Isolation

The confinement principle

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

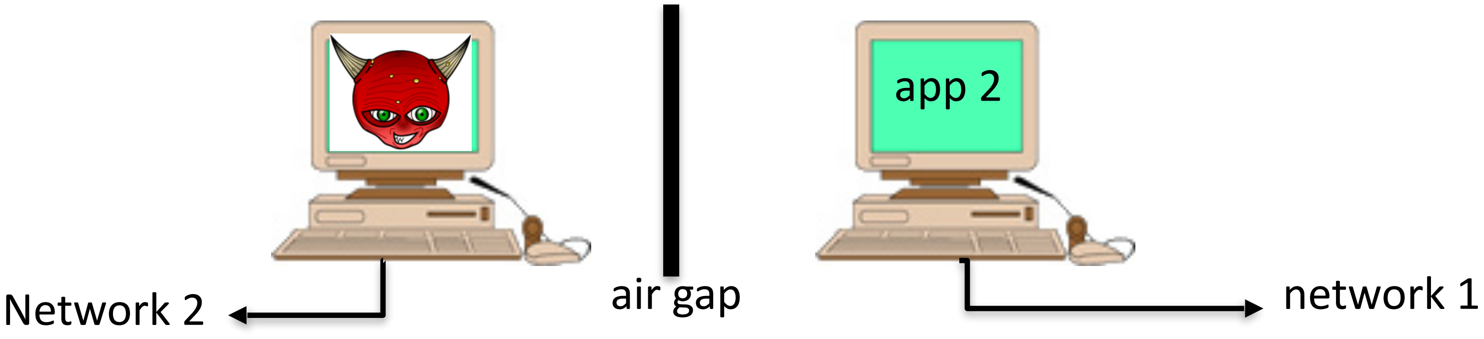
<u>Goal</u>: if application "misbehaves" ⇒ kill it

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)



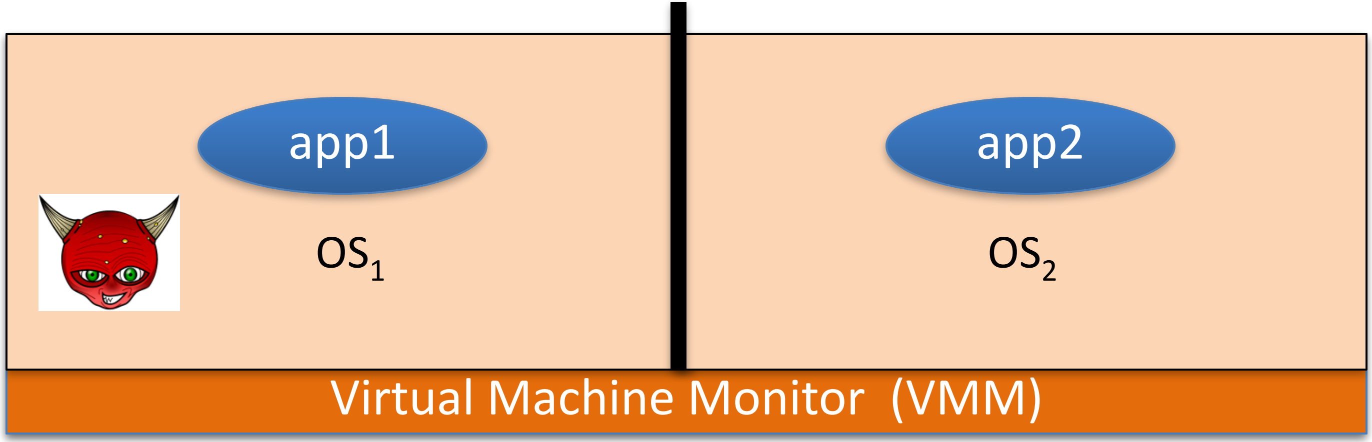
⇒ difficult to manage

Approach: confinement

Confinement: ensure misbehaving app cannot harm rest of system

Can be implemented at many levels:

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



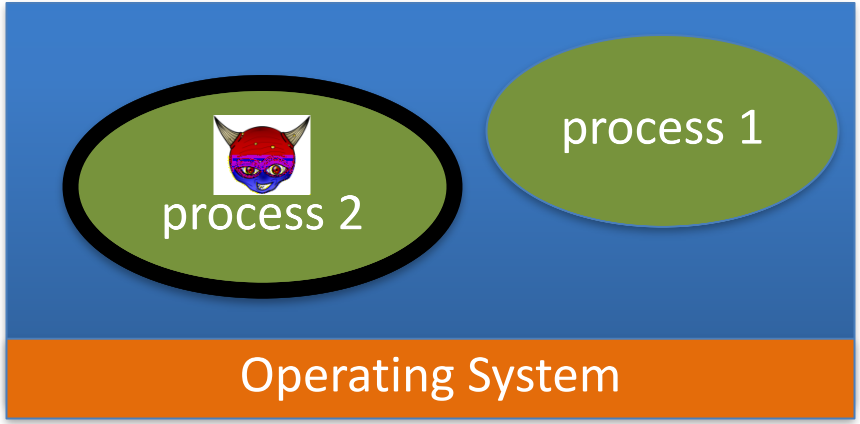
Approach: confinement

Confinement: 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)

Many ways to escape jail as root

- Create device that lets you access raw disk
- Send signals to non chrooted process
- Reboot system
- Bind to privileged ports

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

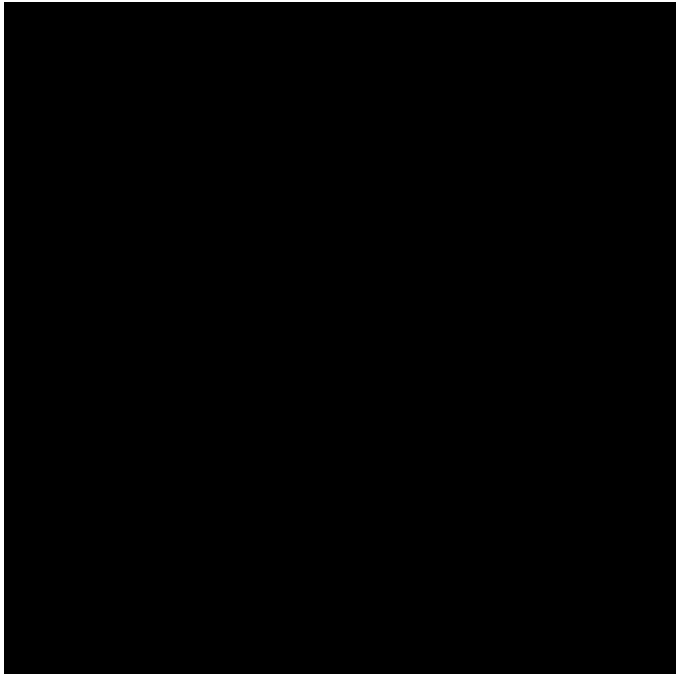
Problems with chroot and jail

<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:

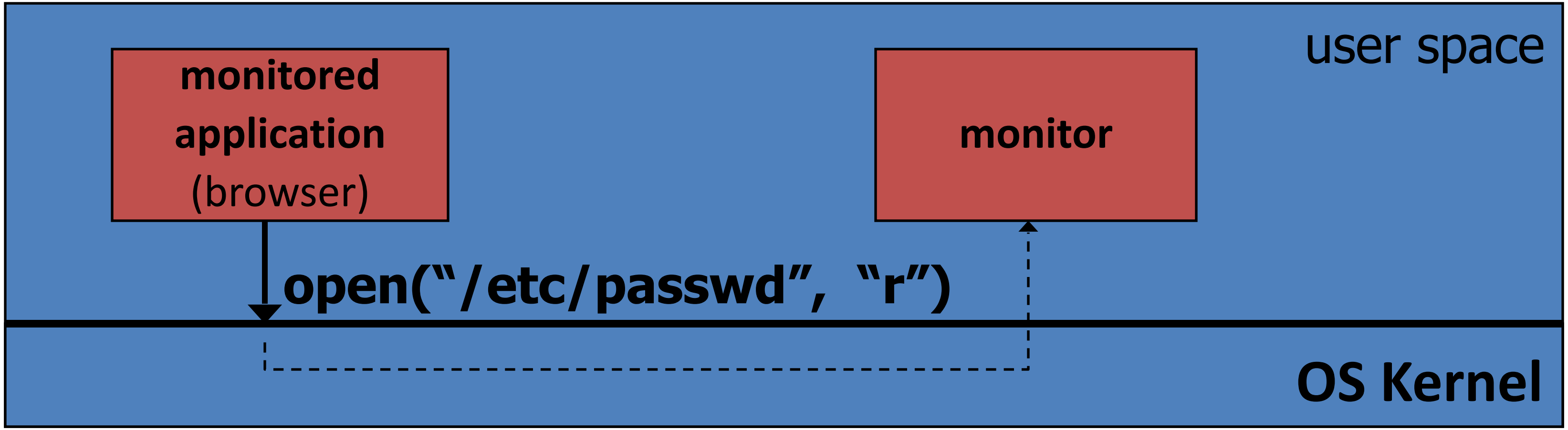
- Completely kernel space (e.g. GSWTK)
- Completely user space (e.g. program shepherding)
- Hybrid (e.g. Systrace)

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" r
    - 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**

- Example: symlink: me ⟶ mydata.dat

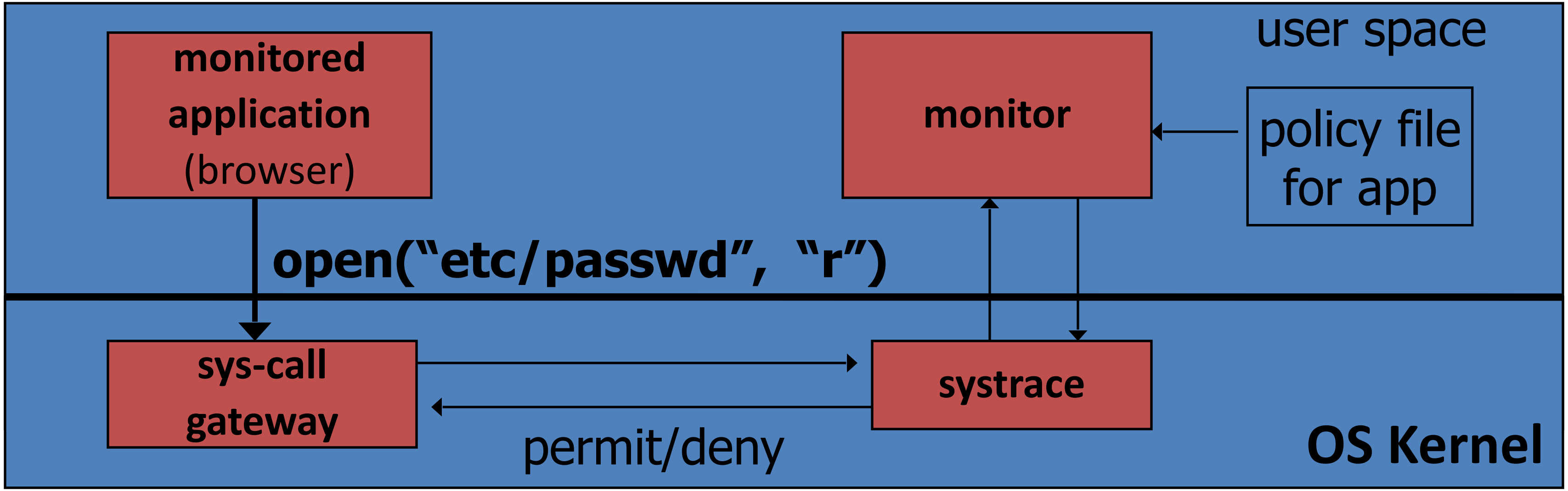
time

proc 1:   open("me")
monitor checks and authorizes
proc 2:   me ⟶ /etc/passwd
OS executes   open("me")

not atomic

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)

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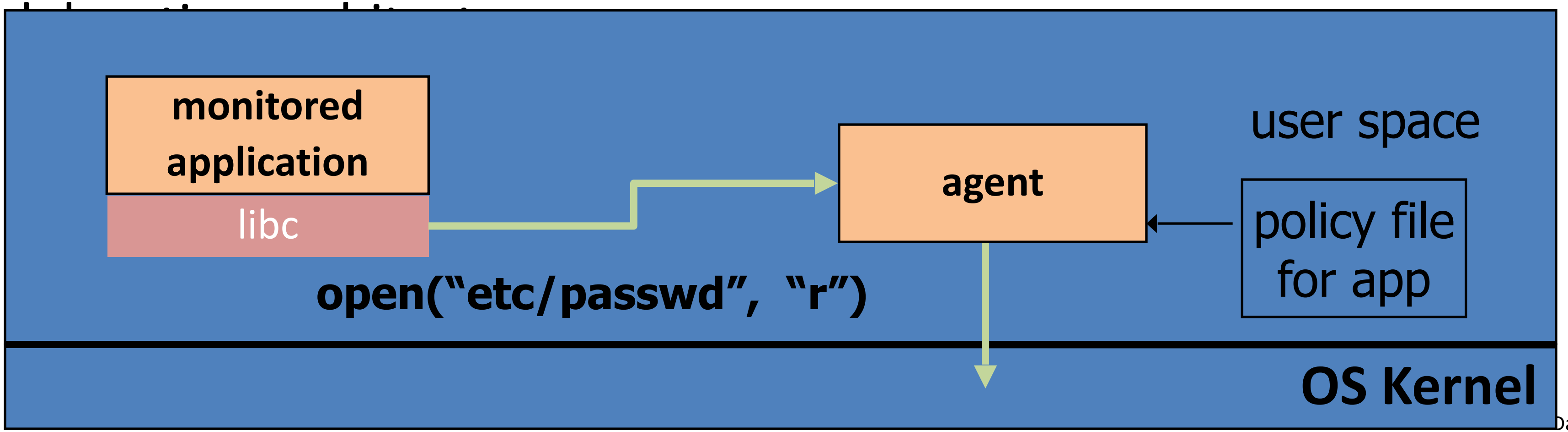


Ostia: a delegation architecture [GPR'04]

- 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
- What should agent do when app calls **execve?**
  –

Policy

Sample policy file:

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

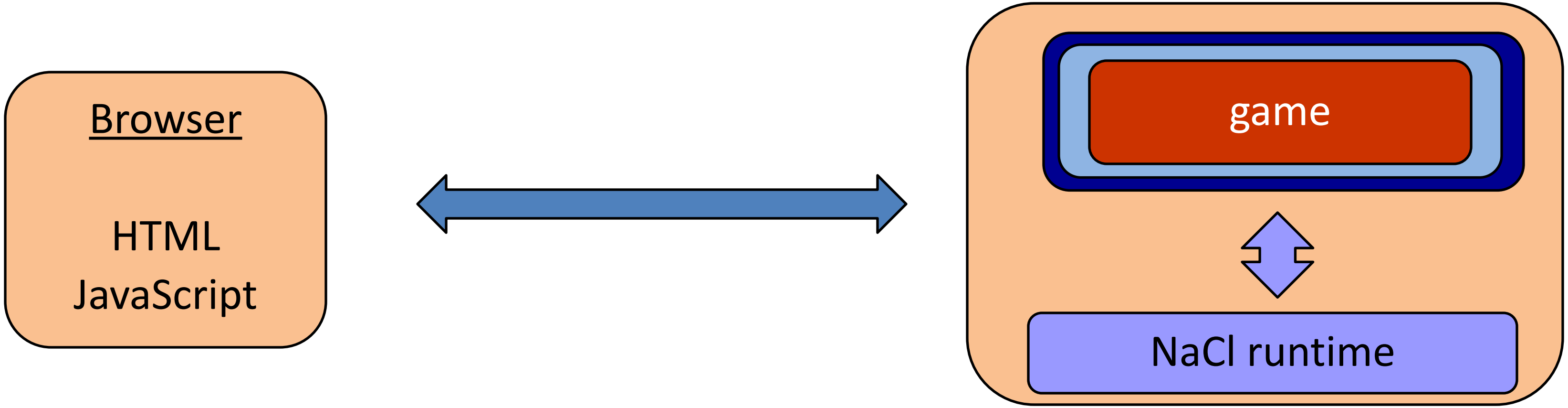
Manually specifying policy for an app can be difficult:

- 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

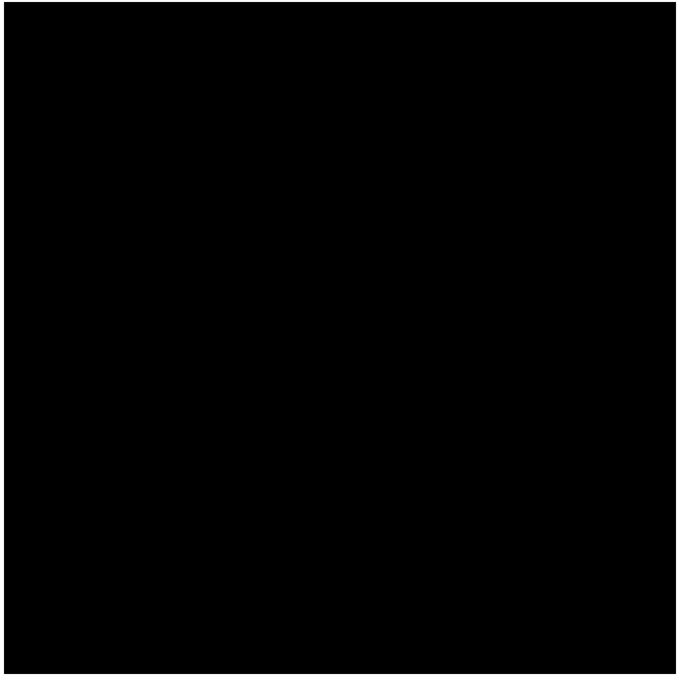
NaCl: a modern day example



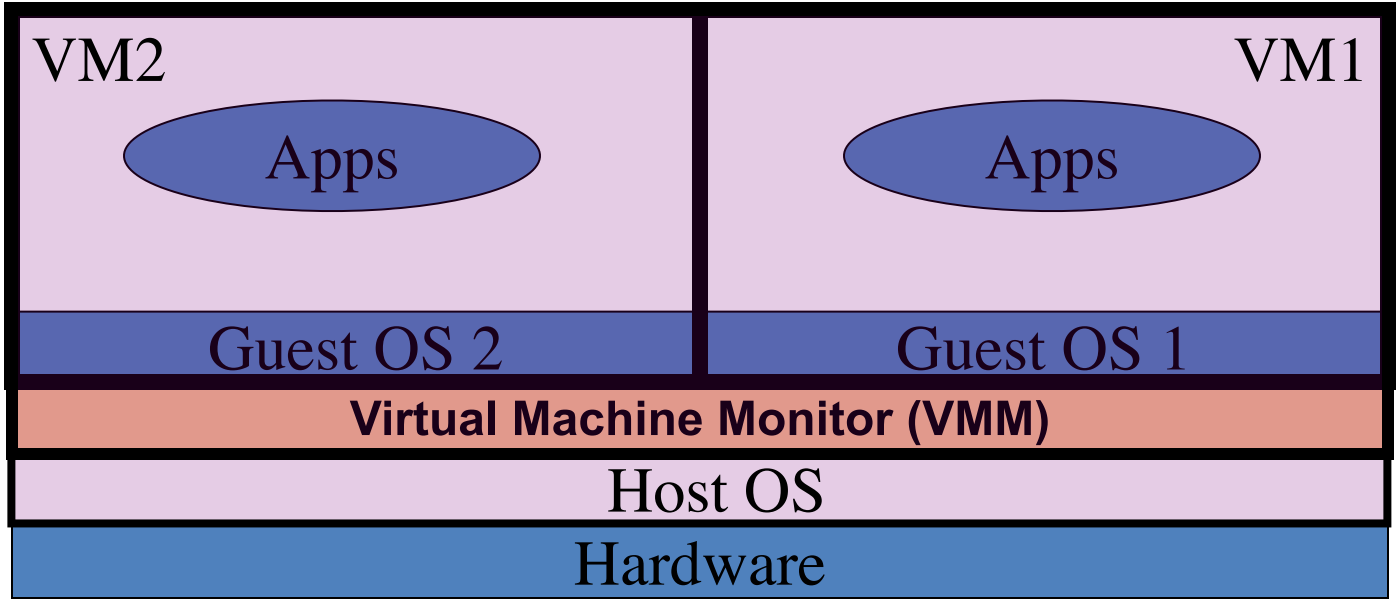
- game: untrusted x86 code
- Two sandboxes:
  - outer sandbox: restricts capabilities using system call interposition
  - Inner sandbox: uses x86 memory segmentation to isolate application memory among apps

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

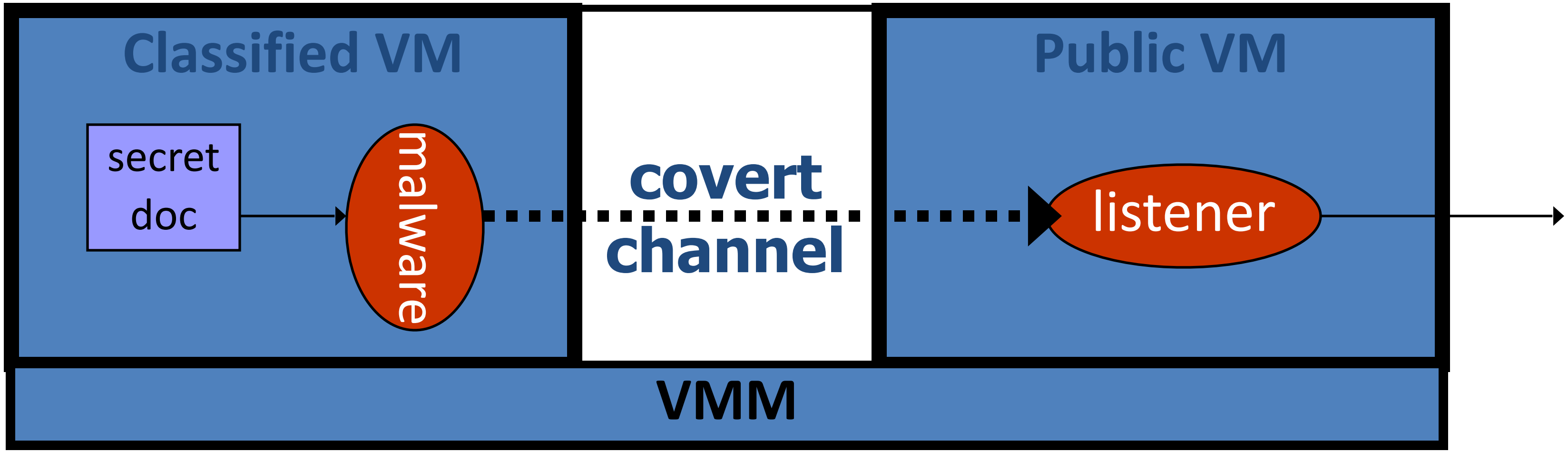
Requires that VMM protect itself and is not buggy

- 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]

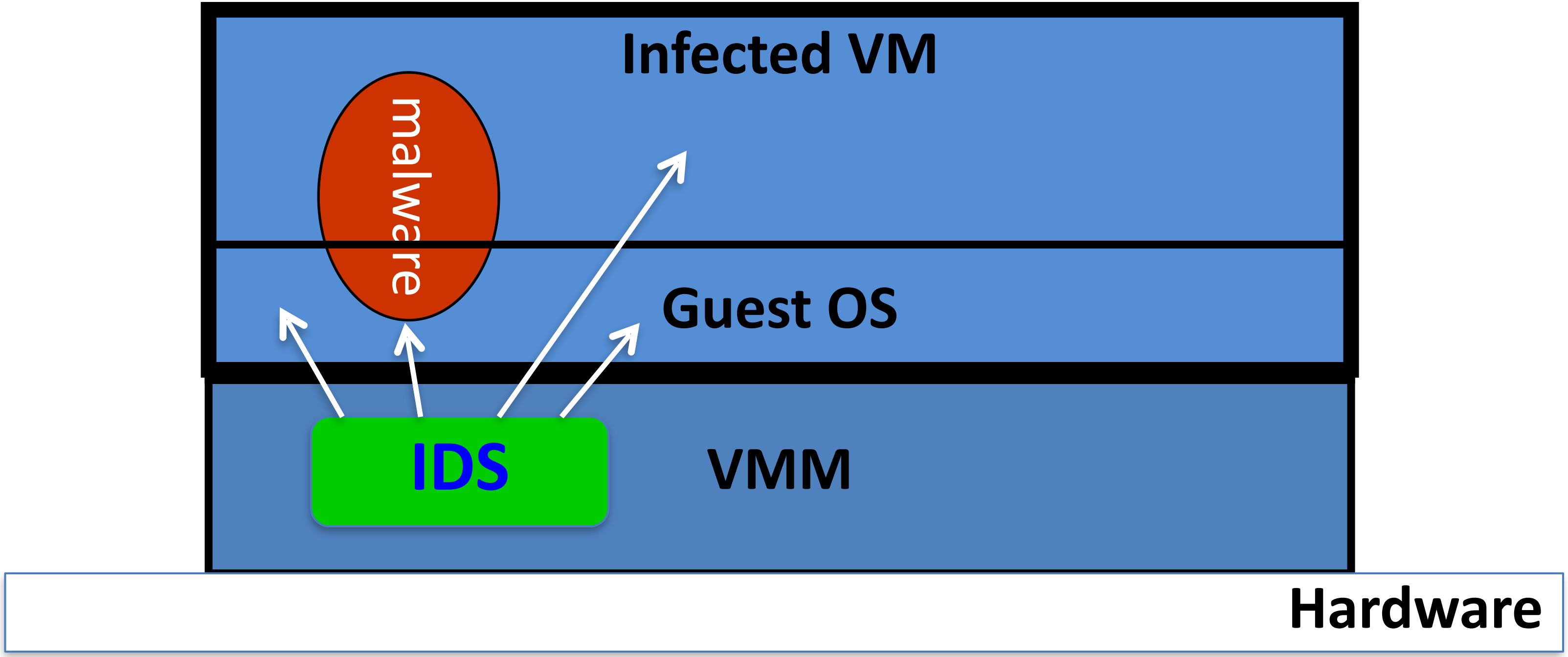
protecting the anti-virus system

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

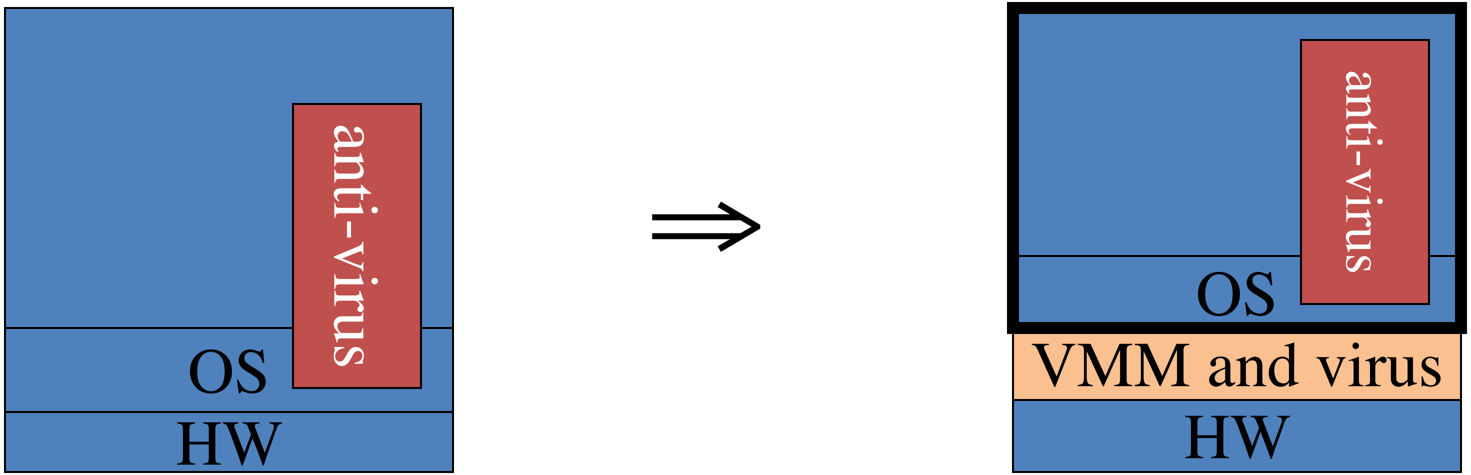
Isolation

Subverting VM Isolation

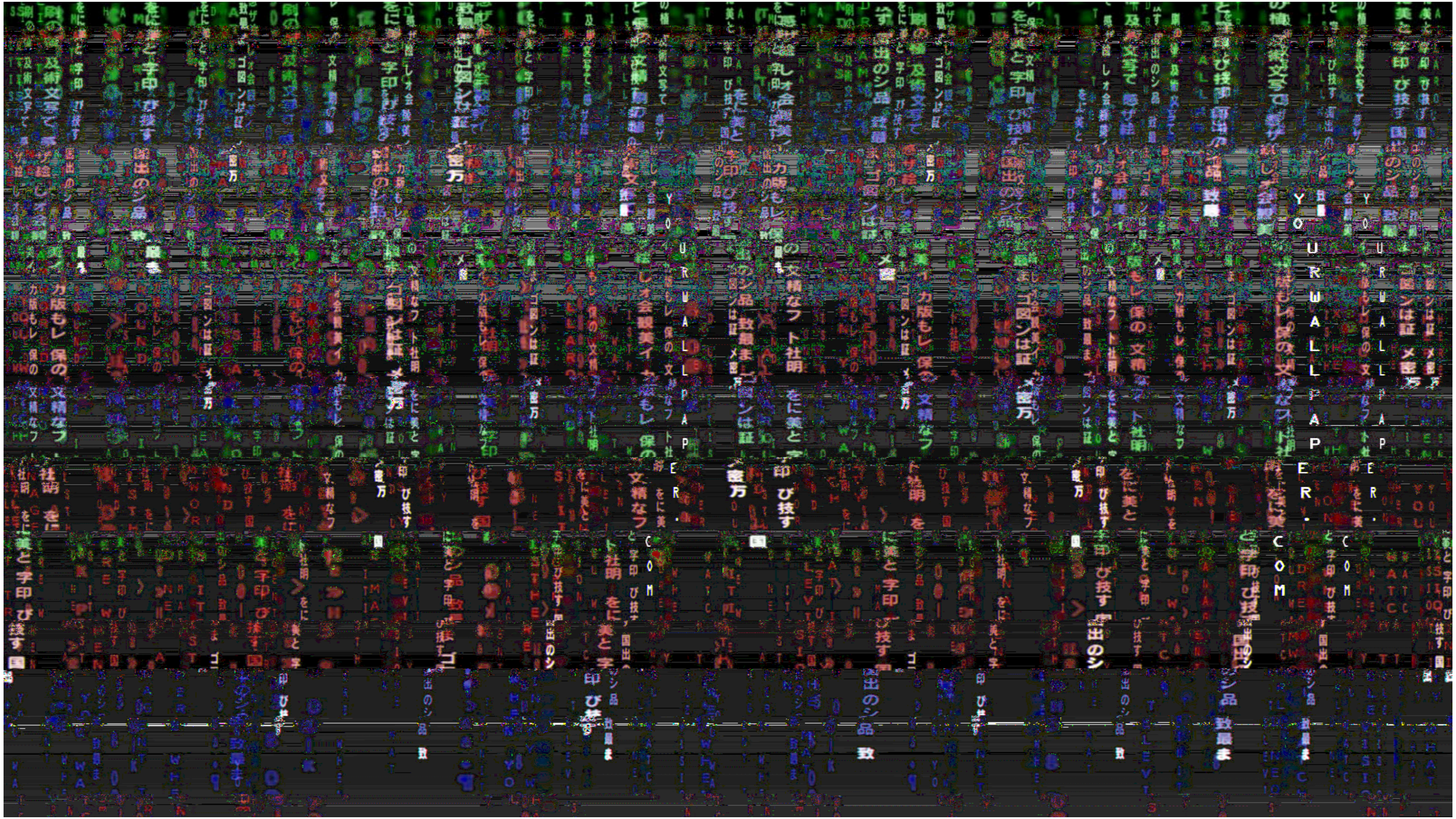
Subvirt [King et al. 2006]

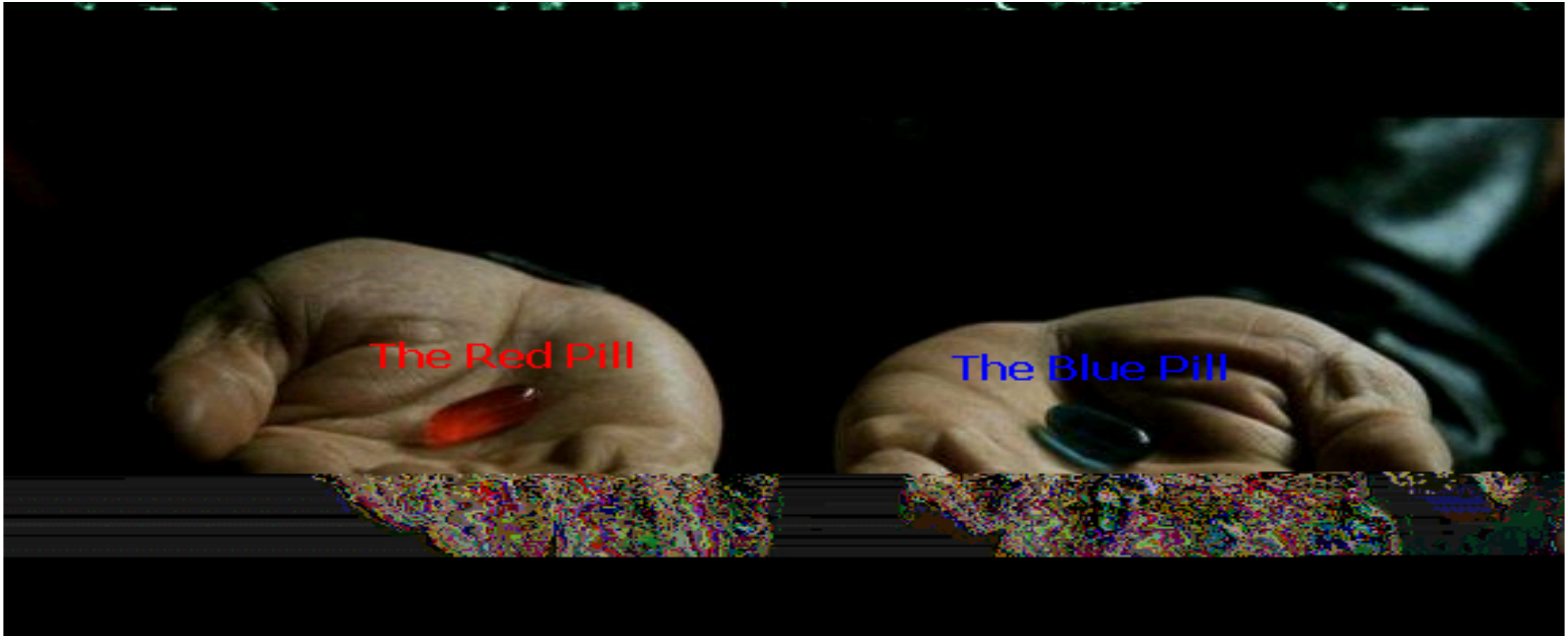
Virus idea:

- 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?

Applications:

- 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

Software Fault Isolation [Whabe et al., 1993]

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

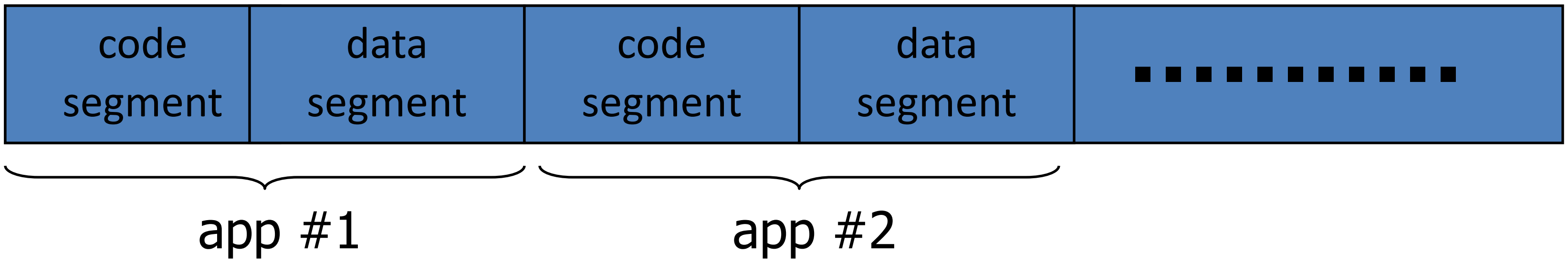
– Problem: slow if apps communicate frequently

- 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 M
- **dr1, dr2**: de
  - compiler pr
  - **dr2** contains segme
- Indirect load instructi **R12 ← [R34]** becomes:

Guard ensures code does not load data from another segment

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

Address sandboxing technique

- **dr2**: holds segment ID
- Indirect load instruction **R12 ← [R34]** 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

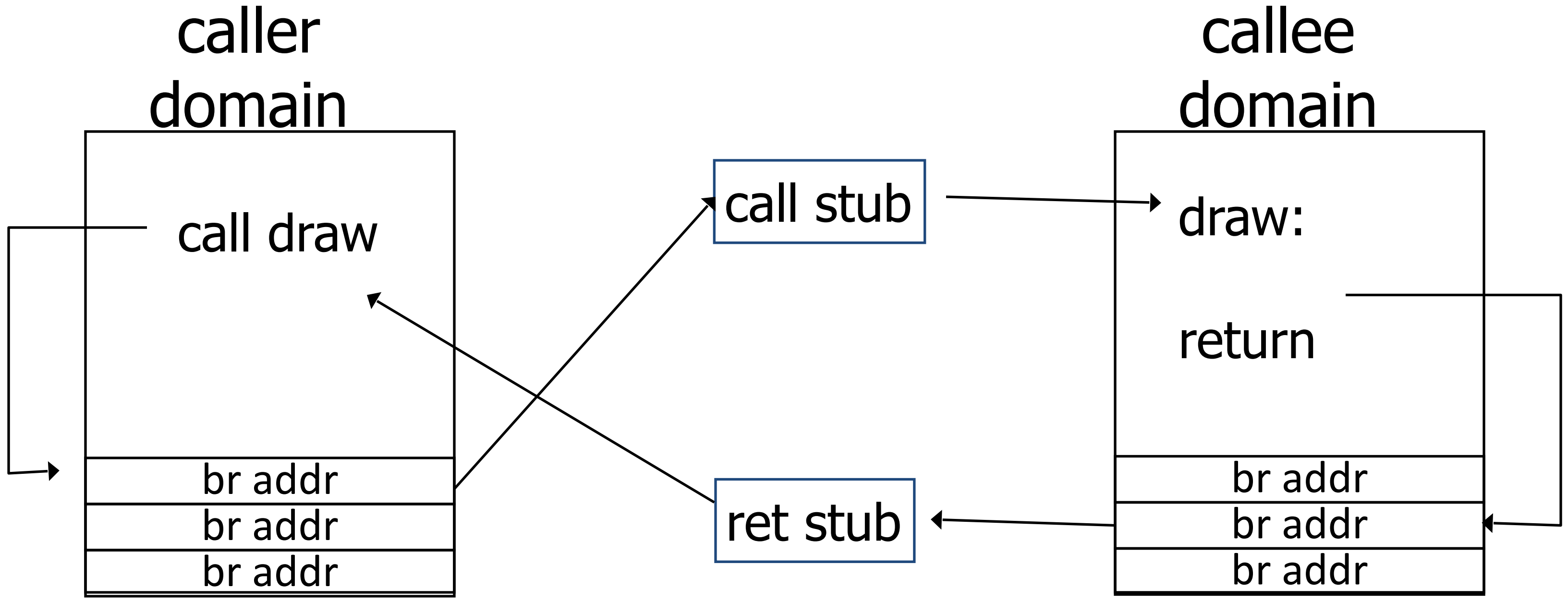
Problem: what if **jmp [addr]** jumps directly into indirect load?

(bypassing guard)

Solution:

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

Cross domain calls



- Only stubs allowed to make cross-domain jumps
- Jump table contains allowed exit points
  - Addresses are hard coded, read-only segment

SFI Summary

- Shared memory: use virtual memory hardware
  - map same physical page to two segments in addr space
- Performance
  - Usually good: mpeg_play, 4% slowdown
- <u>Limitations of SFI</u>: harder to implement on x86 :
  - variable length instructions: unclear where to put guards
  - few registers: can't dedicate three to SFI
  - many instructions affect memory: more guards needed

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