Meltdown: Reading Kernel Memory from User Space

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ABSTRACT

A clear and well-documented LaTeX document is presented as an article formatted for publication by ACM in a conference proceedings or journal publication. Based on the "acmart" document class, this article presents and explains many of the common variations, as well as many of the formatting elements an author may use in the preparation of the documentation of their work.

KEYWORDS

out-of-order execution, side-channel attack, transient instruction, + others

1 INTRODUCTION

Content to be added later

2 BACKGROUND

2.1 Memory Hierarchy

2.1.1 Caching. The need for fast memory that could keep up with the CPU frequency is limited by the high cost per byte these high-performance memories come with. To address this issue, extremely fast registers are placed inside the CPU, small but fast memory is assigned to the CPU, a slightly slower but random-based accessable memory is assigned to the running applications, and the secondary memory for storing data at rest.

The memory close to the CPU, called a cache, takes advantage of *spatial locality* (data to be processed tend to be close to the data already being processed) and *temporal locality* (processed data tends to be requested multiple times during execution).

A typical architecture consists of 3 levels of caches, with two being private per core and the third one being shared. For efficiency, data is moved in *blocks* (or lines) which contain a fixed size of words. Placing the blocks in cache can be made via different schemes, such as *set associative* (each block has a pre-determined position in cache), *n-way set associative* (each block can be placed in one of n possible positions in cache) or *fully associative* (the block can be placed anywhere in cache).

2.1.2 Virtual Memory. Each process runs within its own address space, so there is a need to share the limited main memory between all running processes. The method used to achieve this is through *virtual memory*; the physical memory is divided into blocks called pages, and allocated to any process in need for memory. The processor issues virtual memory addresses for memory operations, which are mapped to physical ones using page translation tables. The translation table is held inside a CPU register, and it is per-process only; the operating system updates them for every process being executed.

In order for processes not to access the blocks of other processes, protection schemes have to apply. Translation tables have privilege checks that are

2.2 CPU Architecture and out-of-order Execution

The CPU architectures affected by the attack mentioned in this paper have all a microarchitecture that is pipelined, super-scalar, out-of-order and with speculative execution. This section will further explain each of these methods used to perform instruction-level parallelism (ILP).

Pipelining is a technique which allows multiple instructions to overlap during execution, each using different resources oft he processor. Standartization of instruction in execution phases such as fetch, decode, execute, memory access and write-back, which do not have hardware dependencies between them.

Superscalar processors can execute more than one instruction during a clock cycle. This is not the same as multi-core processor, but rather having multiple execution resources inside the CPU, for example ALUs.

Speculative execution means that the compiler or the processor tries to guess the outcome of an instruction, thus removing it as a dependency in the execution path of other instructions. Since out focus is the hardware architecture, the main speculative execution on a processor ist hat of branch predicition, explained below.

Out-of-order execution makes it possible for instructions to continue execution the moment all the required resources are available, even when the previous one is blocked and waitting for other operations to be completed. This is not to be confused with speculative execution below; in out-of-order execution all the instructions are correctly executed and no assumptions are made. Still, all the execution results stay at an microarchitecture state till all prior instructions are commited.

The first step to achieve out-of-order execution is to solve data hazards (data dependencises from previous instructions), such as read-after-write, write-after-read and write-after-write (RAW, WAR, WAW). Normally, even in a pipelined datapath, the output from a previous instruction would be available only after the last phase, memory writeback. Tomasulo [7] suggested the use of a unified reservation station that would make the outputs available the moment they were ready, and not having to wait for it to be stored and re-read using common data bus (CDB), that connects all execution units with each-other.

In the front-end, instructions are decoded into micro-ops (μ-ops), and are sent into the IDQ (μ-op queue). Breaking every instruction into μ-ops makes it possible for any procesor to execute commands without the need of modifying the instruction set. They are later

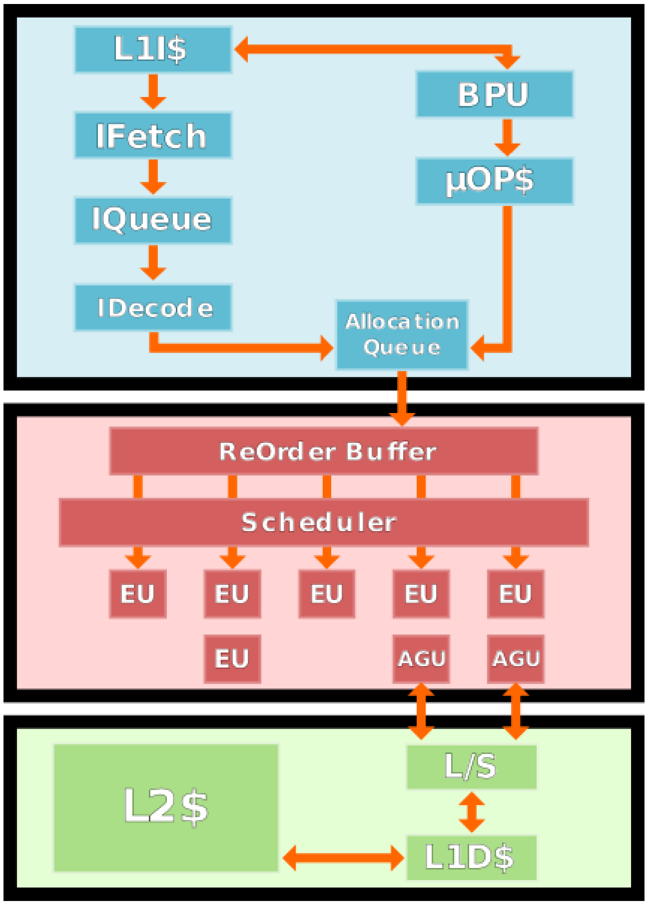

Figure 1: Simplified design of a Skylake Core. for detailed picture, choose skylake_block_diagram [Public domain maybe? check!!!], via (https://en.wikichip.org/wiki/intel/microarchitectures/skylake_(client)).

sent to the back-end (execution engine) where the logic of out-of-order is implemented. They are later forwarded to the scheduler, which decides on which execution unit u-ops should be send depending on their specific task.

BPU (Branch Prediction Unit) decides on branch instructions which block of code will be executed, before knowing for sure the correct flow of the execution. This prediction is usually a trade secret, and only the manufacterer knows the algorithm used, but the main ways to predict a path are : —content here— Instructions on the path that is going to be executed, start executing immediately as long as they don't have any dependencies. Upon realizing that the prediction was incorrect, the reorder buffer is rolled-back to a correct state (flushed) and the unified reservation station is re-initialized. This way, unauthorized instructions are executed and can change the microarchitectural state, but the change will not be reflected on the architecture state.

2.3 Flush+Reload

Content to be added : FLUSH+RELOAD : a high resolution, low-noise L3cacche side channel attack.

3 RELATED WORKS

Exploitation can be observed during multiple steps of ILP. In the front-end this can happen during speculation via branch prediction (BPU), albeit difficult to exploit in the wild due to the mechanics of dynamic branch prediction not being publicly known. Exploitations can further be performed during dynamic scheduling (BPU & IFU) and speculative execution (IDQ).

In the back-end exploitations can be observed during the register renaming (allocate/rename/retire unit), superscalar and out-of-order (scheduler) and in-order commit (retirement).

3.1 Spectre

While Meltdown makes use of the out-of-order execution to read and leak kernel memory that under normal execution they should not have, Spectre uses speculative execution property of branch prediction (conditional and indirect branches) to read arbitrary memory. Before BPU realizes the branch was wrongly predicted, some instructions are already speculatively executed, and through a side channel the confidential information is sent from a microarchitectural state to an architectural one.

Unlike Meltdown, Spectre works on a wide range of processors, including most ARM and AMD models and not just Intel and some ARM. Also, KAISER mechanism used to mitigate Meltdown, doesn't protect against Spectre.

3.2 ZombieLoad

ZombieLoad is another Meltdown-like attack that benefits from fault-driven transient instruction execution. This exploitation is performed on the fill-buffer using faulty Load instructions that have to be re-issued internally but don't become architecturaly visible. The values accessed by these Load instructions are those of recent registers belonging to previous memory operations from the current or a sibling hyperthread, unlike Meltdown that has to use explicit address-based selectors. Protection against ZombieLoad can be achived only by disabling hyperthreading.

3.3 Cache Side-channel Attacks

4 TYPEFACES

The "`acmart`" document class requires the use of the "Libertine" typeface family. Your TeX installation should include this set of packages. Please do not substitute other typefaces. The "`lmodern`" and "`ltimes`" packages should not be used, as they will override the built-in typeface families.

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```
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```

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```
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```

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8 CCS CONCEPTS AND USER-DEFINED KEYWORDS

Two elements of the "acmart" document class provide powerful taxonomic tools for you to help readers find your work in an online search.

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User-defined keywords are a comma-separated list of words and phrases of the authors' choosing, providing a more flexible way of describing the research being presented.

CCS concepts and user-defined keywords are required for all short- and full-length articles, and optional for two-page abstracts.

Table 1: Frequency of Special Characters

Non-English or Math	Frequency	Comments
Ø	1 in 1,000	For Swedish names
π	1 in 5	Common in math
$	4 in 5	Used in business
Ψ_1^2	1 in 40,000	Unexplained usage

9 SECTIONING COMMANDS

Your work should use standard LaTeX sectioning commands: `section`, `subsection`, `subsubsection`, and `paragraph`. They should be numbered; do not remove the numbering from the commands.

Simulating a sectioning command by setting the first word or words of a paragraph in boldface or italicized text is **not allowed.**

10 TABLES

The "`acmart`" document class includes the "`booktabs`" package — https://ctan.org/pkg/booktabs — for preparing high-quality tables.

Table captions are placed *above* the table.

Because tables cannot be split across pages, the best placement for them is typically the top of the page nearest their initial cite. To ensure this proper "floating" placement of tables, use the environment **table** to enclose the table's contents and the table caption. The contents of the table itself must go in the **tabular** environment, to be aligned properly in rows and columns, with the desired horizontal and vertical rules. Again, detailed instructions on **tabular** material are found in the *LaTeX User's Guide*.

Immediately following this sentence is the point at which Table 1 is included in the input file; compare the placement of the table here with the table in the printed output of this document.

To set a wider table, which takes up the whole width of the page's live area, use the environment **table*** to enclose the table's contents and the table caption. As with a single-column table, this wide table will "float" to a location deemed more desirable. Immediately following this sentence is the point at which Table 2 is included in the input file; again, it is instructive to compare the placement of the table here with the table in the printed output of this document.

11 MATH EQUATIONS

You may want to display math equations in three distinct styles: inline, numbered or non-numbered display. Each of the three are discussed in the next sections.

Table 2: Some Typical Commands

Command	A Number	Comments
\author	100	Author
\table	300	For tables
\table*	400	For wider tables

11.1 Inline (In-text) Equations

A formula that appears in the running text is called an inline or in-text formula. It is produced by the **math** environment, which can be invoked with the usual `\begin . . . \end` construction or with the short form `$ . . . $`. You can use any of the symbols and structures, from α to ω, available in LaTeX [20]; this section will simply show a few examples of in-text equations in context. Notice how this equation: $\lim_{n\rightarrow \infty}x=0$, set here in in-line math style, looks slightly different when set in display style. (See next section).

11.2 Display Equations

A numbered display equation—one set off by vertical space from the text and centered horizontally—is produced by the **equation** environment. An unnumbered display equation is produced by the **displaymath** environment.

Again, in either environment, you can use any of the symbols and structures available in LaTeX; this section will just give a couple of examples of display equations in context. First, consider the equation, shown as an inline equation above:

$$\lim_{n\rightarrow \infty}x=0 \tag{1}$$

Notice how it is formatted somewhat differently in the **displaymath** environment. Now, we'll enter an unnumbered equation:

$$\sum_{i=0}^{\infty} x + 1$$

and follow it with another numbered equation:

$$\sum_{i=0}^{\infty}x_i=\int_{0}^{\pi+2} f \tag{2}$$

just to demonstrate LaTeX's able handling of numbering.

12 FIGURES

The "`figure`" environment should be used for figures. One or more images can be placed within a figure. If your figure contains third-party material, you must clearly identify it as such, as shown in the example below.

Figure 2: 1907 Franklin Model D roadster. Photograph by Harris & Ewing, Inc. [Public domain], via Wikimedia Commons. (https://goo.gl/VLCRBB).

Your figures should contain a caption which describes the figure to the reader. Figure captions go below the figure. Your figures should **also** include a description suitable for screen readers, to assist the visually-challenged to better understand your work.

Figure captions are placed *below* the figure.

12.1 The "Teaser Figure"

A "teaser figure" is an image, or set of images in one figure, that are placed after all author and affiliation information, and before the body of the article, spanning the page. If you wish to have such a figure in your article, place the command immediately before the `\maketitle` command:

```
\begin{teaserfigure}
  \includegraphics[width=\textwidth]{sampleteaser}
  \caption{figure caption}
  \Description{figure description}
\end{teaserfigure}
```

13 CITATIONS AND BIBLIOGRAPHIES

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The bibliography is included in your source document with these two commands, placed just before the `\end{document}` command:

```
\bibliographystyle{ACM-Reference-Format}
\bibliography{bibfile}
```

where "`bibfile`" is the name, without the "`.bib`" suffix, of the BibTeX file.

Citations and references are numbered by default. A small number of ACM publications have citations and references formatted in the "author year" style; for these exceptions, please include this command in the **preamble** (before "`\begin{document}`") of your LaTeX source:

```
\citestyle{acmauthoryear}
```

Some examples. A paginated journal article [2], an enumerated journal article [7], a reference to an entire issue [6], a monograph (whole book) [19], a monograph/whole book in a series (see 2a in spec. document) [13], a divisible-book such as an anthology or compilation [9] followed by the same example, however we only output the series if the volume number is given [10] (so Editor00a's series should NOT be present since it has no vol. no.), a chapter in a divisible book [30], a chapter in a divisible book in a series [8], a multi-volume work as book [18], an article in a proceedings (of a conference, symposium, workshop for example) (paginated proceedings article) [3], a proceedings article with all possible elements [29], an example of an enumerated proceedings article [11], an informally published work [12], a doctoral dissertation [5], a master's thesis: [4], an online document / world wide web resource [1, 24, 31], a video game (Case 1) [23] and (Case 2) [22] and [21] and (Case 3) a patent [28], work accepted for publication [25], 'YYYYb'-test for prolific author [26] and [27]. Other cites might contain 'duplicate' DOI and URLs (some SIAM articles) [17]. Boris / Barbara Beeton: multi-volume works as books [15] and [14]. A couple of citations with DOIs: [16, 17]. Online citations: [31–33].

14 ACKNOWLEDGMENTS

Identification of funding sources and other support, and thanks to individuals and groups that assisted in the research and the preparation of the work should be included in an acknowledgment section, which is placed just before the reference section in your document.

This section has a special environment:

```
\begin{acks}
...
\end{acks}
```

so that the information contained therein can be more easily collected during the article metadata extraction phase, and to ensure consistency in the spelling of the section heading.

Authors should not prepare this section as a numbered or unnumbered `\section`; please use the "`acks`" environment.

15 APPENDICES

If your work needs an appendix, add it before the "`\end{document}`" command at the conclusion of your source document.

Start the appendix with the "`appendix`" command:

```
\appendix
```

and note that in the appendix, sections are lettered, not numbered. This document has two appendices, demonstrating the section and subsection identification method.

16 SIGCHI EXTENDED ABSTRACTS

The "`sigchi-a`" template style (available only in LaTeX and not in Word) produces a landscape-orientation formatted article, with a wide left margin. Three environments are available for use with the "`sigchi-a`" template style, and produce formatted output in the margin:

- `sidebar`: Place formatted text in the margin.
- `marginfigure`: Place a figure in the margin.
- `margintable`: Place a table in the margin.

ACKNOWLEDGMENTS

To Robert, for the bagels and explaining CMYK and color spaces.

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A RESEARCH METHODS

A.1 Part One

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A.2 Part Two

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