Meltdown and Spectre Samples

Written in Assembly

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April 4, 2018

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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⟩≡ (11f 18c 21a 23c 33)

```
bits 64

⟨license 76⟩

        global          _start
        pagesize        equ 4096
```

Defines:
`_start`, used in chunks 9a, 14a, 21b, and 24b.
`pagesize`, used in chunks 8b, 9c, 13, 14c, 16c, 22c, 24a, 27a, and 32.

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

Return

`RAX` the relative time of the cache access

8a ⟨*calculate-cache-access-time* 8a⟩≡ (11f 18c 21a 23c 33)
```
  _calccachetime:
        lfence
  ⟨tsc-64bit 7⟩
        mov       R8,RAX
        mov       RCX,[RDI]
        lfence
  ⟨tsc-64bit 7⟩
        sub       RAX,R8
        ret
```
Defines:
`_calccachetime`, used in chunks 10b, 11b, and 15b.

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 one pages for our data.

8b ⟨*data-udata* 8b⟩≡ (11f 18c 21a 23c 33)
```
        alignb        pagesize
        data:         resb pagesize
```
Defines:
`data`, used in chunks 9, 11b, 14b, 17a, 18a, 22c, 23b, 27a, and 32b.
Uses `pagesize` 5.

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

8c ⟨*scratch-udata* 8c⟩≡ (11f 18c 21a 23c 33)
```
        scratch:      resb 32
```
Defines:
`scratch`, used in chunks 10f, 11d, 17, 18a, 23b, 28c, 29d, and 32d.

The program begins with the label `_start`.

9a ⟨*cachetiming-program* 9a⟩≡ (11f) 9f▷
```
  _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.

9b ⟨*init-random-data* 9b⟩≡ (9f 14a 21b 24b) 9c▷
```
        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`.

9c ⟨*init-random-data* 9b⟩+≡ (9f 14a 21b 24b) ◁9b 9d▷
```
        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.

9d ⟨*init-random-data* 9b⟩+≡ (9f 14a 21b 24b) ◁9c 9e▷
```
        rdtsc
        mov         EDX,EAX
```

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

9e ⟨*init-random-data* 9b⟩+≡ (9f 14a 21b 24b) ◁9d
```
        call        _xorshift
```
Uses `_xorshift` 38a.

Now we add this `data` initialization to our program.

9f ⟨*cachetiming-program* 9a⟩+≡ (11f) ◁9a 9g▷
  ⟨*init-random-data* 9b⟩

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.

9g ⟨*cachetiming-program* 9a⟩+≡ (11f) ◁9f 10a▷
```
        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).

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

```
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.

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

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

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

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

Additionally we define some helper data, in this case line feed (LF).

10d ⟨*common-rodata* 10d⟩≡ (10c 18c 21a 23c 33)

```
slf:            db 0x0a
```

Defines:
`slf`, used in chunks 11, 17, 18a, 23b, 30, and 32d.

Now we can store `RAX` and print the text.

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

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

Uses `_print` 40a and `scached` 10c.

We now restore the value and print the measured time to `stdout`.

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

```
pop       RDI
mov       RSI,scratch
call      _printdu64bit
```

Uses `_printdu64bit` 41a and `scratch` 8c.

At last we append a LF to the output.

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

```
        mov     RSI,slf
        mov     RDI,1
        call    _nprint
```

Uses `_nprint` 39b and `slf` 10d.

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

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

```
        suncached:    db "Uncached Access Time: ",0x00
```

Defines:
`suncached`, used in chunk 11d.

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

```
        push    RAX
        mov     RDI,suncached
        call    _print
        pop     RDI
        mov     RSI,scratch
        call    _printdu64bit
        mov     RSI,slf
        mov     RDI,1
        call    _nprint
```

Uses `_nprint` 39b, `_print` 40a, `_printdu64bit` 41a, `scratch` 8c, `slf` 10d, and `suncached` 11c.

At last we exit the program.

11e ⟨*cachetiming-program* 9a⟩+≡ (11f) ◁11d
⟨*exitProgram* 37b⟩

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

11f ⟨*cachetiming.asm* 11f⟩≡
⟨*preamble* 5⟩

```
section .rodata
⟨cachetiming-rodata 10c⟩

section .bss
⟨data-udata 8b⟩
⟨scratch-udata 8c⟩

section .text
⟨cachetiming-program 9a⟩

⟨calculate-cache-access-time 8a⟩

⟨xorshift-prng 38a⟩

⟨utilities 37a⟩
```

The program source 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.

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

2.4 Read Byte via Cache Access Time

2.4.1 Introduction

We have seen that we can determine if the content of a memory address is in the cache or not (see 2.3 Measure Cache Access Time).

So next we try to read a single byte from the memory by only detecting the cache access time.

2.4.2 Clear Cache for Measurement

Before we can determine the cache access times we need to clear the cache. We define a subroutine for this.

Parameters

`RDI` the address of the probe memory

`RSI` the step size in the probe memory

13a ⟨*clearcache* 13a⟩≡ (18c 21a 23c 33)

```
  _clearcache:
       mov      RCX,256
       cld
  .nextflush:
       clflush  [RDI]
       add      RDI,RSI
       loop     .nextflush
       lfence
       ret
```

Defines:
`_clearcache`, used in chunks 13b, 22a, and 25c.

Now we add this to our program.

13b ⟨*cachereadbyte-program* 13b⟩≡ (18c 21a) 14a ▷

```
       mov      RDI,probe
       mov      RSI,pagesize
       call     _clearcache
```

Uses `_clearcache` 13a, `pagesize` 5, and `probe` 13c.

2.4.3 Indexed Array Access

To read the value of a byte via the cache we use the byte to index into a probe array and then determine the cache access times of this probe array.

For this we will first create a `probe` array.

13c ⟨*probe-udata* 13c⟩≡ (18c 21a 23c 33)

```
       alignb         pagesize
       probe          times 256 resb pagesize
```

Defines:
`probe`, used in chunks 13, 14c, 16c, 22c, and 27a.
Uses `pagesize` 5.

Next we will fill this `probe` array with some random data (similar to the chunks for `data` 9b, 9c, 9d and 9e).

13d ⟨*init-random-probe* 13d⟩≡ (14a 21b 24b)

```
       mov      RDI,probe
       mov      RSI,pagesize
       shl      RSI,8
       rdtsc
       mov      EDX,EAX
       call     _xorshift
```

Uses `_xorshift` 38a, `pagesize` 5, and `probe` 13c.

Now we add the initialization of the `data` and `probe` area to the program.

14a ⟨*cachereadbyte-program* 13b⟩+≡ (18c 21a) ◁13b 14b▷

```
_start:
⟨init-random-data 9b⟩
⟨init-random-probe 13d⟩
```

Uses `_start` 5.

Now we can read a byte from `data` into `AL`.

14b ⟨*cachereadbyte-program* 13b⟩+≡ (18c 21a) ◁14a 14c▷

```
        mov     RDI,data
        xor     RAX,RAX
        mov     AL,[RDI]
```

Uses `data` 8b.

We use the value in RAX to access the probe array.

14c ⟨*cachereadbyte-program* 13b⟩+≡ (18c 21a) ◁14b 16c▷

```
        mov     RDX,pagesize
        mul     RDX
        mov     RSI,probe
        mov     AL,[RSI+RAX]
```

Uses `pagesize` 5 and `probe` 13c.

Now we read the datum back via the cache access times. For this we create subroutines.

2.4.4 Read a Byte from the Cache

First we create a subroutine to read the cache access timings for the probe area.

Parameters

`RDI`	the address of the probe memory
`RSI`	the step size in the probe memory
`RDX`	an area to keep the detected cache access times (256 * 8 bytes)

14d ⟨*readcachetiming* 14d⟩≡ (18c 21a 23c 33) 15a▷

```
_readcachetiming:
⟨enterstackframe 37c⟩
```

Defines:
`_readcachetiming`, used in chunks 16c, 22c, and 26b.

Now we create space on the stack to keep the variables. Next we save the parameters to the stack space created.

15a ⟨*readcachetiming* 14d⟩+≡ (18c 21a 23c 33) ◁14d 15b▷

```
        sub      RSP,32
        mov      [RBP-8],RDI
        mov      [RBP-16],RSI
        mov      [RBP-24],RDX
```

Now we can start detecting the cache access times.

15b ⟨*readcachetiming* 14d⟩+≡ (18c 21a 23c 33) ◁15a 15c▷

```
        mov      RCX,256
  .nextcacheread:
        mov      [RBP-32],RCX
        call     _calccachetime
        mov      RDX,[RBP-24]
        mov      [RDX],RAX
        add      RDX,8
        mov      [RBP-24],RDX
        mov      RDI,[RBP-8]
        add      RDI,[RBP-16]
        mov      [RBP-8],RDI
        mov      RCX,[RBP-32]
        loop     .nextcacheread
```

Uses `_calccachetime` 8a.

At the end we clean up the stack again and return to the caller.

15c ⟨*readcachetiming* 14d⟩+≡ (18c 21a 23c 33) ◁15b

```
  ⟨leavestackframe 37d⟩
        ret
```

After we determined all cache access times we can now find the lowest access time and with this the possible byte. We return two results from this subroutine, in `AL` the byte with the lowest cache access time and in `AH` the count of the lowest cache access time. Only if `AH` is 1 then the value in `AL` is valid.

Parameters

`RDI` the area with the detected cache access times (256 * 8 bytes)

Return

`AL` the read byte (in `AL`) with the lowest cache access time

`AH` the number of bytes read with the lowest cache access time

16a ⟨*analyzecachemintiming* 16a⟩≡ (18c 33)

```
_analyzecachetiming:
        push    RDI
        mov     R8,0xffffffffffffff
        xor     R9,R9
        xor     RCX,RCX
        mov     RSI,RDI
.nexttry:
        lodsq
        cmp     RAX,R8
        ja      .nohit
        mov     R8,RAX
        mov     R9,RCX
.nohit:
        inc     RCX
        cmp     RCX,256
        jb      .nexttry
        xor     RCX,RCX
        pop     RSI
.nextcount:
        lodsq
        cmp     RAX,R8
        ja      .nomin
        inc     R10
.nomin:
        inc     RCX
        cmp     RCX,256
        jb      .nextcount
        mov     RAX,R10
        shl     RAX,8
        mov     AL,R9b
        ret
```

2.4.5 The Whole Program to Read a Byte from Cache

Before we can start using our new subroutine `_readcachetiming` we need to define a data area for the cache access times.

16b ⟨*timings-udata* 16b⟩≡ (18c 21a 23c 33)

```
        timings         resq 256
```

Now we have all subroutines together we now can start implementing the main program and output the byte read.

16c ⟨*cachereadbyte-program* 13b⟩+≡ (18c 21a) ◁14c 17b▷

```
        mov     RDI,probe
        mov     RSI,pagesize
        mov     RDX,timings
        call    _readcachetiming
        mov     RDI,timings
        call    _analyzecachetiming
```

Uses `_readcachetiming` 14d, `pagesize` 5, and `probe` 13c.

Now we define a string to output for the read byte and the expected byte.

17a ⟨*cachereadbyte-rodata* 17a⟩≡ (18c 21a 23c)

```
        sreadbyte:     db "Byte read via cache access:     ",0x00
        ssountbyte:    db "Count of bytes with min timing: ",0x00
        sexpectedbyte: db "Expected byte from data:        ",0x00
```

Uses `data` 8b.

We save the value from `RAX` (only `AL` is interesting to us) to the stack and print out the text.

17b ⟨*cachereadbyte-program* 13b⟩+≡ (18c 21a) ◁16c 17c▷

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

Uses `_print` 40a.

Now we print the read byte and end the line with a LF.

17c ⟨*cachereadbyte-program* 13b⟩+≡ (18c 21a) ◁17b 17d▷

```
        pop     RDI
        push    RDI
        and     RDI,0xff
        mov     RSI,scratch
        call    _printh8bit
        mov     RDI,1
        mov     RSI,slf
        call    _nprint
```

Uses `_nprint` 39b, `_printh8bit` 43b, `scratch` 8c, and `slf` 10d.

Next we print (for information) the number of bytes read with the minimum cache access timing.

17d ⟨*cachereadbyte-program* 13b⟩+≡ (18c 21a) ◁17c 18a▷

```
        mov     RDI,ssountbyte
        call    _print
        pop     RDI
        shr     RDI,8
        and     RDI,0xff
        mov     RSI,scratch
```

```
        call      _printdu64bit
        mov       RDI,1
        mov       RSI,slf
        call      _nprint
```

Uses _nprint 39b, _print 40a, _printdu64bit 41a, scratch 8c, and slf 10d.

Now we read the byte from the original data array and print this also.

18a ⟨*cachereadbyte-program* 13b⟩+≡ (18c 21a) ◁17d 18b▷

```
        mov       RDI,sexpectedbyte
        call      _print
        mov       RSI,data
        xor       RAX,RAX
        mov       AL,[RSI]
        mov       RDI,RAX
        mov       RSI,scratch
        call      _printh8bit
        mov       RDI,1
        mov       RSI,slf
        call      _nprint
```

Uses _nprint 39b, _print 40a, _printh8bit 43b, data 8b, scratch 8c, and slf 10d.

At last we exit the program.

18b ⟨*cachereadbyte-program* 13b⟩+≡ (18c 21a) ◁18a

```
  ⟨exitProgram 37b⟩
```

Now we put all together to get the program `cachereadbyte` that we can execute.

18c ⟨*cachereadbyte.asm* 18c⟩≡

```
  ⟨preamble 5⟩

  section .rodata
  ⟨common-rodata 10d⟩
  ⟨cachereadbyte-rodata 17a⟩

  section .bss
  ⟨data-udata 8b⟩
  ⟨probe-udata 13c⟩
  ⟨scratch-udata 8c⟩
  ⟨timings-udata 16b⟩

  section .text
  ⟨cachereadbyte-program 13b⟩

  ⟨clearcache 13a⟩
```

⟨*calculate-cache-access-time* 8a⟩

⟨*readcachetiming* 14d⟩

⟨*analyzecachemintiming* 16a⟩

⟨*xorshift-prng* 38a⟩

⟨*utilities* 37a⟩

2.4.6 Improve Cache Access Time Analysis

As we can see – when running the program `cachereadbyte` – the result is not always as clear as it could be. Simply getting the lowest cache access time seems not to be enough.

Sample outputs of the program are

```
$ bin/cachereadbyte
Byte read via cache access:     2b
Count of bytes with min timing: 1
Expected byte from data:        2b
$ bin/cachereadbyte
Byte read via cache access:     ff
Count of bytes with min timing: 11
Expected byte from data:        b3
$ bin/cachereadbyte
Byte read via cache access:     2f
Count of bytes with min timing: 1
Expected byte from data:        87
$
```

So we have to improve our cache time detection routine. We will change the implementation of the chunk 16a to define a thrshold that is a little bit above the min access time and run the cache detection routine multiple times if no clear result is returned.

First start with the subrotuine to analyze the cache access timing. We define a threshold 25 % above the minimum cache access time.

First we search for the minimum cache access time.

Parameters

`RDI` the area with the detected cache access times (256 * 8 bytes)

Return

`AL` the first byte (in `AL`) with a cache access time below the threshold

`AH` the number of bytes read with a cache access time below the threshold

20a ⟨*analyzecachesimpthrestiming* 20a⟩≡ (21a 23c) 20b ▷

```
_analyzecachetiming:
      push    RDI
      mov     R8,0xffffffffffffffff
      xor     RCX,RCX
      mov     RSI,RDI
.nextmin:
      lodsq
      cmp     RAX,R8
      ja      .nonewmin
      mov     R8,RAX
.nonewmin:
      inc     RCX
      cmp     RCX,256
      jb      .nextmin
```

Now we have the minimum cache access time in R8. Next we will add $\frac{1}{4}$ to this to have our threshold.

20b ⟨*analyzecachesimpthrestiming* 20a⟩+≡ (21a 23c) ◁ 20a 20c ▷

```
      mov     RAX,R8
      shr     RAX,4
      add     R8,RAX
```

Now we scan the cache access times a second time and take all values below the threshold into account.

20c ⟨*analyzecachesimpthrestiming* 20a⟩+≡ (21a 23c) ◁ 20b

```
      pop     RSI
      xor     RCX,RCX
      xor     R9,R9
.nextbyte:
      lodsq
      cmp     RAX,R8
      ja      .nonewbyte
      inc     R9
      mov     R10,RCX
.nonewbyte:
      inc     RCX
      cmp     RCX,256
      jb      .nextbyte
      mov     RAX,R9
      shl     RAX,8
      mov     AL,R10b
      ret
```

Now we put all together to get the program `cachereadbyte2` that we can execute.

21a ⟨*cachereadbyte2.asm* 21a⟩≡

```
⟨preamble 5⟩

section .rodata
⟨common-rodata 10d⟩
⟨cachereadbyte-rodata 17a⟩

section .bss
⟨data-udata 8b⟩
⟨probe-udata 13c⟩
⟨scratch-udata 8c⟩
⟨timings-udata 16b⟩

section .text
⟨cachereadbyte-program 13b⟩

⟨clearcache 13a⟩

⟨calculate-cache-access-time 8a⟩

⟨readcachetiming 14d⟩

⟨analyzecachesimpthrestiming 20a⟩

⟨xorshift-prng 38a⟩

⟨utilities 37a⟩
```

Now when we only find a single hit then the possibility that the byte from the cache timing is the original byte is much higher.

Next we will create a program that tries to read the value from the cache until we have a single result.

First we initialize our data and probe areas.

21b ⟨*cachereadbyte3-program* 21b⟩≡ (23c) 22c ▷

```
_start:
⟨init-random-data 9b⟩
⟨init-random-probe 13d⟩
```

Uses `_start` 5.

Next we create a subroutine that clears the cache and reads in a byte via the probe array.

Parameters

RDI	the address of the byte to read
RSI	the address of the probe memory
RDX	the step size in the probe memory

22a ⟨*readbyte2cache* 22a⟩≡ (23c) 22b ▷

```
_readbyte2cache:
      push    RDI
      push    RSI
      push    RDX
      mov     RDI,RSI
      mov     RSI,RDX
      call    _clearcache
```

Defines:
`_readbyte2cache`, used in chunk 22c.
Uses `_clearcache` 13a.

Next we can add the read of the byte and caching the data from the probe array.

22b ⟨*readbyte2cache* 22a⟩+≡ (23c) ◁ 22a

```
      pop     RDX
      pop     RSI
      pop     RDI
      xor     RAX,RAX
      mov     AL,[RDI]
      mul     RDX
      mov     AL,[RSI+RAX]
      ret
```

Now we add the call to this subroutine to our program and determine the byte by analyzing the cache access times.

22c ⟨*cachereadbyte3-program* 21b⟩+≡ (23c) ◁ 21b 23a ▷

```
.startreadcache:
      mov     RDI,data
      mov     RSI,probe
      mov     RDX,pagesize
      call    _readbyte2cache
      mov     RDI,probe
      mov     RSI,pagesize
      mov     RDX,timings
      call    _readcachetiming
      mov     RDI,timings
      call    _analyzecachetiming
```

Uses `_readbyte2cache` 22a, `_readcachetiming` 14d, `data` 8b, `pagesize` 5, and `probe` 13c.

Now we check if the read byte was a single byte, else we will do this again.

23a ⟨*cachereadbyte3-program* 21b⟩+≡ (23c) ◁22c 23b▷

```
cmp     AH,1
ja      .startreadcache
```

Now we print out our result.

23b ⟨*cachereadbyte3-program* 21b⟩+≡ (23c) ◁23a

```
push    RAX
mov     RDI,sreadbyte
call    _print
pop     RDI
and     RDI,0xff
mov     RSI,scratch
call    _printh8bit
mov     RDI,1
mov     RSI,slf
call    _nprint
mov     RDI,sexpectedbyte
call    _print
mov     RSI,data
xor     RAX,RAX
mov     AL,[RSI]
mov     RDI,RAX
mov     RSI,scratch
call    _printh8bit
mov     RDI,1
mov     RSI,slf
call    _nprint
```

⟨*exitProgram* 37b⟩

Uses `_nprint` 39b, `_print` 40a, `_printh8bit` 43b, `data` 8b, `scratch` 8c, and `slf` 10d.

23c ⟨*cachereadbyte3.asm* 23c⟩≡

⟨*preamble* 5⟩

```
section .rodata
```

⟨*common-rodata* 10d⟩
⟨*cachereadbyte-rodata* 17a⟩

```
section .bss
```

⟨*data-udata* 8b⟩
⟨*probe-udata* 13c⟩
⟨*scratch-udata* 8c⟩
⟨*timings-udata* 16b⟩

```
section .text
⟨cachereadbyte3-program 21b⟩

⟨readbyte2cache 22a⟩

⟨clearcache 13a⟩

⟨calculate-cache-access-time 8a⟩

⟨readcachetiming 14d⟩

⟨analyzecachesimpthrestiming 20a⟩

⟨xorshift-prng 38a⟩

⟨utilities 37a⟩
```

Even if this program is not perfect because it is not reliable all the time it is reliable enough to demonstrate the next steps.

2.5 Read Array via Cache Access Time

2.5.1 Introduction

Now we have read a byte via the cache access times. Now it is time to read a complete memory area.

2.5.2 Setup

For this we use the `data` defined before and read in the complete area. For this we need additionally a memory area that holds the read data.

24a ⟨*readback-udata* 24a⟩≡ (33)

```
        alignb          pagesize
        readbackdata    resb pagesize
```

Defines:
`readbackdata`, used in chunks 27a and 32b.
Uses `pagesize` 5.

First we initialize the `data` and `probe` areas in our program with some random data.

24b ⟨*cacheread-program* 24b⟩≡ (33) 27a ▷

```
_start:
⟨init-random-data 9b⟩
⟨init-random-probe 13d⟩
```

Uses `_start` 5.

Next we will define a subroutine that reads the `data` area and writes the results of the cache read into `readbackdata`.

Parameters

`RDI` the address of the data memory

`RSI` the size of the data memory

`RDX` the address of the probe memory

`RCX` the step size in the probe memory (the probe area needs to be at least 256 * RCX bytes in size)

`R8` the address of the readback area (must be at least the same size as the data area)

`R9` the address of the the area to keep the timing data (at least 256 * 8 bytes)

25a ⟨*readarea* 25a⟩≡ (33) 25b ▷

```
_readarea:
```

Defines:
`_readarea`, used in chunk 27a.

Now we create some place on the stack and store the parameters on it. We reserve an extra place at `[RBP-56]` for a counter into the data memory.

25b ⟨*readarea* 25a⟩+≡ (33) ◁ 25a 25c ▷

```
⟨enterstackframe 37c⟩
      sub       RSP,56
      mov       [RBP-8],RDI
      mov       [RBP-16],RSI
      mov       [RBP-24],RDX
      mov       [RBP-32],RCX
      mov       [RBP-40],R8
      mov       [RBP-48],R9
      xor       RAX,RAX
      mov       [RBP-56],RAX
```

First we have to clear the cache before we can measure any cache access times.

25c ⟨*readarea* 25a⟩+≡ (33) ◁ 25b 26a ▷

```
.startread:
      mov       RDI,[RBP-24]
      mov       RSI,[RBP-32]
      call      _clearcache
```

Uses `_clearcache` 13a.

Now we can load the byte from the memory and cache the according value from the `probe` memory.

26a ⟨*readarea* 25a⟩+≡ (33) ◁25c 26b▷

```
        mov     RSI,[RBP-8]
        add     RSI,[RBP-56]
        xor     RAX,RAX
        mov     AL,[RSI]
        mov     RDX,[RBP-32]
        mul     RDX
        mov     RSI,[RBP-24]
        mov     AL,[RSI+RAX]
```

Now that we have filled our cache we can determine the cache access times.

26b ⟨*readarea* 25a⟩+≡ (33) ◁26a 26c▷

```
        mov     RDI,[RBP-24]
        mov     RSI,[RBP-32]
        mov     RDX,[RBP-48]
        call    _readcachetiming
```

Uses `_readcachetiming` 14d.

Now we can analyze the cache access times.

26c ⟨*readarea* 25a⟩+≡ (33) ◁26b 26d▷

```
        mov     RDI,[RBP-48]
        call    _analyzecachetiming
```

If we have more than 1 hit then we retry the reading of the byte.

26d ⟨*readarea* 25a⟩+≡ (33) ◁26c 26e▷

```
        cmp     AH,1
        ja      .startread
```

Now that we found a byte we store it in the resulting memory area.

26e ⟨*readarea* 25a⟩+≡ (33) ◁26d 26f▷

```
        mov     RDI,[RBP-40]
        mov     RCX,[RBP-56]
        add     RDI,RCX
        mov     [RDI],AL
        inc     RCX
        mov     [RBP-56],RCX
        cmp     RCX,[RBP-16]
        jb      .startread
```

Now we clean up the stack frame and return to the caller.

26f ⟨*readarea* 25a⟩+≡ (33) ◁26e

```
    ⟨leavestackframe 37d⟩
        ret
```

Now we can add this to our program and read the area.

27a ⟨*cacheread-program* 24b⟩+≡ (33) ◁24b 32b▷

```
        mov     RDI,data
        mov     RSI,pagesize
        mov     RDX,probe
        mov     RCX,pagesize
        mov     R8,readbackdata
        mov     R9,timings
        call    _readarea
```

Uses `_readarea` 25a, `data` 8b, `pagesize` 5, `probe` 13c, and `readbackdata` 24a.

Now we want to display the results. This means we need a routine that displays the original `data` and the `readbackdata` side by side. Additionally we want to highlight the value from the `readbackdata` if it differs from the original data.

So start with defining some highlighting and some usefull helper strings.

27b ⟨*cacheread-rodata* 27b⟩≡ (33) 32c▷

```
        sbgred:         db 0x1b,"[1;41m",0x00
        sresetstyle:    db 0x1b,"[0m",0x00
        sseparator:     db "- ",0x00
        sblank:         db " "
        semptybyte:     db "    ",0x00
```

Defines:
- `sbgred`, used in chunk 29d.
- `sblank`, used in chunks 28c and 29d.
- `semptybyte`, used in chunk 29a.
- `sresetstyle`, used in chunks 29d and 30.
- `sseparator`, used in chunk 29b.

Next we define a subroutine which prints out up to 16 bytes each side by side on the screen. If two bytes in the arrays are different then the value at the right side (from the second array) will be printed with red background. The routine should also return the number of values that are different in both areas.

Parameters

`RDI`	the address of the first array
`RSI`	the address of the second array
`RDX`	number of bytes to print (up to 16). If the value is above 16 then only 16 values are printed

Return

`RAX`	number of bytes that differ between both memory areas

28a ⟨*print-comparision16* 28a⟩≡ (33) 28b▷

```
  _printcompare16:
```

Defines:
`_printcompare16`, used in chunk 31b.

At the start of the subroutine we prepare a stack frame for further operations as we will need to save and restore the registers `RDI`, `RSI`, `RDX` and `RCX` multiple times. Additionally we store `R12` and `R13` to the stack to use this registers as scratch registers.

28b ⟨*print-comparision16* 28a⟩+≡ (33) ◁28a 28c▷

```
  ⟨enterstackframe 37c⟩
        sub       RSP,32
        mov       [RBP-8],RDI
        mov       [RBP-16],RSI
        cmp       RDX,0x10
        jb        .valueok
        mov       RDX,0x10
  .valueok:
        mov       [RBP-24],RDX
        push      R12
        push      R13
        xor       R13,R13
```

Next we can start and handle the "left" side of the output. We output up to 16 bytes and then continue at `.leftbytesdone` (29a).

28c ⟨*print-comparision16* 28a⟩+≡ (33) ◁28b 29a▷

```
        xor       RCX,RCX
  .nextbyteleft:
        cmp       RCX,RDX
        mov       [RBP-32],RCX
        jae       .leftbytesdone
        mov       AL,[RDI+RCX]
        xor       AH,AH
        mov       DI,AX
        mov       RSI,scratch
        call      _printh8bit
        mov       RDI,1
        mov       RSI,sblank
        call      _nprint
        mov       RDI,[RBP-8]
        mov       RDX,[RBP-24]
        mov       RCX,[RBP-32]
        inc       RCX
        jmp       .nextbyteleft
  .leftbytesdone:
```

Uses `_nprint` 39b, `_printh8bit` 43b, `sblank` 27b, and `scratch` 8c.

Now we fill up the space so that the space of 16 bytes is occupied.

29a ⟨*print-comparision16* 28a⟩+≡ (33) ◁28c 29b▷

```
.leftemptybyte:
      cmp       RCX,0x10
      jae       .leftdone
      mov       RDI,semptybyte
      call      _print
      inc       RCX
      jmp       .leftemptybyte
.leftdone:
```

Uses `_print` 40a and `semptybyte` 27b.

Next we print out the separator between the two compare block.

29b ⟨*print-comparision16* 28a⟩+≡ (33) ◁29a 29c▷

```
      mov       RDI,sseparator
      call      _print
```

Uses `_print` 40a and `sseparator` 27b.

To print the second half (for comparision) we restore the values of the parameters first.

29c ⟨*print-comparision16* 28a⟩+≡ (33) ◁29b 29d▷

```
      mov       RDI,[RBP-8]
      mov       RSI,[RBP-16]
      mov       RDX,[RBP-24]
```

Now we compare each byte with the original value first and then print it out. If the value differs from the original value we additionally mark the byte.

29d ⟨*print-comparision16* 28a⟩+≡ (33) ◁29c 30▷

```
      xor       RCX,RCX
.nextbyteright:
      mov       [RBP-32],RCX
      cmp       RCX,RDX
      jae       .rightbytesdone
      mov       AL,[RSI+RCX]
      mov       AH,[RDI+RCX]
      mov       R12W,AX
      cmp       AH,AL
      je        .printplain
      inc       R13
      mov       RDI,sbgred
      call      _print
.printplain:
      xor       RDI,RDI
      mov       AX,R12W
```

```
        xor     AH,AH
        mov     DI,AX
        mov     RSI,scratch
        call    _printh8bit
        mov     AX,R12W
        cmp     AH,AL
        je      .printdone
        mov     RDI,sresetstyle
        call    _print
  .printdone:
        mov     RDI,1
        mov     RSI,sblank
        call    _nprint
        mov     RDI,[RBP-8]
        mov     RSI,[RBP-16]
        mov     RDX,[RBP-24]
        mov     RCX,[RBP-32]
        inc     RCX
        jmp     .nextbyteright
  .rightbytesdone:
```

Uses _nprint 39b, _print 40a, _printh8bit 43b, sbgred 27b, sblank 27b, scratch 8c, and sresetstyle 27b.

Now we fill up the place up to 16 bytes on the right side.

30 ⟨*print-comparision16* 28a⟩+≡ (33) ◁29d

```
  .rightemptybyte:
        cmp     RCX,0x10
        jae     .rightdone
        inc     RCX
        jmp     .rightemptybyte
  .rightdone:
        mov     RDI,sresetstyle
        call    _print
        mov     RDI,1
        mov     RSI,slf
        call    _nprint
        mov     RAX,R13
        pop     R13
        pop     R12
  ⟨leavestackframe 37d⟩
        ret
```

Uses _nprint 39b, _print 40a, slf 10d, and sresetstyle 27b.

Now that we can print 16 bytes in a line we simply divide the requested number of bytes into 16 bytes chunks and output them.

First we set up the stack frame and save R12 to the stack to use it as scratch register.

Parameters

RDI	the address of the first array
RSI	the address of the second array
RDX	number of bytes to print

Return

RAX	number of bytes that differ between both memory areas

31a ⟨*print-comparision* 31a⟩≡ (33) 31b ▷

```
_printcompare:
⟨enterstackframe 37c⟩
      sub      RSP,40
      mov      [RBP-8],RDI
      mov      [RBP-16],RSI
      mov      [RBP-24],RDX
      push     R12
      xor      R12,R12
```

Defines:
`_printcompare`, used in chunk 32b.

So first we calculate how many 16 bytes chunks there are. For each chunk with 16 bytes we will print out a line.

31b ⟨*print-comparision* 31a⟩+≡ (33) ◁ 31a 32a ▷

```
      shr      RDX,4
      mov      [RBP-32],RDX
      xor      RCX,RCX
.nextline:
      mov      [RBP-40],RCX
      cmp      RCX,[RBP-32]
      jae      .linesdone
      mov      RAX,RCX
      shl      RAX,4
      mov      RDI,[RBP-8]
      add      RDI,RAX
      mov      RSI,[RBP-16]
      add      RSI,RAX
      mov      RDX,0x10
      call     _printcompare16
      add      R12,RAX
      mov      RCX,[RBP-40]
```

```
        inc       RCX
        jmp       .nextline
  .linesdone:
```
Uses _printcompare16 28a.

32a ⟨*print-comparision* 31a⟩+≡ (33) ◁31b
```
        mov       RAX,R12
        pop       R12
  ⟨leavestackframe 37d⟩
        ret
```

Now we can print the complete memory compare.

32b ⟨*cacheread-program* 24b⟩+≡ (33) ◁27a 32d▷
```
        mov       RDI,data
        mov       RSI,readbackdata
        mov       RDX,pagesize
        call      _printcompare
```
Uses _printcompare 31a, data 8b, pagesize 5, and readbackdata 24a.

Now we will print some statistics and then leave the program.

32c ⟨*cacheread-rodata* 27b⟩+≡ (33) ◁27b
```
        sstatistics:   db "Failed read relation: ",0x00
        sper:          db "/"
```
Defines:
  sper, used in chunk 32d.
  sstatistics, used in chunk 32d.

32d ⟨*cacheread-program* 24b⟩+≡ (33) ◁32b
```
        push      RAX
        mov       RDI,sstatistics
        call      _print
        pop       RDI
        mov       RSI,scratch
        call      _printdu64bit
        mov       RDI,1
        mov       RSI,sper
        call      _nprint
        mov       RDI,pagesize
        mov       RSI,scratch
        call      _printdu64bit
        mov       RDI,1
        mov       RSI,slf
        call      _nprint
  ⟨exitProgram 37b⟩
```
Uses _nprint 39b, _print 40a, _printdu64bit 41a, pagesize 5, scratch 8c, slf 10d, sper 32c, and sstatistics 32c.

Now we can put all together and create the program `cacheread.asm`.

33 ⟨*cacheread.asm* 33⟩≡
```
⟨preamble 5⟩

section .rodata
⟨common-rodata 10d⟩
⟨cacheread-rodata 27b⟩

section .bss
⟨data-udata 8b⟩
⟨probe-udata 13c⟩
⟨readback-udata 24a⟩
⟨timings-udata 16b⟩
⟨scratch-udata 8c⟩

section .text
⟨cacheread-program 24b⟩

⟨clearcache 13a⟩

⟨calculate-cache-access-time 8a⟩

⟨readcachetiming 14d⟩

⟨analyzecachemintiming 16a⟩

⟨readarea 25a⟩

⟨print-comparision 31a⟩

⟨print-comparision16 28a⟩

⟨xorshift-prng 38a⟩

⟨utilities 37a⟩
```

Now we have created a program that reads a complete memory area via the covert channel. When executing the pogram an output like the following should occur. In the example additionally `time` is used to get some timing in the end. We have approx. 13 % errors while read (in the example), which we will accept at this point. This rate also differs depending on the processor and the load of the computer. In the following output the arrays are omitted.

```
$ time bin/cacheread
```

```
[snip]
Failed read relation: 543/4096

real    0m16.653s
user    0m16.510s
sys     0m0.032s
$
```

3 Signals

3.1 Basics

TBD

3.2 Detecting Signals

TBD

3.3 Handling Signals

TBD

4 Utilities

4.1 Introduction

TBD

37a ⟨*utilities* 37a⟩≡ (11f 18c 21a 23c 33)
⟨*nprint* 39b⟩

⟨*print* 40a⟩

⟨*printdu64bit* 41a⟩

⟨*printh8bit* 43b⟩

4.2 Common Chunks

4.2.1 Exit Program

This chunk ends the program with exit code 0.

37b ⟨*exitProgram* 37b⟩≡ (11e 18b 23b 32d)

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

4.2.2 Stack Frame

A chunk to create a stack frame.

37c ⟨*enterstackframe* 37c⟩≡ (14d 25b 28b 31a)

```
        push    RBP
        mov     RBP,RSP
```

A chunk to clean up the created stack frame.

37d ⟨*leavestackframe* 37d⟩≡ (15c 26f 30 32a)

```
        mov     RSP,RBP
        pop     RBP
```

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

38a ⟨*xorshift-prng* 38a⟩≡ (11f 18c 21a 23c 33) 38b▷

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

Defines:
_xorshift, used in chunks 9e and 13d.

Now we can generate the next 32bit random number.

38b ⟨*xorshift-prng* 38a⟩+≡ (11f 18c 21a 23c 33) ◁38a 39a▷

```
.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.

39a ⟨*xorshift-prng* 38a⟩+≡ (11f 18c 21a 23c 33) ◁38b

```
        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

39b ⟨*nprint* 39b⟩≡ (37a)

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

Defines:
_nprint, used in chunks 11, 17, 18a, 23b, 28–30, 32d, 40d, 43a, and 44a.

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`

40a ⟨*print* 40a⟩≡ (37a) 40b ▷

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

Defines:
`_print`, used in chunks 10e, 11d, 17, 18a, 23b, 29, 30, and 32d.

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.

40b ⟨*print* 40a⟩+≡ (37a) ◁ 40a 40c ▷

```
.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.

40c ⟨*print* 40a⟩+≡ (37a) ◁ 40b 40d ▷

```
      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`.

40d ⟨*print* 40a⟩+≡ (37a) ◁ 40c

```
      call      _nprint
      ret
```

Uses `_nprint` 39b.

4.5 Printing Numbers

4.5.1 Printing a Decimal 64bit Unsigned Integer

The routine `_printdu64bit` prints a given 64bit integer as unsigned decimal number 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

41a ⟨*printdu64bit* 41a⟩≡ (37a) 41b ▷

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

Defines:
_printdu64bit, used in chunks 10f, 11d, 17d, and 32d.

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.

41b ⟨*printdu64bit* 41a⟩+≡ (37a) ◁ 41a 41c ▷

```
.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.

41c ⟨*printdu64bit* 41a⟩+≡ (37a) ◁ 41b 41d ▷

```
        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.

41d ⟨*printdu64bit* 41a⟩+≡ (37a) ◁ 41c 42a ▷

```
        xchg    RDX,RAX
        add     AL,'0'
        stosb
```

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

42a ⟨*printdu64bit* 41a⟩+≡ (37a) ◁41d 42b▷

```
        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.

42b ⟨*printdu64bit* 41a⟩+≡ (37a) ◁42a 42c▷

```
  .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.

42c ⟨*printdu64bit* 41a⟩+≡ (37a) ◁42b 42d▷

```
        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.

42d ⟨*printdu64bit* 41a⟩+≡ (37a) ◁42c 43a▷

```
  .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.

43a ⟨*printdu64bit* 41a⟩+≡ (37a) ◁42d

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

Uses _nprint 39b.

4.5.2 Printing a Hexadecimal 8bit Integer

The routine _printh8bit prints a given 8bit integer as hexadecimal number to stdout.

To print a hexadecimal number we mask a nibble (4bit) and have the number to print.

First we clear the register RAX and move the number to AX for further processing and clear the higher 8bit (AH). Additionally we move it to R8 for later restore.

Additionally we need the address of the scratch area in RDI for storing the result.

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

Parameters

DI the number number to print to stdout. Only the lower 8bit are used.

RSI the address of a scratch area with a size of at least 2 bytes

43b ⟨*printh8bit* 43b⟩≡ (37a) 43c▷

```
_printh8bit:
    xor     RAX,RAX
    mov     AX,DI
    xor     AH,AH
    mov     R8,RAX
    mov     RDI,RSI
    cld
```

Defines:
_printh8bit, used in chunks 17c, 18a, 23b, 28c, and 29d.

Now we mask the higher 4 bit of AL by shifting it 4 bits to the right and mask out all but the lower 4 bit. Next we call the internal method printh8bit.printh4bit to print out this nibble.

43c ⟨*printh8bit* 43b⟩+≡ (37a) ◁43b 44a▷

```
shr     AL,4
and     AL,0x0f
call    .printh4bit
```

Next we restore the number and print out the lower 4 bits.

44a ⟨*printh8bit* 43b⟩+≡ (37a) ◁43c

```
        mov     RAX,R8
        and     AL,0x0f
        call    .printh4bit
        mov     RDI,2
        call    _nprint
        ret
  ⟨printh8bit.printh4bit 44b⟩
```

Uses `_nprint` 39b.

Now we define the internal method to print a hexadecimal digit.

First we test if the digit is above or equal to 10. In this case we have to print out a character between `'a'` and `'f'` else we print out a decimal digit (between `'0'` and `'9'`).

Parameters (internal)

`AL` the lower 4 bit contain the hexadecimal digit print to `stdout`

`RDI` the address of a scratch area

44b ⟨*printh8bit.printh4bit* 44b⟩≡ (44a) 44c▷

```
  .printh4bit:
        cmp     AL,10
        jae     .printa2f
```

Defines:
`printh8bit.printh4bit`, never used.

Now we add `'0'` to get the code for the digit between `'0'` and `'9'`.

44c ⟨*printh8bit.printh4bit* 44b⟩+≡ (44a) ◁44b 44d▷

```
        add     AL,'0'
        jmp     .printout
```

Else we print a digit between `'a'` and `'f'`. We first subtract 10 because the value in `AL` is now between 10 and 15.

44d ⟨*printh8bit.printh4bit* 44b⟩+≡ (44a) ◁44c 44e▷

```
  .printa2f:
        sub     AL,10
        add     AL,'a'
```

Now we store the character into the storage area.

44e ⟨*printh8bit.printh4bit* 44b⟩+≡ (44a) ◁44d

```
  .printout:
        stosb
        ret
```

A Glossary

x86 x86 denotes a microprocessor architecture based on the 8086/8088 38

B Acronyms

ASCII American Standard Code for Information Interchange 41, 42

LF line feed 10, 11, 17

RNG random number generator 38

C x86-Instructions

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

`lfence` Load Fence, introduced with Intel® Pentium® 4 7, 10

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

D Code Chunks

⟨*analyzecachemintiming* 16a⟩
⟨*analyzecachesimpthrestiming* 20a⟩
⟨*cacheread-program* 24b⟩
⟨*cacheread-rodata* 27b⟩
⟨*cacheread.asm* 33⟩
⟨*cachereadbyte-program* 13b⟩
⟨*cachereadbyte-rodata* 17a⟩
⟨*cachereadbyte.asm* 18c⟩
⟨*cachereadbyte2.asm* 21a⟩
⟨*cachereadbyte3-program* 21b⟩
⟨*cachereadbyte3.asm* 23c⟩
⟨*cachetiming-program* 9a⟩
⟨*cachetiming-rodata* 10c⟩
⟨*cachetiming.asm* 11f⟩
⟨*calculate-cache-access-time* 8a⟩
⟨*clearcache* 13a⟩
⟨*common-rodata* 10d⟩
⟨*data-udata* 8b⟩
⟨*enterstackframe* 37c⟩
⟨*exitProgram* 37b⟩
⟨*init-random-data* 9b⟩
⟨*init-random-probe* 13d⟩
⟨*leavestackframe* 37d⟩
⟨*license* 76⟩
⟨*nprint* 39b⟩
⟨*preamble* 5⟩
⟨*print* 40a⟩
⟨*print-comparision* 31a⟩
⟨*print-comparision16* 28a⟩
⟨*printdu64bit* 41a⟩
⟨*printh8bit* 43b⟩
⟨*printh8bit.printh4bit* 44b⟩
⟨*probe-udata* 13c⟩
⟨*readarea* 25a⟩
⟨*readback-udata* 24a⟩
⟨*readbyte2cache* 22a⟩
⟨*readcachetiming* 14d⟩

⟨*scratch-udata* 8c⟩
⟨*timings-udata* 16b⟩
⟨*tsc-64bit* 7⟩
⟨*utilities* 37a⟩
⟨*xorshift-prng* 38a⟩

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```

E.2.2 Code Chunk of GPL

This is a code chunk to be included by the generated asm files.

76 ⟨*license* 76⟩≡ (5)

```
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