Meltdown and Spectre Samples

Written in Assembly

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April 2, 2018

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1.1 Overview

TBD

1.2 Conventions

1.2.1 Introduction

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

1.2.2 Data Sections

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

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

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

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

1.3 Nasm

TBD

5 ⟨*preamble* 5⟩≡ (12c 20 23 35)

```
bits 64

⟨license 80⟩

        global          _start
        pagesize        equ 4096
```

Defines:
`_start`, used in chunks 9c, 14c, and 24a.
`pagesize`, used in chunks 9, 13, 14, 18b, 24, 25a, 28, 29, and 35.

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 20 23 35)

```
_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 26.

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 20 23 35)

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

Defines:
`data`, used in chunks 9–11, 14d, 18c, 19c, 24a, 25a, 28d, 34c, and 35.
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 20 23)

```
        scratch:        resb 32
```

Defines:
`scratch`, used in chunks 11c, 12a, 19, 26, 30c, 31c, and 33.

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 40a.

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 20 23 30a)

```
slf:          db 0x0a
```

Defines:
slf, used in chunks 11d, 12a, 19, 26, and 34a.

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 42a 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 43a 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 41b 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` 41b, `_print` 42a, `_printdu64bit` 43a, `scratch` 9b, `slf` 11a, and `suncached` 11f.

At last we exit the program.

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

⟨*exitProgram* 39b⟩

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 40a⟩

⟨utilities 39a⟩
```

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⟩≡ (20 23)

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

Defines:
`_clearcache`, used in chunks 13b and 28c.

Now we add this to our program.

13b ⟨*cachereadbyte-program* 13b⟩≡ (20 23) 14c ▷

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

Uses `_clearcache` 13a 25b, `pagesize` 5, and `probe` 14a 24b.

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⟩≡ (20 23)

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

Defines:
probe, used in chunks 13, 14, 18b, 24c, 25a, 28, and 29.
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 40a, pagesize 5, and probe 14a 24b.

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

14c ⟨*cachereadbyte-program* 13b⟩+≡ (20 23) ◁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⟩+≡ (20 23) ◁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⟩+≡ (20 23) ◁14d 18b▷

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

Uses pagesize 5 and probe 14a 24b.

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

2.4.4 Read a Byte from the Cache

First we create a subroutine to read the cache access timings for the probe area.

Parameters

`RDI` the address of the probe memory

`RSI` the step size in the probe memory

`RDX` an area to keep the detected cache access times (256 * 8 bytes)

15a ⟨*readcachetiming* 15a⟩≡ (20 23) 15b ▷

```
  _readcachetiming:
  ⟨enterstackframe 39c⟩
```

Defines:
`_readcachetiming`, used in chunk 18b.

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

15b ⟨*readcachetiming* 15a⟩+≡ (20 23) ◁ 15a 15c ▷

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

Now we can start detecting the cache access times.

15c ⟨*readcachetiming* 15a⟩+≡ (20 23) ◁ 15b 16 ▷

```
        mov      RCX,256
  .nextcacheread:
        mov      [RBP-32],RCX
        call     _calccachetime
        mov      RDX,[RBP-24]
        mov      [RDX],RAX
        add      RDX,8
        mov      [RBP-24],RDX
        mov      RDI,[RBP-8]
        add      RDI,[RBP-16]
        mov      [RBP-8],RDI
        mov      RCX,[RBP-32]
        loop     .nextcacheread
```

Uses `_calccachetime` 8.

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

16 ⟨*readcachetiming* 15a⟩+≡ (20 23) ◁15c

```
⟨leavestackframe 39d⟩
      ret
```

After we determined all cache access times we can now find the lowest access time and with this the possible byte. We return two results from this subroutine, in `AL` the byte with the lowest cache access time and in `AH` the count of the lowest cache access time. Only if `AH` is 1 then the value in `AL` is valid.

Parameters

`RDI` the area with the detected cache access times (256 * 8 bytes)

Return

`AL` the read byte (in `AL`) with the lowest cache access time

`AH` the number of bytes read with the lowest cache access time

17 ⟨*analyzecachemintiming* 17⟩≡ (20)

```
_analyzecachetiming:
     push      RDI
     mov       R8,0xffffffffffffff
     xor       R9,R9
     xor       RCX,RCX
     mov       RSI,RDI
.nexttry:
     lodsq
     cmp       RAX,R8
     ja        .nohit
     mov       R8,RAX
     mov       R9,RCX
.nohit:
     inc       RCX
     cmp       RCX,256
     jb        .nexttry
     xor       RCX,RCX
     pop       RSI
.nextcount:
     lodsq
     cmp       RAX,R8
     ja        .nomin
     inc       R10
.nomin:
     inc       RCX
     cmp       RCX,256
     jb        .nextcount
     mov       RAX,R10
     shl       RAX,8
```

```
mov       AL,R9b
ret
```

2.4.5 The Whole Program to Read a Byte from Cache

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

18a ⟨*timings-udata* 18a⟩≡ (20 23)

```
timings       resq 256
```

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

18b ⟨*cachereadbyte-program* 13b⟩+≡ (20 23) ◁14e 18d▷

```
mov       RDI,probe
mov       RSI,pagesize
mov       RDX,timings
call      _readcachetiming
mov       RDI,timings
call      _analyzecachetiming
```

Uses `_readcachetiming` 15a, `pagesize` 5, and `probe` 14a 24b.

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

18c ⟨*cachereadbyte-rodata* 18c⟩≡ (20 23)

```
sreadbyte:     db "Byte read via cache access:     ",0x00
ssountbyte:    db "Count of bytes with min timing: ",0x00
sexpectedbyte: db "Expected byte from data:        ",0x00
```

Uses `data` 9a.

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

18d ⟨*cachereadbyte-program* 13b⟩+≡ (20 23) ◁18b 19a▷

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

Uses `_print` 42a.

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

19a ⟨*cachereadbyte-program* 13b⟩+≡ (20 23) ◁18d 19b▷

```
pop     RDI
push    RDI
and     RDI,0xff
mov     RSI,scratch
call    _printh8bit
mov     RDI,1
mov     RSI,slf
call    _nprint
```

Uses `_nprint` 41b, `_printh8bit` 46a, `scratch` 9b, and `slf` 11a.

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

19b ⟨*cachereadbyte-program* 13b⟩+≡ (20 23) ◁19a 19c▷

```
mov     RDI,ssountbyte
call    _print
pop     RDI
shr     RDI,8
and     RDI,0xff
mov     RSI,scratch
call    _printdu64bit
mov     RDI,1
mov     RSI,slf
call    _nprint
```

Uses `_nprint` 41b, `_print` 42a, `_printdu64bit` 43a, `scratch` 9b, and `slf` 11a.

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

19c ⟨*cachereadbyte-program* 13b⟩+≡ (20 23) ◁19b 19d▷

```
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` 41b, `_print` 42a, `_printh8bit` 46a, `data` 9a, `scratch` 9b, and `slf` 11a.

At last we exit the program.

19d ⟨*cachereadbyte-program* 13b⟩+≡ (20 23) ◁19c

⟨*exitProgram* 39b⟩

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

20 ⟨*cachereadbyte.asm* 20⟩≡
```
⟨preamble 5⟩

section .rodata
⟨common-rodata 11a⟩
⟨cachereadbyte-rodata 18c⟩

section .bss
⟨data-udata 9a⟩
⟨probe-udata 14a⟩
⟨scratch-udata 9b⟩
⟨timings-udata 18a⟩

section .text
⟨cachereadbyte-program 13b⟩

⟨clearcache 13a⟩

⟨calculate-cache-access-time 8⟩

⟨readcachetiming 15a⟩

⟨analyzecachemintiming 17⟩

⟨xorshift-prng 40a⟩

⟨utilities 39a⟩
```

2.4.6 Improve Cache Access Time Analysis

As we can see – when running the program `cachereadbyte` – the result is not always as clear as it could be. Simply getting the lowest cache access time seems not to be enough.

Sample outputs of the program are

```
$ bin/cachereadbyte
Byte read via cache access:     2b
Count of bytes with min timing: 1
Expected byte from data:        2b
$ bin/cachereadbyte
Byte read via cache access:     ff
Count of bytes with min timing: 11
Expected byte from data:        b3
$ bin/cachereadbyte
Byte read via cache access:     2f
Count of bytes with min timing: 1
Expected byte from data:        87
$
```

So we have to improve our cache time detection routine. We will change the implementation of the chunk 17 to define a thrshold that is a little bit above the min access time and run the cache detection routine multiple times if no clear result is returned.

First start with the subrotuine to analyze the cache access timing. We define a threshold 25 % above the minimum cache access time.

First we search for the minimum cache access time.

Parameters

`RDI` the area with the detected cache access times (256 * 8 bytes)

Return

`AL` the first byte (in `AL`) with a cache access time below the threshold

`AH` the number of bytes read with a cache access time below the threshold

21 ⟨*analyzecachesimpthrestiming* 21⟩≡ (23) 22a ▷

```
  _analyzecachetiming:
        push      RDI
        mov       R8,0xffffffffffffff
        xor       RCX,RCX
        mov       RSI,RDI
  .nextmin:
        lodsq
        cmp       RAX,R8
```

```
        ja      .nonewmin
        mov     R8,RAX
  .nonewmin:
        inc     RCX
        cmp     RCX,256
        jb      .nextmin
```

Now we have the minimum cache access time in R8. Next we will add $\frac{1}{4}$ to this to have our threshold.

22a ⟨*analyzecachesimpthrestiming* 21⟩+≡ (23) ◁21 22b▷

```
        mov     RAX,R8
        shr     RAX,4
        add     R8,RAX
```

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

22b ⟨*analyzecachesimpthrestiming* 21⟩+≡ (23) ◁22a

```
        pop     RDI
        xor     RCX,RCX
        xor     R9,R9
  .nextbyte:
        lodsq
        cmp     RAX,R8
        ja      .nonewbyte
        inc     R9
        mov     R10,RCX
  .nonewbyte:
        inc     RCX
        cmp     RCX,256
        jb      .nextbyte
        mov     RAX,R9
        shl     RAX,8
        mov     AL,R10b
        ret
```

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

23 ⟨*cachereadbyte2.asm* 23⟩≡

```
⟨preamble 5⟩

section .rodata
⟨common-rodata 11a⟩
⟨cachereadbyte-rodata 18c⟩

section .bss
⟨data-udata 9a⟩
⟨probe-udata 14a⟩
⟨scratch-udata 9b⟩
⟨timings-udata 18a⟩

section .text
⟨cachereadbyte-program 13b⟩

⟨clearcache 13a⟩

⟨calculate-cache-access-time 8⟩

⟨readcachetiming 15a⟩

⟨analyzecachesimpthrestiming 21⟩

⟨xorshift-prng 40a⟩

⟨utilities 39a⟩
```

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.

24a ⟨*cacheread-program* 24a⟩≡ (35) 24c ▷

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

Uses `_start` 5, `_xorshift` 40a, `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.

24b ⟨*cacheread-udata* 24b⟩≡ (35) 28a ▷

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

Defines:
`probe`, used in chunks 13, 14, 18b, 24c, 25a, 28, and 29.

Uses `pagesize` 5.

Next we fill this area also with some random data.

24c ⟨*cacheread-program* 24a⟩+≡ (35) ◁ 24a 29e ▷

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

Uses `_xorshift` 40a, `pagesize` 5, and `probe` 14a 24b.

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`.

25a ⟨*cacheread-sample* 25a⟩≡

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

Uses `data` 9a, `pagesize` 5, and `probe` 14a 24b.

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

25b ⟨*clear-cache* 25b⟩≡ (35)

```
_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 28c.

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

26 ⟨*detect-cache-area-time* 26⟩≡ (35)

```
_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 27.
Uses `_calccachetime` 8, `_nprint` 41b, `_printdu64bit` 43a, `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

27 ⟨*detect-byte* 27⟩≡ (35)

```
_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` 26.

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.

28a ⟨*cacheread-udata* 24b⟩+≡ (35) ◁24b 30c▷

```
        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.

28b ⟨*readback-udata* 28b⟩≡ (35)

```
  ;     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.

28c ⟨*cache-readback* 28c⟩≡ (35) 28d▷

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

Defines:
`_cachereadback`, used in chunk 29e.

Uses `_clearcache` 13a 25b, `pagesize` 5, and `probe` 14a 24b.

Next we read in the data from the array.

28d ⟨*cache-readback* 28c⟩+≡ (35) ◁28c 29a▷

```
        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.

29a ⟨*cache-readback* 28c⟩+≡ (35) ◁28d 29b▷
```
mov     RDX,pagesize
mul     RDX
mov     RSI,probe
mov     AL,[RSI+RAX]
```
Uses `pagesize` 5 and `probe` 14a 24b.

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.

29b ⟨*cache-readback* 28c⟩+≡ (35) ◁29a 29c▷
```
mov     RDI,probe
mov     RSI,pagesize
mov     RDX,timing
push    R8
call    _detectbytebycl
pop     R8
```
Uses `pagesize` 5 and `probe` 14a 24b.

Next we store the read byte into our result array.

29c ⟨*cache-readback* 28c⟩+≡ (35) ◁29b 29d▷
```
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.

29d ⟨*cache-readback* 28c⟩+≡ (35) ◁29c
```
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.

29e ⟨*cacheread-program* 24a⟩+≡ (35) ◁24c 34c▷
```
call    _cachereadback
```
Uses `_cachereadback` 28c.

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.

30a ⟨*cacheread-rodata* 30a⟩≡ (35)

```
  ⟨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 33.
  `sblank`, used in chunks 31c and 33.
  `sresetstyle`, used in chunks 33 and 34a.
  `sseparator`, used in chunk 32b.

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

30b ⟨*print-comparision16* 30b⟩≡ (35) 31a ▷

```
  _printcompare16:
```

Defines:
  `_printcompare16`, used in chunk 34b.

Additionally we need some scratch area for the printing.

30c ⟨*cacheread-udata* 24b⟩+≡ (35) ◁ 28a

```
      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.

31a ⟨*print-comparision16* 30b⟩+≡ (35) ◁30b 31b▷

```
        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.

31b ⟨*print-comparision16* 30b⟩+≡ (35) ◁31a 31c▷

```
        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 (32a).

31c ⟨*print-comparision16* 30b⟩+≡ (35) ◁31b 32a▷

```
        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 41b, _printh8bit 46a, sblank 30a, and scratch 9b.

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

32a ⟨*print-comparision16* 30b⟩+≡ (35) ◁31c 32b▷

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

Uses _print 42a.

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

32b ⟨*print-comparision16* 30b⟩+≡ (35) ◁32a 32c▷

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

Uses _print 42a and sseparator 30a.

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

32c ⟨*print-comparision16* 30b⟩+≡ (35) ◁32b 33▷

```
     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.

33 ⟨*print-comparision16* 30b⟩+≡ (35) ◁32c 34a▷

```
      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` 41b, `_print` 42a, `_printh8bit` 46a, `sbgred` 30a, `sblank` 30a, `scratch` 9b, and `sresetstyle` 30a.

34a ⟨*print-comparision16* 30b⟩+≡ (35) ◁33

```
        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` 41b, `_print` 42a, `slf` 11a, and `sresetstyle` 30a.

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

34b ⟨*print-comparision* 34b⟩≡ (35)

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

Defines:
`_printcompare`, used in chunk 34c.
Uses `_printcompare16` 30b.

TBD

34c ⟨*cacheread-program* 24a⟩+≡ (35) ◁29e

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

Uses `_printcompare` 34b and `data` 9a.

35 ⟨*cacheread.asm* 35⟩≡

```
⟨preamble 5⟩

section .bss
    align       pagesize
⟨data-udata 9a⟩
⟨cacheread-udata 24b⟩
⟨readback-udata 28b⟩

section .data
⟨cacheread-rodata 30a⟩

section .text
⟨cacheread-program 24a⟩

⟨exitProgram 39b⟩

⟨print-comparision 34b⟩

⟨print-comparision16 30b⟩

⟨cache-readback 28c⟩

⟨clear-cache 25b⟩

⟨calculate-cache-access-time 8⟩

⟨detect-cache-area-time 26⟩

⟨detect-byte 27⟩

⟨xorshift-prng 40a⟩

⟨utilities 39a⟩
```

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

39a ⟨*utilities* 39a⟩≡ (12c 20 23 35)

⟨*nprint* 41b⟩

⟨*print* 42a⟩

⟨*printdu64bit* 43a⟩

⟨*printh8bit* 46a⟩

4.2 Common Chunks

4.2.1 Exit Program

This chunk ends the program with exit code 0.

39b ⟨*exitProgram* 39b⟩≡ (12b 19d 35)

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

4.2.2 Stack Frame

A chunk to create a stack frame.

39c ⟨*enterstackframe* 39c⟩≡ (15a)

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

A chunk to clean up the created stack frame.

39d ⟨*leavestackframe* 39d⟩≡ (16)

```
      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

40a ⟨*xorshift-prng* 40a⟩≡ (12c 20 23 35) 40b ▷

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

Defines:
_xorshift, used in chunks 10a, 14b, and 24.

Now we can generate the next 32bit random number.

40b ⟨*xorshift-prng* 40a⟩+≡ (12c 20 23 35) ◁ 40a 41a ▷

```
.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.

41a ⟨*xorshift-prng* 40a⟩+≡ (12c 20 23 35) ◁40b

```
        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`

41b ⟨*nprint* 41b⟩≡ (39a)

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

Defines:
`_nprint`, used in chunks 11d, 12a, 19, 26, 31c, 33, 34a, 42d, 45b, and 46c.

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

42a ⟨*print* 42a⟩≡ (39a) 42b ▷

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

Defines:
_print, used in chunks 11b, 12a, 18, 19, and 32–34.

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.

42b ⟨*print* 42a⟩+≡ (39a) ◁ 42a 42c ▷

```
.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.

42c ⟨*print* 42a⟩+≡ (39a) ◁ 42b 42d ▷

```
      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`.

42d ⟨*print* 42a⟩+≡ (39a) ◁ 42c

```
      call      _nprint
      ret
```

Uses _nprint 41b.

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

43a ⟨*printdu64bit* 43a⟩≡ (39a) 43b ▷

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

Defines:
`_printdu64bit`, used in chunks 11c, 12a, 19b, and 26.

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.

43b ⟨*printdu64bit* 43a⟩+≡ (39a) ◁ 43a 43c ▷

```
.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`.

43c ⟨*printdu64bit* 43a⟩+≡ (39a) ◁ 43b 44a ▷

```
      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.

44a ⟨*printdu64bit* 43a⟩+≡ (39a) ◁43c 44b▷

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

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

44b ⟨*printdu64bit* 43a⟩+≡ (39a) ◁44a 44c▷

```
        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.

44c ⟨*printdu64bit* 43a⟩+≡ (39a) ◁44b 44d▷

```
  .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.

44d ⟨*printdu64bit* 43a⟩+≡ (39a) ◁44c 45a▷

```
        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.

45a ⟨*printdu64bit* 43a⟩+≡ (39a) ◁44d 45b▷

```
.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.

45b ⟨*printdu64bit* 43a⟩+≡ (39a) ◁45a

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

Uses _nprint 41b.

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

46a ⟨*printh8bit* 46a⟩≡ (39a) 46b ▷

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

Defines:
_printh8bit, used in chunks 19, 31c, and 33.

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.

46b ⟨*printh8bit* 46a⟩+≡ (39a) ◁ 46a 46c ▷

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

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

46c ⟨*printh8bit* 46a⟩+≡ (39a) ◁ 46b

```
        mov     RAX,R8
        and     AL,0x0f
        call    .printh4bit
        mov     RDI,2
        call    _nprint
        ret
⟨printh8bit.printh4bit 47a⟩
```

Uses _nprint 41b.

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

47a ⟨*printh8bit.printh4bit* 47a⟩≡ (46c) 47b ▷

```
.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'`.

47b ⟨*printh8bit.printh4bit* 47a⟩+≡ (46c) ◁ 47a 47c ▷

```
      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.

47c ⟨*printh8bit.printh4bit* 47a⟩+≡ (46c) ◁ 47b 47d ▷

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

Now we store the character into the storage area.

47d ⟨*printh8bit.printh4bit* 47a⟩+≡ (46c) ◁ 47c

```
.printout:
      stosb
      ret
```

A Glossary

x86 x86 denotes a microprocessor architecture based on the 8086/8088 40

B Acronyms

ASCII American Standard Code for Information Interchange 44

LF line feed 11, 19

RNG random number generator 40

C x86-Instructions

D Code Chunks

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You may convey a work based on the Program, or the modifications to produce it from the Program, in the form of source code under the terms of section 4, provided that you also meet all of these conditions:

a) The work must carry prominent notices stating that you modified it, and giving a relevant date.

b) The work must carry prominent notices stating that it is released under this License and any conditions added under section

```
    7.  This requirement modifies the requirement in section 4 to
    "keep intact all notices".

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works, which are not by their nature extensions of the covered work,
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in an aggregate does not cause this License to apply to the other
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  6. Conveying Non-Source Forms.

  You may convey a covered work in object code form under the terms
of sections 4 and 5, provided that you also convey the
machine-readable Corresponding Source under the terms of this License,
in one of these ways:

    a) Convey the object code in, or embodied in, a physical product
    (including a physical distribution medium), accompanied by the
    Corresponding Source fixed on a durable physical medium
    customarily used for software interchange.

    b) Convey the object code in, or embodied in, a physical product
    (including a physical distribution medium), accompanied by a
    written offer, valid for at least three years and valid for as
    long as you offer spare parts or customer support for that product
    model, to give anyone who possesses the object code either (1) a
    copy of the Corresponding Source for all the software in the
    product that is covered by this License, on a durable physical
    medium customarily used for software interchange, for a price no
    more than your reasonable cost of physically performing this
    conveying of source, or (2) access to copy the
    Corresponding Source from a network server at no charge.
```

c) Convey individual copies of the object code with a copy of the written offer to provide the Corresponding Source. This alternative is allowed only occasionally and noncommercially, and only if you received the object code with such an offer, in accord with subsection 6b.

d) Convey the object code by offering access from a designated place (gratis or for a charge), and offer equivalent access to the Corresponding Source in the same way through the same place at no further charge. You need not require recipients to copy the Corresponding Source along with the object code. If the place to copy the object code is a network server, the Corresponding Source may be on a different server (operated by you or a third party) that supports equivalent copying facilities, provided you maintain clear directions next to the object code saying where to find the Corresponding Source. Regardless of what server hosts the Corresponding Source, you remain obligated to ensure that it is available for as long as needed to satisfy these requirements.

e) Convey the object code using peer-to-peer transmission, provided you inform other peers where the object code and Corresponding Source of the work are being offered to the general public at no charge under subsection 6d.

A separable portion of the object code, whose source code is excluded from the Corresponding Source as a System Library, need not be included in conveying the object code work.

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"Installation Information" for a User Product means any methods, procedures, authorization keys, or other information required to install and execute modified versions of a covered work in that User Product from a modified version of its Corresponding Source. The information must suffice to ensure that the continued functioning of the modified object code is in no case prevented or interfered with solely because modification has been made.

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```

```
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