CS155: Computer Security

Isolation

The confinement principle

Acknowledgments: Lecture slides are from the Computer Security course taught by Dan Boneh and Zakir Durumeric 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:
  - mobile apps, Javascript, browser extensions
- exposed applications: browser, pdf viewer, outlook
- legacy daemons: sendmail, bind
- honeypots

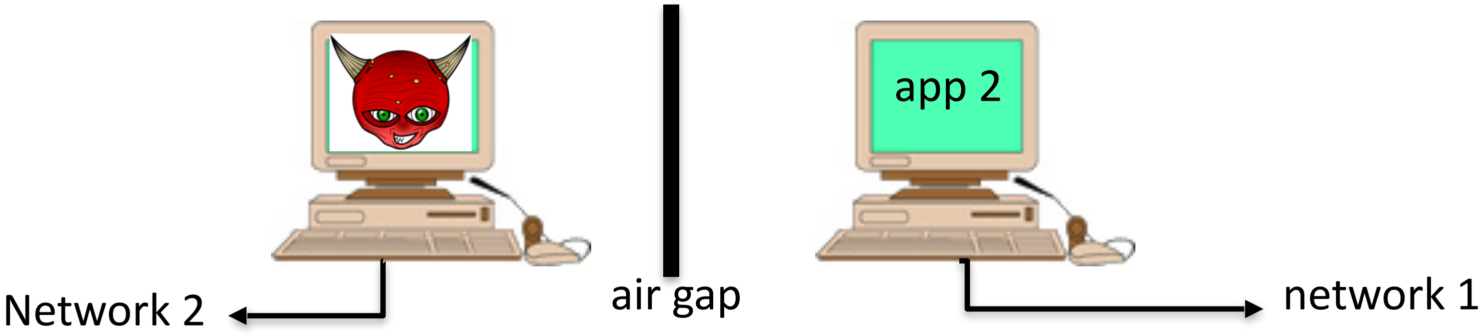
<u>Goal</u>: if application "misbehaves" ⇒ kill it

Approach: confinement

Confinement: ensure misbehaving app cannot harm rest of system

Can be implemented at many levels:

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



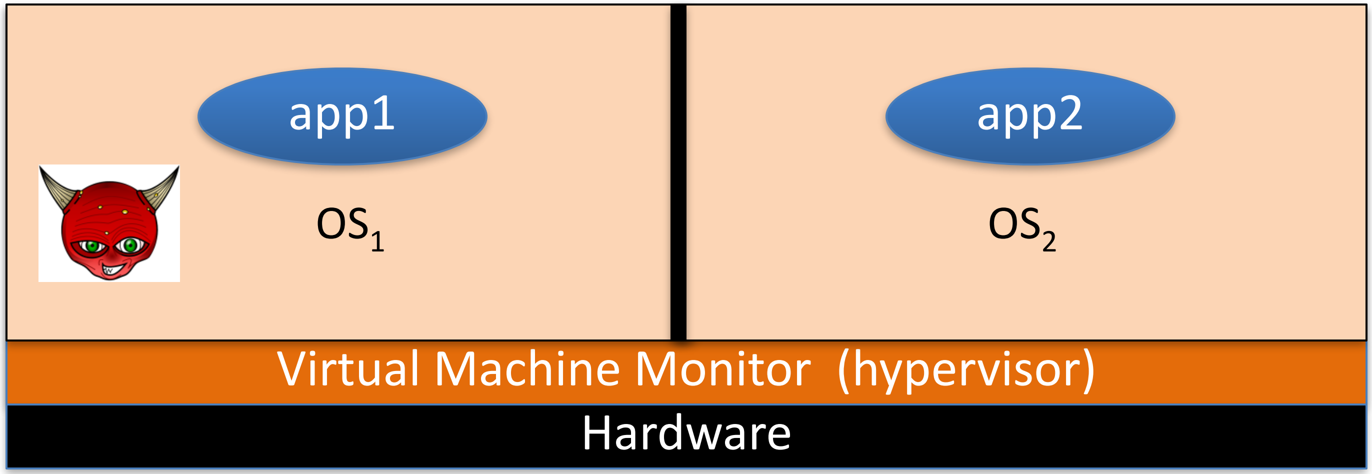
⇒ difficult to manage

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



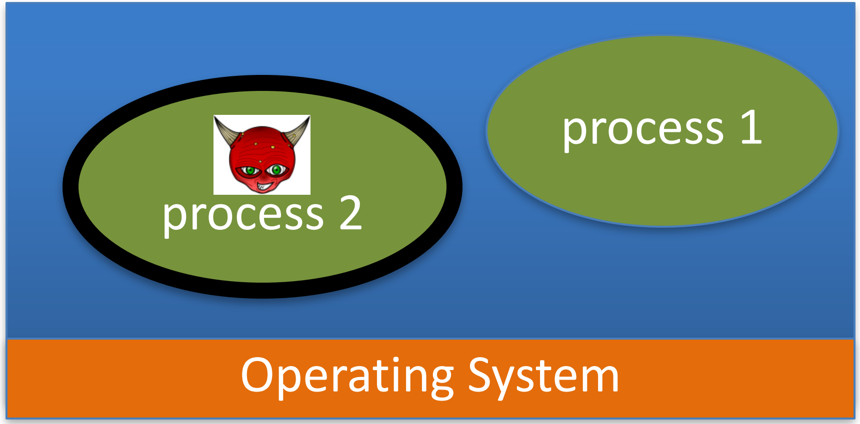
Approach: confinement

Confinement: ensure misbehaving app cannot harm rest of system

Can be implemented at many levels:

– **Process:** System Call Interposition (containers)

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 level confinement**:
  e.g. browser sandbox for Javascript and WebAssembly

Implementing confinement

Key component: **reference monitor**

- **Mediates requests** from applications
  - Enforces confinement
  - Implements a specified protection policy
- Must **always** 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

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 every file system accesses:

fopen("/etc/passwd", "r") ⇒

fopen("/tmp/guest/etc/passwd" , "r")

⇒ application (e.g., web server) cannot access files outside of jail

Escaping from jails

Early escapes: relative paths

fopen("../../etc/passwd", "r") ⇒

fopen("/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

To run: **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

Problems with chroot and jail

Coarse policies:

- 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: sanboxing a process

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:

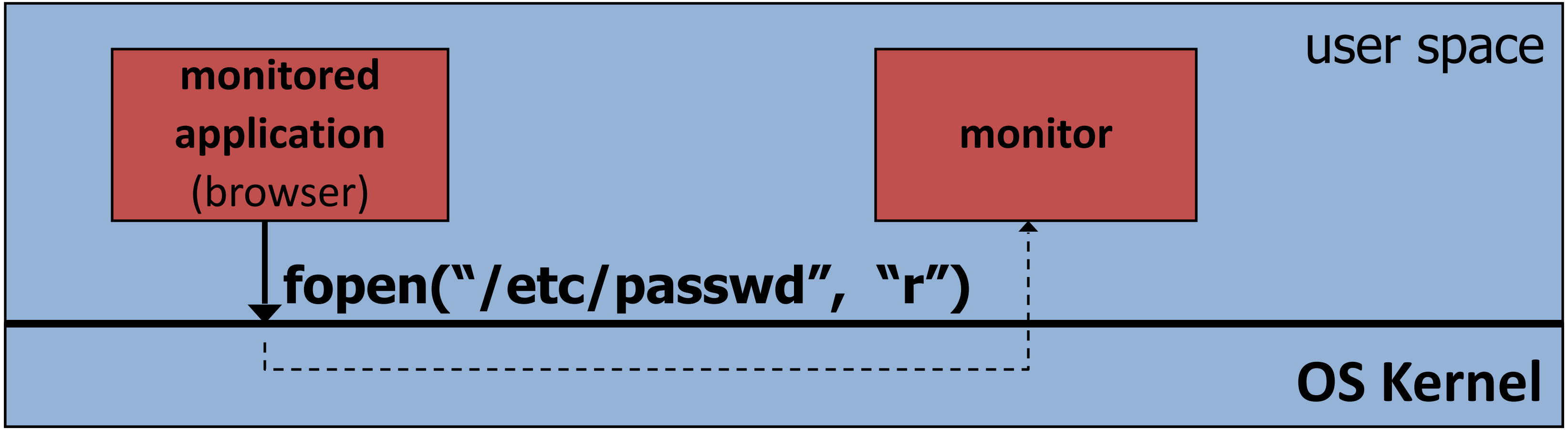
- Completely kernel space (e.g., Linux seccomp)
- Completely user space (e.g., program shepherding)
- Hybrid (e.g., Systrace)

Early 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

Example policy

Sample policy file (e.g., for PDF reader)

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

Manually specifying policy for an app can be difficult:

- Recommended default policies are available

… can be made more restrictive as needed.

Complications

- 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

```
cd("/tmp")
open("passwd", "r")

cd("/etc")
open("passwd", "r")
```

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")

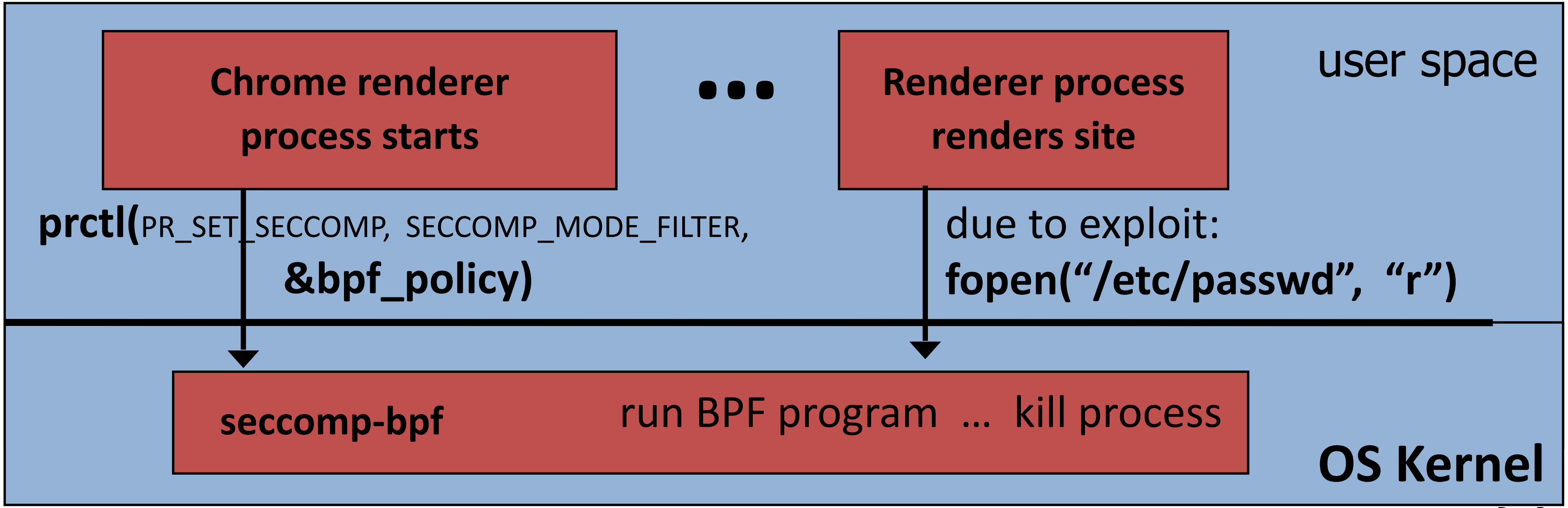
not atomic

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

SCI in Linux: seccomp-bpf

Seccomp-BPF: Linux kernel facility used to filter process sys calls

- Sys-call filter written in the BPF language (use BPFC compiler)
- Used in **Chromium,** in **Docker containers**, …



BPF filters (policy programs)

Process can install multiple BPF filters:

- once installed, filter cannot be removed (all run on every syscall)
- if program forks, child inherits all filters
- if program calls execve, all filters are preserved

BPF filter input: syscall number, syscall args., arch. (x86 or ARM)

Filter returns one of:

- SECCOMP_RET_KILL: kill process
- SECCOMP_RET_ERRNO: return specified error to caller
- SECCOMP_RET_ALLOW: allow syscall

Installing a BPF filter

- Must be called before setting BPF filter.
- Ensures set-UID, set-GID ignored on subequent execve()

  ⇒ attacker cannot elevate privilege

```
int main (int argc , char **argv )  {
    prctl(PR_SET_NO_NEW_PRIVS , 1);
    prctl(PR_SET_SECCOMP,  SECCOMP_MODE_FILTER,  &bpf_policy)
    fopen("file.txt",  "w");
    printf("… will not be printed. \n" );
}
```

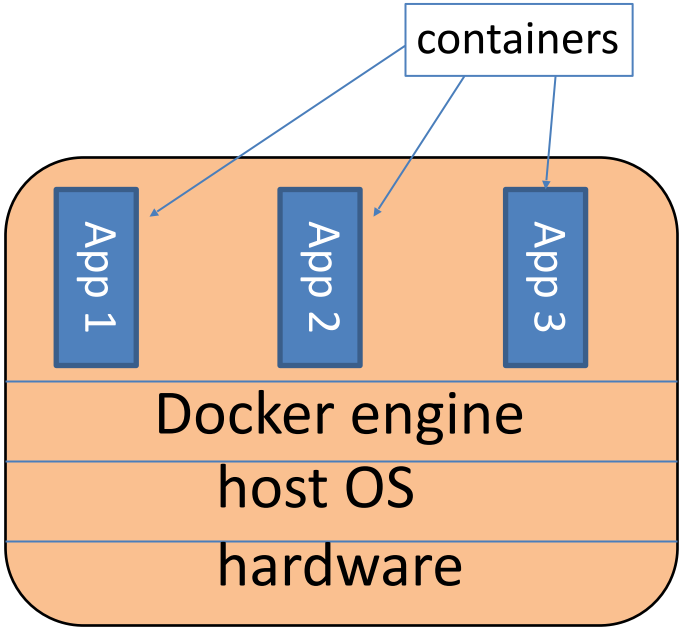
Kill if call open() for write

Docker: isolating containers using seccomp-bpf

Container: process level isolation

- Container prevented from making sys calls filtered by secomp-BPF

- Whoever starts container can specify BPF policy
  - default policy blocks many syscalls, including ptrace



Docker sys call filtering

Run nginx container with a specific filter called filter.json:

$ docker run --security-opt seccomp=filter.json nginx

Example filter:

```
"defaultAction": "SCMP_ACT_ERRNO",        // deny by default

"syscalls": [

      { "names": ["accept"],                  // sys-call name
        "action": "SCMP_ACT_ALLOW",           // allow (whitelist)
        "args": [ ] } ,                       // what args to allow
          …
   ]
```

Ostia: SCI with minimal kernel support

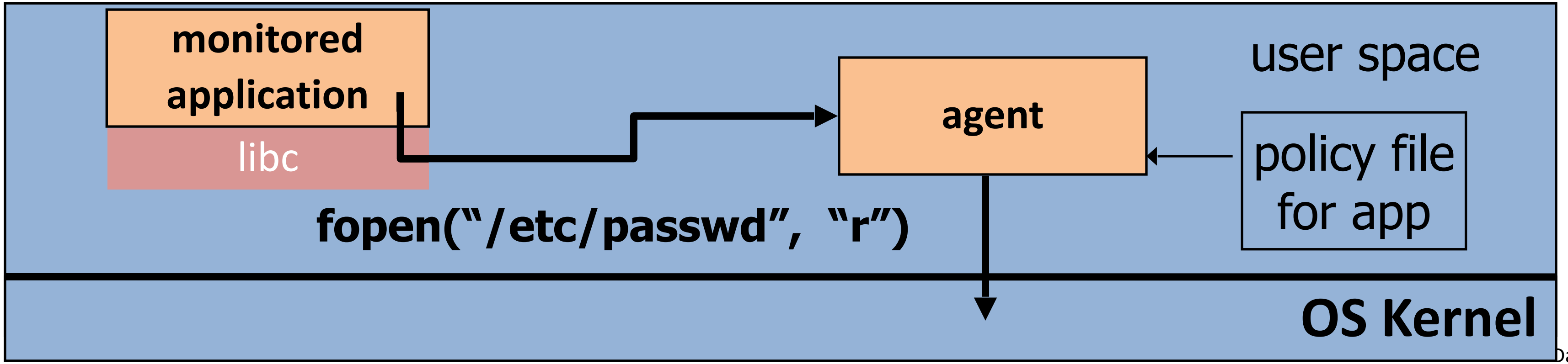
Monitored app disallowed from making monitored sys calls

- 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 … using a libc stub

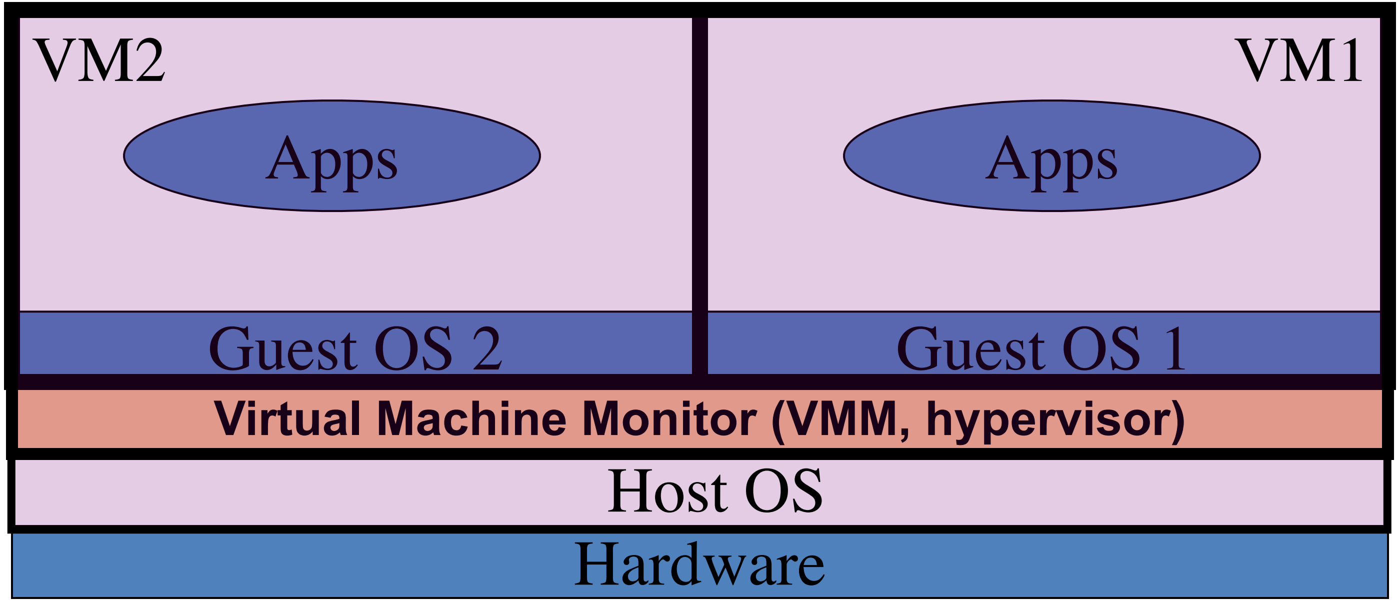
⇒ Incorrect state syncing will not result in policy violation



Isolation

Isolation via Virtual Machines

Virtual Machines



single HW platform with isolated components

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 , …
- VMs heavily used in private and public clouds

Hypervisor security assumption

Hypervisor 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

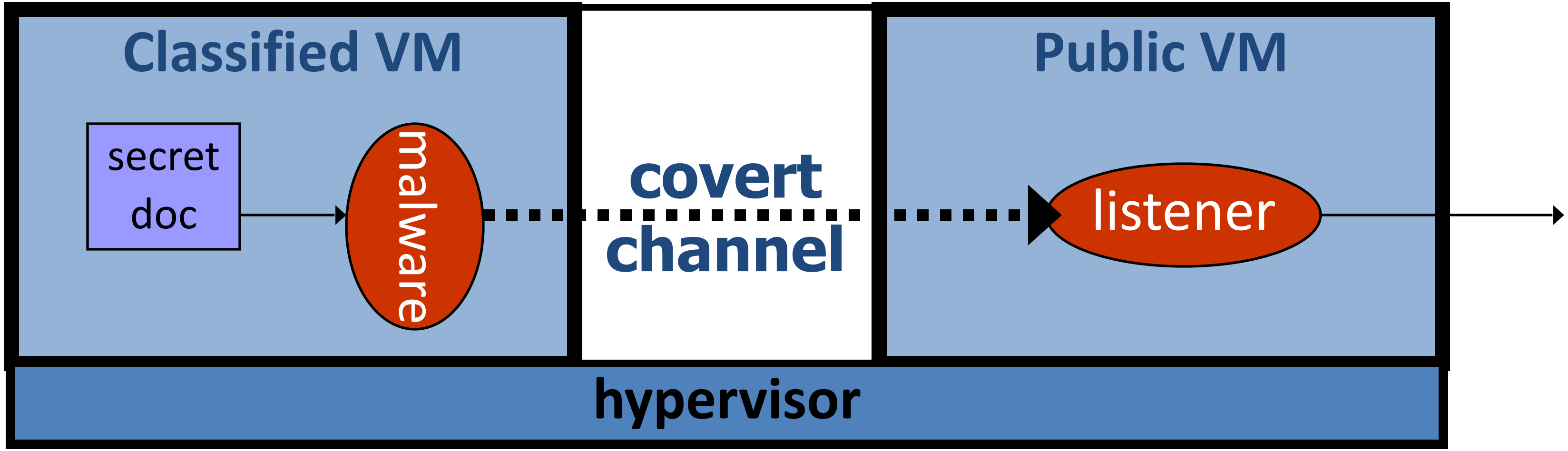
Requires that hypervisor protect itself and is not buggy

- (some) hypervisors are much simpler than a full OS

Problem: covert channels

Covert channel: unintended communication channel between isolated components

– Can 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

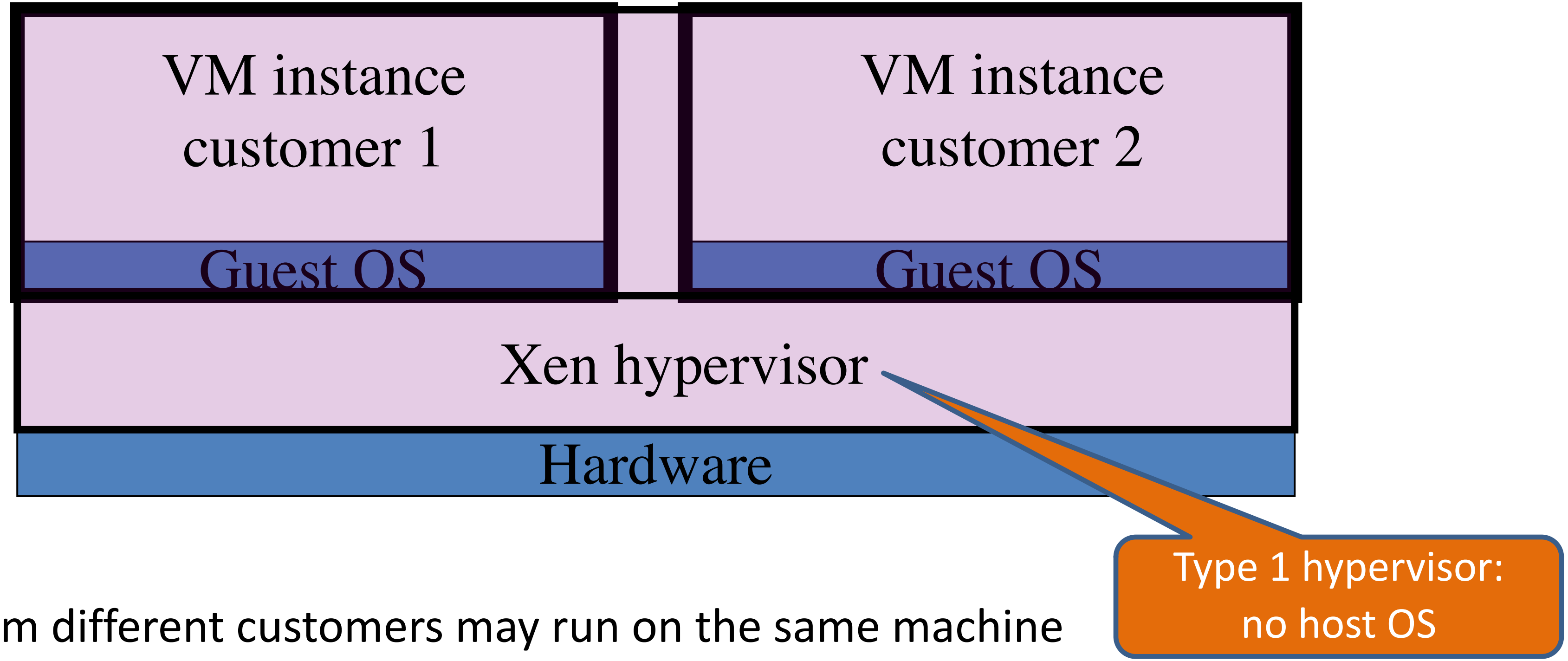
At 1:00am listener does CPU intensive calc. and measures completion time

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

Many covert channels exist in running system:

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

VM isolation in practice: cloud



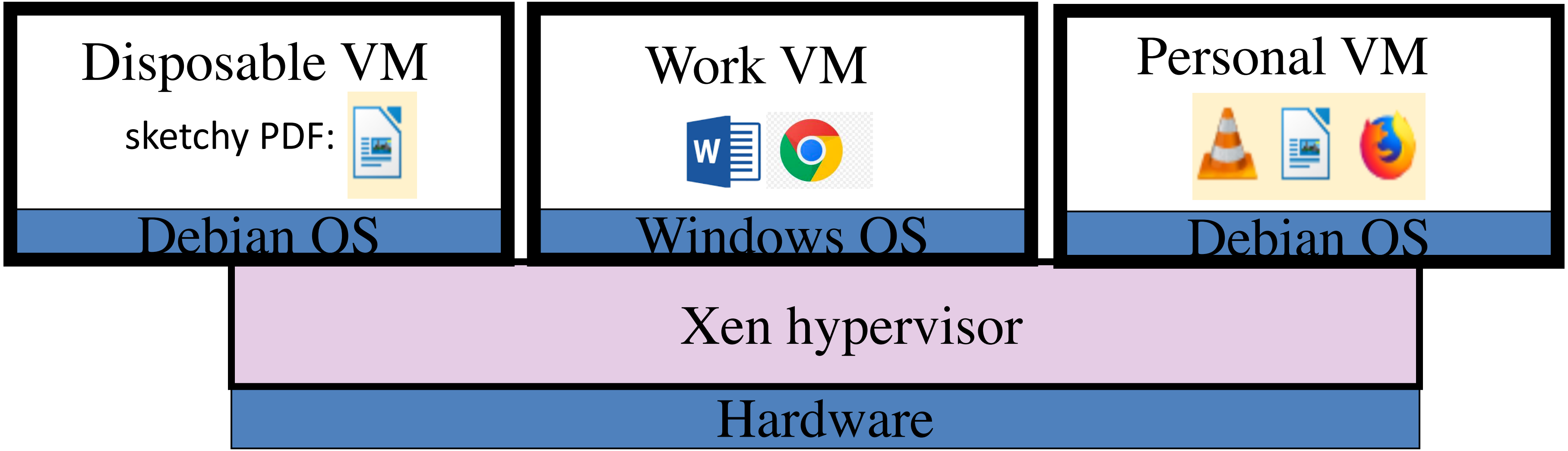
VMs from different customers may run on the same machine

- Hypervisor must isolate VMs … but some info leaks

VM isolation in practice: end-user

Qubes OS: a desktop/laptop OS where everything is a VM

- Runs on top of the Xen hypervisor
- Access to peripherals (mic, camera, usb, …) controlled by VMs



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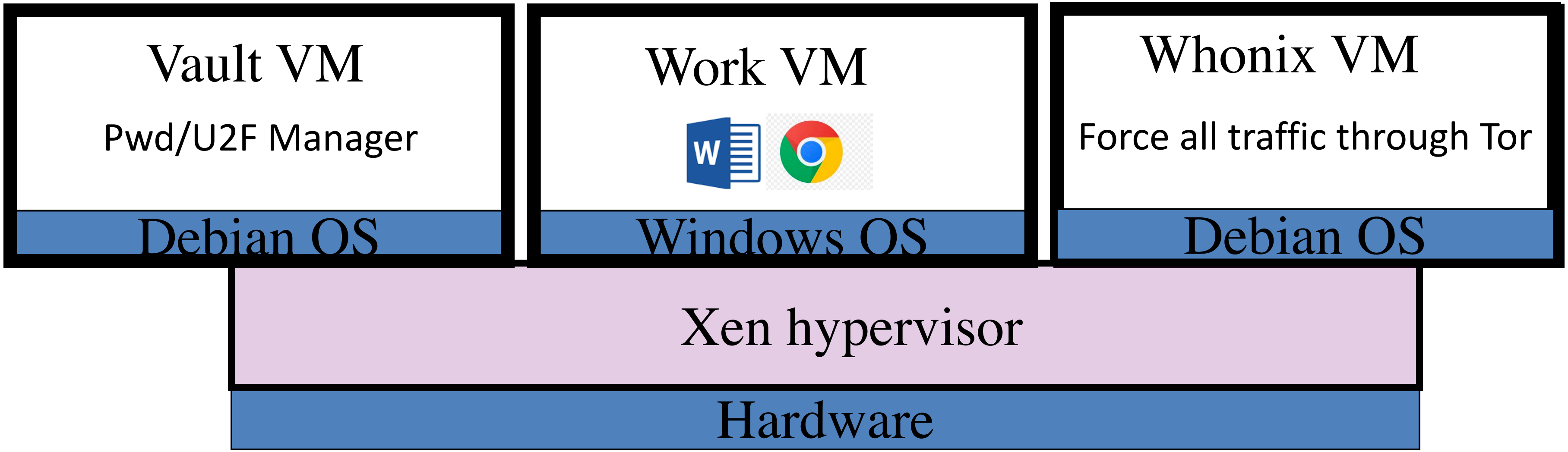
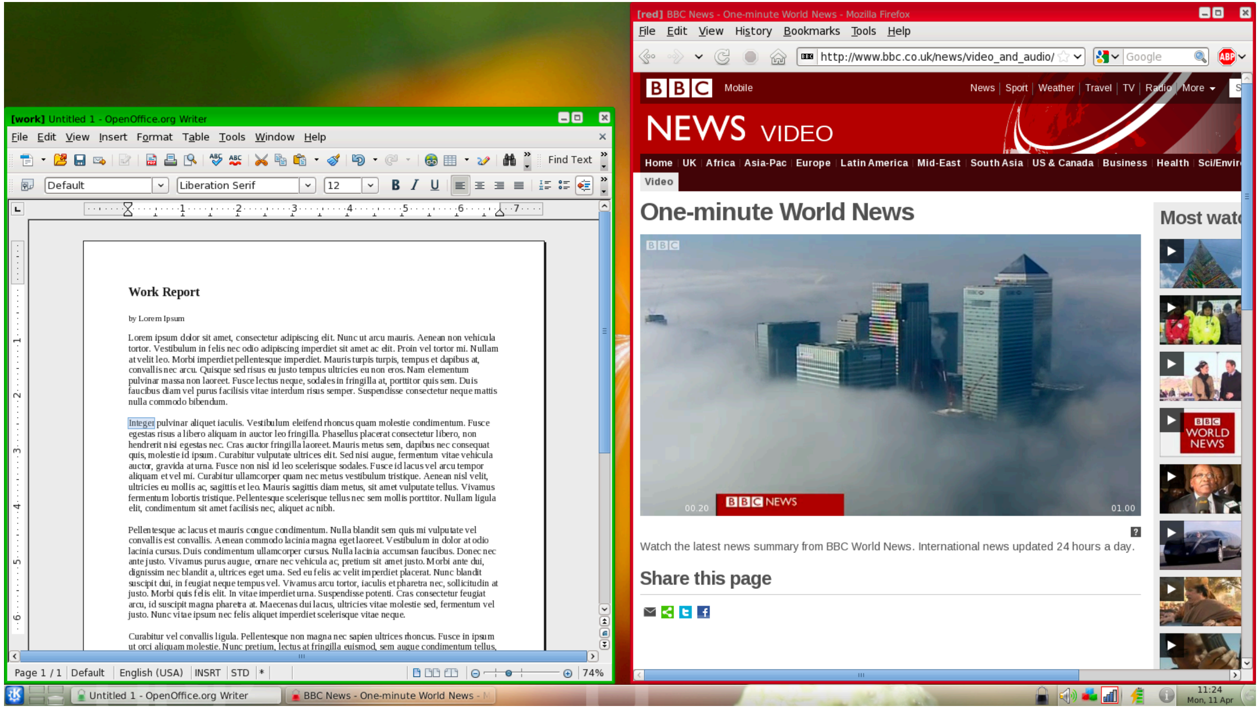


Every window frame identifies VM source



GUI VM ensures frames are drawn correctly

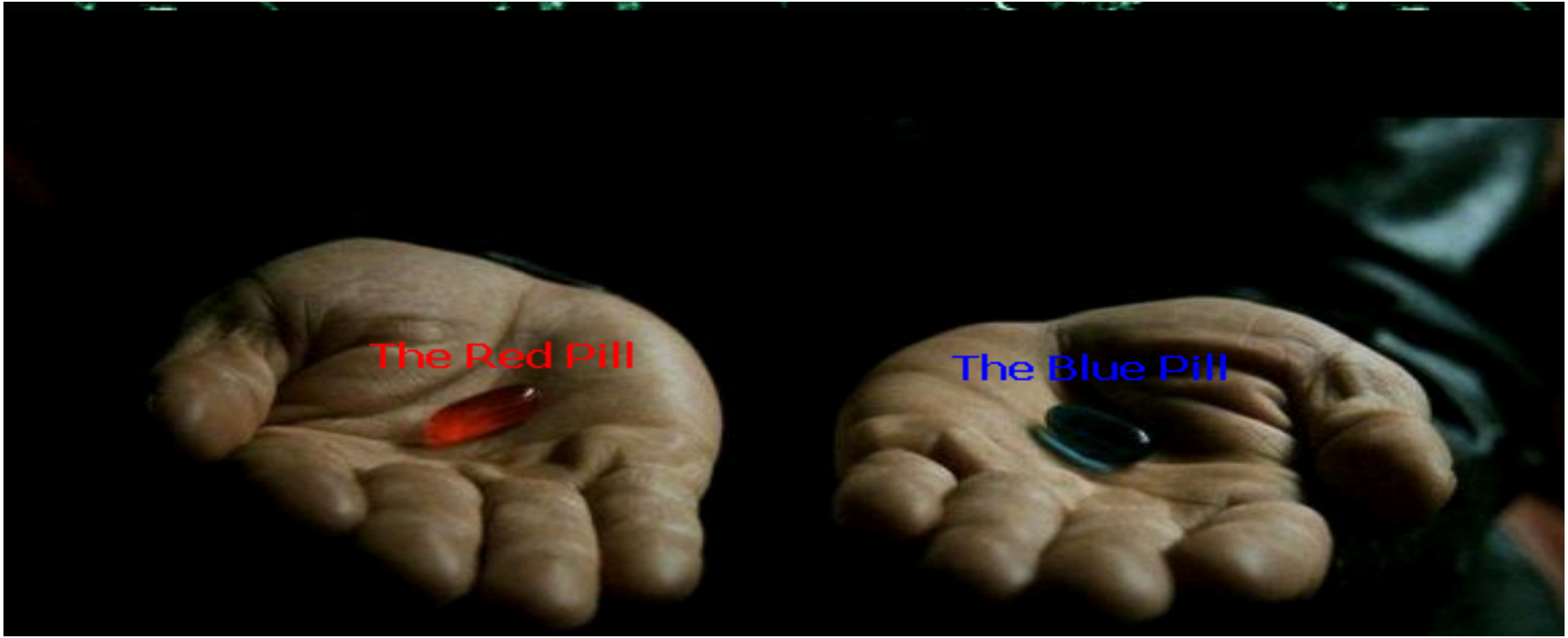
Hypervisor detection

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

Applications:

- Malware can detect hypervisor
  - refuse to run to avoid reverse engineering
- Software that binds to hardware can refuse to run in VM
- DRM systems may refuse to run on top of hypervisor

Hypervisor detection



Hypervisor detection (red pill techniques)

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

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

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

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

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

Hypervisor detection in the browser [HBBP'14]

Can we identify malware web sites?

- Approach: crawl web,
  load pages in a browser running in a VM,
  look for pages that damage VM

- The problem: Web page can detect it is running in a VM
  How? Using timing variations in writing to screen

- Malware in web page becomes benign when in a VM
  ⇒ evade detection

Hypervisor detection

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

Hypervisors today focus on:

Compatibility: ensure off the shelf software works

Performance: minimize virtualization overhead

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

Isolation

Software Fault Isolation:

isolating threads

Software Fault Isolation [Whabe et al., 1993]

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

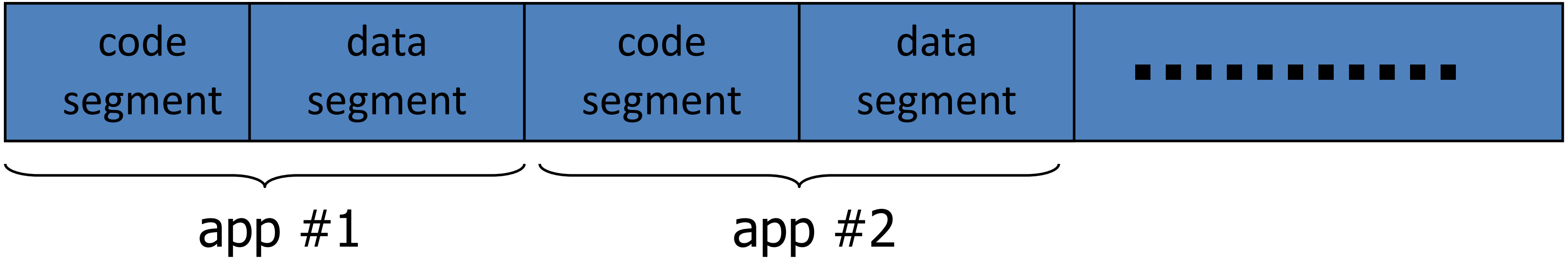
- Kernel module should not corrupt kernel
- Native libraries should not corrupt JVM

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

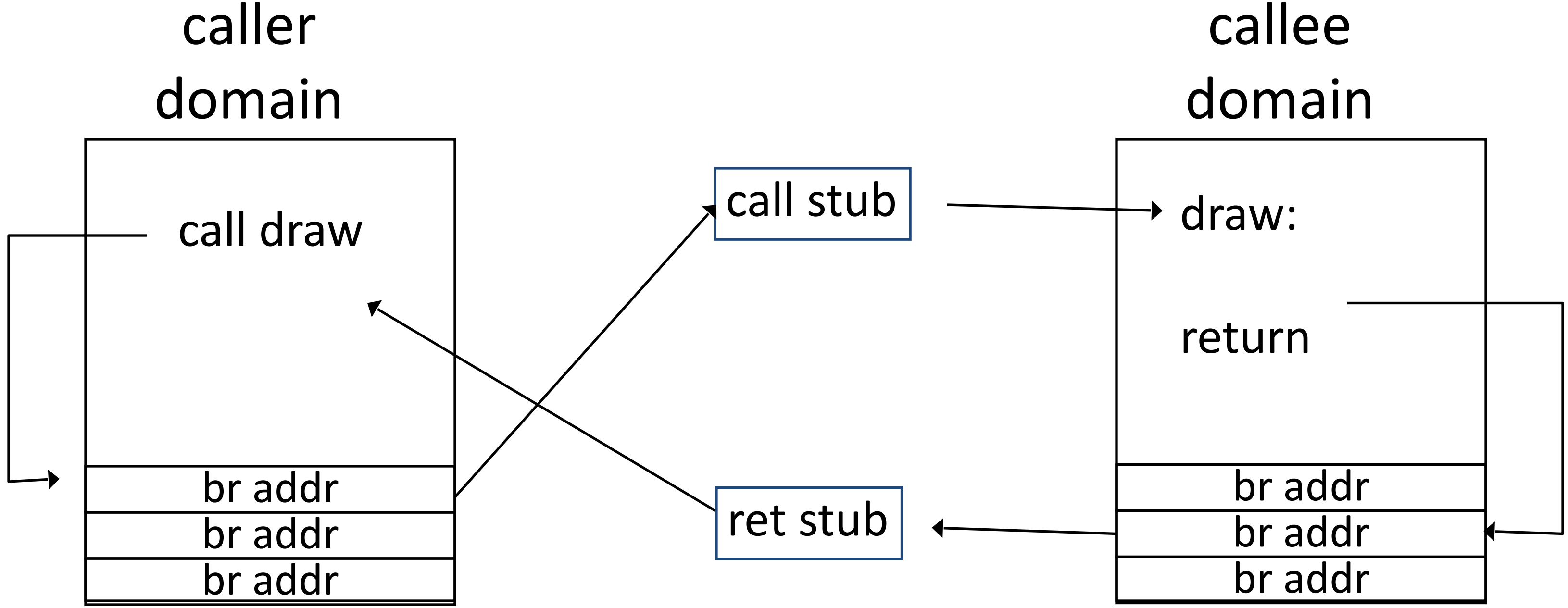
Problem: what if **jmp [addr]** jumps directly into indirect load?

(bypassing guard)

Solution:

This is why **jmp** instructions need a guard:
jmp guard ensures **[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

- Performance
  - Usually good: mpeg_play, 4% slowdown

- Limitations of SFI: 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 (hypervisor),

    System call interposition (SCI), Software Fault isolation (SFI)

    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