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 18 30)

```
bits 64

⟨license 74⟩

      global        _start
      pagesize      equ 4096
```

Defines:
`_start`, used in chunks 9c, 14c, and 19a.
`pagesize`, used in chunks 9, 13, 14, 16d, 19, 20a, 23, 24, and 30.

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 18 30)

```
_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, 15c, and 21.

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 ⟨*data-udata* 9a⟩≡ (12c 18 30)

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

Defines:
`data`, used in chunks 9–11, 14d, 17, 19a, 20a, 23d, 29c, and 30.
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 18)

```
        scratch:        resb 32
```

Defines:
`scratch`, used in chunks 11c, 12a, 17, 21, 25c, 26c, and 28.

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 14c) 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 14c) ◁ 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 14c) ◁ 9e 10a ▷

```
        rdtsc
        mov         EDX,EAX
```

Now we call _xorshift to fill the data area.

10a ⟨*init-random-data* 9d⟩+≡ (10b 14c) ◁9f

```
        call        _xorshift
```

Uses _xorshift 34a.

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 18 25a)

```
        slf:            db 0x0a
```

Defines:
`slf`, used in chunks 11d, 12a, 17, 21, and 29a.

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` 36a 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` 37a 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` 35b 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` 35b, `_print` 36a, `_printdu64bit` 37a, `scratch` 9b, `slf` 11a, and `suncached` 11f.

At last we exit the program.

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

⟨*exitProgram* 33b⟩

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
⟨data-udata 9a⟩
⟨scratch-udata 9b⟩

section .text
⟨cachetiming-program 9c⟩

⟨calculate-cache-access-time 8⟩

⟨xorshift-prng 34a⟩

⟨utilities 33a⟩
```

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

13a ⟨*clearcache* 13a⟩≡ (18)

```
_clearcache:
      mov      RCX,256
      cld
.nextflush:
      clflush  [RDI]
      add      RDI,RSI
      loop     .nextflush
      lfence
      ret
```

Defines:
`_clearcache`, used in chunks 13b and 23c.

Now we add this to our program.

13b ⟨*cachereadbyte-program* 13b⟩≡ (18) 14c ▷

```
      mov      RDI,probe
      mov      RSI,pagesize
      call     _clearcache
```

Uses `_clearcache` 13a 20b, `pagesize` 5, and `probe` 14a 19b.

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.

14a ⟨*probe-udata* 14a⟩≡ (18)

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

Defines:
`probe`, used in chunks 13, 14, 16d, 19c, 20a, 23, and 24.
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).

14b ⟨*init-random-probe* 14b⟩≡ (14c)

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

Uses `_xorshift` 34a, `pagesize` 5, and `probe` 14a 19b.

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

14c ⟨*cachereadbyte-program* 13b⟩+≡ (18) ◁13b 14d▷

```
_start:
⟨init-random-data 9d⟩
⟨init-random-probe 14b⟩
```

Uses `_start` 5.

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

14d ⟨*cachereadbyte-program* 13b⟩+≡ (18) ◁14c 14e▷

```
mov       RDI,data
xor       RAX,RAX
mov       AL,[RDI]
```

Uses `data` 9a.

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

14e ⟨*cachereadbyte-program* 13b⟩+≡ (18) ◁14d 16d▷

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

Uses `pagesize` 5 and `probe` 14a 19b.

Now we read the datum back via the cache access times. For this we create a subroutine.

2.4.4 Read a Byte from the Cache

Parameters

RDI	the address of the probe memory
RSI	the step size in the probe memory
RDX	a scratch area to keep the detected cache access times (256 * 8 bytes)

Return

RAX	the read byte indirectly from the cache access times

15a ⟨*readcachebyte* 15a⟩≡ (18) 15b▷

```
_readcachebyte:
⟨enterstackframe 33c⟩
```

Defines:
_readcachebyte, used in chunk 16d.

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

15b ⟨*readcachebyte* 15a⟩+≡ (18) ◁15a 15c▷

```
      sub       RSP,40
      mov       [RBP-8],RDI
      mov       [RBP-16],RSI
      mov       [RBP-24],RDX
      mov       [RBP-32],RDX
```

Now we can start detecting the cache access times.

15c ⟨*readcachebyte* 15a⟩+≡ (18) ◁15b 16a▷

```
      mov       RCX,256
.nextcacheread:
      mov       [RBP-40],RCX
      call      _calccachetime
      mov       RDX,[RBP-32]
      mov       [RDX],RAX
      add       RDX,8
      mov       [RBP-32],RDX
      mov       RDI,[RBP-8]
      add       RDI,[RBP-16]
      mov       [RBP-8],RDI
      mov       RCX,[RBP-40]
      loop      .nextcacheread
```

Uses _calccachetime 8.

After we determined all cache access times we can now find the lowest access time and with this the possible byte.

16a ⟨*readcachebyte* 15a⟩+≡ (18) ◁15c 16b▷
```
        mov     R8,0xffffffffffffffff
        mov     R9,0
        xor     RCX,RCX
        mov     RSI,[RBP-24]
  .nexttry:
        lodsq
        cmp     RAX,R8
        ja      .nohit
        mov     R8,RAX
        mov     R9,RCX
  .nohit:
        inc     RCX
        cmp     RCX,256
        jb      .nexttry
        mov     RAX,R9
```

At the end we clean up the stack again and return to the caller.

16b ⟨*readcachebyte* 15a⟩+≡ (18) ◁16a
```
  ⟨leavestackframe 33d⟩
        ret
```

2.4.5 The Whole Program to Read a Byte from Cache

Before we can start using our new subroutine `_readcachebyte` we need to define a data area for the cache access times.

16c ⟨*timings-udata* 16c⟩≡ (18)
```
        timings         resq 256
```

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

16d ⟨*cachereadbyte-program* 13b⟩+≡ (18) ◁14e 17b▷
```
        mov     RDI,probe
        mov     RSI,pagesize
        mov     RDX,timings
        call    _readcachebyte
```
Uses `_readcachebyte` 15a, `pagesize` 5, and `probe` 14a 19b.

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

17a ⟨*cachereadbyte-rodata* 17a⟩≡ (18)

```
sreadbyte:     db "Byte read via cache access: ",0x00
sexpectedbyte: db "Expected byte from data:    ",0x00
```

Uses `data` 9a.

We save the value from `RAX` (only `AL` is interesting to us) to the stack and print out the text.

17b ⟨*cachereadbyte-program* 13b⟩+≡ (18) ◁16d 17c▷

```
push       RAX
mov        RDI,sreadbyte
call       _print
```

Uses `_print` 36a.

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

17c ⟨*cachereadbyte-program* 13b⟩+≡ (18) ◁17b 17d▷

```
pop        RDI
mov        RSI,scratch
call       _printh8bit
mov        RDI,1
mov        RSI,slf
call       _nprint
```

Uses `_nprint` 35b, `_printh8bit` 40a, `scratch` 9b, and `slf` 11a.

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

17d ⟨*cachereadbyte-program* 13b⟩+≡ (18) ◁17c 17e▷

```
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` 35b, `_print` 36a, `_printh8bit` 40a, `data` 9a, `scratch` 9b, and `slf` 11a.

At last we exit the program.

17e ⟨*cachereadbyte-program* 13b⟩+≡ (18) ◁17d

⟨*exitProgram* 33b⟩

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

18 ⟨*cachereadbyte.asm* 18⟩≡

```
⟨preamble 5⟩

section .rodata
⟨common-rodata 11a⟩
⟨cachereadbyte-rodata 17a⟩

section .bss
⟨data-udata 9a⟩
⟨probe-udata 14a⟩
⟨scratch-udata 9b⟩
⟨timings-udata 16c⟩

section .text
⟨cachereadbyte-program 13b⟩

⟨clearcache 13a⟩

⟨calculate-cache-access-time 8⟩

⟨readcachebyte 15a⟩

⟨xorshift-prng 34a⟩

⟨utilities 33a⟩
```

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.

19a ⟨*cacheread-program* 19a⟩≡ (30) 19c ▷

```
_start:
      mov       RDI,data
      mov       RSI,pagesize
      rdtsc
      mov       EDX,EAX
      call      _xorshift
```

Uses `_start` 5, `_xorshift` 34a, `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.

19b ⟨*cacheread-udata* 19b⟩≡ (30) 23a ▷

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

Defines:
`probe`, used in chunks 13, 14, 16d, 19c, 20a, 23, and 24.

Uses `pagesize` 5.

Next we fill this area also with some random data.

19c ⟨*cacheread-program* 19a⟩+≡ (30) ◁ 19a 24e ▷

```
      mov       RDI,probe
      mov       RAX,pagesize
      mov       RCX,256
      mul       RCX
      mov       RSI,RCX
      rdtsc
      mov       EDX,EAX
      call      _xorshift
```

Uses `_xorshift` 34a, `pagesize` 5, and `probe` 14a 19b.

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`.

20a ⟨*cacheread-sample* 20a⟩≡

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

Uses `data` 9a, `pagesize` 5, and `probe` 14a 19b.

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

20b ⟨*clear-cache* 20b⟩≡ (30)

```
  _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 chunks 13b and 23c.

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

21 ⟨*detect-cache-area-time* 21⟩≡ (30)

```
_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 22.

Uses `_calccachetime` 8, `_nprint` 35b, `_printdu64bit` 37a, `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

22 ⟨*detect-byte* 22⟩≡ (30)

```
_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 21.

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.

23a ⟨*cacheread-udata* 19b⟩+≡ (30) ◁19b 25c▷

```
        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.

23b ⟨*readback-udata* 23b⟩≡ (30)

```
  ;      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.

23c ⟨*cache-readback* 23c⟩≡ (30) 23d▷

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

Defines:
  `_cachereadback`, used in chunk 24e.
Uses `_clearcache` 13a 20b, `pagesize` 5, and `probe` 14a 19b.

Next we read in the data from the array.

23d ⟨*cache-readback* 23c⟩+≡ (30) ◁23c 24a▷

```
        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.

24a ⟨*cache-readback* 23c⟩+≡ (30) ◁23d 24b▷

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

Uses `pagesize` 5 and `probe` 14a 19b.

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.

24b ⟨*cache-readback* 23c⟩+≡ (30) ◁24a 24c▷

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

Uses `pagesize` 5 and `probe` 14a 19b.

Next we store the read byte into our result array.

24c ⟨*cache-readback* 23c⟩+≡ (30) ◁24b 24d▷

```
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.

24d ⟨*cache-readback* 23c⟩+≡ (30) ◁24c

```
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.

24e ⟨*cacheread-program* 19a⟩+≡ (30) ◁19c 29c▷

```
call    _cachereadback
```

Uses `_cachereadback` 23c.

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.

25a ⟨*cacheread-rodata* 25a⟩≡ (30)

```
⟨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 28.
`sblank`, used in chunks 26c and 28.
`sresetstyle`, used in chunks 28 and 29a.
`sseparator`, used in chunk 27b.

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

25b ⟨*print-comparision16* 25b⟩≡ (30) 26a ▷

```
_printcompare16:
```

Defines:
`_printcompare16`, used in chunk 29b.

Additionally we need some scratch area for the printing.

25c ⟨*cacheread-udata* 19b⟩+≡ (30) ◁ 23a

```
    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.

26a ⟨*print-comparision16* 25b⟩+≡ (30) ◁25b 26b▷

```
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.

26b ⟨*print-comparision16* 25b⟩+≡ (30) ◁26a 26c▷

```
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` (27a).

26c ⟨*print-comparision16* 25b⟩+≡ (30) ◁26b 27a▷

```
    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` 35b, `_printh8bit` 40a, `sblank` 25a, and `scratch` 9b.

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

27a ⟨*print-comparision16* 25b⟩+≡ (30) ◁26c 27b▷

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

Uses `_print` 36a.

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

27b ⟨*print-comparision16* 25b⟩+≡ (30) ◁27a 27c▷

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

Uses `_print` 36a and `sseparator` 25a.

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

27c ⟨*print-comparision16* 25b⟩+≡ (30) ◁27b 28▷

```
      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.

28 ⟨*print-comparision16* 25b⟩+≡ (30) ◁27c 29a▷

```
        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` 35b, `_print` 36a, `_printh8bit` 40a, `sbgred` 25a, `sblank` 25a, `scratch` 9b, and `sresetstyle` 25a.

29a ⟨*print-comparision16* 25b⟩+≡ (30) ◁28
```
      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` 35b, `_print` 36a, `slf` 11a, and `sresetstyle` 25a.

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

29b ⟨*print-comparision* 29b⟩≡ (30)
```
 _printcompare:
      mov     RDX,16
      call    _printcompare16
      ret
```
Defines:
`_printcompare`, used in chunk 29c.
Uses `_printcompare16` 25b.

TBD

29c ⟨*cacheread-program* 19a⟩+≡ (30) ◁24e
```
      mov     RDI,data
      mov     RSI,result
      call    _printcompare
```
Uses `_printcompare` 29b and `data` 9a.

30 ⟨*cacheread.asm* 30⟩≡

```
⟨preamble 5⟩

section .bss
     align          pagesize
⟨data-udata 9a⟩
⟨cacheread-udata 19b⟩
⟨readback-udata 23b⟩

section .data
⟨cacheread-rodata 25a⟩

section .text
⟨cacheread-program 19a⟩

⟨exitProgram 33b⟩

⟨print-comparision 29b⟩

⟨print-comparision16 25b⟩

⟨cache-readback 23c⟩

⟨clear-cache 20b⟩

⟨calculate-cache-access-time 8⟩

⟨detect-cache-area-time 21⟩

⟨detect-byte 22⟩

⟨xorshift-prng 34a⟩

⟨utilities 33a⟩
```

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

33a ⟨*utilities* 33a⟩≡ (12c 18 30)

```
⟨nprint 35b⟩

⟨print 36a⟩

⟨printdu64bit 37a⟩

⟨printh8bit 40a⟩
```

4.2 Common Chunks

4.2.1 Exit Program

This chunk ends the program with exit code 0.

33b ⟨*exitProgram* 33b⟩≡ (12b 17e 30)

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

4.2.2 Stack Frame

A chunk to create a stack frame.

33c ⟨*enterstackframe* 33c⟩≡ (15a)

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

A chunk to clean up the created stack frame.

33d ⟨*leavestackframe* 33d⟩≡ (16b)

```
      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

34a ⟨*xorshift-prng* 34a⟩≡ (12c 18 30) 34b ▷

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

Defines:
`_xorshift`, used in chunks 10a, 14b, and 19.

Now we can generate the next 32bit random number.

34b ⟨*xorshift-prng* 34a⟩+≡ (12c 18 30) ◁ 34a 35a ▷

```
.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.

35a ⟨*xorshift-prng* 34a⟩+≡ (12c 18 30) ◁34b

```
        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

35b ⟨*nprint* 35b⟩≡ (33a)

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

Defines:
_nprint, used in chunks 11d, 12a, 17, 21, 26c, 28, 29a, 36d, 39b, and 40c.

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`

36a ⟨*print* 36a⟩≡ (33a) 36b ▷

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

Defines:
`_print`, used in chunks 11b, 12a, 17, and 27–29.

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.

36b ⟨*print* 36a⟩+≡ (33a) ◁ 36a 36c ▷

```
.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.

36c ⟨*print* 36a⟩+≡ (33a) ◁ 36b 36d ▷

```
      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`.

36d ⟨*print* 36a⟩+≡ (33a) ◁ 36c

```
      call      _nprint
      ret
```

Uses `_nprint` 35b.

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

37a ⟨*printdu64bit* 37a⟩≡ (33a) 37b ▷

```
_printdu64bit:
        mov     RAX,RDI
        mov     RDI,RSI
        mov     R8,RDI
        mov     RCX,10
        cld
```

Defines:
`_printdu64bit`, used in chunks 11c, 12a, and 21.

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.

37b ⟨*printdu64bit* 37a⟩+≡ (33a) ◁ 37a 37c ▷

```
.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`.

37c ⟨*printdu64bit* 37a⟩+≡ (33a) ◁ 37b 38a ▷

```
        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.

38a ⟨*printdu64bit* 37a⟩+≡ (33a) ◁37c 38b▷

```
        xchg      RDX,RAX
        add       AL,'0'
        stosb
```

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

38b ⟨*printdu64bit* 37a⟩+≡ (33a) ◁38a 38c▷

```
        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.

38c ⟨*printdu64bit* 37a⟩+≡ (33a) ◁38b 38d▷

```
  .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.

38d ⟨*printdu64bit* 37a⟩+≡ (33a) ◁38c 39a▷

```
        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.

39a ⟨*printdu64bit* 37a⟩+≡ (33a) ◁38d 39b▷

```
.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.

39b ⟨*printdu64bit* 37a⟩+≡ (33a) ◁39a

```
        mov     RSI,R8
        mov     RDI,RDX
        call    _nprint
        ret
```

Uses _nprint 35b.

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

40a ⟨*printh8bit* 40a⟩≡ (33a) 40b ▷

```
_printh8bit:
        xor     RAX,RAX
        mov     AX,DI
        xor     AH,AH
        mov     R8,RAX
        mov     RDI,RSI
        cld
```

Defines:
_printh8bit, used in chunks 17, 26c, and 28.

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.

40b ⟨*printh8bit* 40a⟩+≡ (33a) ◁ 40a 40c ▷

```
        shr     AL,4
        and     AL,0x0f
        call    .printh4bit
```

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

40c ⟨*printh8bit* 40a⟩+≡ (33a) ◁ 40b

```
        mov     RAX,R8
        and     AL,0x0f
        call    .printh4bit
        mov     RDI,2
        call    _nprint
        ret
    ⟨printh8bit.printh4bit 41a⟩
```

Uses _nprint 35b.

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

41a ⟨*printh8bit.printh4bit* 41a⟩≡ (40c) 41b ▷

```
.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'`.

41b ⟨*printh8bit.printh4bit* 41a⟩+≡ (40c) ◁ 41a 41c ▷

```
      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.

41c ⟨*printh8bit.printh4bit* 41a⟩+≡ (40c) ◁ 41b 41d ▷

```
.printa2f:
      sub      AL,10
      add      AL,'a'
```

Now we store the character into the storage area.

41d ⟨*printh8bit.printh4bit* 41a⟩+≡ (40c) ◁ 41c

```
.printout:
      stosb
      ret
```

A Glossary

x86 x86 denotes a microprocessor architecture based on the 8086/8088 34

B Acronyms

ASCII American Standard Code for Information Interchange 38

LF line feed 11, 17

RNG random number generator 34

C x86-Instructions

D Code Chunks

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