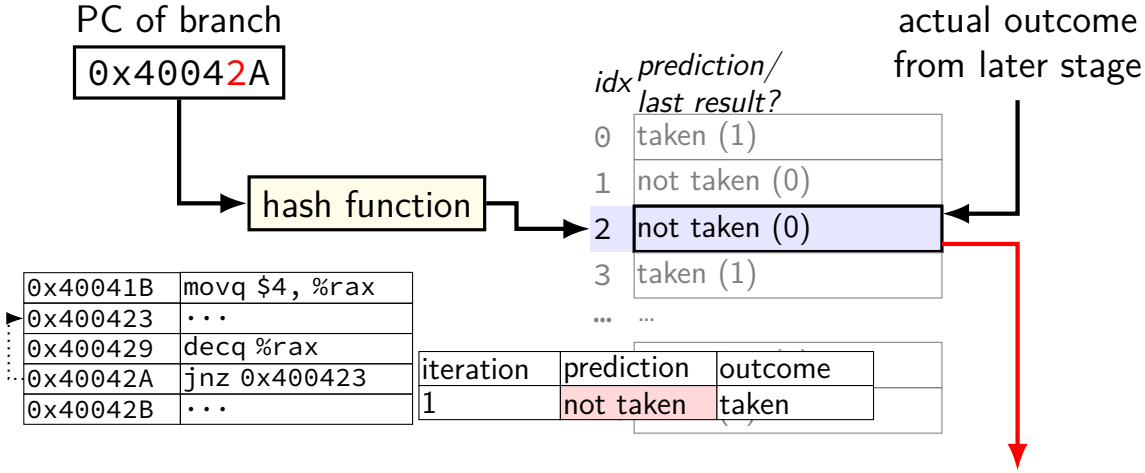
example


PC of branch
0x40042A
hash function
idx
prediction/
last result?
0 taken (1)
1 not taken (0)
2 not taken (0)
3 taken (1)
... ...
14 not taken (0)
15 taken (1)
actual outcome
from later stage
prediction
to fetch stage
0x40041B movq $4, %rax
0x400423 ...
0x400429 decq %rax
0x40042A jnz 0x400423
0x40042B ...
assembly version of:
i = 4; do { ...; i -= 1; } while (i)

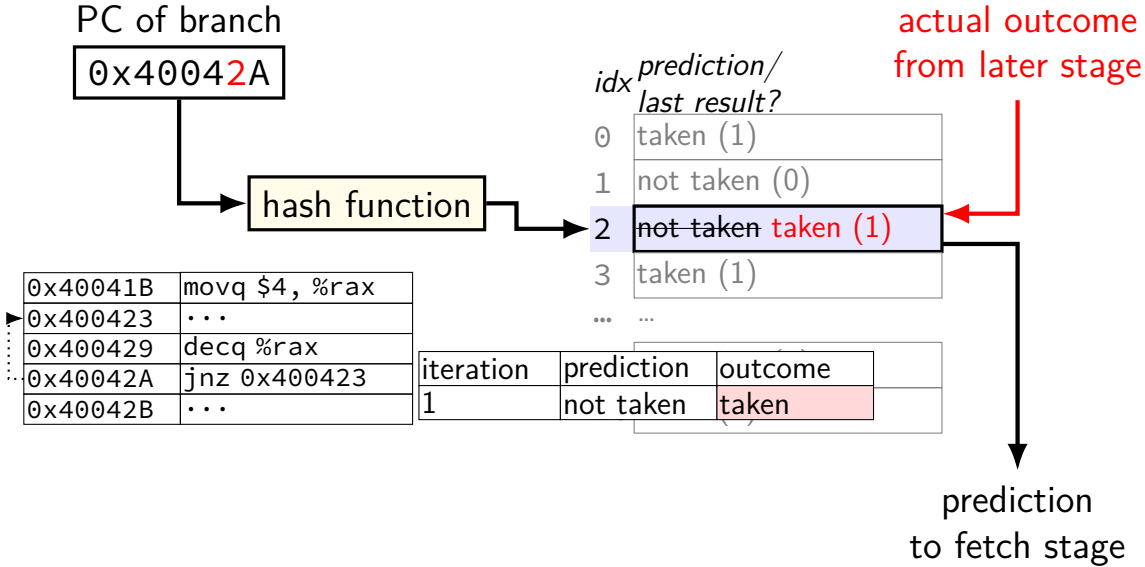
example


PC of branch
0x40042A
hash function
idx
prediction/
last result?
0
taken (1)
1
not taken (0)
2
not taken (0)
3
taken (1)
...
actual outcome
from later stage
0x40041B
movq $4, %rax
0x400423
...
0x400429
decq %rax
0x40042A
jnz 0x400423
0x40042B
...
iteration
prediction
outcome
1
not taken
taken
prediction
to fetch stage

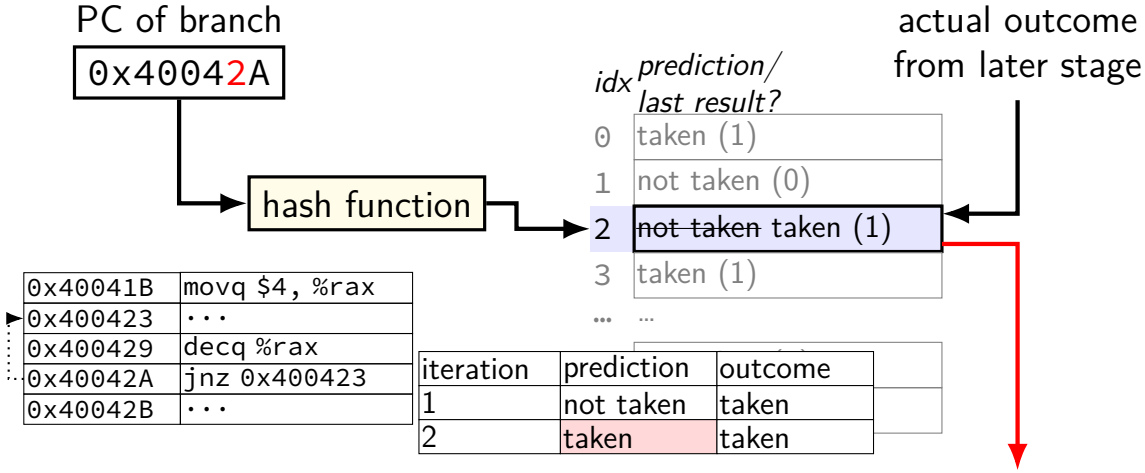
example


PC of branch
0x40042A
hash function
idx
prediction/
last result?
0
taken (1)
1
not taken (0)
2
not taken (0)
3
taken (1)
...
...
actual outcome
from later stage
0x40041B
movq $4, %rax
0x400423
...
0x400429
decq %rax
0x40042A
jnz 0x400423
0x40042B
...
iteration
prediction
outcome
1
not taken
taken
prediction
to fetch stage

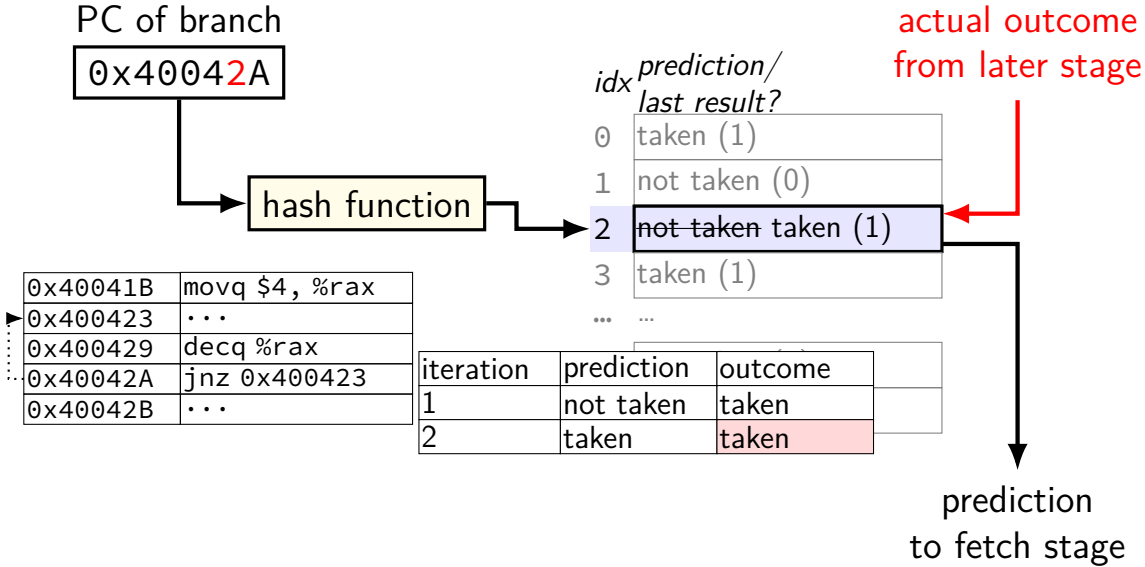
example


PC of branch
0x40042A
hash function
idx
prediction/
last result?
0
taken (1)
1
not taken (0)
2
not taken taken (1)
3
taken (1)
...
actual outcome
from later stage
0x40041B
movq $4, %rax
0x400423
...
0x400429
decq %rax
0x40042A
jnz 0x400423
0x40042B
...
iteration
prediction
outcome
1
not taken
taken
prediction
to fetch stage

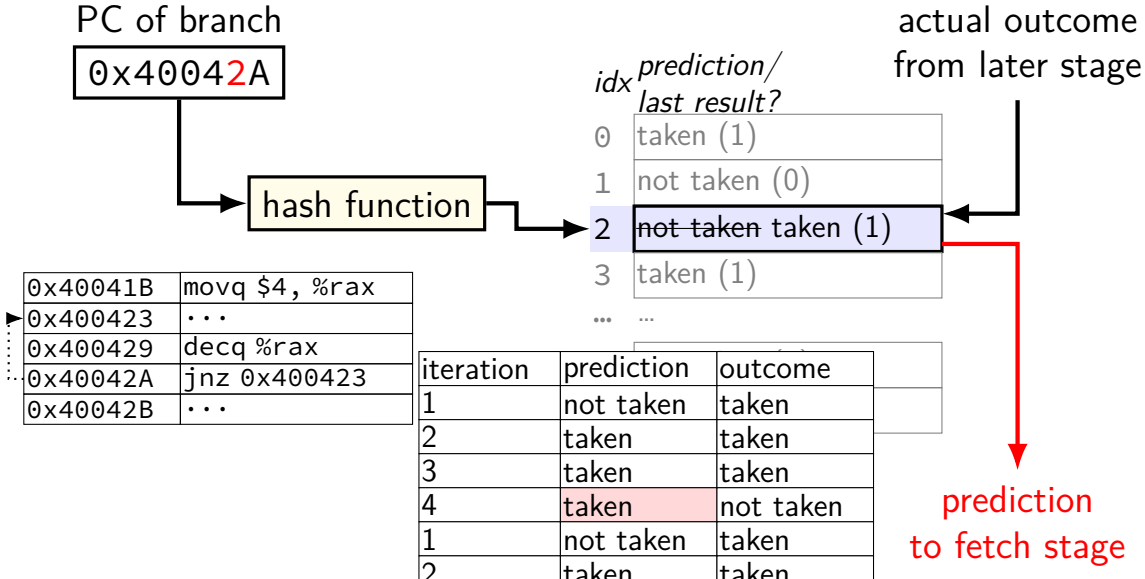
example


PC of branch
0x40042A
hash function
idx
prediction/
last result?
0
taken (1)
1
not taken (0)
2
not taken taken (1)
3
taken (1)
...
actual outcome
from later stage
0x40041B
movq $4, %rax
0x400423
...
0x400429
decq %rax
0x40042A
jnz 0x400423
0x40042B
...
iteration
prediction
outcome
1
not taken
taken
2
taken
taken
prediction
to fetch stage

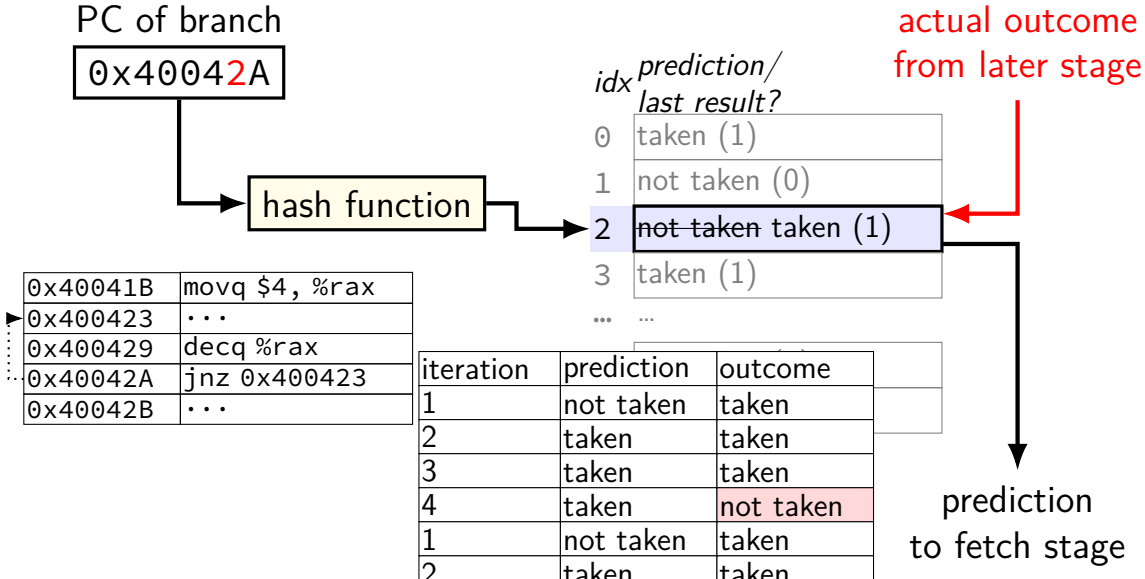
example


PC of branch
0x40042A
hash function
idx
prediction/
last result?
0
taken (1)
1
not taken (0)
2
not taken taken (1)
3
taken (1)
...
actual outcome
from later stage
prediction
to fetch stage
0x40041B movq $4, %rax
0x400423 ...
0x400429 decq %rax
0x40042A jnz 0x400423
0x40042B ...
iteration prediction outcome
1 not taken taken
2 taken taken

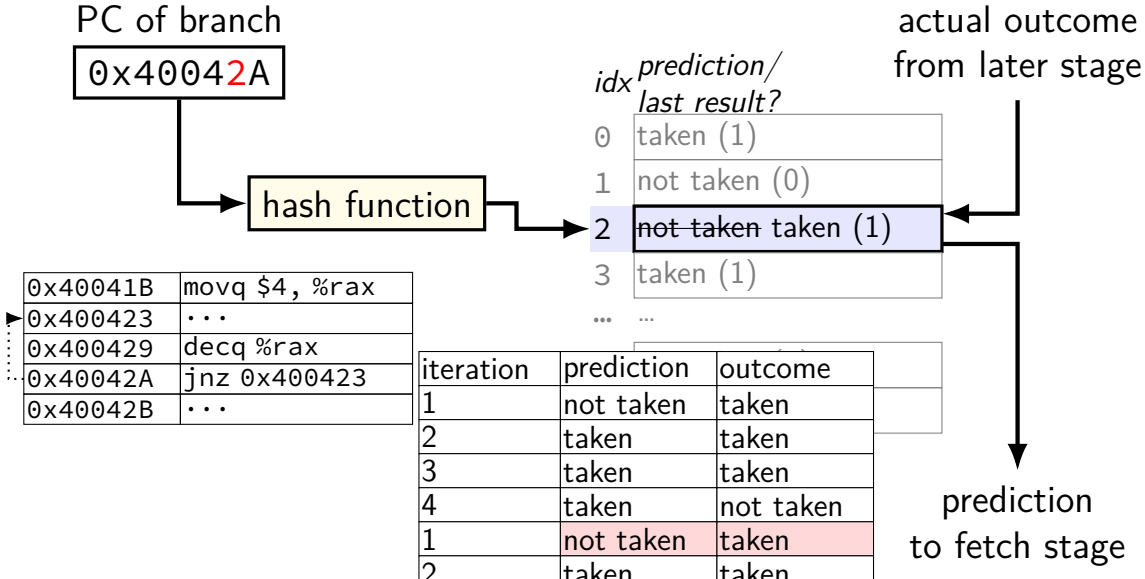
example


PC of branch
0x40042A
hash function
idx
prediction/ last result?
0
taken (1)
1
not taken (0)
2
not taken taken (1)
3
taken (1)
...
actual outcome from later stage
prediction to fetch stage
0x40041B movq $4, %rax
0x400423 ...
0x400429 decq %rax
0x40042A jnz 0x400423
0x40042B ...
iteration prediction outcome
1 not taken taken
2 taken taken
3 taken taken
4 taken not taken
1 not taken taken
2 taken taken

example


PC of branch
0x40042A
hash function
idx
prediction/ last result?
0
taken (1)
1
not taken (0)
2
not taken taken (1)
3
taken (1)
...
actual outcome from later stage
prediction to fetch stage
0x40041B movq $4, %rax
0x400423 ...
0x400429 decq %rax
0x40042A jnz 0x400423
0x40042B ...
iteration prediction outcome
1 not taken taken
2 taken taken
3 taken taken
4 taken not taken
1 not taken taken
2 taken taken

example


PC of branch
0x40042A
hash function
idx
prediction/
last result?
0
taken (1)
1
not taken (0)
2
not taken taken (1)
3
taken (1)
...
actual outcome
from later stage
prediction
to fetch stage
0x40041B
movq $4, %rax
0x400423
...
0x400429
decq %rax
0x40042A
jnz 0x400423
0x40042B
...
iteration
prediction
outcome
1
not taken
taken
2
taken
taken
3
taken
taken
4
taken
not taken
1
not taken
taken
2
taken
taken

collisions?

two branches could have same hashed PC

nothing in table tells us about this

versus direct-mapped cache: had *tag bits* to tell

is it worth it?

adding tag bits makes table *much* larger and/or slower

but does anything go wrong when there's a collision?

collision results

possibility 1: both branches usually taken

- no actual conflict — prediction is better(!)

possibility 2: both branches usually not taken

- no actual conflict — prediction is better(!)

possibility 3: one branch taken, one not taken

- performance probably worse

1-bit predictor for loops

predicts first and last iteration wrong

- example: branch to beginning — but same for branch from beginning to end

everything else correct

exercise (pt 1)

use 1-bit predictor on this loop

executed in outer loop (not shown) many, many times

what is the conditional jump misprediction rate for `i % 3 == 0`?

```
int i = 0;
while (true) {
  if (i % 3 == 0)
    goto next;
  ...
next:
  i += 1;
  if (i == 50)
    break;
}
```

exercise (pt 1)

use 1-bit predictor on this loop

executed in outer loop (not shown) many, many times

what is the conditional jump misprediction rate for `i % 3 == 0`?

```
int i = 0;
while (true) {
  if (i % 3 == 0)
    goto next;
  ...
next:
  i += 1;
  if (i == 50)
    break;
}
```

i =	branch	pred	outcome	correct?
0	mod 3	???	T	???
1	mod 3	T	F	no
2	mod 3	F	F	yes
3	mod 3	F	T	no
...	...	...	...	...

exercise (pt 1)

use 1-bit predictor on this loop

executed in outer loop (not shown) many, many times

what is the conditional jump misprediction rate for `i % 3 == 0`?

```
int i = 0;
while (true) {
  if (i % 3 == 0)
    goto next;
  ...
next:
  i += 1;
  if (i == 50)
    break;
}
```

i =	branch	pred	outcome	correct?
0	mod 3	???	T	???
1	mod 3	T	F	no
2	mod 3	F	F	yes
3	mod 3	F	T	no
...	...	...	...	...

exercise (pt 1)

use 1-bit predictor on this loop

executed in outer loop (not shown) many, many times

what is the conditional jump misprediction rate for `i % 3 == 0`?

```
int i = 0;
while (true) {
  if (i % 3 == 0)
    goto next;
  ...
next:
  i += 1;
  if (i == 50)
    break;
}
```

i =	branch	pred	outcome	correct?
0	mod 3	???	T	???
1	mod 3	T	F	no
2	mod 3	F	F	yes
3	mod 3	F	T	no
...	...	...	...	...

exercise (pt 2)

use 1-bit predictor on this loop

executed in outer loop (not shown) many, many times

what is the conditional jump misprediction rate for `i == 50`?

```
int i = 0;
while (true) {
  if (i % 3 == 0)
    goto next;
  ...
next:
  i += 1;
  if (i == 50)
    break;
}
```

exercise (full)

use 1-bit predictor on this loop

executed in outer loop (not shown) many, many times

what is the conditional jump misprediction rate?

```
int i = 0;
while (true) {
  if (i % 3 == 0)
    goto next;
  ...
next:
  i += 1;
  if (i == 50)
    break;
}
```

exercise (full)

use 1-bit predictor on this loop

executed in outer loop (not shown) many, many times

what is the conditional jump misprediction rate?

```
int i = 0;
while (true) {
  if (i % 3 == 0)
    goto next;
  ...
next:
  i += 1;
  if (i == 50)
    break;
}
```

i =	branch	pred	outcome	correct?
0	mod 3	???	T	???
1	== 50	???	F	???
1	mod 3	T	F	—
2	== 50	F	F	✓
...	...	...	...	...

exercise (full)

use 1-bit predictor on this loop

executed in outer loop (not shown) many, many times

what is the conditional jump misprediction rate?

```
int i = 0;
while (true) {
  if (i % 3 == 0)
    goto next;
  ...
next:
  i += 1;
  if (i == 50)
    break;
}
```

i =	branch	pred	outcome	correct?
0	mod 3	???	T	???
1	== 50	???	F	???
1	mod 3	T	F	—
2	== 50	F	F	✓
...	...	...	...	...

exercise soln (1)

i=	branch	predicted	outcome	correct?
0	mod 3	???	T	???
1	== 50	???	N	???
1	mod 3	T	N	
2	== 50	N	N	✓
2	mod 3	N	N	✓
3	== 50	N	N	✓
3	mod 3	N	T	
4	== 50	N	N	✓
…	…	…	…	…
48	mod 3	N	T	
49	== 50	N	N	✓
49	mod 3	T	N	
50	== 50	N	T	
0	mod 3	N	T	
1	== 50	T	N	

mod 3: correct for i=2,5,8,…,49 (16/50)
break: correct for i=2,3,…,48 (48/50)
overall: 64/100

```
int i = 0;
while (true) {
  if (i % 3 == 0) goto next;
  ...
next:
  i += 1;
  if (i == 50) break;
}
```

exercise soln (1)

i=	branch	predicted	outcome	correct?
0	mod 3	???	T	???
1	== 50	???	N	???
1	mod 3	T	N	
2	== 50	N	N	✓
2	mod 3	N	N	✓
3	== 50	N	N	✓
3	mod 3	N	T	
4	== 50	N	N	✓
…	…	…	…	…
48	mod 3	N	T	
49	== 50	N	N	✓
49	mod 3	T	N	
50	== 50	N	T	
0	mod 3	N	T	
1	== 50	T	N	

mod 3: correct for i=2,5,8,…,49 (16/50)
break: correct for i=2,3,…,48 (48/50)
overall: 64/100

```
int i = 0;
while (true) {
  if (i % 3 == 0) goto next;
  ...
next:
  i += 1;
  if (i == 50) break;
}
```

exercise soln (1)

i=	branch	predicted	outcome	correct?
0	mod 3	???	T	???
1	== 50	???	N	???
1	mod 3	T	N	
2	== 50	N	N	✓
2	mod 3	N	N	✓
3	== 50	N	N	✓
3	mod 3	N	T	
4	== 50	N	N	✓
…	…	…	…	…
48	mod 3	N	T	
49	== 50	N	N	✓
49	mod 3	T	N	
50	== 50	N	T	
0	mod 3	N	T	
1	== 50	T	N	

mod 3: correct for i=2,5,8,…,49 (16/50)
break: correct for i=2,3,…,48 (48/50)
overall: 64/100

```
int i = 0;
while (true) {
  if (i % 3 == 0) goto next;
  ...
next:
  i += 1;
  if (i == 50) break;
}
```

exercise soln (1)

i=	branch	predicted	outcome	correct?
0	mod 3	???	T	???
1	== 50	???	N	???
1	mod 3	T	N	
2	== 50	N	N	✓
2	mod 3	N	N	✓
3	== 50	N	N	✓
3	mod 3	N	T	
4	== 50	N	N	✓
…	…	…	…	…
48	mod 3	N	T	
49	== 50	N	N	✓
49	mod 3	T	N	
50	== 50	N	T	
0	mod 3	N	T	
1	== 50	T	N	

mod 3: correct for i=2,5,8,…,49 (16/50)
break: correct for i=2,3,…,48 (48/50)
overall: 64/100

```
int i = 0;
while (true) {
  if (i % 3 == 0) goto next;
  ...
next:
  i += 1;
  if (i == 50) break;
}
```

exercise soln (1)

i=	branch	predicted	outcome	correct?
0	mod 3	???	T	???
1	== 50	???	N	???
1	mod 3	T	N	
2	== 50	N	N	✓
2	mod 3	N	N	✓
3	== 50	N	N	✓
3	mod 3	N	T	
4	== 50	N	N	✓
…	…	…	…	…
48	mod 3	N	T	
49	== 50	N	N	✓
49	mod 3	T	N	
50	== 50	N	T	
0	mod 3	N	T	
1	== 50	T	N	

mod 3: correct for i=2,5,8,…,49 (16/50)
break: correct for i=2,3,…,48 (48/50)
overall: 64/100

```
int i = 0;
while (true) {
  if (i % 3 == 0) goto next;
  ...
next:
  i += 1;
  if (i == 50) break;
}
```

branch target buffer

what if we can't decode LABEL from machine code for `jmp` LABEL or `jle` LABEL fast?

- will happen in more complex pipelines

what if we can't decode that there's a RET, CALL, etc. fast?

BTB: cache for branch targets

idx	valid	tag	ofst	type	target	(more info?)
0x00	1	0x400	5	Jxx	0x3FFFF3	…
0x01	1	0x401	C	JMP	0x401035	---
0x02	0	---	---	---	---	---
0x03	1	0x400	9	RET	---	…
…	…	…	…	…	…	…
0xFF	1	0x3FF	8	CALL	0x404033	…

valid	…
1	…
0	…
0	…
0	…
…	…
0	…

```
0x3FFFF3:  movq %rax, %rsi
0x3FFFF7:  pushq %rbx
0x3FFFF8:  call 0x404033
0x400001:  popq %rbx
0x400003:  cmpq %rbx, %rax
0x400005:  jle 0x3FFFF3
…          …
0x400031:  ret
…          …
```

BTB: cache for branch targets

idx	valid	tag	ofst	type	target	(more info?)	valid	…
0x00	1	0x400	5	Jxx	0x3FFFF3	…	1	…
0x01	1	0x401	C	JMP	0x401035	---	0	…
0x02	0	---	---	---	---	---	0	…
0x03	1	0x400	9	RET	---	…	0	…
…	…	…	…	…	…	…	…	…
0xFF	1	0x3FF	8	CALL	0x404033	…	0	…

```
0x3FFFF3:  movq %rax, %rsi
0x3FFFF7:  pushq %rbx
0x3FFFF8:  call 0x404033
0x400001:  popq %rbx
0x400003:  cmpq %rbx, %rax
0x400005:  jle 0x3FFFF3
…          …
0x400031:  ret
…          …
```

BTB: cache for branch targets

idx	valid	tag	ofst	type	target	(more info?)
0x00	1	0x400	5	Jxx	0x3FFFF3	…
0x01	1	0x401	C	JMP	0x401035	---
0x02	0	---	---	---	---	---
0x03	1	0x400	9	RET	---	…
…	…	…	…	…	…	…
0xFF	1	0x3FF	8	CALL	0x404033	…

valid	…
1	…
0	…
0	…
0	…
…	…
0	…

```
0x3FFFF3:  movq %rax, %rsi
0x3FFFF7:  pushq %rbx
0x3FFFF8:  call 0x404033
0x400001:  popq %rbx
0x400003:  cmpq %rbx, %rax
0x400005:  jle 0x3FFFF3
…          …
0x400031:  ret
…          …
```

indirect branch prediction

`jmp *%rax` or `jmp *(%rax, %rcx, 8)`

BTB can provide a prediction

but can do better with more context

example—predict based on other recent computed jumps

- good for polymophic method calls

table lookup with Hash(last few jmps)
instead of Hash(this jmp)

beyond 1-bit predictor

devote *more space* to storing history

main goal: rare exceptions don't immediately change prediction

example: branch taken 99% of the time

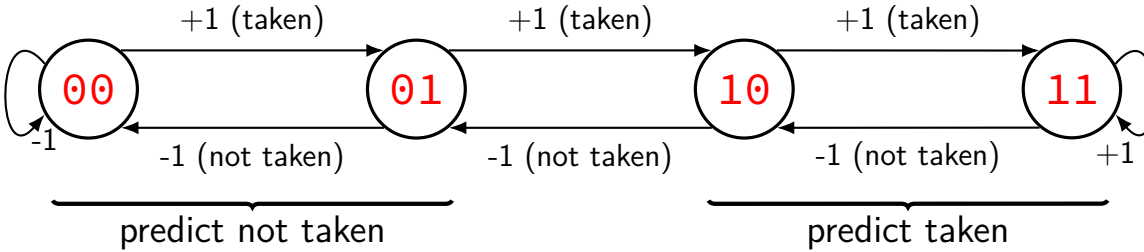
1-bit predictor: wrong about 2% of the time

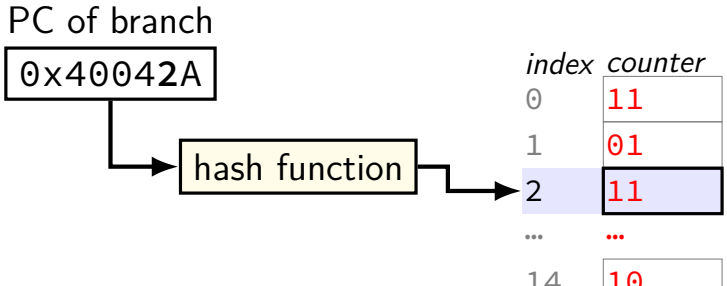
- 1% when branch not taken
- 1% of taken branches right after branch not taken

new predictor: wrong about 1% of the time

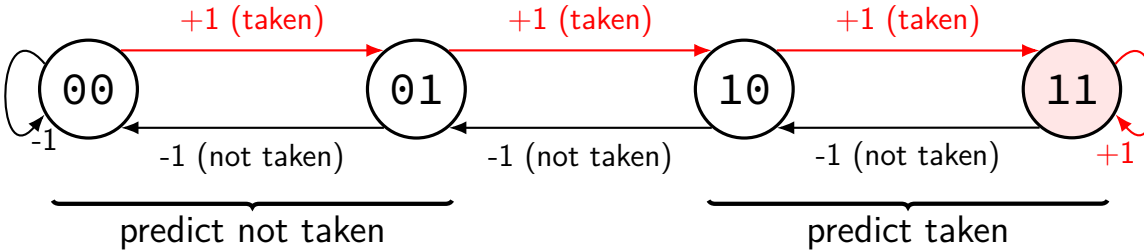
- 1% when branch not taken

2-bit saturating counter



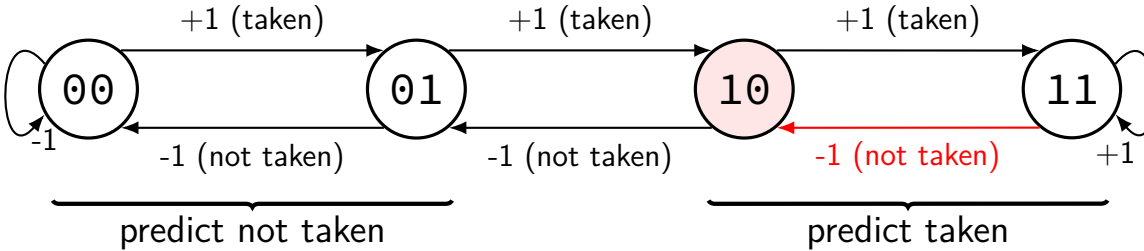


2-bit saturating counter



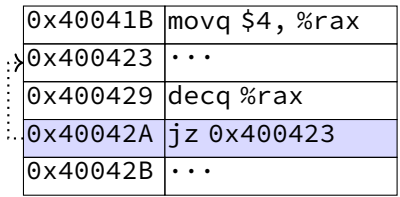
branch always taken:
value increases to 'strongest' taken value

2-bit saturating counter



branch almost always taken, then not taken once:
still predicted as taken

example



iter.	table before	prediction	outcome	table after
1	01	not taken	taken	10
2	10	taken	taken	11
3	11	taken	taken	11
4	11	taken	not taken	10
1	10	taken	taken	11
2	11	taken	taken	11
3	11	taken	taken	11
4	11	taken	not taken	10
1	10	taken	taken	11
...	...	...	...	...

generalizing saturating counters

2-bit counter: ignore one exception to taken/not taken

3-bit counter: ignore more exceptions

`000` $\leftrightarrow$ `001` $\leftrightarrow$ `010` $\leftrightarrow$ `011` $\leftrightarrow$ `100` $\leftrightarrow$ `101` $\leftrightarrow$ `110` $\leftrightarrow$ `111`

`000-011`: not taken

`100-111`: taken

exercise

use 2-bit predictor on this loop

executed in outer loop (not shown) many, many times

what is the conditional branch misprediction rate?

```
int i = 0;
while (true) {
  if (i % 3 == 0) goto next;
  ...
next:
  i += 1;
  if (i == 50) break;
}
```

exercise soln (1)

i=	branch	predicted	outcome	correct?
0	mod 3	01 (N)	T	
1	break	01 (N)	N	✓
1	mod 3	10 (T)	N	
2	break	00 (N)	N	✓
2	mod 3	01 (N)	N	✓
3	break	00 (N)	N	✓
3	mod 3	00 (N)	T	
4	break	00 (N)	N	✓
…	…	…	…	…
48	mod 3	00 (N)	T	
49	break	00 (N)	N	✓
49	mod 3	01 (N)	N	✓
50	break	00 (N)	T	
0	mod 3	00 (N)	T	
1	break	01 (N)	N	✓

mod 3: correct for i=1,2,4,5,7,8,…,49 (33/50)

mod 3: ends up always predicting not ta

break: correct for i=2,3,…,48 (49/50)

break: ends up always predicting not tak

overall: 82/100

```
int i = 0;
while (true) {
  if (i % 3 == 0) goto next;
  ...
next:
  i += 1;
  if (i == 50) break;
}
```

branch patterns

```
i = 4;
do {
    ...
    i -= 1;
} while (i != 0);
```

typical pattern for jump to top of do-while above:

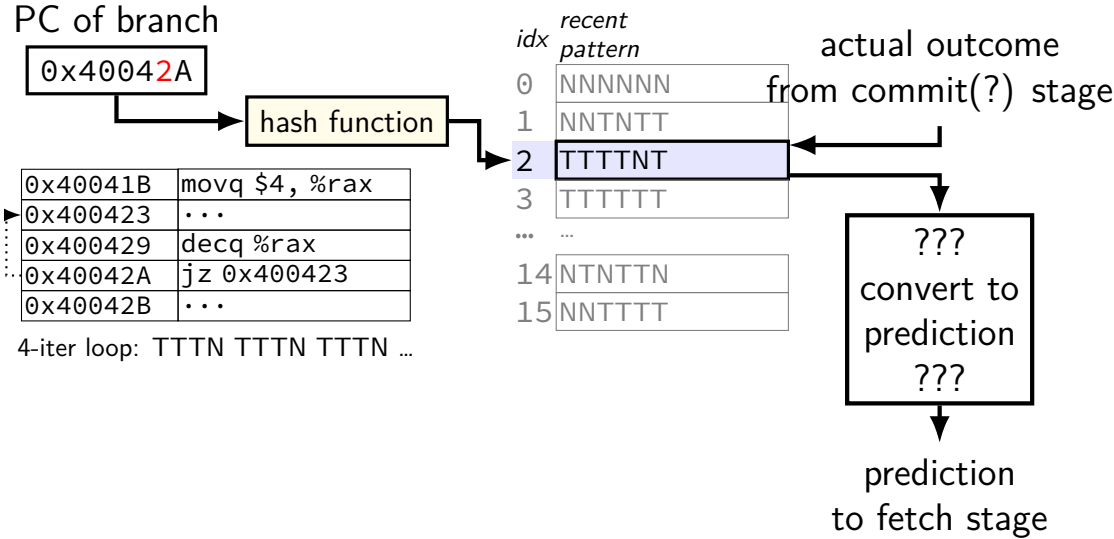
TTTN TTTN TTTN TTTN TTTN... (T = taken, N = not taken)

goal: take advantage of recent pattern to make predictions

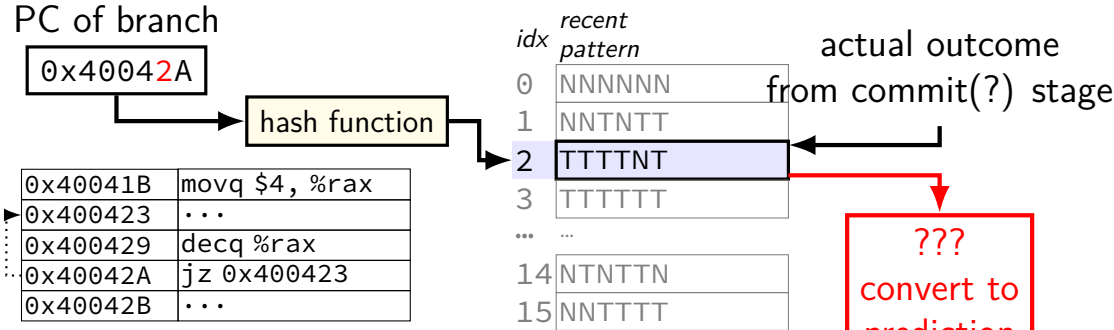
just saw 'NTTTNT'? predict T next

'TNTTTN'? predict T; 'TTNTTT'? predict N next

local pattern predictor (incomplete)



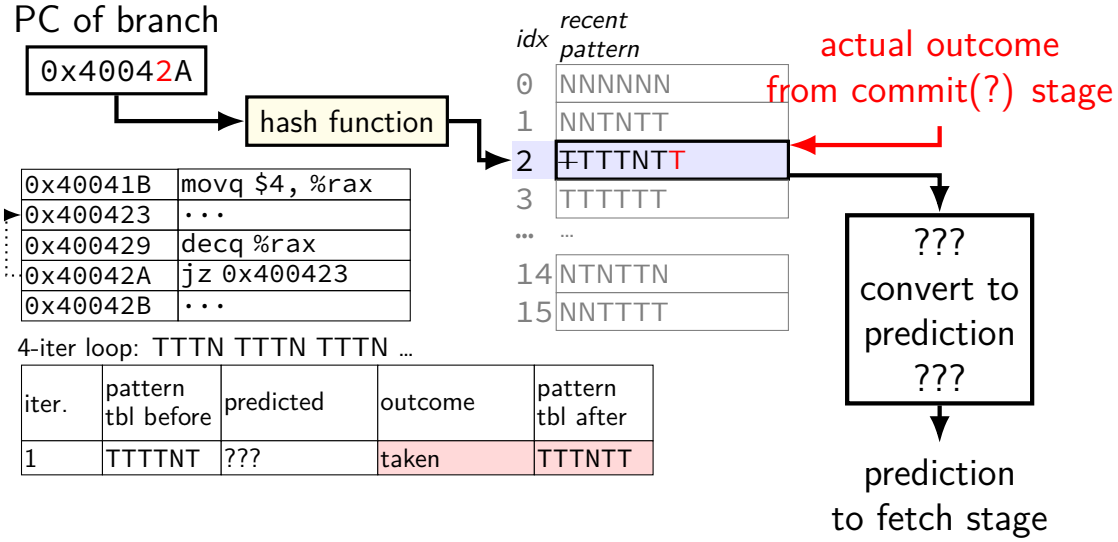
local pattern predictor (incomplete)



4-iter loop: TTTN TTTN TTTN ...

iter.	pattern tbl before	predicted	outcome	pattern tbl after
1	TTTTNT	???	taken	TTTNTT

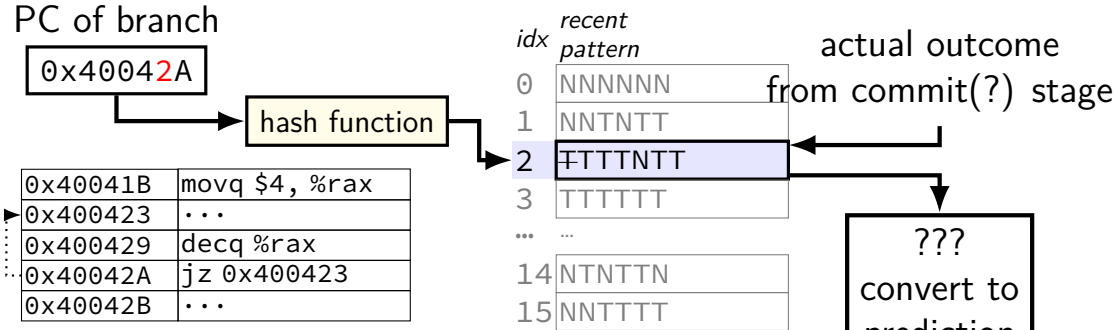
local pattern predictor (incomplete)



4-iter loop: TTTN TTTN TTTN ...

iter.	pattern tbl before	predicted	outcome	pattern tbl after
1	TTTTNT	???	taken	TTTNTT

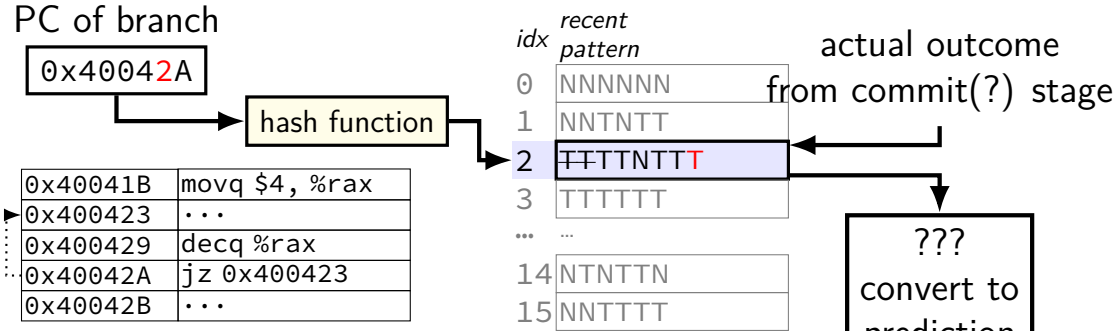
local pattern predictor (incomplete)



4-iter loop: TTTN TTTN TTTN ...

iter.	pattern tbl before	predicted	outcome	pattern tbl after
1	TTTTNT	???	taken	TTTNTT
2	TTTNTT	???	taken	TTNTTT

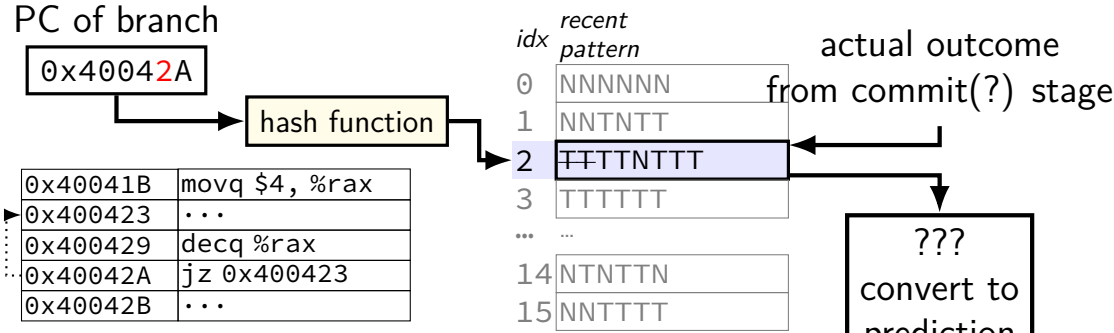
local pattern predictor (incomplete)



4-iter loop: TTTN TTTN TTTN ...

iter.	pattern tbl before	predicted	outcome	pattern tbl after
1	TTTTNT	???	taken	TTTNTT
2	TTTNTT	???	taken	TTNTTT
3	TTNTTT	???	taken	TNTTTT

local pattern predictor (incomplete)



4-iter loop: TTTN TTTN TTTN ...

iter.	pattern tbl before	predicted	outcome	pattern tbl after
1	TTTTNT	???	taken	TTTNTT
2	TTTNTT	???	taken	TTNTTT
3	TTNTTT	???	taken	TNTTTT
4	TNTTTT	???	not taken	NTTTTN

recent pattern to prediction?

easy cases:

just saw TTTTTT: predict T

just saw NNNNNN: predict N

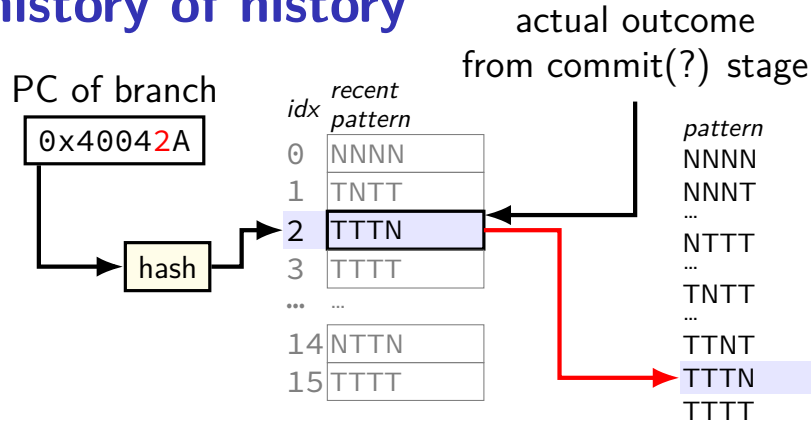
just saw TNTNTN: predict T

hard cases:

TTNTTTT

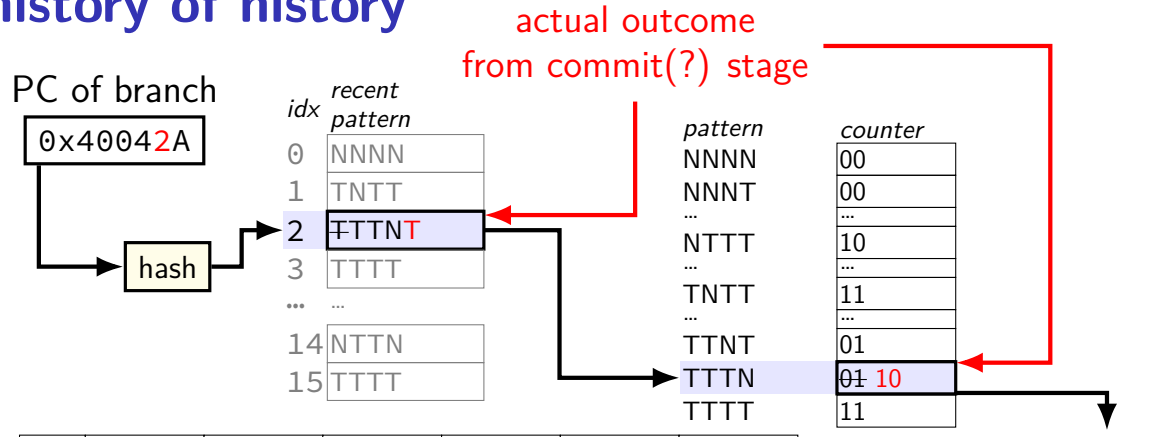
predict T? loop with many iterations
(NTTTTTTTNTTTTTTTNTTTTTT...)
predict T? if statement mostly taken
(TTTTNTTNTTTTTTTTTTNTTTT...)

history of history



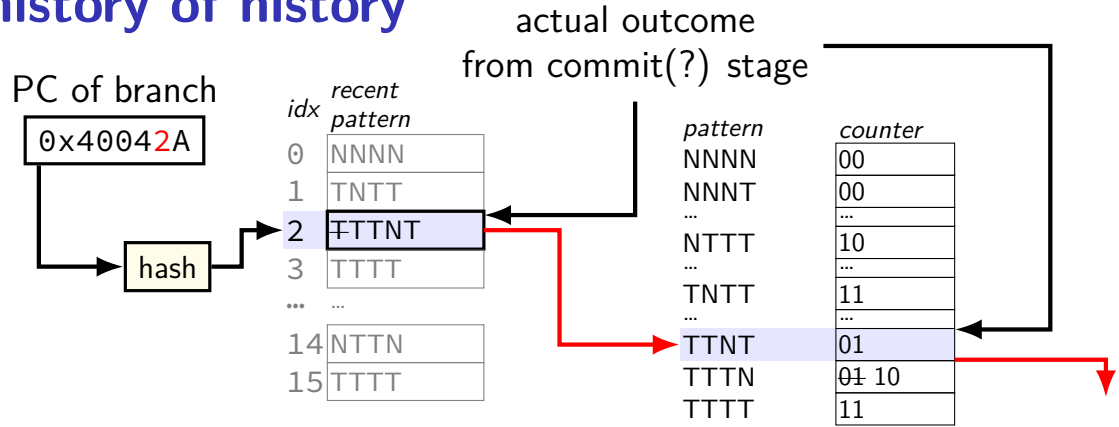
iter.	branch to pat. tbl before	pat. to counter before	predict	actual	pat. to counter after	branch to pat. tbl after
1	TTTN	01	not taken	taken	10	TTNT

history of history



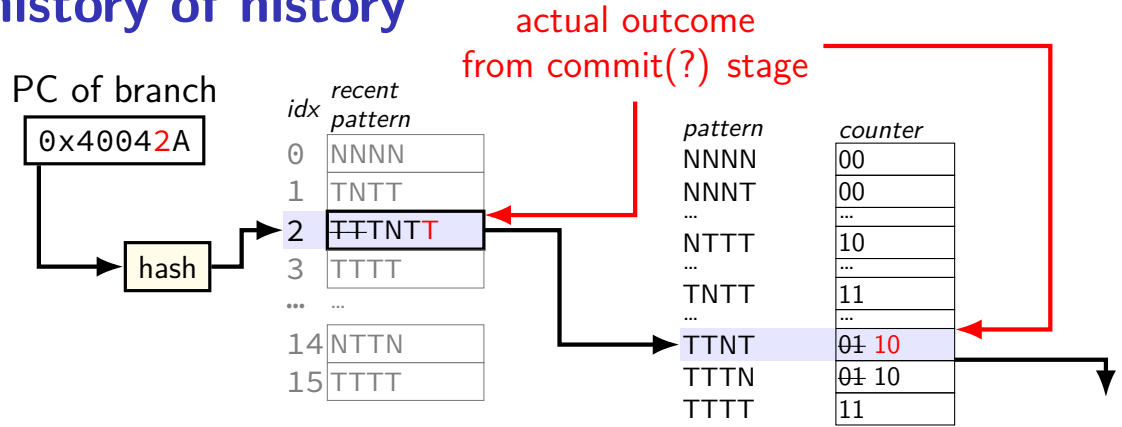
iter.	branch to pat. tbl before	pat. to counter before	predict	actual	pat. to counter after	branch to pat. tbl after
1	TTTN	01	not taken	taken	10	TTNT

history of history



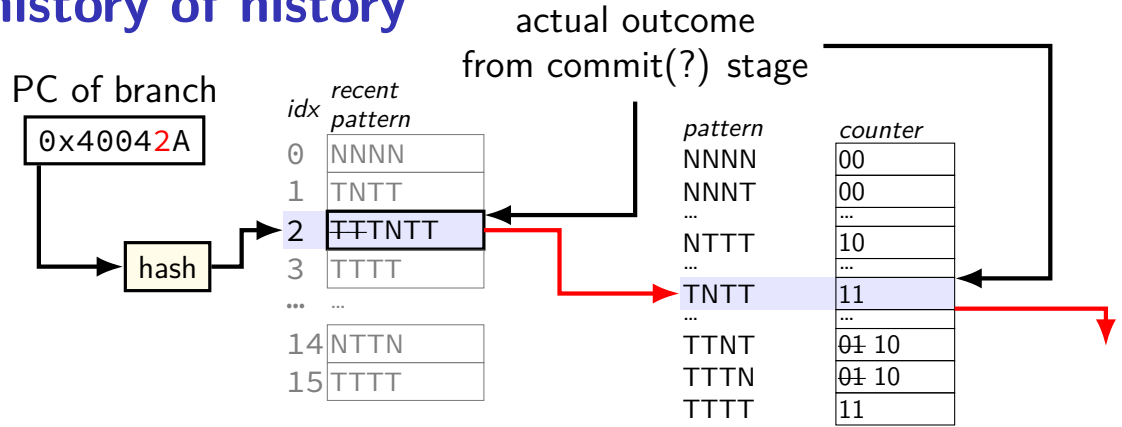
iter.	branch to pat. tbl before	pat. to counter before	predict	actual	pat. to counter after	branch to pat. tbl after
1	TTTN	01	not taken	taken	10	TTNT
2	TTNT	01	not taken	taken	10	TNTT

history of history



iter.	branch to pat. tbl before	pat. to counter before	predict	actual	pat. to counter after	branch to pat. tbl after
1	TTTN	01	not taken	taken	10	TTNT
2	TTNT	01	not taken	taken	10	TNTT

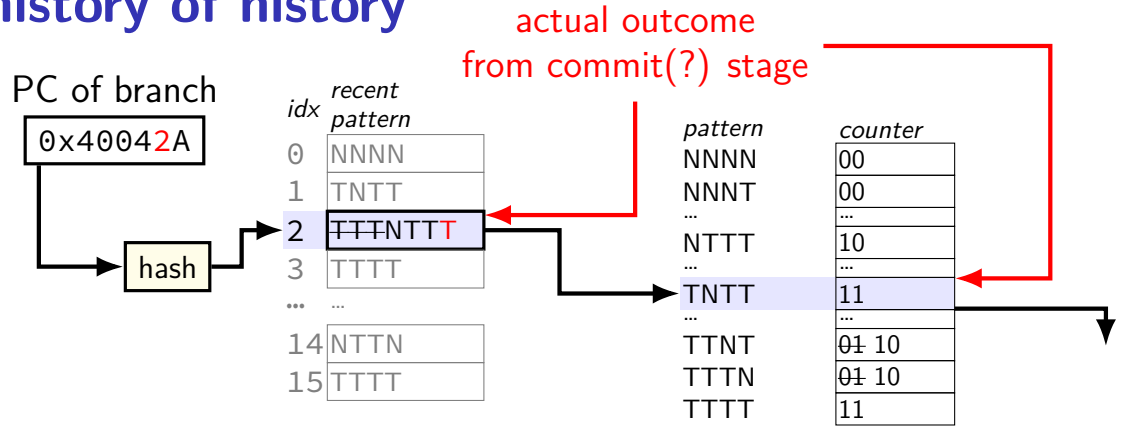
history of history



iter.	branch to pat. tbl before	pat. to counter before	predict	actual	pat. to counter after	branch to pat. tbl after
1	TTTN	01	not taken	taken	10	TTNT
2	TTNT	01	not taken	taken	10	TNTT
3	TNTT	11	taken	taken	11	NTTT

prediction
to fetch sta

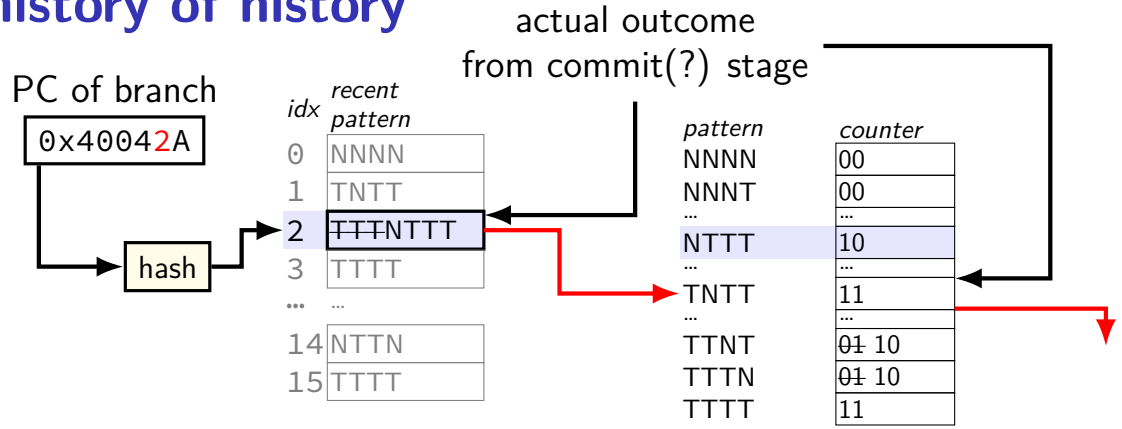
history of history



iter.	branch to pat. tbl before	pat. to counter before	predict	actual	pat. to counter after	branch to pat. tbl after
1	TTTN	01	not taken	taken	10	TTNT
2	TTNT	01	not taken	taken	10	TNTT
3	TNTT	11	taken	taken	11	NTTT

prediction
to fetch sta

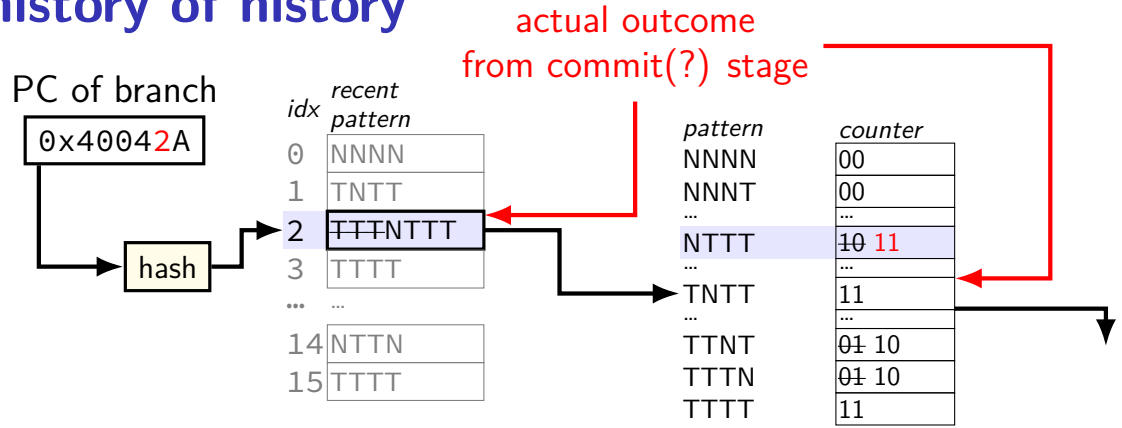
history of history



iter.	branch to pat. tbl before	pat. to counter before	predict	actual	pat. to counter after	branch to pat. tbl after
1	TTTN	01	not taken	taken	10	TTNT
2	TTNT	01	not taken	taken	10	TNTT
3	TNTT	11	taken	taken	11	NTTT

prediction
to fetch sta

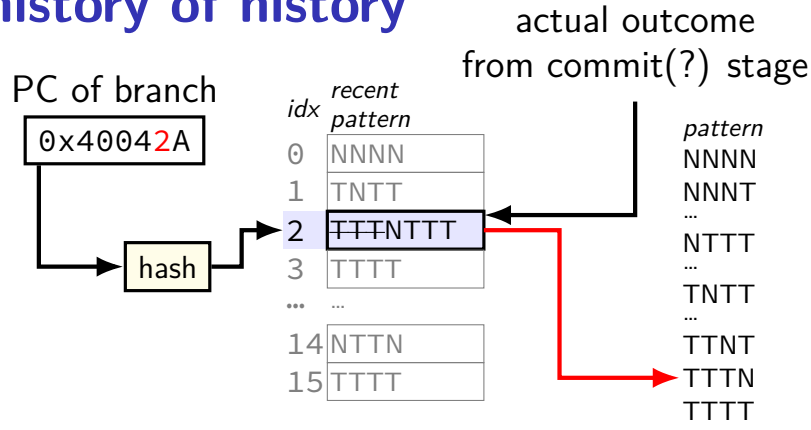
history of history



iter.	branch to pat. tbl before	pat. to counter before	predict	actual	pat. to counter after	branch to pat. tbl after
1	TTTN	01	not taken	taken	10	TTNT
2	TTNT	01	not taken	taken	10	TNTT
3	TNTT	11	taken	taken	11	NTTT
4	NTTT	01	taken	taken	11	TTTT

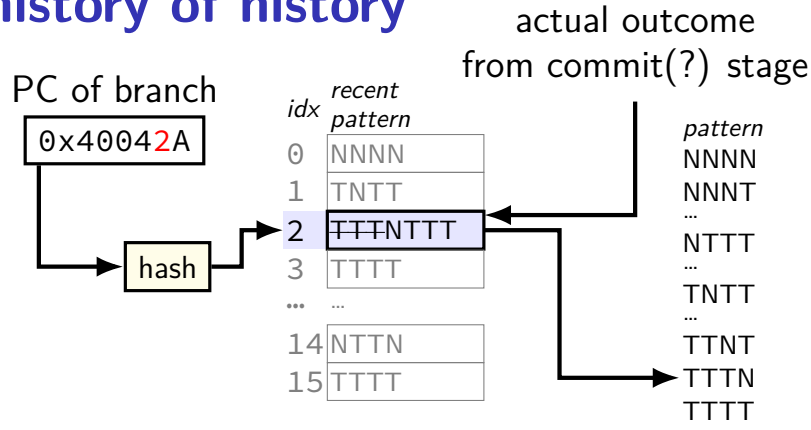
prediction
to fetch sta

history of history



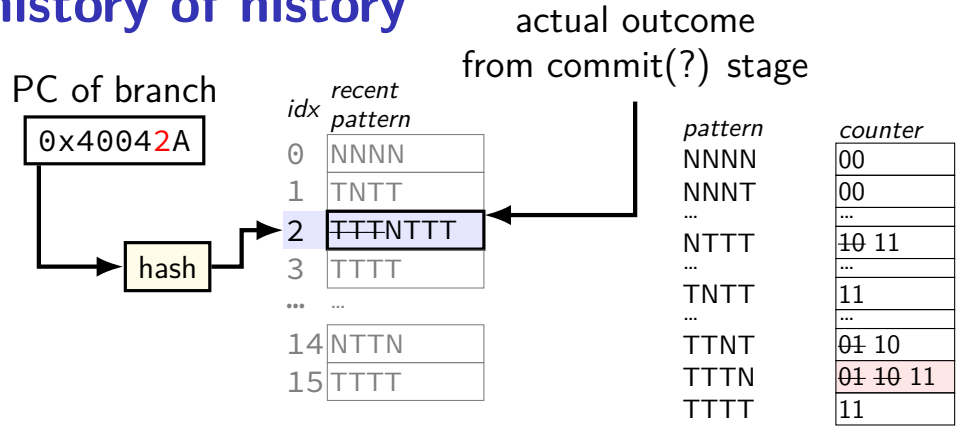
iter.	branch to pat. tbl before	pat. to counter before	predict	actual	pat. to counter after	branch to pat. tbl after
1	TTTN	01	not taken	taken	10	TTNT
2	TTNT	01	not taken	taken	10	TNTT
3	TNTT	11	taken	taken	11	NTTT

history of history



iter.	branch to pat. tbl before	pat. to counter before	predict	actual	pat. to counter after	branch to pat. tbl after
1	TTTN	01	not taken	taken	10	TTNT
2	TTNT	01	not taken	taken	10	TNTT
3	TNTT	11	taken	taken	11	NTTT

history of history



iter.	branch to pat. tbl before	pat. to counter before	predict	actual	pat. to counter after	branch to pat. tbl after
1	TTTN	01	not taken	taken	10	TTNT
2	TTNT	01	not taken	taken	10	TNTT
3	TNTT	11	taken	taken	11	NTTT

predictior
to fetch sta

local patterns and collisions (1)

```
i = 10000;
do {
    p = malloc(...);
    if (p == NULL) goto error;  // BRANCH 1
    ...
} while (i-- != 0); // BRANCH 2
```

---

what if branch 1 and branch 2 hash to same table entry?

local patterns and collisions (1)

```
i = 10000;
do {
    p = malloc(...);
    if (p == NULL) goto error;  // BRANCH 1
    ...
} while (i-- != 0); // BRANCH 2
```

---

what if branch 1 and branch 2 hash to same table entry?

pattern: TNTNTNTNTNTNTNTNT...

actually no problem to predict!

local patterns and collisions (2)

```
i = 10000;
do {
    if (i % 2 == 0) goto skip; // BRANCH 1
    ...
    p = malloc(...);
    if (p == NULL) goto error;  // BRANCH 2
skip: ...
} while (i-- != 0); // BRANCH 3
```

what if branch 1 and branch 2 and branch 3 hash to same table entry?

local patterns and collisions (2)

```
i = 10000;
do {
    if (i % 2 == 0) goto skip; // BRANCH 1
    ...
    p = malloc(...);
    if (p == NULL) goto error;  // BRANCH 2
skip: ...
} while (i-- != 0); // BRANCH 3
```

---

what if branch 1 and branch 2 and branch 3 hash to same table entry?

pattern: TTNNTTNNTTNNTTNNTT

also no problem to predict!

local patterns and collisions (3)

```
i = 10000;
do {
    if (A) goto one  // BRANCH 1
    ...
one:
    if (B) goto two  // BRANCH 2
    ...
two:
    if (A or B) goto three // BRANCH 3
    ...
    if (A and B) goto three // BRANCH 4
    ...
three:
    ... // changes A, B
} while (i-- != 0);
```

what if branch 1-4 hash to same table entry?

better for prediction of branch 2 and 4

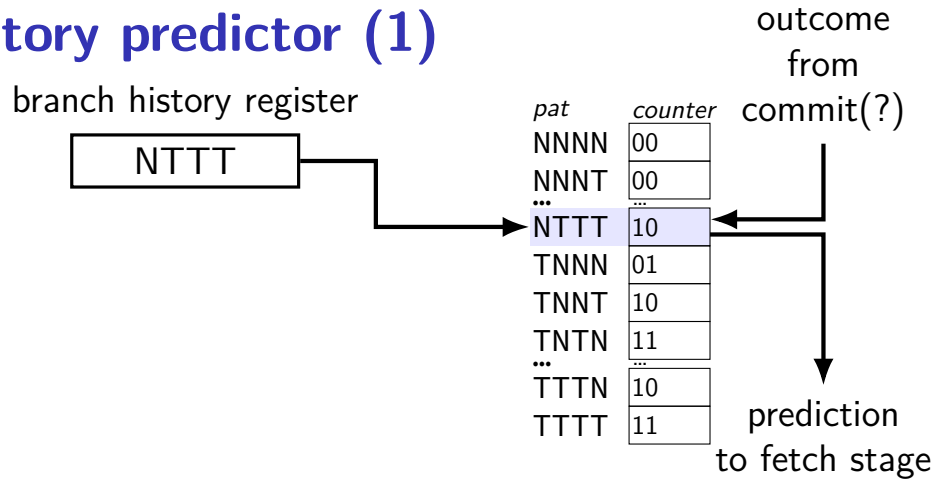
global history predictor: idea

one predictor idea: ignore the PC

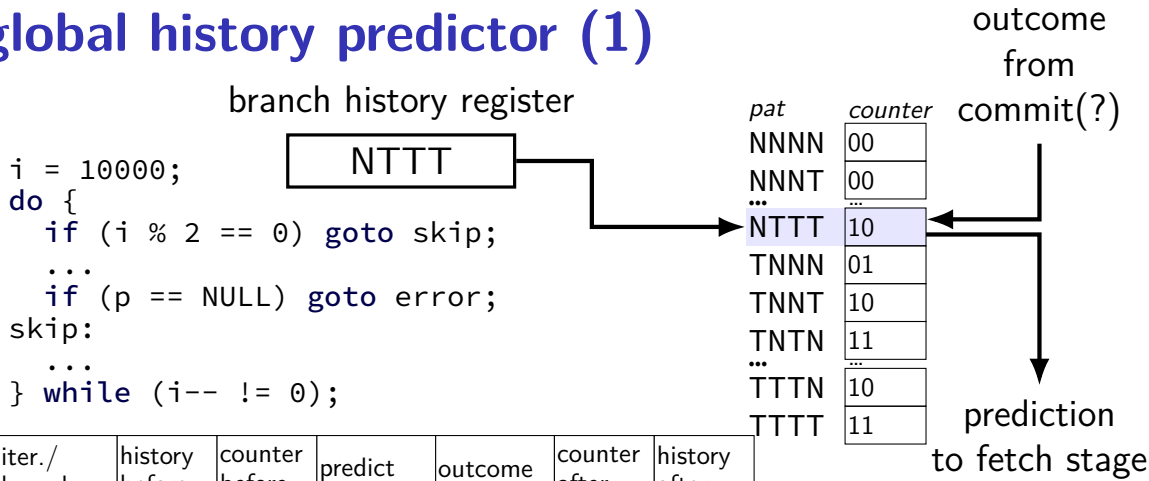
just record taken/not-taken pattern for all branches

lookup in big table like for local patterns

global history predictor (1)



global history predictor (1)

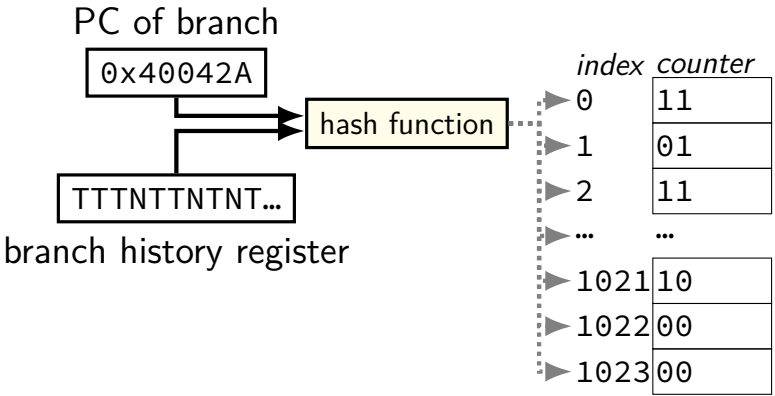


iter./ branch	history before	counter before	predict	outcome	counter after	history after
0/mod 2	NTTT	10	taken	taken	11	TTTT
0/loop	TTTT			taken		TTTT
1/mod 2	TTTT			not taken		TTTN
1/error	TTTN			not taken		TTNN
1/loop	TNNT			taken		NNTT

correlating predictor

global history *and* local info good together

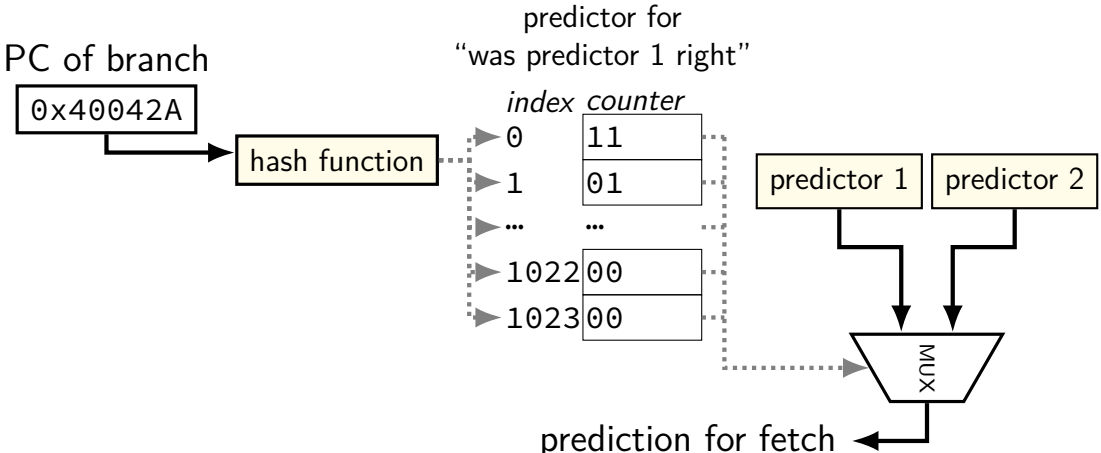
one idea: combine history register + PC ("gshare")



mixing predictors

different predictors good at different times

one idea: have two predictors, + predictor to predict which is right



loop count predictors (1)

```
for (int i = 0; i < 64; ++i)
    ...
```

can we predict this perfectly with predictors we've seen

yes — local or global history with 64 entries

but this is very important — more efficient way?

loop count predictors (2)

loop count predictor idea: look for NNNNNNT+repeat (or TTTTTTN+repeat)

track for each possible loop branch:

- how many repeated Ns (or Ts) so far
- how many repeated Ns (or Ts) last time before one T (or N)
- something to indicate this pattern is useful?

known to be used on Intel

benchmark results

from 1993 paper

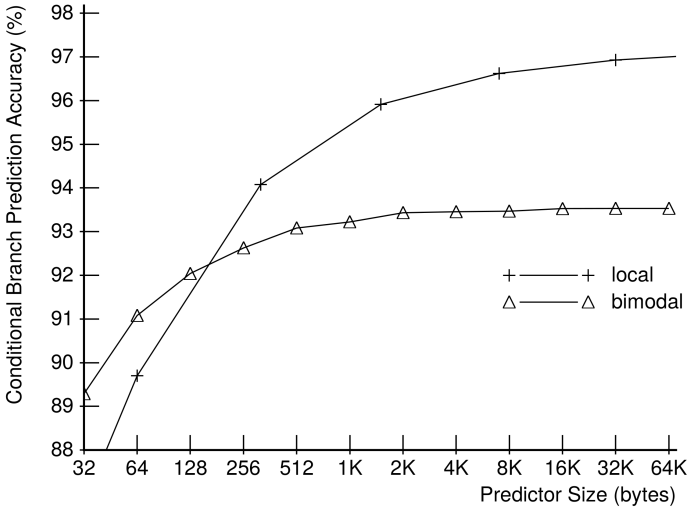
(not representative of modern workloads?)

rate for conditional branches on benchmark

variable table sizes

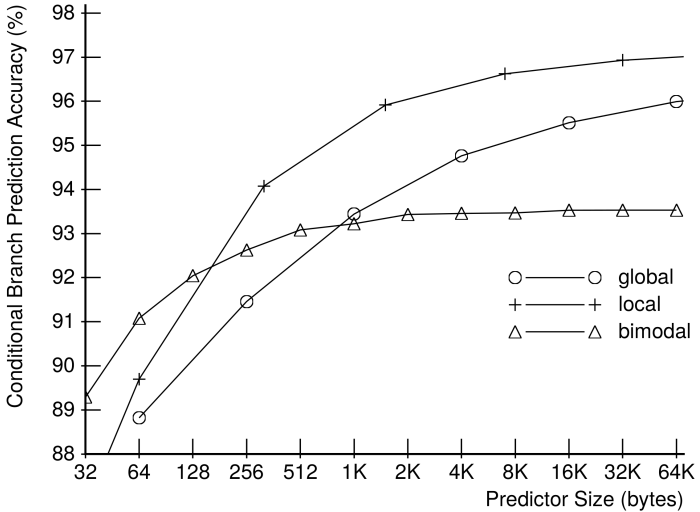
2-bit ctr + local history

from McFarling, "Combining Branch Predictors" (1993)



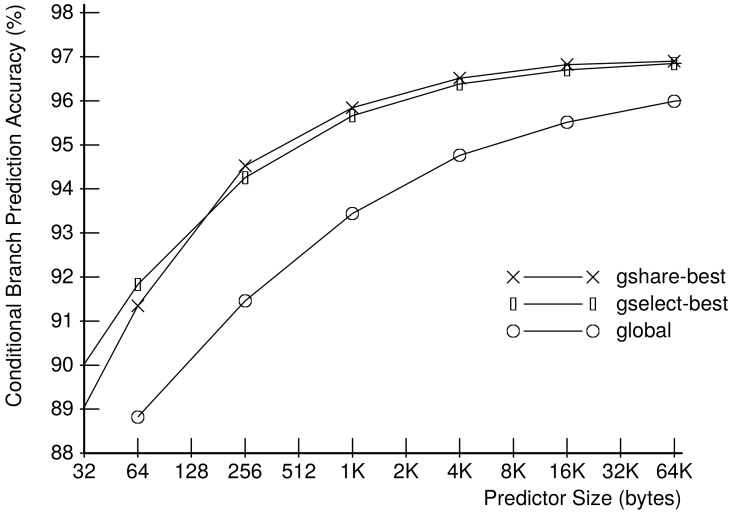
2-bit (bimodal) + local + global hist

from McFarling, "Combining Branch Predictors" (1993)



global + hash(global+PC) (gshare/gselect)

from McFarling, "Combining Branch Predictors" (1993)



real BP?

details of modern CPU's branch predictors often not public

but...

Google Project Zero blog post with reverse engineered details

https://googleprojectzero.blogspot.com/2018/01/reading-privileged-memory-with-side.html

for RE'd BTB size:

https://xania.org/201602/haswell-and-ivy-btb

reverse engineering Haswell BPs

branch target buffer

- 4-way, 4096 entries
- ignores bottom 4 bits of PC?
- hashes PC to index by shifting + XOR
- seems to store 32 bit offset from PC (not all 48+ bits of virtual addr)

indirect branch predictor

- like the global history + PC predictor we showed, but...
- uses history of recent branch addresses instead of taken/not taken
- keeps some info about last 29 branches

what about conditional branches??? loops???

- couldn't find a reasonable source

backup slides

backup slides

exercise: static prediction

```
.global foo
foo:
    xor %eax, %eax // eax <- 0
foo_loop_top:
    test $0x1, %edi
    je foo_loop_bottom  // if (edi & 1 == 0) goto for_loop_bottom
    add %edi, %eax
foo_loop_bottom:
    dec %edi             // edi = edi - 1
    jg for_loop_top // if (edi > 0) goto for_loop_top
    ret
```

suppose %edi = 3 (initially)

and using forward-not-taken, backwards-taken strategy:

how many mispreditions for je? for jg?