

Meltdown and Spectre Samples

Written in Assembly

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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 suffices.

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 23)
`bits 64`

`<license 68>`

```
global      _start
pagesize    equ 4096
```

Defines:

`_start`, used in chunks 9c and 13a.
`pagesize`, used in chunks 8, 9, 13, 14, 17–19, and 23.

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 $\langle tsc-64bit \ 7 \rangle \equiv$ (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 23)
    _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 one pages for our data.

```
8b  <cache-data 8b>≡ (9b 23)
    data:          resb pagesize
```

Defines:

`data`, used in chunks 9–11, 13a, 14b, 18b, 22b, and 23.

Uses `pagesize` 5.

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

9a $\langle scratch-udata\ 9a \rangle \equiv$ (9b)
`scratch: resb 32`

Defines:

`scratch`, used in chunk 11.

9b $\langle cachetiming-udata\ 9b \rangle \equiv$ (12)
`align pagesize`
 $\langle cache-data\ 8b \rangle$
 $\langle scratch-udata\ 9a \rangle$

Uses `pagesize` 5.

The program begins with the label `_start`.

9c $\langle cachetiming-program\ 9c \rangle \equiv$ (12) 9d \triangleright
`_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 $\langle cachetiming-program\ 9c \rangle + \equiv$ (12) $\langle 9c\ 9e \rangle$
`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 $\langle cachetiming-program\ 9c \rangle + \equiv$ (12) $\langle 9d\ 9f \rangle$
`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 $\langle cachetiming-program\ 9c \rangle + \equiv$ (12) $\langle 9e\ 9g \rangle$
`rdtsc`
`mov EDX, EAX`

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

9g $\langle cachetiming-program\ 9c \rangle + \equiv$ (12) $\langle 9f\ 10a \rangle$
`call _xorshift`

Uses `_xorshift` 28a.

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 10f>
      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.

```
10d  <cachetiming-rodata 10d>≡ (12) 11c>
      <common-rodata 10e>
      scached:      db "Cached Access Time: ",0x00
Defines:
      scached, used in chunk 10f.
```

Additionally we define some helper data, in this case `carriage return (CR)`.

```
10e  <common-rodata 10e>≡ (10d 19d)
      scr:          db 0x0a
Defines:
      scr, used in chunks 11 and 21.
```

Now we can print the text.

```
10f  <cachetiming-program 9c>+≡ (12) <10c 11a>
      push     RAX
      mov      RDI,scached
      call     _print
Uses _print 30a and scached 10d.
```

2.3 Measure Cache Access Time

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) <10f 11b>
 `pop RDI`
 `mov RSI,scratch`
 `call _printdu64bit`
 `mov RSI,scr`
 `mov RDI,1`
 `call _nprint`

Uses `_nprint 29b`, `_printdu64bit 31a`, `scr 10e`, 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 29b`, `_print 30a`, `_printdu64bit 31a`, `scr 10e`, `scratch 9a`, and `suncached 11c`.

At last we exit the program.

11e `<cachetiming-program 9c>+≡` (12) <11d
 `<exitProgram 27b>`

2 Cache Access Timing

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 28a>  
  
    <utilities 27a>
```

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>≡ (23) 14a>
    _start:
        mov     RDI,data
        mov     RSI,pagesize
        rdtsc
        mov     EDX,EAX
        call    _xorshift
```

Uses `_start` [5](#), `_xorshift` [28a](#), `data` [8b](#), and `pagesize` [5](#).

Next we will create a probe area that is $256 * \text{pagesize}$. 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>≡ (23) 17b>
    probe:      times 256 resb pagesize
```

Defines:

`probe`, used in chunks [14](#) and [18](#).

Uses `pagesize` [5](#).

2 Cache Access Timing

Next we fill this area also with some random data.

```
14a  <cacheread-program 13a>+≡ (23) <13a 19c>
      mov     RDI,probe
      mov     RAX,pagesize
      mov     RCX,256
      mul     RCX
      mov     RSI,RCX
      rdtsc
      mov     EDX,EAX
      call    _xorshift
```

Uses `_xorshift` 28a, `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 $256 * \text{pagesize}$ 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 arbitrary value (we use `pagesize`) and then 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 $\langle \text{clear-cache 15} \rangle \equiv$ (23)
 `_clearcache:`
 `cld`
 `mov RCX,256`
 `xor RAX,RAX`
 `.clear_next:`
 `clflush [RDI+RAX]`
 `add RAX,RSI`
 `loop .clear_next`
 `lfence`
 `ret`

Defines:

`_clearcache`, used in chunk 18a.

2 Cache Access Timing

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 `_clearcache` 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 $\langle \text{detect-cache-area-time } 16 \rangle \equiv$ (23)

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

Defines:

`_calcareacachetime`, used in chunk 17a.

Uses `_calccachetime` 8a.

We now can determine the cache line with the lowest access time. This is the cache line that was cached before.

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

Return

RAX the byte (in AL) which is found by cache timing analysis

TBD

17a $\langle \text{detect-byte 17a} \rangle \equiv$ (23)

```

_detectbytebycl:
    push    RDI
    call    _calcareacachetime
    pop     RDI
    mov     RSI, RDX
    xor     RCX, RCX
    mov     R8, 0xffffffffffffffff
    xor     R9, R9
.nextbyte:
    mov     RAX, [RDI+8*RCX]
    cmp     RAX, R8
    jb      .foundbyte
    inc     RCX
    cmp     RCX, 256
    jae     .done
.foundbyte:
    mov     R8, RAX
    mov     R9, RCX
    jmp     .nextbyte
.done:
    mov     RAX, R9
    ret

```

Uses `_calcareacachetime` 16.

Now we need some area to store all the data. Once we use an area for the timing data and another area for the read memory data.

17b $\langle \text{cacheread-udata 13b} \rangle + \equiv$ (23) <13b

```

    result:      resb    pagesize
    timing:      resq    256

```

Uses `pagesize` 5.

Now we have the base for reading a complete memory area via a cache covert channel.

We now create a subroutine to loop over the memory we want to read and read the values back via the cache access time.

First we create a area where we can store the read bytes.

17c $\langle \text{readback-udata 17c} \rangle \equiv$ (23)

```

    readback:    align    pagesize, resb    pagesize

```

Defines:

`readback`, used in chunk 22b.

Uses `pagesize` 5.

2 Cache Access Timing

Now we create the subroutine that reads the bytes from the source array `data` and writes the results from the cache access time into `readback`.

First we setup a counter in `R8` and clear the cache.

```
18a  <cache-readback 18a>≡ (23) 18b>
      _cachereadback:
          xor        R8,R8
      .nextbyte:
          push       R8
          mov        RDI,probe
          mov        RSI,pagesize
          call       _clearcache
          pop        R8
```

Defines:

`_cachereadback`, used in chunk 19c.

Uses `_clearcache` 15, `pagesize` 5, and `probe` 13b.

Next we read in the data from the array.

```
18b  <cache-readback 18a>+≡ (23) <18a 18c>
          mov        RSI,data
          xor        RAX,RAX
          mov        AL,[RSI+R8]
```

Uses `data` 8b.

Next we use the read byte to index into our probe array.

```
18c  <cache-readback 18a>+≡ (23) <18b 18d>
          mov        RDX,pagesize
          mul        RDX
          mov        RSI,probe
          mov        AL,[RSI+RAX]
```

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

Now we have put data into the cache that depends on the value read from `data`. Next we will read the cache access times to determine the data read.

```
18d  <cache-readback 18a>+≡ (23) <18c 19a>
          mov        RDI,probe
          mov        RSI,pagesize
          mov        RDX,timing
          push       R8
          call       _detectbytebycl
          pop        R8
```

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

Next we store the read byte into our result array.

```
19a  <cache-readback 18a>+≡ (23) <18d 19b>
      mov     RDI,result
      mov     [RDI+R8],AL
```

Now we can increment our counter and check if there are more bytes to read. If no more bytes need to be read we leave our subroutine.

```
19b  <cache-readback 18a>+≡ (23) <19a
      inc     R8
      cmp     R8,pagesize
      jb      .nextbyte
      ret
```

Uses `pagesize` 5.

After all we can now call this new subroutine and read our data by detecting the cache access times.

```
19c  <cacheread-program 13a>+≡ (23) <14a 22b>
      call    _cachereadback
      Uses _cachereadback 18a.
```

2.4.4 Printing the Results

Now we want to see the results so we now read a byte from the origin (`data`) and from our read back data (`readback`).

First we define some helpful data for colorizing the output.

```
19d  <cacheread-rodata 19d>≡ (23)
      <common-rodata 10e>
      sbgred:      db 0x1b,"[1;41m",0x00
      sresetstyle: db 0x1b,"[0m",0x00
      sblank:      db " - ",0x00
```

Defines:

`sbgred`, never used.

`sresetstyle`, never used.

2 Cache Access Timing

First 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 read background.

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 nothing is printed out

20a $\langle \text{print-comparision16 } 20a \rangle \equiv$ (23) 20b \triangleright
 `_printcompare16:`
 Uses `_printcompare16` 21.

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

20b $\langle \text{print-comparision16 } 20a \rangle + \equiv$ (23) $\triangleleft 20a \ 20c \triangleright$
 `push RBP`
 `mov RBP,RSP`
 `sub RSP,32`
 `mov [RBP-8],RDI`
 `mov [RBP-16],RSI`
 `mov [RBP-24],RDX`

Next we can start and handle the "left" side of the output. We output up to 16 bytes and the continue at `.leftbytesdone` (21).

20c $\langle \text{print-comparision16 } 20a \rangle + \equiv$ (23) $\triangleleft 20b \ 21 \triangleright$
 `cmp RDX,0x10`
 `ja .done`
 `xor RCX,RCX`
 `.nextbyteleft:`
 `cmp RCX,RDX`
 `jb .leftbytesdone`
 `inc RCX`
 `jmp .nextbyteleft`

21 $\langle \text{print-comparison16 } 20a \rangle + \equiv$ (23) $\triangleleft 20c$

```

.leftbytesdone:
    cmp     RCX,0x10
    jb      .leftdone
    inc     RCX
    jmp     .leftbytesdone
.leftdone:
    mov     RDI,sblank
    call    _print
    mov     RDX,[RBP-24]
    xor     RCX,RCX
.nextbyteright:
    cmp     RCX,RDX
    jb      .rightbytesdone
    inc     RCX
    jmp     .nextbyteright
.rightbytesdone:
    cmp     RCX,0x10
    jb      .rightdone
    inc     RCX
    jmp     .rightbytesdone
.rightdone:
.done:
    mov     RDI,1
    mov     RSI,scr
    call    _nprint
    mov     RSP,RBP
    pop     RBP
    ret

```

Defines:

`_printcompare16`, used in chunks 20a and 22a.

Uses `_nprint` 29b, `_print` 30a, and `scr` 10e.

2 Cache Access Timing

TBD

Parameters

RDI the address of the first array

RSI the address of the second array

RDX number of bytes to print. In each line 16 bytes from the first and 16 bytes from the right side are printed

22a $\langle \text{print-comparison } 22a \rangle \equiv$ (23)
 `_printcompare:`
 `call _printcompare16`
 `ret`

Defines:

`_printcompare`, used in chunk 22b.

Uses `_printcompare16` 21.

TBD

22b $\langle \text{cacheread-program } 13a \rangle + \equiv$ (23) <19c
 `mov RDI, data`
 `mov RSI, readback`
 `mov RDX, 16`
 `call _printcompare`

Uses `_printcompare` 22a, `data` 8b, and `readback` 17c.

```

23  <cacheread.asm 23>≡
    <preamble 5>

    section .bss
        align      pagesize
    <cache-data 8b>
    <cacheread-udata 13b>
    <readback-udata 17c>

    section .data
    <cacheread-rodata 19d>

    section .text
    <cacheread-program 13a>

    <exitProgram 27b>

    <print-comparision 22a>

    <print-comparision16 20a>

    <cache-readback 18a>

    <clear-cache 15>

    <calculate-cache-access-time 8a>

    <detect-cache-area-time 16>

    <detect-byte 17a>

    <xorshift-prng 28a>

    <utilities 27a>
    Uses data 8b and pagesize 5.

```


3 Signals

3.1 Basics

TBD

3.2 Detecting Signals

TBD

3.3 Handling Signals

TBD

4 Utilities

4.1 Introduction

TBD

27a $\langle utilities\ 27a \rangle \equiv$ (12 23)
 $\langle nprint\ 29b \rangle$

 $\langle print\ 30a \rangle$

 $\langle printdu64bit\ 31a \rangle$

 $\langle printh8bit\ 34a \rangle$

4.2 Exit Program

TBD

27b $\langle exitProgram\ 27b \rangle \equiv$ (11e 23)
 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

```

28a  <xorshift-prng 28a>≡ (12 23) 28b>
      _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.

```

28b  <xorshift-prng 28a>+≡ (12 23) <28a 29a>
      .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.

29a `<xorshift-prng 28a>+≡` (12 23) <28b

```

    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`

29b `<nprint 29b>≡` (27a)

```

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

```

Defines:

`_nprint`, used in chunks 11, 21, 30d, and 33b.

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**

30a $\langle \textit{print 30a} \rangle \equiv$ (27a) 30b \triangleright

```

    _print:
        cld
        xor     AL,AL
        mov     RSI,RDI

```

Defines:

`_print`, used in chunks 10f, 11d, and 21.

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.

30b $\langle \textit{print 30a} \rangle + \equiv$ (27a) \triangleleft 30a 30c \triangleright

```

    .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.

30c $\langle \textit{print 30a} \rangle + \equiv$ (27a) \triangleleft 30b 30d \triangleright

```

        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`.

30d $\langle \textit{print 30a} \rangle + \equiv$ (27a) \triangleleft 30c

```

        call    _nprint
        ret

```

Uses `_nprint` 29b.

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

```
31a  <printdu64bit 31a>≡ (27a) 31b>
    _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.

```
31b  <printdu64bit 31a>+≡ (27a) <31a 31c>
    .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`.

```
31c  <printdu64bit 31a>+≡ (27a) <31b 32a>
        xor     RDX,RDX
        div     RCX
```

4 Utilities

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.

```
32a  <printdu64bit 31a>+≡ (27a) <31c 32b>
      xchg      RDX,RAX
      add       AL,'0'
      stosb
```

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

```
32b  <printdu64bit 31a>+≡ (27a) <32a 32c>
      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.

```
32c  <printdu64bit 31a>+≡ (27a) <32b 32d>
      .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.

```
32d  <printdu64bit 31a>+≡ (27a) <32c 33a>
      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.

```
33a  <printdu64bit 31a>+≡ (27a) <32d 33b>
      .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 `RDY`) to `RDI` and can the call `_nprint` to print the number.

```
33b  <printdu64bit 31a>+≡ (27a) <33a
      mov     RSI,R8
      mov     RDI,RDX
      call    _nprint
      ret
```

Uses `_nprint` 29b.

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

```

34a  <printh8bit 34a>≡ (27a) 34b>
      _printh8bit:
          xor     RAX,RAX
          mov     AX,DI
          xor     AH,AH
          mov     R8,RAX
          mov     RDI,RSI
          cld

```

Defines:

`_printh8bit`, never used.

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.

```

34b  <printh8bit 34a>+= (27a) <34a 34c>
          shr     AL,4
          and     AL,0x0f
          call    .printh4bit

```

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

```

34c  <printh8bit 34a>+= (27a) <34b
          mov     RAX,R8
          and     AL,0x0f
          call    .printh4bit
          ret
      <printh8bit.printh4bit 35a>

```

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

```
35a  <printh8bit.printh4bit 35a>≡ (34c) 35b>
      .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'.

```
35b  <printh8bit.printh4bit 35a>+≡ (34c) <35a 35c>
      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.

```
35c  <printh8bit.printh4bit 35a>+≡ (34c) <35b 35d>
      .printa2f:
          sub     AL,10
          add     AL,'a'
```

Now we store the character into the storage area.

```
35d  <printh8bit.printh4bit 35a>+≡ (34c) <35c
      .printout:
          stosb
          ret
```


A Glossary

x86 x86 denotes a microprocessor architecture based on the 8086/8088 [28](#)

B Acronyms

ASCII American Standard Code for Information Interchange [32](#)

CR carriage return [10](#), [11](#)

RNG random number generator [28](#)

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

<cache-data 8b>
<cache-readback 18a>
<cacheread-program 13a>
<cacheread-rodata 19d>
<cacheread-sample 14b>
<cacheread-udata 13b>
<cacheread.asm 23>
<cachetiming-program 9c>
<cachetiming-rodata 10d>
<cachetiming-udata 9b>
<cachetiming.asm 12>
<calculate-cache-access-time 8a>
<clear-cache 15>
<common-rodata 10e>
<detect-byte 17a>
<detect-cache-area-time 16>
<exitProgram 27b>
<license 68>
<nprint 29b>
<preamble 5>
<print 30a>
<print-comparision 22a>
<print-comparision16 20a>
<printdu64bit 31a>
<printh8bit 34a>
<printh8bit.printh4bit 35a>
<readback-udata 17c>
<scratch-udata 9a>
<tsc-64bit 7>
<utilities 27a>
<xorshift-prng 28a>

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