Meltdown and Spectre Samples

Written in Assembly

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Contents

1 Introduction

1.1 Overview

TBD

1.2 Nasm

TBD

5 ⟨*preamble* 5⟩≡ (11a)

```
bits 64
        global          _start
        pagesize        equ  4096
```

Defines:
`_start`, used in chunk 9c.
`pagesize`, used in chunk 9.

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⟩≡ (8)

```
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

8 ⟨*calculate-cache-access-time* 8⟩≡ (11b)

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

Defines:
  `_calccachetime`, used in chunk 10d.

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.

9a ⟨*cachetiming-uninitialized-data* 9a⟩≡ (11a) 9b ▷

```
  section .bss
        align          pagesize
        data:          times 2 resb pagesize
```

Defines:
`data`, used in chunks 9d and 10b.
Uses `pagesize` 5.

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

9b ⟨*cachetiming-uninitialized-data* 9a⟩+≡ (11a) ◁ 9a

```
        scratch:       resb 32
```

Defines:
`scratch`, used in chunk 10e.

The program begins with the label `_start` and is in the section `.text`.

9c ⟨*cachetiming-program* 9c⟩≡ (11a) 9d ▷

```
  section .text
  _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⟩+≡ (11a) ◁ 9c 9e ▷

```
        mov       RDI,data
```

Uses `data` 9a.

Next we load the number of bytes to fill into `RSI`. For this we load the `pagesize` into `RSI` and multiply it with 2 by shifting the value 1 bit to the left.

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

```
        mov       RSI,pagesize
        shl       RSI,1
```

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⟩+≡ (11a) ◁ 9e 10a ▷

```
        rdtsc
        mov       EDX,EAX
```

Now we call _xorshift to fill the data area.

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

```
        call      _xorshift
```

Uses _xorshift 16a.

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.

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

```
        mov       RDI,data
```

Uses data 9a.

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 that we will load the data into a register.

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

```
        clflush   [RDI]
        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.

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

```
        call      _calccachetime
```

Uses _calccachetime 8.

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

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

```
        push      RAX
        mov       RDI,scached
        call      _print
        pop       RDI
        mov       RSI,scratch
        call      _printdu64bit
        mov       RSI,scr
        mov       RDI,1
        call      _nprint
```

Uses _nprint 17b, _print 18a, _printdu64bit 19a, scached 11c, scr 11c, and scratch 9b.

TBD

11a ⟨*cachetiming.asm* 11a⟩≡

```
⟨preamble 5⟩

⟨cachetiming-rodata 11c⟩

⟨cachetiming-uninitialized-data 9a⟩

⟨cachetiming-program 9c⟩
```

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

```
        mov       RDI,suncached
        call      _print
        mov       RSI,scr
        mov       RDI,1
        call      _nprint
⟨exitProgram 15b⟩

⟨calculate-cache-access-time 8⟩

⟨xorshift-prng 16a⟩

⟨utilities 15a⟩
```

Uses _nprint 17b, _print 18a, scr 11c, and suncached 11c.

TBD

11c ⟨*cachetiming-rodata* 11c⟩≡ (11a)

```
section .rodata
        suncached:    db "Uncached Access Time: ",0x00
        scached:      db "Cached Access Time: ",0x00
        scr:          db 0x0a
```

Defines:
scached, used in chunk 10e.
scr, used in chunks 10e and 11b.
suncached, used in chunk 11b.

2.4 Read Array via Cache Access Time

TBD

3 Signals

3.1 Basics

TBD

3.2 Detecting Signals

TBD

3.3 Handling Signals

TBD

4 Utilities

4.1 Introduction

TBD

15a ⟨*utilities* 15a⟩≡ (11b)

⟨*nprint* 17b⟩

⟨*print* 18a⟩

⟨*printdu64bit* 19a⟩

4.2 Exit Program

TBD

15b ⟨*exitProgram* 15b⟩≡ (11b)

```
        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

16a ⟨*xorshift-prng* 16a⟩≡ (11b) 16b ▷

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

Defines:
  `_xorshift`, used in chunk 10a.

Now we can generate the next 32bit random number.

16b ⟨*xorshift-prng* 16a⟩+≡ (11b) ◁ 16a 17a ▷

```
  .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.

17a ⟨*xorshift-prng* 16a⟩+≡ (11b) ◁16b

```
        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`

17b ⟨*nprint* 17b⟩≡ (15a)

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

Defines:
`_nprint`, used in chunks 10e, 11b, 18d, and 21b.

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

18a ⟨*print* 18a⟩≡ (15a) 18b▷
```
  _print:
        cld
        xor        AL,AL
        mov        RSI,RDI
```
Defines:
_print, used in chunks 10e and 11b.

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.

18b ⟨*print* 18a⟩+≡ (15a) ◁18a 18c▷
```
  .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.

18c ⟨*print* 18a⟩+≡ (15a) ◁18b 18d▷
```
        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.

18d ⟨*print* 18a⟩+≡ (15a) ◁18c
```
        call       _nprint
        ret
```
Uses _nprint 17b.

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

19a ⟨*printdu64bit* 19a⟩≡ (15a) 19b▷

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

Defines:
`_printdu64bit`, used in chunk 10e.

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.

19b ⟨*printdu64bit* 19a⟩+≡ (15a) ◁19a 19c▷

```
.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`.

19c ⟨*printdu64bit* 19a⟩+≡ (15a) ◁19b 20a▷

```
        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 American Standard Code for Information Interchange (ASCII) character '0' to AL and have the correct ASCII value in AL. Now we can store the ASCII character to the scratch area.

20a ⟨*printdu64bit* 19a⟩+≡ (15a) ◁19c 20b▷
```
        xchg      RDX,RAX
        add       AL,'0'
        stosb
```

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

20b ⟨*printdu64bit* 19a⟩+≡ (15a) ◁20a 20c▷
```
        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.

20c ⟨*printdu64bit* 19a⟩+≡ (15a) ◁20b 20d▷
```
  .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.

20d ⟨*printdu64bit* 19a⟩+≡ (15a) ◁20c 21a▷
```
        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.

21a ⟨*printdu64bit* 19a⟩+≡ (15a) ◁20d 21b▷

```
 .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.

21b ⟨*printdu64bit* 19a⟩+≡ (15a) ◁21a

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

Uses _nprint 17b.

A Glossary

x86 x86 denotes a microprocessor architecture based on the 8086/8088 16

B Acronyms

ASCII American Standard Code for Information Interchange 20

RNG random number generator 16

C x86-Instructions

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

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

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

D Code Chunks

⟨*cachetiming-program* 9c⟩
⟨*cachetiming-rodata* 11c⟩
⟨*cachetiming-uninitialized-data* 9a⟩
⟨*cachetiming.asm* 11a⟩
⟨*calculate-cache-access-time* 8⟩
⟨*exitProgram* 15b⟩
⟨*nprint* 17b⟩
⟨*preamble* 5⟩
⟨*print* 18a⟩
⟨*printdu64bit* 19a⟩
⟨*tsc-64bit* 7⟩
⟨*utilities* 15a⟩
⟨*xorshift-prng* 16a⟩