Virtualization and Security

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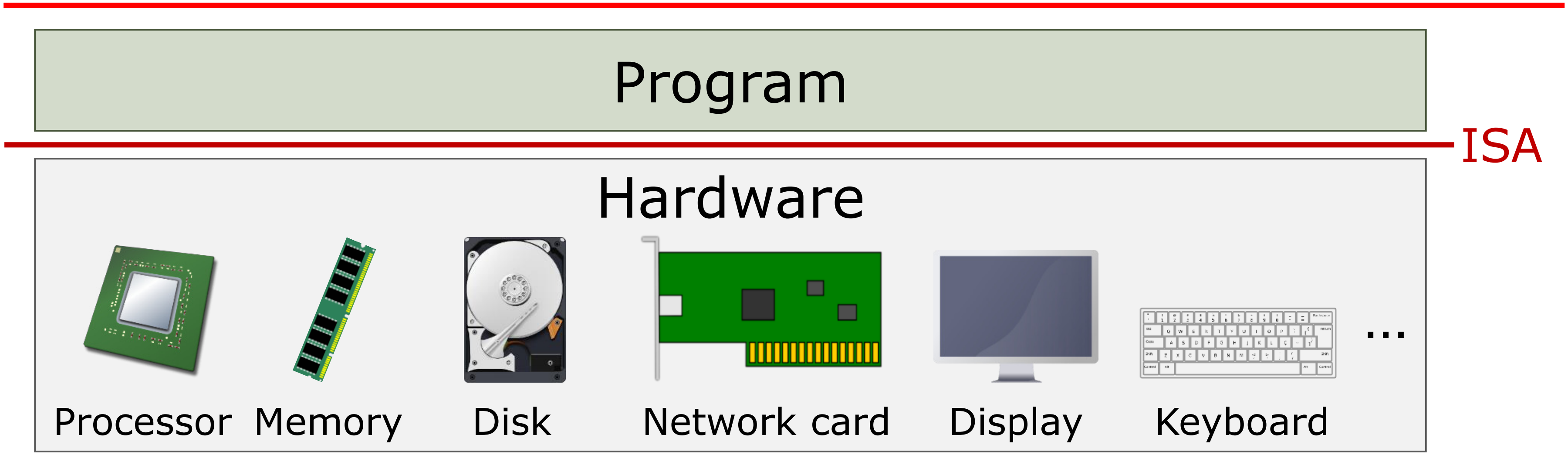
Evolution in Number of Users

IBM 1620 1959	IBM 360 1960s	IBM PC 1980s	Cloud Servers 1990s
			
Single User	Multiple Users	Single User	Multiple Users
Runtime loaded with program	OS for sharing resources	OS for sharing resources	Multiple OSs

Single-Program Machine



Program

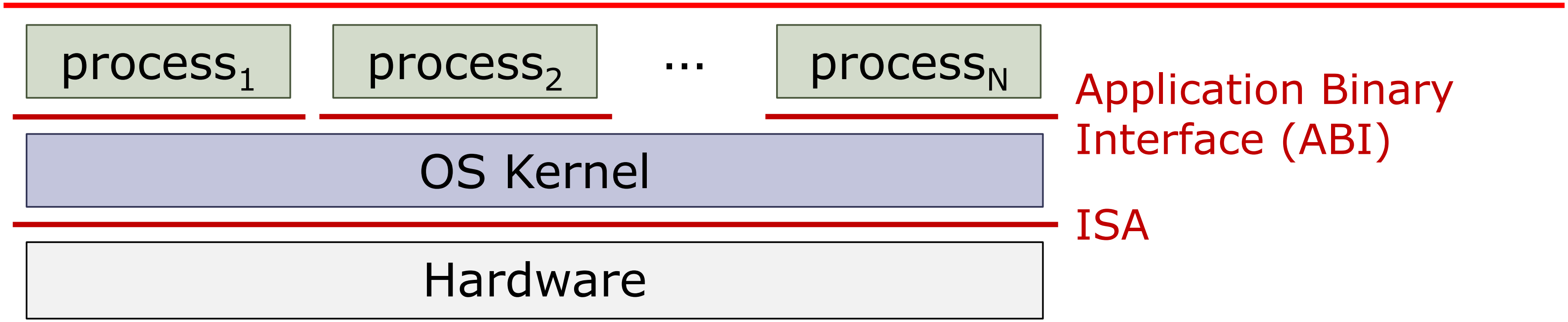
ISA

Hardware

Processor Memory Disk Network card Display Keyboard …

- Hardware executes a single program
- This program has direct and complete access to all hardware resources in the machine
- The instruction set architecture (ISA) is the interface between software and hardware

Operating Systems



process$_1$ process$_2$ … process$_N$

Application Binary Interface (ABI)

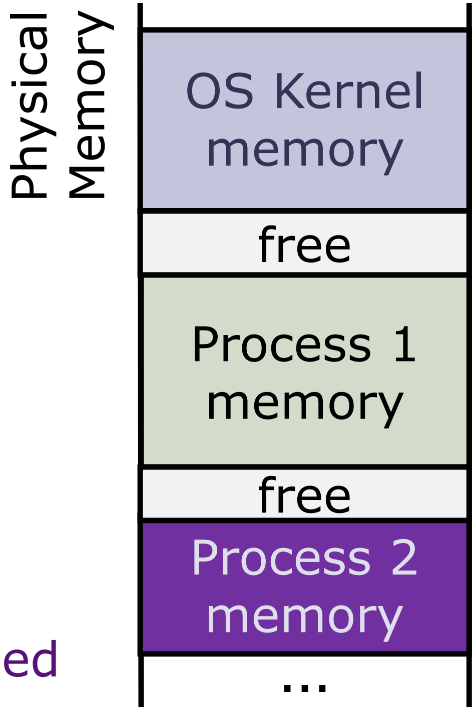
OS Kernel

ISA

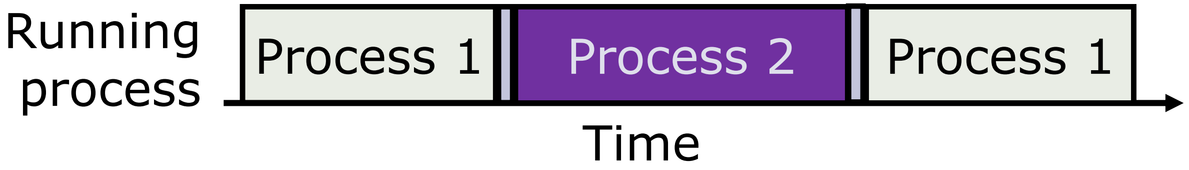
Hardware

- Operating System (OS) goals:
  - Protection and privacy: Processes cannot access each other's data
  - Abstraction: OS hides details of underlying hardware
    - e.g., processes open and access files instead of issuing raw commands to the disk
  - Resource management: OS controls how processes share hardware (CPU, memory, disk, etc.)

Operating System Mechanisms



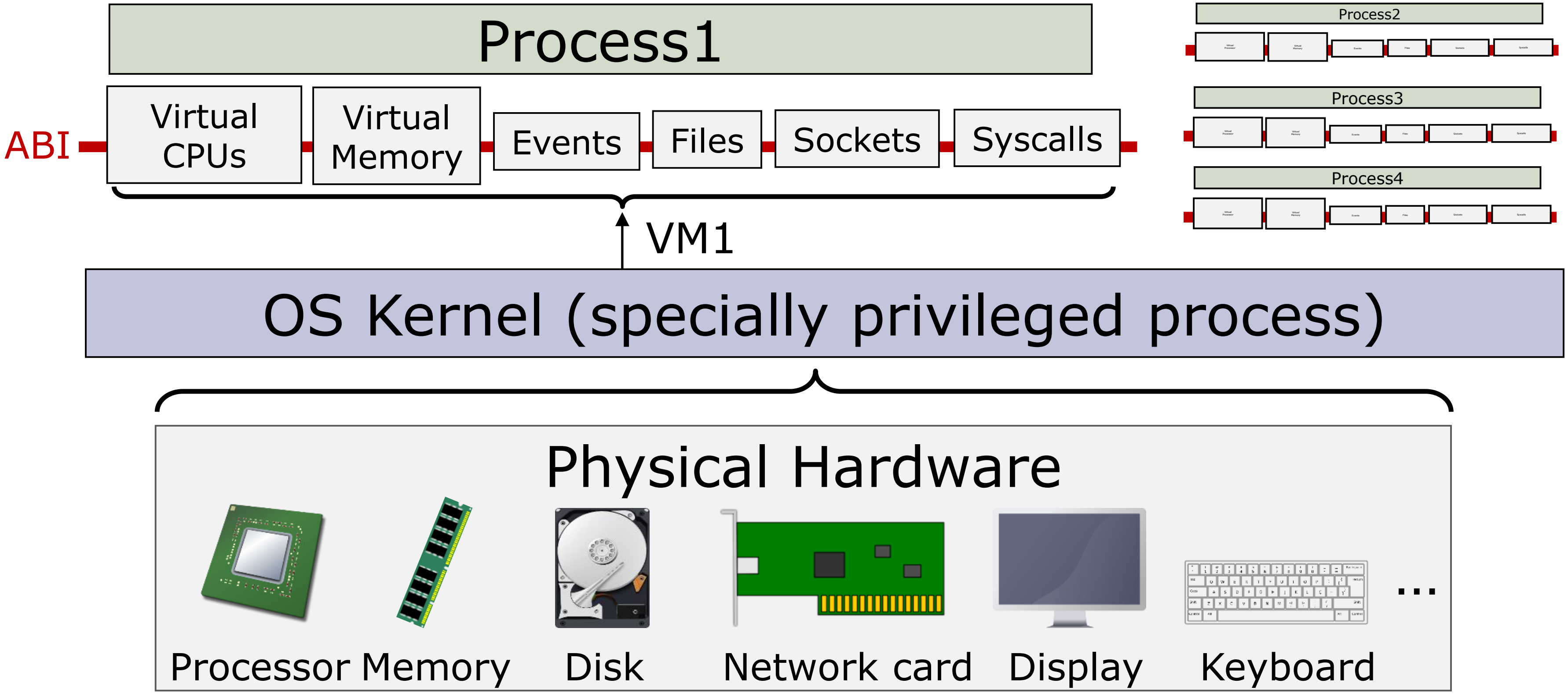
- The OS kernel provides a private address space to each process
  - Each process is allocated space in physical memory by the OS
  - A process is not allowed to access the memory of other processes
- The OS kernel schedules processes into cores
  - Each process is given a fraction of CPU time
  - A process cannot use more CPU time than allowed



- The OS kernel lets processes invoke system services (e.g., access files or network sockets) via system calls

Virtual Machines

- The OS gives a Virtual Machine (VM) to each process
  - Each process believes it runs on its own machine…
  - …but this machine does not exist in physical hardware



Process1

ABI

Virtual CPUs

Virtual Memory

Events

Files

Sockets

Syscalls

VM1

Process2

Process3

Process4

OS Kernel (specially privileged process)

Physical Hardware

Processor

Memory

Disk

Network card

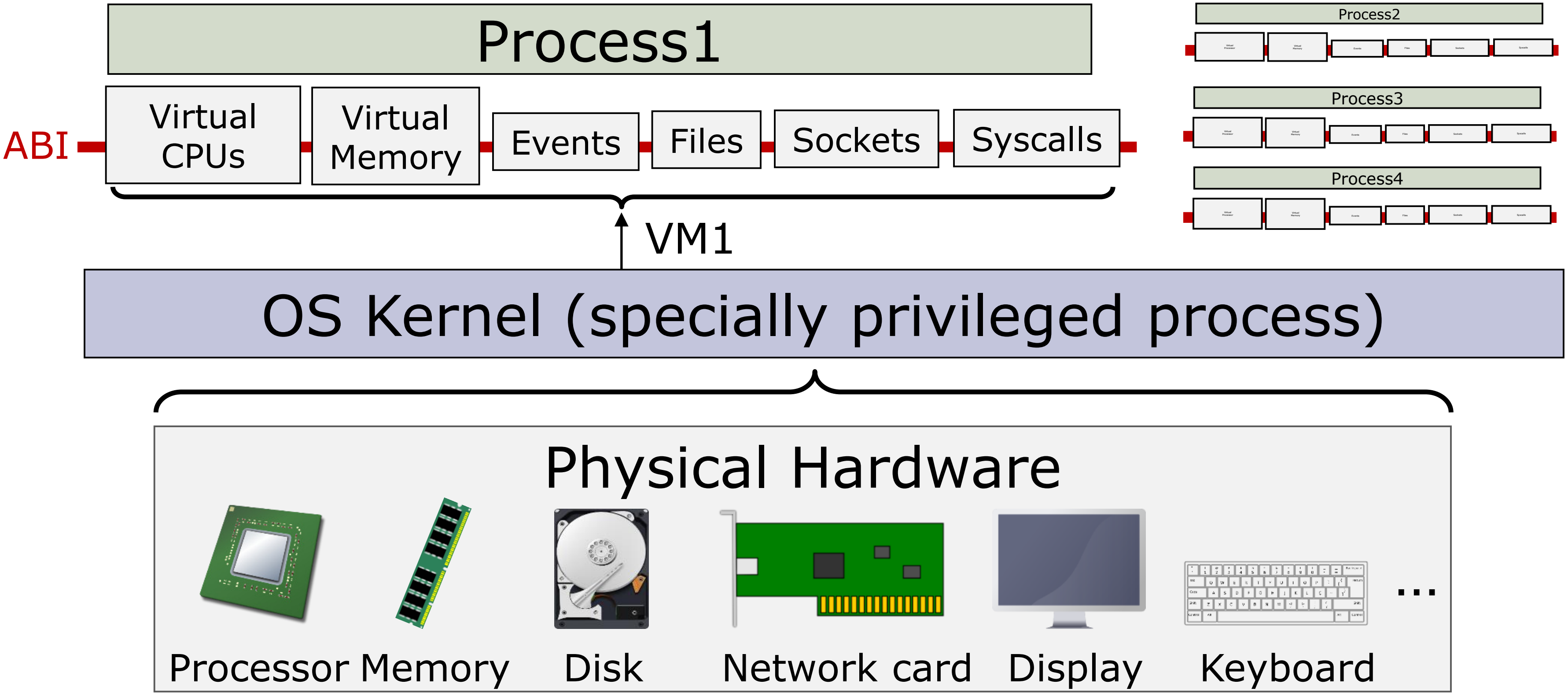
Display

Keyboard

…

Virtual Machines

- A Virtual Machine (VM) is an emulation of a computer system
  - Very general concept, used beyond operating systems



Process1

ABI

Virtual CPUs

Virtual Memory

Events

Files

Sockets

Syscalls

VM1

Process2

Process3

Process4

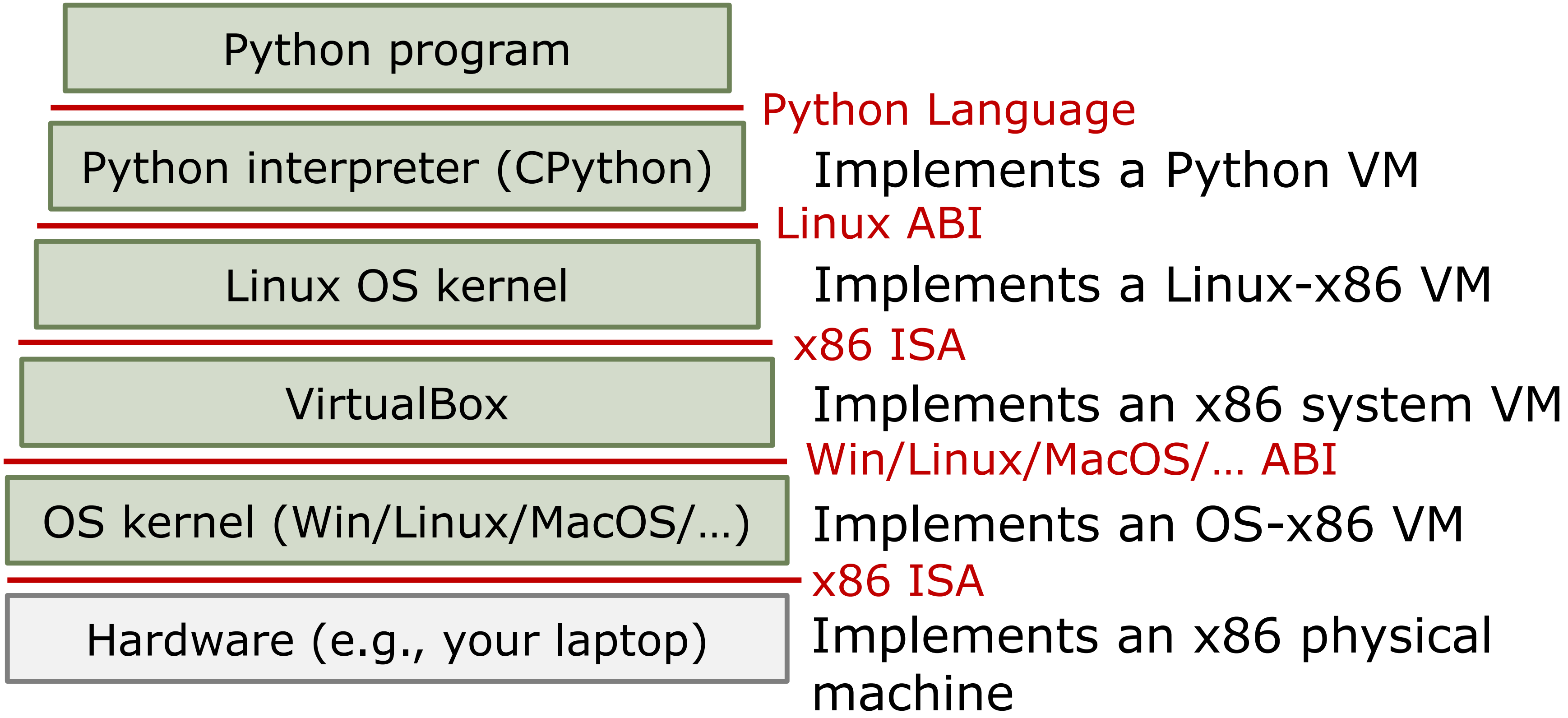
OS Kernel (specially privileged process)

Physical Hardware

Processor Memory Disk Network card Display Keyboard …

Virtual Machines Are Everywhere

- Example: Consider a Python program running on a Linux Virtual Machine



Python program

Python Language

Python interpreter (CPython)

Implements a Python VM

Linux ABI

Linux OS kernel

Implements a Linux-x86 VM

x86 ISA

VirtualBox

Implements an x86 system VM

Win/Linux/MacOS/… ABI

OS kernel (Win/Linux/MacOS/…)

Implements an OS-x86 VM

x86 ISA

Hardware (e.g., your laptop)

Implements an x86 physical machine

Implementing Virtual Machines

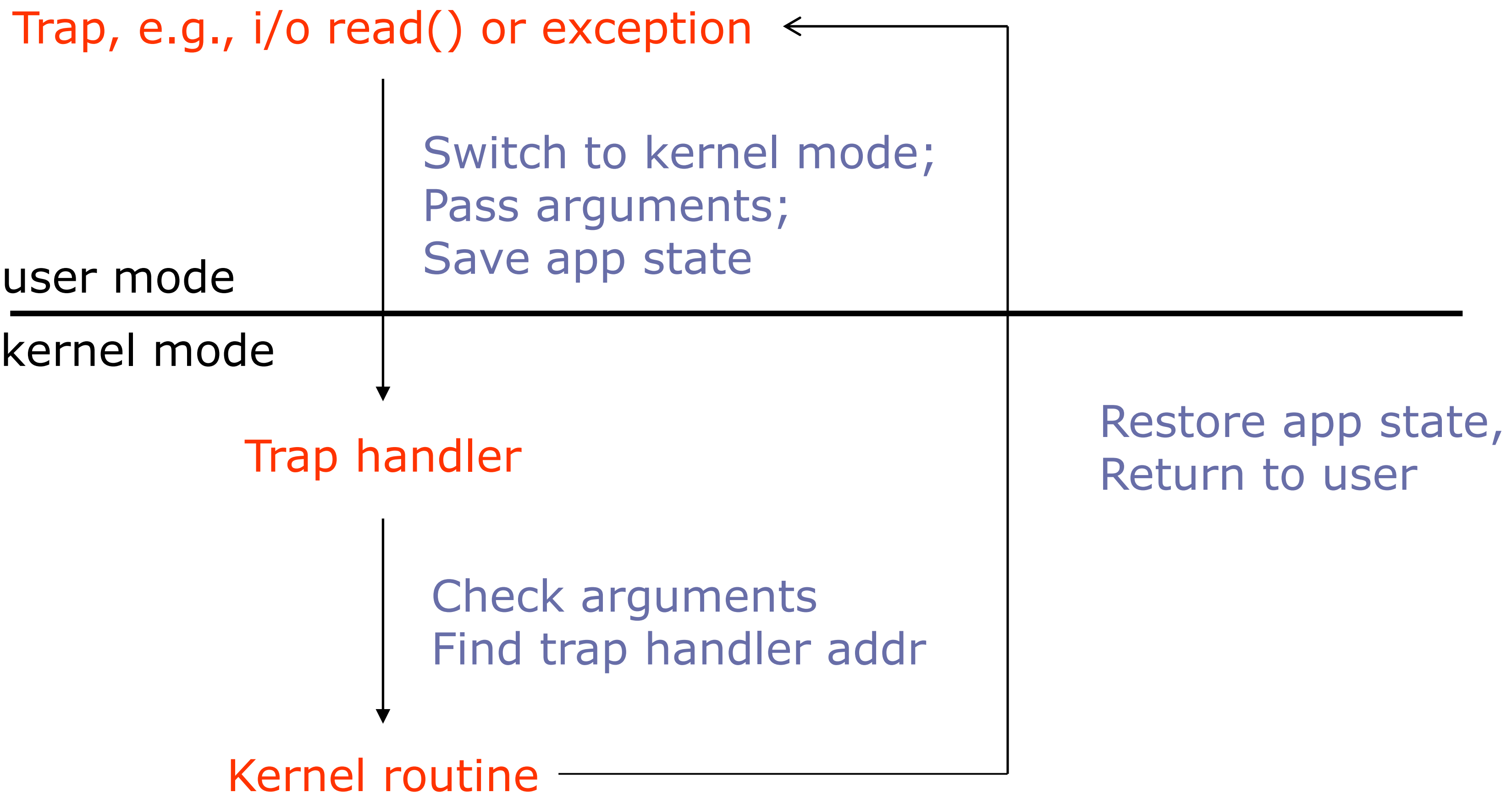
- Virtual machines can be implemented entirely in software, but at a performance cost
  - e.g., Python programs are 10-100x slower than native Linux programs due to Python interpreter overheads

- We want to support virtual machines with minimal overheads → need hardware support!

ISA Extensions to Support OS

- Two modes of execution: user and supervisor
  - OS kernel runs in supervisor mode
  - All other processes run in user mode
- Privileged instructions and registers that are only available in supervisor mode
- Traps (exceptions) to safely transition from user to supervisor mode
- Virtual memory to provide private address spaces and abstract the storage resources of the machine

Process Mode Switching



Trap, e.g., i/o read() or exception

Switch to kernel mode;
Pass arguments;
Save app state

user mode

kernel mode

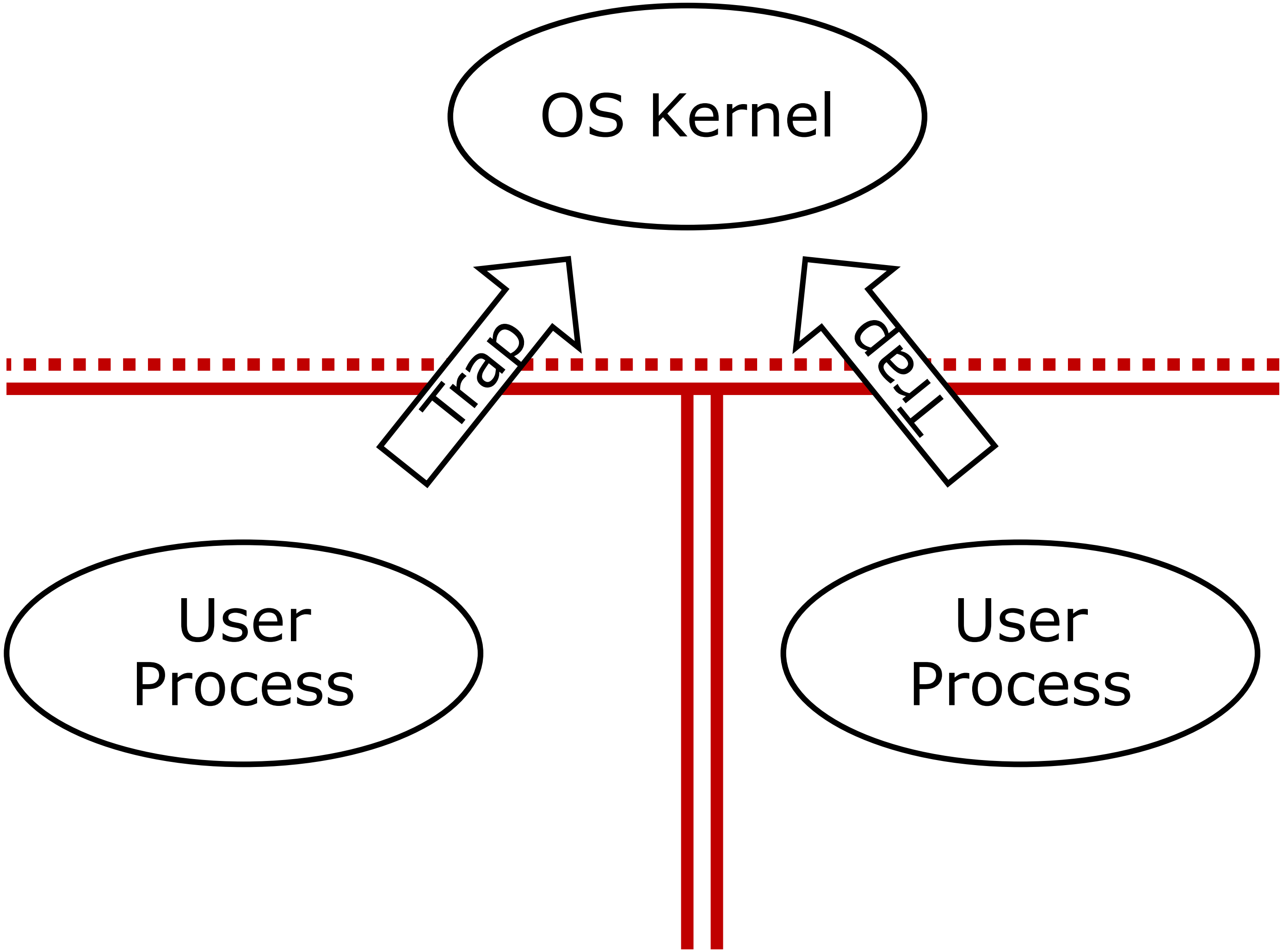
Trap handler

Restore app state,
Return to user

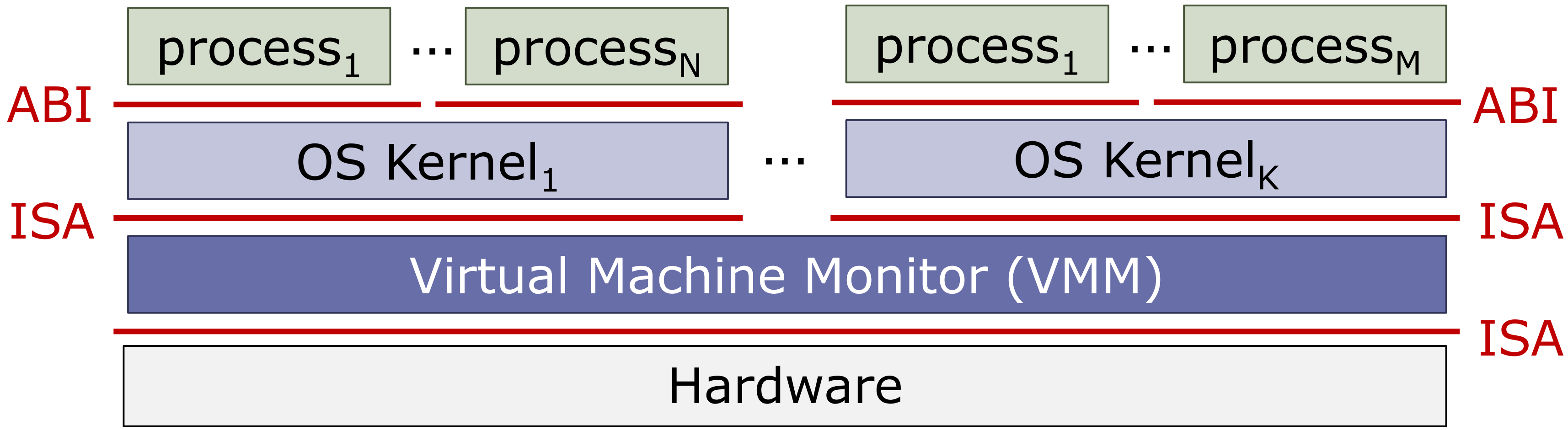
Check arguments
Find trap handler addr

Kernel routine

Protection – Single OS



Supporting Multiple OSs



- A VMM (aka Hypervisor) provides a system virtual machine to each OS
- VMM can run directly on hardware (as above) or on another OS
  - Precisely, VMM can be implemented against an ISA (as above) or a process-level ABI. Who knows what lays below the interface…

Motivation for Multiple OSs

Some motivations for using multiple operating systems on a single computer:

- Allows use of capabilities of multiple distinct operating systems
- Allows different users to share a system while using completely independent software stacks
- Allows for load balancing and migration across multiple machines
- Allows operating system development without making entire machine unstable or unusable

Virtualization Nomenclature

From (Machine we are attempting to execute)

- Guest
- Client
- Foreign ISA

To (Machine that is doing the real execution)

- Host
- Target
- Native ISA

Virtual Machine Requirements
[Popek and Goldberg, 1974]

- Equivalence/Fidelity: A program running on the VMM should exhibit a behavior essentially identical to that demonstrated when running on an equivalent machine directly.
- Resource control/Safety: The VMM must be in complete control of the virtualized resources.
- Efficiency/Performance: A statistically dominant fraction of machine instructions must be executed without VMM intervention.

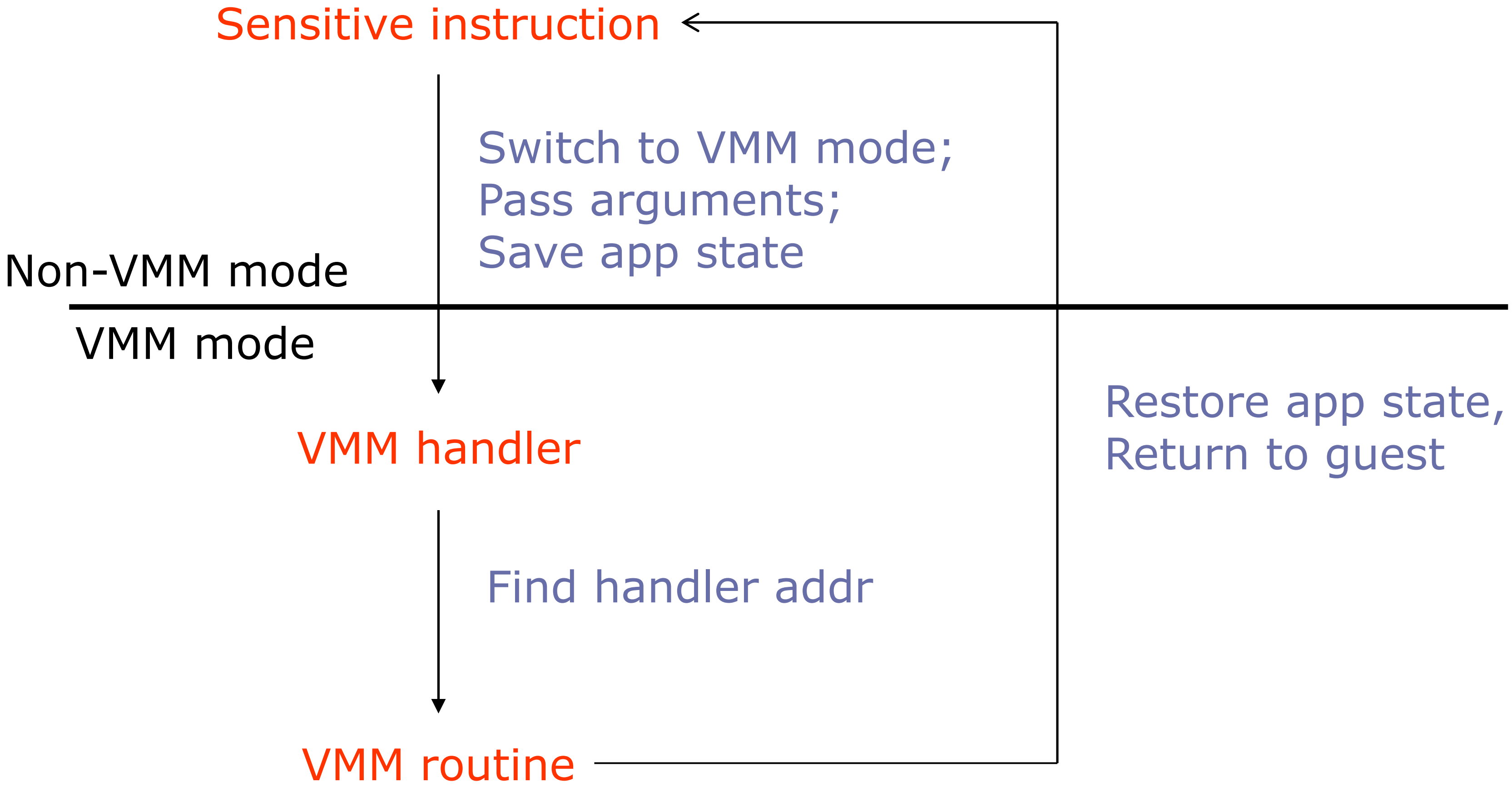
Virtual Machine Requirements
[Popek and Goldberg, 1974]

Classification of instructions into 3 groups:

- Privileged instructions: Instructions that trap if the processor is in user mode and do not trap if it is in a more privileged mode.
- Control-sensitive instructions: Instructions that attempt to change the configuration of resources in the system.
- Behavior-sensitive instructions: Those whose behavior depends on the configuration of resources, e.g., mode

Building an *effective* VMM for an architecture is possible if the set of sensitive instructions is a subset of the set of privileged instructions.

Sensitive instruction handling


Sensitive instruction

Switch to VMM mode;
Pass arguments;
Save app state

Non-VMM mode

VMM mode

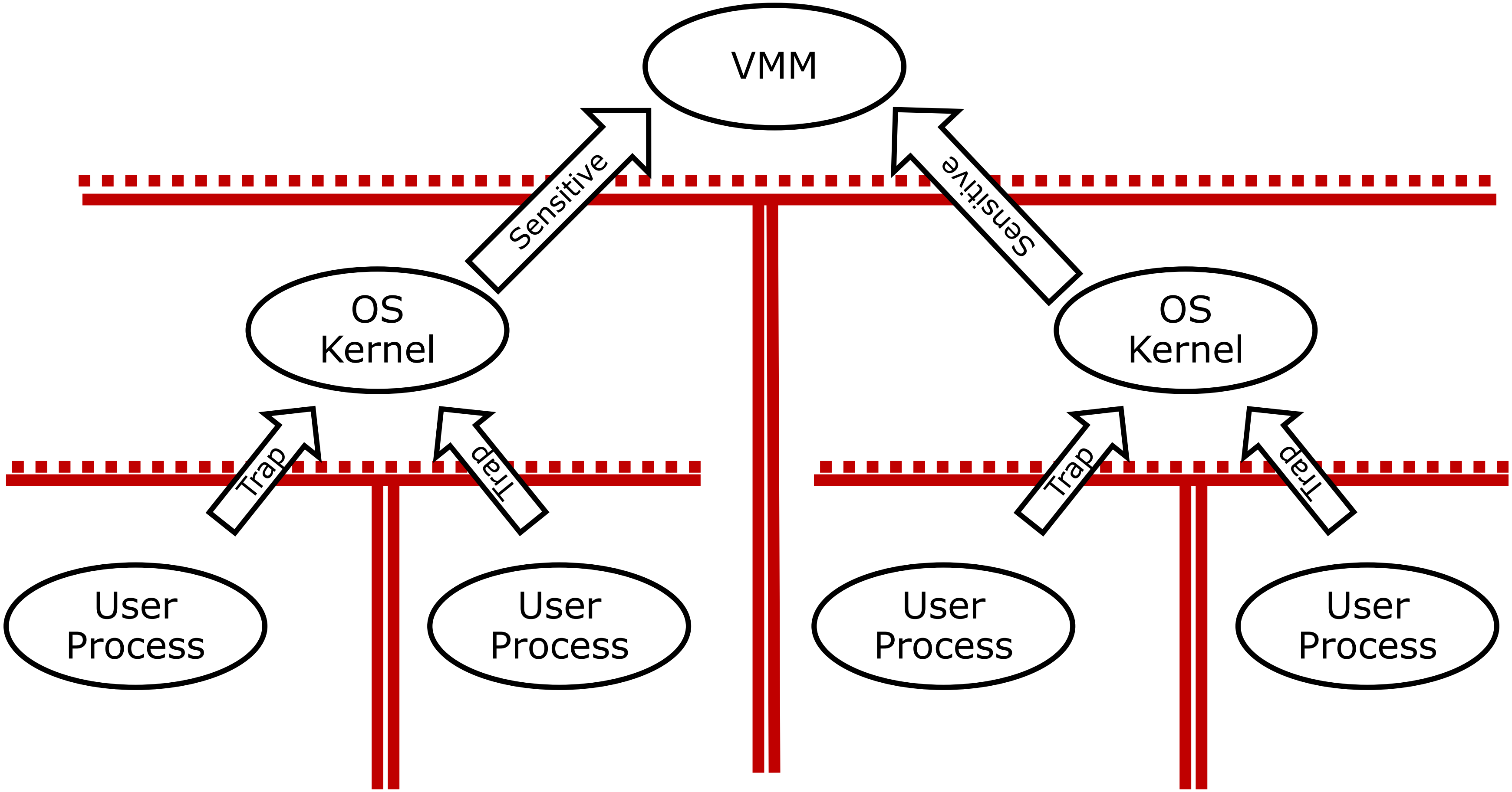
VMM handler

Restore app state,
Return to guest

Find handler addr

VMM routine

Protection – Multiple OS



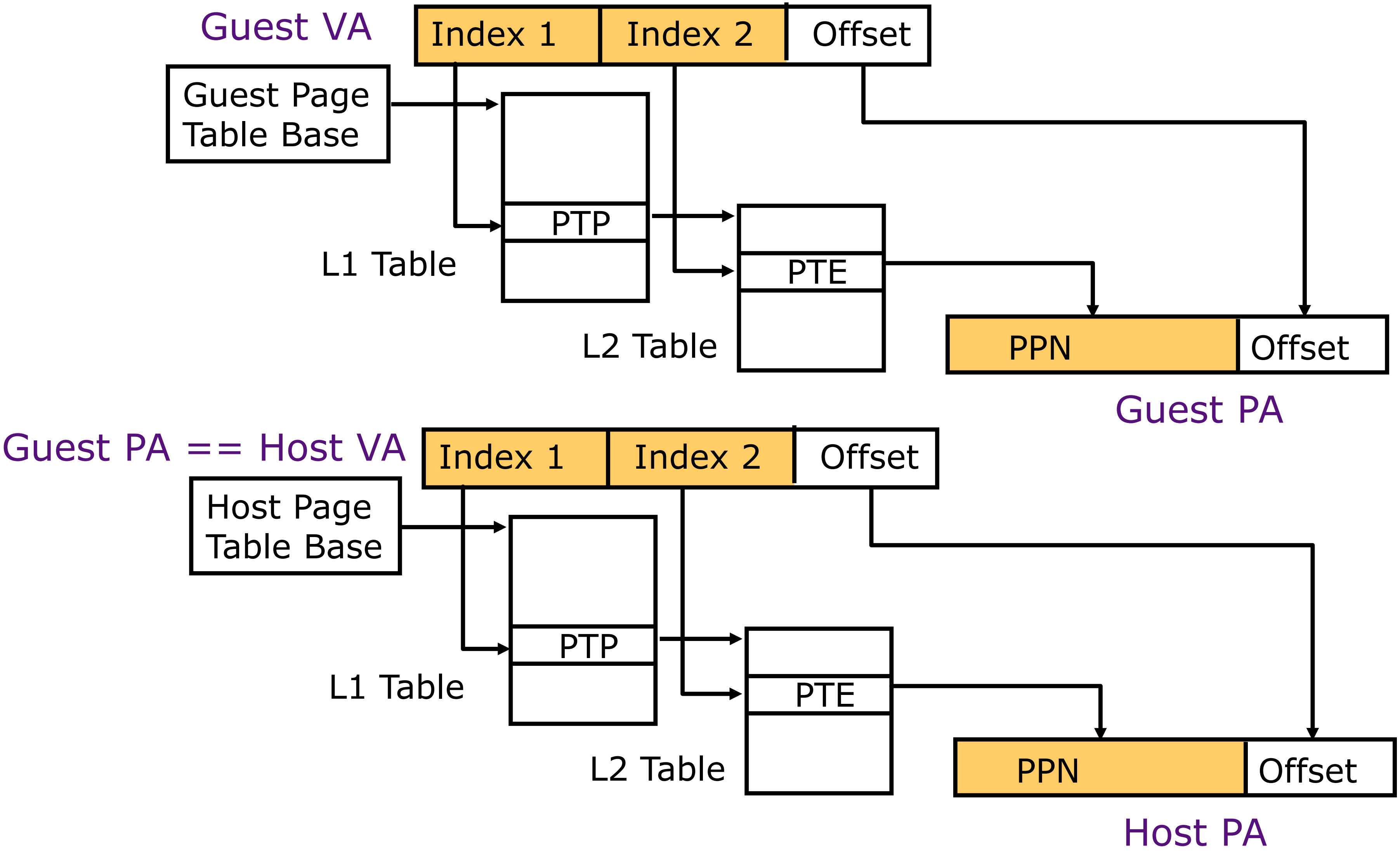
Virtual Memory Operations

TLB can be designed to translate guest virtual addresses (gVA) to a host physical address (hPA), but…

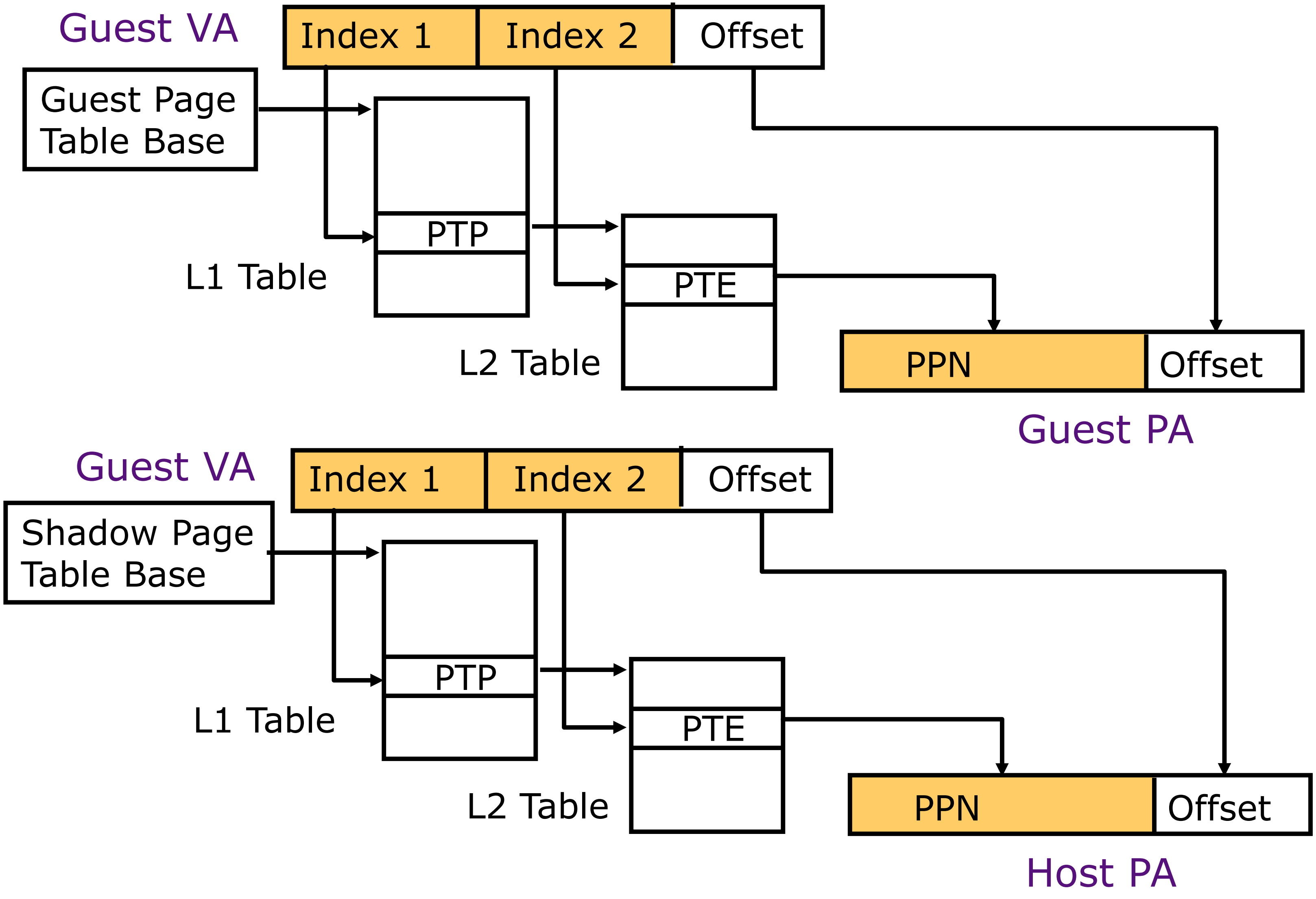
- TLB misses are a ‘sensitive’ operation
- TLB misses happen very very frequently

- So how expensive are TLB fills?

Nested Page Tables



Shadow Page Tables



Nested vs Shadow Paging

	Native	Nested Paging	Shadow Paging
TLB Hit	VA->PA	gVA->hPA	gVA->hPA
TLB Miss (max)	4	24	4
PTE Updates	Fast	Fast	Uses VMM

On x86-64

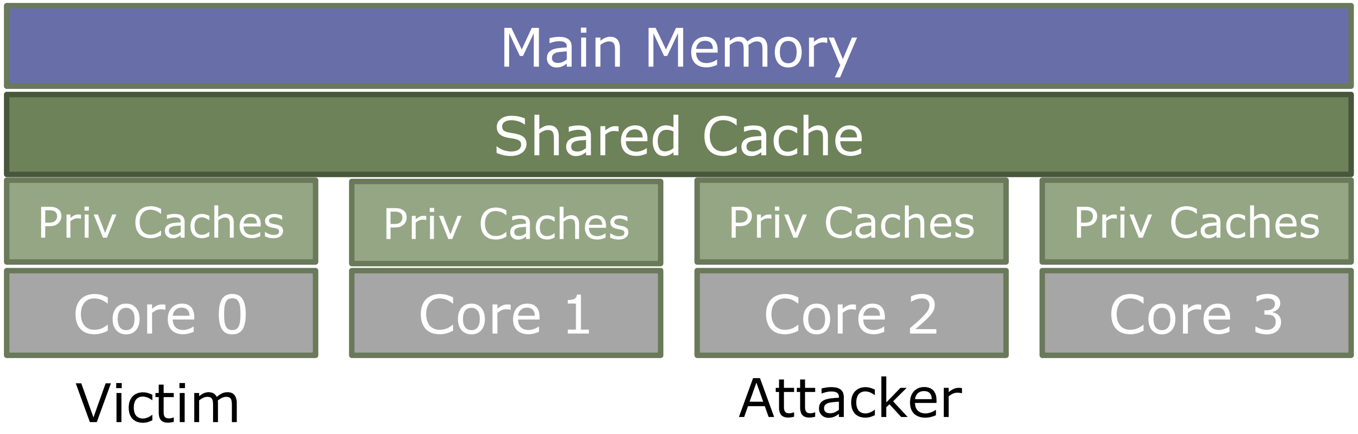
Security and Side Channels

- ISA and ABI are timing-independent interfaces
  - Specify *what* should happen, not *when*

- Hardware isolation mechanisms like virtual memory guarantee that architectural state will not be directly exposed to other processes…

- …but timing and other implementation details (e.g., microarchitectural state, power, etc.) may be used as side channels to leak information!

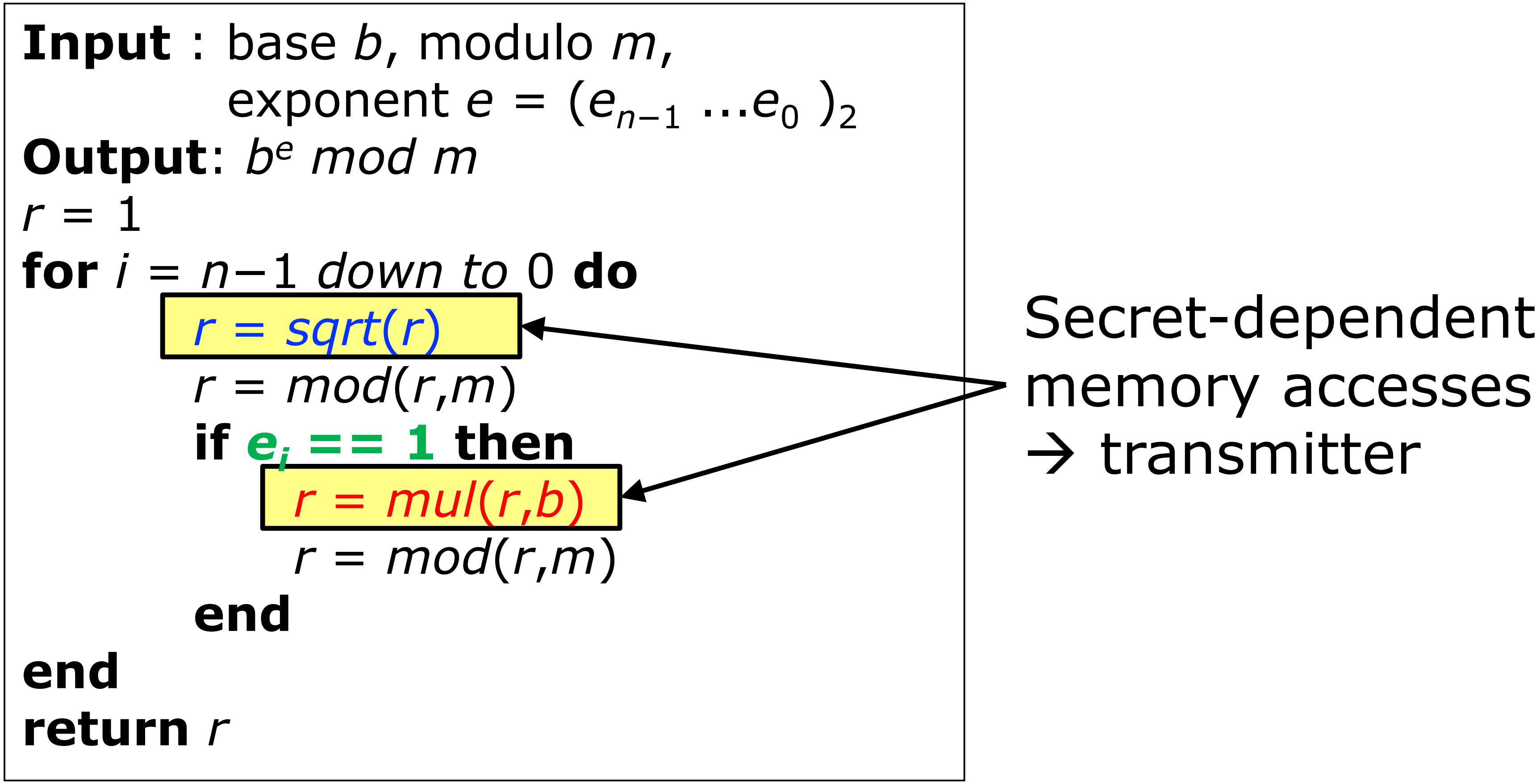
Cache-Based Side Channels



- Attacker can infer shared cache behavior of victim
  - e.g., prime+probe attack: Attacker fills cache with own data, then times accesses to data to see which hit and miss, inferring which lines the victim is using
  - Leaks address-dependent information, e.g., RSA [Percival 2005] and AES keys [Osvik et al. 2005]
- *Microarch side channels among threads running on same SMT core?*

Example: Side Channel in RSA

- Assume square-and-multiply based exponentiation

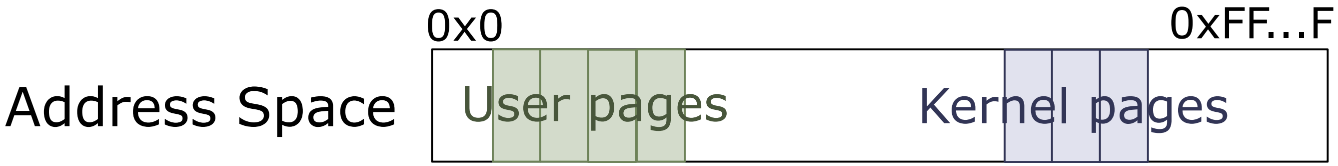


```
Input : base $b$, modulo $m$,
        exponent $e = (e_{n-1} \ldots e_0)_2$
Output: $b^e \bmod m$
$r = 1$
for $i = n-1$ down to 0 do
    $r = sqrt(r)$
    $r = mod(r,m)$
    if $e_i == 1$ then
        $r = mul(r,b)$
        $r = mod(r,m)$
    end
end
return $r$
```

Secret-dependent memory accesses → transmitter

Exploiting Speculative Execution in Side-Channel Attacks

- OoO cores run instructions speculatively and out of order
- Problem: Speculative instructions can change microarchitectural state → can leak data via side channel
- Example: In x86, process page table can have kernel pages, but kernel pages only accessible in kernel mode



  - Avoids switching page tables on context switches
  - *What does the following code do when run in user mode?*

```
val = *kernel_address;
```

Meltdown

[Lipp et al. 2018]

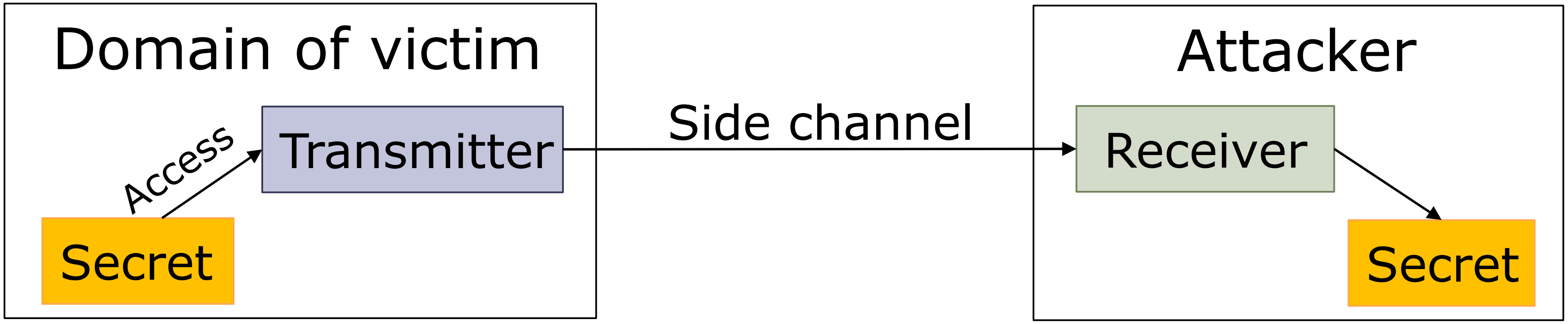
1. Setup: Attacker allocates 256-line `probe_array`, flushes all its cache lines
2. Transmit: Attacker executes

```
uint8_t byte = *kernel_address;
probe_array[byte] = 1;
```

3. Receive: After handling protection fault, attacker times accesses to all cache lines of `probe_array`, finds which one hits → recovers `byte`

- Result: Attacker can read arbitrary kernel data!
  - For higher performance, use transactional memory (protection fault aborts transaction on exception instead of invoking kernel)
  - Mitigation: Do not map kernel data in user page tables

General Attack Schema
[Belay, Devadas, Emer]



- Types of transmitter:
  1. Pre-existing (the victim itself leaks secret, e.g., RSA/AES keys)
  2. Programmed by attacker (e.g., Meltdown)
  3. Synthesized from existing victim code by attacker (e.g., Spectre)

Spectre variant 1 — Exploiting Conditional Branches [Kocher et al. 2018]

- Consider the following kernel code, e.g., in a system call

```
if (x < array1_size)
  y = array2[array1[x] * 4096];
```

1. Setup: Attacker invokes this kernel code with small values of `x` to train the branch predictor to taken
2. Transmit: Attacker invokes this code with an out-of-bounds `x`, so that `&array1[x]` maps to some desired kernel address. Core mispredicts branch, fetches `array2[array1[x] * 4096]`'s line into the cache.
3. Receive: Attacker probes cache to infer which line of `array2` was fetched, learns data at kernel address
   - array2 may or may not be accessible to attacker (can use prime+probe)

Spectre variant 2—Branch Target Injection [Kocher et al. 2018]

- Assume the BTB stores partial tags but full target PCs. How can this be exploited?
  1. Setup: Attacker chooses any jump in kernel code, mistrains BTB so that it predicts a target PC under the control of the attacker that leaks information, e.g.,

```
uint8_t byte = *kernel_address;
probe_array[byte] = 1;
```

  2. Transmit & receive: Like in Spectre v1
- Most BTBs store partial tags and targets…
  - Hard to get BTB to jump from a kernel address to a far-away user address
- But most cores add an indirect branch predictor that stores full targets (e.g., to predict virtual function calls)
  - Spectre v2 exploits this predictor instead

Spectre variants and mitigations

- Spectre relies on speculative execution, not late exception checks → Much harder to fix than Meltdown
- Several other Spectre variants reported
  - Leveraging the speculative store buffer, return address stack, leaking privileged registers, etc.
- Can attack any type of VM, including OSs, VMMs, JavaScript engines in browsers, and the OS network stack (NetSpectre)
- Short-term mitigations:
  - Microcode updates (disable sharing of speculative state when possible)
  - OS and compiler patches to selectively avoid speculation
- Long-term mitigations:
  - Disabling speculation?
  - Closing side channels?

Thank you!