black hat ASIA 2019

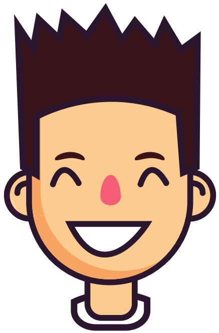
NetSpectre

A Truly Remote Spectre Variant

Michael Schwarz @misc0110

Martin Schwarzl @marv0x90

Who am I?



Michael Schwarz

PhD candidate @ Graz University of Technology

@misc0110

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Who am I?

Martin Schwarzl

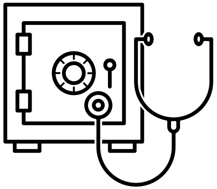
Master student @ Graz University of Technology

@marv0x90

m.schwarzl@student.tugraz.at

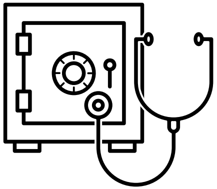
Side-Channel Attacks

- Bug-free software does not mean safe execution



Side-Channel Attacks

- Bug-free software does not mean safe execution
- Information leaks due to underlying hardware



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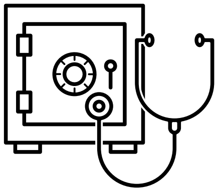

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- Information leaks due to underlying hardware
- Exploit leakage through side-effects

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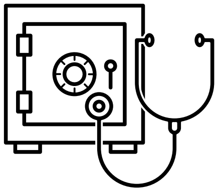

Power consumption

Execution time

CPU caches

●●●

Architecture and Microarchitecture

- Instruction Set Architecture (ISA) is an abstract model of a computer (x86, ARMv8, SPARC, ...)

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Microarchitectural Components

- Modern CPUs contain multiple microarchitectural elements

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Caches and buffers

Predictors

●●●

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Predictors

- Transparent for the programmer

Microarchitectural Components

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Caches and buffers

Predictors

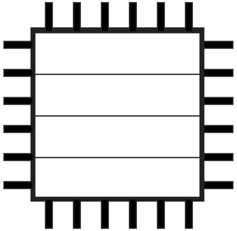
●●●

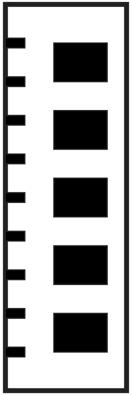
- Transparent for the programmer
- Timing optimizations → side-channel leakage

Let’s have a deeper look at the cache

CPU Cache

```
printf("%d", i);
printf("%d", i);
```





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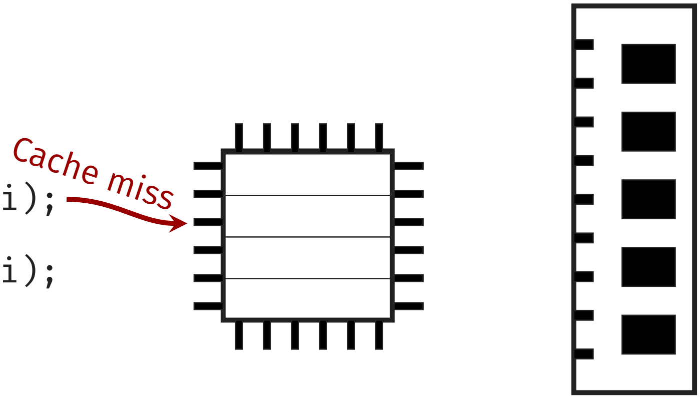

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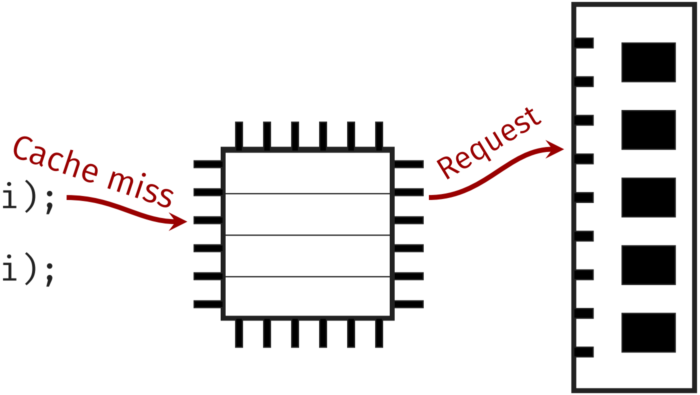

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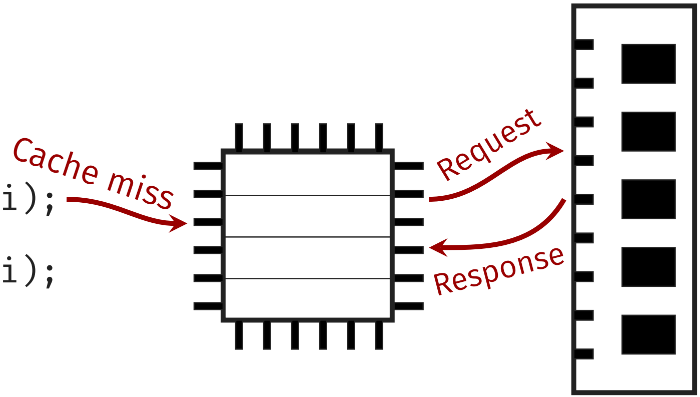

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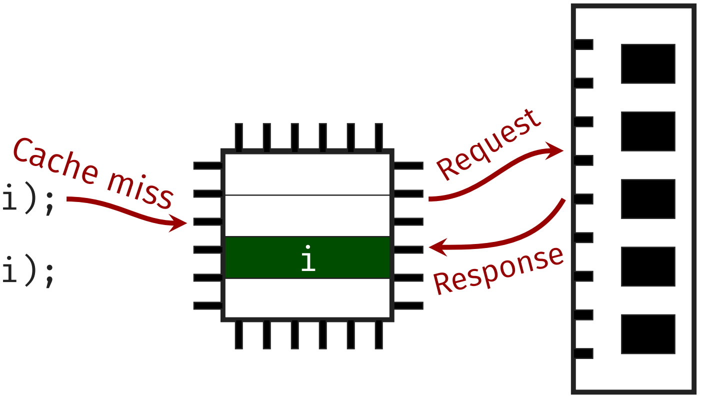

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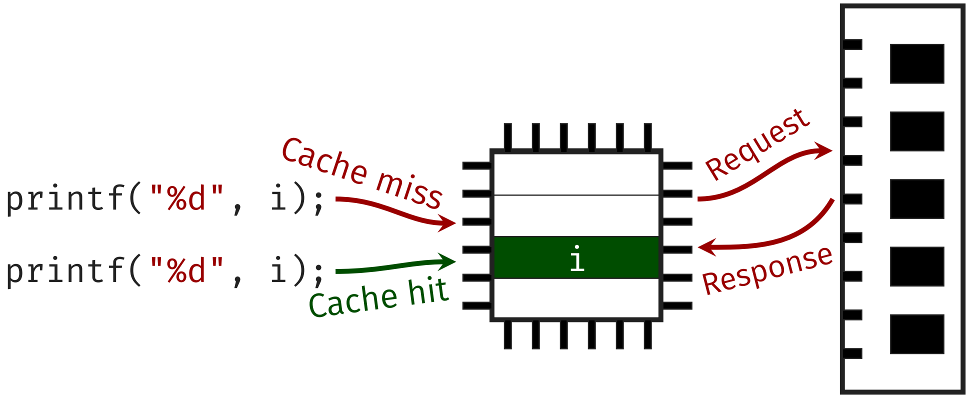

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CPU Cache

DRAM access,
slow

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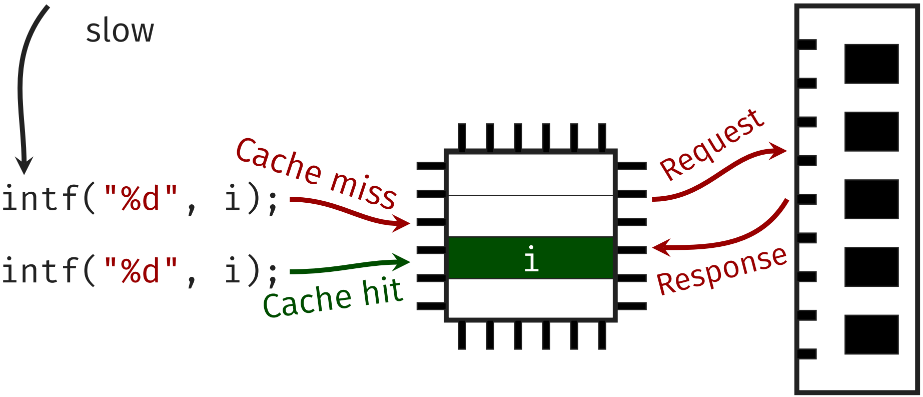
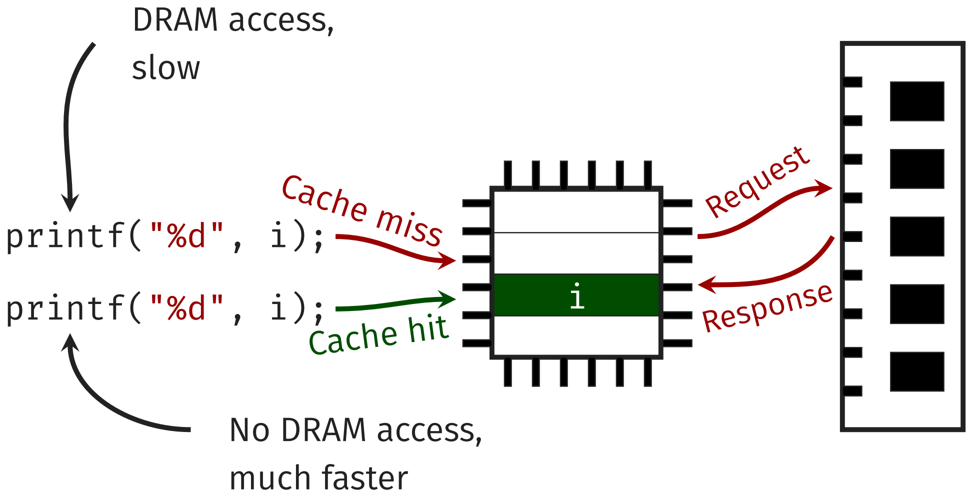
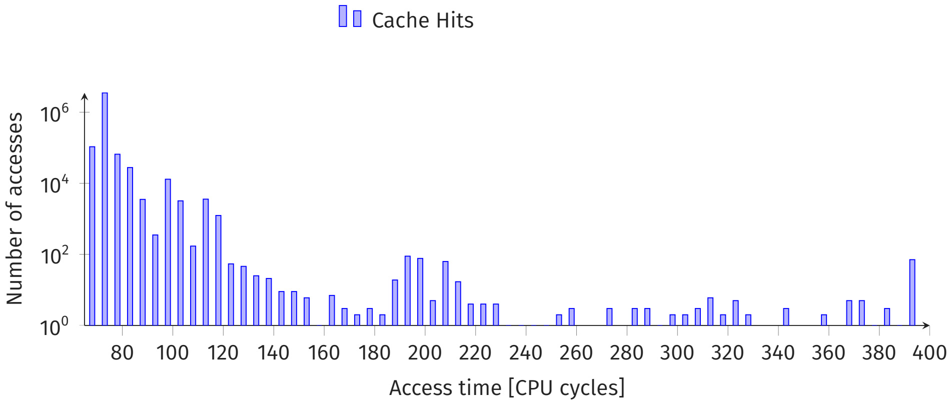


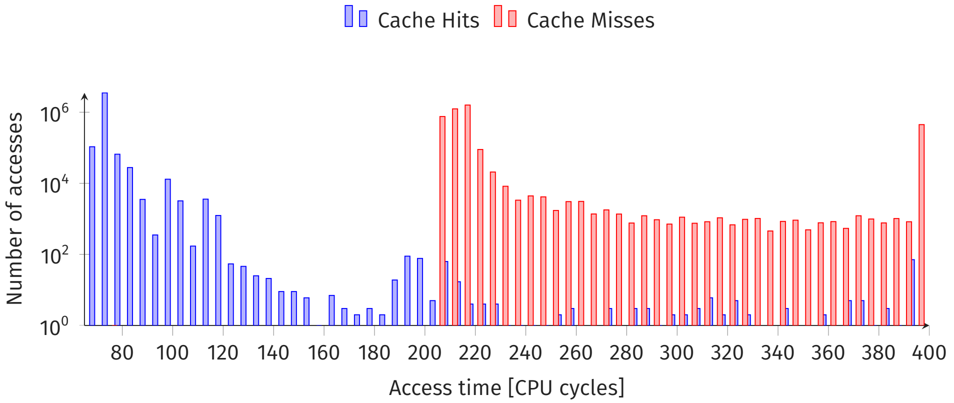
CPU Cache


DRAM access,
slow
printf("%d", i);
Cache miss
printf("%d", i);
Cache hit
i
Request
Response
No DRAM access,
much faster

Caching speeds up Memory Accesses



Caching speeds up Memory Accesses



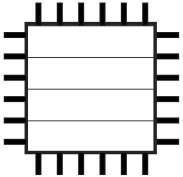
Evict+Reload

Shared Memory

Attacker

evict

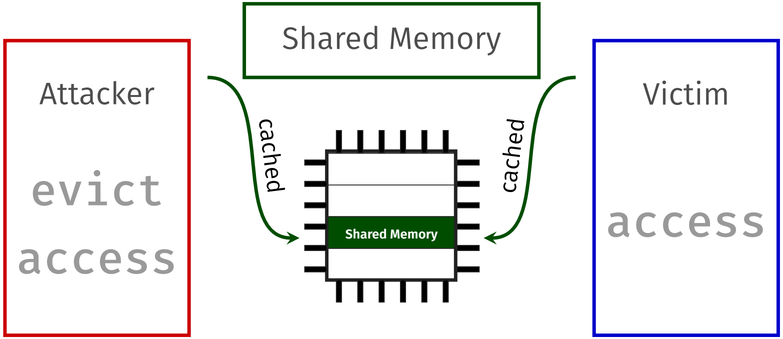
access



Victim

access

Evict+Reload



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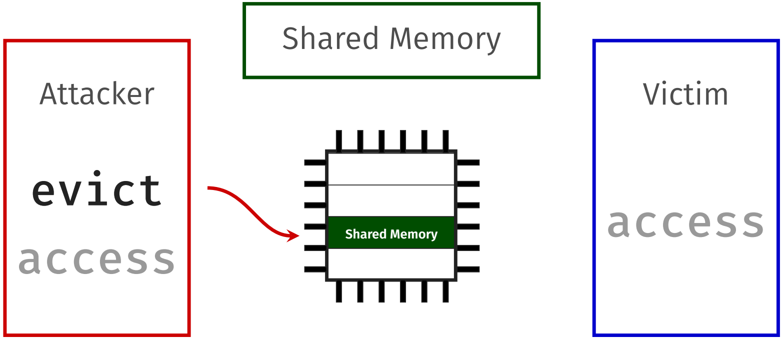

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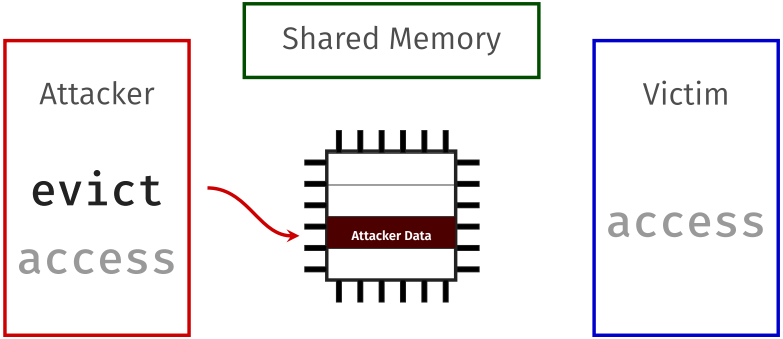

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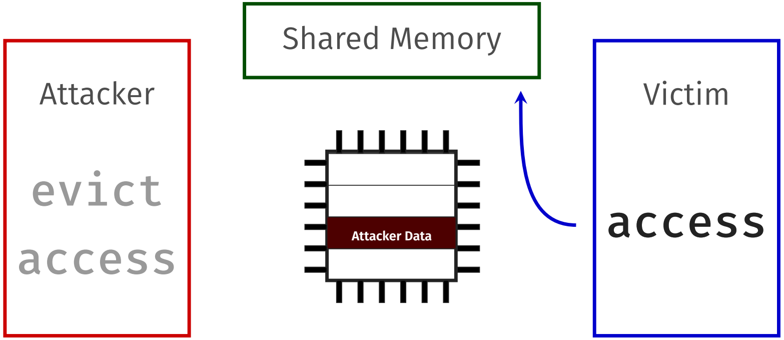

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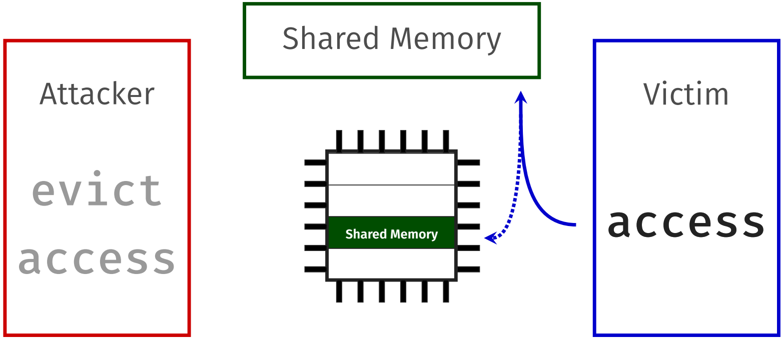

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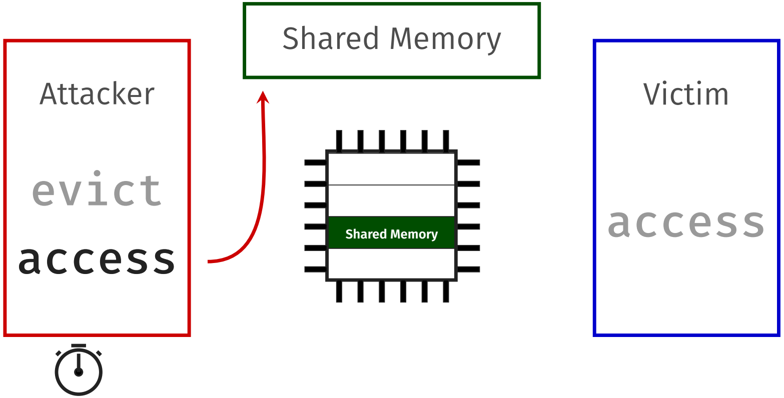

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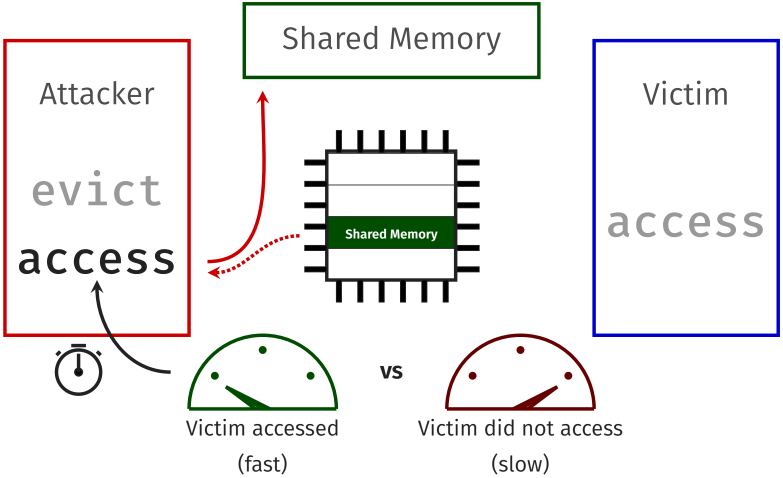


Speculative execution

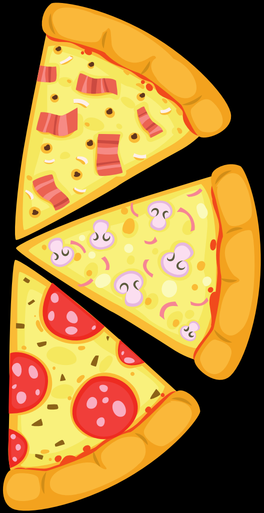
Speculative Execution

- CPU tries to predict the future (branch predictor), ...
  - ...based on events learned in the past
- Speculative execution of instructions
- If the prediction was correct, ...
  - ...very fast
  - otherwise: Discard results
- Measurable side-effects

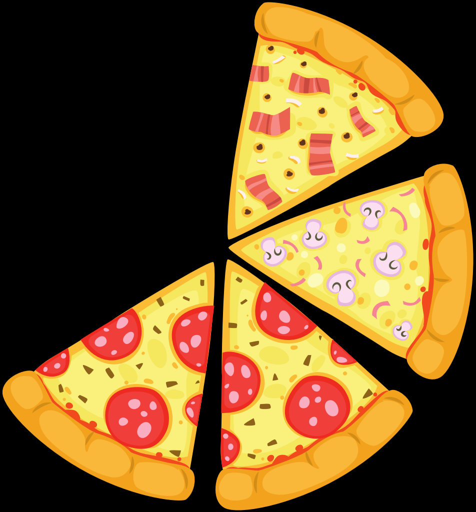
PIZZA
SPECIAL RECIPES

Prosciutto

Funghi



Diavolo



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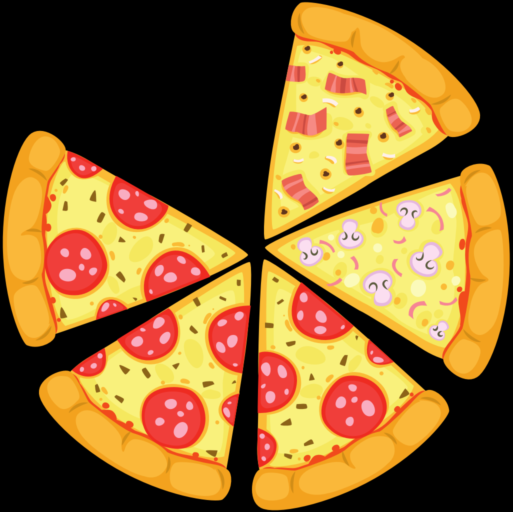

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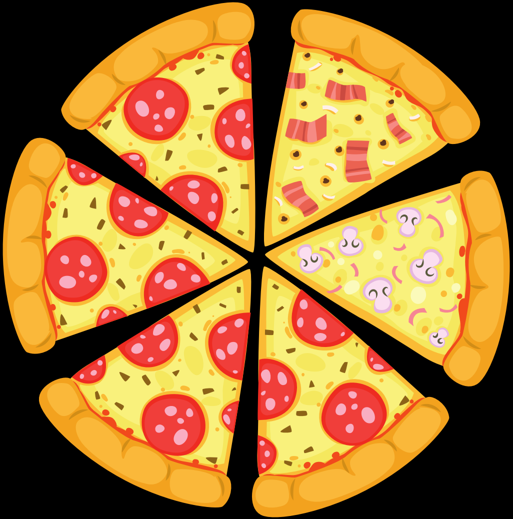

Diavolo

»A table for 6 please«

Speculative Cooking

»A table for 6 please«

PIZZA
SPECIAL RECIPES

PIZZA
SPECIAL RECIPES

Pizza

PIZZA
SPECIAL RECIPES

Pizza

PIZZA
SPECIAL RECIPES

Pizza

SPECTRE

Spectre Requirements

- On Intel and AMD CPUs

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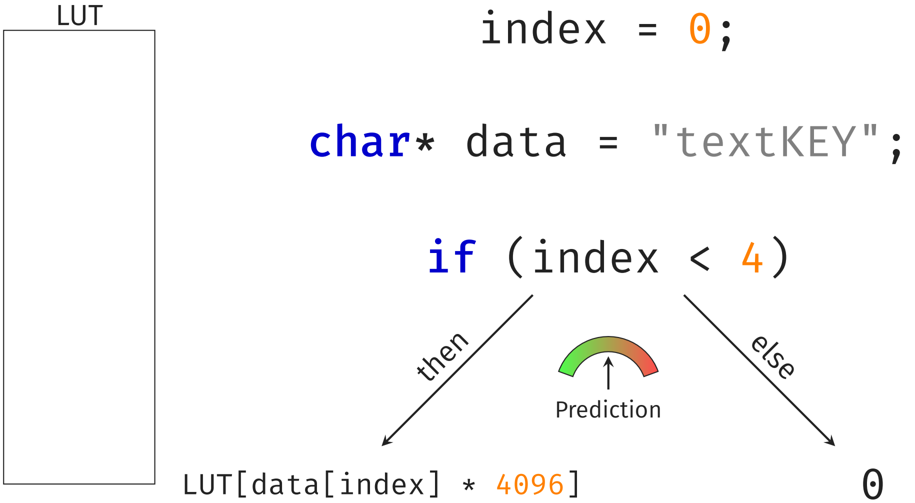
- On Intel and AMD CPUs
- Some ARMs (Cortex R and Cortex A) are also affected
- Common cause: speculative execution of branches
- Speculative execution leaves microarchitectural traces which leak secret

Spectre-PHT (aka Spectre Variant 1)



```
index = 0;

char* data = "textKEY";

if (index < 4)

LUT[data[index] * 4096]                    0
```

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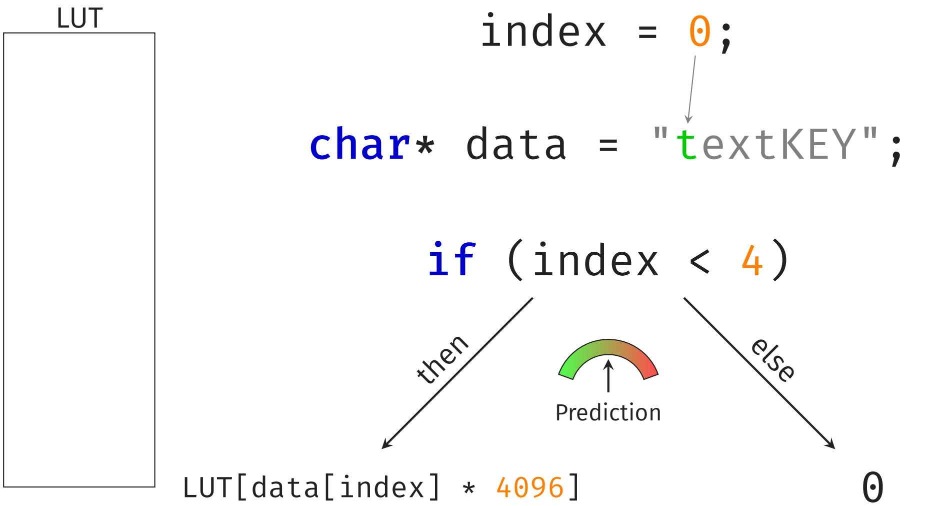

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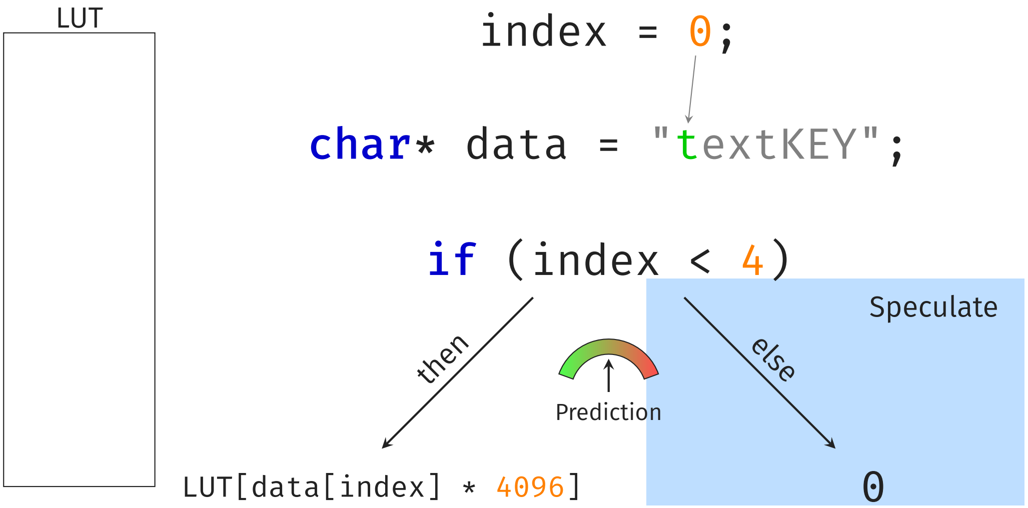

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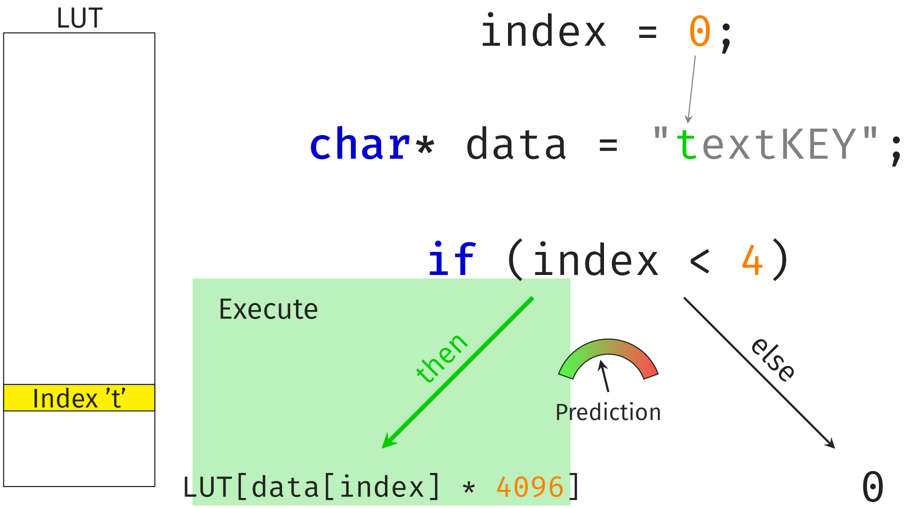

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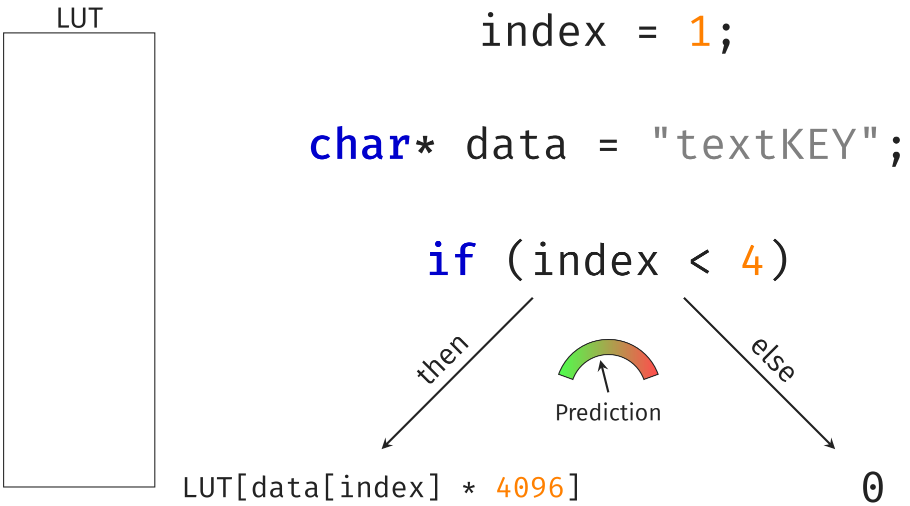

```
index = 1;

char* data = "textKEY";

if (index < 4)

LUT[data[index] * 4096]          0
```

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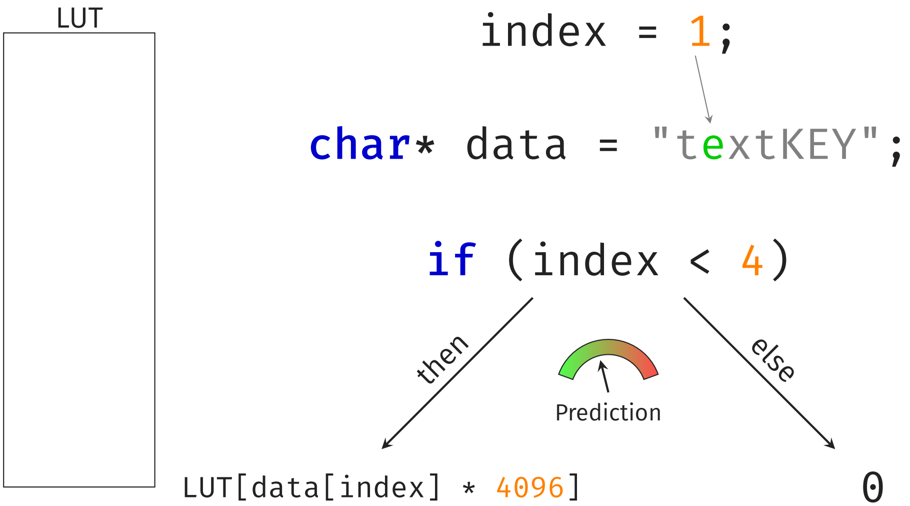

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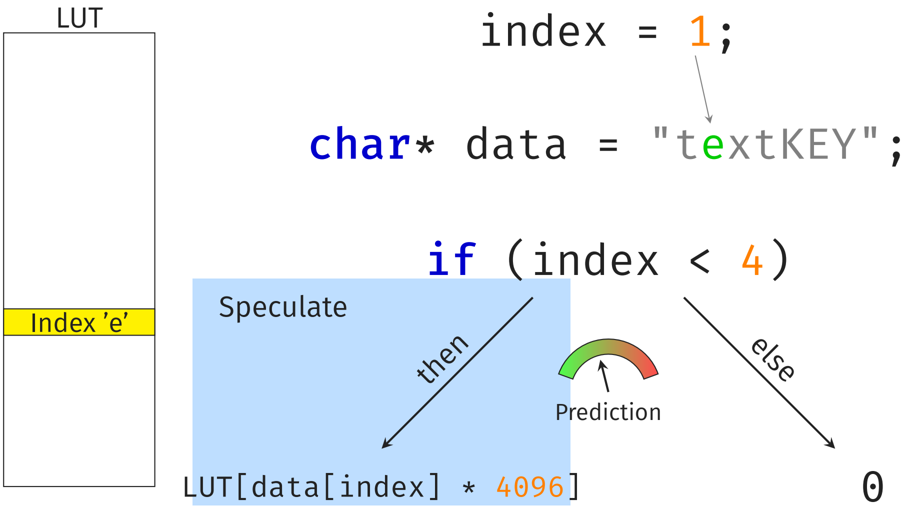

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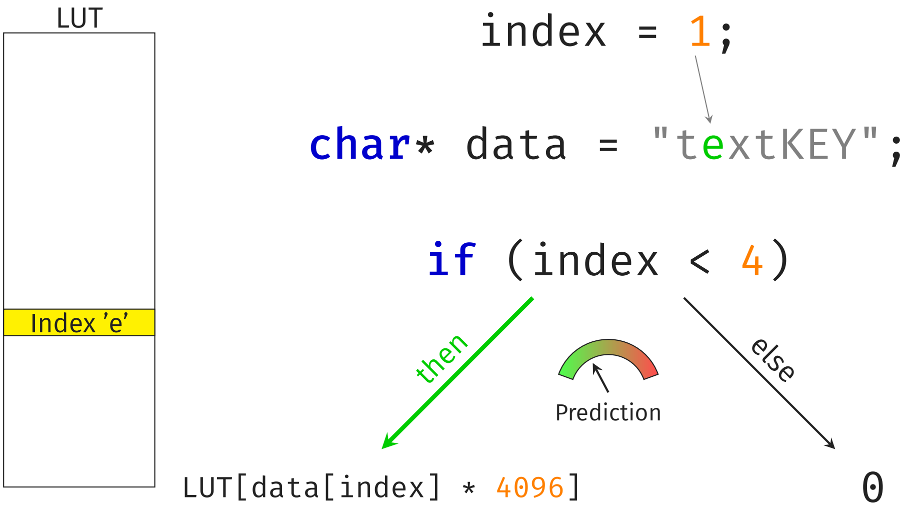

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char* data = "textKEY";

if (index < 4)

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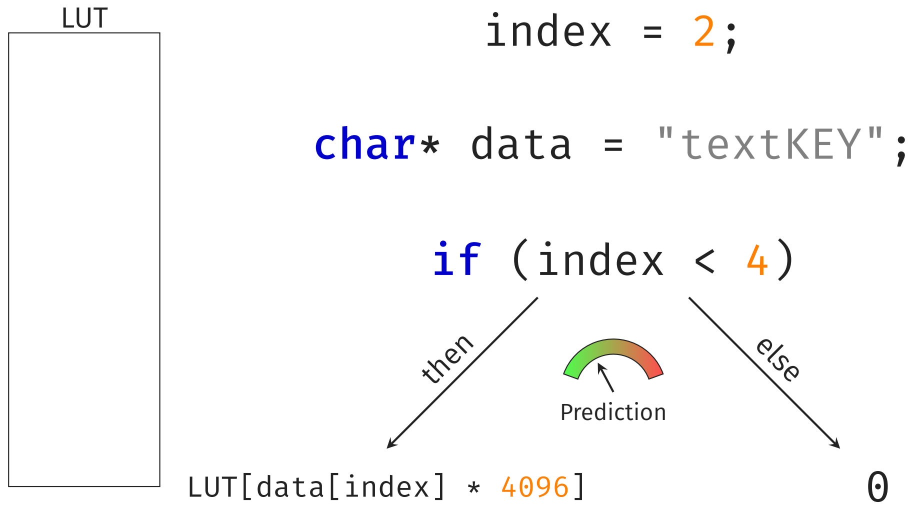

```
index = 2;

char* data = "textKEY";

if (index < 4)
```

```
LUT[data[index] * 4096]
```

```
0
```

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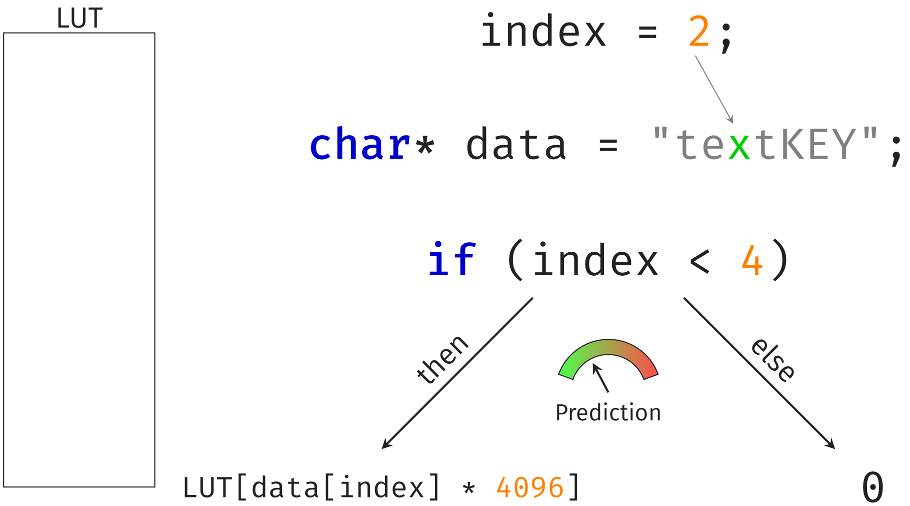

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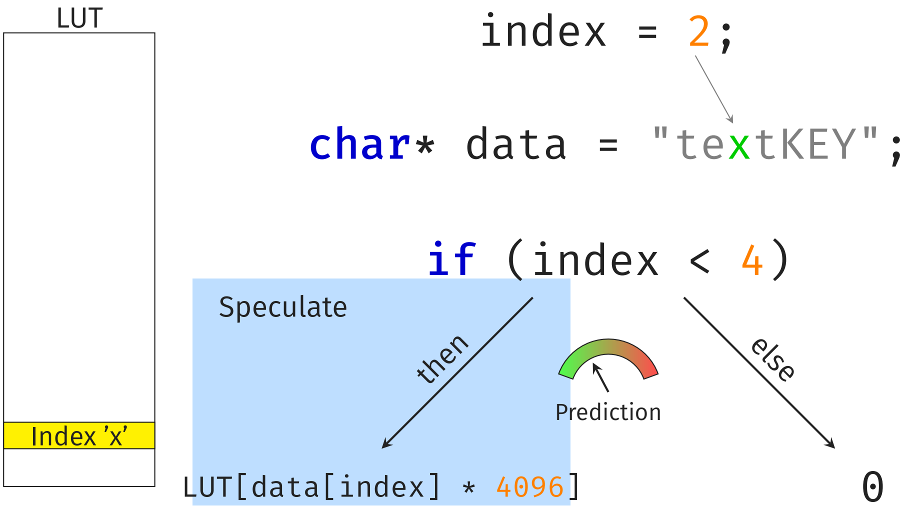

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index = 2;

char* data = "textKEY";

if (index < 4)

LUT[data[index] * 4096]        0
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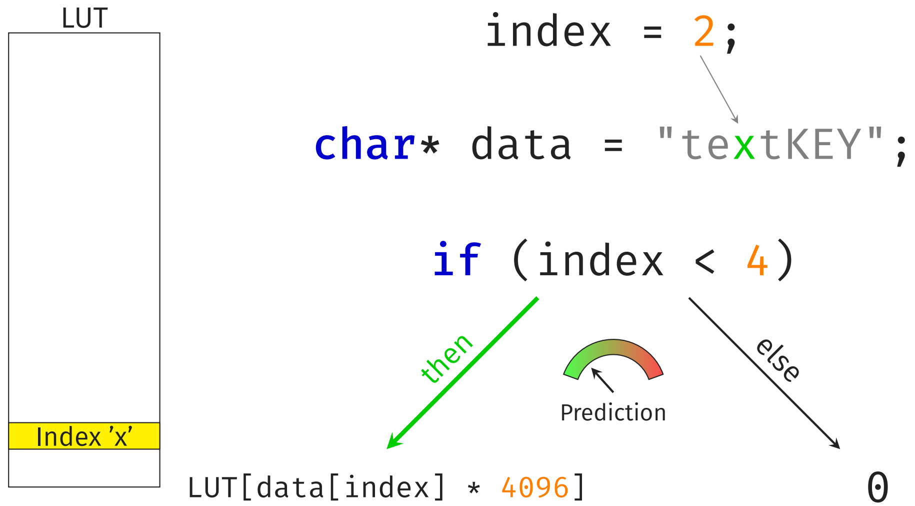

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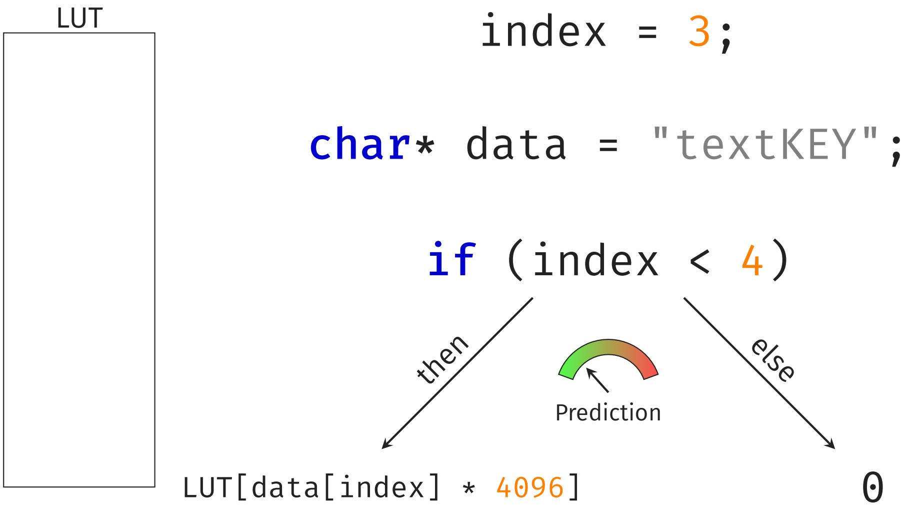

```
index = 3;

char* data = "textKEY";

if (index < 4)

LUT[data[index] * 4096]                    0
```

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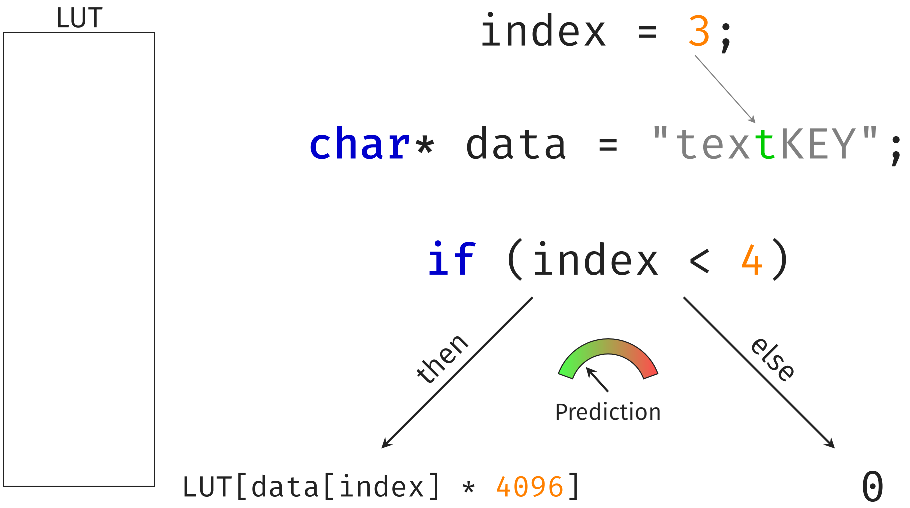

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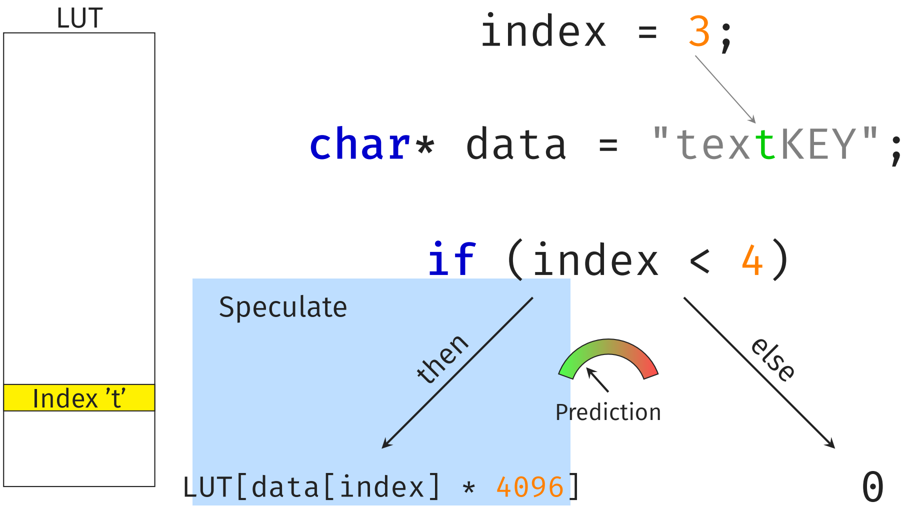

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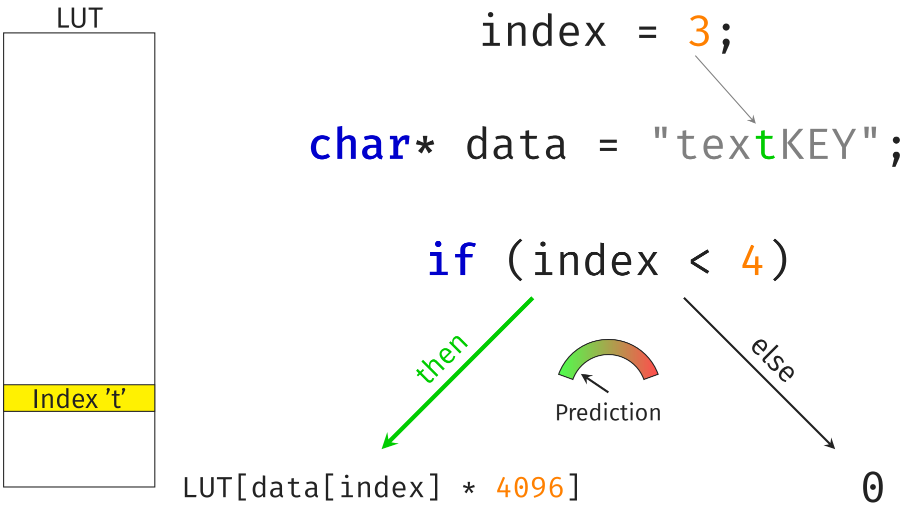

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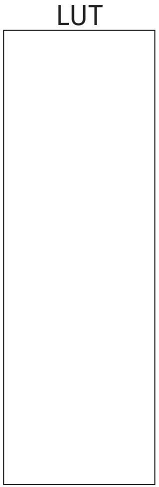

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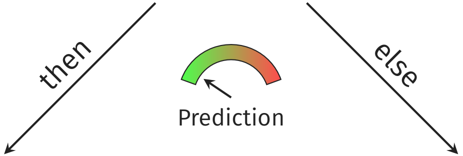

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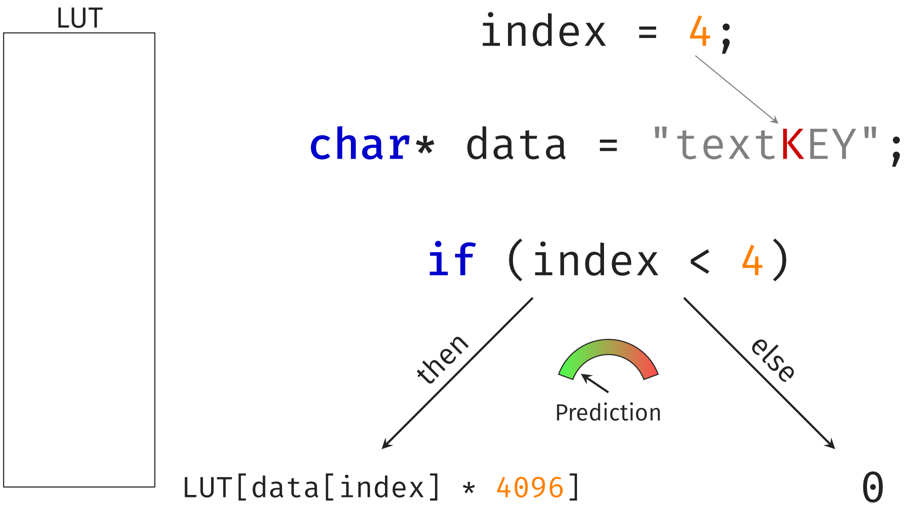

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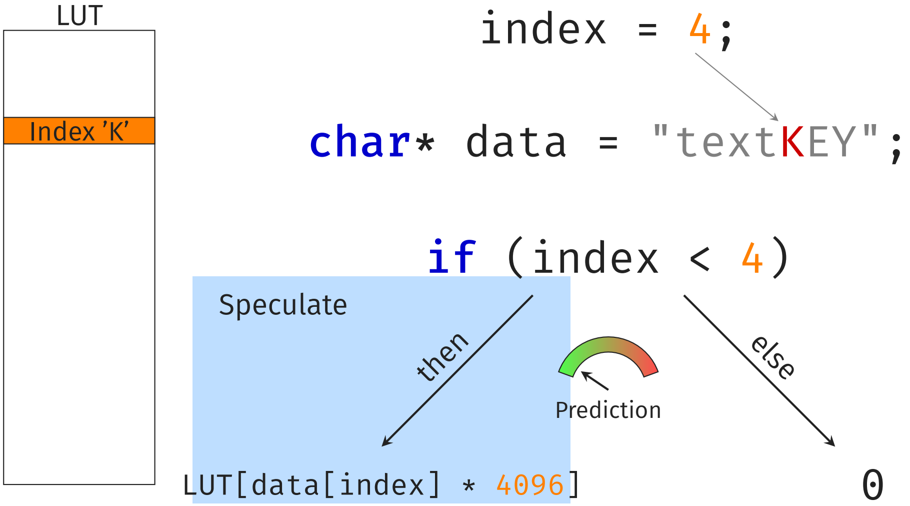

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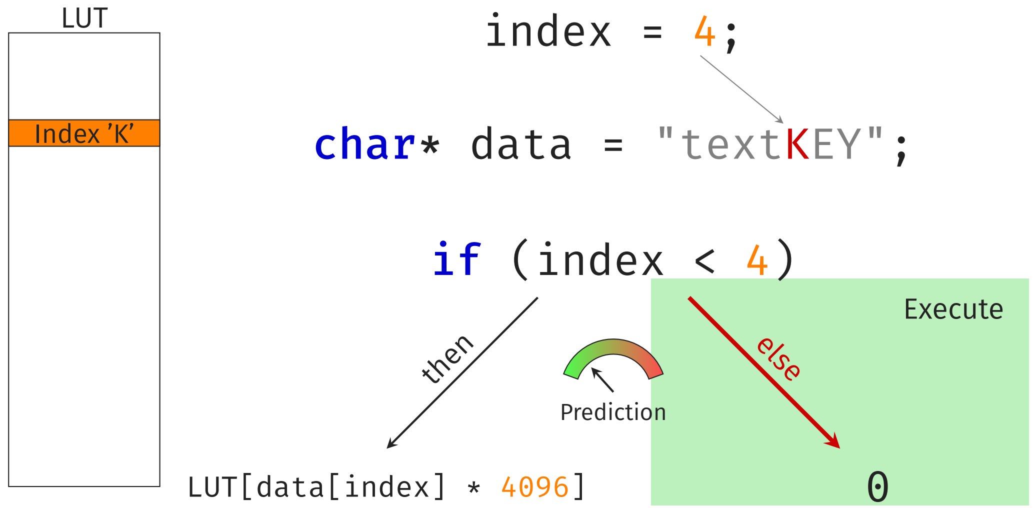

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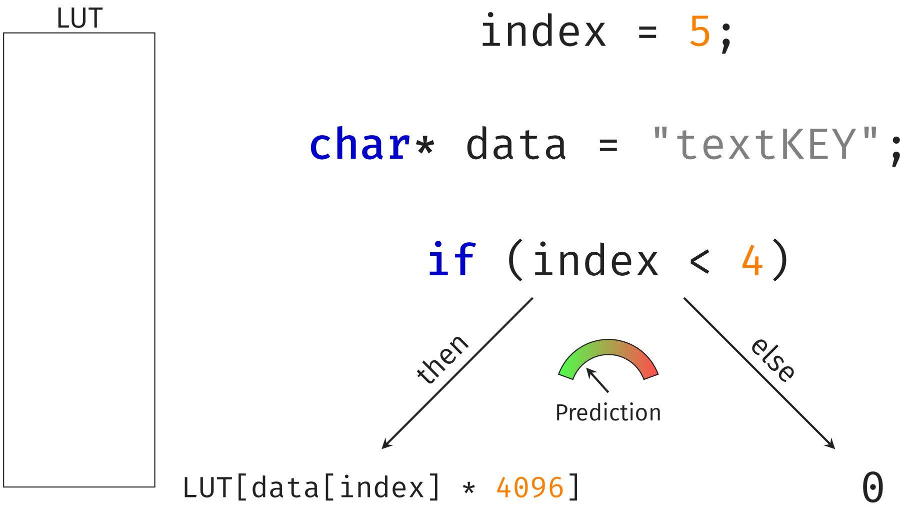

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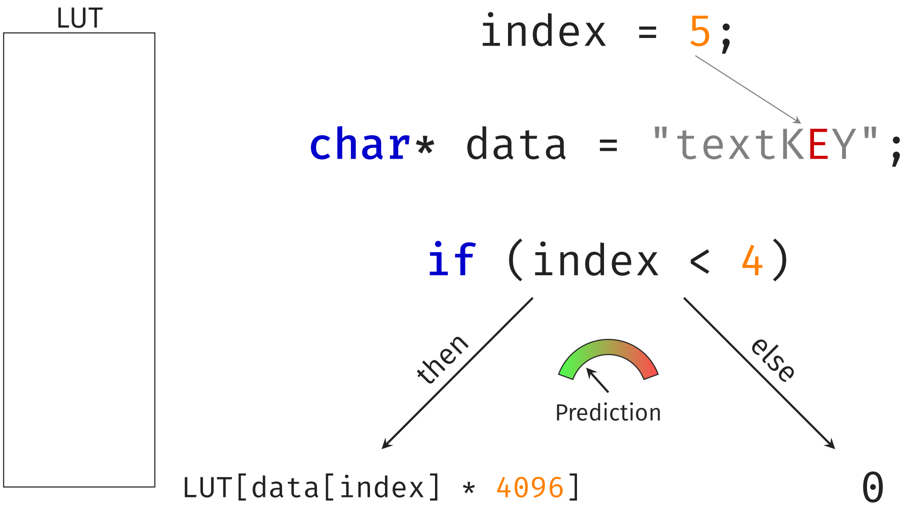

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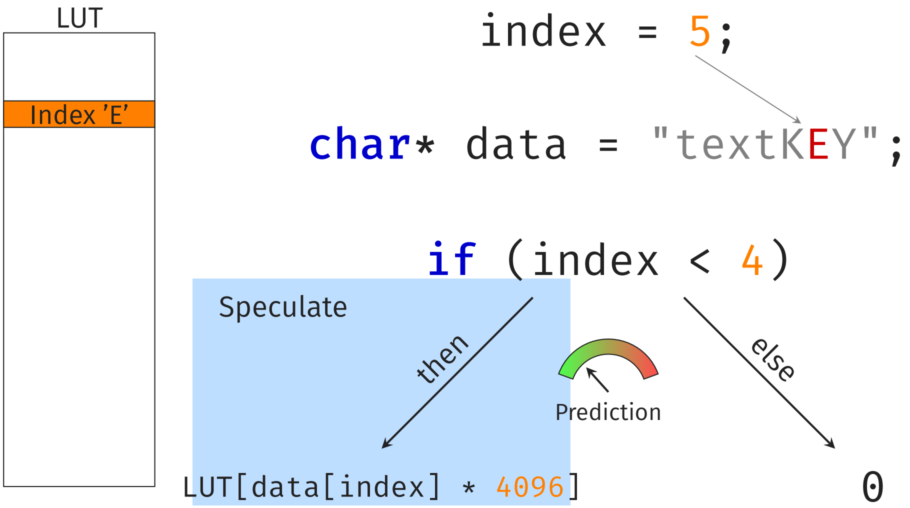

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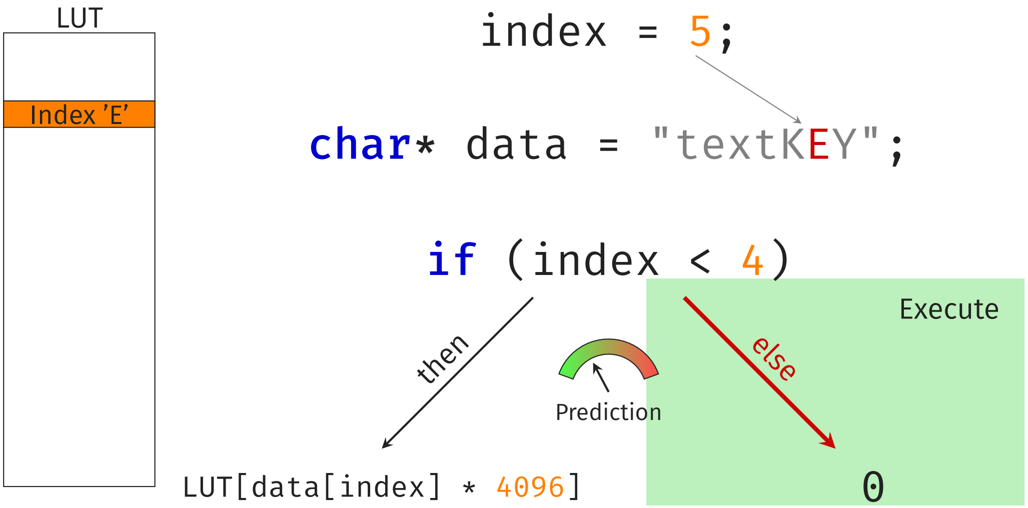

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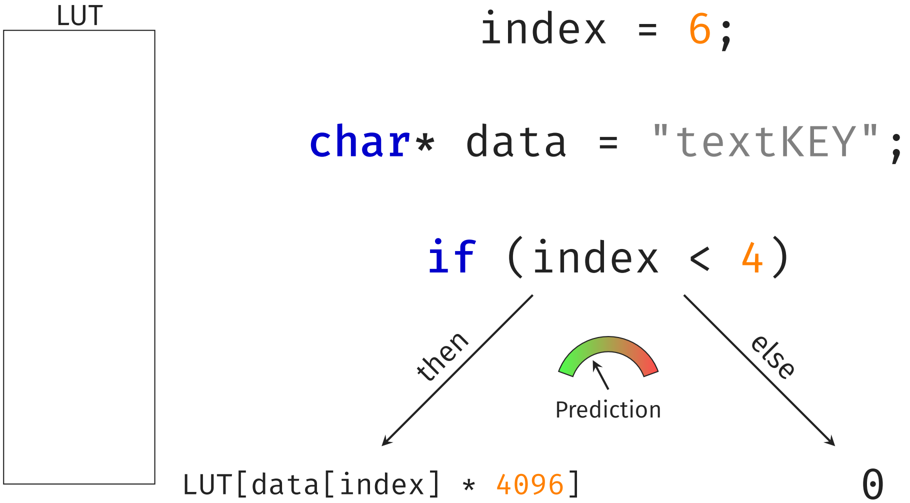

```
index = 6;

char* data = "textKEY";

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```

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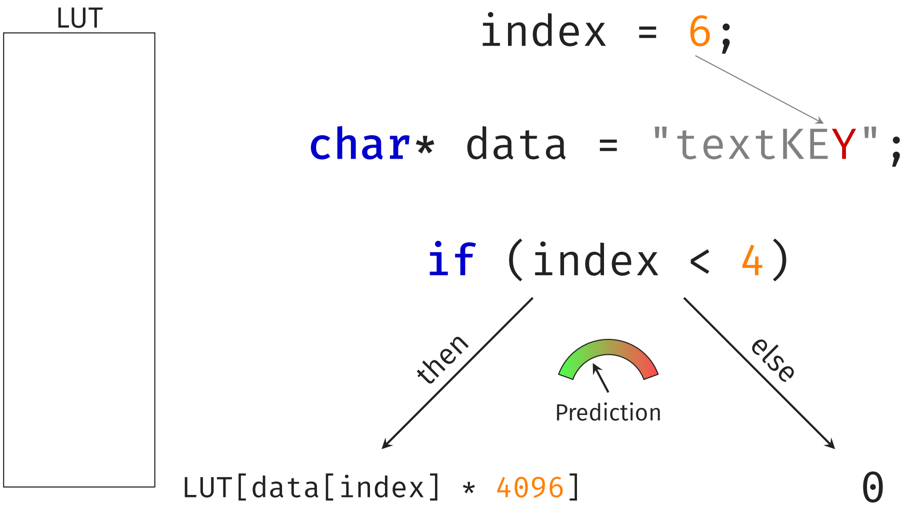

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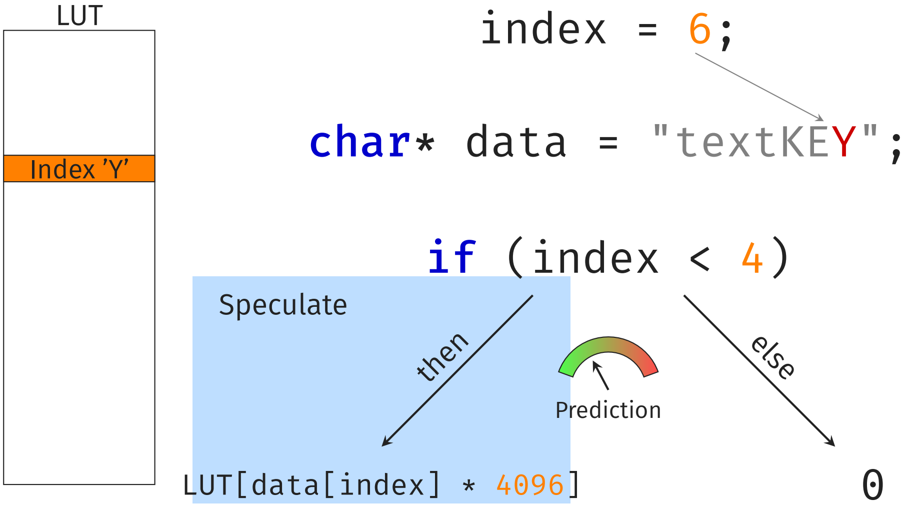

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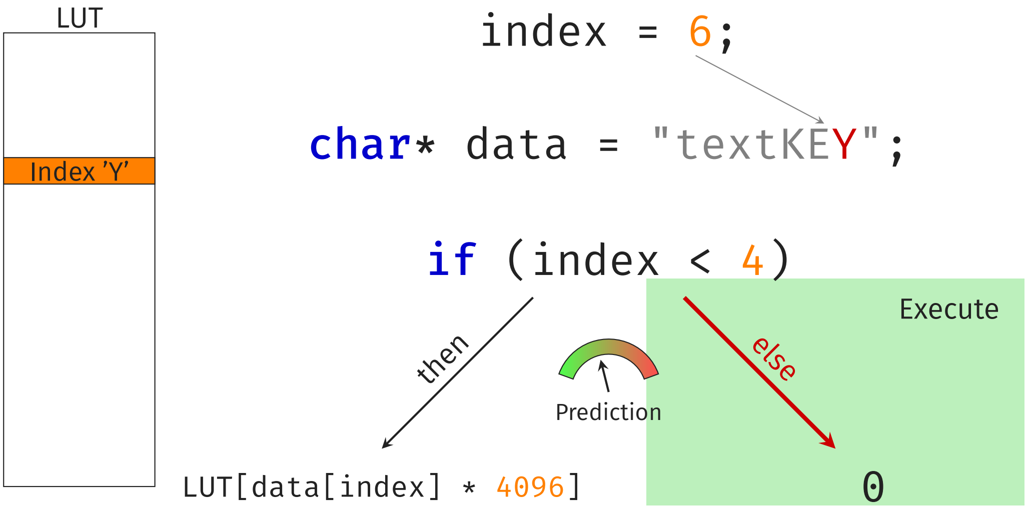

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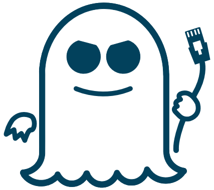
```

NetSpectre: A Remote Spectre Variant

The goal



We want to build a Spectre attack which...

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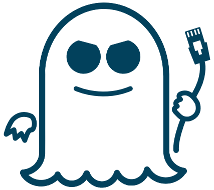

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- is capable of leaking secrets from a remote system

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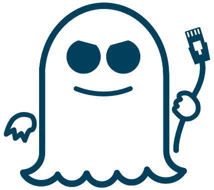

We want to build a Spectre attack which...

- is capable of leaking secrets from a remote system
- has neither physical access nor code execution on system

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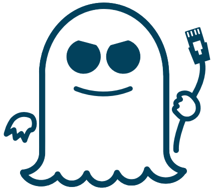

We want to build a Spectre attack which...

- is capable of leaking secrets from a remote system
- has neither physical access nor code execution on system
- does not rely on software vulnerabilities

Wait a minute...

CVSS v3 for CVE-2017-5753 (Spectre)

Attack Vector

Network	Adjacent Network	[✓ Local]	Physical

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CVSS v3 for CVE-2017-5753 (Spectre)

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Low	[✓ High]

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Privilege Required

None	[✓ Low]	High

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Attack Vector

Network | Adjacent Network | [✓ Local] | Physical

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None | [✓ Low] | High

User Interaction

[✓ None] | Required

Problems

Spectre without code execution is complicated

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Spectre without code execution is complicated

- Which branch can be exploited
- Cannot observe the cache state
- Spectre gadgets will be different
- No timing measurement on the attacked system
- How to select the data to leak

Exploiting Branches

- No code can be injected

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- No code can be injected
- Public interface (API) accessing data
- Branches in API can be mistrained remotely
- Attacker only calls the API via network requests

API Example

```
def check_user_privileges(user_id):
  [...]
  if user_id < len(users):
    if test_bit(privileges, user_id) == True:
      admin = True

  return SUCCESS
```

API Example

```
def check_user_privileges(user_id):
  [...]
  if user_id < len(users):     Bounds check
    if test_bit(privileges, user_id) == True:
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  return SUCCESS
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Bounds check

Speculative out-of-bounds read

API Example

```
def is_admin():
  return admin
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API Example

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- If bit in array was set → `admin` is cached
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- Observe cache state via function execution time

Timing Measurement

- Cannot measure time directly on the attacked system

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$\rightarrow$ Measure the network roundtrip time

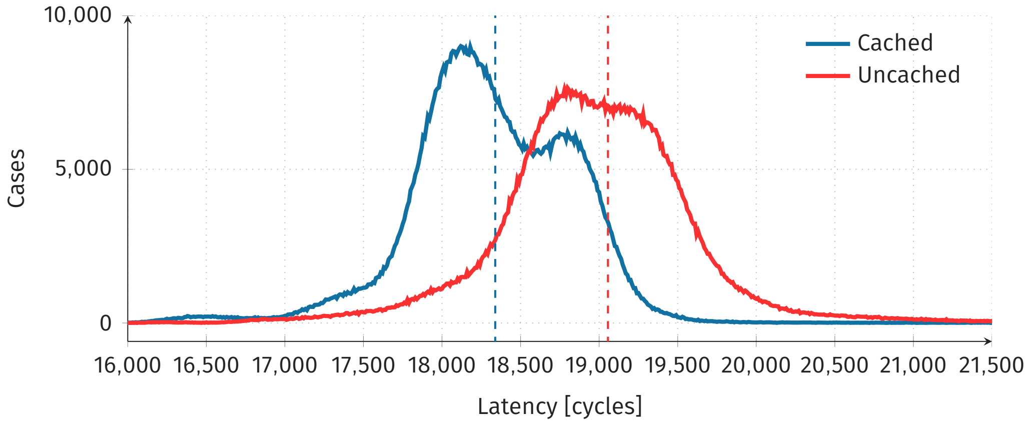
Timing Measurement

- Cannot measure time directly on the attacked system
- Network latency depends on API execution time

→ Measure the network roundtrip time

- Reveals whether the variable is cached

Network Measurement



Resetting Cache State

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- Constantly evict the cache via a file download

Resetting Cache State

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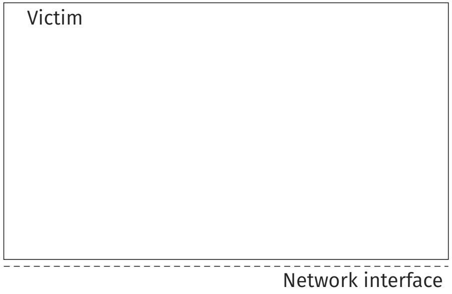
- Constantly evict the cache via a file download
- Thrash+Reload $\rightarrow$ crude form of Evict+Reload

NetSpectre - The Big Picture



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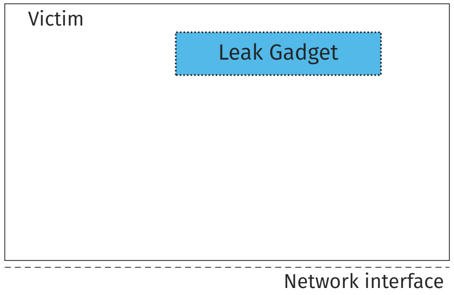

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if (x < bitstream_length)
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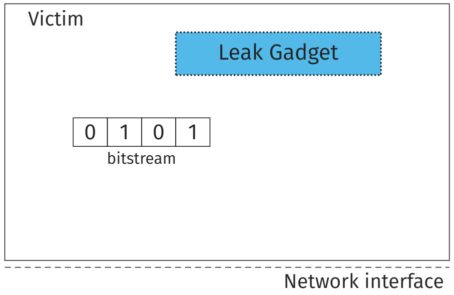

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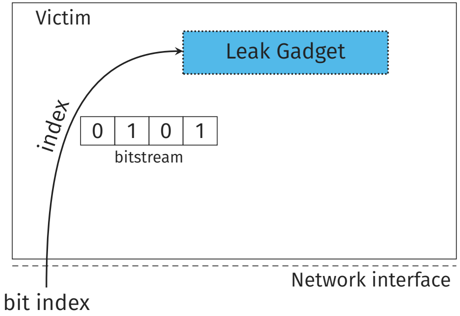

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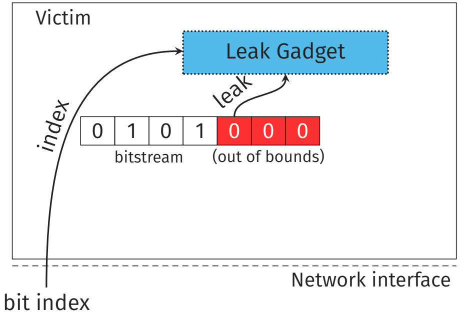

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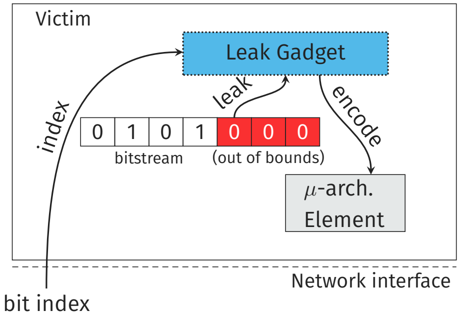

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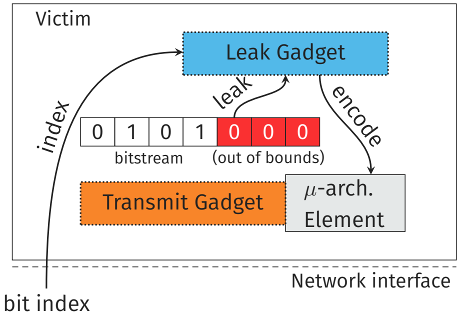

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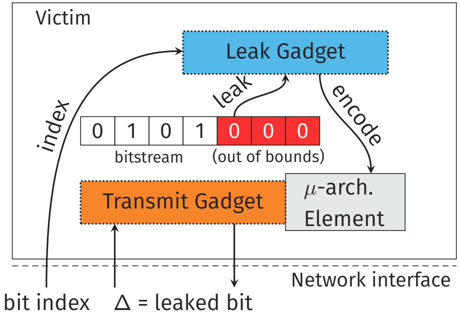

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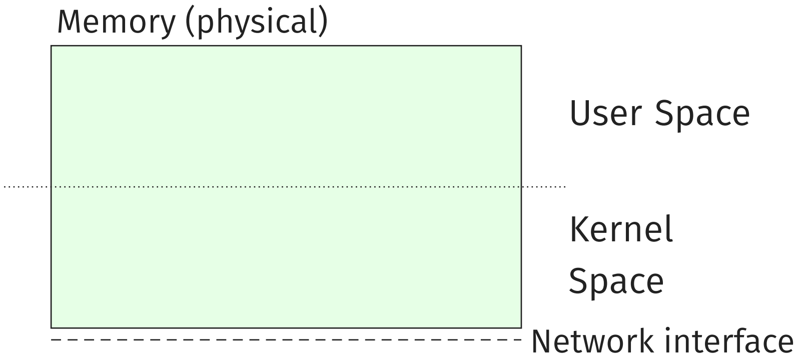
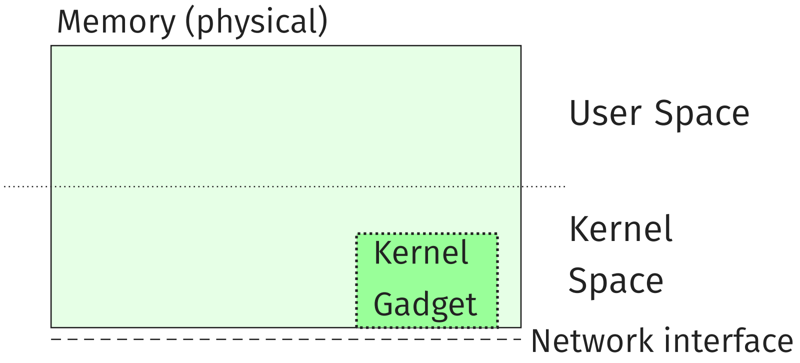
Gadgets


Memory (physical)
User Space
Kernel Space
Network interface

Gadgets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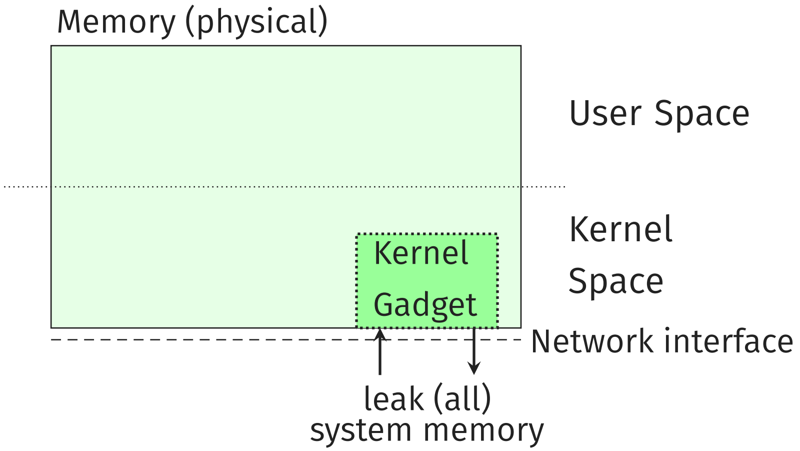
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leak (all) system memory

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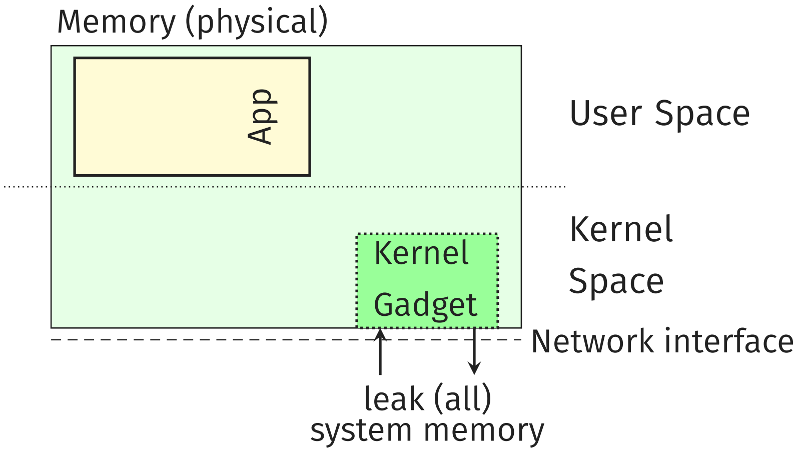
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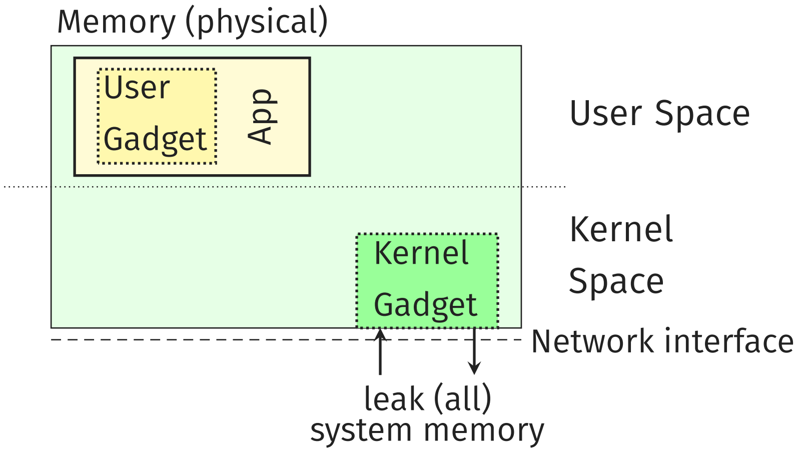
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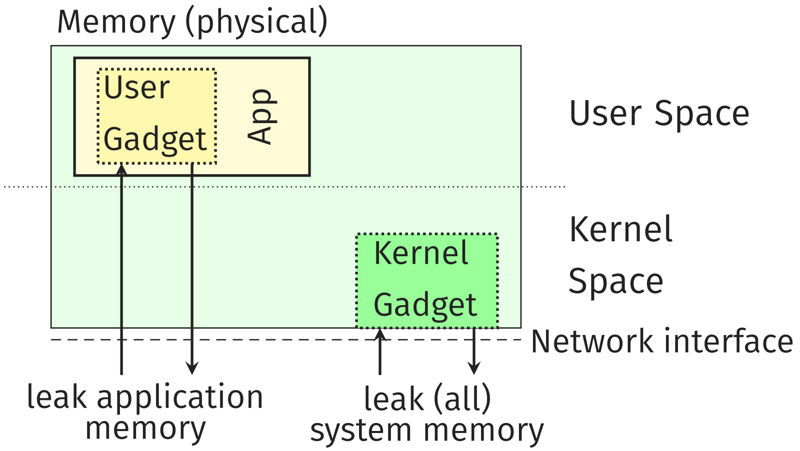
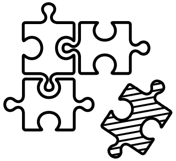


Memory (physical)
User Gadget
App
User Space
Kernel Space
Kernel Gadget
Network interface
leak application memory
leak (all) system memory

Combining Everything



- Mistrain branch predictor with in-bounds requests

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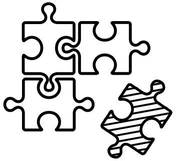

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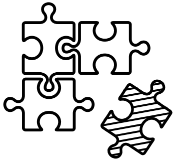

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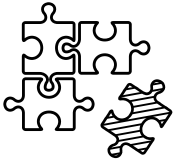
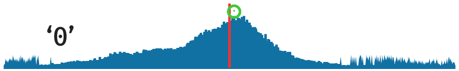


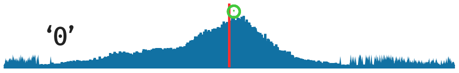
- Mistrain branch predictor with in-bounds requests
- Evict everything from cache via file download
- Leak a bit: do nothing (‘0’) or cache a memory location (‘1’)
- Measure function latency which uses the memory location

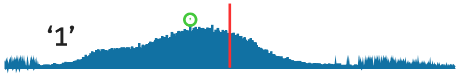
Leaking



Leaking byte ’d’ (0   )

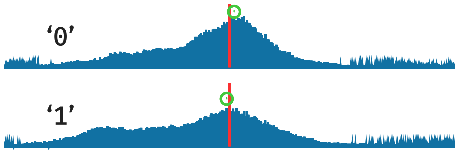
Leaking

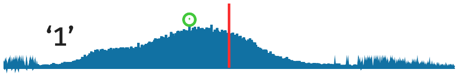




Leaking byte ’d’ (`01`)

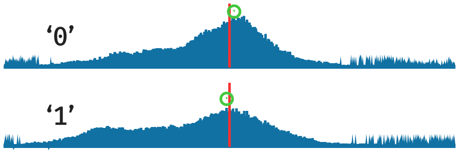
Leaking

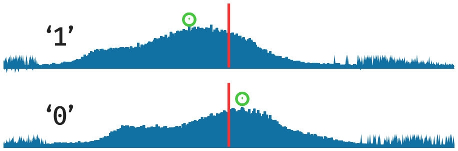




Leaking byte ’d’ (011)

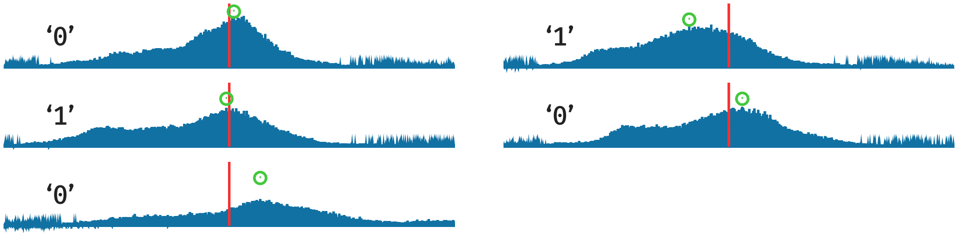
Leaking





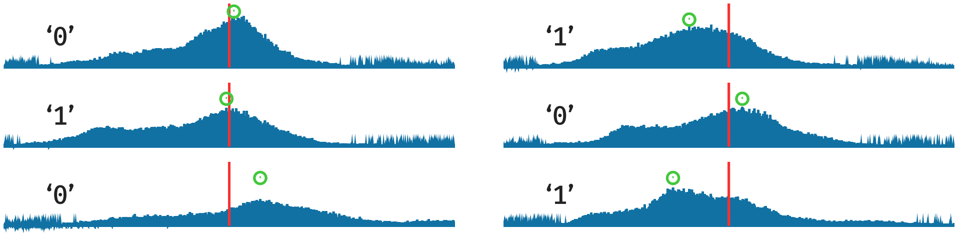
Leaking byte ’d’ (`0110`)

Leaking



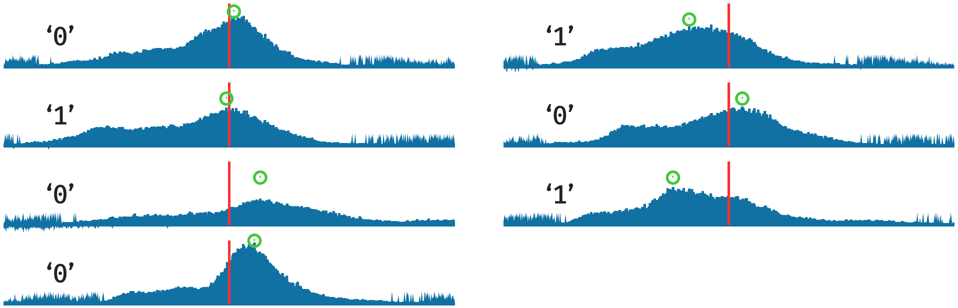
Leaking byte ’d’ (01100)

Leaking



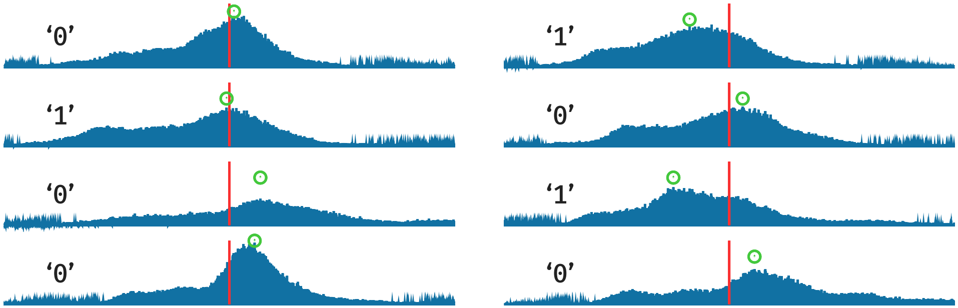
Leaking byte ’d’ (011001)

Leaking



Leaking byte 'd' (`0110010  `)

Leaking



Leaking byte ’d’ (`01100100`)

What can we exploit with them?

Attack Targets

- Several possible attack targets

Attack Targets

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- Different impacts depending on target

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Web/FTP Servers
(user gadget)

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SSH Daemons
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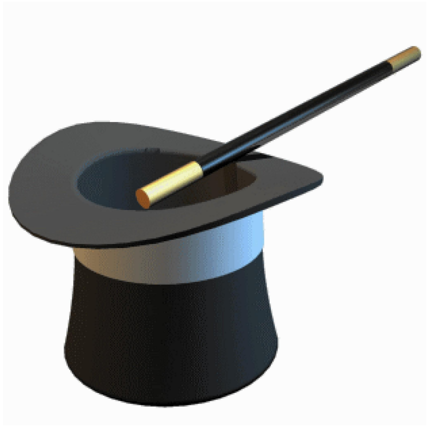
Network Drivers
(kernel gadget)

Live Demo



That’s nice but how do we find the gadgets?

How to Find a Gadget

- Finding Spectre gadgets is still an open problem

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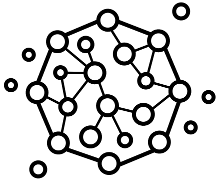
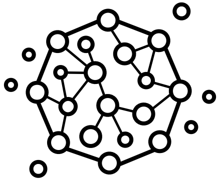
- Out of all papers, only 4 show real-world gadgets
- Among them, only 2 Spectre-PHT (v1) gadgets
- Still no fully automated approach

Automated Gadget Detection



- Linux kernel uses static code analysis

Automated Gadget Detection



- Linux kernel uses static code analysis
- High false positive rate

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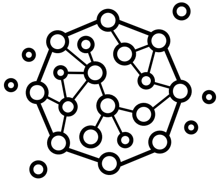

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→ Out of 736 reports only 15 real gadgets

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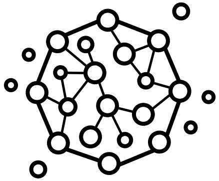

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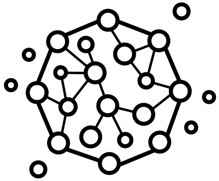

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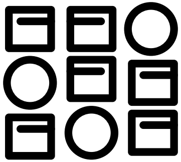
- Ongoing effort, $>$ 100 patches applied to Linux kernel
- $>$ 930 Spectre patches in open-source projects

Automated Gadget Detection

- Built 21 toy examples, 18 containing Spectre gadgets

Automated Gadget Detection



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- We created two static approaches on detecting (Net)Spectre gadgets
    - Coccinelle (Matching the code pattern)
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- All Gadgets were detected, only 3 false positives
- Adapted oo7 approach to masscan open-source software

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- If input x flows into branch $x < size$, the branch is marked as tainted

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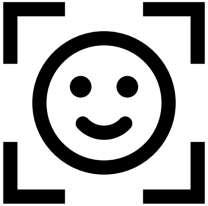
- If input x flows into branch $x < size$, the branch is marked as tainted
- $\exists$ a memory access relative within an array in a time window, report it as susceptible

Challenges in Identifying Gadgets

- Not clear how a Spectre gadget can look like

Challenges in Identifying Gadgets



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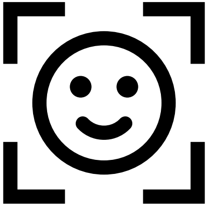

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- Similar to finding ROP chains

Challenges in Identifying Gadgets

- Not clear how a Spectre gadget can look like
- Potentially many different forms
- Can be scattered over many instructions
- Similar to finding ROP chains
- While searching, discovered novel type of gadget

Previously Ignored Spectre Gadgets

- No indirection, simple array access

Previously Ignored Spectre Gadgets

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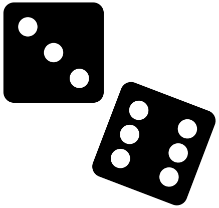
```
if (x < array_length)
  y = array[x];
```

Weaker Gadgets



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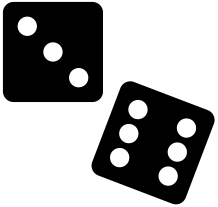

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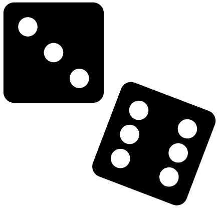

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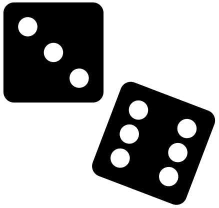
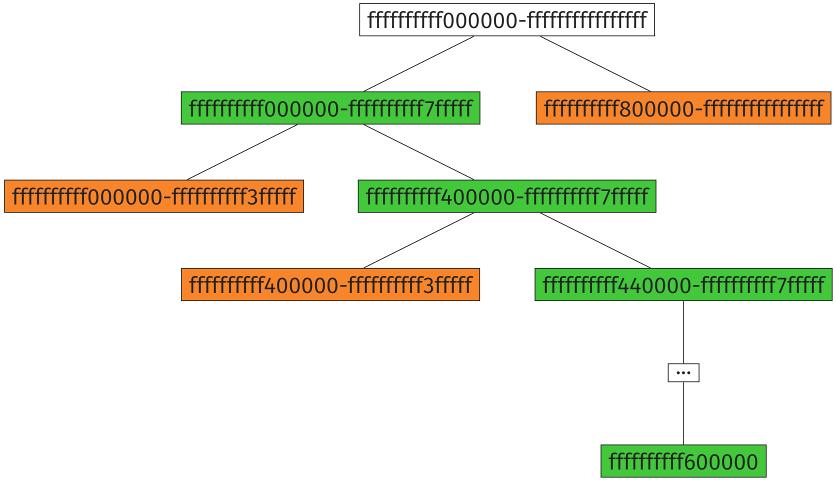


- What to do with weaker gadgets?

→ Break ASLR

- Not relevant for local Spectre attacks
- Valuable in a remote scenario

Break ASLR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ffffffffff000000-ffffffffff7fffff
ffffffffff800000-ffffffffffffffff
ffffffffff000000-ffffffffff3fffff
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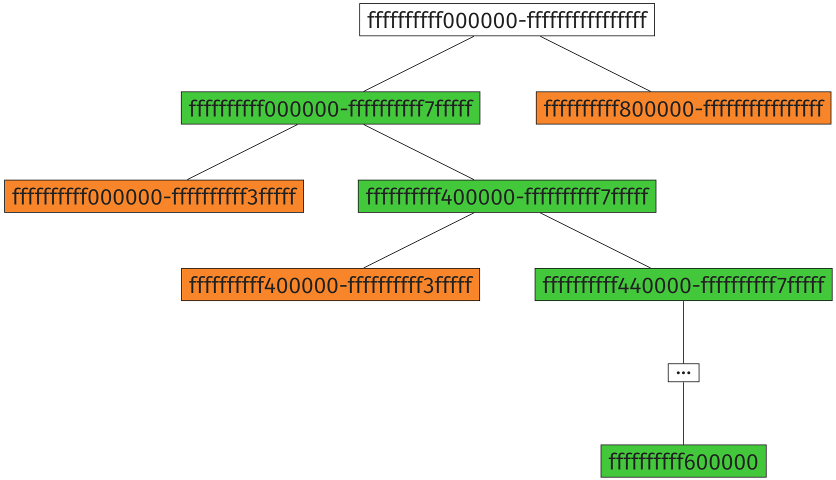
ffffffffff440000-ffffffffff7fffff
...
ffffffffff600000

Break ASLR



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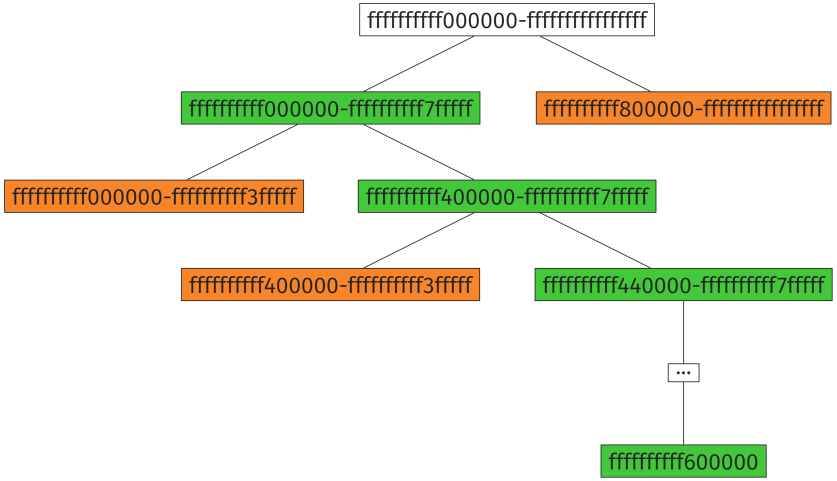
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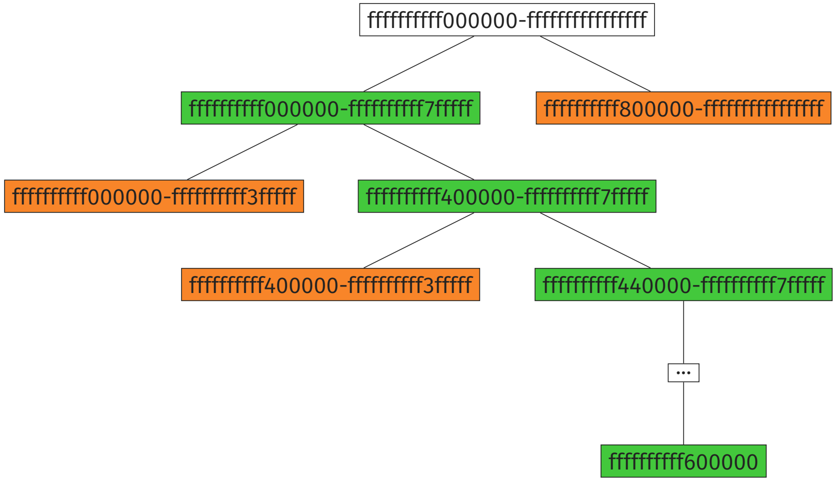

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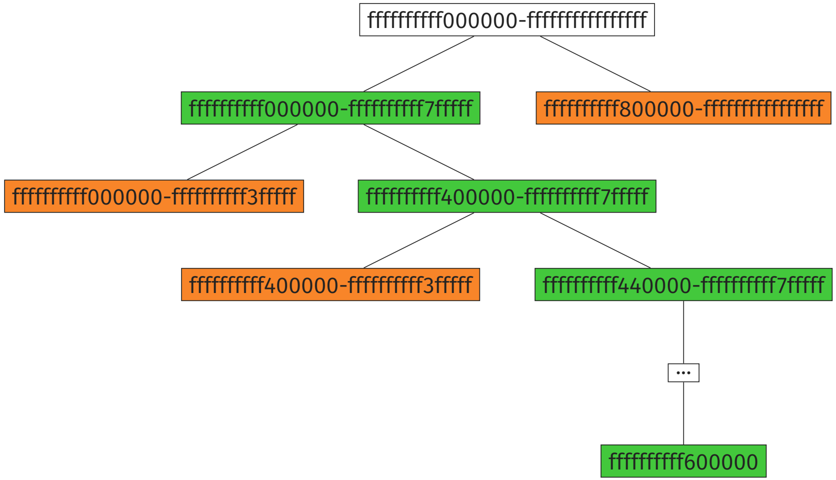
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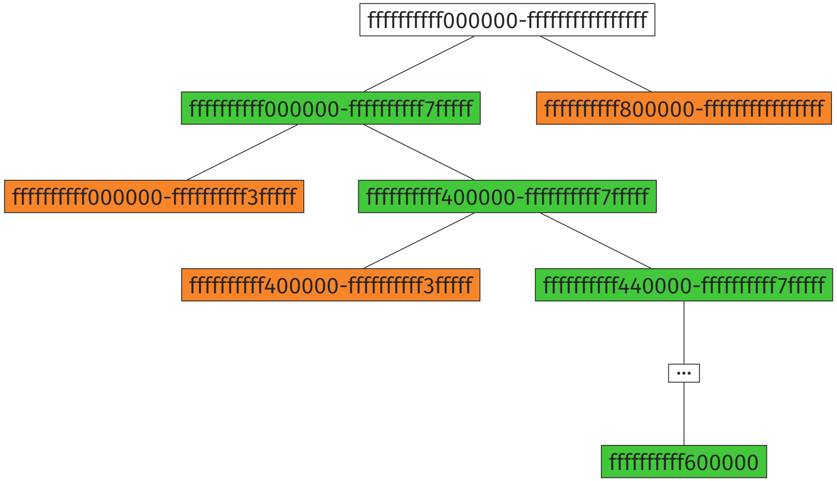
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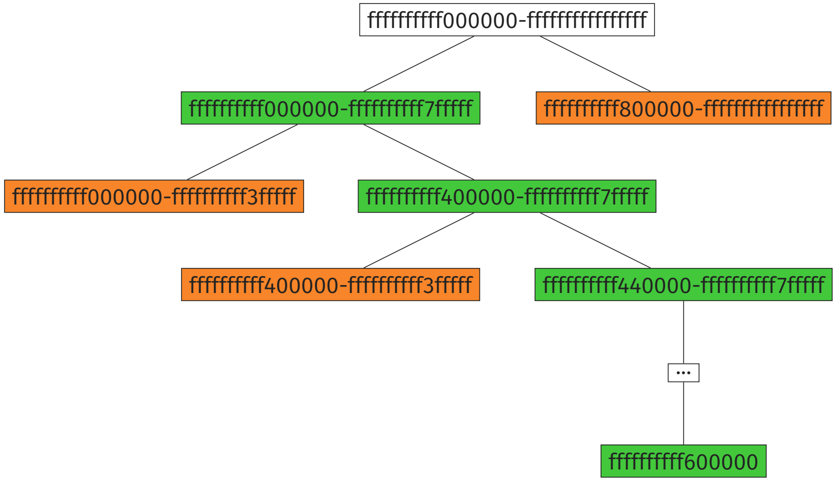
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Is cache the only channel to exploit Spectre Remotely?

Spectre and the Cache

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- Is this a requirement?
- Can we encode the data somewhere else?

Advanced Vector Instructions (AVX)

- Allow performing an operation in parallel on multiple data

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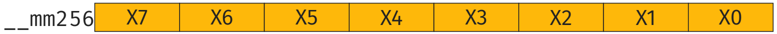

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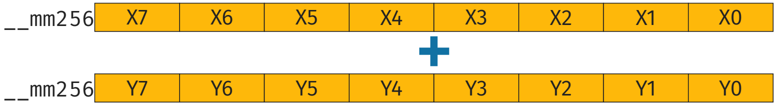

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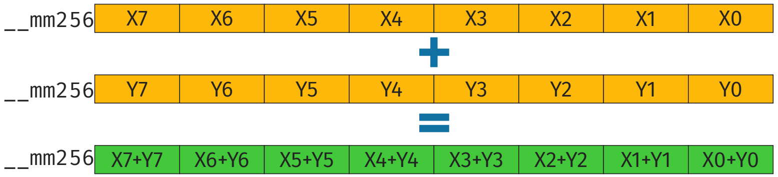

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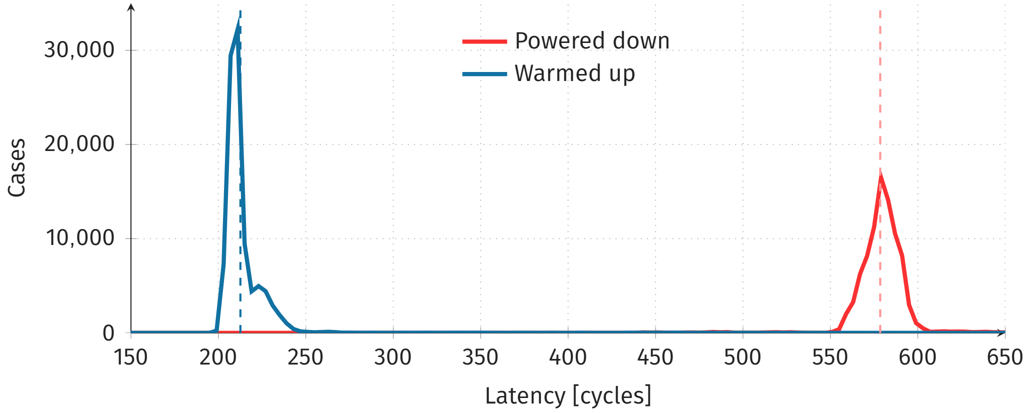
→ Leak timing information

AVX Latency

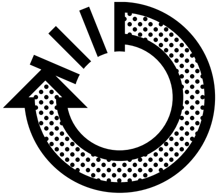


Powered down
Warmed up
Cases
30,000
20,000
10,000
0
150
200
250
300
350
400
450
500
550
600
650
Latency [cycles]

AVX Leak Gadget

```
if (x < bitstream_length)
    if(bitstream[x])
        _mm256_instruction();
```

Resetting Microarchitectural State



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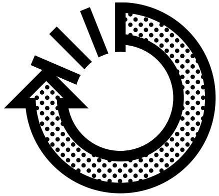

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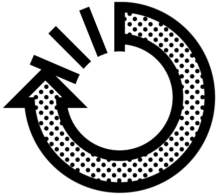

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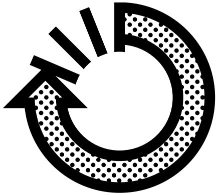
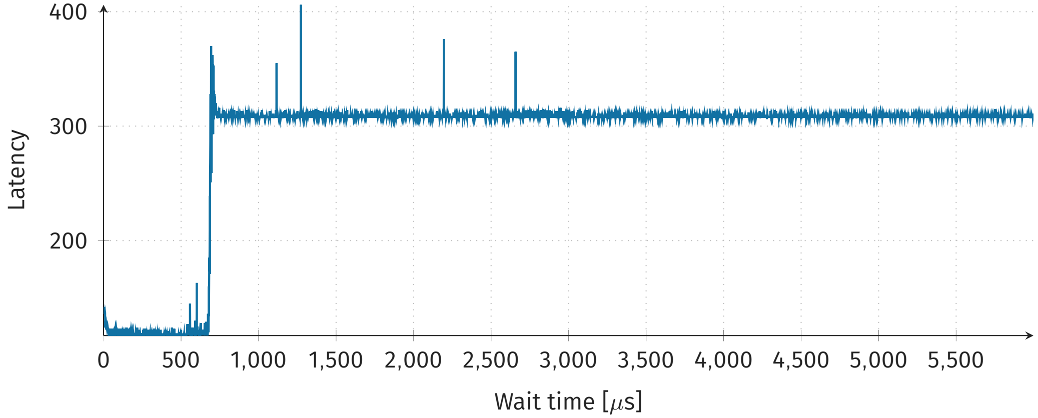
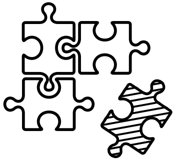


- We had to thrash cache to reset state
- Wait $\approx$1 ms $\rightarrow$ AVX unit powers off
- More efficient and stealthier than constantly downloading a file
- $\rightarrow$ higher performance than cache covert channel

AVX Cooldown



AVX-based NetSpectre



1. Mistrain branch predictor with in-bounds requests

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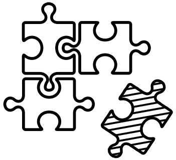

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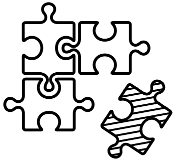

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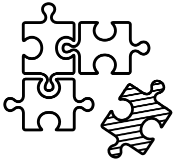

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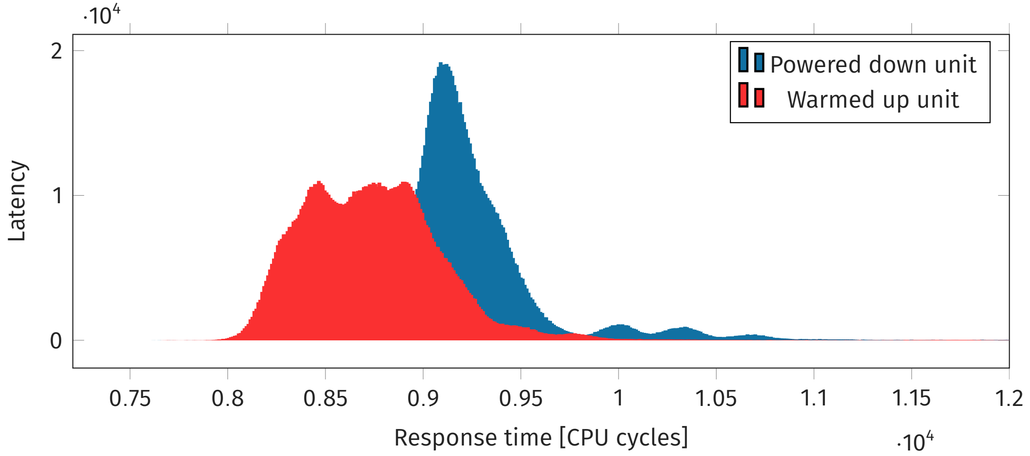
4. Measure function latency which uses AVX instruction

AVX Network



·10^4
2
1
0
Latency
Powered down unit
Warmed up unit
0.75
0.8
0.85
0.9
0.95
1
1.05
1.1
1.15
1.2
Response time [CPU cycles]
·10^4

Results

Test Environments

- NetSpectre tested in various environments

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i5-6200U, i7-8550U

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ARM Cortex A75

Attack Results

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1 h/bit

How to prevent NetSpectre

Network Countermeasures

- Mitigating NetSpectre

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Network side

Network Countermeasures

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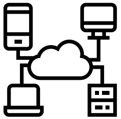

Network side

Fix Spectre

Network Countermeasures

- Prevent NetSpectre on the network side

Network Countermeasures

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Firewalls and DDoS protections

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Spectre Countermeasures

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Hardware Fixes

Spectre Countermeasures

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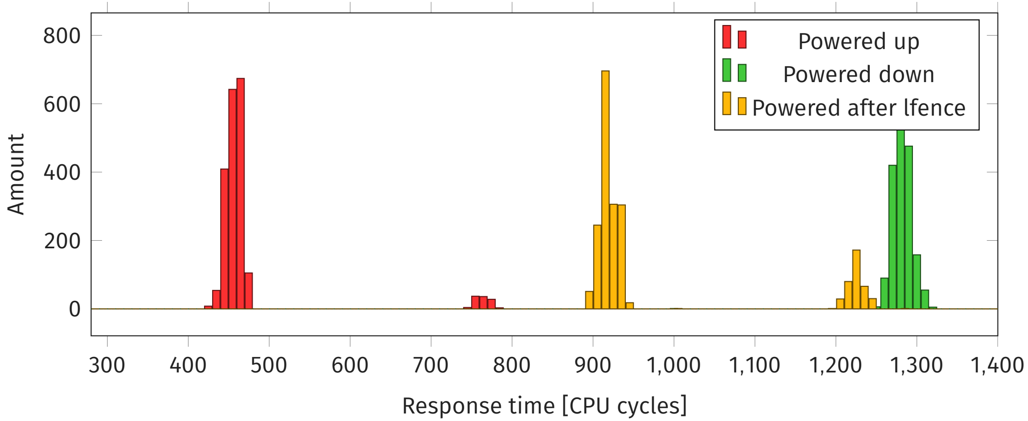
Hardware Fixes

Software Changes

AVX vs single lfence



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  - Dedicated measuring hardware

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- Proposed security mechanisms are incomplete
  - focus only on the cache
  - often assume (local) code execution
- Root problem has to be solved $\rightarrow$ more research required

Take Aways

- Speculative execution leaks secrets without exploiting bugs
- Spectre attacks are not limited to local attackers
- Spectre attacks have a larger impact than assumed

black hat ASIA 2019

NetSpectre

A Truly Remote Spectre Variant

Michael Schwarz @misc0110

Martin Schwarzl @marv0x90