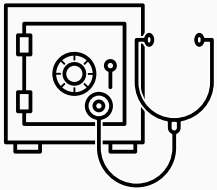
Microarchitectural Attacks and Beyond

Daniel Gruss

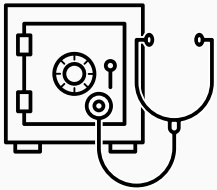
February 21, 2019

Graz University of Technology

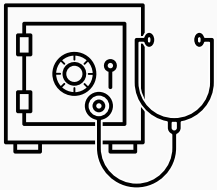
- Bug-free software does not mean safe execution



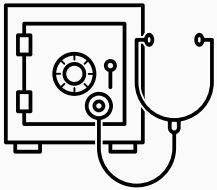
- Bug-free software does not mean safe execution
- Information leaks due to underlying hardware



Side-Channel Attacks



- Bug-free software does not mean safe execution
- Information leaks due to underlying hardware
- Exploit leakage through side-effects

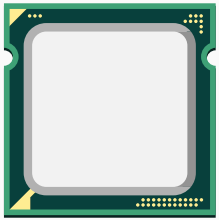


- Bug-free software does not mean safe execution
- Information leaks due to underlying hardware
- Exploit leakage through side-effects

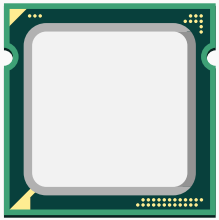
Power consumption

Execution time

CPU caches



- Instruction Set Architecture (ISA) is an abstract model of a computer (x86, ARMv8, SPARC, . . .)



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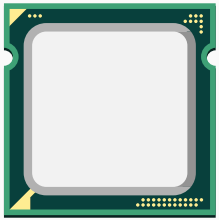
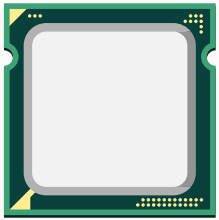
- Interface between hardware and software



- Instruction Set Architecture (ISA) is an abstract model of a computer (x86, ARMv8, SPARC, . . .)
- Interface between hardware and software
- Microarchitecture is an ISA implementation



- Instruction Set Architecture (ISA) is an abstract model of a computer (x86, ARMv8, SPARC, . . .)
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- Microarchitecture is an ISA implementation

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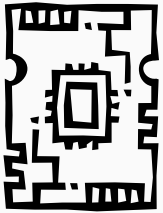
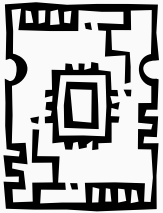


- Modern CPUs contain multiple microarchitectural elements



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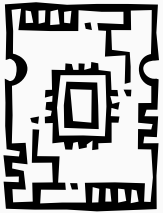
Caches and buffer

Predictor

Microarchitectural Elements



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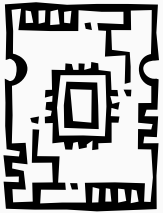
Caches and buffer

Predictor

- Transparent for the programmer

Microarchitectural Elements



- Modern CPUs contain multiple microarchitectural elements

Caches and buffer

Predictor

- Transparent for the programmer
- Timing optimizations → side-channel leakage

1996

1996

2004

1996

2004

2006

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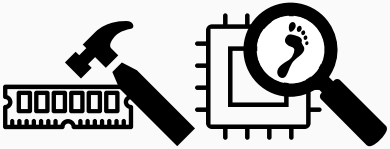


2014

1996

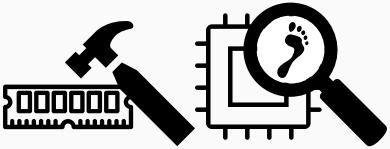
2004

2006

2009

2011

2013



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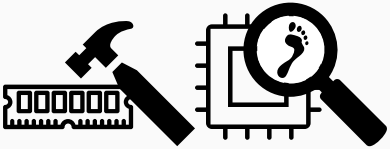

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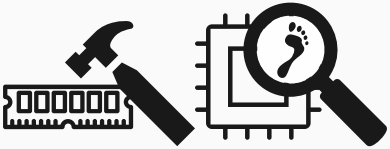
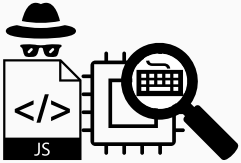


2014



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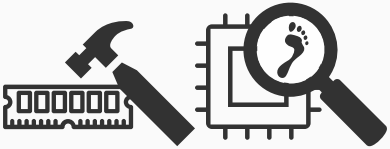
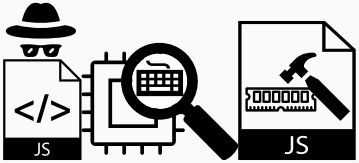


2014



2015

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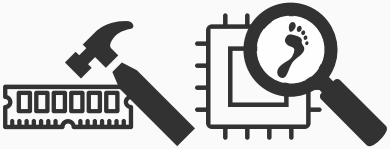
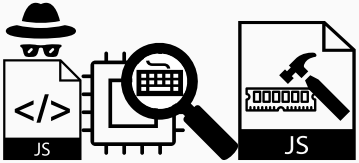
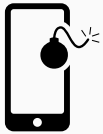


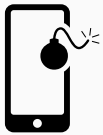
2014



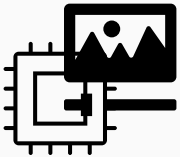
2015



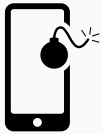
2016



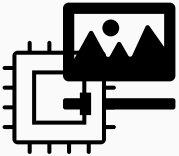
2016



2017



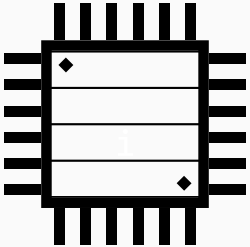
2016

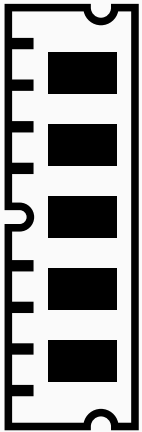


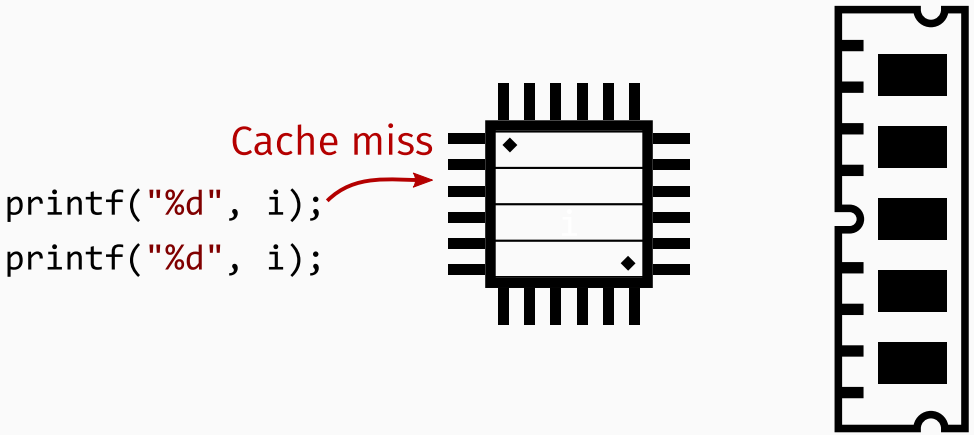
2017

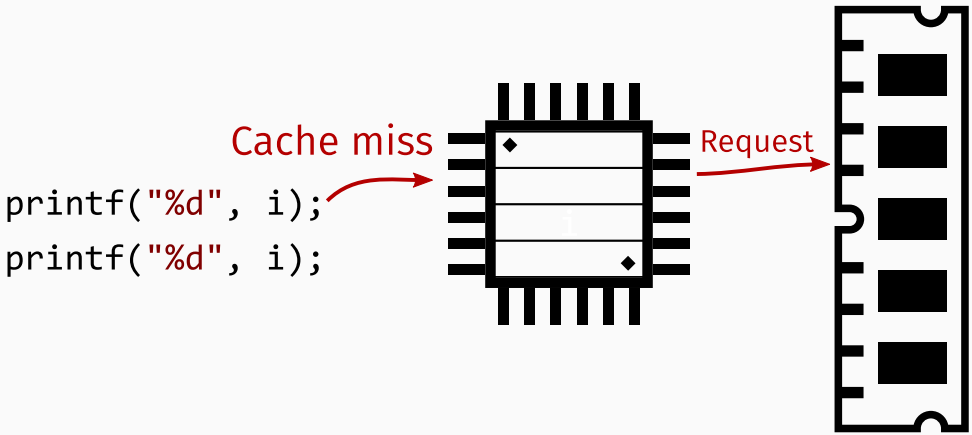
2018

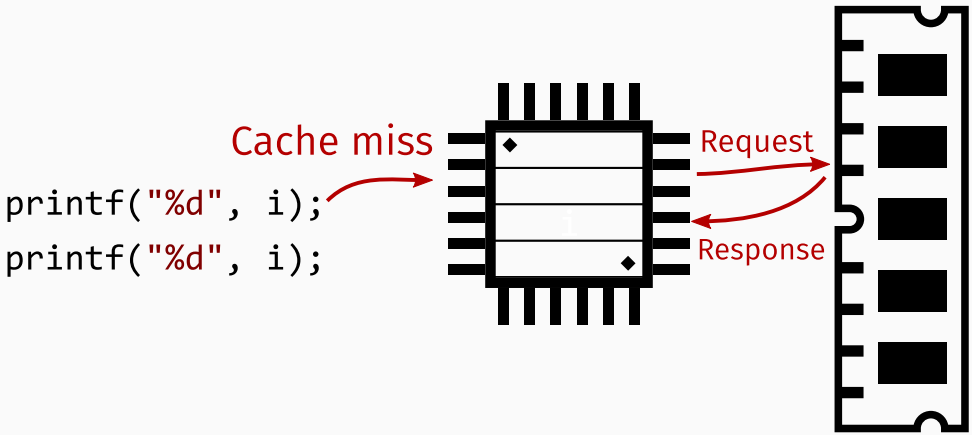
```
printf("%d", i);
printf("%d", i);
```

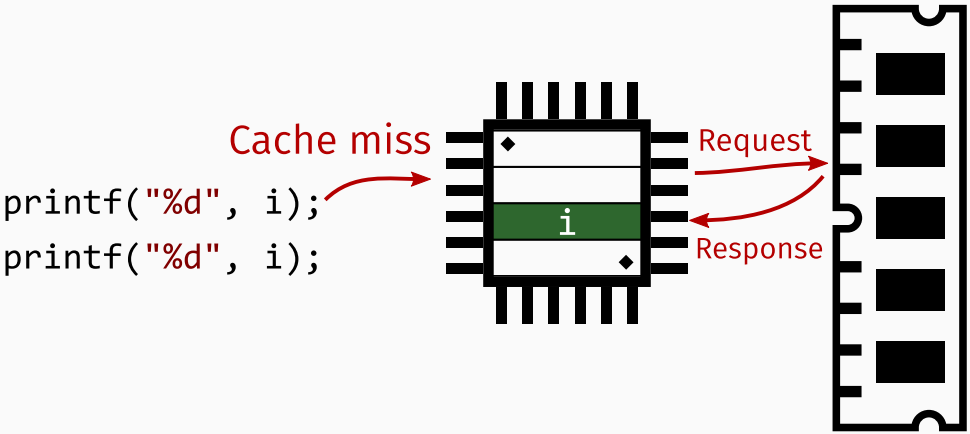


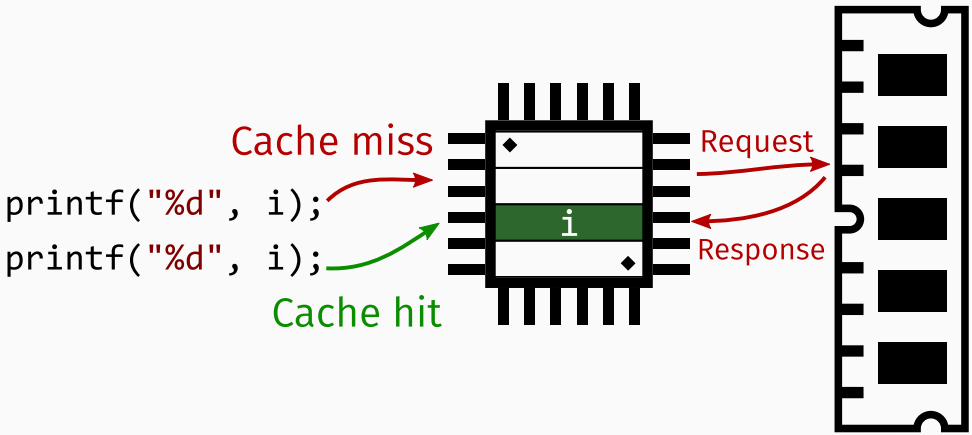


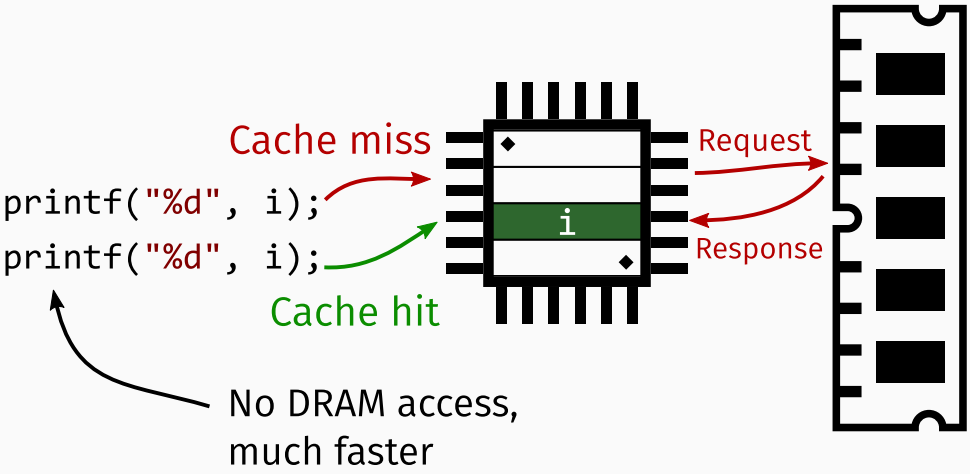

Cache miss
printf("%d", i);
printf("%d", i);

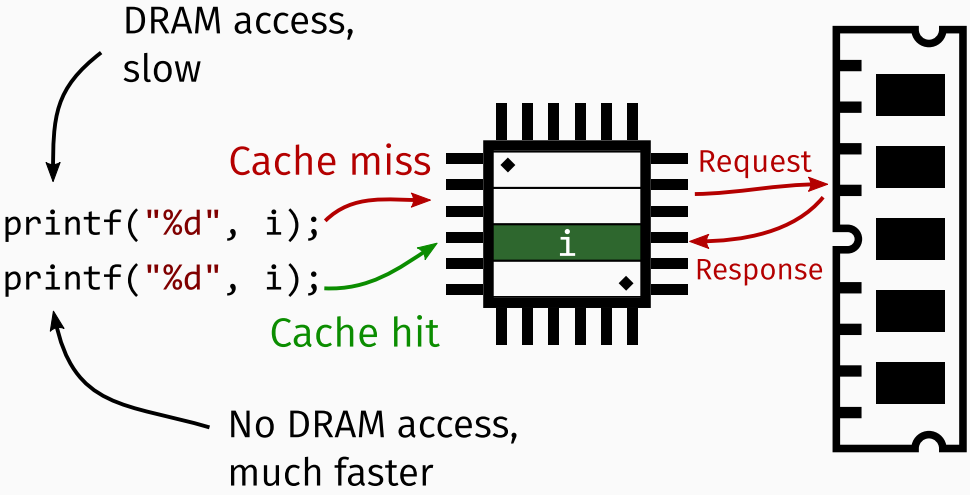

Cache miss
Request
printf("%d", i);
printf("%d", i);


Cache miss
printf("%d", i);
printf("%d", i);
Request
Response


Cache miss
printf("%d", i);
printf("%d", i);
i
Request
Response


Cache miss
printf("%d", i);
printf("%d", i);
Cache hit
i
Request
Response


Cache miss
printf("%d", i);
printf("%d", i);
Cache hit
i
Request
Response
No DRAM access,
much faster

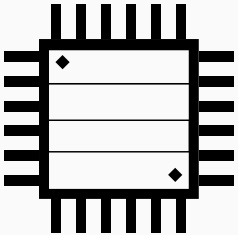

DRAM access,
slow
Cache miss
printf("%d", i);
printf("%d", i);
Cache hit
No DRAM access,
much faster
i
Request
Response

Shared Memory

ATTACKER

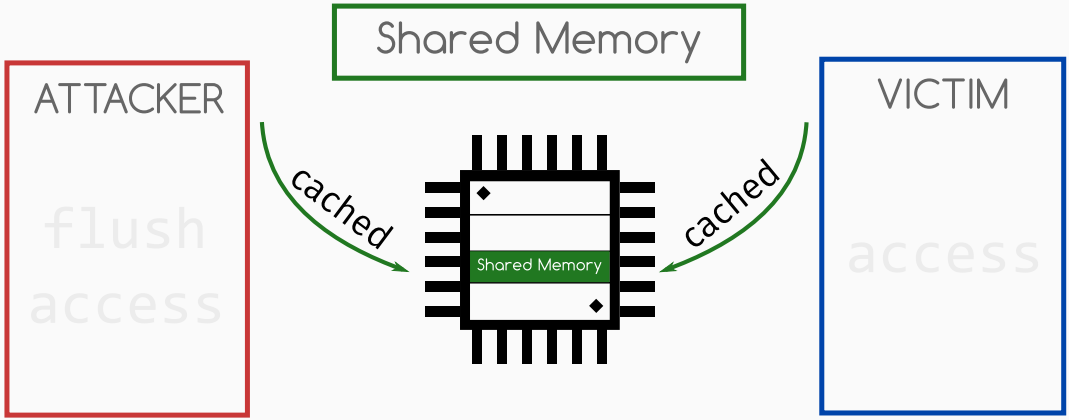
flush

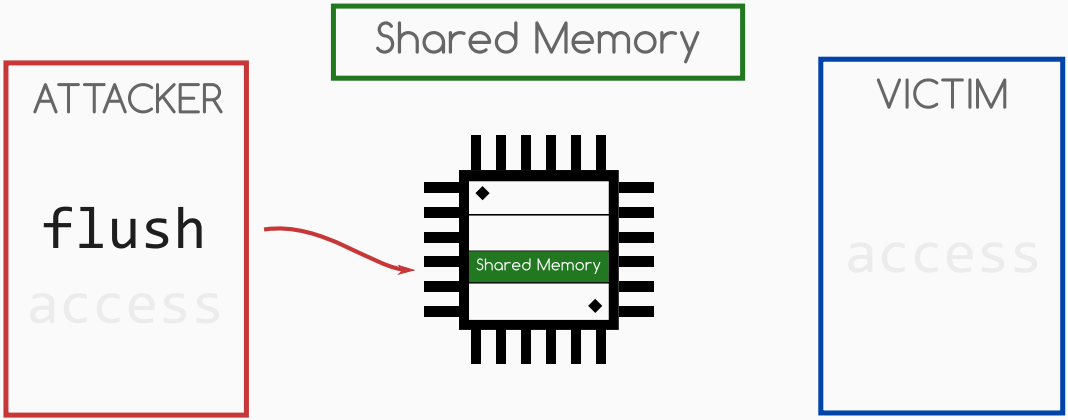
access



VICTIM

access


Shared Memory
ATTACKER
flush
access
cached
Shared Memory
cached
VICTIM
access

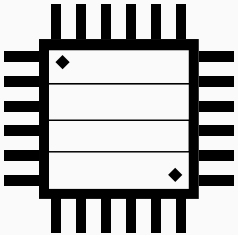

Shared Memory
ATTACKER
flush
access
Shared Memory
VICTIM
access

Shared Memory

ATTACKER

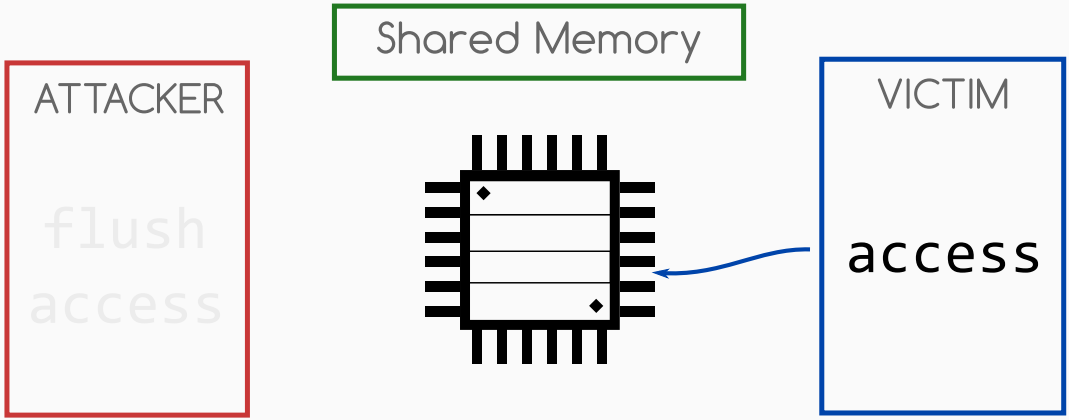
flush

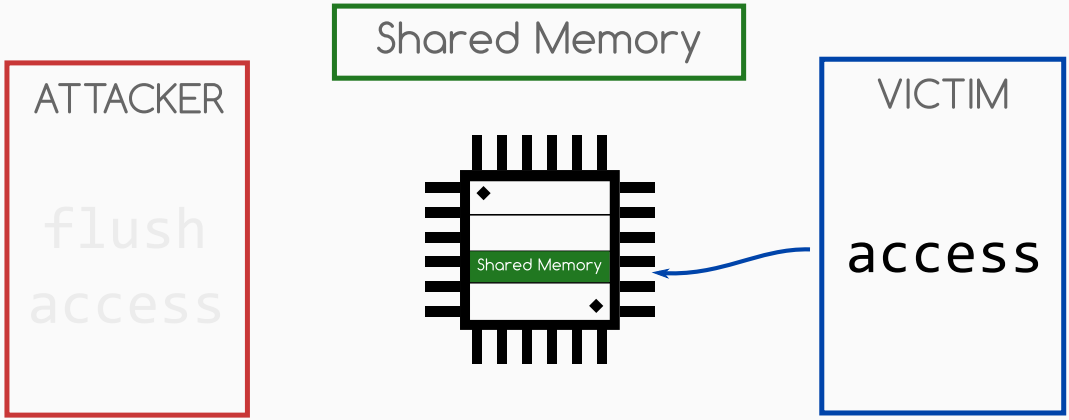
access

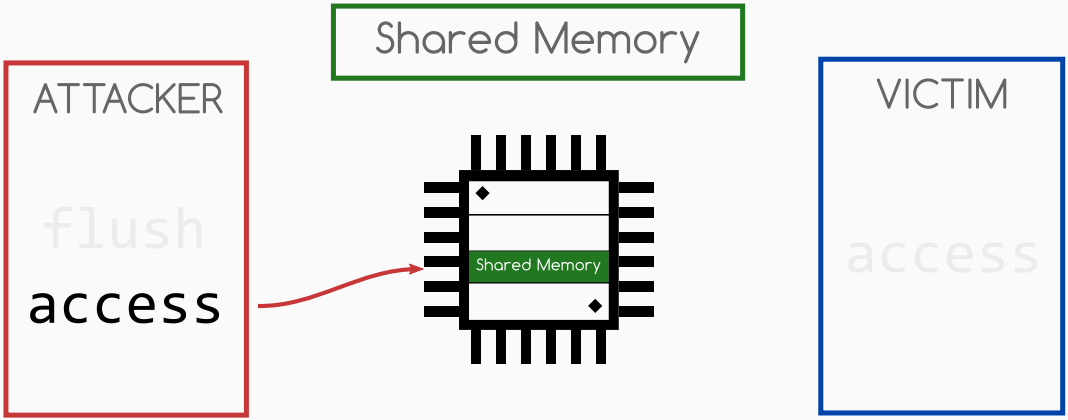


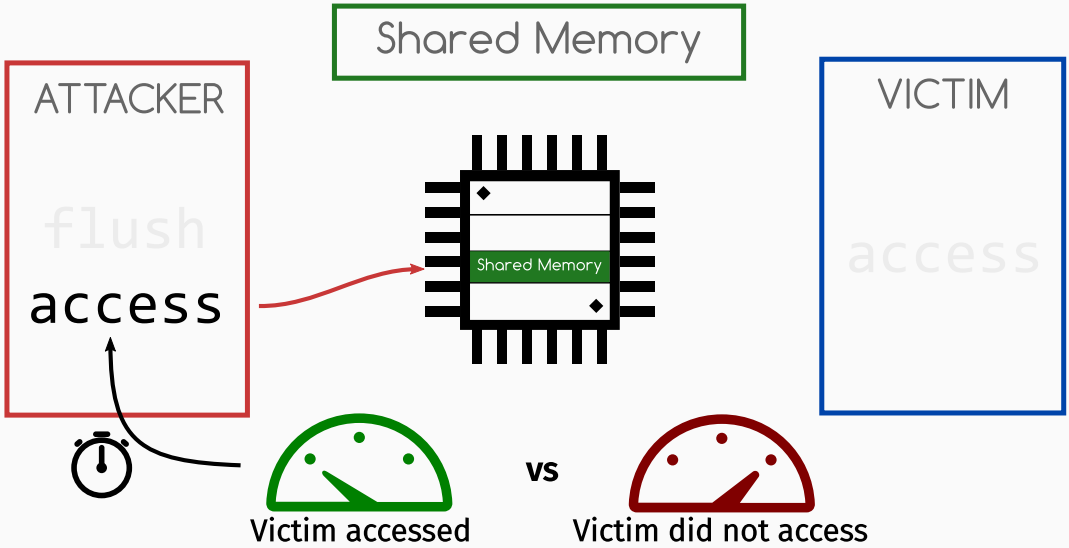
VICTIM

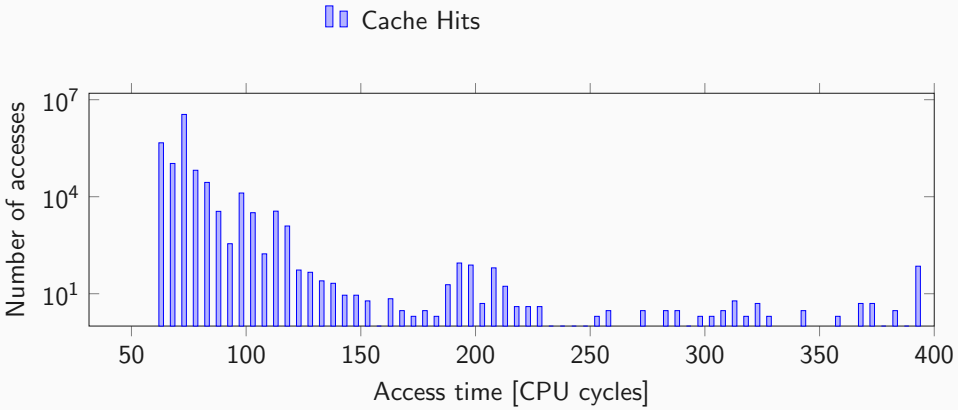
access

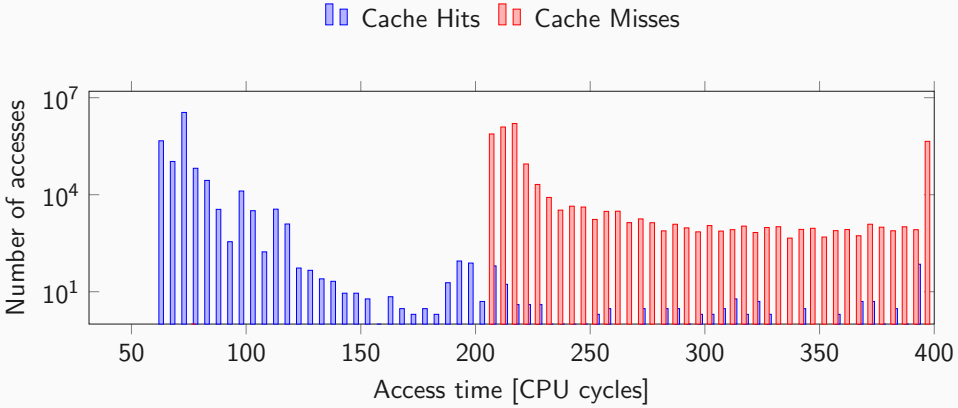

Shared Memory
ATTACKER
flush
access
VICTIM
access

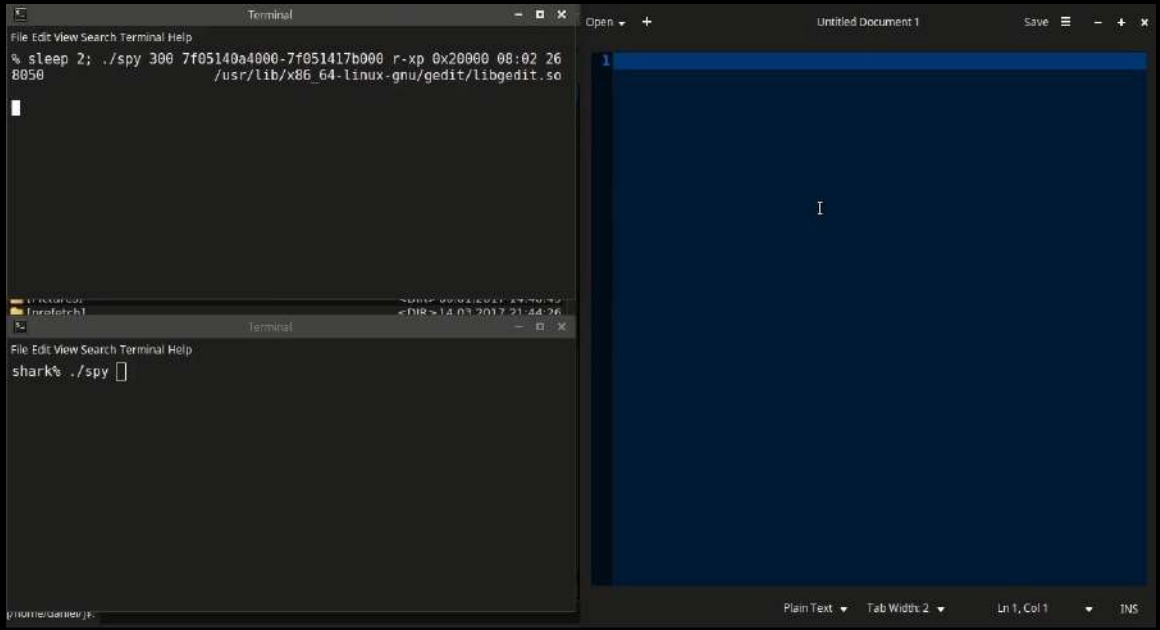

Shared Memory
ATTACKER
flush
access
Shared Memory
VICTIM
access


Shared Memory
ATTACKER
flush
access
Shared Memory
VICTIM
access

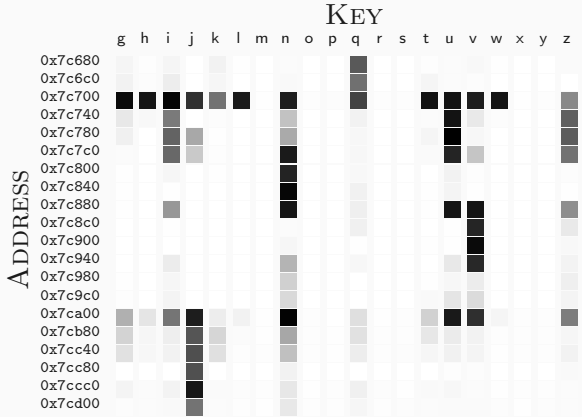

Shared Memory
ATTACKER
flush
access
Shared Memory
VICTIM
access
vs
Victim accessed
Victim did not access


Cache Hits
Number of accesses
10^7
10^4
10^1
50
100
150
200
250
300
350
400
Access time [CPU cycles]


Cache Hits
Cache Misses
Number of accesses
10^7
10^4
10^1
50
100
150
200
250
300
350
400
Access time [CPU cycles]



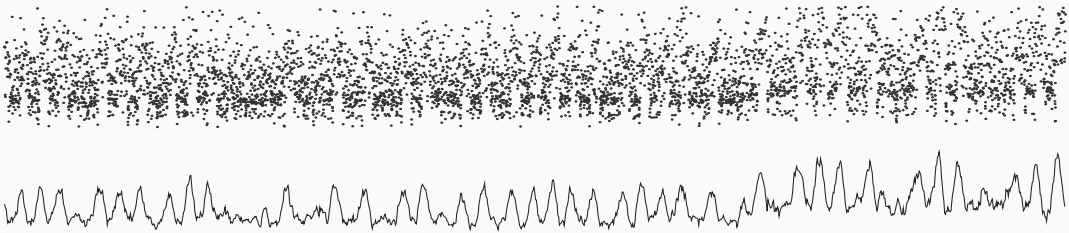
Cache Template Attack Demo


Key
g h i j k l m n o p q r s t u v w x y z
Address
0x7c680
0x7c6c0
0x7c700
0x7c740
0x7c780
0x7c7c0
0x7c800
0x7c840
0x7c880
0x7c8c0
0x7c900
0x7c940
0x7c980
0x7c9c0
0x7ca00
0x7cb80
0x7cc40
0x7cc80
0x7ccc0
0x7cd00

Raw Prime+Probe trace...[1]

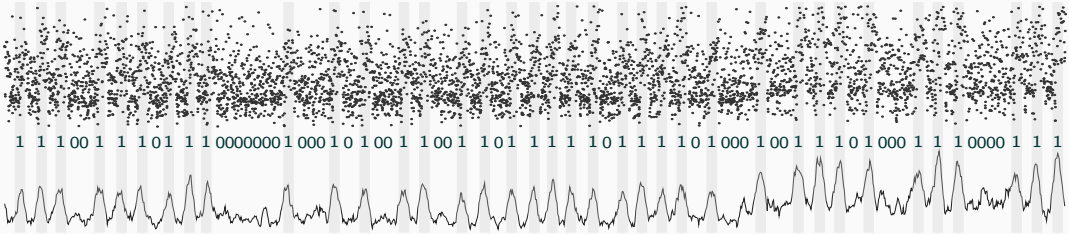
[1] Michael Schwarz et al. Malware Guard Extension: Using SGX to Conceal Cache Attacks. In: DIMVA. 2017.

...processed with a simple moving average...[1]

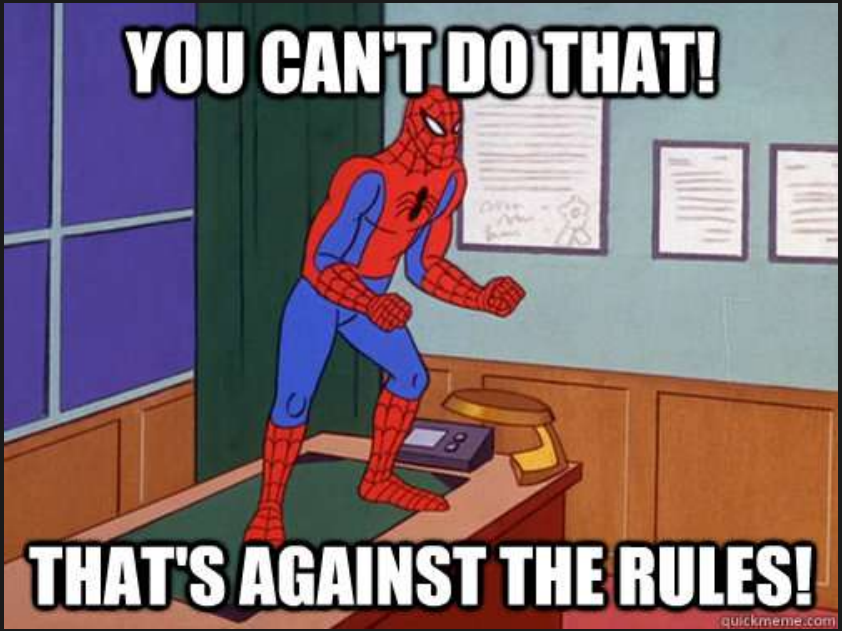


[1] Michael Schwarz et al. Malware Guard Extension: Using SGX to Conceal Cache Attacks. In: DIMVA. 2017.

...allows to clearly see the bits of the exponent[1]



[1] Michael Schwarz et al. Malware Guard Extension: Using SGX to Conceal Cache Attacks. In: DIMVA. 2017.

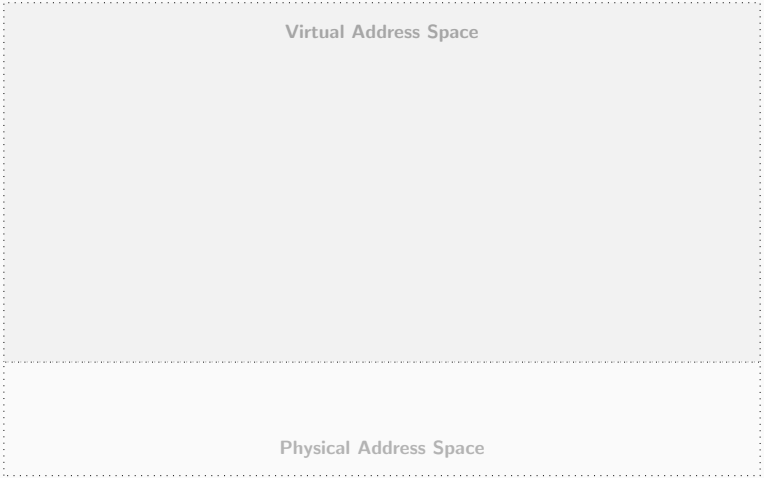

YOU CAN'T DO THAT!
THAT'S AGAINST THE RULES!
quickmeme.com

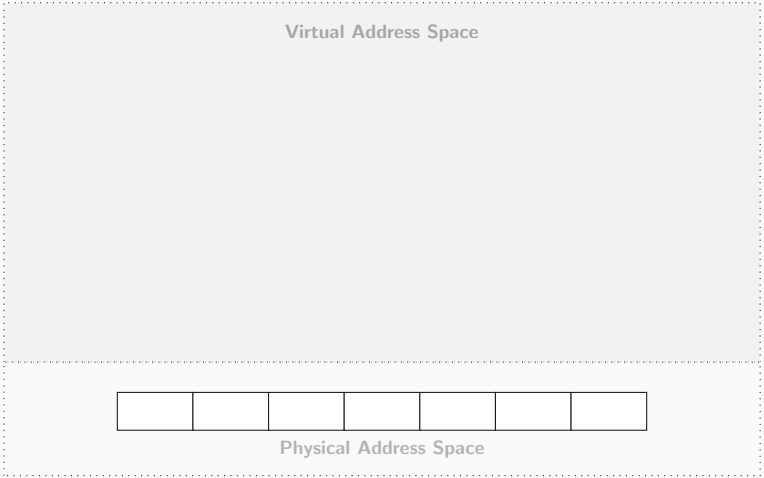
Yet another cache: Linux page cache

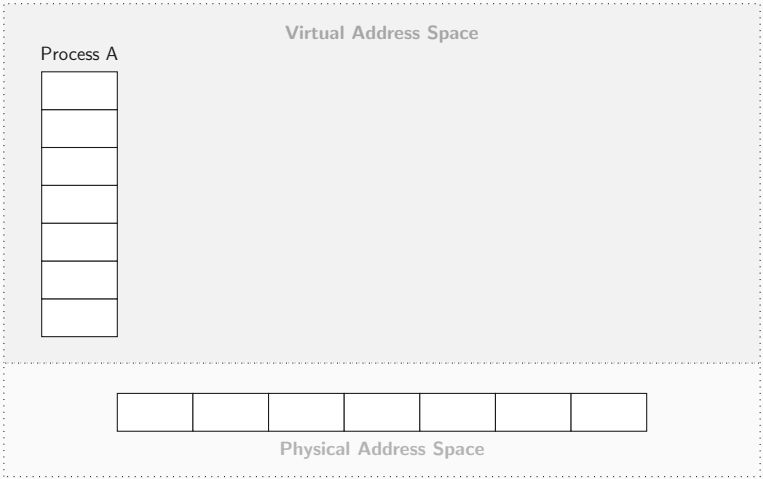
- Files buffered page-wise in “page cache”
- Lower access time for frequently accessed data

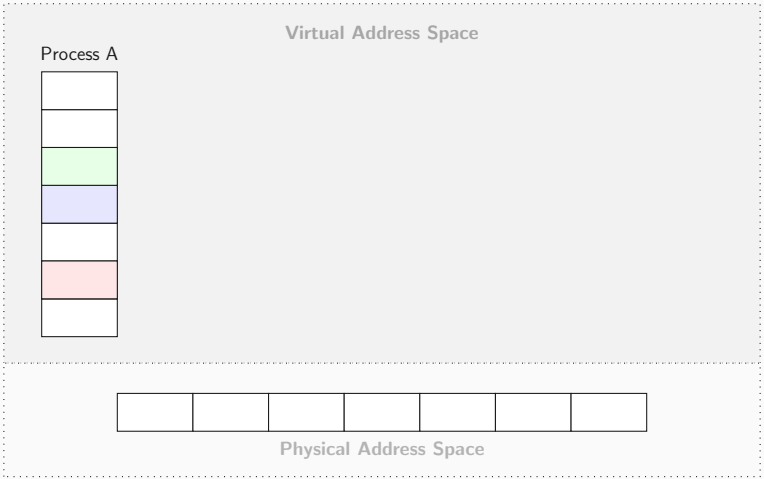
Yet another cache: Linux page cache

- Files buffered page-wise in “page cache”
- Lower access time for frequently accessed data
- Use up all the memory
- Pages are freed on demand
- Deduplicate pages (copy-on-write)

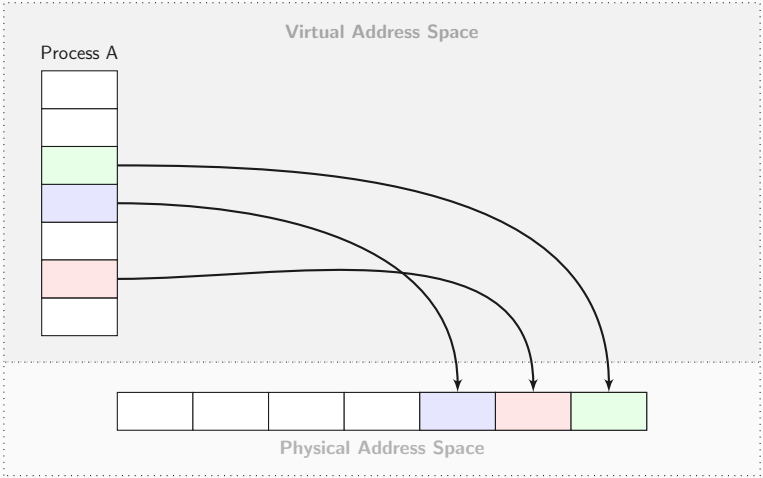

Virtual Address Space
Physical Address Space

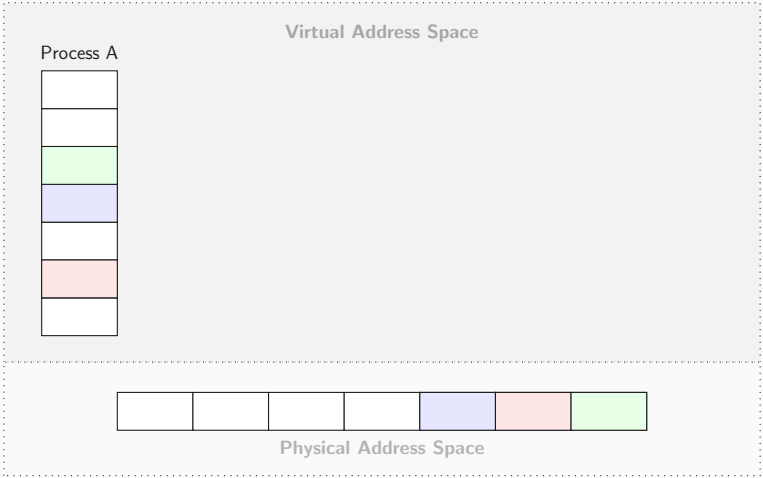

Virtual Address Space
Physical Address Space


Virtual Address Space
Process A
Physical Address Space

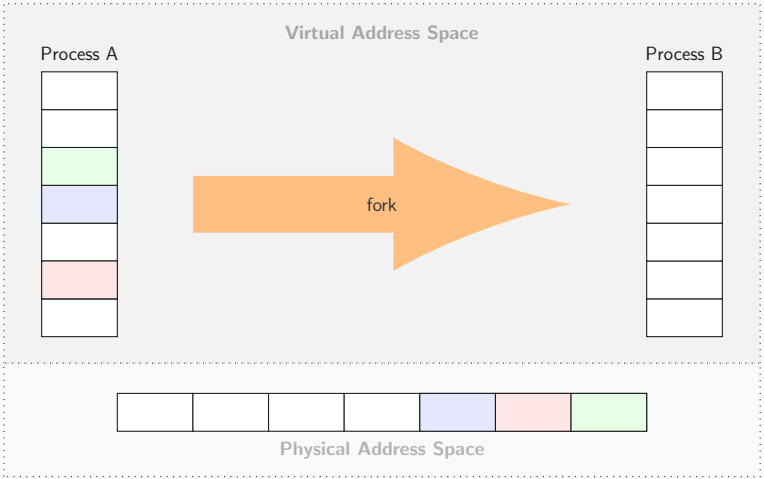

Virtual Address Space
Process A
Physical Address Space

Copy-on-Write

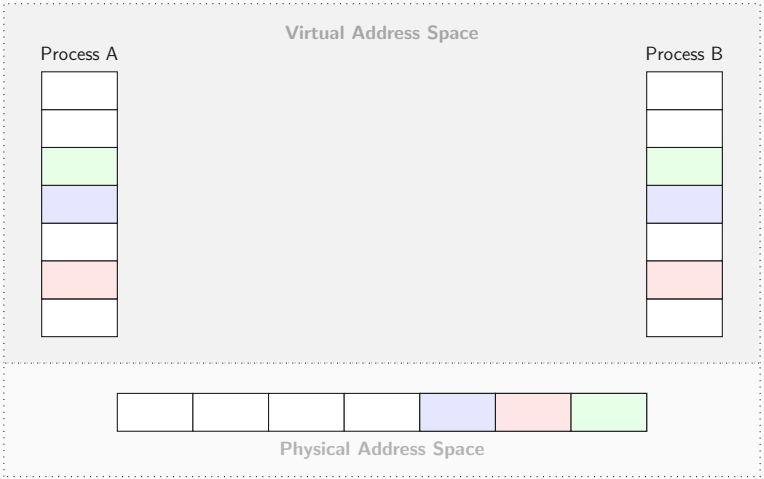



Virtual Address Space
Process A
Physical Address Space

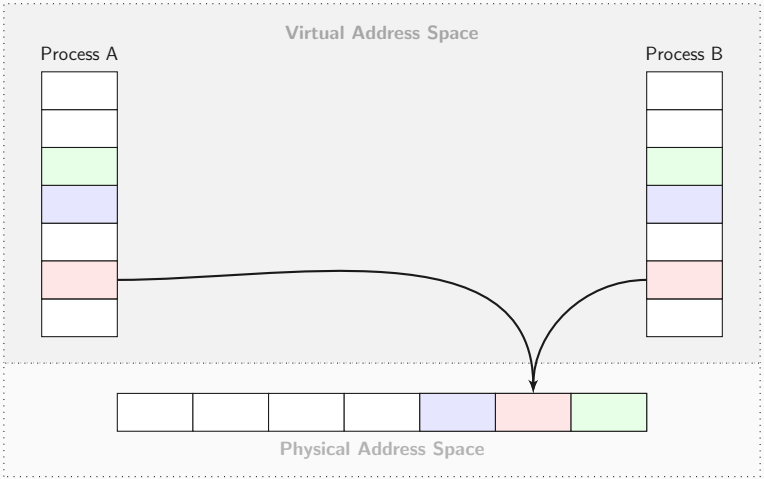
Copy-on-Write



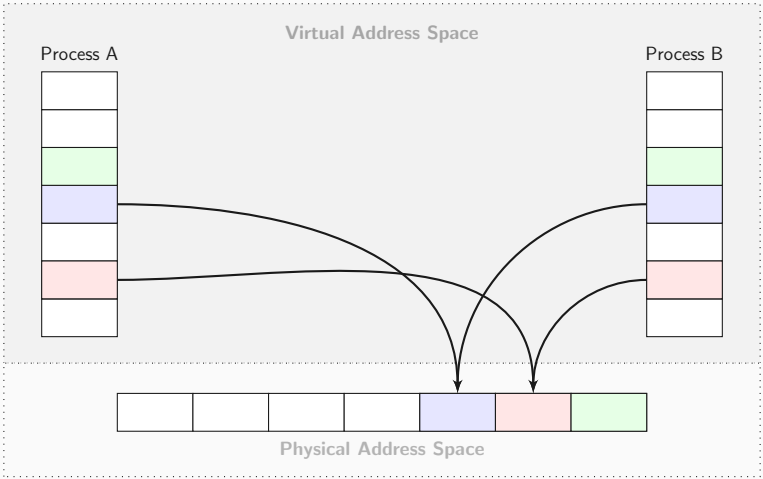
Copy-on-Write



Copy-on-Write



Copy-on-Write



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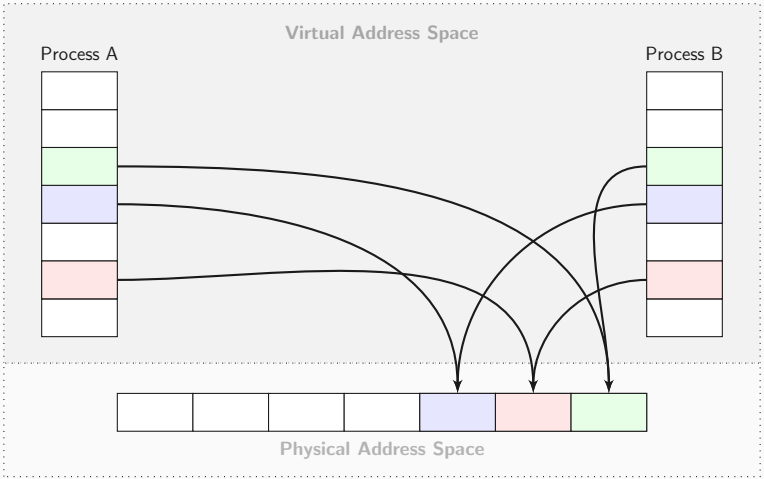
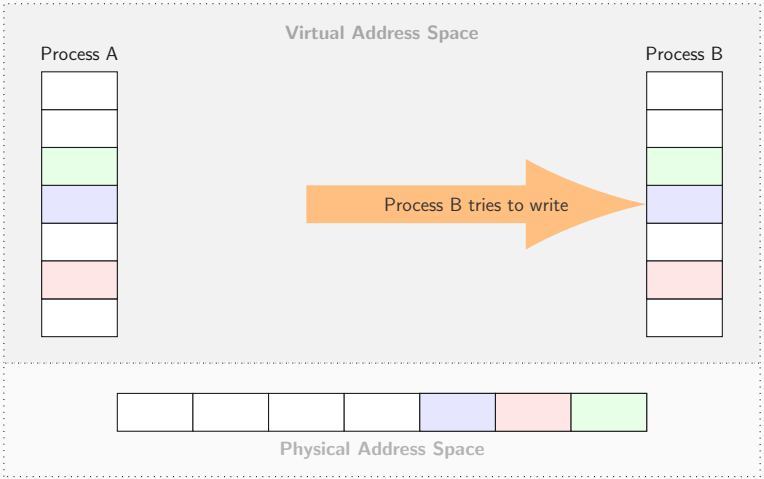
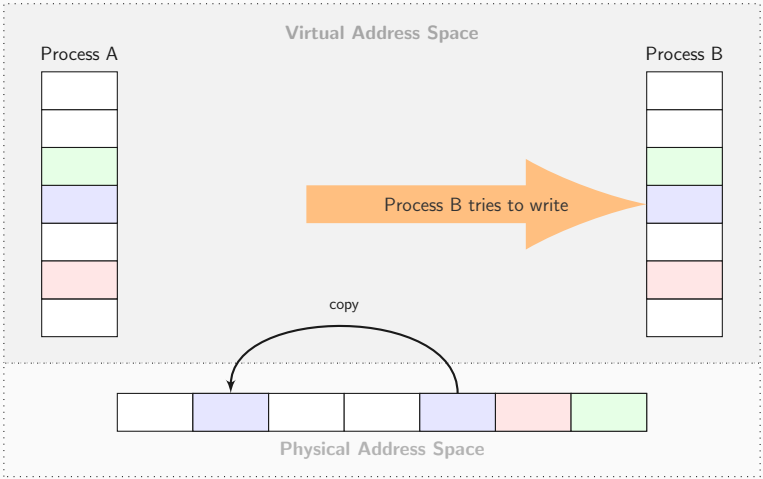


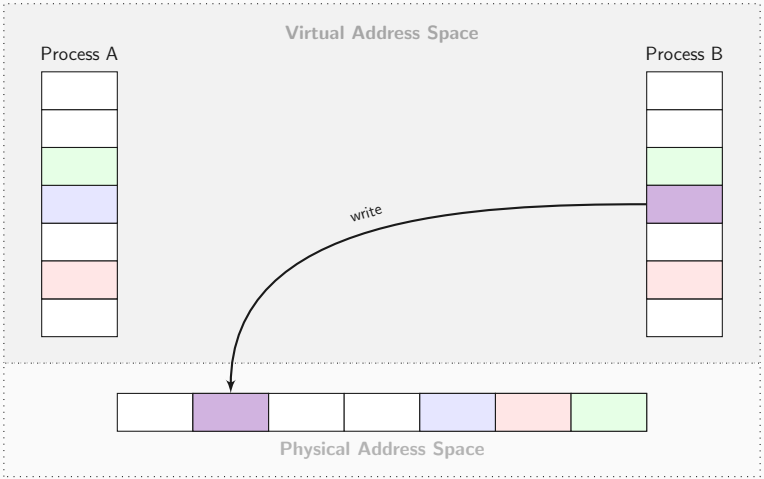
Copy-on-Write



Copy-on-Write



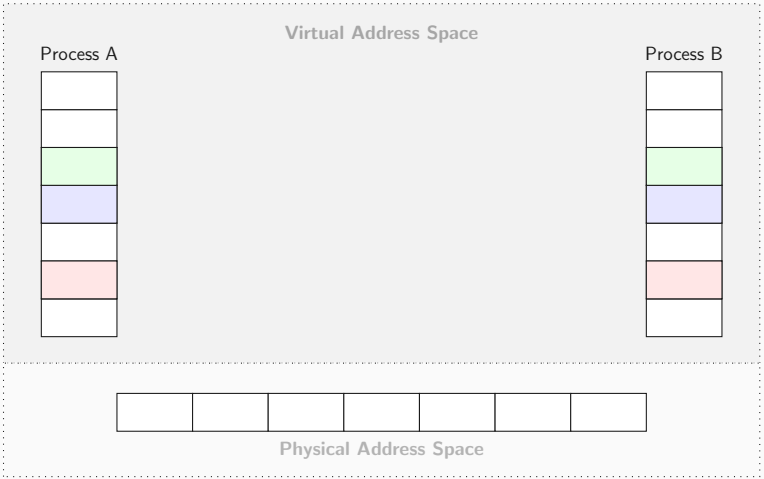
Copy-on-Write



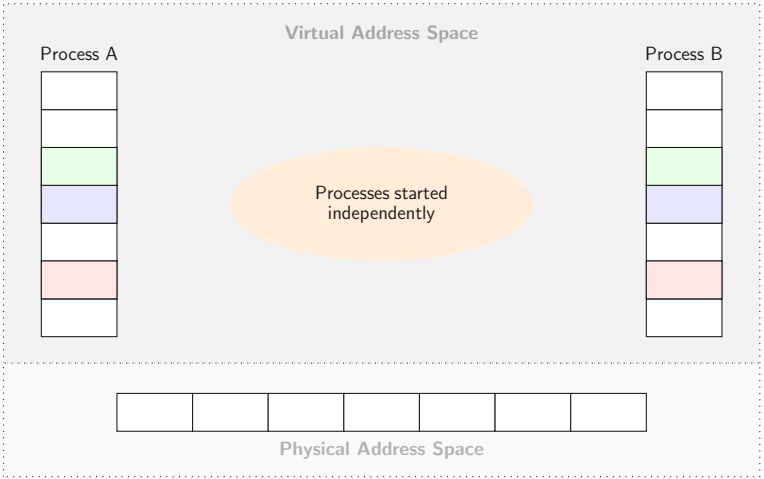
Write vs. Copy-on-Write

- Regular write access $< 0.2\mu s$
- Write access with copy-on-write pagefault $> 3.0\mu s$
- Clearly distinguishable

Page Deduplication



Page Deduplication



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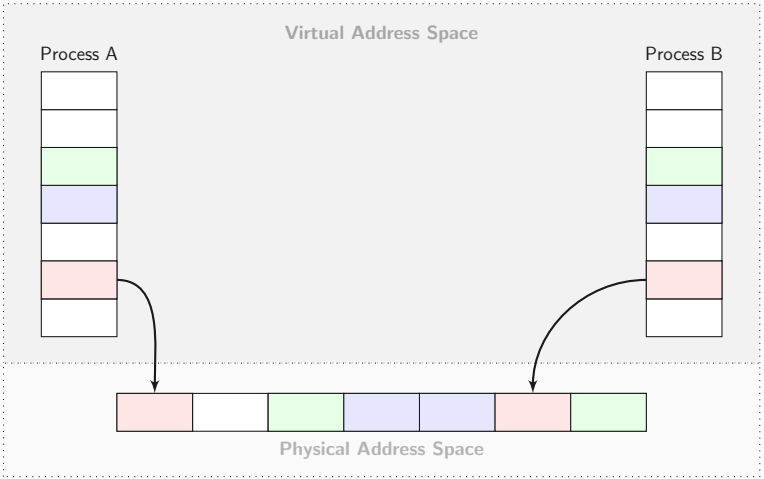

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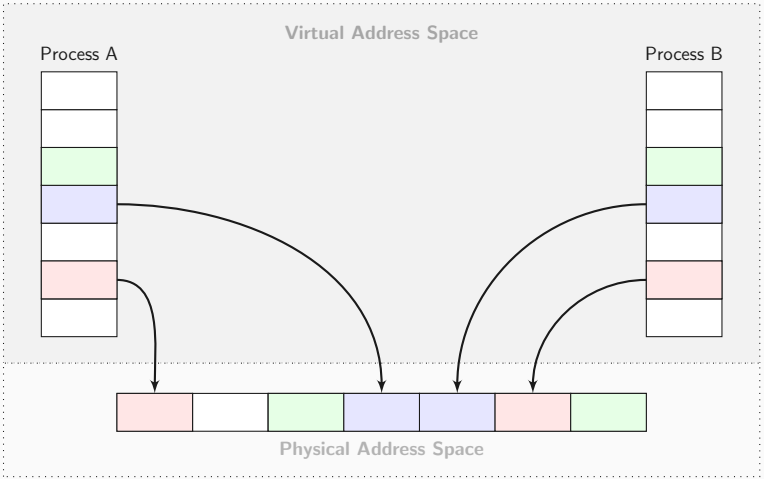

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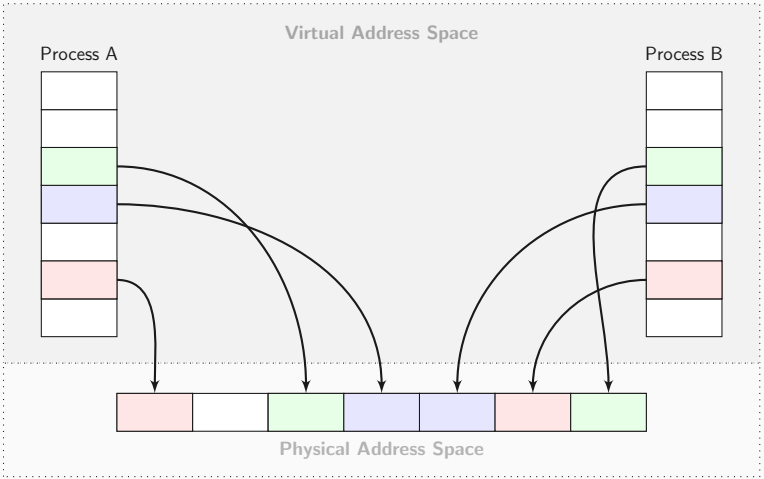

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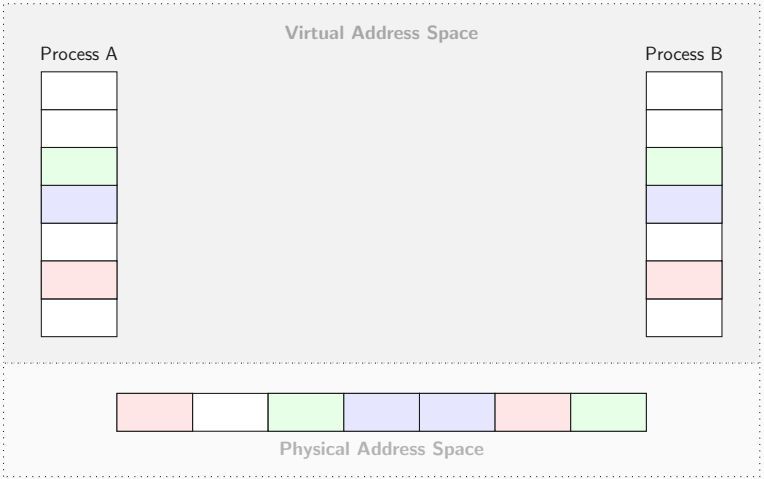

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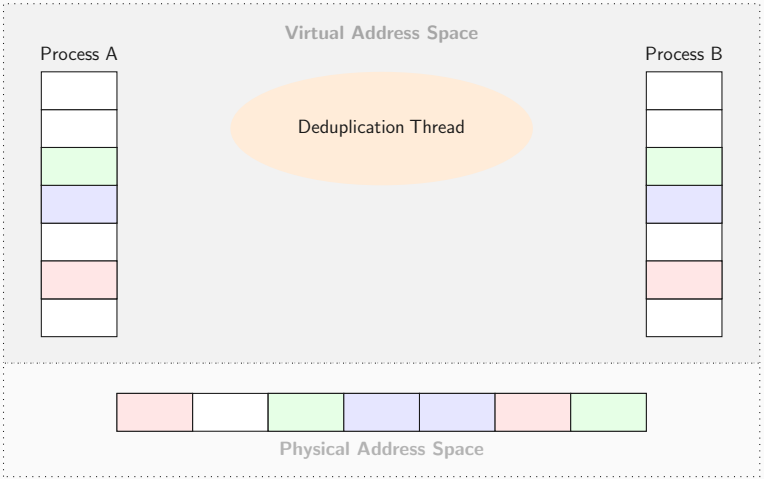

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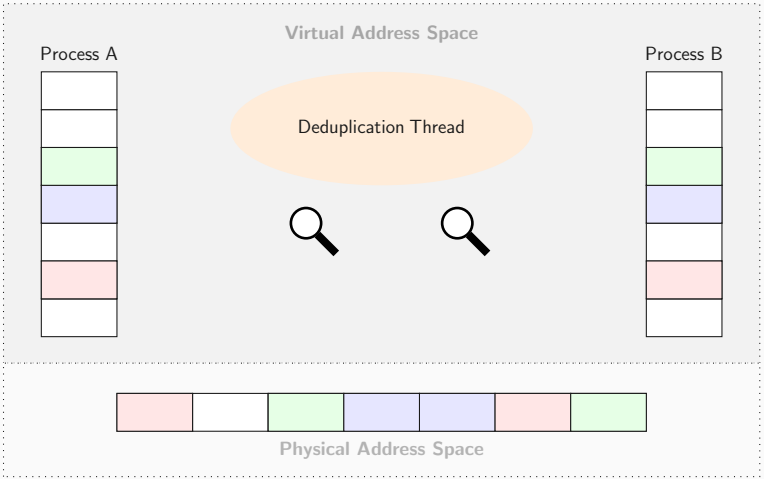

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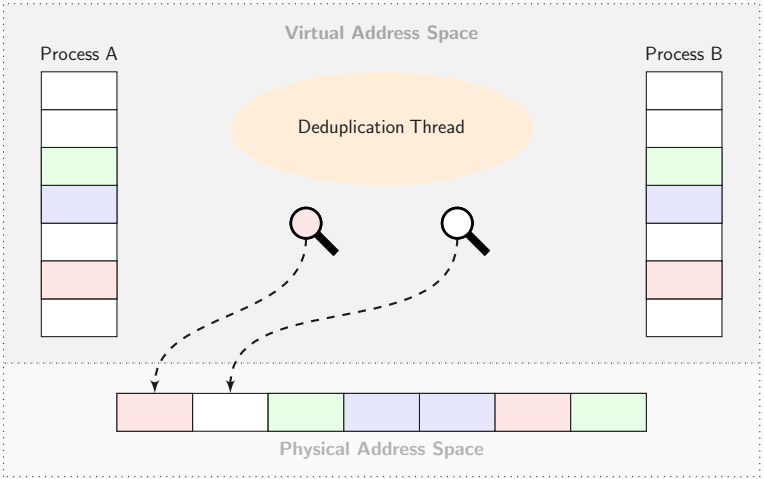

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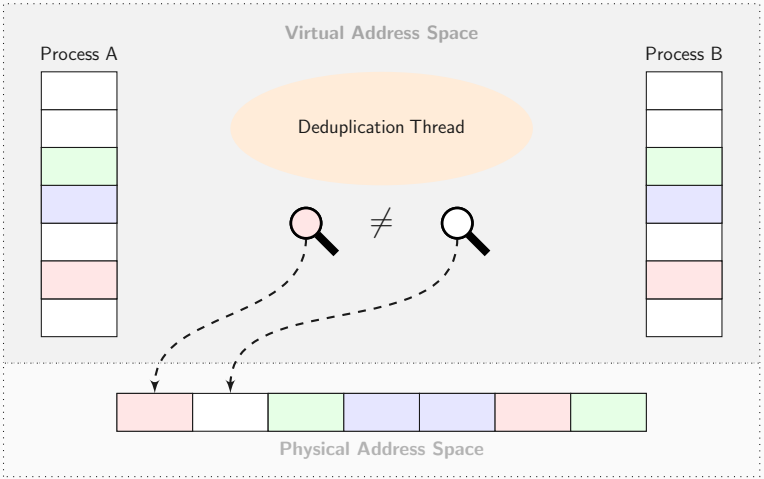
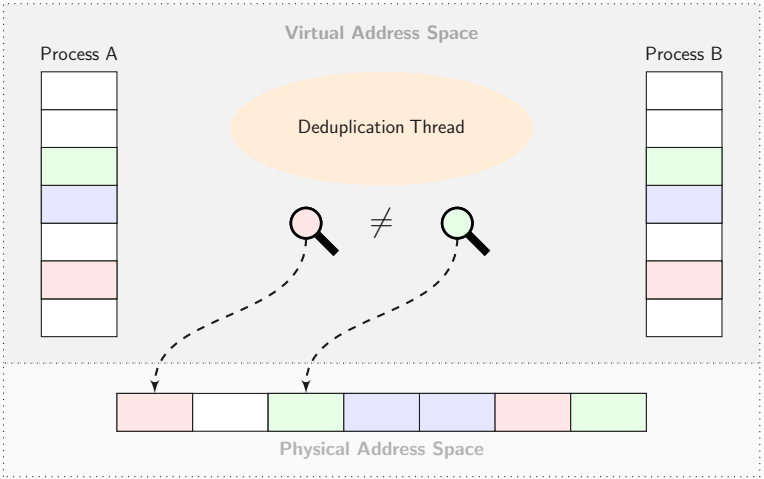
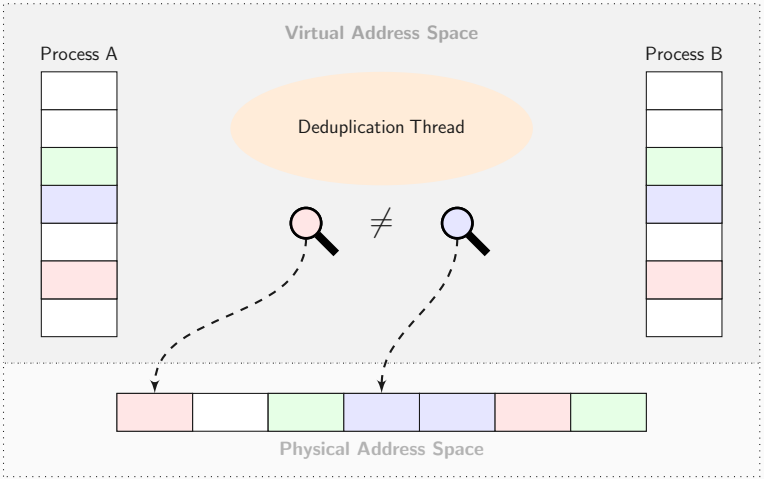



Virtual Address Space
Process A
Process B
Deduplication Thread
≠
Physical Address Space

Page Deduplication



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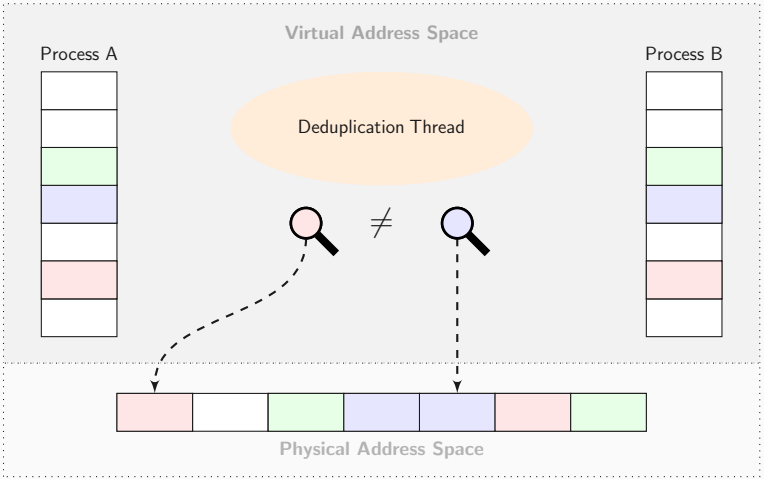
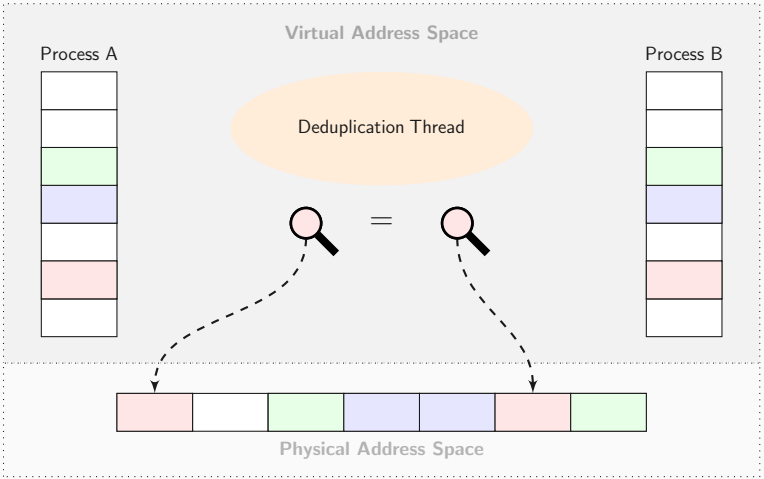
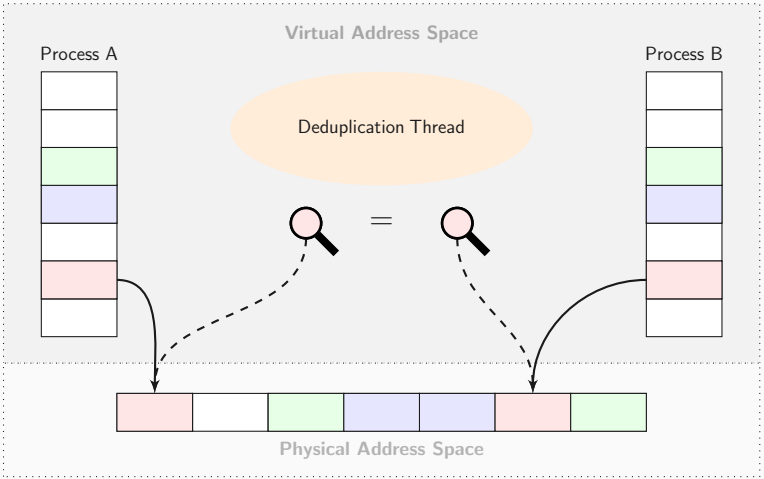
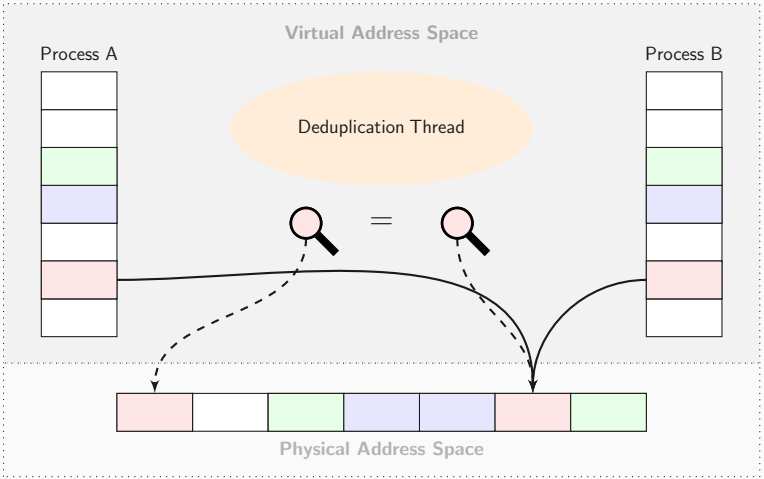
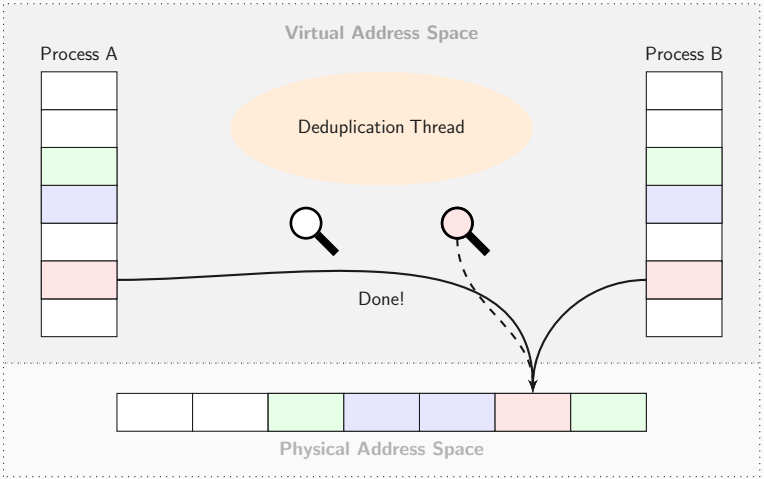


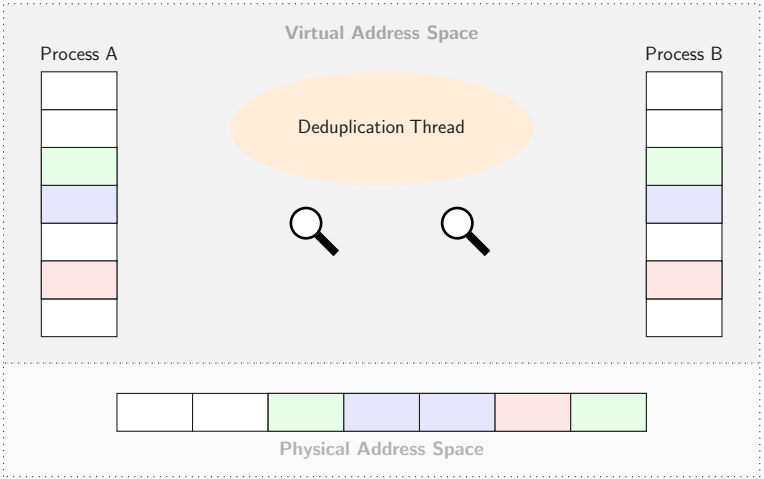

Virtual Address Space
Process A
Process B
Deduplication Thread
=
Physical Address Space


Virtual Address Space
Process A
Process B
Deduplication Thread
=
Physical Address Space


Virtual Address Space
Process A
Process B
Deduplication Thread
=
Physical Address Space


Virtual Address Space
Process A
Process B
Deduplication Thread
Done!
Physical Address Space

Page Deduplication

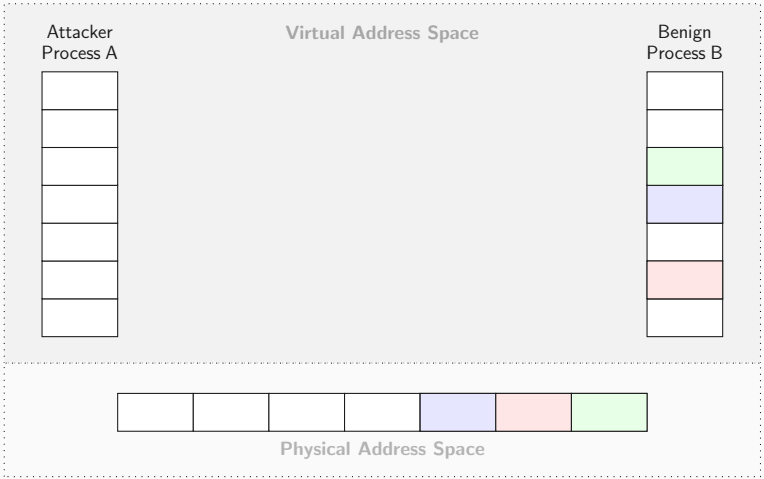


- Deduplication between processes:
  1. in same OS instance (Android, Windows)
  2. in different VMs (KVM, VMWare, ...)

Page Deduplication (without fork)

- Deduplication between processes:
  1. in same OS instance (Android, Windows)
  2. in different VMs (KVM, VMWare, ...)
- Code pages, data pages - even kernel pages
- Time until deduplication 2-45 minutes
  - depends on system configuration

Page Deduplication Attack



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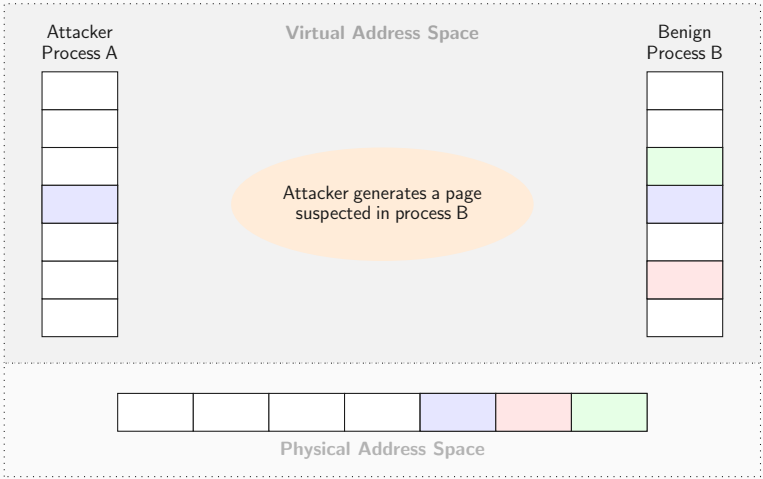

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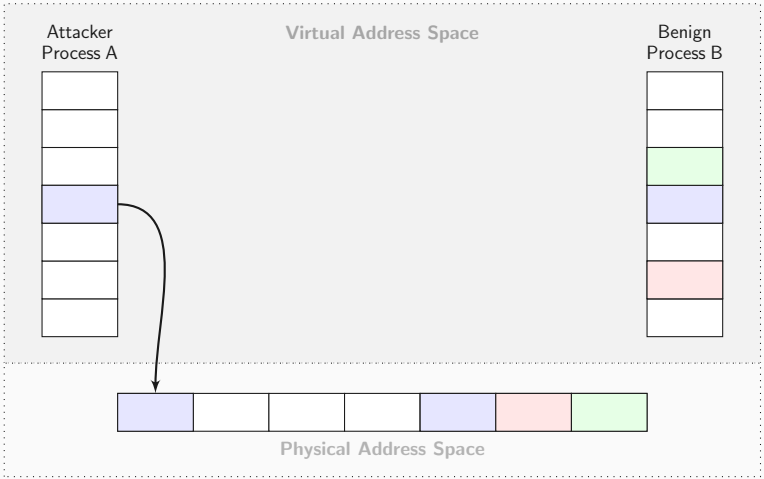

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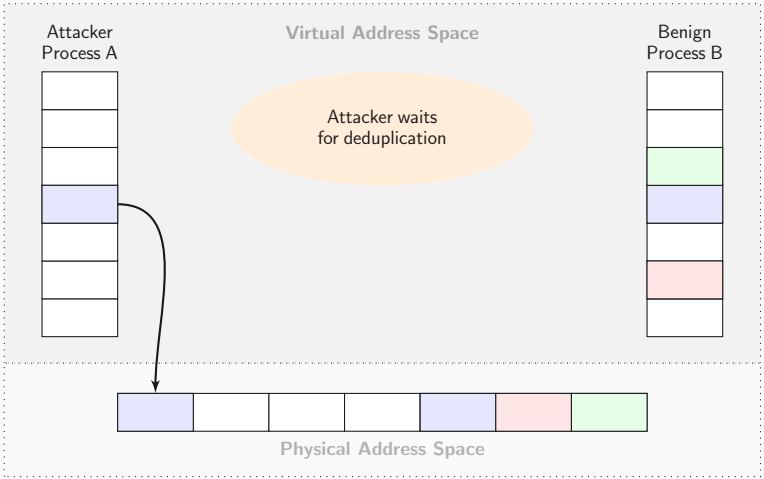

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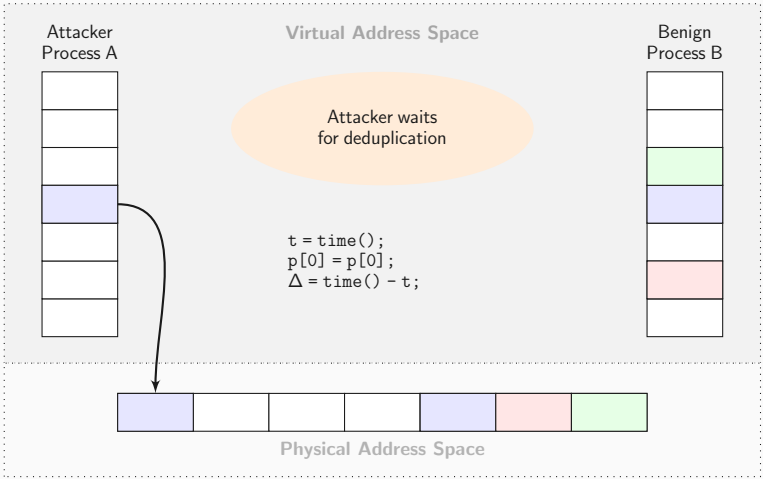

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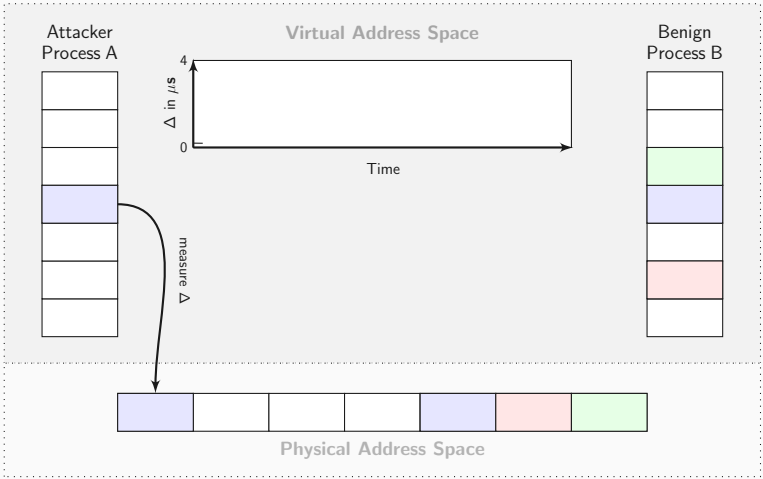

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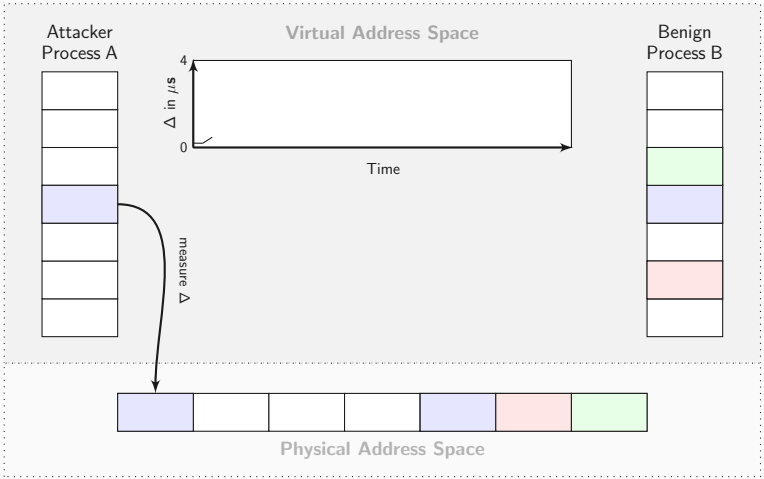

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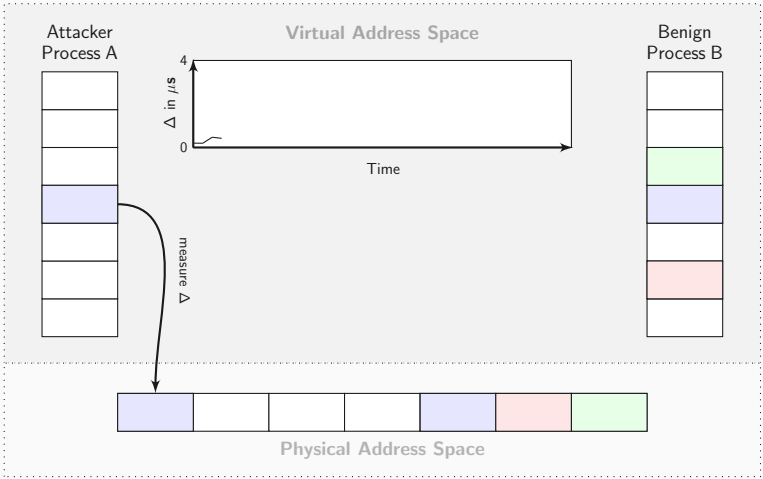

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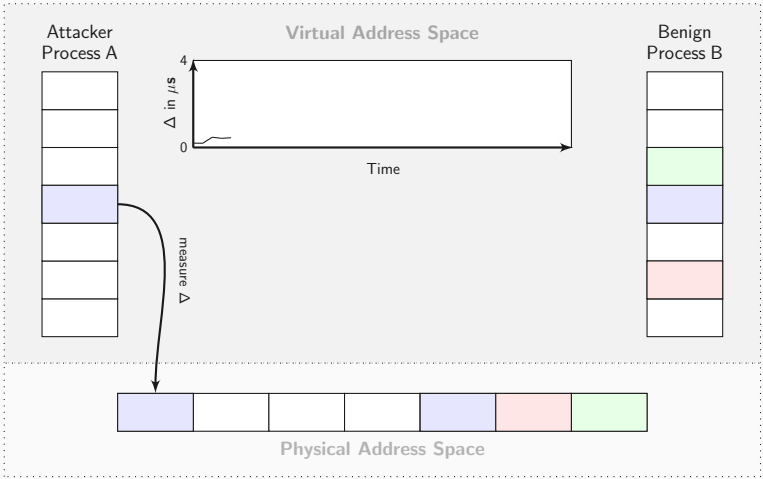

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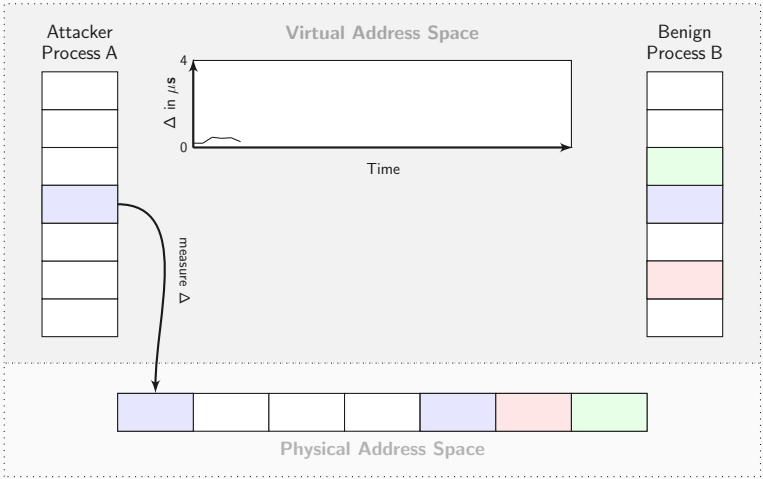

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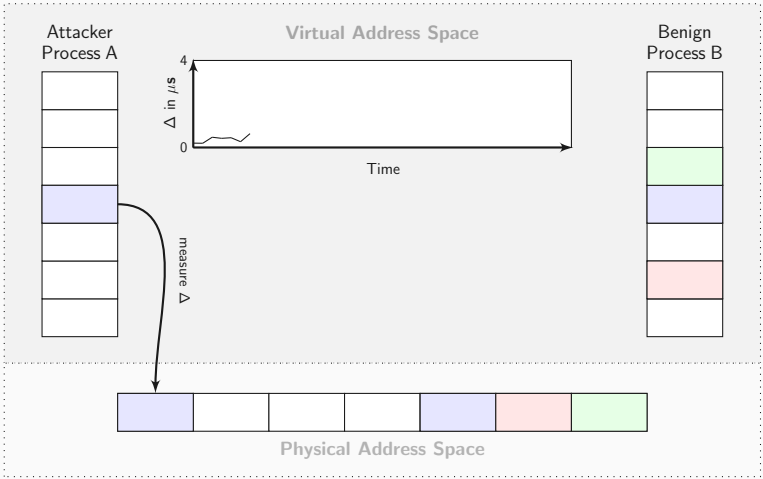

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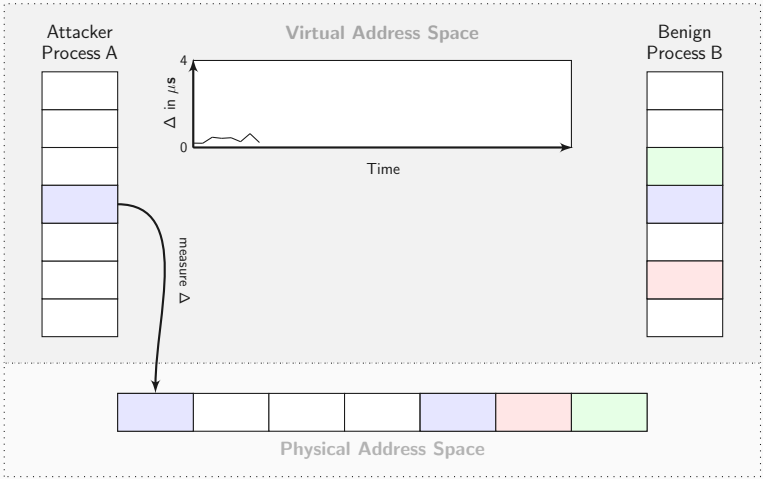

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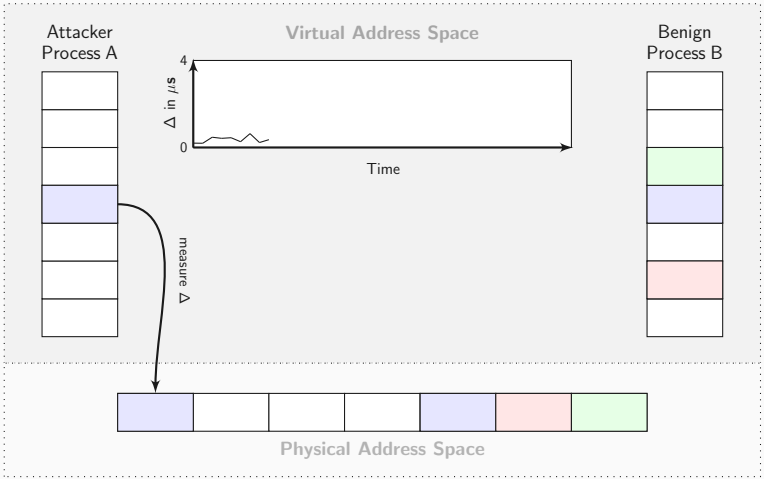

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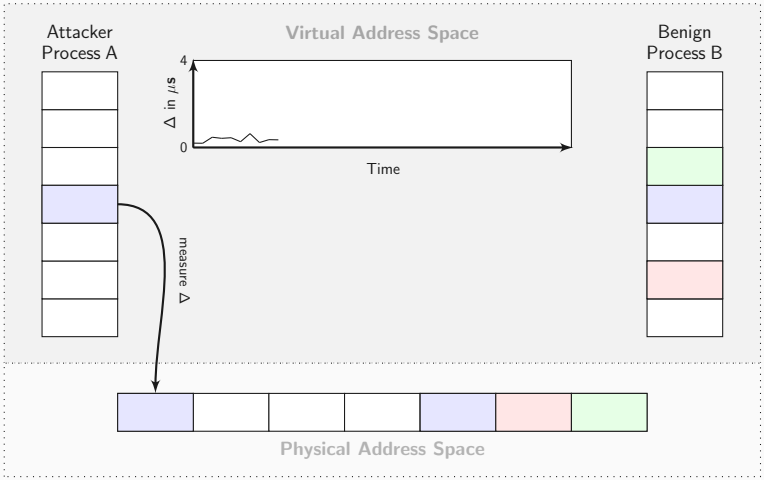

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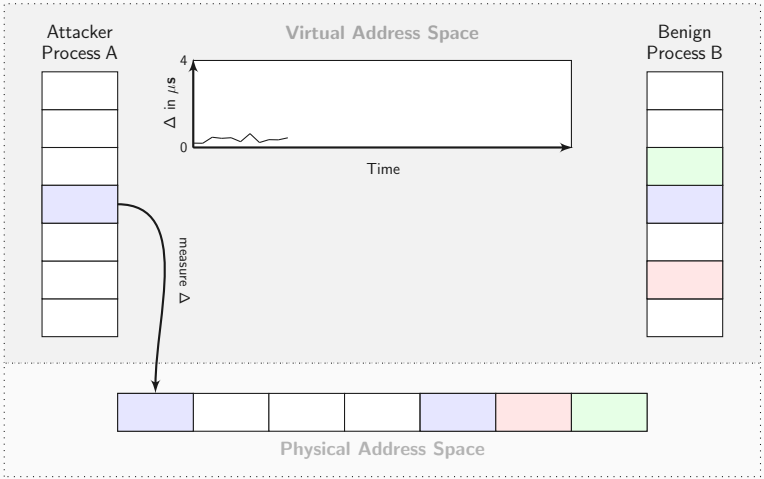

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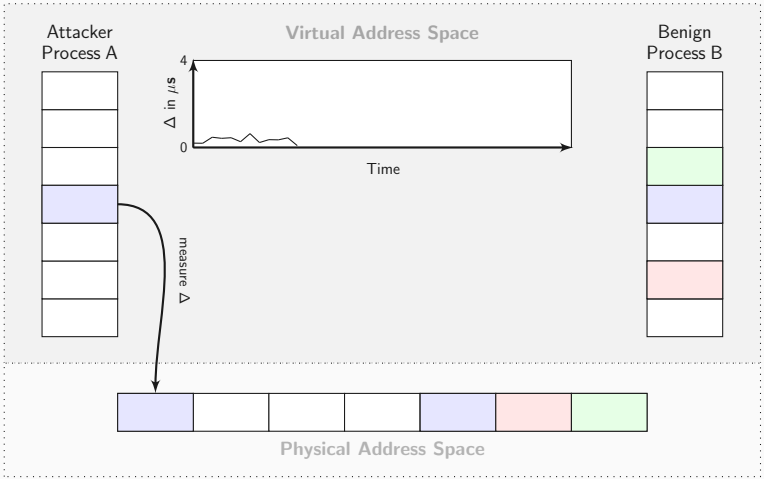

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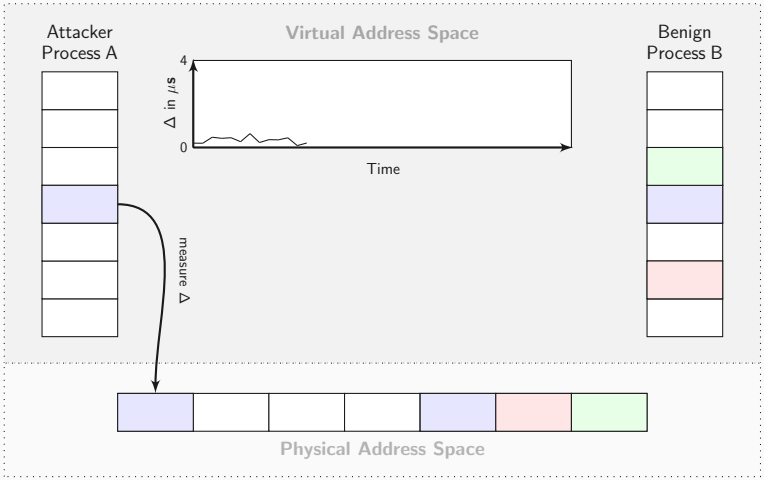

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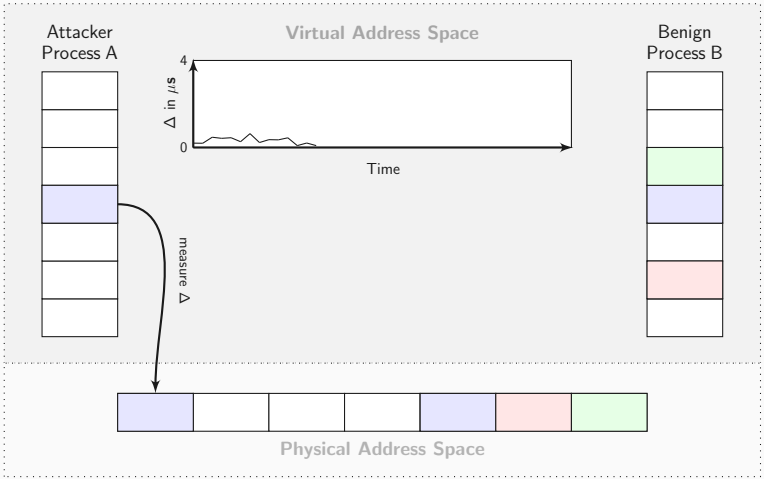

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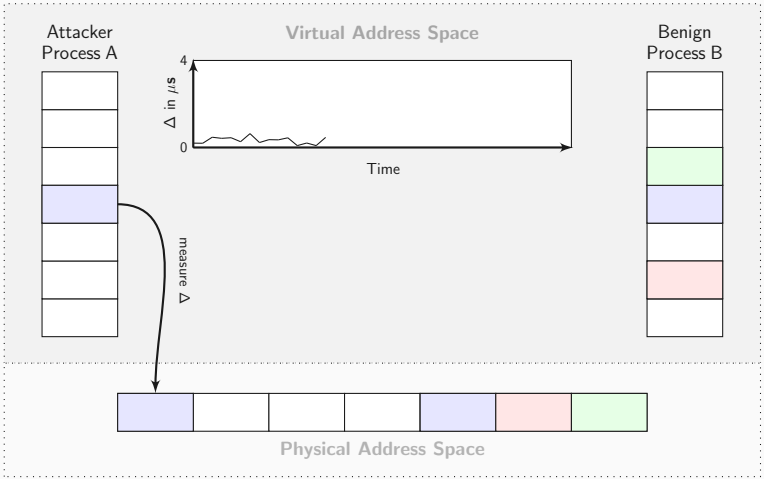

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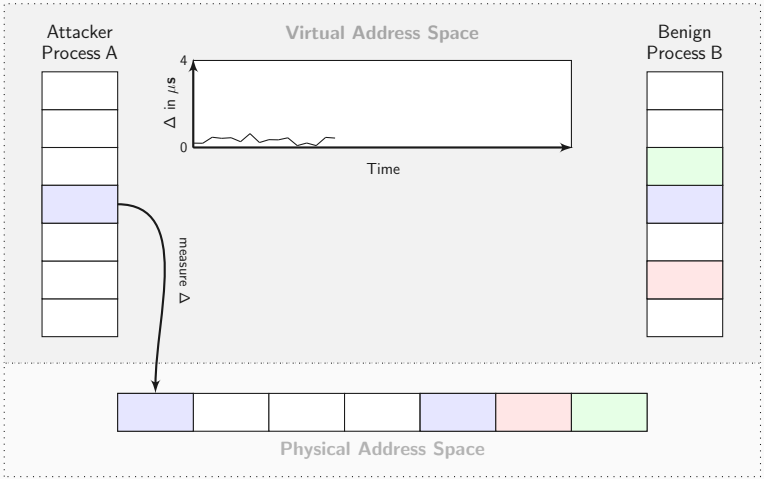

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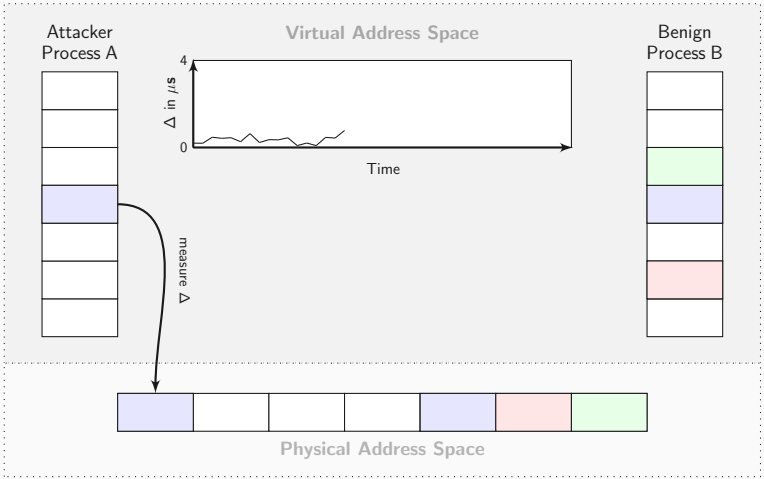

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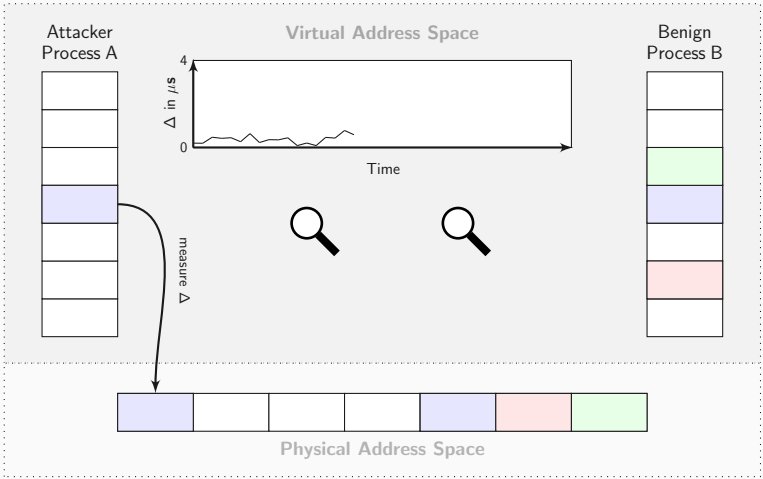

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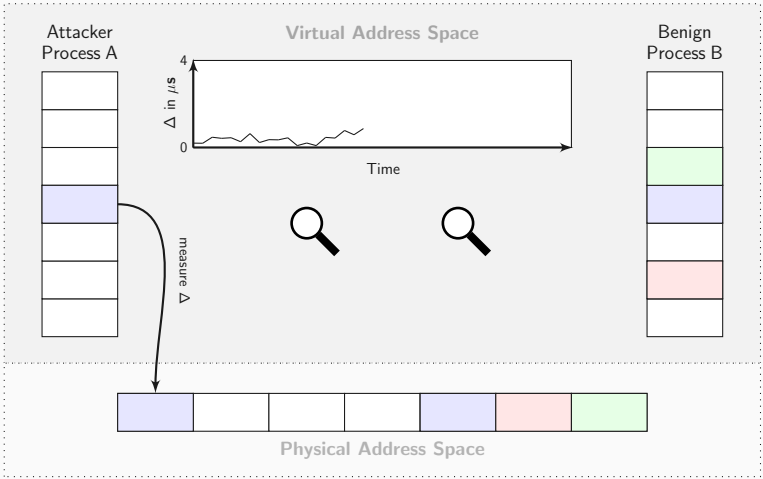

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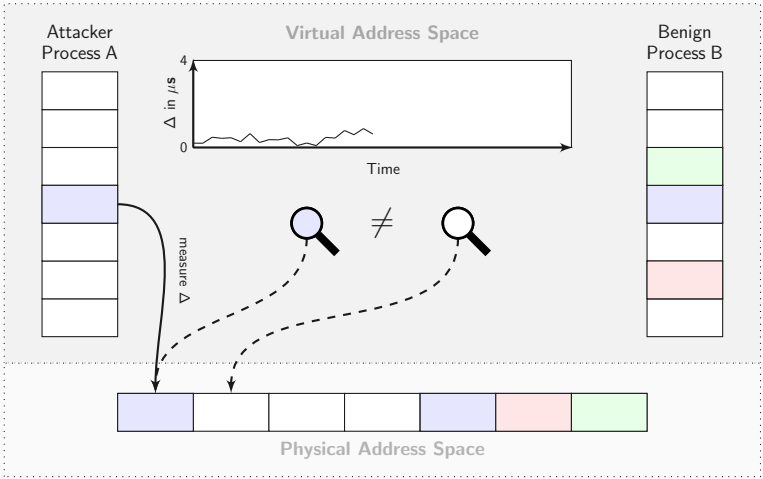
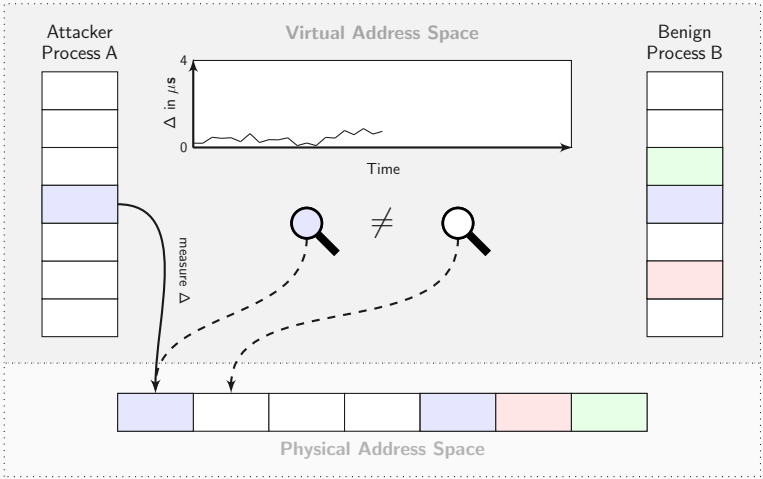


Page Deduplication Attack



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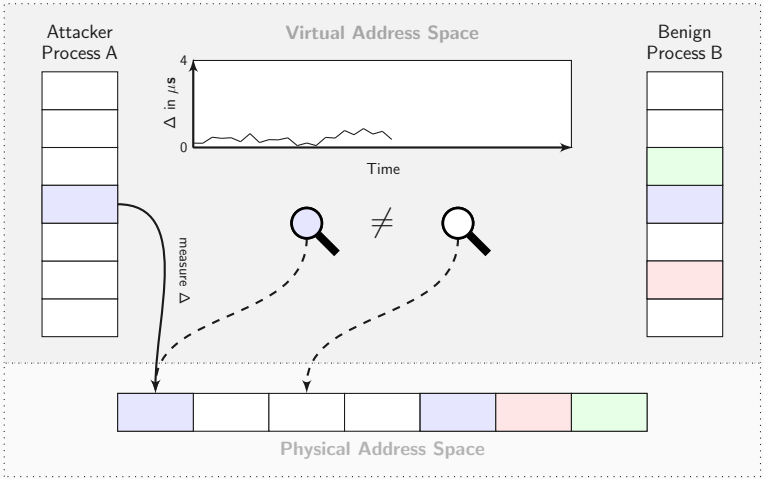

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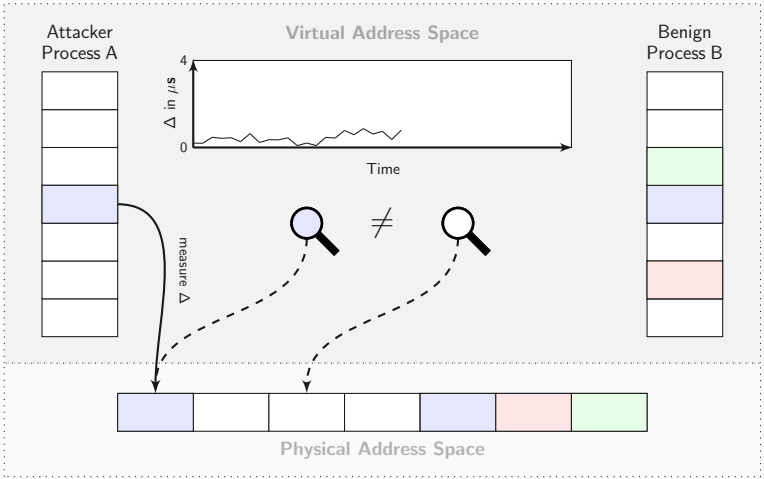

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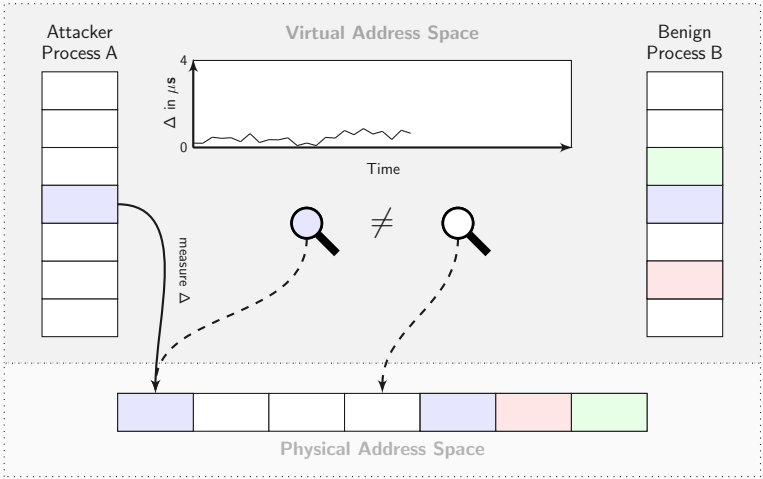

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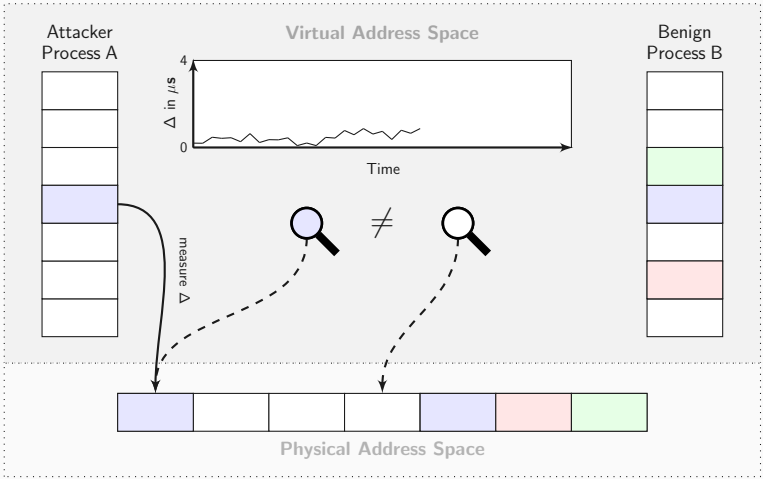

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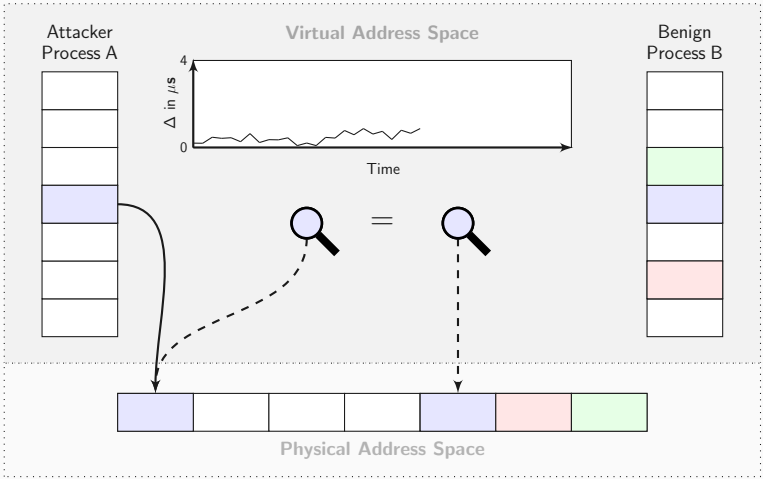

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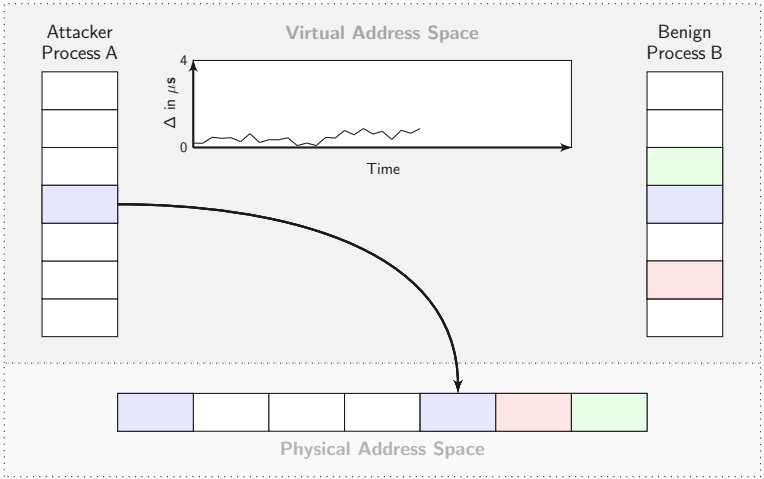

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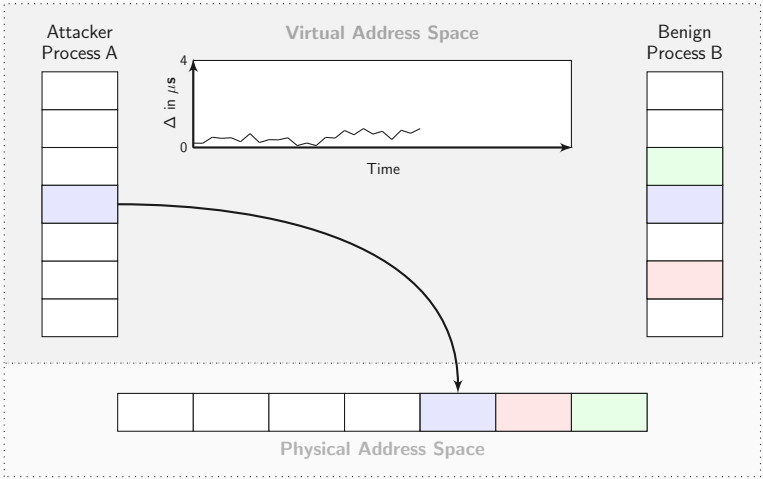

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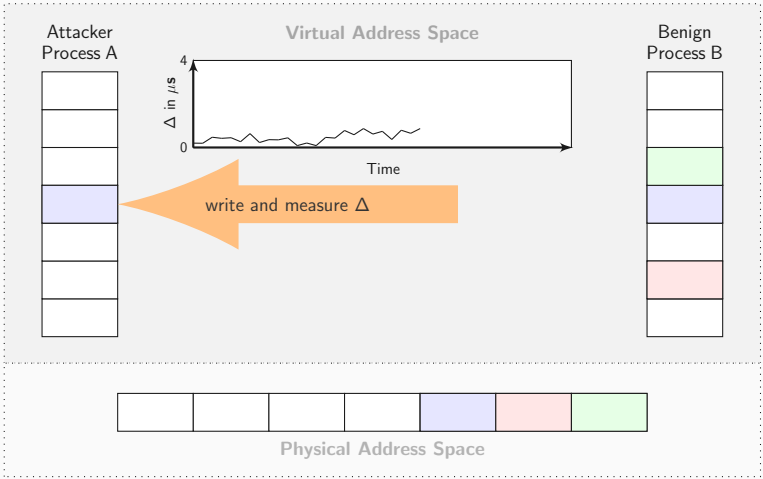

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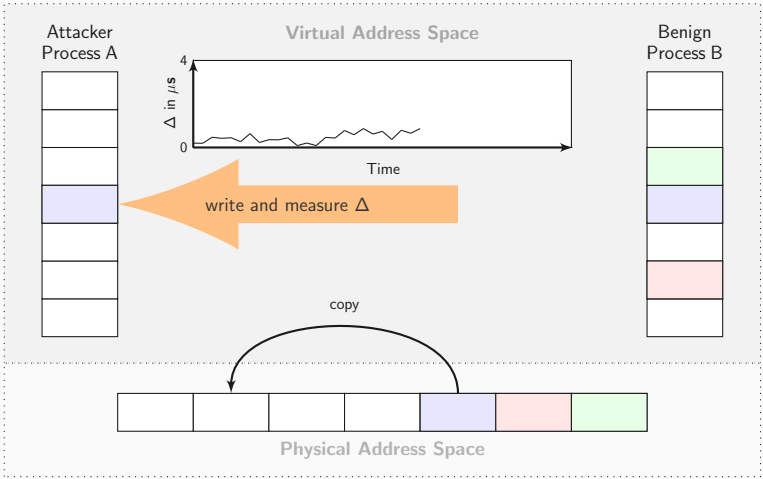

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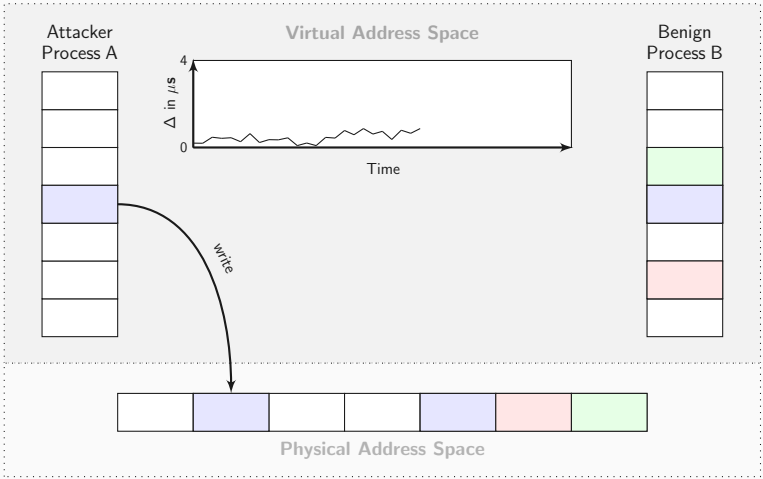

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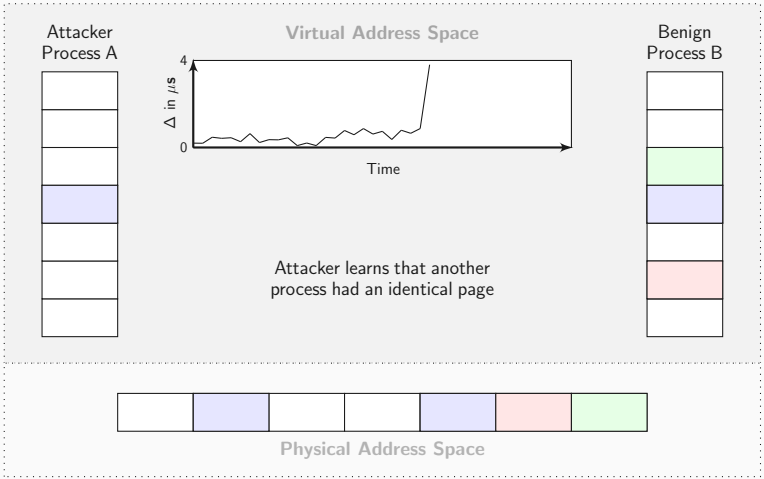

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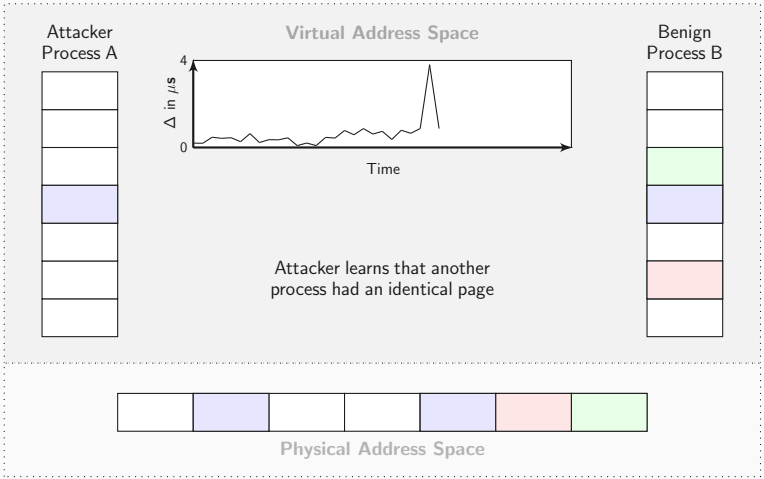

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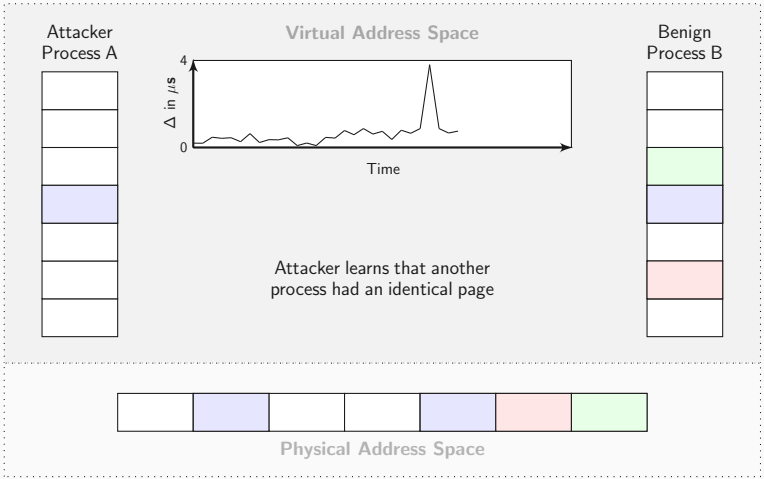

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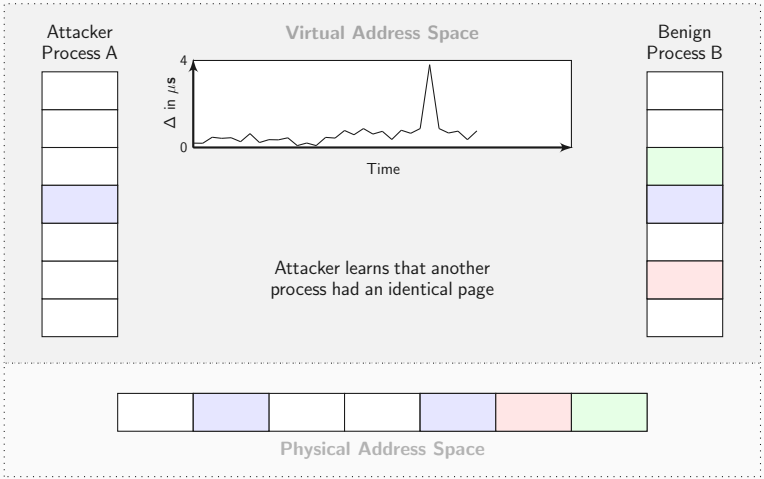

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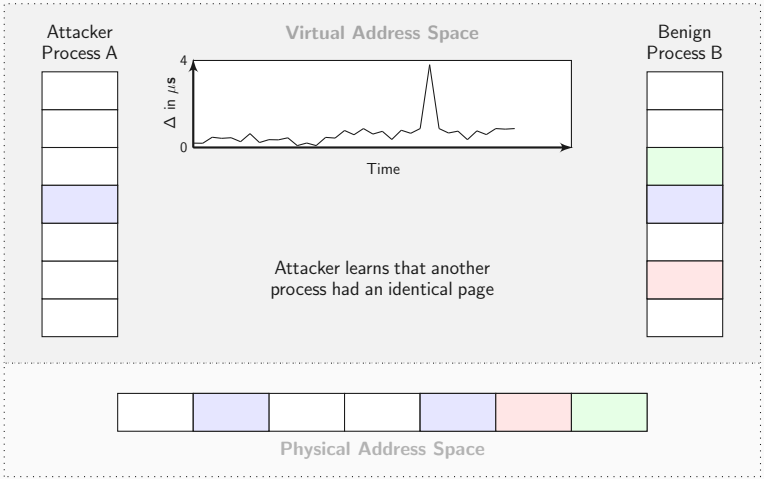

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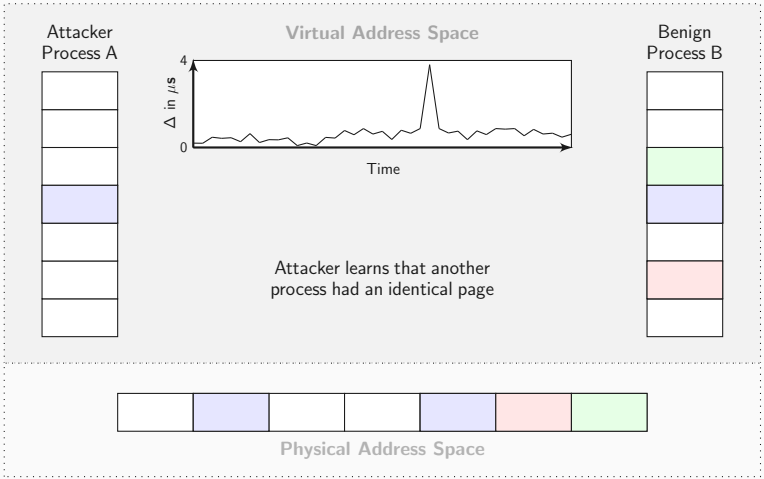

What can be attacked?

- Detect binary versions in co-located VMs
- Detect downloaded image in Firefox under certain conditions

→ Attacks on hypervisors

- Native code only

What can be attacked?

- Detect CSS files and images of opened websites
  - Chrome, Firefox and Internet Explorer
- Perform the attack in JavaScript

$\rightarrow$ Attacks on KVM, Windows 8.1 and Android

- Images and CSS files are page-aligned in memory
- Load them into memory for all websites of interest
- Detect deduplication

→ Malicious ad networks: alternative to tracking pixels?

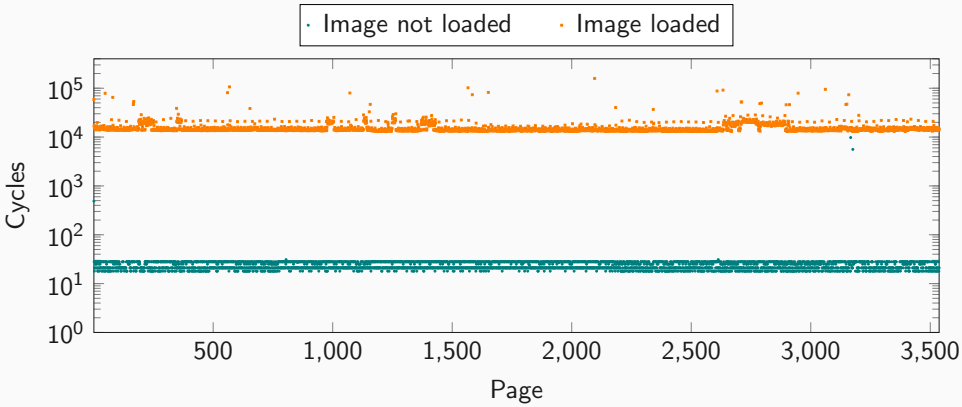
Image not loaded
Image loaded
Cycles
10^5
10^4
10^3
10^2
10^1
10^0
500
1,000
1,500
2,000
2,500
3,000
3,500
Page

- No cycle counting (`rdtsc`)
- No access to virtual addresses

- Only require microsecond accuracy
  - `performance.now()` is accurate enough
  - Can even work with millisecond accuracy
    - Accumulate time difference
    - Only possible with enough image/CSS data
- Large typed arrays are allocated page-aligned


Image not loaded
Image loaded
Nanoseconds
10^5
10^4
10^3
10^2
500
1,000
1,500
2,000
2,500
3,000
3,500
Page

- Attacker chosen set of websites
- Load website images and CSS files into arrays
- Reuse HTTP headers of system under attack

JavaScript:

- Reduce timer accuracy?
- Prevent page-aligned arrays?
- Website diversification?
- Prevent control over full pages
  - Every n-th byte not part of JavaScript array

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Generic:

- Disable page deduplication (for writable pages)

- Can we mount an attack without page deduplication?

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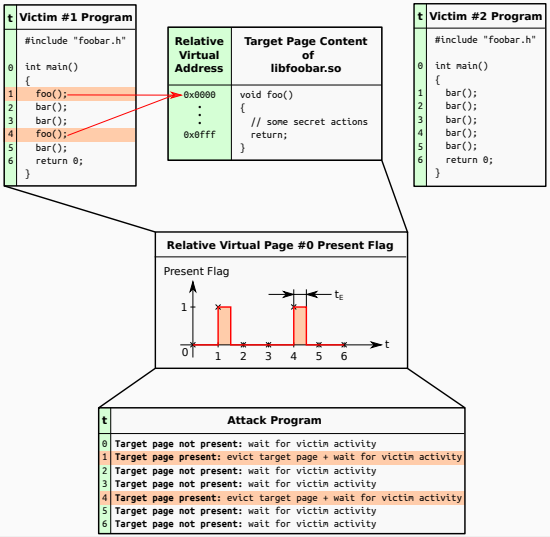
- Shared pages are in the page cache

- Can we mount an attack without page deduplication?
- Shared pages are in the page cache
- Non-shared pages too

Where to get the signal from?

```
MINCORE(2)                Linux Programmer's Manual               MINCORE(2)

NAME        top

       mincore - determine whether pages are resident in memory

SYNOPSIS        top

       #include <unistd.h>
       #include <sys/mman.h>

       int mincore(void *addr, size_t length, unsigned char *vec);

   Feature Test Macro Requirements for glibc (see feature_test_macros(7)):

       mincore():
           Since glibc 2.19:
                _DEFAULT_SOURCE
           Glibc 2.19 and earlier:
                _BSD_SOURCE || _SVID_SOURCE

DESCRIPTION        top

       mincore() returns a vector that indicates whether pages of the
       calling process's virtual memory are resident in core (RAM), and so
       will not cause a disk access (page fault) if referenced.  The kernel
       returns residency information about the pages starting at the address
       addr, and continuing for length bytes.
```

Attack Idea / Overview



Challenge: Flush / Evict

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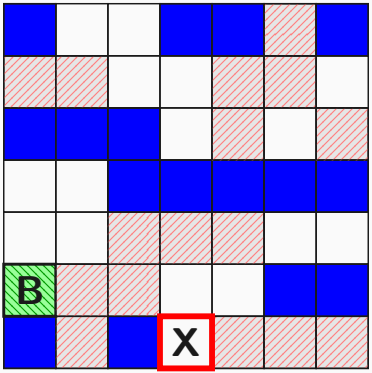
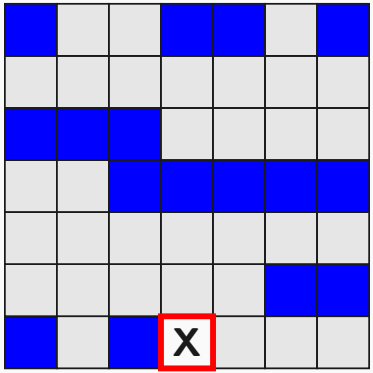
- Eviction? Well...
- Filling your entire memory with garbage takes long, makes your system unstable and laggy
- Got down to around 2–10 seconds with that approach in 2015.
- Idea: use page cache pages for eviction

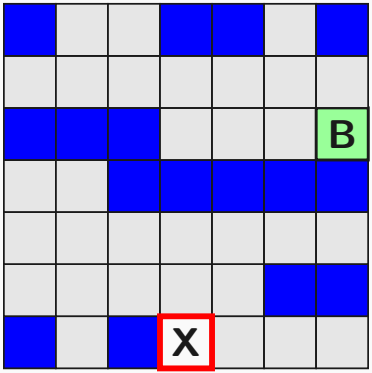
(1) Start



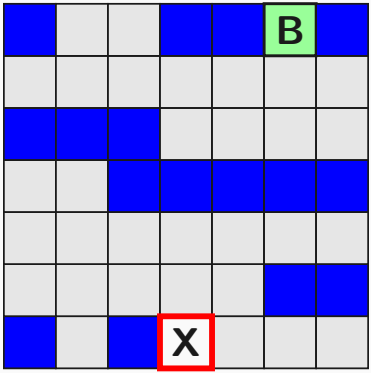
(2) Evict Page Cache



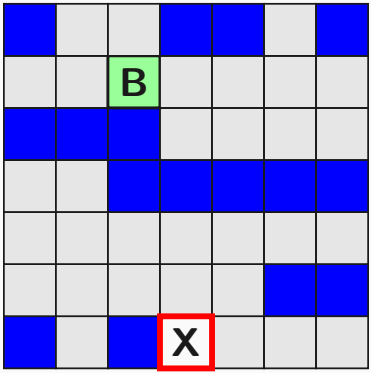
(3) Access Binary



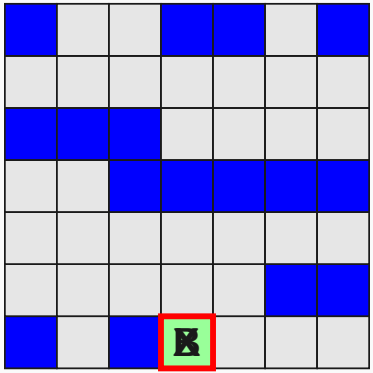
(4) Evict + Access



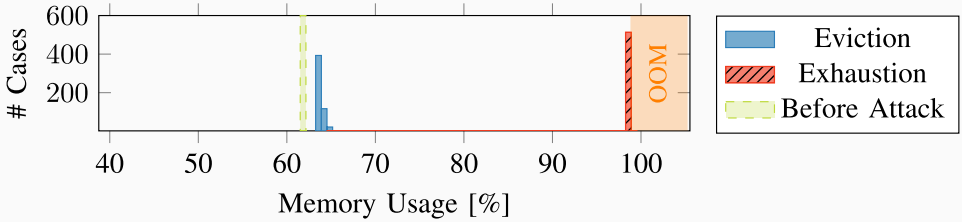
(5) Evict + Access



(6) Stop if target reached



- Great advantage over memory exhaustion: only negligible memory footprint



But...

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- Idea: Let's build the eviction set more cleverly

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→ 149 ms for one eviction

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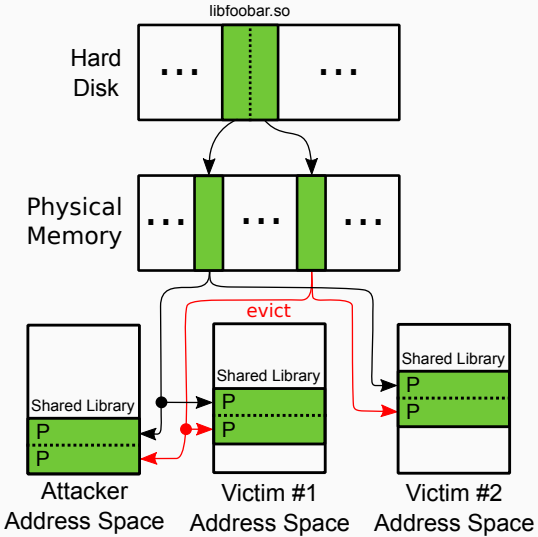

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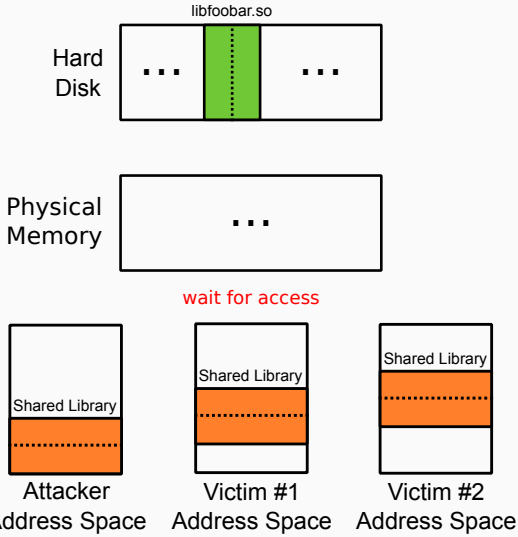

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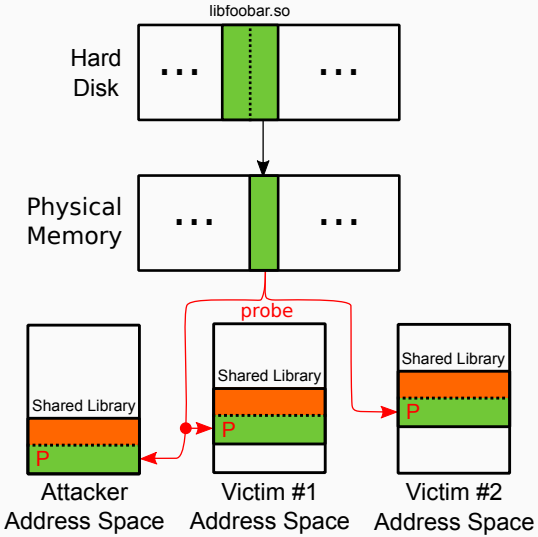

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→ 4.48 ms for one eviction

- Cross-container / cross-sandbox covert channel:

Attack Examples

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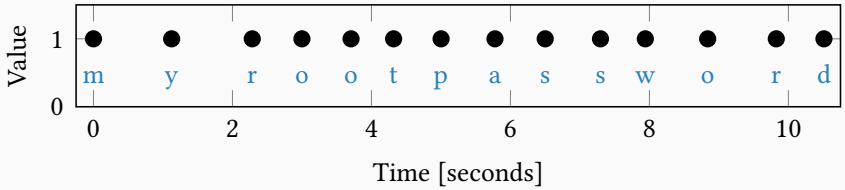
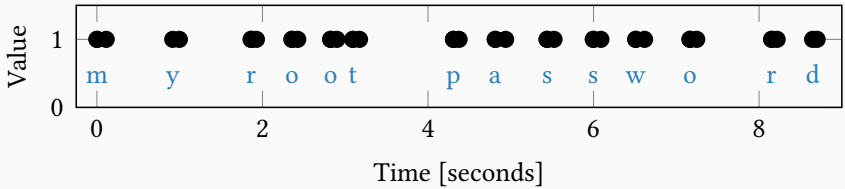
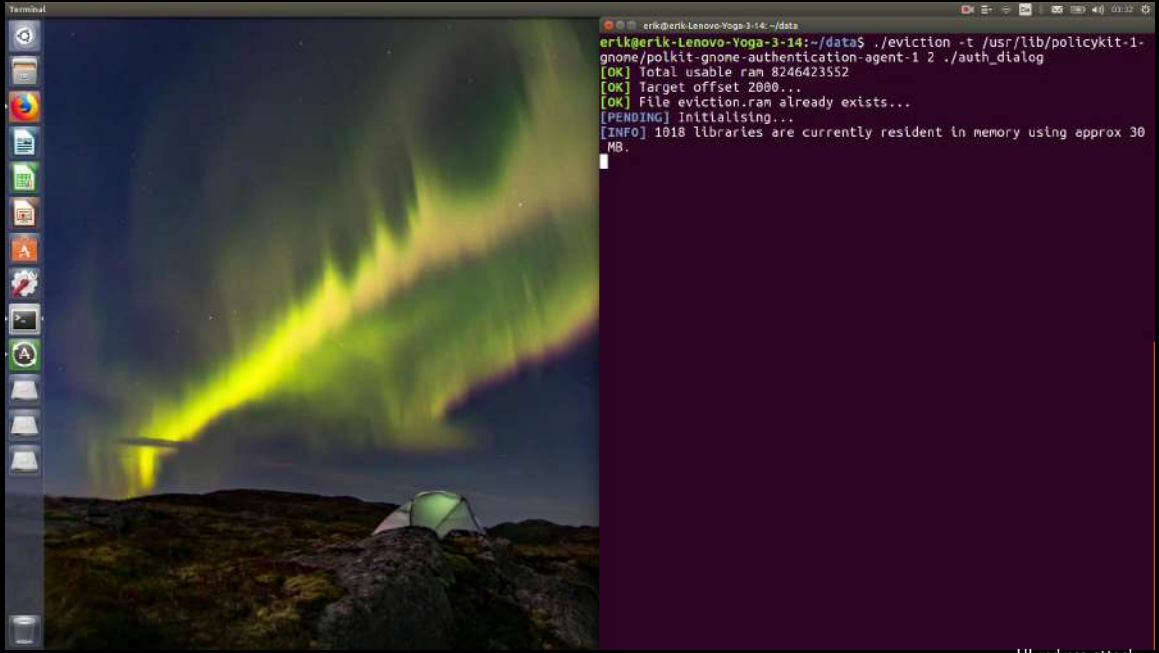


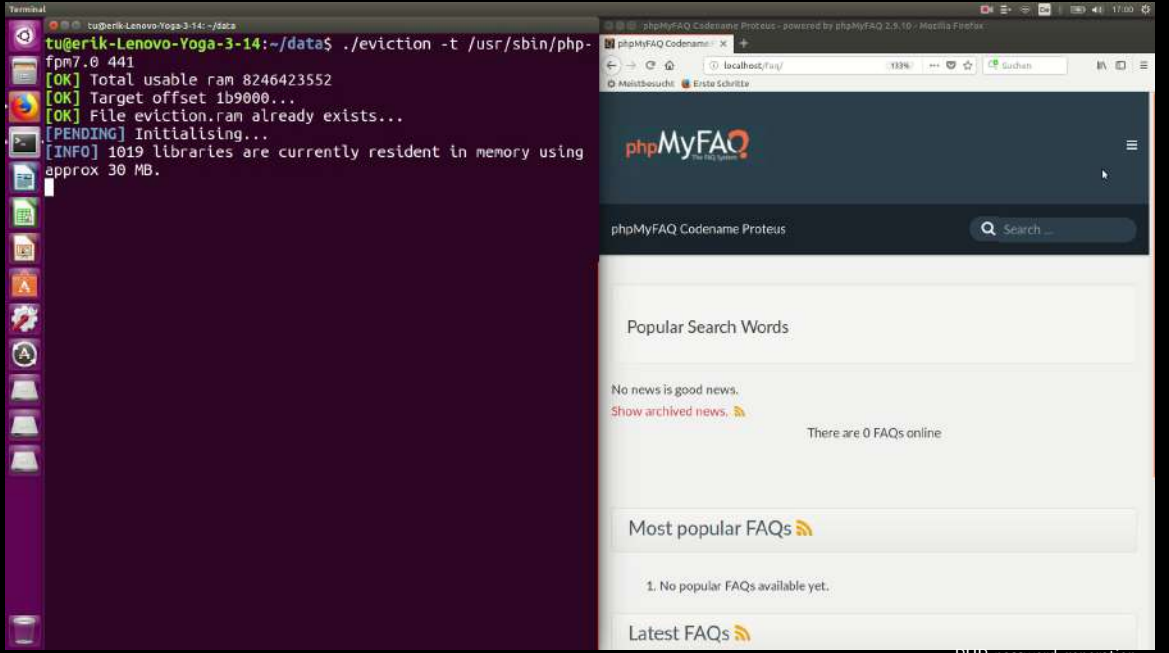
(Linux)



(Windows)



UI redress attack


Terminal
tu@erik-Lenovo-Yoga-3-14: ~/data
tu@erik-Lenovo-Yoga-3-14:~/data$ ./eviction -t /usr/sbin/php-fpm7.0 441
[OK] Total usable ram 8246423552
[OK] Target offset 1b9000...
[OK] File eviction.ram already exists...
[PENDING] Initialising...
[INFO] 1019 libraries are currently resident in memory using approx 30 MB.
phpMyFAQ Codename Proteus - powered by phpMyFAQ 2.9.10 - Mozilla Firefox
phpMyFAQ Codename
localhost/faq/
Meistbesucht
Erste Schritte
phpMyFAQ
phpMyFAQ Codename Proteus
Search ...
Popular Search Words
No news is good news.
Show archived news.
There are 0 FAQs online
Most popular FAQs
1. No popular FAQs available yet.
Latest FAQs

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Microarchitectural Attacks and Beyond

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February 21, 2019

Graz University of Technology