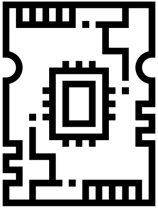
# Page Cache Attacks

## Microarchitectural Attacks on Flawless Hardware

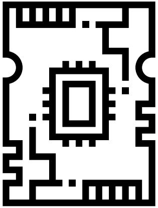
Daniel Gruss, Trishita Tiwari, Michael Schwarz, Erik Kraft

# Microarchitectural Components



- Modern CPUs contain multiple microarchitectural elements

# Microarchitectural Components



- Modern CPUs contain multiple microarchitectural elements

Caches and buffers

Predictors

...

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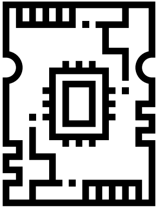


- Modern CPUs contain multiple microarchitectural elements

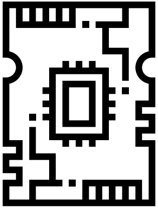
Caches and buffers

Predictors

...

- Transparent for the programmer

# Microarchitectural Components



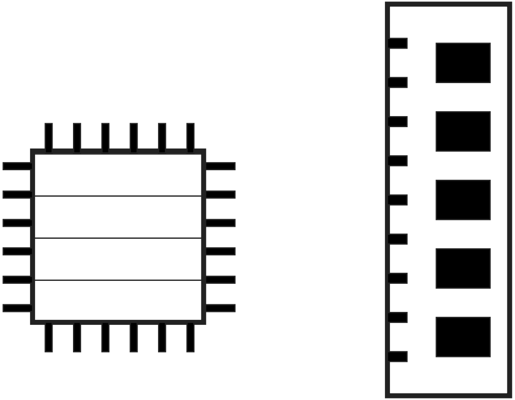
- Modern CPUs contain multiple microarchitectural elements

Caches and buffers

Predictors

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

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



# CPU Cache

```
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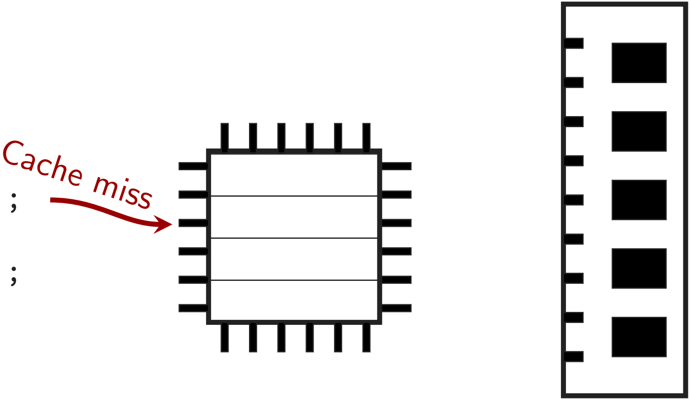

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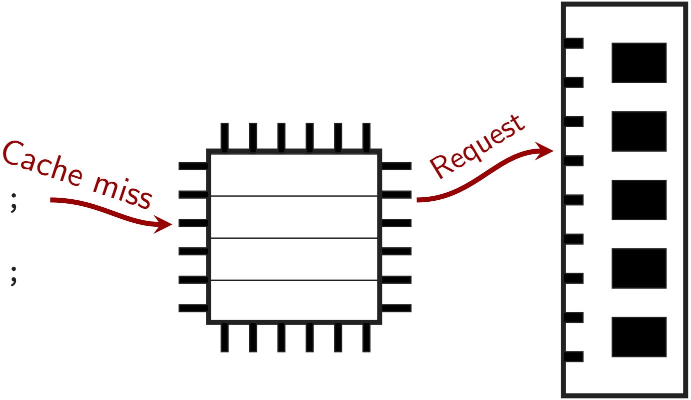

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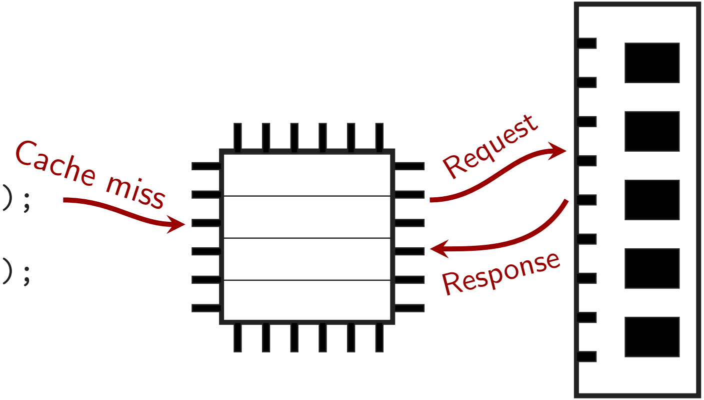

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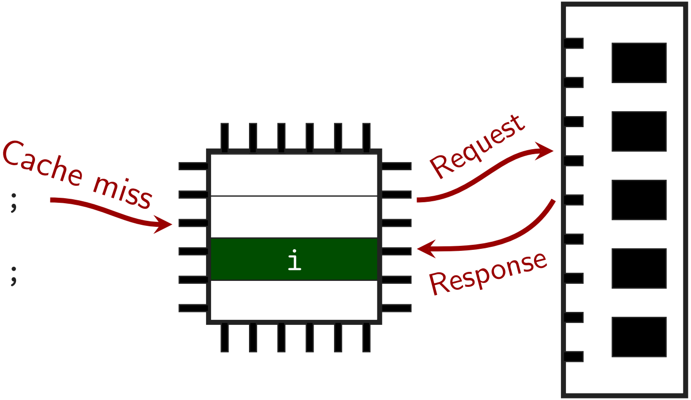
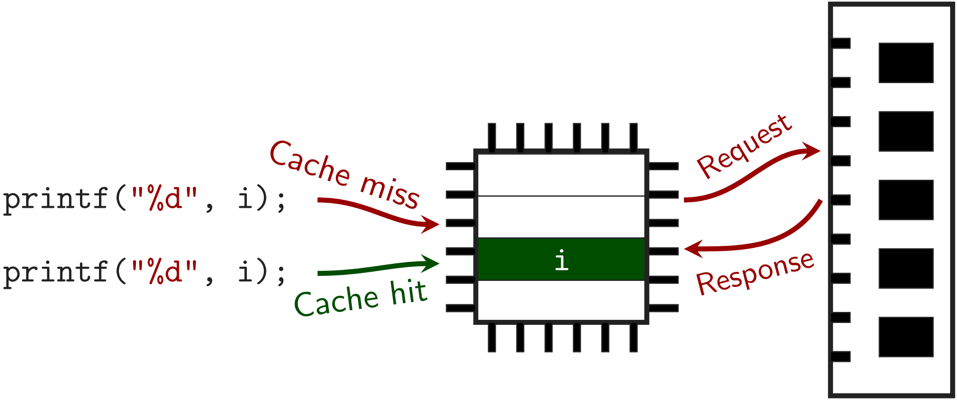


# CPU Cache



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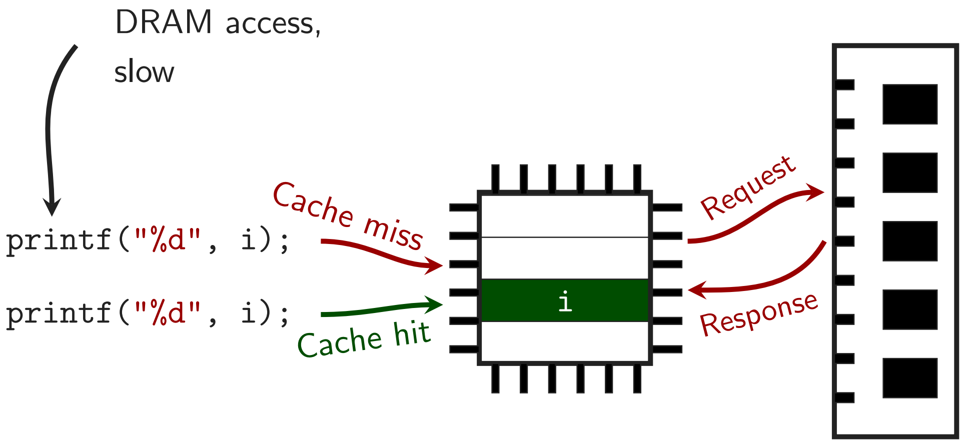
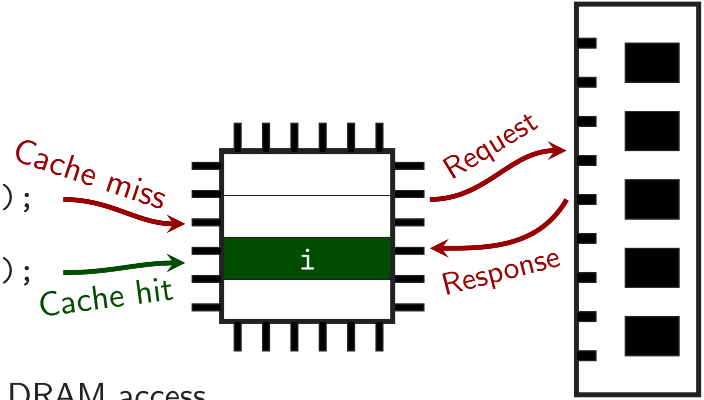

DRAM access,
slow
printf("%d", i);
printf("%d", i);
Cache miss
Cache hit
i
Request
Response

# CPU Cache

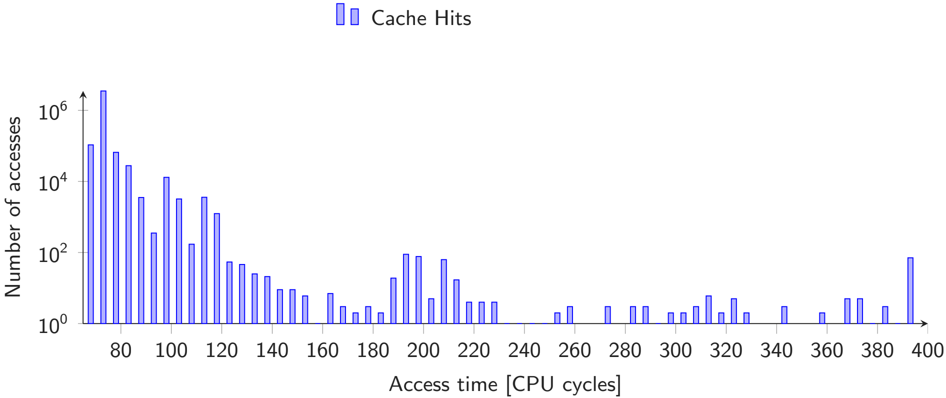
DRAM access,
slow

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




No DRAM access,
much faster

# Caching speeds up Memory Accesses



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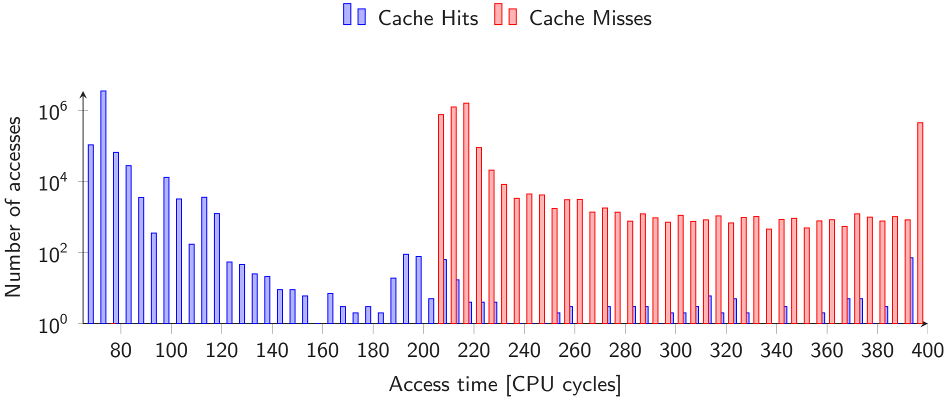
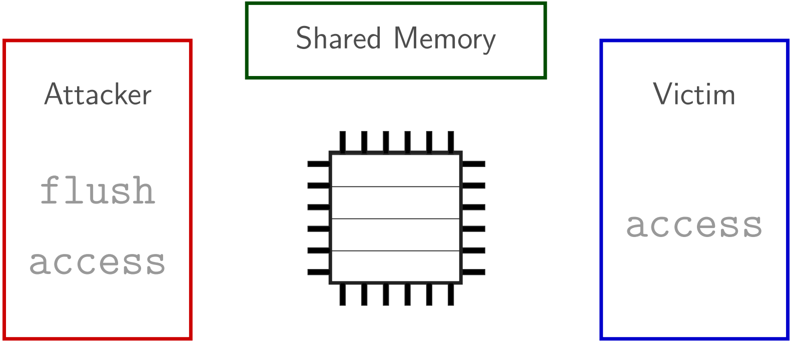
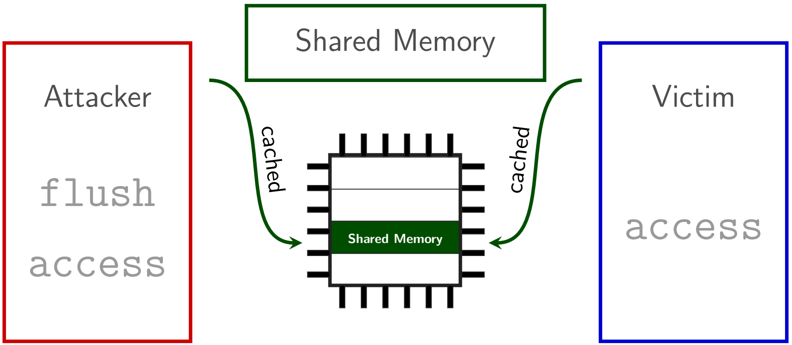
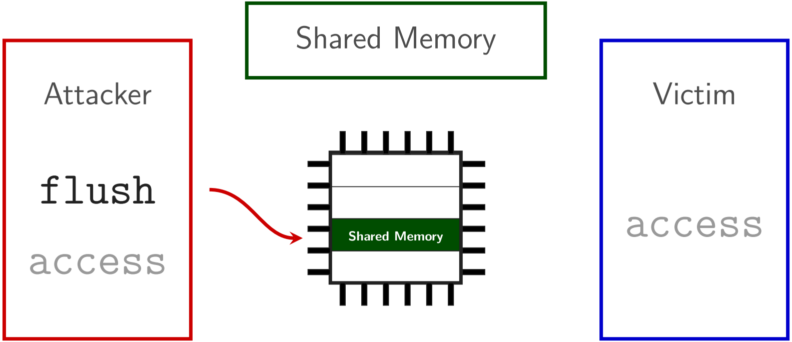


# Flush+Reload




Shared Memory
Attacker
flush
access
cached
Shared Memory
cached
Victim
access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Attacker
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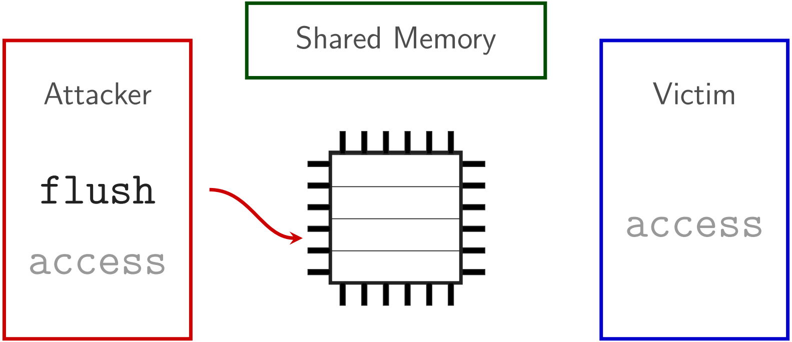
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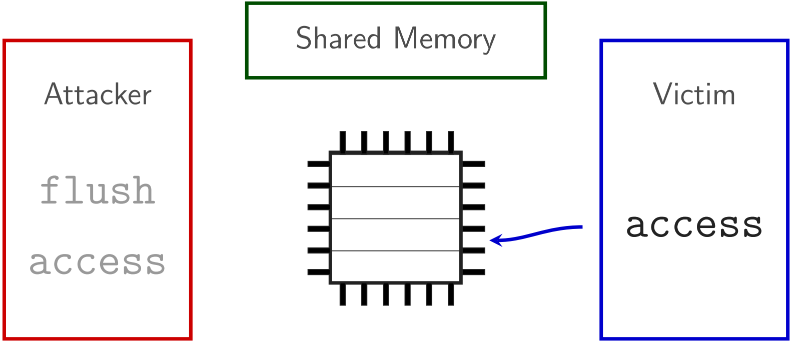
Attacker
flush
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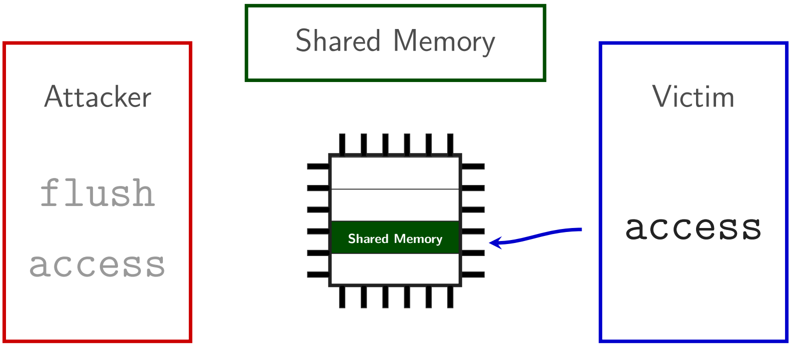
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flush
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Shared Memory
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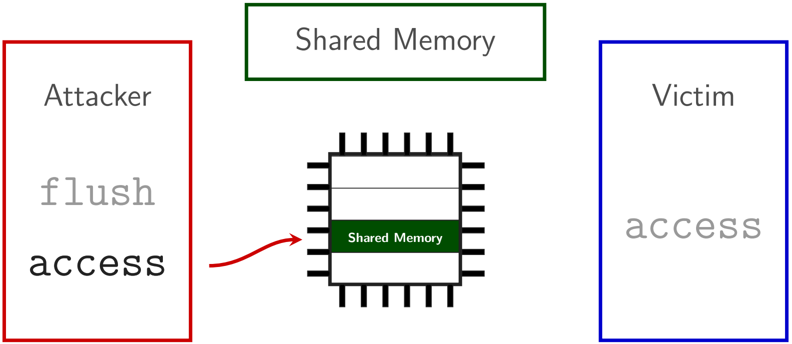
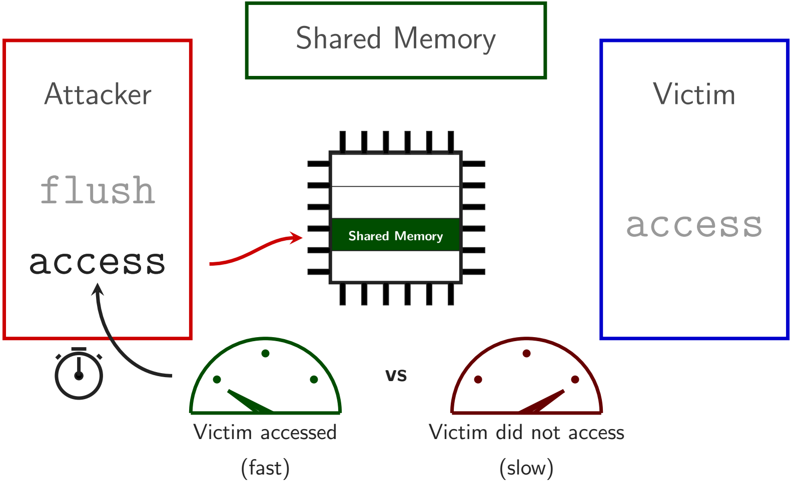
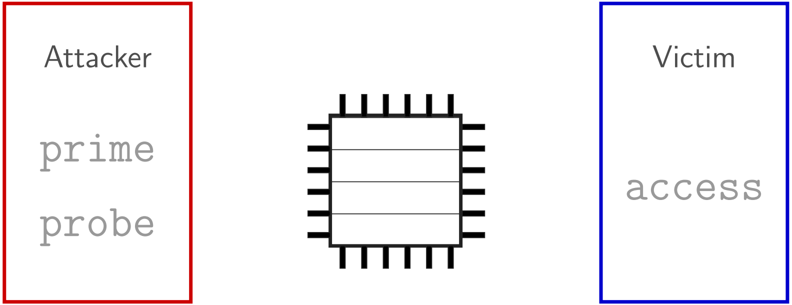


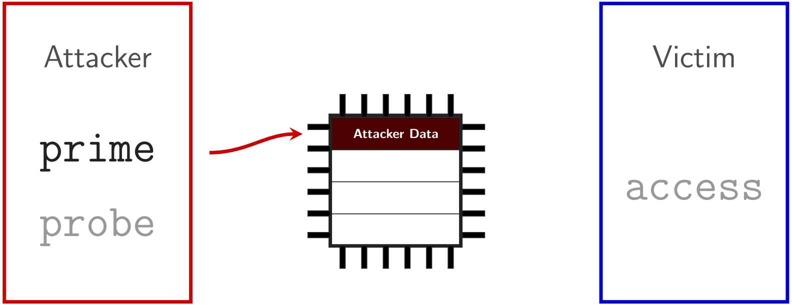


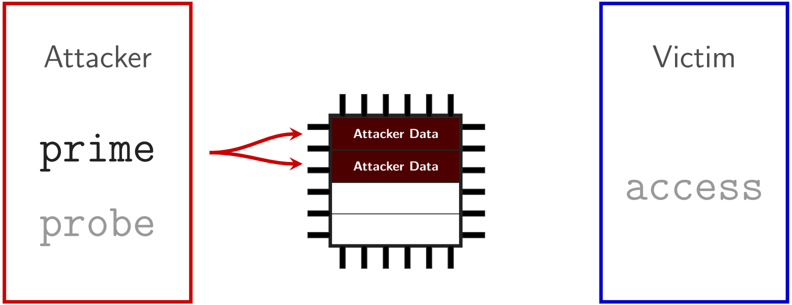
Daniel Gruss (@lavados), Trishita Tiwari (@fork_while_1), Michael Schwarz (@misc0110), Erik Kraft (@ekraft95)


Shared Memory
Attacker
flush
access
Shared Memory
Victim
access
vs
Victim accessed
(fast)
Victim did not access
(slow)

# Prime+Probe




Attacker
prime
probe
Attacker Data
Victim
access





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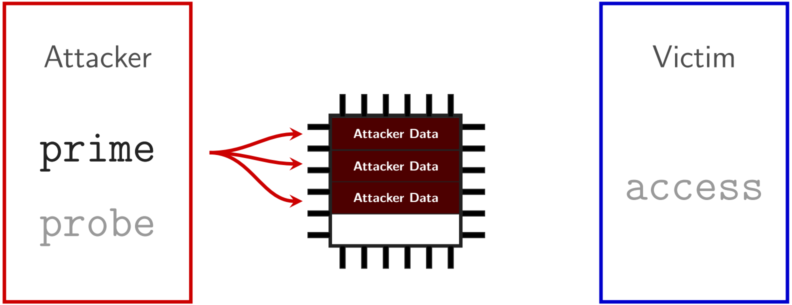
Attacker
prime
probe
Attacker Data
Attacker Data
Attacker Data
Victim
access

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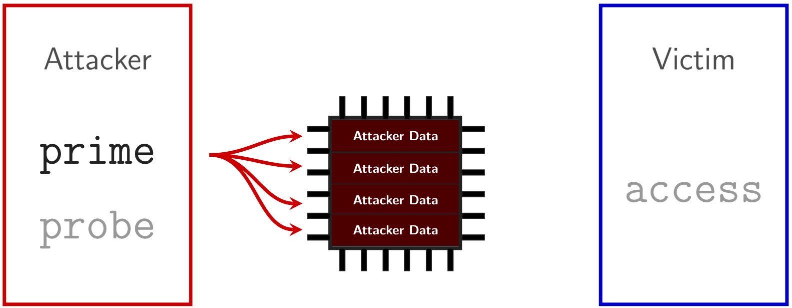
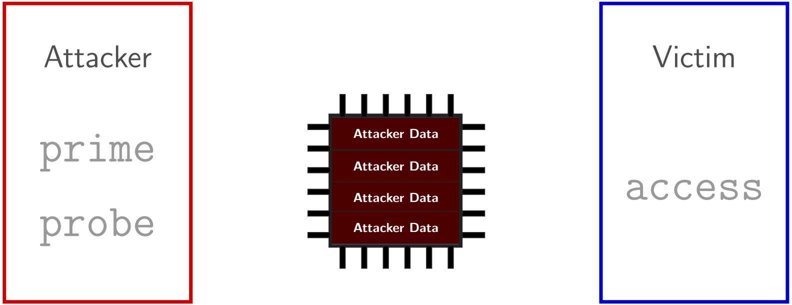

Attacker
prime
probe
Attacker Data
Attacker Data
Attacker Data
Attacker Data
Victim
access


Attacker
prime
probe
Attacker Data
Attacker Data
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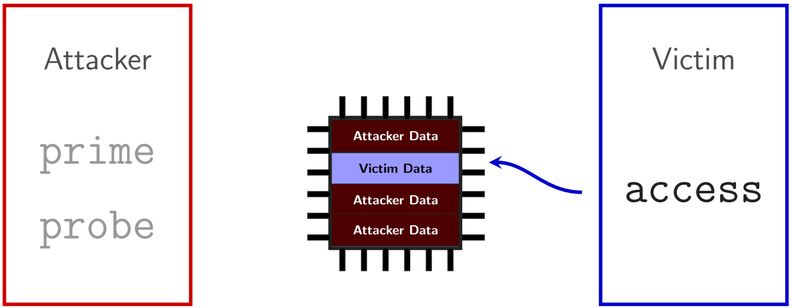
Attacker Data
Victim
access


Attacker
prime
probe
Attacker Data
Victim Data
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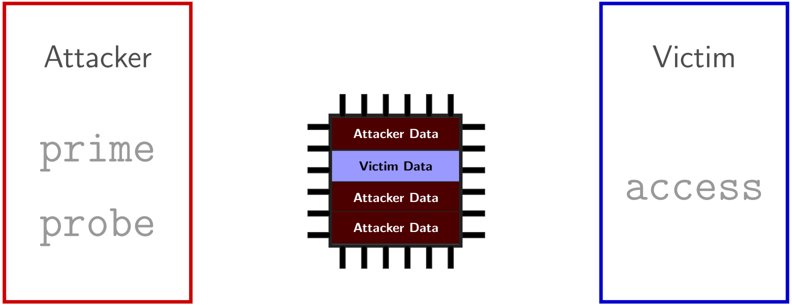
Victim
access


Attacker
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Victim
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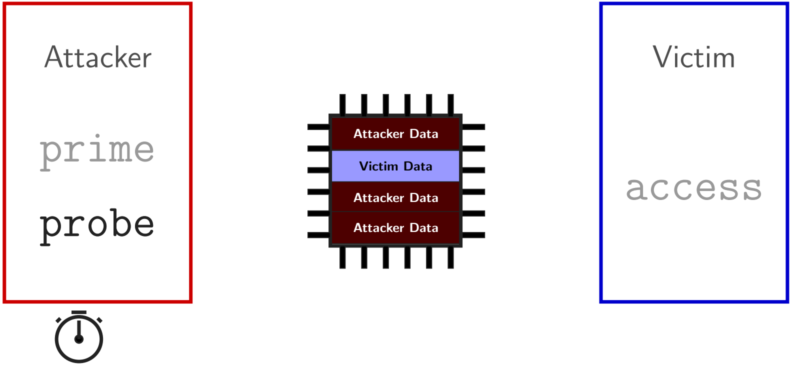
Attacker
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Victim Data
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Victim
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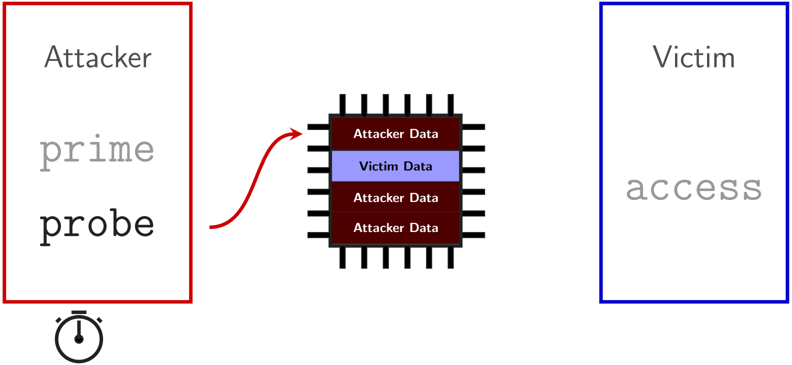
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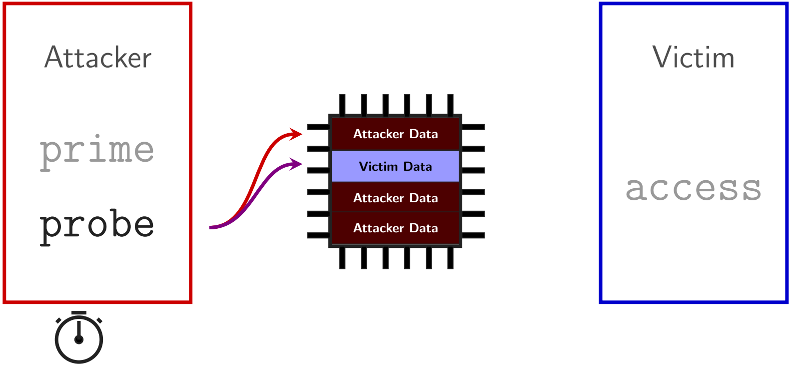
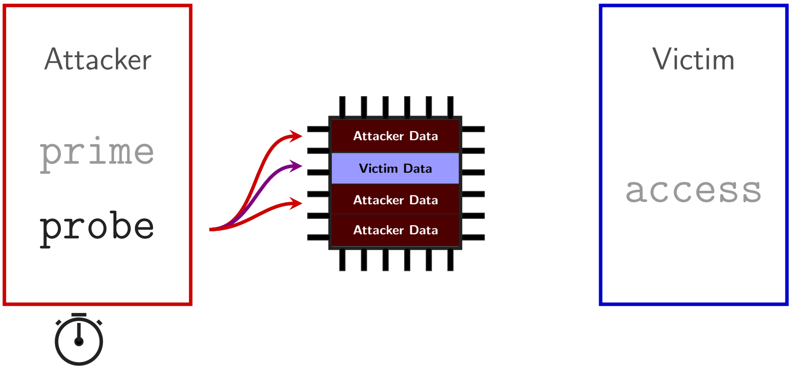
Attacker Data
Victim Data
Attacker Data
Attacker Data
Victim
access


Attacker
prime
probe
Attacker Data
Victim Data
Attacker Data
Attacker Data
Victim
access

# Prime+Probe


Attacker
prime
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Attacker Data
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Attacker Data
Attacker Data
Victim
access

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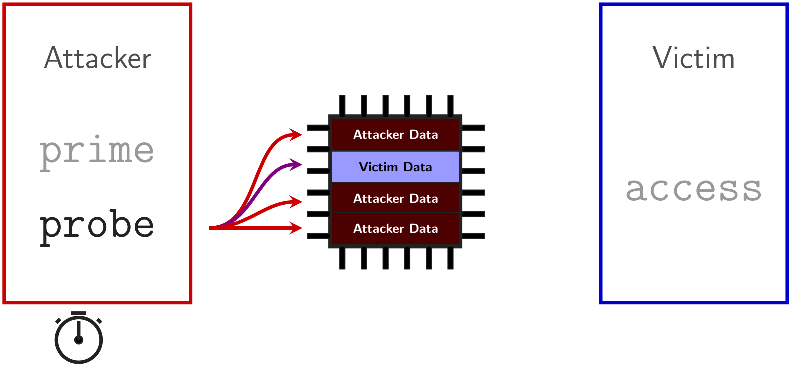
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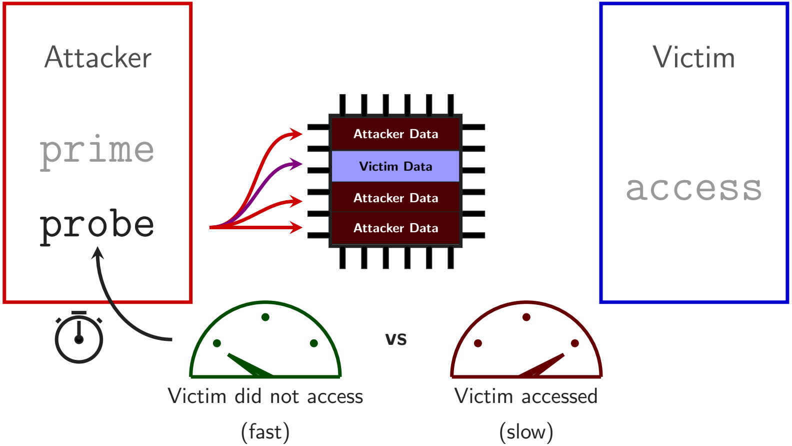
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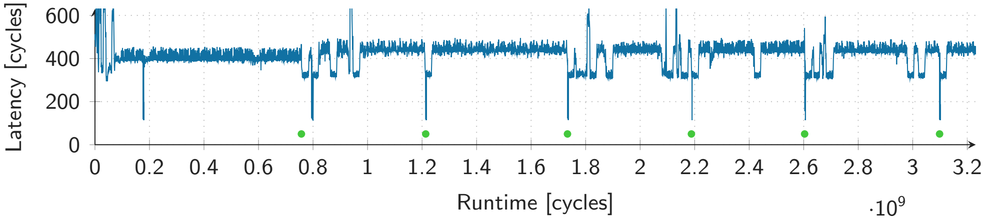
Attacker Data
Victim Data
Attacker Data
Attacker Data
Victim
access
vs
Victim did not access
(fast)
Victim accessed
(slow)

# Flush+Reload on Keystrokes




- Key presses trigger code execution in shared library (e.g., `libgdk`)

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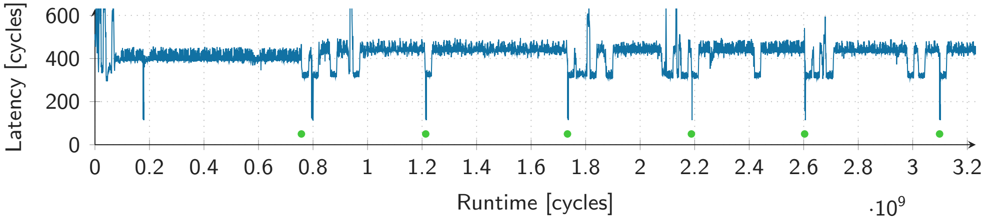


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- Flush+Reload does not reveal actual key, only time difference between keys


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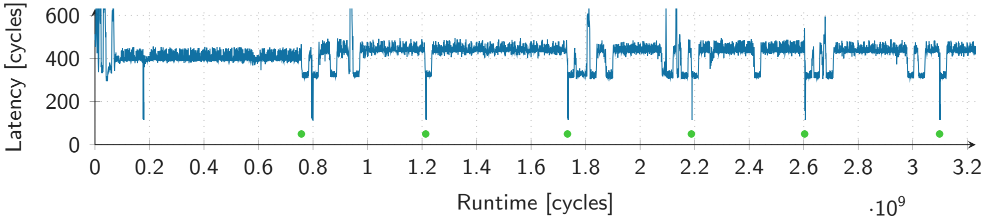
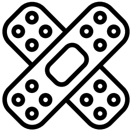


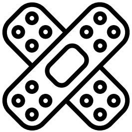

- Key presses trigger code execution in shared library (e.g., `libgdk`)
- Flush+Reload does not reveal actual key, only time difference between keys
- → Recover text with machine learning

# Meltdown, Foreshadow, ZombieLoad, Spectre

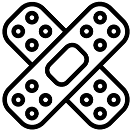


- Deeply rooted in hardware $\rightarrow$ no real fixes

# Countermeasures for $\mu$-arch. Attacks



- Deeply rooted in hardware $\rightarrow$ no real fixes
- More isolation $\rightarrow$ make exploitation harder



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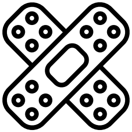

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  - Caches → we want timing differences

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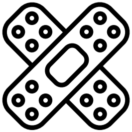

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    - Prediction → we don't want stalls

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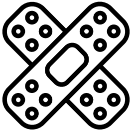

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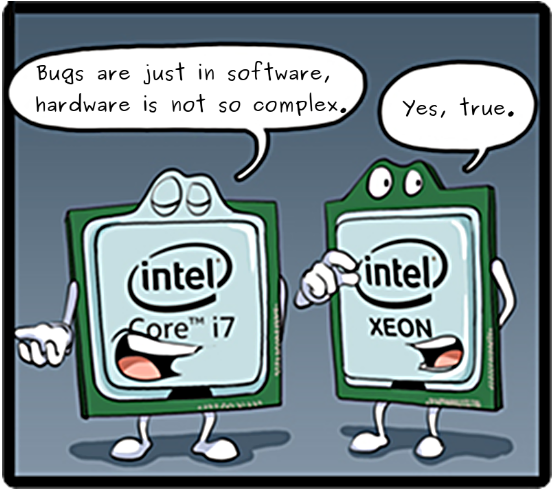
- More isolation → make exploitation harder
- Attacks on design difficult to fix
  - Caches → we want timing differences
  - Prediction → we don't want stalls
- So far: fixing symptoms




Original image from commitstrip.com

Thought experiment: what if there were no hardware side channels?

# Operating System and CPU Microarchitecture

OS

CPU

# Operating System and CPU Microarchitecture

| | OS | CPU |
|---|---|---|
| **$\mu$-arch. Interface** | Non-standard Syscall | x86<br>ISA Extension |

# Operating System and CPU Microarchitecture

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# Operating System and CPU Microarchitecture

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| | Software Prefetcher | Hardware Prefetcher |


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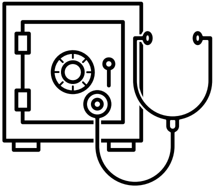
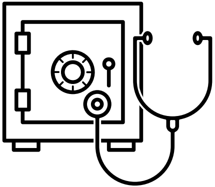
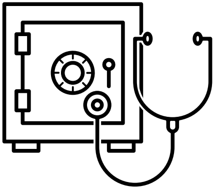
| | ... | ... |



- Hardware $\rightarrow$ Software?



- Hardware → Software?
- Hardware-Agnostic Side Channel through the OS Page Cache



- Hardware → Software?
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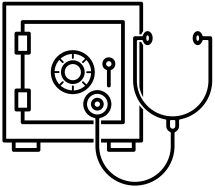
- Temporal resolution:
  - 2 µs ($\leq$ 6.7 measurements per second)
  - 466 ns ($\leq$ 223 measurements per second)

# OS Side Channel



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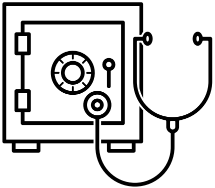
# OS Side Channel



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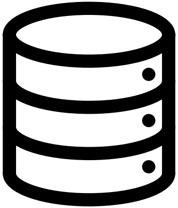
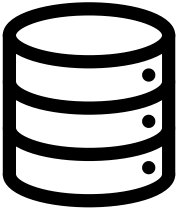
- Hardware-Agnostic Side Channel through the OS Page Cache
- Temporal resolution:
  - 2 µs ($\leq$ 6.7 measurements per second)
  - 466 ns ($\leq$ 223 measurements per second)
- Spatial resolution of 4 KiB
- Various attacks: PHP RNG, UI-Redress, Windows ASLR, Keystroke Timings, Covert channels (local + remote)



- Managed by operating system

# Page Cache



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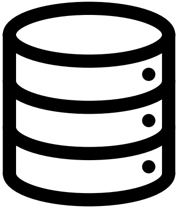

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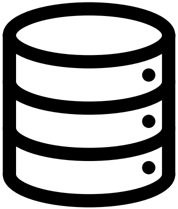
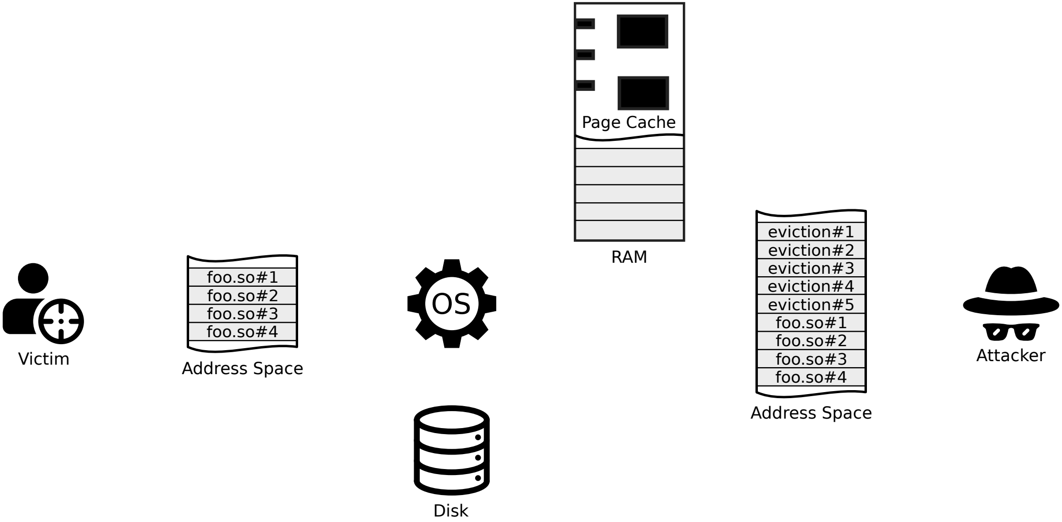


- Managed by operating system
- Buffers file pages in RAM for faster accesses
- Ideally all file pages in page cache
- Implemented by all major operating systems

# Page Cache Attacks



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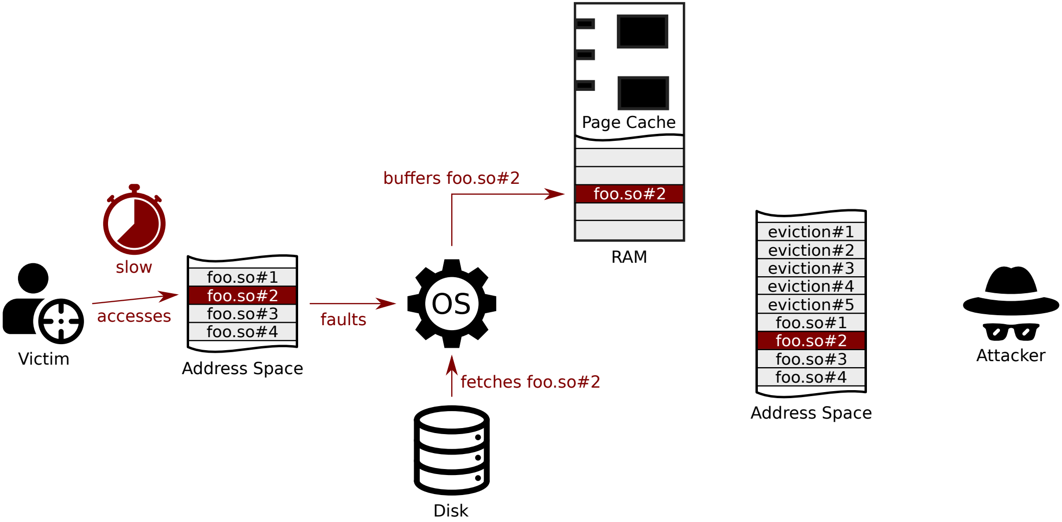

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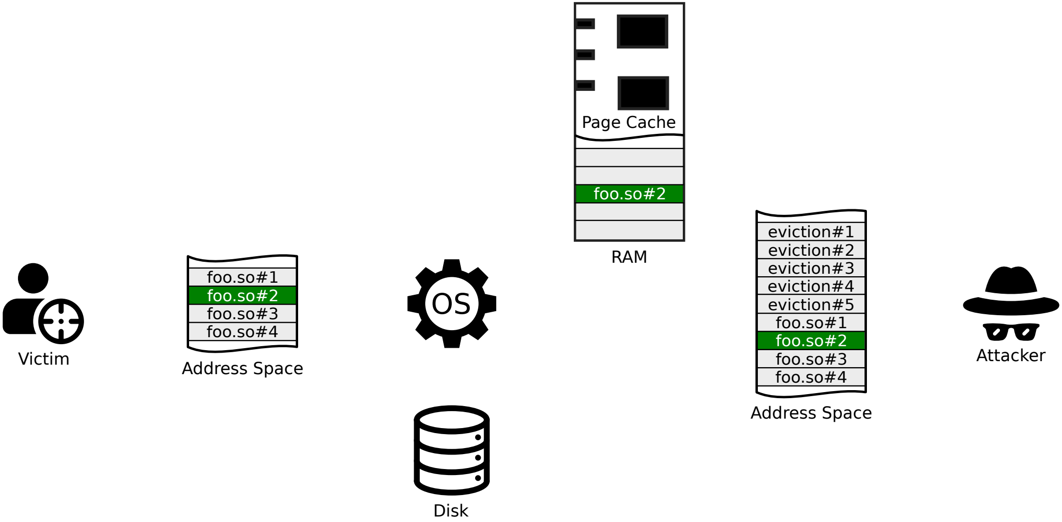

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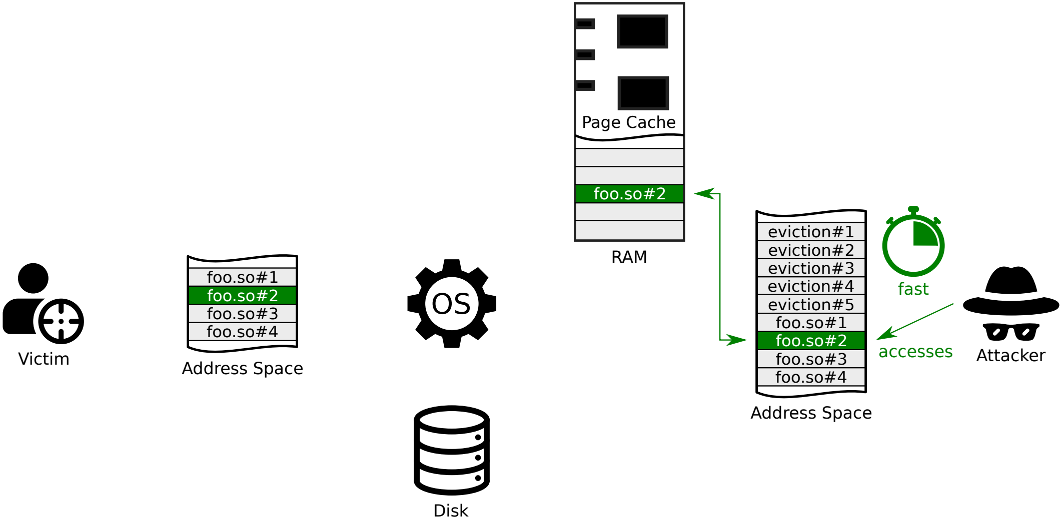

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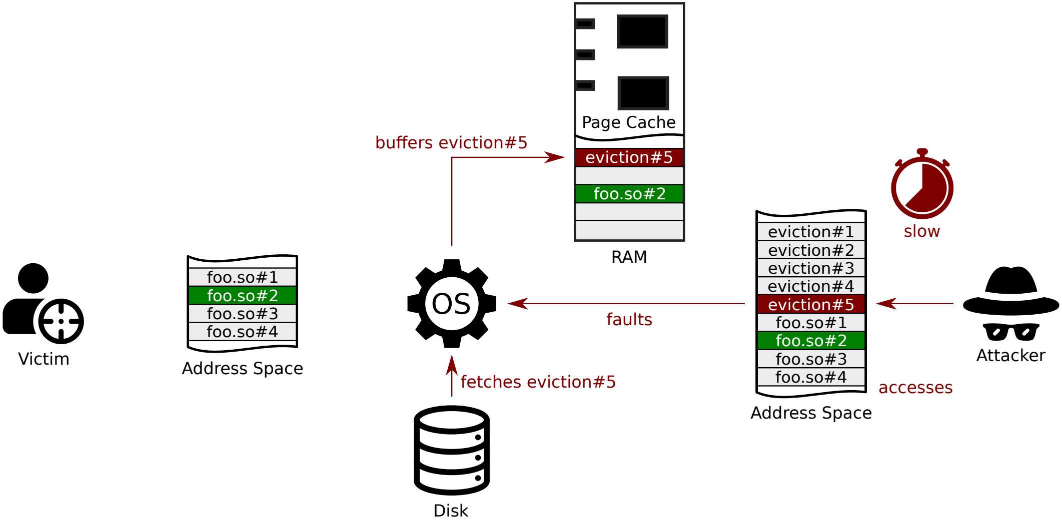

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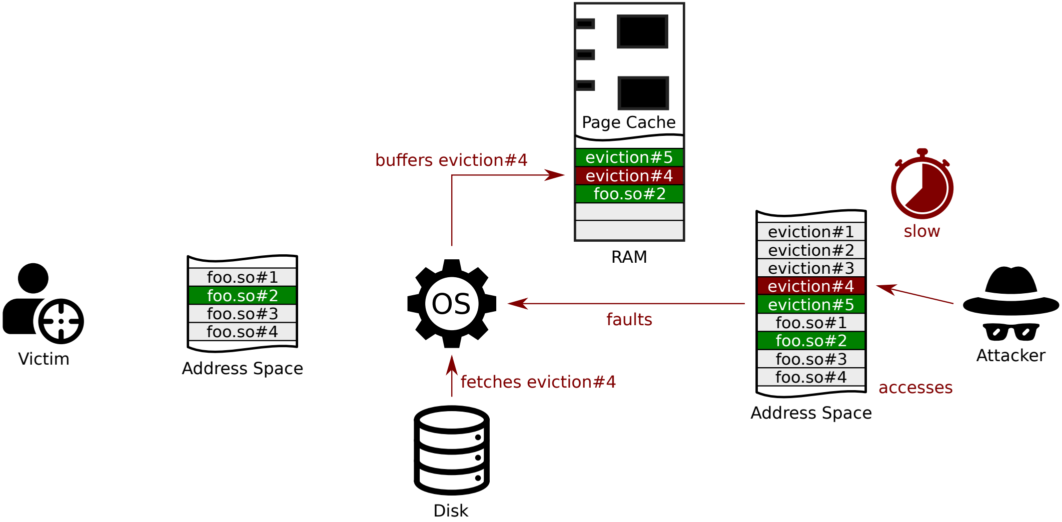

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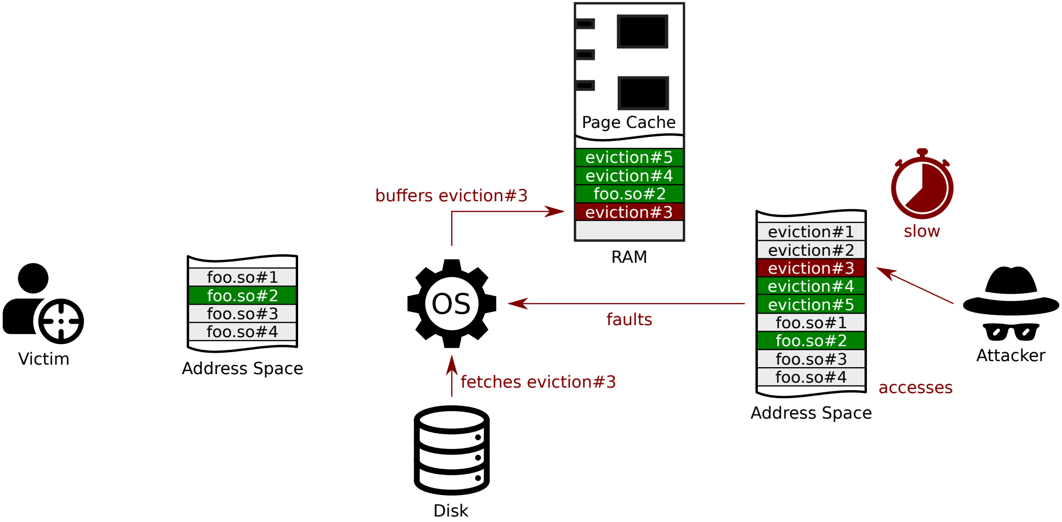
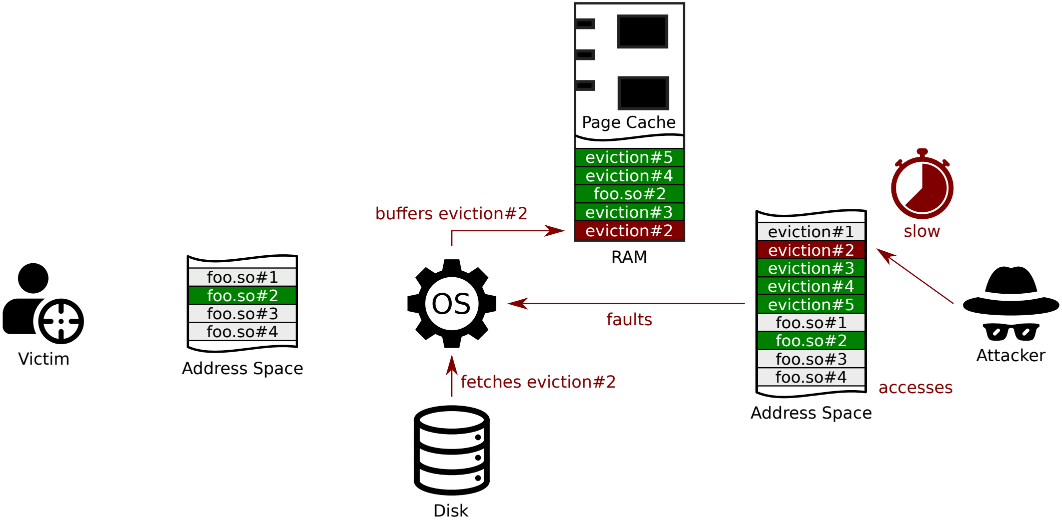
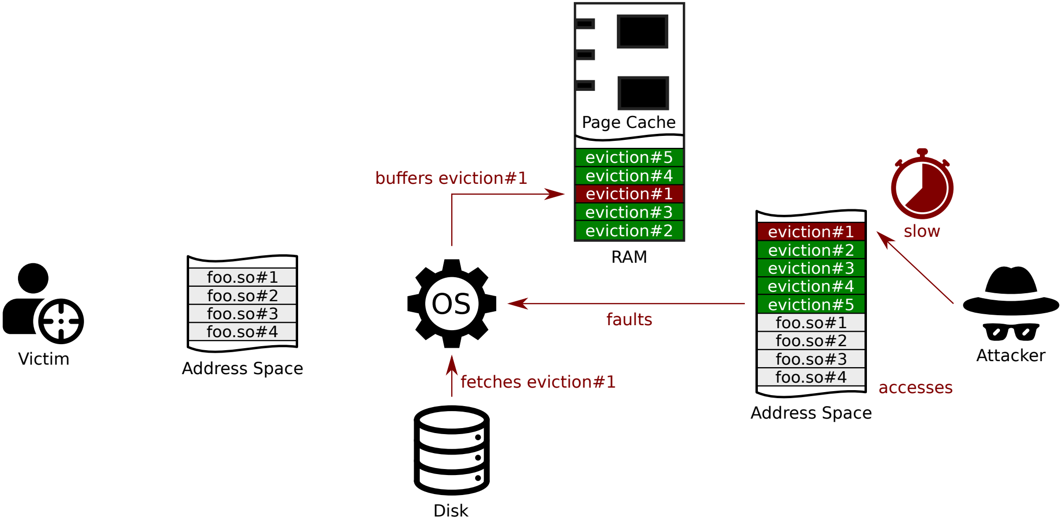



Page Cache
eviction#5
eviction#4
foo.so#2
eviction#3
eviction#2
RAM
buffers eviction#2
slow
Victim
foo.so#1
foo.so#2
foo.so#3
foo.so#4
Address Space
OS
faults
eviction#1
eviction#2
eviction#3
eviction#4
eviction#5
foo.so#1
foo.so#2
foo.so#3
foo.so#4
Address Space
Attacker
accesses
fetches eviction#2
Disk


Page Cache
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Attacker
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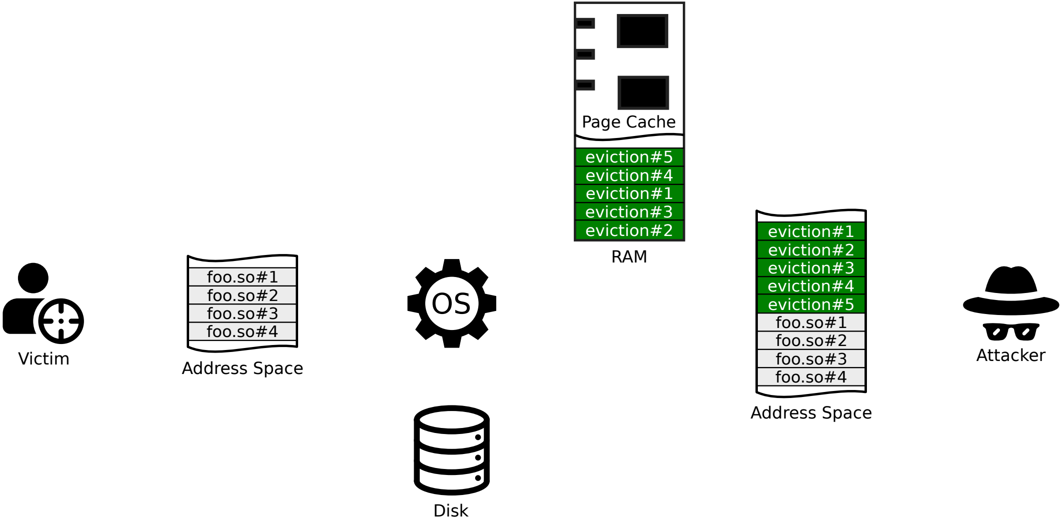
Victim
foo.so#1
foo.so#2
foo.so#3
foo.so#4
Address Space
fetches eviction#1
Disk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foo.so#1
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Address Space
Attacker

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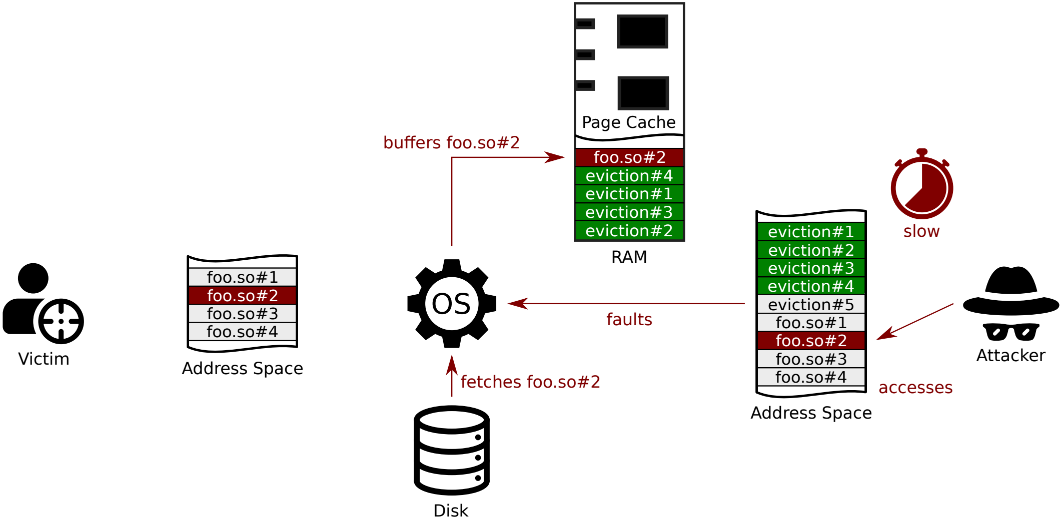
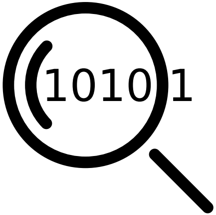



I AM
WATCHING YOU
imgflip.com

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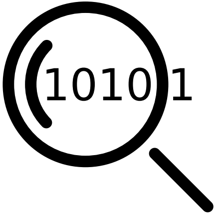
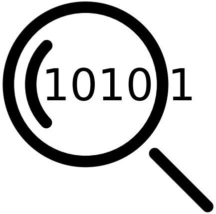



First idea:

- Measure page access time

# Observe Page Cache State

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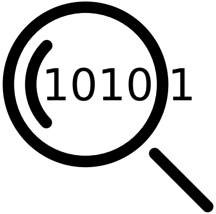


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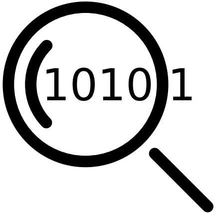


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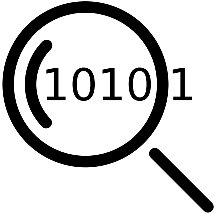


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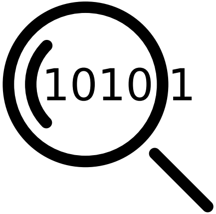


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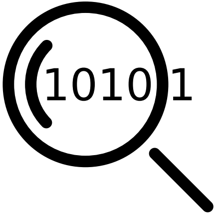


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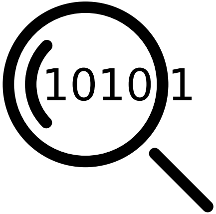


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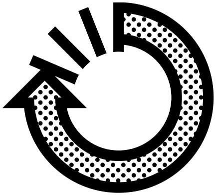
- Non-destructive → higher average resolution

## Reset Page Cache State



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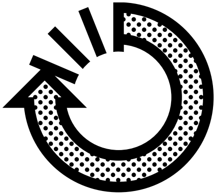

- Necessary for detecting multiple accesses
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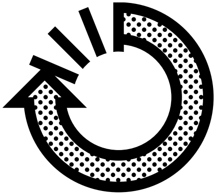

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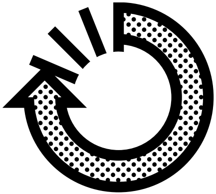

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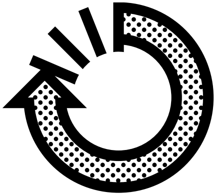

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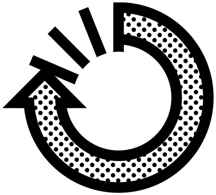

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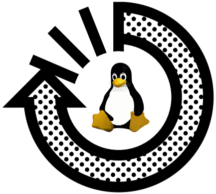
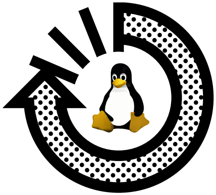
  - Per-process working sets with Aging algorithm



- Access pages until target page is replaced



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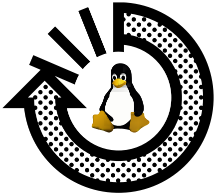

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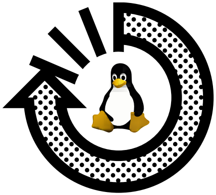

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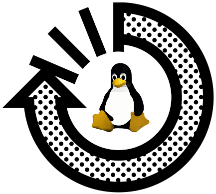

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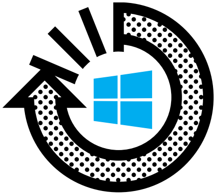
- Average run time down to 149 ms depending on optimisations

# Eviction Windows



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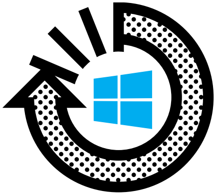

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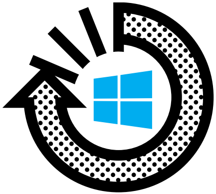

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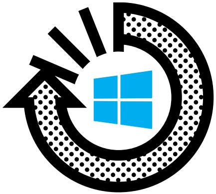

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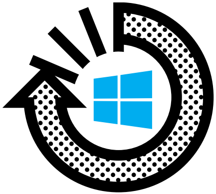

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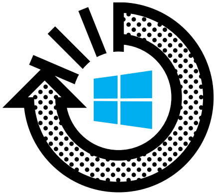

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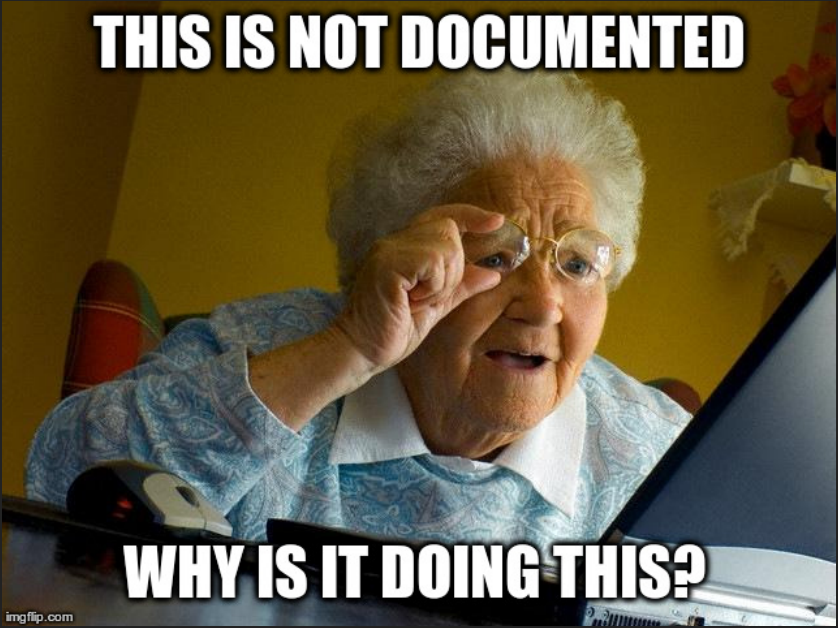
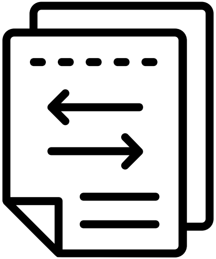
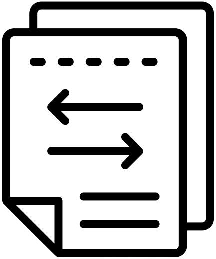
    - for processes with same integrity level as attacker
  - Evicting pages you have in your own working set

    $\rightarrow$ `VirtualUnlock` (17.69 $\mu$s)


THIS IS NOT DOCUMENTED
WHY IS IT DOING THIS?
imgflip.com

- Shared file as information carrier





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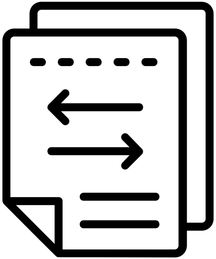

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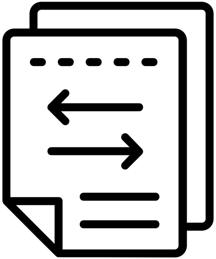

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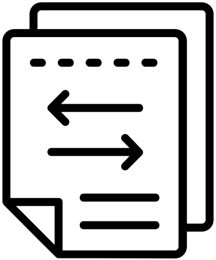
Different implementation approaches:



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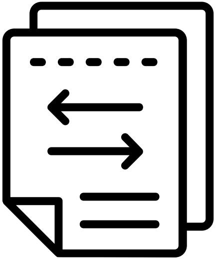
Different implementation approaches:

| OS | Eviction | Observation | Speed |
|---|---|---|---|
| Linux | like side channel | `mincore` | 20.20 kB/s |
| Linux | `madvise` `posix_fadvise` | `mincore` | 81.16 kB/s |
| Windows | process WS `VirtualUnlock` | `QueryWorkingSetEx` (`ShareCount`) | 100.11 kB/s |



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- Low bit error rate for all approaches (down to 0.000 03 %)

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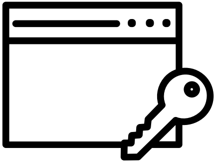
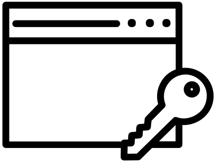
  - `PHP 7.3.5`, depends on build environment/configuration
- Average detection accuracy: $\pm 1$ ms

# Live Demo



- Detect opening of interesting window



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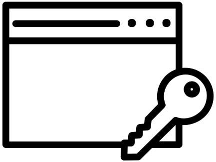

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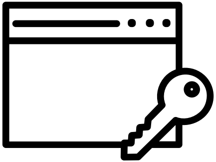

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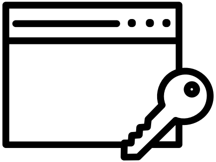
# UI Redressing Attack



- Detect opening of interesting window
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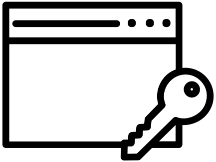
- Provides low latency → hardly noticeable

# UI Redressing Attack



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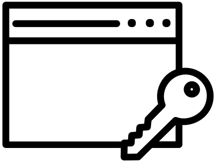

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PATCHES
PATCHES EVERYWHERE
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  - Page-cache eviction already harder than on Linux

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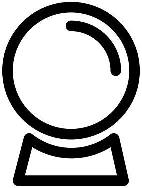
- Every optimization is potentially a side channel



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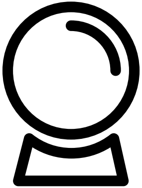
# The Future



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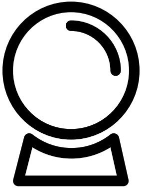

- We won't get rid of side channels
- More optimizations → more side channels
- More attacks on the "OS microarchitecture"

- Abstraction leads to side channels

# Take Aways

{...}

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- Software-cache attacks are similar to hardware-cache attacks

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- Finding countermeasures is difficult

# Acknowledgements

We want to thank James Forshaw for helpful discussions on COM use cases and Simon Gunacker for early explorative work on this topic. Daniel Gruss and Michael Schwarz were supported by a generous gift from ARM and also by a generous gift from Intel. Ari Trachtenberg and Trishita Tiwari were supported, in part, by the National Science Foundation under Grant No. CCF-1563753 and Boston University's Distinguished Summer Research Fellowship, Undergraduate Research Opportunities Program, and the department of Electrical and Computer Engineering. Any opinions, findings, and conclusions or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of the funding parties.

# Page Cache Attacks

## Microarchitectural Attacks on Flawless Hardware

Daniel Gruss, Trishita Tiwari, Michael Schwarz, Erik Kraft