BranchSpec: Information Leakage Attacks Exploiting Speculative Branch Instruction Executions

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Background

- ❖ Security issues of speculation are raising critical concerns.
- ❖ Microarchitectural state changes remain beyond speculation.
- ❖ Unintended data could be exfiltrated via side channels.
  - E.g., Spectre and Meltdown.
  - Demonstrated using Cache, TLB and function units.

Motivation

- ❖ Branch predictor unit (BPU) is one of the most critical components
- ❖ BPU is used to trigger mis-speculation in transient execution attacks
- ❖ BPU can transfer secret in non-speculative domain (e.g., BranchScope[1])

1. BranchScope: A New Side-Channel Attack on Directional Branch Predictor, ASPLOS’2018

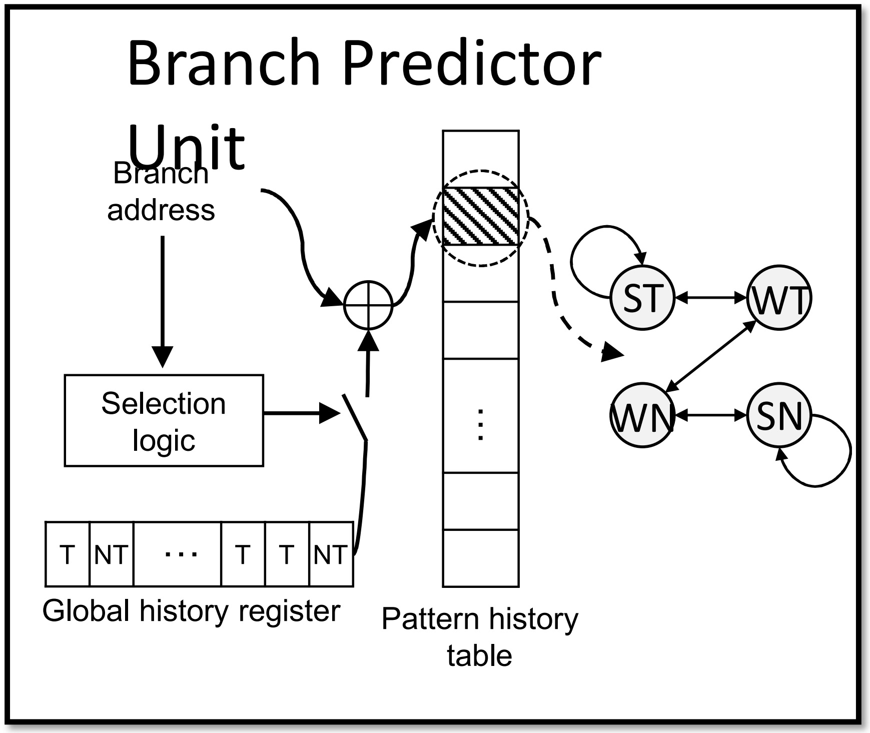
Motivation

- ❖ Branch predictor unit (BPU) is one of the most critical components
- ❖ BPU is used to trigger mis-speculation in transient execution attacks
- ❖ BPU can transfer secret in non-speculative domain (e.g., BranchScope[1])

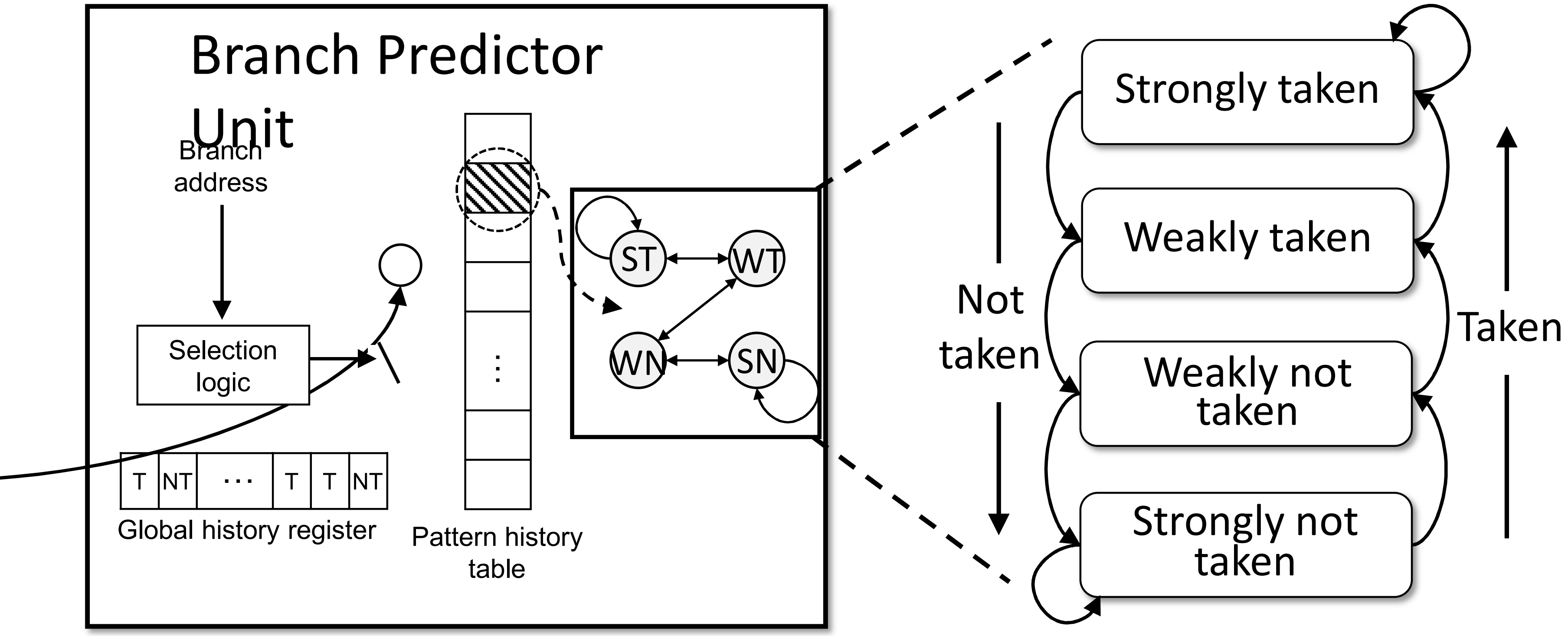
- ❖ Can we use branch predictor as **transmitting medium** in transient execution domain?

1. BranchScope: A New Side-Channel Attack on Directional Branch Predictor, ASPLOS'2018

Modern Branch Predictor Architecture



Modern Branch Predictor Architecture



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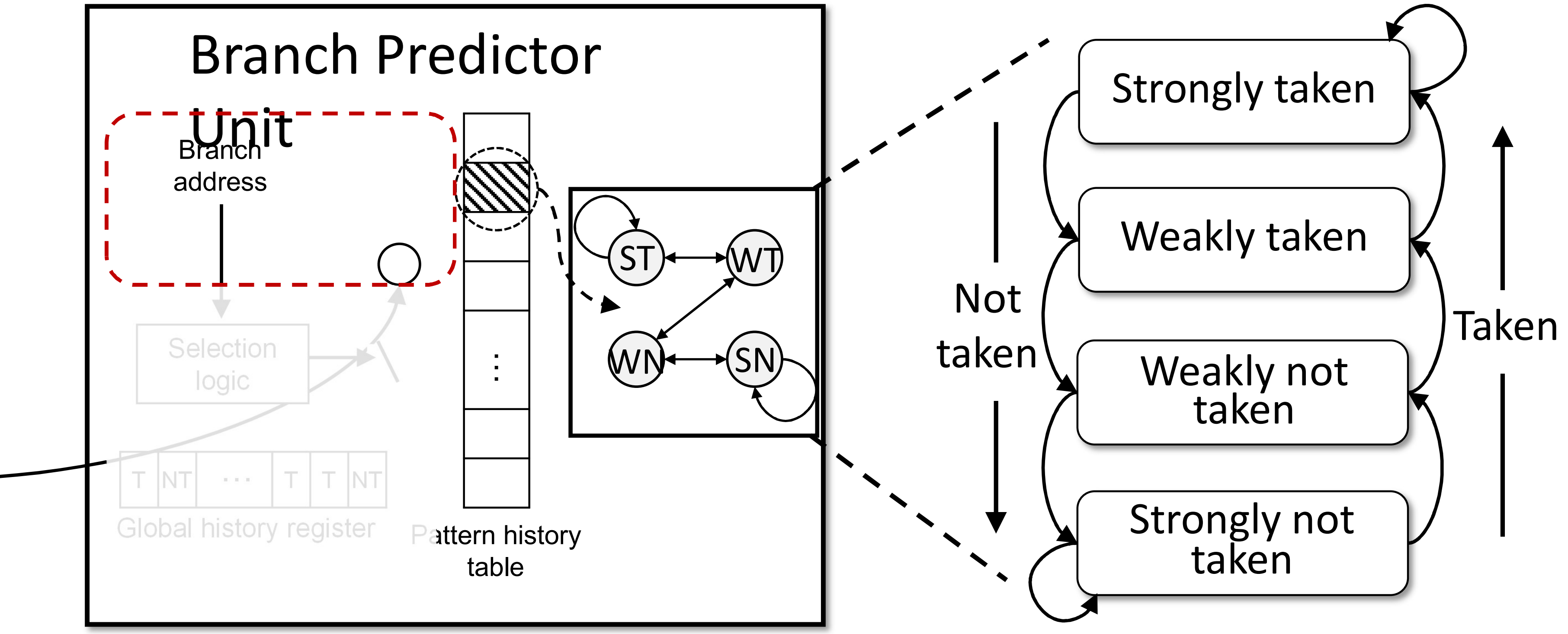

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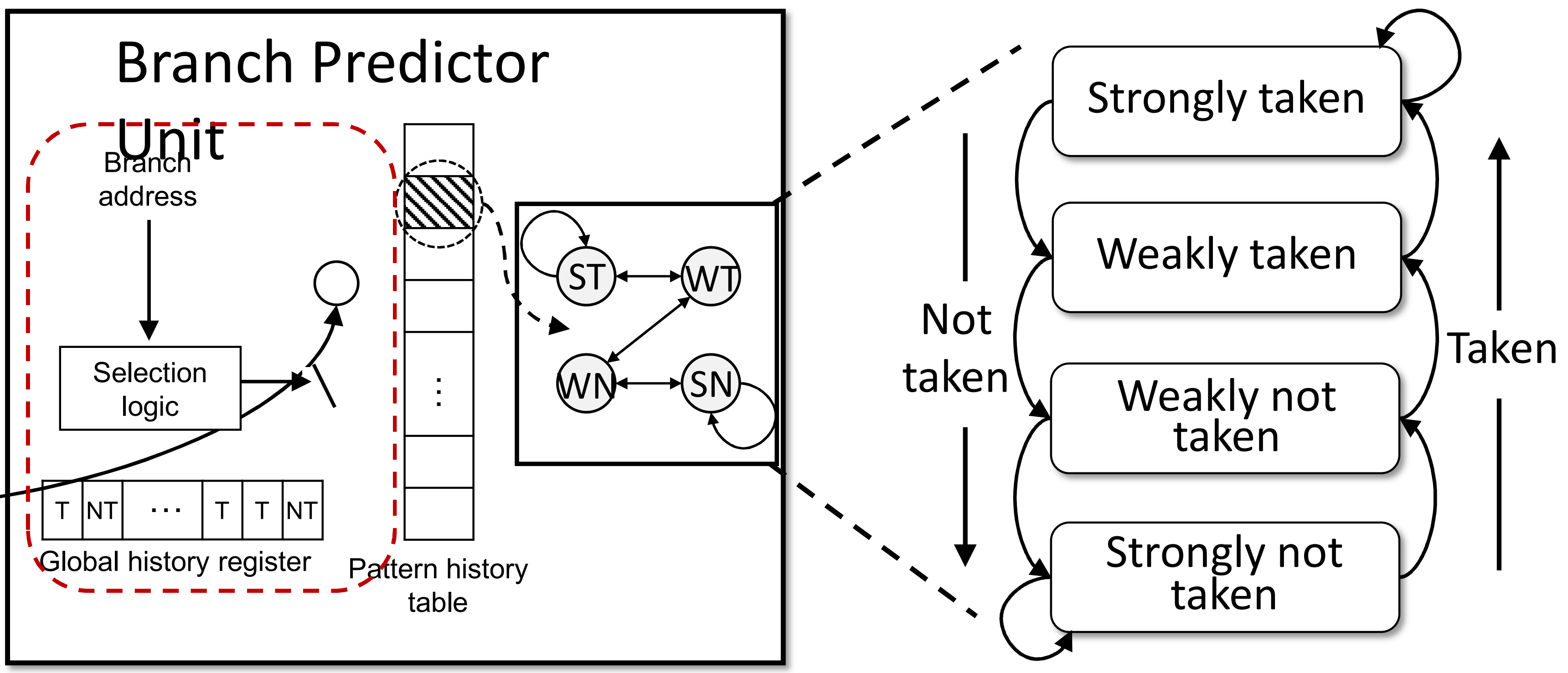
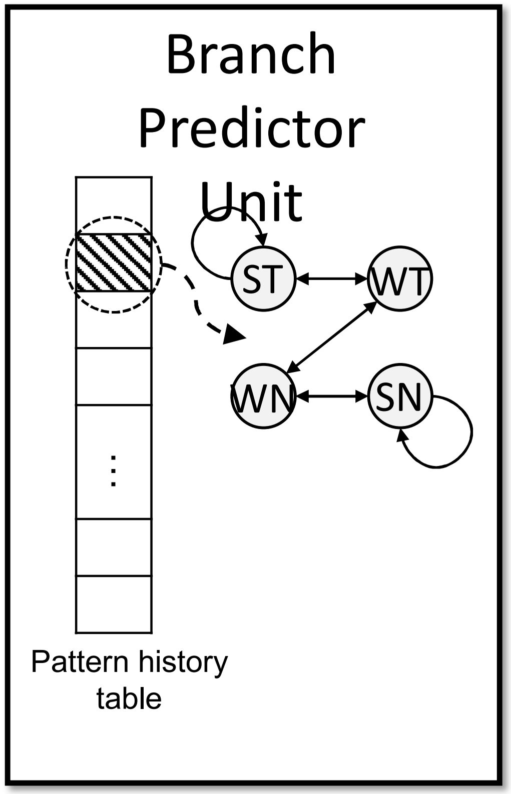


Do PHT Changes Remain After Speculation?



```
  bool control;
① if (i < bound)
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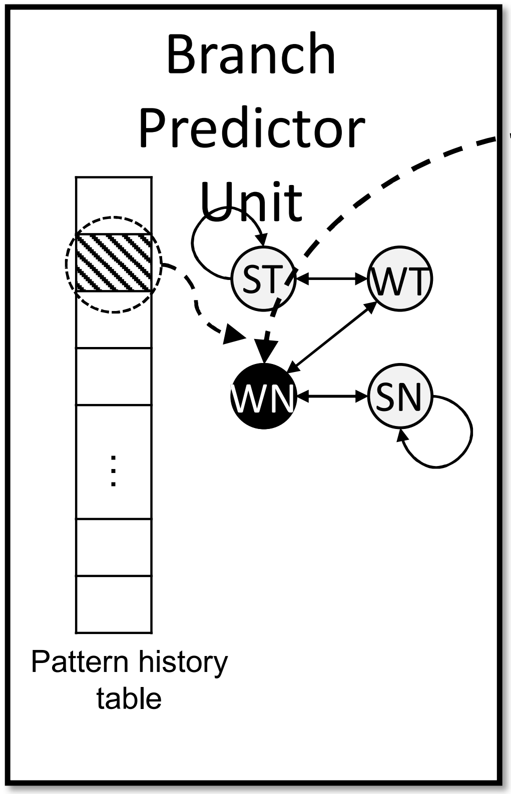
      <some_operations>;
```

Do PHT Changes Remain After Speculation?



1. *Initialize {not-taken}* the PHT state

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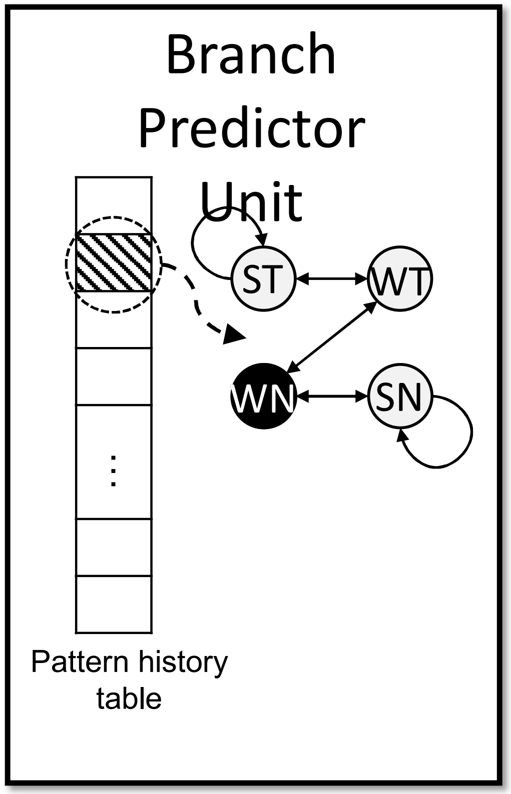

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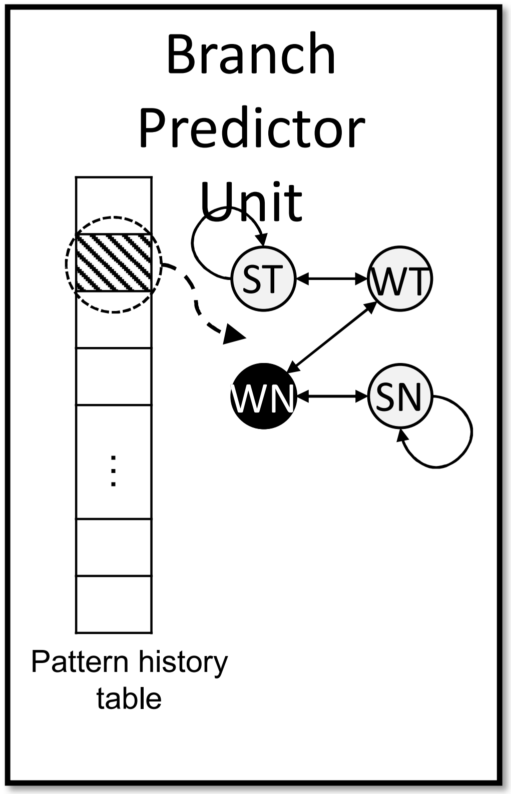

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2. Trigger ***speculation***

```
   bool control;
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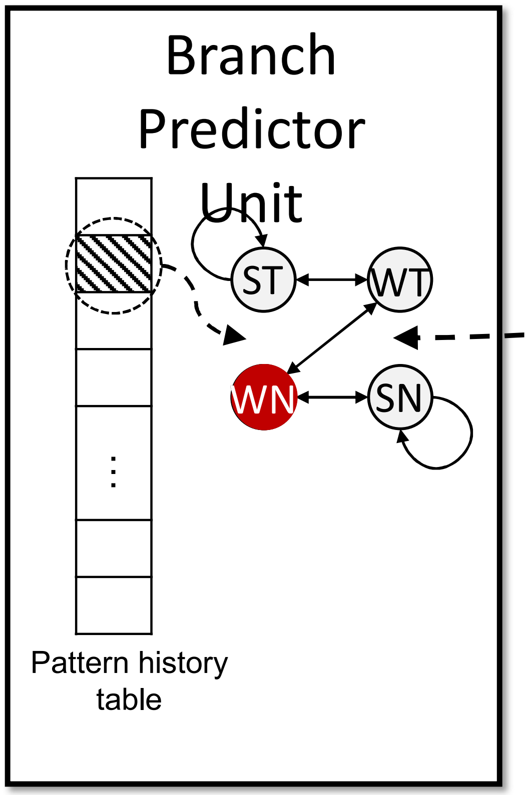
        <some_operat
```

Start of ***Speculation***

Speculative Execution

Do PHT Changes Remain After Speculation?



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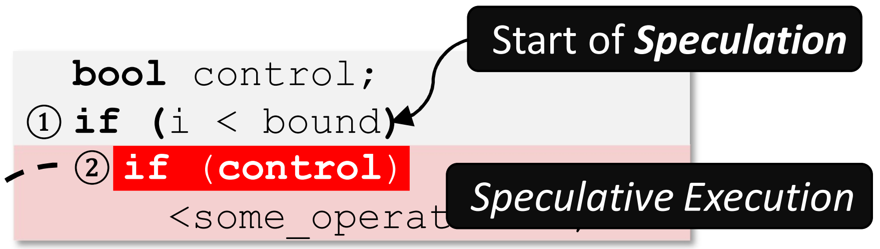

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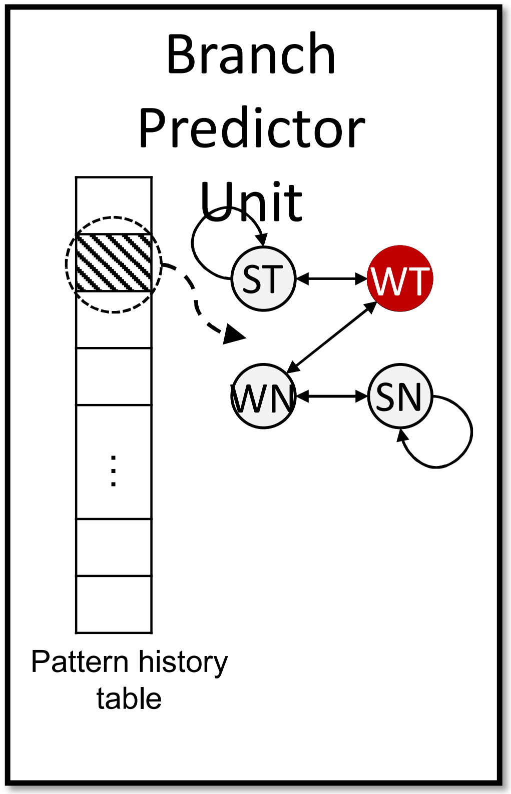

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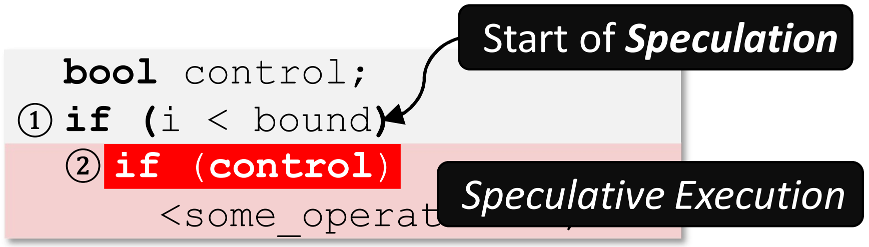

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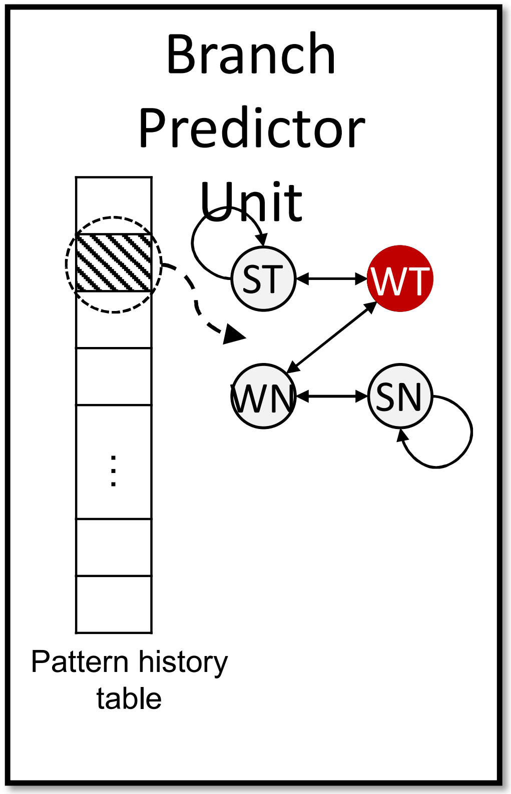

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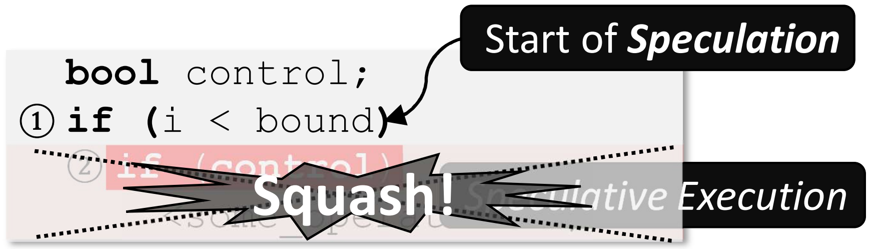
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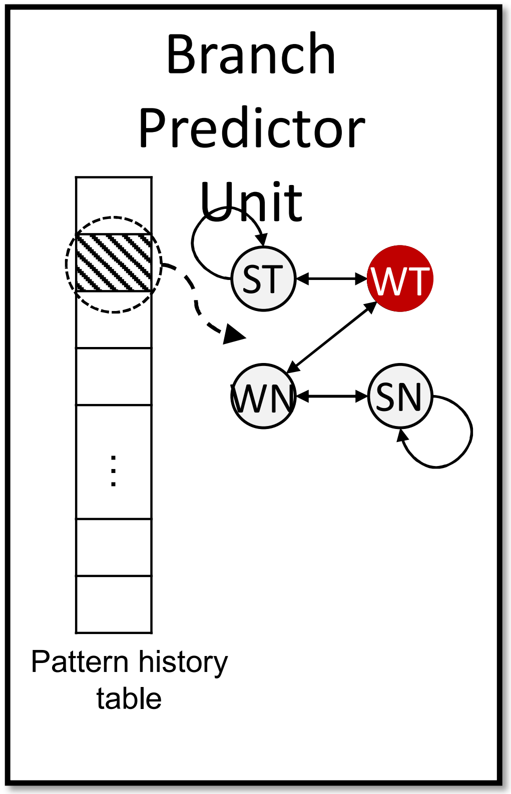

1. ***Initialize {not-taken}*** the PHT state

2. Trigger ***speculation***

3. Measure execution time ***{taken}***

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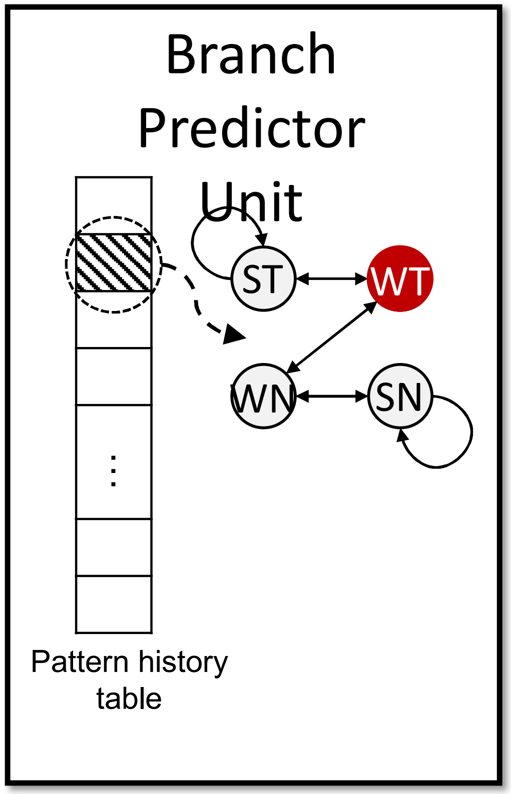

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2. Trigger ***speculation***

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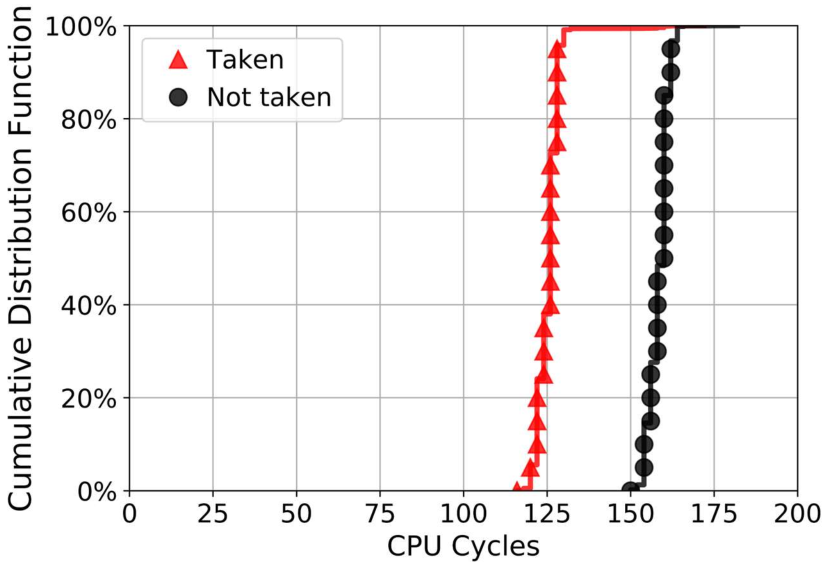
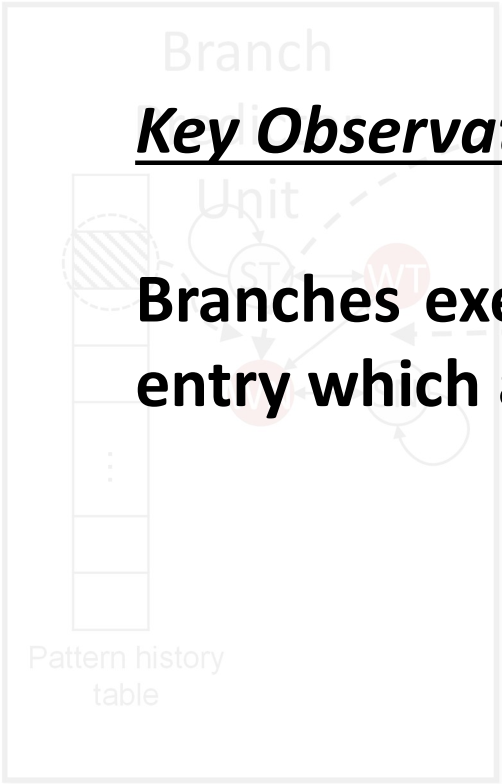


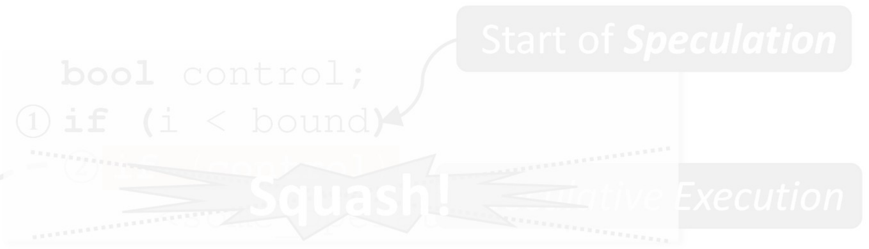
Figure 1: Execution time of branch ② in step 3 for different outcome of the branch in step 2.

Do PHT Changes Remain After Speculation?



1. ***Initialize {not-taken}*** the PHT state

Key Observation:



```
bool control;
① if (i < bound)
```

Branches executed in the speculative path change PHT entry which are not restored in case of mis-speculation.

3. Measure execution time ***{taken}***

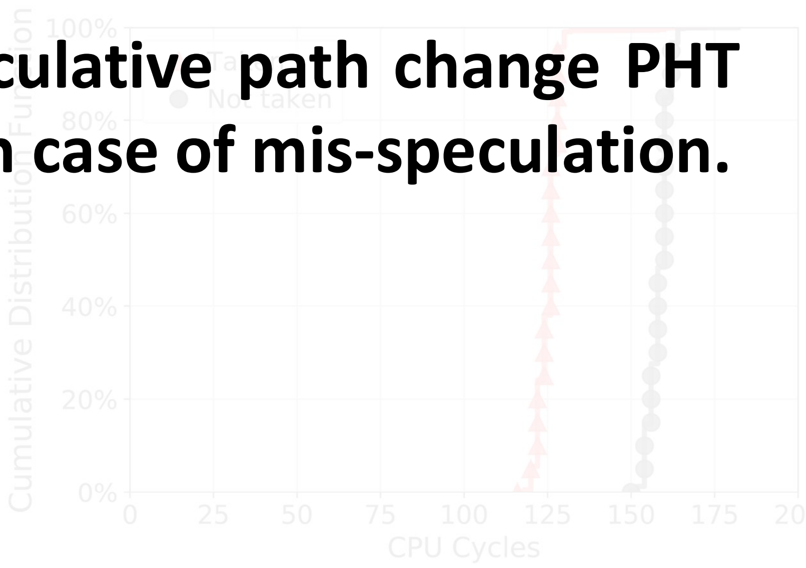


Figure 1: Execution time of branch ② in step 3 for different outcome of the branch in step 2

BranchSpec: Side Channel Attack

Victim

```
// Parent branch
if (x < bound)
  ....
  ....
  // Victim branch, b_V
  if (array1[x])
    <some_operations>;
```

BranchSpec: Side Channel Attack

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// Parent branch
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BranchSpec: Side Channel Attack

Step 1: Preset PHT entry (PHT_v) of victim branch (b_v)

- Attacker uses a **congruent branch** of b_v (i.e., b_a)
- Executes b_a twice with *taken* outcome

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// Parent branch
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BranchSpec: Side Channel Attack

Step 1: Preset PHT entry (PHT$_v$) of victim branch (b$_v$)

- Attacker uses a **congruent branch** of b$_v$ (i.e., b$_a$)
- Executes b$_a$ twice with *taken* outcome

Victim

```
// Parent branch
if (x < bound)
  ....
  ....
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  if (array1[x])
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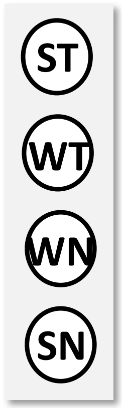

Initial state (PHT$_v$)

BranchSpec: Side Channel Attack

Step 1: Preset PHT entry (PHT_V) of victim branch (b_V)

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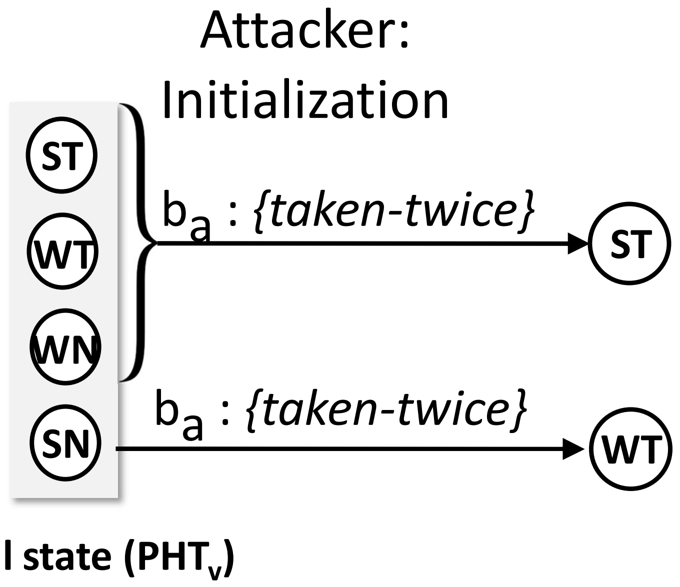

BranchSpec: Side Channel Attack

Step 2: Victim executes b_V **speculatively**

Victim

```
// Parent branch
if (x < bound)
  ....
  ....
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  if (array1[x])
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Step 2: Victim executes b_V **speculatively**

- Attacker can trigger mis-speculation of parent branch using congruent branch

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BranchSpec: Side Channel Attack

Step 2: Victim executes b_v **speculatively**

- Attacker can trigger mis-speculation of parent branch using congruent branch
- PHT entry of victim branch (PHT_v) is updated based on b_v outcome

Victim

```
// Parent branch
if (x < bound)
   ....
   ....
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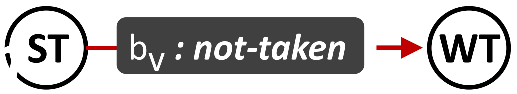
// Parent branch
if (x < bound)
   ....
   ....
   // Victim branch, bV
   if (array1[x])
     <some_operations>;
```

Victim b_V
Speculative execution

b_V resolved as ***Not take***



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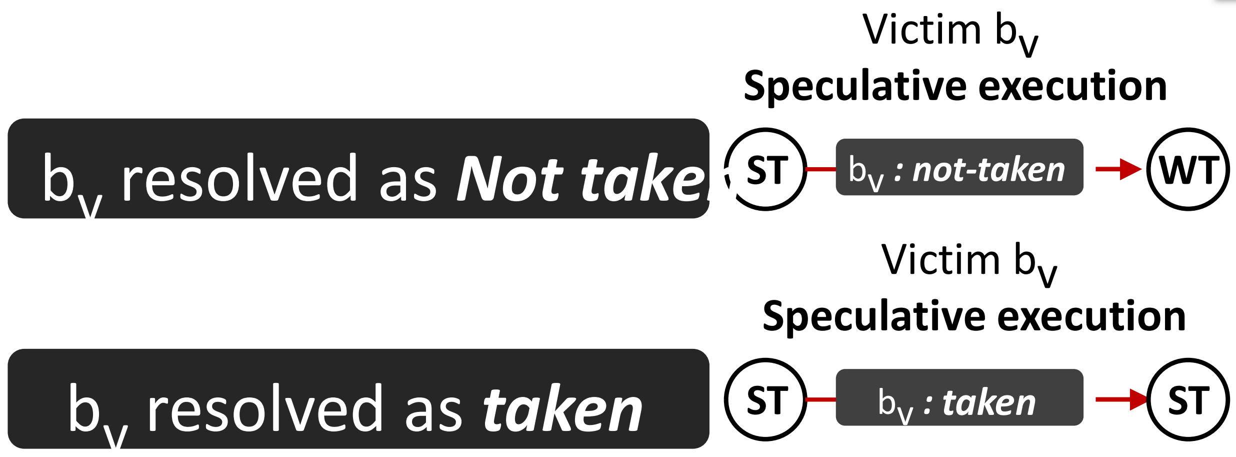


BranchSpec: Side Channel Attack

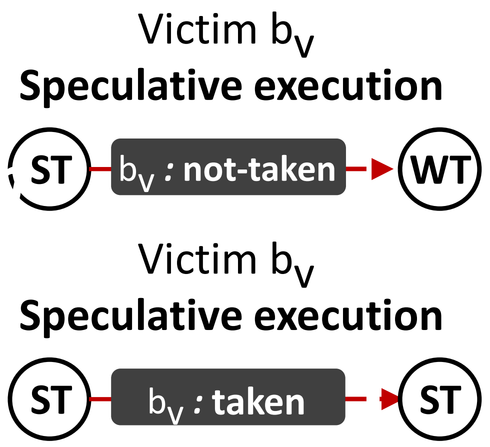
Step 3: Attacker probes PHT_v to infer b_v outcome

Victim

```
// Parent branch, bv0
if (x < bound)
   ....
   ....
   // Victim branch, bv
   if (array1[x])
     <some_operations>;
```

b_v resolved as ***Not take***

b_v resolved as ***taken***



BranchSpec: Side Channel Attack

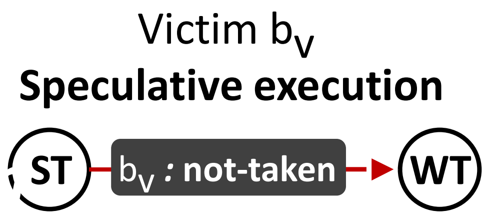
Step 3: Attacker probes PHT_V to infer b_V outcome

- Execute b_a twice with ***not taken*** outcome

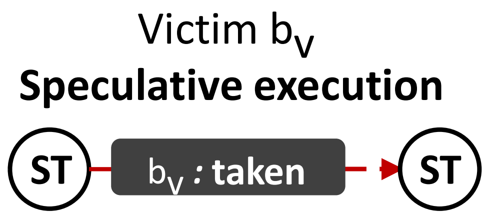
Victim

```
// Parent branch, b_v0
if (x < bound)
    ....
    ....
    // Victim branch, b_v
    if (array1[x])
      <some_operations>;
```

b_V resolved as ***Not take***



b_V resolved as ***taken***



BranchSpec: Side Channel Attack

Victim

```
// Parent branch, b_v0
if (x < bound)
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  ....
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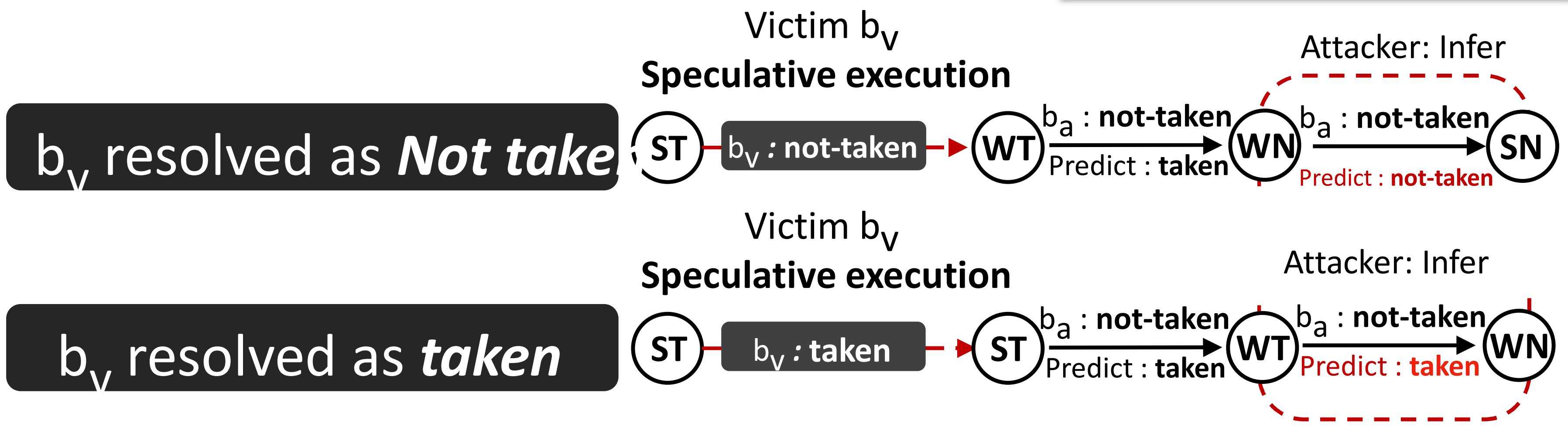
```

Step 3: Attacker probes PHT_v to infer b_v outcome

- Execute b_a twice with ***not taken*** outcome



BranchSpec: Side Channel Attack

Step 3: Attacker probes PHT_v to infer b_v outcome

- Execute b_a twice with ***not taken*** outcome
- Measure execution time of **second** execution

Victim

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// Parent branch, b_v0
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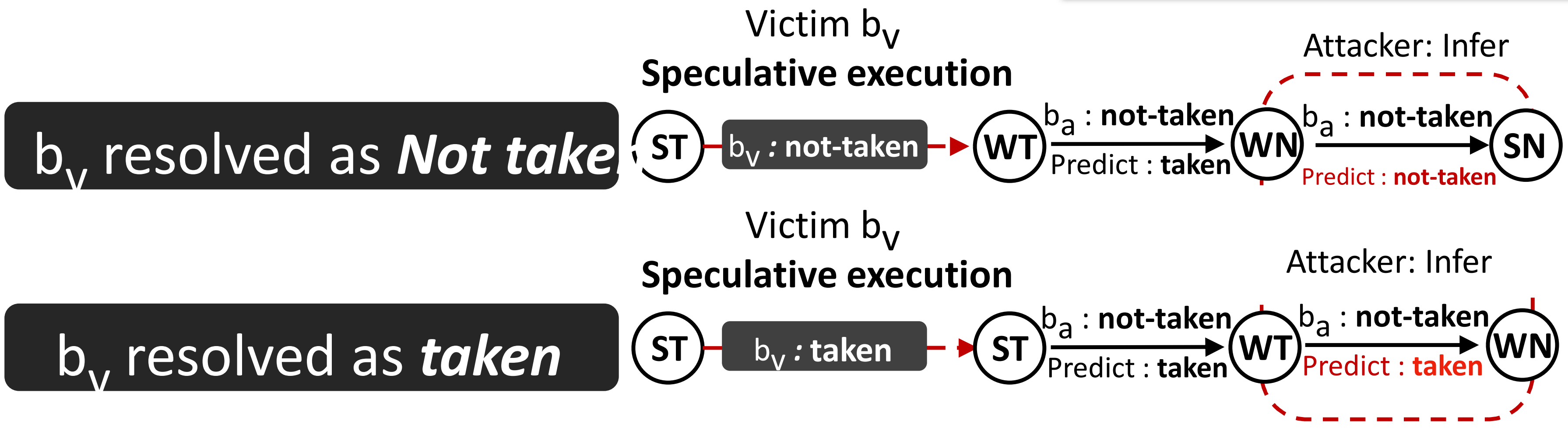
    ....
    ....
    // Victim branch, b_v
    if (array1[x])
      <some_operations>;
```



BranchSpec: Side Channel Attack

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```
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// Victim branch, b_v
if (array1[x])
  <some_operations>;
```

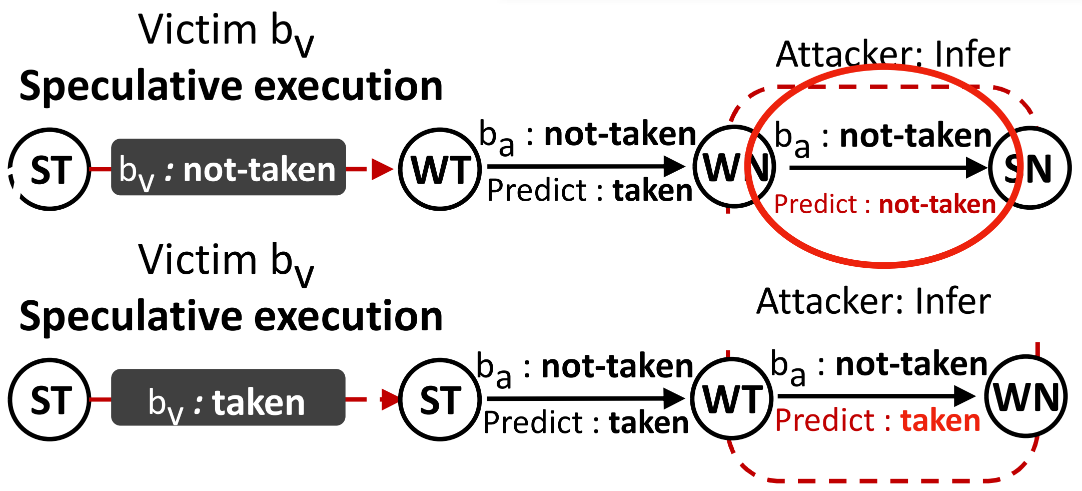
Step 3: Att

- Execute b_a twice with ***not taken*** outcome
- Measure execution time of **second** execution

Correct prediction of b_a -> Shorter execution time

b_v resolved as ***Not take***

b_v resolved as ***taken***



BranchSpec: Side Channel Attack

Victim

```
// Parent branch, b_v0
    ....
// ...anch, b_v
    <some_operations>;
```

Step 3: Att

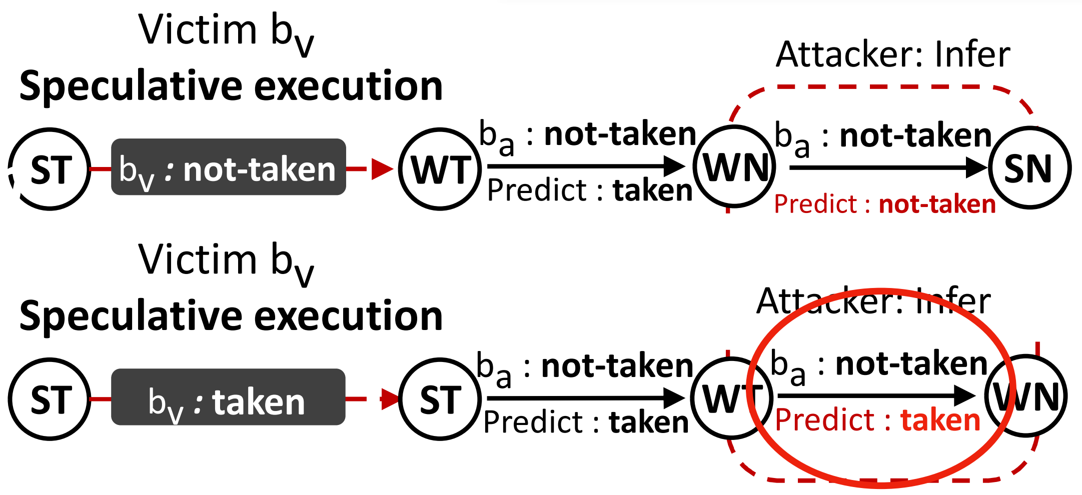
- Execute b_a twice with *not taken* outcome
- Measu

Correct prediction of b_a -> Shorter execution time

Mis-prediction of b_a -> Longer execution

b_v resolved as ***Not taken***

b_v resolved as ***taken***



Results and Characteristics of BranchSpec

- First work to show information leakage via branch predictor in transient execution attacks
  - Implemented on processors **with and w/o SMT**
  - Bit error rate is less than **4%**
  - Potentially targeted applications: **Crypto algorithms, image processing** and **ML programs**

- Enables even stronger attack capabilities
  - Completely uses BPU for end-to-end attack
  - Utilizes more common code patterns than Spectre V1

Spectre V1 Gadgets

```
if (x < array1_size)
  y = array2(array1[x] * 4096);
```

BranchSpec Gadgets

```
if (x < bound)
  if (array1[x])    // b_V
    <some_operations>;
```

```
if (x < bound)
  for (i = 0; i < bound; i++)
    if (array1[x + i]) // b_V
      <some_operations>;
```

```
for (i = x; i < bound; i++)
  if (array1[i]) // b_V
    <some_operations>;
```

BranchSpec: Covert Channel Attack

- Covert channel using BranchSpec
  - With optimizations, 131 Kbps transmission rate within 3.7% error rate

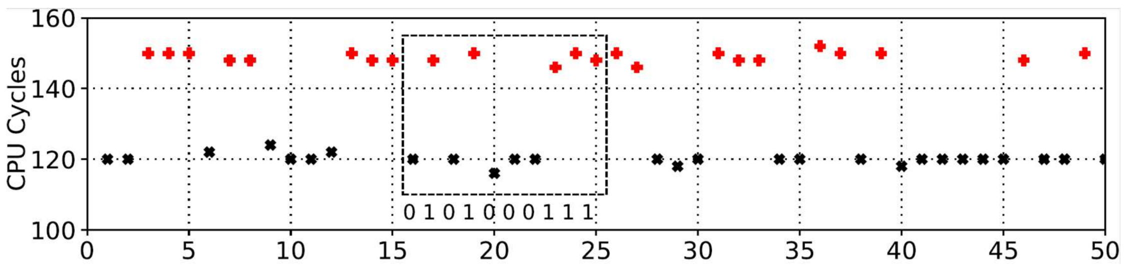


Figure 3: Latency traces for a 50-bit transmission by Spy corresponding to the covert channel in Figure 2.

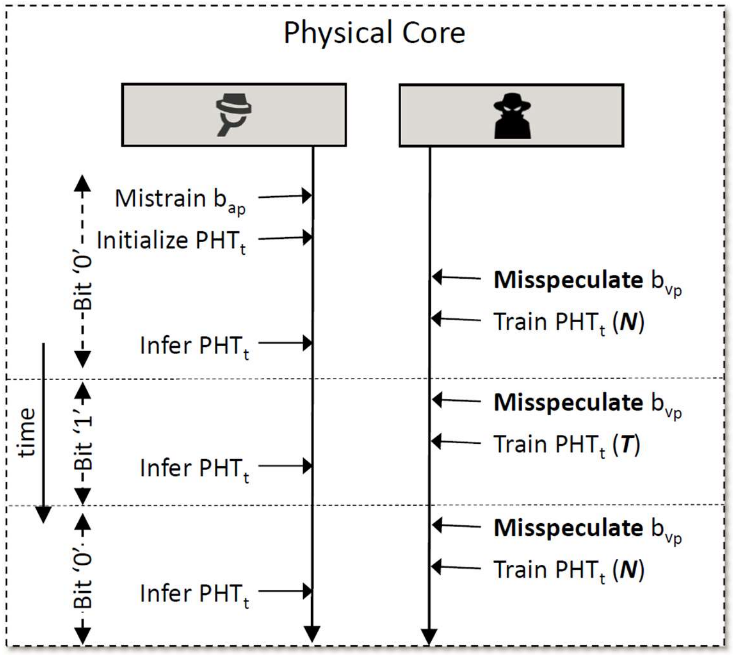


Figure 2: Illustration of BranchSpec covert channel protocol.

Potential Mitigations

- Existing system level defenses are ineffective
  - E.g., Retpoline, IBRS and others
- Potential architecture level mitigations
  - Restoring states for transient branches
  - Delaying PHT update
  - Enabling invisible PHT entry update

Conclusion

- Branches executed in speculation change PHT states, which are not restored after transient execution finishes.
- The vulnerability allows BPU to be used as *transmitting medium* in transient execution attacks.
- We demonstrate new forms of side and covert channels exploiting the discovered threat.
- We discuss potential mitigations to secure branch executions in speculative domain.

Thanks! Questions?

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Email: reyad@knights.ucf.edu

Source code available: https://github.com/fanyao/branchspec