

# Meltdown and Spectre Samples

Written in Assembly

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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>≡` (12 18)  
`bits 64`

`<license 60>`

```
global      _start
pagesize   equ 4096
```

Defines:

`_start`, used in chunks 9c and 13a.

`pagesize`, used in chunks 8, 9, 13, 14, 17b, and 18.



## 2 Cache Access Timing

### 2.1 Introduction

TBD

### 2.2 Detect Cache Access Time

#### 2.2.1 High Resolution Timer

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

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

7  $\langle tsc-64bit \ 7 \rangle \equiv$  (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.

### Parameters

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

```
8a  <calculate-cache-access-time 8a>≡ (12 18)
    _calccachetime:
        lfence
        <tsc-64bit 7>
        mov     R8,RAX
        mov     RCX,[RDI]
        lfence
        <tsc-64bit 7>
        sub     RAX,R8
        ret
```

Defines:

`_calccachetime`, used in chunks 10c, 11b, and 16.

## 2.3 Measure Cache Access Time

### 2.3.1 Setup

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

First we need some area in memory with data which we can later read from. This data area goes into the area `.bss` which contains uninitialized data. We align the data at a page boundary and reserve 2 pages for our data.

```
8b  <cache-data 8b>≡ (9b 18)
    data:           resb pagesize
```

Defines:

`data`, used in chunks 9–11, 13a, and 14b.

Uses `pagesize` 5.



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

9a  $\langle \text{scratch-data } 9a \rangle \equiv$  (9b)  
`scratch: resb 32`

Defines:

`scratch`, used in chunk 11.

9b  $\langle \text{cachetiming-udata } 9b \rangle \equiv$  (12)  
`align pagesize`  
 $\langle \text{cache-data } 8b \rangle$   
 $\langle \text{scratch-data } 9a \rangle$

Uses `pagesize` 5.

The program begins with the label `_start`.

9c  $\langle \text{cachetiming-program } 9c \rangle \equiv$  (12) 9d $\triangleright$   
`_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  $\langle \text{cachetiming-program } 9c \rangle + \equiv$  (12)  $\triangleleft 9c \ 9e \triangleright$   
`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.

9e  $\langle \text{cachetiming-program } 9c \rangle + \equiv$  (12)  $\triangleleft 9d \ 9f \triangleright$   
`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  $\langle \text{cachetiming-program } 9c \rangle + \equiv$  (12)  $\triangleleft 9e \ 9g \triangleright$   
`rdtsc`  
`mov EDX, EAX`

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

9g  $\langle \text{cachetiming-program } 9c \rangle + \equiv$  (12)  $\triangleleft 9f \ 10a \triangleright$   
`call _xorshift`

Uses `_xorshift` 22a.

### 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.

```
10a  <cachetiming-program 9c>+≡ (12) <9g 10b>
      mov      RDI,data
      Uses data 8b.
```

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).

```
10b  <cachetiming-program 9c>+≡ (12) <10a 10c>
      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.

```
10c  <cachetiming-program 9c>+≡ (12) <10b 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 and (as a helper) a carriage return (`CR`).

```
10d  <cachetiming-rodata 10d>≡ (12) 11c>
      scr:      db 0x0a
      scached:   db "Cached Access Time: ",0x00
      Defines:
      scached, used in chunk 10e.
      scr, used in chunk 11.
```

Now we can print the text.

```
10e  <cachetiming-program 9c>+≡ (12) <10c 11a>
      push     RAX
      mov      RDI,scached
      call     _print
      Uses _print 24a and scached 10d.
```

Then we restore the value and print the measured time to `stdout`. At last we append a **CR** to the output.

```
11a  <cachetiming-program 9c>+≡ (12) <10e 11b>
      pop     RDI
      mov     RSI,scratch
      call    _printdu64bit
      mov     RSI,scr
      mov     RDI,1
      call    _nprint
```

Uses `_nprint 23b`, `_printdu64bit 25a`, `scr 10d`, and `scratch 9a`.

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

```
11b  <cachetiming-program 9c>+≡ (12) <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 10d>+≡ (12) <10d
      suncached:    db "Uncached Access Time: ",0x00
```

Defines:

`suncached`, used in chunk `11d`.

```
11d  <cachetiming-program 9c>+≡ (12) <11b 11e>
      push    RAX
      mov     RDI,suncached
      call    _print
      pop     RDI
      mov     RSI,scratch
      call    _printdu64bit
      mov     RSI,scr
      mov     RDI,1
      call    _nprint
```

Uses `_nprint 23b`, `_print 24a`, `_printdu64bit 25a`, `scr 10d`, `scratch 9a`, and `suncached 11c`.

At last we exit the program.

```
11e  <cachetiming-program 9c>+≡ (12) <11d
      <exitProgram 21b>
```

## 2 Cache Access Timing

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

```
12  <cachetiming.asm 12>≡  
    <preamble 5>  
  
    section .rodata  
    <cachetiming-rodata 10d>  
  
    section .bss  
    <cachetiming-udata 9b>  
  
    section .text  
    <cachetiming-program 9c>  
  
    <calculate-cache-access-time 8a>  
  
    <xorshift-prng 22a>  
  
    <utilities 21a>
```

The program 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.

```
$ ./cachetiming
Cached Access Time: 72
Uncached Access Time: 372
$
```

## 2.4 Read Array via Cache Access Time

### 2.4.1 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.

### 2.4.2 Setup

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

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

```
13a <cacheread-program 13a>≡ (18) 14a>
    _start:
        mov     RDI,data
        mov     RSI,pagesize
        rdtsc
        mov     EDX,EAX
        call    _xorshift
```

Uses `_start 5`, `_xorshift 22a`, `data 8b`, and `pagesize 5`.

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

```
13b <cacheread-udata 13b>≡ (18) 17b>
    probe:      times 256 resb pagesize
```

Defines:

`probe`, used in chunk [14](#).

Uses `pagesize 5`.

## 2 Cache Access Timing

Next we fill this area also with some random data.

```
14a  <cacheread-program 13a>+≡ (18) <13a
      mov     RDI,probe
      mov     RAX,pagesize
      mov     RCX,256
      mul     RCX
      mov     RSI,RCX
      rdtsc
      mov     EDX,EAX
      call    _xorshift
```

Uses `_xorshift 22a`, `pagesize 5`, and `probe 13b`.

### 2.4.3 Reading Bytes via Cache

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

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

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

Uses `data 8b`, `pagesize 5`, and `probe 13b`.

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

### Parameters

RDI            the address of the probe array

RSI            the interval between the probe addresses used

```

15  <clear-cache 15>≡
    _clear_cache:
        cld
        mov     RCX,256
        xor     RAX,RAX
    .clear_next:
        mul     RSI
        clflush [RDI+RAX]
        add     RAX,RSI
        loop    .clear_next
        lfence
        ret

```

Defines:

`_clear_cache`, never used.

## 2 Cache Access Timing

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

### Parameters

RDI        the address of the probe array

RSI        the interval between the probe addresses used

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

16     $\langle \text{detect-cache-area-time } 16 \rangle \equiv$  (18)

```
_calcareacachetime:
    xor     RCX,RCX
.next_timing:
    push    RCX
    call    _calccachetime
    pop     RCX
    mov     [RDX+8*RCX],RAX
    add     RDI,RSI
    inc     RCX
    cmp     RCX,256
    jb      .next_timing
    ret
```

Defines:

`_calcareacachetime`, used in chunk 17a.

Uses `_calccachetime` 8a.



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

### Parameters

RDI        the address of the probe array

RSI        the interval between the probe addresses used

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

### Return

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

TBD

17a     $\langle \text{detect-byte 17a} \rangle \equiv$  (18)

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

Uses `_calcareacachetime` 16.

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

17b     $\langle \text{cacheread-udata 13b} \rangle + \equiv$  (18) <13b

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

Uses `pagesize` 5.

## 2 Cache Access Timing

TBD

```
18  <cacheread.asm 18>≡  
    <preamble 5>  
  
    section .bss  
        align      pagesize  
    <cache-data 8b>  
    <cacheread-udata 13b>  
  
    section .text  
    <cacheread-program 13a>  
  
    <exitProgram 21b>  
  
    <clear-cache 15>  
  
    <calculate-cache-access-time 8a>  
  
    <detect-cache-area-time 16>  
  
    <detect-byte 17a>  
  
    <xorshift-prng 22a>  
  
    <utilities 21a>  
Uses pagesize 5.
```

## **3 Signals**

### **3.1 Basics**

TBD

### **3.2 Detecting Signals**

TBD

### **3.3 Handling Signals**

TBD



## 4 Utilities

### 4.1 Introduction

TBD

21a  $\langle utilities\ 21a \rangle \equiv$  (12 18)

$\langle nprint\ 23b \rangle$

$\langle print\ 24a \rangle$

$\langle printdu64bit\ 25a \rangle$

### 4.2 Exit Program

TBD

21b  $\langle exitProgram\ 21b \rangle \equiv$  (11e 18)

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

### 4.3 Random Number Generator

To initialize the data a [random number generator \(RNG\)](#) is used. The sample programs use xorshift<sup>1</sup> 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 <a href="#">RNG</a>

22a  $\langle \text{xorshift-prng } 22a \rangle \equiv$  (12 18) 22b  $\triangleright$

```

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

```

Defines:

\_xorshift, used in chunks 9g, 13a, and 14a.

Now we can generate the next 32bit random number.

22b  $\langle \text{xorshift-prng } 22a \rangle + \equiv$  (12 18)  $\triangleleft 22a \ 23a \triangleright$

```

.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

```

---

<sup>1</sup><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.

23a `<xorshift-prng 22a>+≡` (12 18) <22b

```

    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`

23b `<nprint 23b>≡` (21a)

```

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

```

Defines:

`_nprint`, used in chunks 11, 24d, and 27b.

### 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**

```
24a  <print 24a>≡ (21a) 24b>
      _print:
          cld
          xor     AL,AL
          mov     RSI,RDI
```

Defines:

`_print`, used in chunks 10e and 11d.

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.

```
24b  <print 24a>+≡ (21a) <24a 24c>
      .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.

```
24c  <print 24a>+≡ (21a) <24b 24d>
          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`.

```
24d  <print 24a>+≡ (21a) <24c>
          call    _nprint
          ret
```

Uses `_nprint` 23b.



## 4.5 Printing Numbers

### 4.5.1 Printing a 64bit Unsigned Integer

The routine `_printdu64bit` print a given number as unsigned decimal number with 64bit 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

```
25a  <printdu64bit 25a>≡ (21a) 25b>
      _printdu64bit:
          mov     RAX,RDI
          mov     RDI,RSI
          mov     R8,RDI
          mov     RCX,10
          cld
```

Defines:

`_printdu64bit`, used in chunk 11.

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.

```
25b  <printdu64bit 25a>+≡ (21a) <25a 25c>
      .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`.

```
25c  <printdu64bit 25a>+≡ (21a) <25b 26a>
          xor     RDX,RDX
          div     RCX
```

## 4 Utilities

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

```
26a  <printdu64bit 25a>+≡ (21a) <25c 26b>
      xchg      RDX,RAX
      add       AL,'0'
      stosb
```

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

```
26b  <printdu64bit 25a>+≡ (21a) <26a 26c>
      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.

```
26c  <printdu64bit 25a>+≡ (21a) <26b 26d>
      .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.

```
26d  <printdu64bit 25a>+≡ (21a) <26c 27a>
      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.

```
27a  <printdu64bit 25a>+≡ (21a) <26d 27b>
      .reverse:
      mov     AL,[RSI]
      mov     AH,[RDI]
      mov     [RSI],AH
      mov     [RDI],AL
      dec     RDI
      inc     RSI
      cmp     RSI,RDI
      jb      .reverse
```

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

```
27b  <printdu64bit 25a>+≡ (21a) <27a
      mov     RSI,R8
      mov     RDI,RDX
      call    _nprint
      ret
```

Uses `_nprint` 23b.



# A Glossary

**x86** x86 denotes a microprocessor architecture based on the 8086/8088 [22](#)



## B Acronyms

**ASCII** American Standard Code for Information Interchange [26](#)

**CR** carriage return [10](#), [11](#)

**RNG** random number generator [22](#)





## C x86-Instructions

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

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

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



## D Code Chunks

*<cache-data 8b>*  
*<cacheread-program 13a>*  
*<cacheread-sample 14b>*  
*<cacheread-udata 13b>*  
*<cacheread.asm 18>*  
*<cachetiming-program 9c>*  
*<cachetiming-rodata 10d>*  
*<cachetiming-udata 9b>*  
*<cachetiming.asm 12>*  
*<calculate-cache-access-time 8a>*  
*<clear-cache 15>*  
*<detect-byte 17a>*  
*<detect-cache-area-time 16>*  
*<exitProgram 21b>*  
*<license 60>*  
*<nprint 23b>*  
*<preamble 5>*  
*<print 24a>*  
*<printdu64bit 25a>*  
*<scratch-data 9a>*  
*<tsc-64bit 7>*  
*<utilities 21a>*  
*<xorshift-prng 22a>*



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