Overshadow:
A Virtualization-Based Approach to Retrofitting Protection in Commodity Operating Systems

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Motivation

Applications Handle Sensitive Data

- Financial, medical, insurance, military …

Commodity Systems Vulnerable

- Large and complex TCB, broad attack surfaces
- OS kernel, file system, daemons, services …
- Hard to configure, manage, maintain
- Privilege escalation ⇒ game over

Data Theft Soaring

- Reached “unprecedented levels” in 2007
- Identity theft, breach notification laws …

Limitations of Existing Solutions

Rewrite OS / Applications

- Split into low- and high-assurance portions
  e.g. microkernels, Microsoft Palladium/NGSCB
- Expensive, high barriers to adoption

Multiple Virtual Machines

- Trusted/untrusted or specialized VMs (*e.g.* Proxos, Terra)
- Cumbersome, still vulnerable to OS compromise

Hardware Approaches

- Special-purpose secure co-processors (*e.g.* IBM 4758)
- XOM and SP processor architectures
- Require substantial modifications to hardware/OS/apps

Goals

Protect Application Data

- Privacy and integrity
- In memory and on disk

Remove OS from TCB

- Provide last line of defense
- Even if attacker compromises guest OS

Backwards Compatibility

- Unmodified commodity OS
- Unmodified application binary

Non-Goal: Availability

Overshadow Topics

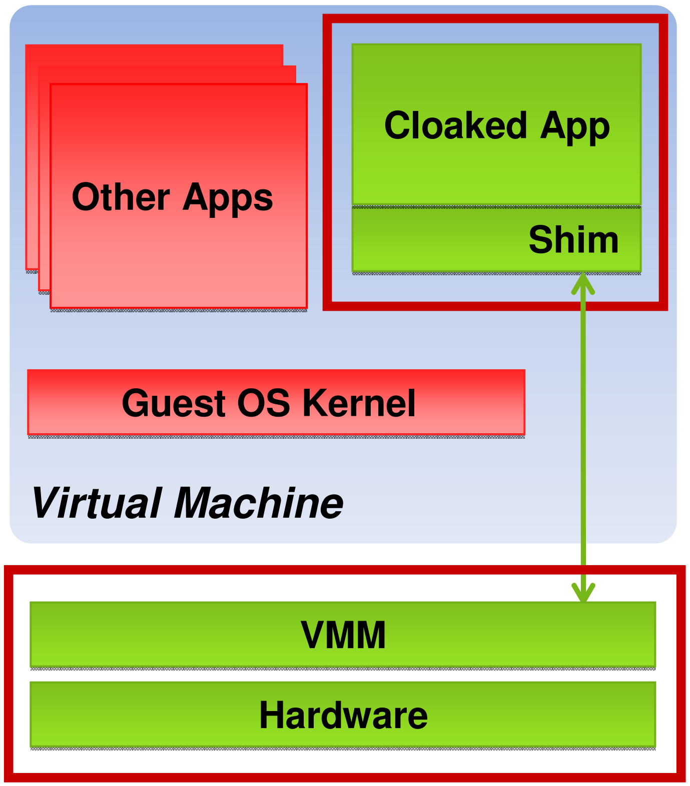
Focus of Talk

- Protecting application memory
- Secure control transfers
- Adapting system call interface
- Performance

In Paper

- Secure context identification
- Managing protection metadata
- Implications of malicious system call interface (work in progress)

Overshadow Architecture



Two Virtualization Barriers

VMM Protects App Memory

- New virtualization barrier
- App trusts VMM, but not OS

Cloaking: Two Views of Memory

- App sees normal view
- OS sees encrypted view

Shim: App/OS Interactions

- Interposes on system calls, interrupts, faults, signals
- Transparent to application

Memory Mapping: OS

virtual → **physical**

OS page table

Memory Mapping: VMM

virtual → physical → machine

guest OS *vmm*

Multi-Shadowing: Context-Dependent Views

view$_1$

machine$_1$

virtual → physical

guest OS

view$_2$

machine$_2$

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Cloaking: Multi-Shadowing + Cryptography

virtual → physical

guest OS

app view → plaintext machine

sys view → X unmapped

Cloaking: System Accesses Page

app view

plaintext / encrypted machine

virtual → physical

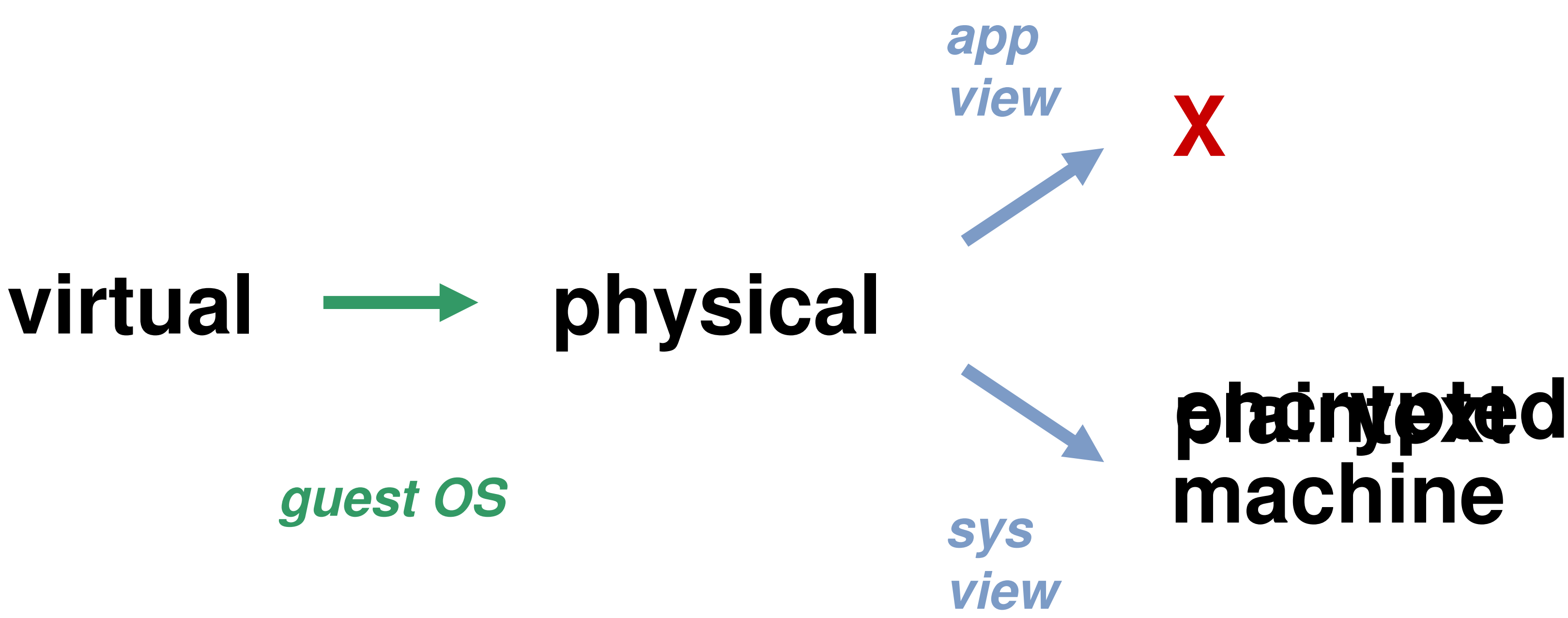
guest OS

sys view

X

Fault into VMM: encrypt/hash contents, remap

Cloaking: Application Accesses Page



Fault into VMM: verify hash, decrypt, remap

Cloaking Application Resources

Basic Strategy

- Protect existing memory-mapped objects
  e.g. stack, heap, mapped files, shared mmaps
- Make everything else look like one
  e.g. emulate file read/write using mmap

OS Still Manages Application Resources

- Including demand-paged application memory
- Moves cloaked data without seeing plaintext contents
- Encryption/decryption typically infrequent

Shim: Supporting Unmodified Applications

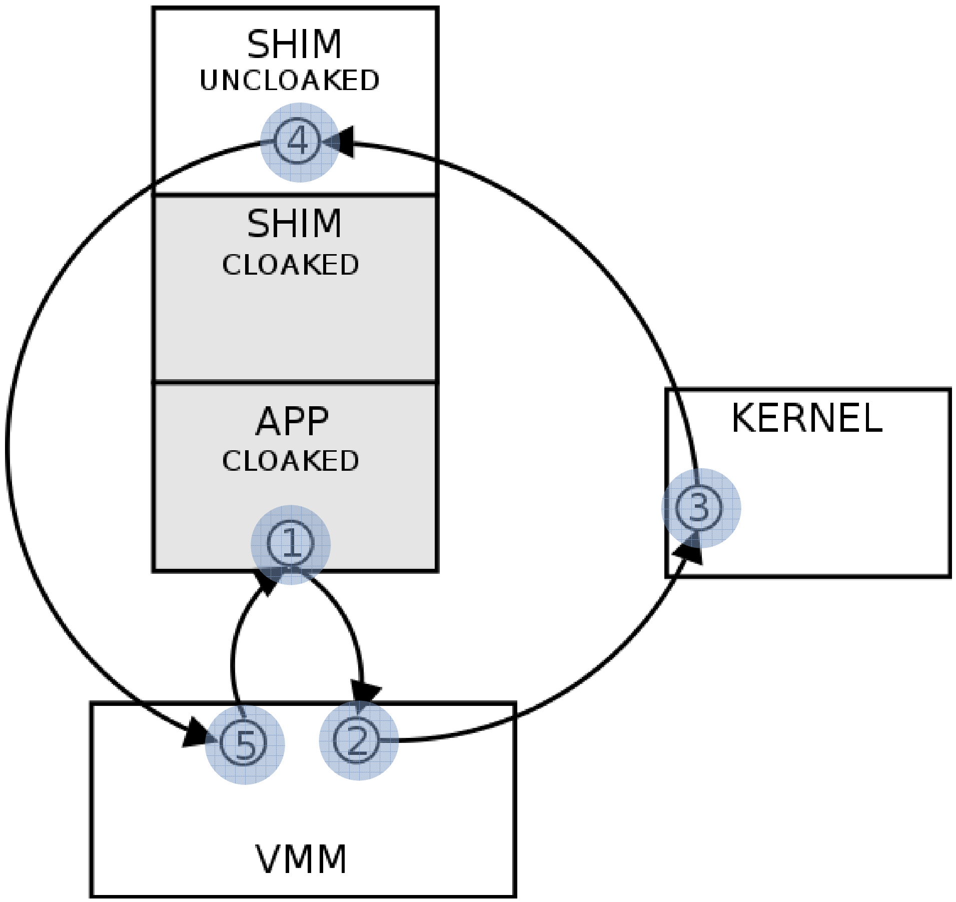
Challenges

- Securely identify which app is running
- Secure control transfers between OS and app
- Adapting system calls

Solution: Shim

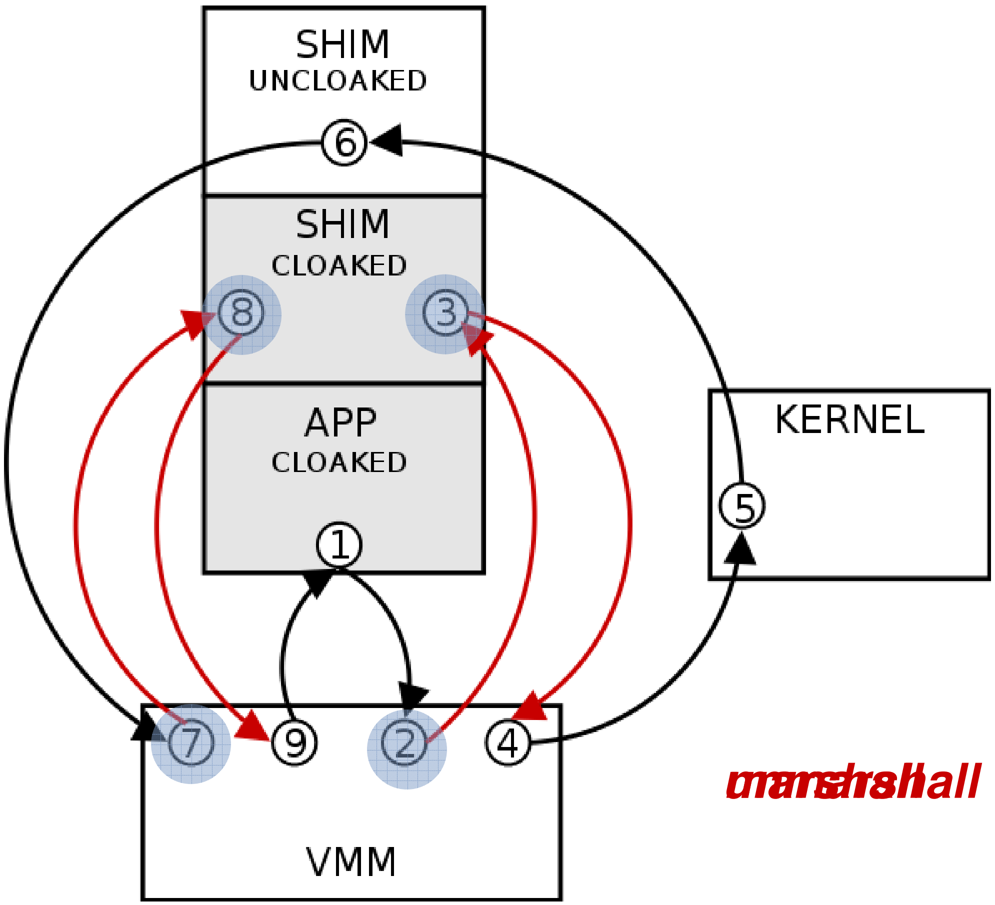
- OS-specific user-level program
- Linked into application address space
- Mostly cloaked, plus uncloaked trampolines and buffers
- Communicates with VMM via hypercalls

Shim: Handling Faults and Interrupts



1. **App is executing**
2. **Fault traps into VMM**
   - Saves and scrubs registers
   - Sets up trampoline to shim
   - Transfers control to kernel
3. **Kernel executes**
   - Handles fault as usual
   - Returns to shim via trampoline
4. **Shim hypercalls into VMM**
   - Resume cloaked execution
5. **VMM returns to app**
   - Restores registers
   - Transfers control to app

Shim: Handling System Calls



Extra Transitions

- Superset of fault handling
- Handlers in cloaked shim interpose on system calls

System Call Adaptation

- Arguments may be pointers to cloaked memory
- Marshall and unmarshall via buffer in uncloaked shim
- More complex: pipes, signals, fork, file I/O

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Protecting Data Integrity

Challenges

- Enforce integrity, ordering, freshness
- For code, data, memory-mapped files …

VMM Manages Per-Page Metadata

- Tracks what’s “supposed to be” in each memory page
- IV – randomly-generated initialization vector
- H – secure integrity hash

Implementation

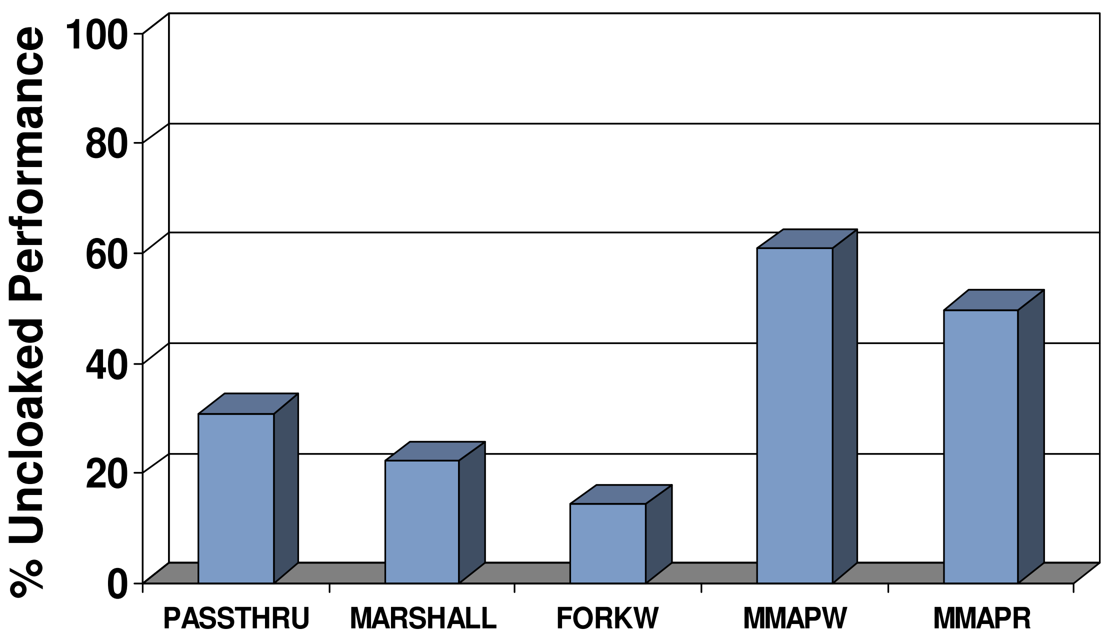
Overshadow System

- Based on 32-bit x86 VMware VMM
- Shim for Linux 2.6.x guest OS
- Full cloaking of application code, data, files
- Lines of code: + 6600 to VMM, ~ 13100 in shim
- Not heavily optimized

Runs Real Applications

- Apache web server, PostgreSQL database
- Emacs, bash, perl, gcc, …

Microbenchmark Performance



System Calls

- Simple PASSTHRU
- MARSHALL args

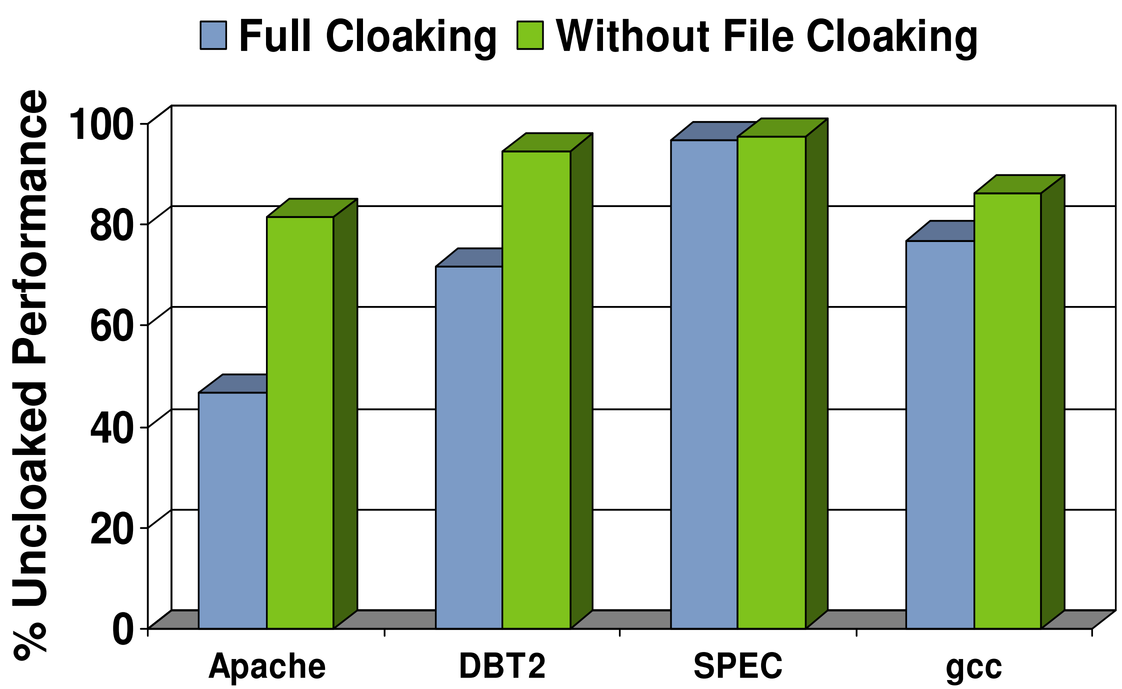
Processes

- FORKW – fork/wait process creation, COW overheads

File-Backed mmaps

- MMAPW – write word per page, flush to disk
- MMAPR – read words back from buffer cache

Benchmark Performance



Web

- Apache web server caching disabled
- Remote load generator ab benchmark tool

Database

- PostgresSQL server DBT2 benchmark

Compute

- SPECint CPU2006
- gcc – worst individual SPEC benchmark

Conclusions

Promising New Approach

- VM-based protection of application data
- Privacy and integrity, even if OS compromised
- Backwards compatible

Powerful New Mechanisms

- Multi-shadowing, cloaking
- Shim extends reach of VMM

Future Directions

- Security implications of a malicious OS
- Additional uses of multi-shadowing

Questions?

For More Information

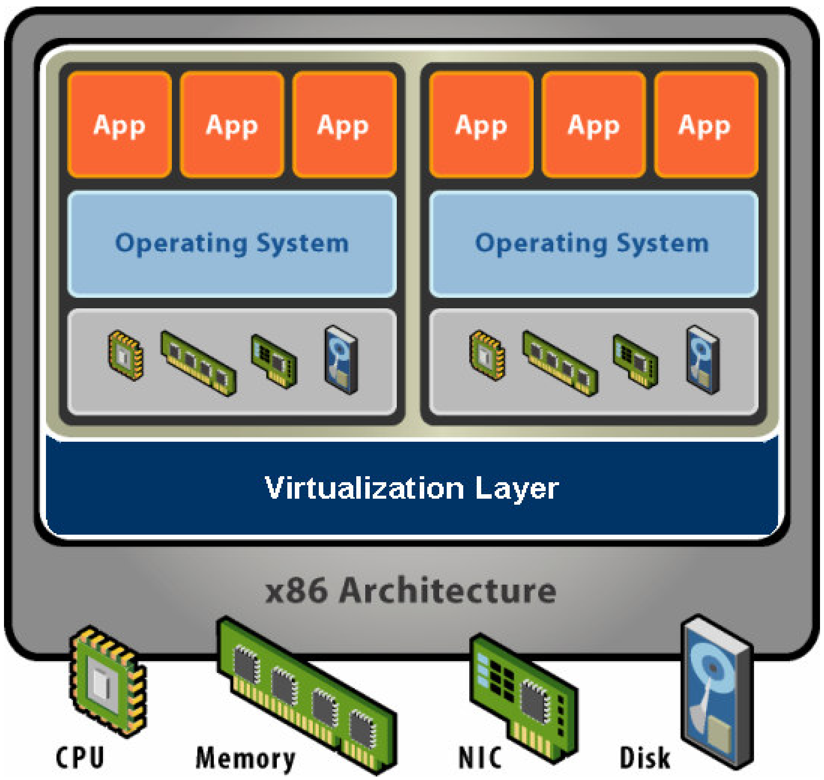
- Read the paper
- Send feedback to mailing list
  overshadow@vmware.com

Job Opportunities

- VMware is hiring!
- Interns and full-time positions
- Feel free to contact me directly
  carl@vmware.com

Backup Slides

What is a Virtual Machine?



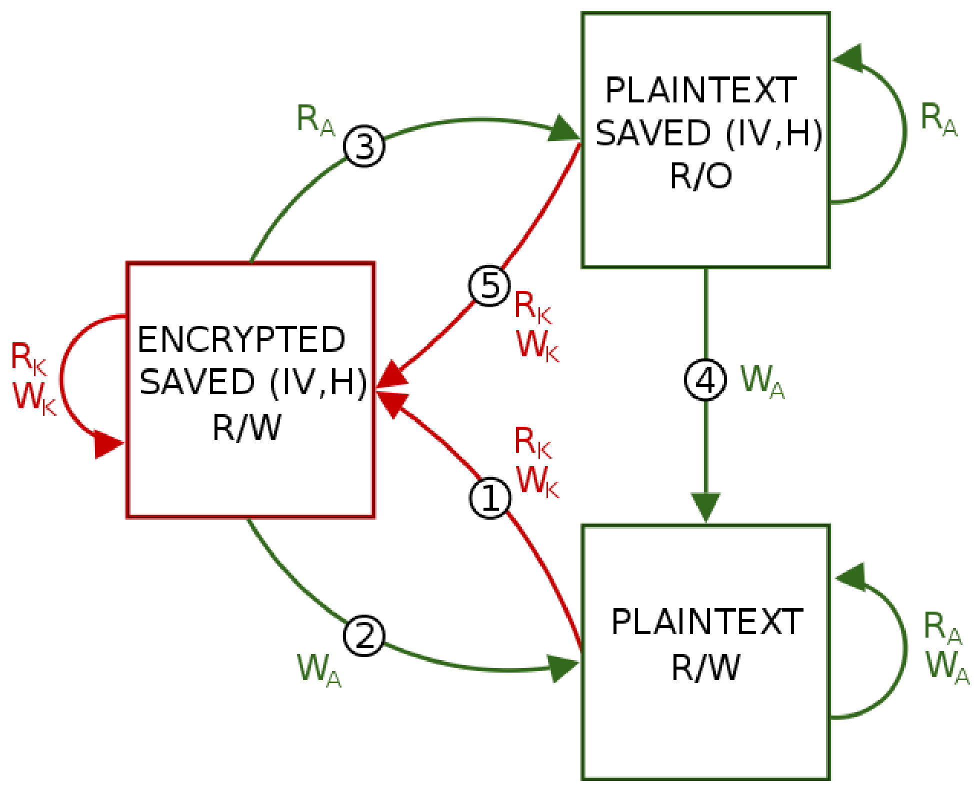
Hardware-Level Abstraction

- Virtual hardware: processors, memory, chipset, I/O devices, etc.
- Encapsulates all OS and application state

Virtualization Software

- Extra level of indirection decouples hardware and OS
- Multiplexes physical hardware across multiple “guest” VMs
- Strong isolation between VMs
- Manages physical resources, improves utilization

Basic Cloaking Protocol



State Transition Diagram

- Single cloaked page
- Privacy and integrity

Single Page, Two Views

- App (A) sees plaintext via application shadow
- Kernel (K) sees ciphertext via system shadow

Protection Metadata

- IV – randomly-generated initialization vector
- H – secure hash

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Secure Context Identification

Application Contexts

- Must identify uniquely to switch shadow page tables
- Must work even with adversarial OS

Shim-Based Approach

- Cloaked Thread Context (CTC) in cloaked shim
- Initialized at startup to contain ASID and random value
- Random value is protected in cloaked memory
- Transitions from uncloaked to cloaked execution
  use self-identifying hypercalls with pointer to CTC
- VMM verifies expected ASID and random value in CTC

Cloaked File I/O

Interpose on I/O System Calls

- Read, write, lseek, fstat, etc.
- Uncloaked files use simple marshalling

Cloaked Files

- Emulate read and write using mmap
- Copy data to/from memory-mapped buffers
- Decrypted automatically when read by app;
  Encrypted automatically when flushed to disk by kernel
- Shim caches mapped file regions (1MB chunks)
- Prepend file header containing size, offset, etc.

Protection Metadata: Details

Protected Resource

- Need indirection to support sharing and persistence
- (RID, RPN) – unique resource identifer, page offset
- Ordered set of (IV, H) pairs in VMM “metadata cache”

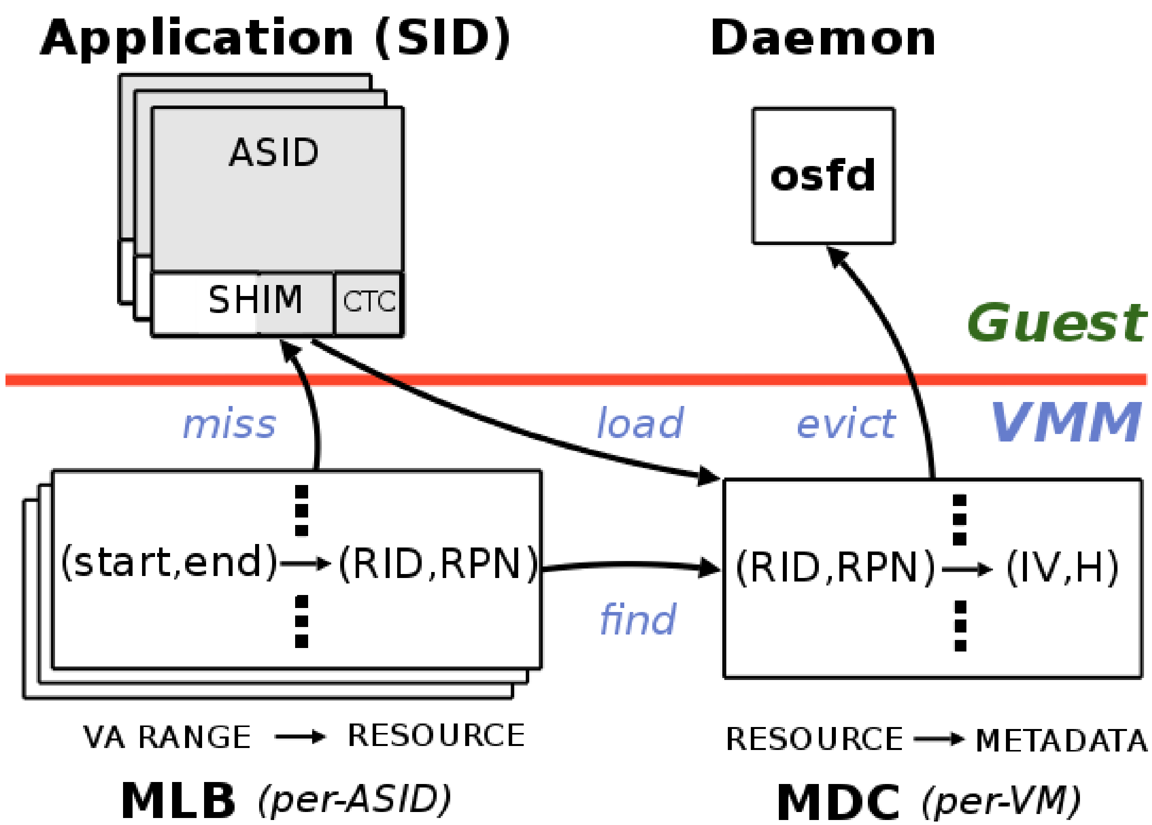
Protected Address Space

- Shim tracks mappings (start, end) $\rightarrow$ (RID, RPN)
- VMM caches in “metadata lookaside buffer”
- VMM upcalls into shim on MLB miss

Metadata Lookup

- (ASID, VPN) $\rightarrow$ (RID, RPN) $\rightarrow$ (IV, H)
- Persistent metadata stored securely in guest filesystem

Managing Protection Metadata



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