2550 Intro to cybersecurity

L20: systems

abhi shelat

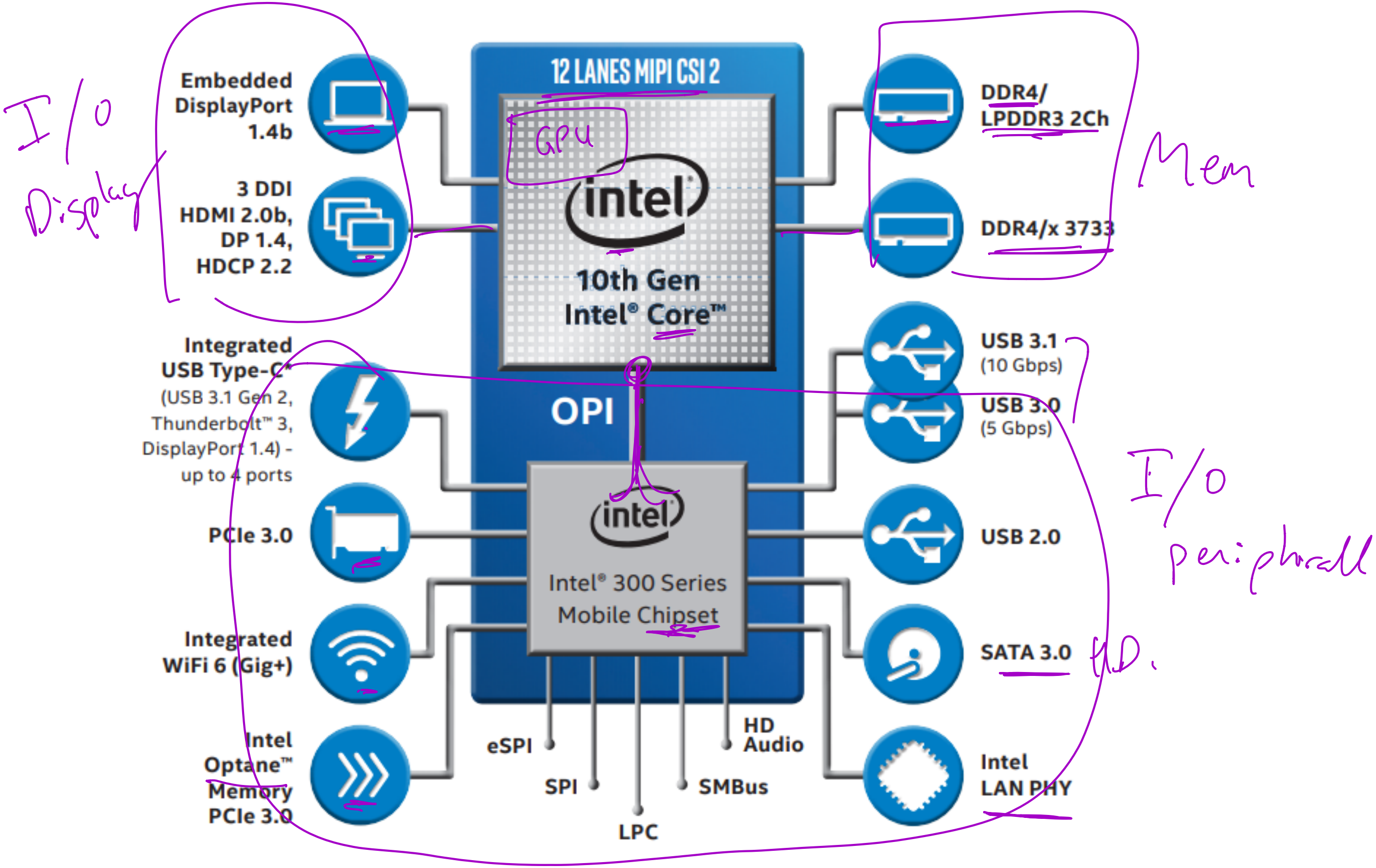
Threat Model
Principles
Intro to System Architecture
Hardware Support for Isolation
Examples

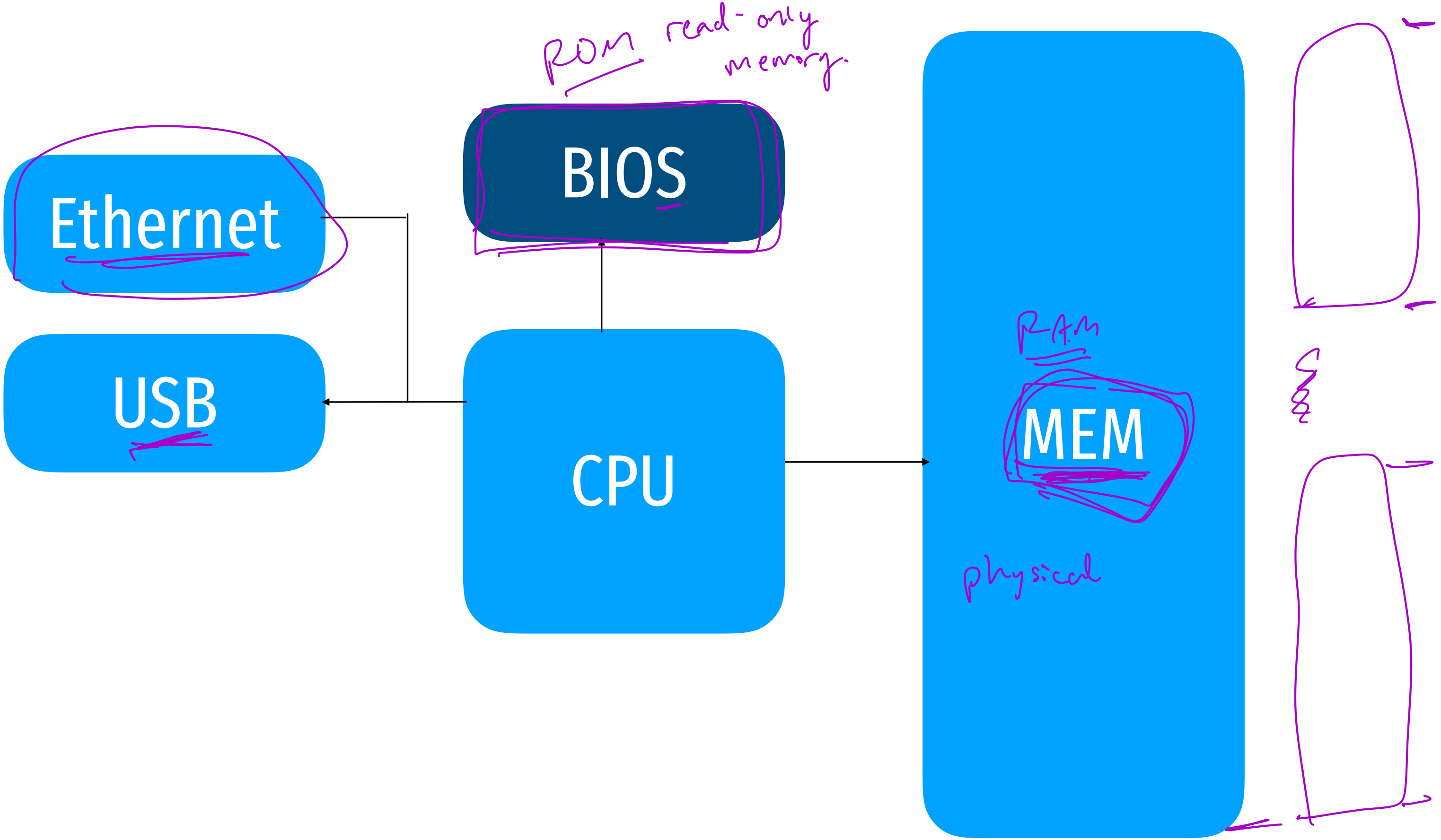
- UNIX - ATT
  Berkeley

- IBM Sys 360

1980 era

PC architecture.


12 LANES MIPI CSI 2
intel
10th Gen
Intel® Core™
OPI
intel
Intel® 300 Series
Mobile Chipset
Embedded
DisplayPort
1.4b
3 DDI
HDMI 2.0b,
DP 1.4,
HDCP 2.2
Integrated
USB Type-C*
(USB 3.1 Gen 2,
Thunderbolt™ 3,
DisplayPort 1.4) -
up to 4 ports
PCIe 3.0
Integrated
WiFi 6 (Gig+)
Intel
Optane™
Memory
PCIe 3.0
eSPI
SPI
LPC
SMBus
HD
Audio
DDR4/
LPDDR3 2Ch
DDR4/x 3733
USB 3.1
(10 Gbps)
USB 3.0
(5 Gbps)
USB 2.0
SATA 3.0
Intel
LAN PHY
I/O
Display
GPU
Mem
I/O
peripherall
H.D.


ROM
read-only memory
BIOS
Ethernet
USB
CPU
RAM
MEM
physical

What is Memory?

Memory is essentially a spreadsheet with a single column

- Every row has a number, called an address
- Every cell holds 1 byte of data

Address	Contents
114	
113	[illegible]
112	[illegible]
111	[illegible]
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109	
108	[illegible]
107	[illegible]
106	[illegible]
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~~32-bit~~

64-bit

Integers are typically four bytes

Address	Contents
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112	0
111	0
110	8
109	
108	[illegible]
107	[illegible]
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int my_num = 8;
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All data and running code are held in memory

```
int my_num = 8;

String my_str = "ABC";
while (my_num > 0) my_num--;
```

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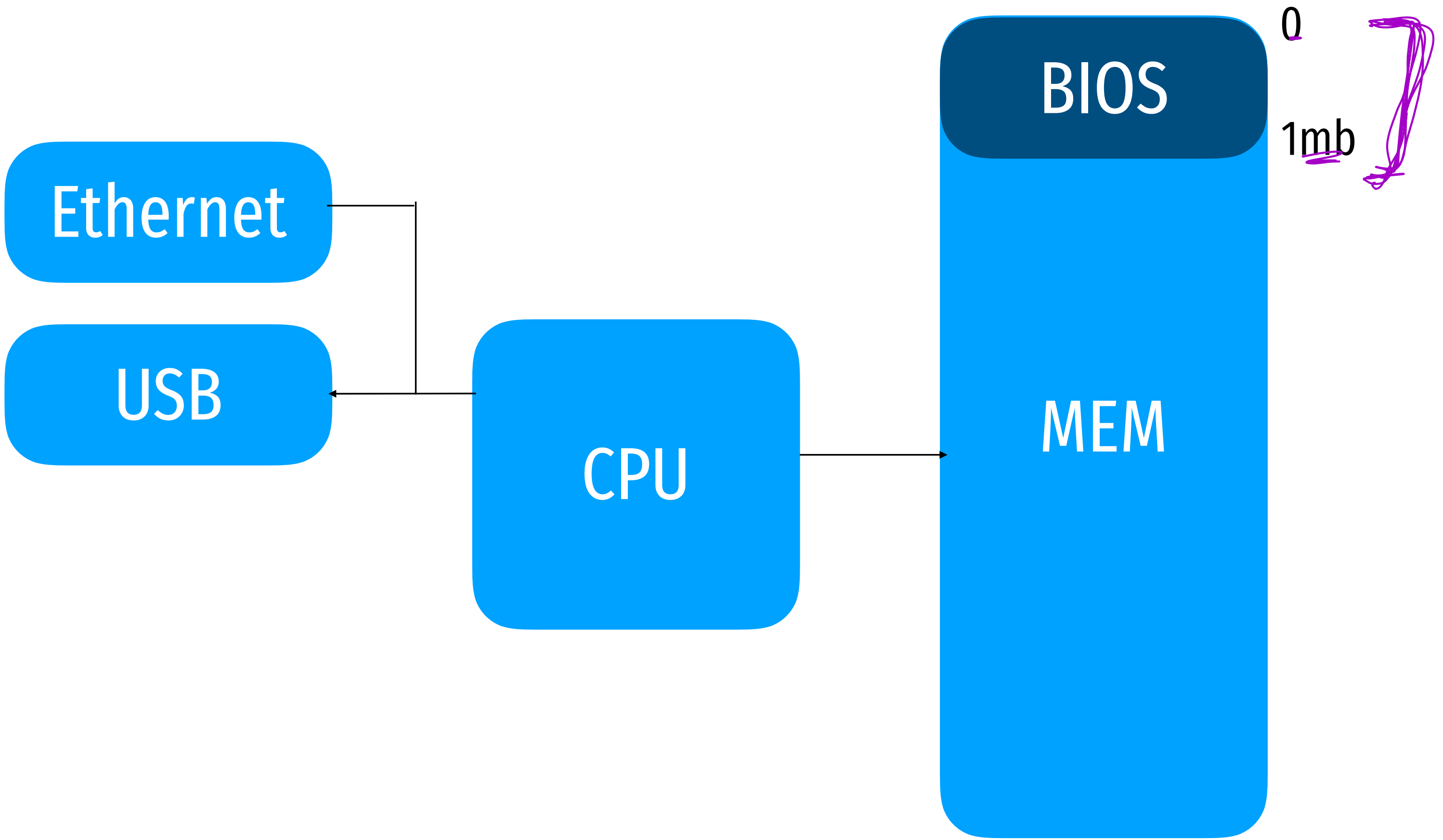
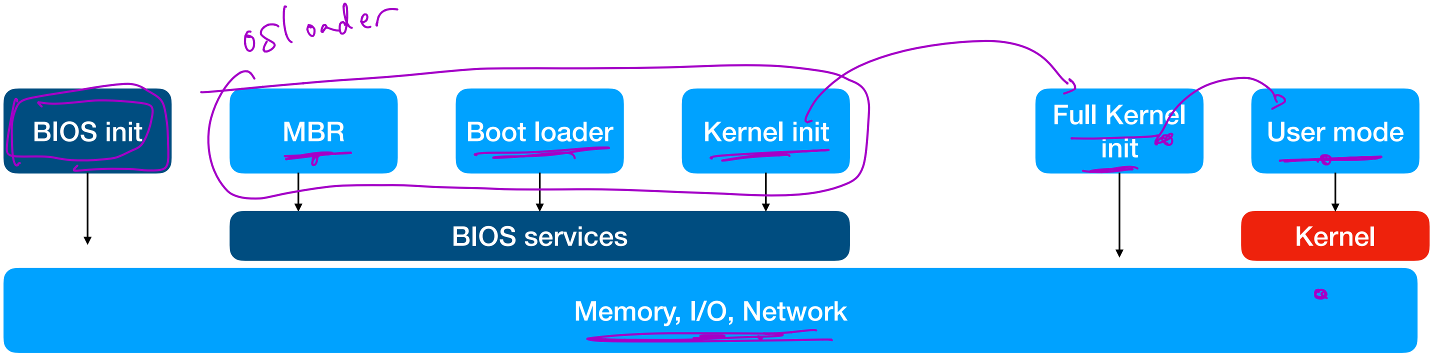
How does a computer boot?

https://youtu.be/MsKb0gR-4AM?t=36


Ethernet
USB
CPU
BIOS
MEM
0
1mb

System Model: how does a computer boot?

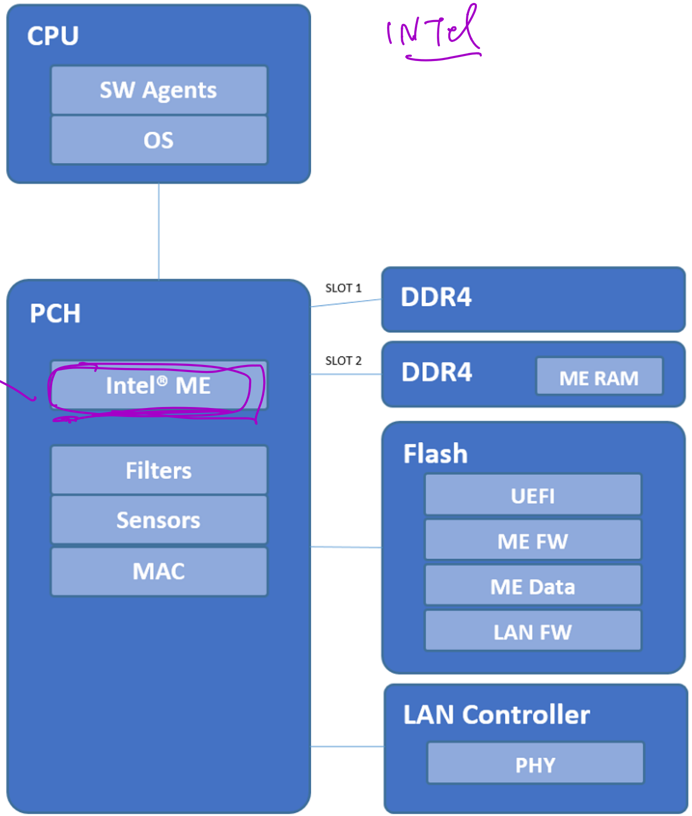


https://www.intel.com/content/www/us/en/intelligent-systems/intel-boot-loader-development-kit/minimal-intel-architecture-boot-loader-paper.html

More details

Intel Management Engine

① turns on the moment your computer has power



Layout of memory at boot

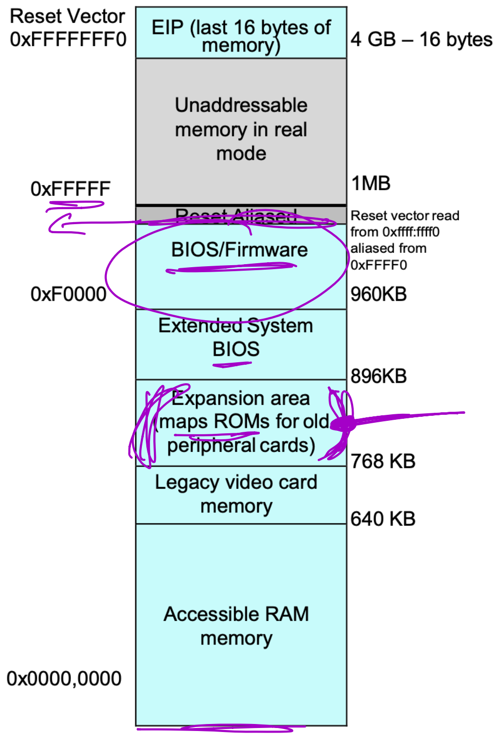
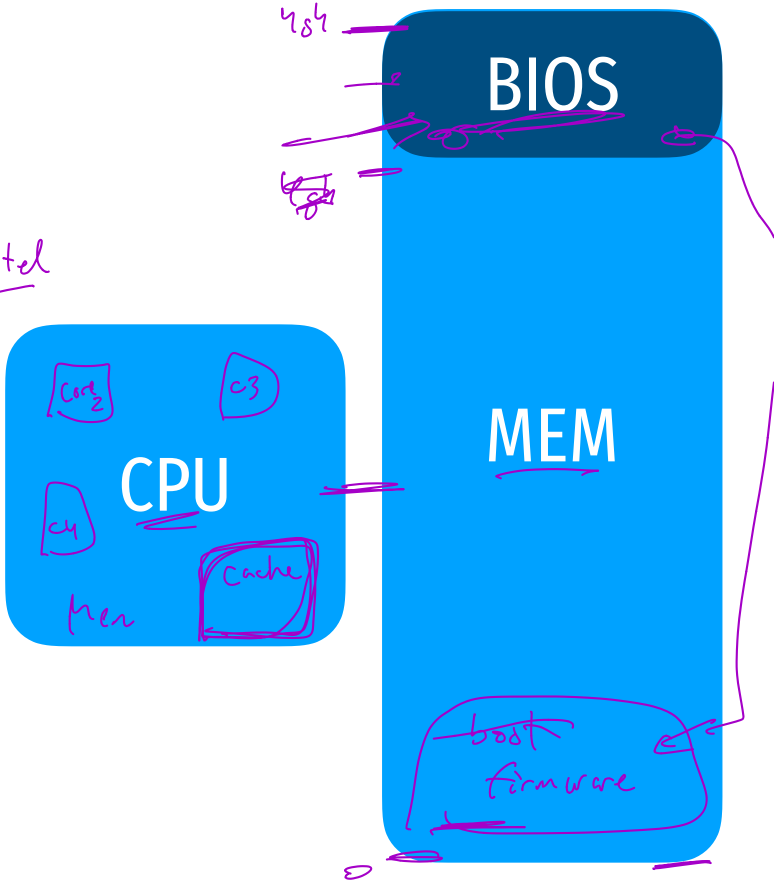


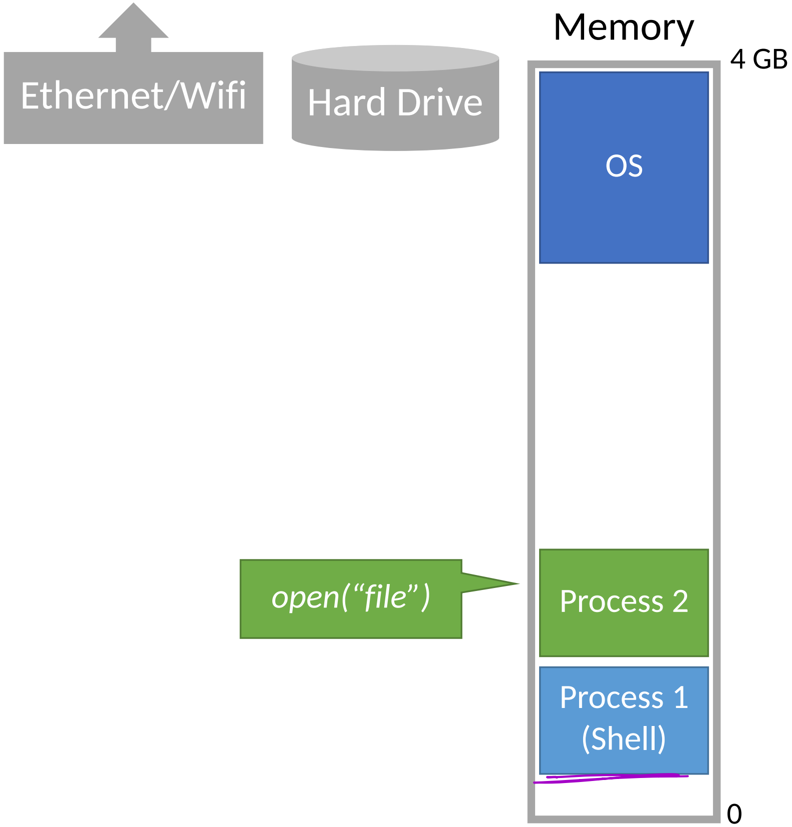
Figure 3 Intel® Architecture Memory Map at Power On

Details

- CPU begins executing at f.fff0
- BIOS firmware begins init of hw
- Applies microcode patches
- Execute Firmware Support Pkg (blob)
- [Ram is setup]
- Copy firmware to RAM
- Begin executing in RAM
- Setup interrupts, timers, clocks
- Bring up other cores
- Setup PCI
- Setup ACPI tables
- Execute OS loader



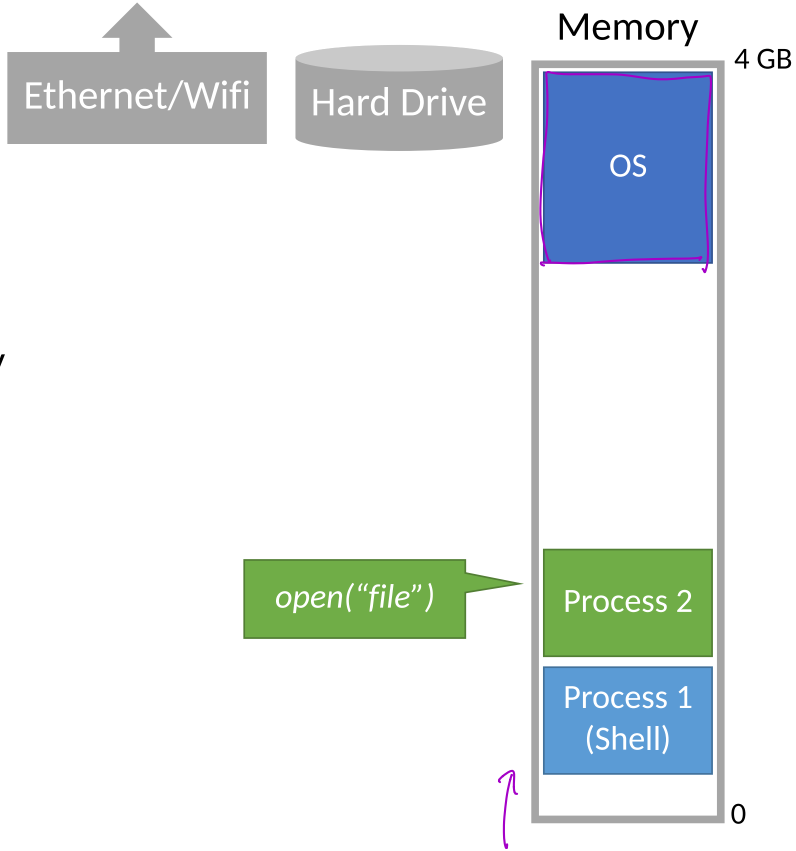
System Model



System Model

On bootup, the Operating System (OS) loads itself into memory

- eg. DOS (before hw isolation)
- Typically places itself in high memory



System Model

(old system like DOS)

On bootup, the Operating System (OS) loads itself into memory

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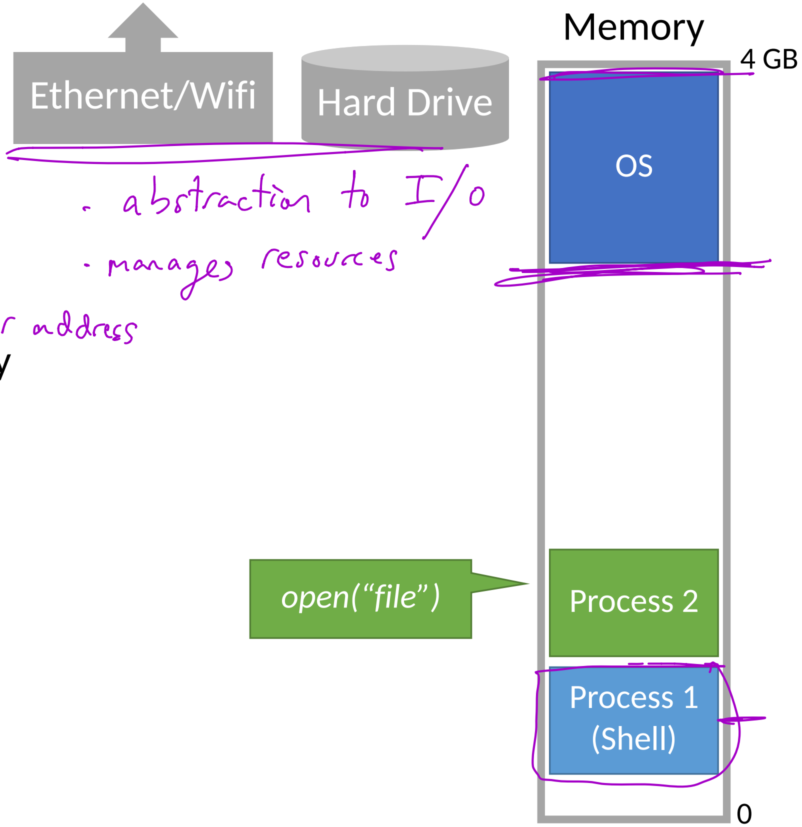
higher address

What is the role of the OS?

- Allow the user to run processes
- Often comes with a shell
  - Text shell like bash
  - Graphical shell like the Windows desktop
- Provides APIs to access devices
  - Offered as a convenience to application developers



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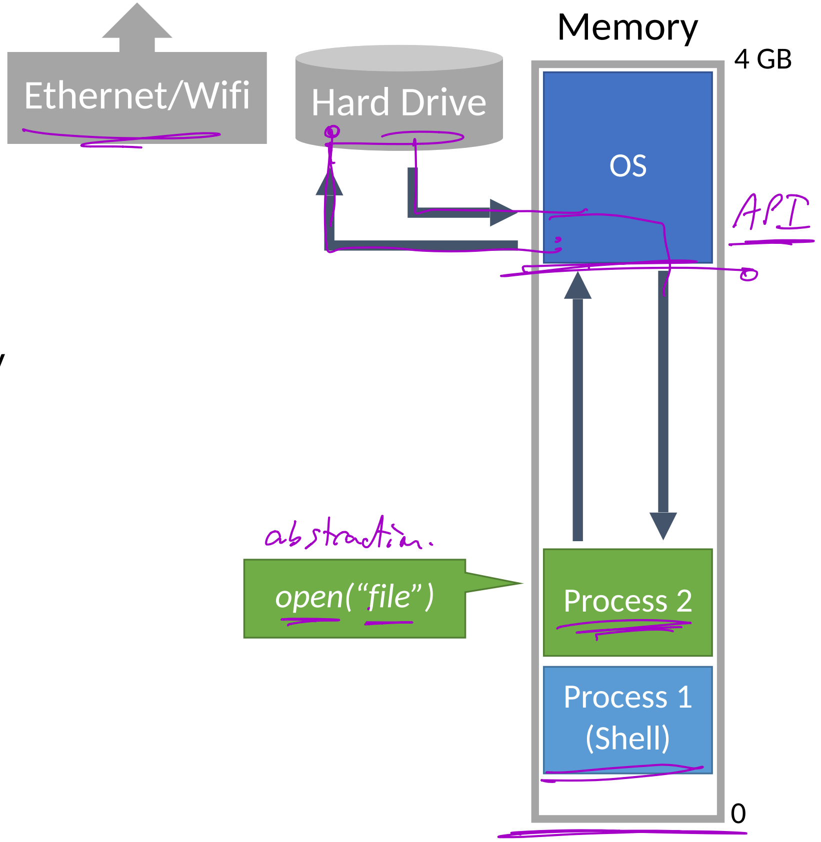
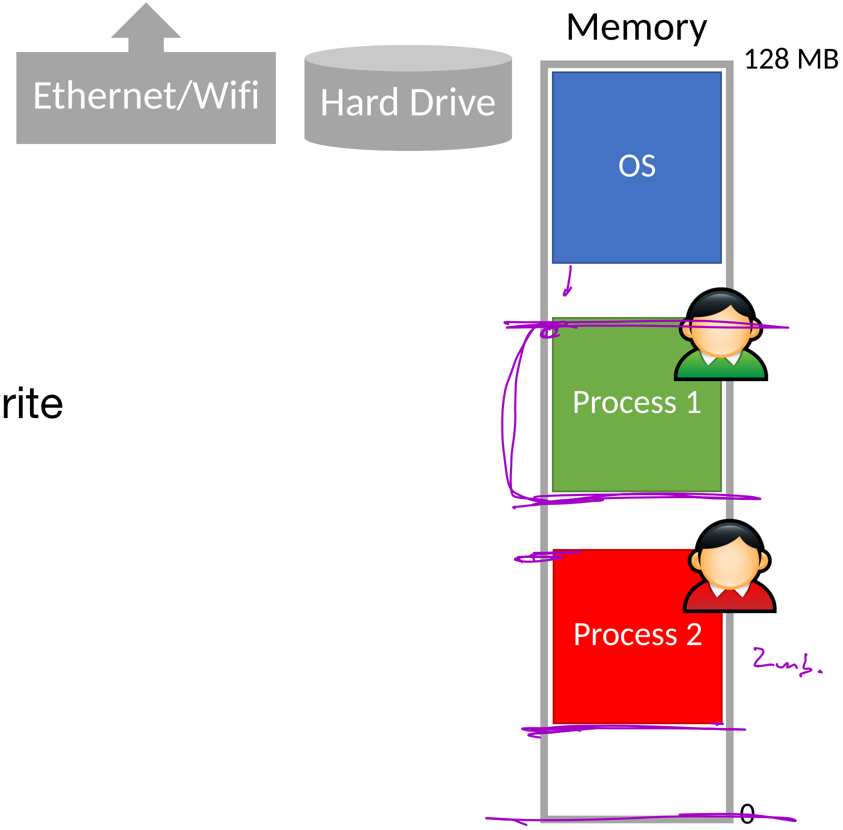


Memory Unsafety

DoS

Problem: any process can read/write any memory



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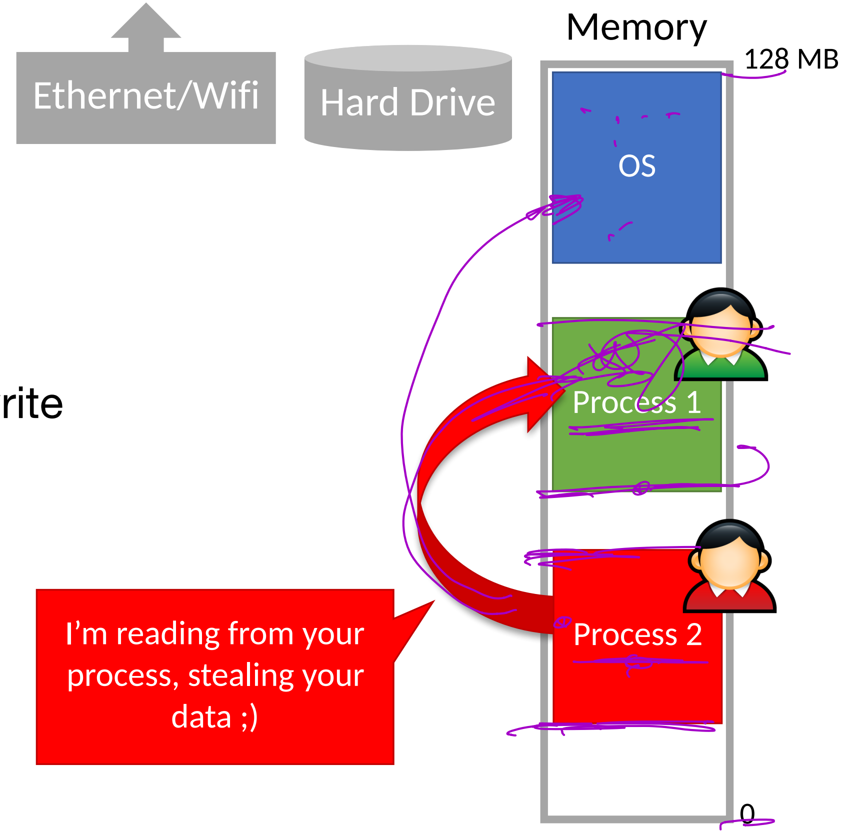

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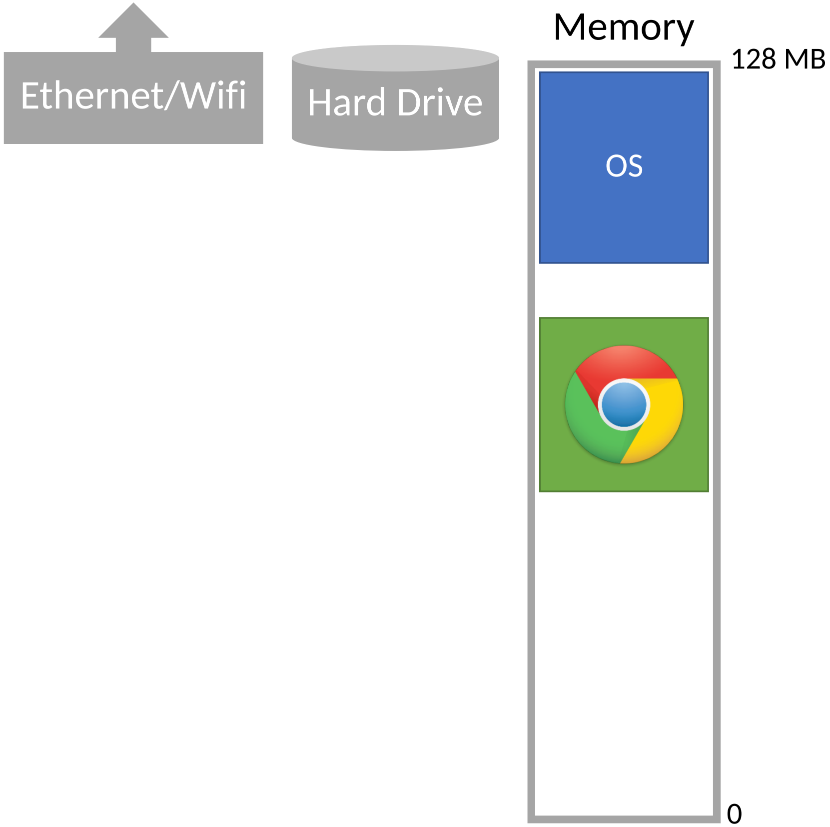

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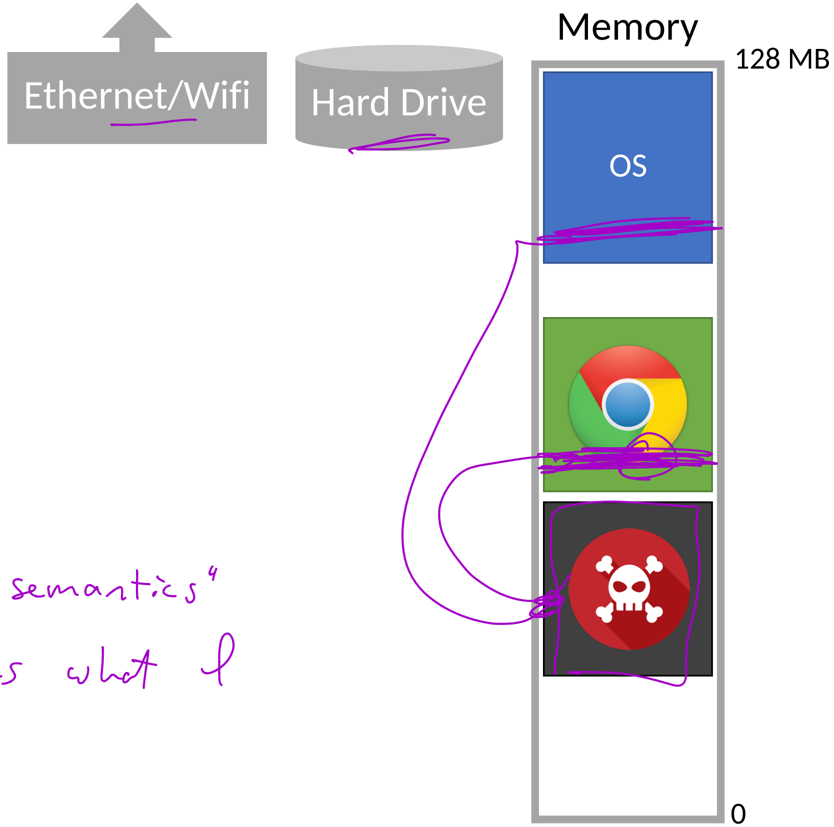

Problem: any process can read/write any memory

and thus no process can rely on a "safe memory semantics"
i.e. "what I wrote before IS what I will read in the future"

Memory Unsafety

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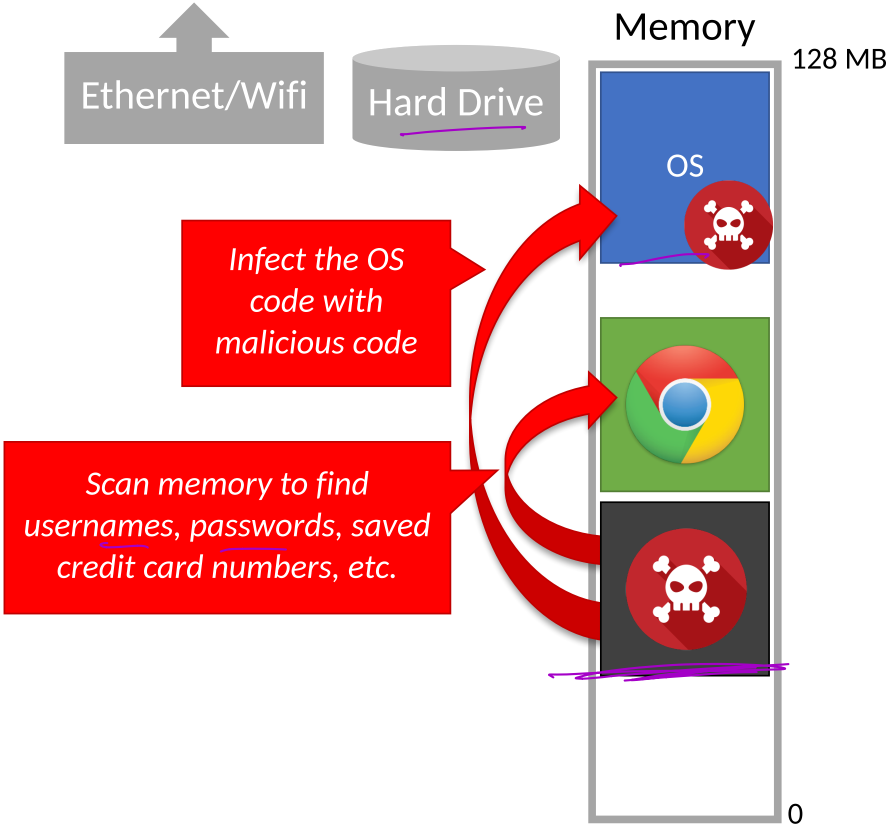
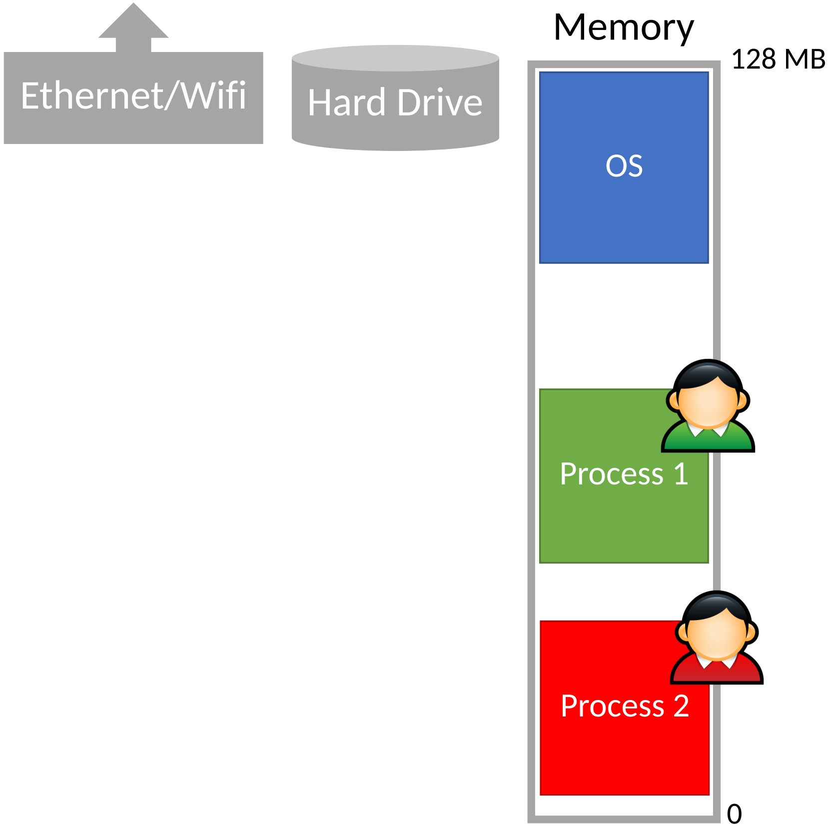


Device Unsafety



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Access control is enforced by the OS, but OS APIs can be bypassed

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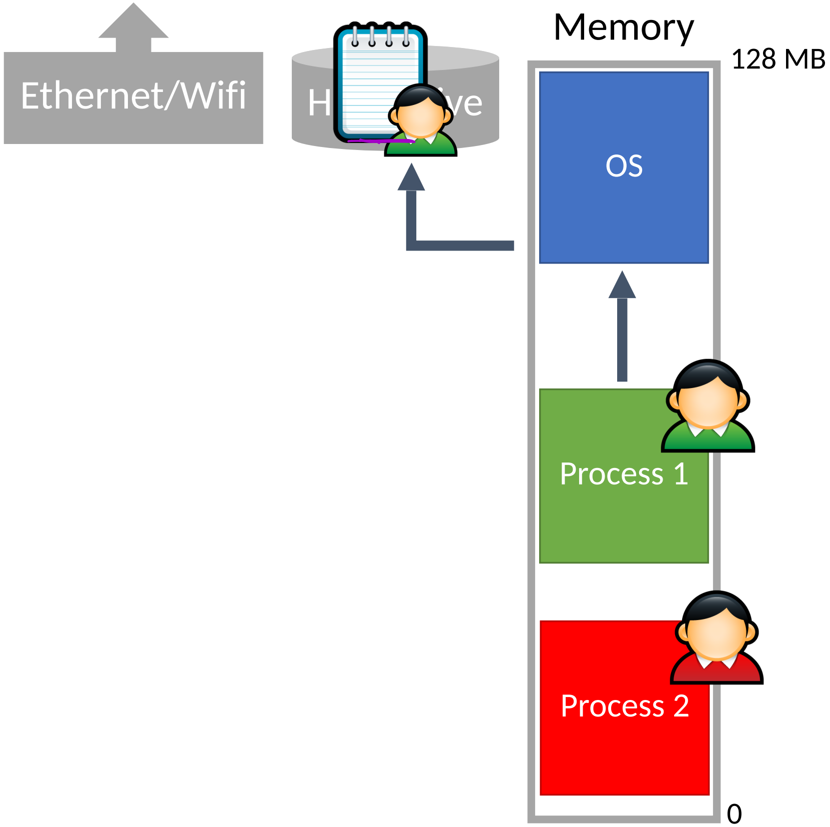

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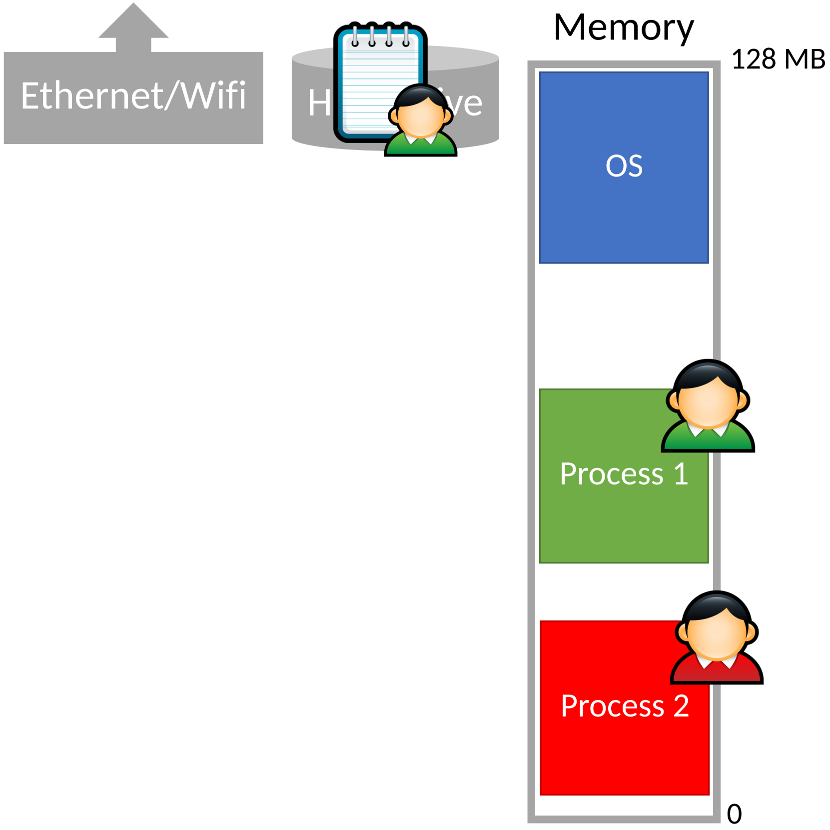

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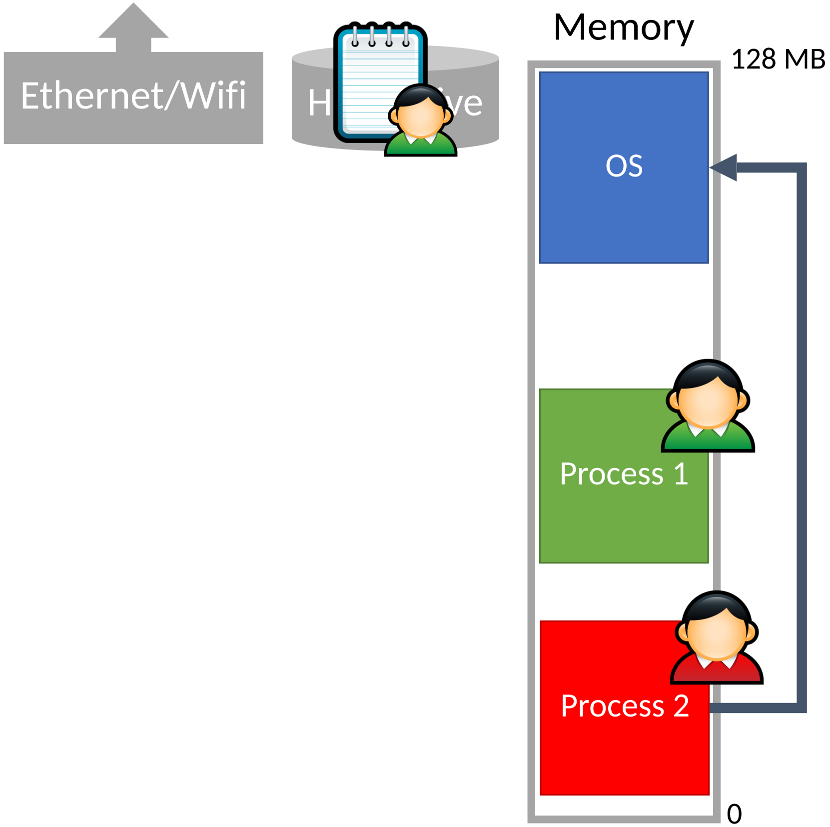

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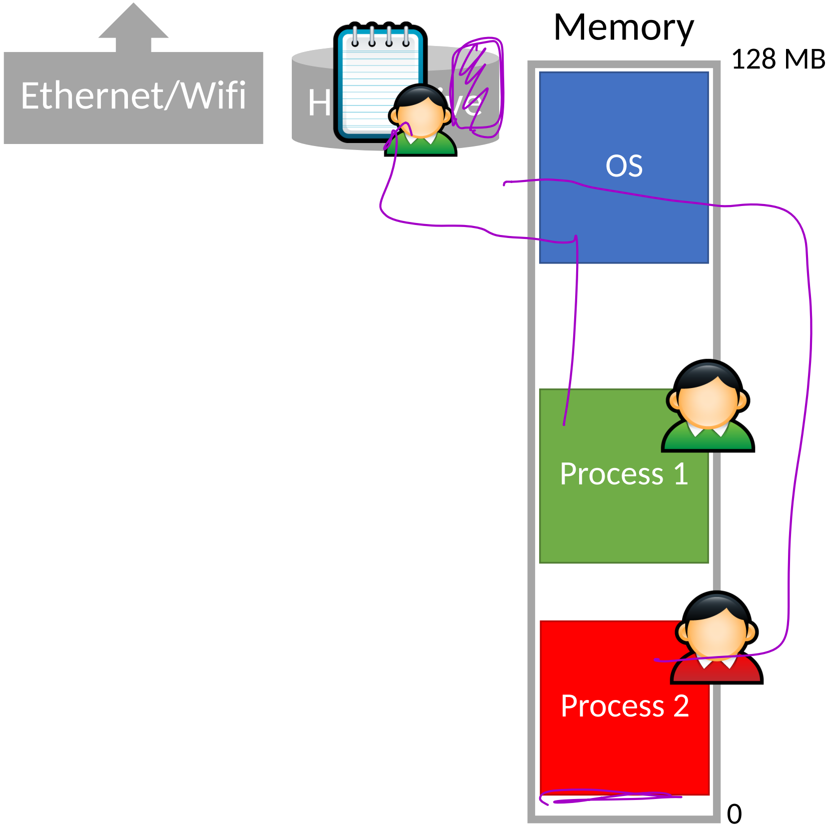

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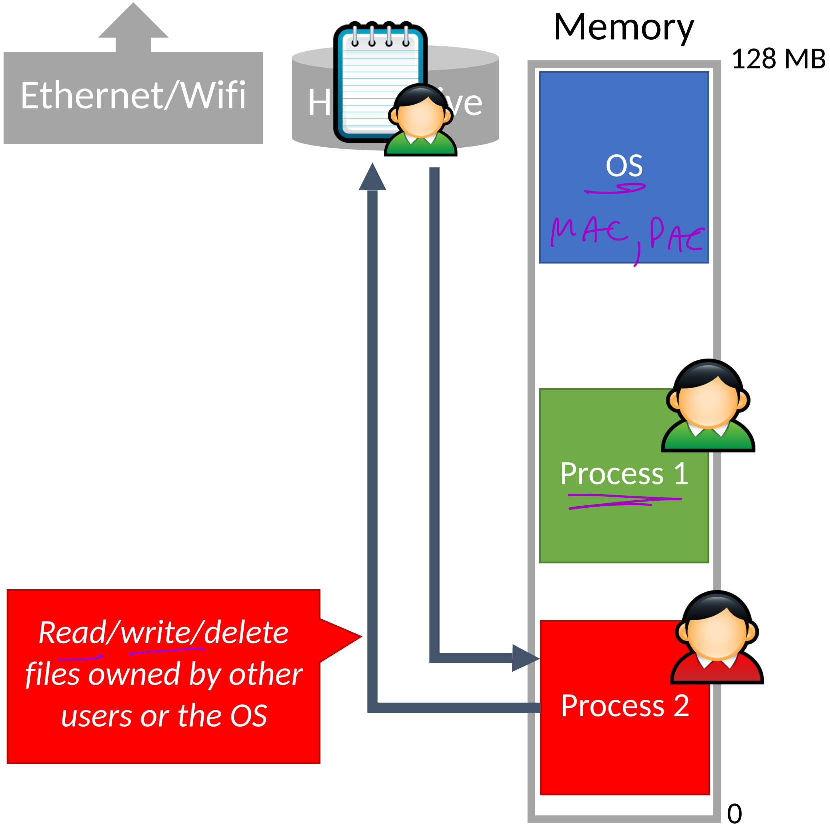

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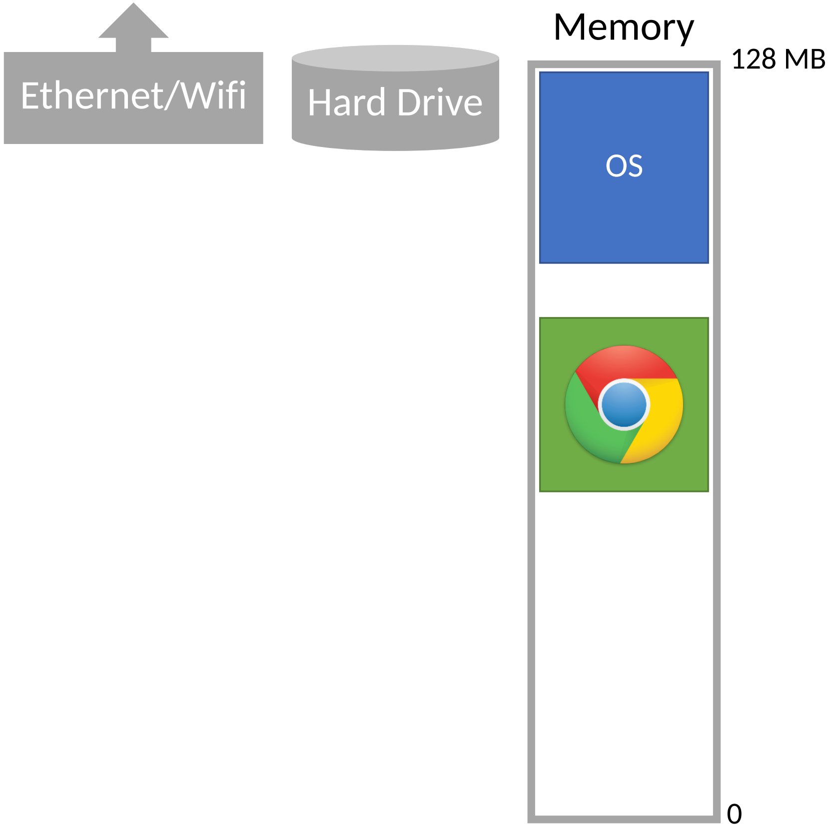

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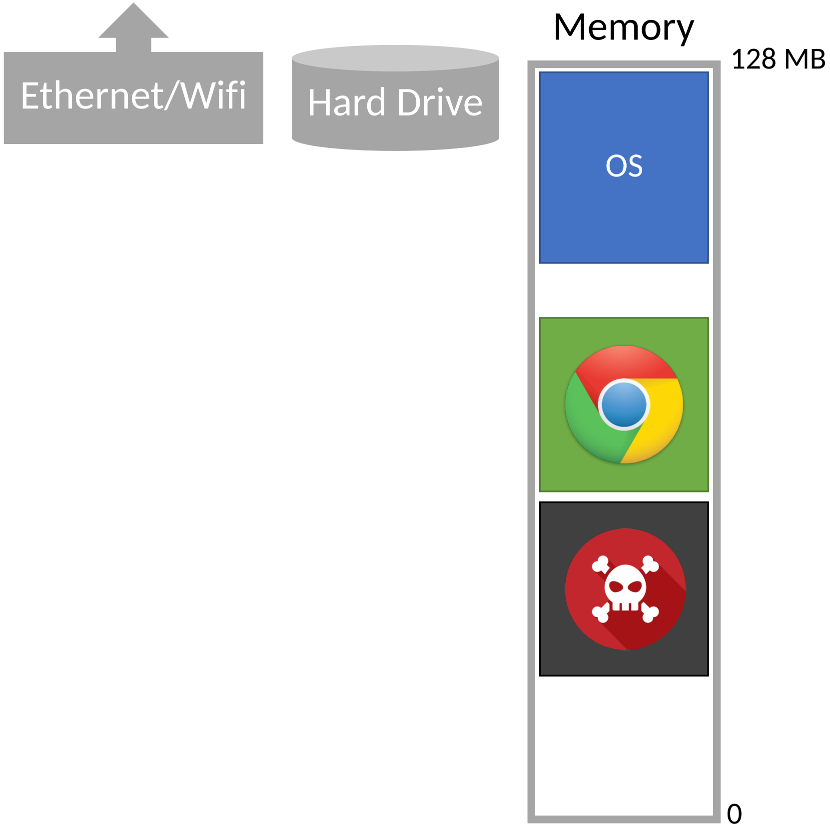

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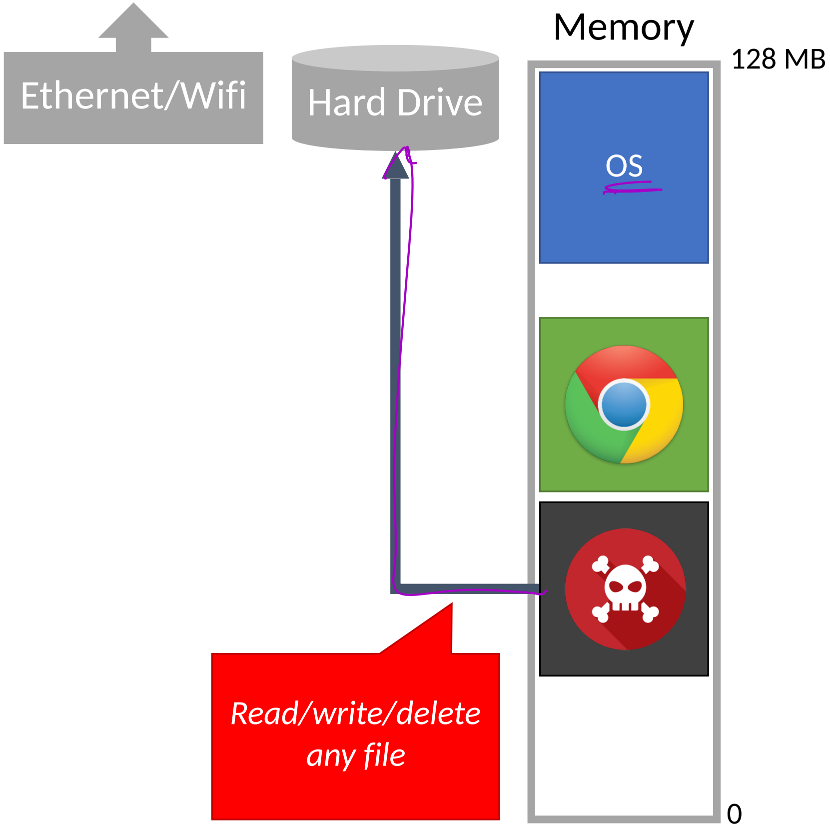


Device Unsafety

- Monolithic memory/address space with no protections.

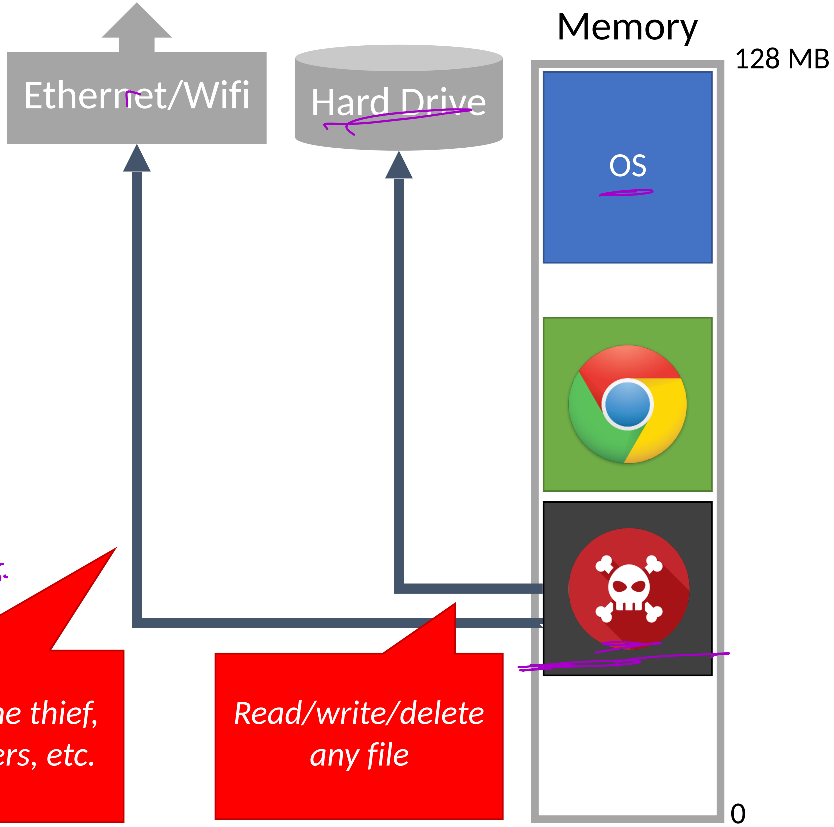
Problem: any process can access any hardware device directly

Access control is enforced by the OS, but OS APIs can be bypassed

- How OS worked for first 15 years.

Explain failures of this model

Send stolen data to the thief, attack other computers, etc.



- UNIX model (1970s)
was way ahead
(needed some hw support)

Review

Old systems did not protect memory or devices

- Any process could access any memory
- Any process could access any device

Problems

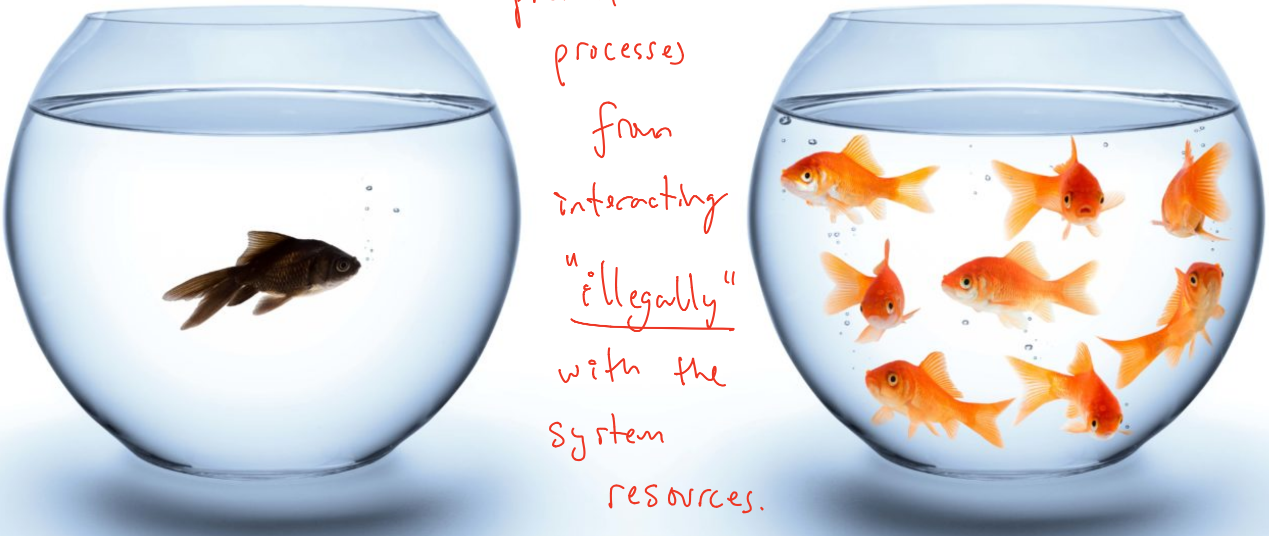
- No way to enforce access controls on users or devices
- Processes can steal from or destroy each other
- Processes can modify or destroy the OS

On old computers, systems security was literally impossible

how??

ISOLATION

prevent processes from interacting "illegally" with the system resources.



Threat Model

Principles

Intro to System Architecture

Hardware Support for Isolation

Examples

Modern hw support strong isolation.

- Rings
- virtual memory
- virtualization instructions

Towards Modern Architecture

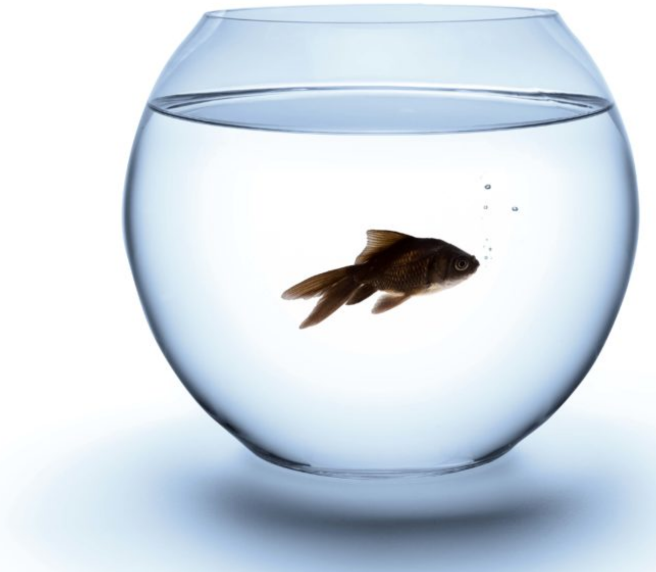
To achieve systems security, we need process isolation

- Processes cannot read/write memory arbitrarily
- Processes cannot access devices directly

How do we achieve this?

Hardware support for isolation

1. Protected mode execution (a.k.a. process rings)
2. Virtual memory



Protected Mode

Protected Mode

Most modern CPUs support protected mode

x86 CPUs support three rings with different privileges

- Ring 0: Operating System
  - Code in this ring may directly access any device

legacy operation.

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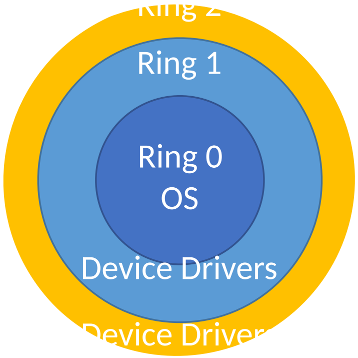
  - Code in these rings may directly access some devices
  - May not change the protection level of the CPU



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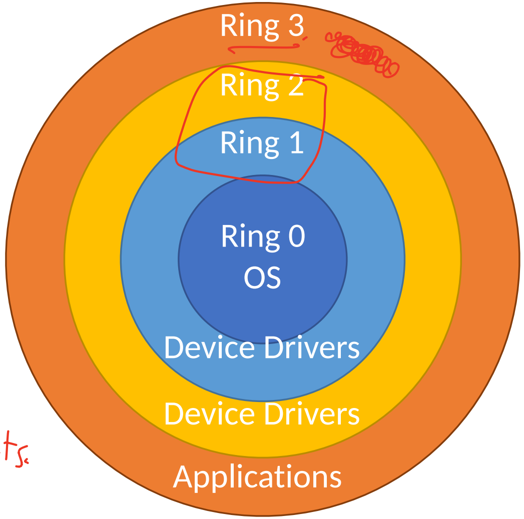
- Ring 3: userland
  - Code in this ring may not directly access devices
  - All device access must be via OS APIs
  - May not change the protection level of the CPU

– memory access constraints

– I/O constraints.



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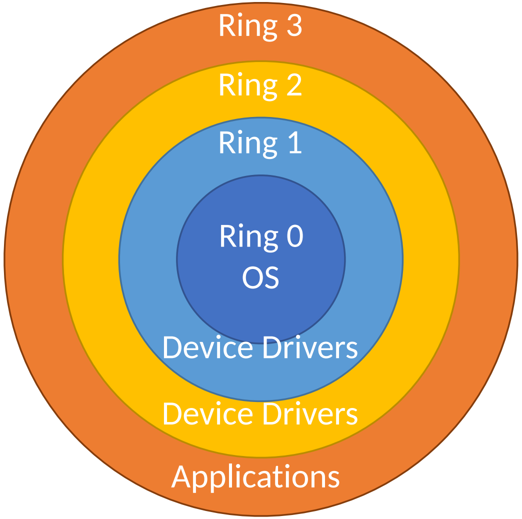
Most OSes only use rings 0 and 3

Kernel OS   user processes



Ring -1,-2,-3

“Google cited worries that the Intel ME (actually MINIX) code runs on their CPU's deepest access level — Ring "-3" — and also runs a web server component that allows anyone to remotely connect to remote computers, even when the main OS is turned off.”

System Boot Sequence

1. On startup, the CPU starts in 16-bit real mode
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   - OS code is now running in Ring 0
   - OS decides what Ring to place other processes in

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    - OS decides what Ring to place other processes in
4. Shell gets executed, user may run programs
    - User processes are placed in Ring 3

Restriction on Privileged Instructions

What CPU instructions are restricted in protected mode?

- Any instruction that modifies the CR0 register
  - Controls whether protected mode is enabled
- Any instruction that modifies the CR3 register
  - Controls the virtual memory configuration
  - More on this later…
- hlt – Halts the CPU
- sti/cli – enable and disable interrupts
- in/out – directly access hardware devices

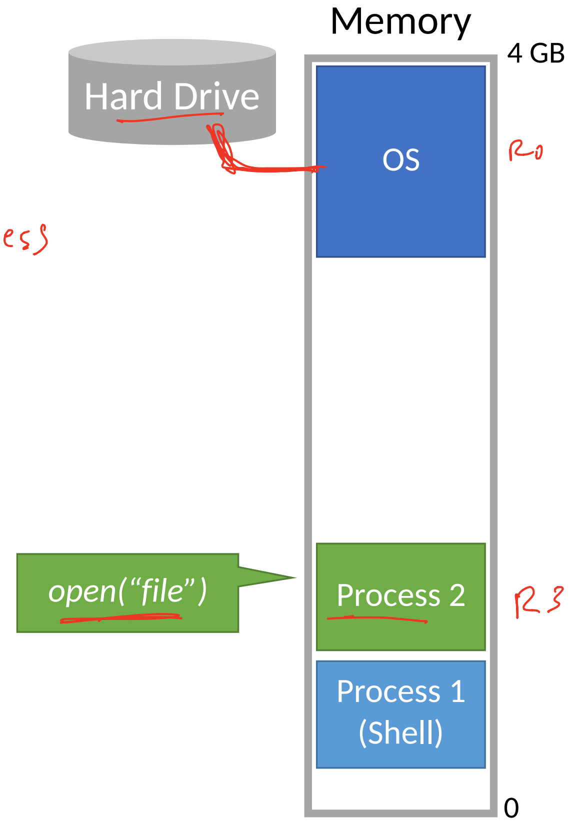
control registers of the cpu indicate, ring level.

If a Ring 3 process tries any of these things, it immediately crashes

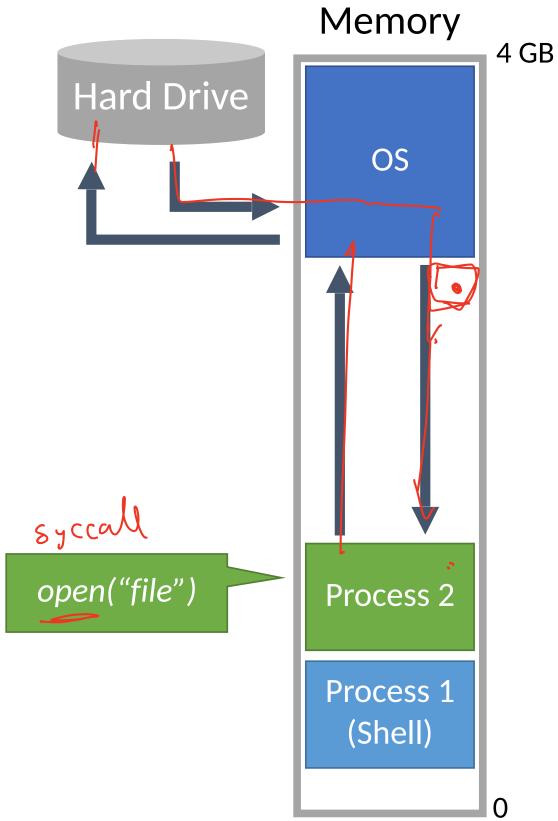
How to change modes

"system call"

- method for a user-land process running at R3 to communicate with the OS running in R0.



How to change modes



Changing Modes

Applications often need to access the OS APIs

- Writing files
- Displaying things on the screen
- Receiving data from the network
- etc...

But the OS is Ring 0, and processes are Ring 3

How do processes get access to the OS?

Changing Modes

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But the OS is Ring 0, and processes are Ring 3

How do processes get access to the OS?

- Invoke OS APIs with special assembly instructions
  - Interrupt: int 0x80
  - System call: sysenter or syscall
- int/sysenter/syscall cause a mode transfer from Ring 3 to Ring 0

properly defined interrupt handler setup in the CPU

standard method
- load arguments to the syscall into registers
- execute int 80

Mode Transfer

Userland

1. Application executes trap (int) instruction
   - EIP, CS, and EFLAGS get pushed onto the stack
   - Mode switches from ring 3 to ring 0

Kernel Mode

Mode Transfer

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5. Place the return value in EAX

Convention
- ensures access controls can be applied by kernel handler

⇒ safety

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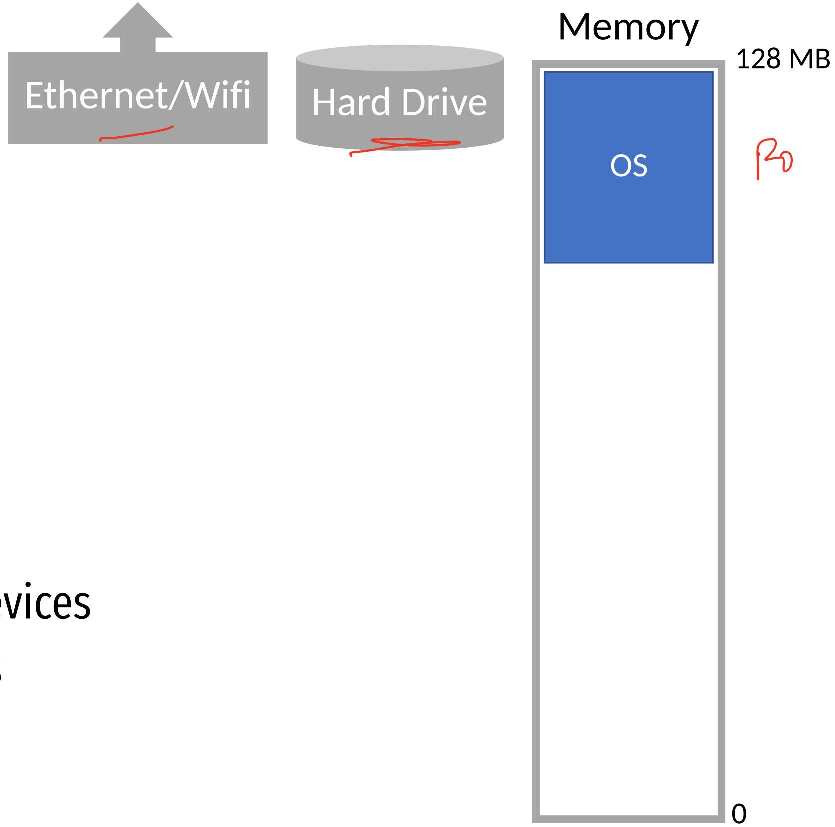
5. Place the return value in EAX
6. Use iret to return to the process
   - Switches back to the original mode (typically 3)

Protection in Action

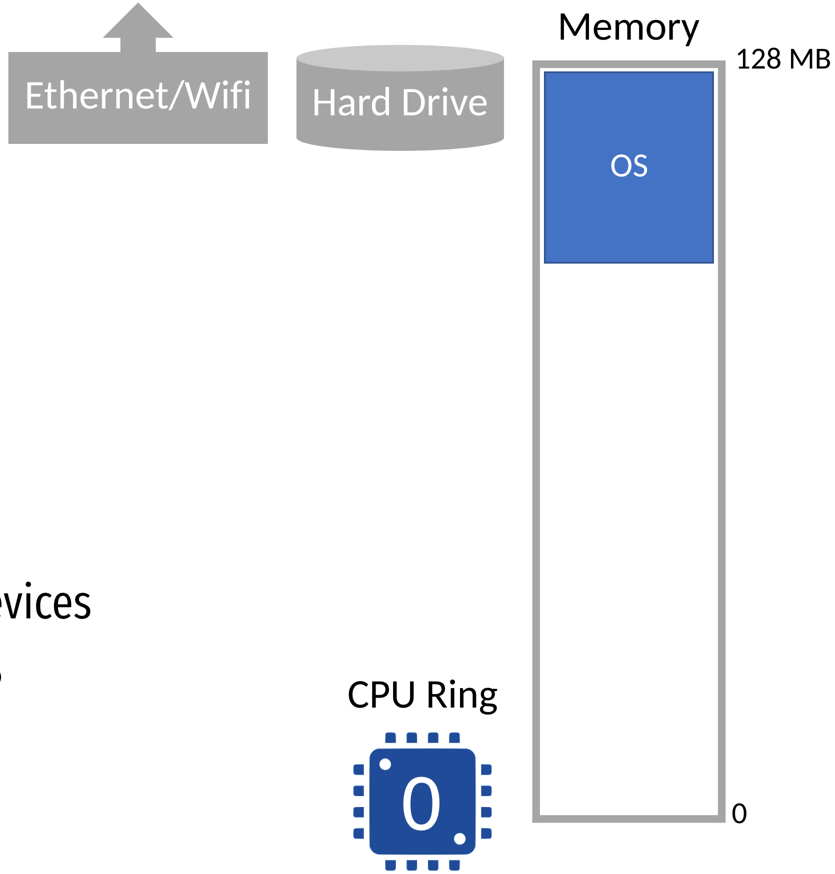


Protected mode stops direct access to devices

All device access must go through the OS

OS will impose access control checks

Protection in Action



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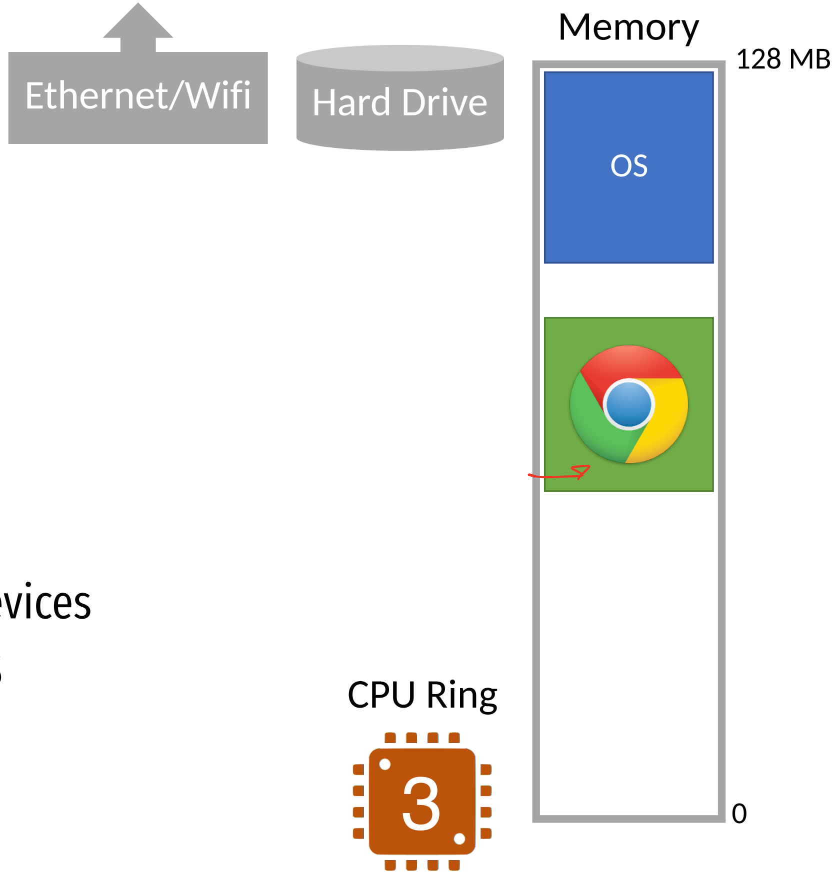

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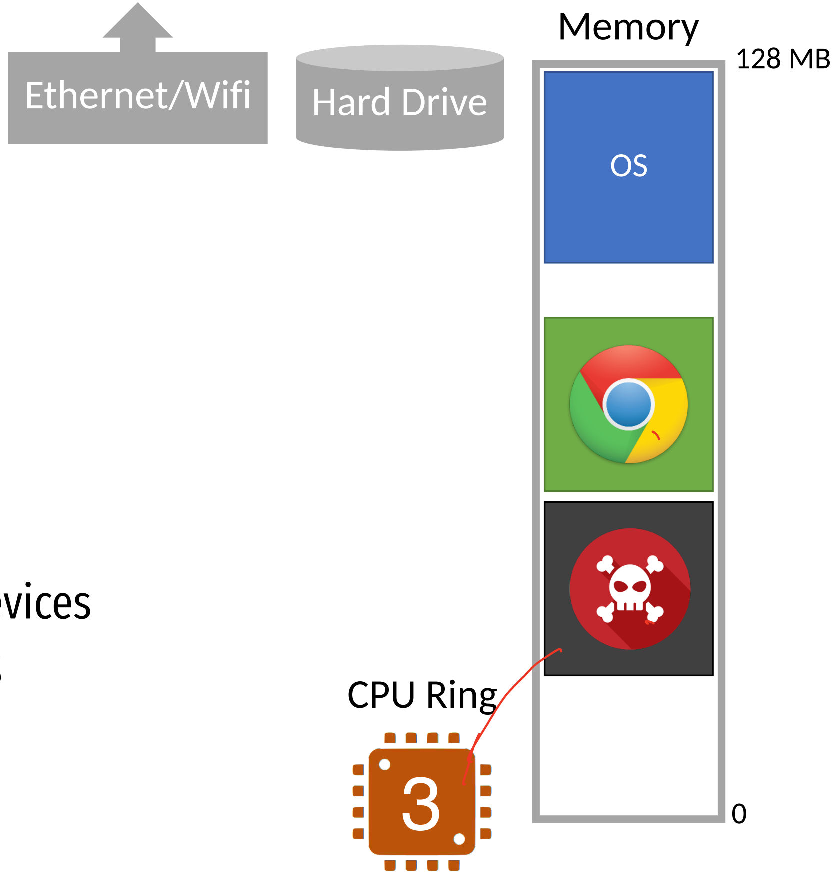

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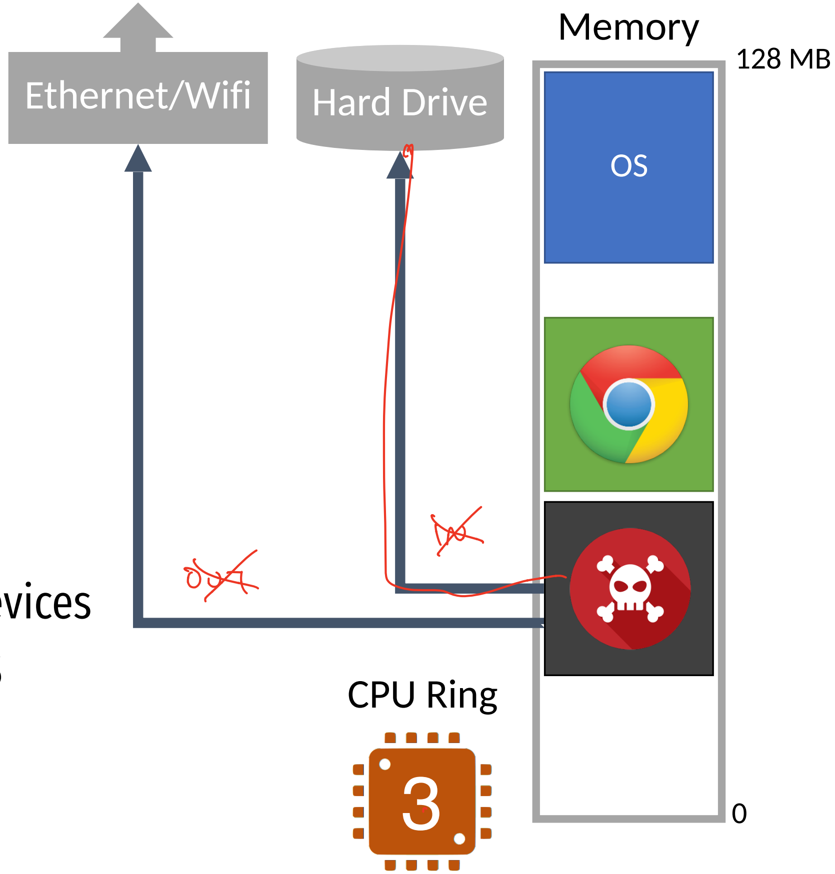

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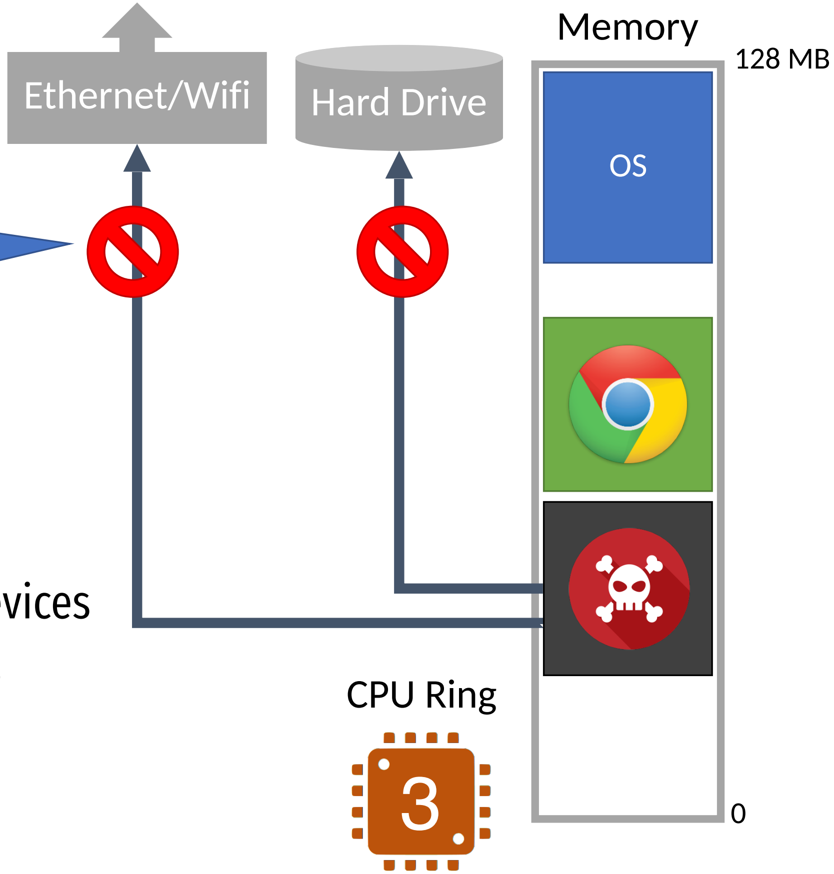
Protection in Action

Ring 3 = protected mode.
No direct device access



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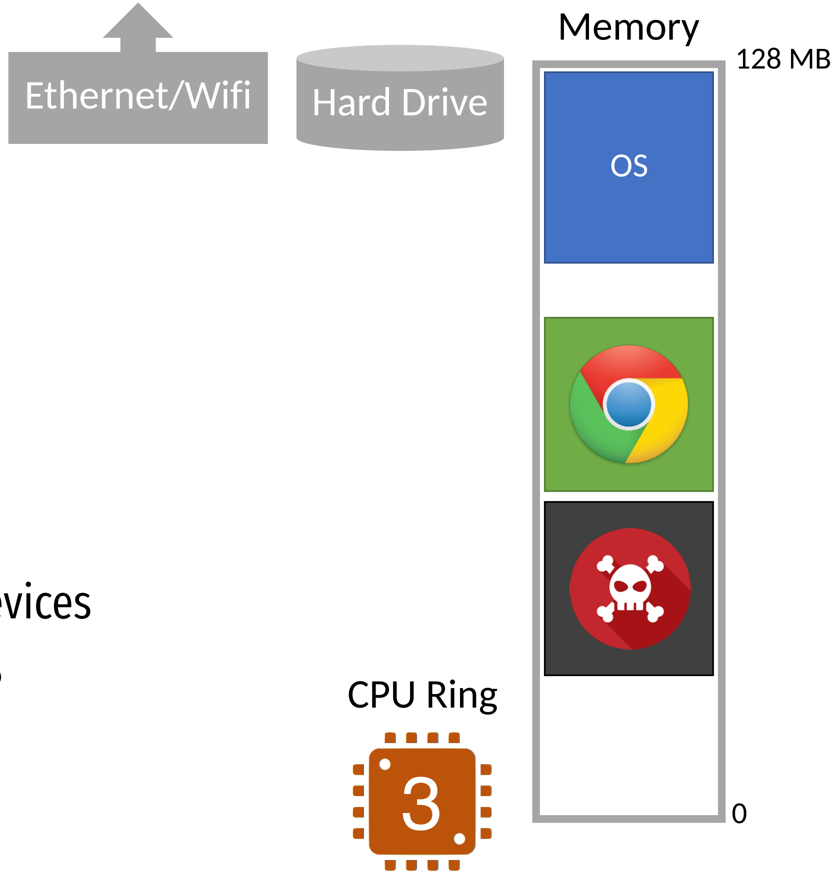

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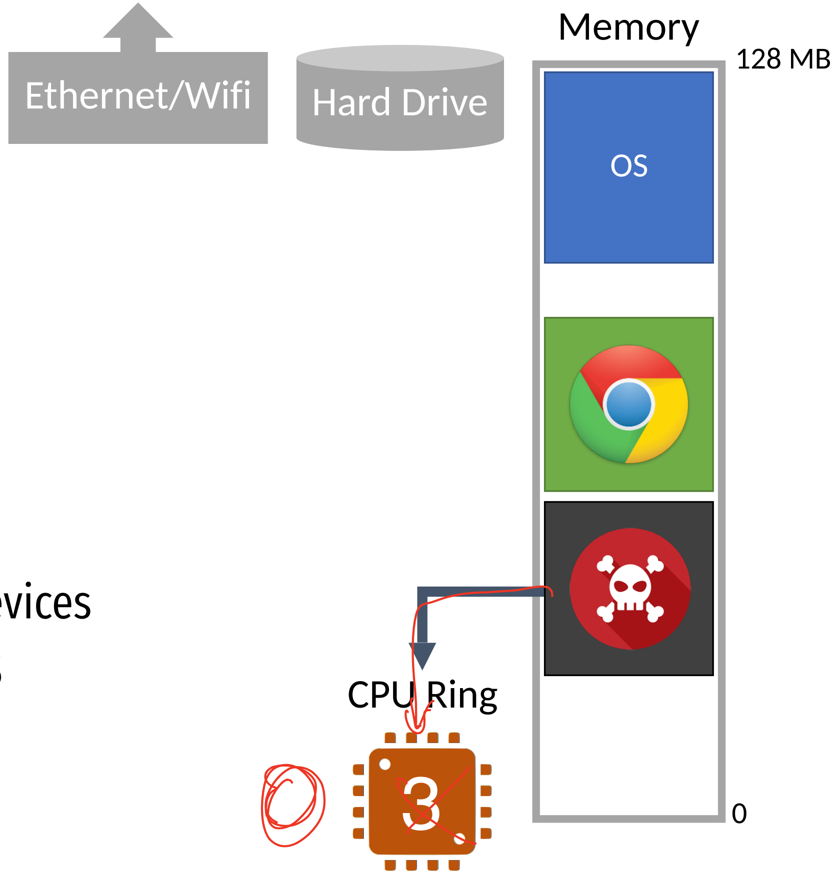

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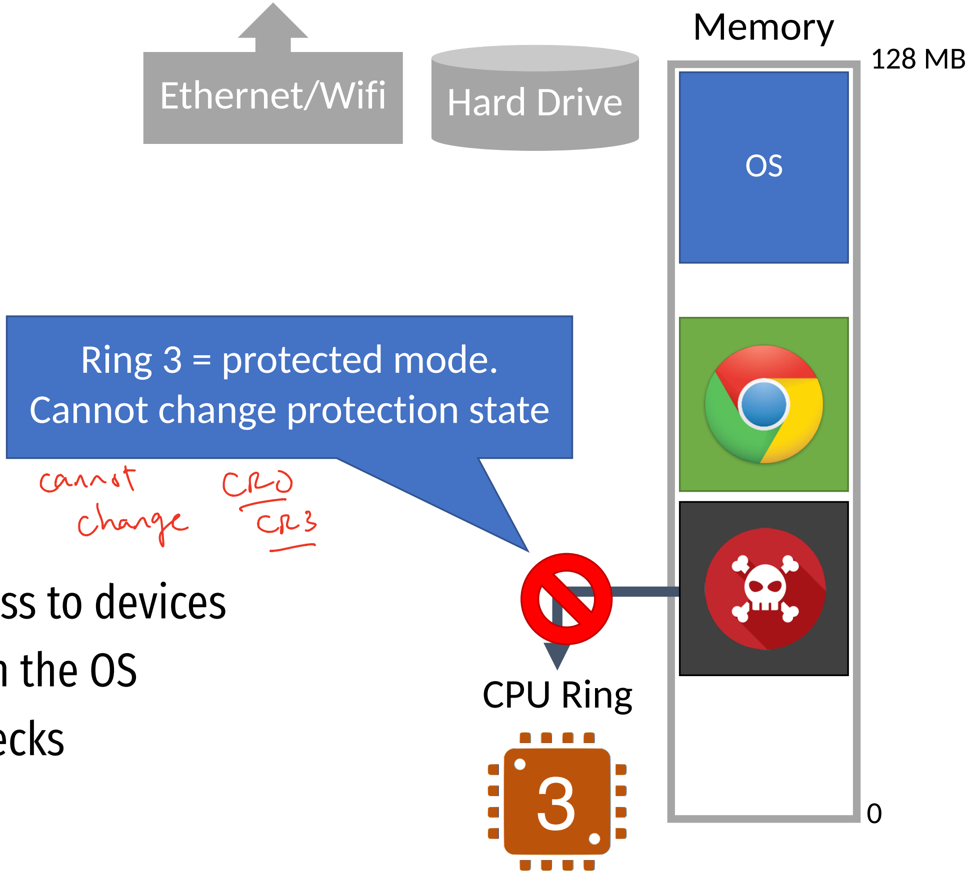

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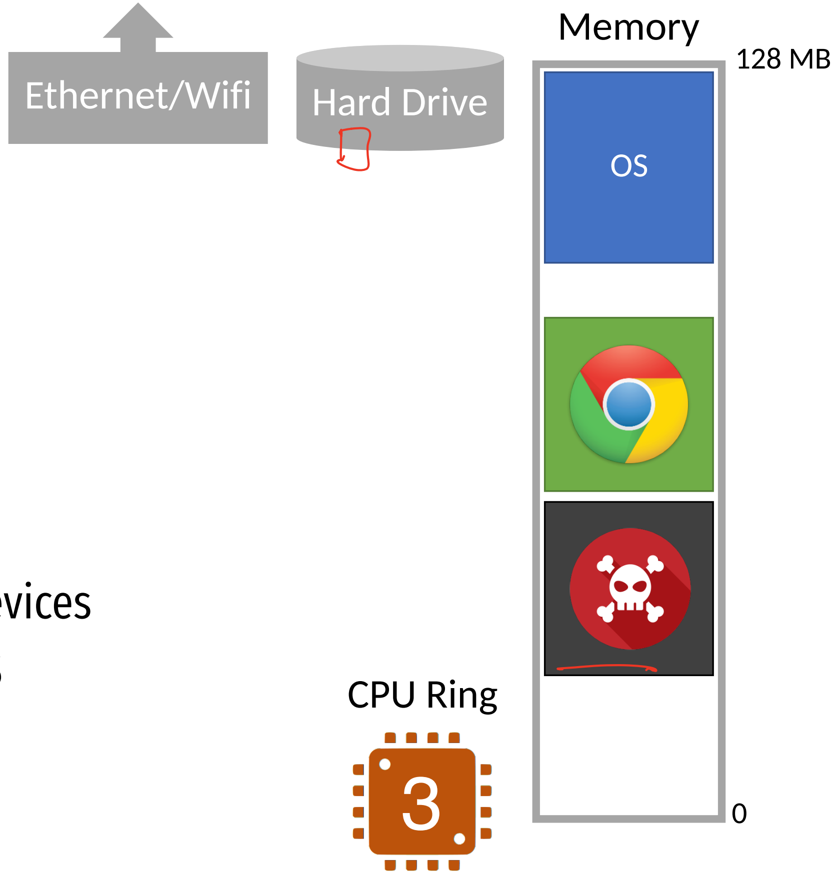

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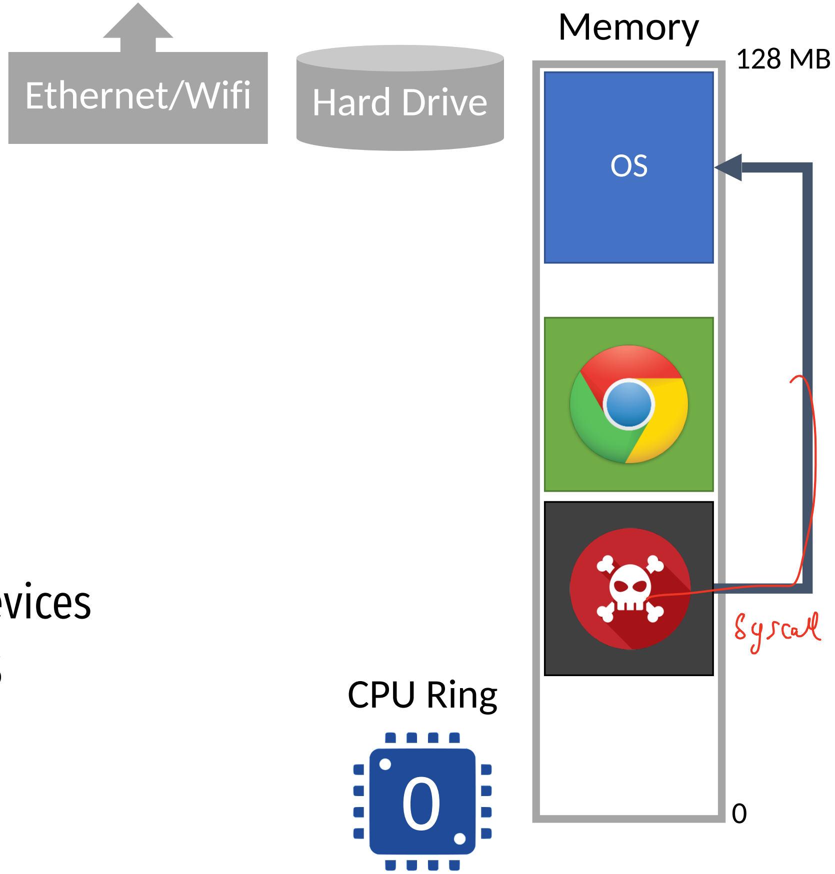

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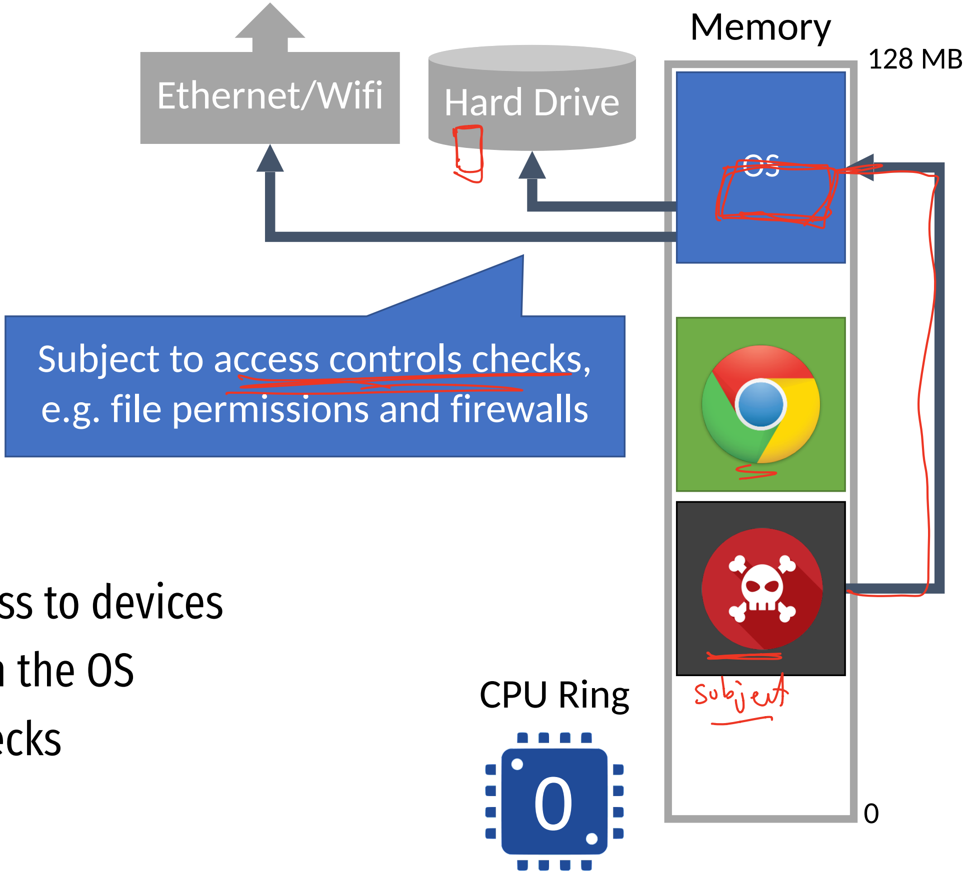

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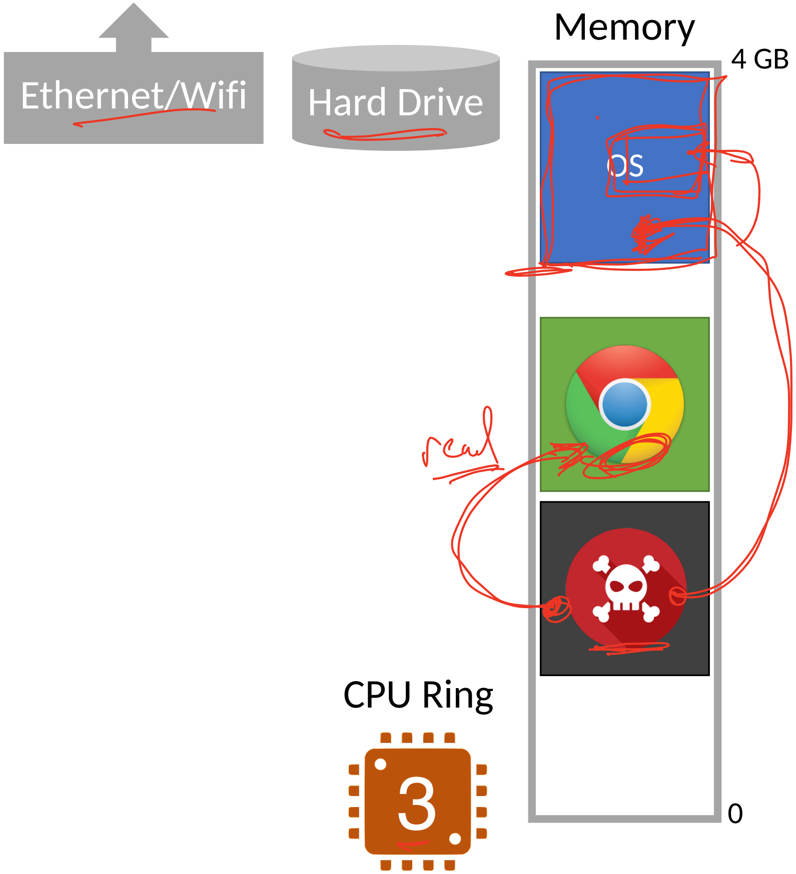
Virtual Memory

Status Check

At this point we have protected the devices attached to the system…

… But we have not protected memory



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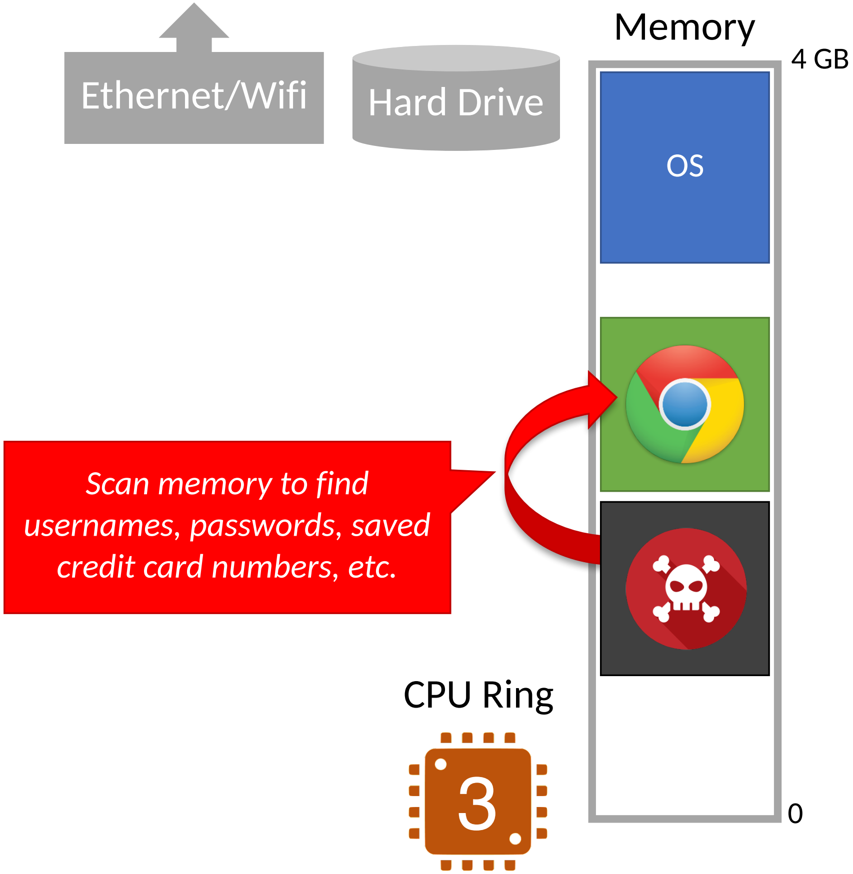

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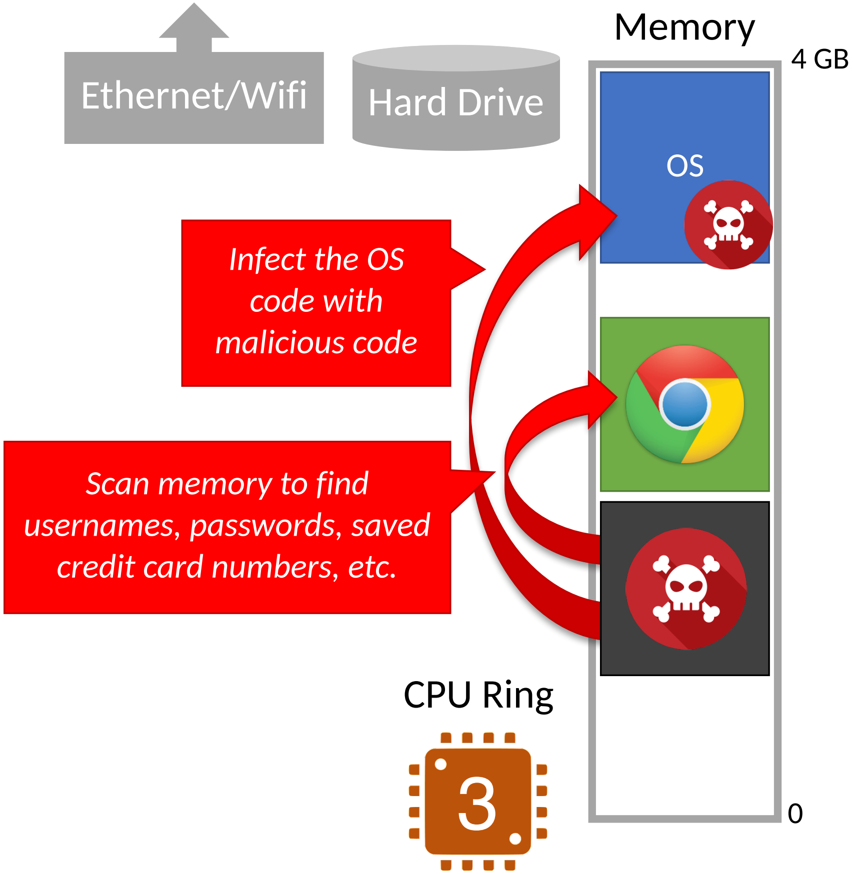

Memory Isolation and Virtual Memory

Modern CPUs support virtual memory

Creates the illusion that each process runs in its own, empty memory space

- Processes can not read/write memory used by other processes
- Processes can not read/write memory used by the OS

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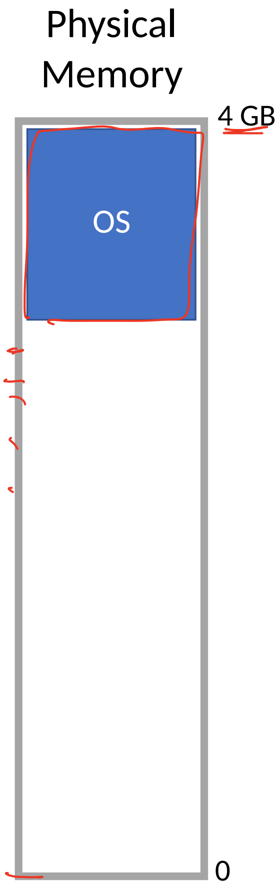
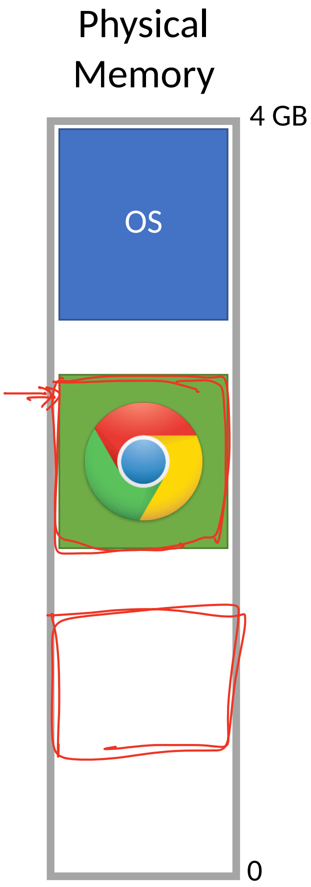
In later courses, you will learn how virtual memory is implemented

- Base and bound registers
- Segmentation
- Page tables

Today, we will do the cliffnotes version…


Physical
Memory
4 GB
OS
0


Physical
Memory
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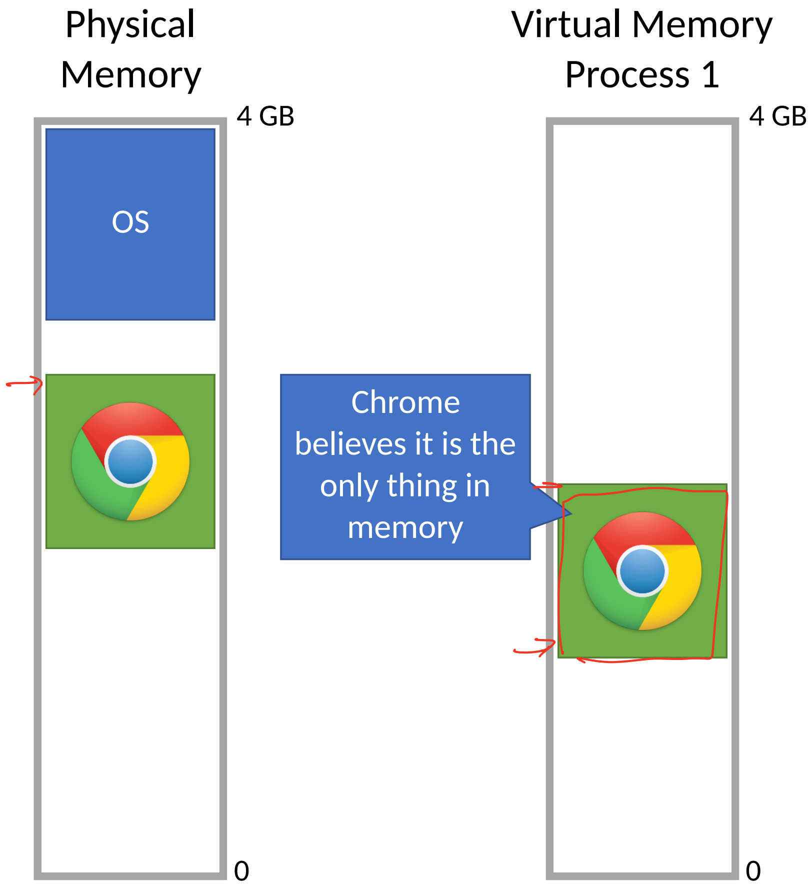
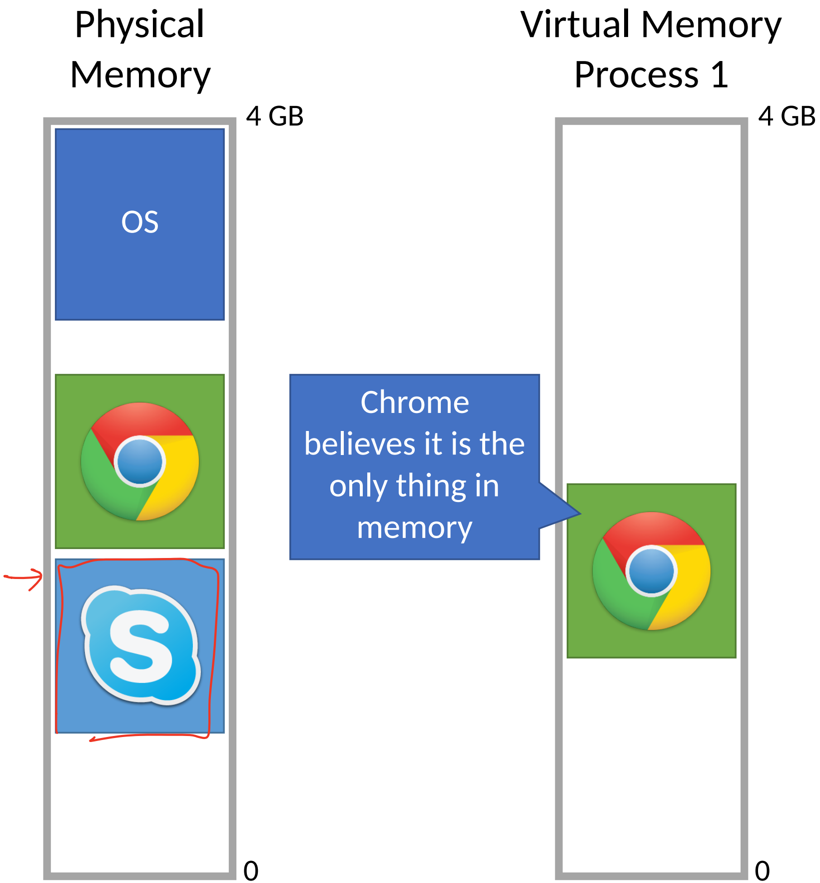

Physical Memory
4 GB
OS
0
Chrome believes it is the only thing in memory
Virtual Memory Process 1
4 GB
0


Physical
Memory
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OS
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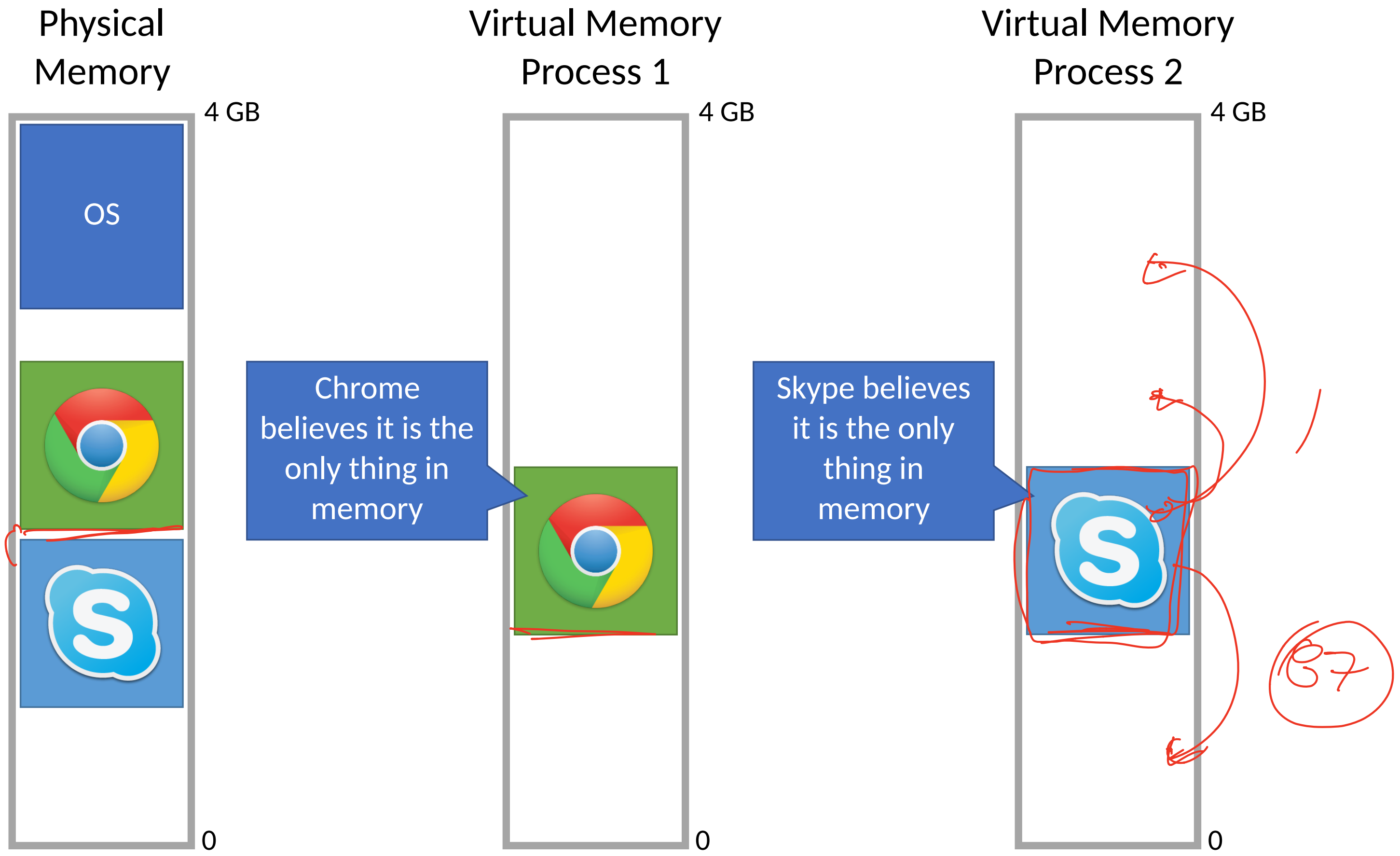
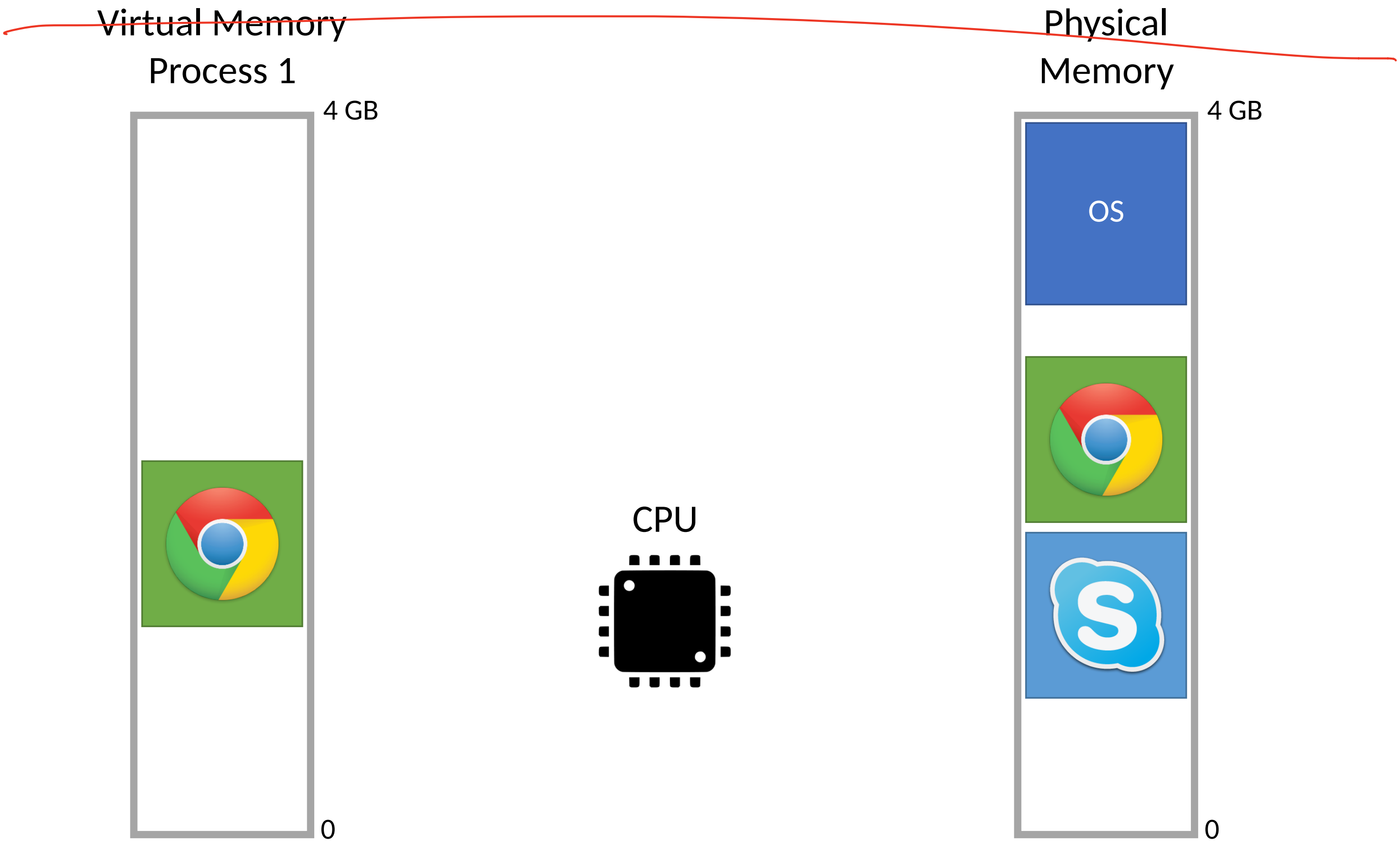
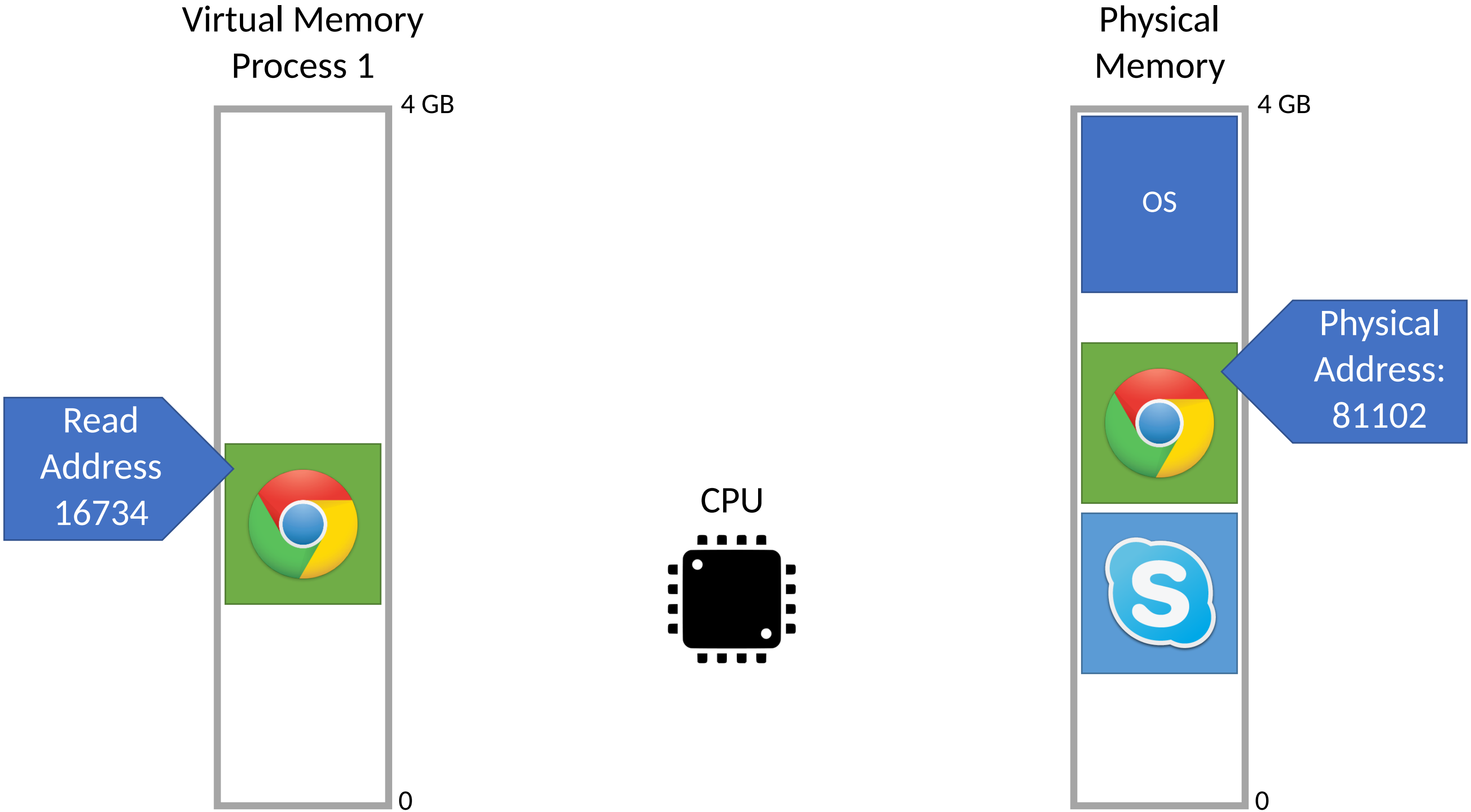
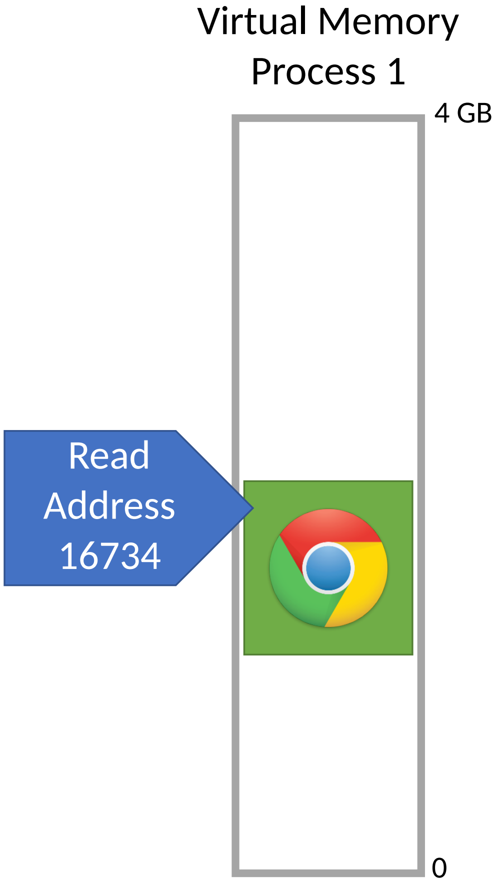

Physical Memory
Virtual Memory Process 1
Virtual Memory Process 2
4 GB
0
OS
Chrome believes it is the only thing in memory
Skype believes it is the only thing in memory

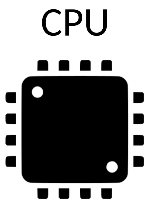

Virtual Memory
Process 1
4 GB
0
CPU
Physical
Memory
4 GB
OS
0

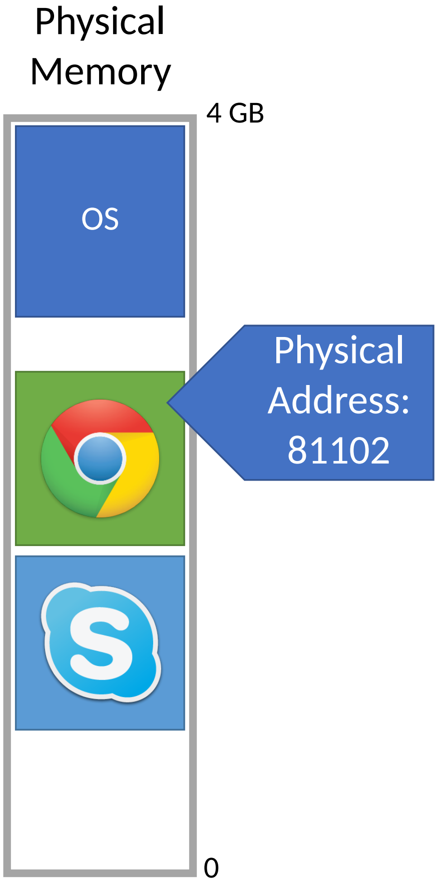

Virtual Memory
Process 1
4 GB
0
Read
Address
16734
CPU
Physical
Memory
4 GB
OS
Physical
Address:
81102
0

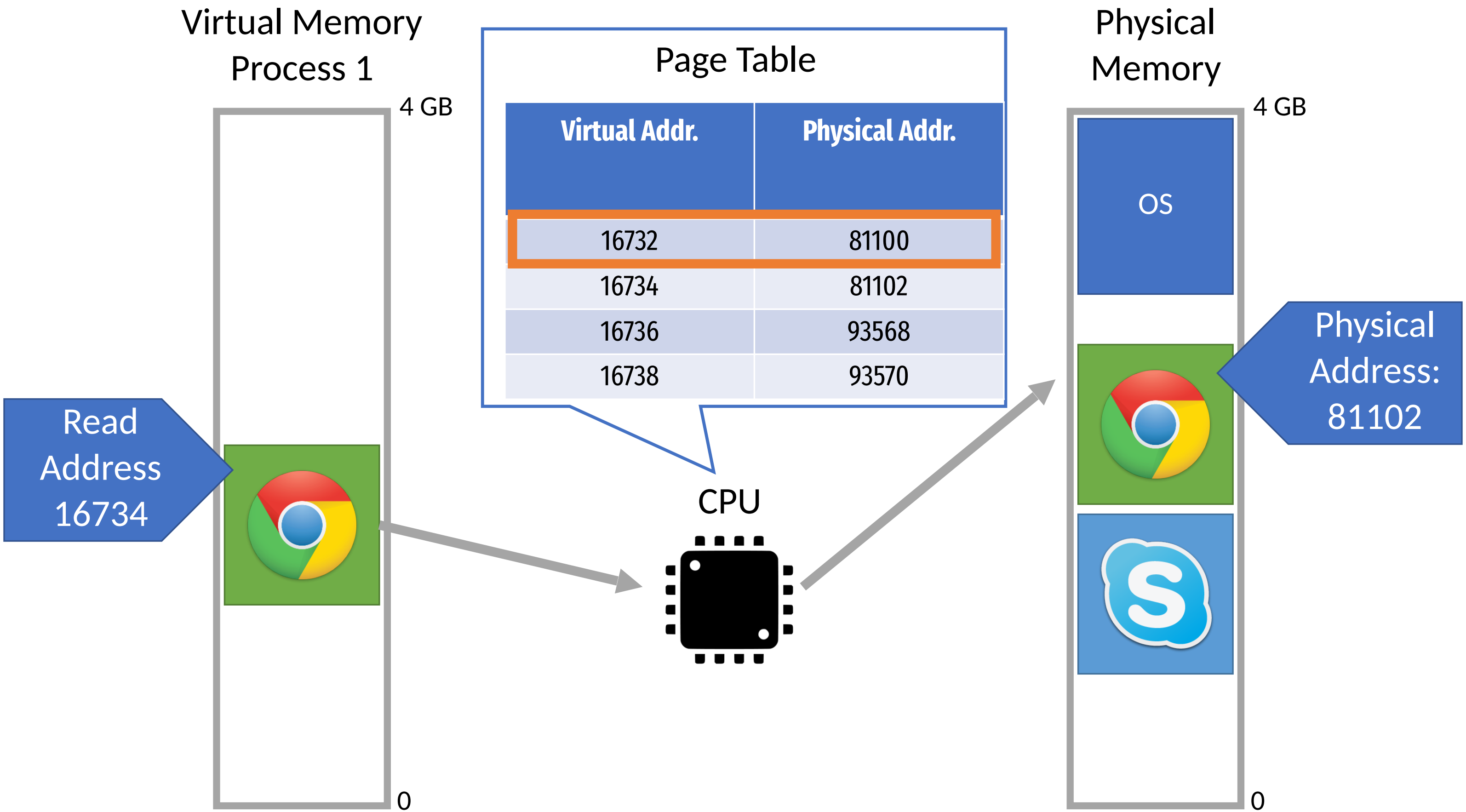


Page Table

Virtual Addr.	Physical Addr.
16732	81100
16734	81102
16736	93568
16738	93570







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Virtual Memory Implementation

Each process has its own virtual memory space

- Each process has a page table that maps is virtual space into physical space
- CPU translates virtual address to physical addresses on-the-fly

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OS creates the page table for each process

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- Processes cannot modify their page tables

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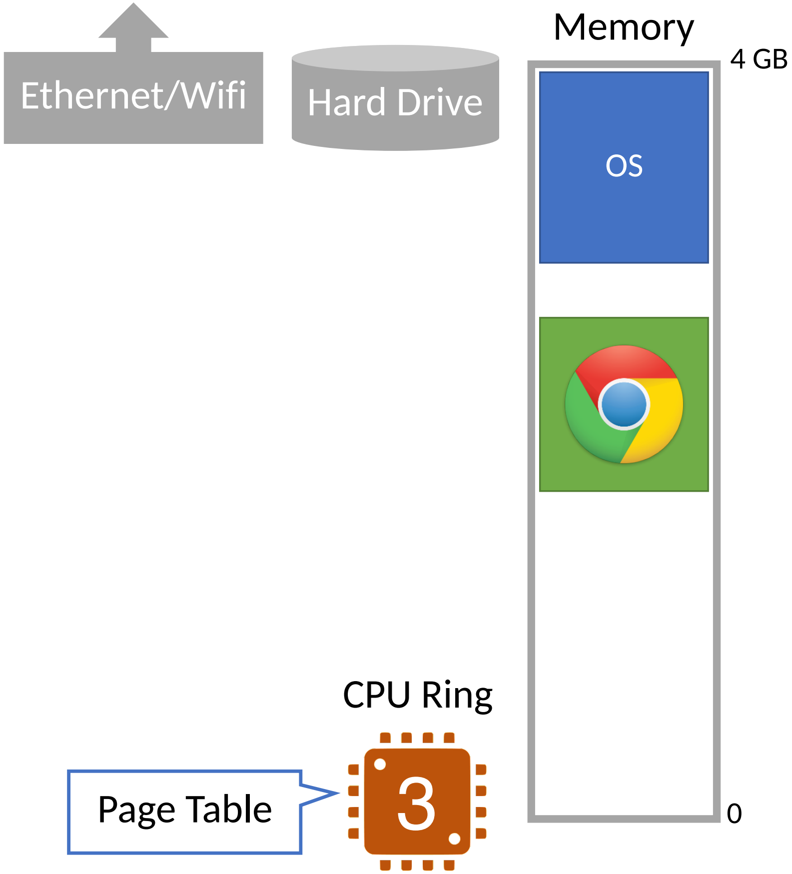
What happens if a process tries to read/write memory outside its page table?

- Segmentation Fault or Page Fault
- Process crashes
- In other words, no way to escape virtual memory

VM in Action

Processes can only read/ write within their own virtual memory

Processes cannot change their own page tables



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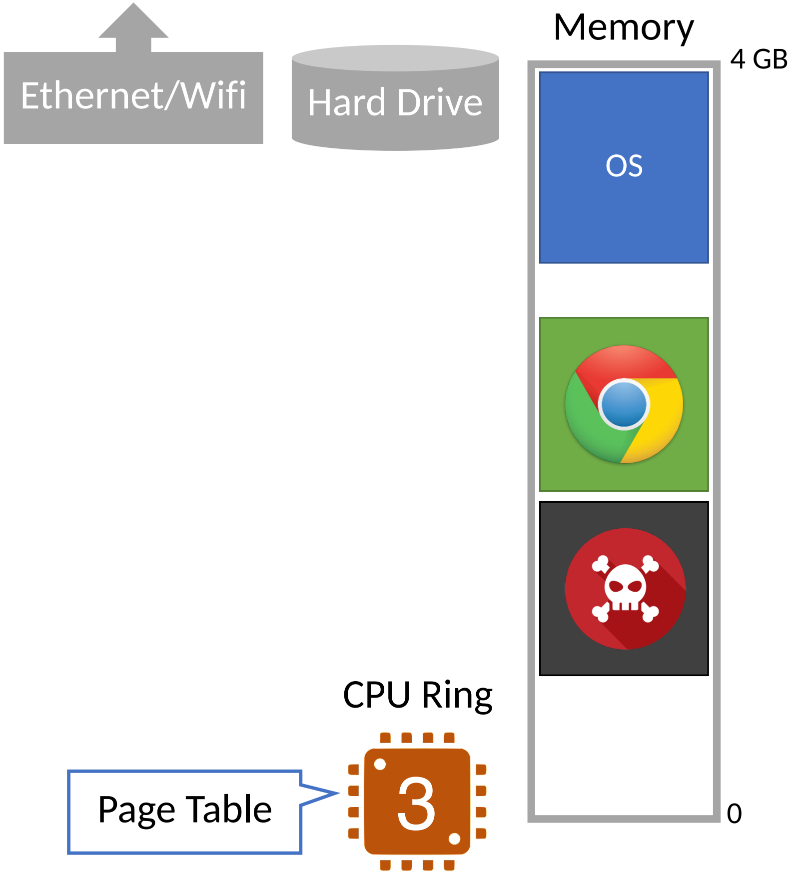

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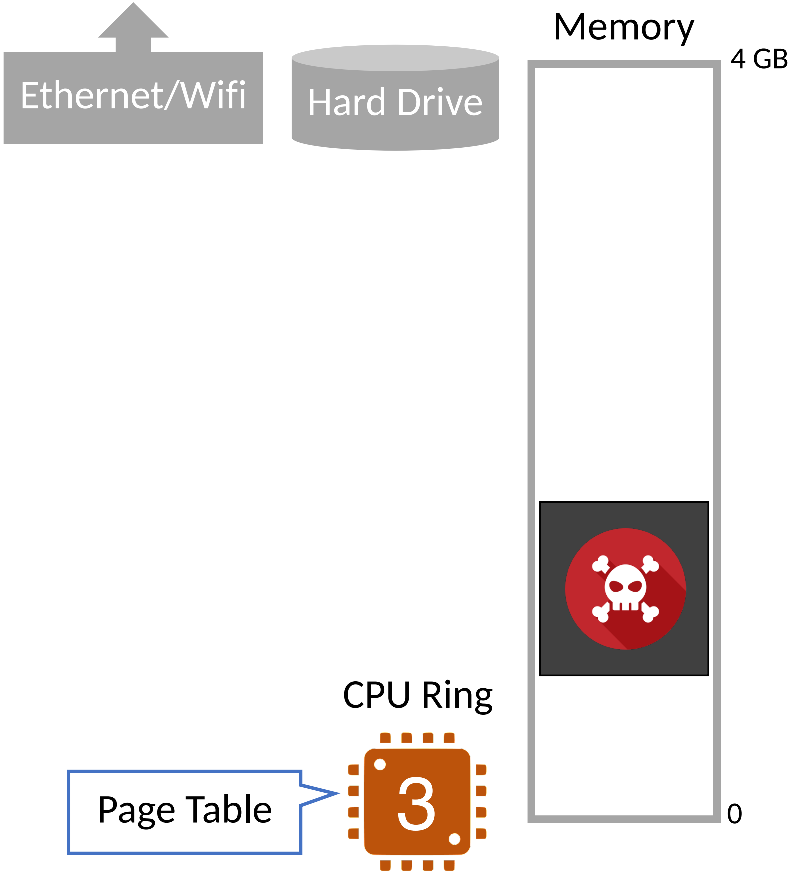

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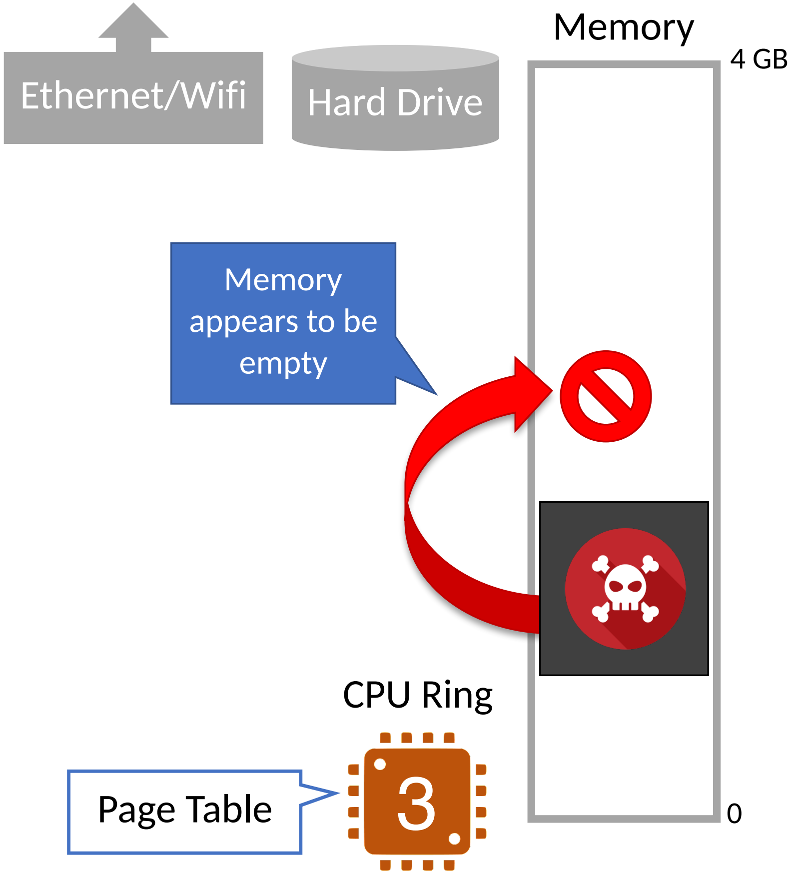

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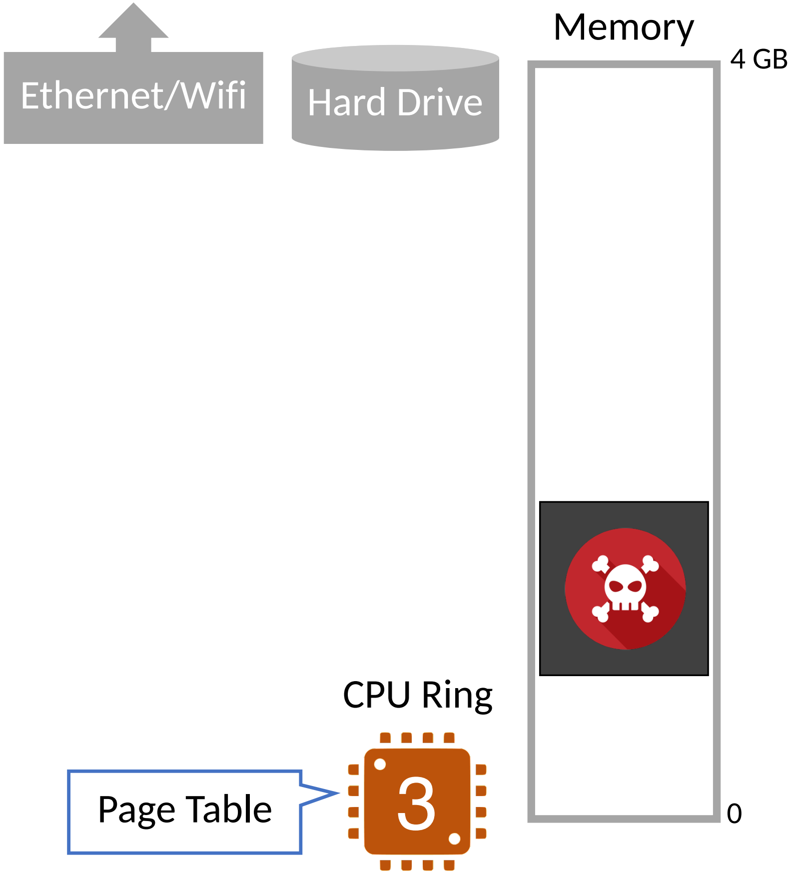

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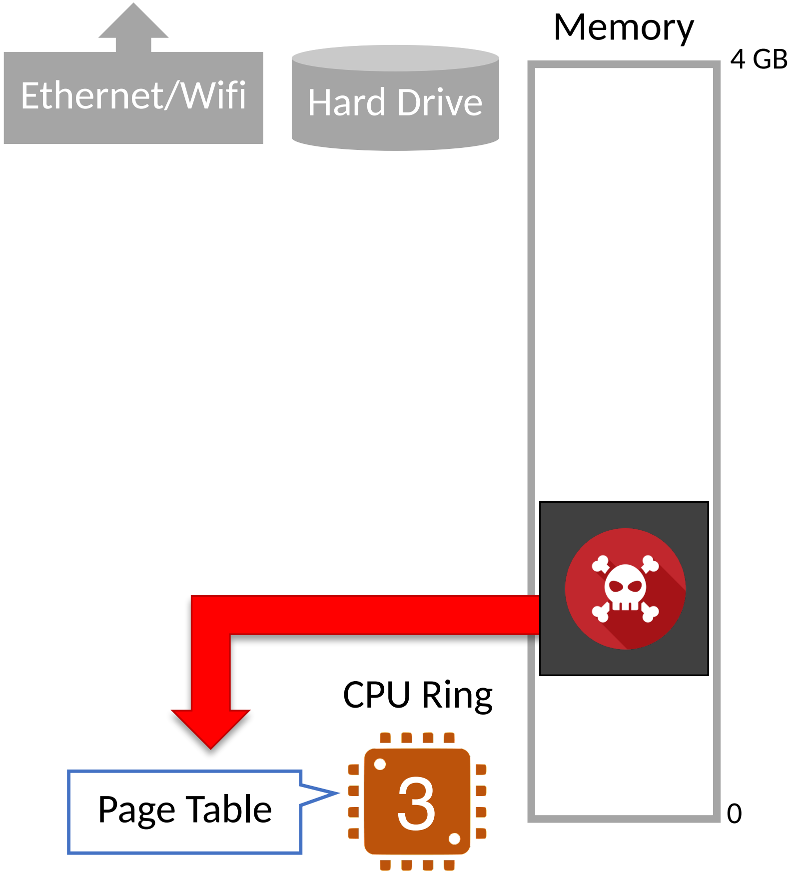

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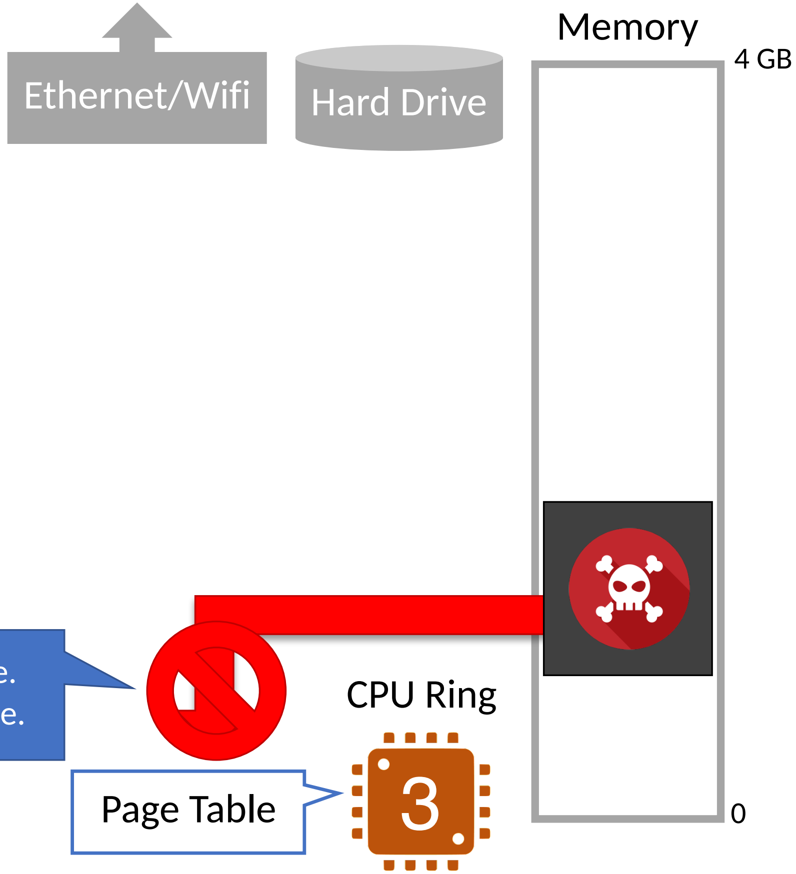


Ring 3 = protected mode.
Cannot change page table.

Threat Model
Intro to System Architecture
Hardware Support for Isolation
Examples
Principles

Review

At this point, we have achieved process isolation

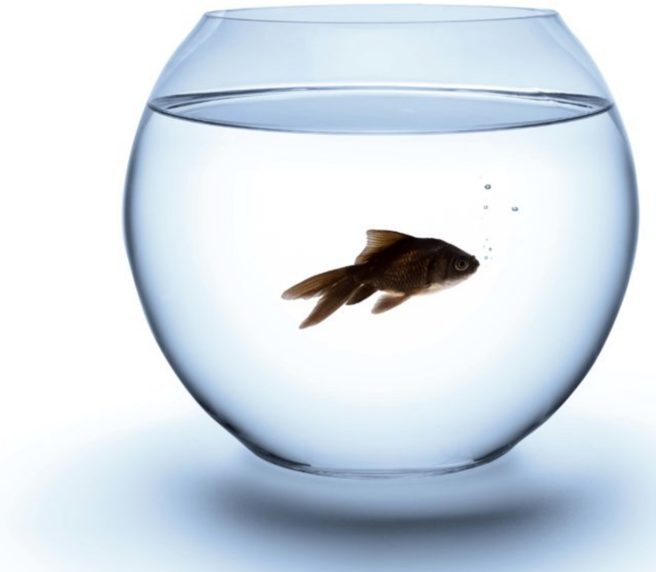
- Protected mode execution prevents direct device access
- Virtual memory prevents direct memory access

Requires CPU support

- All moderns CPUs support these techniques

Requires OS support

- All moderns OS support these techniques
- OS controls process rings and page tables



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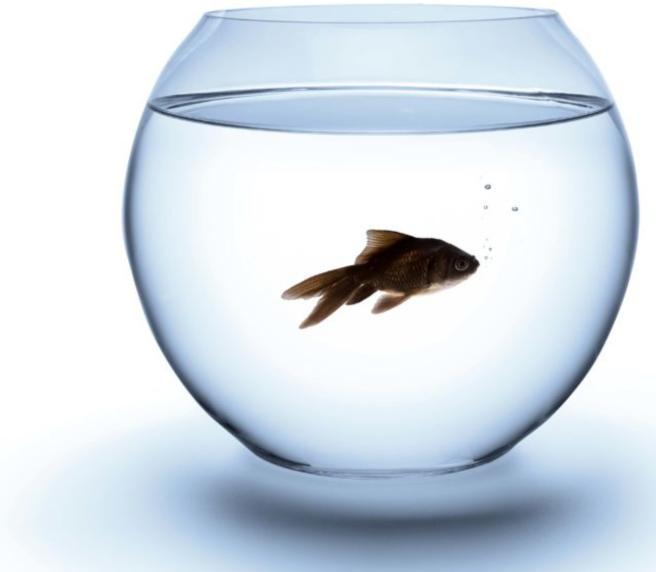
Warning: bugs in the OS may compromise process isolation



Towards Secure Systems

Now that we have process isolation, we can build more complex security features

File Access Control

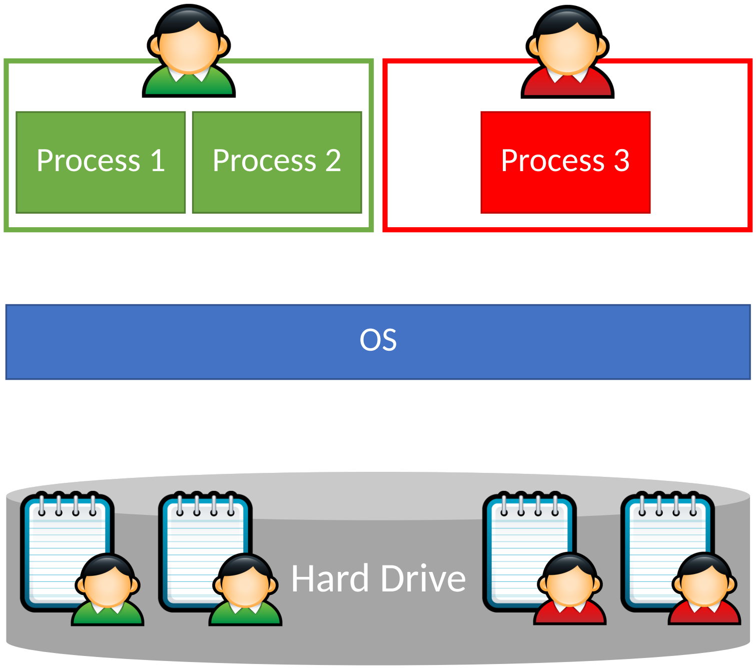
Anti-virus

Firewall

Secure Logging

File Access Control

- All disk access is mediated by the OS
- OS enforces access controls



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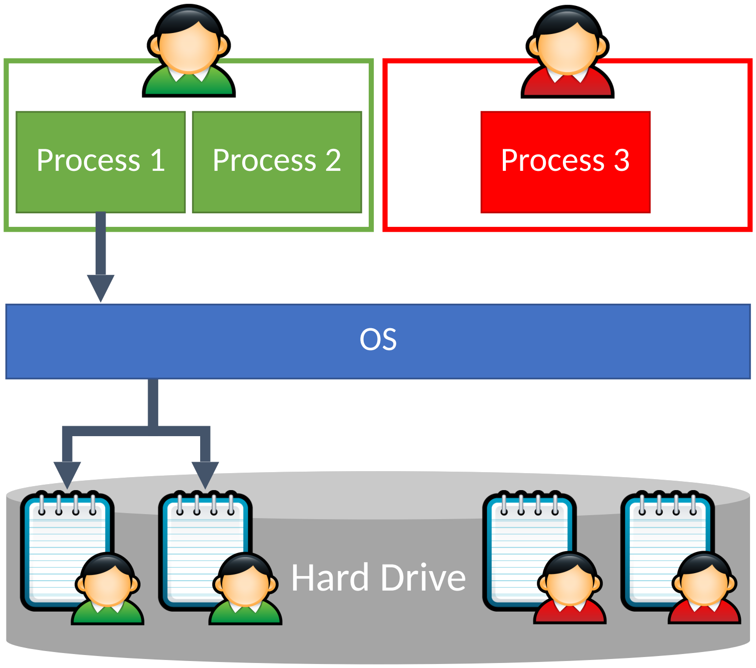

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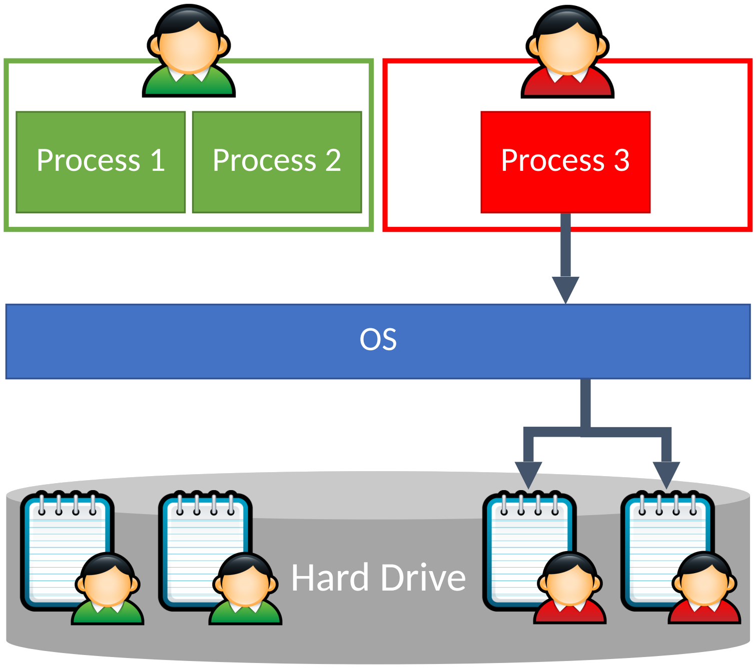

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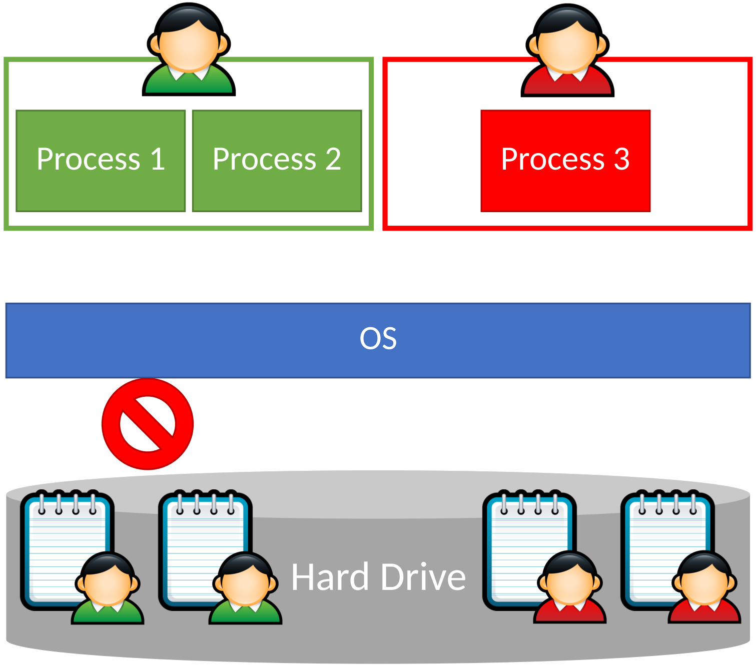
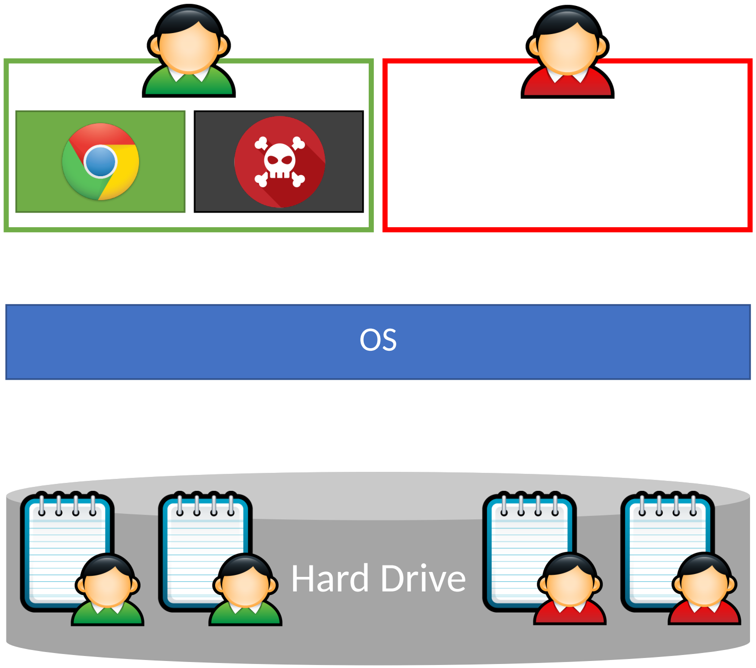


Limitations

Malware can still cause damage

Discretionary access control means that isolation is incomplete



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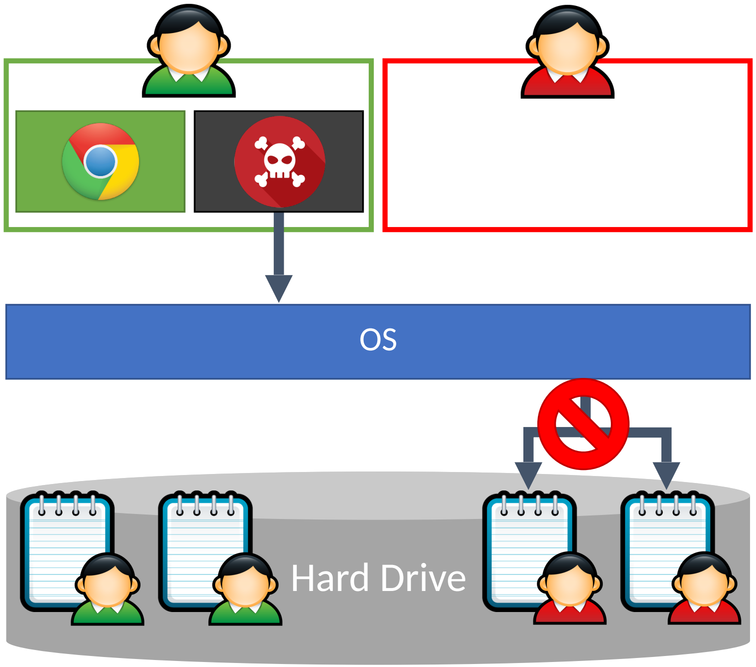

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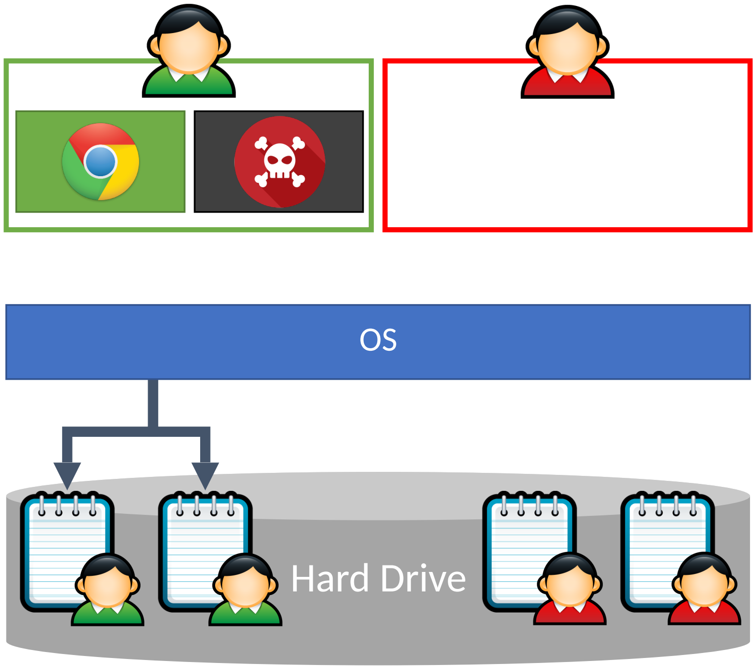


Anti-virus

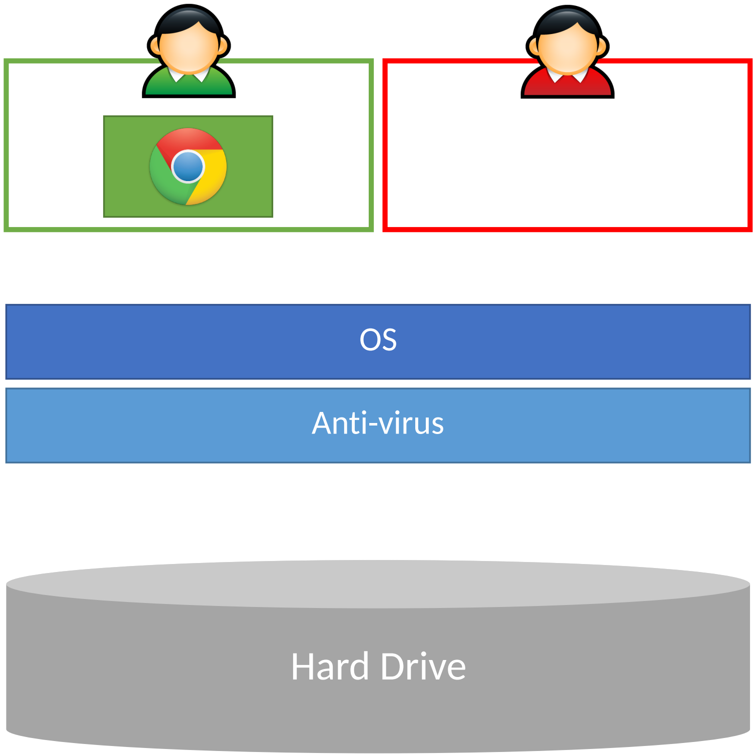
Anti-virus process is privileged

- Often runs in Ring 0

Scans all files looking for signatures

- Each signature uniquely identifies a piece of malware

Files scanned on creation and access



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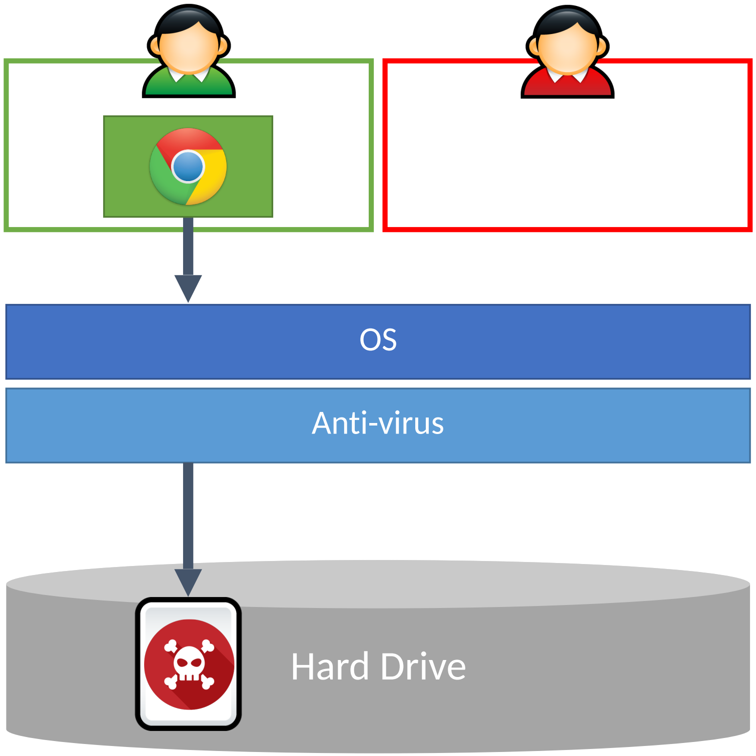

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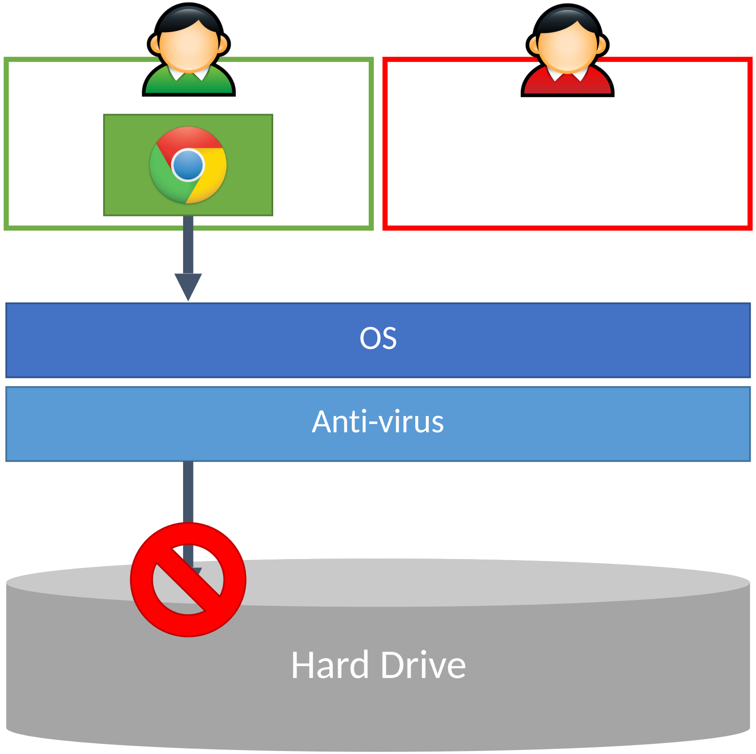

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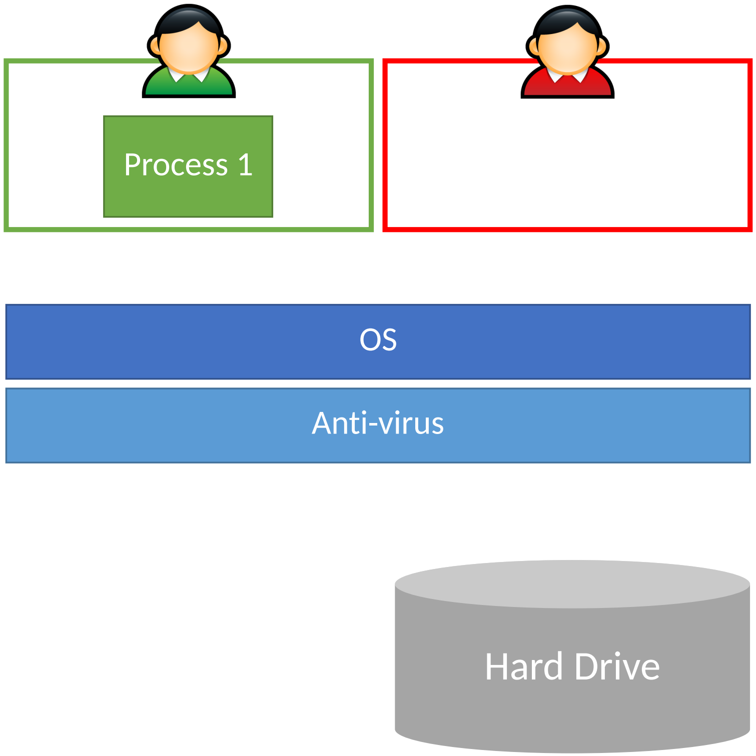

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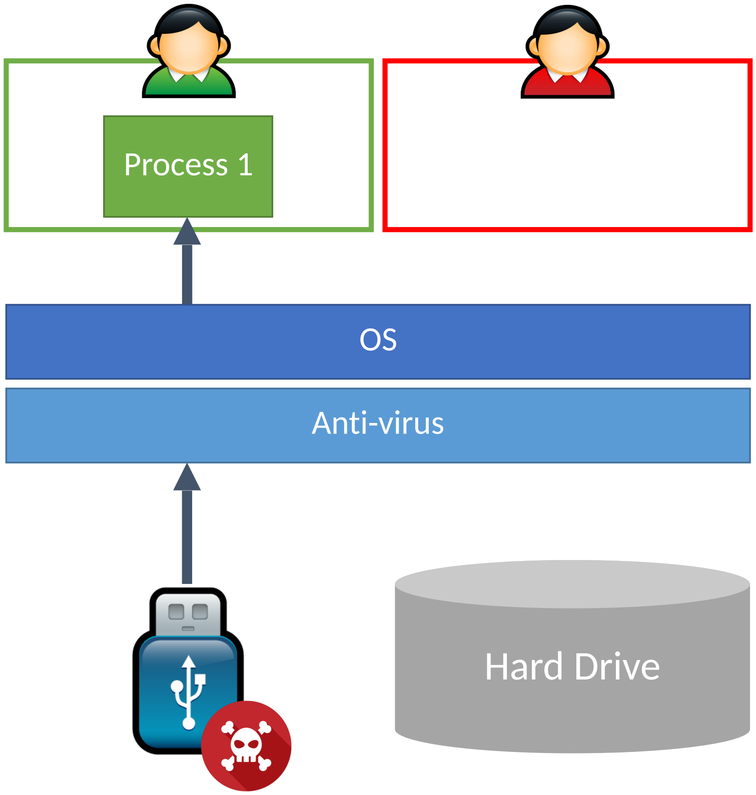

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