Dynamic Process Isolation

Black Hat Asia 2022

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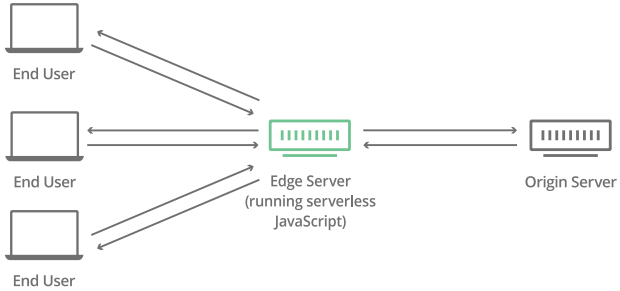
Graz University of Technology

Andreas Kogler
Graz University of Technology

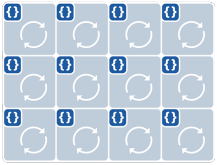
Daniel Gruss
Graz University of Technology

- Cloudflare Workers is one of the top edge-computing systems



Pietro Borrello (@borrello_pietro) Andreas Kogler (@0xhilbert)

- Cloudflare Workers is one of the top edge-computing systems
- Single-process design



Pietro Borrello (@borrello_pietro) Andreas Kogler (@0xhilbert)

- Cloudflare Workers is one of the top edge-computing systems
- Single-process design
- Vulnerable to Spectre attacks?

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- No local timers

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- Vulnerable to Spectre attacks?
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- Number of memory, (sub-)requests, runtime is limited

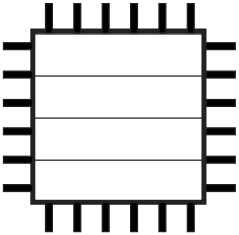
Pietro Borrello (@borrello_pietro) Andreas Kogler (@0xhilbert)

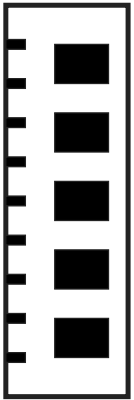
- Cloudflare Workers is one of the top edge-computing systems
- Single-process design
- Vulnerable to Spectre attacks?
- No local timers
- Number of memory, (sub-)requests, runtime is limited
- If an attack is possible, we need a low-overhead solution!

Pietro Borrello (@borrello_pietro) Andreas Kogler (@0xhilbert)

```
maccess(i);

maccess(i);
```





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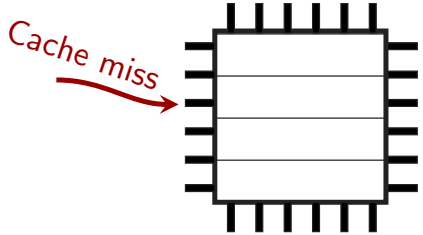
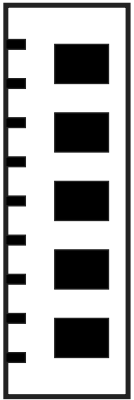
```





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```
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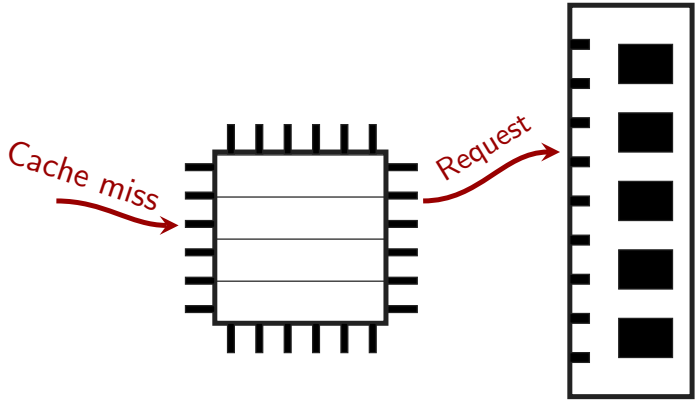
```



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```
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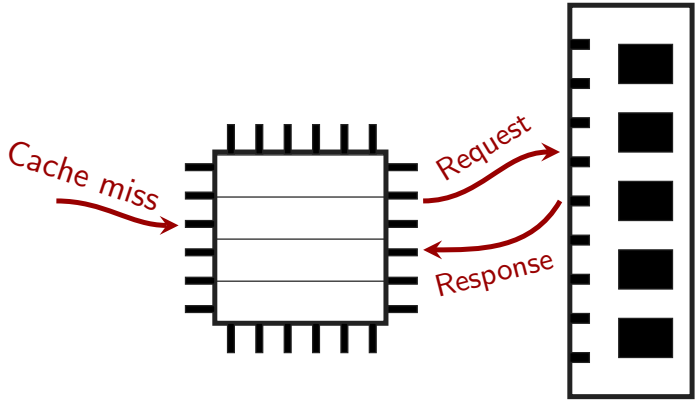
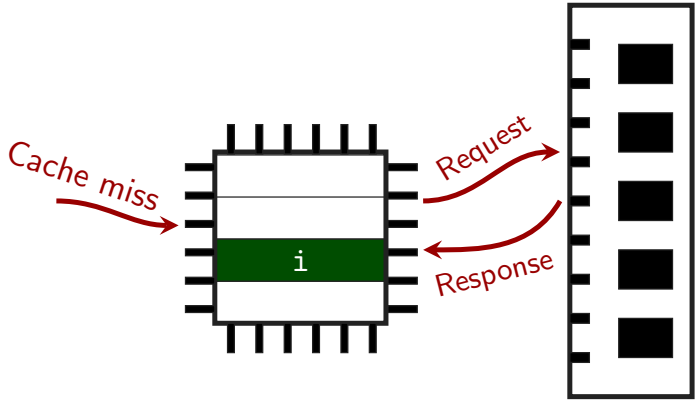
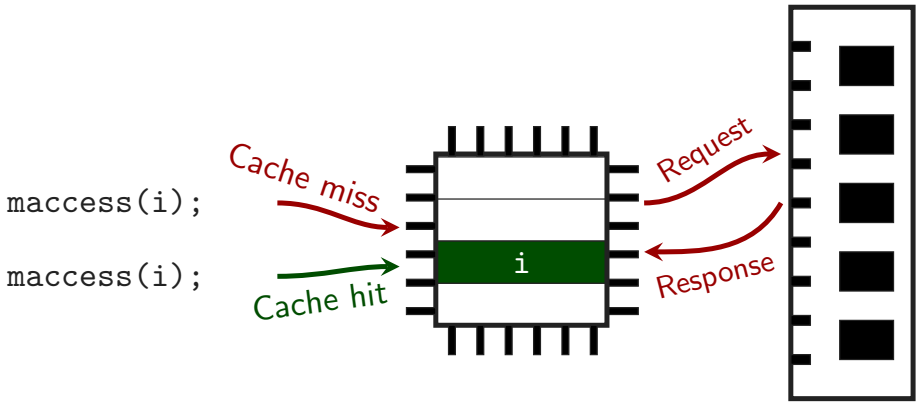
maccess(i);
```

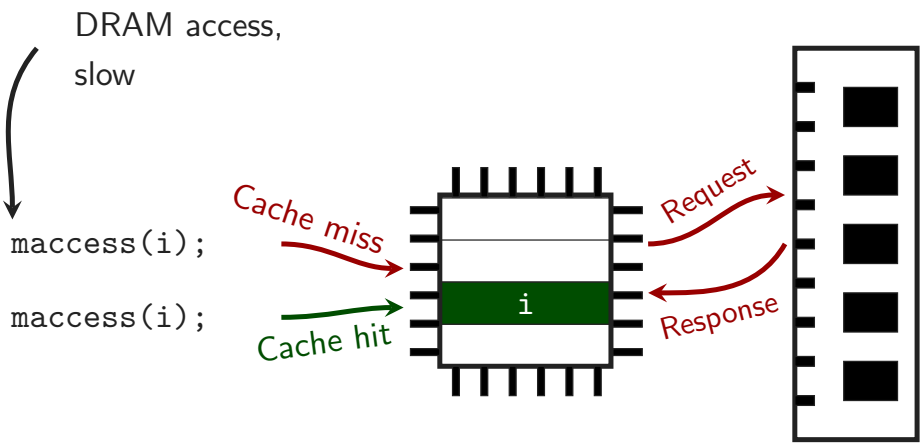


```
maccess(i);

maccess(i);
```




maccess(i);
maccess(i);
Cache miss
Cache hit
i
Request
Response



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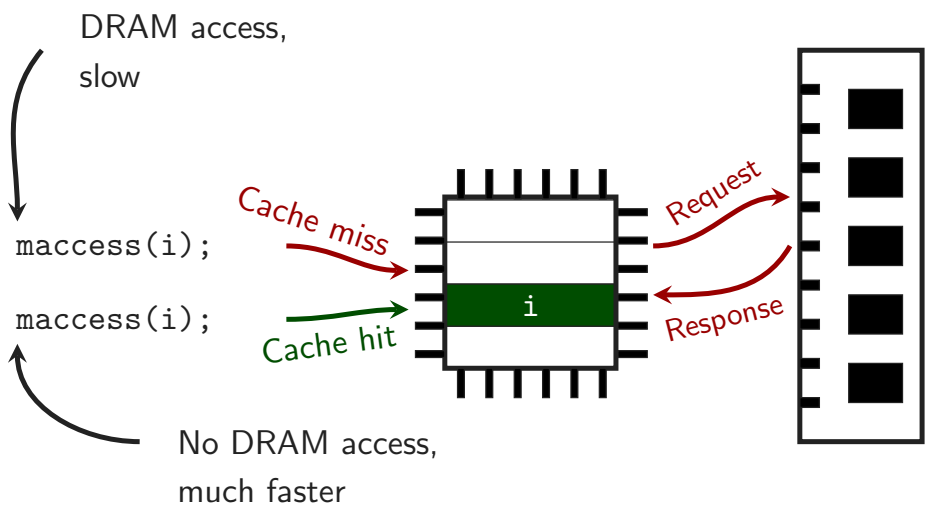

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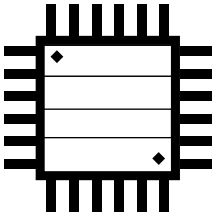
Shared Memory

ATTACKER

flush

access



VICTIM

access

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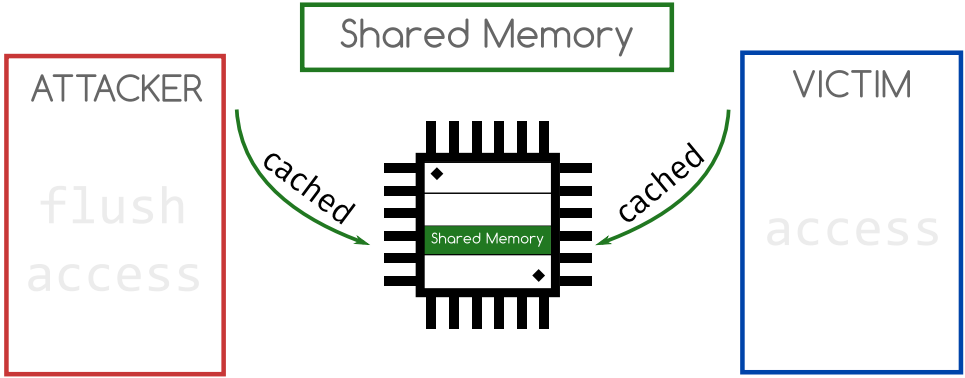

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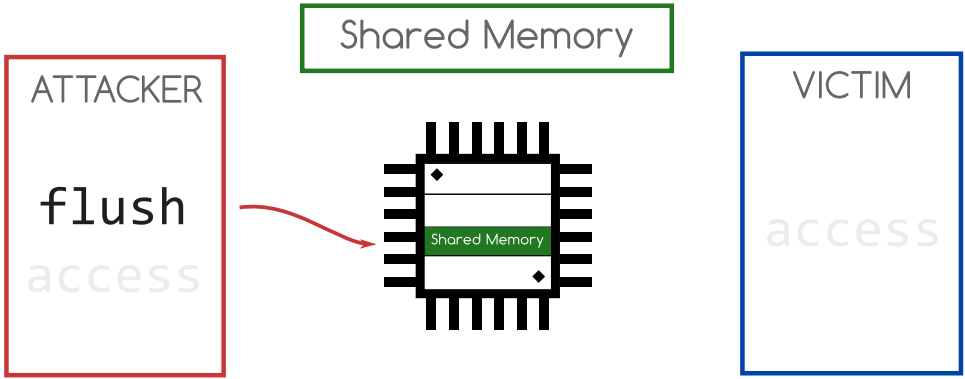
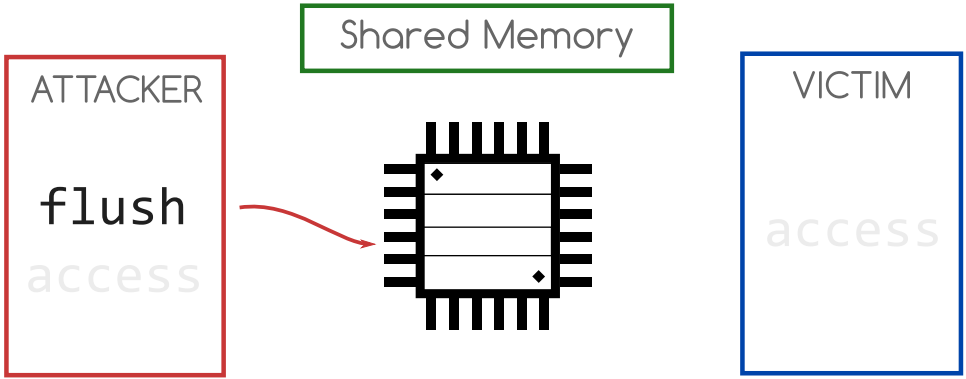

Shared Memory
ATTACKER
flush
access
Shared Memory
VICTIM
access



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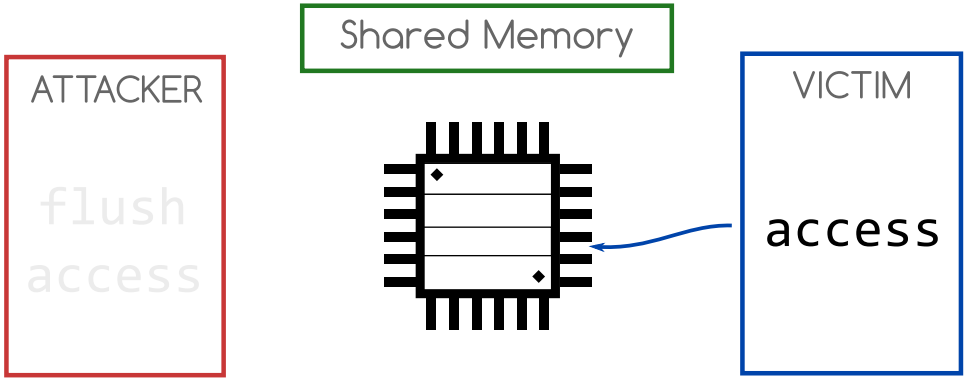

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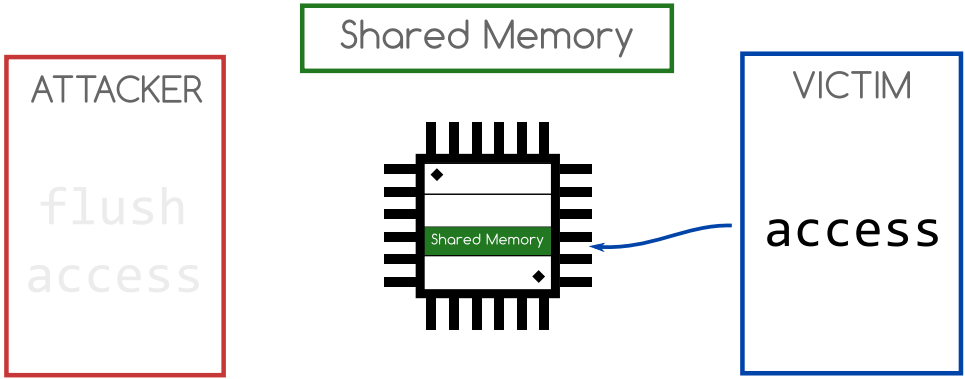
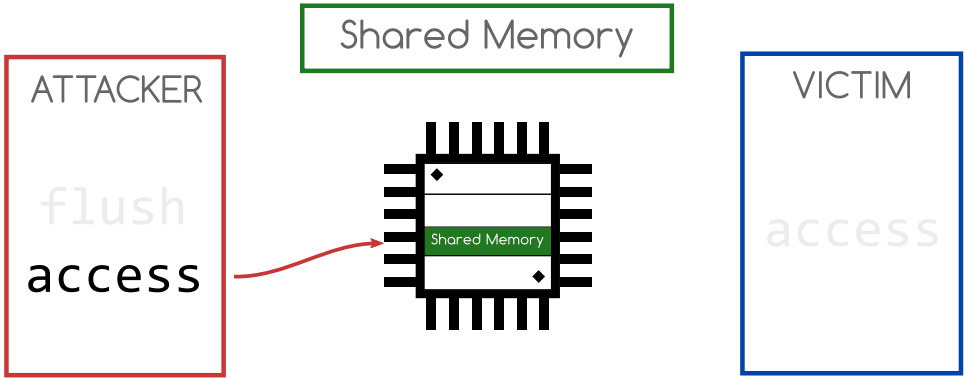

Shared Memory
ATTACKER
flush
access
Shared Memory
VICTIM
access


Shared Memory
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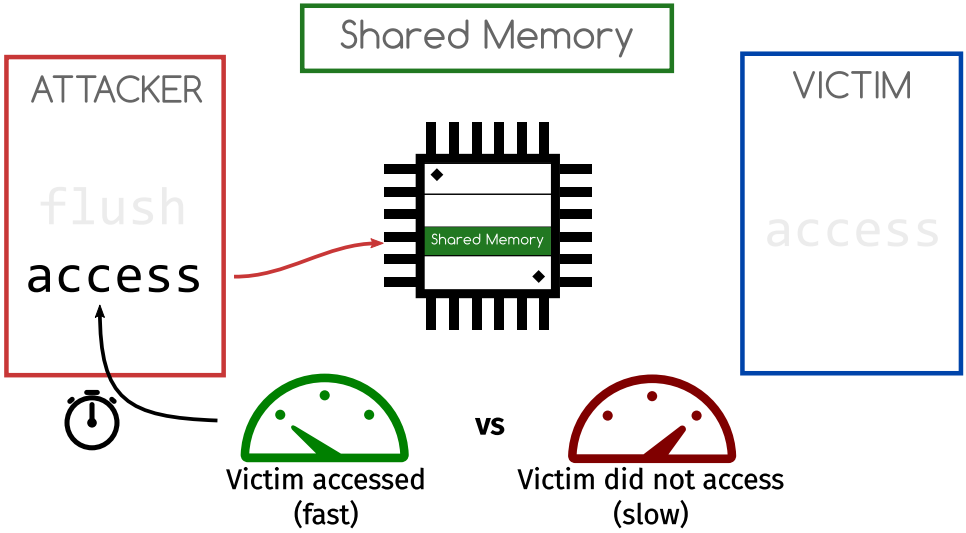


Pietro Borrello (@borrello_pietro) Andreas Kogler (@0xhilbert)

Spectre-PHT gadget

```
if (index < data_size)
{
  y = lut[data[index]*4096]
}
```


Pietro Borrello (@borrello_pietro) Andreas Kogler (@0xhilbert)

```
index = 0
```

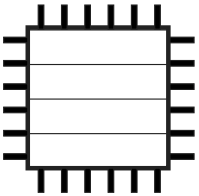
Lookup Table

	A	B
C	D	E
F	G	H
I	J	K
L	M	N
O	P	Q
R	S	T
U	V	W
X	Y	Z

```
if (index < 4)
```

then → `lut[data[index]]`

else → `{}`



Memory

D	data[0]
A	data[1]
T	data[2]
A	data[3]
K	
E	
Y	
...	

Pietro Borrello (@borrello_pietro) Andreas Kogler (@0xhilbert)

Spectre-PHT (aka Spectre Variant 1)

```
index = 0
```

```
if (index < 4)
```

then

```
lut[data[index]]
```

else

Speculate

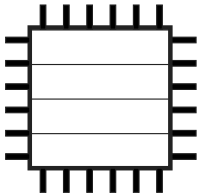
{}

Lookup Table

	A	B
C	D	E
F	G	H
I	J	K
L	M	N
O	P	Q
R	S	T
U	V	W
X	Y	Z

Memory

D	data[0]
A	data[1]
T	data[2]
A	data[3]
K	
E	
Y	
...	



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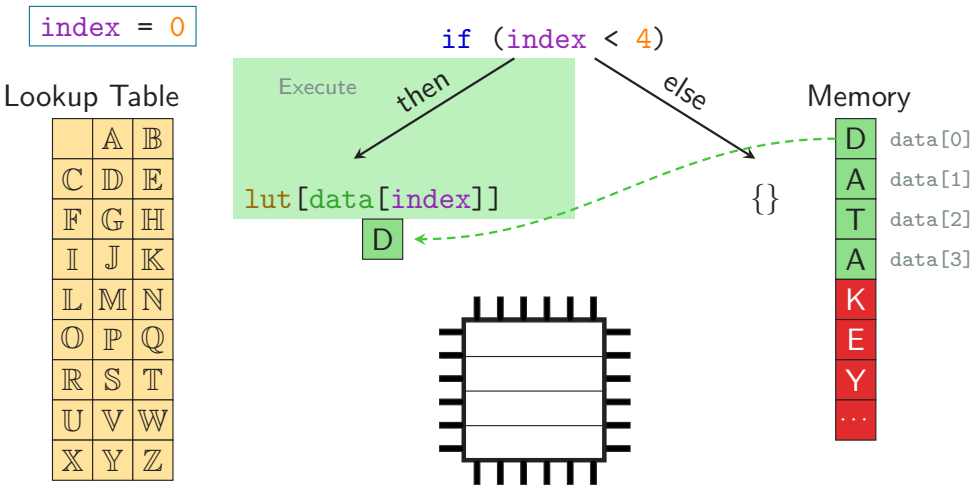

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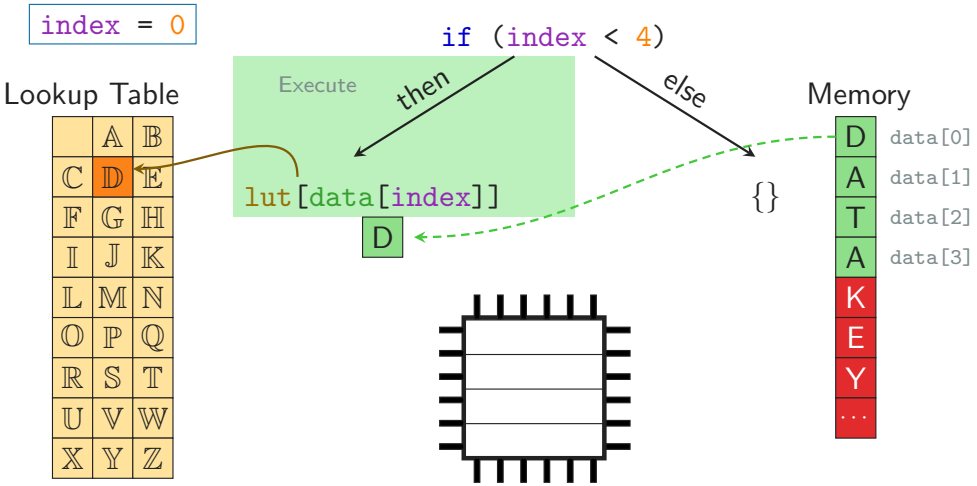
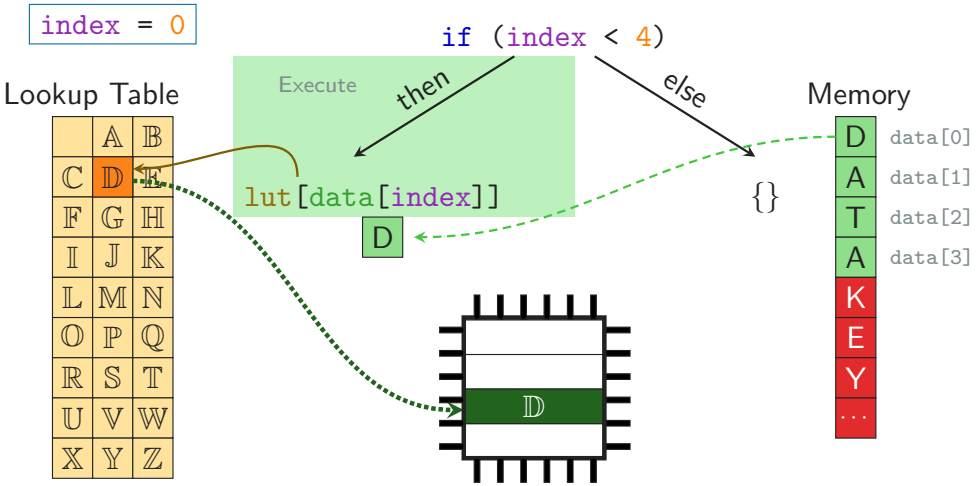
Spectre-PHT (aka Spectre Variant 1)



Spectre-PHT (aka Spectre Variant 1)



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```
index = 1
```

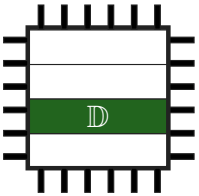
Lookup Table

	A	B
C	D	E
F	G	H
I	J	K
L	M	N
O	P	Q
R	S	T
U	V	W
X	Y	Z

```
if (index < 4)
```

then → `lut[data[index]]`

else → `{}`



Memory

D	data[0]
A	data[1]
T	data[2]
A	data[3]
K	
E	
Y	
...	

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```
index = 1
```

```
if (index < 4)
```

Speculate

then

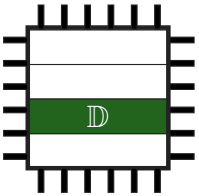
else

```
lut[data[index]]
```

{}

Lookup Table

	A	B
C	D	E
F	G	H
I	J	K
L	M	N
O	P	Q
R	S	T
U	V	W
X	Y	Z



Memory

D	data[0]
A	data[1]
T	data[2]
A	data[3]
K	
E	
Y	
...	

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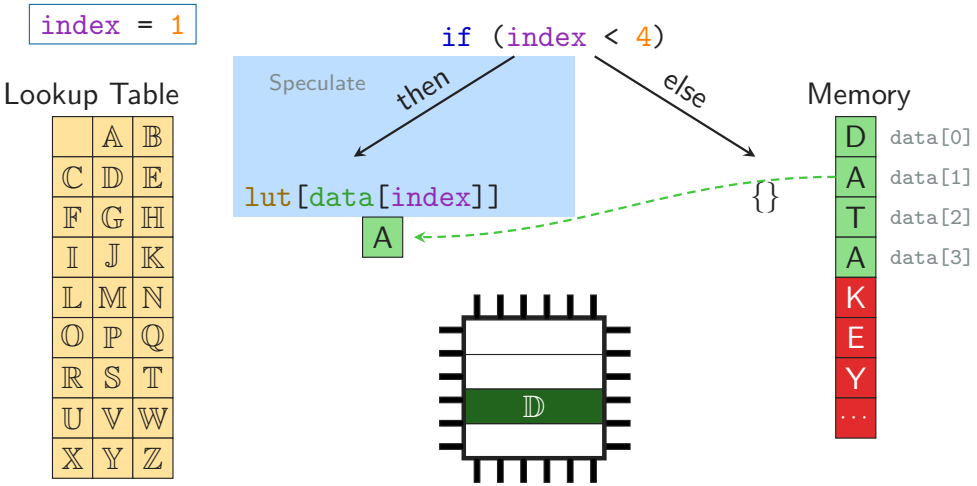
Spectre-PHT (aka Spectre Variant 1)



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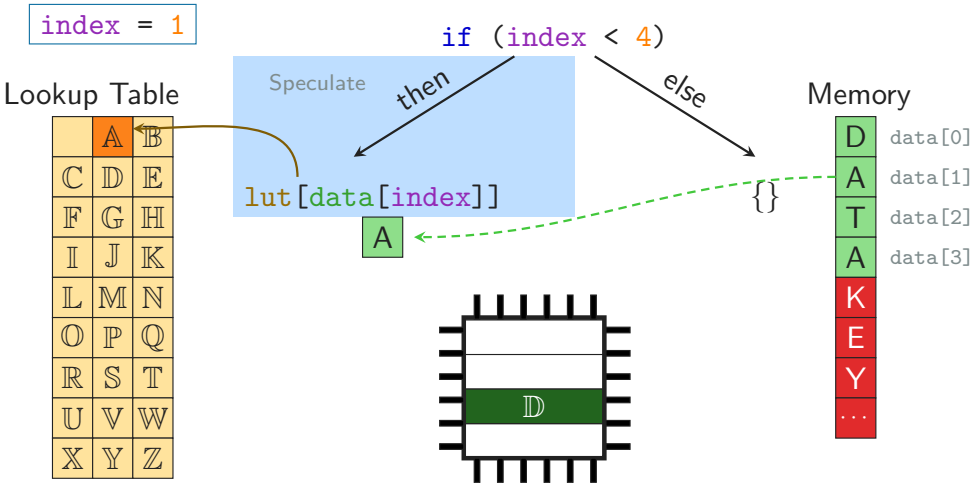

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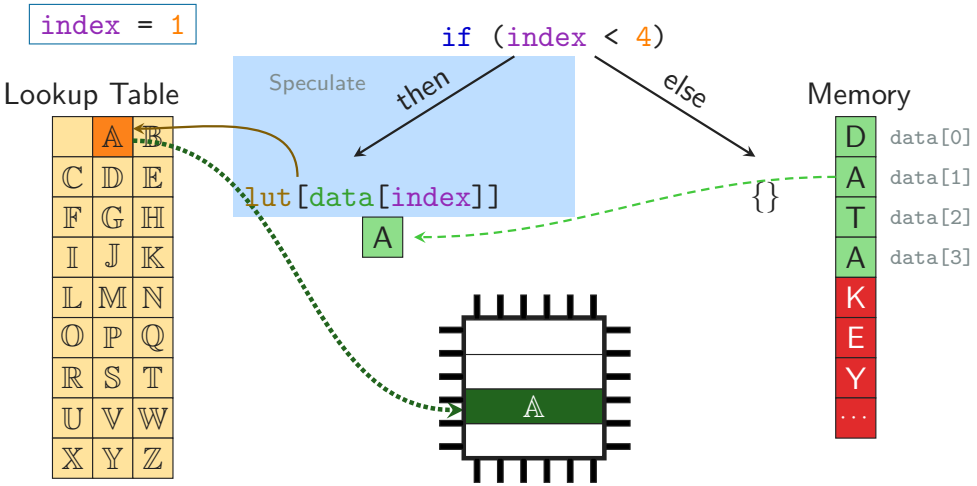


Pietro Borrello (@borrello_pietro) Andreas Kogler (@0xhilbert)

```
index = 1
```

```
if (index < 4)
```

then

Execute

```
lut[data[index]]
```

else

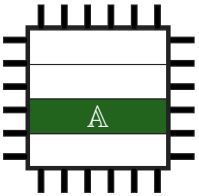
{}

Lookup Table

	A	B
C	D	E
F	G	H
I	J	K
L	M	N
O	P	Q
R	S	T
U	V	W
X	Y	Z

Memory

D	data[0]
A	data[1]
T	data[2]
A	data[3]
K	
E	
Y	
...	



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Spectre-PHT (aka Spectre Variant 1)

```
index = 2
```

```
if (index < 4)
```

Speculate

then

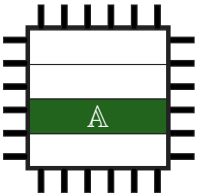
```
lut[data[index]]
```

else

{}

Lookup Table

	A	B
C	D	E
F	G	H
I	J	K
L	M	N
O	P	Q
R	S	T
U	V	W
X	Y	Z



Memory

D	data[0]
A	data[1]
T	data[2]
A	data[3]
K	
E	
Y	
...	

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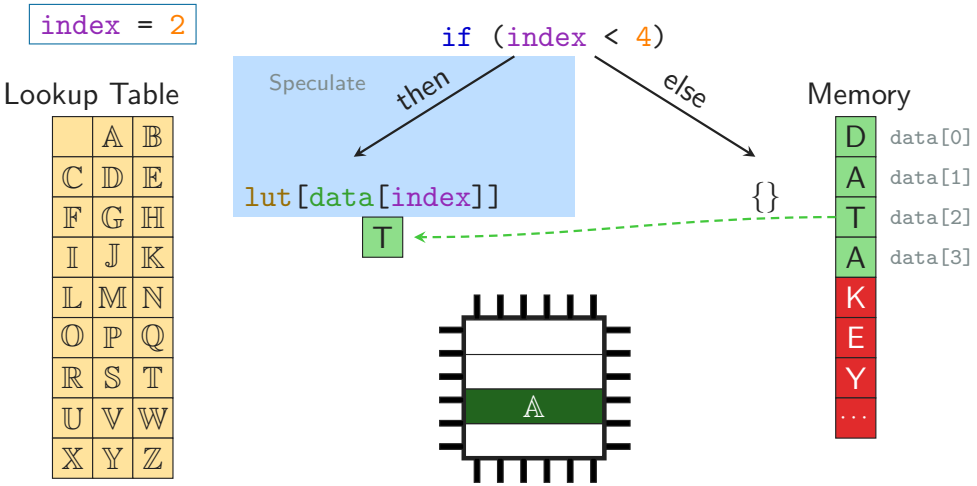

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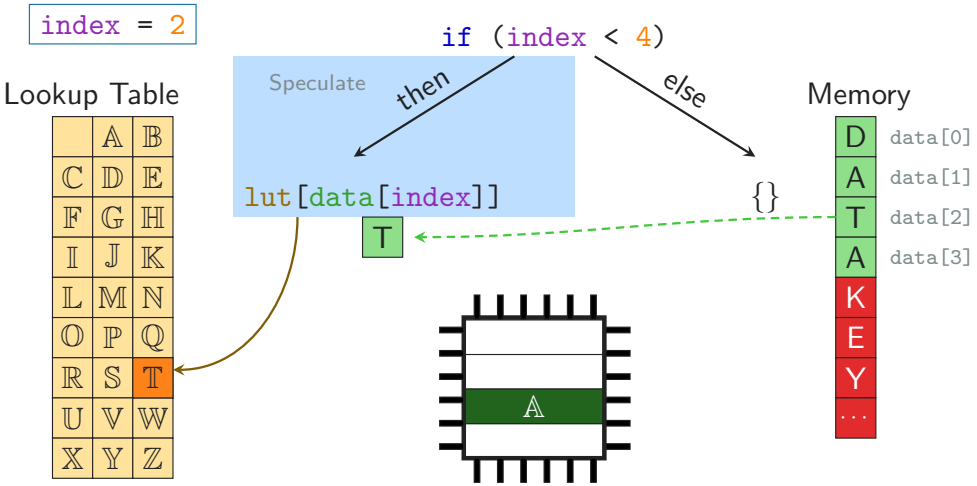

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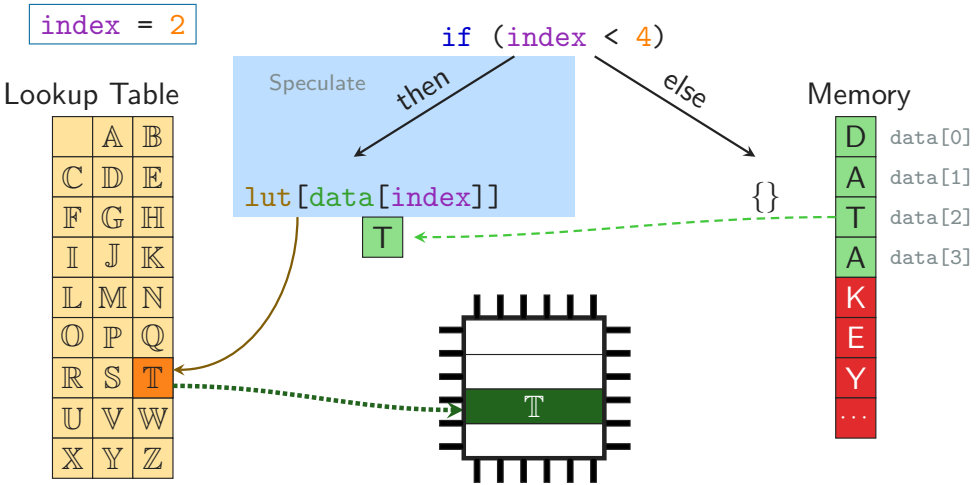
Spectre-PHT (aka Spectre Variant 1)



Pietro Borrello (@borrello_pietro) Andreas Kogler (@0xhilbert)

```
index = 2
```

```
if (index < 4)
```

Execute

then

```
lut[data[index]]
```

else

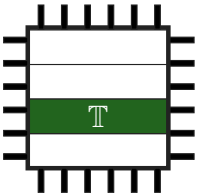
{}

Lookup Table

	A	B
C	D	E
F	G	H
I	J	K
L	M	N
O	P	Q
R	S	T
U	V	W
X	Y	Z

Memory

D	data[0]
A	data[1]
T	data[2]
A	data[3]
K	
E	
Y	
...	



Spectre-PHT (aka Spectre Variant 1)

```
index = 3
```

```
if (index < 4)
```

Speculate

then

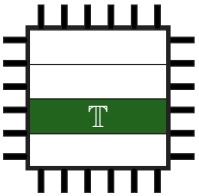
```
lut[data[index]]
```

else

{}

Lookup Table

	A	B
C	D	E
F	G	H
I	J	K
L	M	N
O	P	Q
R	S	T
U	V	W
X	Y	Z



Memory

D	data[0]
A	data[1]
T	data[2]
A	data[3]
K	
E	
Y	
...	

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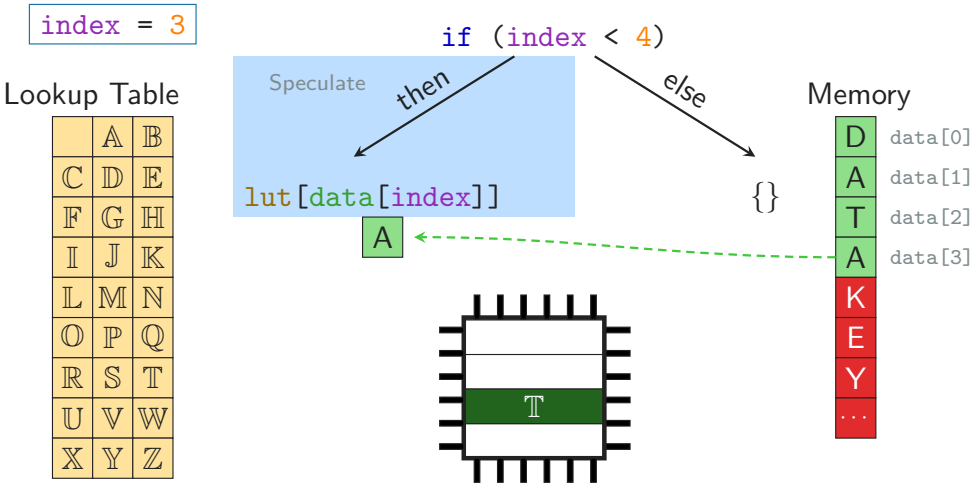
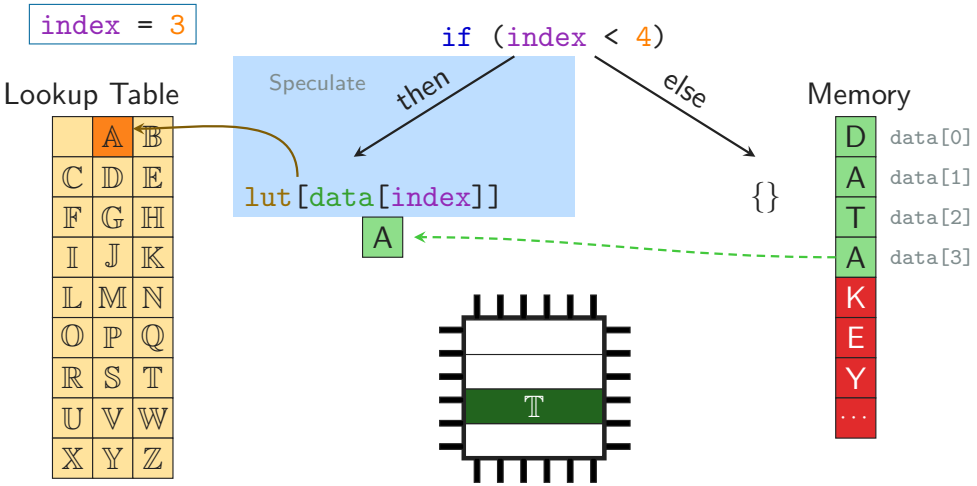
Spectre-PHT (aka Spectre Variant 1)



Pietro Borrello (@borrello_pietro) Andreas Kogler (@0xhilbert)

Spectre-PHT (aka Spectre Variant 1)



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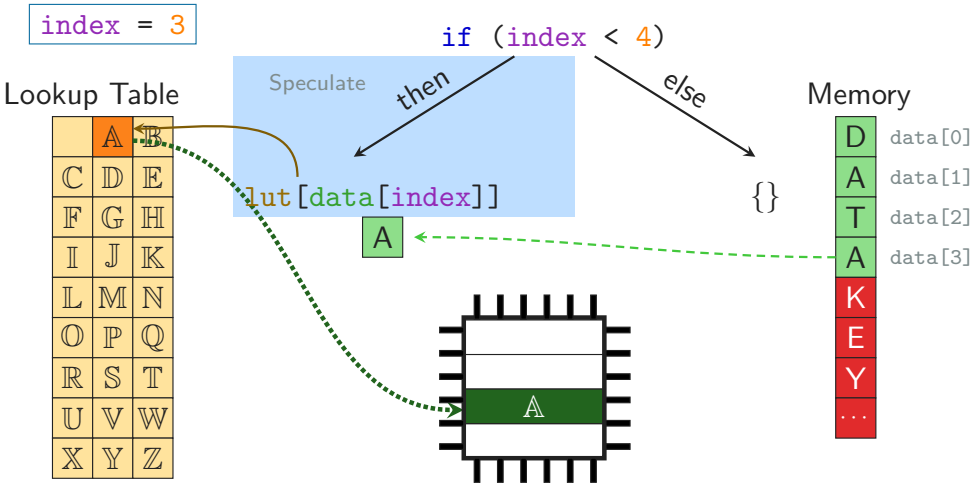
Spectre-PHT (aka Spectre Variant 1)



Pietro Borrello (@borrello_pietro) Andreas Kogler (@0xhilbert)

```
index = 3
```

```
if (index < 4)
```

Execute

then

else

```
lut[data[index]]
```

{}

Lookup Table

	A	B
C	D	E
F	G	H
I	J	K
L	M	N
O	P	Q
R	S	T
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Memory

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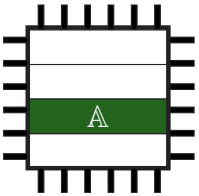


Pietro Borrello (@borrello_pietro) Andreas Kogler (@0xhilbert)

```
index = 4
```

```
if (index < 4)
```

Speculate

then

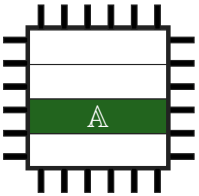
```
lut[data[index]]
```

else

{}

Lookup Table

	A	B
C	D	E
F	G	H
I	J	K
L	M	N
O	P	Q
R	S	T
U	V	W
X	Y	Z



Memory

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A	data[1]
T	data[2]
A	data[3]
K	
E	
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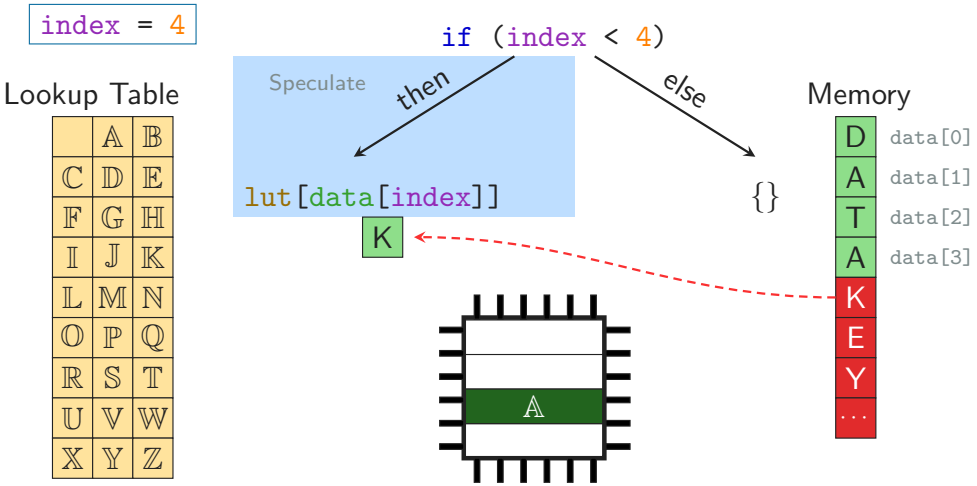
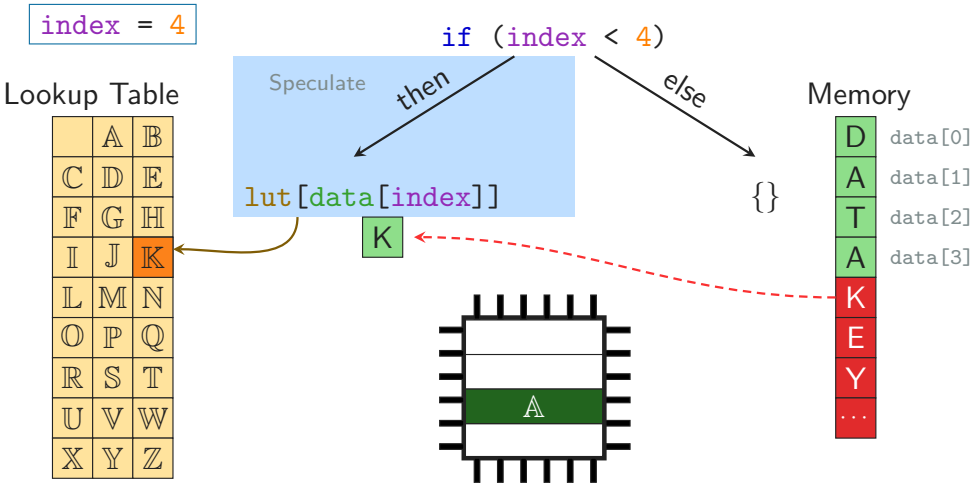
...	

Pietro Borrello (@borrello_pietro) Andreas Kogler (@0xhilbert)

Spectre-PHT (aka Spectre Variant 1)



Pietro Borrello (@borrello_pietro) Andreas Kogler (@0xhilbert)



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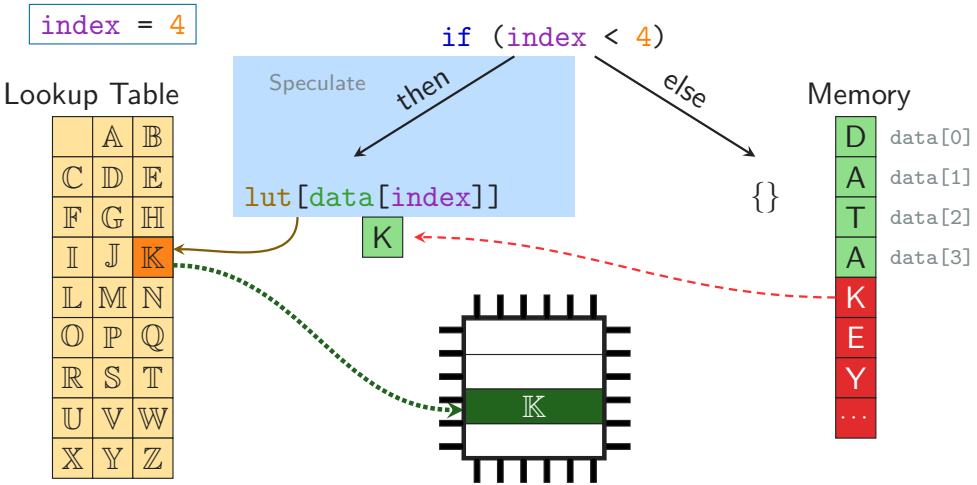
Spectre-PHT (aka Spectre Variant 1)



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```
index = 4
```

Lookup Table

	A	B
C	D	E
F	G	H
I	J	K
L	M	N
O	P	Q
R	S	T
U	V	W
X	Y	Z

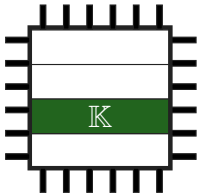
```
if (index < 4)
```

then

```
lut[data[index]]
```

else

Execute {}



Memory

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A	data[1]
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A	data[3]
K	
E	
Y	
...	

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Application-Level

Spectre Mitigations

Application-Level

System-Level

Pietro Borrello (@borrello_pietro) Andreas Kogler (@0xhilbert)

Spectre Mitigations

Application-Level

System-Level

Hardware-Level

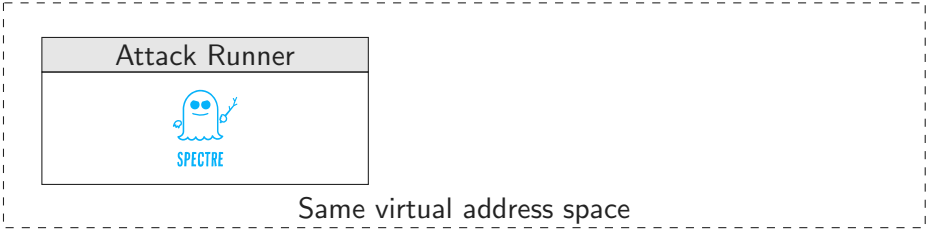
- Freeze the time during execution

- Freeze the time during execution
- No native code

- Freeze the time during execution
- No native code
- No shared-memory

- Freeze the time during execution
- No native code
- No shared-memory
- No multithreading

High-level Attack Overview



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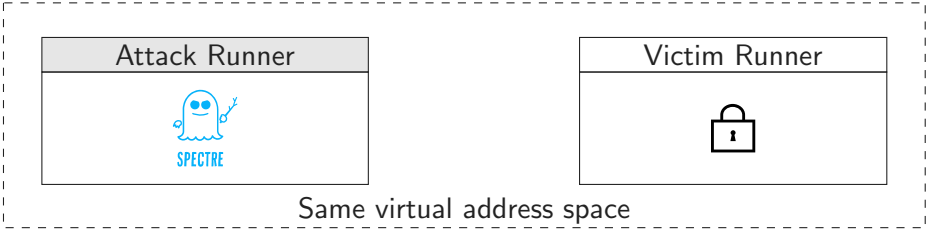
High-level Attack Overview



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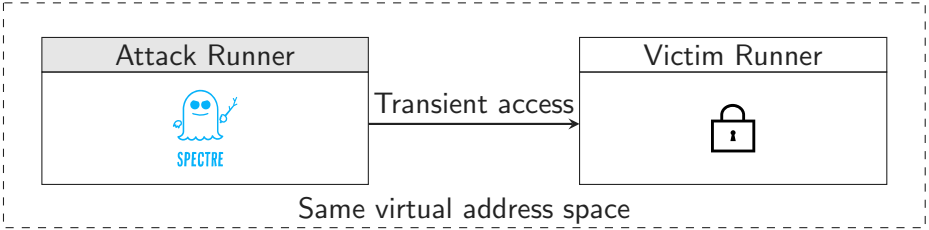
High-level Attack Overview



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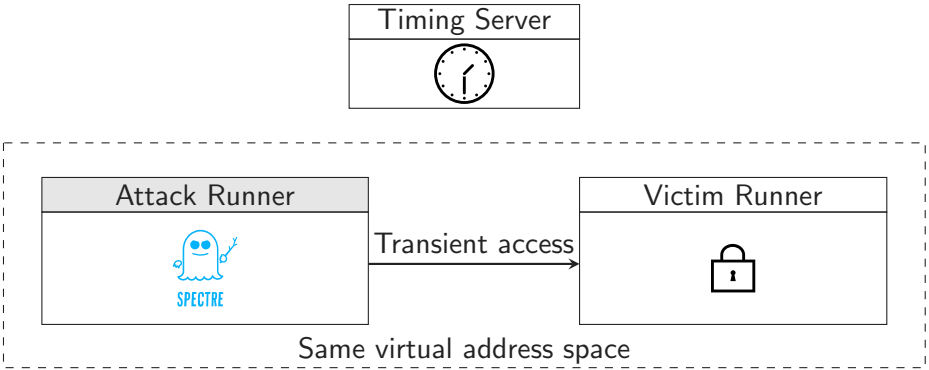
High-level Attack Overview



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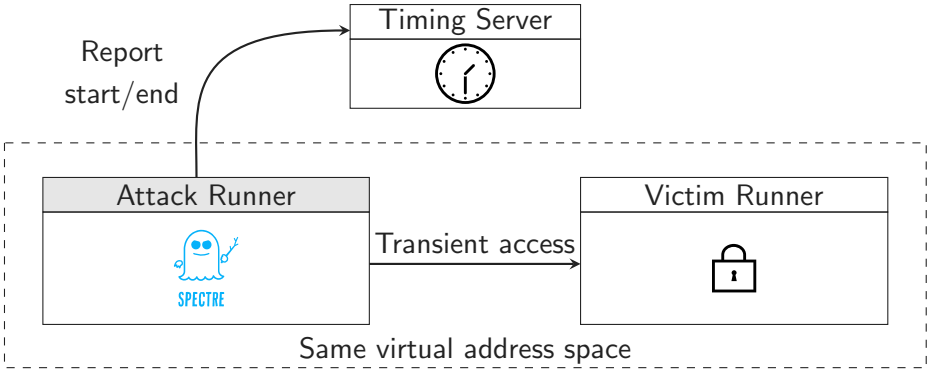
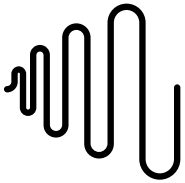
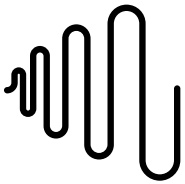
High-level Attack Overview

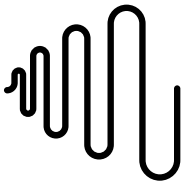


- **Amplify** timing either:

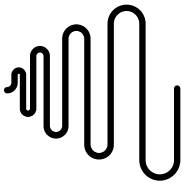




- **Amplify** timing either:
  - Encode secret into **multiple** cache lines



- **Amplify** timing either:
  - Encode secret into **multiple** cache lines
  - Loop over gadget *n* times



- **Amplify** timing either:
  - Encode secret into **multiple** cache lines
  - Loop over gadget *n* times

```
for (int i = 0; i < N; i++) {
  // evict A and B
  // ...
  if (secret_bit) { access A } // transient
  else { access B }
  access A
}
```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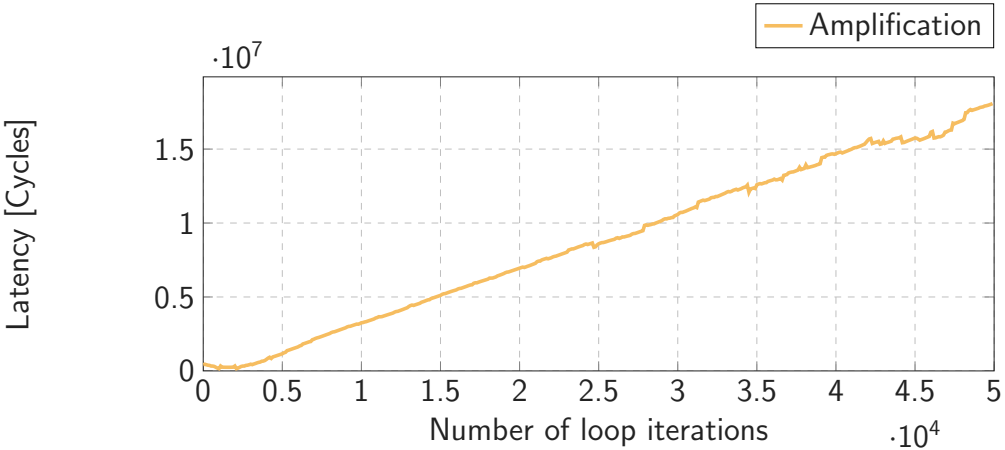

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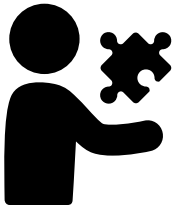
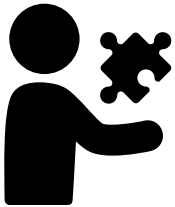
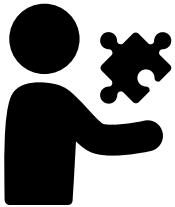


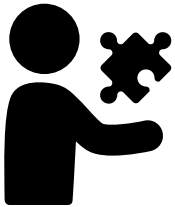
- No native code execution



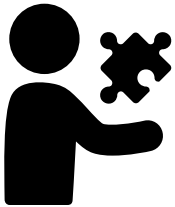
- No native code execution
  - Cannot **Flush & Reload** memory



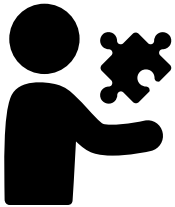
- No native code execution
  - Cannot **Flush & Reload** memory
  - Cannot even build **eviction sets**



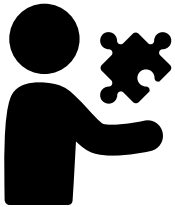
- No native code execution
  - Cannot **Flush & Reload** memory
  - Cannot even build **eviction sets**
  - ✓ Evict the whole cache iterating over a huge array



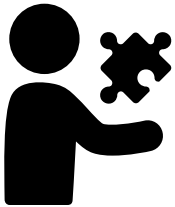
- JavaScript is optimized and deoptimized



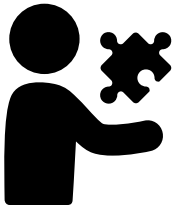
- JavaScript is optimized and deoptimized
  - Use **assumptions** on variables



- JavaScript is optimized and deoptimized
  - Use **assumptions** on variables
  - Deoptimize if **invalidated**



- JavaScript is optimized and deoptimized
  - Use **assumptions** on variables
  - Deoptimize if **invalidated**
  - ✓ Hide the attack behind a **mispredicted** branch



- JavaScript is optimized and deoptimized
  - Use **assumptions** on variables
  - Deoptimize if **invalidated**
  - ✓ Hide the attack behind a **mispredicted** branch
  - ✓ **Prevent** inlining and further optimizations using huge functions

- JavaScript objects cannot index the whole memory

Pietro Borrello (@borrello_pietro) Andreas Kogler (@0xhilbert)

- JavaScript objects cannot index the whole memory
- To leak from different workers you need **64-bit addresses**

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- To leak from different workers you need **64-bit addresses**

✓ Use **ArrayBuffers** to leak the whole 64-bit address space

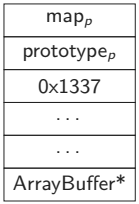
Speculative Type Confusion I

- JavaScript objects cannot index the whole memory
- To leak from different workers you need **64-bit addresses**

✓ Use **ArrayBuffers** to leak the whole 64-bit address space

✓ Create objects of different types and **confuse** branch predictor

Speculative Type Confusion II

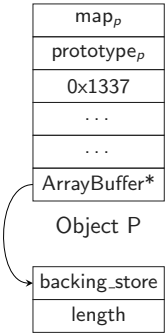


Object P

```
obj = {
  i: 0x1337,
  ...,
  ptr: new ArrayBuffer(0x1000),
};

if (obj instanceof ObjP) {
  leak(obj.ptr[0])
}
```


Pietro Borrello (@borrello_pietro) Andreas Kogler (@0xhilbert)




```
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if (obj instanceof ObjP) {
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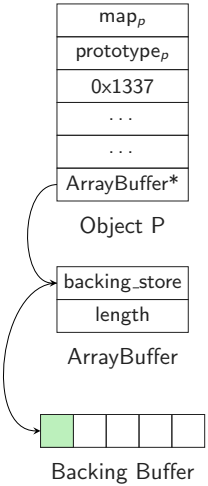
Speculative Type Confusion II

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  i: 0x1337,
  ...,
  ptr: new ArrayBuffer(0x1000),
};

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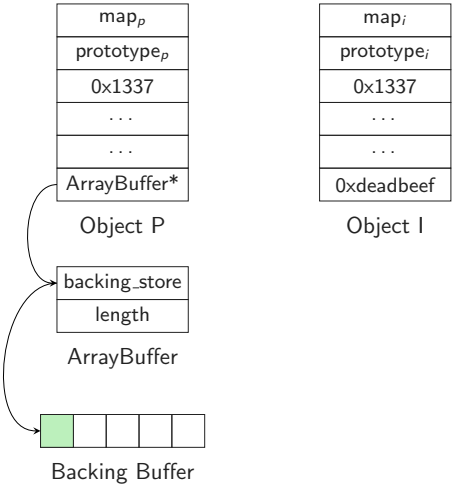
Pietro Borrello (@borrello_pietro) Andreas Kogler (@0xhilbert)

Speculative Type Confusion II

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Pietro Borrello (@borrello_pietro) Andreas Kogler (@0xhilbert)

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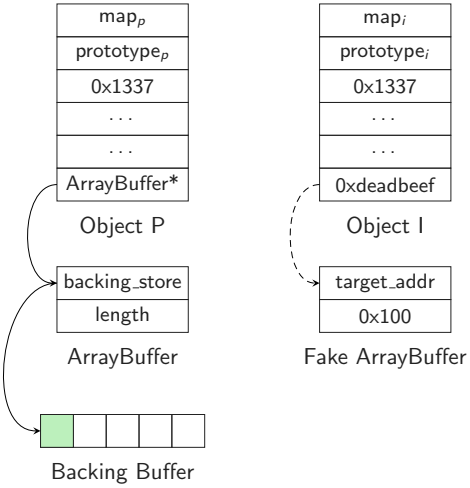


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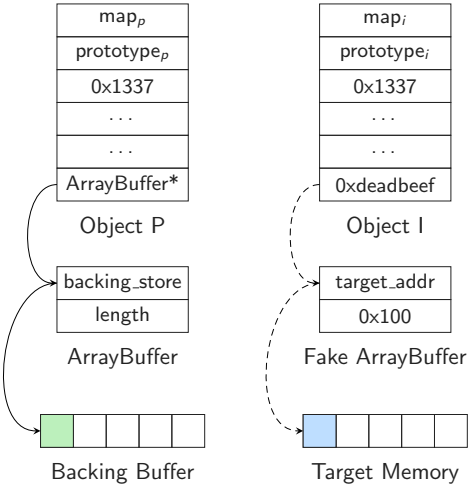


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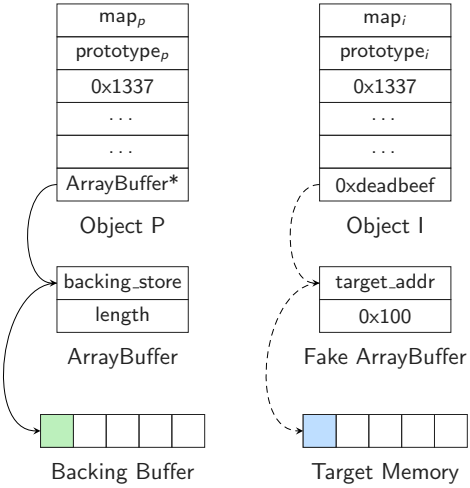


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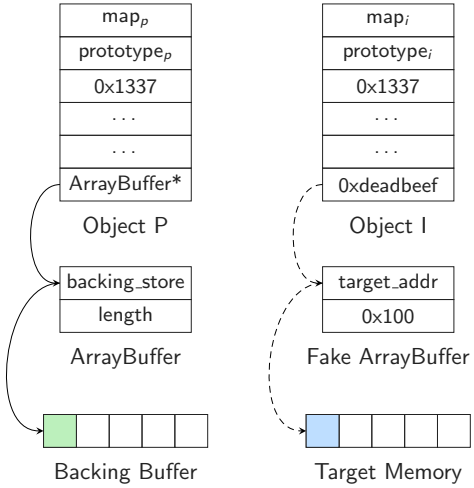


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Pietro Borrello (@borrello_pietro) Andreas Kogler (@0xhilbert)

DEMO

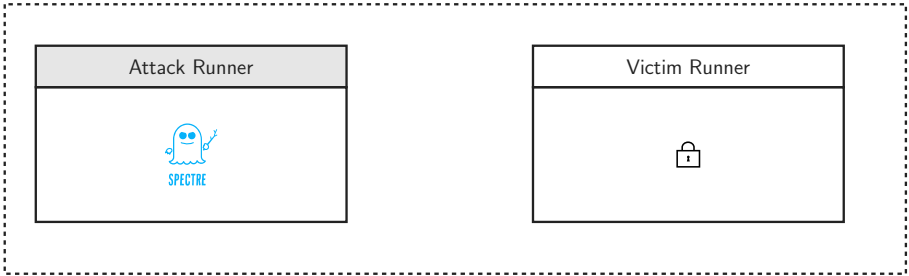
- **Leak** 120 bit/hour over the network

- **Leak** 120 bit/hour over the network
- Works within the offered runtime of 30 seconds

- **Leak** 120 bit/hour over the network
- Works within the offered runtime of 30 seconds
- Use speculative **type confusion** to create 64-bit leak primitive

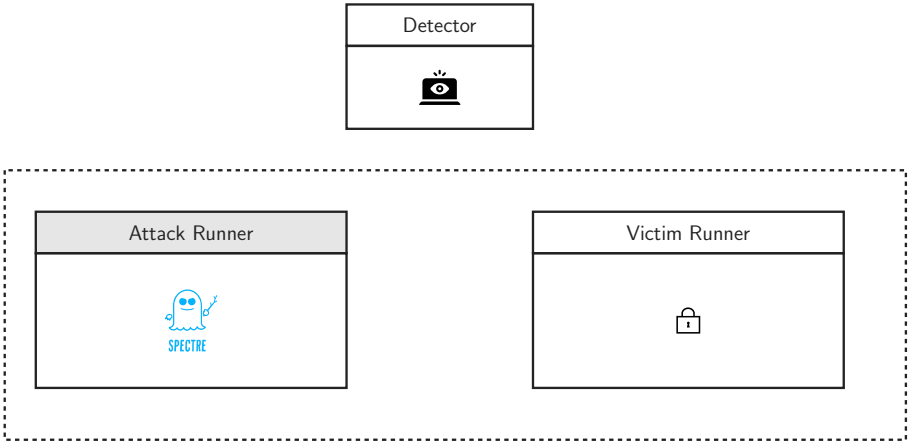
Defense

Dynamic Process Isolation - High Level Idea



Pietro Borrello (@borrello_pietro) Andreas Kogler (@0xhilbert)

Dynamic Process Isolation - High Level Idea



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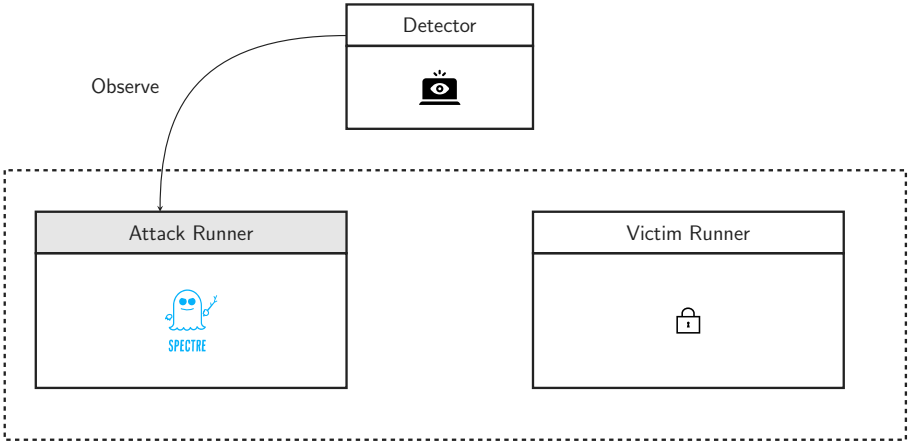
Dynamic Process Isolation - High Level Idea



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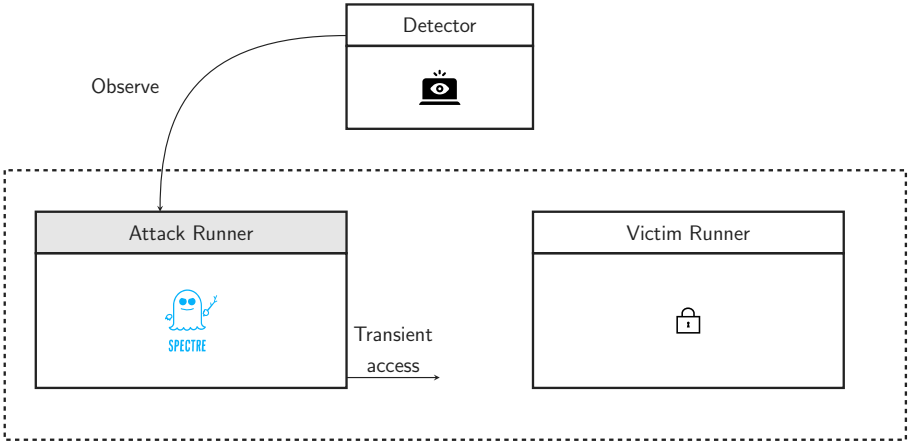

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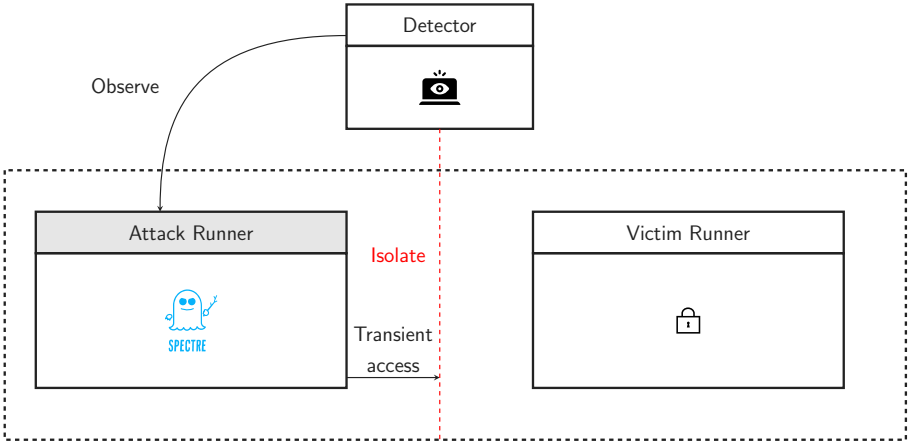
Dynamic Process Isolation - High Level Idea



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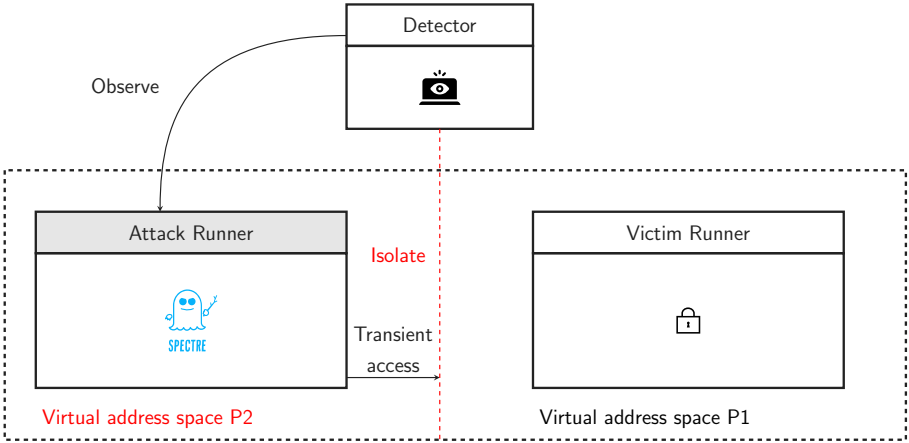
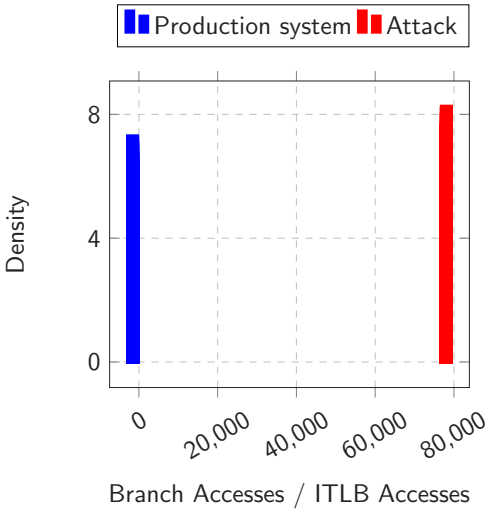
Dynamic Process Isolation - High Level Idea



Pietro Borrello (@borrello_pietro) Andreas Kogler (@0xhilbert)

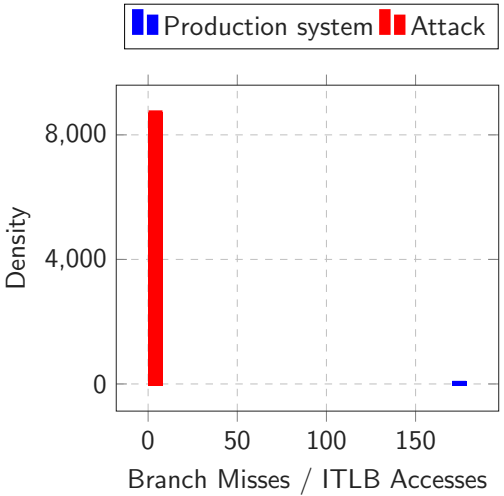
- How to observe the Attacker?

- How to observe the Attacker?
  - ✓ Performance Monitoring Counters



- How to observe the Attacker?
  - ✓ Performance Monitoring Counters
- Branch **Misses**

Pietro Borrello (@borrello_pietro) Andreas Kogler (@0xhilbert)



- How to observe the Attacker?
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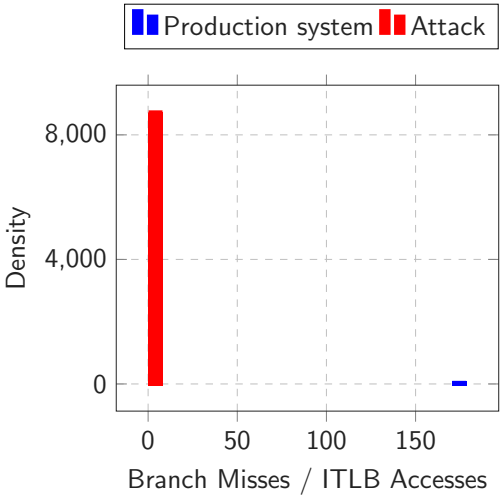
- Branch **Misses**
- Branch **Accesses**

Pietro Borrello (@borrello_pietro) Andreas Kogler (@0xhilbert)



- How to observe the Attacker?
  - ✓ Performance Monitoring Counters
- Branch **Misses**
- Branch **Accesses**
- Per **Code** Executed

Pietro Borrello (@borrello_pietro) Andreas Kogler (@0xhilbert)

- What is the overhead?

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- Different **Interfaces**
  - **PERF**
  - **rdmsr**
  - **rdpmc**

- What is the overhead?
- Different **Interfaces**
  - **PERF**
  - **rdmsr**
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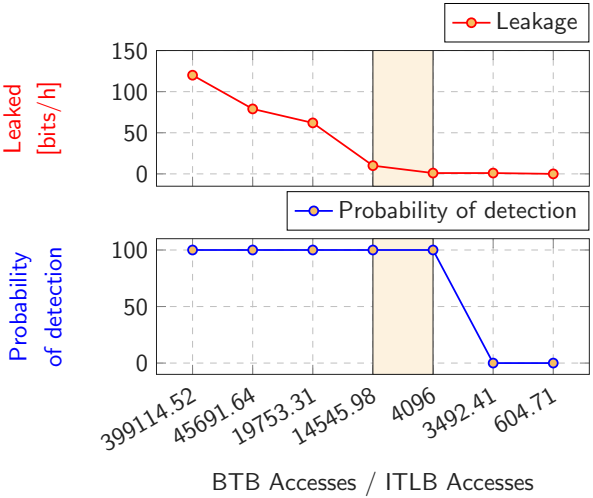
✓ **rdpmc** → 2% overhead

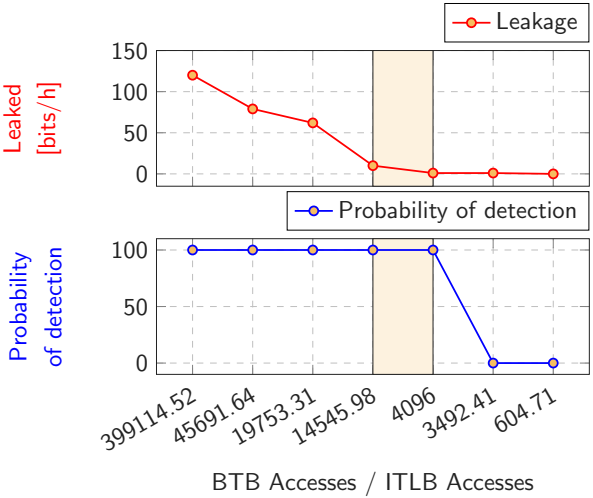
Dynamic Process Isolation - Success Rate



- What is the success rate?

Pietro Borrello (@borrello_pietro) Andreas Kogler (@0xhilbert)

Dynamic Process Isolation - Success Rate



- What is the success rate?
- Detection vs leakage rate

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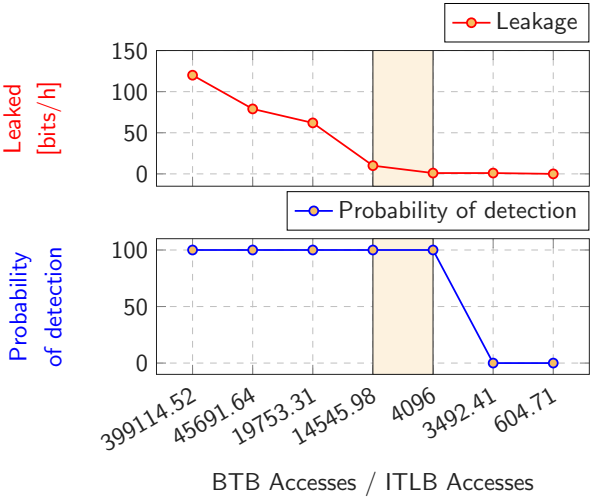
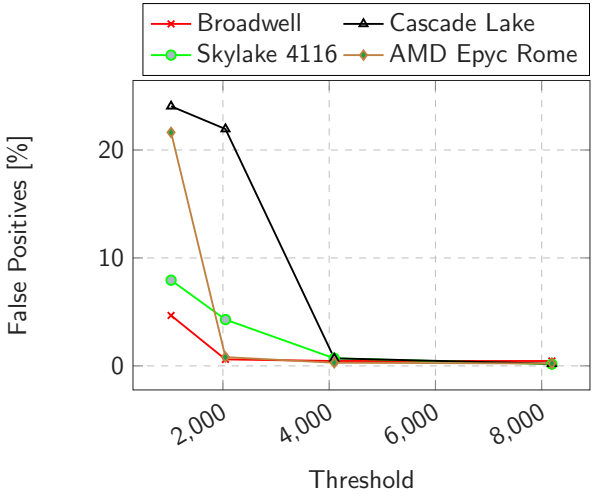
Dynamic Process Isolation - Success Rate



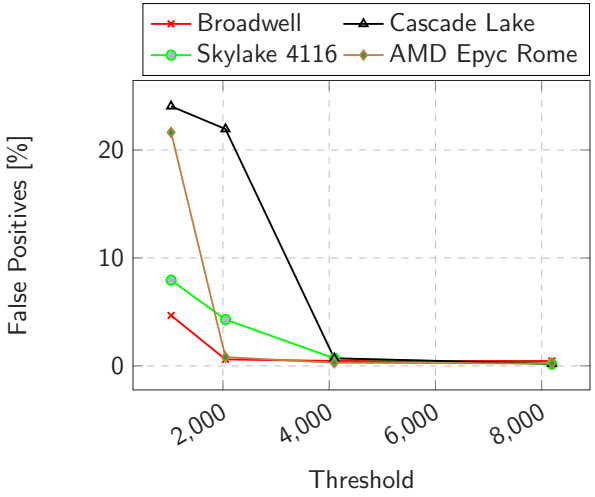
- What is the success rate?
- Detection vs leakage rate
- ✓ Strong **reduction**

Pietro Borrello (@borrello_pietro) Andreas Kogler (@0xhilbert)



- Are there false positives?

Pietro Borrello (@borrello_pietro) Andreas Kogler (@0xhilbert)



- Are there false positives?
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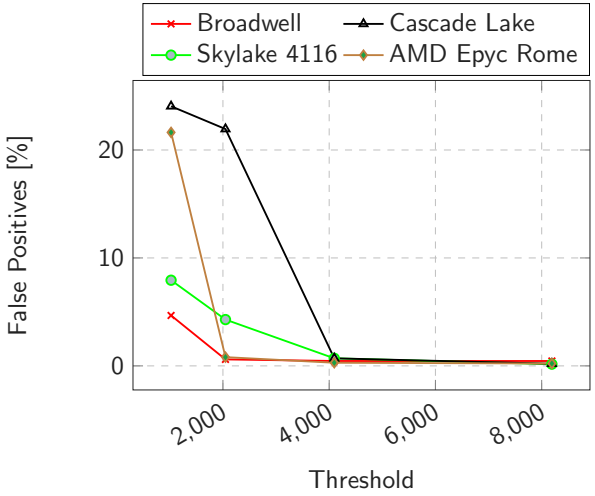
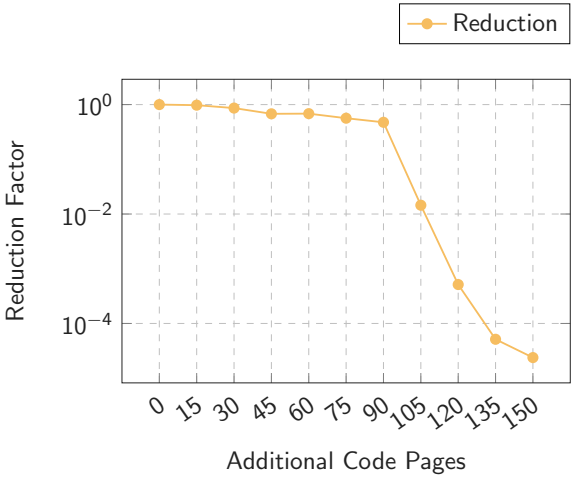


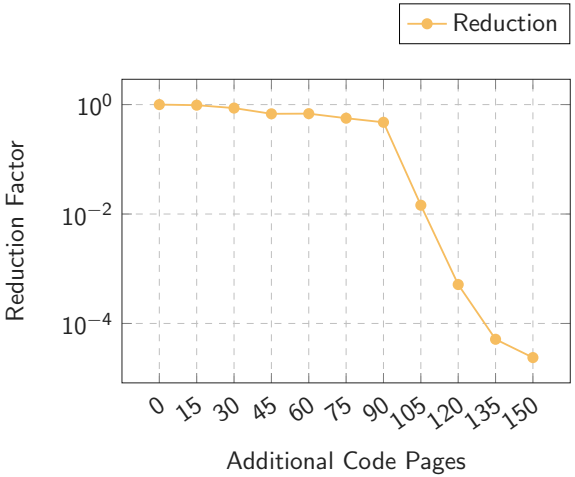
- Are there false positives?
- Different CPUs
- ✓ 4096 → 0.61%

Pietro Borrello (@borrello_pietro) Andreas Kogler (@0xhilbert)



- Can the observer be tricked?

Pietro Borrello (@borrello_pietro) Andreas Kogler (@0xhilbert)



- Can the observer be tricked?
- Additional Code Pages

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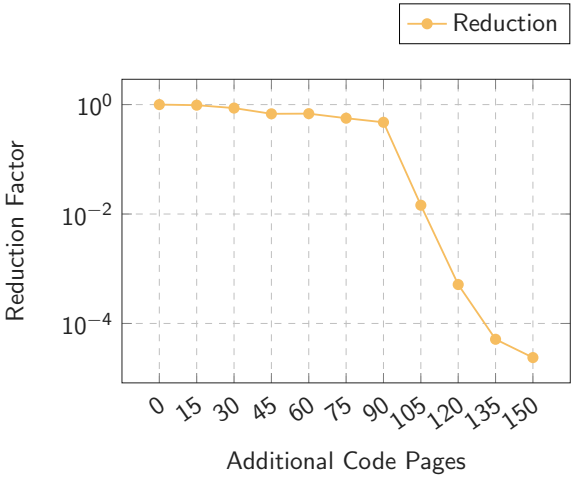

- Can the observer be tricked?
- Additional Code Pages
- Increase ITLB Accesses

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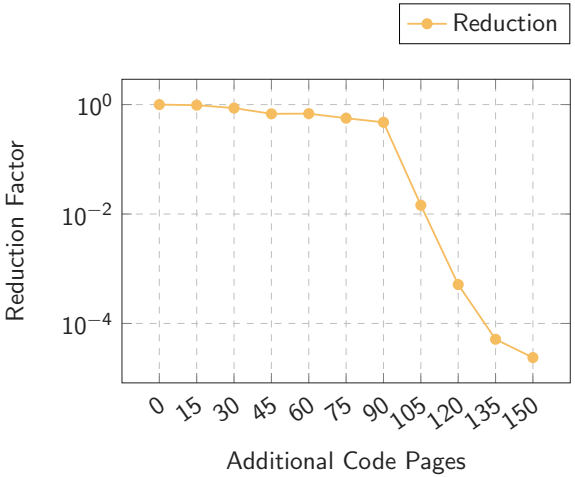

- Can the observer be tricked?
- Additional Code Pages
- Increase ITLB Accesses
- Reduction factor

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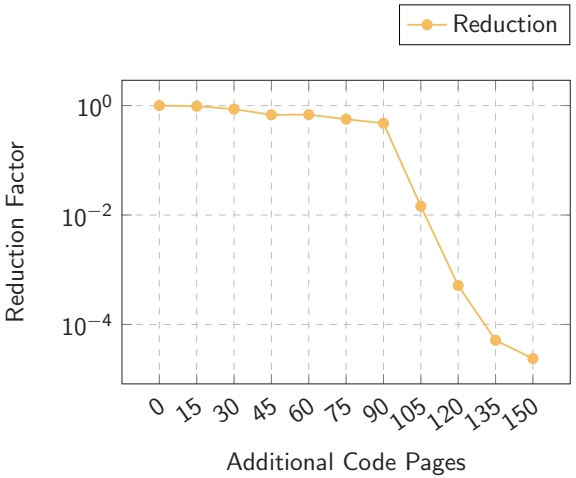

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✓ Not **compiled** by JavaScript

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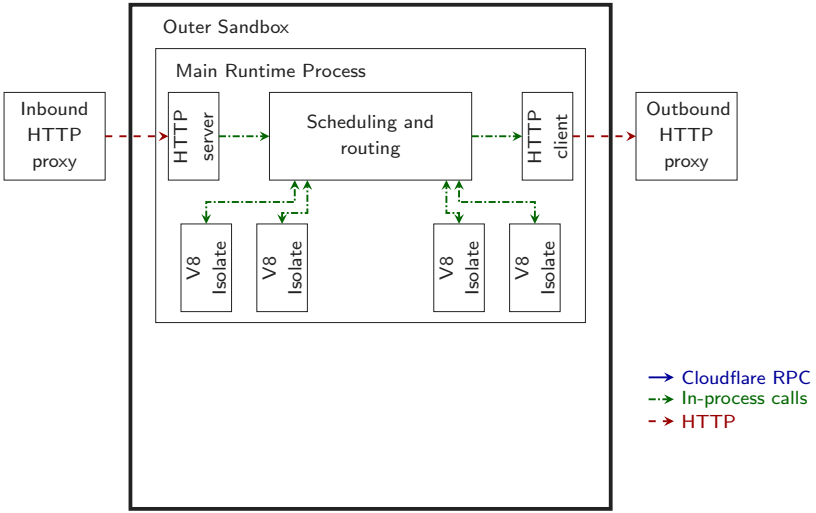
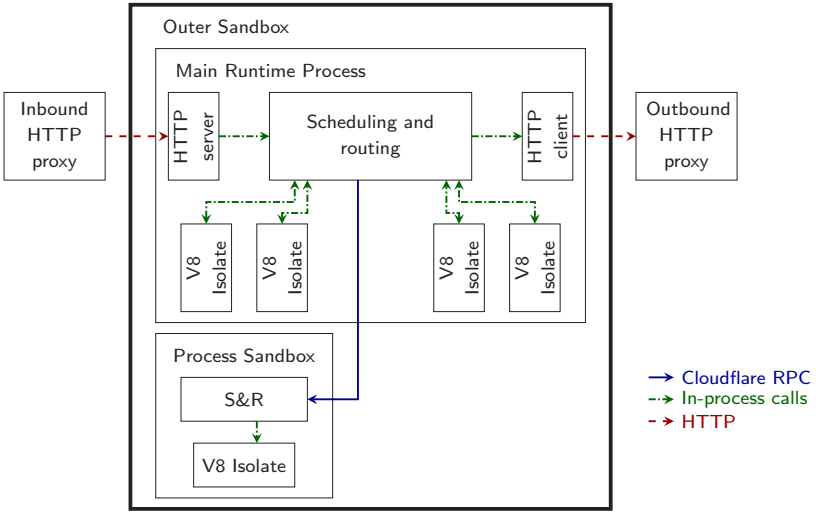
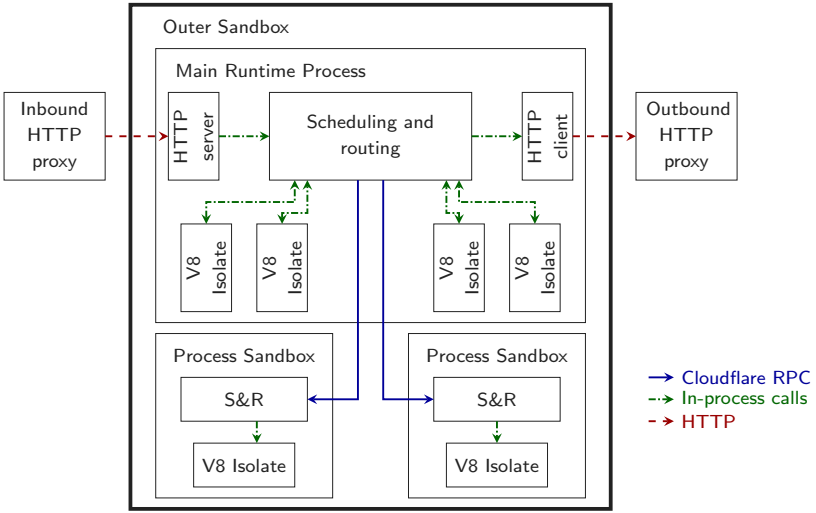
Dynamic Process Isolation - Implementation



Dynamic Process Isolation - Implementation



Dynamic Process Isolation - Implementation



Pietro Borrello (@borrello_pietro) Andreas Kogler (@0xhilbert)

- Remote Spectre attacks were possible on Cloudflare Workers

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- **Production-deployed** with a low false-positive rate

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Dynamic Process Isolation

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