Eternal Sunshine of the Spotless Machine: Protecting Privacy with Ephemeral Channels

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OSDI 2012
October 8, 2012

Wanted: Application Privacy

- Goal: Run programs without leaving traces

VoIP conversation with lawyer

Biomedical researcher accessing data

Website access

- Current state: Private browsing
  - Popular feature in web browsers
  - Ideal: When private browsing session terminates, all traces erased

A Privacy Problem

- Private browsing unachieved
  - Evidence of site visits leaks into OS [Aggrawal, 2010]
- Problem: No system support
  - Applications interact with user and world
  - Data leaks into OS, system services
  - Applications cannot remove traces they leave

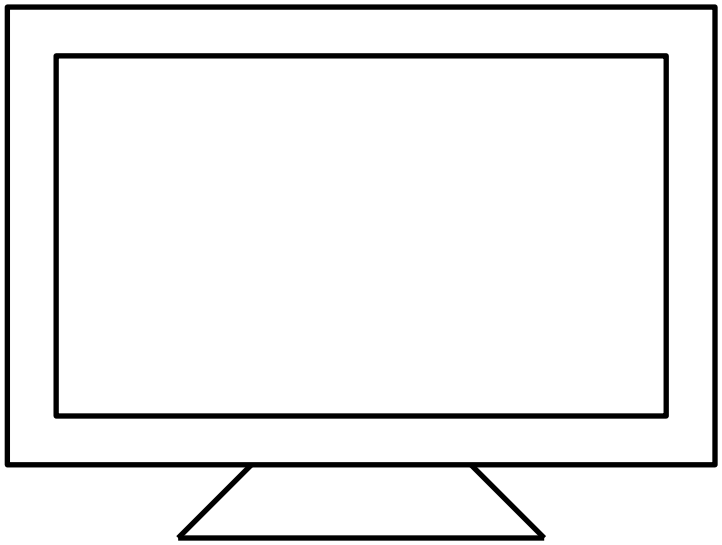
Example: Browsing a Website

Network

Audio

What traces still remain on the computer?

Leaks From Browsing



Network

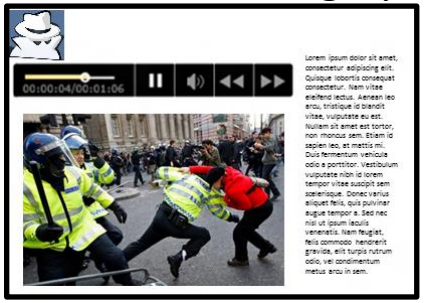
Memory contents:

Complete packets, like:

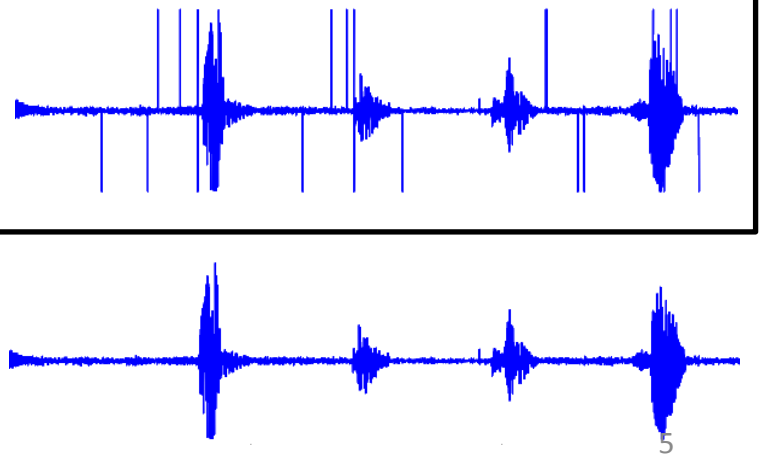
```
HTTP/1.1 200 OK
Date: Mon, 17 Sep 2012 …
Server: Apache/2.2.14 …
…
```

Audio

X server caches, graphics drivers



PulseAudio server



Secure Deallocation Is Not Enough

- **Secure deallocation**: Zero memory when freed
  - Research implementation [Chow, 2005]
  - PaX: Security patch for Linux kernel
- Sensitive data remains allocated
  - X caches, PulseAudio buffers not freed

Resisting a Strong Adversary

- Goal: Provide **forensic deniability** – no evidence left for non-concurrent attacker
- Once program terminated, protection maintained under extreme circumstances

Root-level compromise
(after program terminates)

Computer physically seized

Goals

- Provide privacy
  - Private sessions with forensic deniability
- Maintain usability
  - Simultaneous private/non-private applications
  - Support a wide variety of private applications
  - “Pay as you go” - costs only for private programs
  - Impose low overhead

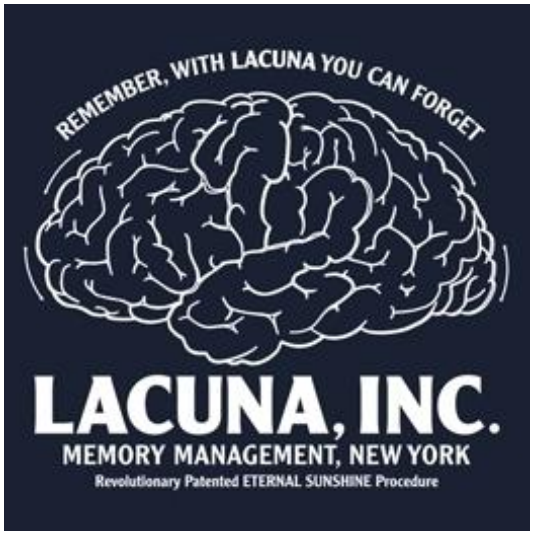
Lacuna

- System to accomplish our privacy and usability goals
- Host OS (Linux), VMM (QEMU-KVM) modified
- Applications unmodified

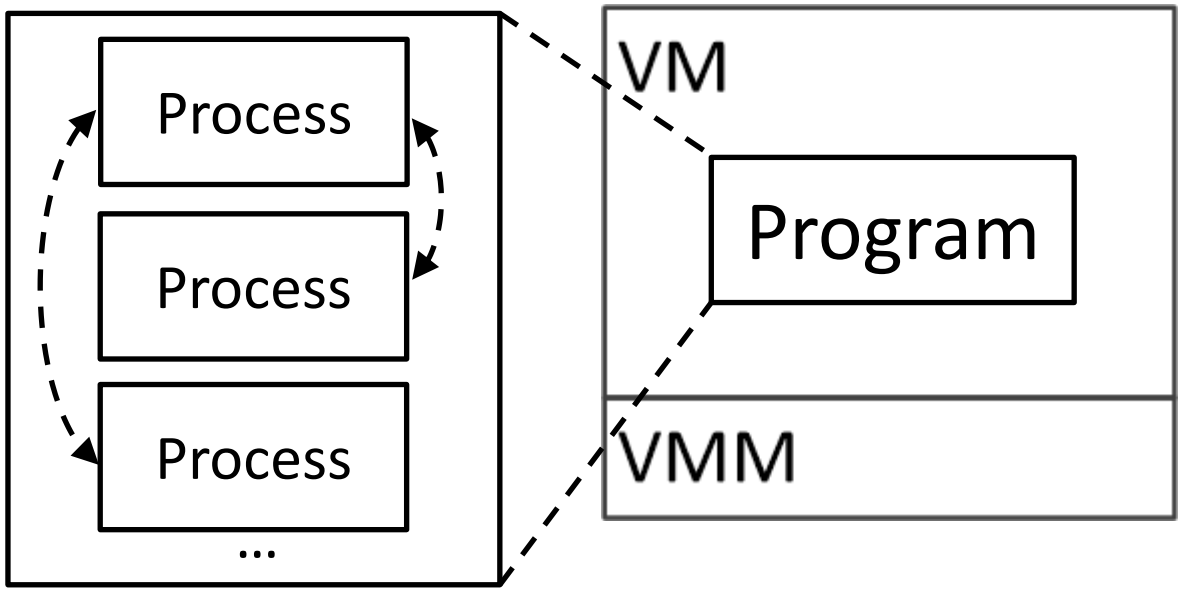
la·cu·na [luh-kyoo-nuh]
1. a gap or missing part, as in a manuscript, series, or logical argument...

Outline

- Design
  - Erasable program container
  - Allow communication with peripherals
- Evaluation
  - Lacuna provides privacy
  - Lacuna maintains usability



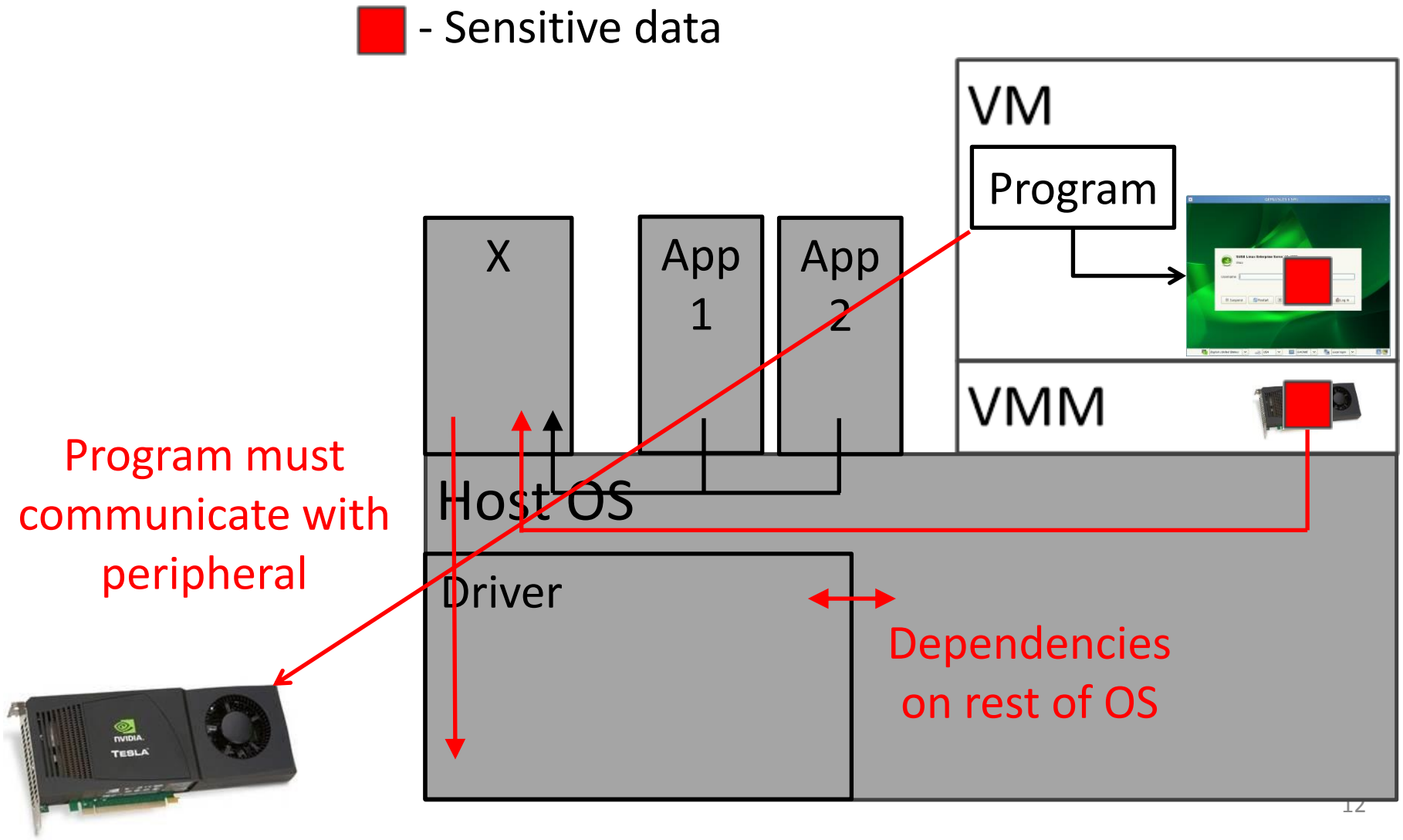
Erasable Program Container



VM contains Inter-Process Communication

VM alone is insufficient

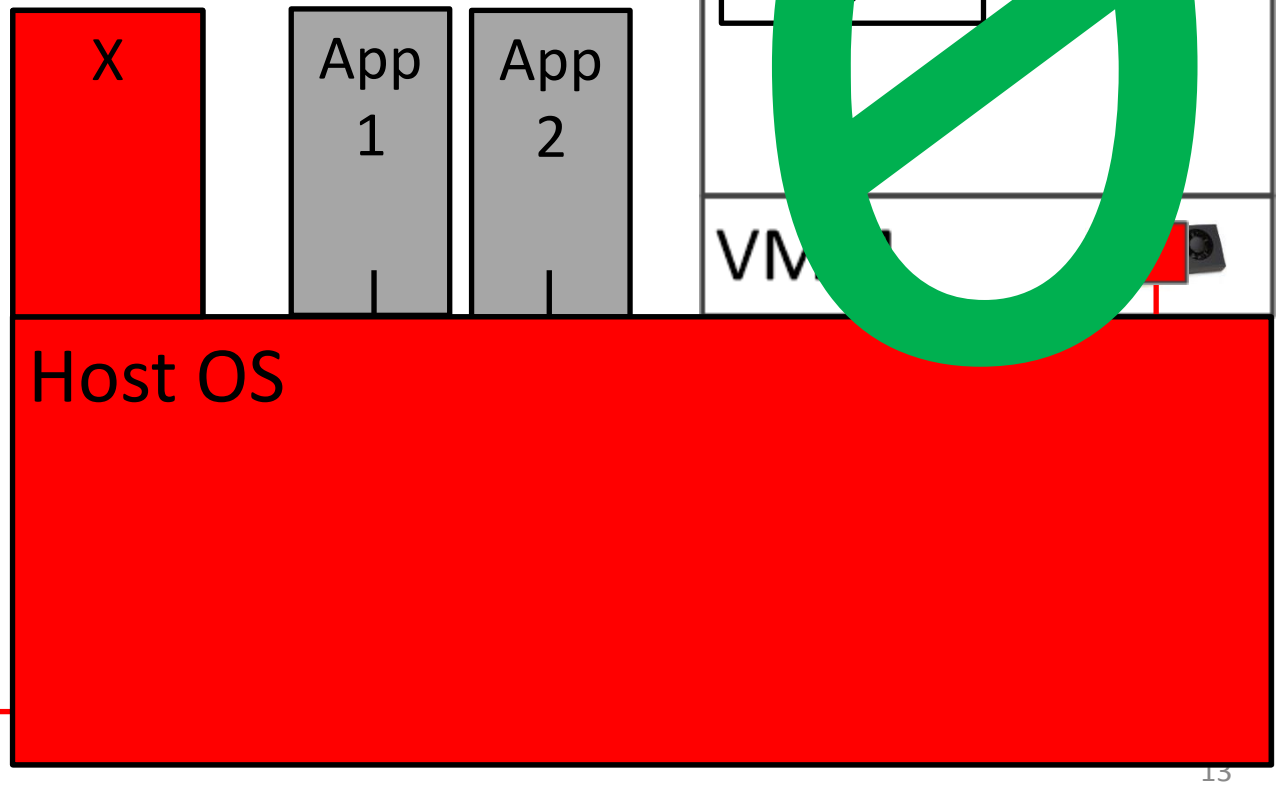
Communicating with Peripherals



Communicating with Peripherals

- Sensitive data

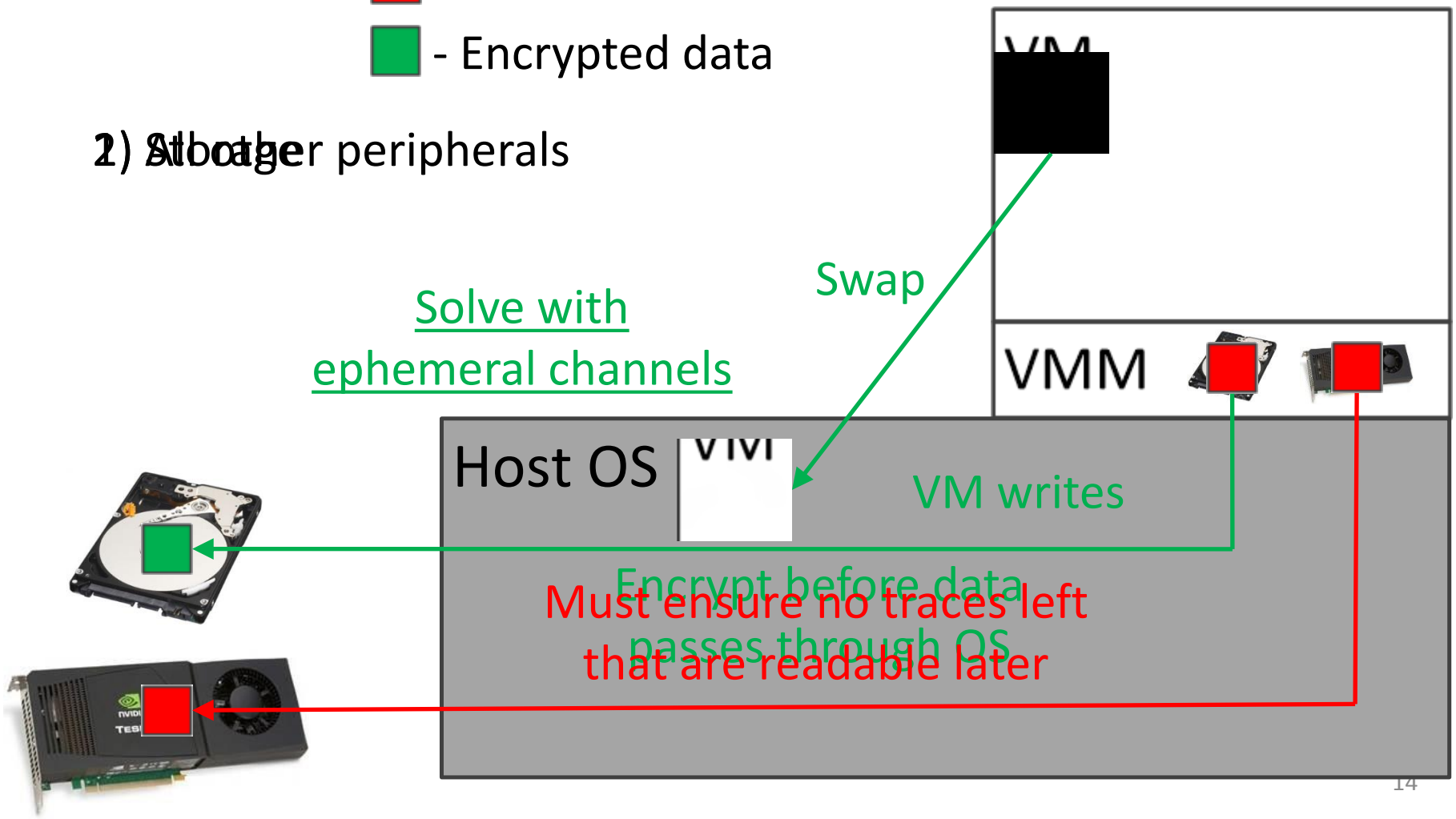
Code with potential data exposure



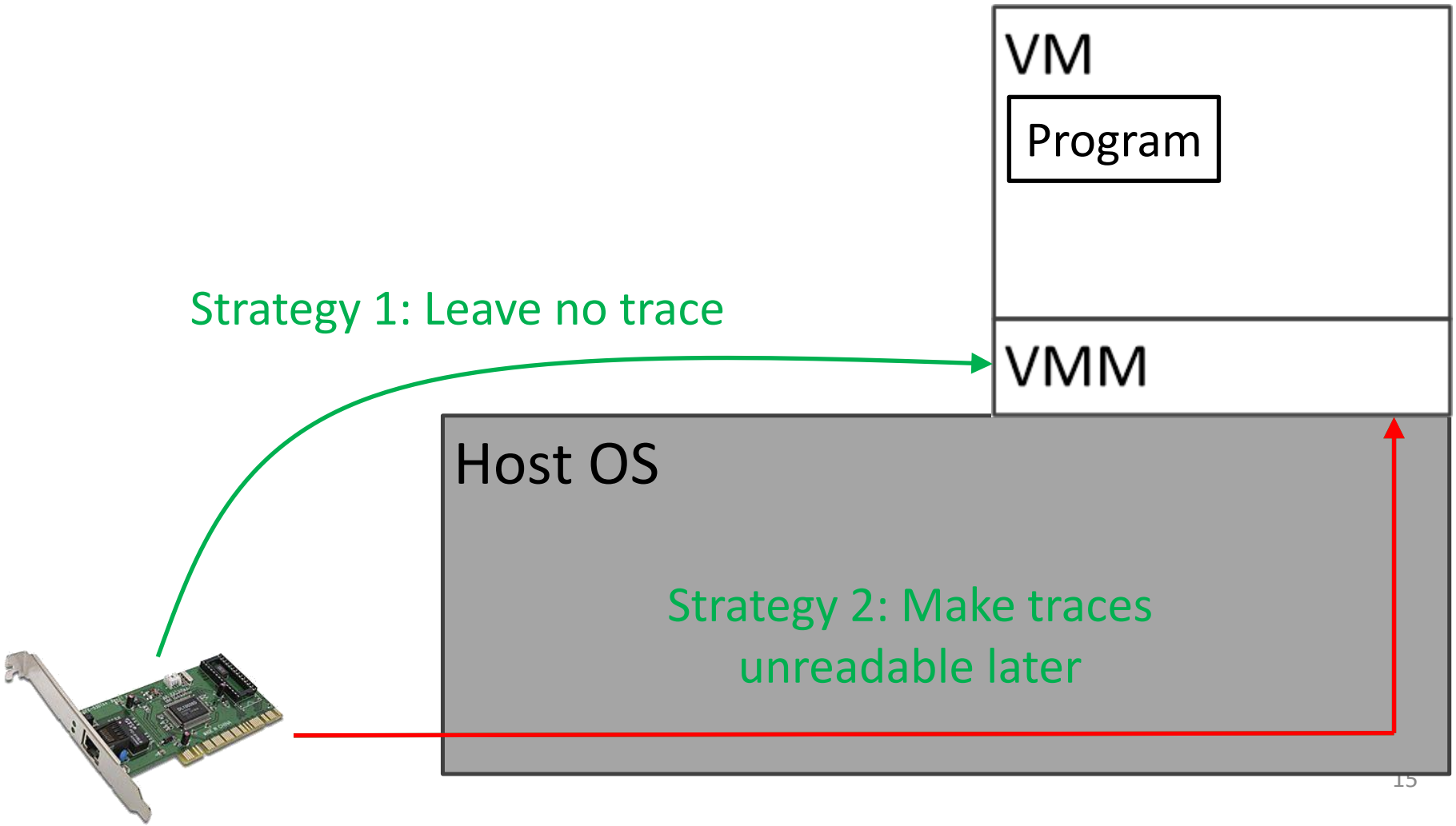
Two Peripheral Types

- Sensitive data
- Encrypted data

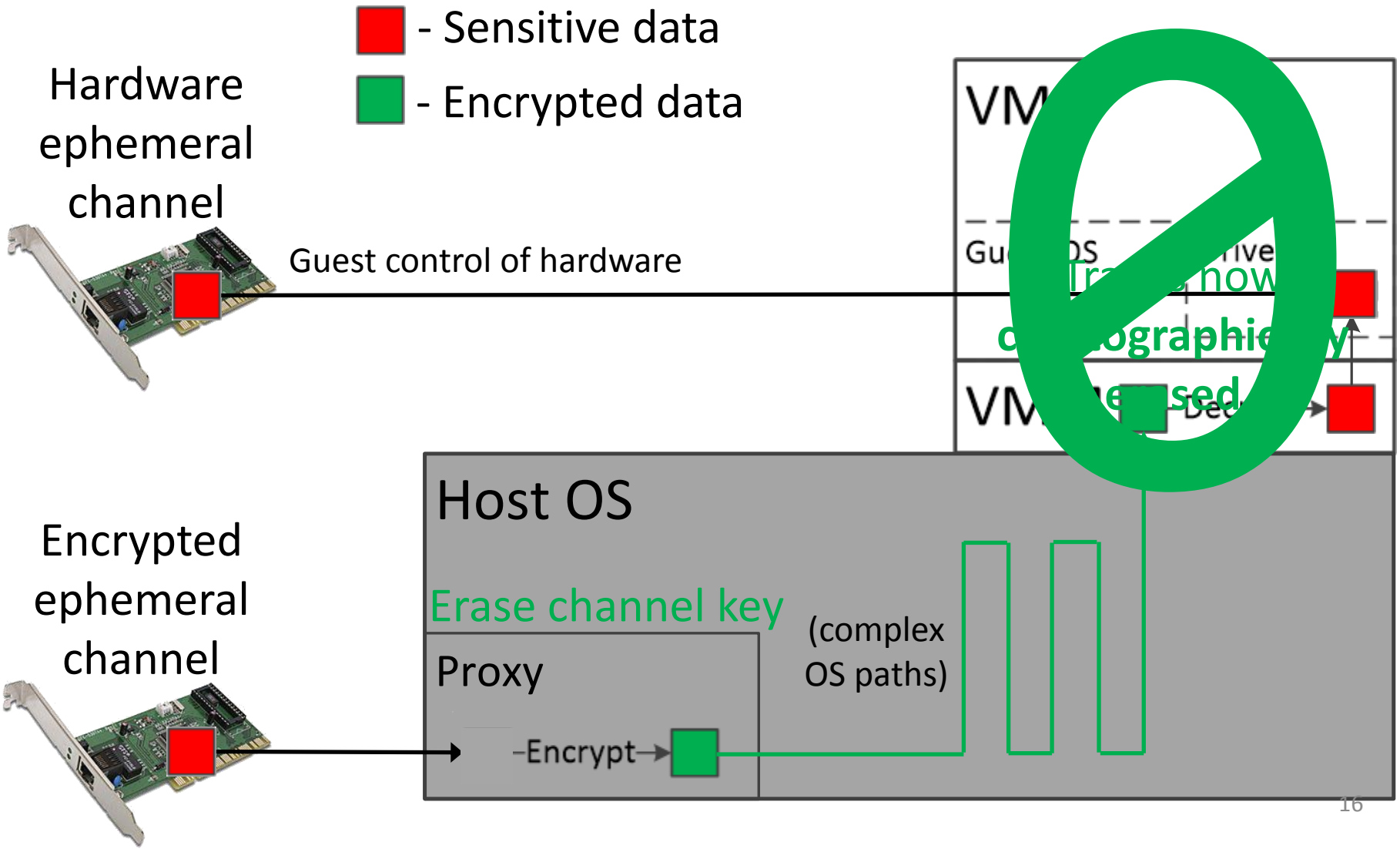
1) Storage
2) All other peripherals



Ensuring No Readable Traces

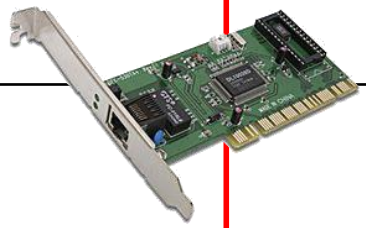


Ephemeral Channels



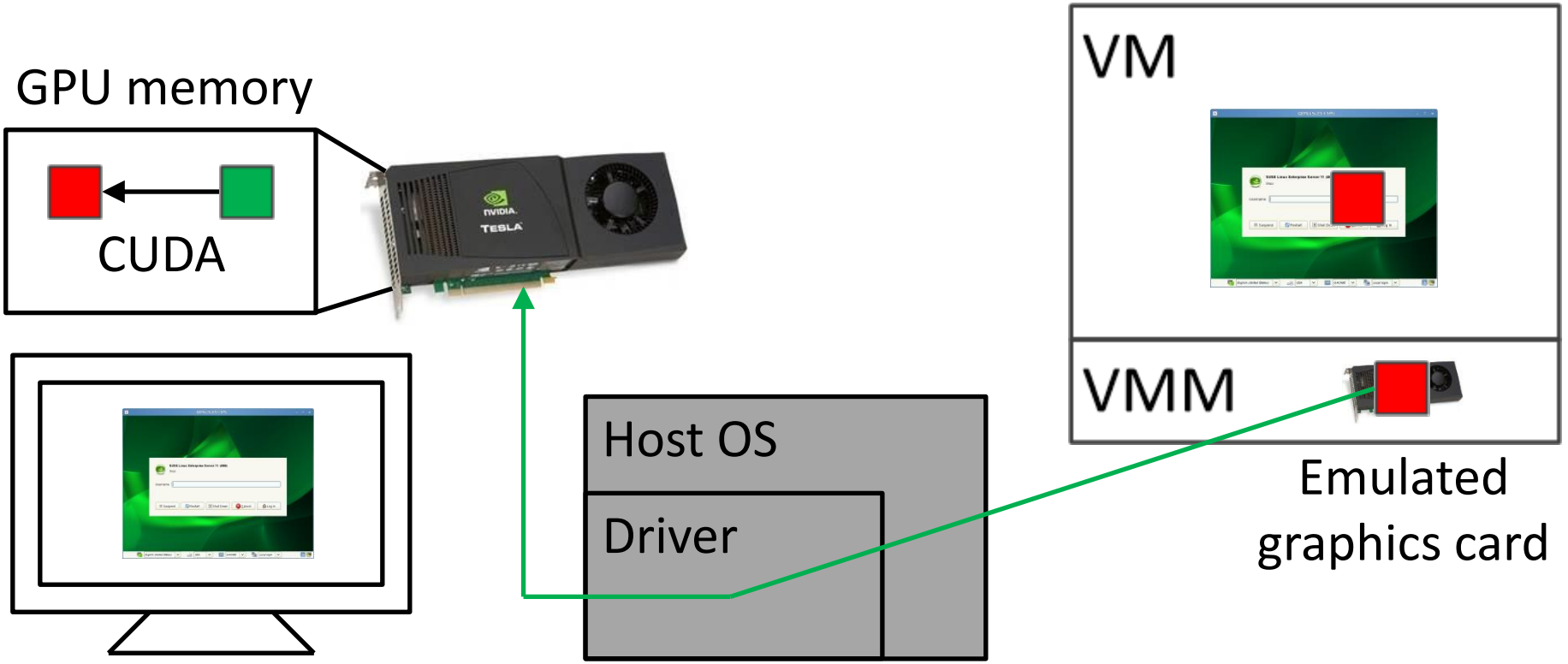
Channel Type Comparison

	Hardware	Encrypted
Host drivers unmodified	✓	✗
Host code never sees unencrypted data	✓	✗
Hardware virtualization support unnecessary	✗ (No graphics)	✓
Guest modification unnecessary	✗	✓ (Run Windows, Linux, unmodified programs)

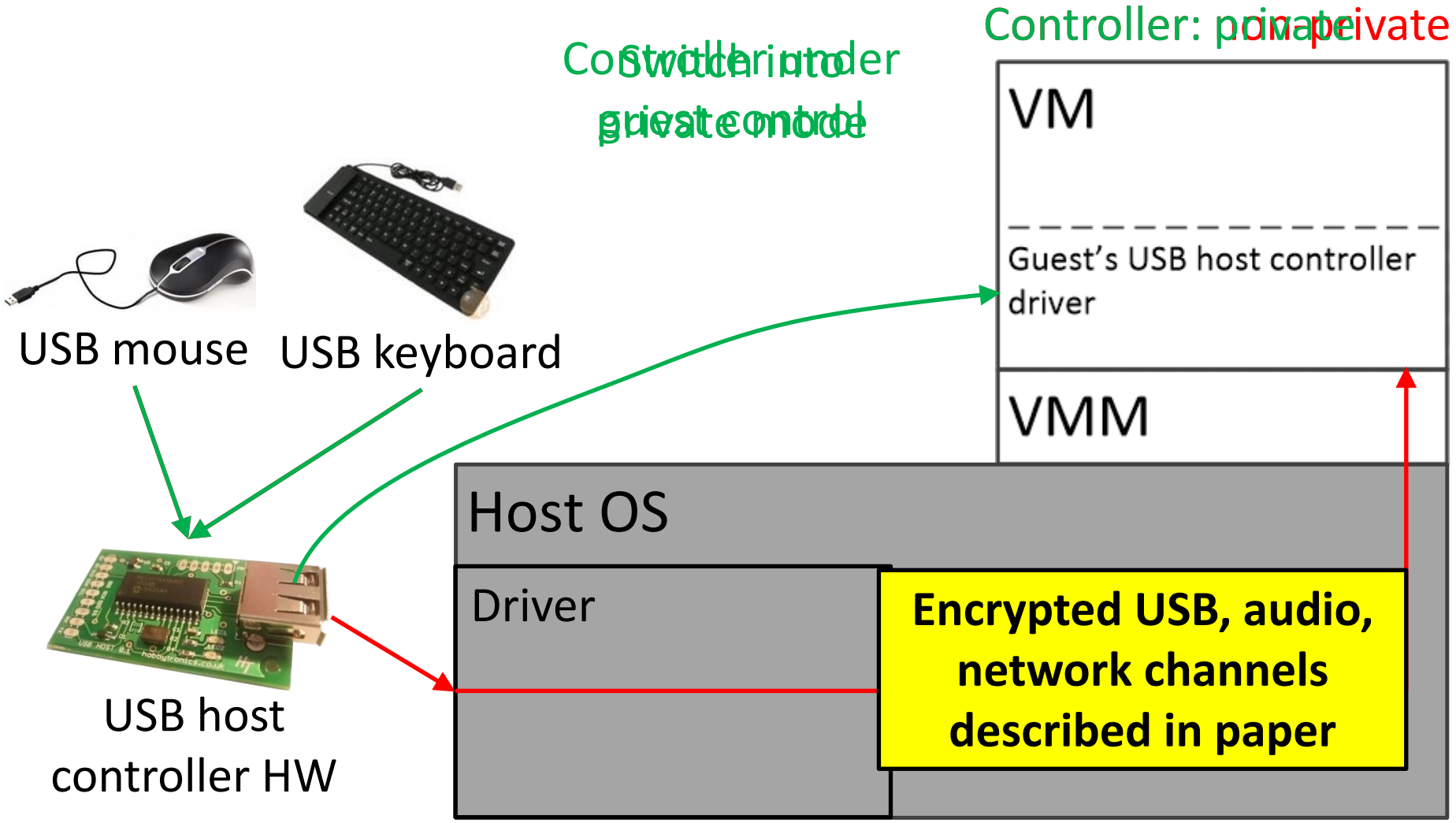


Encrypted Graphics Channel

- No hardware virtualization support for graphics
- Solution: Encrypt VM output to GPU memory



Hardware USB Channel



Sanitizing Storage

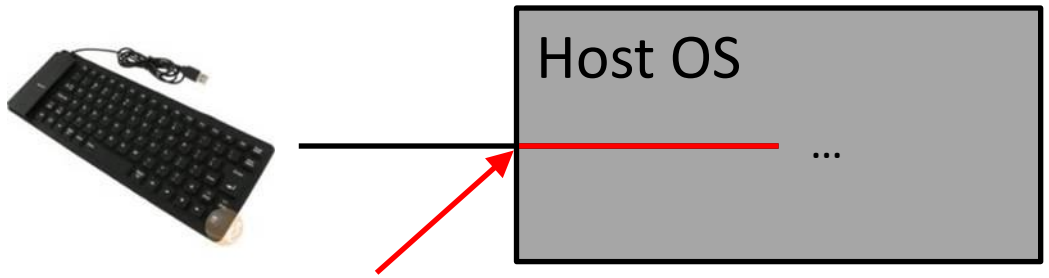
- Encrypt VM writes to storage
  - VM image file unmodified
  - **Diffs file** contains VM writes to storage
  - Diffs file encrypted
- Leave no evidence of which storage locations read
  - Free buffer cache pages for VM image file only
- Encrypt swapped memory from private VM
  - Encrypt swapped pages for VMM process only
- Encryption keys erased on VM exit
- Techniques here “pay as you go”

Evaluation

- Lacuna provides privacy
  - Measure that Lacuna does not leak private data
  - Quantify size of code that handles sensitive data
- Lacuna maintains usability
  - Low switch time to private environment
  - Application performance near that of running program in VM
- More evaluation in paper

Lacuna Protects Privacy

- Experiment to locate leaks
- Inject random “tokens” into peripheral I/O paths, scan memory to locate [Chow, 2005]
- Tokens <u>almost always</u> found without Lacuna
- Tokens <u>never</u> found with Lacuna



Little Code Handles Sensitive Data

Subsystem	Lines of Code
Graphics	725 (CUDA)
Sound	200 (out) 108 (in)
USB	414
Network	208

- Measurements are lines of code outside of QEMU that handle unencrypted data
  - Data within QEMU erased at VM exit

Time to Switch to Private Programs is Low

Channel Type	Switch Time (s)
USB passthrough (encrypted)	
keyboard	1.4 ± 0.2
keyboard + mouse	2.3 ± 0.2
PCI assignment (hardware)	
keyboard	2.4 ± 0.2
keyboard + mouse	3.8 ± 0.2

- USB driver disconnect significant (0.8-1.0 s)
- Switch time achieved by eliminating two extra disconnects in guest USB initialization

Impact on Full-System Workloads is Low

- Benchmarks
  - MPlayer: Watch video in across network
  - Firefox: Browse Alexa top 20 websites
  - LibreOffice: Create 2,994-character, 32-image document
- No execution slowdown, higher CPU utilization

	Video (75 s)	**Browser** (20 s)	**Office Suite** (175 s)
QEMU	32.2 ± 7.4	25.9 ± 1.3	8.1 ± 1.2
Lacuna	49.7 ± 0.3 (+ 17.5)	46.2 ± 1.5 (+ 20.3)	21.1 ± 0.6 (+ 13.0)

Measurements are % CPU util

Worst case: additional 20 percentage points

- CPU utilization lowered by hardware AES (AES-NI)

Conclusion

- Modern computer systems leak secrets
- Lacuna provides **forensic deniability**: secrets removed after program termination
- **Ephemeral channels** provide private peripheral I/O
- Lacuna runs full-system workloads efficiently