Prefetch Side-Channel Attacks: Bypassing SMAP and Kernel ASLR

D. Gruss, C. Maurice, A. Fogh†, M. Lipp, S. Mangard
Graz University of Technology, † G DATA Advanced Analytics

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Overview

- prefetch instructions don't check privileges
- prefetch instructions leak timing information

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exploit this to:

- locate a driver in kernel = defeat KASLR
- translate virtual to physical addresses

Intel being overspecific

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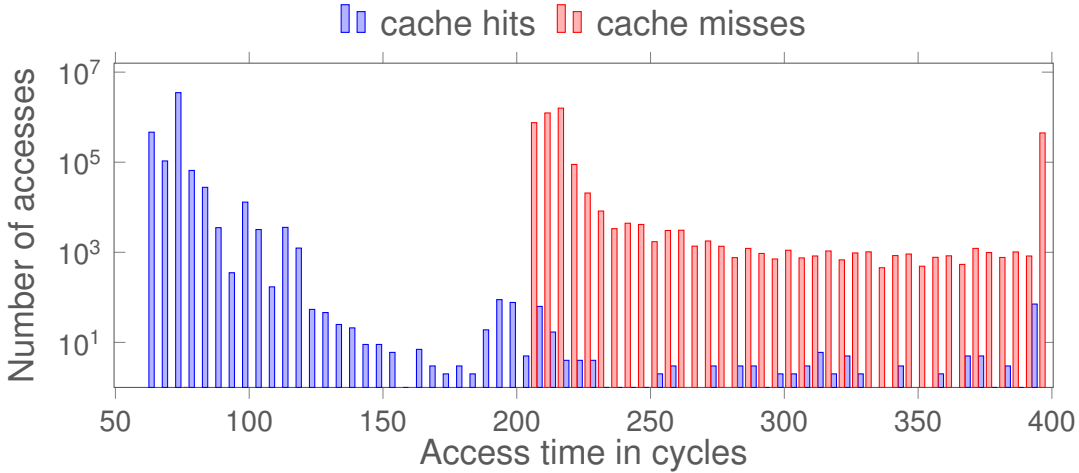
CPU Caches

Memory (DRAM) is slow compared to the CPU

- buffer frequently used memory
- every memory reference goes through the cache
- based on physical addresses

Memory Access Latency



Unprivileged cache maintainance

Optimize cache usage:

- `prefetch`: suggest CPU to load data into cache
- `clflush`: throw out data from all caches

... based on virtual addresses

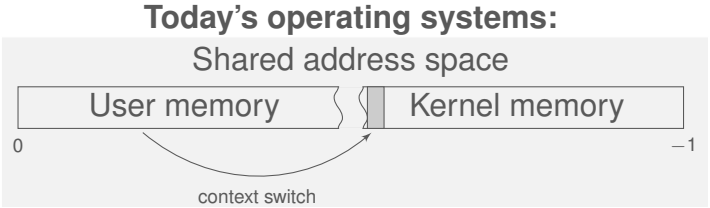
Software prefetching

`prefetch` instructions are somewhat unusual

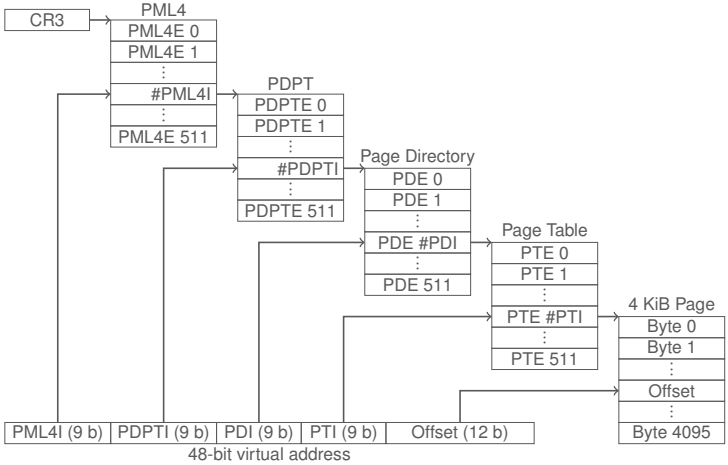
- hints – can be ignored by the CPU
- do not check privileges or cause exceptions

but they do need to translate virtual to physical

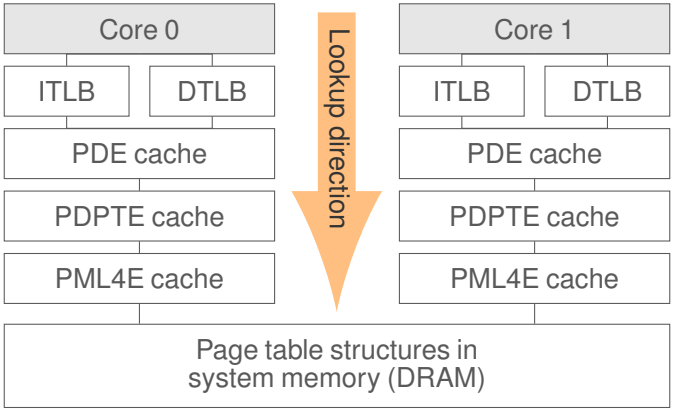
Kernel must be mapped in every address space



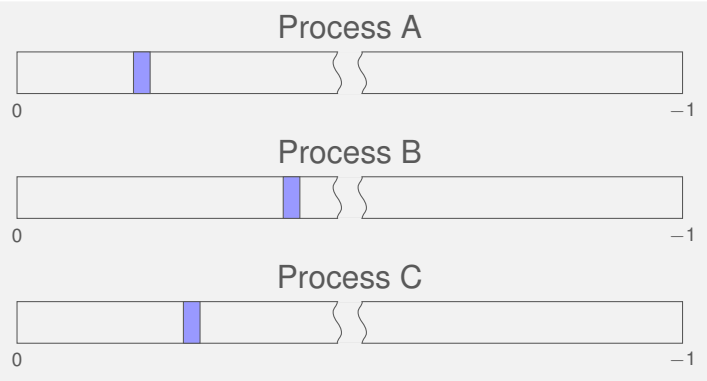
Address translation on x86-64



Address Translation Caches



Address Space Layout Randomization (ASLR)



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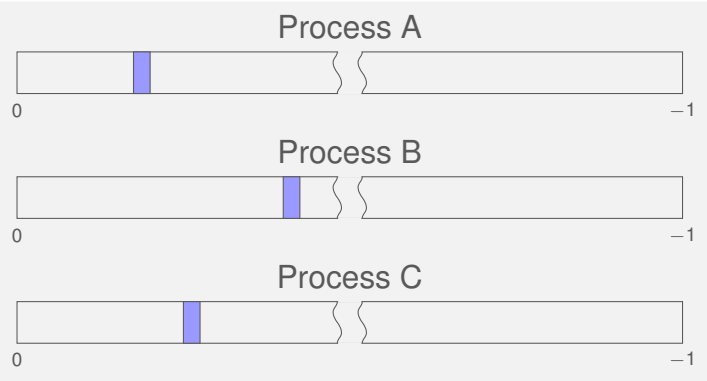
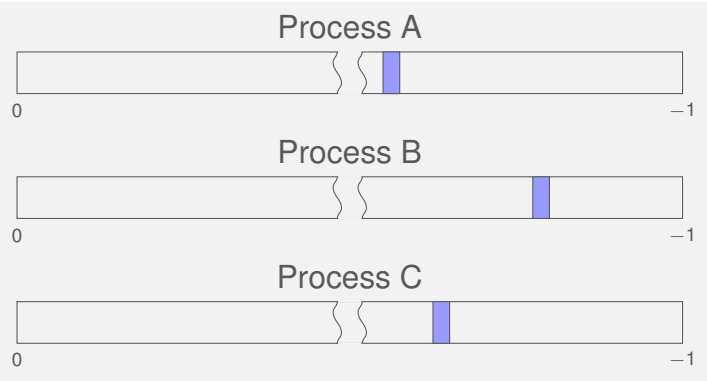


Same library – different offset!

Kernel Address Space Layout Randomization (KASLR)



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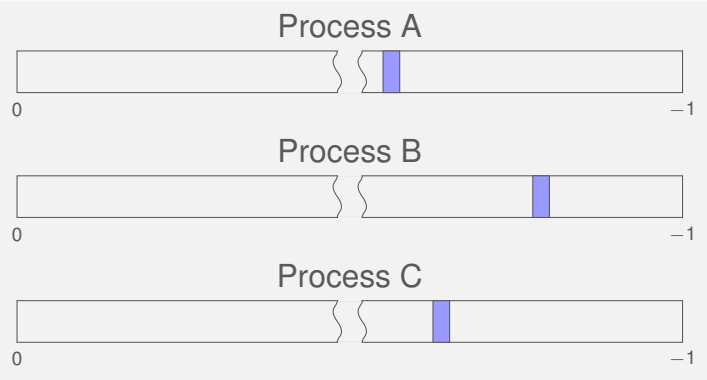
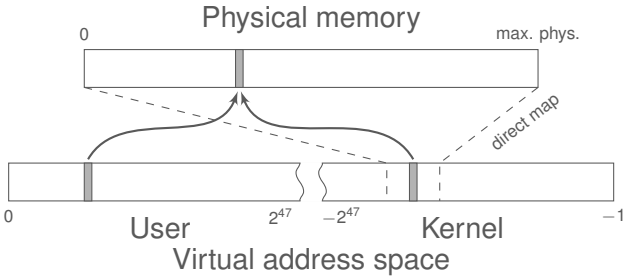


Same driver – different offset!

Kernel direct-physical map



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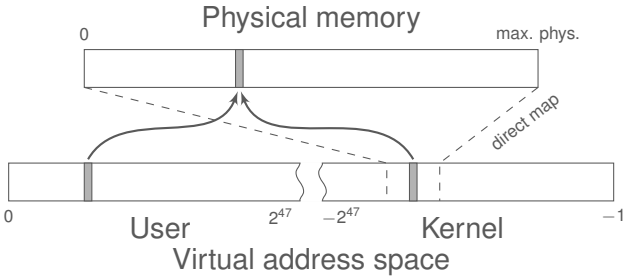
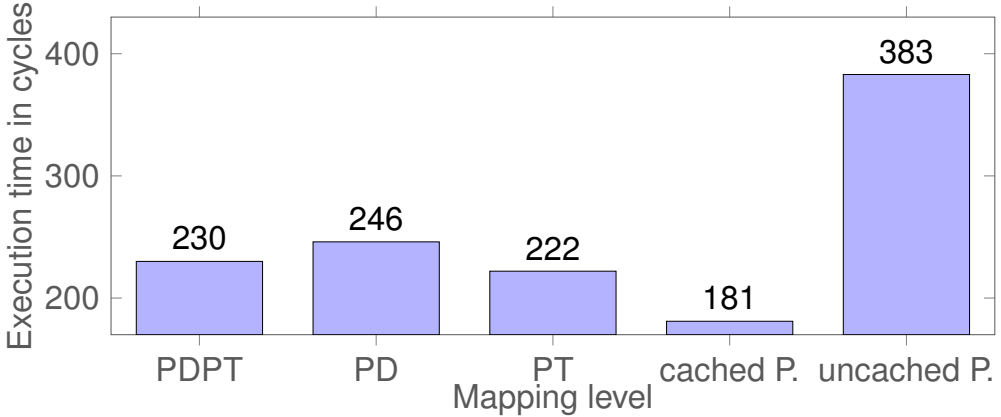
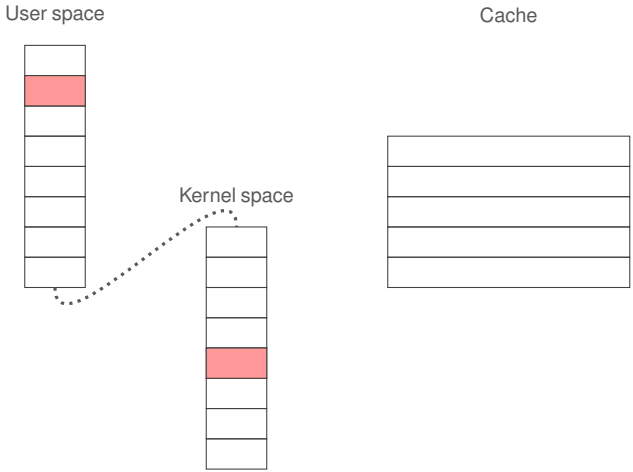


OS X, Linux, BSD, Xen PVM (Amazon EC2)

Translation-Level Oracle



Address-Translation Oracle



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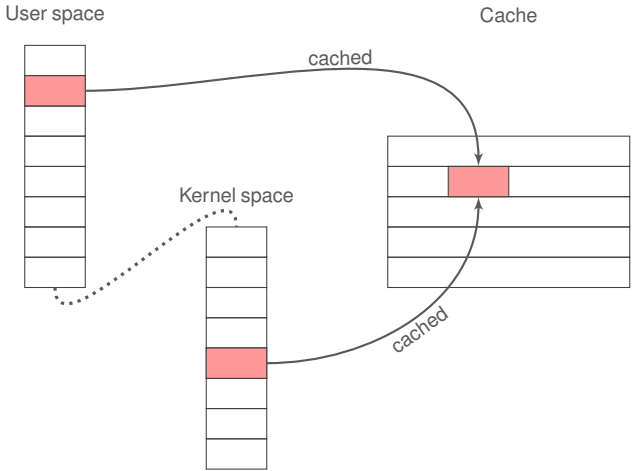

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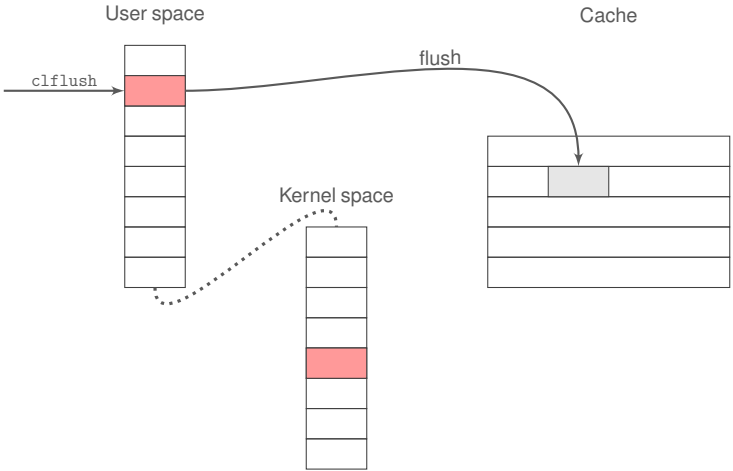

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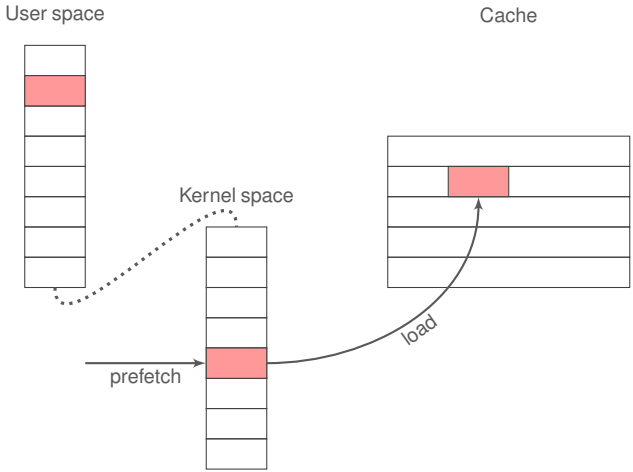

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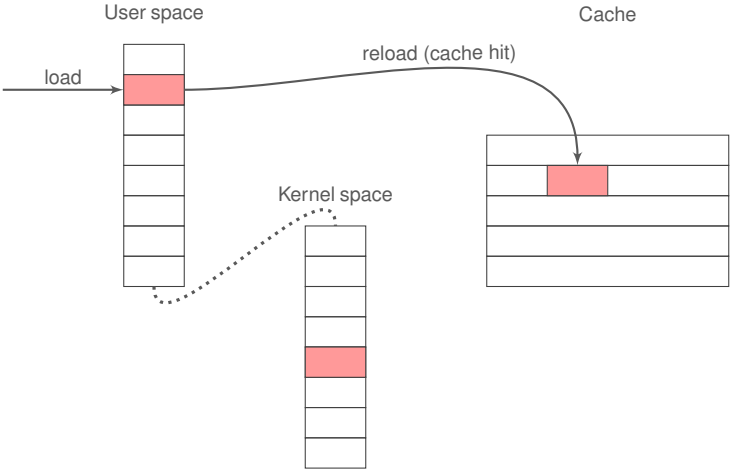

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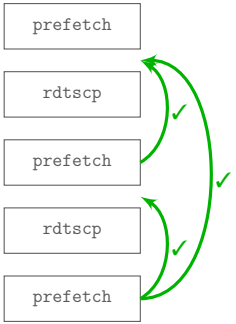

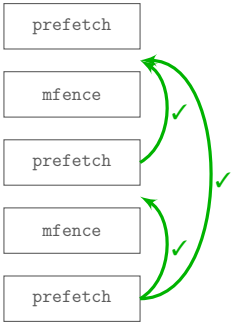

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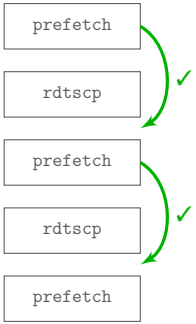

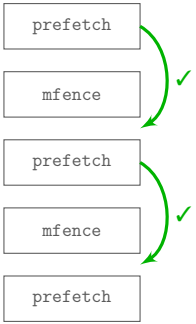

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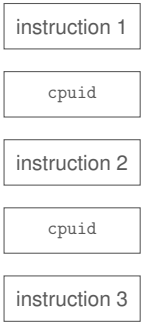

but not over `cpuid`!

Windows 10 Memory layout

- HAL, kernel, kernel drivers located bewetween
  - start: `0xffff 8000 0000 0000`
  - end : `0xffff 9fff ffff ffff`

Breaking Windows KASLR

for all mapped pages (found via translation-level oracle):

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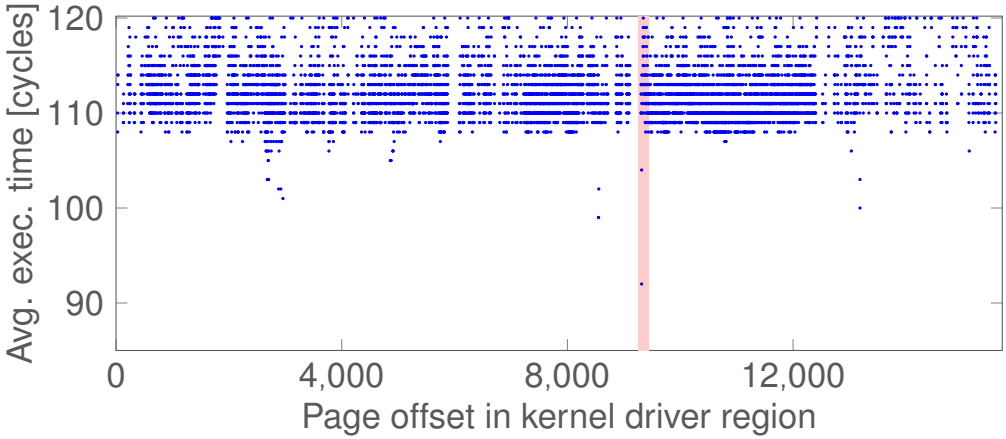
Full attack on Windows 10 in $<$ 12 seconds

Locate Kernel Driver (defeat KASLR)



Kernel exploits (10 years ago)

- overwrite return address

→ jump to userspace code

- overwrite stack pointer

→ switch to userspace stack

Mitigating kernel exploits

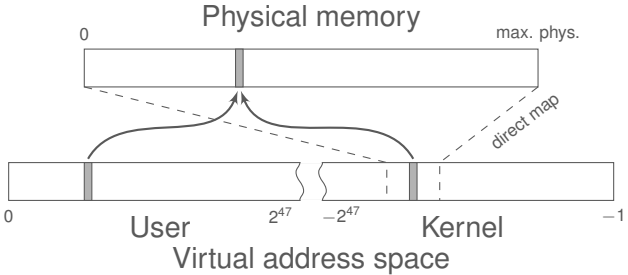
- Jump to userspace code? Nope! Hardware prevents that.

= supervisor-mode execution prevention (SMEP)

- Switch to userspace stack? Nope! Hardware prevents that.

= supervisor-mode access prevention (SMAP)

Kernel direct-physical map



Evading the mitigation

- get direct-physical-map address of userspace address

$\rightarrow$ jump/switch there

known as “ret2dir” attacks (Kemerlis et al. 2014)

Mitigating the evasion

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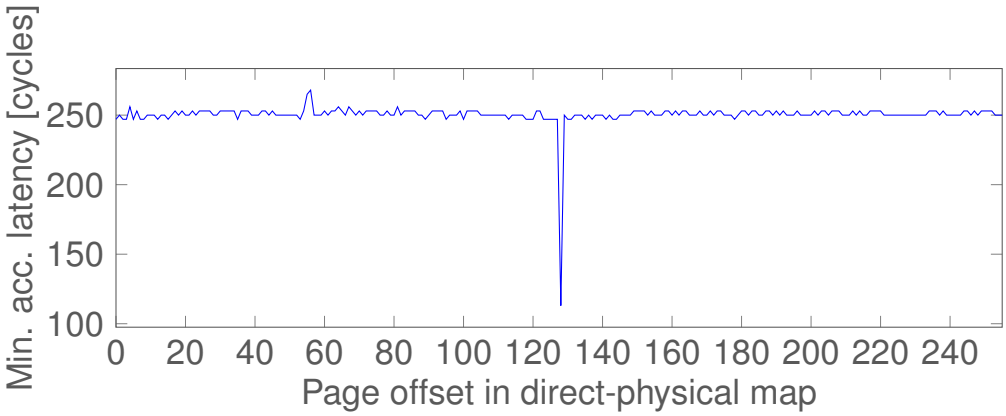
- getting rid of direct-physical map? Apparently not.

$\rightarrow$ do not leak physical addresses to user

Prefetching via direct-physical map



Prefetching via direct-physical map

- immediately leaks a direct-physical map address

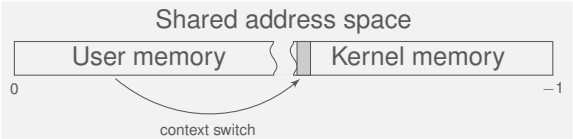
  → no physical address necessary (compared to ret2dir)

- if direct-physical map offset is known

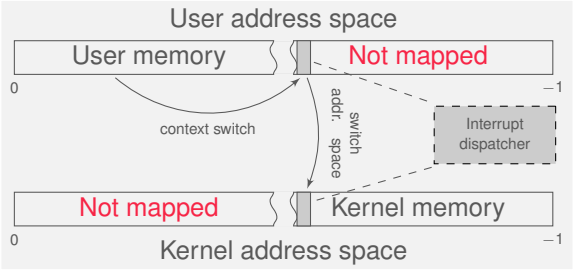
  → leaks physical address

Countermeasure

Today's operating systems:



Stronger kernel isolation:



Conclusion

- prefetch leaks significant information
- we can locate a driver in the kernel and thus break KASLR
- break SMAP/SMEP and get physical addresses
- countermeasure could be implemented in software

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