



Isolation

The confinement principle

Running untrusted code

We often need to run buggy/untrusted code:

- programs from untrusted Internet sites:
 - mobile apps, Javascript, browser extensions
- exposed applications: browser, pdf viewer, outlook
- legacy daemons: sendmail, bind
- honeypots

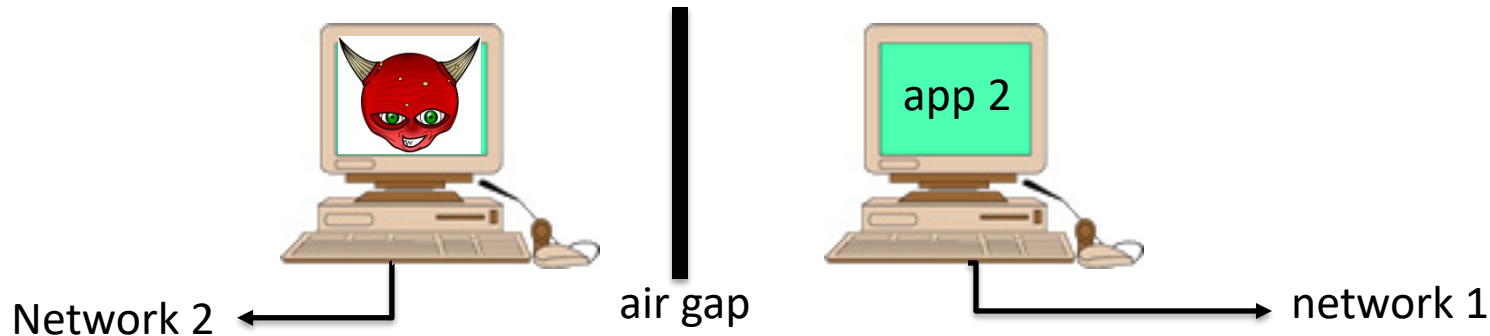
Goal: if application “misbehaves” \Rightarrow kill it

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)



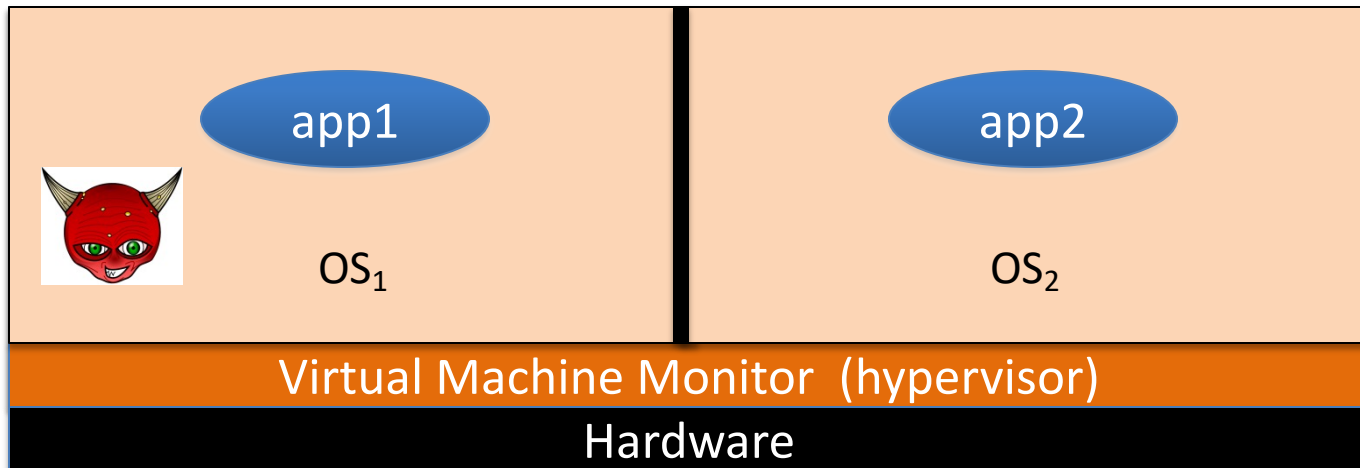
⇒ difficult to manage

Approach: confinement

Confinement: ensure misbehaving app cannot harm rest of system

Can be implemented at many levels:

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

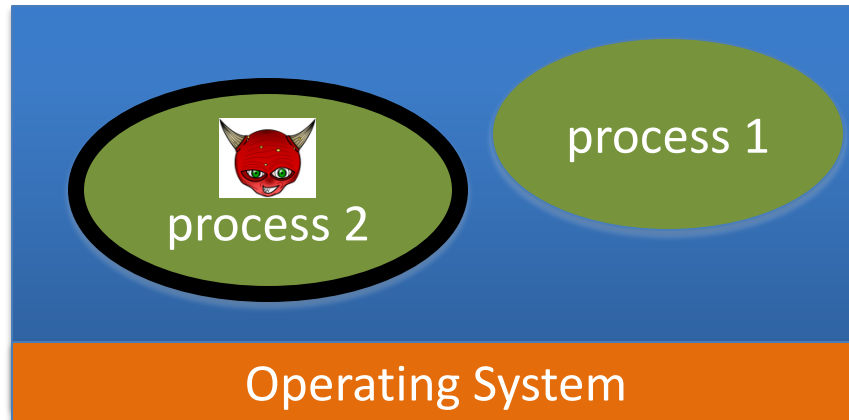


Approach: confinement

Confinement: ensure misbehaving app cannot harm rest of system

Can be implemented at many levels:

- **Process**: System Call Interposition (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

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)

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

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



Confinement

System Call Interposition:
sandboxing 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)

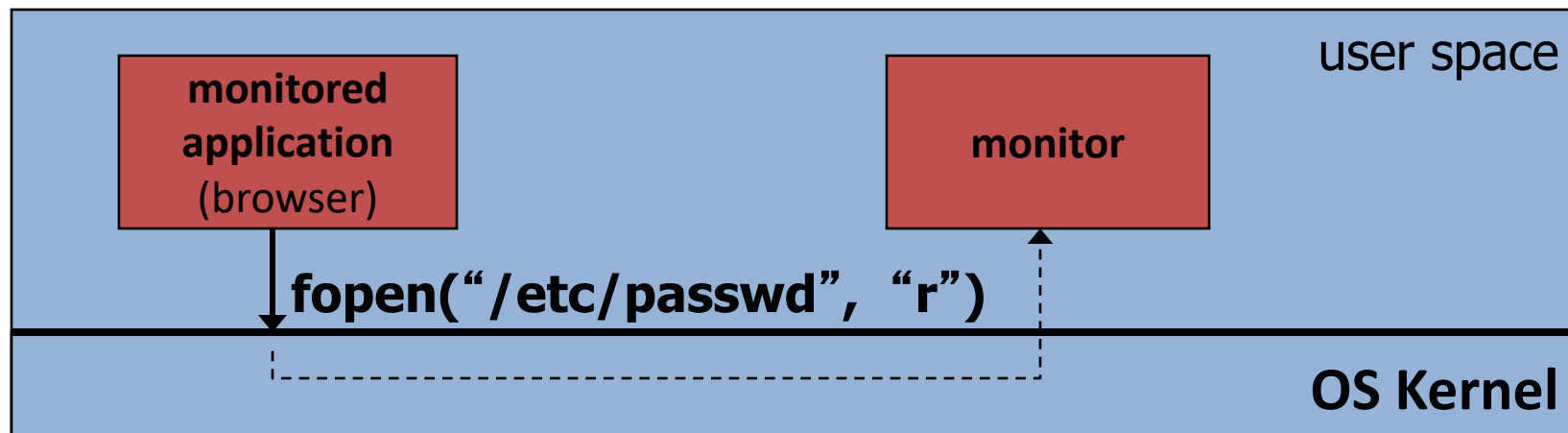
Early implementation (Janus)

[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")
```

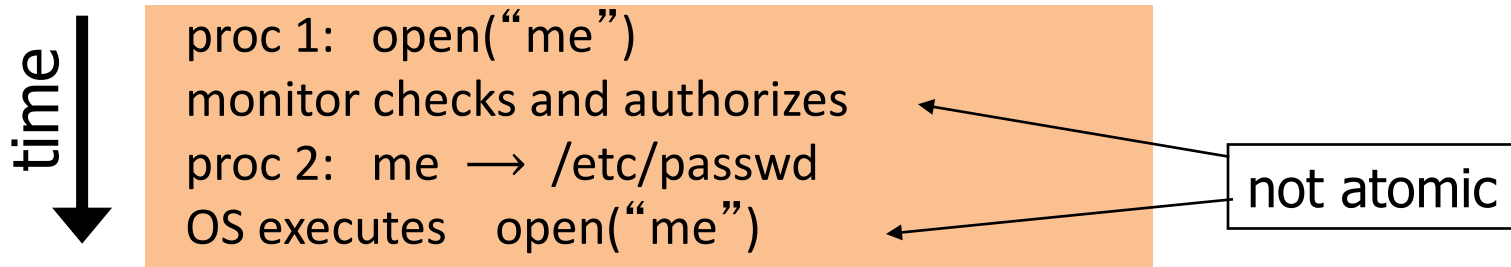
Problems with ptrace

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

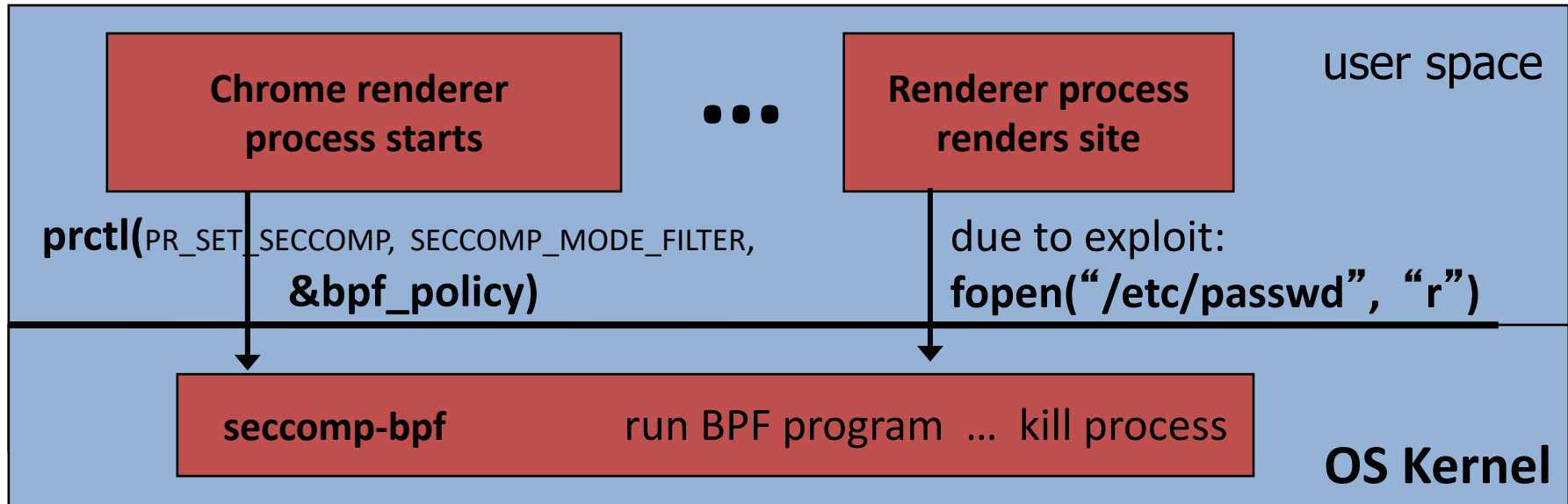


Classic **TOCTOU bug**: time-of-check / time-of-use

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 BPF 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 subsequent `execve()`
⇒ attacker cannot elevate privilege

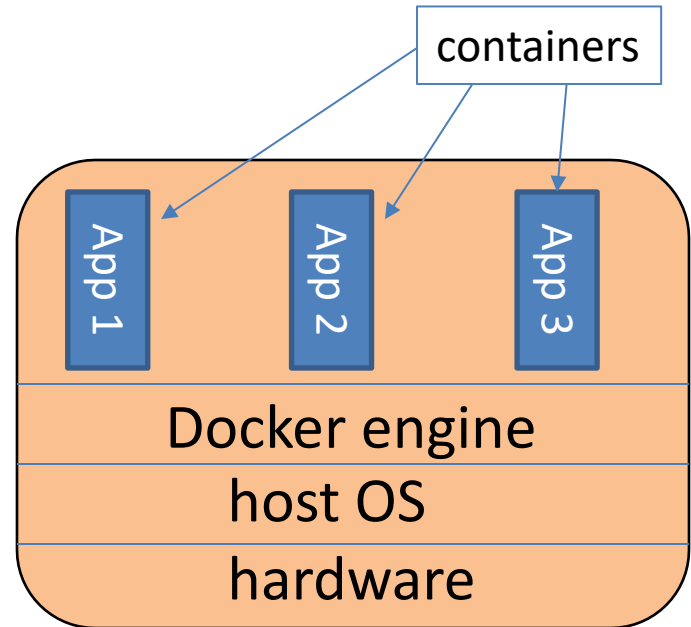
```
int main (int argc , char **argv ) {  
    prctl(PR_SET_NO_NEW_PRIVS , 1);  
    prctl(PR_SET_SECCOMP, SECCOMP_MODE_FILTER, &bpf_policy)  
    fopen("file.txt", "w");  
    printf("... will not be printed. \n" );  
}
```

Kill if call `open()` for write

Docker: isolating containers using seccomp-bpf

Container: process level isolation

- Container prevented from making sys calls filtered by seccomp-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
    ...
  ]
```

More Docker confinement flags

Specify as an unprivileged user:

```
$ docker run --user www nginx
```

drop all capabilities

allow to bind to privileged ports

Limit Linux capabilities:

```
$ docker run --cap-drop all --cap-add NET_BIND_SERVICE nginx
```

Prevent process from becoming privileged (e.g., by a setuid binary)

```
$ docker run --security-opt=no-new-privileges:true nginx
```

Limit number of restarts and resources:

```
$ docker run --restart=on-failure:<max-retries>
```

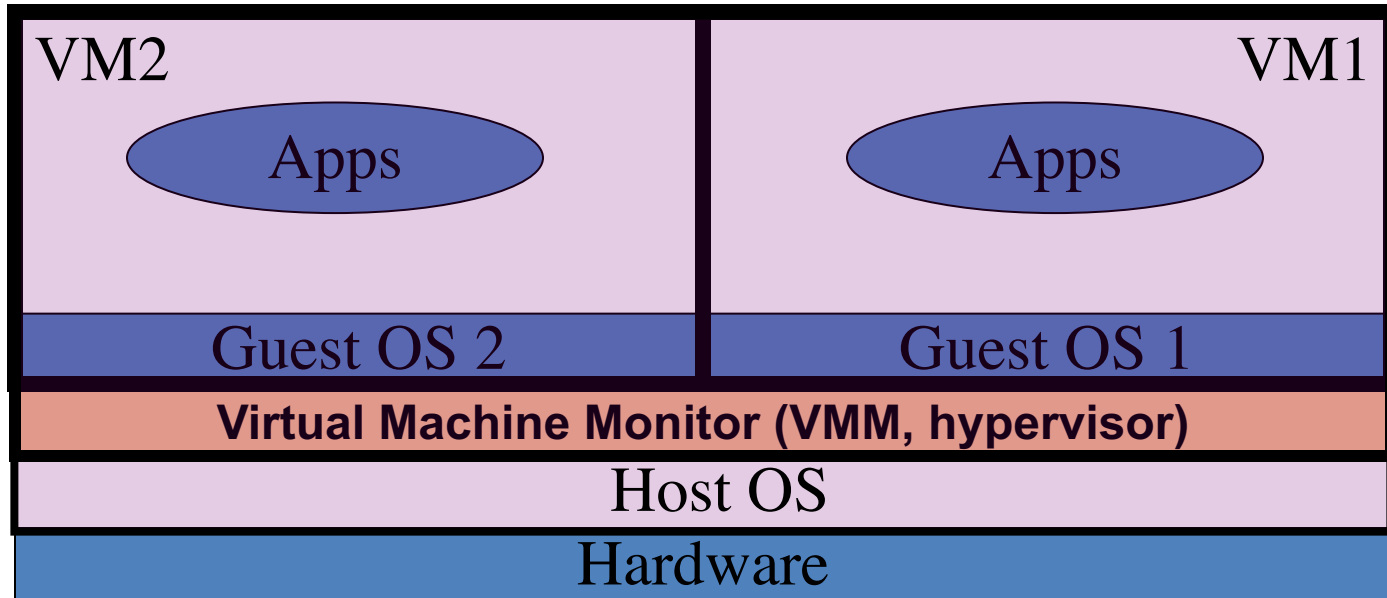
```
--ulimit nofile=<max-fd> --ulimit nproc=<max-proc> nginx
```




Confinement

Via Virtual Machines

Virtual Machines



single HW platform with isolated components

Why so popular?

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

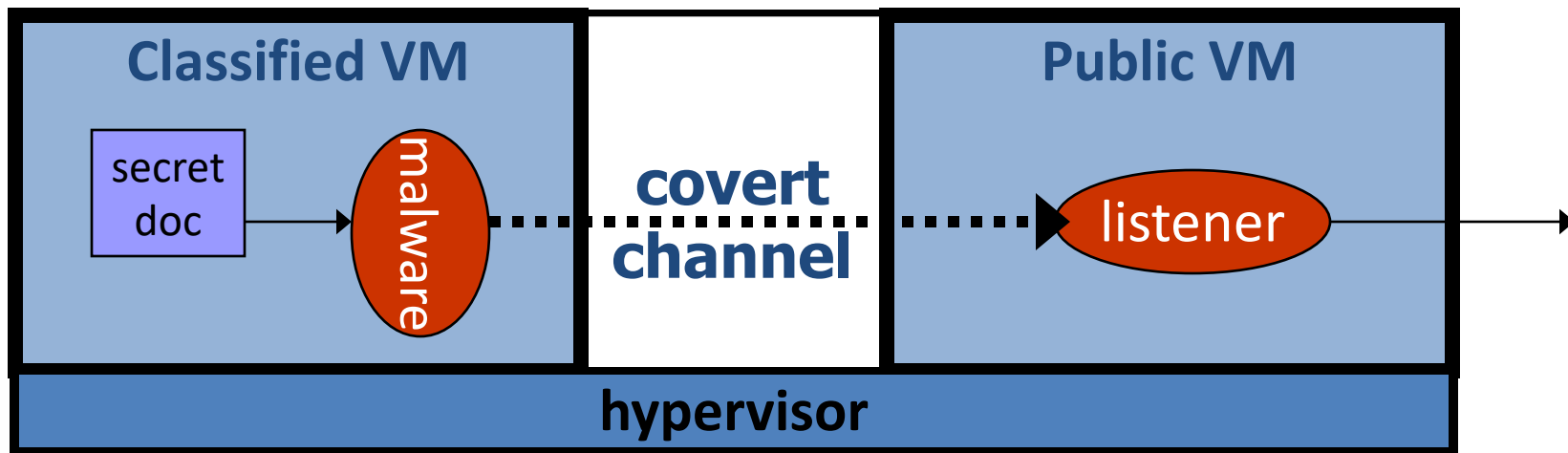
Requires that hypervisor protect itself and is not buggy

- (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

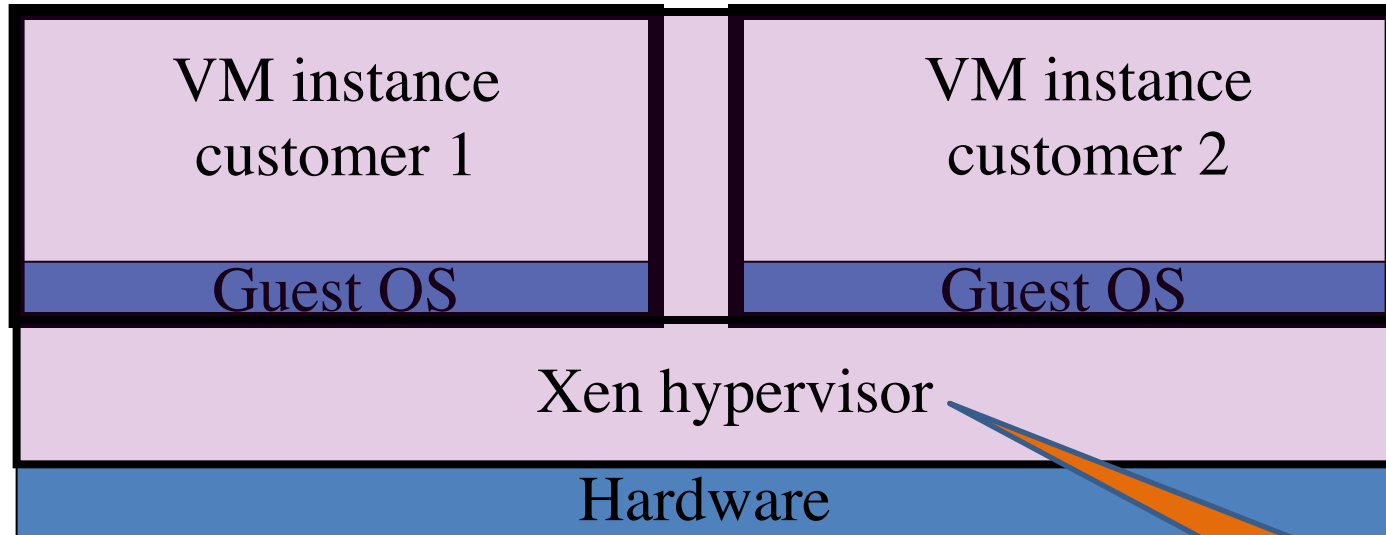
At 1:00am listener does CPU intensive calc. and measures completion time

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

Many covert channels exist in running system:

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

VM isolation in practice: cloud



Type 1 hypervisor:
no host OS

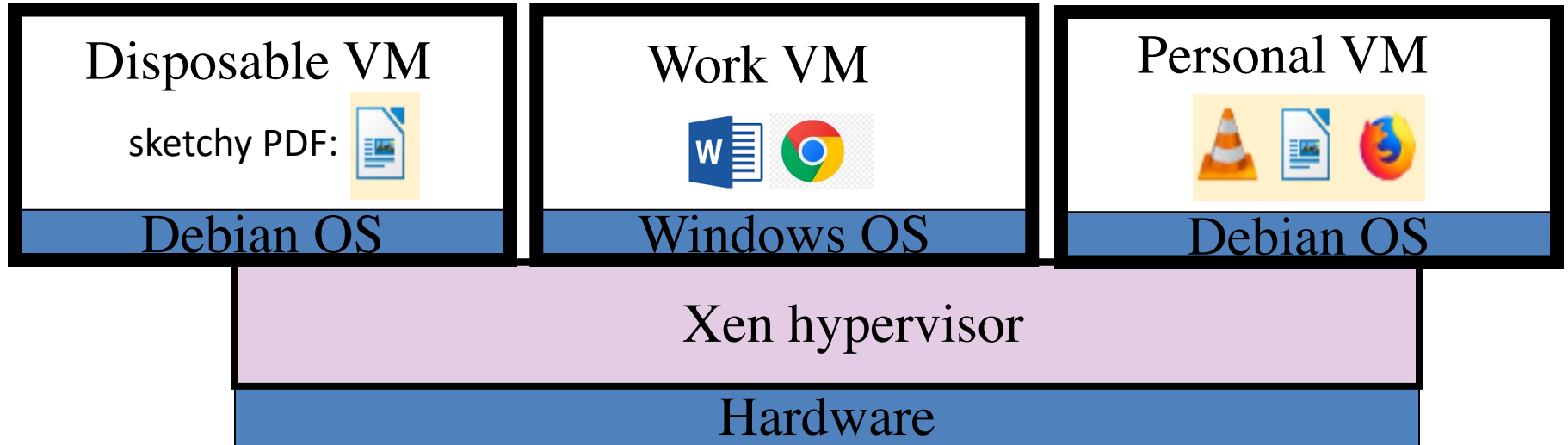
VMs from different customers may run on the same machine

- 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

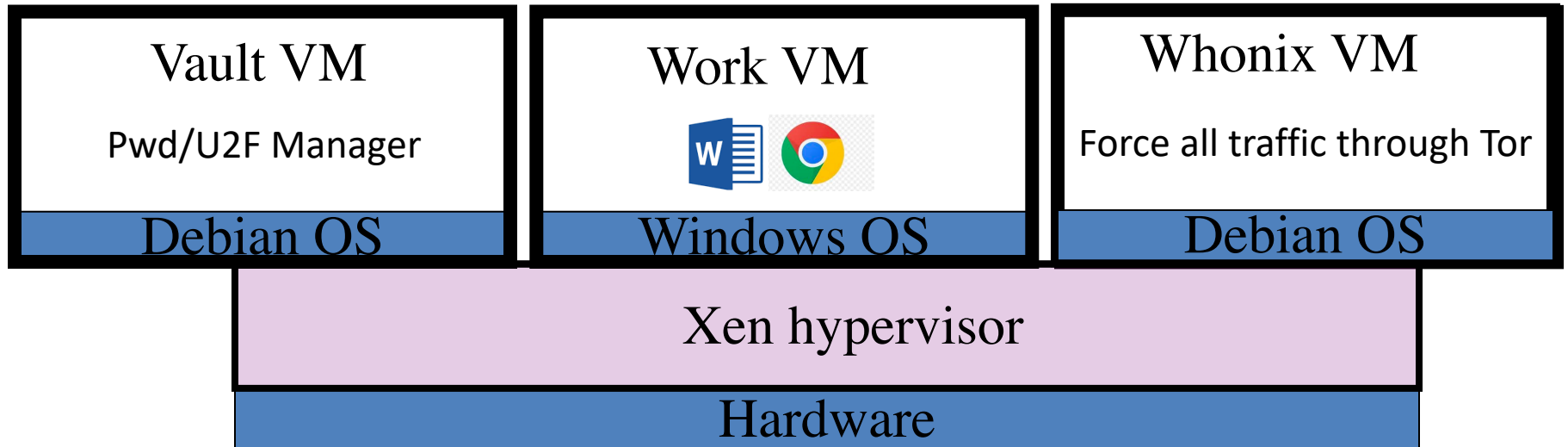
- Runs on top of the Xen hypervisor
- Access to peripherals (mic, camera, usb, ...) controlled by VMs



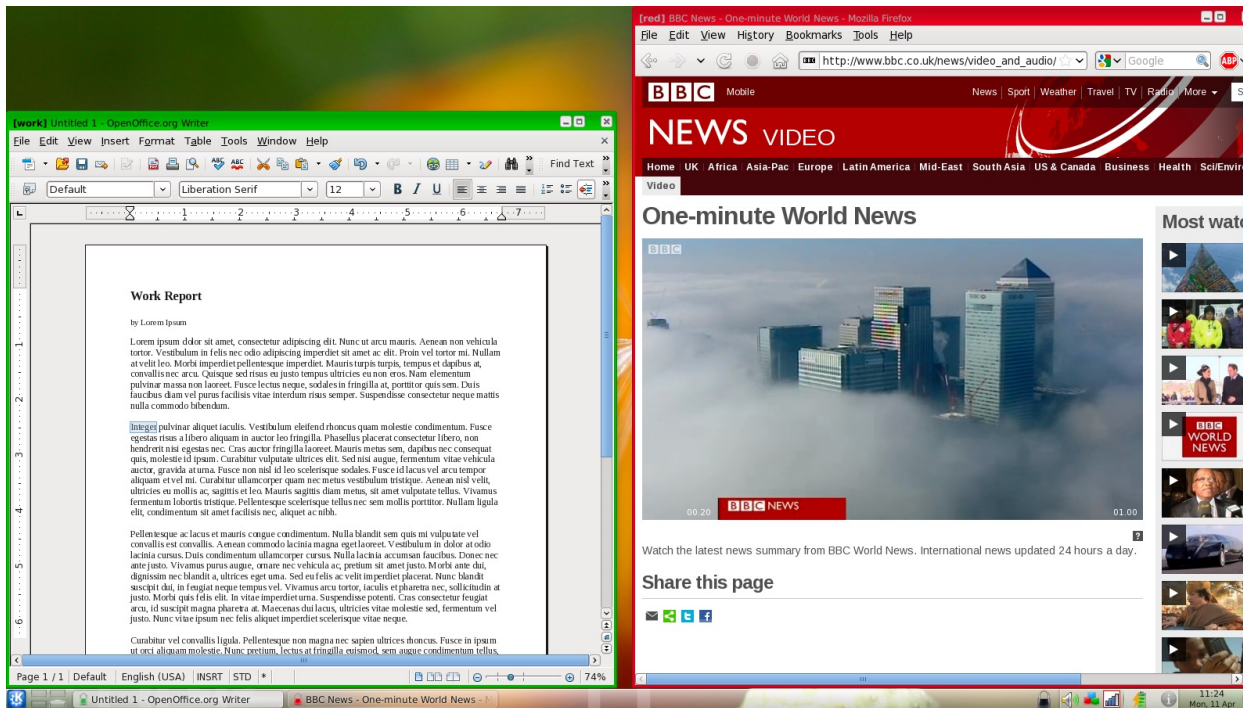
VM isolation in practice: end-user

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

- Runs on top of the Xen hypervisor
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Every window frame identifies VM source



GUI VM ensures frames are drawn correctly

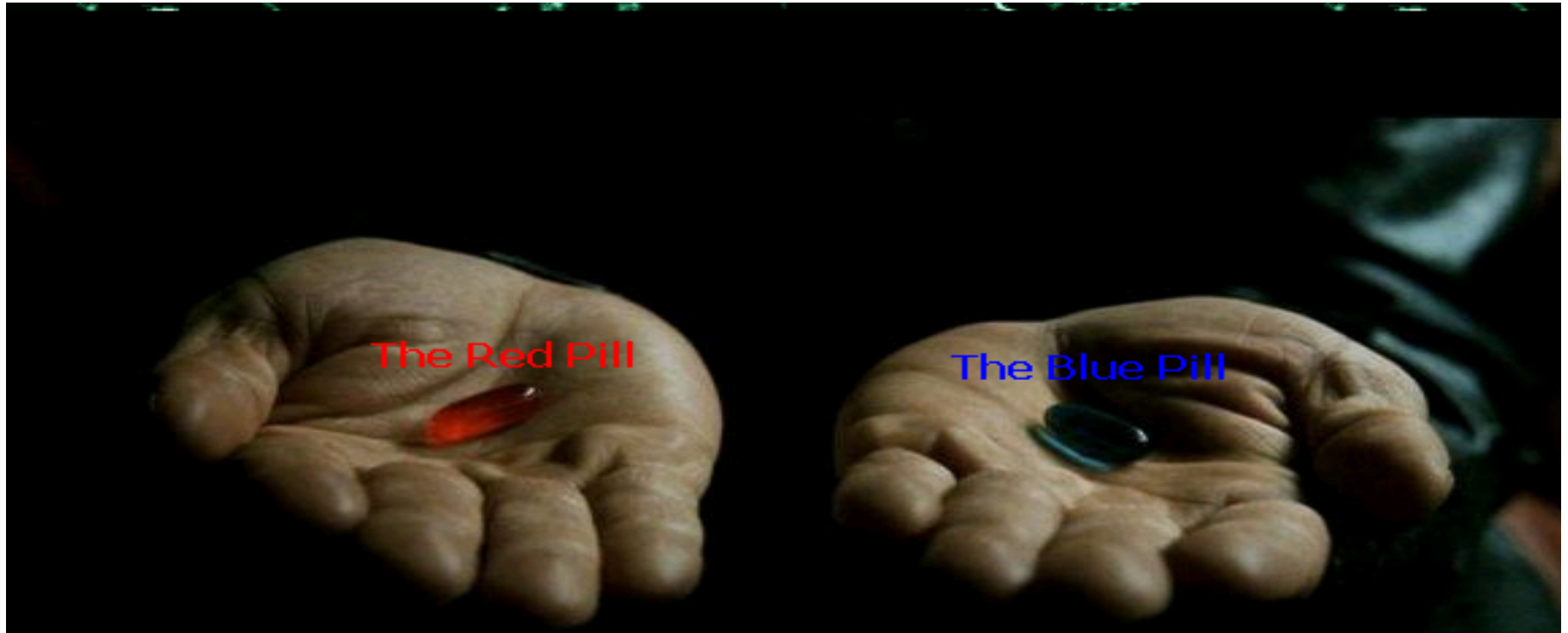
Hypervisor detection

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**



Confinement

Software Fault Isolation:
isolating threads

Software Fault Isolation [Whabe et al., 1993]

Goal: confine apps running in same address space

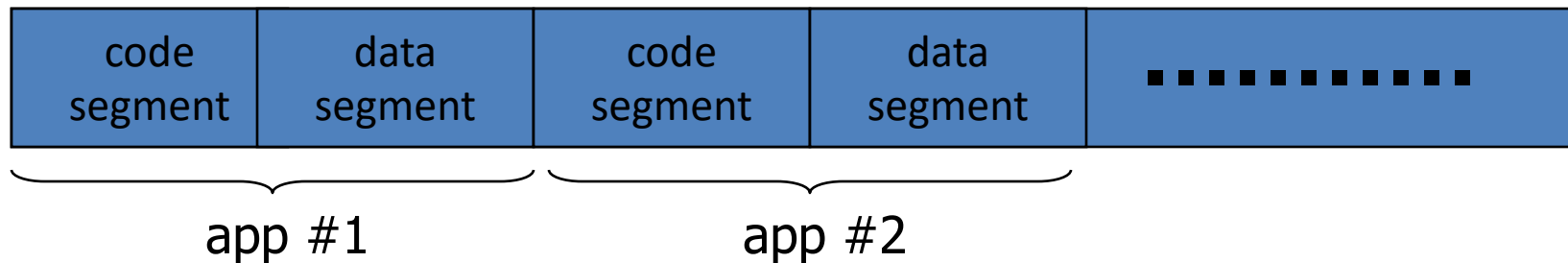
- Kernel module should not corrupt kernel
- Native libraries should not corrupt JVM

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 M...
- **dr1, dr2**: dedicated registers
 - compiler pre...
 - **dr2** contains segment...
- Indirect load instruction

Guard ensures code does not load data from another segment

```
dr1 ← R34  
scratch-reg ← (dr1 >> 20)  
compare scratch-reg and dr2  
trap if not equal
```

```
R12 ← [dr1]
```

R12 ← [R34] becomes:

: get segment ID

: validate seg. ID

: do load

Address sandboxing technique

- **dr2**: holds segment ID
- Indirect load instruction $R12 \leftarrow [R34]$ becomes:

$dr1 \leftarrow R34 \ \& \ \text{segment-mask}$

: zero out seg bits

$dr1 \leftarrow dr1 \ | \ dr2$

: set valid seg ID

$R12 \leftarrow [dr1]$

: do load

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

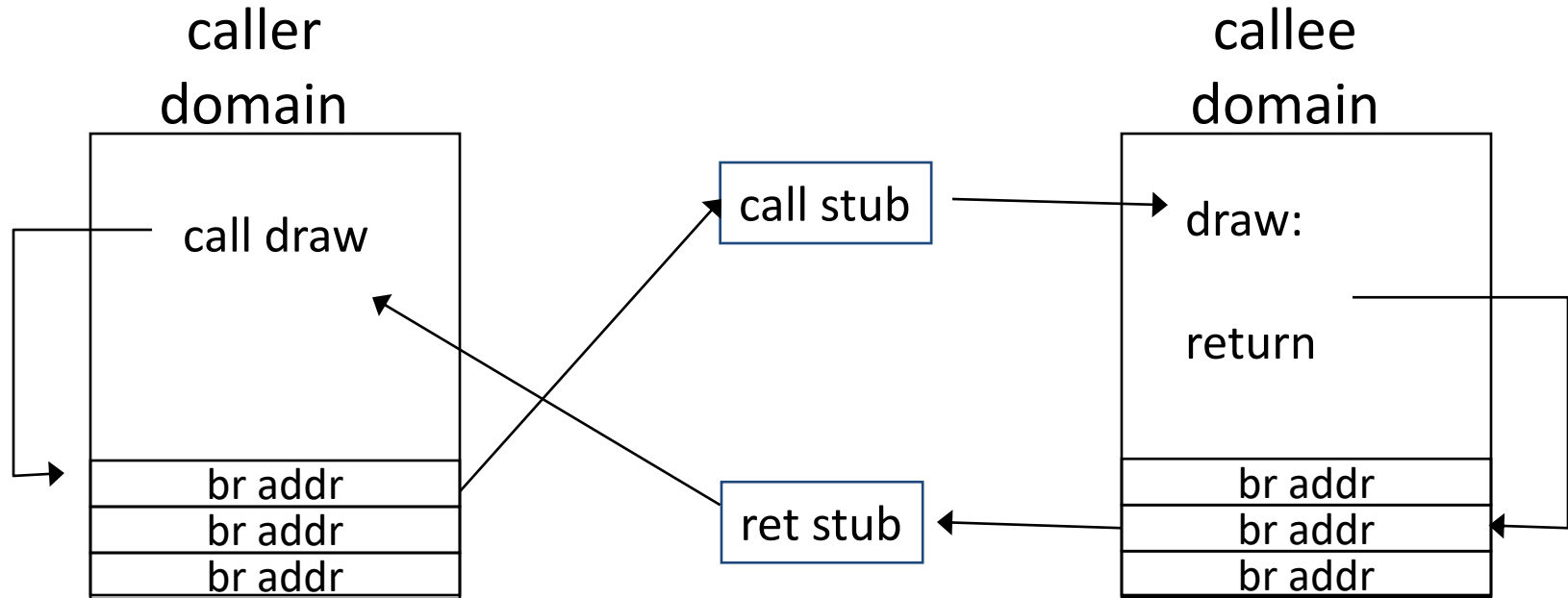
Problem: what if `jmp [addr]` jumps directly into indirect load?
(bypassing guard)

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

Confinement: 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