Breaking and Fixing Speculative Load Hardening

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Outline

Zhiyuan Zhang, Gilles Barthe, Chitchanok Chuengsatiansup, Peter Schwabe, Yuval Yarom, “Breaking and Fixing Speculative Load Hardening”, eprint https://eprint.iacr.org/2022/715.

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Attack

Mitigation

Semantic Proof

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- Speculative Execution
- Spectre Attack and Speculative Load Hardening (SLH)
- Break SLH via control flow transfer and variant-time executions
- Fix SLH → Ultimate SLH and performance evaluation

Speculative Execution

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if (index < arrayLen) {
  x = array[index];
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Resolve condition takes time

- Compute condition
- Fetch value from main memory

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Let’s predict the branch condition

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Check branch history

Condition used to be true

The condition may also be true this time

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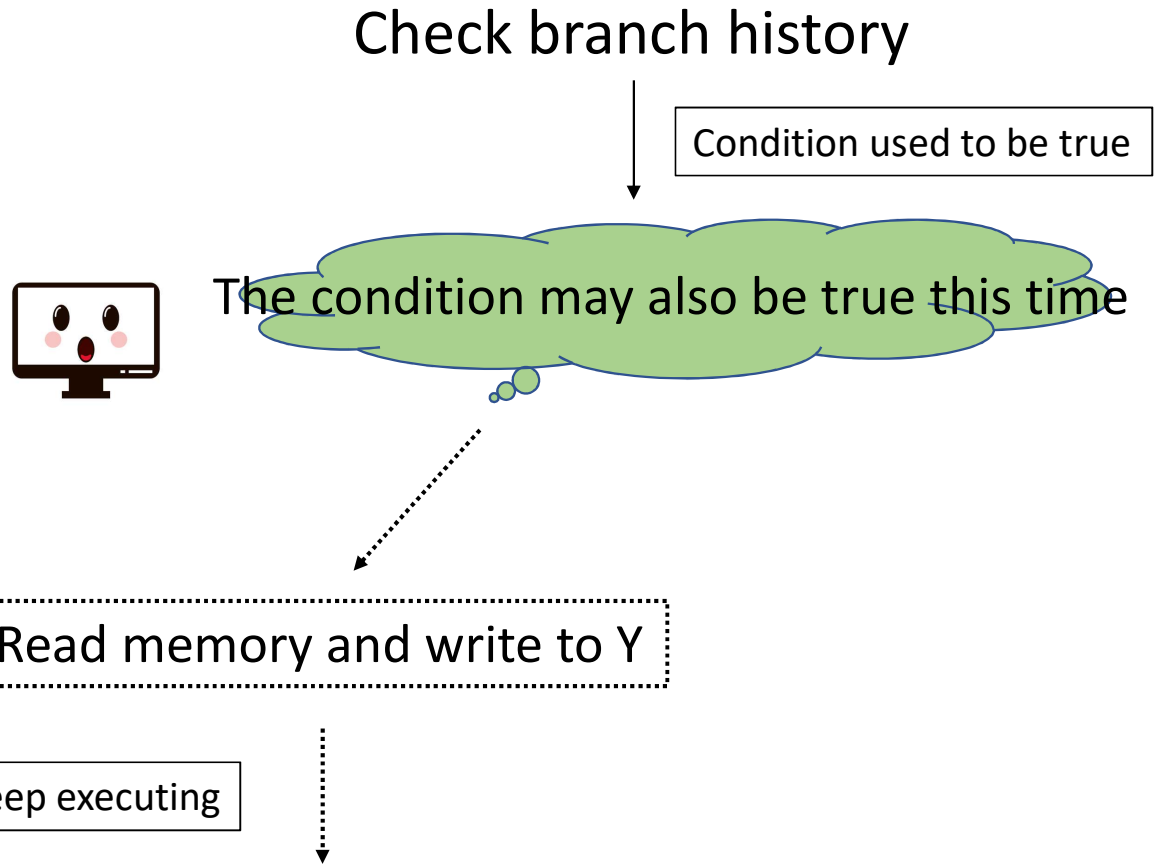

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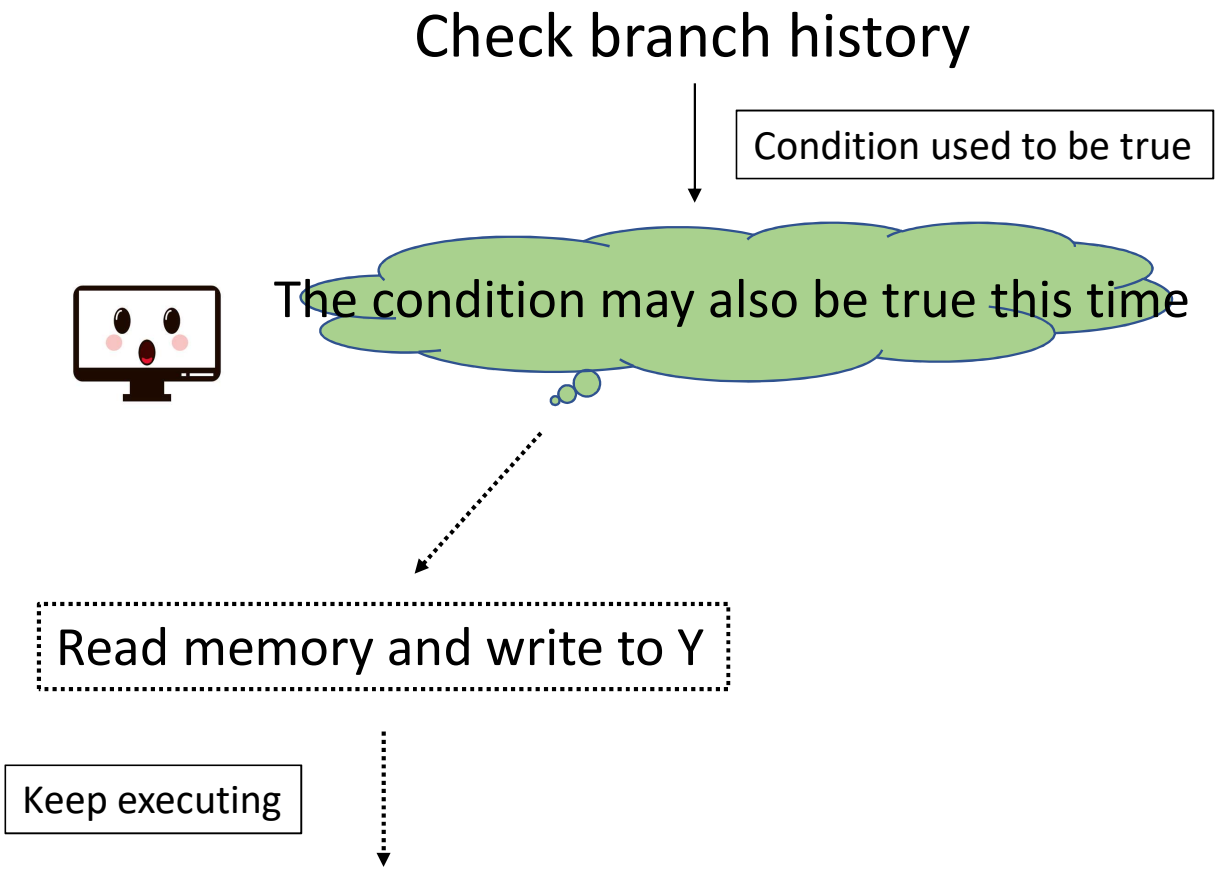

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if (index < arrayLen) {
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Let's retire these executions

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Read memory and write to Y

Keep executing

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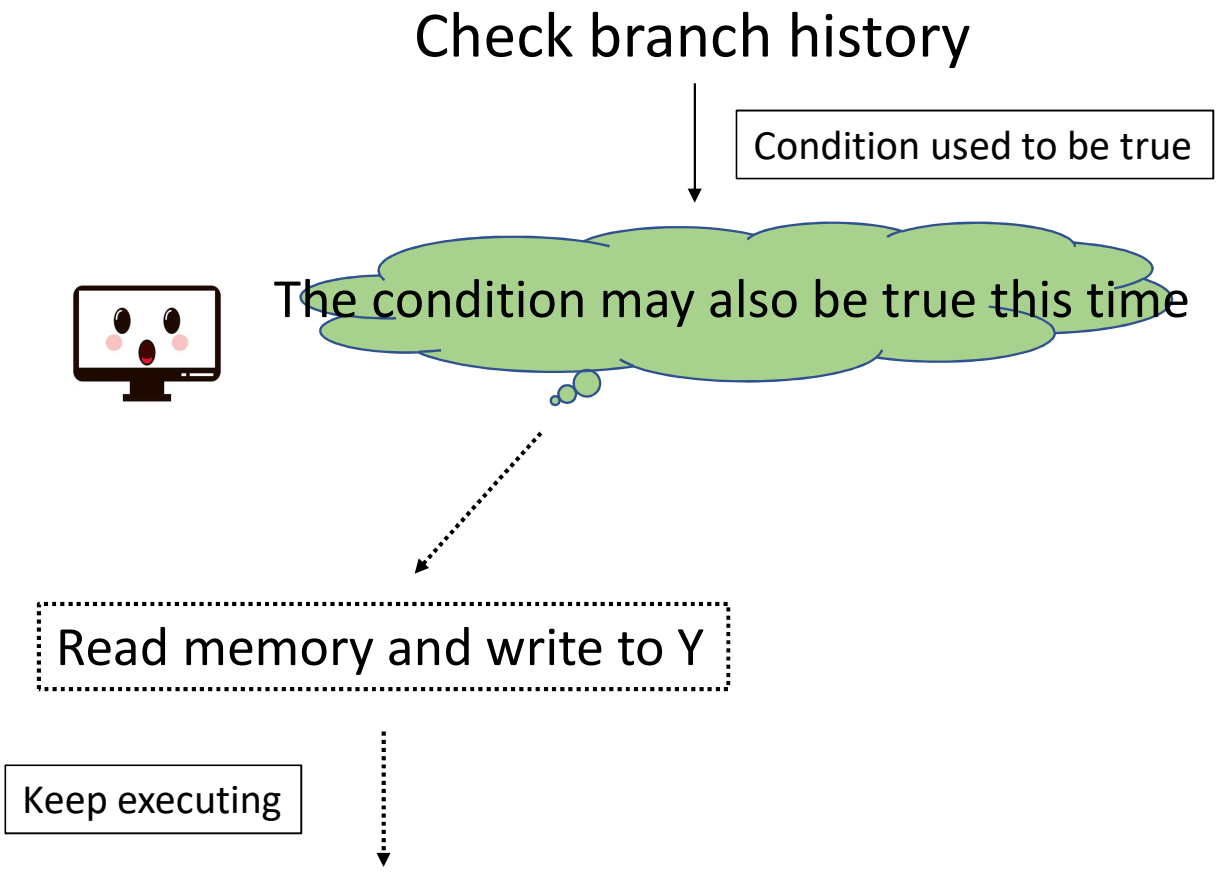

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Don't want misprediction next time, update branch history

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The speculative execution is based on branch history.
I think I could poison the branch history…

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You leak architecture changes

- Cache status
- Execution port contention
- Power consumptions
- ……

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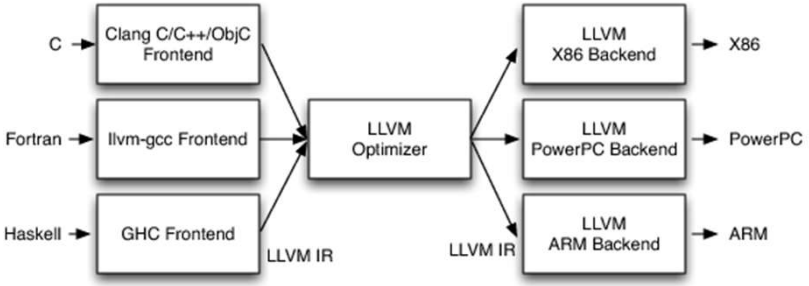

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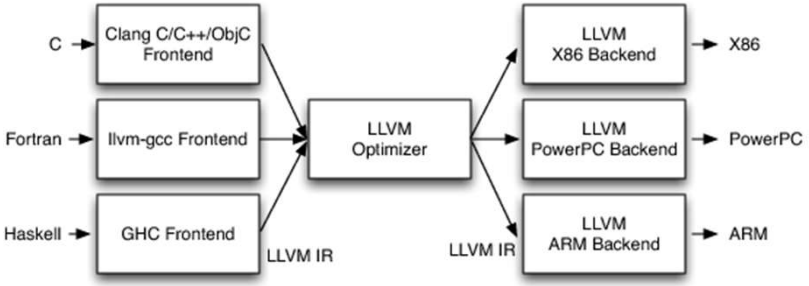

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Poison the value with -1 to avoid race condition between flushing the pipeline and loading memory

Limitation of SLH

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  - Control flow transfer
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  - Limited execution resources
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```
victim(int value, int isPublic) {
  if (isPublic) {
    //Leaky code
  }
}
```

Leak via control flow transfer

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  // Boundary Check
  if (isPublic) {
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      a2 = a1 | a2;
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    } else {
      a1 = crc32(a1, a1);
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Instructions are sent to various execution ports
I measure which port is being used.

Port Contention

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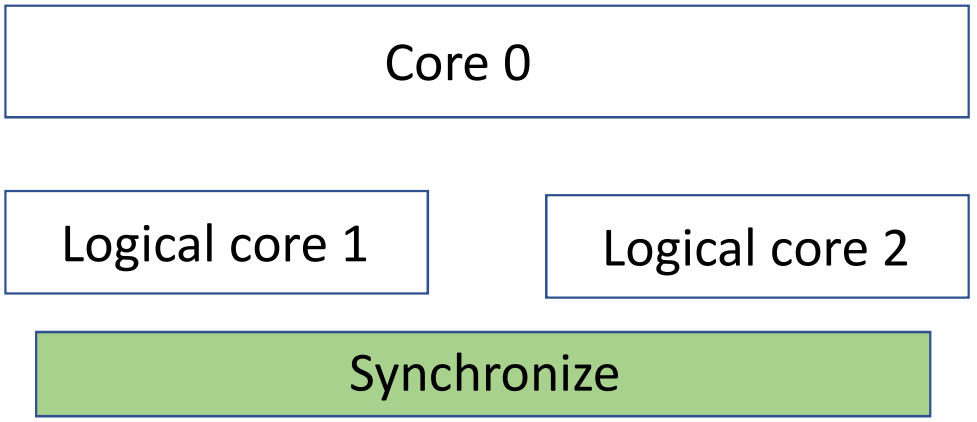

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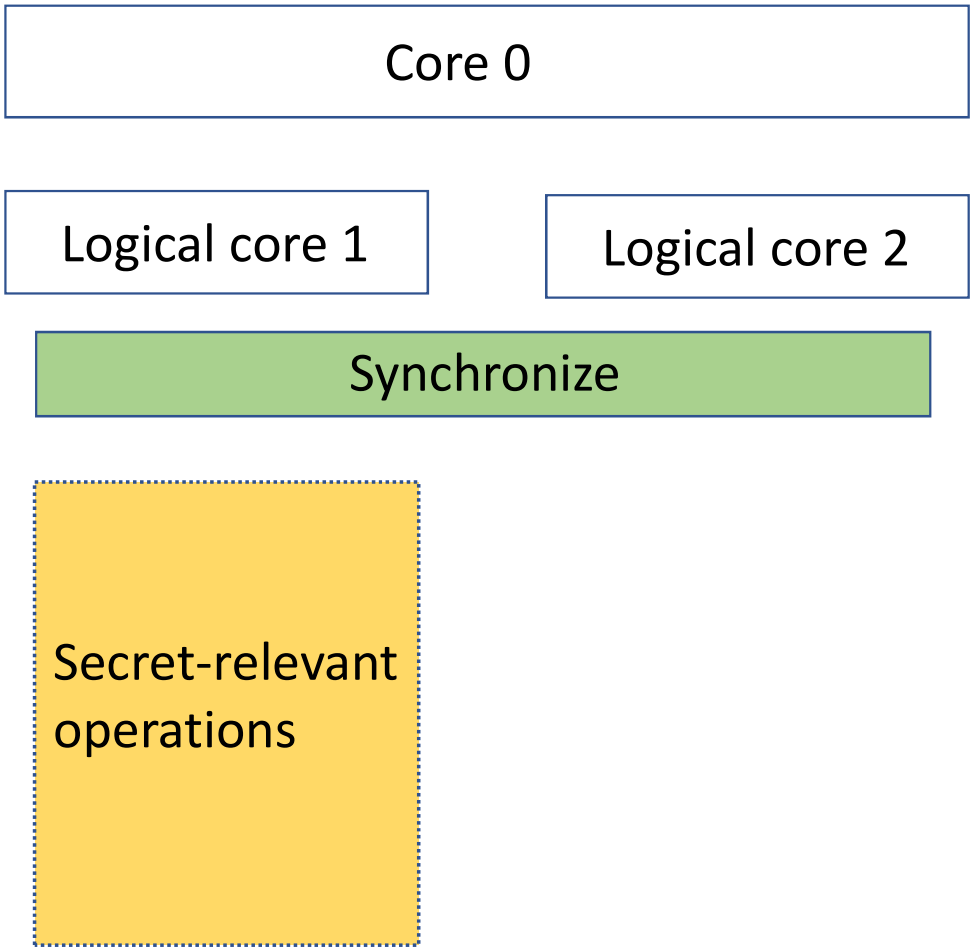

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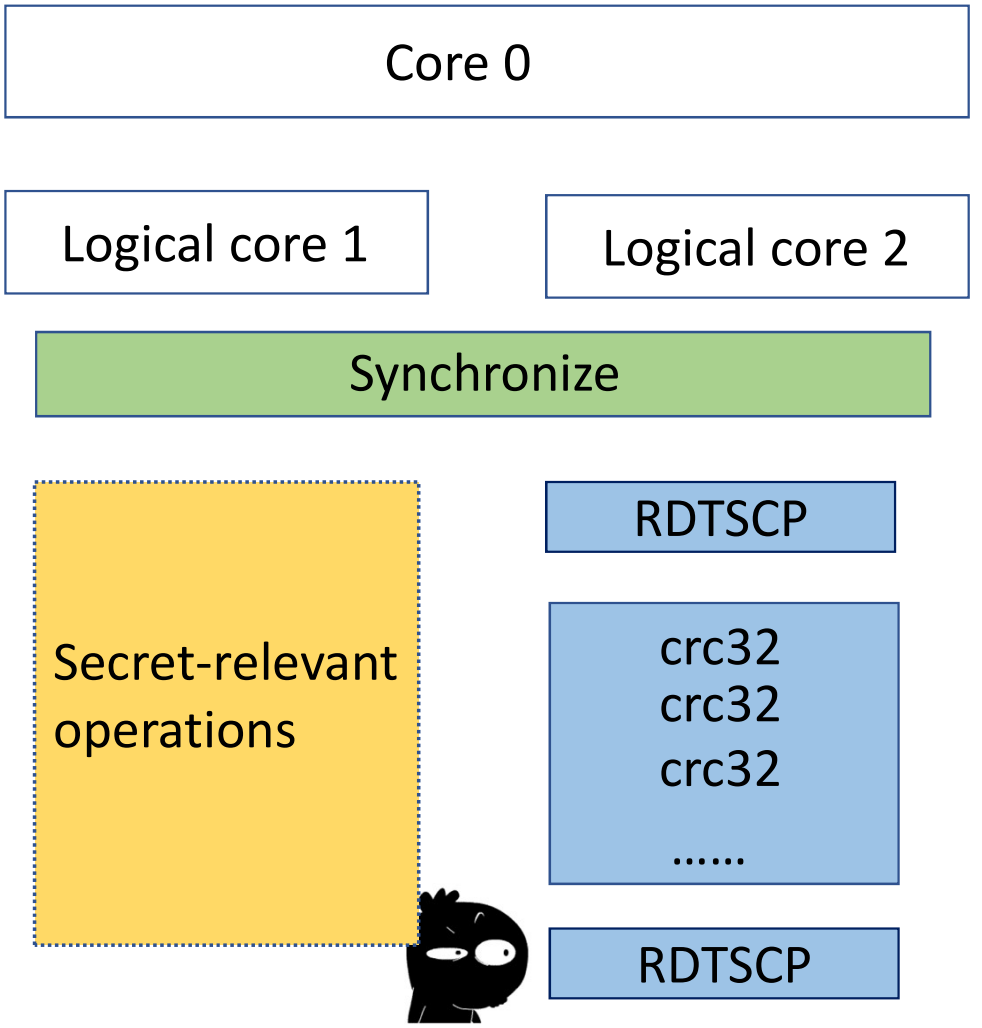

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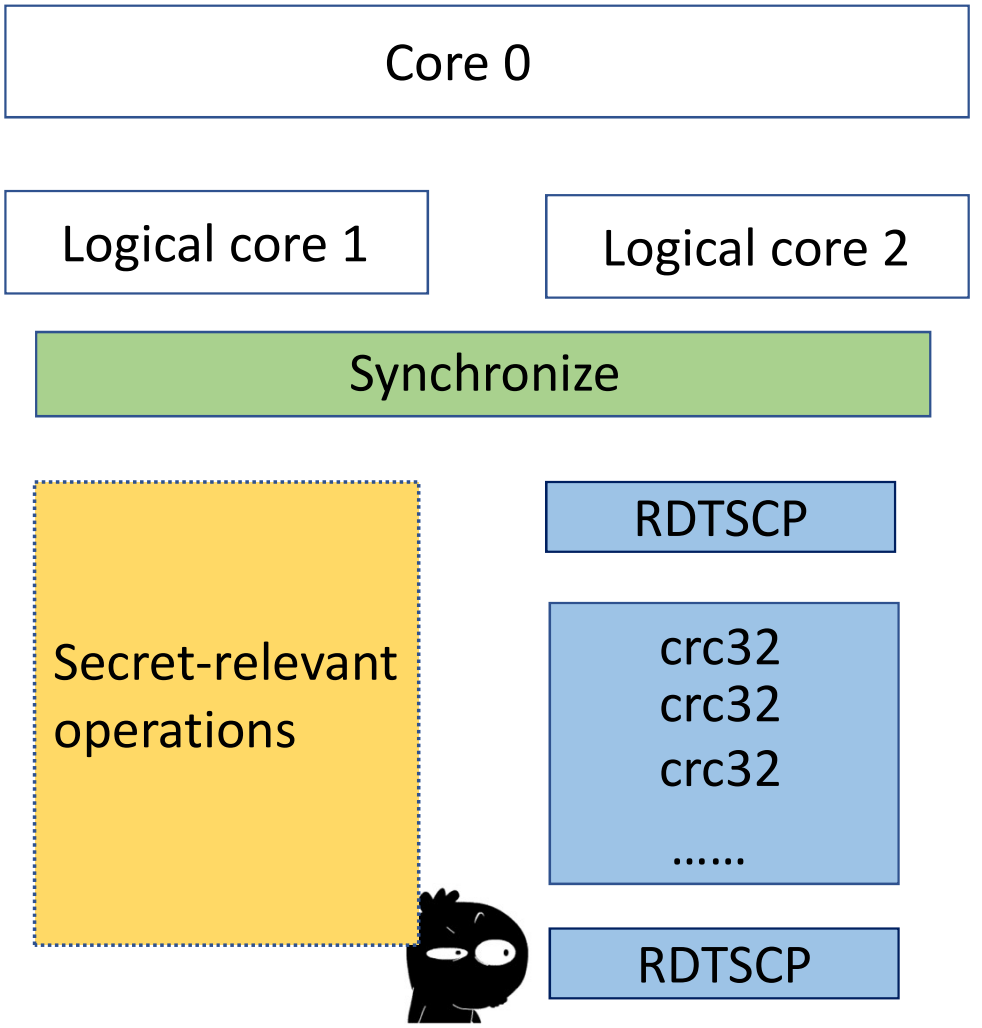

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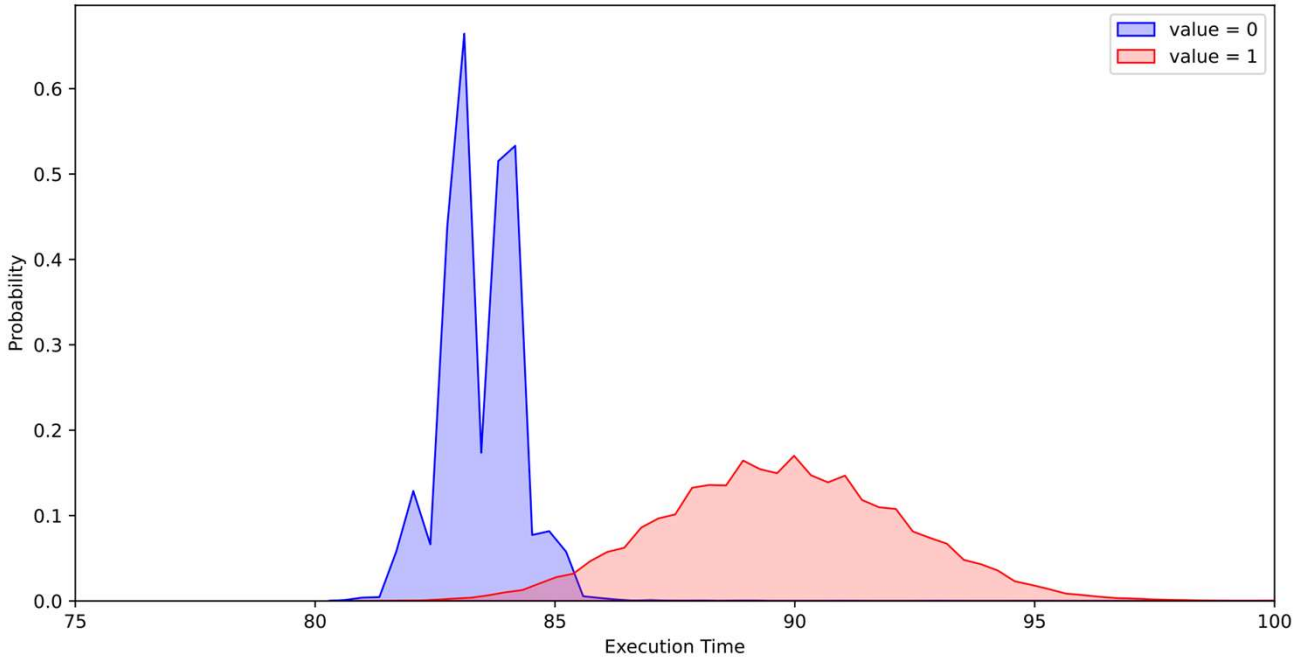

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Compiled by SLH

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isPublic |= mask;
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Mitigation Result

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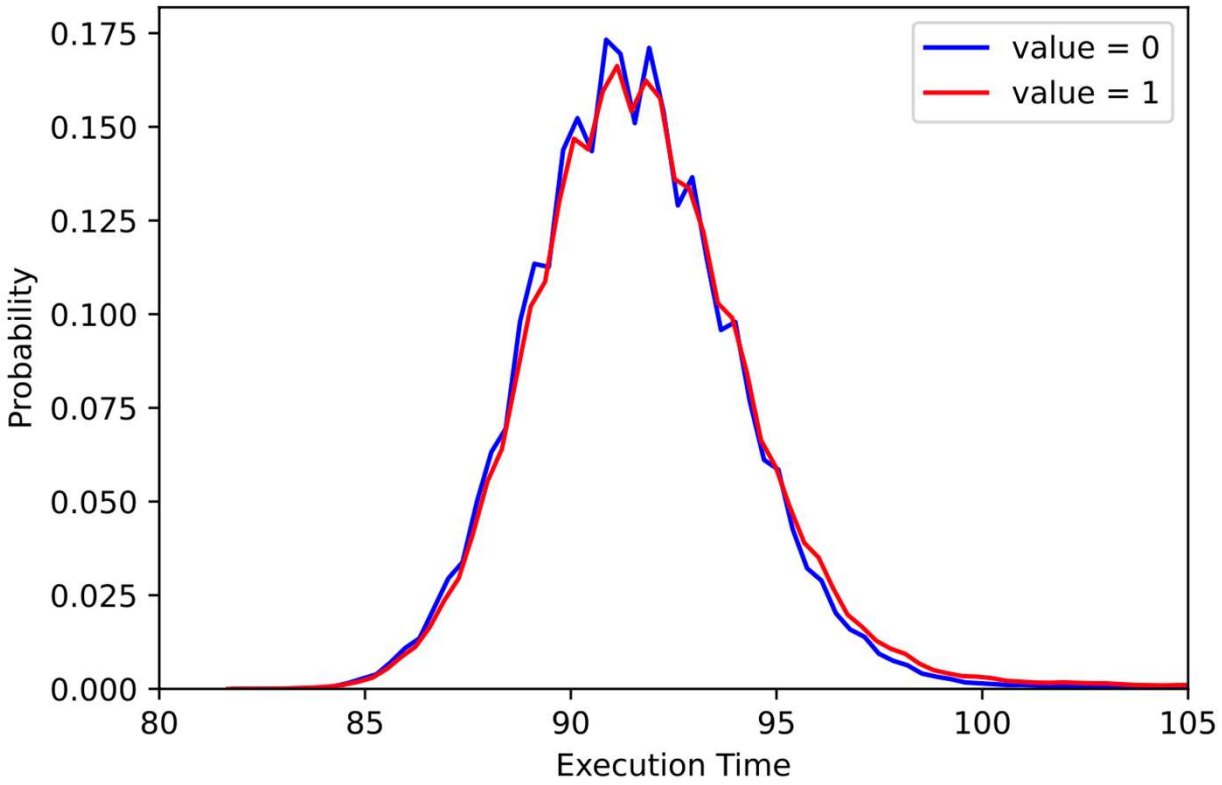

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Do constant-time computing

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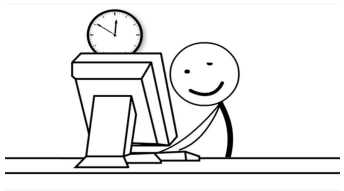

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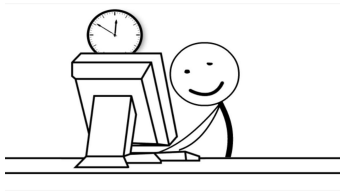

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Review pipeline stages

How is an instruction handled by the processer

Front-end

Back-end

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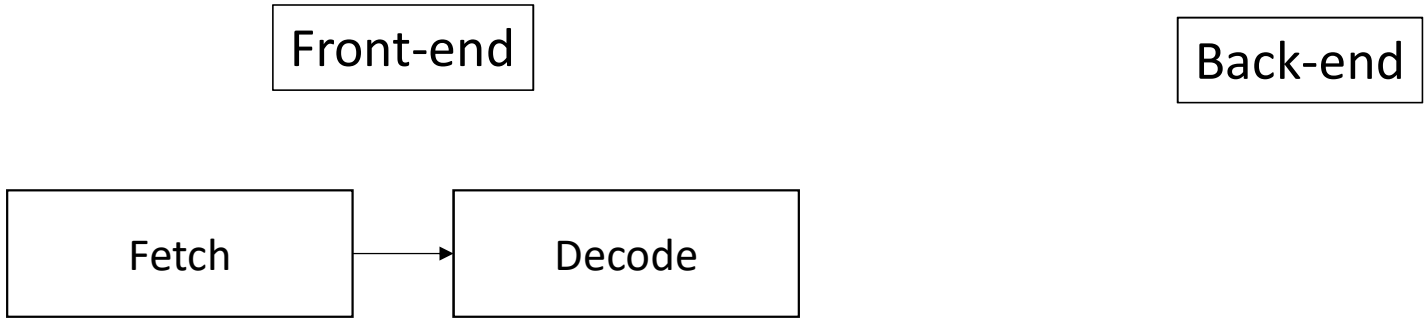
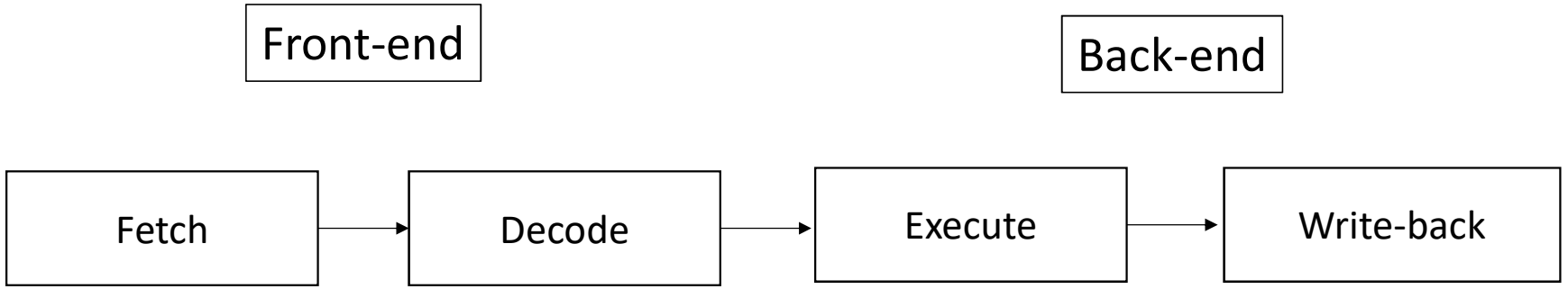
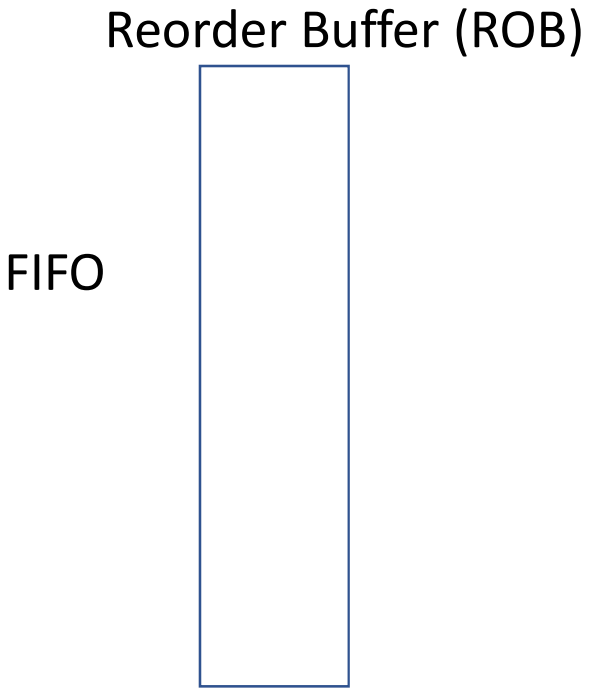


Review pipeline stages

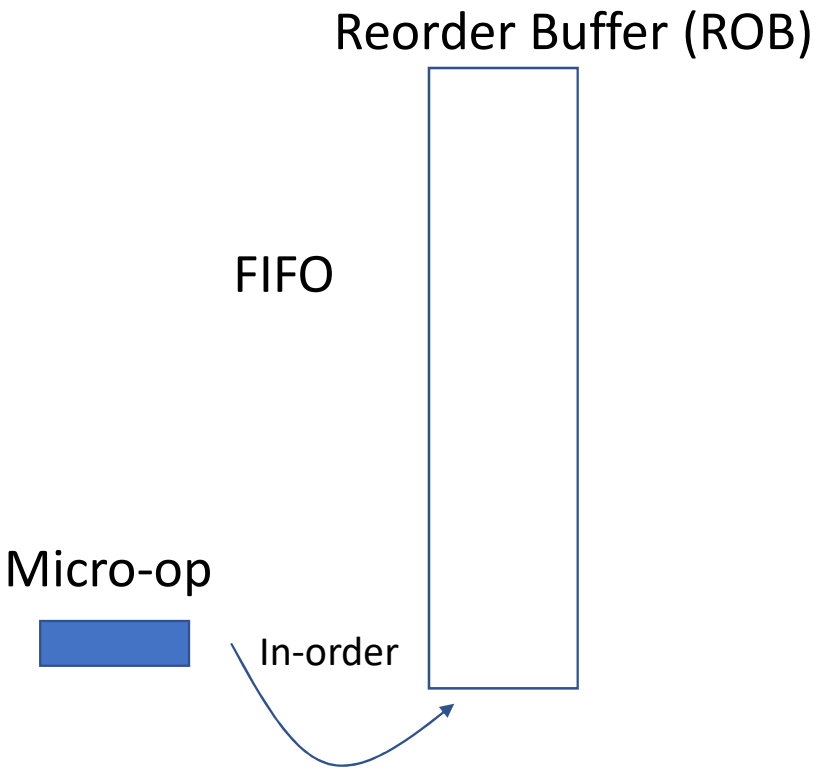
How is an instruction handled by the processer



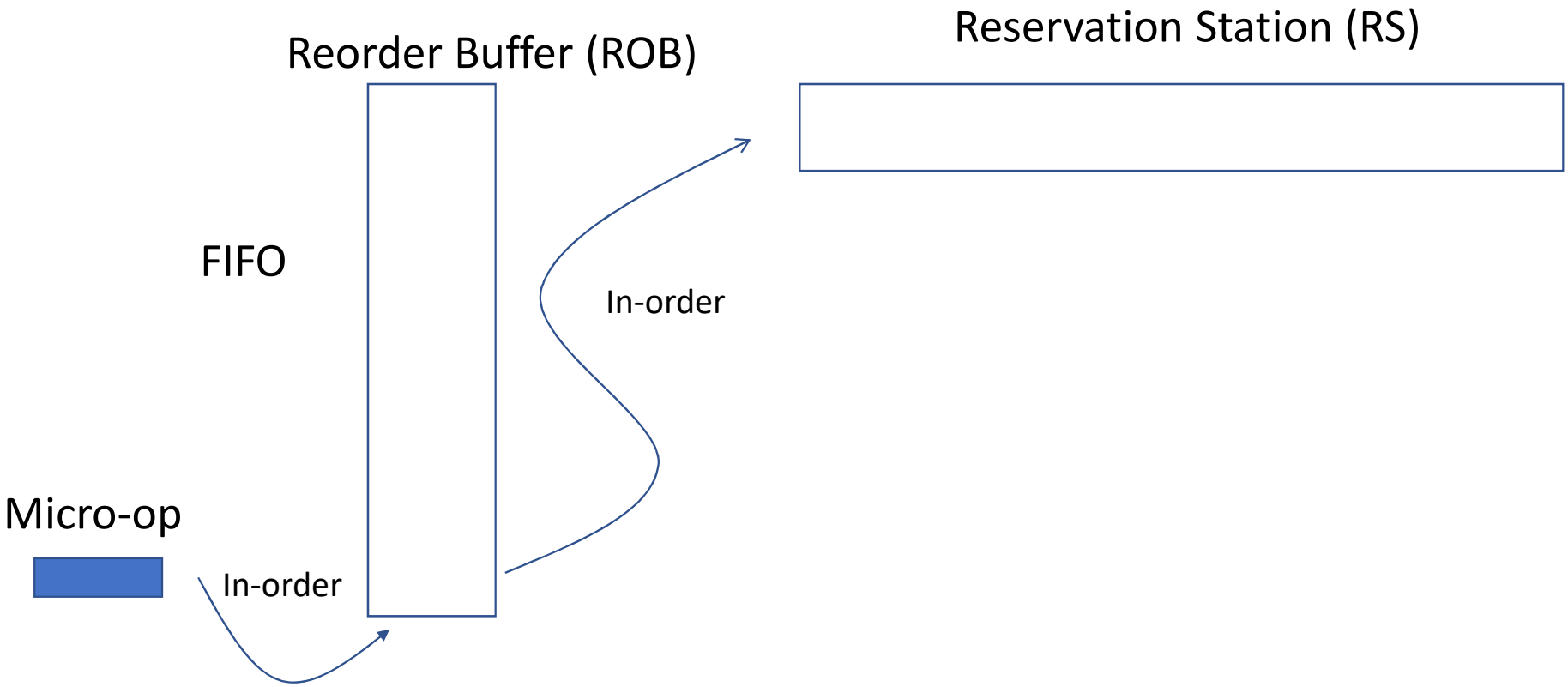
Execution Engine



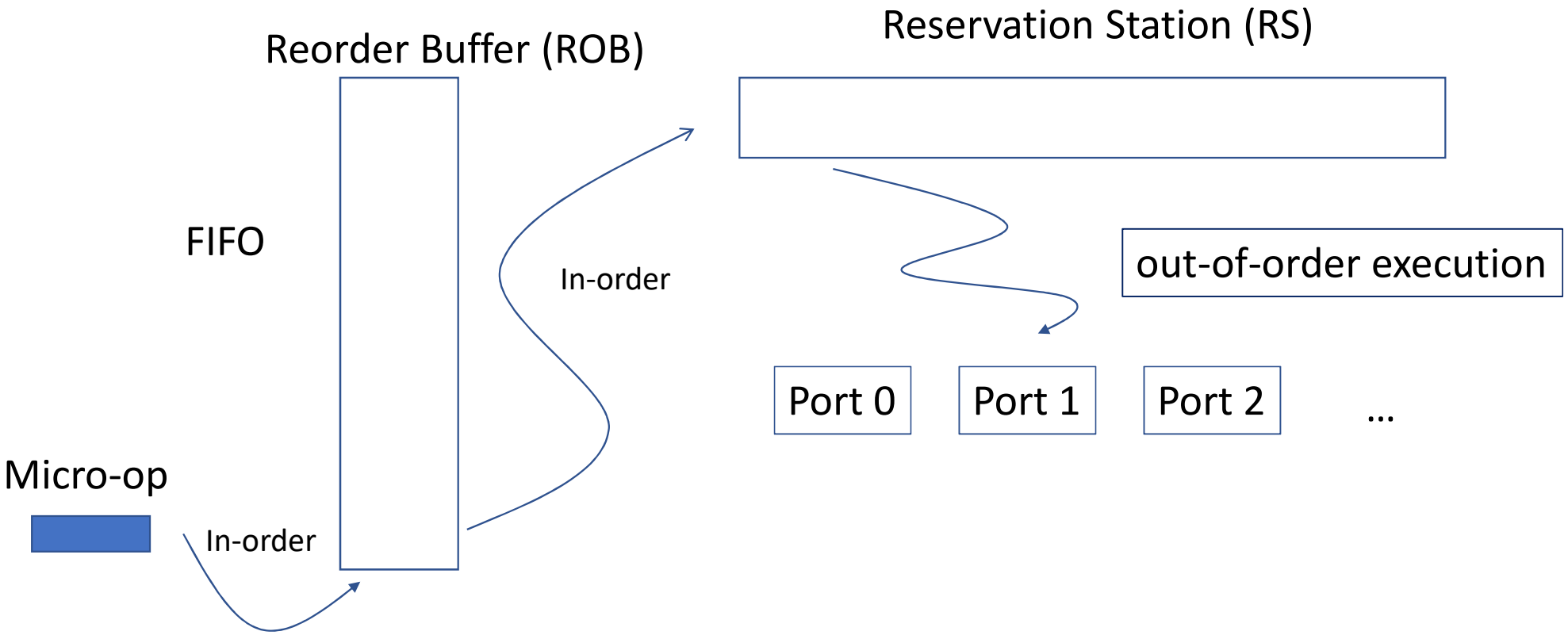
Execution Engine



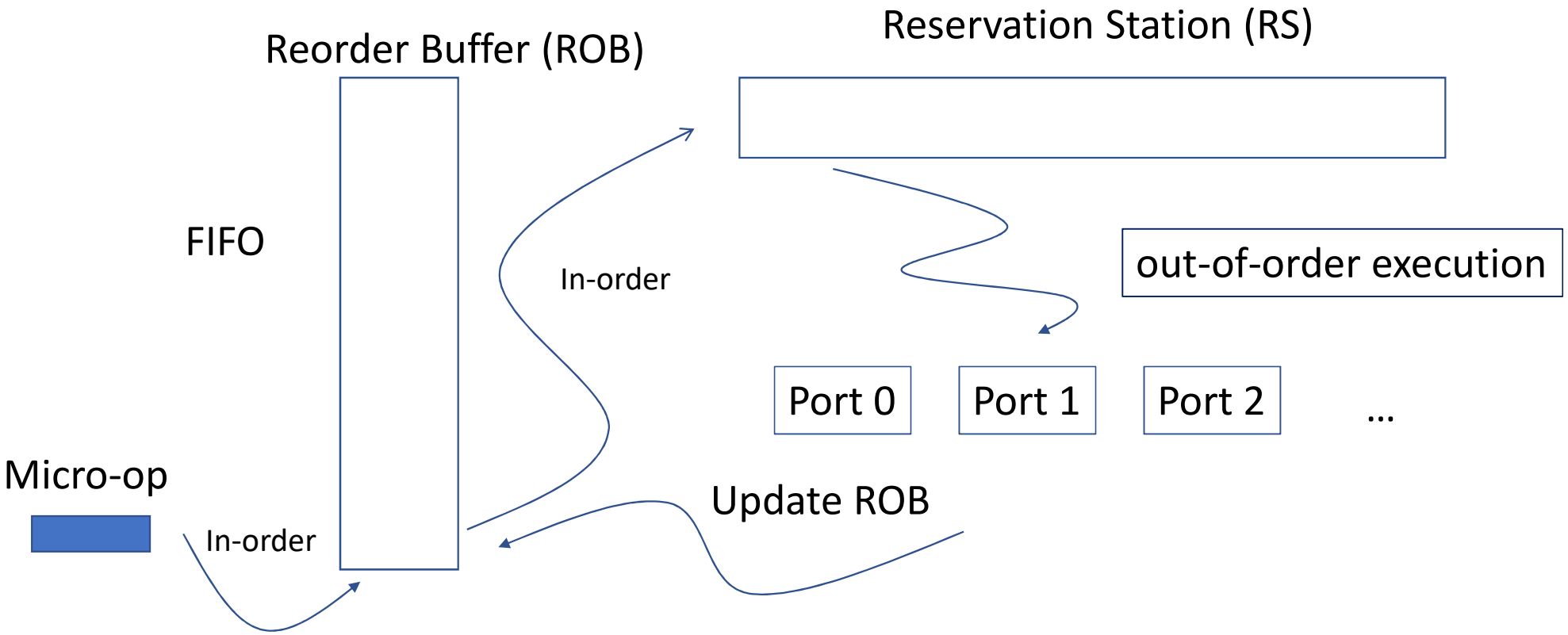
Execution Engine



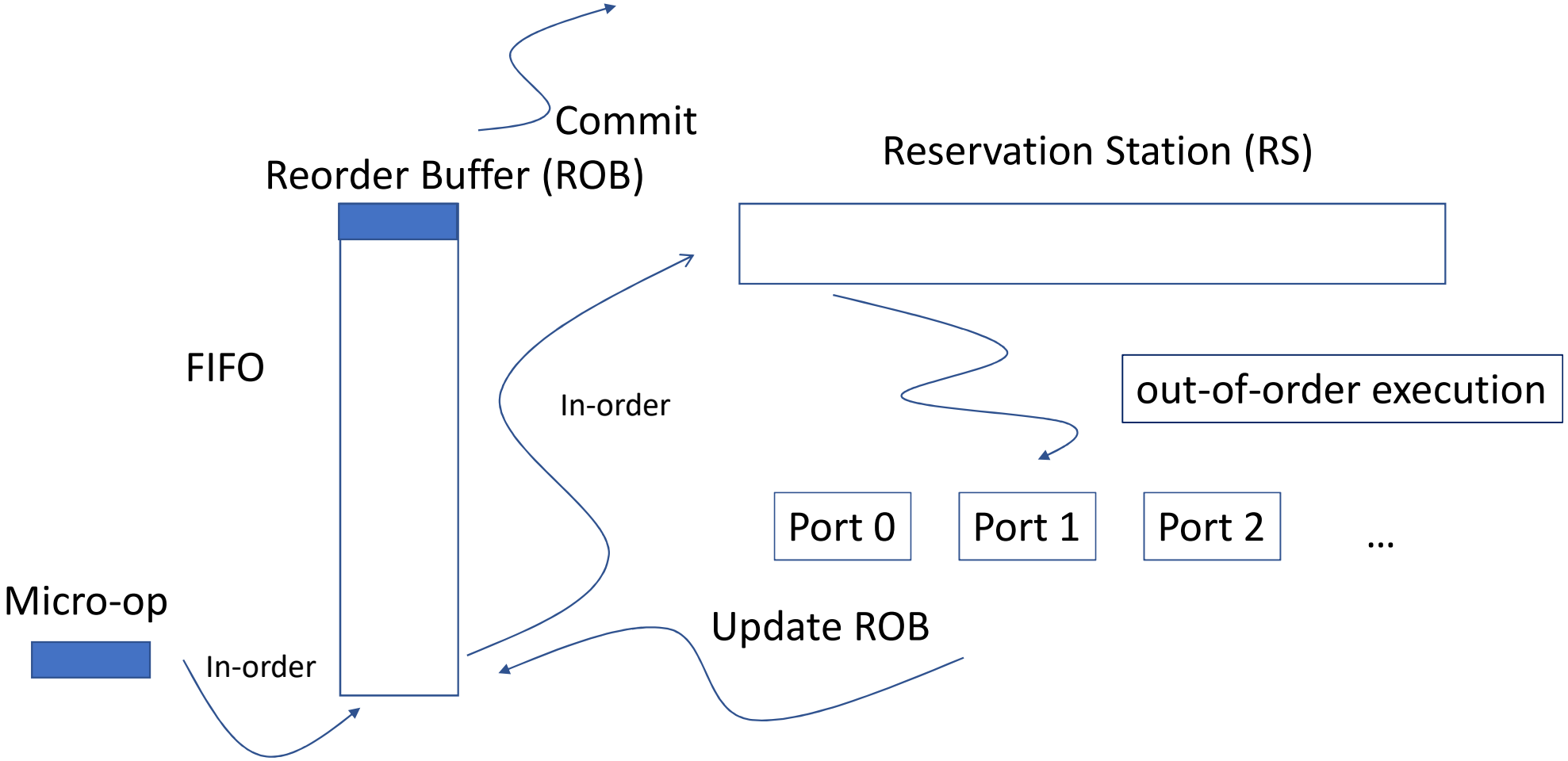
Execution Engine



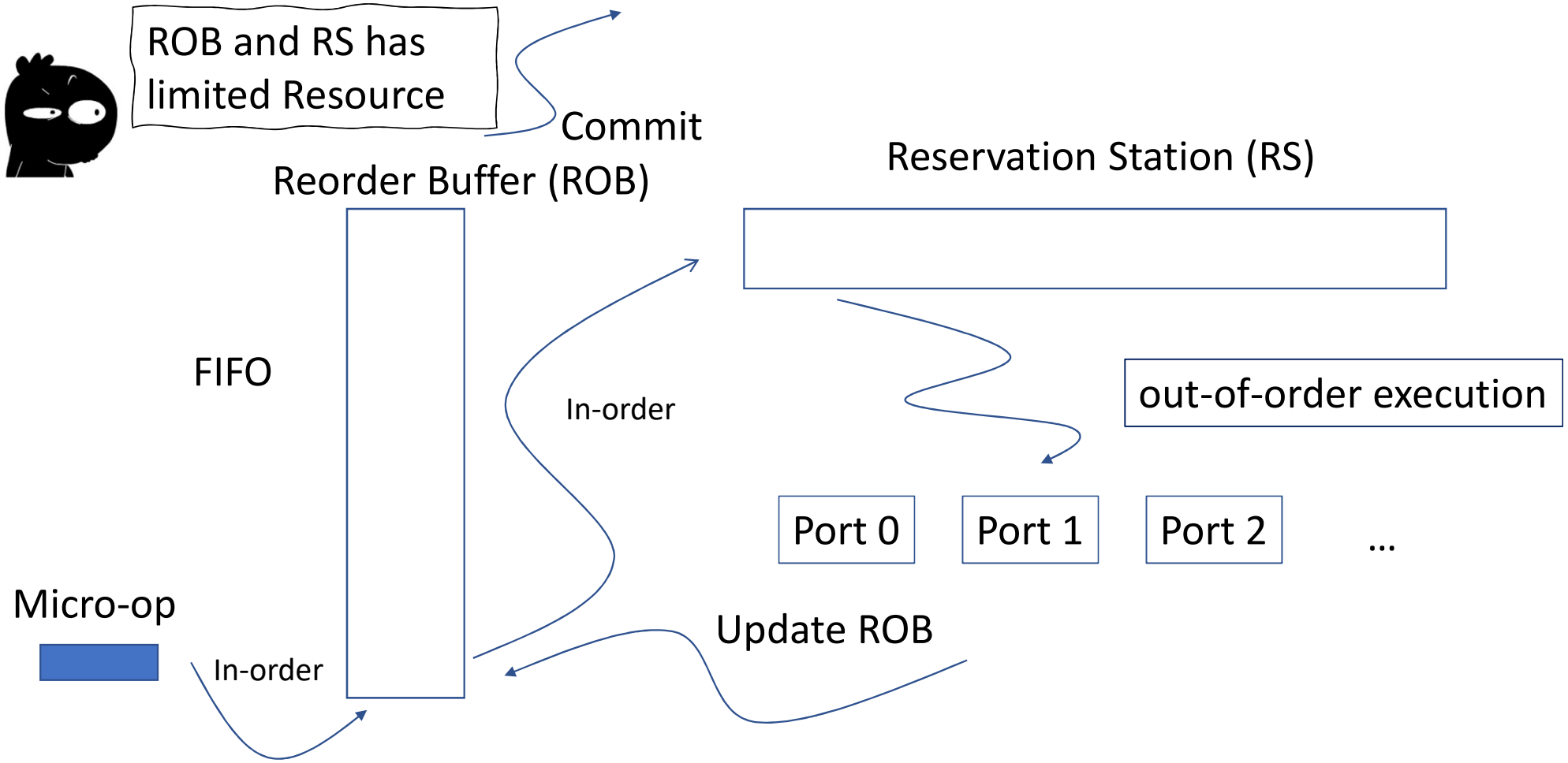
Execution Engine



Execution Engine



Execution Engine



Variant-time execution under speculation

```
// Boundary Check
if (isPublic) {
  value = sqrtsd(value);
  value = mulsd(value, value);
}
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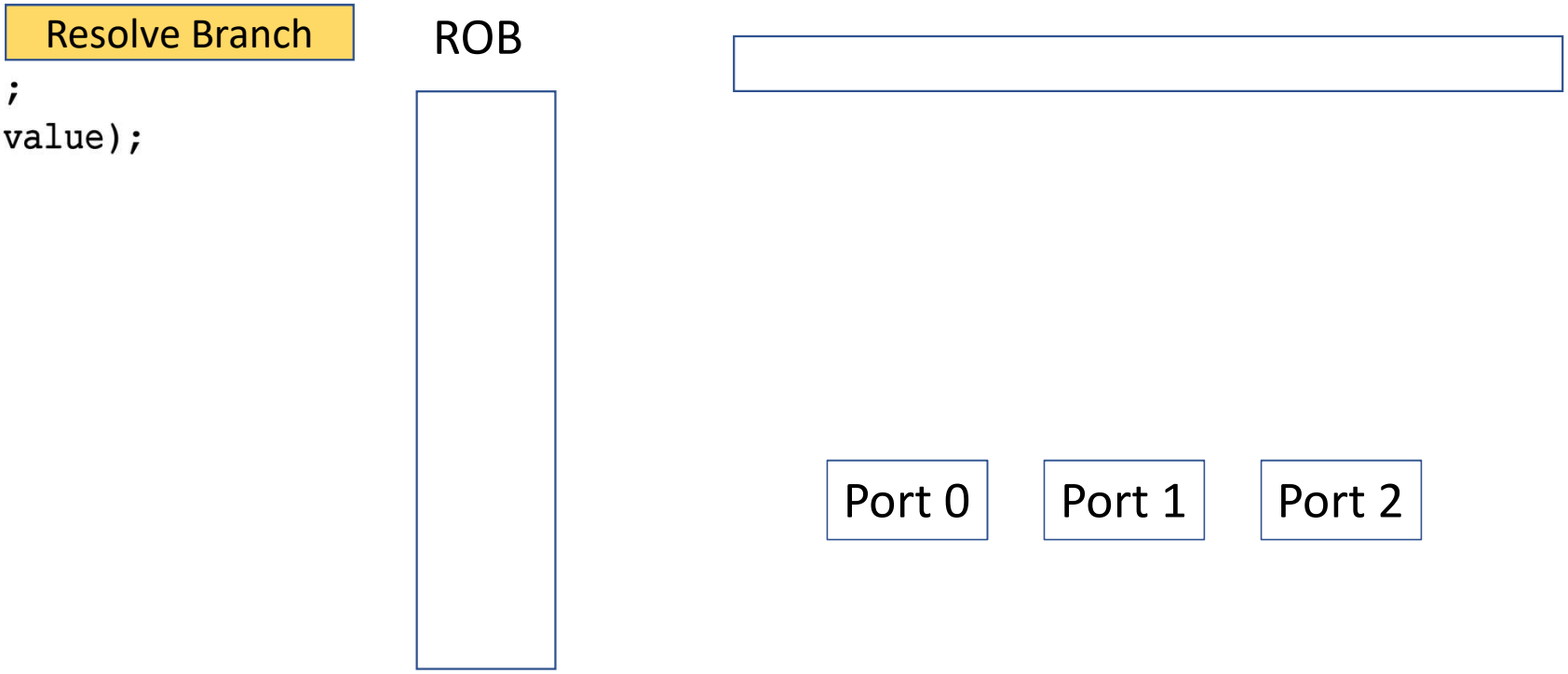

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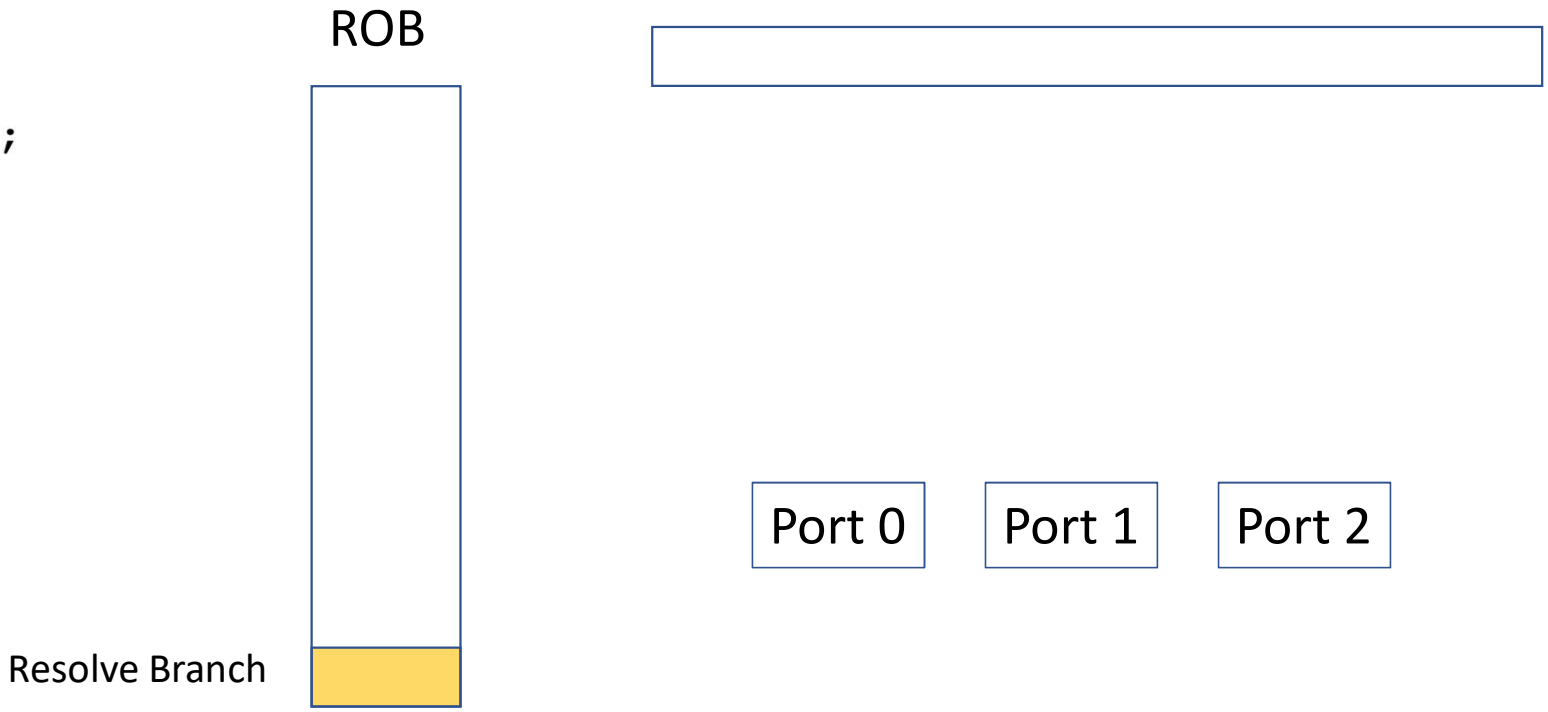

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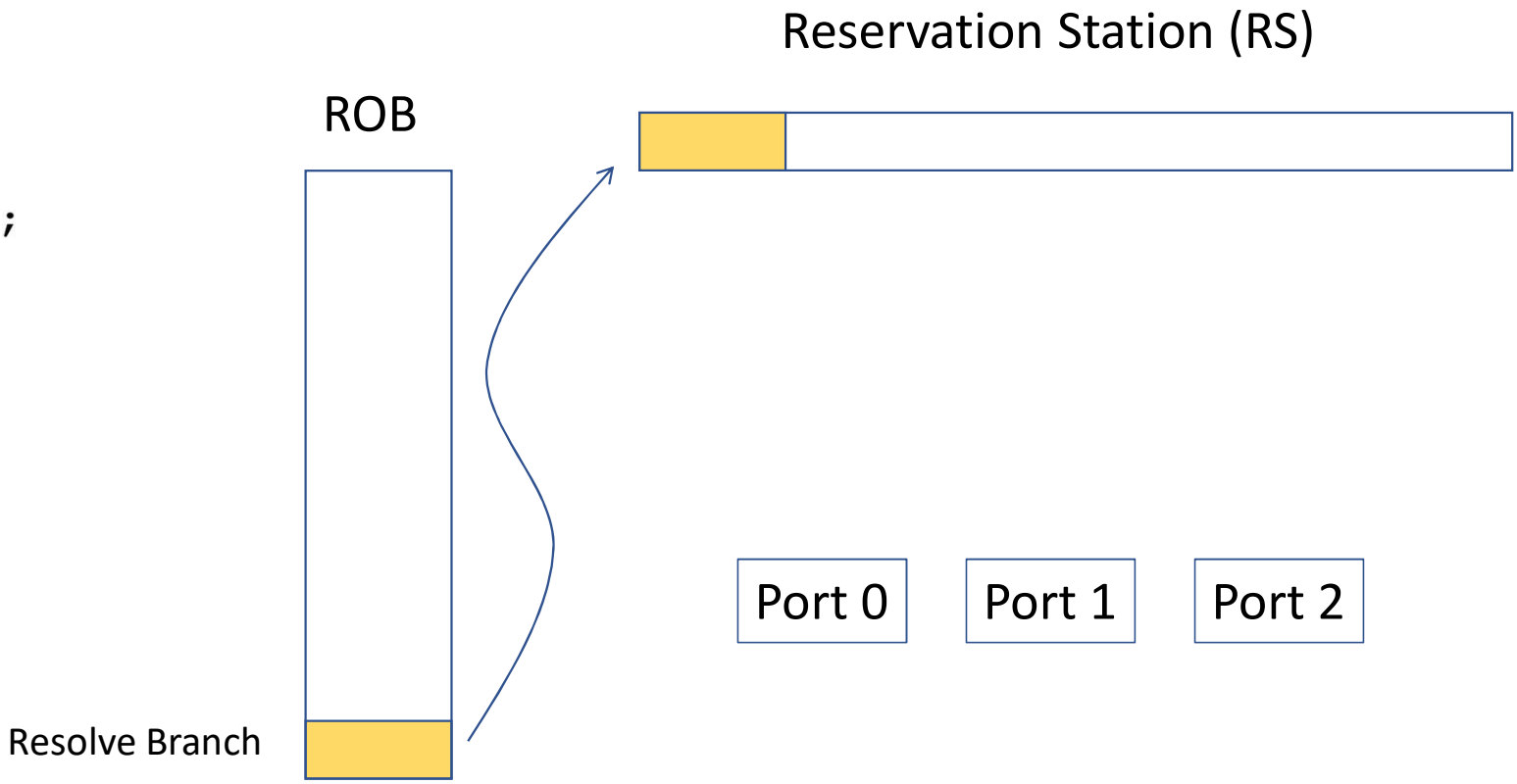

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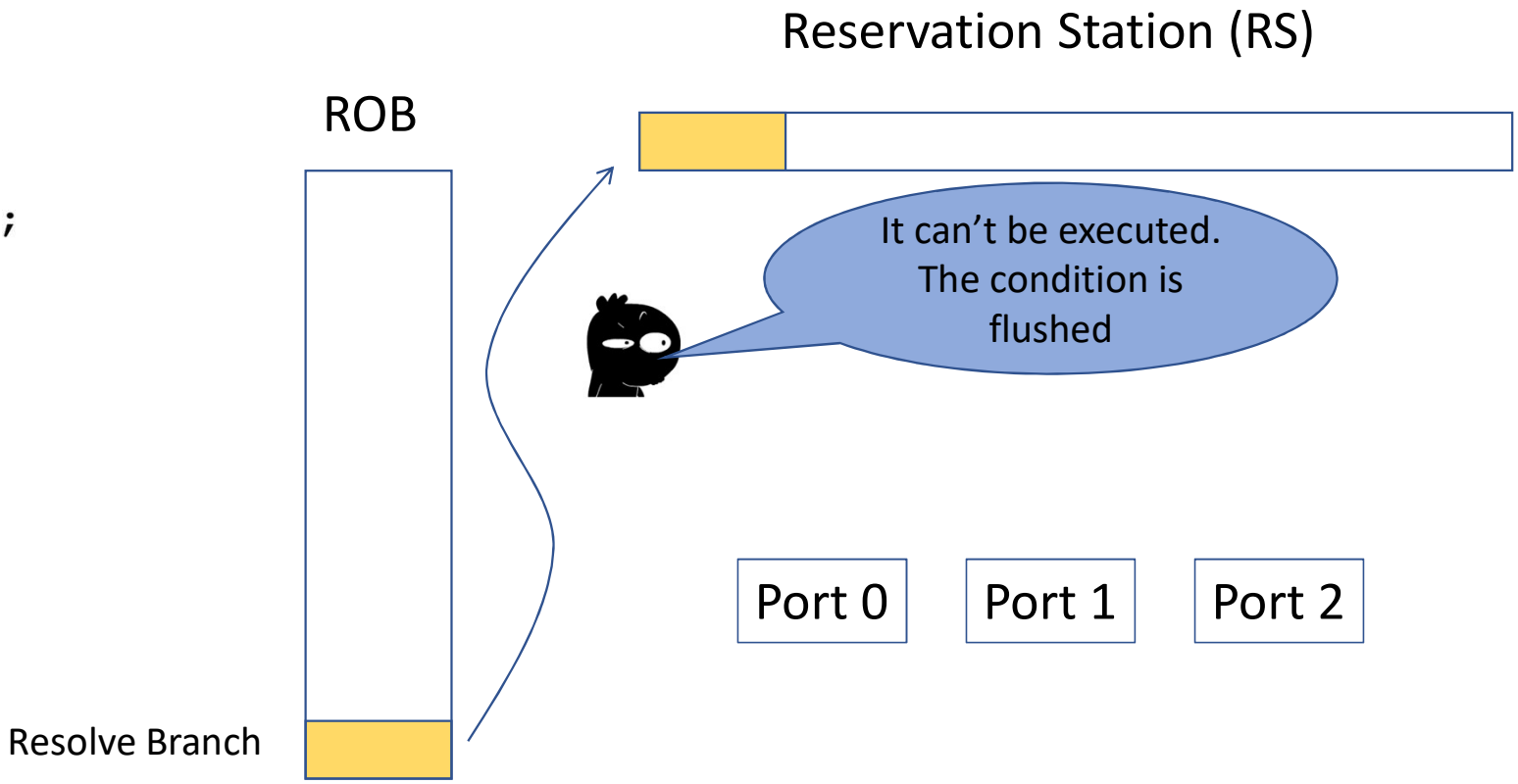

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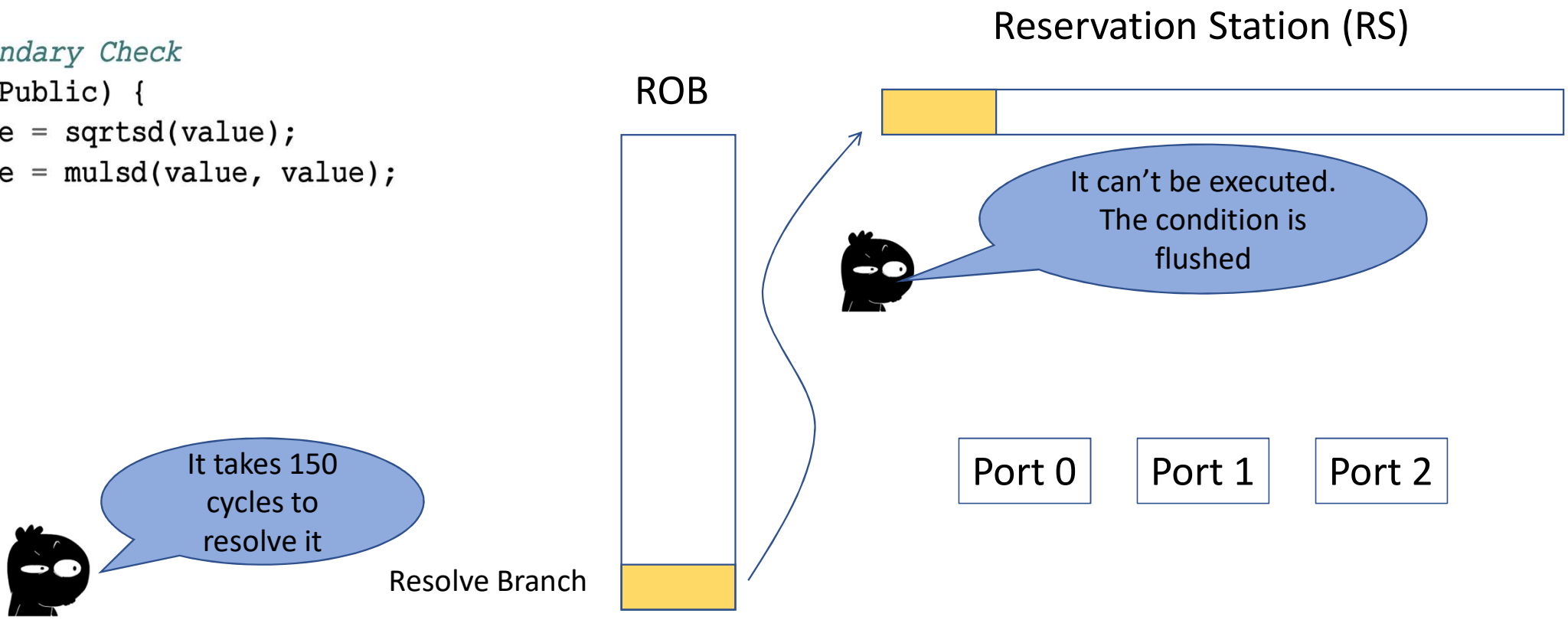

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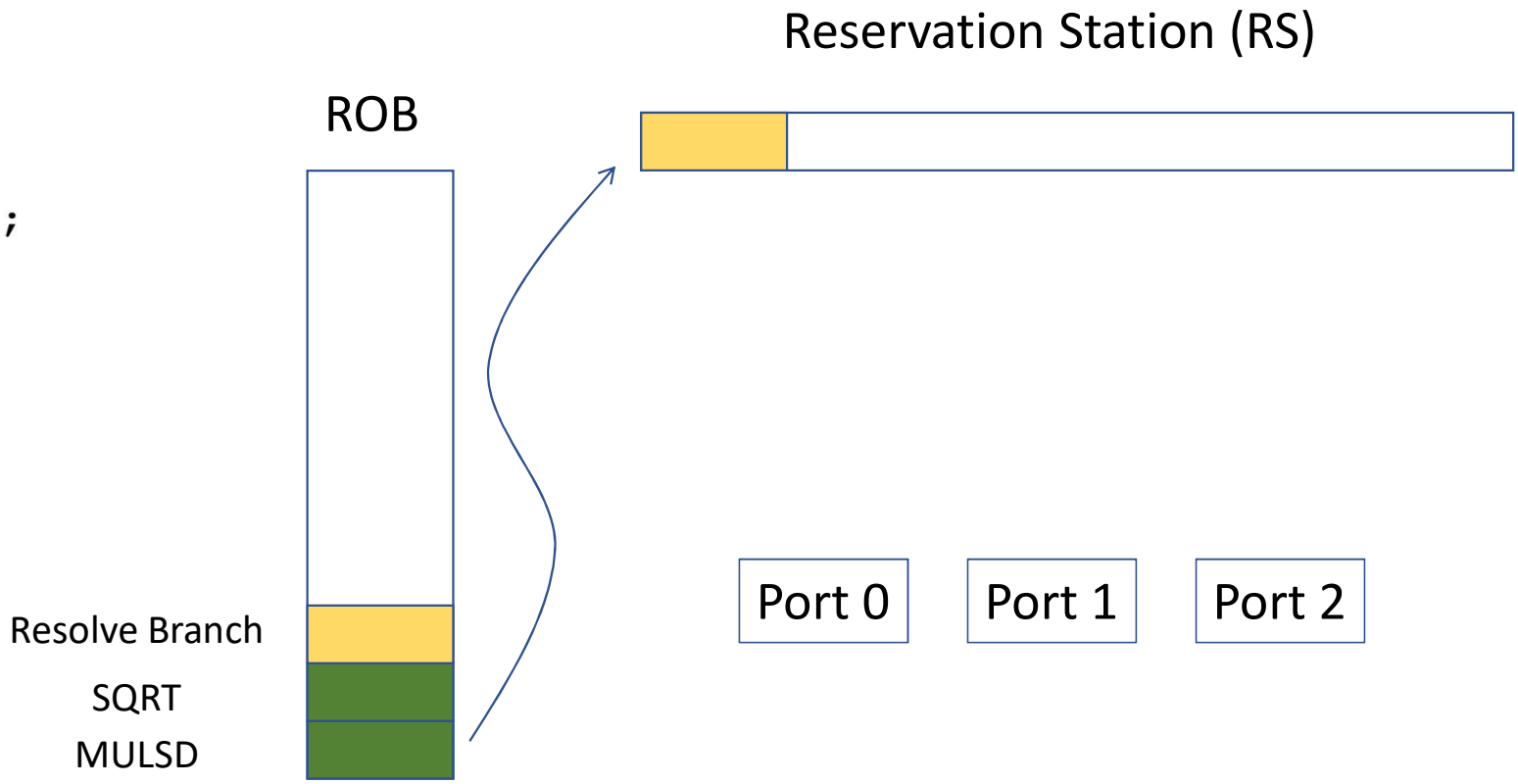

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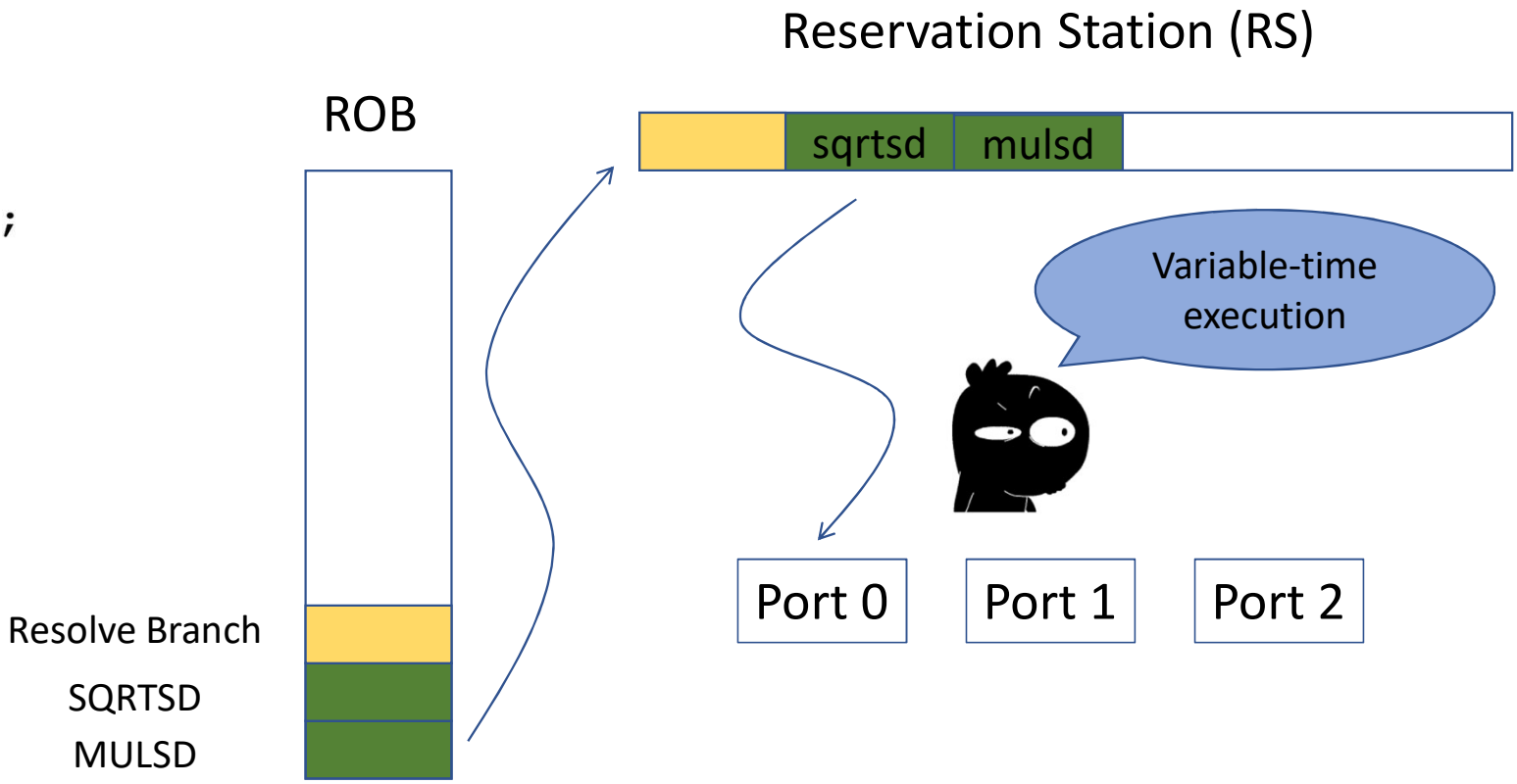

Variant-time execution under speculation

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```
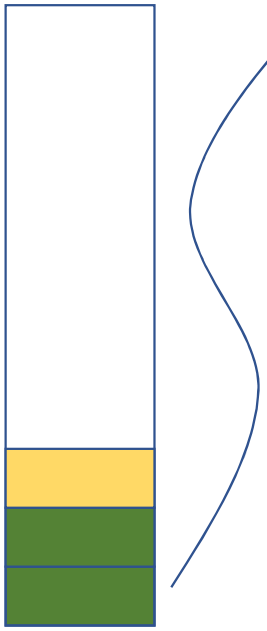

What if we have more variable-time instructions?

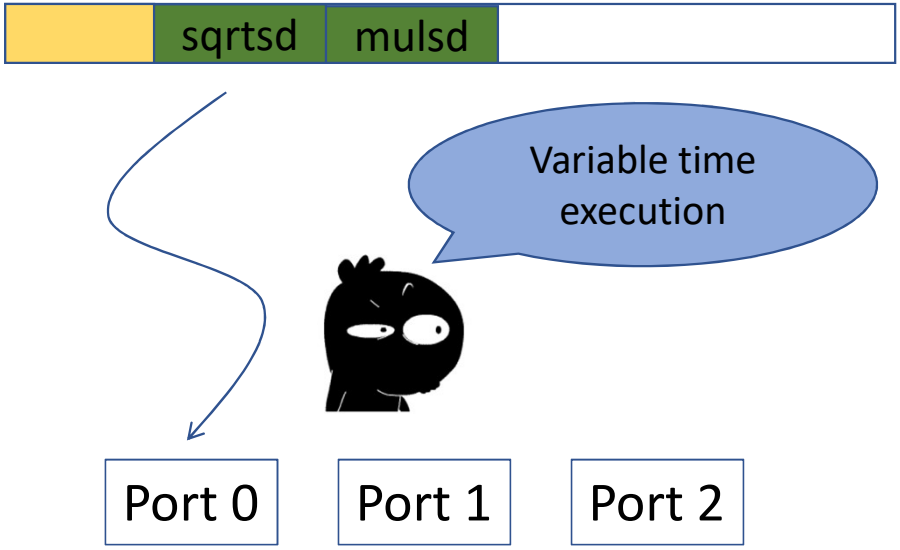
Resolve Branch

SQRTSD

MULSD



Reservation Station (RS)



Spectre Attack on variant-time executions

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// Boundary Check
if (isPublic) {
  value = sqrtsd(value);
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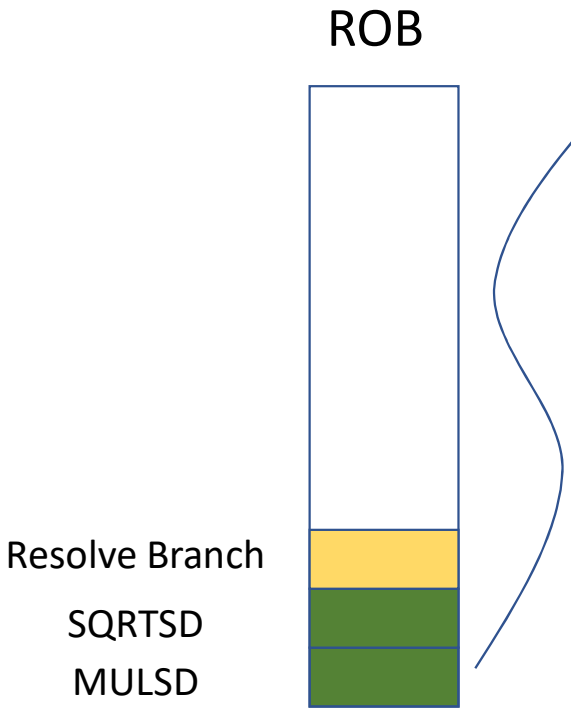
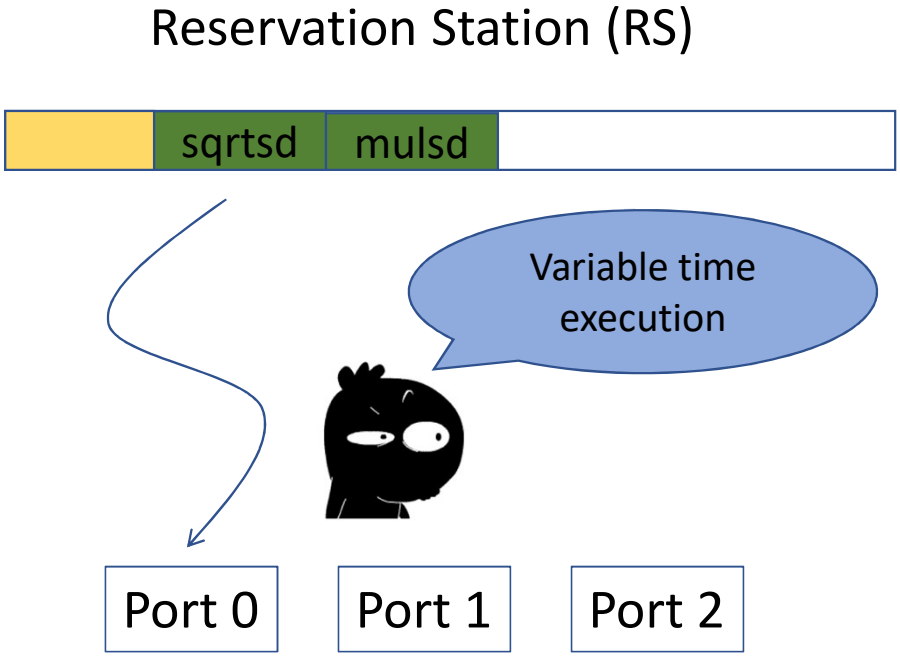
  value = mulsd(value, value);
  ...
}
```

What if we have more variable time instructions?





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}
```

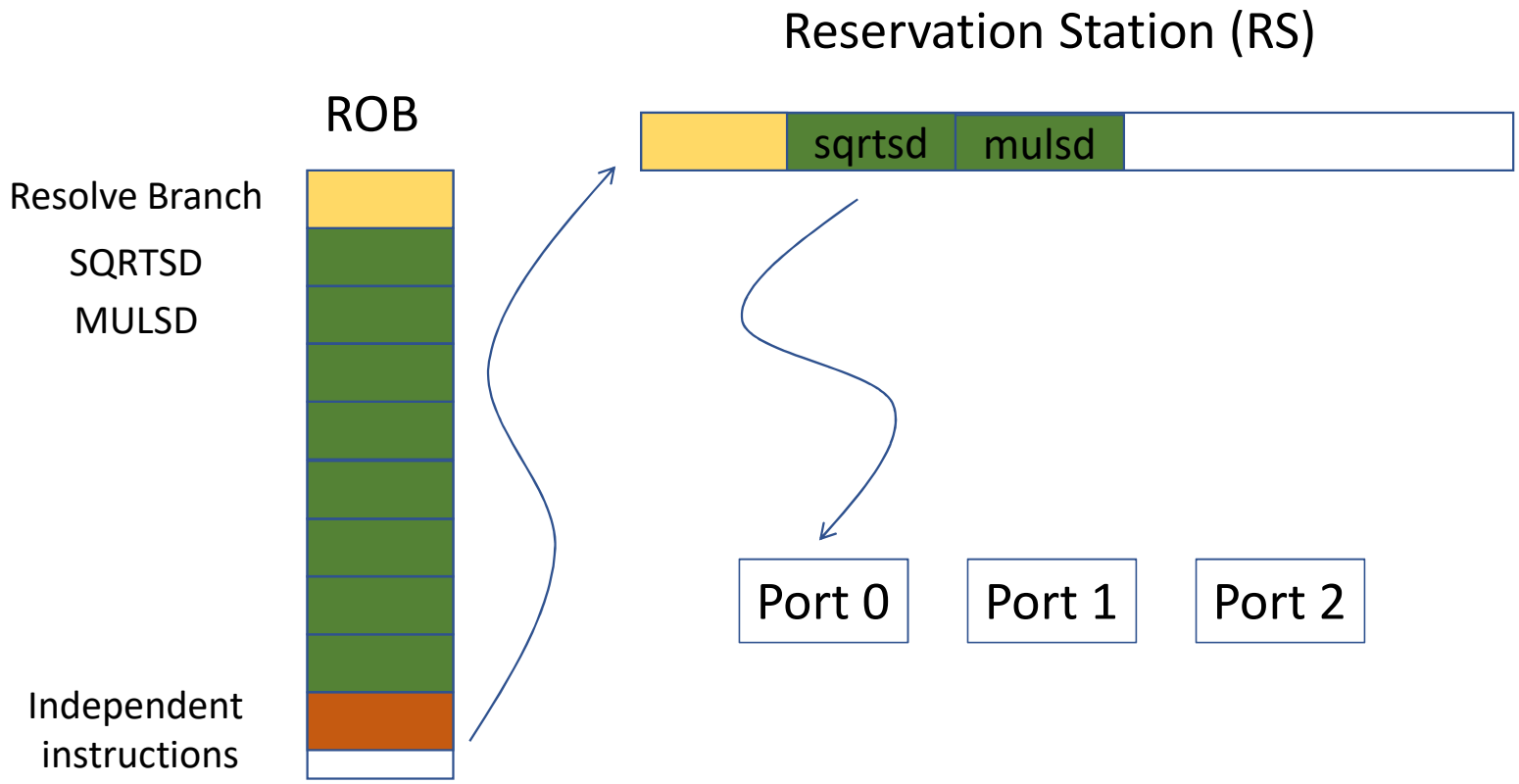

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  value = mulsd(value, value);
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  ...
}
```

Instructions in ROB is always fixed

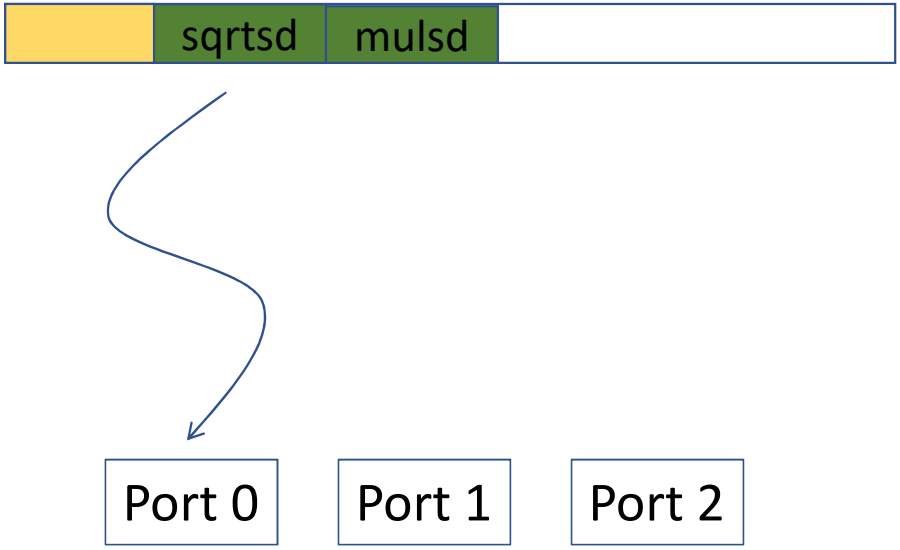
Resolve Branch

SQRTSD

MULSD

Independent instructions

Reservation Station (RS)



Spectre Attack on variant-time executions

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  value = mulsd(value, value);
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  ...
}
```

Instructions in ROB is always fixed

ROB

Resolve Branch

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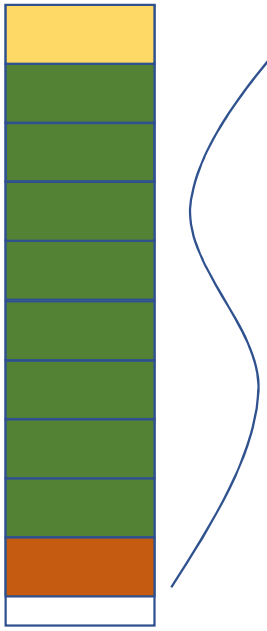
Independent instructions



Reservation Station (RS)

RS will be filled up

Port 0 Port 1 Port 2

Spectre Attack on variant-time executions

```
// Boundary Check
if (isPublic) {
  value = sqrtsd(value);
  value = mulsd(value, value);
  value = sqrtsd(value);
  value = mulsd(value, value);
  ...
}
```

Instructions in ROB is always fixed

Independent instruction may be blocked

Resolve Branch

SQRTSD

MULSD

ROB

Independent instructions

Reservation Station (RS)

RS will be filled up

Port 0

Port 1

Port 2

Spectre Attack on variant-time executions

```
// Boundary Check
if (isPublic) {
  value = sqrtsd(value);
  value = mulsd(value, value);
  value = sqrtsd(value);
  value = mulsd(value, value);
  ...
  independent_memory_access(adrs);
}
```

Instructions in ROB is always fixed

Independent instruction may be blocked

ROB

Resolve Branch

SQRTSD

MULSD

Independent instructions

Reservation Station (RS)

RS will be filled up

Port 0 Port 1 Port 2

Spectre Attack on variant-time executions

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// Boundary Check
if (isPublic) {
  value = sqrtsd(value);
  value = mulsd(value, value);
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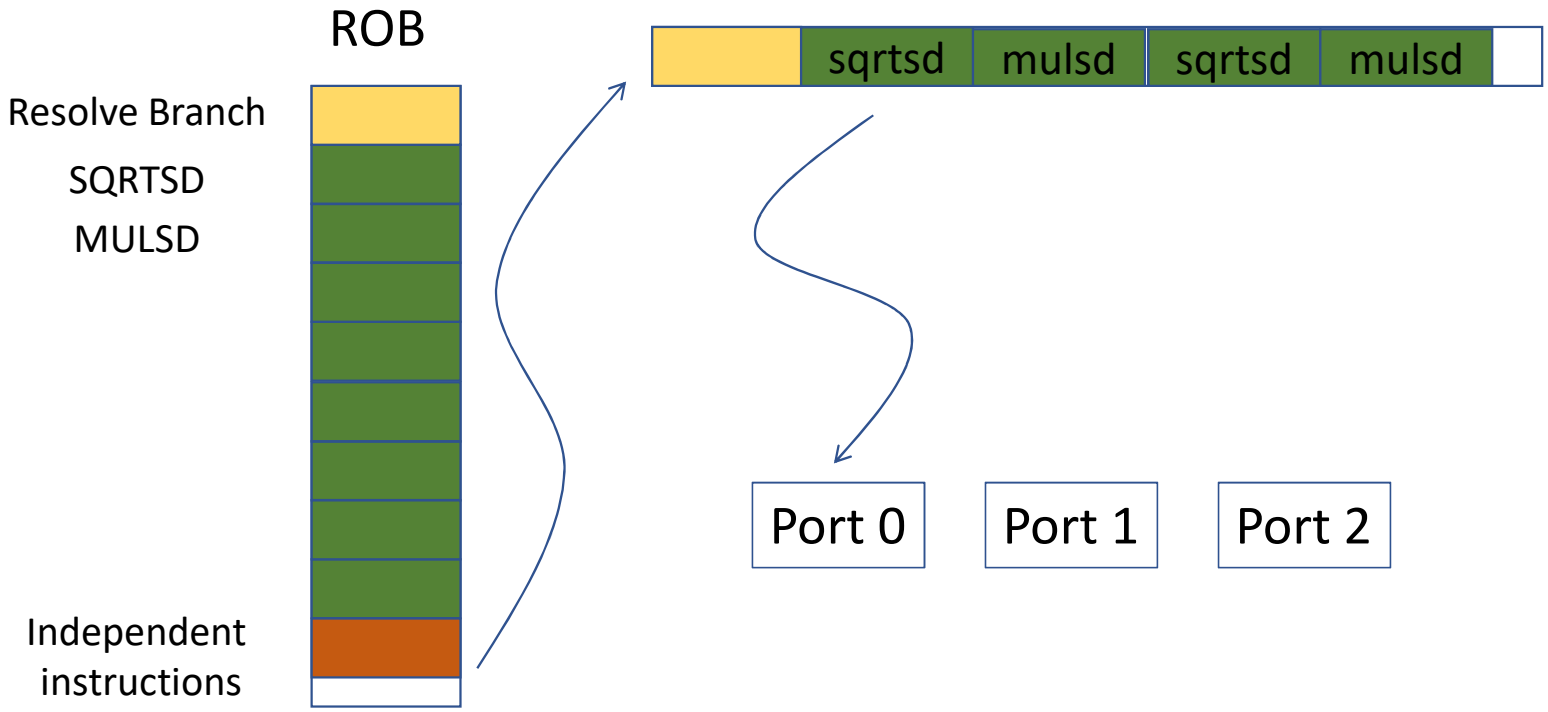
  ...
  independent_memory_access(adrs);
}
```

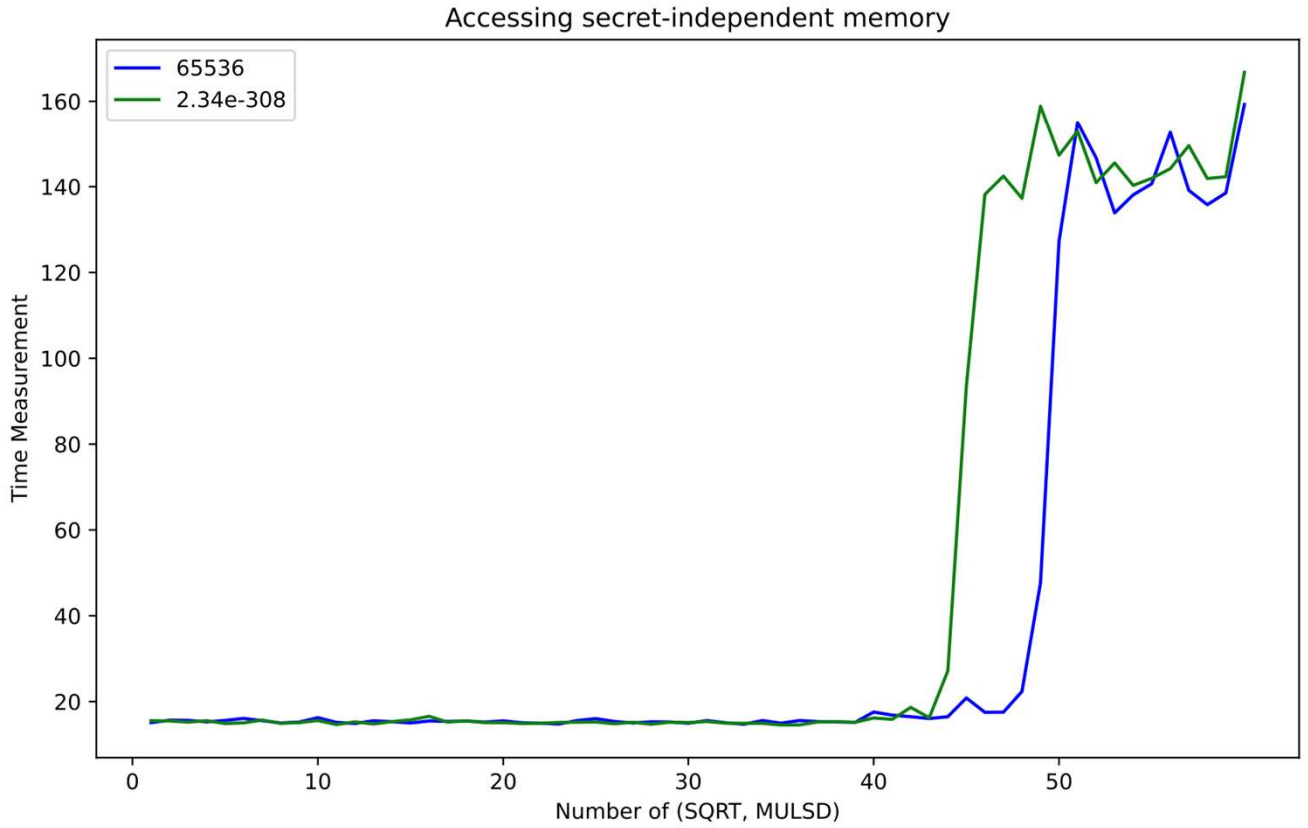
the load may not happen, if RS is not freed before the resolve of branch



Limitation of resources

```
victim(double value, int isPublic) {
  // Branch training
  for (volatile int i = 0; i < 200; i++);

  // Boundary Check
  if (isPublic) {
    value = sqrtsd(value);
    value = mulsd(value, value);
    ...
    value = sqrtsd(value);
    value = mulsd(value, value);
    memory_access(adrs);
  }
}
```



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    value = sqrtsd(value);
    value = mulsd(value, value);
    ...
    value = sqrtsd(value);
    value = mulsd(value, value);
    memory_access(adrs);
  }
}
```
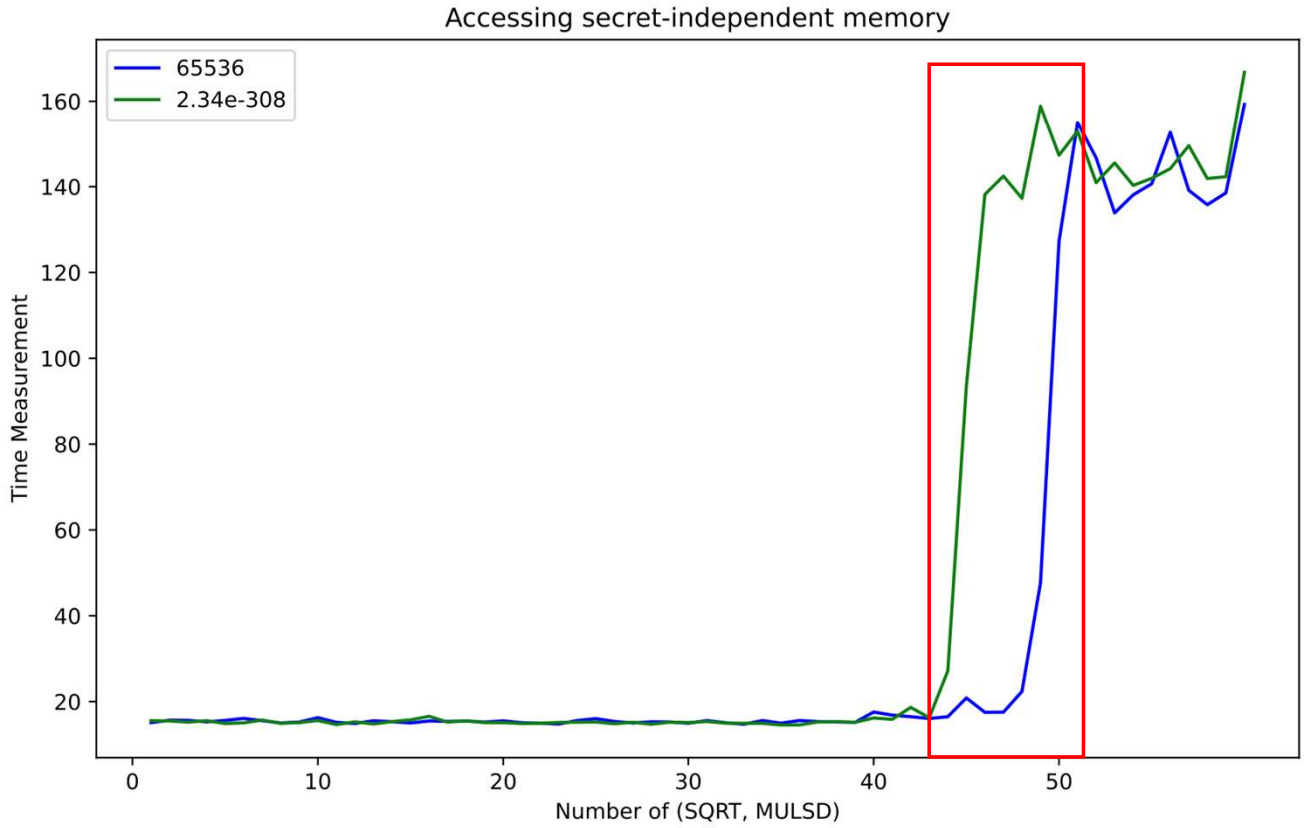



Fixing SLH

```
  // Boundary Check
  if (isPublic) {
    value = sqrtsd(value);
    value = mulsd(value, value);
    ...
    value = sqrtsd(value);
    value = mulsd(value, value);
    memory_access(adrs);
  }
}
```

Fixing SLH

```
mask = 0;
// Boundary Check
if (isPublic) {
  mask = isPublic ? mask : -1;
  value = sqrtsd(value);
  value = mulsd(value, value);
  ...
  value = sqrtsd(value);
  value = mulsd(value, value);
  memory_access(adrs);
}
```

Compiled by SLH

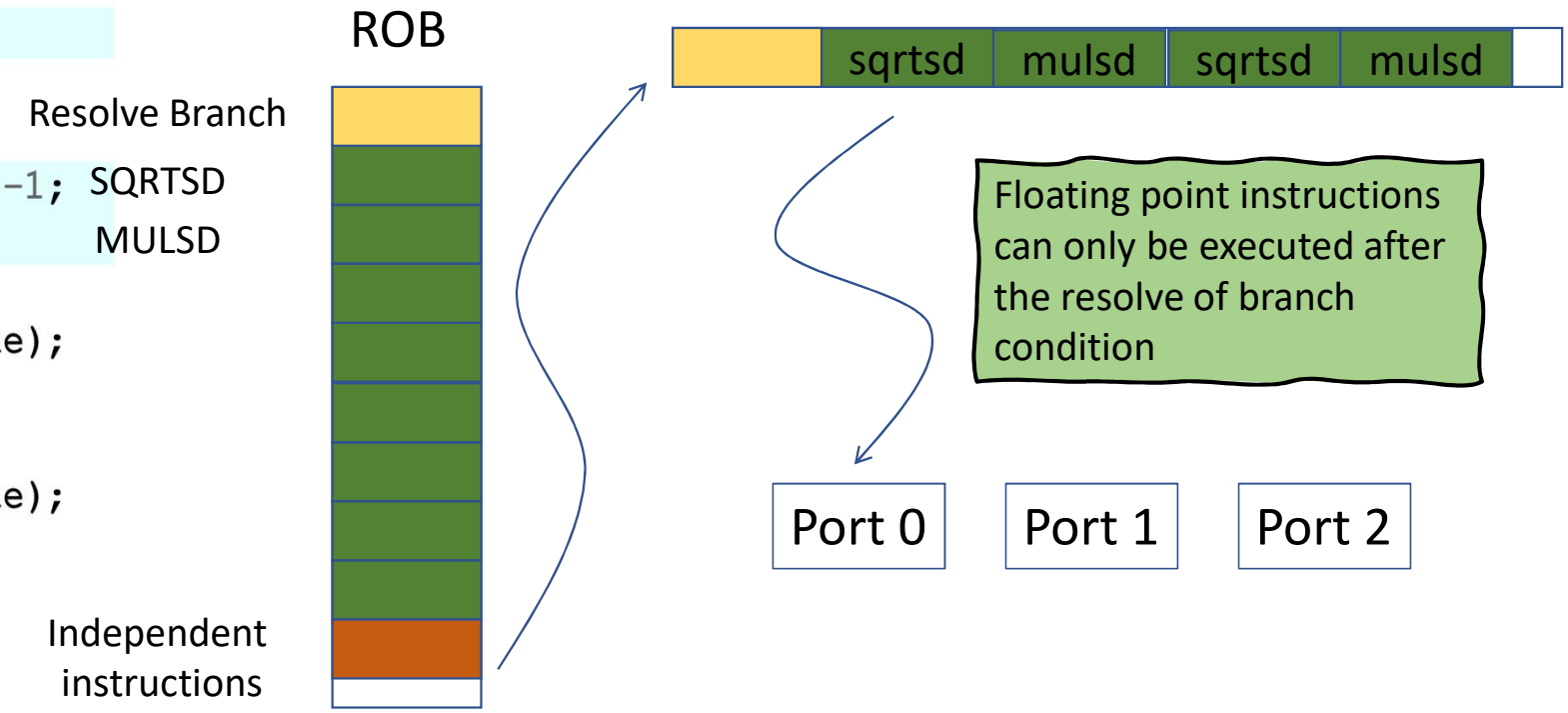
Fixing SLH

```
mask = 0;
// Boundary Check
if (isPublic) {
  mask = isPublic ? mask : -1;
  value |= mask;
  value = sqrtsd(value);
  value = mulsd(value, value);
  ...
  value = sqrtsd(value);
  value = mulsd(value, value);
  memory_access(adrs);
}
```

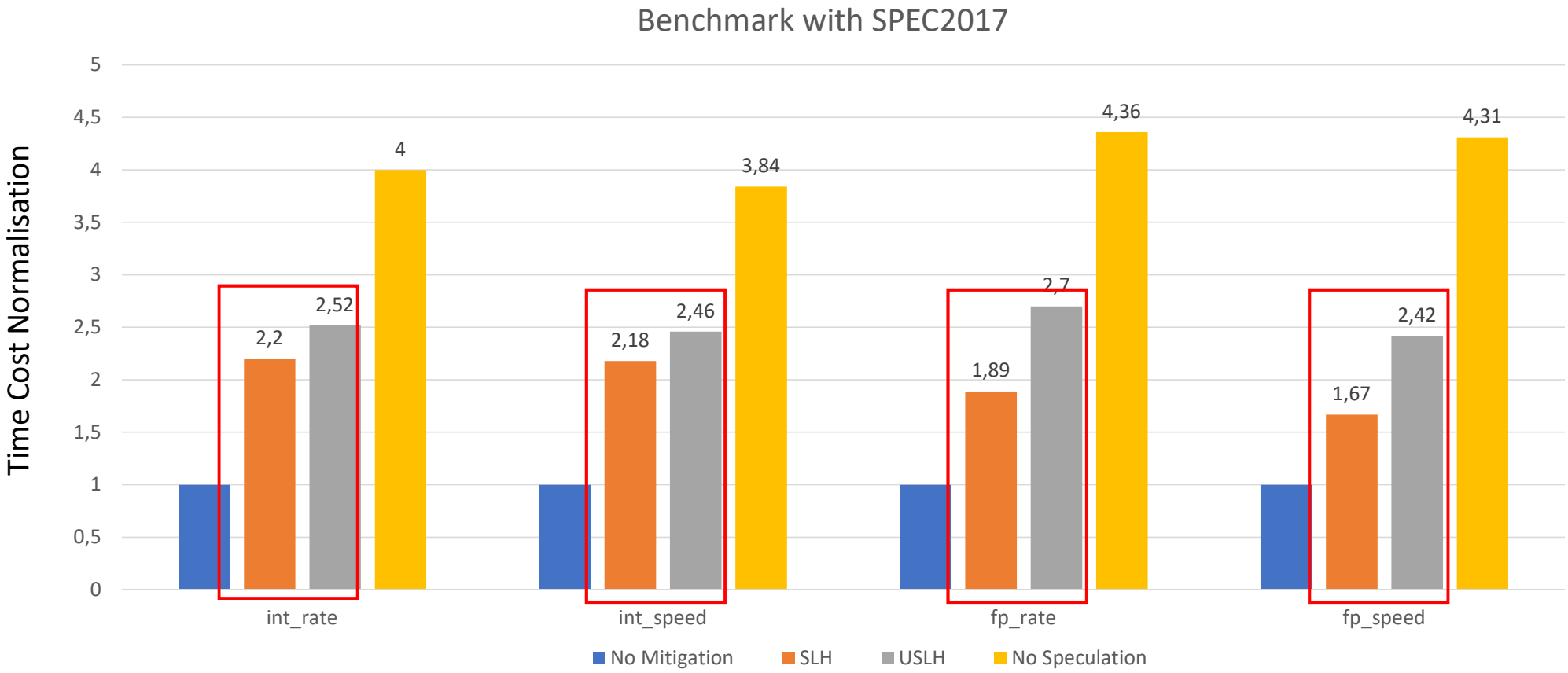
Compiled by USLH

Fixing SLH

```
mask = 0;
// Boundary Check
if (isPublic) {
  mask = isPublic ? mask : -1;
  value |= mask;
  value = sqrtsd(value);
  value = mulsd(value, value);
  ...
  value = sqrtsd(value);
  value = mulsd(value, value);
  memory_access(adrs);
}
```



Performance



Summary

- SLH is good, but it is not perfect
- Variable-time executions also leak secret in speculative execution
- Accessing a secret-independent memory may also leak information
- USLH costs more, but it is still better than disabling speculative execution