ETH zürich

Meltdown: Reading Kernel Memory from User Space

Independently discovered and reported by three teams:

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You may have already known…

Executive Summary of Meltdown

- Observation: Out-of-order execution allows access of invalid memory address before checking the validation.
- Attack description (briefly):
  - Raise exception before accessing an invalid address.
  - Out-of-order execution causes microarchitectural change.
  - Use side-channel attack to recover the secret.
- Mitigation: KAISER -- kernel address isolation to have side-channels efficiently removed

Outline

- Introduction
- Background
  - Out-of-order execution
  - Address spaces
- Meltdown attack
- Countermeasure
- Evaluation
- Strengths and weaknesses
- Discussion

Introduction

- What is Meltdown?

Meltdown breaks the most fundamental isolation between user applications and the operating system. This attack allows a program to access the memory, and thus also the secrets, of other programs and the operating system.

Introduction

- How is it different from other attacks?

  No software vulnerability

  Exploit side-channel information

- Which systems are affected by Meltdown?

  Every Intel processor which implements out-of-order execution since 1995.

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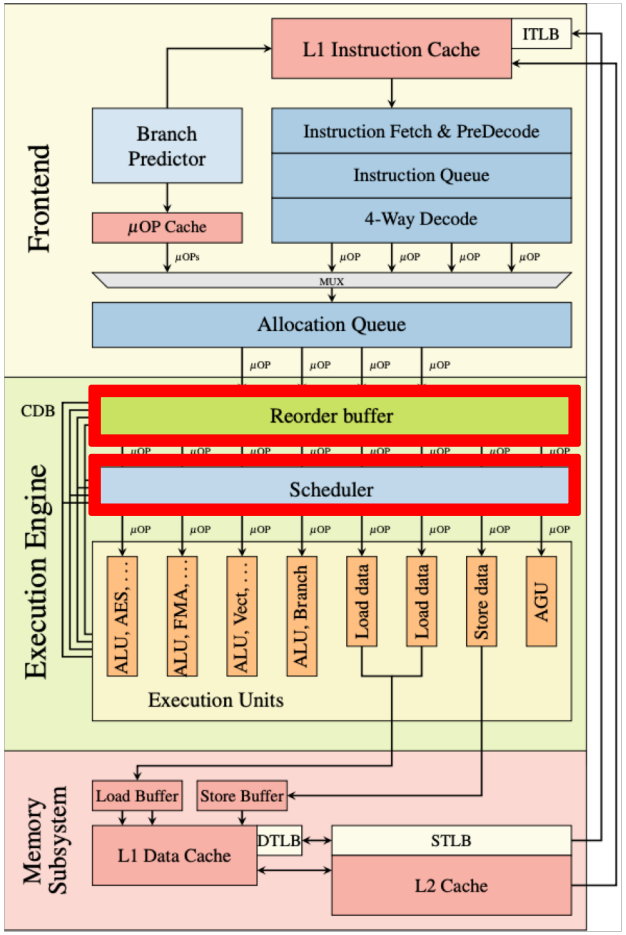
Background – Out-of-order execution

- Out-of-order execution:
  - Optimization technique
  - CPU executes instructions as soon as all required resources are available.

- In practice, running operations *speculatively* before the CPU is certain whether the instruction will be needed and committed.

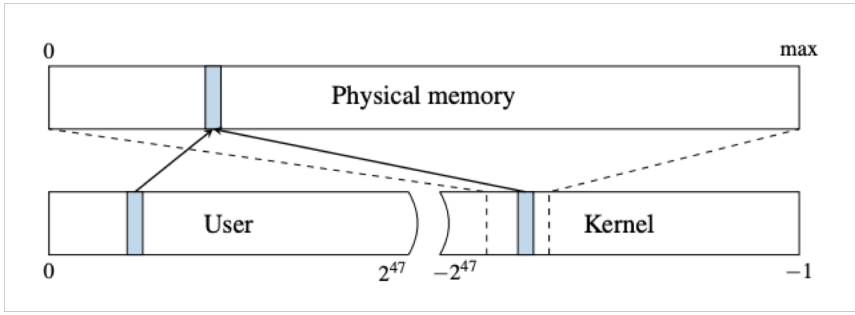
Background – Out-of-order execution

- Intel Architecture
  - *Reorder buffer:* register allocation, register renaming, and retiring.
  - *Unified reservation station:* queues the operations on exit ports that are connected to *Execution Units*
  - Tomasulo Algorithm



Background – Address space

- Virtual address space: virtual addresses are translated to physical addresses to isolate processes from each other
- Virtual space is spilt into a user and a kernel space
- The entire physical memory is typically mapped in the kernel space
  - Direct map: Linux and OS X
  - Paged pool, non-paged pool and system cache: Windows



Background – Address space

- In order to protect the kernel from memory corruption bugs, address space layout randomization (ASLR) has been introduced
- KASLR randomizes the offsets where drivers are located on every boot.
  - Still not sufficient to prevent all attacks
- Solution to KASLR attacks (KAISER) solves the Meltdown Attack as well!

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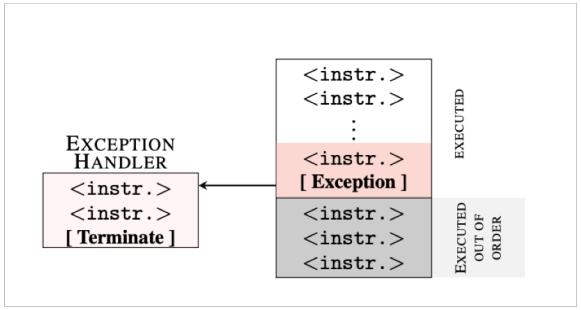
Meltdown – A toy example

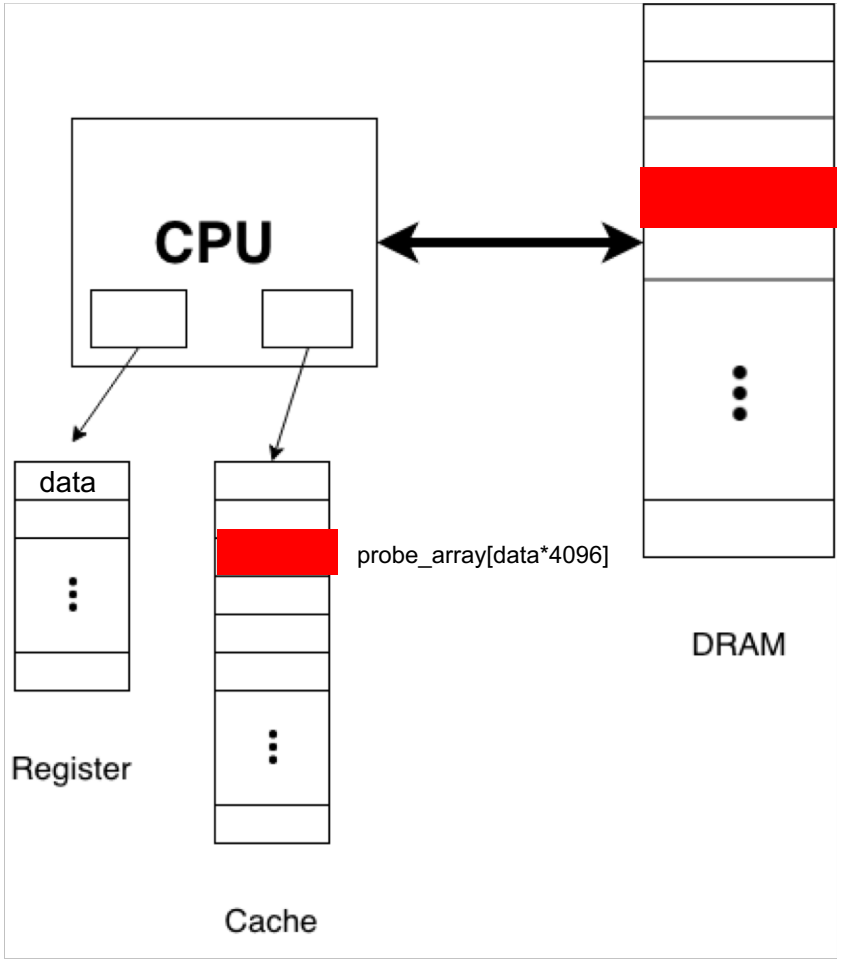
- Let's first look at a code snippet



- In theory: cannot access the array
- In reality: may have already executed instructions

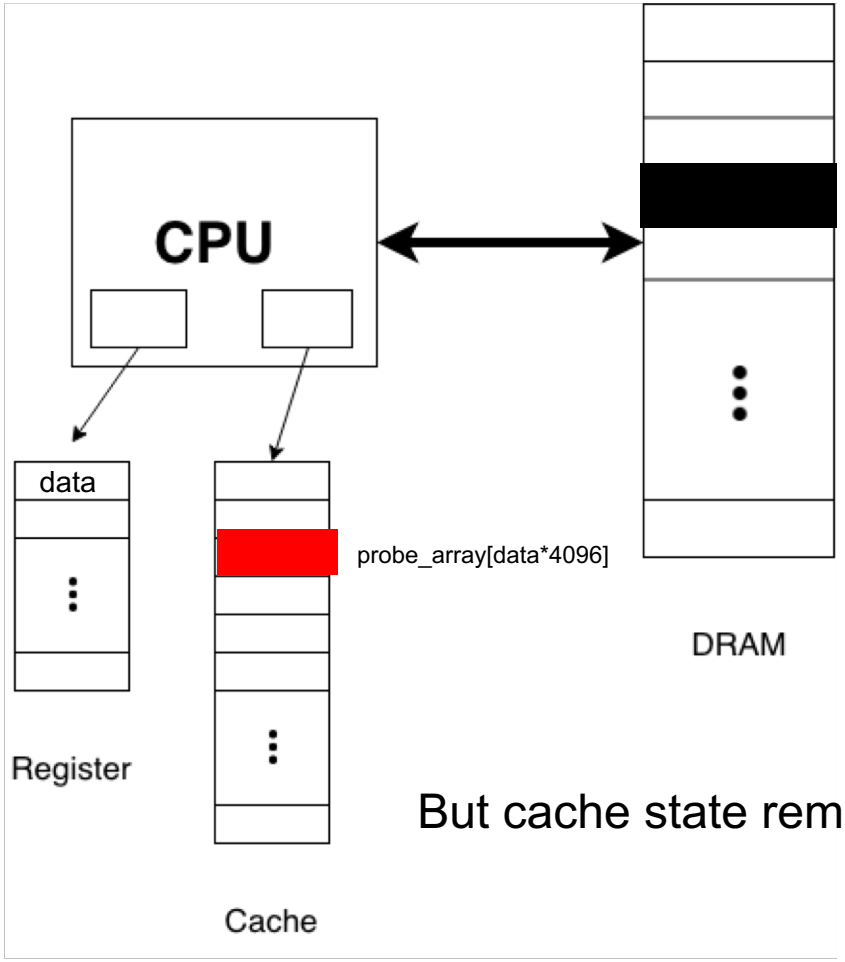
```
1 raise_exception();
2 // the line below is never reached
3 access(probe_array[data * 4096]);
```

Meltdown – A toy example



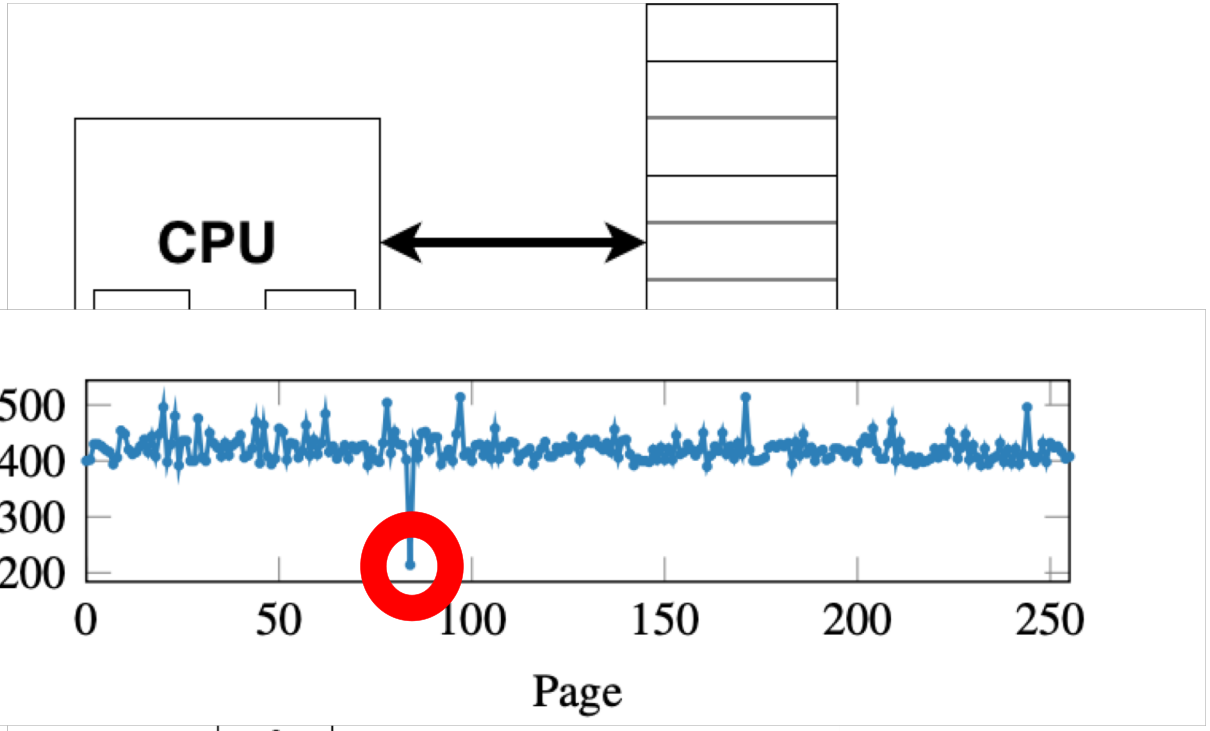
Meltdown – A toy example

Register is cleared

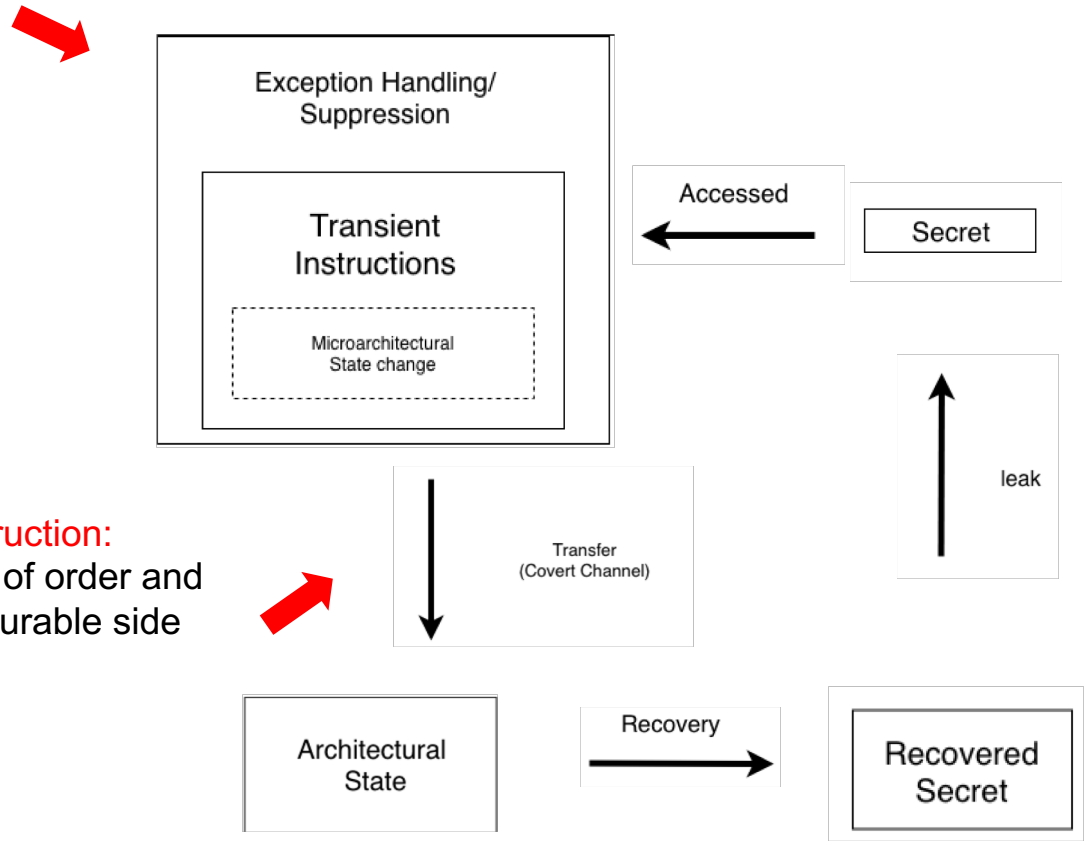


But cache state remains!

Meltdown – A toy example



Meltdown – Building Block



transient instruction:
executed out of order and leaving measurable side effects

Issue in Executing Transient Instructions

- Reason: prevent the process from being killed
- Exception handling:
  - Fork the attacking application before accessing the invalid memory location
  - Install a signal handler that is executed when a certain exception occurs

Reducing performance overhead

Issue in Executing Transient Instructions

- Exception suppression:
  - Transactional memory

  - Put the invalid memory access after a never-taken branch:
    - Setup phase: Mistrain CPU into speculatively executing these instructions.
    - Second phase: speculatively execute an instruction that leak information
    - Final phase: Recover data by retrieving over covert. channel

Issue in Building a Covert Channel

- Sending end: the transient instruction sequence
- Receiving end: can be a different thread or even a different process

- The covert channel is not limited to rely on cache:
  - ALU contention

- But here we use Flush+Reload cache attack

Meltdown – Attack description

- Meltdown consists of 3 steps:
  - The content of an attacker-chosen memory location, which is inaccessible to the attacker, is loaded into a register.
  - A transient instruction accesses a cache line based on the secret content of the register.
  - The attacker uses Flush+Reload to determine the accessed cache line and hence the secret stored at the chosen memory location.

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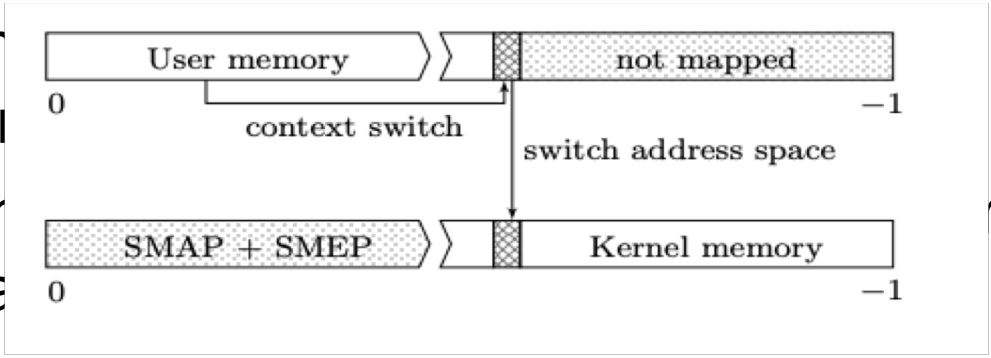
Countermeasures – Hardware

- Trivial solution: completely disable out-of-order execution
  - The performance impacts would be devastating
- Serializing the permission check and the register fetch can prevent Meltdown attack.
  - This involves a significant overhead to every memory fetch
- Introduce a hard split of user space and kernel space
  - Expect minimal performance impacts
- Note: the above methods only solve Meltdown, not Spectre

Countermeasures – Software (KAISER)

- A kernel r kernel mapped i
- Reason: r physical memory a



- However, there exists a residual attack surface for Meltdown.
- Still, the best short-time solution currently available.

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Evaluation– Sample Code

- Assembly code given by the paper:

```
1 ; rcx = kernel address, rbx = probe array
2 xor rax, rax
3 retry:
4 mov al, byte [rcx]
5 shl rax, 0xc
6 jz retry
7 mov rbx, qword [rbx + rax]
```

Look not so nice…

Evaluation – Sample Code

- A more readable one:

```
char detectArray[256*64];

flush_array(detectArray);

try{
    char a = *kernel_address;
    detectArray[a*64] ++;
}catch(segfault){}

for(int i=0; i<256; i++){
    if(is_in_cache(detectArray[i*64]))
        printf("secret byte was %d\n", i);
}
```

Evaluation – Environment

- Tested platform :
  - Linux without KAISER ✓
  - Windows 10 without KAISER ✓
  - Linux with KAISER ✗
  - Containers such as Docker ✓
  - Android (ARM) ✗

Environment	CPU Model	Cores
Lab	Celeron G540	2
Lab	Core i5-3230M	2
Lab	Core i5-3320M	2
Lab	Core i7-4790	4
Lab	Core i5-6200U	2
Lab	Core i7-6600U	2
Lab	Core i7-6700K	4
Lab	Core i7-8700K	12
Lab	Xeon E5-1630 v3	8
Cloud	Xeon E5-2676 v3	12
Cloud	Xeon E5-2650 v4	12
Phone	Exynos 8890	8

Evaluation – Performance

- With exception handling:
  - More universal implementation
  - Achieve an average reading speed of 123 KB/s when leaking 12 MB of kernel memory
  - Error rate of 0.03 %
  - Channel capacity is 122 KB/s

Evaluation – Performance

- With exception suppression:
  - Conditional branches or Intel TSX
  - Achieve an average reading speed of 503 KB/s when leaking 12 MB of kernel memory
  - Error rate of 0.02 %
  - Channel capacity is 502KB/s

Evaluation – In Practice

- Memory dump showing HTTP Headers on Ubuntu 16.10 on a Intel Core i7-6700K

```
79cbb30: 616f 61 4e 6b 32 38 46 31  34 67 65 68 61 7a 34 |aoaNk28F14gehaz4|
79cbb40: 5a74 4d 79 78 68 76 41 57  69 69 63 77 59 62 61 |ZtMyxhvAWiicwYba|
79cbb50: 356a 4c 76 4d 70 4b 56 56  32 4b 6a 37 4b 5a 4e |5jLvMpKVV2Kj7KZN|
79cbb60: 6655 6c 6e 72 38 64 74 35  54 62 43 63 7a 6f 44 |fUlnr8dt5TbCczoD|
79cbb70: 494e 46 71 58 6d 4a 69 34  58 50 39 62 43 53 47 |INFqXmJi4XP9bCSG|
79cbb80: 6c4c 48 32 5a 78 66 56 44  73 4b 57 39 34 68 6d |lLH2ZxfVDsKW94hm|
79cbb90: 3364 2f 41 4d 41 45 44 41  41 41 41 41 51 45 42 |3d/AMAEDAAAAAQEB|
79cbba0: 4141 41 41 41 41 3d 3d XX  XX XX XX XX XX XX XX |AAAAAA==........|
79cbbb0: XXXX XX XX XX XX XX XX XX  XX XX XX XX XX XX XX |................|
79cbbc0: XXXX XX 65 2d 68 65 61 64  XX XX XX XX XX XX XX |...e-head.......|
79cbbd0: XXXX XX XX XX XX XX XX XX  XX XX XX XX XX XX XX |................|
79cbbe0: XXXX XX XX XX XX XX XX XX  XX XX XX XX XX XX XX |................|
79cbbf0: XXXX XX XX XX XX XX XX XX  XX XX XX XX XX XX XX |................|
79cbc00: XXXX XX XX XX XX XX XX XX  XX XX XX XX XX XX XX |................|
79cbc10: XXXX XX XX XX XX XX XX XX  XX XX XX XX XX XX XX |................|
79cbc20: XXXX XX XX XX XX XX XX XX  XX XX XX XX XX XX XX |................|
79cbc30: XXXX XX XX XX XX XX XX XX  XX XX XX XX XX XX XX |................|
79cbc40: XXXX XX XX XX XX XX XX XX  XX XX XX XX XX XX XX |................|
79cbc50: XXXX XX XX 0d 0a XX 6f 72  69 67 69 6e 61 6c 2d |.......original-|
79cbc60: 7265 73 70 6f 6e 73 65 2d  68 65 61 64 65 72 73 |response-headers|
79cbc70: XX44 61 74 65 3a 20 53 61  74 2c 20 30 39 20 44 |.Date: Sat, 09 D|
79cbc80: 6563 20 32 30 31 37 20 32  32 3a 32 39 3a 32 35 |ec 2017 22:29:25|
79cbc90: 2047 4d 54 0d 0a 43 6f 6e  74 65 6e 74 2d 4c 65 | GMT..Content-Le|
79cbca0: 6e67 74 68 3a 20 31 0d 0a  43 6f 6e 74 65 6e 74 |ngth: 1..Content|
79cbcb0: 2d54 79 70 65 3a 20 74 65  78 74 2f 68 74 6d 6c |-Type: text/html|
79cbcc0: 3b20 63 68 61 72 73 65 74  3d 75 74 66 2d 38 0d |; charset=utf-8.|
79cbcd0: 0a53 65 72 76 65 72 3a 20  54 77 69 73 74 65 64 |.Server: Twisted|
79cbce0: 5765 62 2f 31 36 2e 33 2e  30 0d 0a XX 75 6e 63 |Web/16.3.0...unc|
79cbcf0: 6f6d 70 72 65 73 73 65 64  2d 6c 65 6e XX XX XX |ompressed-len...|
```

- The XX cases represent bytes where the side channel did not yield any results

Evaluation – In Practice

- Memory dump of Firefox 56 on Ubuntu 16.10 on a Intel Core i7-6700K disclosing saved passwords

```
f94b7690: e5 e5 e5 e5 e5 e5 e5 e5  e5 e5 e5 e5 e5 e5 e5 |................|
f94b76a0: e5 e5 e5 e5 e5 e5 e5 e5  e5 e5 e5 e5 e5 e5 e5 |................|
f94b76b0: 70 52 b8 6b 96 7f XX XX  XX XX XX XX XX XX XX |pR.k............|
f94b76c0: 09 XX XX XX XX XX XX XX  XX XX XX XX XX XX XX |................|
f94b76d0: XX XX XX XX XX XX XX XX  XX XX XX XX XX XX XX |................|
f94b76e0: XX XX XX XX XX XX XX XX  XX XX XX XX XX XX 81 |................|
f94b76f0: 12 XX e0 81 19 XX e0 81  44 6f 6c 70 68 69 6e 31 |........Dolphin1|
f94b7700: 38 e5 e5 e5 e5 e5 e5 e5  e5 e5 e5 e5 e5 e5 e5 |8...............|
f94b7710: 70 52 b8 6b 96 7f XX XX  XX XX XX XX XX XX XX |pR.k............|
f94b7720: XX XX XX XX XX XX XX XX  XX XX XX XX XX XX XX |................|
f94b7730: XX XX XX XX 4a XX XX XX  XX XX XX XX XX XX XX |....J...........|
f94b7740: XX XX XX XX XX XX XX XX  XX XX XX XX XX XX XX |................|
f94b7750: XX XX XX XX XX XX XX XX  XX e0 81 69 6e 73 74 |...........inst|
f94b7760: 61 5f 30 32 30 33 e5 e5  e5 e5 e5 e5 e5 e5 e5 |a_0203..........|
f94b7770: 70 52 18 7d 28 7f XX XX  XX XX XX XX XX XX XX |pR.}(...........|
f94b7780: XX XX XX XX XX XX XX XX  XX XX XX XX XX XX XX |................|
f94b7790: XX XX XX XX 54 XX XX XX  XX XX XX XX XX XX XX |....T...........|
f94b77a0: XX XX XX XX XX XX XX XX  XX XX XX XX XX XX XX |................|
f94b77b0: XX XX XX XX XX XX XX XX  XX XX XX 73 65 63 72 |...........secr|
f94b77c0: 65 74 70 77 64 30 e5 e5  e5 e5 e5 e5 e5 e5 e5 |etpwd0..........|
f94b77d0: 30 b4 18 7d 28 7f XX XX  XX XX XX XX XX XX XX |0..}(...........|
f94b77e0: XX XX XX XX XX XX XX XX  XX XX XX XX XX XX XX |................|
f94b77f0: XX XX XX XX XX XX XX XX  XX XX XX XX XX XX XX |................|
f94b7800: e5 e5 e5 e5 e5 e5 e5 e5  e5 e5 e5 e5 e5 e5 e5 |................|
f94b7810: 68 74 74 70 73 3a 2f 2f  61 64 64 6f 6e 73 2e 63 |https://addons.c|
f94b7820: 64 6e 2e 6d 6f 7a 69 6c  6c 61 2e 6e 65 74 2f 75 |dn.mozilla.net/u|
f94b7830: 73 65 72 2d 6d 65 64 69  61 2f 61 64 64 6f 6e 5f |ser-media/addon_|
f94b7840: 69 63 6f 6e 73 2f 33 35  34 2f 33 35 34 33 39 39 |icons/354/354399|
f94b7850: 2d 36 34 2e 70 6e 67 3f  6d 6f 64 69 66 69 65 64 |-64.png?modified|
f94b7860: 3d 31 34 35 32 32 34 34  38 31 35 XX XX XX XX XX |=1452244815.....|
```

Evaluation – Limitation

- They did not manage to successfully leak kernel memory with the meltdown attack neither on ARM nor on AMD.
- Reasons:
  - The implementation might simply be too slow
  - Processor lacks certain features
- However, the toy example works reliably.

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Strengths

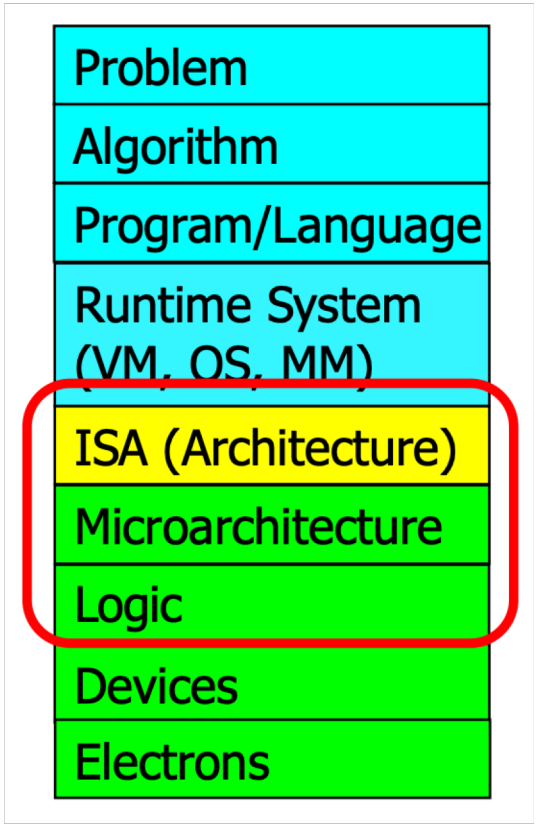
- The paper presented a potential attack on a wide range of modern processors which could cause catastrophic problems
- This attack didn’t exploit any software vulnerability and therefore can be launched in all operating systems
- The paper gave both short-term software solution and long-term hardware solution and verified the former’s effectiveness

Weaknesses

- They included too much background information and made the paper not easy to read
- They didn't give a practical attack on platforms other than Intel and didn't know the exact reason
- They didn't propose a better software solution
- They didn't evaluate the performance impacts by the KAISER patch

Takeaway

- From a computer security perspective:
  - Attacks can happen at any level – previously we've seen memory performance attack and Row-hammer attack
  - Knowledge in computer architecture can aid security professions to find out new "bugs"
  - Covert channel (side channel) is a fascinating topic



Onur Mutlu, Computer Architecture Lecture 1, Fall 2018

Takeaway

- From a computer architecture perspective:
  - Design new architecture with a high-security guarantee at the very beginning
  - Balance cost, performance, and security when designing
  - Look back at the architecture from time to time in order to look for new faults

Meltdown: Reading Kernel Memory from User Space

Questions?

Open discussion question

Timing Attacks on RSA: Revealing Your Secrets through the Fourth Dimension

by *Wing H. Wong*

Introduction

If Alice wants to secure her home, she could buy high–quality locks and install several of them on her door. However, a clever burglar might simply unscrew the hinges, remove the door and walk away with all of Alice's valuables with minimal effort. This example of an indirect attack on household security is somewhat artificial but there exists a parallel in the world of encryption that is quite real. It is called the timing attack and it has been used to defeat some of the most popular encryption techniques.

Do you think your computer system is secure because you use strong cryptography? Do you know attackers may be able to attack your cryptography in a completely unexpected direction without directly breaking the cryptographic algorithm?

RSA [7] is a public key cryptographic algorithm that is widely used today to secure electronic data transfer. It is included as part of the Web browsers from Microsoft and Netscape and is used by the SSL (Secure Sockets Layer) which provides security and privacy over the internet. The RSA algorithm was invented by the team of Rivest, Shamir, and Adleman at MIT in 1978. Independently, Cliff Cocks discovered the same idea in the early 1970's [5]. A public key cryptosystem uses a one way function that is easy to compute in one direction and hard to compute in the reverse direction. For example, it is relatively easy to generate two prime numbers p, q and compute their product $N = pq$. But given N it is difficult to find its factors p and q. Encryption uses a public value, or key, which is distributed and known to anyone who wants to send a message. Decryption involves a related private key which is kept secret by the intended recipient and cannot be deduced from the public key. Public key cryptography works without requiring both parties involved to keep an agreed upon secret; the private key never needs to be sent to the sender.

RSA's public key includes a number N which is the product of two large prime numbers p, q. The strength of RSA comes from the fact that factoring large numbers is difficult. The best–known factoring methods are still very slow. For example, in a recent RSA challenge (August 1999), a 512–bit RSA challenge number was factored using 292 workstations and high–speed computers. The factoring took 35.7 CPU–years to accomplish which is equivalent to approximately 80,000 MIPS years. The feat required 3.7 months of calendar time [8]. Because so many people have been trying to find efficient ways to factor large numbers, so far without great success, we can probably assume that RSA is safe from a factoring attack for a typical key N of 1024 bits in length. RSA can be made more secure against factoring by increasing the key length to 2048 bits or more.

Despite this formidable mathematical strength, research has shown that it is feasible to recover RSA private keys without directly breaking RSA. This type of attack is known as a "timing attack" in which an attacker observes the running time of a cryptographic algorithm and thereby deduces the secret parameter involved in the operations. While it is generally agreed that RSA is secure from a direct attack, RSA's vulnerability to timing attacks is not so well known and often overlooked. This paper explains the principles of timing attacks on RSA, summarizes the results of timing attacks implemented by various researchers, and discusses defenses against such attacks.

Timing Attacks on RSA

Kocher [4] was the first to discuss timing attacks. At the RSA Data Security and CRYPTO conferences in 1996, Kocher presented his preliminary result, warned vendors about his attack, and caught the attention of cryptographers including the inventors of the RSA cryptosystem. Timing attacks are a form of "side channel attack" where an attacker gains information from the implementation of a cryptosystem rather than from any inherent weakness in the mathematical properties of the system. Unintended channels of information arise due to the way an operation is performed or the media used. Side channel attacks exploit information about timing, power consumption, electromagnetic emanations or even sound to recover secret information about a cryptosystem [9].

Timing attacks exploit the timing variations in cryptographic operations. Because of performance optimizations, computations performed by a cryptographic algorithm often take different amounts of time depending on the input and the value of the secret parameter. If RSA private key operations can be timed reasonably accurately, in some cases statistical analysis can be applied to recover the secret key involved in the computations.

Before discussing timing attacks on RSA, we must first consider the mathematics of the cryptosystem. RSA is a public key cryptosystem that uses a public exponent e for encryption and a private exponent d for decryption. It uses a modulus N which is a product of two large prime numbers p and q , i.e., $N = pq$. The exponents e and d must be chosen to satisfy the condition $ed = 1 \bmod (p - 1)(q - 1)$. Then the RSA key pair consists of the public key (N, e) and the private key d. For example, if we select two prime numbers $p = 11$ and $q = 3$, then $N = 11 * 3 = 33$. Now compute $(p - 1)(q - 1) = 10 * 2 = 20$ and choose a value e relatively prime to 20, say 3. Then d has to be chosen such that $ed = 1 \bmod 20$. One possible value for d is 7 since $3 * 7 = 21 = 1 \bmod 20$. So we get the public key $(N = 33, e = 3)$ and the corresponding private key $d = 7$. We discard the original factors p, q.

semiconductor and logic gates (made of
e measured. First of all, this attack can't be easily

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```

Open discussion question

TLBLEED

Overview

TLBleed is a new side channel attack that has been proven to work on Intel CPU's with Hyper-threading (generally Simultaneous Multi-threading, or SMT, or HT on Intel) enabled. It relies on concurrent access to the TLB, and it being shared between threads. We find that the L1dtlb and the STLB (L2 TLB) is shared between threads on Intel CPU cores.

Result

This means that co-resident hyperthreads can get a certain amount of information on the *data* memory accesses of the other HT, without needing any shared cache. Whereas the cache can be partitioned to protect against cache attacks (such as in Cloak using TSX, or using CAT, or using page coloring), this is practically impossible for the TLB, and no such systems have been proposed. Thus in the presence of cache defenses, TLBleed remains a risk in this threat model.

Requirements (a.k.a. threat model)

The threat model is identical to Colin Pervical's seminal 2005 work, Cache Missing for Fun and Profit, which arguably introduced practical cache side channels. Different from TLBleed, it requires concurrent access to the cache shared between Hyperthreads. TLBleed gets all information through the shared TLB, which can't be partitioned between processes in software (either application or OS).

Meltdown Attack Lab

- Website

- Hands-on experience and very detailed instruction

Meltdown Attack Lab

SEED Lab: A Hands-on Lab for Security Education

Overview

Discovered in 2017 and publicly disclosed in January 2018, the Meltdown exploits critical vulnerabilities existing in many modern processors, including those from Intel and ARM. The vulnerabilities allow a user-level program to read data stored inside the kernel memory. Such an access is not allowed by the hardware protection mechanism implemented in most CPUs, but a vulnerability exists in the design of these CPUs that makes it possible to defeat the hardware protection. Because the flaw exists in the hardware, it is very difficult to fundamentally fix the problem, unless we change the CPUs in our computers. The Meltdown vulnerability represents a special genre of vulnerabilities in the design of CPUs. Along with the Spectre vulnerability, they provide an invaluable lesson for security education.

The learning objective of this lab is for students to gain first-hand experiences on the Meltdown attack. The attack itself is quite sophisticated, so we break it down into several small steps, each of which is easy to understand and perform. Once students understand each step, it should not be difficult for them to put everything together to perform the actual attack.

Lab Tasks (Description)

- **VM version:** This lab has been tested on our pre-built `SEEDUbuntu16.04` VM.
- **Note:**
  - Meltdown only works against Intel CPU, so if the host machine does not use Intel CPU, the attack in this lab will not work.
  - Even if the OS of the host machine is patched, the attack still works, because we did not patch the Linux OS running inside the VM.

Recommended Time:

- Supervised situation (e.g. a closely-guided lab session): **2 hours**
- Unsupervised situation (e.g. take-home project): **1 week**

Files that are Needed

- Meltdown_Attack.zip

Helpful Documents

- Meltdown and Spectre

SEED Project

- Home Page

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Useful Resources

- YouTube video of attack demos:
  - https://youtu.be/L1N1P2zxaZE
  - https://youtu.be/bReA1dvGJ6Y
  - https://youtu.be/RbHbFkh6eeE
  - https://youtu.be/kwnh7q356Jk
- Recommended papers:
  - FLUSH+RELOAD: a High Resolution, Low Noise, L3 Cache Side-Channel Attack
  - KASLR is Dead: Long Live KASLR
  - Breaking Kernel Address Space Layout Randomization with Intel TSX

Thanks for your listening!

Meltdown: Reading Kernel Memory from User Space

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Supplementary Slides

Meltdown – Optimization

```
1 ; rcx = kernel address, rbx = probe array
2 xor rax, rax
3 retry:
4 mov al, byte [rcx]
5 shl rax, 0xc
6 jz retry
7 mov rbx, qword [rbx + rax]
```

- Case of 0:
  - If the exception is triggered while trying to read from an inaccessible kernel address, the register where the data should be stored, appears to be zeroed out.
  - If the zeroing out of the register is faster than the execution of the subsequent instruction, the attacker may read a false value in the third step.
  - Meltdown retries reading the address until it encounters a value different from ‘0’.
  - Meltdown assumes that the secret value is indeed ‘0’ if there is no cache hit at all

Meltdown – Optimization

- Single-bit transmission:
  - The performance bottleneck in the generic attack is Flush+Reload
  - By transmitting only one bit, we only have to perform one Flush+Reload at one time.

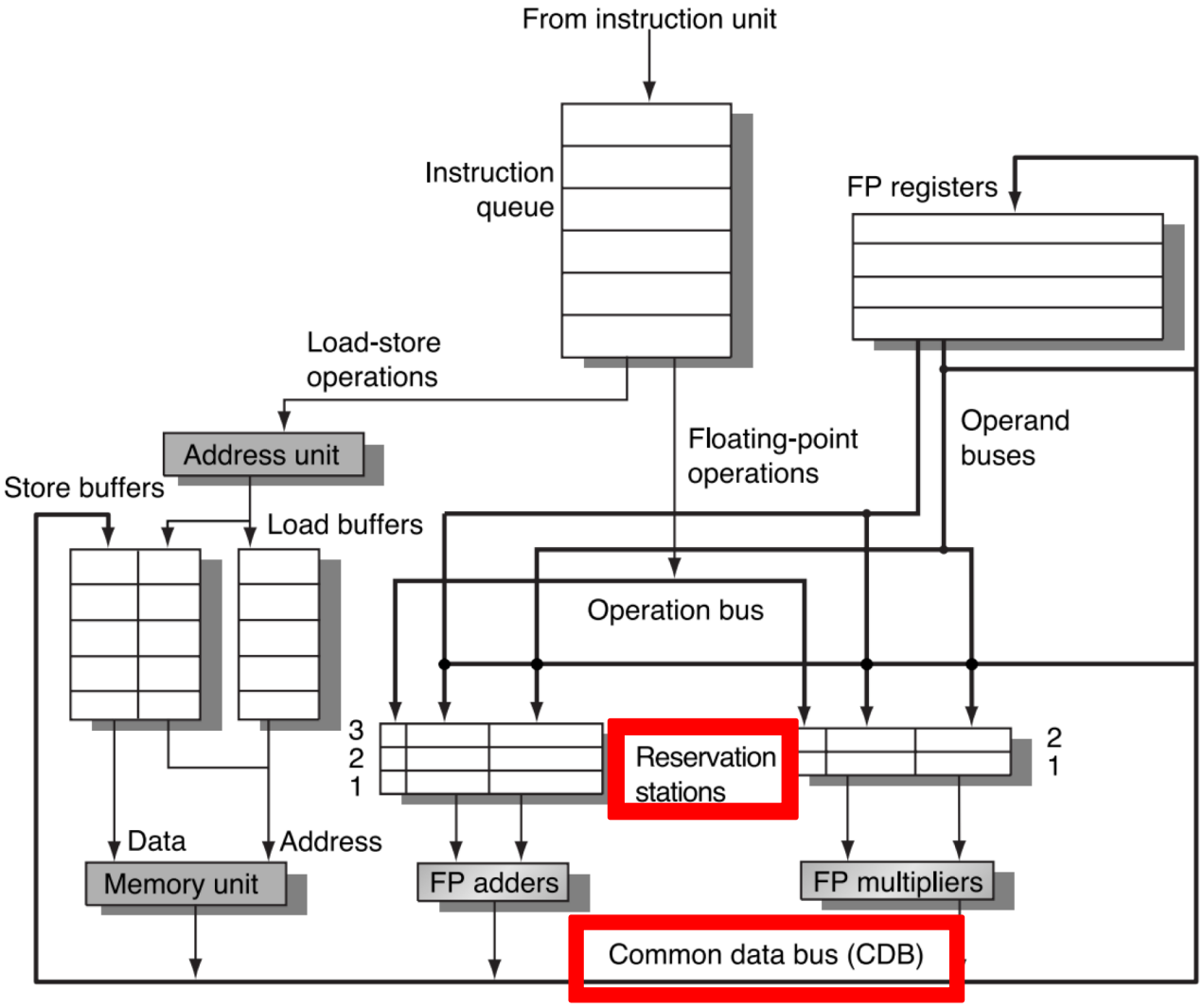
  - Drawback: our side channel has a bias towards a secret value of '0'.

    The number of bits read and transmitted at once is a tradeoff between some implicit error-reduction and the overall transmission rate of the covert channel.

Meltdown – Optimization

- Dealing with KASLR:
  - With KASLR, the direct-physical map is randomized and not fixed at a certain address.
  - Need to obtain the randomized offset before mounting the Meltdown attack.
  - However, the randomization is limited to 40 bit – we can find out the randomized address quickly.

Background – Out-of-order execution



Background – Cache Attack

- Exploit timing differences that are introduced by the caches.
- Evict+Time, Prim+Probe, and Flush+Reload
- We use Flush+Reload: exploits the shared, inclusive last-level cache
  - Frequently flush a targeted memory location (clflush)
  - Measure the time it takes to reload the data
  - Determine whether data was loaded into the cache by another process
- Building a covert channel to leak information from one security domain to another.