PKU Pitfalls:

Attacks on PKU-based Memory Isolation Systems

Joseph Connor

Tyler McDaniel

Jared M. Smith

Max Schuchard

University of Tennessee

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Overview

- Intraprocess isolation: separating components within a process
- Improves security
- Allows finer-grained privilege separation
- But:
  - Not widely adopted
  - Has suffered from performance and complexity issues

Overview

- Recent research shows **improved performance** using new hardware feature:
  - Protection Keys for Userspace (**PKU**)
- Our contribution: identify challenges and gaps in current approach
  - Researchers, OS devs have different goals and views on hardware, process security
  - Commonly-used assumptions may not hold in real-world systems

Background - PKU

- Assigns a 4-bit “protection key” (0-15) to each page-table entry
- Adds a new **unprivileged** 32-bit register – PKRU
  - Modified with new instruction: `wrpkru`
  - Pairs of bits control access to the 16 protection keys
- MMU hardware checks PKRU on each memory access

PKRU Register

Protection Key	PKEY 15		PKEY 14			PKEY 1		PKEY 0	
Access/Write Disable	WD	AD	WD	AD	•••	WD	AD	WD	AD
Bit	31	30	29	28		3	2	1	0

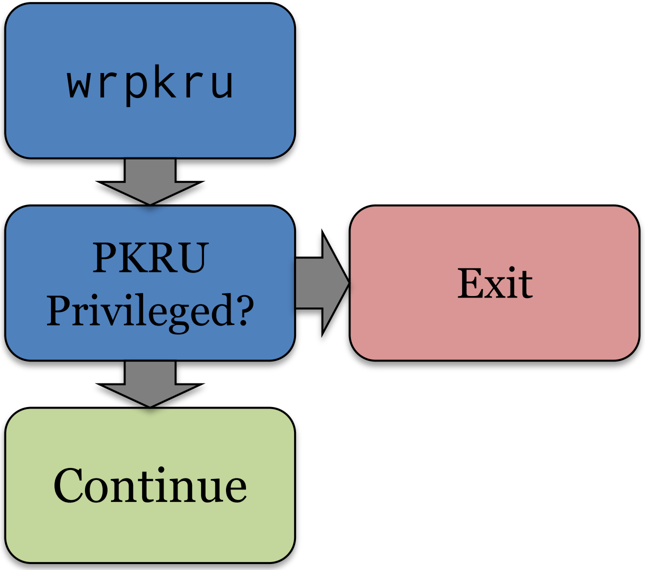
Bits 2*i* and 2*i*+1 control read/write access to pages with protection key *i*

Background - PKU

- PKRU register is **unprivileged**
- On its own, does not stop an attacker who has already hijacked control flow in a process
  - Code may contain `wrpkru` gadgets
  - Attacker may `mmap()` new code
- Proposed solutions to this problem:
  - ERIM (Vahldiek-Oberwagner et al.)
  - Hodor (Hedayati et al.)

Background – ERIM/Hodor

- Divide process into separate "components" using PKU to control memory access
- Ensure there are no `wrpkru` gadgets available for an attacker to exploit:
  - ERIM: using static binary rewriting
  - Hodor: using x86 hardware watchpoints
- Efficient context switching via safe "call gates"
  - `wrpkru` followed by jmp to trusted code
  - `wrpkru` followed by code to ensure PKRU is unprivileged



Background – ERIM/Hodor

- Monitor newly executable pages created by `mmap()` or `mprotect()`
  - Using `seccomp` + `ptrace`
  - Using kernel modifications
- Scan new code for unsafe `wrpkru` gadgets
- Enforce “W^X”: No memory is both writable and executable
  - Otherwise, attacker may create new `wrpkru` gadgets without interception

Our Approach

- Examined kernel documentation, code, and developer communications in context of PKU-based sandboxes
- Tested attacks on prototype in a realistic Linux system
- Assumptions:
  - Attacker can execute control-flow hijacking attack (e.g. ROP chain) in **untrusted** context
  - Attacker must access memory of **trusted** component without using a legitimate call gate
- Developed 12 proof-of-concepts

Challenges for Intraprocess Isolation

- Fundamental departure from traditional OS security boundaries
- Researchers/OS devs have different perspectives on security models for processes and PKU
  - Kernel can act as “confused deputy”
- Lack of a method for systemic validation

Kernel As Confused Deputy

- Mailing list discussions show that kernel developers envisioned PKU use cases for *reliability*, not security
- Linux kernel intentionally does not absolutely enforce:
  - PKRU access checks
  - Page table entry read/write permissions
- `get_user_pages_remote()` circumvents these checks
  - `ptrace()`
  - `process_vm_readv/writev()`
  - `/proc/<pid>/mem`

Difficulty of W^X

- Research often assumes W^X – memory is not simultaneously writable and executable
  - PKU-based sandboxes rely on W^X to ensure `wrpkru` gadgets cannot be written without being intercepted
  - Enforced via userspace syscall interception (*ptrace+seccomp)* or kernel modifications
- In practice, non-trivial to fully enforce on Linux

Difficulty of W^X

- Page permissions apply to *mappings*, not the physical memory
  - Pages may also be backed by other resources (e.g. files)
- Writes to memory-mapped files are reflected even in non-writable mappings
- Shared memory can be mapped more than once, with different permissions
- Some kernel interfaces ignore PTE permissions: `ptrace()`, `/proc/<pid>mem`

Conclusions

- Seemingly simple assumptions (W^X) may not apply as expected in realistic settings
- Retrofitting different security models is especially challenging:
  - One developer's design choice is another developer's vulnerability
- Systematic approach to validating security boundaries is needed

Thank You

Joseph Connor – *rconnor6@utk.edu*
Tyler McDaniel – bmcdan16@utk.edu
Jared M. Smith – jms@utk.edu
Max Schuchard – mschucha@utk.edu

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