

Meltdown and Spectre Samples

Written in Assembly

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March 30, 2018

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1 Introduction

1.1 Overview

TBD

1.2 Conventions

1.2.1 Introduction

In this section we define some convention that are specific for this document.

1.2.2 Data Sections

The data is divided into three parts: read-only data, initialized data and uninitialized data. Code chunks with this type of data will all have defined suffices.

Definition 1 *Read-only data is data that is not modified during program execution. The suffix for read-only data is **-rodata**.*

Definition 2 *Initialized data is data that is changeable during program execution. The data is already initialized with data when the program starts. The suffix for initialized data is **-idata**.*

Definition 3 *Uninitialized data is data that is changeable during program execution. The data is not initialized. The suffix for uninitialized data is **-udata**.*

1.3 Nasm

TBD

5 `<preamble 5>≡` (12c 25)
 `bits 64`

`<license 70>`

```
global      _start
pagesize    equ 4096
```

Defines:

`_start`, used in chunks 9c and 13a.
 `pagesize`, used in chunks 9, 13, 14, 17–19, and 25.

2 Cache Access Timing

2.1 Introduction

TBD

2.2 Detect Cache Access Time

2.2.1 High Resolution Timer

First we need a high resolution timer to determine the cache access time. For this we use the time stamp counter. The time stamp counter is monotonically incrementing. When reading the time stamp counter (with `rdtsc`) the result is delivered back in the registers `EDX` and `EAX` forming a 64bit value. The time stamp counter is not an absolute value but a relative value, meaning that you cannot (easily) calculate from the time stamp counter to some time units (e.g. ns). But this is no problem as we only want to measure relative times.

To retrieve a 64bit value for the time we shift the value in `EDX` 32 bits to the left and add the value of `EAX` to this.

7 $\langle tsc-64bit \ 7 \rangle \equiv$ (8)

```
rdtsc
shl    RDX,32
add    RAX,RDX
```

2.2.2 Cache Access Time Routine

Next we need a routine that calculates the cache access time for us.

First we have to ensure in this routine that the speculative execution of the processor does not interfere with our time measurement. For this we use the instruction `lfence` which ensures that all previous reads are done before executing the next instructions.

Next we access a memory location with the address `RDI` by loading this into `RCX` and measure the time before and after the access.

The command `lfence` before reading the time stamp counter is needed because we have to ensure that all reads before the time measurements are done.

At last we calculate the relative time needed to access the memory location. In theory we should see a difference whether the memory location is accessed before or not.

Parameters

`RDI` the address of the memory which is loaded either from the cache or from memory

Return

`RAX` the relative time of the cache access

```

8  <calculate-cache-access-time 8>≡ (12c 25)
    _calccachetime:
        lfence
        <tsc-64bit 7>
        mov     R8,RAX
        mov     RCX,[RDI]
        lfence
        <tsc-64bit 7>
        sub     RAX,R8
        ret

```

Defines:

`_calccachetime`, used in chunks 10e, 11e, and 16.

2.3 Measure Cache Access Time

2.3.1 Setup

To measure the cache timing we create a standalone program that shows us the time for a cached and for an uncached memory access.

First we need some area in memory with data which we can later read from. This data area goes into the area `.bss` which contains uninitialized data. We align the data at a page boundary and reserve one pages for our data.

```
9a  <cache-udata 9a>≡ (12c 25)
      alignb      pagesize
      data:      resb pagesize
```

Defines:

`data`, used in chunks 9–11, 13a, 14b, 18c, 24c, and 25.

Uses `pagesize` 5.

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

```
9b  <scratch-udata 9b>≡ (12c)
      scratch:      resb 32
```

Defines:

`scratch`, used in chunks 11c, 12a, 16, 20c, 21c, and 23.

The program begins with the label `_start`.

```
9c  <cachetiming-program 9c>≡ (12c) 10b>
      _start:
```

Uses `_start` 5.

Now we start with initialising the `data` area with some random data. For this we load RDI with the address of the `data` area.

```
9d  <init-random-data 9d>≡ (10b) 9e>
      mov      RDI,data
```

Uses `data` 9a.

Next we load the number of bytes to fill into RSI. For this we load the `pagesize` into RSI.

```
9e  <init-random-data 9d>+≡ (10b) <9d 9f>
      mov      RSI,pagesize
```

Uses `pagesize` 5.

At last we load EDX with some random seed. For this we use `rdtsc` and only use the lower 32 bit of the value.

```
9f  <init-random-data 9d>+≡ (10b) <9e 10a>
      rdtsc
      mov      EDX,EAX
```

2 Cache Access Timing

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

```
10a  <init-random-data 9d>+≡ (10b) <9f>
      call    _xorshift
```

Uses `_xorshift` 30a.

Now we add this data initialization to our program.

```
10b  <cachetiming-program 9c>+≡ (12c) <9c 10c>
      <init-random-data 9d>
```

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.

```
10c  <cachetiming-program 9c>+≡ (12c) <10b 10d>
      mov     RDI,data
```

Uses `data` 9a.

Before we load the data into a register now we will clear the cache lines with the given address. For this we use the instruction `clflush`. After 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).

```
10d  <cachetiming-program 9c>+≡ (12c) <10c 10e>
      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.

```
10e  <cachetiming-program 9c>+≡ (12c) <10d 11b>
      call    _calccachetime
```

Uses `_calccachetime` 8.

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

For this we define the text to print.

```
10f  <cachetiming-rodata 10f>≡ (12c) 11f>
      <common-rodata 11a>
      scached:      db "Cached Access Time: ",0x00
```

Defines:

`scached`, used in chunk 11b.

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

```
11a <common-rodata 11a>≡ (10f 20a)
    slf:          db 0x0a
```

Defines:

`slf`, used in chunks [11d](#), [12a](#), [16](#), and [24a](#).

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

```
11b <cachetiming-program 9c>+≡ (12c) <10e 11c>
    push        RAX
    mov         RDI,scached
    call        _print
```

Uses `_print` [32a](#) and `scached` [10f](#).

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

```
11c <cachetiming-program 9c>+≡ (12c) <11b 11d>
    pop         RDI
    mov         RSI,scratch
    call        _printdu64bit
```

Uses `_printdu64bit` [33a](#) and `scratch` [9b](#).

At last we append a [LF](#) to the output.

```
11d <cachetiming-program 9c>+≡ (12c) <11c 11e>
    mov         RSI,slf
    mov         RDI,1
    call        _nprint
```

Uses `_nprint` [31b](#) and `slf` [11a](#).

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

```
11e <cachetiming-program 9c>+≡ (12c) <11d 12a>
    mov         RDI,data
    clflush     [RDI]
    lfence
    call        _calccachetime
```

Uses `_calccachetime` [8](#) and `data` [9a](#).

Now we have the time of the uncached data access in `RAX` and can print it out with some explaining text.

```
11f <cachetiming-rodata 10f>+≡ (12c) <10f
    suncached:   db "Uncached Access Time: ",0x00
```

Defines:

`suncached`, used in chunk [12a](#).

2 Cache Access Timing

12a $\langle \text{cachetiming-program } 9c \rangle + \equiv$ (12c) $\triangleleft 11e \text{ } 12b \triangleright$

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

Uses `_nprint` 31b, `_print` 32a, `_printdu64bit` 33a, `scratch` 9b, `slf` 11a, and `suncached` 11f.

At last we exit the program.

12b $\langle \text{cachetiming-program } 9c \rangle + \equiv$ (12c) $\triangleleft 12a$
 $\langle \text{exitProgram } 29b \rangle$

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

12c $\langle \text{cachetiming.asm } 12c \rangle \equiv$
 $\langle \text{preamble } 5 \rangle$

```
section .rodata
   $\langle \text{cachetiming-rodata } 10f \rangle$ 
```

```
section .bss
   $\langle \text{cache-udata } 9a \rangle$ 
   $\langle \text{scratch-udata } 9b \rangle$ 
```

```
section .text
   $\langle \text{cachetiming-program } 9c \rangle$ 
```

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

```
   $\langle \text{xorshift-prng } 30a \rangle$ 
```

```
   $\langle \text{utilities } 29a \rangle$ 
```

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.

For this we will create a `probe` array and fill it with some random data.

2.5 Read Array via Cache Access Time

2.5.1 Introduction

Now that we have seen that we can determine if a value was in the cache or not (see [2.3 Measure Cache Access Time](#)) we will read a complete array of data by only measuring the cache access time.

2.5.2 Setup

For this we start with some `data` area that we can read later as defined before.

So start with the program and fill the `data` area with some random data (similar to the chunks [10b](#), [9d](#), [9e](#), [9f](#) and [10a](#)).

```
13a  <cacheread-program 13a>≡ (25) 14a>
      _start:
          mov     RDI,data
          mov     RSI,pagesize
          rdtsc
          mov     EDX,EAX
          call    _xorshift
```

Uses `_start` 5, `_xorshift` 30a, `data` 9a, and `pagesize` 5.

Next we will create a probe area that is $256 * \text{pagesize}$. We only access the first byte of each page but we divide the data over such a large area (1 MiB) to ensure that the cache lines that we use do not interfere each other.

```
13b  <cacheread-udata 13b>≡ (25) 17b>
      probe:      times 256 resb pagesize
```

Defines:

`probe`, used in chunks [14](#), [18](#), and [19a](#).

Uses `pagesize` 5.

2 Cache Access Timing

Next we fill this area also with some random data.

```
14a  <cacheread-program 13a>+≡ (25) <13a 19d>
      mov     RDI,probe
      mov     RAX,pagesize
      mov     RCX,256
      mul     RCX
      mov     RSI,RCX
      rdtsc
      mov     EDX,EAX
      call    _xorshift
```

Uses `_xorshift 30a`, `pagesize 5`, and `probe 13b`.

2.5.3 Reading Bytes via Cache

As we saw we can determine if a memory datum is in cache or not. For reading a complete byte we have to do a little bit more. Basically we use the byte accessed to index a different `probe` area. Because the memory is not cached byte by byte but in so called cache lines we cannot use a simple 256 bytes sized probe array but must at least have a space between the accessed bytes that is larger than a cache line size. This is the reason why we use a probe array of $256 * \text{pagesize}$ bytes of size.

Basically we use the following code to access the data. We load the content of the address we want to probe into a register. Then we multiply the register with some arbitrary value (we use `pagesize`) and then access the probe area with the calculated offset. We can then test the cache which page was cached and have our value from the `data`.

```
14b  <cacheread-sample 14b>≡
      mov     RAX,[data]
      mul     RAX,pagesize
      mov     RBX,[probe+RAX]
```

Uses `data 9a`, `pagesize 5`, and `probe 13b`.

First we write a subroutine to clear the cache lines from data from our **probe** area. We assume that we use 256 values (0...255) for the indexing into the probe array. Also the **probe** area must be at least 256 * RSI bytes in size.

Parameters

RDI the address of the probe array

RSI the interval between the probe addresses used

```
15  <clear-cache 15>≡ (25)
    _clearcache:
        cld
        mov     RCX,256
        xor     RAX,RAX
    .clear_next:
        clflush [RDI+RAX]
        add     RAX,RSI
        loop    .clear_next
        lfence
        ret
```

Defines:

 _clearcache, used in chunk 18b.

2 Cache Access Timing

Next we need a subroutine that determines the cache line access times for the data in the `probe` area. So we create a subroutine that loops similar to the `_clearcache` subroutine over all addresses and measures the cache access time for each page.

Parameters

RDI the address of the probe array

RSI the interval between the probe addresses used

RDX the address of the results of the cache measurements. The area needs to be $256 * 8$ bytes in size

```
16  <detect-cache-area-time 16>≡ (25)
    _calcareacachetime:
        xor     RCX,RCX
    .next_timing:
        push    RCX
        push    RDX
        push    RDI
        push    RSI
        call    _calccachetime
        push    RAX
        mov     RDI,RAX
        mov     RSI,scratch
        call    _printdu64bit
        mov     RDI,1
        mov     RSI,slf
        call    _nprint
        pop     RAX
        pop     RSI
        pop     RDI
        pop     RDX
        pop     RCX
        mov     [RDX+8*RCX],RAX
        add     RDI,RSI
        inc     RCX
        cmp     RCX,256
        jb      .next_timing
        ret
```

Defines:

`_calcareacachetime`, used in chunk 17a.

Uses `_calccachetime` 8, `_nprint` 31b, `_printdu64bit` 33a, `scratch` 9b, and `slf` 11a.

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

Parameters

RDI	the address of the probe array
RSI	the interval between the probe addresses used
RDX	the address of the results of the cache measurements. The area needs to be 256 * 8 bytes in size

Return

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

TBD

17a $\langle \text{detect-byte 17a} \rangle \equiv$ (25)

```

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

```

Uses `_calcareacachetime` 16.

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

17b $\langle \text{cacheread-udata 13b} \rangle + \equiv$ (25) $\langle 13b \ 20c \rangle$

```

    result:    resb    pagesize
    timing:    resq    256

```

Uses `pagesize` 5.

2 Cache Access Timing

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

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

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

18a $\langle \text{readback-udata 18a} \rangle \equiv$ (25)

```
;    readback:    align pagesize, resb pagesize
```

Defines:

readback, never used.

Uses **pagesize** 5.

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

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

18b $\langle \text{cache-readback 18b} \rangle \equiv$ (25) 18c>

```
_cachereadback:
```

```
    xor        R8,R8
```

```
    .nextbyte:
```

```
        push    R8
```

```
        mov     RDI,probe
```

```
        mov     RSI,pagesize
```

```
        call    _clearcache
```

```
        pop     R8
```

Defines:

_cachereadback, used in chunk 19d.

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

Next we read in the data from the array.

18c $\langle \text{cache-readback 18b} \rangle + \equiv$ (25) <18b 18d>

```
        mov     RSI,data
```

```
        xor     RAX,RAX
```

```
        mov     AL,[RSI+R8]
```

Uses **data** 9a.

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

18d $\langle \text{cache-readback 18b} \rangle + \equiv$ (25) <18c 19a>

```
        mov     RDX,pagesize
```

```
        mul     RDX
```

```
        mov     RSI,probe
```

```
        mov     AL,[RSI+RAX]
```

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

2.5 Read Array via Cache Access Time

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

```
19a  <cache-readback 18b>+≡ (25) <18d 19b>
      mov     RDI,probe
      mov     RSI,pagesize
      mov     RDX,timing
      push    R8
      call    _detectbytebycl
      pop     R8
```

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

Next we store the read byte into our result array.

```
19b  <cache-readback 18b>+≡ (25) <19a 19c>
      mov     RDI,result
      mov     [RDI+R8],AL
```

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

```
19c  <cache-readback 18b>+≡ (25) <19b
      inc     R8
      cmp     R8,pagesize
      jb      .nextbyte
      ret
```

Uses `pagesize 5`.

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

```
19d  <cacheread-program 13a>+≡ (25) <14a 24c>
      call    _cachereadback
```

Uses `_cachereadback 18b`.

2.5.4 Printing the Results

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

First we define some helpful data for colorizing the output.

20a $\langle \text{cacheread-rodata } 20a \rangle \equiv$ (25)

$\langle \text{common-rodata } 11a \rangle$

```

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

```

Defines:

sbgred, used in chunk 23.

sblank, used in chunks 21c and 23.

sresetstyle, used in chunks 23 and 24a.

sseparator, used in chunk 22b.

First we define a subroutine which prints out up to 16 bytes each side by side on the screen. If two bytes in the arrays are different then the value at the right side (from the second array) will be printed with read background.

Parameters

RDI the address of the first array

RSI the address of the second array

RDX number of bytes to print (up to 16). If the value is above 16 then nothing is printed out

20b $\langle \text{print-comparision16 } 20b \rangle \equiv$ (25) 21a▷

_printcompare16:

Defines:

_printcompare16, used in chunk 24b.

Additionally we need some scratch area for the printing.

20c $\langle \text{cacheread-udata } 13b \rangle + \equiv$ (25) <17b

scratch: resb 64

Uses **scratch** 9b.

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 to the stack to use this register as scratch register.

```
21a  <print-comparision16 20b>+≡ (25) <20b 21b>
      push    RBP
      mov     RBP,RSP
      sub     RSP,32
      mov     [RBP-8],RDI
      mov     [RBP-16],RSI
      mov     [RBP-24],RDX
      push    R12
```

Now we first start and check that no more than 16 bytes should be printed, otherwise we will end the subroutine immediately.

```
21b  <print-comparision16 20b>+≡ (25) <21a 21c>
      cmp     RDX,0x10
      ja      .done
```

Next we can start and handle the "left" side of the output. We output up to 16 bytes and then continue at `.leftbytesdone` (22a).

```
21c  <print-comparision16 20b>+≡ (25) <21b 22a>
      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
```

Uses `_nprint` 31b, `_printh8bit` 36a, `sblank` 20a, and `scratch` 9b.

2 Cache Access Timing

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

22a $\langle \text{print-comparison16 } 20b \rangle + \equiv$ (25) $\langle 21c \ 22b \rangle$

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

Uses `_print` 32a.

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

22b $\langle \text{print-comparison16 } 20b \rangle + \equiv$ (25) $\langle 22a \ 22c \rangle$

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

Uses `_print` 32a and `sseparator` 20a.

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

22c $\langle \text{print-comparison16 } 20b \rangle + \equiv$ (25) $\langle 22b \ 23 \rangle$

```
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.

```

23  <print-comparision16 20b>+≡ (25) <22c 24a>
    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
        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      .prindtdone
        mov     RDI,sresetstyle
        call    _print
    .prindtdone:
        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` 31b, `_print` 32a, `_printh8bit` 36a, `sbged` 20a, `sblank` 20a, `scratch` 9b, and `sresetstyle` 20a.

2 Cache Access Timing

24a $\langle \text{print-comparision16 } 20b \rangle + \equiv$ (25) $\triangleleft 23$

```

    cmp     RCX,0x10
    jae     .rightdone
    inc     RCX
    jmp     .rightbytesdone
.rightdone:
.done:
    mov     RDI,sresetstyle
    call    _print
    mov     RDI,1
    mov     RSI,slf
    call    _nprint
    pop     R12
    mov     RSP,RBP
    pop     RBP
    ret

```

Uses `_nprint` 31b, `_print` 32a, `slf` 11a, and `sresetstyle` 20a.

TBD

Parameters

RDI the address of the first array

RSI the address of the second array

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

24b $\langle \text{print-comparision } 24b \rangle \equiv$ (25)

```

_printcompare:
    mov     RDX,16
    call    _printcompare16
    ret

```

Defines:

`_printcompare`, used in chunk 24c.

Uses `_printcompare16` 20b.

TBD

24c $\langle \text{cacheread-program } 13a \rangle + \equiv$ (25) $\triangleleft 19d$

```

    mov     RDI,data
    mov     RSI,result
    call    _printcompare

```

Uses `_printcompare` 24b and `data` 9a.


```

25  <cacheread.asm 25>≡
    <preamble 5>

    section .bss
        align      pagesize
    <cache-udata 9a>
    <cacheread-udata 13b>
    <readback-udata 18a>

    section .data
    <cacheread-rodata 20a>

    section .text
    <cacheread-program 13a>

    <exitProgram 29b>

    <print-comparision 24b>

    <print-comparision16 20b>

    <cache-readback 18b>

    <clear-cache 15>

    <calculate-cache-access-time 8>

    <detect-cache-area-time 16>

    <detect-byte 17a>

    <xorshift-prng 30a>

    <utilities 29a>
    Uses data 9a and pagesize 5.

```


3 Signals

3.1 Basics

TBD

3.2 Detecting Signals

TBD

3.3 Handling Signals

TBD

4 Utilities

4.1 Introduction

TBD

29a $\langle utilities\ 29a \rangle \equiv$ (12c 25)
 $\langle nprint\ 31b \rangle$

 $\langle print\ 32a \rangle$

 $\langle printdu64bit\ 33a \rangle$

 $\langle printh8bit\ 36a \rangle$

4.2 Exit Program

TBD

29b $\langle exitProgram\ 29b \rangle \equiv$ (12b 25)
 xor RDI,RDI
 mov RAX,60
 syscall

4.3 Random Number Generator

To initialize the data a [random number generator \(RNG\)](#) is used. The sample programs use [xorshift](#)¹ as [RNG](#).

First we clear the direction flag to ensure that we are incrementing the data pointer RDI.

Next we move the number of values to be generated to RCX (which is a counter in [x86](#) processors) and divide it by 4 (because we use a 32bit [RNG](#)). Additionally we move the seed to EAX.

Parameters

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

```

30a  <xorshift-prng 30a>≡ (12c 25) 30b>
      _xorshift:
          cld
          mov     RCX,RSI
          shr     RCX,2
          mov     EAX,EDX

```

Defines:

`_xorshift`, used in chunks 10a, 13a, and 14a.

Now we can generate the next 32bit random number.

```

30b  <xorshift-prng 30a>+≡ (12c 25) <30a 31a>
      .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.

31a `<xorshift-prng 30a>+≡` (12c 25) <30b

```

    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`

31b `<nprint 31b>≡` (29a)

```

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

```

Defines:

`_nprint`, used in chunks 11d, 12a, 16, 21c, 23, 24a, 32d, 35b, and 36c.

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**

32a $\langle \textit{print 32a} \rangle \equiv$ (29a) 32b \triangleright
 `_print:`
 `cld`
 `xor` `AL,AL`
 `mov` `RSI,RDI`

Defines:

`_print`, used in chunks 11b, 12a, and 22–24.

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.

32b $\langle \textit{print 32a} \rangle + \equiv$ (29a) \triangleleft 32a 32c \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.

32c $\langle \textit{print 32a} \rangle + \equiv$ (29a) \triangleleft 32b 32d \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`.

32d $\langle \textit{print 32a} \rangle + \equiv$ (29a) \triangleleft 32c
 `call` `_nprint`
 `ret`

Uses `_nprint 31b`.

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

```
33a  <printdu64bit 33a>≡ (29a) 33b>
      _printdu64bit:
          mov     RAX,RDI
          mov     RDI,RSI
          mov     R8,RDI
          mov     RCX,10
          cld
```

Defines:

`_printdu64bit`, used in chunks 11c, 12a, and 16.

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.

```
33b  <printdu64bit 33a>+≡ (29a) <33a 33c>
      .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`.

```
33c  <printdu64bit 33a>+≡ (29a) <33b 34a>
          xor     RDX,RDX
          div     RCX
```

4 Utilities

We now exchange the result and the remainder because we now need the remainder in RAX (or AL) for further processing. Now we can add the [ASCII](#) character '0' to AL and have the correct [ASCII](#) value in AL. Now we can store the [ASCII](#) character to the scratch area.

```
34a  <printdu64bit 33a>+≡ (29a) <33c 34b>
      xchg      RDX,RAX
      add       AL,'0'
      stosb
```

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

```
34b  <printdu64bit 33a>+≡ (29a) <34a 34c>
      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.

```
34c  <printdu64bit 33a>+≡ (29a) <34b 34d>
      .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.

```
34d  <printdu64bit 33a>+≡ (29a) <34c 35a>
      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.

```
35a  <printdu64bit 33a>+≡ (29a) <34d 35b>
      .reverse:
      mov     AL,[RSI]
      mov     AH,[RDI]
      mov     [RSI],AH
      mov     [RDI],AL
      dec     RDI
      inc     RSI
      cmp     RSI,RDI
      jb      .reverse
```

Now we restore the address of the scratch area to `RSI` and move the number of digits (which we stored in `RDY`) to `RDI` and can the call `_nprint` to print the number.

```
35b  <printdu64bit 33a>+≡ (29a) <35a
      mov     RSI,R8
      mov     RDI,RDX
      call    _nprint
      ret
```

Uses `_nprint` 31b.

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

```
36a  <printh8bit 36a>≡ (29a) 36b>
      _printh8bit:
          xor     RAX,RAX
          mov     AX,DI
          xor     AH,AH
          mov     R8,RAX
          mov     RDI,RSI
          cld
```

Defines:

`_printh8bit`, used in chunks 21c and 23.

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.

```
36b  <printh8bit 36a>+= (29a) <36a 36c>
          shr     AL,4
          and     AL,0x0f
          call     .printh4bit
```

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

```
36c  <printh8bit 36a>+= (29a) <36b
          mov     RAX,R8
          and     AL,0x0f
          call     .printh4bit
          mov     RDI,2
          call     _nprint
          ret
      <printh8bit.printh4bit 37a>
```

Uses `_nprint` 31b.

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

```
37a  <printh8bit.printh4bit 37a>≡ (36c) 37b>
      .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'.

```
37b  <printh8bit.printh4bit 37a>+≡ (36c) <37a 37c>
      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.

```
37c  <printh8bit.printh4bit 37a>+≡ (36c) <37b 37d>
      .printa2f:
          sub     AL,10
          add     AL,'a'
```

Now we store the character into the storage area.

```
37d  <printh8bit.printh4bit 37a>+≡ (36c) <37c>
      .printout:
          stosb
          ret
```


A Glossary

x86 x86 denotes a microprocessor architecture based on the 8086/8088 [30](#)

B Acronyms

ASCII American Standard Code for Information Interchange [34](#)

LF line feed [11](#)

RNG random number generator [30](#)

C x86-Instructions

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

`lfence` Load Fence, introduced with Intel[®] Pentium[®] 4 [8](#), [10](#)

`rdtsc` Read Time Stamp Counter, introduced with Intel[®] Pentium[®] [7](#), [9](#)

D Code Chunks

<cache-readback 18b>
<cache-udata 9a>
<cacheread-program 13a>
<cacheread-rodata 20a>
<cacheread-sample 14b>
<cacheread-udata 13b>
<cacheread.asm 25>
<cachetiming-program 9c>
<cachetiming-rodata 10f>
<cachetiming.asm 12c>
<calculate-cache-access-time 8>
<clear-cache 15>
<common-rodata 11a>
<detect-byte 17a>
<detect-cache-area-time 16>
<exitProgram 29b>
<init-random-data 9d>
<license 70>
<nprint 31b>
<preamble 5>
<print 32a>
<print-comparision 24b>
<print-comparision16 20b>
<printdu64bit 33a>
<printh8bit 36a>
<printh8bit.printh4bit 37a>
<readback-udata 18a>
<scratch-udata 9b>
<tsc-64bit 7>
<utilities 29a>
<xorshift-prng 30a>

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```
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