Meltdown and Spectre Samples

Written in Assembly

U. Plonus
u.plonus@gmail.com

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Contents

1 Introduction

1.1 Overview

TBD

1.2 Conventions

1.2.1 Introduction

In this section we define some convention that are specific for this document.

1.2.2 Data Sections

The data is divided into three parts: read-only data, initialized data and uninitialized data. Code chunks with this type of data will all have defined sufficies.

Definition 1 *Read-only data is data that is not modified during program execution. The suffix for read-only data is* ***-rodata****.*

Definition 2 *Initialized data is data that is changeable during program execution. The data is already initialized with data when the program starts. The suffix for initialized data is* ***-idata****.*

Definition 3 *Uninitialized data is data that is changeable during program execution. The data is not initialized. The suffix for uninitialized data is* ***-udata****.*

1.3 Nasm

TBD

5 ⟨*preamble* 5⟩≡ (12 17)

```
bits 64

⟨license 60⟩

        global          _start
        pagesize        equ 4096
```

Defines:
`_start`, used in chunks 9c and 13a.
`pagesize`, used in chunks 8, 9, 13, 14, and 17.

2 Cache Access Timing

2.1 Introduction

TBD

2.2 Detect Cache Access Time

2.2.1 High Resolution Timer

First we need a high resolution timer to determine the cache access time. For this we use the time stamp counter. The time stamp counter is monotonically incrementing. When reading the time stamp counter (with `rdtsc`) the result is delivered back in the registers `EDX` and `EAX` forming a 64bit value. The time stamp counter is not an absolute value but a relative value, meaning that you cannot (easily) calculate from the time stamp counter to some time units (e.g. ns). But this is no problem as we only want to measure relative times.

To retrieve a 64bit value for the time we shift the value in `EDX` 32 bits to the left and add the value of `EAX` to this.

7 ⟨*tsc-64bit* 7⟩≡ (8a)

```
rdtsc
shl     RDX,32
add     RAX,RDX
```

2.2.2 Cache Access Time Routine

Next we need a routine that calculates the cache access time for us.

First we have to ensure in this routine that the speculative execution of the processor does not interfere with our time measurement. For this we use the instruction `lfence` which ensures that all previous reads are done before executing the next instructions.

Next we access a memory location with the address `RDI` by loading this into `RCX` and measure the time before and after the access.

The command `lfence` before reading the time stamp counter is needed because we have to ensure that all reads before the time measurements are done.

At last we calculate the relative time needed to access the memory location. In theory we should see a difference whether the memory location is accessed before or not.

Parameters

`RDI` the address of the memory which is loaded either from the cache or from memory

8a ⟨*calculate-cache-access-time* 8a⟩≡ (12 17)

```
 _calccachetime:
      lfence
 ⟨tsc-64bit 7⟩
      mov       R8,RAX
      mov       RCX,[RDI]
      lfence
 ⟨tsc-64bit 7⟩
      sub       RAX,R8
      ret
```

Defines:
`_calccachetime`, used in chunks 10c, 11b, and 16.

2.3 Measure Cache Access Time

2.3.1 Setup

To measure the cache timing we create a standalone program that shows us the time for a cached and for an uncached memory access.

First we need some area in memory with data which we can later read from. This data area goes into the area `.bss` which contains uninitialized data. We align the data at a page boundary and reserve 2 pages for our data.

8b ⟨*cache-data* 8b⟩≡ (9b 17)

```
      data:           resb pagesize
```

Defines:
`data`, used in chunks 9–11, 13a, and 14b.
Uses `pagesize` 5.

From time to time we need a small scratch area so we define an area with 32 bytes.

9a ⟨*scratch-data* 9a⟩≡ (9b)
```
scratch:        resb 32
```
Defines:
`scratch`, used in chunk 11.

9b ⟨*cachetiming-udata* 9b⟩≡ (12)
```
        align           pagesize
  ⟨cache-data 8b⟩
  ⟨scratch-data 9a⟩
```
Uses `pagesize` 5.

The program begins with the label `_start`.

9c ⟨*cachetiming-program* 9c⟩≡ (12) 9d ▷
```
  _start:
```
Uses `_start` 5.

Now we start with initialising the `data` area with some random data. For this we load `RDI` with the address of the `data` area.

9d ⟨*cachetiming-program* 9c⟩+≡ (12) ◁ 9c 9e ▷
```
        mov     RDI,data
```
Uses `data` 8b.

Next we load the number of bytes to fill into `RSI`. For this we load the `pagesize` into `RSI`.

9e ⟨*cachetiming-program* 9c⟩+≡ (12) ◁ 9d 9f ▷
```
        mov     RSI,pagesize
```
Uses `pagesize` 5.

At last we load `EDX` with some random seed. For this we use `rdtsc` and only use the lower 32 bit of the value.

9f ⟨*cachetiming-program* 9c⟩+≡ (12) ◁ 9e 9g ▷
```
        rdtsc
        mov     EDX,EAX
```

Now we call `_xorshift` to fill the `data` area.

9g ⟨*cachetiming-program* 9c⟩+≡ (12) ◁ 9f 10a ▷
```
        call    _xorshift
```
Uses `_xorshift` 22a.

2.3.2 Measure Time

Now that we have setup our `data` area we can now cache data from the first page by loading it into a register which also loads this into the cache.

For this we load `RDI` with the address of the `data` area.

10a ⟨*cachetiming-program* 9c⟩+≡ (12) ◁9g 10b▷

```
        mov         RDI,data
```

Uses `data` 8b.

Before we load the data into a register now we will clear the cache lines with the given address. For this we use the instruction `clflush`. After flushing the cache line we ensure (with `lfence`) that all reads from memory are finished before we load the data into a register again (and filling the cache).

10b ⟨*cachetiming-program* 9c⟩+≡ (12) ◁10a 10c▷

```
        clflush     [RDI]
        lfence
        mov         RCX,[RDI]
```

Now we can determine the time that is needed to load this data once again. We do not need to load `RDI` again because it has not changed.

10c ⟨*cachetiming-program* 9c⟩+≡ (12) ◁10b 10e▷

```
        call        _calccachetime
```

Uses `_calccachetime` 8a.

Now we have the relative cache access time in register `RAX`. We store this value to the stack and print out an explaining text.

For this we define the text to print and (as a helper) a carriage return (CR).

10d ⟨*cachetiming-rodata* 10d⟩≡ (12) 11c▷

```
        scr:            db 0x0a
        scached:        db "Cached Access Time: ",0x00
```

Defines:
  `scached`, used in chunk 10e.
  `scr`, used in chunk 11.

Now we can print the text.

10e ⟨*cachetiming-program* 9c⟩+≡ (12) ◁10c 11a▷

```
        push        RAX
        mov         RDI,scached
        call        _print
```

Uses `_print` 24a and `scached` 10d.

Then we restore the value and print the measured time to `stdout`. At last we append a CR to the output.

11a ⟨*cachetiming-program* 9c⟩+≡ (12) ◁10e 11b▷
```
        pop       RDI
        mov       RSI,scratch
        call      _printdu64bit
        mov       RSI,scr
        mov       RDI,1
        call      _nprint
```
Uses `_nprint` 23b, `_printdu64bit` 25a, `scr` 10d, and `scratch` 9a.

Now we do the same with an uncached value. The difference is that we do not load the value before.

11b ⟨*cachetiming-program* 9c⟩+≡ (12) ◁11a 11d▷
```
        mov       RDI,data
        clflush   [RDI]
        lfence
        call      _calccachetime
```
Uses `_calccachetime` 8a and `data` 8b.

Now we have the time of the uncached data access in `RAX` and can print it out with some explaining text.

11c ⟨*cachetiming-rodata* 10d⟩+≡ (12) ◁10d
```
        suncached:     db "Uncached Access Time: ",0x00
```
Defines:
`suncached`, used in chunk 11d.

11d ⟨*cachetiming-program* 9c⟩+≡ (12) ◁11b 11e▷
```
        push      RAX
        mov       RDI,suncached
        call      _print
        pop       RDI
        mov       RSI,scratch
        call      _printdu64bit
        mov       RSI,scr
        mov       RDI,1
        call      _nprint
```
Uses `_nprint` 23b, `_print` 24a, `_printdu64bit` 25a, `scr` 10d, `scratch` 9a, and `suncached` 11c.

At last we exit the program.

11e ⟨*cachetiming-program* 9c⟩+≡ (12) ◁11d
⟨*exitProgram* 21b⟩

Now we can put everything together and have our `cachetiming` program that we can now execute.

12 ⟨*cachetiming.asm* 12⟩≡
```
⟨preamble 5⟩

section .rodata
⟨cachetiming-rodata 10d⟩

section .bss
⟨cachetiming-udata 9b⟩

section .text
⟨cachetiming-program 9c⟩

⟨calculate-cache-access-time 8a⟩

⟨xorshift-prng 22a⟩

⟨utilities 21a⟩
```

The program is placed in `asm/`. With `make` in the folder we can create an executable which is moved to `bin/`. There we can execute this program.

```
$ ./cachetiming
Cached Access Time: 72
Uncached Access Time: 372
$
```

2.4 Read Array via Cache Access Time

2.4.1 Introduction

Now that we have seen that we can determine if a value was in the cache or not (see 2.3 Measure Cache Access Time) we will read a complete array of data by only measuring the cache access time.

2.4.2 Setup

For this we start with some `data` area that we can read later as defined before.

So start with the program and fill the `data` area with some random data (similar to the chunks 9c, 9d, 9e, 9f and 9g).

13a ⟨*cacheread-program* 13a⟩≡ (17) 14a▷

```
_start:
      mov       RDI,data
      mov       RSI,pagesize
      rdtsc
      mov       EDX,EAX
      call      _xorshift
```

Uses `_start` 5, `_xorshift` 22a, `data` 8b, and `pagesize` 5.

Next we will create a probe area that is $256 * pagesize$. We only access the first byte of each page but we divide the data over such a large area (1 MiB) to ensure that the cache lines that we use do not interfere each other.

13b ⟨*cacheread-udata* 13b⟩≡ (17)

```
      probe:          times 256 resb pagesize
```

Defines:
`probe`, used in chunk 14.
Uses `pagesize` 5.

Next we fill this area also with some random data.

14a ⟨*cacheread-program* 13a⟩+≡ (17) ◁13a

```
        mov     RDI,probe
        mov     RAX,pagesize
        mov     RCX,256
        mul     RCX
        mov     RSI,RCX
        rdtsc
        mov     EDX,EAX
        call    _xorshift
```

Uses `_xorshift` 22a, `pagesize` 5, and `probe` 13b.

2.4.3 Reading Bytes via Cache

As we saw we can determine if a memory datum is in cache or not. For reading a complete byte we have to do a little bit more. Basically we use the byte accessed to index a different `probe` area. Because the memory is not cached byte by byte but in so called cache lines we cannot use a simple 256 bytes sized probe array but must at least have a space between the accessed bytes that is larger than a cache line size. This is the reason why we use a probe array of 256 * `pagesize` bytes of size.

Basically we use the following code to access the data. We load the content of the address we want to probe into a register. Then we multiply the register with some arbitary value (we use `pagesize`) and the access the probe area with the calculated offset. We can then test the cache which page was cached and have our value from the `data`.

14b ⟨*cacheread-sample* 14b⟩≡

```
        mov     RAX,[data]
        mul     RAX,pagesize
        mov     RBX,[probe+RAX]
```

Uses `data` 8b, `pagesize` 5, and `probe` 13b.

First we write a subroutine to clear the cache lines from data from our `probe` area. We assume that we use 256 values (0 . . . 255) for the indexing into the probe array. Also the `probe` area must be at least 256 * RSI bytes in size.

Parameters

`RDI` the address of the probe array

`RSI` the interval between the probe addresses used

15 ⟨*clear-cache* 15⟩≡ (17)

```
_clear_cache:
     cld
     mov      RCX,256
     xor      RAX,RAX
.clear_next:
     mul      RSI
     clflush  [RDI+RAX]
     add      RAX,RSI
     loop     .clear_next
     lfence
     ret
```

Defines:
`_clear_cache`, never used.

Next we need a subroutine that determines the cache line access times for the data in the `probe` area. So we create a subroutine that loops similar to the `_clear_cache` subroutine over all addresses and measures the cache access time for each page.

Parameters

`RDI` the address of the probe array

`RSI` the interval between the probe addresses used

`RDX` the address of the results of the cache measurements. The area needs to be 256 * 8 bytes in size

16 ⟨*detect-cache-area-time* 16⟩≡ (17)

```
_calcareacachetime:
     cld
     xor       RCX,RCX
.next_timing:
     push      RCX
     call      _calccachetime
     pop       RCX
     mov       [RDX+8*RCX],RAX
     add       RDI,RSI
     inc       RCX
     cmp       RCX,256
     jb        .next_timing
     ret
```

Defines:
`_calcareacachetime`, never used.
Uses `_calccachetime` 8a.

TBD

17 ⟨*cacheread.asm* 17⟩≡
```
⟨preamble 5⟩

section .bss
     align           pagesize
⟨cache-data 8b⟩
⟨cacheread-udata 13b⟩

section .text
⟨cacheread-program 13a⟩

⟨exitProgram 21b⟩

⟨clear-cache 15⟩

⟨calculate-cache-access-time 8a⟩

⟨detect-cache-area-time 16⟩

⟨xorshift-prng 22a⟩

⟨utilities 21a⟩
```
Uses `pagesize` 5.

3 Signals

3.1 Basics

TBD

3.2 Detecting Signals

TBD

3.3 Handling Signals

TBD

4 Utilities

4.1 Introduction

TBD

21a ⟨*utilities* 21a⟩≡ (12 17)

⟨*nprint* 23b⟩

⟨*print* 24a⟩

⟨*printdu64bit* 25a⟩

4.2 Exit Program

TBD

21b ⟨*exitProgram* 21b⟩≡ (11e 17)

```
        xor      RDI,RDI
        mov      RAX,60
        syscall
```

4.3 Random Number Generator

To initialize the data a random number generator (RNG) is used. The sample programs use xorshift[1] as RNG.

First we clear the direction flag to ensure that we are incrementing the data pointer RDI.

Next we move the number of values to be generated to RCX (which is a counter in x86 processors) and divide it by 4 (because we use a 32bit RNG). Additionally we move the seed to EAX.

Parameters

RDI the address of the memory which is to be filled with random numbers

RSI the number of bytes that are filled with random numbers. This must be a multiple of 4

EDX the seed of the RNG

22a ⟨*xorshift-prng* 22a⟩≡ (12 17) 22b ▷

```
_xorshift:
      cld
      mov      RCX,RSI
      shr      RCX,2
      mov      EAX,EDX
```

Defines:
_xorshift, used in chunks 9g, 13a, and 14a.

Now we can generate the next 32bit random number.

22b ⟨*xorshift-prng* 22a⟩+≡ (12 17) ◁ 22a 23a ▷

```
.next_random:
      mov      EBX,EAX
      shl      EAX,13
      xor      EAX,EBX
      mov      EBX,EAX
      shr      EAX,17
      xor      EAX,EBX
      mov      EBX,EAX
      shl      EAX,5
      xor      EAX,EBX
```

[1] https://en.wikipedia.org/wiki/Xorshift

Because we want to generate multiple random numbers we store the value of EAX to [RDI] and loop for the next random number.

23a ⟨*xorshift-prng* 22a⟩+≡ (12 17) ◁22b

```
        stosd
        loop      .next_random
        ret
```

4.4 Printing Strings

4.4.1 Printing Strings with Length

The routine _nprint prints a string with the given length to stdout.

We move the number of bytes to print to RDX which is the 3rd parameter to the systemcall. Next we move the address of the bytes to print to RSI which is the 2nd parameter to the systemcall. The 1st argument (in RDI) to the systemcall is the file descriptor (1 is stdout). Additionally the number of the systemcall (1) is passed in RAX. The systemcall (syscall) now prints RDX bytes from [RSI] to the file descriptor RDI.

At the end we return to the caller.

Parameters

RDI the number of bytes to print to stdout

RSI the address to the bytes to print to stdout

23b ⟨*nprint* 23b⟩≡ (21a)

```
  _nprint:
        mov       RDX,RDI
        mov       RDI,1
        mov       RAX,1
        syscall
        ret
```

Defines:
_nprint, used in chunks 11, 24d, and 27b.

4.4.2 Printing C-Strings

The routine _print prints a null-terminated string to stdout.

First we clear the direction flag to increment the address in RDI while scanning the data.

Next we start with clearing AL (setting it to null) and saving the address of the string to RSI. We're using RSI because we later need the address to calculate the length of the string.

Parameters

RDI the address to the null-terminated bytes to print to stdout

24a ⟨*print* 24a⟩≡ (21a) 24b ▷

```
_print:
      cld
      xor       AL,AL
      mov       RSI,RDI
```

Defines:
_print, used in chunks 10e and 11d.

Next we search for the terminating `null` ('\0') character. For this we use the instruction `scasb` (scan string byte) which compares the byte at the address `[RDI]` with the value in `AL` and sets the flags accordingly. When the byte at `[RDI]` is not the value of `AL` the next instruction (`jne`) jumps to the given label (`.next_char` in this case).

`scasb` additionally increments `RDI` so that we go through the string until '\0' is found.

24b ⟨*print* 24a⟩+≡ (21a) ◁ 24a 24c ▷

```
.next_char:
      scasb
      jne       .next_char
```

After we have found the string termination we calculate the number of bytes that the string has. In `RSI` we now have the starting address of the bytes to print and in `RDI` we have the end address of the bytes to print. After that we calculate the number of bytes to print.

24c ⟨*print* 24a⟩+≡ (21a) ◁ 24b 24d ▷

```
      sub       RDI,RSI
```

Now we have the address of the string in `RDI` and the length of the string in `RSI` which are the 1st and 2nd argument in the call of `_nprint`.

24d ⟨*print* 24a⟩+≡ (21a) ◁ 24c

```
      call      _nprint
      ret
```

Uses _nprint 23b.

4.5 Printing Numbers

4.5.1 Printing a 64bit Unsigned Integer

The routine `_printdu64bit` print a given number as unsigned decimal number with 64bit to `stdout`.

To print a decimal number we have to divide the number by 10 and get the remainder for printing (from right to left). For this we move the divisor to a register and the dividend to `RAX`. We have to use `RAX` because this is the only register we can use for division.

Additionally we need the address of the scratch area in `RDI` for storing the result. We also save the address of the scratch area to `R8` for later use.

To increment the address during the processing we clear the direction flag.

Parameters

`RDI` the number number to print to `stdout`

`RSI` the address of a scratch area with a size of at least 20 bytes

25a ⟨*printdu64bit* 25a⟩≡ (21a) 25b ▷

```
_printdu64bit:
        mov     RAX,RDI
        mov     RDI,RSI
        mov     R8,RDI
        mov     RCX,10
        cld
```

Defines:
`_printdu64bit`, used in chunk 11.

Now we define a label to jump back when we see that there are still more digits to print. Then we test `RAX` for 0 and end the processing of the digits.

25b ⟨*printdu64bit* 25a⟩+≡ (21a) ◁ 25a 25c ▷

```
.next:
        cmp     RAX,0
        je      .done
```

Next we divide `RAX` by `RCX`. For this we have to clear `RDX` because this is the higher value of the dividend. The result is then placed into `RAX` and the remainder into `RDX`.

25c ⟨*printdu64bit* 25a⟩+≡ (21a) ◁ 25b 26a ▷

```
        xor     RDX,RDX
        div     RCX
```

We now exchange the result and the remainder because we now need the remainder in `RAX` (or `AL`) for further processing. Now we can add the ASCII character '0' to AL and have the correct ASCII value in AL. Now we can store the ASCII character to the scratch area.

26a ⟨*printdu64bit* 25a⟩+≡ (21a) ◁25c 26b▷
```
        xchg    RDX,RAX
        add     AL,'0'
        stosb
```

Now we restore `RAX` (which we saved to `RDX`) to go into the next round.

26b ⟨*printdu64bit* 25a⟩+≡ (21a) ◁26a 26c▷
```
        mov     RAX,RDX
        jmp     .next
```

Now that we have all the numbers as ASCII characters we are nearly done. We now have to reverse the number in memory because the number saved at the lowest address is the digit with the least significance.

We now start with checking if we have written any character. If not then we write the ASCII character '0' into the memory. We use the instruction `stosb` for this to adjust the address in `RDI` at the same time.

26c ⟨*printdu64bit* 25a⟩+≡ (21a) ◁26b 26d▷
```
  .done:
        cmp     RDI,RSI
        jne     .printout
        mov     AL,'0'
        stosb
  .printout:
```

Next we calculate the number of digits that the number has. For this we move the address of the last digit to `RDX` and subtract the start of the scratch area from this. Next we adjust `RDI` because it points to the first address after the number.

26d ⟨*printdu64bit* 25a⟩+≡ (21a) ◁26c 27a▷
```
        mov     RDX,RDI
        sub     RDX,RSI
        dec     RDI
```

We now have RSI with the address of the start of the number and RDI with the address of the end. We now have to exchange the digits from the front and the end to get the right number. For this we increment RSI and decrement RDI after each exchange and when the addresses pass each other we are done.

27a ⟨*printdu64bit* 25a⟩+≡ (21a) ◁26d 27b▷

```
.reverse:
    mov     AL,[RSI]
    mov     AH,[RDI]
    mov     [RSI],AH
    mov     [RDI],AL
    dec     RDI
    inc     RSI
    cmp     RSI,RDI
    jb      .reverse
```

Now we restore the address of the scratch area to RSI and move the number of digits (which we stored in RDX) to RDI and can the call _nprint to print the number.

27b ⟨*printdu64bit* 25a⟩+≡ (21a) ◁27a

```
    mov     RSI,R8
    mov     RDI,RDX
    call    _nprint
    ret
```

Uses _nprint 23b.

A Glossary

x86 x86 denotes a microprocessor architecture based on the 8086/8088 22

B Acronyms

ASCII American Standard Code for Information Interchange 26

CR carriage return 10, 11

RNG random number generator 22

C x86-Instructions

`clflush` Flush Cache Line, introduced with Intel® Pentium® 4 10

`lfence` Load Fence, introduced with Intel® Pentium® 4 8, 10

`rdtsc` Read Time Stamp Counter, introduced with Intel® Pentium® 7, 9

D Code Chunks

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suffice to ensure that the continued functioning of the modified object
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