0x1A Great Papers in Computer Security

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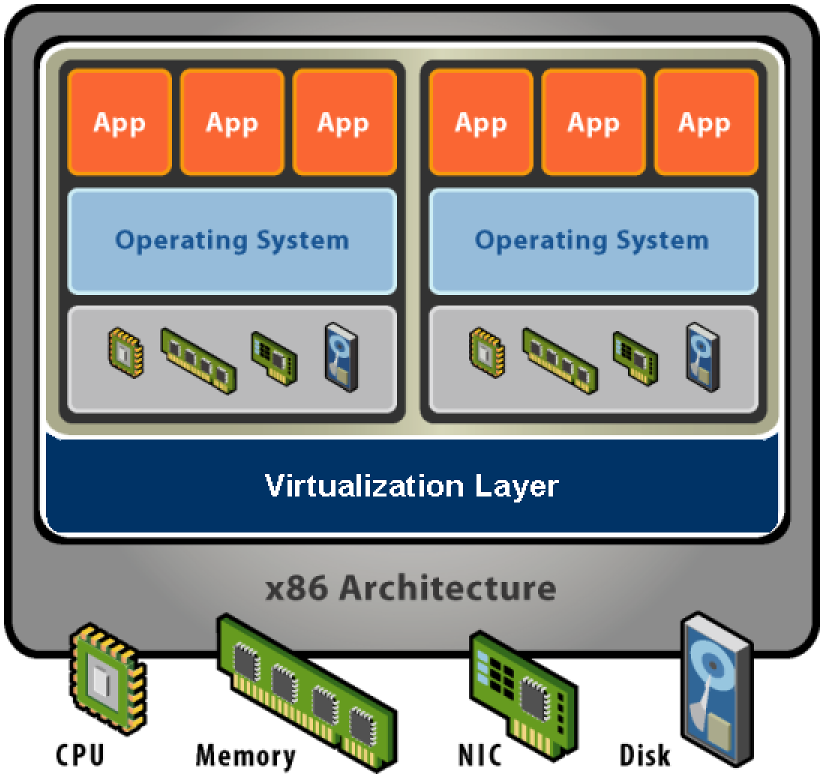
Overshadow:
A Virtualization-Based Approach to Retrofitting Protection in Commodity Operating Systems

(ASPLOS 2008)

Goal: Bypass an Insecure OS

- Secure software runs on commodity OS, thus even a 100% secure application can be compromised if the OS is compromised
- Goal of Overshadow: securely execute application even if the OS is not trusted
  - Guarantee confidentiality and integrity for application's data in memory and on disk
  - Trust only VMM, not the OS
- Backward compatibility!
  - No modifications to OS or application binary

Virtual Machines

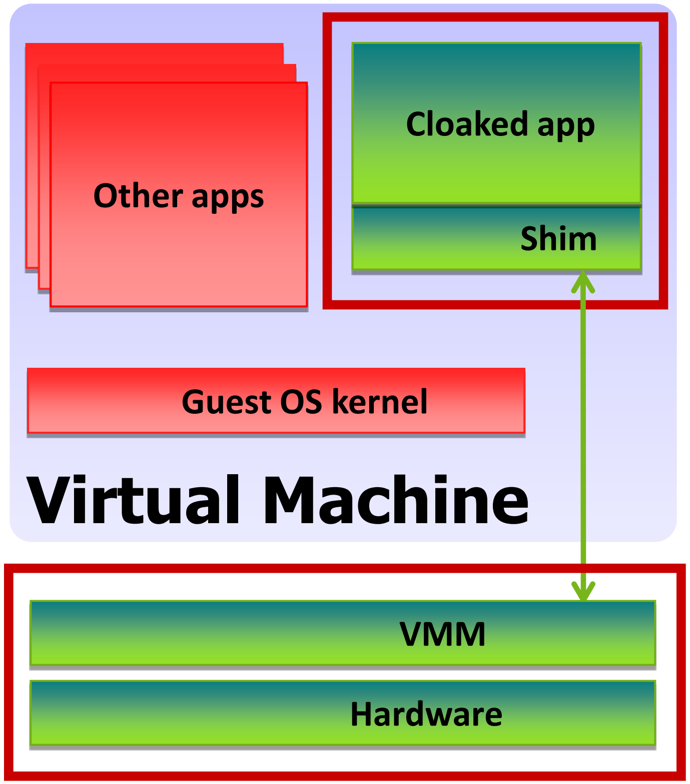


- Hardware-level abstraction
  - Virtual hardware: CPU, memory, chipset, I/O devices, etc.
  - Encapsulates all OS and application state
- Virtualization software
  - Extra level of indirection decouples hardware and OS
  - Multiplexes physical hardware across multiple “guest” VMs
  - Strong isolation between VMs
  - Manages physical resources, improves utilization

Key Idea: Cloaking

- VMM provides multiple views of application's memory depending on who is looking
  - Application: unencrypted read-write access
  - Guest OS: "cloaked" view
    - Encrypted and integrity-protected
- Application/OS interaction mediated by shim
  - Public (unprotected) shim on guest OS
  - Private (protected) shim on application

Overshadow Architecture



<u>Two</u> Virtualization Barriers

- VMM switches between two views of memory
  - App sees normal view
  - OS sees encrypted view
- Shim manages application/OS interactions
  - Interposes on system calls, interrupts, faults, signals
  - Transparent to application

Memory Mapping: OS and VMM

virtual → **"physical"** → **machine**

guest OS ***VMM***

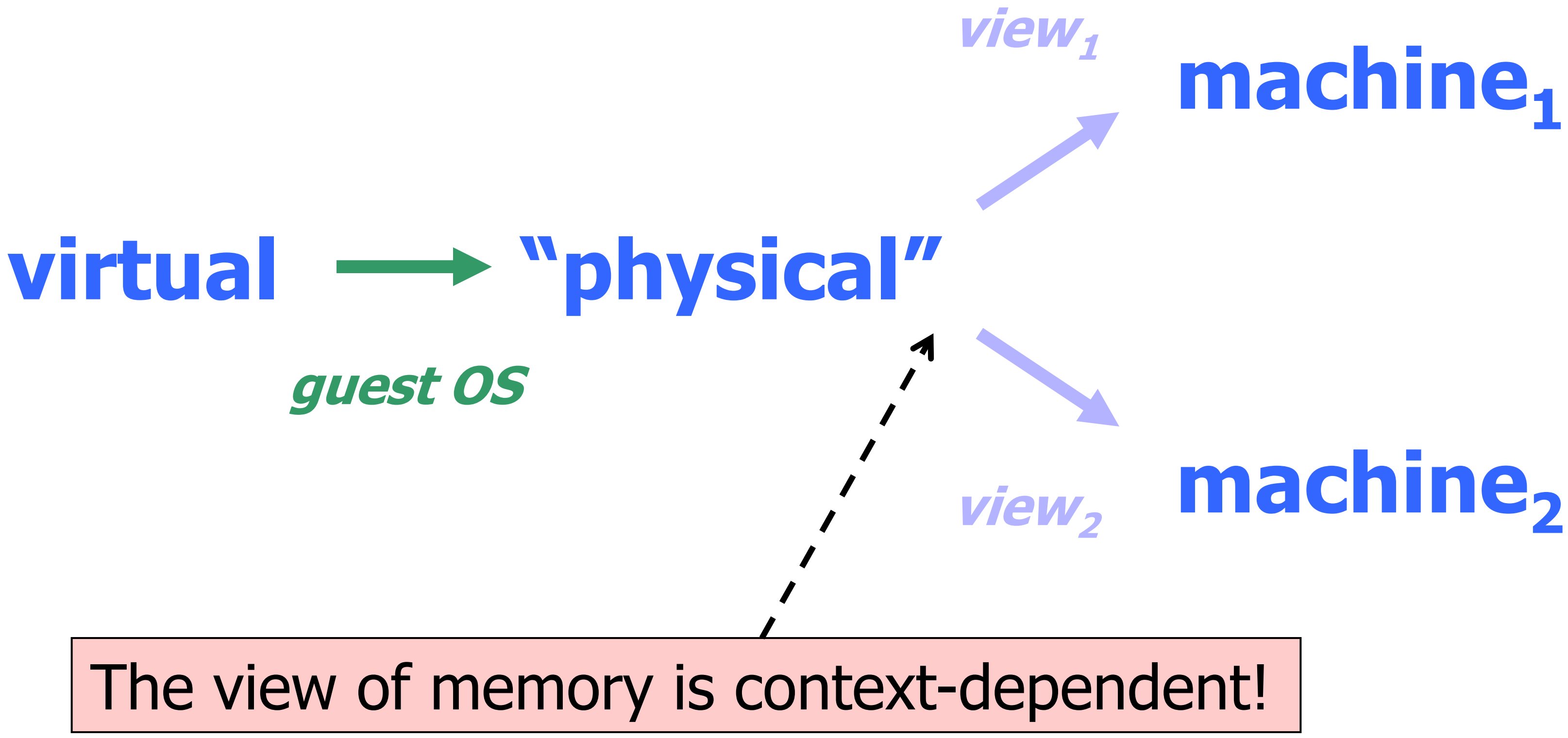
GVPN
(guest virtual
page number)

GPPN
(guest physical
page number)

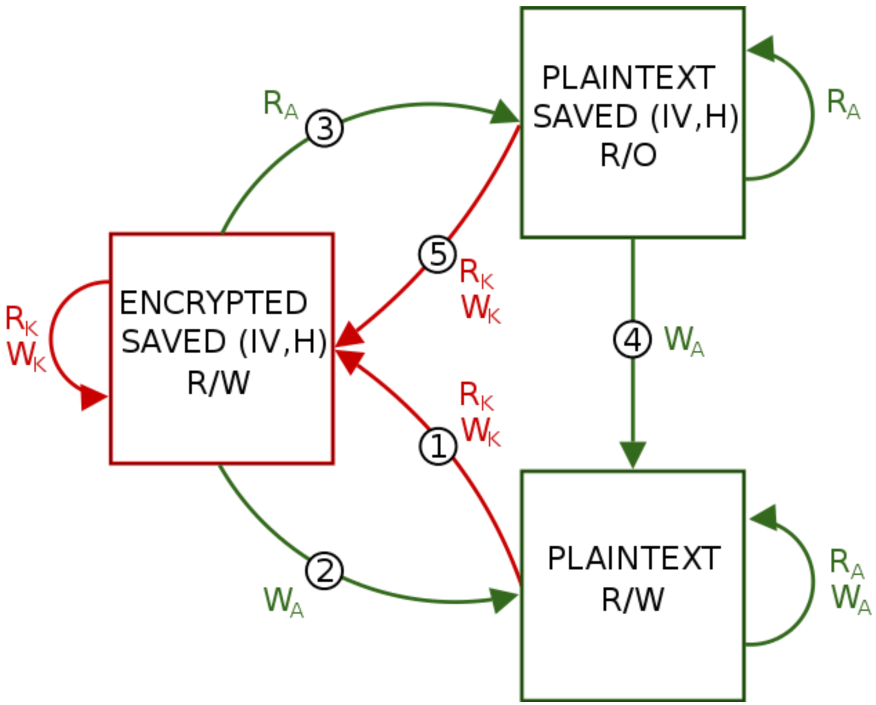
MPN
(machine
page number)

shadow page tables

Multi-Shadowing

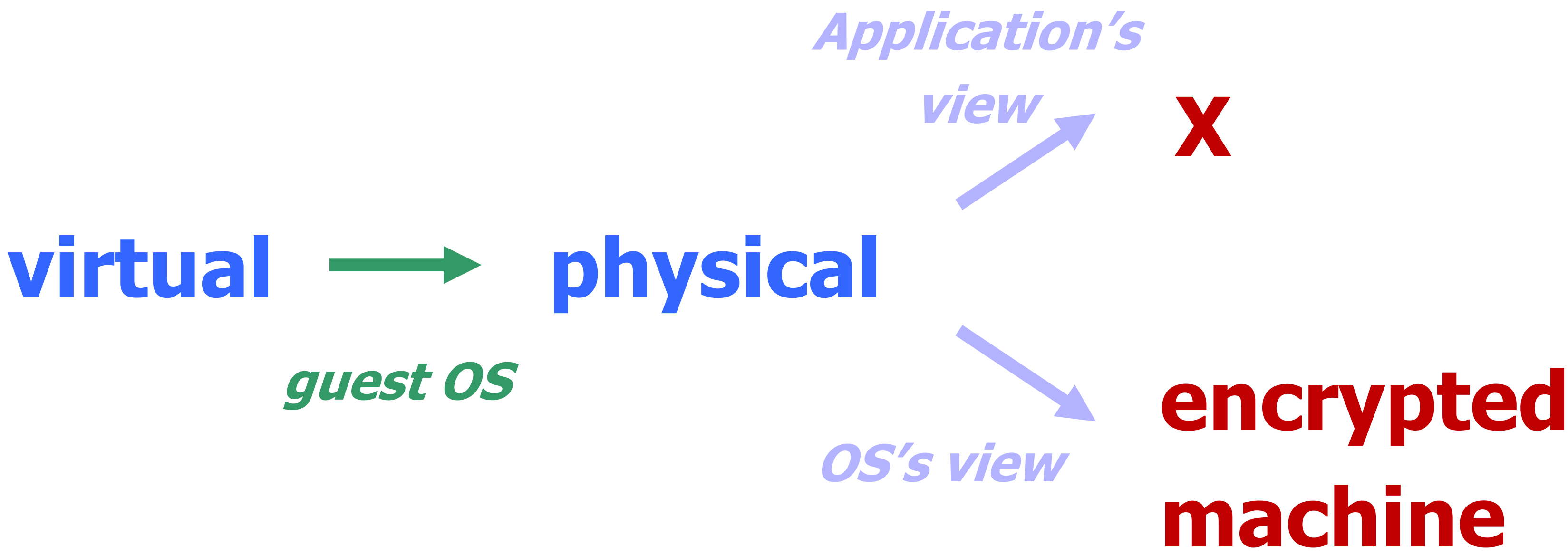


Basic Cloaking Protocol



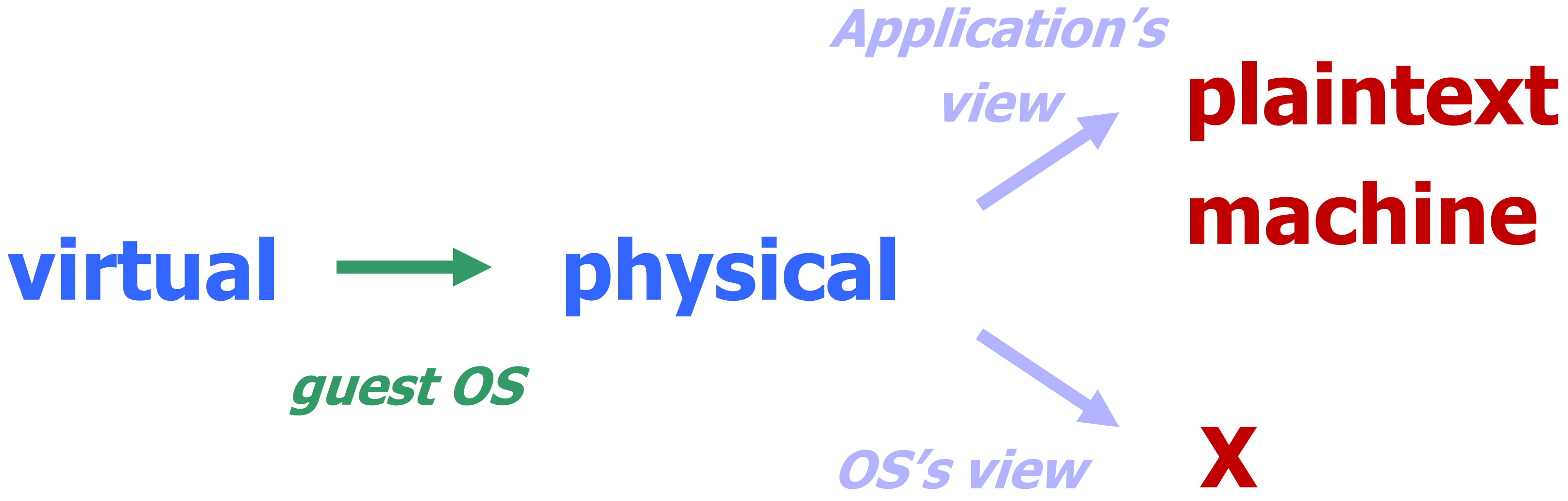
- At any time, each page is mapped into only one of the two shadows
  - App (A) sees plaintext via application shadow
  - Kernel (K) sees ciphertext via system shadow
- Protection metadata
  - IV – random initialization vector
  - H – secure hash of page contents

OS Accesses a Page



Page is unmapped in current shadow ⇒ fault into VMM
VMM encrypts the page, computes integrity hash,
remaps encrypted page into system shadow

Application Accesses a Page



Page is unmapped in current shadow ⇒ fault into VMM
VMM verifies the integrity hash, decrypts the page,
remaps plaintext page into application shadow

Cloaking Application Resources

- Protect memory-mapped objects
  - Stack, heap, mapped files, shared mmaps
- Make everything else look like a memory-mapped object
  - For example, emulate file read/write using mmap
- OS still manages application resources
  - Including demand-paged application memory
  - Moves cloaked data without seeing its true contents
  - Encryption/decryption typically infrequent
    - OS accesses application's page $\Rightarrow$ encrypt
    - Application accesses OS-touched page $\Rightarrow$ decrypt

Shim

- Challenges
  - Securely identify which application is running
  - Securely transfer control between OS and application
  - Adapt 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

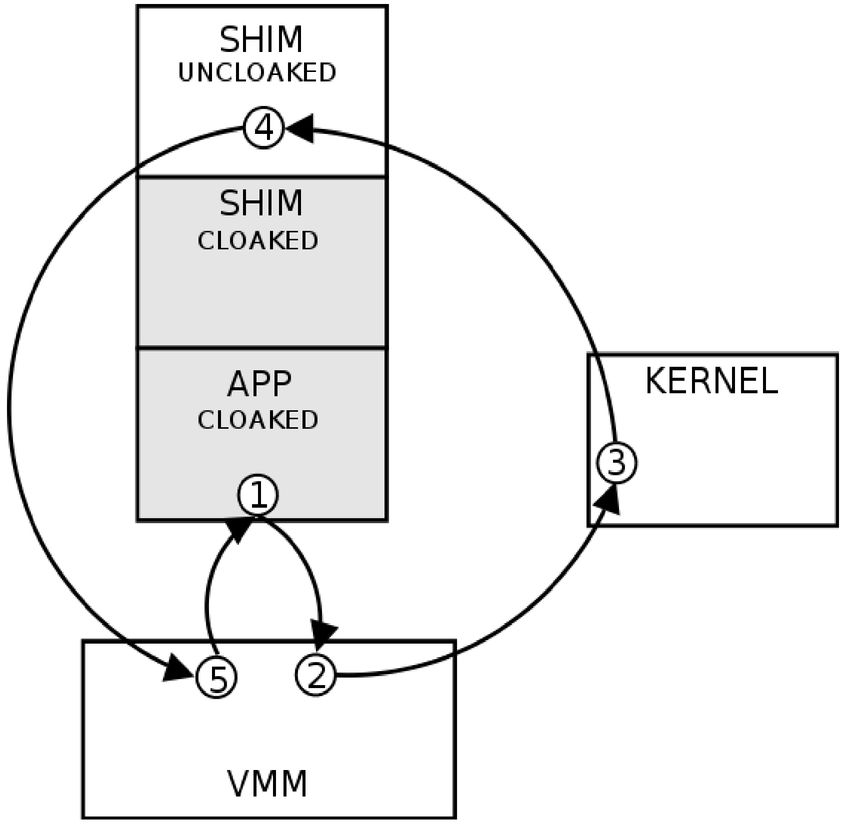
Hypercalls

- Used by shims to invoke VMM
- Uncloaked shim (untrusted, invoked by OS)
  - Can initialize a new cloaked context
    - When starting an application
  - Can enter and resume existing cloaked execution
    - When returning to a running application
- Cloaked shim (trusted, invoked by application)
  - Can cloak new memory regions (when is this needed?), unseal cloaked data, create new shadow contexts, access metadata cache

Secure Context Identification

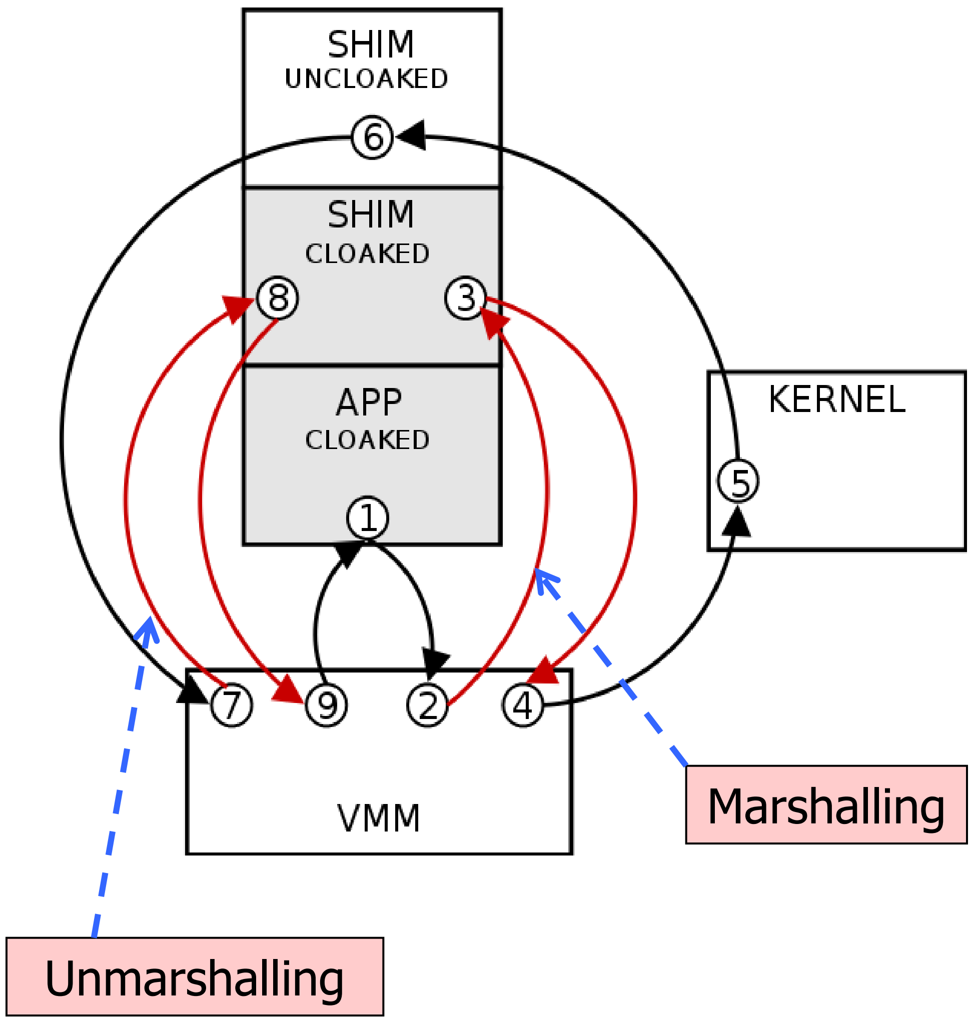
- VMM must identify unique application contexts in order to switch shadow page tables
- Cloaked Thread Context (CTC)
  - Sensitive data used for OS-application control transfers
    - Saved registers, entry points to shim functions, ASID (address space identifier – used to identify context), a special random value generated during initialization
  - Uncloaked → cloaked (OS → application) transition: uncloaked shim makes a hypercall, passes ASID and the pointer to CTC to VMM, VMM verifies expected ASID and the random value
    - What prevents malicious OS from messing with CTC?

Handling Faults and Interrupts



1. App is executing
2. Fault traps into VMM
   - Saves and scrubs registers
   - Sets up trampoline back to shim so kernel can return
   - 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

Handling Systems 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
  - Marshal and unmarshal via buffer in uncloaked shim
  - More complex: pipes, signals, fork, file I/O

Marshalling Syscall Arguments

- For some system calls, OS needs to read or modify arguments in caller's address space
  - Path names, socket structures, etc.
  - This does not work with cloaked applications (why?)
- Instead, arguments are marshalled into a buffer in the uncloaked shim and registers are modified so that the call uses this buffer as the new source or destination
- Results are copied back into the cloaked application's memory

Resuming Cloaked Execution

- OS can ask to resume cloaked execution from a "wrong" point, but integrity checking will fail unless the CTC is mapped in the proper location
  - What's the "right" point to resume execution?
- VMM will always enter cloaked execution with proper saved registers, including the IP, and all application pages unaltered (why?)
- Thus, OS can only cause a cloaked execution to be resumed at the proper point in the proper application code

Signal Handling

- Parts of the shim cannot be preempted
- Application registers a signal handler $\Rightarrow$ the shim emulates the OS and records it in a table
- Signal is received $\Rightarrow$ shim passes to VMM the signal, parameters, context in which it occurred
  - If during a cloaked execution, VMM passes control to a proper signal entry point in the shim
  - If during a shim execution, VMM either rolls back the execution to the last application system call entry, or defers signal delivery until shim returns to application

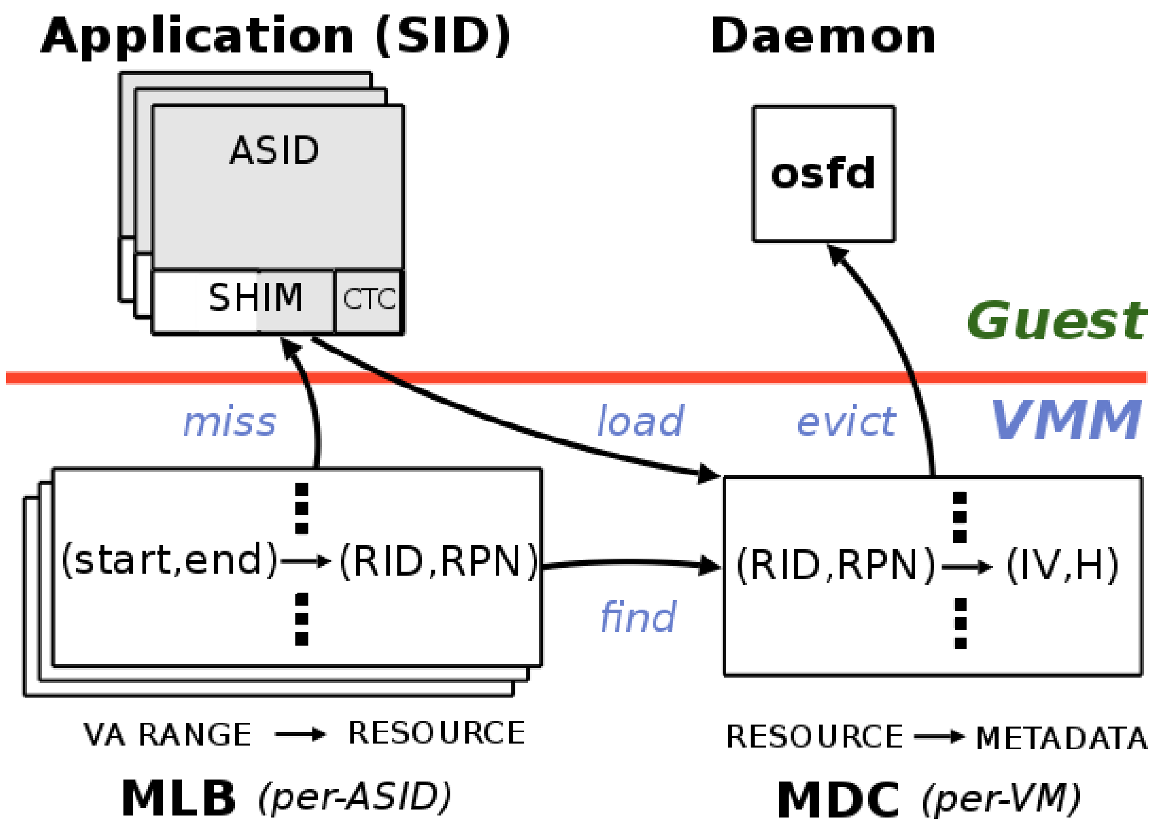
Cloaked File I/O

- Interpose on I/O system calls
  - Read, write, lseek, fstat, etc.
- Uncloaked files use simple marshalling
- Cloaked files emulated using memory
  - Emulate read and write using mmap
    - Copy data to/from memory-mapped buffers
  - Decrypted automatically when read by application, encrypted automatically when flushed to disk by OS
  - Shim caches mapped file regions (1MB chunks)
  - Prepend file header containing size, offset, etc.

Protection Metadata

- VMM enforces integrity, ordering, freshness for application's memory pages
- Metadata for each memory page tracks what's supposed to be in it
  - IV – random initialization vector
  - H – secure integrity hash of page content
  - VMM keeps the mapping (ASID, GVPN) → (IV, H)
    - ASID = "application" (address space) identifier
    - GVPN = guest virtual page number

Managing Protection Metadata



Details of Metadata Protection

- Protected resources: files and memory regions
  - (RID, RPN) – unique resource id, app page number
- Metadata lookup in VMM:

  (ASID, VPN) $\rightarrow$ (RID, RPN) $\rightarrow$ (IV, H)
  - Shim tracks mappings (start, end) $\rightarrow$ (RID, RPN)
    - VMM caches these mappings in "metadata lookaside buffer" (MLB), upcalls into shim on MLB miss
  - Indirection needed to support sharing and persistence
    - Two processes of the same app may access same resource
    - Application may want to keep a resource between executions
    - Persistent metadata is stored securely in the guest filesystem

Cloning a Cloaked Process

- Allocate local storage for new thread
- Copy parent's CTC and fix pointers to the new thread's local storage
- Change instruction pointer and stack pointer in the child's CTC
- Set up the uncloaked stack so that the child starts execution in a special **child_start** function within the child's shim, it finishes initialization

Cloning Metadata

- Problem: copy-on-write private memory regions shared between a process and its clone
- If parent encrypts shared memory after the fork, how does the child find metadata for decrypting?
- Solution: data structure with metadata information, mirroring the process trees
  - Whenever a page is encrypted, new metadata (random IV, hash) is propagated to all children with pages whose contents existed prior to the fork

Security Guarantees (1)

- OS cannot modify or inject application code
  - Application code resides in cloaked memory, where it is encrypted and integrity-protected
  - Any modifications detected because page contents won't match the hash in VMM's metadata cache
- OS cannot modify application's instruction pointer
  - All application registers are saved in the cloaked thread context (CTC) after all faults/interrupts/syscalls and restored when cloaked execution resumes
  - CTC resides in cloaked memory and is encrypted and integrity-protected, so the OS can't read or modify it

Security Guarantees (2)

- OS cannot tamper with the loader
  - Before entering cloaked execution, VMM verifies that the shim was loaded properly by comparing hashes of the appropriate memory pages with expected values
    - If check fails, the application can access resources only in encrypted form
- OS can execute an arbitrary program instead, but it cannot access any protected data

Overshadow: Key Ideas

- VM-based protection of application data – even if the OS is compromised!
- No modifications to OS or applications
  - Shim extends the “reach” of VMM
- Multi-shadowing and cloaking
  - Use the shim and faults into VMM to switch between encrypted and unencrypted views on all transitions between the application and the OS