Computing Science

Impact of Meltdown & Spectre Mitigations

Konrad Dryja

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CS4040 Report

Department of Computing Science   **November 2019**
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King's College
Aberdeen   AB24 3UE

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Konrad Dryja

Department of Computing Science
University of Aberdeen

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Abstract: In my CS4040 report I'd like to evaluate the impact of the discovery of Side-Channel Attacks back in January 2018 with Spectre & Meltdown leading. As those were utilizing many of the performance reliant features - which had to be rolled back or squashed due to security concerns. The removal resulted in many reports about grossly deteriorated performance. With the patches already in place, I have gone ahead and removed them to compare before and after performance of one- and multi-core performance in different tasks, such as prime calculation or rendering. I will be aiming to diversify tested hardware and software, including platforms such as Windows, Linux and Intel, AMD. Final points will close off the results, concluding with recommendation whether it's reasonable to leave the mitigation disabled in lights of potential vulnerabilities.

1   Introduction

Speculative execution is a feature that was included in modern CPUs by almost all chip designers, significantly boosting the execution time on some very complex operations. With time, those solutions became more and more aggressive, as the competition between manufacturers was very fierce, fighting to beat the competitors in benchmarks, thus winning the favours of reviewers & consumers.

Perhaps one of the most daunting days that security professionals faced happened on January 3rd, 2018 - when Meltdown & Spectre attacks were publicized, explaining a serious flaw with speculative execution approach. With the enhancement no longer considered safe, modern CPU manufacturers were forced to drop these features in favour of enhancing security. But at the same time, it resulted in sacrificing the performance of the chips. Perhaps the most harming aspect was that speculative execution was at the time an industry standard.

Personally, I found the topic the most interesting, as the aftermath is still haunting security researches to this day, since the fault was not the software, but inherent architecture was found to be flawed. Moreover, nowadays we are frequently hearing news (most recent being "Fallout"[11]) how the newest vulnerability based on side-channel execution has been discovered - with the definite fix being complete hardware replacement with a chip produced after 2017. This forced Intel, AMD, ARM to release very aggressive patches, greatly hurting the benchmarks.

This has also raised ethical questions - since some of the affected machines suffered as much as 50% drop in performance. In the eyes of law, it could be classified as false advertising which naturally was followed by many class-action lawsuits. As stated by Intel in their 2017 Annual report, as of

1

February 2018, they were facing 30 customer suits along with two securities [3]. Intel perhaps is the company that was the most under fire, since Variant 1, also known as Meltdown, was mostly apparent in their chips, although Variant 2 & 2 were replicated in almost all consumer chips (including AMD et al.).

Computing community and hardware architects were faced with a difficult dilemma - how much of security are we willing to sacrifice in favour of increased performance?

2   Background and related work

When speaking about Spectre and Meltdown, it's very important to start from the very beginning - when in July 2017, a researcher Jann Horn from Google's Project Zero has discovered the vulnerability. Due to the severity and potential implications resulting from premature releasing of the findings, those were first communicated directly - on NDA basis - with manufacturers, hoping for an immediate fix. On January 2018, two papers were released by J. Horn et al. illustrating in-depth the vulnerabilities and how they could be replicated [8, 7]. The papers present a throughout overview of the potential attack - the exploitation here is based on **Branch Prediction** (BP) along with **Out of Order Execution** (OOE). Those are optimizations techniques used by almost all CPUs on the market:

- BP lets the processor "predict" direction where the program's execution flow will go towards without explicitly evaluating the condition. For example, in a situation where **if** statement was successful for 100 iterations, it can assume that 101st will be successful as well and thus prematurely execute the included code-block, storing the result in L-cache (high speed, low capacity memory located directly on the CPU core)
- OOE, on the other hand will often reorder scheduled operations leaving the most time-consuming actions till the end, executing the ones containing required data present in CPU cache immediately - assuming that those do not depend on each other, e.g., it's a simple summation, not relying on the prior information.

Together, they create a cheap and clever way to speed up the execution of binaries, but unbeknownst opened a pathway for side-channel attacks, exploiting the fact that CPU was executing the code that it wasn't meant to in the first place. Normally, the results are only stored in fast-access L-cache (which is only accessible from kernel-mode and is purely used to increase performance), with no way to read those blocks from user mode. A proof-of-concept presented by the researches [7] illustrated how it's possible to measure how long it takes to access particular variable in order to determine whether it's coming from RAM or L-cache and then make statistical assumption whether the piece of data was evaluated inside of block of code which was executed speculatively.

There is also a subtle difference between the nature of attacks described by **Meltdown** (Variant 3) and **Spectre** (Variant 1, 2). The former allowed for any arbitary process to access kernel-space memory, which contains restricted data such as password or even latest keystroke information. The latter - on the other hand - was capable of crossing process or sandbox boundaries, effectively nullyfying the protections provided by virtualised environment or JIT (just-in-time) compilers. This potentially

might allow an attacker to deploy malicious binary onto VM cluster (run by a cloud provider such as GCP or AWS) and access information of other users.

Listing 1: Meltdown PoC

```
 1  char testArray[256 * 64];
 2  evictCache(testArray); // Clear L-cache
 3  char x = * kernelSpace; // Will cause segmentation fault
 4  testArray[x * 64]++; // Will be executed speculatively
 5  for(int i=0; i<256; i++) {
 6     // Measure how long it takes to access the element
 7     if(is_cached(testArray[i * 64]) {
 8        // Cache hit! Found secret bit.
 9     }
10  }
```

Multiple patches have been created ever since to mitigate the negative effect, trying to minimize the impact on performance. M. Löw[9] provides an overview of created mitigations and affected hardware. The major and immediate patches which had the biggest performance effect included:

KAISER [5] - also known as Kernel Page-Table Isolation. Meltdown is exploiting the fact that for the purposes of reduced access times, the entire kernel address page is mapped to every process. This is not directly accessible from user-mode and is protected by privileged bit. Unfortunately, with side-channel attacks, this data can be speculatively loaded and then later retrieved via a covert channel. KAISER aims to drop that mapping and leave only necessary signals.

Retpoline [13] - retroactive trampoline, it's a mitigation aiming to catch Branch Predictor in an infinite loop, effectively never speculatively executing sensitive code.

It is also important to mention that software mitigation can only be helpful to a specific point. From month to month more ways of performing side-channel attacks are discovered, bypassing completely the mitigations, thus manufacturers are force to deploy more and more restrictive patches, decreasing the benefits of BP and OOE.

3   Research question

Having introduced the basics of side-channel attacks in previous sections, we are now ready to tackle the implications of the released patches. The research question that could be formed following the aforementioned considerations would be " **How significant is the performance degradation, after enabling mitigations for Side-Channel Attacks? "**.

Fortunately, majority of the flaws were already patched with immediate effect, meaning that the vulnerability cannot be replicated on up-to-date software. This leaves us with necessity of either simulating the hardware via software or rolling back the updates. To this day, Dell claims that no malicious use has been spotted[6], which introduces question of how severe the incident was and

whether the sacrifice was worth it. We can speculate that this announcement and others pushed the Linux team to introduce an option for kernel versions starting from 5.2 allowing the users to disable the mitigations, regaining the performance but opening the system for potential attacks.

Listing 2: Vulnerable Linux system with disabled mitigations

```
% lscpu
[...]
Model name:                    Intel(R) Core(TM) i5-6500 CPU
[...]
Vulnerability L1tf:            Mitigation; PTE Inversion;
Vulnerability Mds:             Vulnerable; SMT disabled
Vulnerability Meltdown:        Vulnerable
Vulnerability Spec store bypass: Vulnerable
Vulnerability Spectre v1:      Vulnerable:
Vulnerability Spectre v2:      Vulnerable, IBPB: disabled
```

For Windows, on the other hand, the mitigations are slightly harder to disable, although it can be achieved by tweaking Windows Registry [10]. While the impact on consumer Windows version can be negligible (according to Microsoft[12]), Server edition of their Operating System was particularly susceptible to slowdowns, especially during Input/Output operations. Microsoft decided to leave the decision of enabling the patch up to system administrators, leaving the option enabled by default. Alas, mitigations for CVE-2017-5753 (Spectre Variant 1) cannot be disabled for Windows at the moment. To work around this, it is still possible to install Windows 10 Version 1607 (From April 2016) and perform all experiments in that environment - with no internet connection to avoid automatic updates. Although this might also cause inconsistency, as newer revision might also have included unrelated performance fixes - thus the test would have to be performed on both older revision of Windows 10 and Windows Server with only disabled mitigations.

At this point, with a vulnerable system, we have several ways to obtain before-after comparison of performance, as mentioned: each platform offering different solutions. Linux has open access to compiled byte-code with an option of disabling optimizers potentially spoiling the results. Usually, to benchmark the performance of a CPU, we would be looking at how quickly it can solve complex operations. One of the examples being prime numbers calculations or matrices multiplication. There are two example open-source packages which wrap around those operations, producing a concise report on performed CPU Cycles, page faults, thermal readings etc. - stress-ng [14] and sysbench. [4]

With Windows, it is slightly more difficult to access direct CPU registers from the OS - additionally, all the compiled code is subject to many optimizations, which might introduce variance and inconsistencies in the results. The most efficient way would be to utilize closed-source, proprietary software created specifically for benchmarking (used mostly to compare and rank consumer-grade products), which can extract raw performance data. Most popular choice nowadays is Cinebench

along with 3DMark which at the same time could determine whether the slowdowns in CPU could also be affecting external GPU.

For the purposes of this research, I will be focusing only on readings obtained from hardware running Linux operating systems, in order to prevent potential noise created by possible performance gains patched alongside Spectre mitigations.

4   Experimental Design

In order to answer the research question and evaluate how big and whether meaningful the impact was, we can devise the following null hypotheses:

- For each of the benchmarking utilities run on the hardware, Spectre mitigations do not cause statistically significant regressions in the results.

- Runtime of CPU-intensive operations (such as encryption) does not significantly increase with enabled mitigations for Spectre.

Since the mitigations for the vulnerabilities described in previous sections heavily modify or straight-up disable a lot of performance features present in modern chips, it will be necessary to perform benchmarking on the CPUs themselves with and without those mitigations installed. Running generic speed tests on the performance of the environments side-to-side with the same CPU without the patches will result in potential runtime differences.

As I have access to two separate machines running Linux, I will be conducting all tests and benchmarks on them in parallel. Since their CPUs and specifications vary, it is important to note it down as an independent variable in the experiment - as the results will vary on both machines. Although, what we are interested in, is the difference before and after applying the patch, rather than raw comparison between those two machines; for example, in some cases one will be outperforming the other - but we are not interested in that.

	Machine A (Workstation)	Machine B (Laptop)
CPU	i5-6500 @ 3.20GHz	i7-8550U @ 4.00GHz
RAM	16GB DDR4 2400MHz	16GB DDR4 2400MHz
GPU	GeForce GTX 1070	Intel UHD 620

Table 1: Specifications of testing population

Table 1 describes the exact specification of the hardware that I used for testing. Both are running 64-bit revision of Archlinux with the following versions:

```
% uname −a
Linux workstation 5.3.11−arch1−1 x86_64 GNU/Linux
% cat /etc/*release*
NAME="Arch Linux"
PRETTY_NAME="Arch Linux"
ID=arch
```

```
BUILD_ID=rolling
ANSI_COLOR="0;36"
HOME_URL="https://www.archlinux.org/"
DOCUMENTATION_URL="https://wiki.archlinux.org/"
SUPPORT_URL="https://bbs.archlinux.org/"
BUG_REPORT_URL="https://bugs.archlinux.org/"
LOGO=archlinux
```

Additionally, I had no access to hardware running other architectures, such as ARM or AMD, so those will also not be compared. Intel architecture was the one that was affected the most when it comes to Meltdown and thus the difference is expected to be the most prominent on those chips.

Another important independent variable can be identified as benchmark / operation performed by the CPU. As there are various operations, sometimes abusing access to L-cache, or simply omitting it, I will be measuring performance with respect to different factors, such as context switching or ray tracing.

To maximise the significance of the results of my experiment, I will be looking to utilise the following testing suites, in addition to the ones that I have mentioned in the previous section:

- **Phoronix Test Suite v9.2.0m2** - from within the suite, I will be running **Hackbench** (performance of communicating, scheduled tasks), **Stress-NG** (tests socket activity) and **ctx_clock** (measures context switching) tests. Phoronix allows for multiple runs in order to establish p-value, so each of them will be executed with 10 trial runs.

- **Geekbench v5.0.4** - mostly geared towards simulating real-world scenarios, produces one and multi-core performance - tests are constructed with Augmented Reality and Machine Learning applications in mind. [2]

Each of them is capable of running and measuring expensive CPU operations such as Blowfish, Jack-The-Ripper password cracker or Text / Image Compression. As all of them incorporate various tests, they will produce different results. Depending on the benchmarking tool, either a numerical score is presented (Geekbench) or raw values in seconds to indicate the duration of given operation (Sysbench). All tests will be performed at least 10 times per machine, per patch installed / removed in order to minimize background noise.

Finally, to test the second hypothesis, it is possible to utilise the openssl binary found on almost every Linux system. Very handy sub-command called "speed" will continuously run various algorithms (MD5, SHA1, SHA256, SHA512, Whirpool) and measure how many hashes were successfully created in 3 seconds. In order to increase sample size, different sized blocks will be used (16, 64, 256, 1024, 8192, 16384)

To measure cryptographic efficiency for symmetric algorithms cryptsetup benchmark can be used. The utility will provide the speed with which particular symmetric encryption algorithms are executed (AES, Twofish, Serpent).

Listing 3: Versions of crypsetup and openssl

```
% cryptsetup --version
 cryptsetup 2.2.2
% openssl version
 OpenSSL 1.1.1d  10 Sep 2019
```

The machines will be running under the same load with the same configuration installed. To eliminate potential noise, no unnecessary background programs will be running and if they are necessary, both before and after tests will have same runtime, which will be monitored using UNIX top command, also verifying reported load average.

5   Results

5.1   Benchmarking suites evaluation

Phoronix Test Suite

Starting off with **Hackbench** test, it was an experiment trying to stress the Linux kernel scheduler responsible for firing off and preparing new jobs for the CPU. Test was repeated for 10 times, for both Machines A & B. Once compared the results from setup with enabled mitigations and the results from the one without, a $p-value$ can be obtained through Paired T-Test - $p_a = 6.25 * 10^{-14}$ and $p_b = 6.38 * 10^{-19}$, confirming statistical significance of my findings.
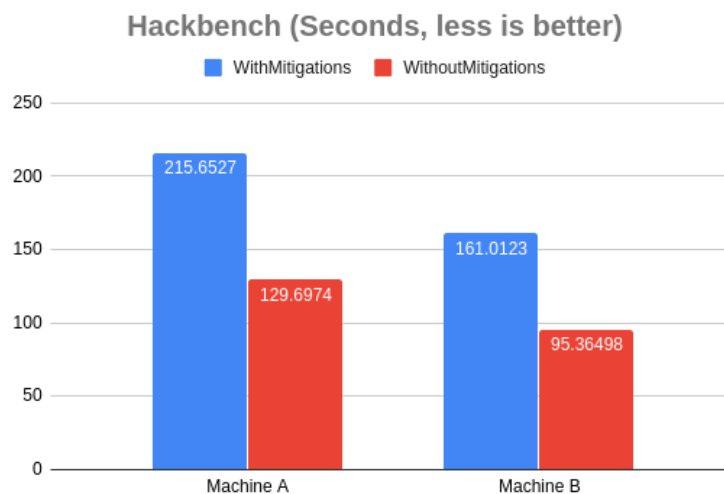

Figure 1: Results from Hackbench

Figure 1 displays the exact differences between data when run with and without mitigations on both Machines. For Machine A we can observe almost 40% regression after applying the patches and for Machine B the regression stands at 41%. The results should be interpreted in "less is better" manner, as the numbers represent amount of time in seconds required to complete all scheduled tasks.

Moving on to the next part of Phoronix, which is **Stress-NG**. It's part of the standard UNIX stress testing, used to verify whether the machine operates correctly over heavy load, albeit it can also

be used to measure the number of operations per second it performs in a given timespan. Same as before, the test was repeated for 10 times, yielding the following $p-values$: $p_a = 3.13 * 10^{-30}$ and $p_b = 2.27 * 10^{-13}$ - in both cases, the value being less than 0.05.
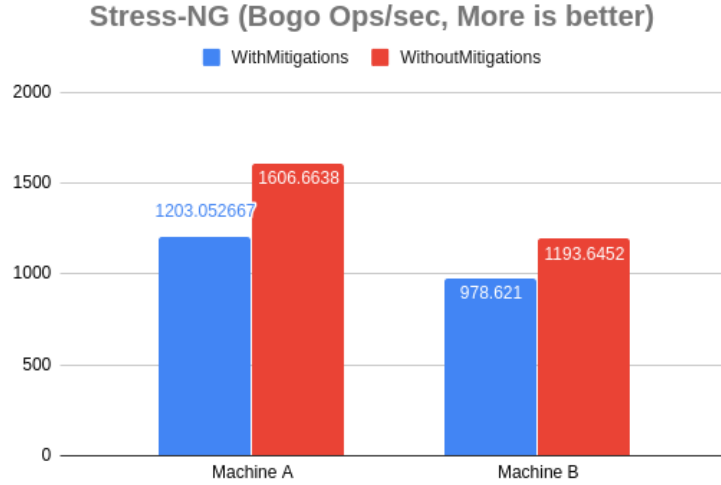

Figure 2: Results from Stress-NG

The regression is slightly less prominent in that situation, with Machine A performing approximately 25% less of "Bogus Operations" (for stress, those are prime numbers calculation), along with Machine B performing approximately 18% less. Contrary to the previous chart, higher number of performed operations indicates better performance, thus putting no mitigations systems at an advantage.

Finally, **ctx_clock** was also evaluated. In that particular case, number of clock cycles required for a context switch (e.g., from user mode into kernel mode) is measured. The test again has been repeated for 10 times, ending up with: $p_a = 1.08 * 10^{-21}$ and $p_b = 2.81 * 10^{-25}$, confirming significance.
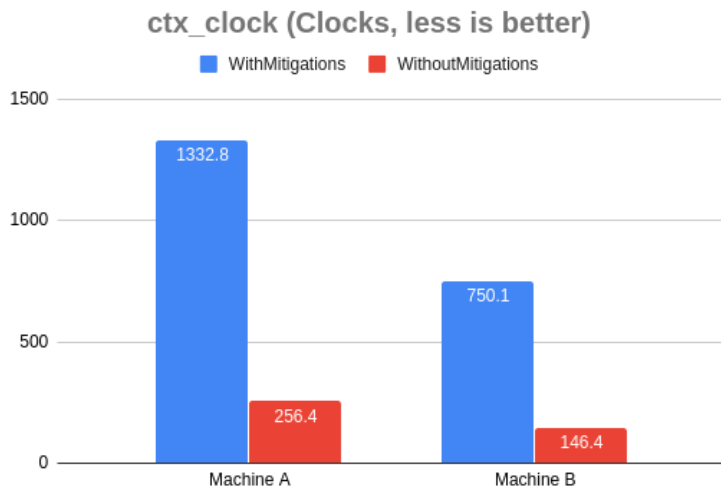

Figure 3: Results from ctx_clock

For that case, the faster the context switch happens (i.e., requires fewer cycles), the better performing the chip is. Out of all three of the tests performed, the regression has been the most significant; with Machine A needing almost 420% extra clock cycles and Machine B needing extra 80%, when the patches for side-channel attacks are enabled.

Geekbench

Geekbench is a fully equipped, all-in-one testing suite, often used for performance in Machine Learning or gaming. As it's a commercially available benchmarking tool, additional tests are performed automatically and unfortunately $p - value$ of the results is not available - the only final outcome is the raw score of the machine. Moreover, the trial version that I was utilising permits only benchmarks on 32-bit applications, so the results may be different for 64-bit architectures.

	Machine A	
	WithMitigations	WithoutMitigations
Single-Core Score	1055	1052
Multi-Core Score	3562	3547

	Machine B	
	WithMitigations	WithoutMitigations
Single-Core Score	1064	1078
Multi-Core Score	3892	3924

Table 2: Scores reported by Geekbench

Although, a T-Test can still be performed against all different performed tests ($21 * 2$ in total) for Single and Multi-Core performance. If the tests were to be statistically significant, we would notice similar standard error and standard deviation between results measuring ray-tracing, text-compression etc. Sadly, it was not the case in this situation, with $p - values$ of $p_a = 0.0534765$ and $p_b = 0.072481043$ - in both situation the value being greater than 0.05 meaning that the obtained numbers yield no statistical significance.

Even with the lack of significance, we can tell that the reported final scores are very similar before / after applied mitigations for both platforms. I will be going into more depth as to what could've spoiled this particular test in the next section, but at first glance, we can speculate negligible Spectre impact on operations needed for tasks such as AR / VR, which confirms the reports from earlier paragraphs mentioning that biggest impact would be on servers and their virtualisation capabilities, rather than end-user use cases.

5.2   Cryptographic performance evaluation

OpenSSL

OpenSSL was used to measure how many hashes the CPU is capable of creating in the span of 10 seconds. To establish statistical significance, for each hashing method the test was repeated for data blocks varying in size. After applying Paired T-Test to each of the 30 samples per Machine, following

values were obtained: $p_a = 0.009730881344$ and $p_b = 0.02688339939$, in both cases $p < 0.05$, so the test holds statistical significance.

Figures 4 and 5 present the differences of standard deviations for each of the considered block size, when executed given hashing algorithm on Machine A or Machine B. The differences are minimal, with environments without mitigations performing slightly better, although the regression is relatively low sitting approximately at $0.18\% \pm 0.04\%$ depending on the hashing method.
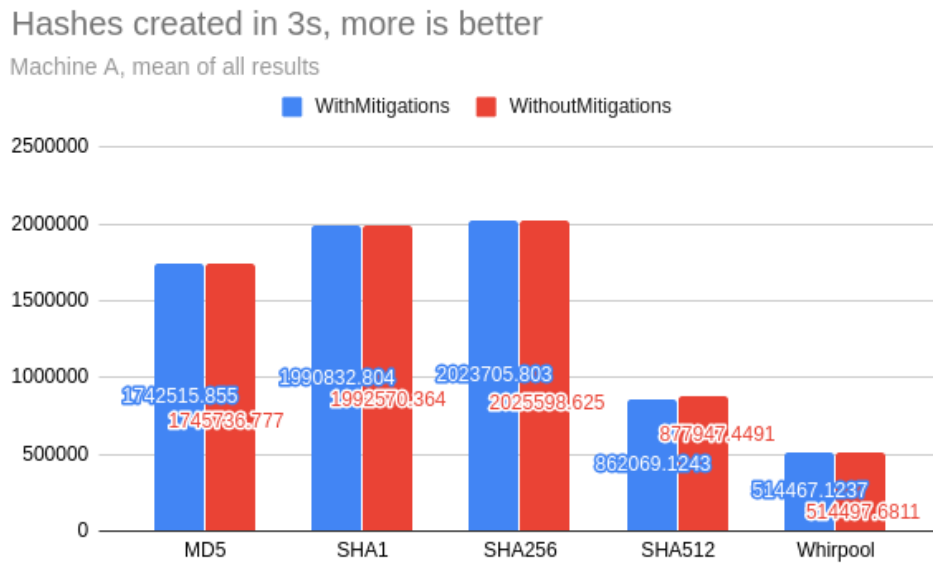

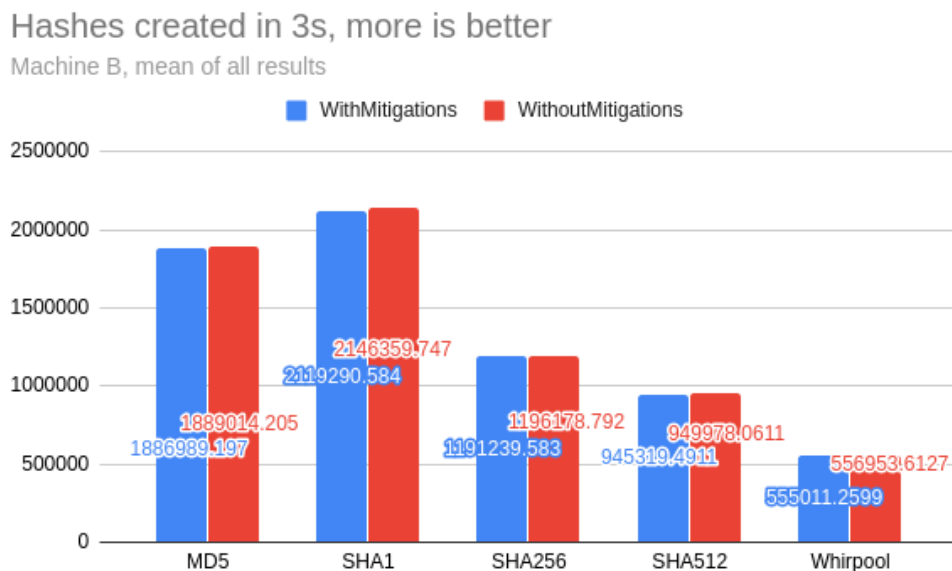**Figure 4:** Hashes created by Machine A

Figure 5: Hashes created by Machine B

Cryptsetup

Contrary to OpenSSL, **cryptsetup** is capable of measuring the speed of modern, symmetric cryptographic algorithms. For the purposes for the experiment, most used and modern methods were used: AES-CBC, AES-XTS, Twofish-XTS and Serpent-CBC. Tables 3 & 4 respectively present the mean results of all trial runs, on both test machines. Once performed paired T-Test, it was found that $p < 0.05$.

Carrying on, we notice the biggest impact on AES algorithms, with the most significant difference on AES-XTS using 512-blocks key, reaching even 957 MiB/s. On the other hand, Twofish and Serpent is more resilient to the mitigations, with differences of circa 15 MiB/s.

Algorithm	Key	WithMitigations		WithoutMitigations	
		Encryption	Decryption	Encryption	Decryption
AES-CBC	128b	1090.6 MiB/s	3255.8 MiB/s	1123.2 MiB/s	3443.5 MiB/s
AES-XTS	512b	1907.2 MiB/s	1910.7 MiB/s	2761.5 MiB/s	2759.7 MiBs
Twofish-XTS	256b	371.4 MiB/s	373.9 MiB/s	383.3 MiB/s	385.4 MiB/s
Serpent-CBC	256b	93.9 MiBs	705.7 MiB/s	93.5 MiB/s	712.3 MiB/s

Table 3: cryptsetup benchmark on MachineA

Algorithm	Key	WithMitigations		WithoutMitigations	
		Encryption	Decryption	Encryption	Decryption
AES-CBC	128b	1185.9 MiB/s	3526.9 MiB/s	1203.9 MiB/s	3749.7 MiB/s
AES-XTS	512b	2024.9 MiB/s	2037.8 MiB/s	2981.7 MiB/s	2988.8 MiBs
Twofish-XTS	256b	402.6 MiB/s	404.5 MiB/s	416.2 MiB/s	417.8 MiB/s
Serpent-CBC	256b	101.1 MiBs	762.9 MiB/s	101.6 MiB/s	780 MiB/s

Table 4: cryptsetup benchmark on Machine B

6   Discussion

Following the tests through Phoronix Suite, there is a clear regression visible for both Machine A and Machine B - the biggest being ctx-clock, which actually was excepted. We can suspect that KAISER (described in section 2) is at fault here - since the address space is no longer mapped directly to each process, the CPU has to compute all address spaces every time context switch is requested in order to switch from User to Kernel mode. For the remaining two tests, they were mostly benchmarking access times to virtual memory and how well the CPU is capable of handling page faults, again, tasks that were normally sped up by a magnitude, thanks to the speculative execution, suffered more than 20% regression with the mitigations enabled.

Interestingly, the Geekbench results had no significance, as the T-Test shown high probability of the differences being caused by random noise. This could have also been caused by the fact that I was using free version of Geekbench limited to only 32-bit instruction set along with limited control

over repeated tests. It's an area definitely worth further exploration in order to determine the exact regression (or perhaps lack of it) on the tests performed by that software.

Moreover, the cryptographic performance wasn't as impactful as the context switching or VM access times, with the exceptions of some algorithms (AES-XTS), the regression is less than 1%. That's the operations most likely to be performed frequently by consumer-level hardware, with problems such as HTTPS/TLS connections being handled regularly.

We can observe see how swapping the variables - machine type and performed test - ends up with different results, yet with similar standard deviation. Moreover, in some situations Machine A was performing better and in others vice versa. This could hint towards the fact that 8th generation and onwards Intel processors (which Machine B was equipped with) have been re-engineered to minimize the impact.

Unfortunately, I did not have available to me CPU architectures other than Intel, so for future work, it'd be worth to see what's the correlation between Intel, AMD or ARM running same benchmarks and whether observed regressions are observable. AMD at first was adamant that Meltdown was not reproducible on their chips at all in the beginning, but eventually changed their stance [1] and deployed relevant microcode updates having some degree of impact on the computation power of their chips, so further experiment would help with confirming or disproving those claims. And also, within Intel architecture itself, it'd be interesting to see how consumer chips (used for the tests) behave compared with enterprise-grade hardware (such as Xeon family), seeing how the biggest impacts reported are for machines inside data centers.

Moreover, all benchmarks were performed only on Linux. When constructing future tests, inclusion of more platforms might be interesting to see, for example to compare how MacOS and Windows platforms degraded in performance before and after deploying the mitigations.

Finally, we are ready to address our hypotheses stated in the experimental design. For the first one, we can clearly see the regression on tests performed on systems with mitigations installed. On the other hand, higher level tests performed by Geekbench haven't produced significance, so the null hypothesis can only be partially rejected with regard to the tasks performed by running benchmarks (task scheduling, context switching and socket activity). Second hypothesis is not going to be rejected, as the noticed regression of 0.05% cannot be classified as significant increase in runtime, thus confirming Microsoft's claims [12].

7   Conclusion

In my report I focused on the impact of the mitigations deployed after the discovery of side-channel attacks by Google's Project Zero. After exploring and providing background of the exact nature of those attacks and the necessity of the fixes, I have performed tests on two different pieces of hardware, each running Linux on Intel architecture. Once the results were analysed, it was apparent that performance drop is visible, with the biggest drop observed at the amount of clocks required for context switch. Not all tasks were affected equally though, with only one encryption algorithm (AES) performing significantly worse. Although further testing would be needed to establish other

potential implications, such as performance on different architectures, different operating systems or examination whether consumer-grade hardware is prone to be less susceptible (e.g. Intel Xeon vs Core).

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