# CS155: Computer Security

## Isolation

# The confinement principle

*Acknowledgments: Lecture slides are from the Computer Security course taught by Dan Boneh at Stanford University. When slides are obtained from other sources, a  a reference will be noted on the bottom of that slide. A full list of references is provided on the last slide.*

## Running untrusted code

We often need to run buggy/unstrusted code:

- programs from untrusted Internet sites:
  - apps, extensions, plug-ins, codecs for media player
- exposed applications: pdf viewers, outlook
- legacy daemons: sendmail, bind
- honeypots

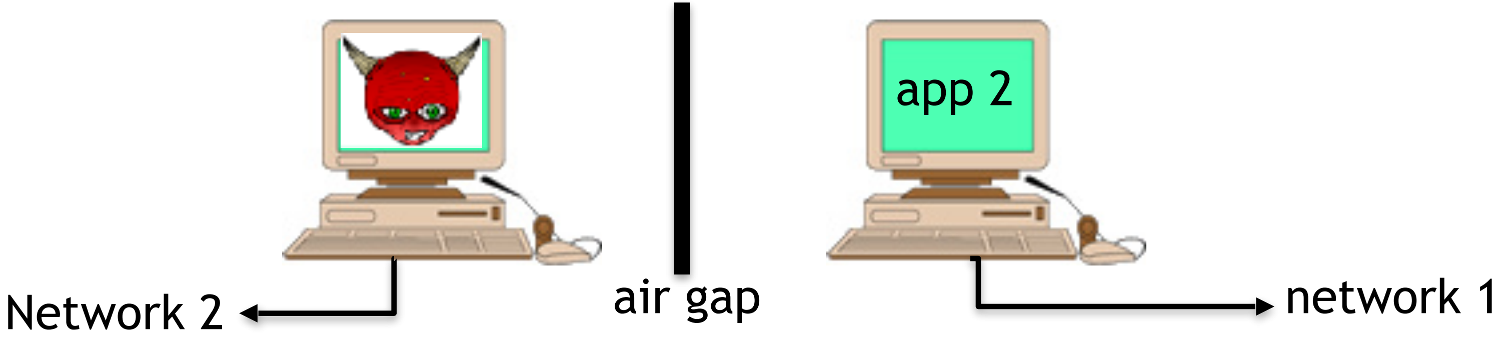
Goal: if application "misbehaves" ⇒ kill it

# Approach: confinement

**<u>Confinement</u>:** ensure misbehaving app cannot harm rest of system

Can be implemented at many levels:

– **Hardware:** run application on isolated hw (air gap)



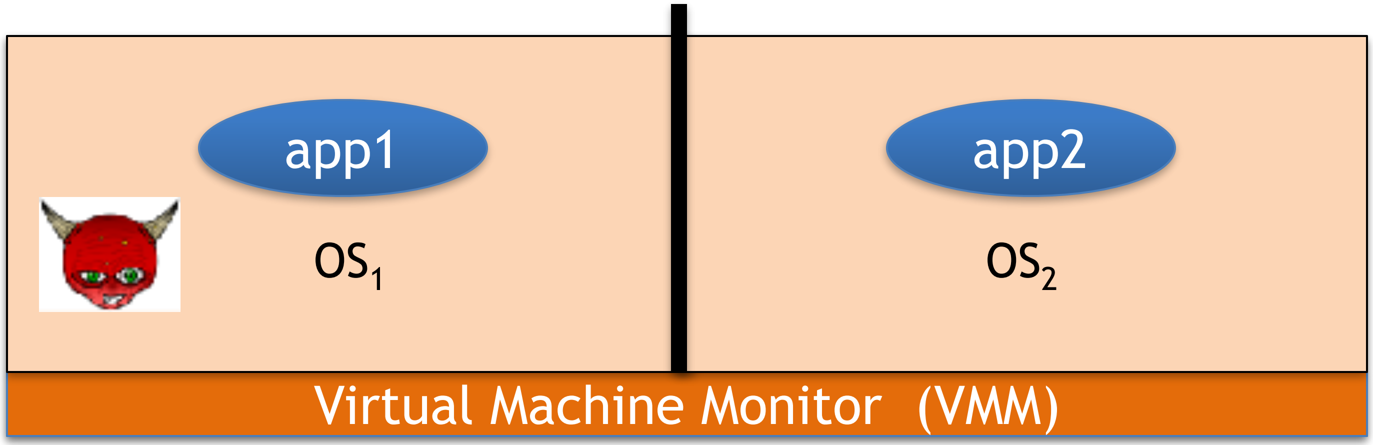
⇒ difficult to manage

# Approach: confinement

<u>**Confinement**</u>: ensure misbehaving app cannot harm rest of system

Can be implemented at many levels:

– **Virtual machines**: isolate OS's on a single machine



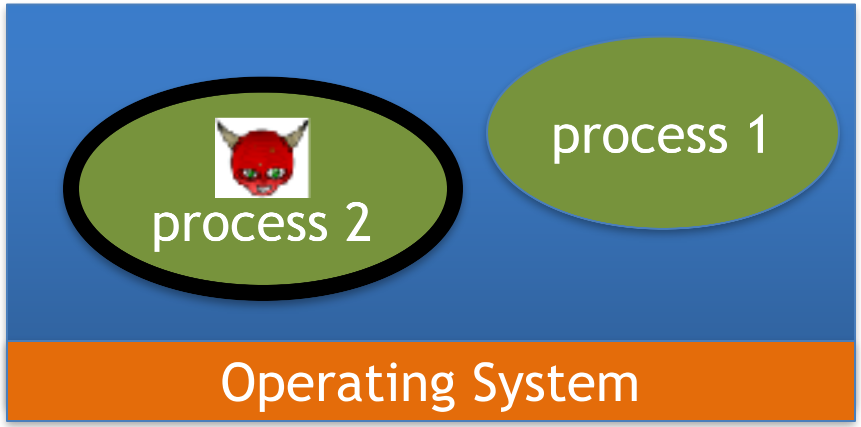
# Approach: confinement

**<u>Confinement</u>**: ensure misbehaving app cannot harm rest of system

Can be implemented at many levels:

- **Process:** System Call Interposition

  Isolate a process in a single operating system



# Approach: confinement

**Confinement**: ensure misbehaving app cannot harm rest of system

Can be implemented at many levels:

- **Threads:** Software Fault Isolation (SFI)
    - Isolating threads sharing same address space

- **Application**: e.g. browser-based confinement

# Implementing confinement

Key component: **reference monitor**

- **Mediates requests** from applications
  - Implements protection policy
  - Enforces isolation and confinement
- Must <u>**always**</u> be invoked:
  - Every application request must be mediated
- **Tamperproof**:
  - Reference monitor cannot be killed
  - … or if killed, then monitored process is killed too
- **Small** enough to be analyzed and validated

# A old example: chroot

Often used for "guest" accounts on ftp sites

To use do: (must be root)

```
chroot /tmp/guest
su guest
```

root dir "/" is now "/tmp/guest"
EUID set to "guest"

Now "/tmp/guest" is added to file system accesses for applications in jail

**open("/etc/passwd", "r") ⇒**

**open("/tmp/guest/etc/passwd" , "r")**

⇒ application cannot access files outside of jail

# Jailkit

Problem: all utility progs (ls, ps, vi) must live inside jail

- **jailkit** project: auto builds files, libs, and dirs needed in jail env
  - **jk_init**: creates jail environment
  - **jk_check:** checks jail env for security problems
    - checks for any modified programs,
    - checks for world writable directories, etc.
  - **jk_lsh**: restricted shell to be used inside jail

- **note:** simple chroot jail does not limit network access

# Escaping from jails

Early escapes: relative paths

**open( "../../etc/passwd", "r")** ⇒

**open("/tmp/guest/../../etc/passwd", "r")**

---

**chroot** should only be executable by root.

- otherwise jailed app can do:
  - create dummy file "/aaa/etc/passwd"
  - run chroot "/aaa"
  - run su root to become root

(bug in Ultrix 4.0)

# Freebsd jail

Stronger mechanism than simple chroot

**<u>To run</u>**: **jail jail-path hostname IP-addr cmd**

- calls hardened chroot (no "../../" escape)
- can only bind to sockets with specified IP address and authorized ports
- can only communicate with processes inside jail
- root is limited, e.g. cannot load kernel modules

# Not all programs can run in a jail

Programs that can run in jail:

- audio player
- web server

Programs that cannot:

- web browser
- mail client

# Problems with chroot and jail

<u>Coarse policies</u>:

- All or nothing access to parts of file system
- Inappropriate for apps like a web browser
    - Needs read access to files outside jail
      (e.g. for sending attachments in Gmail)

Does not prevent malicious apps from:

- Accessing network and messing with other machines
- Trying to crash host OS

## Isolation

# System Call Interposition

# System call interposition

Observation: to damage host system (e.g. persistent changes) app must make system calls:

- To delete/overwrite files: unlink, open, write
- To do network attacks: socket, bind, connect, send

Idea: monitor app's system calls and block unauthorized calls

**Implementation options:**

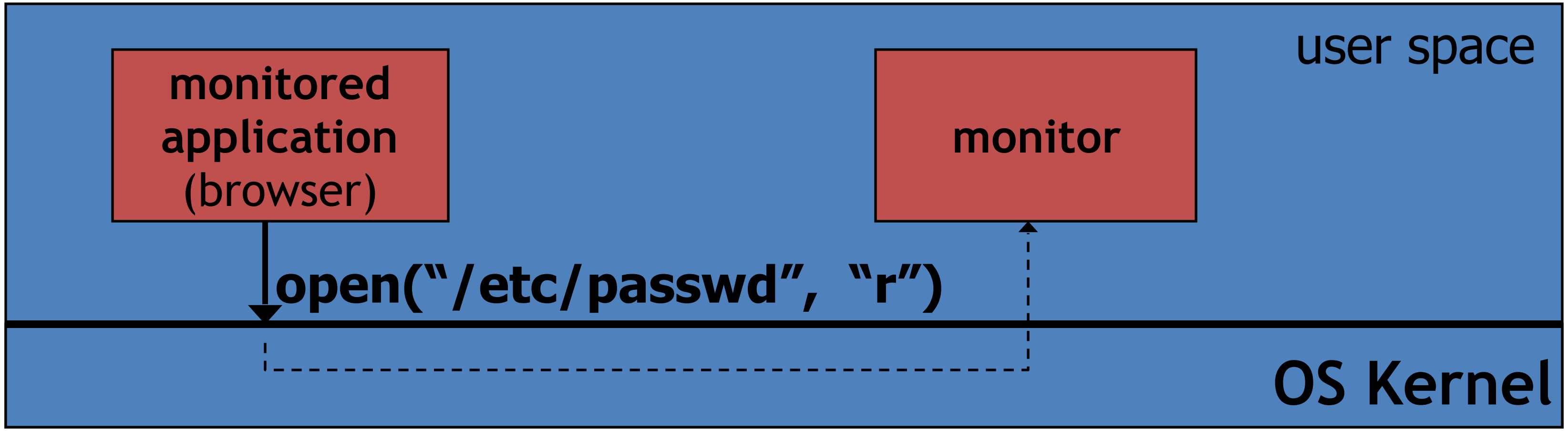
- Completely kernel space (e.g. GSWTK)
- Completely user space (e.g. program shepherding)
- Hybrid (e.g. Systrace)

# Initial implementation (Janus) [GWTB'96]

Linux **ptrace**: process tracing

process calls: **ptrace (… , pid_t pid , …)**

and wakes up when **pid** makes sys call.



Monitor kills application if request is disallowed

# Complications

```
cd(“/tmp”)
open(“passwd”,  “r”)


cd(“/etc”)
open(“passwd”,  “r”)
```

- If app forks, monitor must also fork
  - forked monitor monitors forked app
- If monitor crashes, app must be killed
- Monitor must maintain all OS state associated with app
  - current-working-dir (**CWD**),   **UID**,  **EUID**,  **GID**
  - When app does “cd path” monitor must update its CWD
    - otherwise:  relative path requests interpreted incorrectly

# Problems with ptrace

**Ptrace** is not well suited for this application:

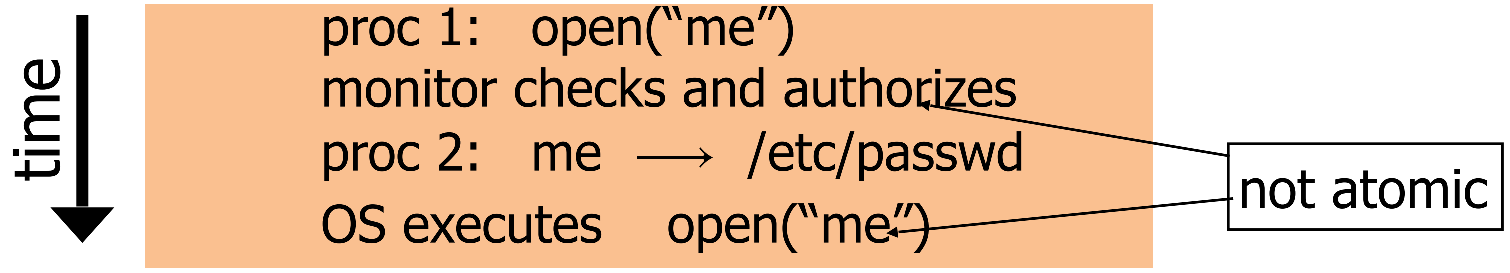
– Trace all system calls or none

  inefficient: no need to trace “close” system call

– Monitor cannot abort sys-call without killing app

Security problems: **race conditions**

– <u>Example</u>: symlink: me $\longrightarrow$ mydata.dat



proc 1: open(“me”)

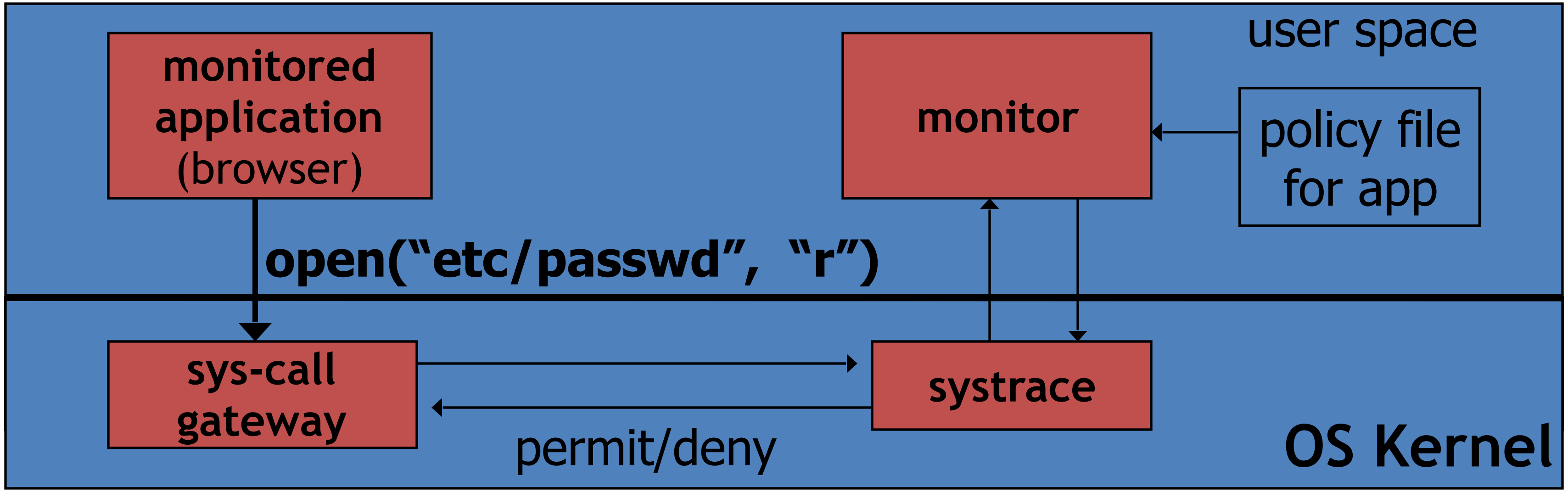
monitor checks and authorizes

proc 2: me $\longrightarrow$ /etc/passwd

OS executes open(“me”)

Classic **TOCTOU bug**: time-of-check / time-of-use

# Alternate design: systrace [P'02]



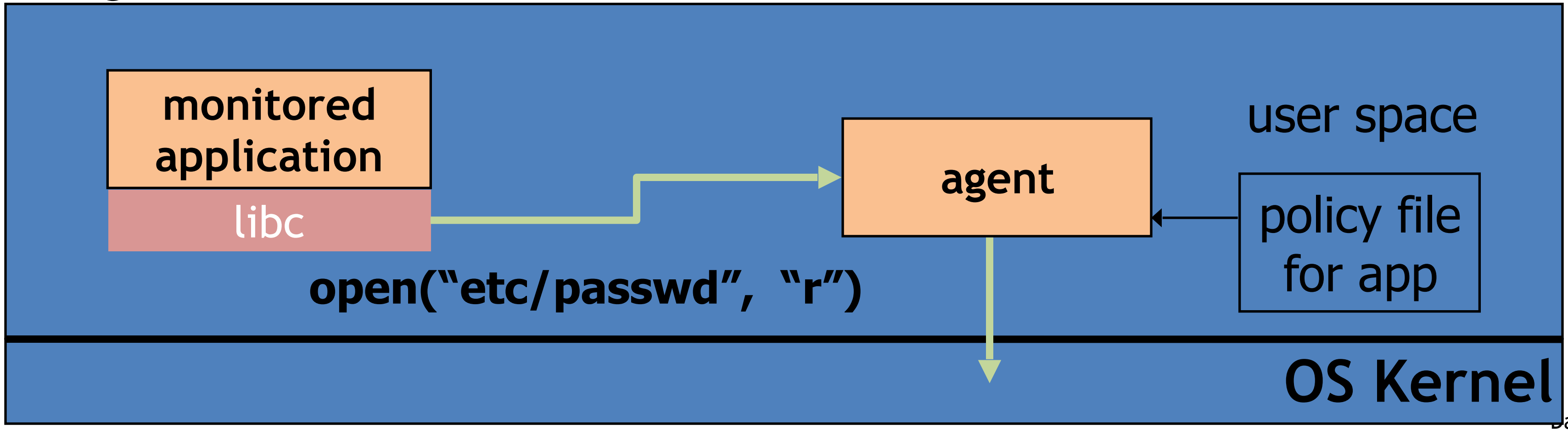
- systrace only forwards monitored sys-calls to monitor (efficiency)
- systrace resolves sym-links and replaces sys-call path arguments by full path to target
- When app calls execve, monitor loads new policy file

## Ostia: a delegation architecture [GPR'04]

Previous designs use filtering:

- Filter examines sys-calls and decides whether to block
- Difficulty with syncing state between app and monitor (CWD, UID, ..)
  - Incorrect syncing results in security vulnerabilities (e.g. disallowed file opened)

A delegation architecture:



## Ostia: a delegation architecture [GPR'04]

- Monitored app disallowed from making monitored sys calls
  - Minimal kernel change (… but app can call **close**() itself )
- Sys-call delegated to an agent that decides if call is allowed
  - Can be done without changing app

    (requires an emulation layer in monitored process)
- Incorrect state syncing will not result in policy violation

# Policy

Sample policy file:

```
path allow  /tmp/*
path deny  /etc/passwd
network deny all
```

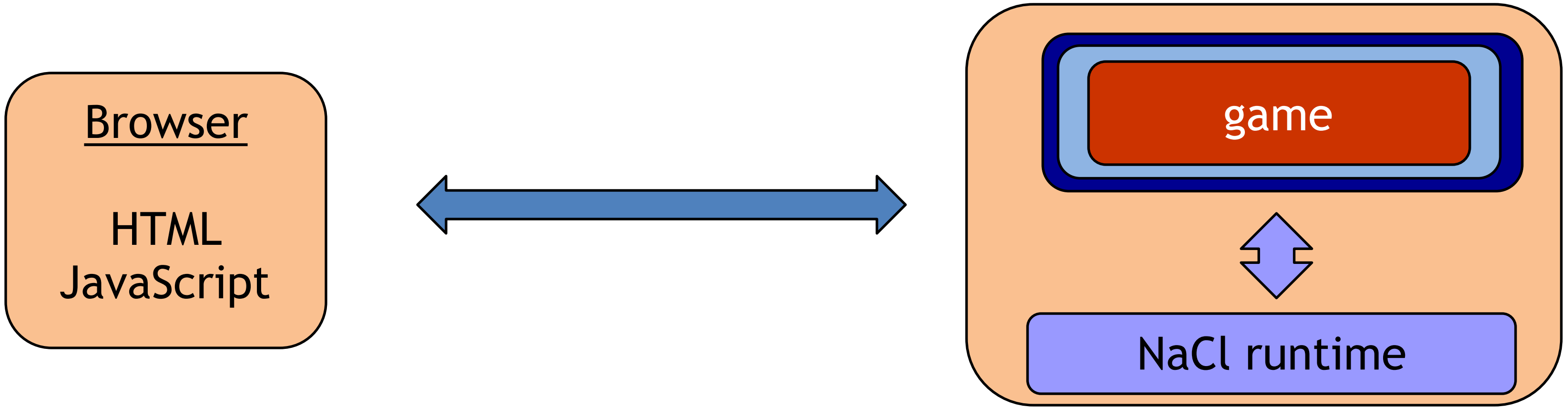
Manually specifying policy for an app can be difficult:

- Systrace can auto-generate policy by learning how app behaves on “good” inputs
- If policy does not cover a specific sys-call, ask user

  … but user has no way to decide

Difficulty with choosing policy for specific apps (e.g. browser) is the main reason this approach is not widely used

# NaCl: a modern day example

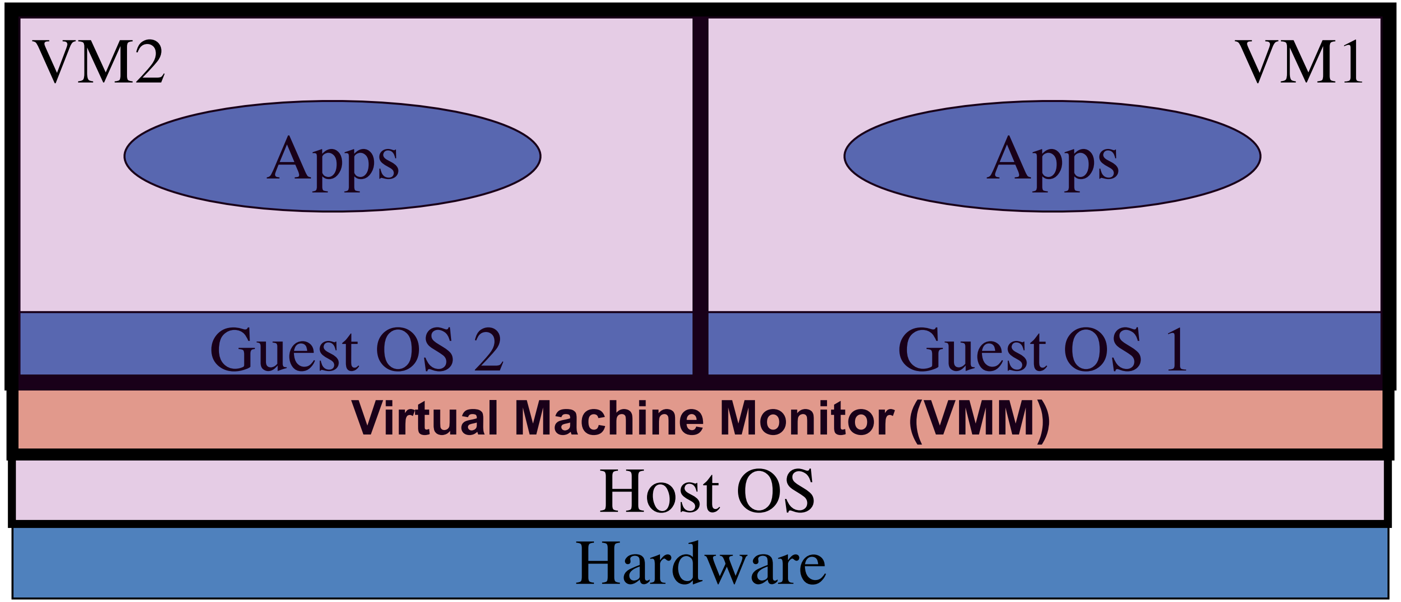


- game: untrusted x86 code
- Two sandboxes:
  - outer sandbox: restricts capabilities using system call interposition
  - Inner sandbox: uses x86 memory segmentation to isolate application memory among apps

## Isolation

# Isolation via Virtual Machines

## Virtual Machines



Example: **NSA NetTop**

single HW platform used for both classified and unclassified data

## Why so popular now?

**VMs in the 1960's**:

- Few computers, lots of users
- VMs allow many users to shares a single computer

**VMs 1970's – 2000**: non-existent

**VMs since 2000**:

- Too many computers, too few users
    - Print server, Mail server, Web server, File server, Database , …
- Wasteful to run each service on different hardware
- More generally: VMs heavily used in cloud computing

# VMM security assumption

**VMM Security assumption**:

- Malware can infect guest OS and guest apps
- But malware cannot escape from the infected VM
  - Cannot infect host OS
  - Cannot infect other VMs on the same hardware

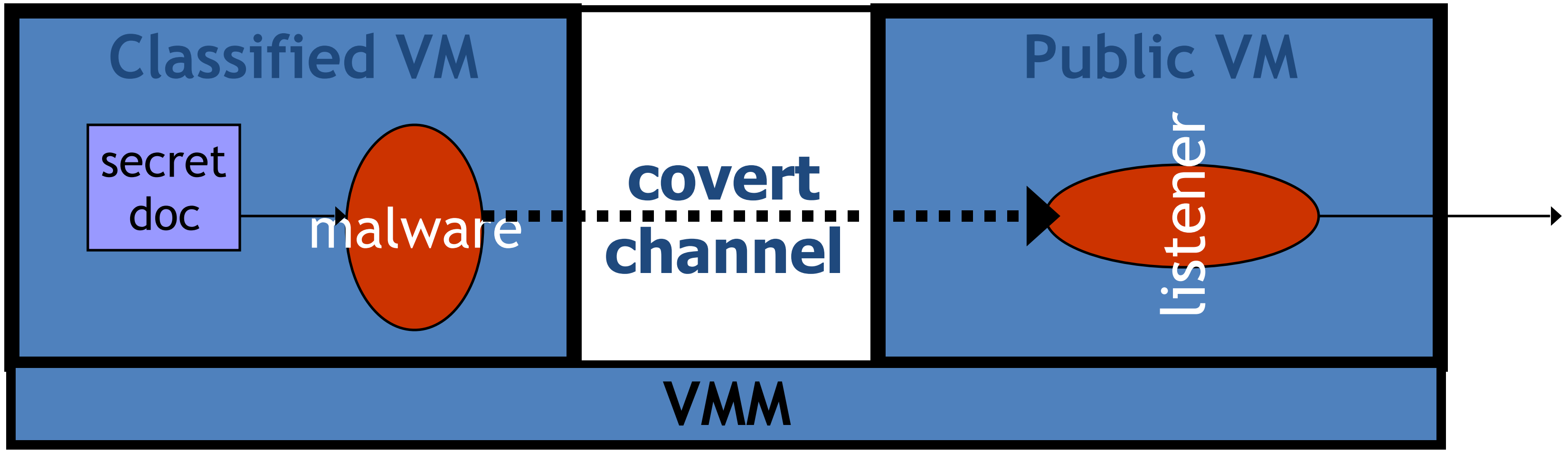
Requires that VMM protect itself and is not buggy

- VMM is much simpler than full OS

  … but device drivers run in Host OS

# Problem: covert channels

- **Covert channel**: unintended communication channel between isolated components
  - Can be used to leak classified data from secure component to public component



# An example covert channel

Both VMs use the same underlying hardware

To send a bit  $b \in \{0,1\}$  malware does:

- b= 1:  at 1:00am do CPU intensive calculation
- b= 0:  at 1:00am do nothing

At 1:00am listener does CPU intensive calc. and measures completion time

$$b = 1 \quad \Rightarrow \quad \text{completion-time} > \text{threshold}$$

Many covert channels exist in running system:

- File lock status,  cache contents,  interrupts, …
- Difficult to eliminate all

Suppose the system in question has two CPUs: the classified VM runs on one and the public VM runs on the other.

Is there a covert channel between the VMs?

There are covert channels, for example, based on the time needed to read from main memory

## VMM Introspection: [GR'03]

protecting the anti-virus system

## Intrusion Detection / Anti-virus

Runs as part of OS kernel and user space process

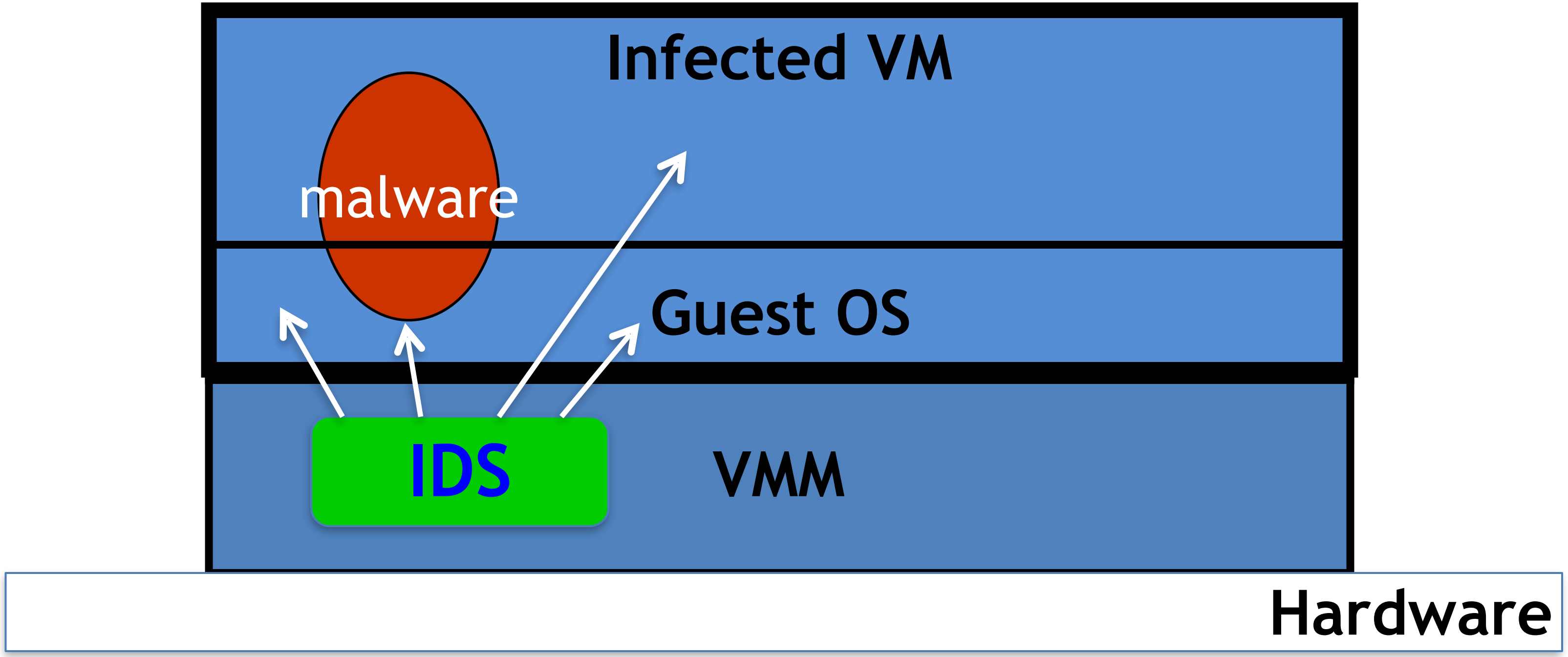
- Kernel root kit can shutdown protection system
- Common practice for modern malware

Standard solution: **run IDS system in the network**

- Problem: insufficient visibility into user's machine

Better: **run IDS as part of VMM (protected from malware)**

- VMM can monitor virtual hardware for anomalies
- VMI: Virtual Machine Introspection
    - Allows VMM to check Guest OS internals


Infected VM
malware
Guest OS
IDS
VMM
Hardware

# Sample checks

**Stealth root-kit malware:**

– Creates processes that are invisible to "ps"
– Opens sockets that are invisible to "netstat"

1. **Lie detector check**
   – Goal: detect stealth malware that hides processes and network activity
   – Method:
     - VMM lists processes running in GuestOS
     - VMM requests GuestOS to list processes (e.g. ps)
     - If mismatch:

# Sample checks

2. **Application code integrity detector**
   - VMM computes hash of user app code running in VM
   - Compare to whitelist of hashes
     - Kills VM if unknown program appears

3. **Ensure GuestOS kernel integrity**
   - example: detect changes to sys_call_table

4. **Virus signature detector**
   - Run virus signature detector on GuestOS memory

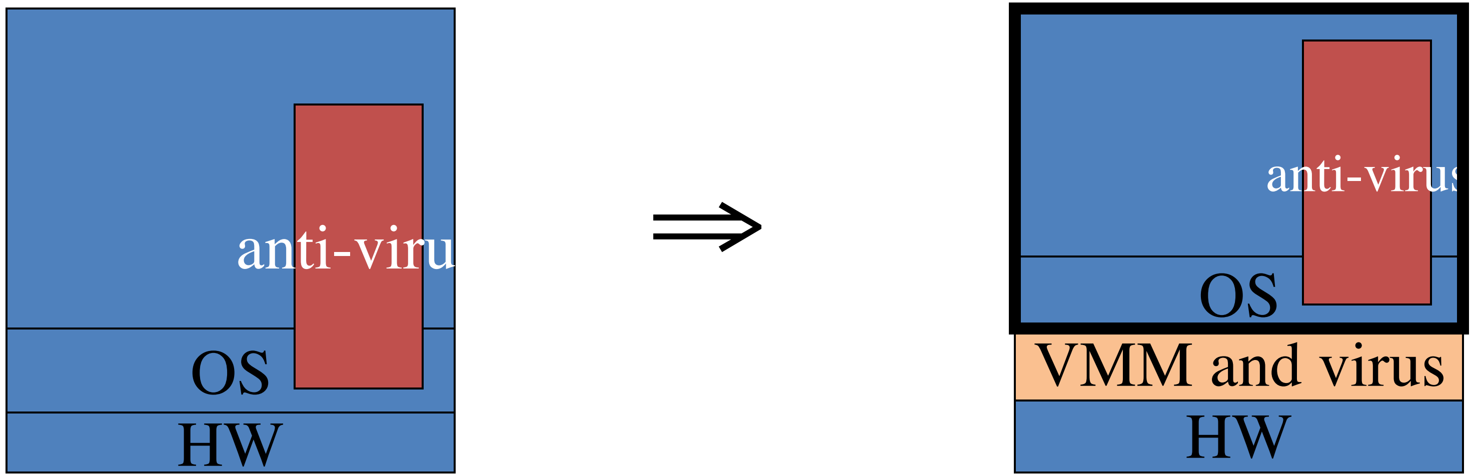
## Isolation

# Subvirting VM Isolation

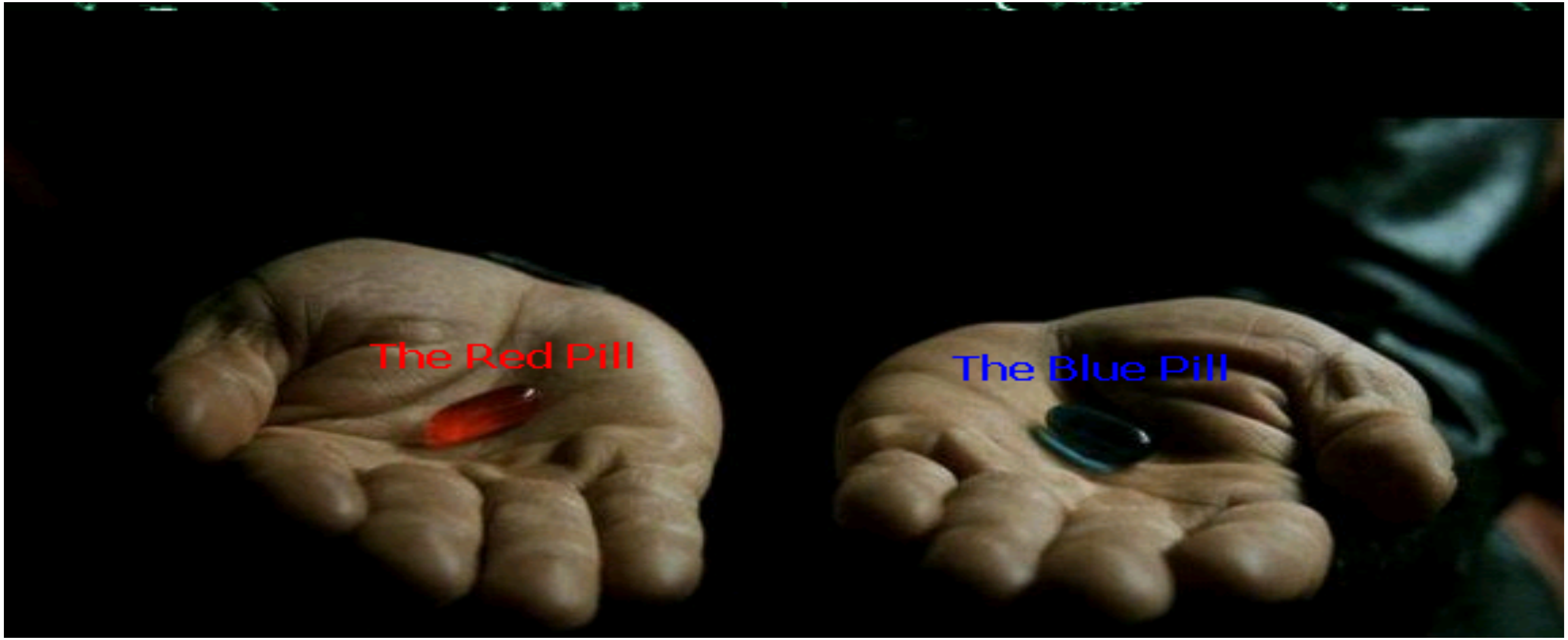
## Subvirt [King et al. 2006]

Virus idea:

- Once on victim machine, install a malicious VMM
- Virus hides in VMM
- Invisible to virus detector running inside VM



## The MATRIX


The Red Pill
The Blue Pill

## VM Based Malware (blue pill virus)

- **VMBR**: a virus that installs a malicious VMM (hypervisor)

- **Microsoft Security Bulletin:**
  - Suggests disabling hardware virtualization features by default for client-side systems

- **But VMBRs are easy to defeat**
  - A guest OS can detect that it is running on top of VMM

# VMM Detection

Can an OS detect it is running on top of a VMM?

<u>Applications</u>:

- Virus detector can detect VMBR
- Normal virus (non-VMBR) can detect VMM
    - refuse to run to avoid reverse engineering
- Software that binds to hardware (e.g. MS Windows) can refuse to run on top of VMM
- DRM systems may refuse to run on top of VMM

## VMM detection (red pill techniques)

- VM platforms often emulate simple hardware
  - VMWare emulates an ancient i440bx chipset

    … but report 8GB RAM, dual CPUs, etc.

- VMM introduces time latency variances
  - Memory cache behavior differs in presence of VMM
  - Results in relative time variations for any two operations

- VMM shares the TLB with GuestOS
  - GuestOS can detect reduced TLB size

- … and many more methods **[GAWF'07]**

## VMM Detection

Bottom line: **The perfect VMM does not exist**

VMMs today (e.g. VMWare) focus on:

Compatibility: ensure off the shelf software works

Performance: minimize virtualization overhead

- VMMs do not provide **transparency**
  - **Anomalies reveal existence of VMM**

Isolation

## Software Fault Isolation

`

**Goal**: confine apps running in <u>same address space</u>

- Codec code should not interfere with media player
- Device drivers should not corrupt kernel

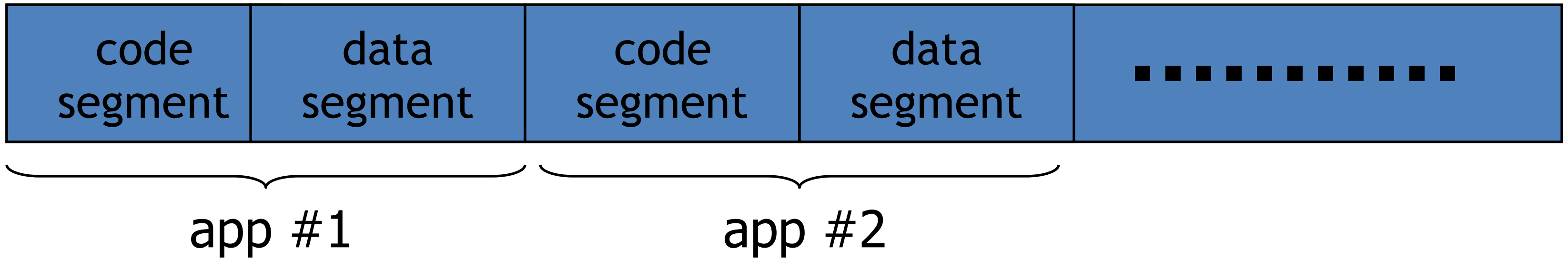
Simple solution: runs apps in separate address spaces

- Problem: slow if apps communicate frequently
  - requires context switch per message

# Software Fault Isolation

SFI approach:

– Partition process memory into segments



- Locate unsafe instructions: **jmp, load, store**
  - At compile time, add guards before unsafe instructions
  - When loading code, ensure all guards are present

# Segment matching technique

- Designed for MIPS processor. Many registers available.
- **dr1, dr2**: dedicated registers not used by the binary.
    - compiler pretend these registers don't exist
    - dr2 contains segment id
- Indirect load instruction R12<— R[34] becomes:

```
dr1 <— R34
scratch-reg <— (dr1 >> 20)        :get segment ID
compare scratch-reg and dr2  : validate seg. ID
trap if not equal
R12 <— [dr1]                          : do load
```

Guard ensures code does not load data from another segment

# Address sandboxing technique

- **dr2** holds segment ID
- indirect load instruction **R12<— R[34]** becomes:

```
dr1 <-- R34 & segment-mask   : zero out seg bits
dr1 <-- dr1 | dr2            : set valid seg ID
R12 <-- [dr1]                : do load
```

- Fewer instructions than segment matching
    - but does not catch offending instructions
- Similar guards places on all unsafe instructions

**Problem:** what if **jmp [addr]** jumps directly into indirect load?

**(bypassing guard)**

**Solution:**

**jmp** guard must ensure **[addr]** does not bypass load guard

# Isolation: summary

- Many sandboxing techniques:

  Physical air gap, Virtual air gap (VMMs),
  System call interposition, Software Fault isolation
  Application specific (e.g. Javascript in browser)

- Often complete isolation is inappropriate
  - Apps need to communicate through regulated interfaces

- Hardest aspects of sandboxing:
  - Specifying policy: what can apps do and not do
  - Preventing covert channels

THE END