Specfuscator: Evaluating Branch Removal as a Spectre Mitigation

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Motivation

- Explore a previously unexplored mitigation space against Spectre attacks - branch removal

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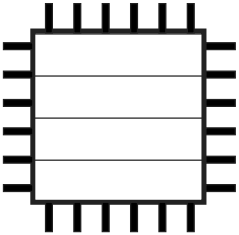
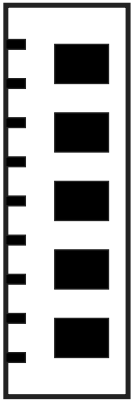
- Present Specfuscator, a solution based on a linearized control-flow
- Evaluate Specfuscator on different set of use cases

CPU Cache

```
maccess(i);

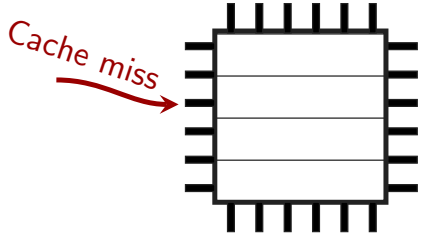
maccess(i);
```

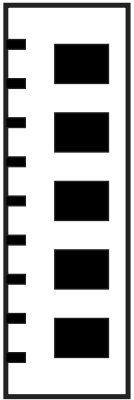




```
maccess(i);

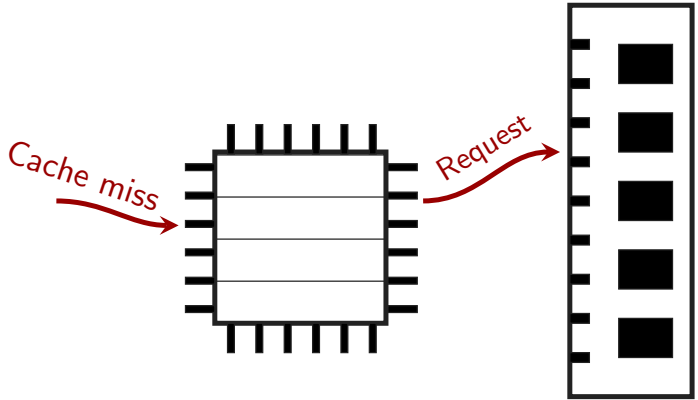
maccess(i);
```





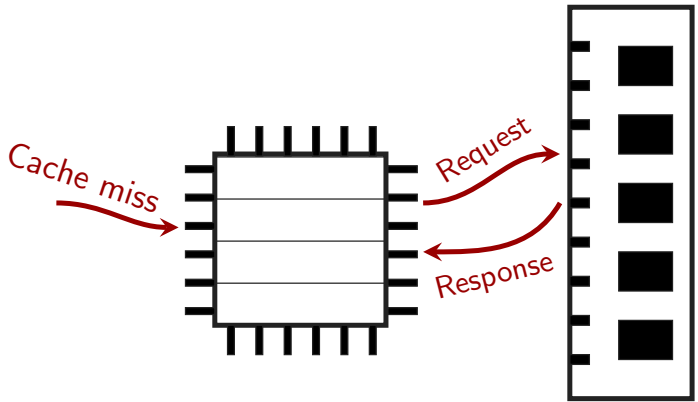
```
maccess(i);

maccess(i);
```



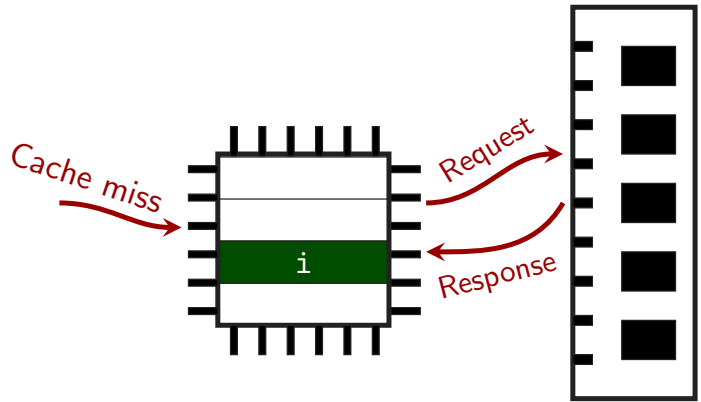
```
maccess(i);

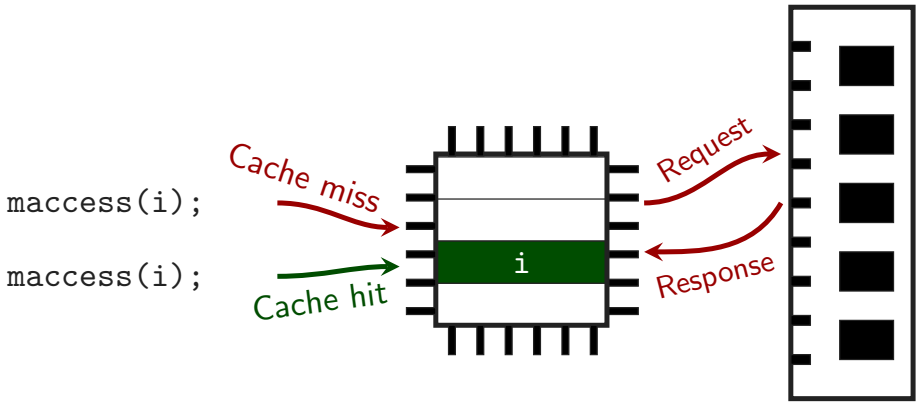
maccess(i);
```

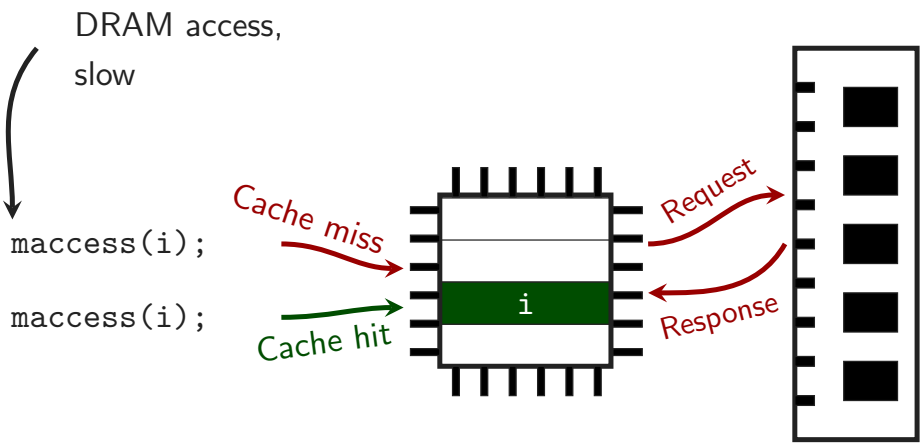


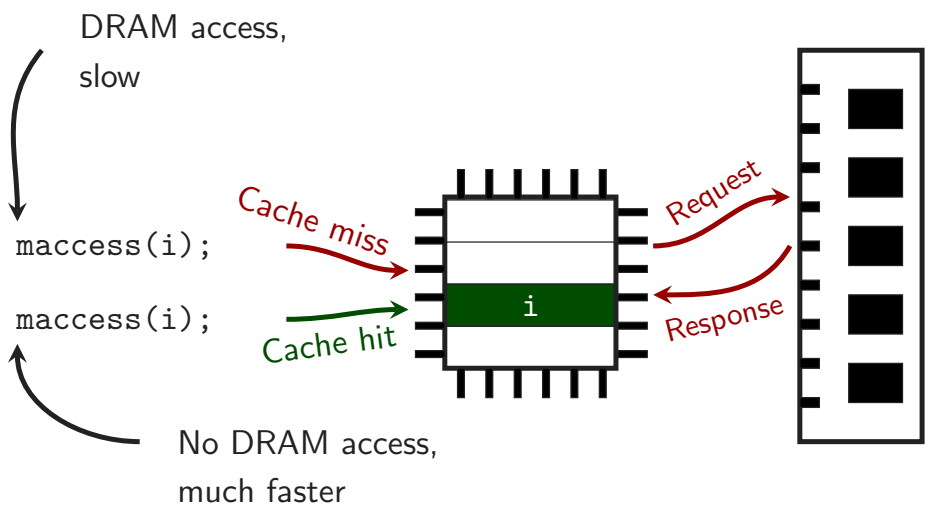
```
maccess(i);

maccess(i);
```




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

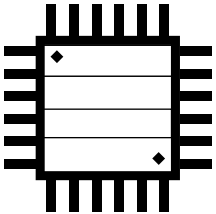

DRAM access,
slow
maccess(i);
maccess(i);
Cache miss
Cache hit
i
Request
Response


DRAM access,
slow
maccess(i);
maccess(i);
Cache miss
Cache hit
i
Request
Response
No DRAM access,
much faster

Shared Memory

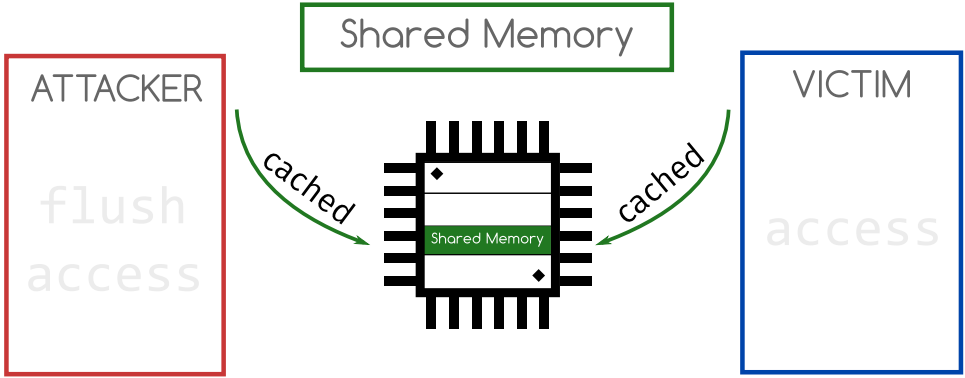
ATTACKER

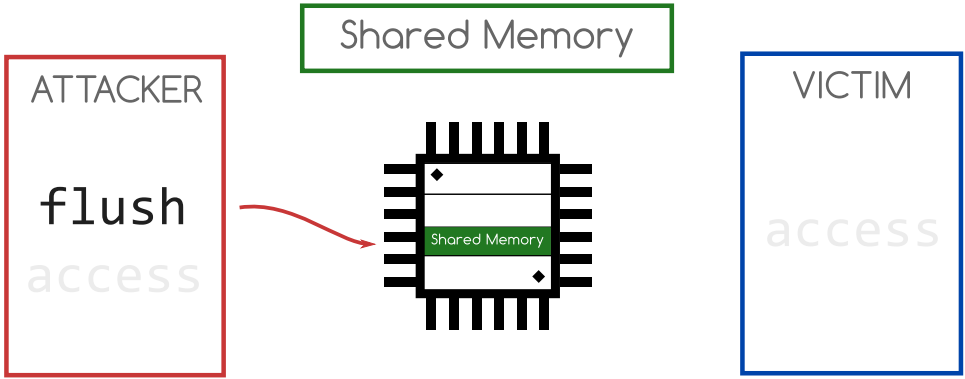
flush
access

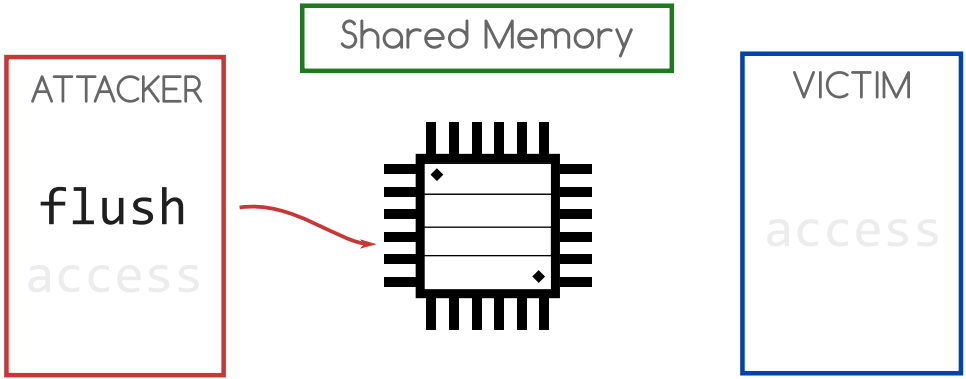


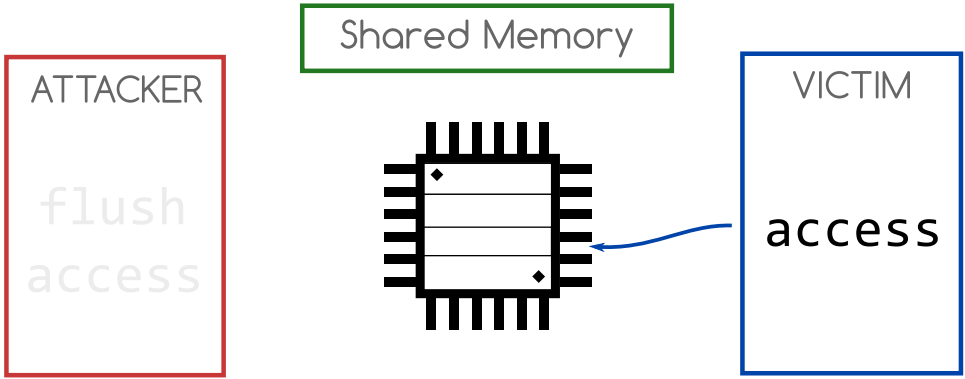
VICTIM

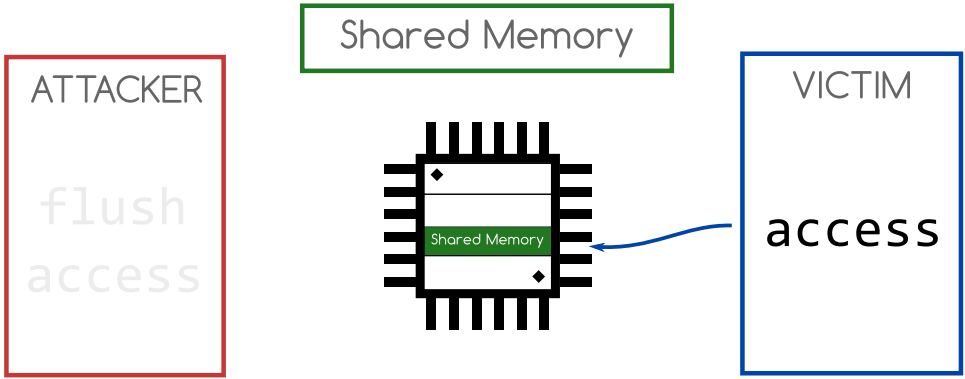
access

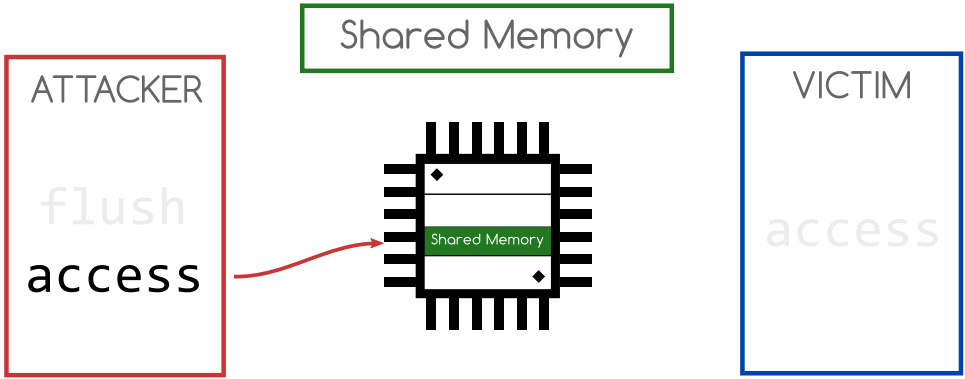

Shared Memory
ATTACKER
flush
access
cached
Shared Memory
cached
VICTIM
access

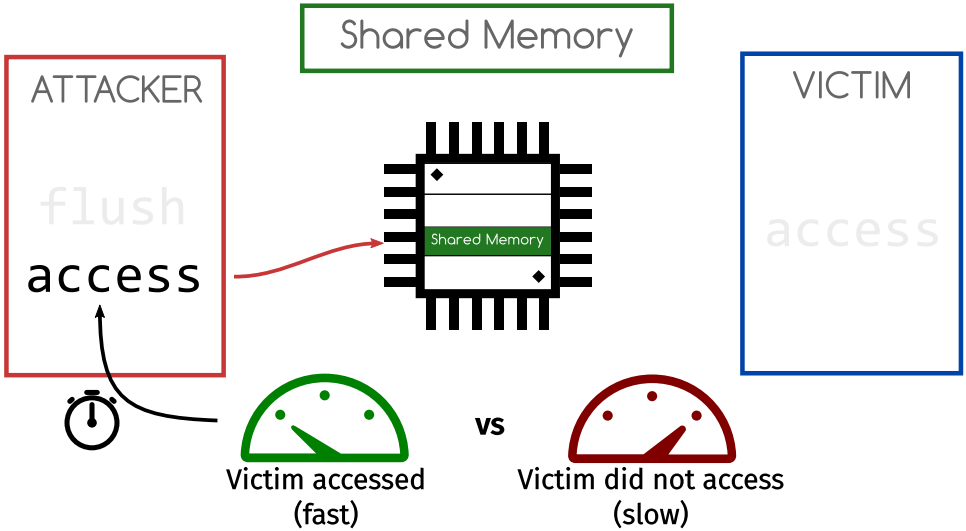

Shared Memory
ATTACKER
flush
access
Shared Memory
VICTIM
access


Shared Memory
ATTACKER
flush
access
VICTIM
access


Shared Memory
ATTACKER
flush
access
VICTIM
access


Shared Memory
ATTACKER
flush
access
Shared Memory
VICTIM
access


Shared Memory
ATTACKER
flush
access
Shared Memory
VICTIM
access


Shared Memory
ATTACKER
flush
access
Shared Memory
VICTIM
access
vs
Victim accessed
(fast)
Victim did not access
(slow)

- CPU tries to predict the future, ...

- CPU tries to predict the future, ...
  - ... based on what happened in the past

- CPU tries to predict the future, ...
  - ... based on what happened in the past
- Speculative execution of instructions

- CPU tries to predict the future, ...
  - ... based on what happened in the past
- Speculative execution of instructions
- Correct prediction, ...

- CPU tries to predict the future, ...
  - ... based on what happened in the past
- Speculative execution of instructions
- Correct prediction, ...
  - ... very fast

- CPU tries to predict the future, ...
  - ... based on what happened in the past
- Speculative execution of instructions
- Correct prediction, ...
  - ... very fast
  - otherwise: Discard results

- Speculative execution is exploitable (Spectre attacks [Koc+19])

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- Speculative execution is exploitable (Spectre attacks [Koc+19])
- Allow it to leak data
- Require a certain code snippet (gadget)
- Execution based on predictions from different mechanisms(PHT,BTB,RSB,STL) [Koc+19; Can+19]
- Via different side channels (AVX, Port contention)

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

```
index = 0
```

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

then

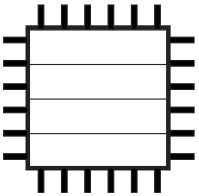
```
lut[data[index]]
```

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	
...	

```
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)
```

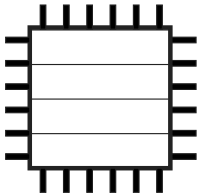
then

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

else

Speculate

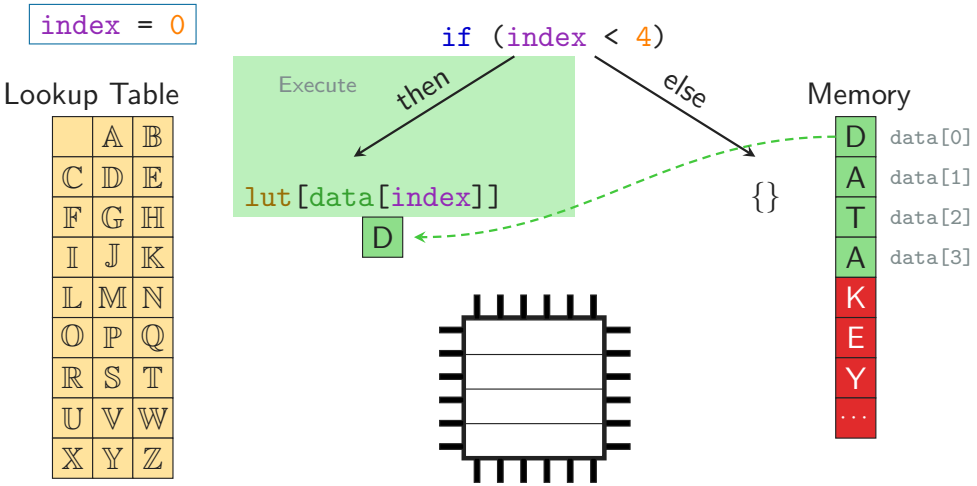
{}

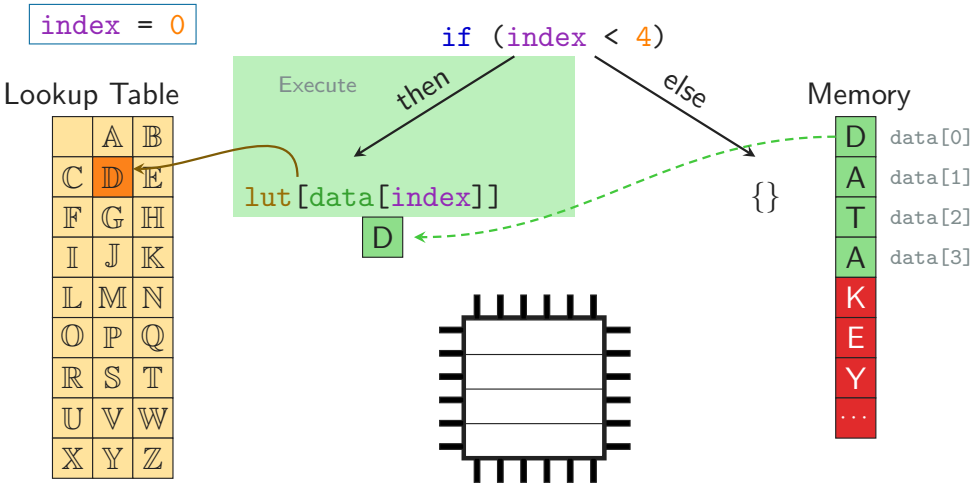


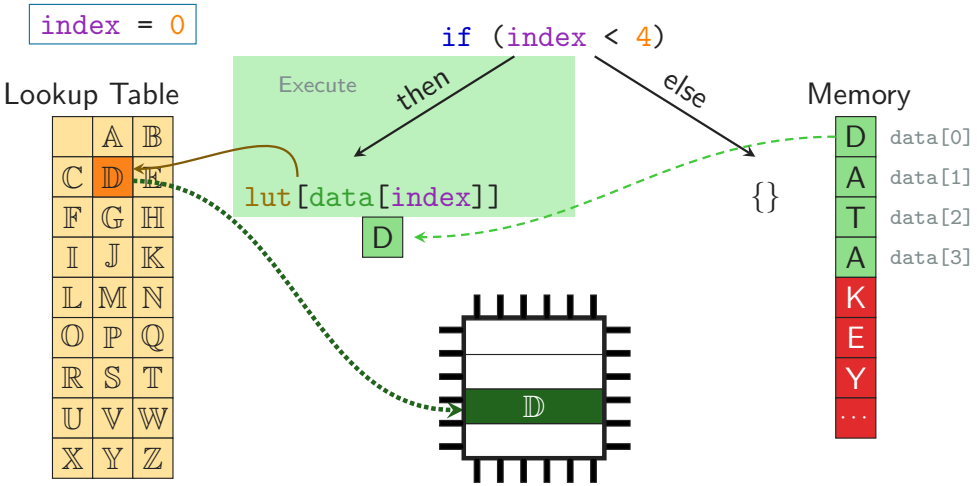
Memory

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

Spectre-PHT (aka Spectre Variant 1)




index = 0
if (index < 4)
then
else
Execute
lut[data[index]]
D
{}
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
A
T
A
K
E
Y
...
data[0]
data[1]
data[2]
data[3]


index = 0
if (index < 4)
then
else
Execute
lut[data[index]]
D
{}
Lookup Table
Memory
data[0]
data[1]
data[2]
data[3]

Spectre-PHT (aka Spectre Variant 1)

```
index = 1
```

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

then

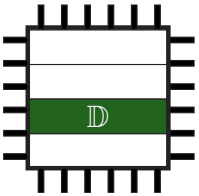
```
lut[data[index]]
```

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	
...	

```
index = 1
```

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

Speculate

then

else

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

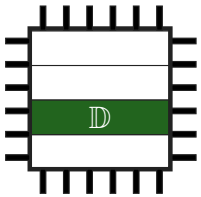
{}

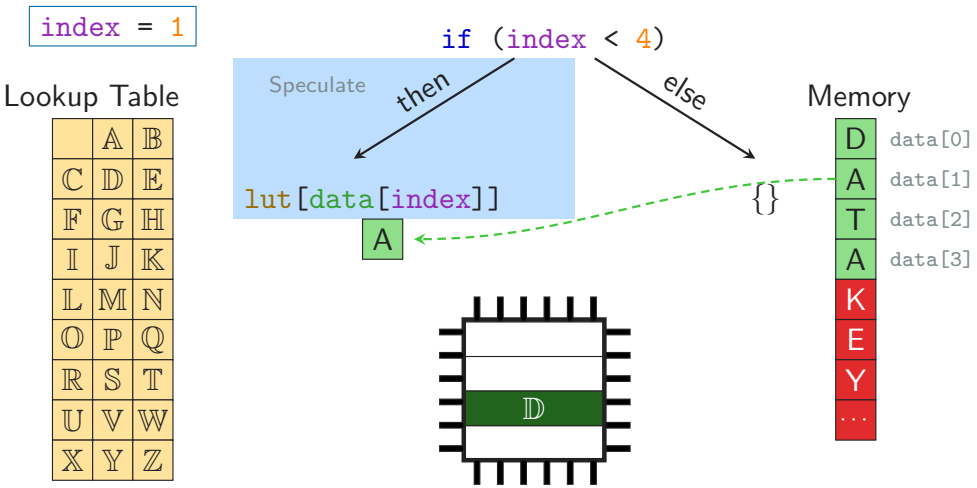
Lookup Table

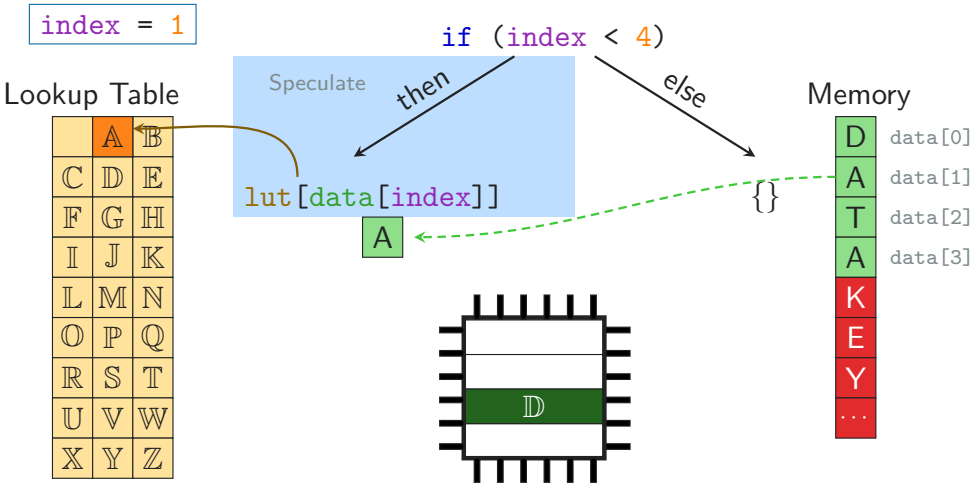
	A	B
C	D	E
F	G	H
I	J	K
L	M	N
O	P	Q
R	S	T
U	V	W
X	Y	Z

Memory

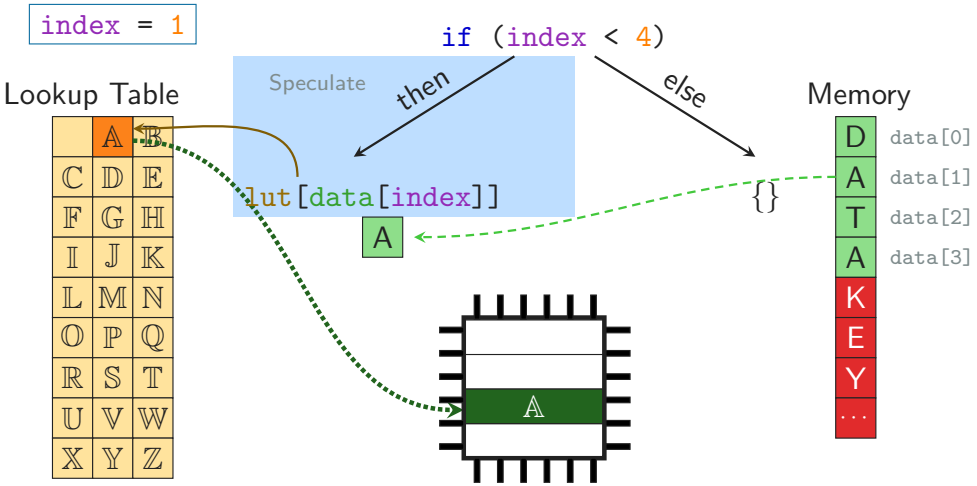
D	data[0]
A	data[1]
T	data[2]
A	data[3]
K	
E	
Y	
...	




index = 1
Lookup Table
if (index < 4)
Speculate
then
else
lut[data[index]]
A
{}
Memory
D
A
T
A
K
E
Y
...
data[0]
data[1]
data[2]
data[3]
D


index = 1
if (index < 4)
Speculate
then
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
lut[data[index]]
A
{}
Memory
D data[0]
A data[1]
T data[2]
A data[3]
K
E
Y
...
D

Spectre-PHT (aka Spectre Variant 1)



```
index = 1
```

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

then

Execute

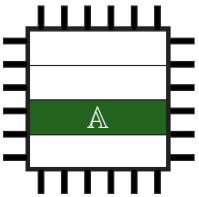
```
lut[data[index]]
```

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	
...	

```
index = 2
```

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

Speculate

then

else

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

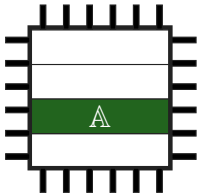
{}

Lookup Table

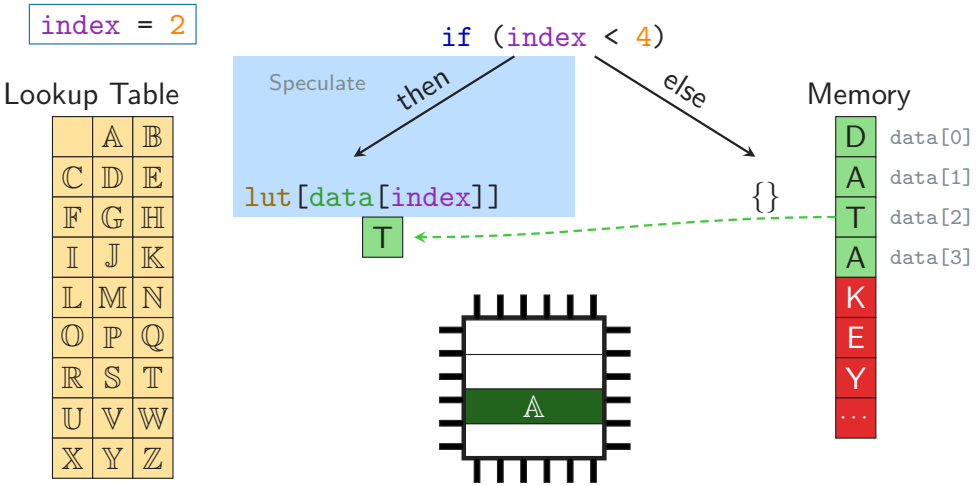
	A	B
C	D	E
F	G	H
I	J	K
L	M	N
O	P	Q
R	S	T
U	V	W
X	Y	Z

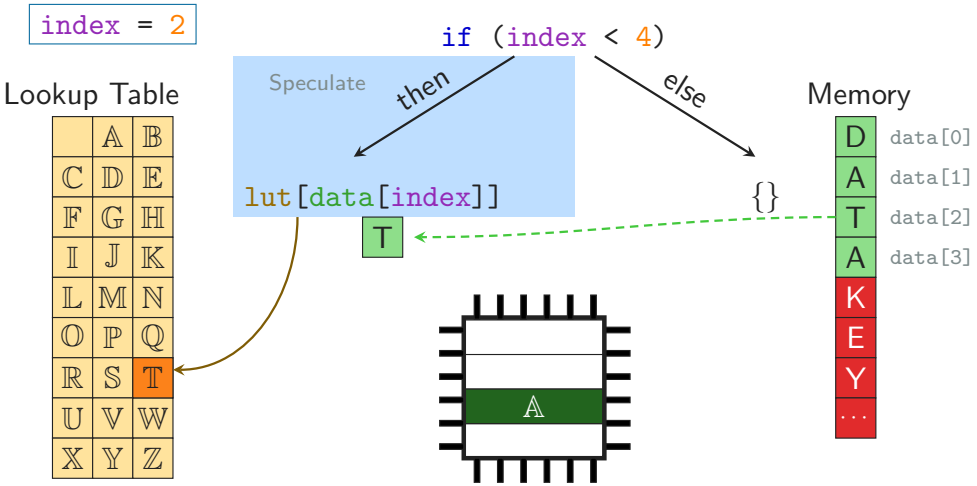
Memory

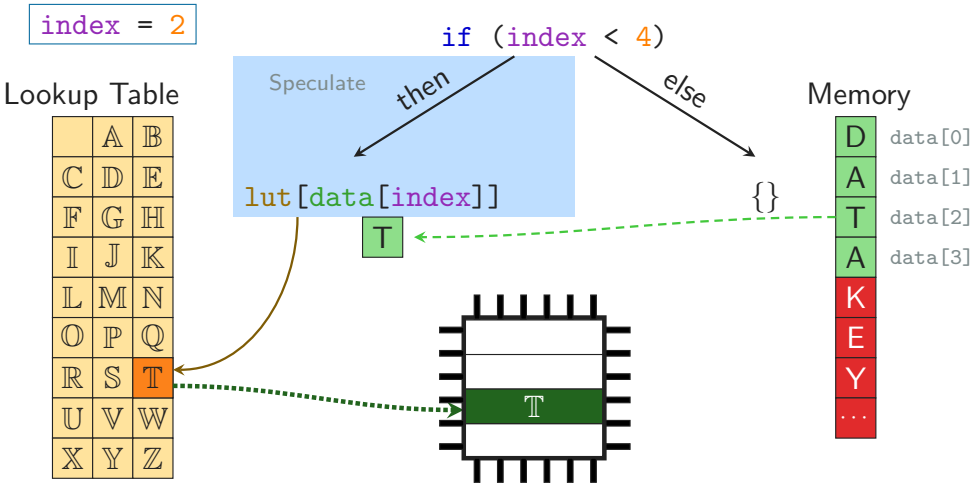
D	data[0]
A	data[1]
T	data[2]
A	data[3]
K	
E	
Y	
...	



Spectre-PHT (aka Spectre Variant 1)




index = 2
if (index < 4)
then
else
Speculate
lut[data[index]]
T
{}
Lookup Table
Memory
D
A
T
A
K
E
Y
...
data[0]
data[1]
data[2]
data[3]
A


index = 2
if (index < 4)
then
else
Speculate
lut[data[index]]
T
{}
Lookup Table
Memory
data[0]
data[1]
data[2]
data[3]
T

Spectre-PHT (aka Spectre Variant 1)

```
index = 2
```

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

then

Execute

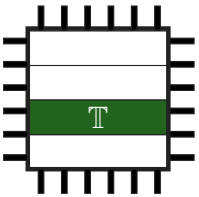
```
lut[data[index]]
```

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	
...	

```
index = 3
```

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)
```

Speculate

then

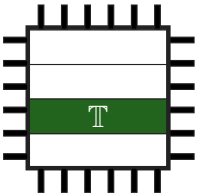
```
lut[data[index]]
```

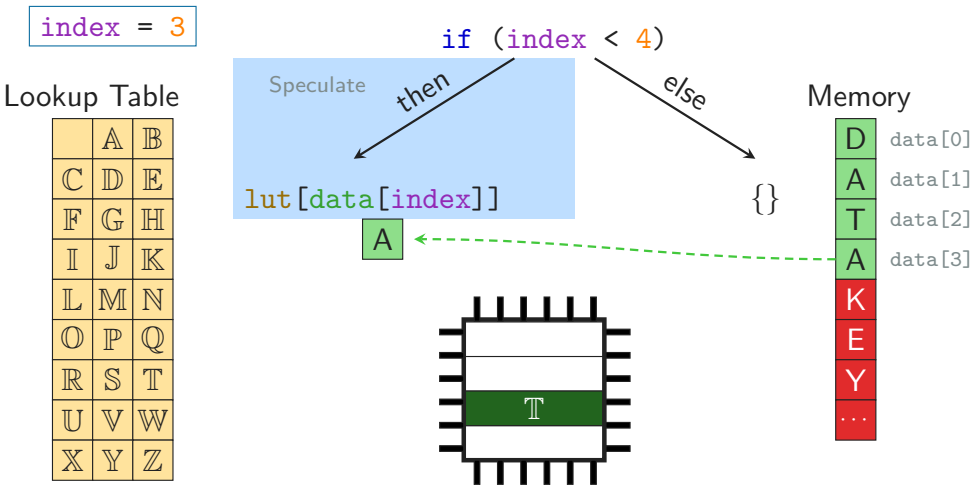
else

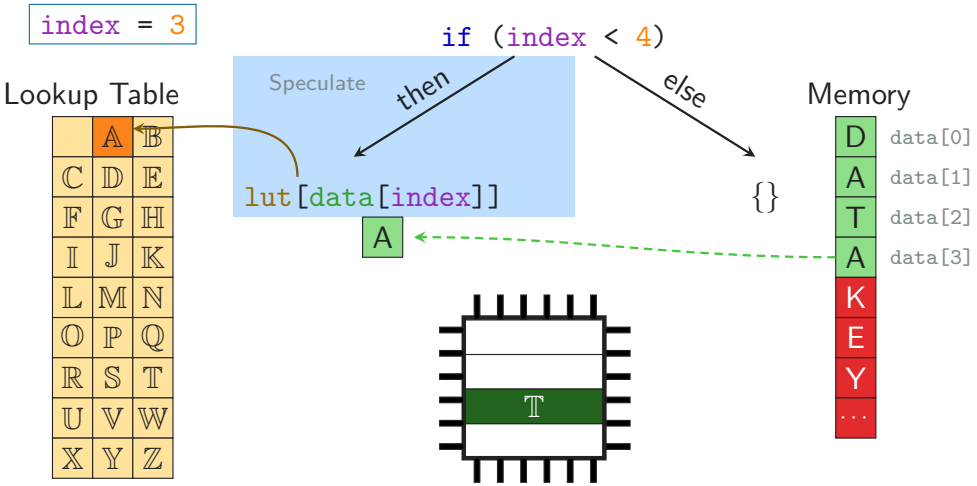
{}

Memory

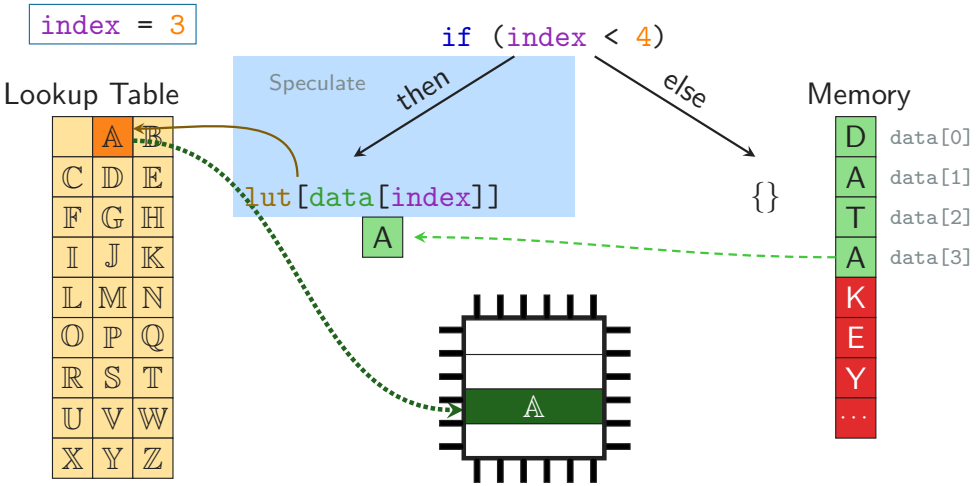
D	data[0]
A	data[1]
T	data[2]
A	data[3]
K	
E	
Y	
...	




index = 3
Lookup Table
if (index < 4)
Speculate
then
else
lut[data[index]]
A
{}
Memory
D
A
T
A
K
E
Y
...
data[0]
data[1]
data[2]
data[3]


index = 3
if (index < 4)
then
else
Speculate
Lookup Table
Memory
lut[data[index]]
A
{}
data[0]
data[1]
data[2]
data[3]
T

Spectre-PHT (aka Spectre Variant 1)



Spectre-PHT (aka Spectre Variant 1)

```
index = 3
```

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

then

Execute

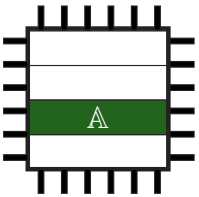
```
lut[data[index]]
```

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	
...	

```
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)
```

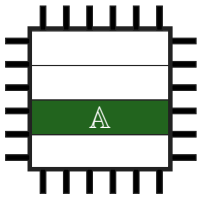
Speculate

then

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

else

{}



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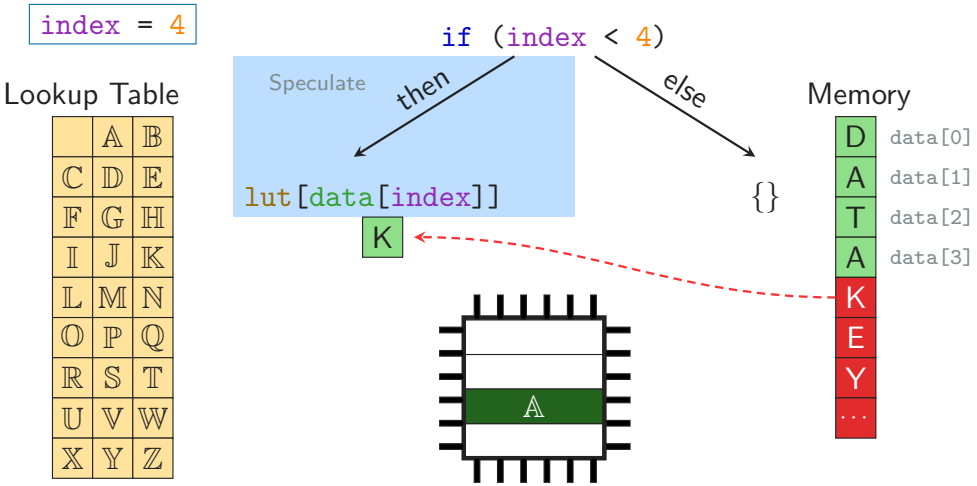
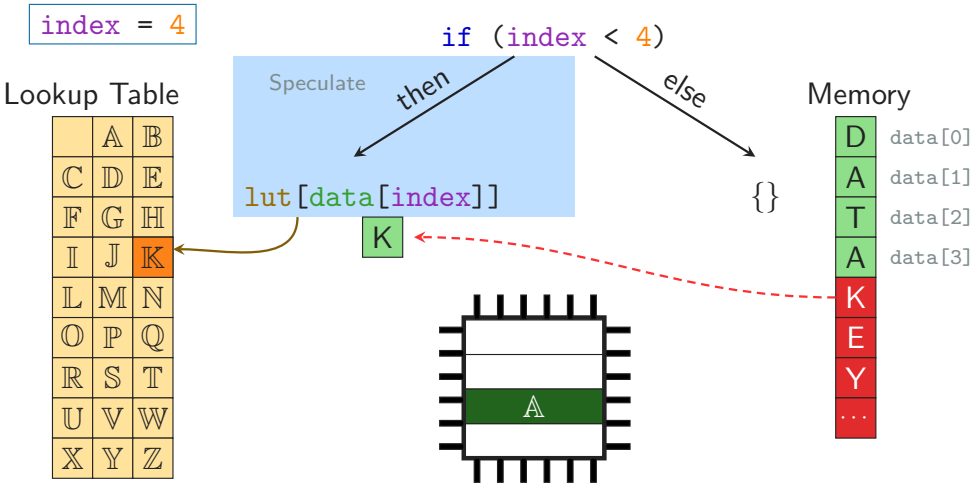

index = 4
Lookup Table
A
B
C
D
E
F
G
H
I
J
K
L
M
N
O
P
Q
R
S
T
U
V
W
X
Y
Z
if (index < 4)
Speculate
then
else
lut[data[index]]
K
{}
Memory
D
A
T
A
K
E
Y
...
data[0]
data[1]
data[2]
data[3]
A


index = 4
if (index < 4)
then
else
Speculate
lut[data[index]]
K
{}
Lookup Table
Memory
data[0]
data[1]
data[2]
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L
M
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Z
D
A
T
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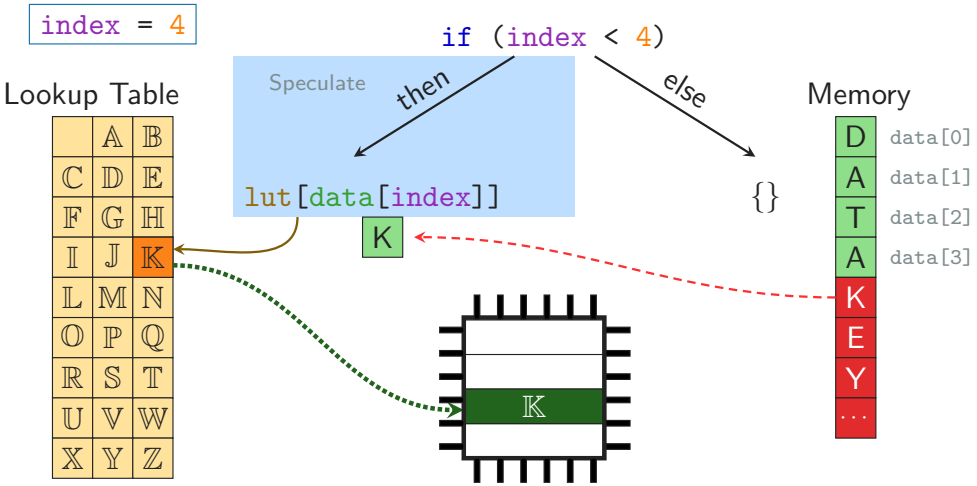
...
A

Spectre-PHT (aka Spectre Variant 1)



Spectre-PHT (aka Spectre Variant 1)

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```

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

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lut[data[index]]
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Execute {}

Lookup Table

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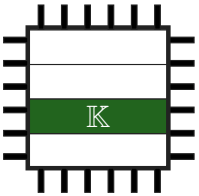

Memory

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Application-Level

Spectre mitigations

Application-Level

System-Level

Spectre mitigations

Application-Level

System-Level

Hardware-Level

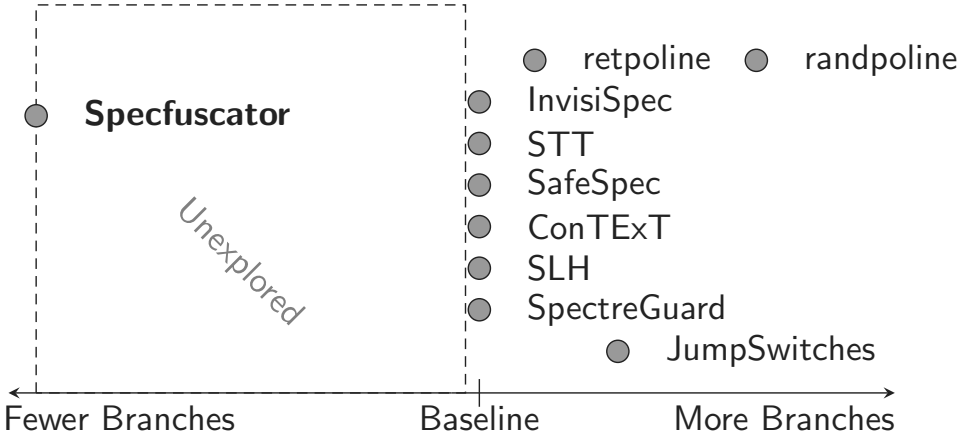
Spectre mitigations

Application-Level

System-Level

Hardware-Level

Placement of our work



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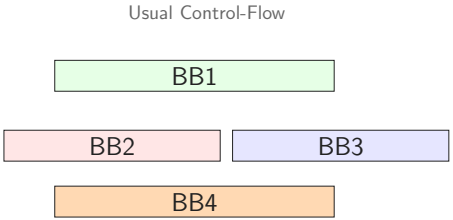
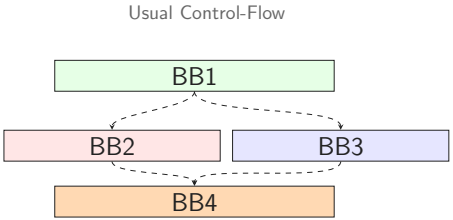
- Arithmetics performed via lookup-tables
- Low-performance solution *i.e.*, Doom with one frame every 7 hours [Chr15]

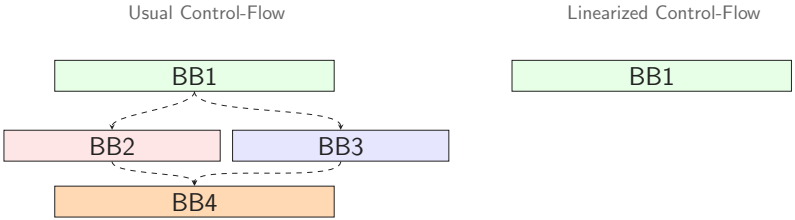
Linearized control-flow



Linearized control-flow



Linearized control-flow



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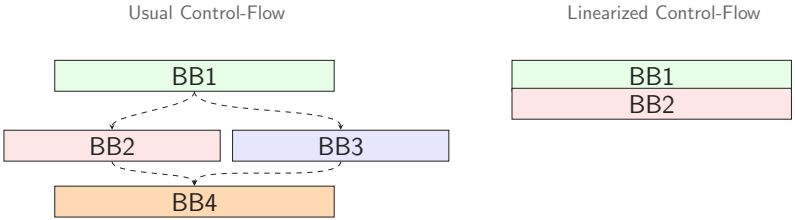

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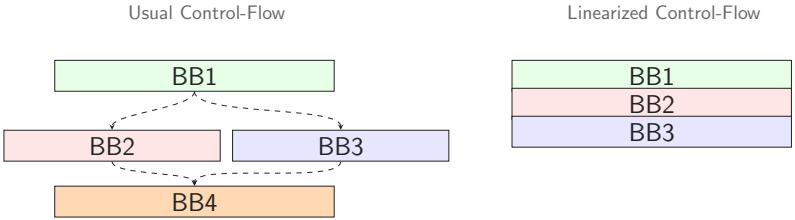

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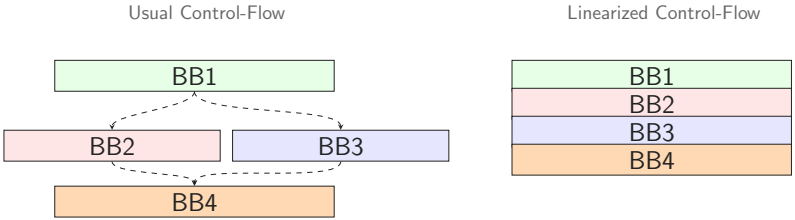
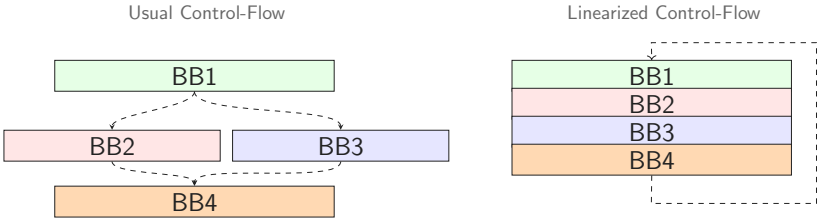


Linearized control-flow



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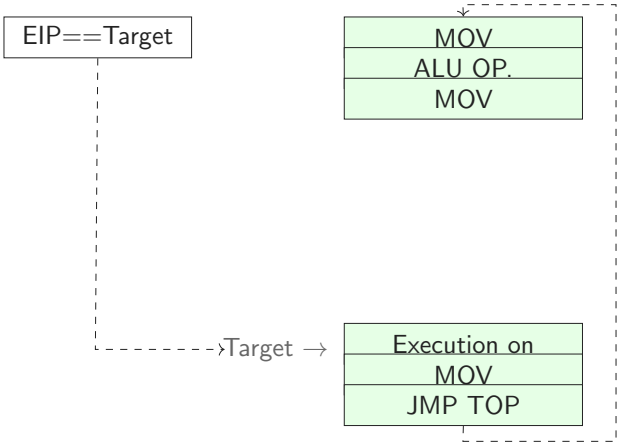
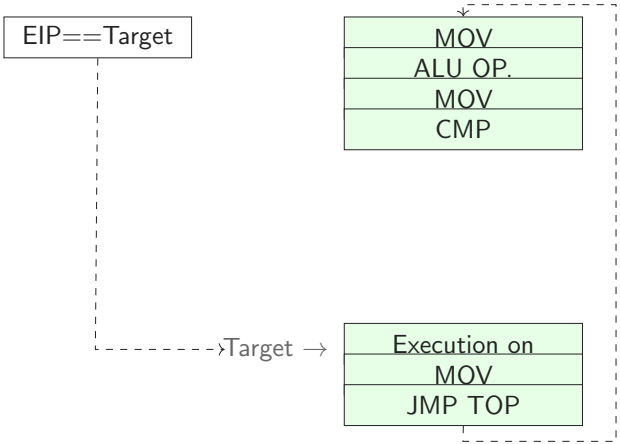
  - stack needs to be prepared accordingly to calling convention


EIP==Target
MOV
ALU OP.
MOV
Target →
Execution on
MOV
JMP TOP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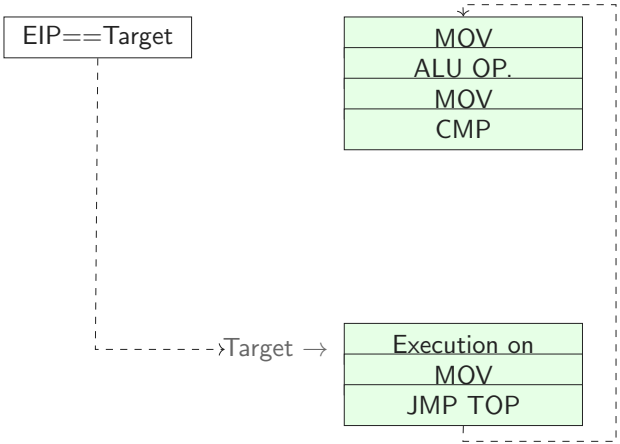
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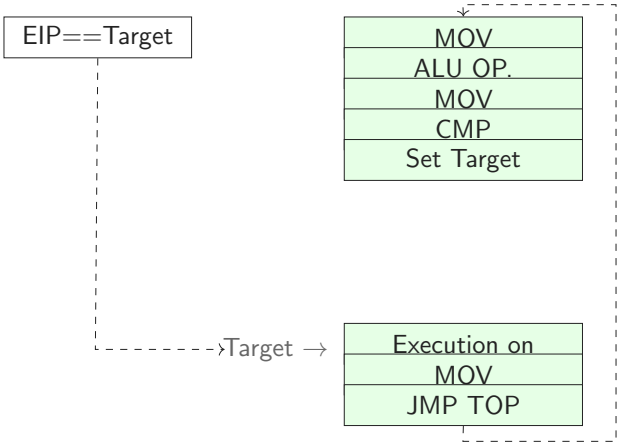
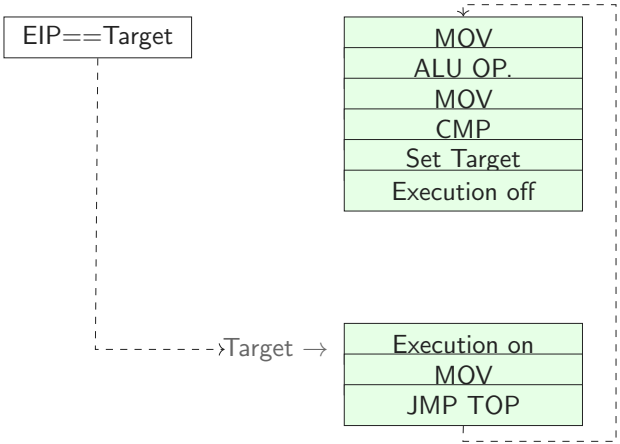

EIP==Target
MOV
ALU OP.
MOV
CMP
Set Target
Target →
Execution on
MOV
JMP TOP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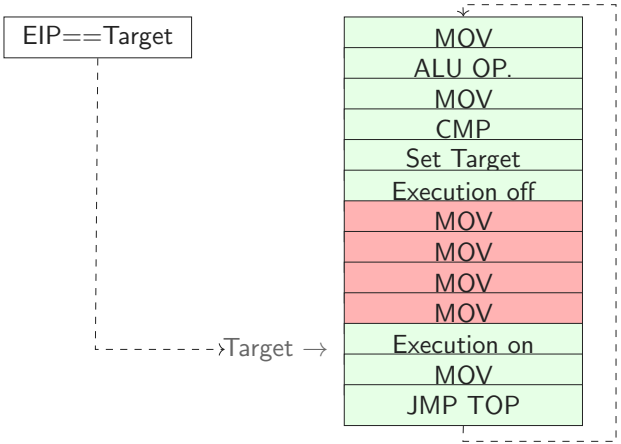
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- `cmp` instruction is used and the emulated cflags are set

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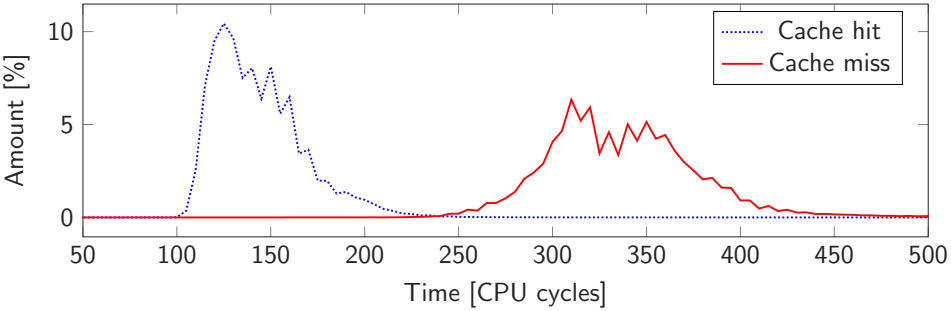
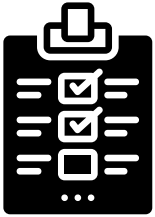
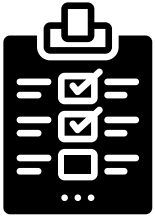
- As expected, the PoCs did not leak any data

Flush+Reload in movfuscated code

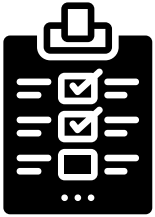




- Choose a different set of test open-source programs



- Choose a different set of test open-source programs
- Clang vs. Clang with lfences vs. LCC vs. *M/o/Vfuscator* vs. Specfuscator



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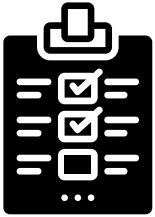
- We compare the `runtime`,`compile time` and `binary size` and calculate the overhead factors



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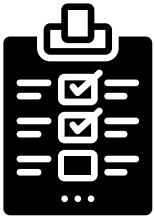
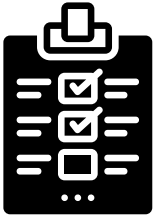
Performance Evaluation: Runtime overhead factor



Test program	M/o/Vfuscator	Specfuscator	Clang (fences)	LCC	Clang (baseline)
	times	times	times	times	baseline
aes	424.17	221.53	1.31	1.17	1.13 ms
hello	1.10	1.11	1.00	1.04	0.89 ms
maze	310.03	88.98	1.10	1.13	0.97 ms
nqueens	319.84	234.46	1.99	4.99	1.89 ms
prime	980.27	161.59	1.93	0.96	1.65 ms
s2	46085.82	981.20	20.89	26.64	0.71 ms
sudoku	656.91	149.69	2.15	1.17	1.13 ms

Performance Evaluation: Compile Time



Test program	M/o/Vfuscator		Specfuscator		Clang (fences)		LCC		Clang (baseline)	
	time	size	time	size	time	size	time	size	time	size
aes	4.80	218.69	2.95	151.15	1.20	1.00	0.53	1.01	101.89 ms	33.21 kB
hello	2.23	388.28	1.86	279.18	1.07	1.01	0.71	0.89	38.36 ms	13.62 kB
maze	3.93	394.09	2.12	274.96	1.05	1.01	0.63	0.86	46.80 ms	13.82 kB
nqueens	2.39	386.75	2.05	278.22	1.17	1.01	0.75	0.88	40.19 ms	13.64 kB
prime	2.39	389.97	1.81	279.47	1.06	1.01	0.62	0.89	39.02 ms	13.64 kB
s2	2.87	395.22	1.89	279.72	1.00	1.01	0.78	0.89	39.34 ms	13.62 kB
sudoku	3.47	398.10	2.05	280.39	1.10	1.01	0.68	0.91	37.76 ms	14.00 kB

Discussion

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Specfuscator: Evaluating Branch Removal as a Spectre Mitigation

Martin Schwarzl (@marv0x90), Thomas Schuster, Michael Schwarz, Daniel Gruss

1st of March, 2021

Graz University of Technology

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Acknowledgments

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