PT-Rand
Practical Mitigation of Data-only Attacks against Page Tables

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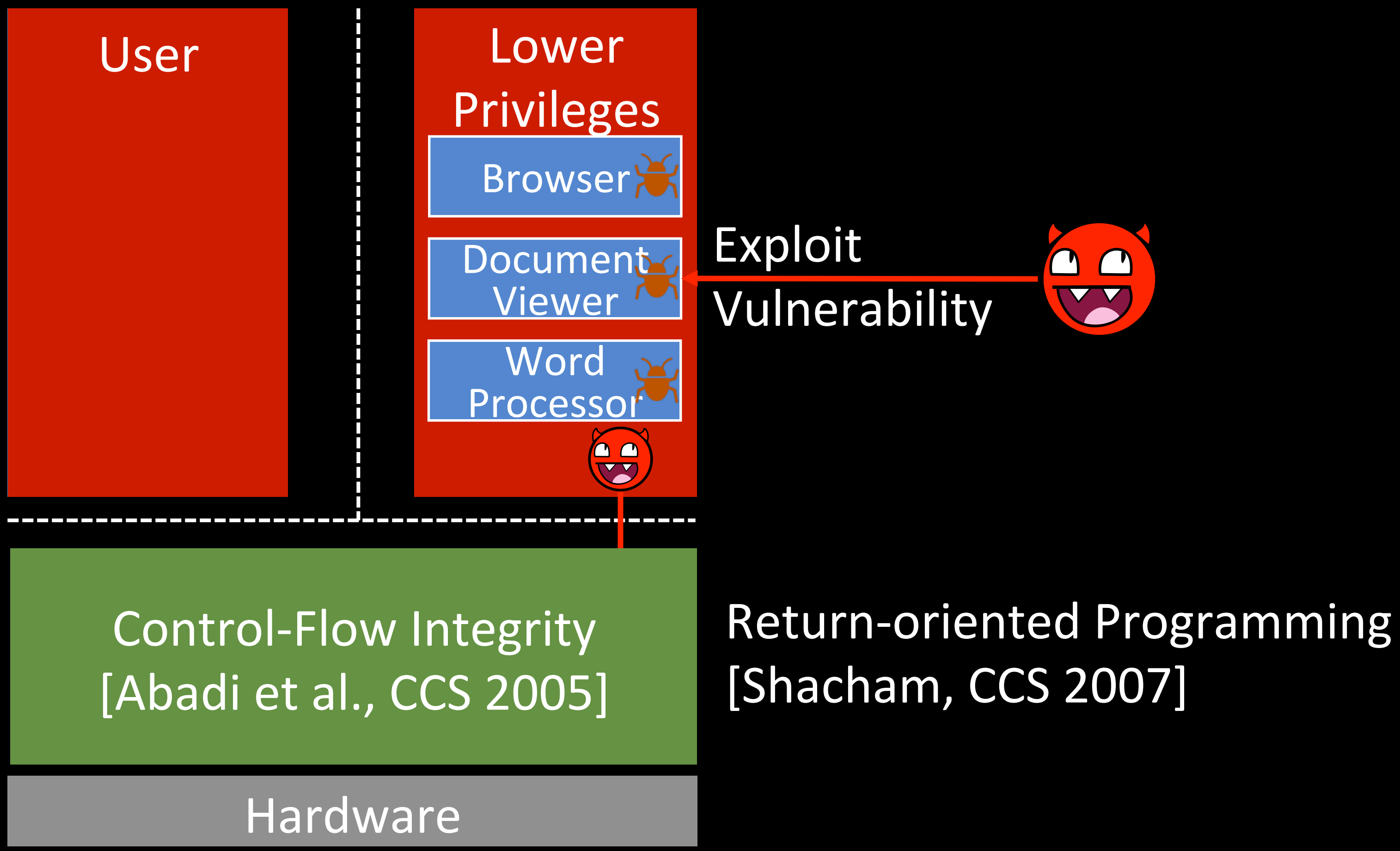
Impact of Kernel Attacks



CFI for Linux Kernel: Return Address Protection (RAP)

Grsecurity ends code reuse attacks with RAP

RAP Demonstrates World-First Fully CFI-Hardened OS Kernel

Type-based, high-performance, high-security, forward/backward-edge CFI

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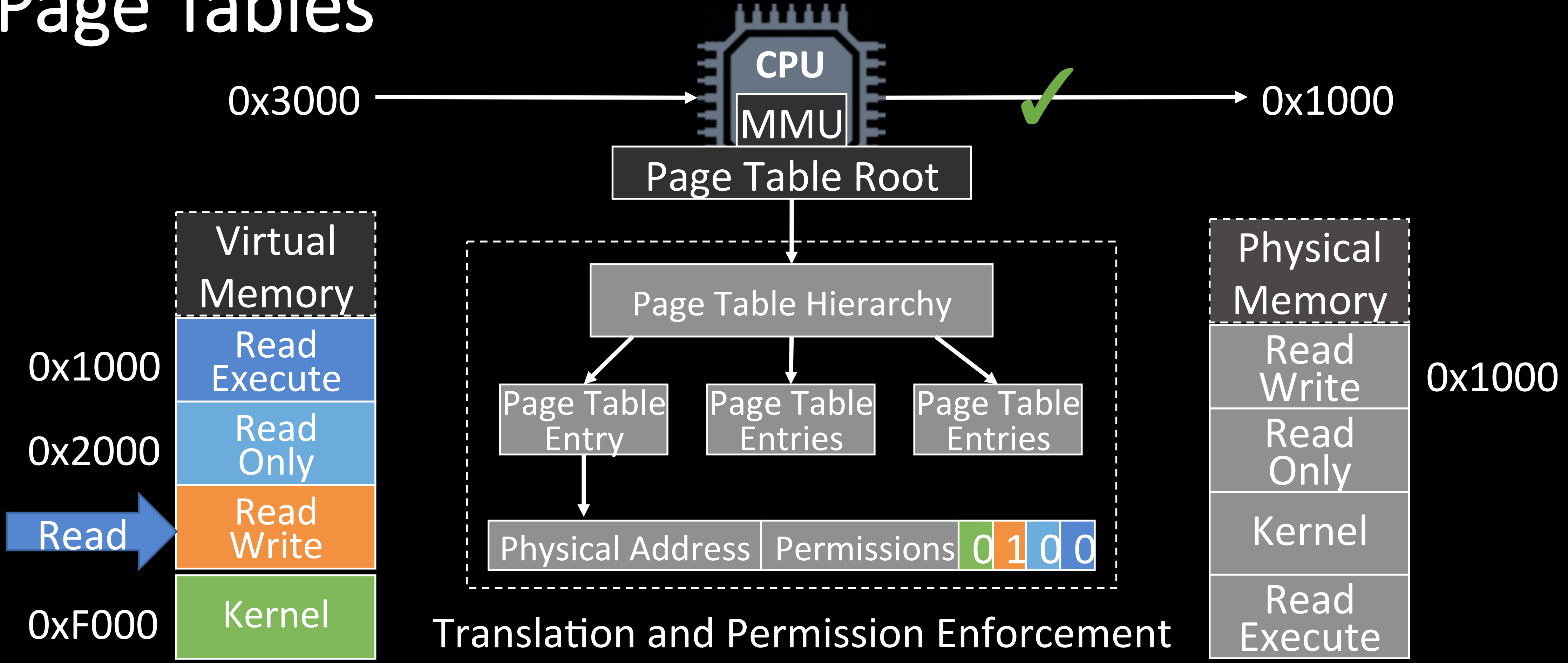
https://grsecurity.net/rap_announce_ret.php

Is Control-Flow Integrity enough?

- Protects against control-flow hijacking*
- Vulnerable to non-control data attack

**Terms and Conditions May Apply*

Virtual Memory: Page Tables



MMU = Memory Management Unit

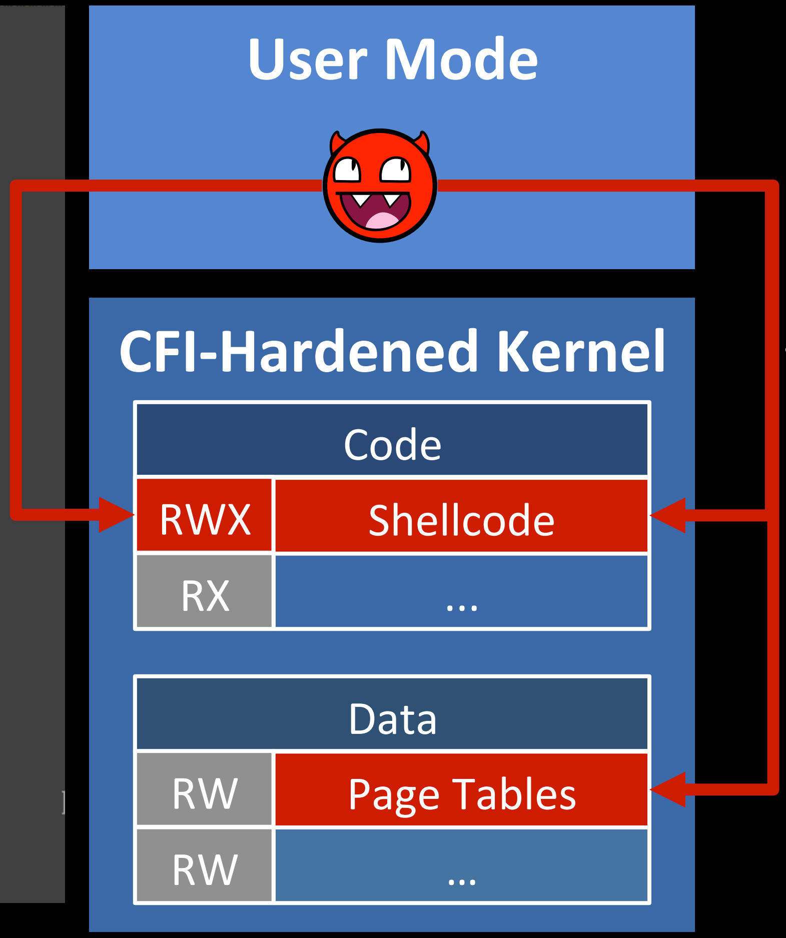
Data-Only against Page Tables of a CFI-hardened Kernel

Data-Only Attacks Against Page Tables

```
0xffff880016d2c000L 1087 kworker/1:0
0xffff88001a9e3540L 1132 kworker/0:2
0xffff88001ab14000L 1133 kworker/1:1
0xffff880016d2d500L 1140 pythonoot
[+] mm: 0xffff880019c01c00L
getting pte for 0xffffffff810a4060L
pl4 0xffff880015a59ff8L -> 0x1d28067L
pl3 0xffff880001d28ff0L -> 0x1d2a063L
2mb page
pte 0xffff880001d2a040L -> 0x10001e1L
[+] mark sysns page as writable
[+] writing shellcode
mov rbx, prepare_kernel_cred
call rbx
mov rbx, commit_creds
call rbx
mov rax, 0x1337
ret

[+] getting r00t...
# id
uid=0(root) gid=0(root) groups=0(root)
#
```

Trigger system call to execute the injected shellcode



Overwrite existing function (e.g. system call) with shellcode

Exploit kernel vulnerability to manipulate the page table

Page-Table Protection: Shortcomings of Related Work

- Proposed schemes to ensure page-table integrity
  - HyperSafe [Wang and Jiang, IEEE S&P 2010]
  - SPROBES [Ge et al., IEEE MoST 2014]
  - KCoFI [Criswell et al., IEEE S&P 2014]
  - SKEE [Azab et al., NDSS 2015]
- However, they suffer from the following problems
  - Require hardware trust anchors
  - Require a trusted hypervisor
  - Inefficient integrity check

Our Approach:
Page-Table Randomization

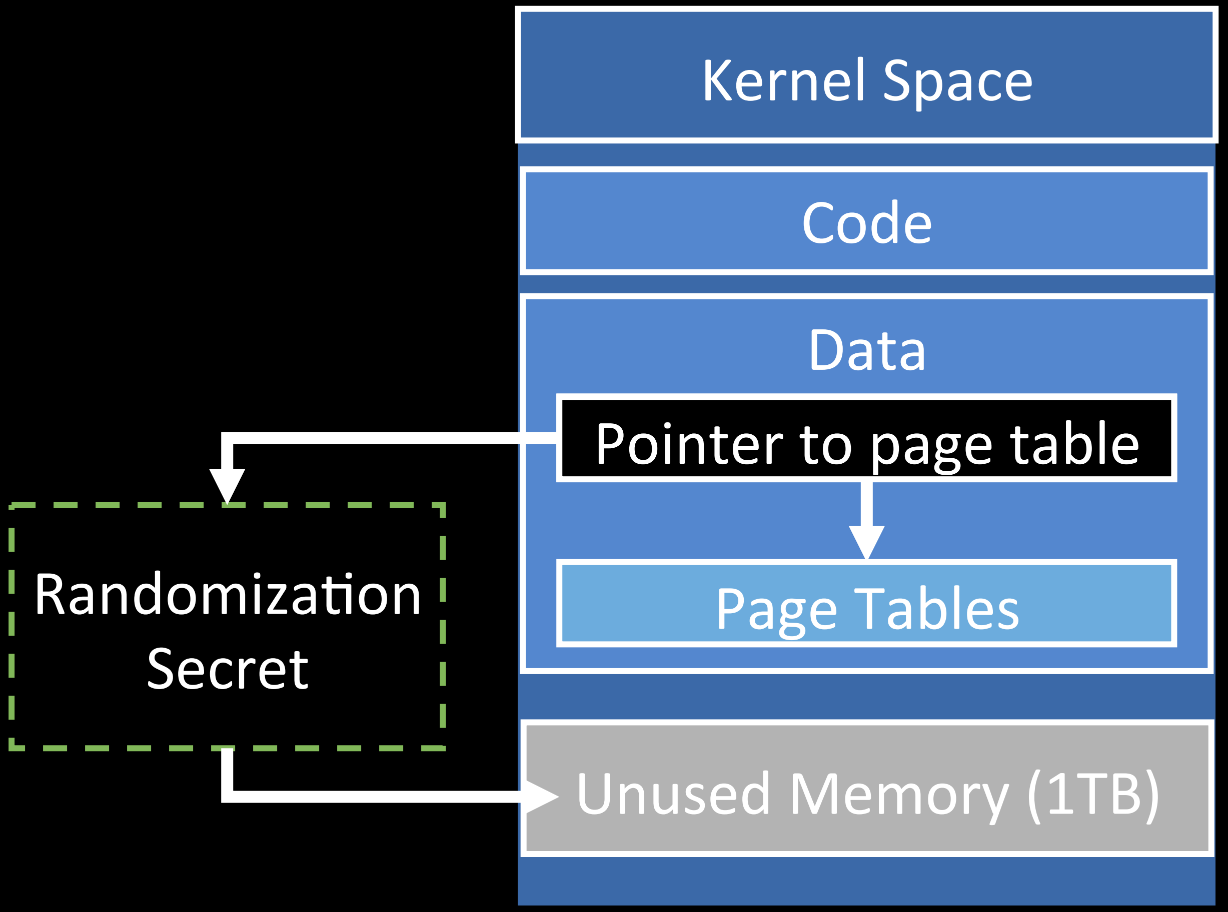
Assumptions and Threat Model

- Modern CPUs prevent ret2usr attacks (SMAP/SMEP)
- Cannot inject new code into the kernel (W^X)
- Code-reuse defense in place (CFI)

- Control over a user application
- Read/Write from/to known addresses

PT-Rand: High-level Idea

- Address space for 64 bit systems is huge
- Move to random location in unused memory page tables
- Protect all pointers



PT-Rand: Challenges & Details

- References to page tables
  - → All references are replaced by physical addresses
  - → Page table management patched process physical addresses
- Protection of the randomization secret
  - → Store in debug register and make it leakage resilient
- Preserve Physmap functionality for regular accesses
  - → Our approach only removes page table data from Physmap

Evaluation

Security

- Guessing Attacks
  - $p = 3.726 \times 10^{-9}$ (Desktop, 4000 Page-Table Entries)
  - $p = 3.762 \times 10^{-9}$ (Server w/ 9 parallel VMs , 33000 PTE)

- Memory-disclosure Attacks
  - Through pointers: All pointers are converted to physical address
  - Spilled registers
    - DR3 are not spilled during interrupts
    - Software interrupts are disabled during page walks

Implementation

- Linux Kernel v4.6 hardened with RAP
  - 45 source files
  - 1382 insertions
  - 15 deletions

- Intel Core i7-4790 CPU
- 8 GB RAM
- Debian 8.2

Performance

- SPEC CPU 2006: avg. 0.22% (max 1.7%)
- Phoronix: 0.08% (max. 1.8%)
- LMBench fork+exec: +0.1 ms
- Chromium
  - Start time (+ < 1ms)
  - Run time avg. –0.294% (JetStream/Octan/Kraken)

Conclusion

- Page-table attacks pose a **serious threat** to kernel security
- First **practical** randomization-based defense for page tables
  - Mitigates data-only attacks
  - No dependencies on higher privileged execution modes
  - Complements kernel CFI
- Proof-of-concept implementation
  - Negligible overhead
  - No impact on the stability of the overall system