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 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

⟨*preamble* 5⟩≡ (12 19 22a 25 36)

```
bits 64

⟨license 82⟩

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

Defines:

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. rdtsc

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.

⟨*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. lfence

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

⟨*calculate-cache-access-time* 8a⟩≡ (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.

⟨*data-udata* 8b⟩≡ (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.

⟨*scratch-udata* 8c⟩≡ (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.

clflush

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⟩
```

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.

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)

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
```

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-rodata* 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.

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,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` 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
```

```
$ 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

⟨*analyzecachesimpthrestiming* 20a⟩≡ (22a 25) 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.

⟨*analyzecachesimpthrestiming* 20a⟩+≡ (22a 25) ◁20a 21▷

```
      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.

⟨*analyzecachesimpthrestiming* 20a⟩+≡ (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
```

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

⟨*readbyte2cache* 23a⟩≡ (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.

⟨*readbyte2cache* 23a⟩+≡ (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.

⟨*cachereadbyte3-program* 22b⟩+≡ (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.

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 `cachreadbyte3.asm` . cachreadbyte3

⟨*cachereadbyte3.asm* 25⟩≡
⟨*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
```
⟨*cachereadbyte3-program* 22b⟩

⟨*readbyte2cache* 23a⟩

⟨*clearcache* 13a⟩

⟨*calculate-cache-access-time* 8a⟩

⟨*readcachetiming* 15a⟩

⟨*analyzecachesimpthrestiming* 20a⟩

⟨*xorshift-prng* 42a⟩

⟨*utilities* 41a⟩

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)

⟨*readarea* 27a⟩≡ (36) 27b▷
```
_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.

⟨*readarea* 27a⟩+≡ (36) ◁27a 27c▷
⟨*enterstackframe* 41c⟩
```
        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.

⟨*readarea* 27a⟩+≡ (36) ◁27b 27d▷
```
.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.

⟨*readarea* 27a⟩+≡ (36) ◁27c 28a▷
```
        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.

⟨*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 " "
semptybyte:     db "   ",0x00
```

Defines:
`sbgred`, used in chunk 32.
`sblank`, used in chunks 30b and 32.
`semptybyte`, 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.

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.

⟨*print-comparision16* 29b⟩+≡ (36) ◁30b 31b▷

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

Uses _print 44a and semptybyte 29a.

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

⟨*print-comparision16* 29b⟩+≡ (36) ◁31a 31c▷

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

Uses _print 44a and sseparator 29a.

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

⟨*print-comparision16* 29b⟩+≡ (36) ◁31b 32▷

```
      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.

⟨*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          .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 43b, _print 44a, _printh8bit 47b, sbgred 29a, sblank 29a, scratch 8c, and sresetstyle 29a.

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

⟨*print-comparision16* 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-comparision* 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.

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.

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.

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 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 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

⟨*utilities* 41a⟩≡ (12 19 22a 25 36)

⟨*nprint* 43b⟩

⟨*print* 44a⟩

⟨*printdu64bit* 45a⟩

⟨*printh8bit* 47b⟩

4.2 Common Chunks

4.2.1 Exit Program

This chunk ends the program with exit code 0.

⟨*exitProgram* 41b⟩≡ (11e 18c 24b 35b)

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

4.2.2 Stack Frame

A chunk to create a stack frame.

⟨*enterstackframe* 41c⟩≡ (15a 27b 30a 33b)

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

A chunk to clean up the created stack frame.

⟨*leavestackframe* 41d⟩≡ (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

`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

⟨*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`

⟨*print* 44a⟩≡ (41a) 44b▷
```
_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.

⟨*print* 44a⟩+≡ (41a) ◁44a 44c▷
```
.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.

⟨*print* 44a⟩+≡ (41a) ◁44b 44d▷
```
        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`.

⟨*print* 44a⟩+≡ (41a) ◁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
```

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.

⟨*printdu64bit* 45a⟩+≡ (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
```

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
```

A Index

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

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

E Code Chunks

⟨*analyzecachemintiming* 16a⟩
⟨*analyzecachesimpthrestiming* 20a⟩
⟨*cacheread-program* 26b⟩
⟨*cacheread-rodata* 29a⟩
⟨*cacheread.asm* 36⟩
⟨*cachereadbyte-program* 13b⟩
⟨*cachereadbyte-rodata* 17b⟩
⟨*cachereadbyte.asm* 19⟩
⟨*cachereadbyte2.asm* 22a⟩
⟨*cachereadbyte3-program* 22b⟩
⟨*cachereadbyte3.asm* 25⟩
⟨*cachetiming-program* 9a⟩
⟨*cachetiming-rodata* 10c⟩
⟨*cachetiming.asm* 12⟩
⟨*calculate-cache-access-time* 8a⟩
⟨*clearcache* 13a⟩
⟨*common-rodata* 10d⟩
⟨*data-udata* 8b⟩
⟨*enterstackframe* 41c⟩
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