

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

`<preamble 5>≡` (12 19 22a 25 36)
`bits 64`

`<license 82>`

```
global      _start
pspower    equ 12
pagesize   equ 1 << pspower
```

Defines:

1 Introduction

`.start`, used in chunks 9a, 14b, 22b, and 26b.

`pagesize`, used in chunks 8b, 9c, 13, 14, 17a, 23c, 26a, 28f, 34c, and 35b.

`pspower`, never used.

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.

$\langle tsc-64bit \rangle \equiv$ (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.

2 Cache Access Timing

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

$\langle \text{calculate-cache-access-time } 8a \rangle \equiv$ (12 19 22a 25 36)

```
_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 15c.

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.

$\langle \text{data-udata } 8b \rangle \equiv$ (12 19 22a 25 36)

```
    alignb    pagesize
    data:     resb pagesize
```

Defines:

`data`, used in chunks 9, 11b, 14c, 17b, 18b, 23c, 24b, 28f, and 34c.

Uses `pagesize` 5.

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

$\langle \text{scratch-udata } 8c \rangle \equiv$ (12 19 22a 25 36)

```
    scratch:  resb 32
```

Defines:

`scratch`, used in chunks 10f, 11d, 17, 18, 24b, 30b, 32, and 35b.

The program begins with the label `_start`.

```
<cachetiming-program 9a>≡ (12) 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.

```
<init-random-data 9b>≡ (9f 14b 22b 26b) 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`.

```
<init-random-data 9b>+≡ (9f 14b 22b 26b) <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.

```
<init-random-data 9b>+≡ (9f 14b 22b 26b) <9c 9e>
    rdtsc
    mov     EDX,EAX
```

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

```
<init-random-data 9b>+≡ (9f 14b 22b 26b) <9d
    call    _xorshift
Uses _xorshift 42a.
```

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

```
<cachetiming-program 9a>+≡ (12) <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.

```
<cachetiming-program 9a>+≡ (12) <9f 10a>
    mov     RDI,data
Uses data 8b.
```

2 Cache Access Timing

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).

```
<cachetiming-program 9a>+≡ (12) <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.

```
<cachetiming-program 9a>+≡ (12) <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.

```
<cachetiming-rodata 10c>≡ (12) 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)`.

```
<common-rodata 10d>≡ (10c 19 22a 25 36)
    slf:        db 0x0a
```

Defines:

`slf`, used in chunks 11, 17, 18, 24b, 33a, and 35b.

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

```
<cachetiming-program 9a>+≡ (12) <10b 10f>
    push        RAX
    mov         RDI,scached
    call        _print
```

Uses `_print` 44a and `scached` 10c.

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

```
<cachetiming-program 9a>+≡ (12) <10e 11a>
    pop         RDI
    mov         RSI,scratch
    call        _printdu64bit
```

Uses `_printdu64bit` 45a and `scratch` 8c.

At last we append a LF to the output.

```

<cachetiming-program 9a>+≡ (12) <10f 11b>
    mov     RSI,slf
    mov     RDI,1
    call    _nprint

```

Uses `_nprint` 43b and `slf` 10d.

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

```

<cachetiming-program 9a>+≡ (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.

```

<cachetiming-rodata 10c>+≡ (12) <10c
    suncached:    db "Uncached Access Time: ",0x00

```

Defines:

`suncached`, used in chunk 11d.

```

<cachetiming-program 9a>+≡ (12) <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` 43b, `_print` 44a, `_printdu64bit` 45a, `scratch` 8c, `slf` 10d, and `suncached` 11c.

At last we exit the program.

```

<cachetiming-program 9a>+≡ (12) <11d
    <exitProgram 41b>

```

2 Cache Access Timing

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

```
<cachetiming.asm 12>≡  
  <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 42a>  
  
    <utilities 41a>
```

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

```

⟨clearcache 13a⟩≡ (19 22a 25 36)
    _clearcache:
        mov     RCX,256
        cld
    .nextflush:
        clflush [RDI]
        add     RDI,RSI
        loop    .nextflush
        lfence
        ret

```

Defines:

`_clearcache`, used in chunks 13b, 23a, and 27c.

Now we add this to our program.

```

⟨cachereadbyte-program 13b⟩≡ (19 22a) 14b▷
    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.

```

⟨probe-udata 13c⟩≡ (19 22a 25 36)
    alignb    pagesize
    probe     times 256 resb pagesize

```

Defines:

`probe`, used in chunks 13, 14, 17a, 23c, and 28f.

Uses `pagesize` 5.

2 Cache Access Timing

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

```
<init-random-probe 14a>≡ (14b 22b 26b)
    mov     RDI,probe
    mov     RSI,pagesize
    shl     RSI,8
    rdtsc
    mov     EDX,EAX
    call    _xorshift
```

Uses **_xorshift 42a**, **pagesize 5**, and **probe 13c**.

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

```
<cachereadbyte-program 13b>+≡ (19 22a) <13b 14c>
    _start:
    <init-random-data 9b>
    <init-random-probe 14a>
```

Uses **_start 5**.

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

```
<cachereadbyte-program 13b>+≡ (19 22a) <14b 14d>
    mov     RDI,data
    xor     RAX,RAX
    mov     AL,[RDI]
```

Uses **data 8b**.

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

```
<cachereadbyte-program 13b>+≡ (19 22a) <14c 17a>
    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)

```

<readcachetiming 15a>≡ (19 22a 25 36) 15b>
    _readcachetiming:
    <enterstackframe 41c>

```

Defines:

_readcachetiming, used in chunks 17a, 23c, and 28a.

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

```

<readcachetiming 15a>+≡ (19 22a 25 36) <15a 15c>
    sub     RSP,32
    mov     [RBP-8],RDI
    mov     [RBP-16],RSI
    mov     [RBP-24],RDX

```

Now we can start detecting the cache access times.

```

<readcachetiming 15a>+≡ (19 22a 25 36) <15b 15d>
    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.

```

<readcachetiming 15a>+≡ (19 22a 25 36) <15c
    <leavestackframe 41d>
    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)

2 Cache Access Timing

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

<analyzecachemintiming 16a>≡

(19 36)

```
_analyzecachetiming:
    push    RDI
    mov     R8,0xffffffffffffffff
    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.

<timings-udata 16b>≡

(19 22a 25 36)

```
    timings    resq 256
```


2.4 Read Byte via Cache Access Time

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

```
<cachereadbyte-program 13b>+≡ (19 22a) <14d 17c>
    mov     RDI,probe
    mov     RSI,pagesize
    mov     RDX,timings
    call    _readcachetiming
    mov     RDI,timings
    call    _analyzecachetiming
```

Uses `_readcachetiming` 15a, `pagesize` 5, and `probe` 13c.

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

```
<cachereadbyte-rodatab 17b>≡ (19 22a 25)
    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.

```
<cachereadbyte-program 13b>+≡ (19 22a) <17a 17d>
    push     RAX
    mov     RDI,sreadbyte
    call    _print
```

Uses `_print` 44a.

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

```
<cachereadbyte-program 13b>+≡ (19 22a) <17c 18a>
    pop     RDI
    push     RDI
    and     RDI,0xff
    mov     RSI,scratch
    call    _printh8bit
    mov     RDI,1
    mov     RSI,slf
    call    _nprint
```

Uses `_nprint` 43b, `_printh8bit` 47b, `scratch` 8c, and `slf` 10d.

2 Cache Access Timing

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

```
⟨cachereadbyte-program 13b⟩+≡ (19 22a) <17d 18b>
    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` 43b, `_print` 44a, `_printdu64bit` 45a, `scratch` 8c, and `slf` 10d.

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

```
⟨cachereadbyte-program 13b⟩+≡ (19 22a) <18a 18c>
    mov     RDI,ssexpectedbyte
    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` 43b, `_print` 44a, `_printh8bit` 47b, `data` 8b, `scratch` 8c, and `slf` 10d.

At last we exit the program.

```
⟨cachereadbyte-program 13b⟩+≡ (19 22a) <18b>
    ⟨exitProgram 41b⟩
```

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

`cachereadbyte`

```

<cachereadbyte.asm 19>≡
  <preamble 5>

  section .rodata
    <common-rodata 10d>
    <cachereadbyte-rodata 17b>

  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 15a>

    <analyzecachemintiming 16a>

    <xorshift-prng 42a>

    <utilities 41a>

```

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

```

2 Cache Access Timing

```
$ 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 threshold 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 subroutine 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

```
<analyzecachesimphrestiming 20a>≡ (22a 25) 20b>
_analyzecachetiming:
    push    RDI
    mov     R8,0xffffffffffffffff
    xor     RCX,RCX
    mov     RSI,RDI
.nextmin:
    lodsq
    cmp     RAX,R8
    ja     .newmin
    mov     R8,RAX
.newmin:
    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.

```
<analyzecachesimphrestiming 20a>+≡ (22a 25) <20a 21>
    mov     RAX,R8
    shr     RAX,4
    add     R8,RAX
```

2.4 Read Byte via Cache Access Time

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

$\langle \text{analyzecachesimpthrestiming } 20a \rangle + \equiv$ (22a 25) < 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
```

2 Cache Access Timing

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

```
⟨cachereadbyte2.asm 22a⟩≡
  ⟨preamble 5⟩

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

  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 15a⟩

    ⟨analyzecachesimpthrestiming 20a⟩

    ⟨xorshift-prng 42a⟩

    ⟨utilities 41a⟩
```

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.

```
⟨cachereadbyte3-program 22b⟩≡ (25) 23c>
  _start:
    ⟨init-random-data 9b⟩
    ⟨init-random-probe 14a⟩
```

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

$\langle \text{readbyte2cache } 23a \rangle \equiv$ (25) 23b▷

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

Defines:

`_readbyte2cache`, used in chunk 23c.

Uses `_clearcache` 13a.

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

$\langle \text{readbyte2cache } 23a \rangle + \equiv$ (25) ◁23a

```
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.

$\langle \text{cachereadbyte3-program } 22b \rangle + \equiv$ (25) ◁22b 24a▷

```
.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` 23a, `_readcachetiming` 15a, `data` 8b, `pagesize` 5, and `probe` 13c.

2 Cache Access Timing

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

```
⟨cachereadbyte3-program 22b⟩+≡ (25) <23c 24b>
    cmp     AH,1
    ja      .startreadcache
```

Now we print out our result.

```
⟨cachereadbyte3-program 22b⟩+≡ (25) <24a>
    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 41b⟩
```

Uses `_nprint 43b`, `_print 44a`, `_printh8bit 47b`, `data 8b`, `scratch 8c`, and `slf 10d`.

Now we can put everything together to get our program `cachereadbyte3.asm` . cachereadbyte3

$\langle \text{cachereadbyte3.asm } 25 \rangle \equiv$
 $\langle \text{preamble } 5 \rangle$

`section .rodata`
 $\langle \text{common-rodata } 10\text{d} \rangle$
 $\langle \text{cachereadbyte-rodata } 17\text{b} \rangle$

`section .bss`
 $\langle \text{data-udata } 8\text{b} \rangle$
 $\langle \text{probe-udata } 13\text{c} \rangle$
 $\langle \text{scratch-udata } 8\text{c} \rangle$
 $\langle \text{timings-udata } 16\text{b} \rangle$

`section .text`
 $\langle \text{cachereadbyte3-program } 22\text{b} \rangle$

$\langle \text{readbyte2cache } 23\text{a} \rangle$

$\langle \text{clearcache } 13\text{a} \rangle$

$\langle \text{calculate-cache-access-time } 8\text{a} \rangle$

$\langle \text{readcachetiming } 15\text{a} \rangle$

$\langle \text{analyzecachesimphthrestiming } 20\text{a} \rangle$

$\langle \text{xorshift-prng } 42\text{a} \rangle$

$\langle \text{utilities } 41\text{a} \rangle$

2 Cache Access Timing

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.

```
<readback-udata 26a>≡ (36)
    alignb    pagesize
    readbackdata    resb pagesize
```

Defines:

`readbackdata`, used in chunks 28f and 34c.

Uses `pagesize` 5.

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

```
<cacheread-program 26b>≡ (36) 28f>
    _start:
    <init-random-data 9b>
    <init-random-probe 14a>
```

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) |

$\langle readarea\ 27a \rangle \equiv$ (36) 27b \triangleright
`_readarea:`

Defines:

`_readarea`, used in chunk 28f.

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.

$\langle readarea\ 27a \rangle + \equiv$ (36) $\triangleleft 27a\ 27c \triangleright$
 $\langle enterstackframe\ 41c \rangle$
`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.

$\langle readarea\ 27a \rangle + \equiv$ (36) $\triangleleft 27b\ 27d \triangleright$
`.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.

$\langle readarea\ 27a \rangle + \equiv$ (36) $\triangleleft 27c\ 28a \triangleright$
`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]`

2 Cache Access Timing

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

`<readarea 27a>+≡` (36) <27d 28b>

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

Uses `_readcachetiming 15a`.

Now we can analyze the cache access times.

`<readarea 27a>+≡` (36) <28a 28c>

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

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

`<readarea 27a>+≡` (36) <28b 28d>

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

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

`<readarea 27a>+≡` (36) <28c 28e>

```
    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.

`<readarea 27a>+≡` (36) <28d

```
    <leavestackframe 41d>
    ret
```

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

`<cacheread-program 26b>+≡` (36) <26b 34c>

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

Uses `_readarea 27a`, `data 8b`, `pagesize 5`, `probe 13c`, and `readbackdata 26a`.

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.

```
<cacheread-rodata 29a>≡ (36) 35a>
    sbgred:      db 0x1b,"[1;41m",0x00
    sresetstyle: db 0x1b,"[0m",0x00
    sseparator:  db "- ",0x00
    sblank:      db " "
    emptybyte:   db " ",0x00
```

Defines:

`sbgred`, used in chunk 32.
`sblank`, used in chunks 30b and 32.
`emptybyte`, used in chunk 31a.
`sresetstyle`, used in chunks 32 and 33a.
`sseparator`, used in chunk 31b.

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

```
<print-comparision16 29b>≡ (36) 30a>
    _printcompare16:
```

Defines:

`_printcompare16`, used in chunk 34a.

2 Cache Access Timing

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.

```
⟨print-comparision16 29b⟩+≡ (36) <29b 30b>
⟨enterstackframe 41c⟩
    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` (31a).

```
⟨print-comparision16 29b⟩+≡ (36) <30a 31a>
    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` 43b, `_printh8bit` 47b, `sblank` 29a, and `scratch` 8c.

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

$\langle \text{print-comparison16 } 29b \rangle + \equiv$ (36) $\langle 30b \ 31b \rangle$

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

Uses `_print` 44a and `emptybyte` 29a.

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

$\langle \text{print-comparison16 } 29b \rangle + \equiv$ (36) $\langle 31a \ 31c \rangle$

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

Uses `_print` 44a and `sseparator` 29a.

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

$\langle \text{print-comparison16 } 29b \rangle + \equiv$ (36) $\langle 31b \ 32 \rangle$

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

2 Cache Access Timing

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.

<print-comparision16 29b>+≡ (36) *<31c 33a>*

```
    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      .prindone
    mov     RDI,sresetstyle
    call    _print
.prindone:
    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 43b*, *_print 44a*, *_printh8bit 47b*, *sbged 29a*, *sblank 29a*, *scratch 8c*,
and *sresetstyle 29a*.

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

<print-comparison16 29b>+≡ (36) <32

```
.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 41d>
    ret
```

Uses *_nprint 43b*, *_print 44a*, *slf 10d*, and *sresetstyle 29a*.

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

<print-comparison 33b>≡ (36) 34a>

```
_printcompare:
<enterstackframe 41c>
    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 *34c*.

2 Cache Access Timing

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

```
⟨print-comparision 33b⟩+≡ (36) <33b 34b>
    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 29b.
```

```
⟨print-comparision 33b⟩+≡ (36) <34a
    mov     RAX,R12
    pop     R12
⟨leavestackframe 41d⟩
    ret
```

Now we can print the complete memory compare.

```
⟨cacheread-program 26b⟩+≡ (36) <28f 35b>
    mov     RDI,data
    mov     RSI,readbackdata
    mov     RDX,pagesize
    call    _printcompare
Uses _printcompare 33b, data 8b, pagesize 5, and readbackdata 26a.
```

2.5 Read Array via Cache Access Time

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

```
⟨cacheread-rodata 29a⟩+≡ (36) <29a
    sstatistics:    db "Failed read relation: ",0x00
    sper:          db "/"
```

Defines:

sper, used in chunk 35b.

sstatistics, used in chunk 35b.

```
⟨cacheread-program 26b⟩+≡ (36) <34c
    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 41b⟩

Uses nprint 43b, _print 44a, _printdu64bit 45a, pagesize 5, scratch 8c, slf 10d, sper 35a,
and sstatistics 35a.

2 Cache Access Timing

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

```
<cacheread.asm 36>≡  
<preamble 5>  
  
section .rodata  
<common-rodata 10d>  
<cacheread-rodata 29a>  
  
section .bss  
<data-udata 8b>  
<probe-udata 13c>  
<readback-udata 26a>  
<timings-udata 16b>  
<scratch-udata 8c>  
  
section .text  
<cacheread-program 26b>  
  
<clearcache 13a>  
  
<calculate-cache-access-time 8a>  
  
<readcachetiming 15a>  
  
<analyzecachemintiming 16a>  
  
<readarea 27a>  
  
<print-comparision 33b>  
  
<print-comparision16 29b>  
  
<xorshift-prng 42a>  
  
<utilities 41a>
```

Now we have created a program that reads a complete memory area via the covert channel. When executing the program 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
```

2.5 Read Array via Cache Access Time

[snip]

Failed read relation: 543/4096

real 0m16.653s

user 0m16.510s

sys 0m0.032s

\$

3 Meltdown

3.1 Introduction

3.2 Signals

3.2.1 Basics

TBD

3.2.2 Detecting Signals

TBD

3.2.3 Handling Signals

TBD

4 Utilities

4.1 Introduction

TBD

$\langle utilities\ 41a \rangle \equiv (12\ 19\ 22a\ 25\ 36)$
 $\langle nprint\ 43b \rangle$
 $\langle print\ 44a \rangle$
 $\langle printdu64bit\ 45a \rangle$
 $\langle printh8bit\ 47b \rangle$

4.2 Common Chunks

4.2.1 Exit Program

This chunk ends the program with exit code 0.

$\langle exitProgram\ 41b \rangle \equiv (11e\ 18c\ 24b\ 35b)$
xor RDI,RDI
mov RAX,60
syscall

4.2.2 Stack Frame

A chunk to create a stack frame.

$\langle enterstackframe\ 41c \rangle \equiv (15a\ 27b\ 30a\ 33b)$
push RBP
mov RBP,RSP

A chunk to clean up the created stack frame.

$\langle leavestackframe\ 41d \rangle \equiv (15d\ 28e\ 33a\ 34b)$
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

| | |
|------------------|---|
| <code>RDI</code> | the address of the memory which is to be filled with random numbers |
| <code>RSI</code> | the number of bytes that are filled with random numbers. This must be a multiple of 4 |
| <code>EDX</code> | the seed of the RNG |

```

<xorshift-prng 42a>≡ (12 19 22a 25 36) 42b▷
  _xorshift:
    cld
    mov     RCX,RSI
    shr     RCX,2
    mov     EAX,EDX

```

Defines:

`_xorshift`, used in chunks [9e](#) and [14a](#).

Now we can generate the next 32bit random number.

```

<xorshift-prng 42a>+≡ (12 19 22a 25 36) <42a 43a▷
  .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.

```

<xorshift-prng 42a>+≡ (12 19 22a 25 36) <42b
    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`

```

<nprint 43b>≡ (41a)
    _nprint:
        mov     RDX,RDI
        mov     RDI,1
        mov     RAX,1
        syscall
        ret

```

Defines:

`_nprint`, used in chunks 11, 17, 18, 24b, 30b, 32, 33a, 35b, 44d, 47a, and 48a.

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`

$\langle \text{print } 44a \rangle \equiv$ (41a) 44b \triangleright

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

Defines:

`_print`, used in chunks 10e, 11d, 17, 18, 24b, 31–33, and 35b.

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.

$\langle \text{print } 44a \rangle + \equiv$ (41a) $\triangleleft 44a$ 44c \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.

$\langle \text{print } 44a \rangle + \equiv$ (41a) $\triangleleft 44b$ 44d \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`.

$\langle \text{print } 44a \rangle + \equiv$ (41a) $\triangleleft 44c$

```
call    _nprint
ret
```

Uses `_nprint` 43b.

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

```

<printdu64bit 45a>≡ (41a) 45b>
    _printdu64bit:
        mov     RAX,RDI
        mov     RDI,RSI
        mov     R8,RDI
        mov     RCX,10
        cld

```

Defines:

`_printdu64bit`, used in chunks 10f, 11d, 18a, and 35b.

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.

```

<printdu64bit 45a>+≡ (41a) <45a 45c>
    .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`.

```

<printdu64bit 45a>+≡ (41a) <45b 45d>
        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.

```

<printdu64bit 45a>+≡ (41a) <45c 46a>
        xchg    RDX,RAX
        add     AL,'0'
        stosb

```

4 Utilities

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

```
<printdu64bit 45a>+≡ (41a) <45d 46b>
    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.

```
<printdu64bit 45a>+≡ (41a) <46a 46c>
.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.

```
<printdu64bit 45a>+≡ (41a) <46b 46d>
    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.

```
<printdu64bit 45a>+≡ (41a) <46c 47a>
.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.

```

<printh8bit 47b>+≡ (41a) <46d
    mov     RSI,R8
    mov     RDI,RDX
    call    _nprint
    ret

```

Uses `_nprint` 43b.

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

```

<printh8bit 47b>≡ (41a) 47c>
    _printh8bit:
        xor     RAX,RAX
        mov     AX,DI
        xor     AH,AH
        mov     R8,RAX
        mov     RDI,RSI
        cld

```

Defines:

`_printh8bit`, used in chunks 17d, 18b, 24b, 30b, and 32.

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.

```

<printh8bit 47b>+≡ (41a) <47b 48a>
    shr     AL,4
    and     AL,0x0f
    call    .printh4bit

```

4 Utilities

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

```
⟨printh8bit 47b⟩+≡ (41a) <47c
    mov     RAX,R8
    and     AL,0x0f
    call    .printh4bit
    mov     RDI,2
    call    _nprint
    ret
⟨printh8bit.printh4bit 48b⟩
Uses _nprint 43b.
```

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

```
⟨printh8bit.printh4bit 48b⟩≡ (48a) 48c>
    .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'.

```
⟨printh8bit.printh4bit 48b⟩+≡ (48a) <48b 48d>
    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.

```
⟨printh8bit.printh4bit 48b⟩+≡ (48a) <48c 48e>
    .printa2f:
        sub     AL,10
        add     AL,'a'
```

Now we store the character into the storage area.

```
⟨printh8bit.printh4bit 48b⟩+≡ (48a) <48d
    .printout:
        stosb
        ret
```


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B Glossary

x86 x86 denotes a microprocessor architecture based on the 8086/8088 [42](#)

C Acronyms

ASCII American Standard Code for Information Interchange [45](#), [46](#)

LF line feed [10](#), [11](#), [17](#)

RNG random number generator [42](#)

D x86-Instructions

`clflush` Flush Cache Line, introduced with Intel[®] Pentium[®] 4 [10](#)

`lfence` Load Fence, introduced with Intel[®] Pentium[®] 4 [7](#), [10](#)

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