



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 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/untrusted code:

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

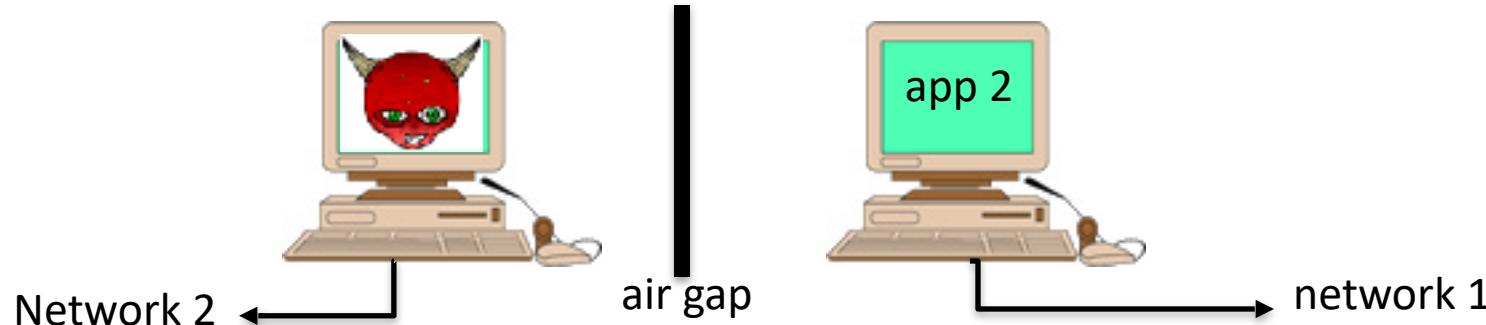
Goal: if application “misbehaves” \Rightarrow kill it

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)



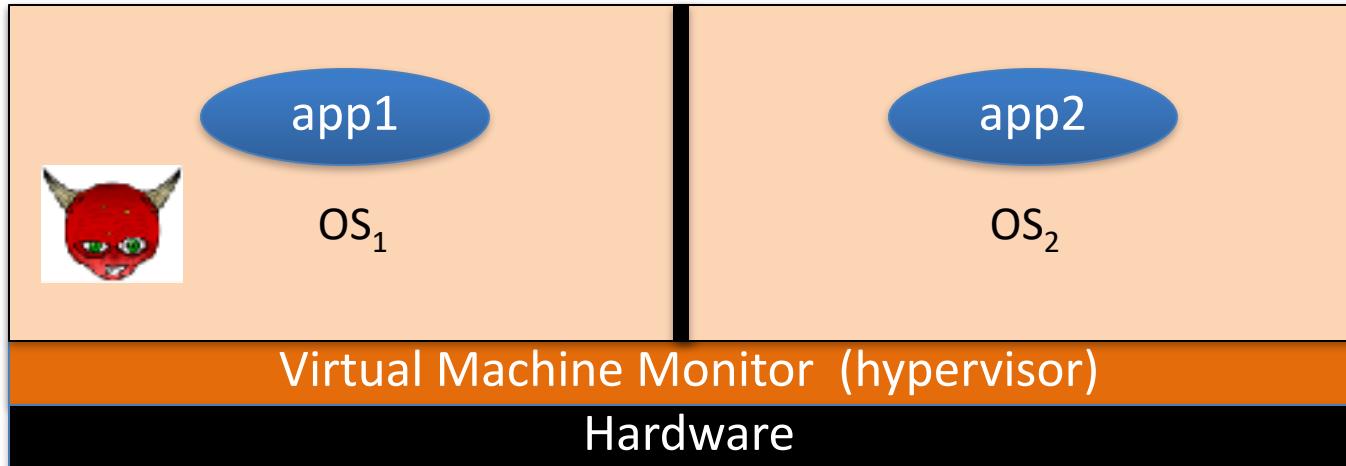
⇒ difficult to manage

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

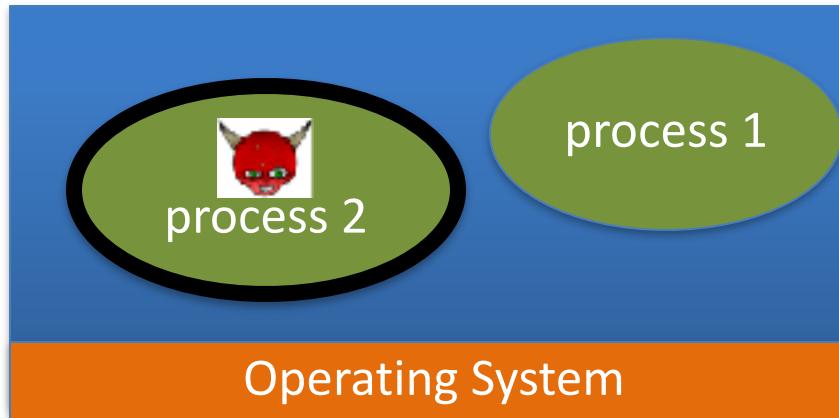


Approach: confinement

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
- **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:
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)

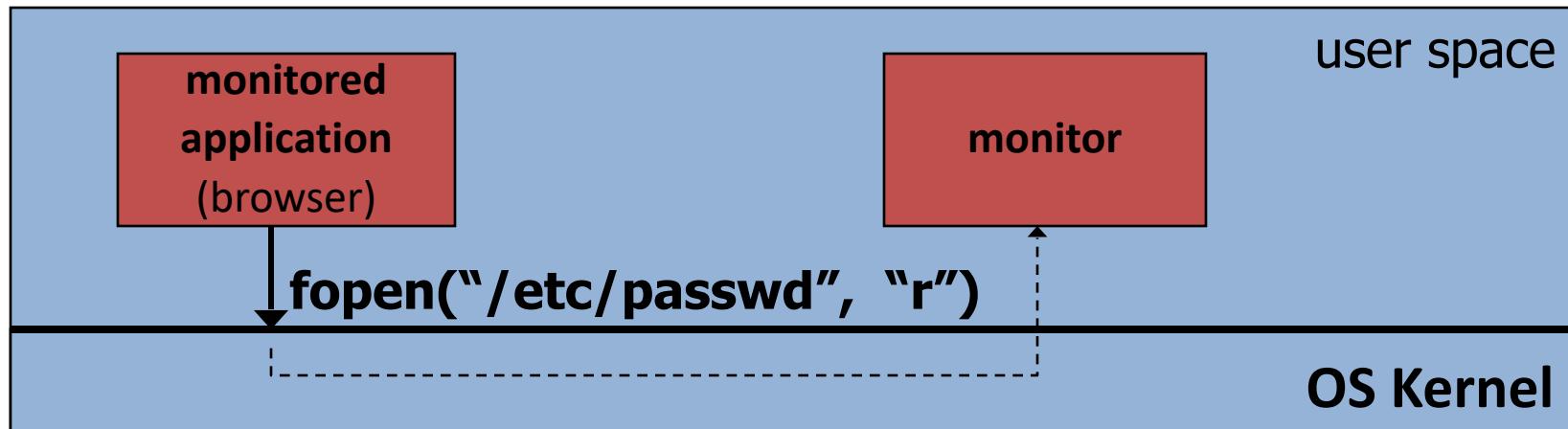
Early implementation (Janus)

[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")
```

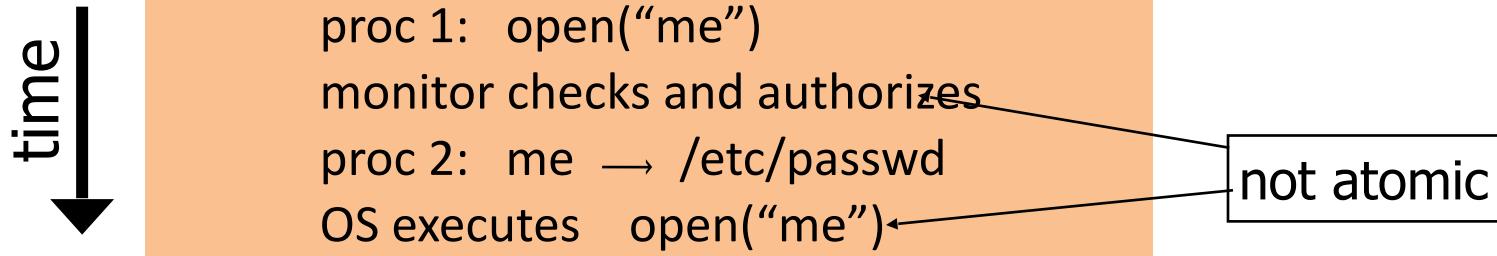
Problems with ptrace

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

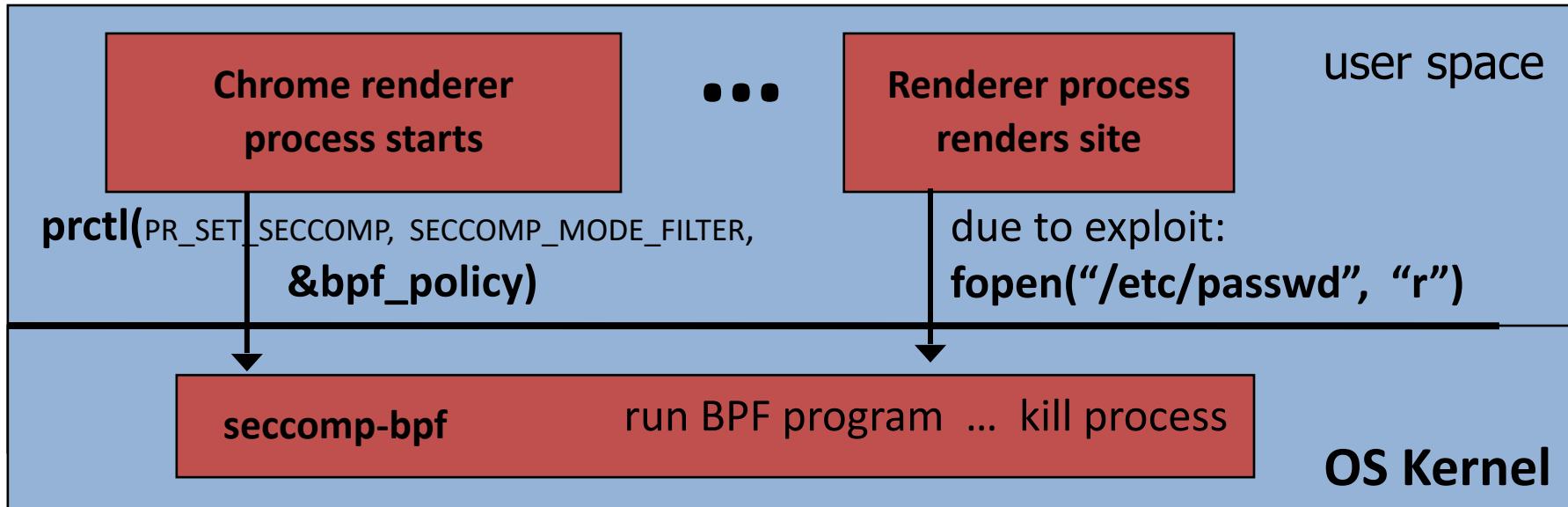


Classic **TOCTOU bug**: time-of-check / time-of-use

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 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 subsequent execve()
⇒ attacker cannot elevate privilege

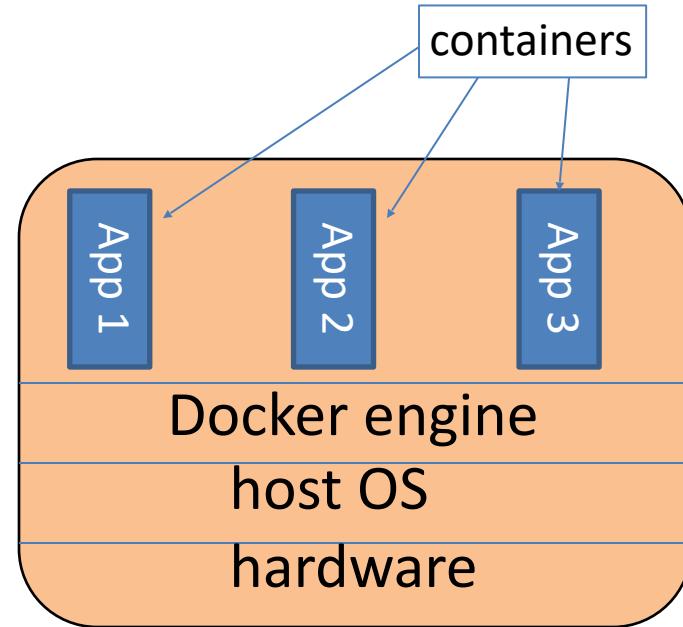
```
int main (int argc , char **argv ) {  
    prctl(PR_SET_NO_NEW_PRIVS , 1); ←  
    prctl(PR_SET_SECCOMP, SECCOMP_MODE_FILTER, &bpf_policy) ←  
    fopen("file.txt", "w");  
    printf("... will not be printed. \n" );  
}
```

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:

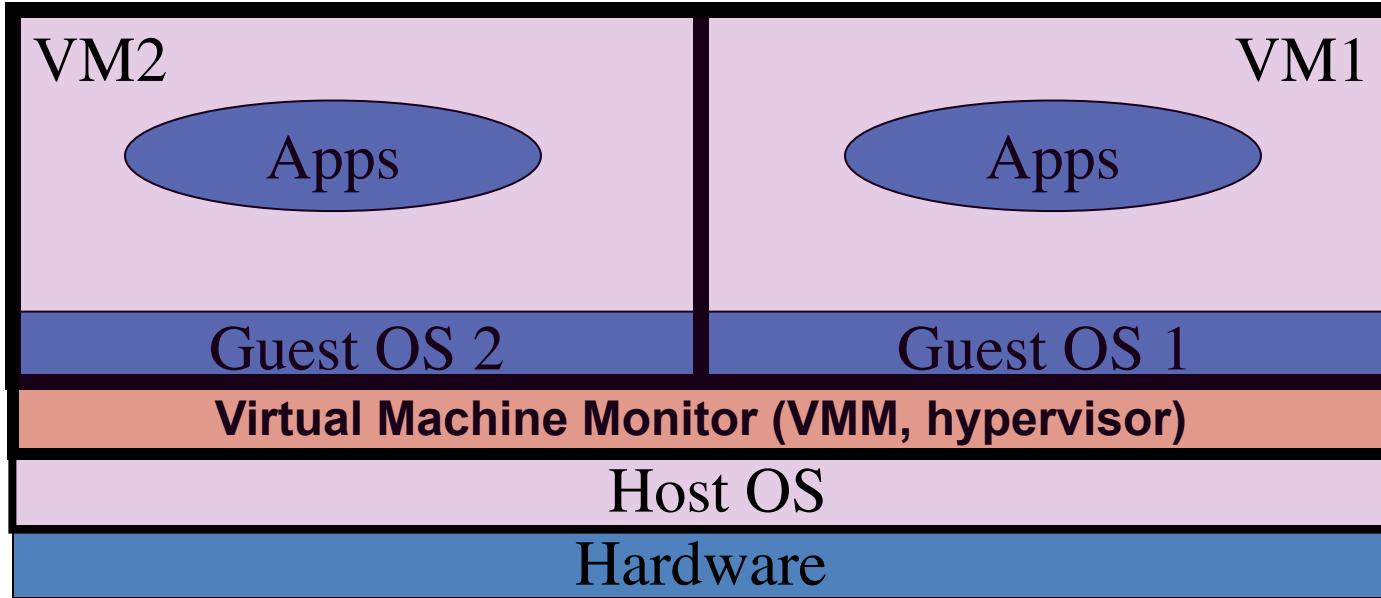
```
"defaultAction": "SCMP_ACT_ERRNO",      // deny by default
"syscalls": [
    { "names": ["accept"],                // sys-call name
      "action": "SCMP_ACT_ALLOW",        // allow (whitelist)
      "args": [ ] },                   // what args to allow
    ...
]
```



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 share 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

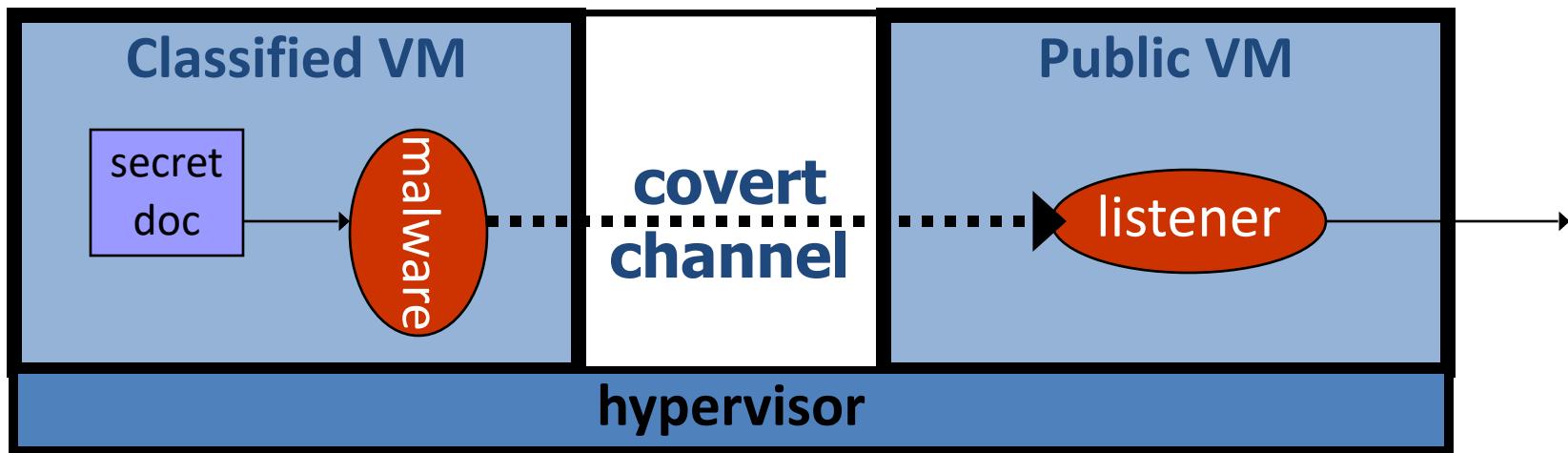
Requires that hypervisor protect itself and is not buggy

- (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

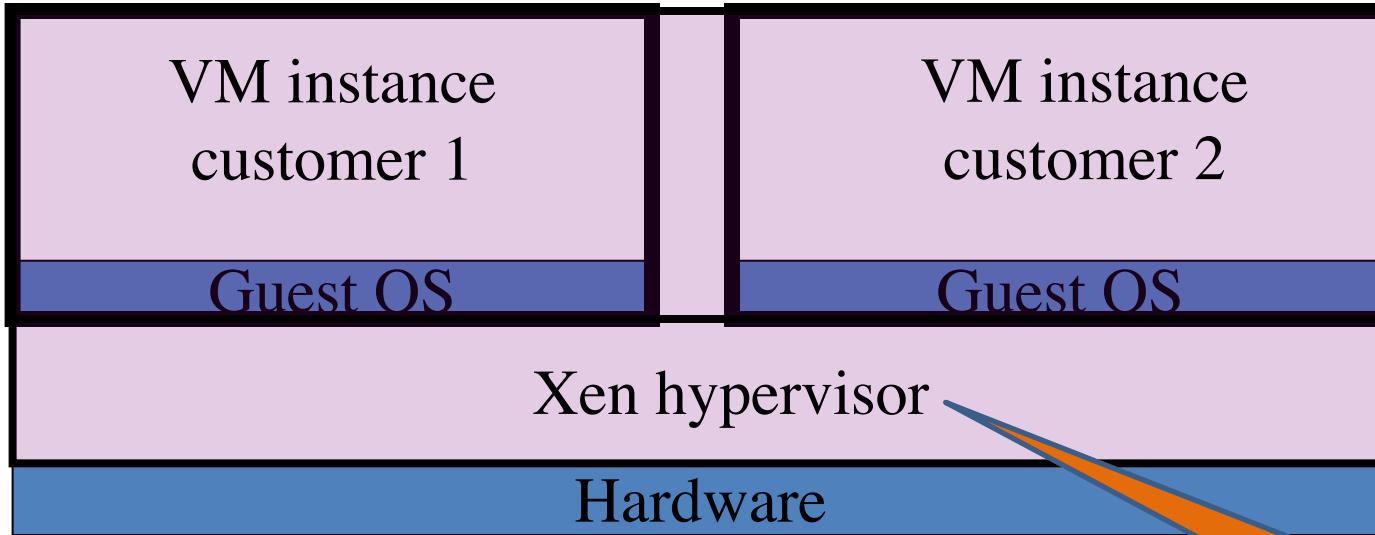
At 1:00am listener does CPU intensive calc. and measures completion time

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

Many covert channels exist in running system:

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

VM isolation in practice: cloud



VMs from different customers may run on the same machine

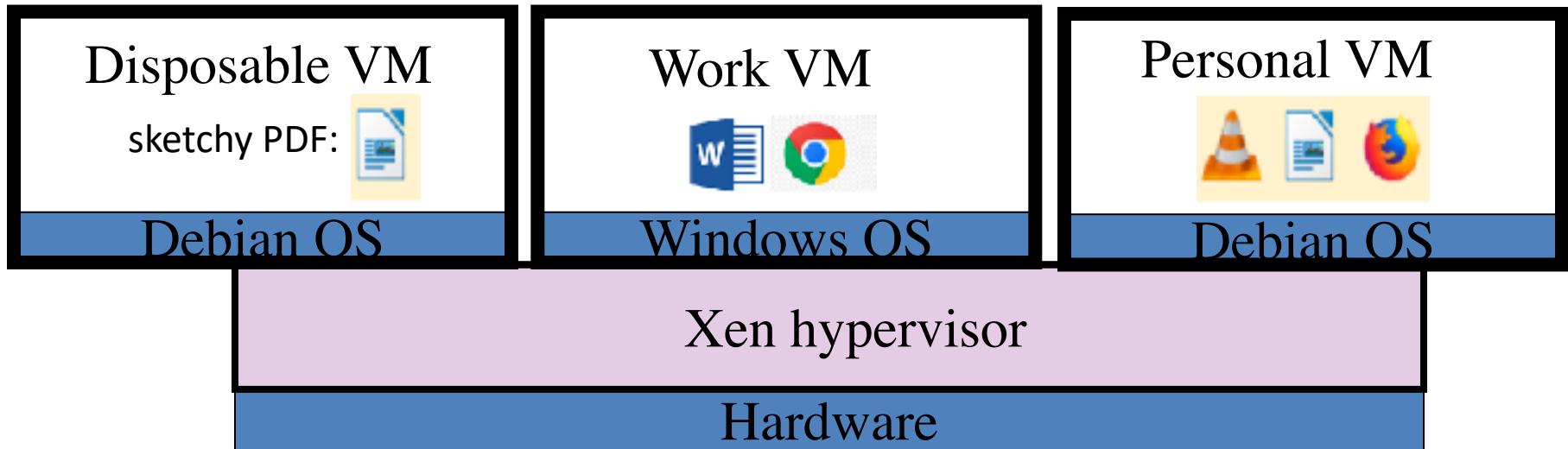
- Hypervisor must isolate VMs ... but some info leaks

Type 1 hypervisor:
no host OS

VM isolation in practice: end-user

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

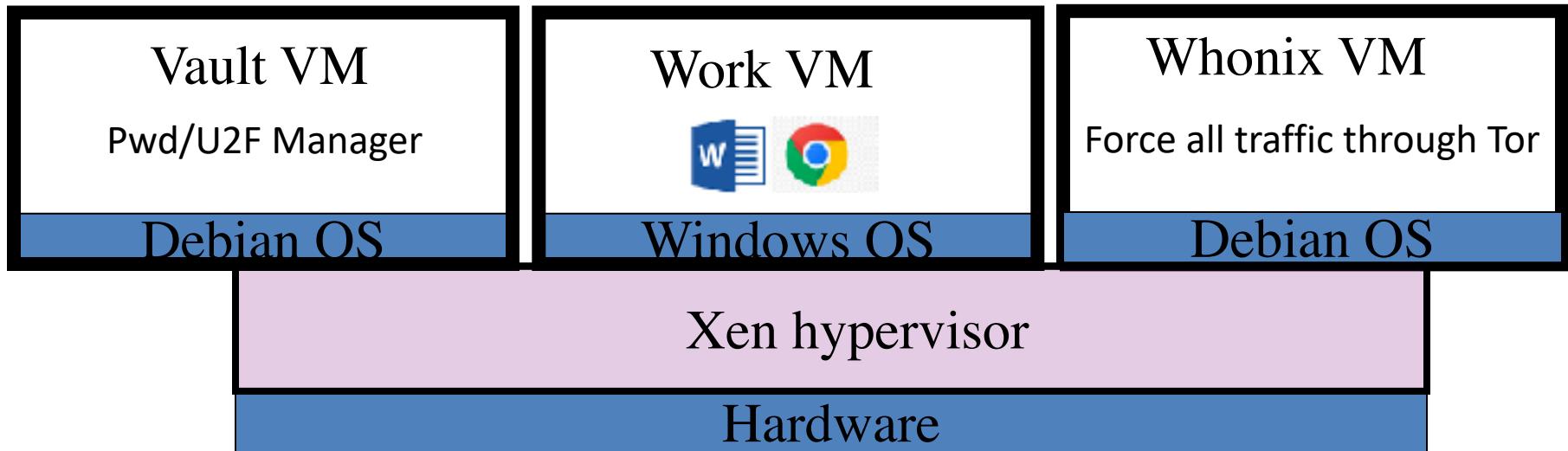
- Runs on top of the Xen hypervisor
- Access to peripherals (mic, camera, usb, ...) controlled by VMs



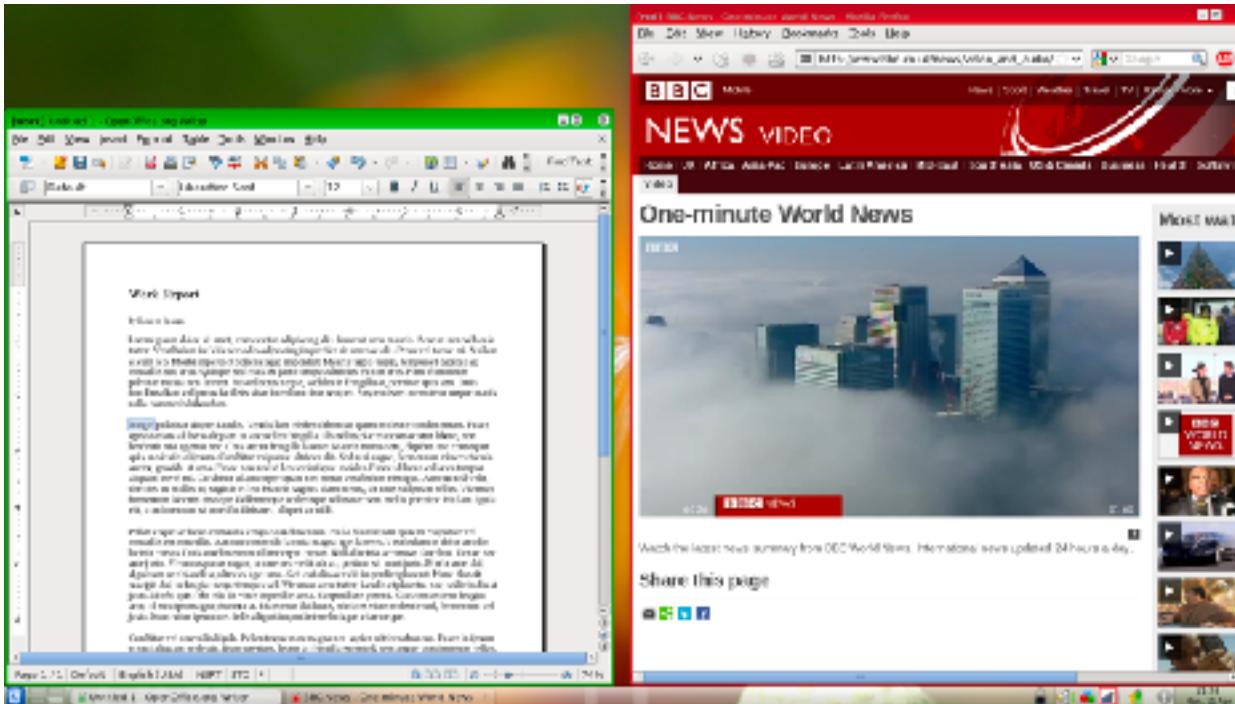
VM isolation in practice: end-user

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

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Every window frame identifies VM source



GUI VM ensures frames are drawn correctly

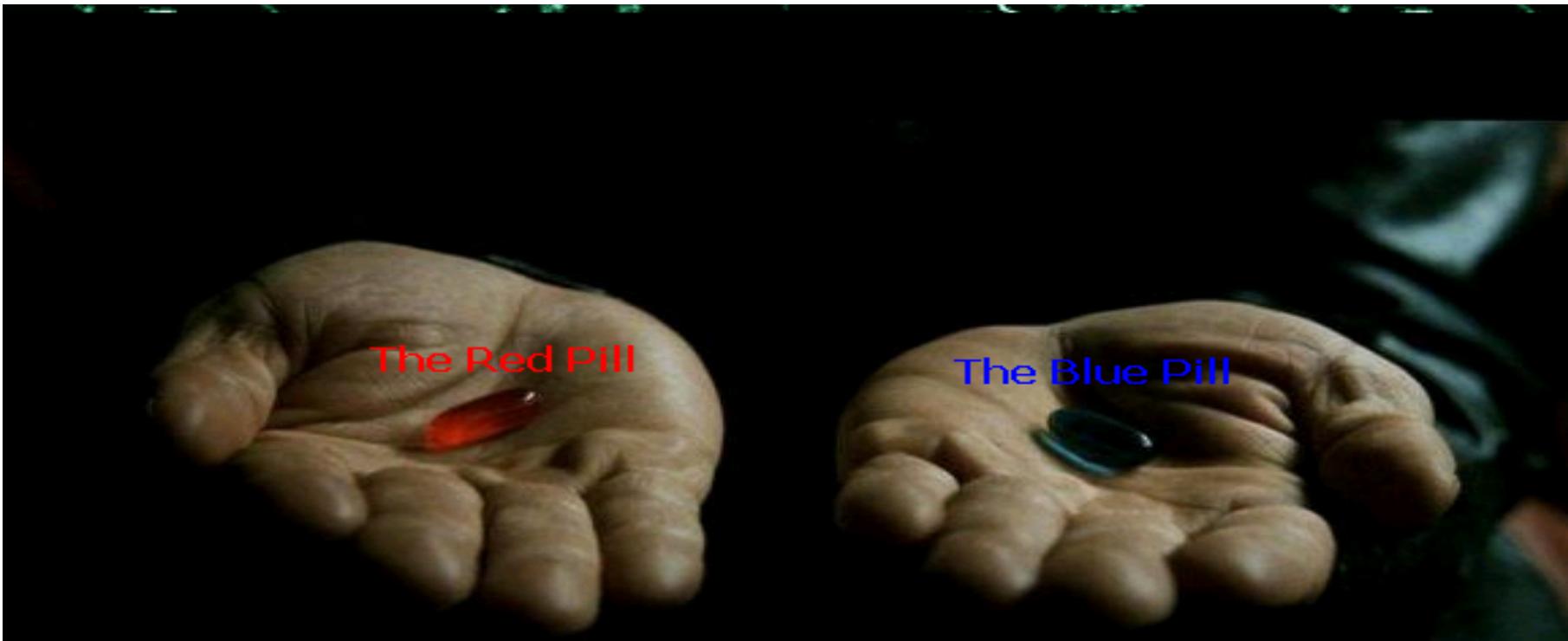
Hypervisor detection

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

- VMs 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 same address space

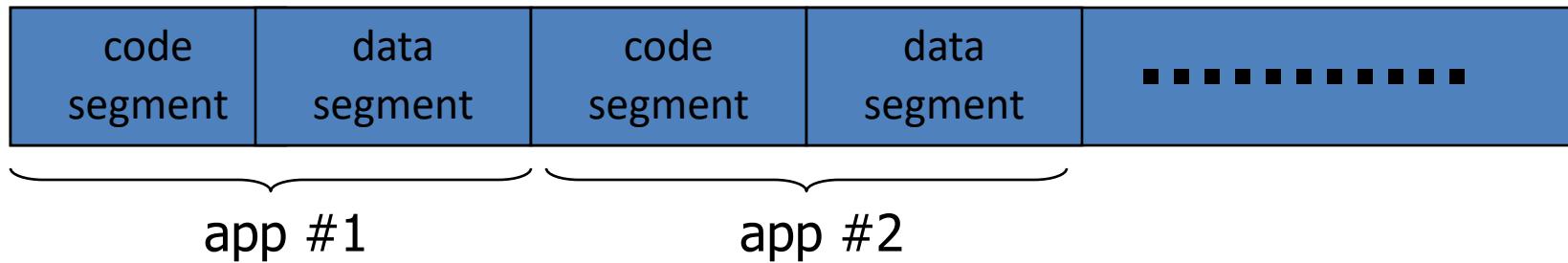
- Kernel module should not corrupt kernel
- Native libraries should not corrupt JVM

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 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:

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
```

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