Meltdown and Spectre Samples

Written in Assembly

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TBD

1.2 Conventions

1.2.1 Introduction

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

1.2.2 Data Sections

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

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

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

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

1.3 Nasm

TBD

5 ⟨*preamble* 5⟩≡ (12c 14a 26)

```
bits 64

⟨license 70⟩

      global          _start
      pagesize        equ 4096
```

Defines:
`_start`, used in chunks 9c, 13c, and 14b.
`pagesize`, used in chunks 9, 13–15, 18–20, and 26.

2 Cache Access Timing

2.1 Introduction

TBD

2.2 Detect Cache Access Time

2.2.1 High Resolution Timer

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

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

7 ⟨*tsc-64bit* 7⟩≡ (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 26)

```
_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 17.

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 14a 26)

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

Defines:
`data`, used in chunks 9–11, 14b, 15c, 19c, 25c, and 26.
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 14a)

```
        scratch:        resb 32
```

Defines:
`scratch`, used in chunks 11c, 12a, 17, 21c, 22c, and 24.

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 13c) 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 13c) ◁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 13c) ◁9e 10a▷

```
        rdtsc
        mov        EDX,EAX
```

Now we call _xorshift to fill the data area.

10a ⟨*init-random-data* 9d⟩+≡ (10b 13c) ◁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 21a)

```
slf:            db 0x0a
```

Defines:
`slf`, used in chunks 11d, 12a, 17, and 25a.

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.

12a ⟨*cachetiming-program* 9c⟩+≡ (12c) ◁11e 12b▷

```
        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 ⟨*cachetiming-program* 9c⟩+≡ (12c) ◁12a

⟨*exitProgram* 29b⟩

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

12c ⟨*cachetiming.asm* 12c⟩≡

```
⟨preamble 5⟩

section .rodata
⟨cachetiming-rodata 10f⟩

section .bss
⟨cache-udata 9a⟩
⟨scratch-udata 9b⟩

section .text
⟨cachetiming-program 9c⟩

⟨calculate-cache-access-time 8⟩

⟨xorshift-prng 30a⟩

⟨utilities 29a⟩
```

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.

13a ⟨*probe-udata* 13a⟩≡ (14a)

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

Defines:
probe, used in chunks 13b, 15, 19, and 20a.
Uses pagesize 5.

Next we will fill this probe array with some random data (similar to the chunks for data 9d, 9e, 9f and 10a).

13b ⟨*init-random-probe* 13b⟩≡ (13c)

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

Uses _xorshift 30a, pagesize 5, and probe 13a 15a.

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

13c ⟨*cachereadbyte-program* 13c⟩≡ (14a) 13d ▷

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

Uses _start 5.

At last we exit the program.

13d ⟨*cachereadbyte-program* 13c⟩+≡ (14a) ◁ 13c

```
  ⟨exitProgram 29b⟩
```

14a ⟨*cachereadbyte.asm* 14a⟩≡
```
⟨preamble 5⟩

section .rodata

section .bss
⟨cache-udata 9a⟩
⟨probe-udata 13a⟩
⟨scratch-udata 9b⟩

section .text
⟨cachereadbyte-program 13c⟩

⟨xorshift-prng 30a⟩

⟨utilities 29a⟩
```

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.

14b ⟨*cacheread-program* 14b⟩≡ (26) 15b ▷
```
_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 $256 * pagesize$. 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.

15a ⟨*cacheread-udata* 15a⟩≡ (26) 18b ▷

```
probe:          times 256 resb pagesize
```

Defines:
`probe`, used in chunks 13b, 15, 19, and 20a.
Uses `pagesize` 5.

Next we fill this area also with some random data.

15b ⟨*cacheread-program* 14b⟩+≡ (26) ◁ 14b 20d ▷

```
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` 13a 15a.

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 * `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 arbitary value (we use `pagesize`) and the 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`.

15c ⟨*cacheread-sample* 15c⟩≡

```
mov       RAX,[data]
mul       RAX,pagesize
mov       RBX,[probe+RAX]
```

Uses `data` 9a, `pagesize` 5, and `probe` 13a 15a.

First we write a subroutine to clear the cache lines from data from our `probe` area. We assume that we use 256 values $(0 \dots 255)$ 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

16 ⟨*clear-cache* 16⟩≡ (26)

```
  _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 19b.

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

17 ⟨*detect-cache-area-time* 17⟩≡ (26)

```
_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 18a.

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

18a ⟨*detect-byte* 18a⟩≡ (26)

```
_detectbytebycl:
      push    RDI
      call    _calcareacachetime
      pop     RDI
      mov     RSI,RDX
      xor     RCX,RCX
      mov     R8,0xffffffffffffff
      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 17.

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.

18b ⟨*cacheread-udata* 15a⟩+≡ (26) ◁15a 21c▷

```
      result:         resb pagesize
      timing:         resq 256
```

Uses pagesize 5.

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

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

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

19a ⟨*readback-udata* 19a⟩≡ (26)

```
;      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.

19b ⟨*cache-readback* 19b⟩≡ (26) 19c ▷

```
_cachereadback:
        xor         R8,R8
.nextbyte:
        push        R8
        mov         RDI,probe
        mov         RSI,pagesize
        call        _clearcache
        pop         R8
```

Defines:
`_cachereadback`, used in chunk 20d.
Uses `_clearcache` 16, `pagesize` 5, and `probe` 13a 15a.

Next we read in the data from the array.

19c ⟨*cache-readback* 19b⟩+≡ (26) ◁ 19b 19d ▷

```
        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.

19d ⟨*cache-readback* 19b⟩+≡ (26) ◁ 19c 20a ▷

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

Uses `pagesize` 5 and `probe` 13a 15a.

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.

20a ⟨*cache-readback* 19b⟩+≡ (26) ◁19d 20b▷

```
mov     RDI,probe
mov     RSI,pagesize
mov     RDX,timing
push    R8
call    _detectbytebycl
pop     R8
```

Uses `pagesize` 5 and `probe` 13a 15a.

Next we store the read byte into our result array.

20b ⟨*cache-readback* 19b⟩+≡ (26) ◁20a 20c▷

```
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.

20c ⟨*cache-readback* 19b⟩+≡ (26) ◁20b

```
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.

20d ⟨*cacheread-program* 14b⟩+≡ (26) ◁15b 25c▷

```
call    _cachereadback
```

Uses `_cachereadback` 19b.

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.

21a ⟨*cacheread-rodata* 21a⟩≡ (26)

```
⟨common-rodata 11a⟩
      sbgred:        db 0x1b,"[1;41m",0x00
      sresetstyle:   db 0x1b,"[0m",0x00
      sseparator:    db "- ",0x00
      sblank:        db " "
      semptybyte:    db "   ",0x00
```

Defines:
`sbgred`, used in chunk 24.
`sblank`, used in chunks 22c and 24.
`sresetstyle`, used in chunks 24 and 25a.
`sseparator`, used in chunk 23b.

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

21b ⟨*print-comparision16* 21b⟩≡ (26) 22a ▷

```
_printcompare16:
```

Defines:
`_printcompare16`, used in chunk 25b.

Additionally we need some scratch area for the printing.

21c ⟨*cacheread-udata* 15a⟩+≡ (26) ◁ 18b

```
      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.

22a ⟨*print-comparision16* 21b⟩+≡ (26) ◁21b 22b▷

```
        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.

22b ⟨*print-comparision16* 21b⟩+≡ (26) ◁22a 22c▷

```
        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 (23a).

22c ⟨*print-comparision16* 21b⟩+≡ (26) ◁22b 23a▷

```
        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 21a, and scratch 9b.

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

23a ⟨*print-comparision16* 21b⟩+≡ (26) ◁22c 23b▷

```
.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.

23b ⟨*print-comparision16* 21b⟩+≡ (26) ◁23a 23c▷

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

Uses `_print` 32a and `sseparator` 21a.

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

23c ⟨*print-comparision16* 21b⟩+≡ (26) ◁23b 24▷

```
    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.

24 ⟨*print-comparision16* 21b⟩+≡ (26) ◁23c 25a▷

```
      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        .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` 31b, `_print` 32a, `_printh8bit` 36a, `sbgred` 21a, `sblank` 21a, `scratch` 9b, and `sresetstyle` 21a.

25a ⟨*print-comparision16* 21b⟩+≡ (26) ◁24

```
      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` 21a.

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

25b ⟨*print-comparision* 25b⟩≡ (26)

```
 _printcompare:
      mov       RDX,16
      call      _printcompare16
      ret
```

Defines:
`_printcompare`, used in chunk 25c.
Uses `_printcompare16` 21b.

TBD

25c ⟨*cacheread-program* 14b⟩+≡ (26) ◁20d

```
      mov       RDI,data
      mov       RSI,result
      call      _printcompare
```

Uses `_printcompare` 25b and `data` 9a.

26 ⟨*cacheread.asm* 26⟩≡
```
  ⟨preamble 5⟩

  section .bss
       align           pagesize
  ⟨cache-udata 9a⟩
  ⟨cacheread-udata 15a⟩
  ⟨readback-udata 19a⟩

  section .data
  ⟨cacheread-rodata 21a⟩

  section .text
  ⟨cacheread-program 14b⟩

  ⟨exitProgram 29b⟩

  ⟨print-comparision 25b⟩

  ⟨print-comparision16 21b⟩

  ⟨cache-readback 19b⟩

  ⟨clear-cache 16⟩

  ⟨calculate-cache-access-time 8⟩

  ⟨detect-cache-area-time 17⟩

  ⟨detect-byte 18a⟩

  ⟨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 ⟨*utilities* 29a⟩≡ (12c 14a 26)
  ⟨*nprint* 31b⟩

  ⟨*print* 32a⟩

  ⟨*printdu64bit* 33a⟩

  ⟨*printh8bit* 36a⟩

4.2 Exit Program

TBD

29b ⟨*exitProgram* 29b⟩≡ (12b 13d 26)

```
        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 14a 26) 30b ▷

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

Defines:
_xorshift, used in chunks 10a and 13–15.

Now we can generate the next 32bit random number.

30b ⟨*xorshift-prng* 30a⟩+≡ (12c 14a 26) ◁ 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 14a 26) ◁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, 17, 22c, 24, 25a, 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 ⟨*print* 32a⟩≡ (29a) 32b ▷

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

Defines:
_print, used in chunks 11b, 12a, and 23–25.

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 ⟨*print* 32a⟩+≡ (29a) ◁ 32a 32c ▷

```
.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 ⟨*print* 32a⟩+≡ (29a) ◁ 32b 32d ▷

```
      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 ⟨*print* 32a⟩+≡ (29a) ◁ 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 17.

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
```

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 RDX) 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 22c and 24.

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

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This is free software, and you are welcome to redistribute it
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```

```
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