Systems and Networking – Unit I

B.Sc. in Applied Computer Science and Artificial Intelligence

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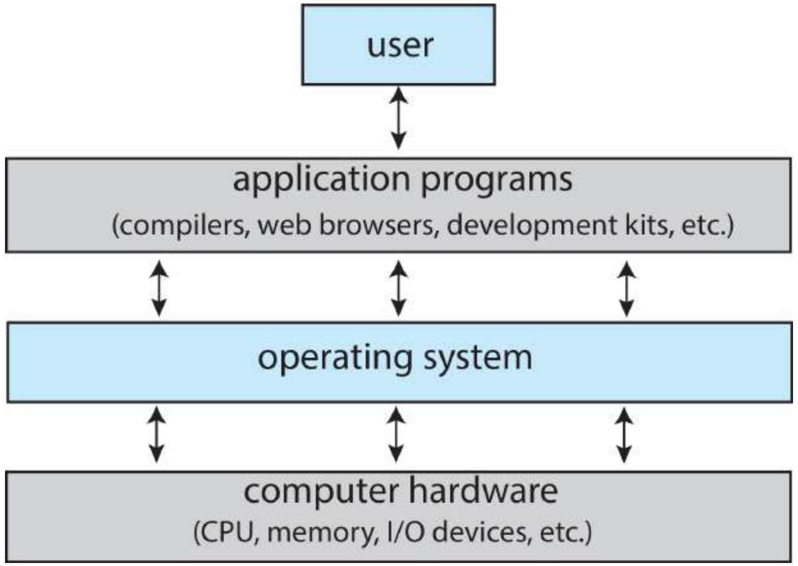
SAPIENZA UNIVERSITÀ DI ROMA

Recap from Last Lecture

- Operating System is a complex system which plays several roles:
  - resource manager
  - virtual machine
  - HW/SW interface



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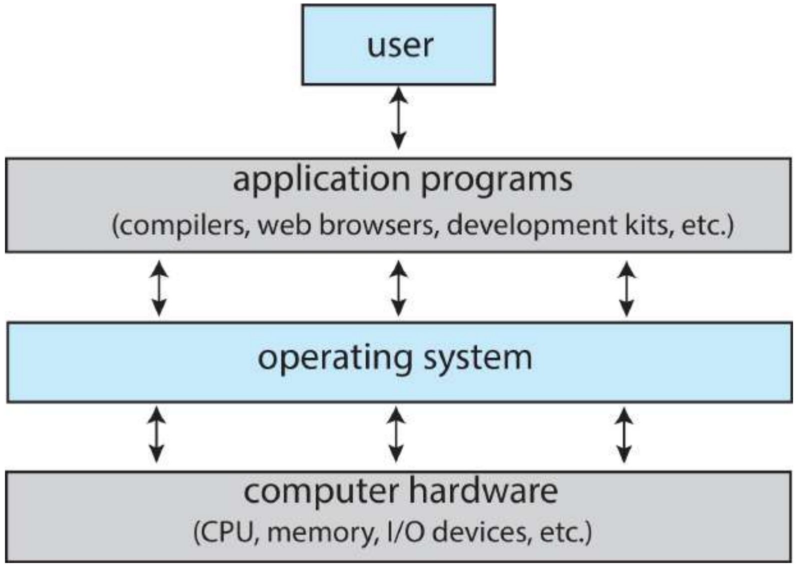

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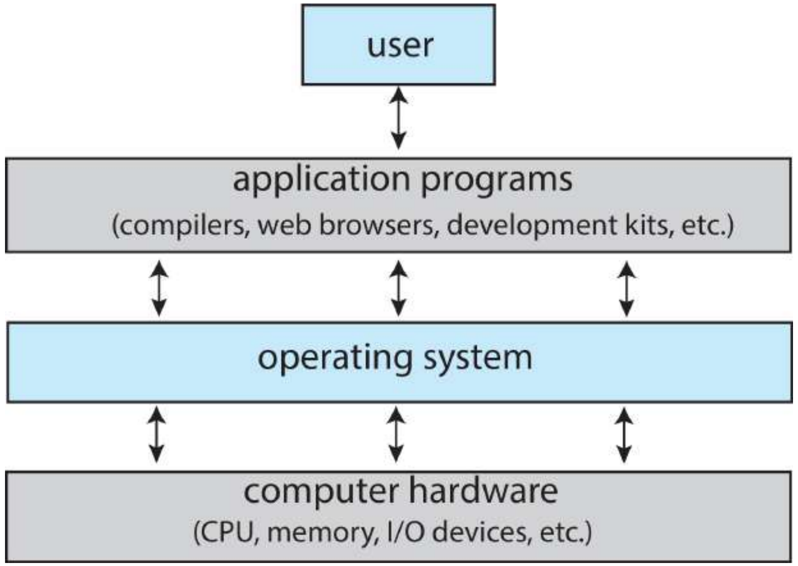
- Changes in HW may affect OS design



Outline of this Lecture

1. Computer architecture review
2. HW support for OS functionalities and services
3. OS design and implementation

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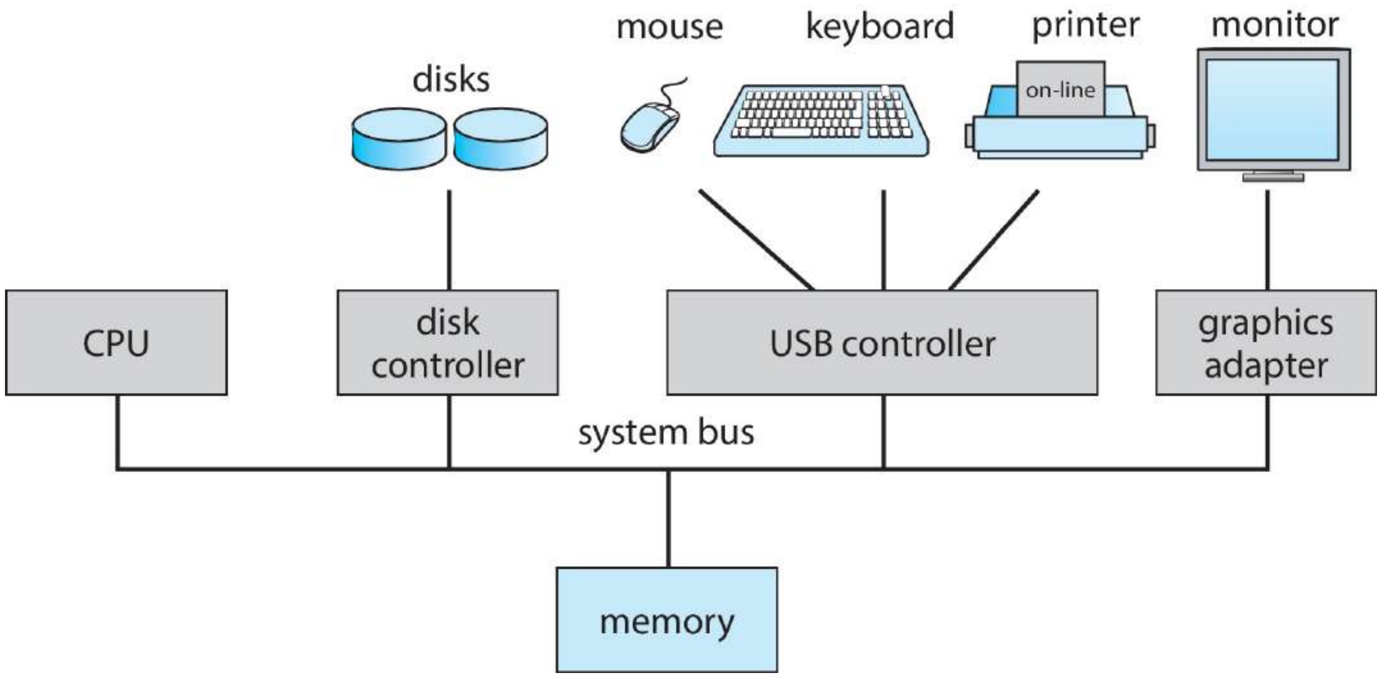
Generic High-Level Computer Architecture



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- I/O devices → terminal, keyboard, disks, etc.
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- System Bus → communication medium between CPU, memory, and peripherals

Computer Architecture Model

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  - PCs/laptops
  - High-end servers
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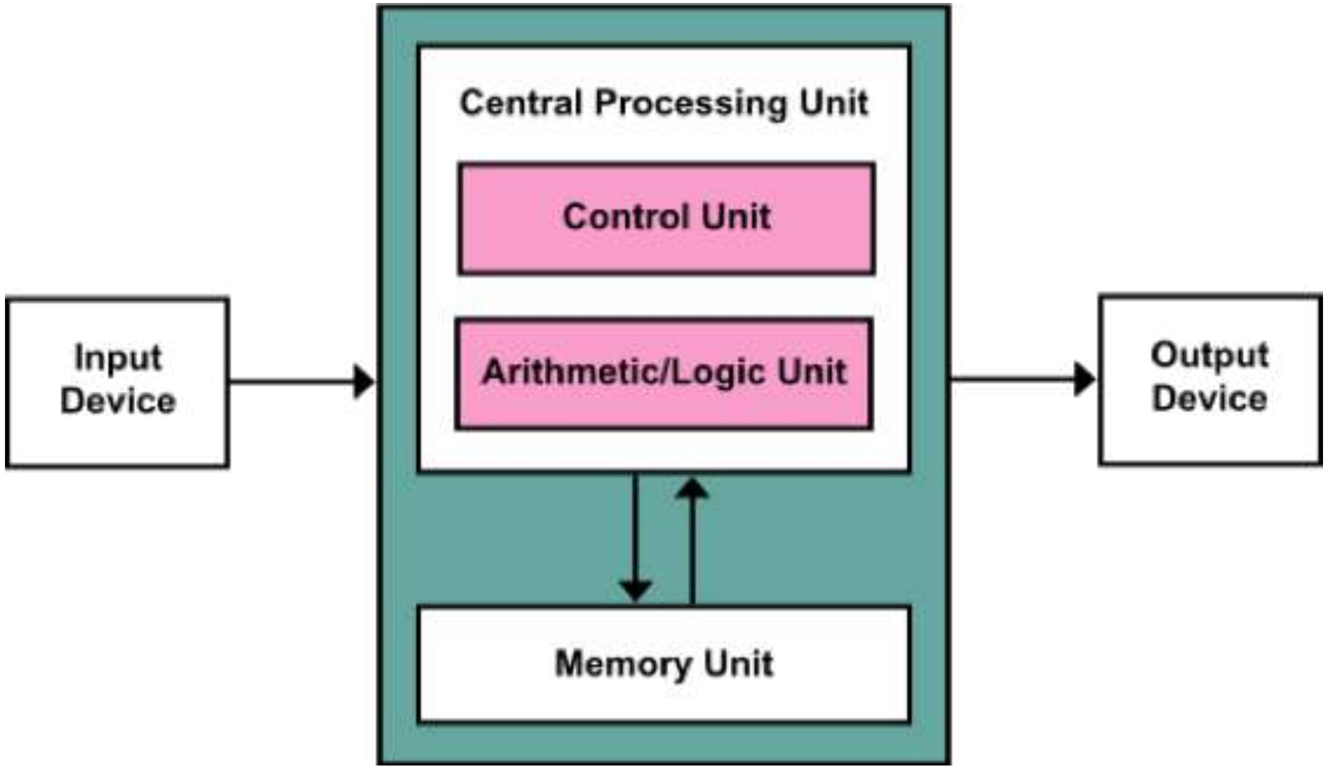
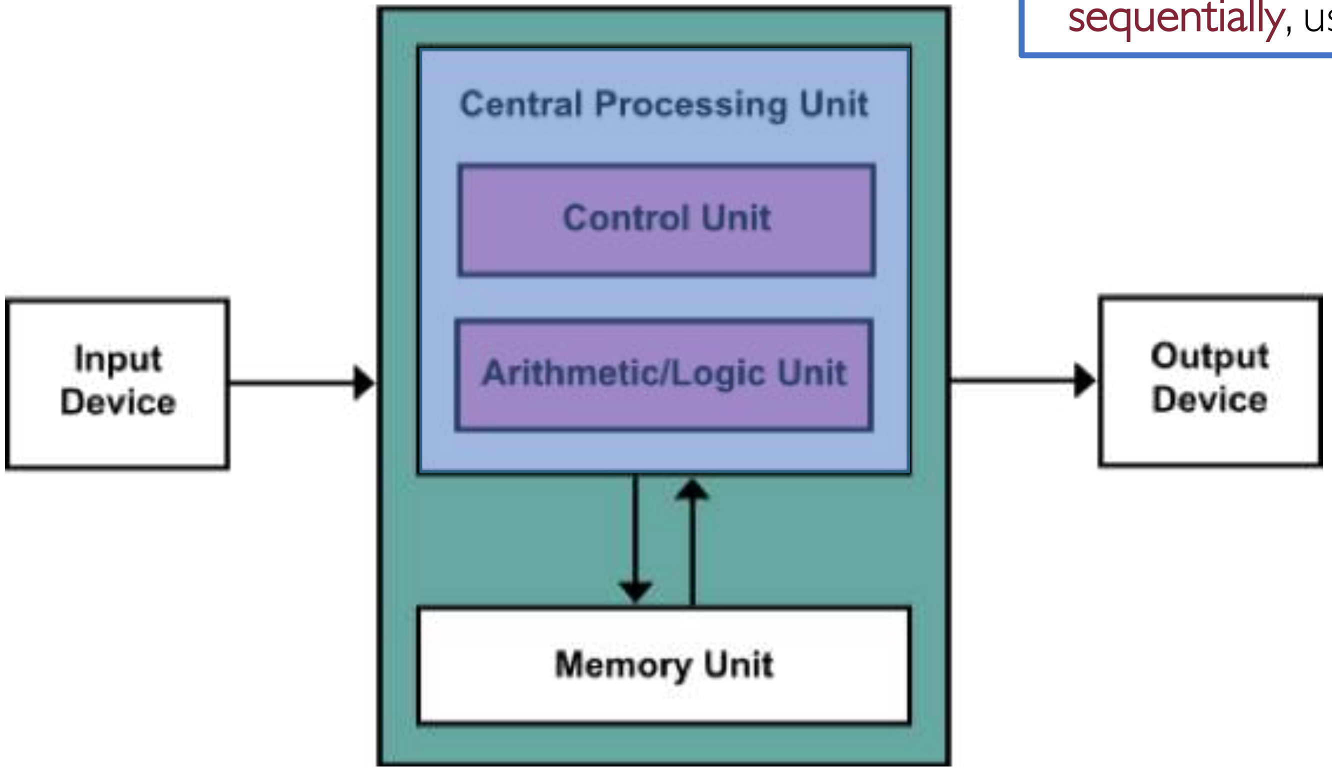
John von Neumann

von Neumann Architecture



von Neumann Architecture

Executes instructions (i.e., basic arithmetical/logical computations) sequentially, using internal registers



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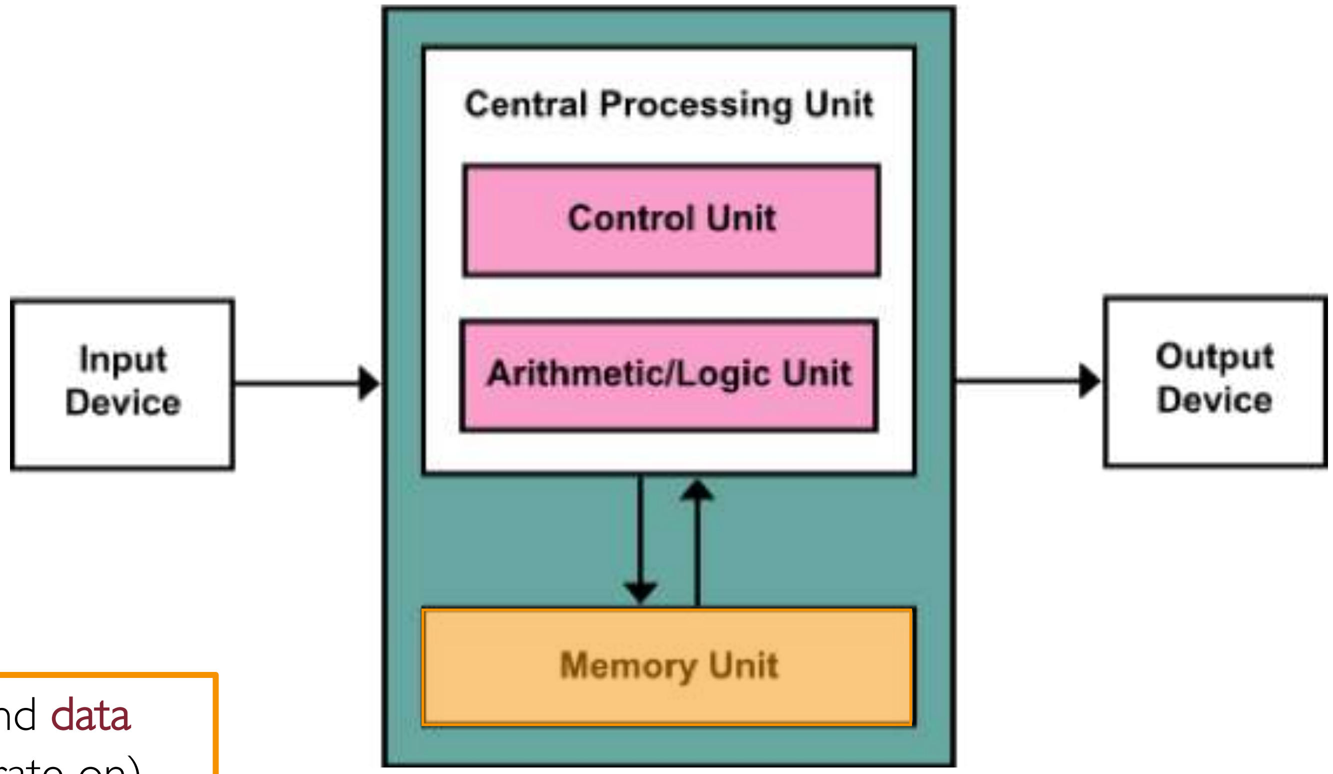

Contains instructions and data
(which instructions operate on)

Central Processing Unit

(CPU)

Instruction Cycle: Fetch-Decode-Execute

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  - Execute: runs the actual decoded instruction

Machine Language

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- Each instruction is encoded as a sequence of bits
  - A single bit is the smallest unit of (digital) information
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- A word is the unit of data the CPU can directly operate on
  - today ranging from 32 to 64 bits

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- In binary system (base-2), each digit is a bit

1	0	1
2^2	2^1	2^0

$1*2^0 + 0*2^1 + 1*2^2 = 5$

A Side Note on Units

Prefixes for multiples of bits (bit) or bytes (B)									
Decimal				Binary					
Value		SI		Value		IEC		JEDEC	
1000	10^3	k	kilo	1024	2^{10}	Ki	kibi	K	kilo
1000^2	10^6	M	mega	1024^2	2^{20}	Mi	mebi	M	mega
1000^3	10^9	G	giga	1024^3	2^{30}	Gi	gibi	G	giga
1000^4	10^{12}	T	tera	1024^4	2^{40}	Ti	tebi	–	
1000^5	10^{15}	P	peta	1024^5	2^{50}	Pi	pebi	–	
1000^6	10^{18}	E	exa	1024^6	2^{60}	Ei	exbi	–	
1000^7	10^{21}	Z	zetta	1024^7	2^{70}	Zi	zebi	–	
1000^8	10^{24}	Y	yotta	1024^8	2^{80}	Yi	yobi	–	

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- An abstraction of the underlying physical (hardware) architecture (e.g., x86, ARM, SPARC, MIPS, etc.)
- Each realization of the same instruction set is an implementation of a physical architecture (e.g., x86 → Intel, AMD, Cyrix, etc.)

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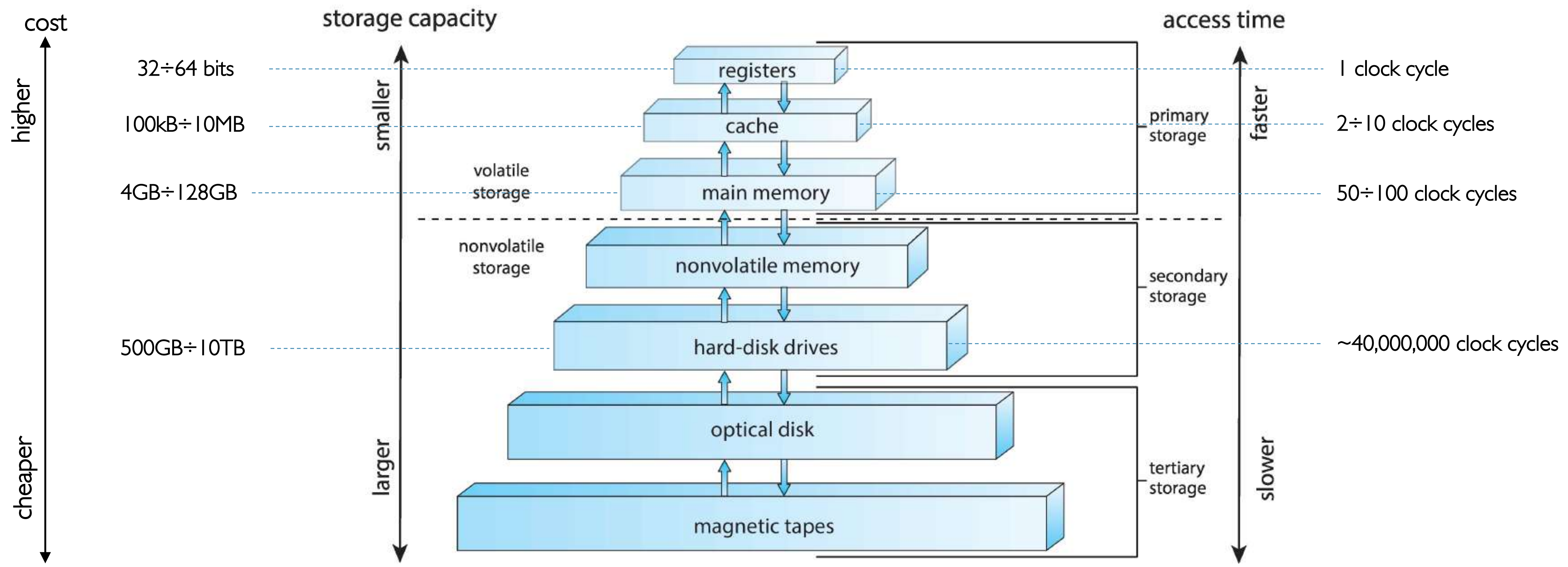
- Special-purpose (x86):
  - `esp` → Stack pointer for top address of the stack
  - `ebp` → Stack base pointer for the address of the current stack frame
  - `eip` → Instruction pointer, holds the program counter (i.e., the address of next instruction)

Memory

Memory Hierarchy



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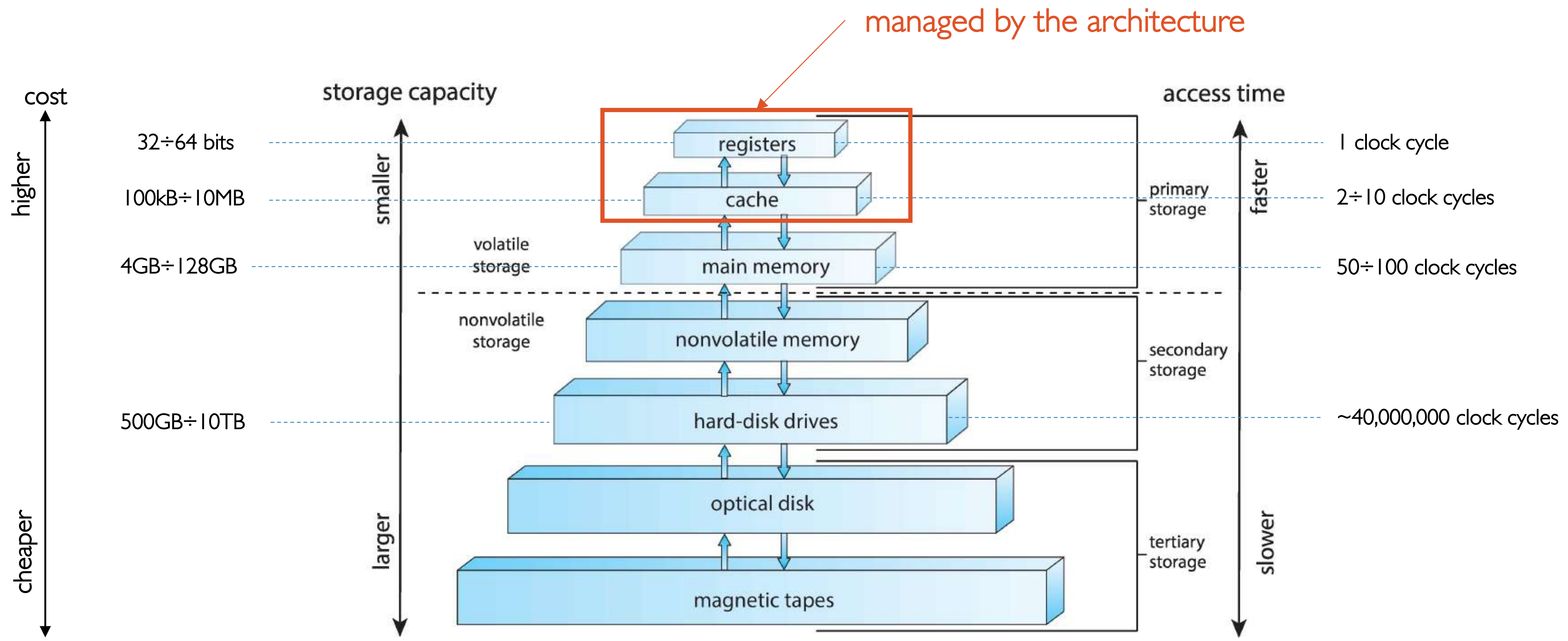

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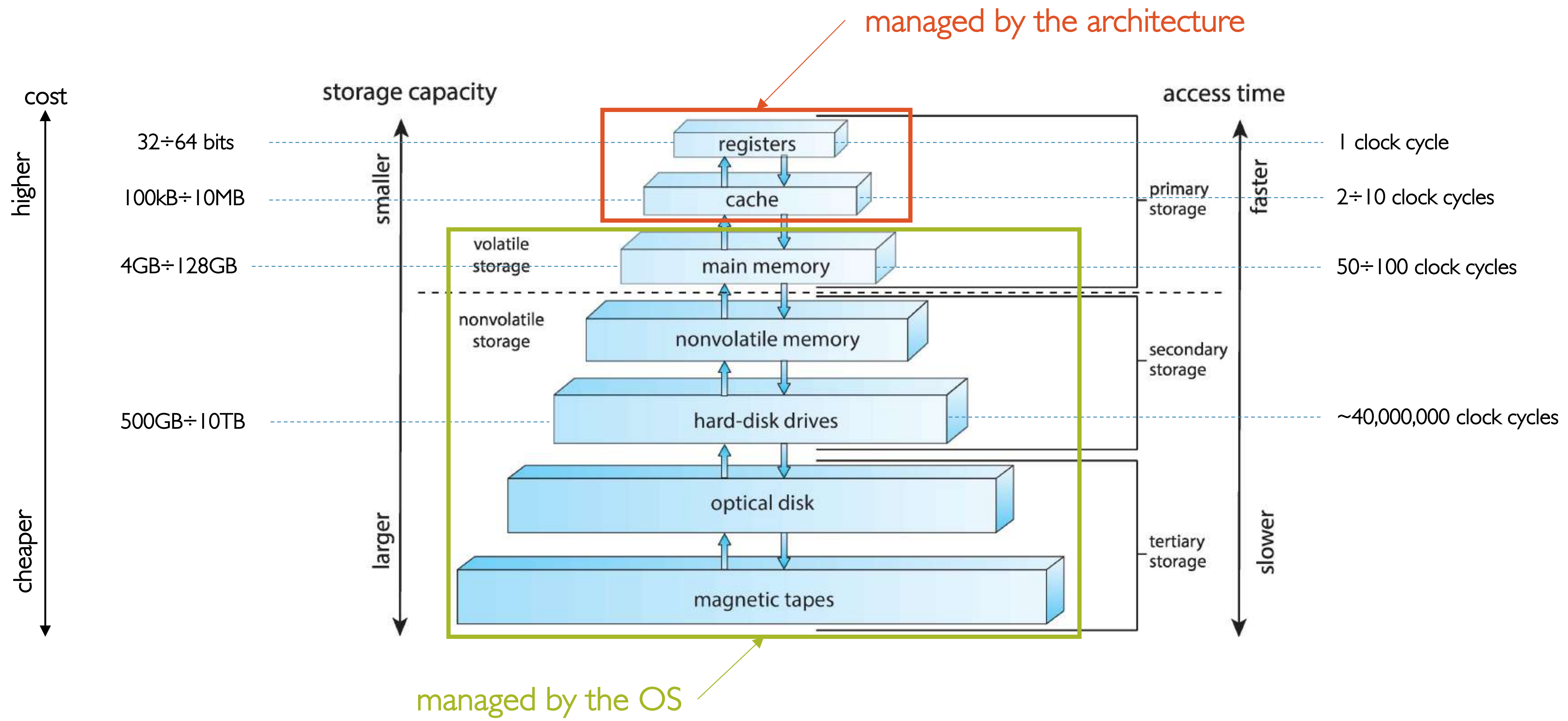

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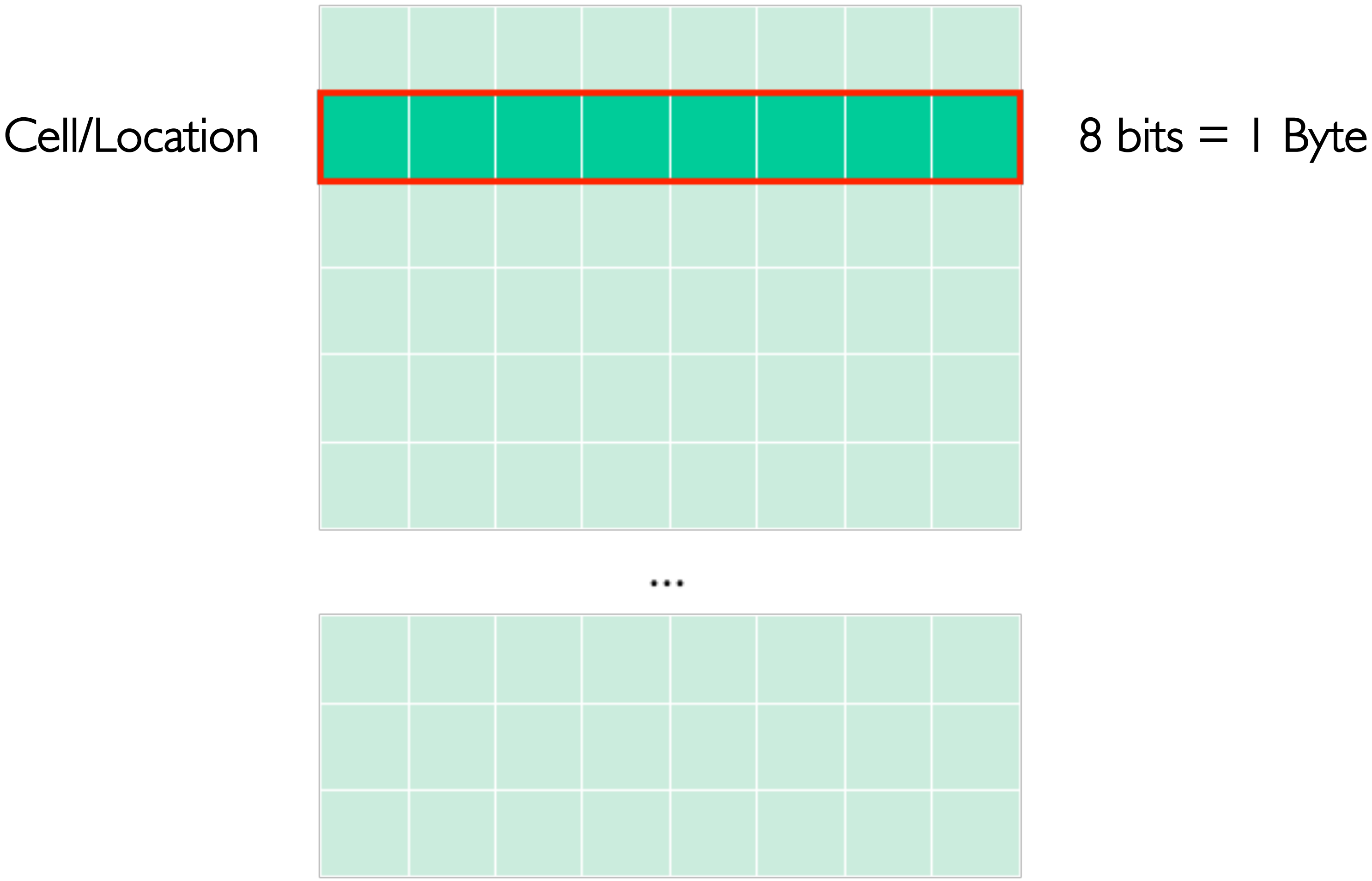
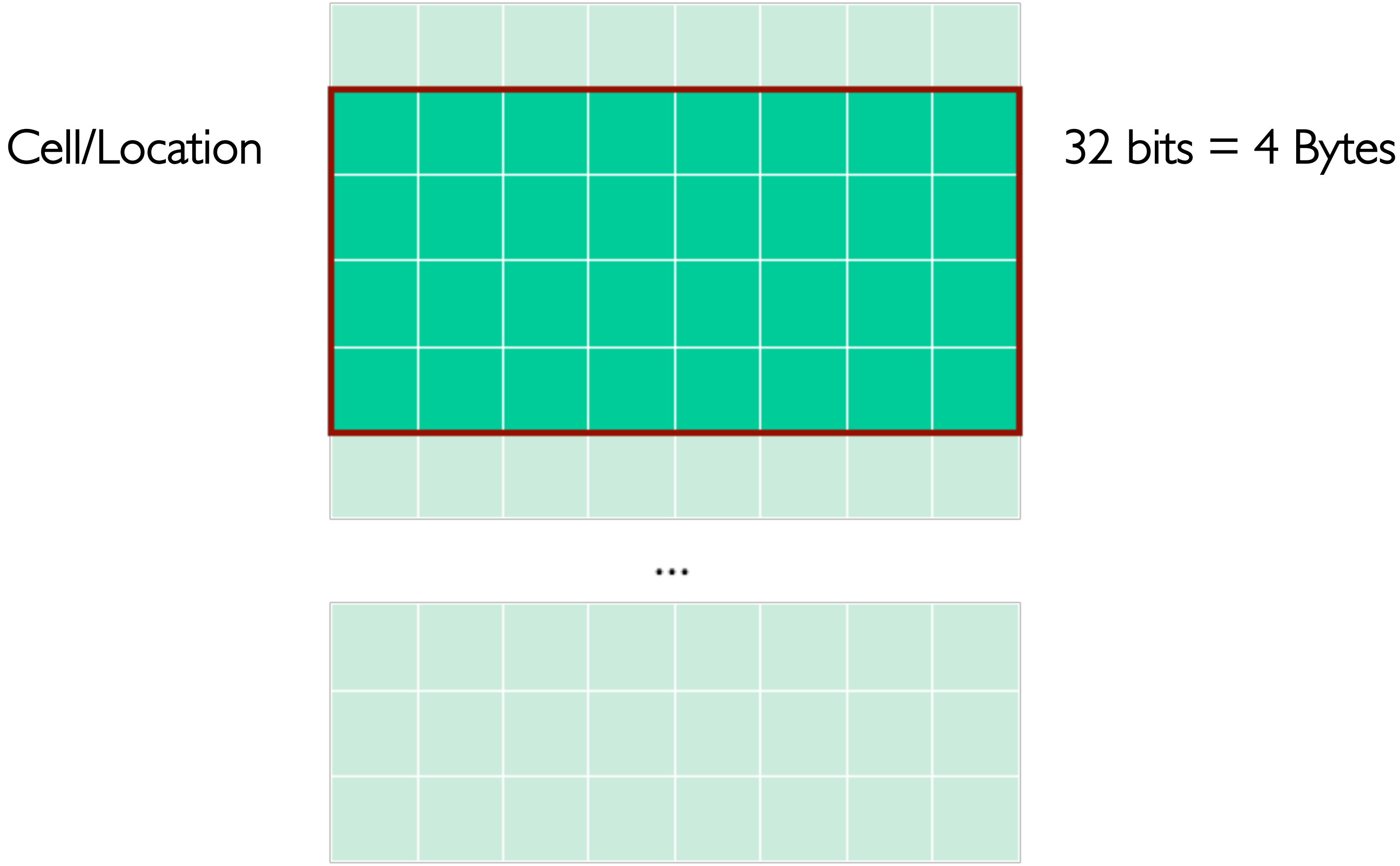
- The smallest addressable unit is usually 1 Byte

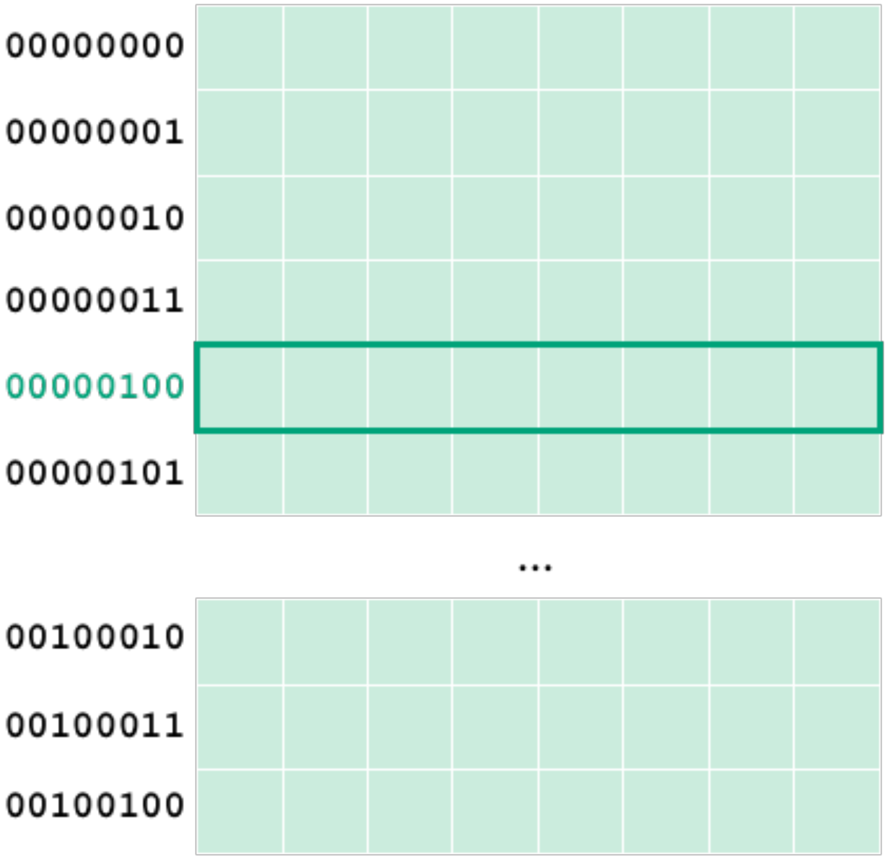
Memory Cell (1)



Memory Cell (2)



Memory Address (Single Byte)



Computer Buses

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- More dedicated buses have been added to manage CPU-to-memory and I/O traffic
  - PCI, SATA, USB, etc.

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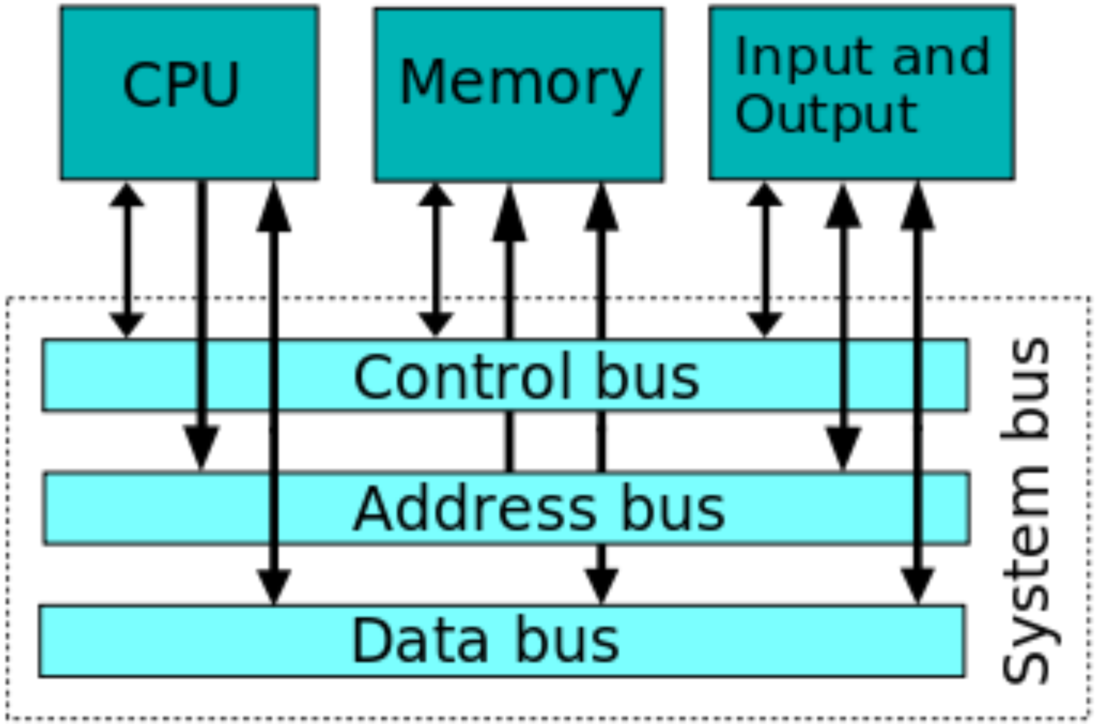
CPU
Memory
Input and Output
Control bus
Address bus
Data bus
System bus

I/O Devices

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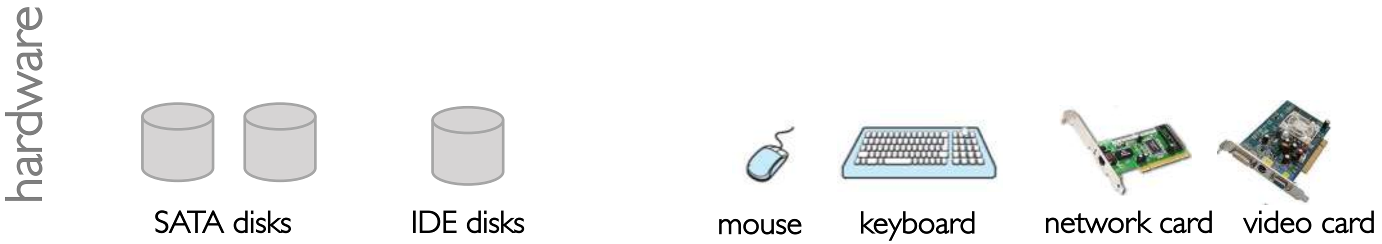
- OS talks to a device controller using a specific device driver

Device Drivers: OS Software Abstraction



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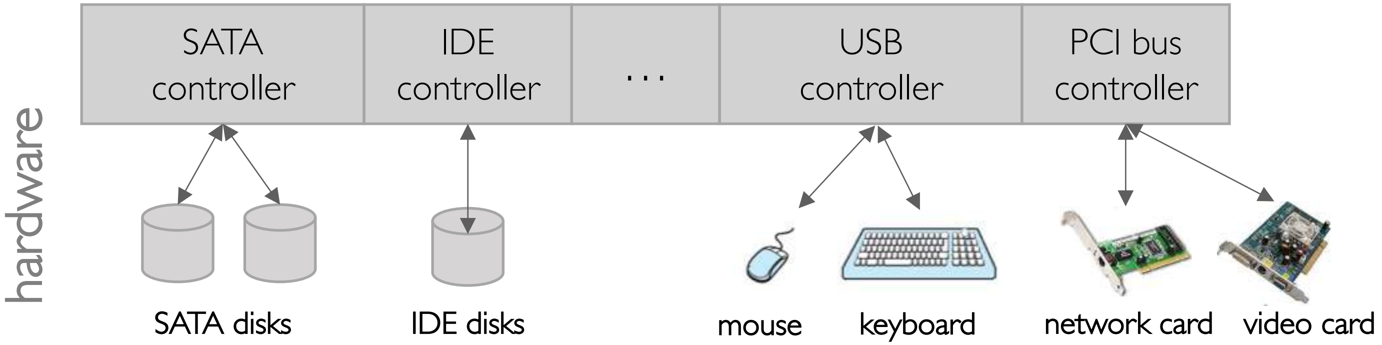

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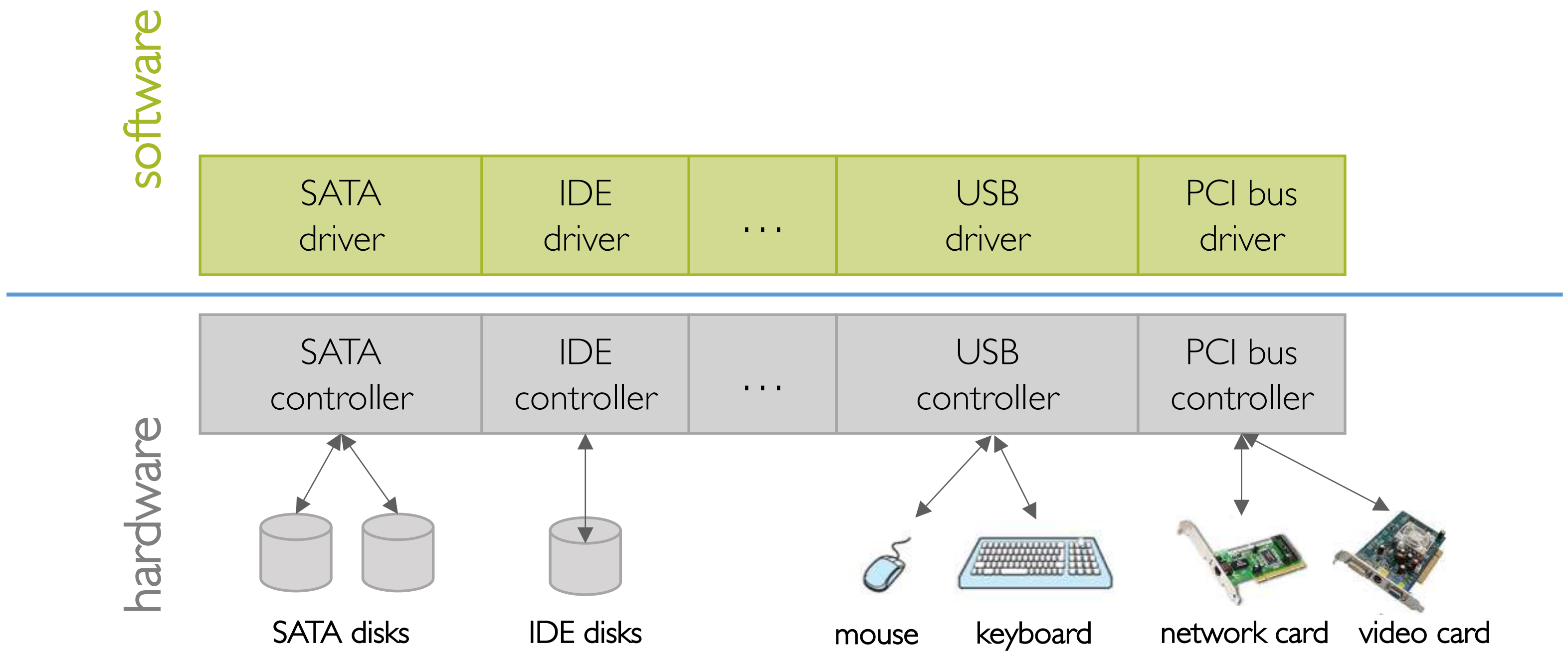

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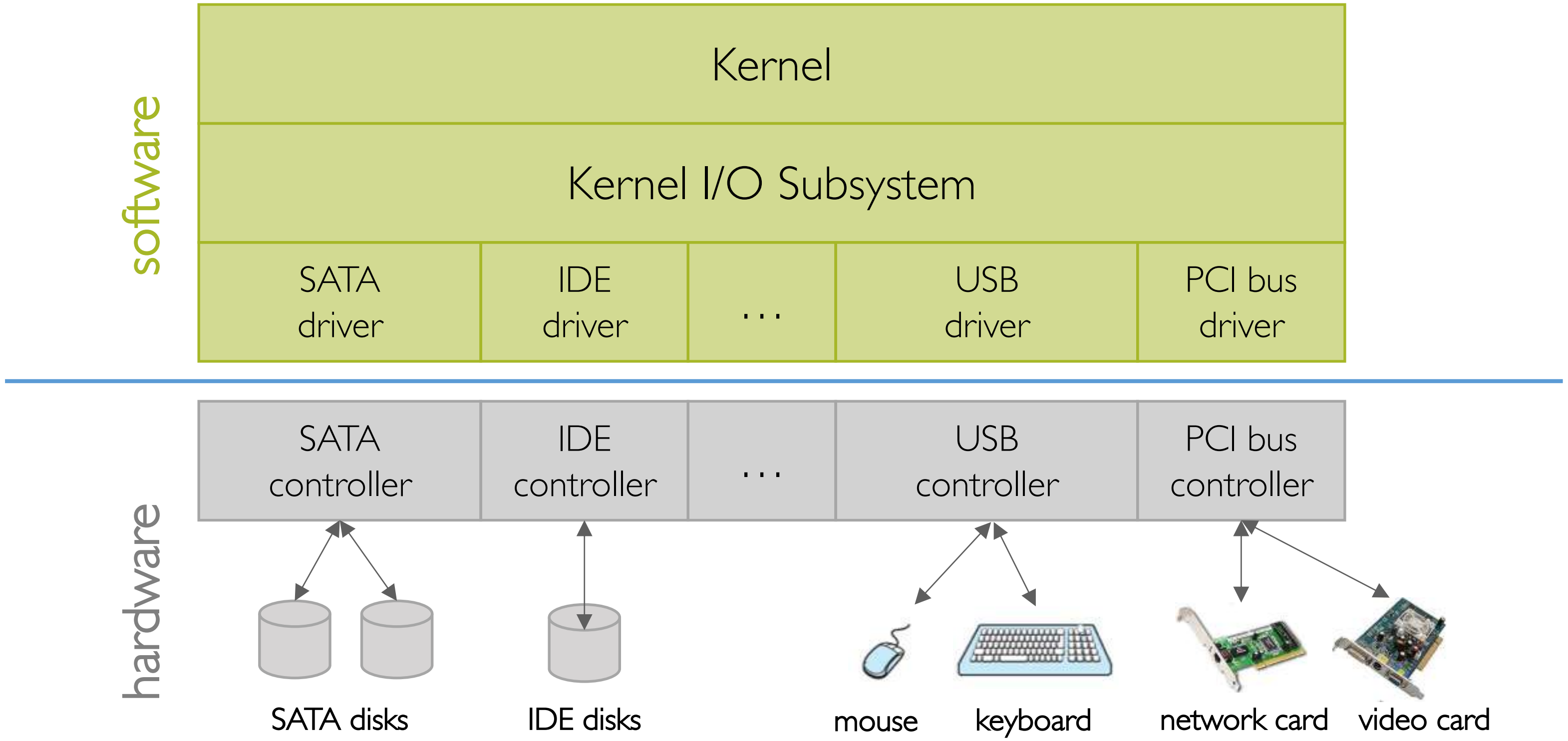

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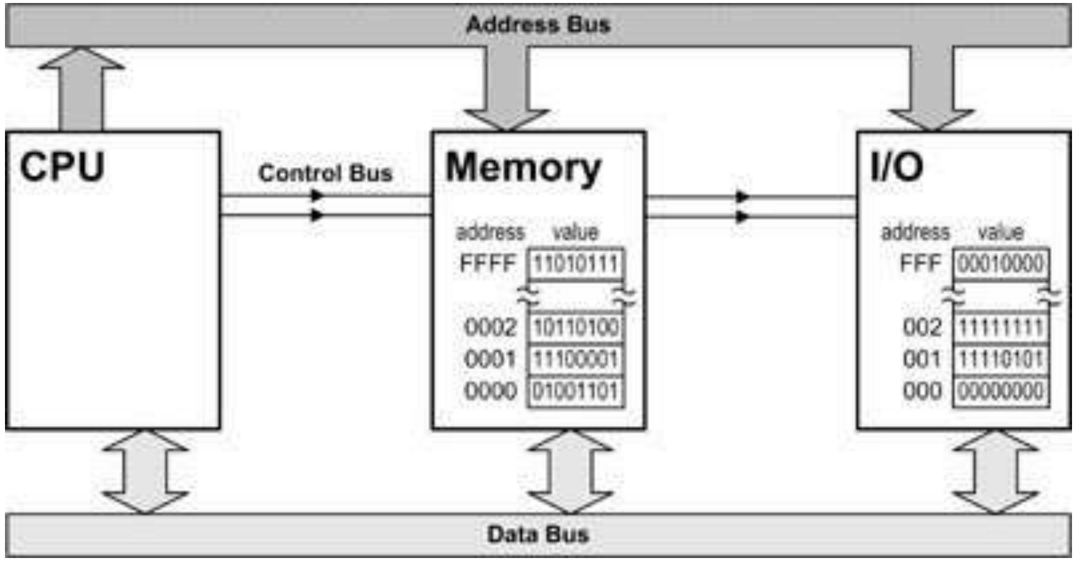
How does the CPU know how to address (registers of) I/O devices?

Addressing Using the System Bus



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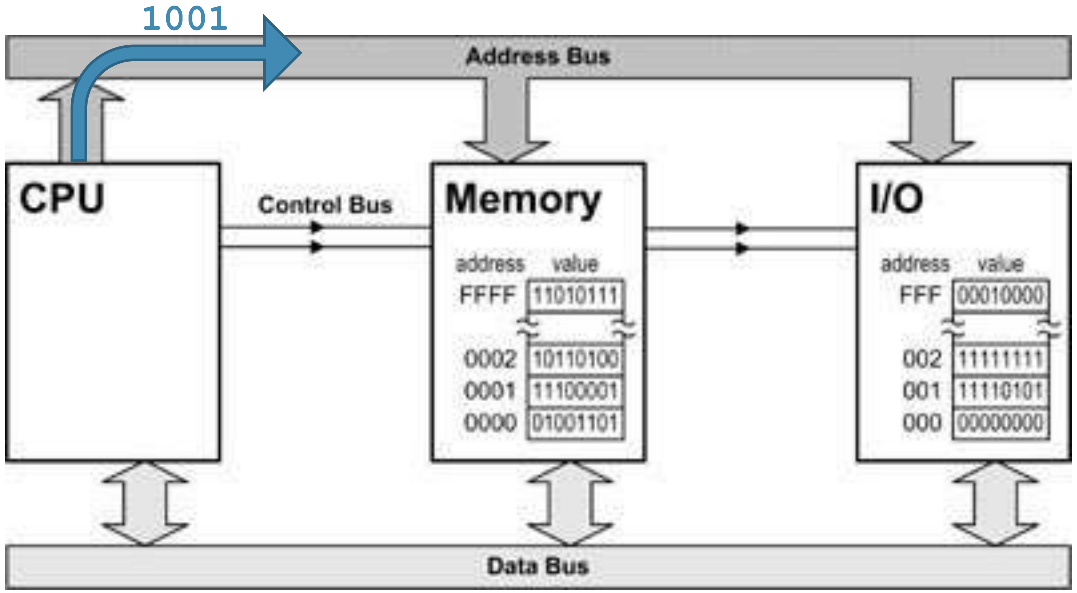

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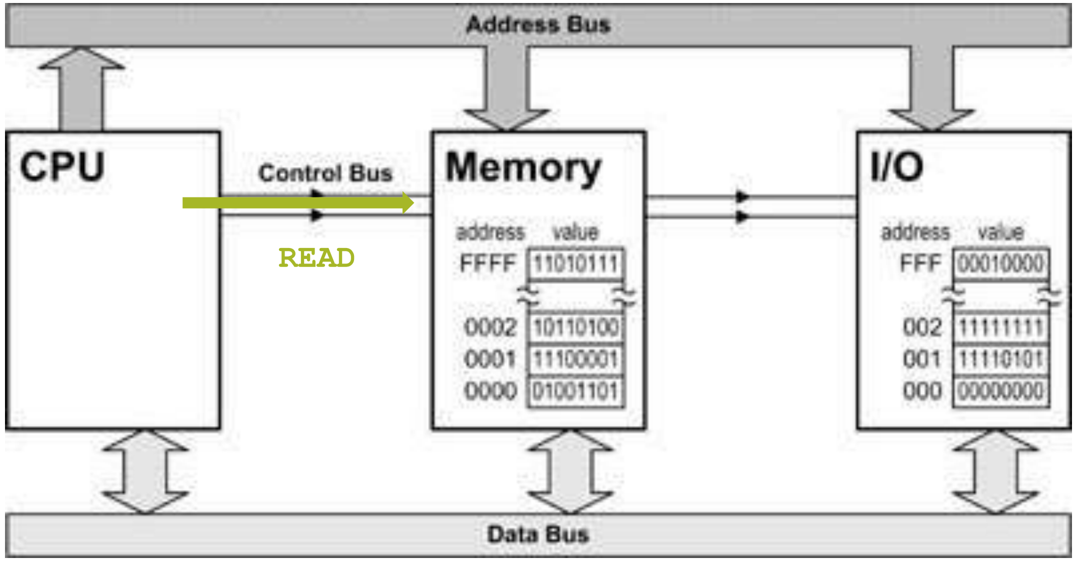

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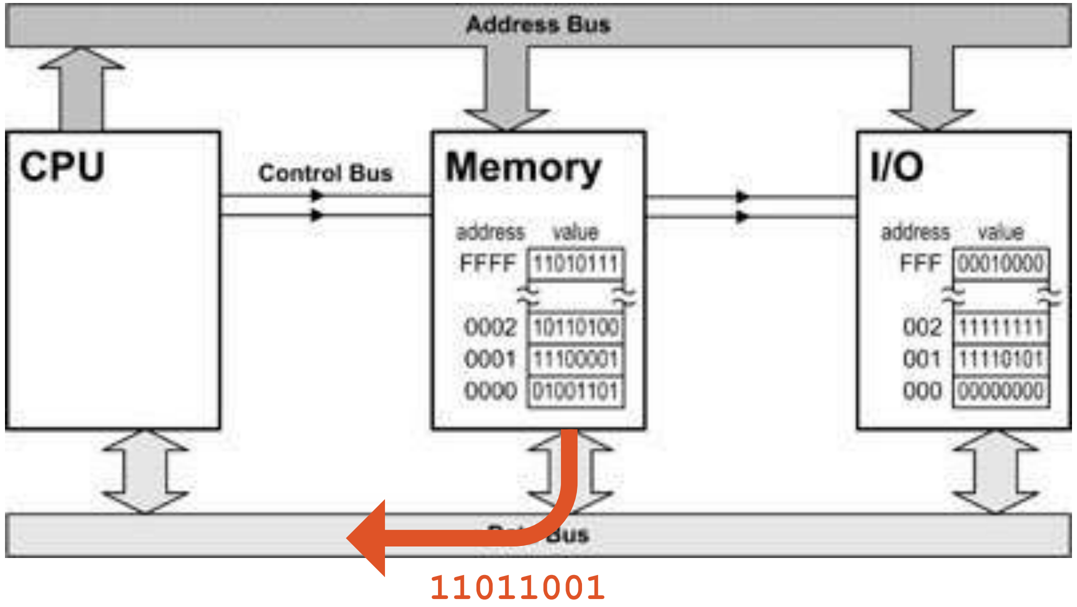

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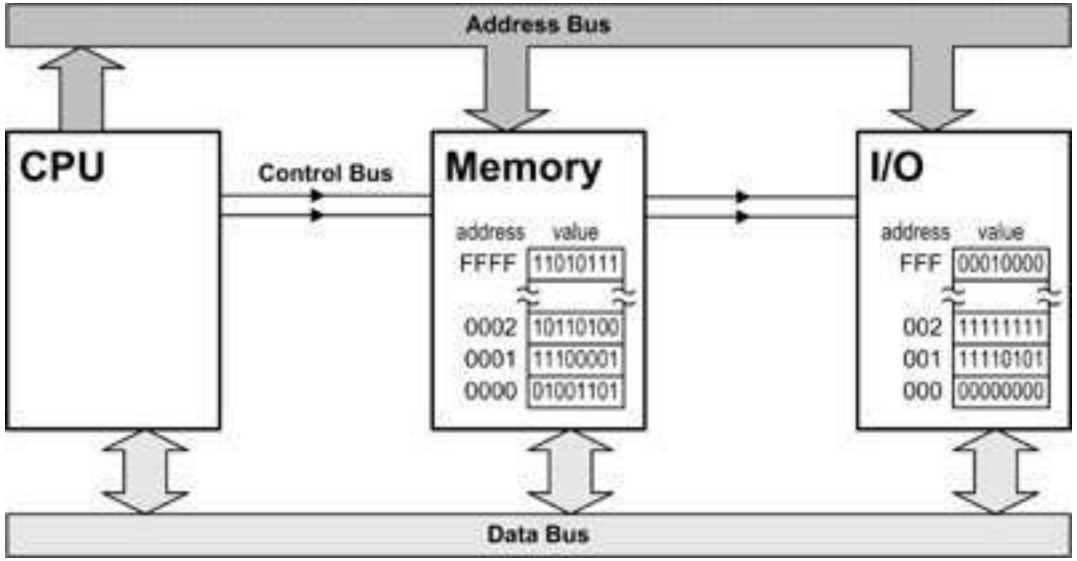

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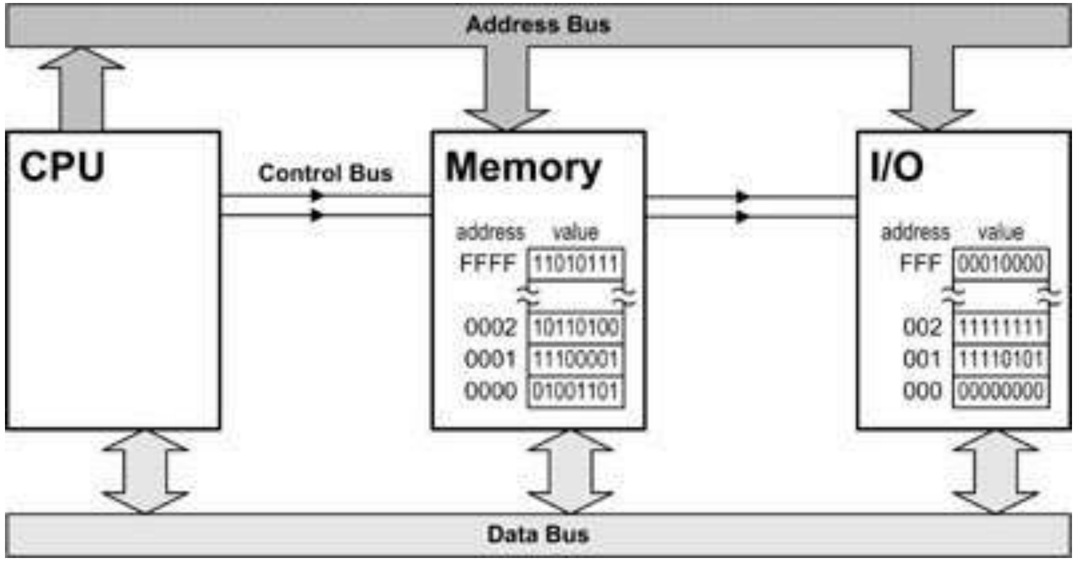

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The control bus has a special line called "**`M/#IO`**" which asserts whether the CPU wants to talk to memory or an I/O device

Port- vs. Memory-Mapped I/O

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  - Memory-mapped I/O → mapping controller's registers to the same address space used for main memory

Port-Mapped I/O

- Each I/O device controller's register is mapped to a specific port (address)
- Requires special class of CPU instructions (e.g., **`IN`**/**`OUT`**)
  - The **`IN`** instruction reads from an I/O device, **`OUT`** writes
- When you use the **`IN`** or **`OUT`** instructions, the **`M/#IO`** is not asserted, so memory does not respond and the I/O chip does

Memory-Mapped I/O

- Memory-mapped I/O "wastes" some address space but doesn't need any special instruction
- To the CPU I/O device ports are just like normal memory addresses
- The CPU use `MOV`-like instructions to access I/O device registers
- In this way, the **`M/#IO`** is asserted indicating the address requested by the CPU refers to main memory

Port- vs. Memory-Mapped I/O

```
MOV DX,1234h
MOV AL,[DX]    ;reads memory address 1234h (memory address space)
IN AL,DX       ;reads I/O port 1234h (I/O address space)
```

Both put the value **`1234h`** on the CPU address bus, and both assert a **`READ`** operation on control bus

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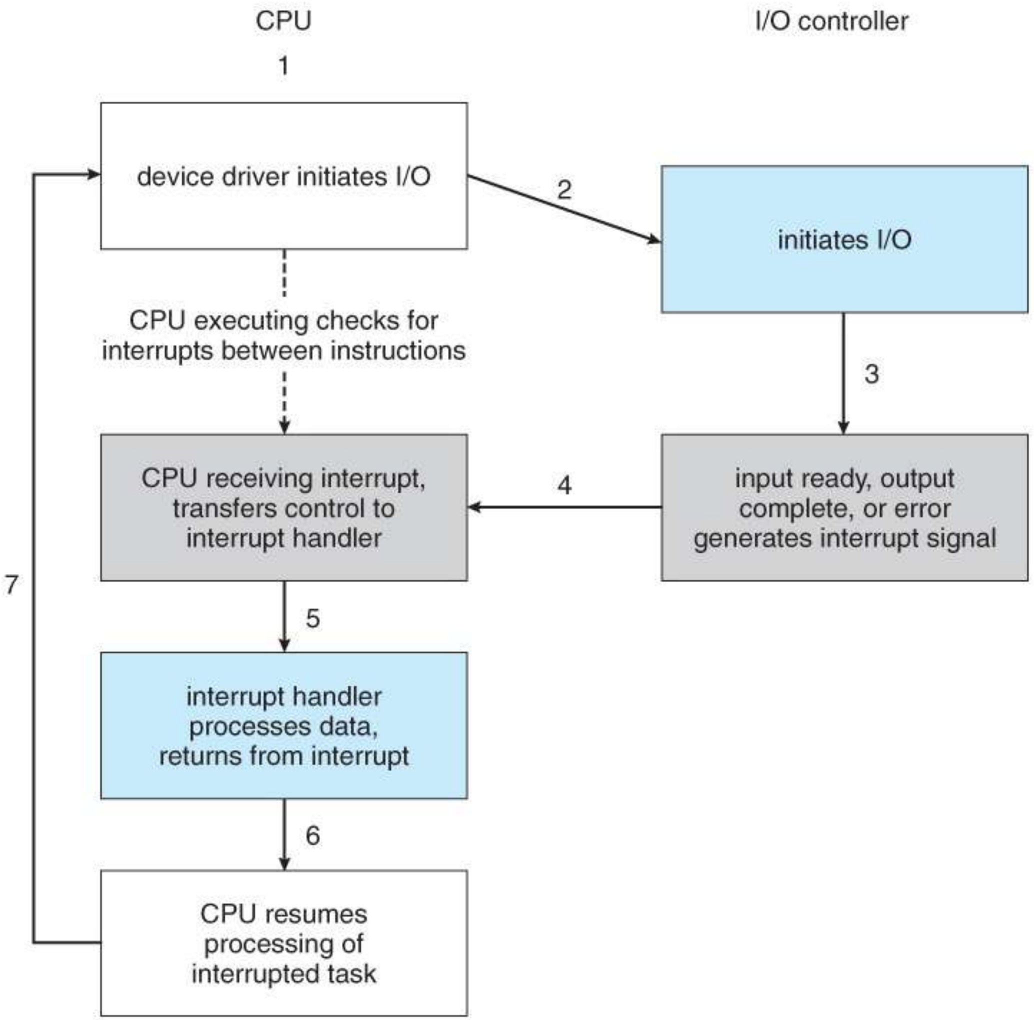
WHO?

How: Interrupt-driven I/O



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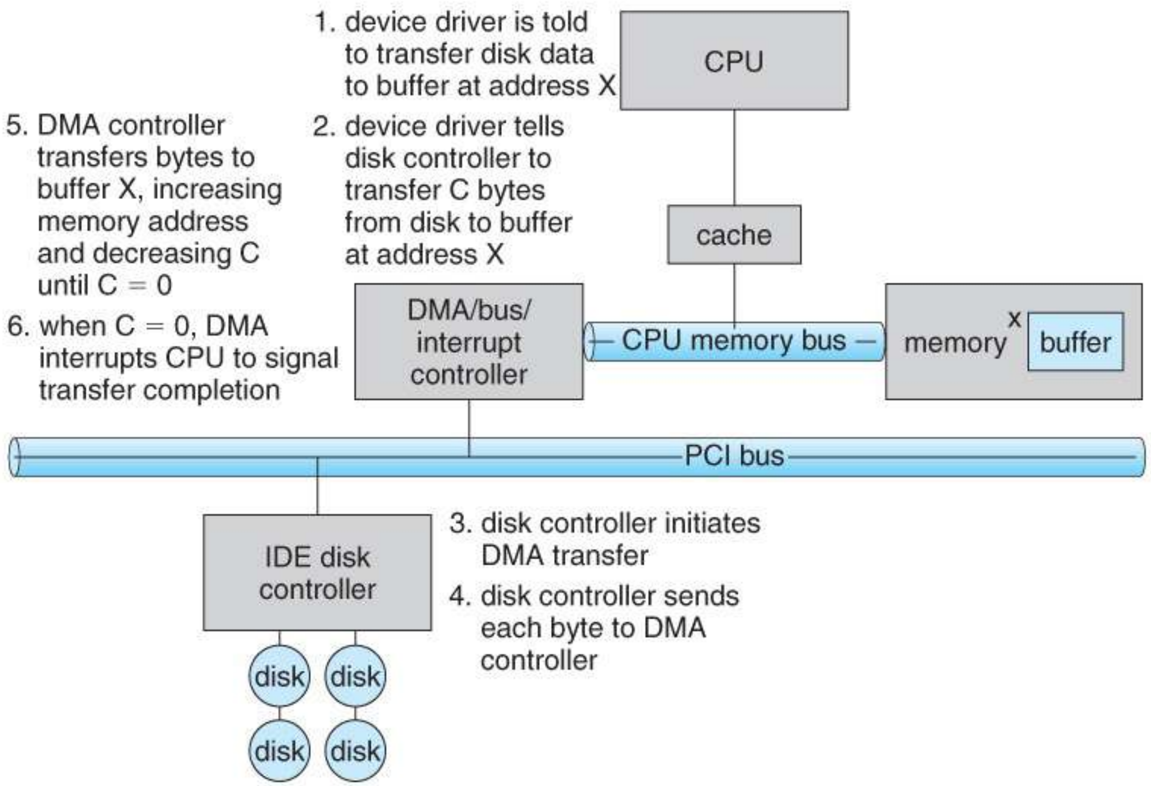

Overcome the limitation of Programmed I/O

Maybe wasteful to tie up the CPU transferring data in and out of registers one byte at a time

Useful for devices that transfer large quantities of data (such as disk controllers)

Typically, used in combination with interrupt-driven I/O

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OS and Computer Architecture

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- Architectural support may significantly simplify or complicate the OS design

Architectural Features Enabling OS Services

OS Service	HW Support
Protection and Security	Kernel/user mode, protected instructions, base/limit registers
System calls	Trap instructions and interrupt vectors
Exception handling	Trap instructions and interrupt vectors
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Privileged Instructions

- Some CPU instructions are more sensitive than others
  - `MOV %eax, %ebx` → move the content of the register `ebx` into `eax`
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Idea: sensitive (privileged) instructions can be executed only by the OS

Kernel vs. User Mode

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Implemented in HW!
A status bit stored in a protected CPU register
(`0`=kernel, `1`=user)

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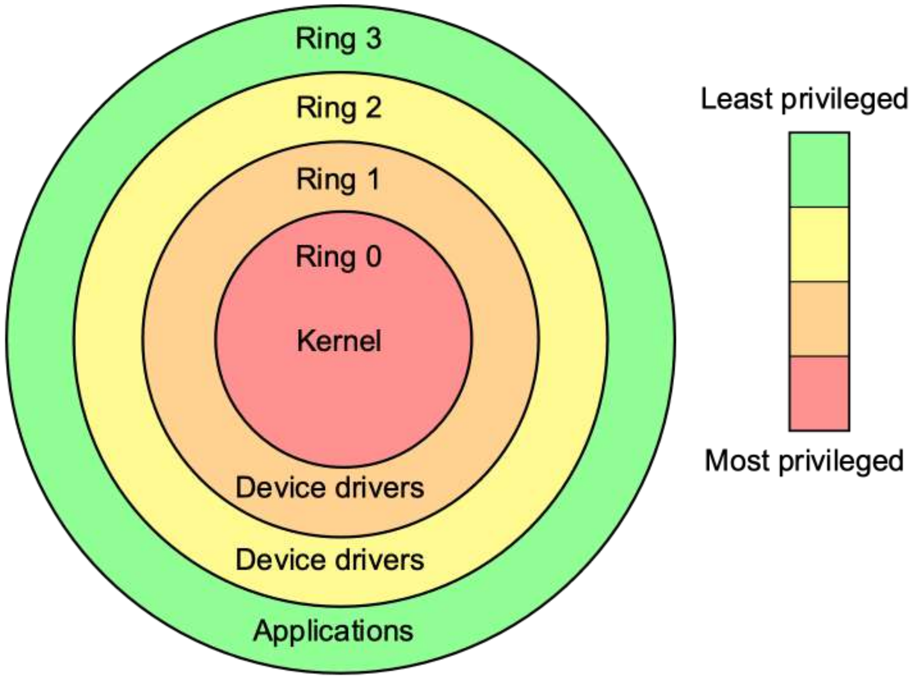
- Protection Rings
  - 4 different privilege levels {0, …, 3}
  - Still implementable in HW (2 bits)



Memory Protection

- Architecture must provide support for the OS to:
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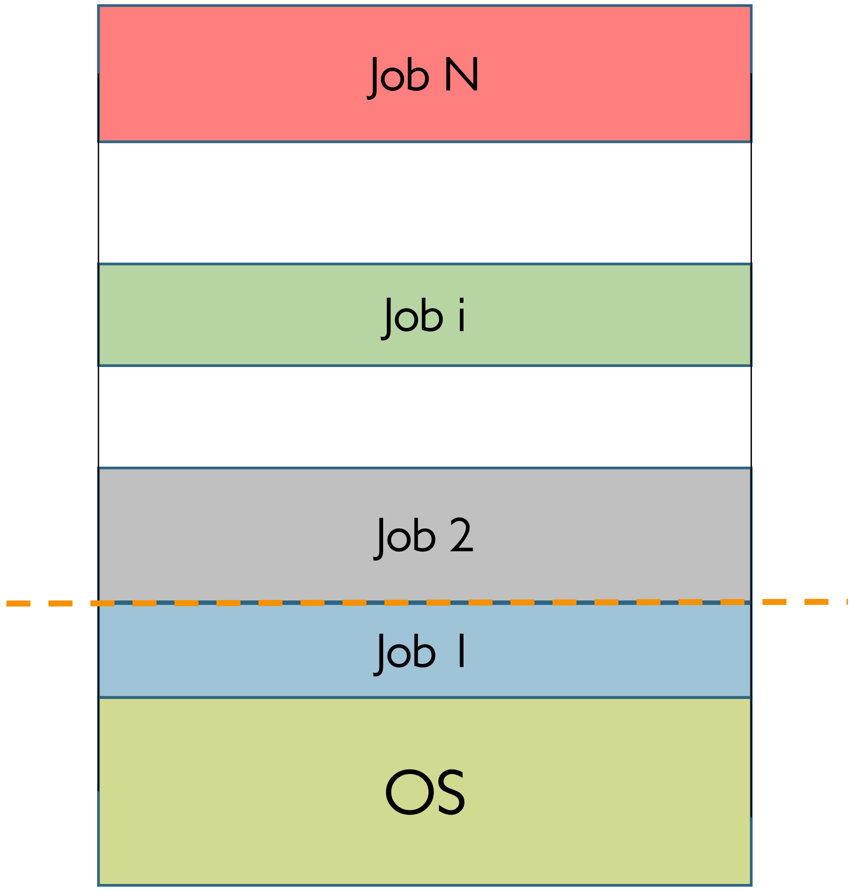

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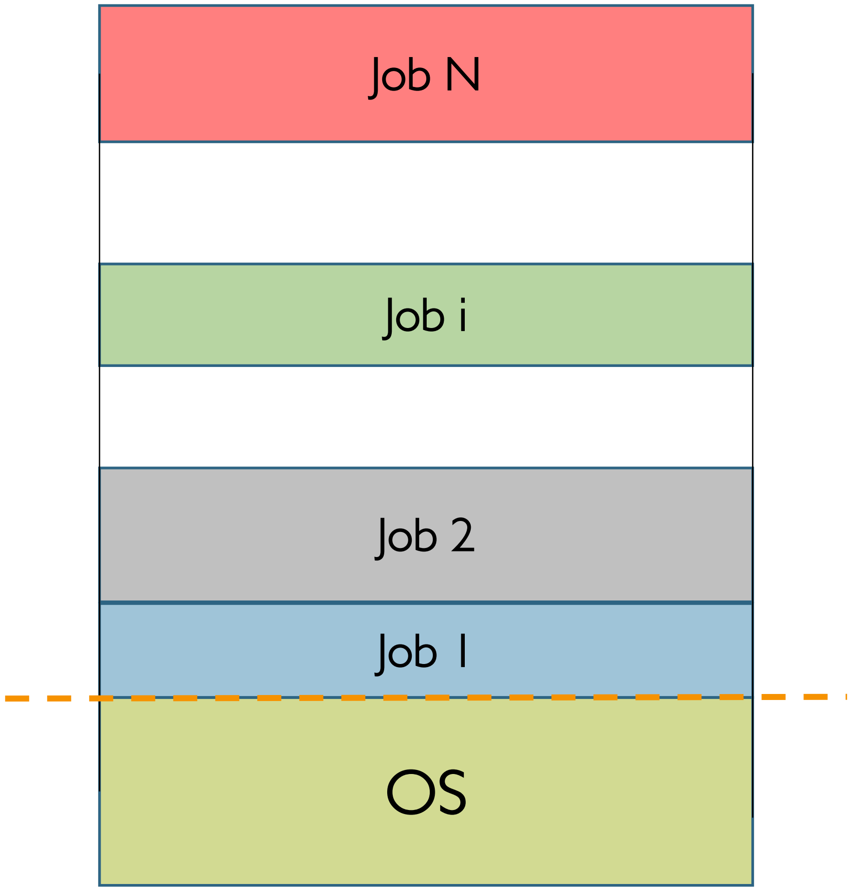

Memory Protection

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  - base → contains the starting valid memory address
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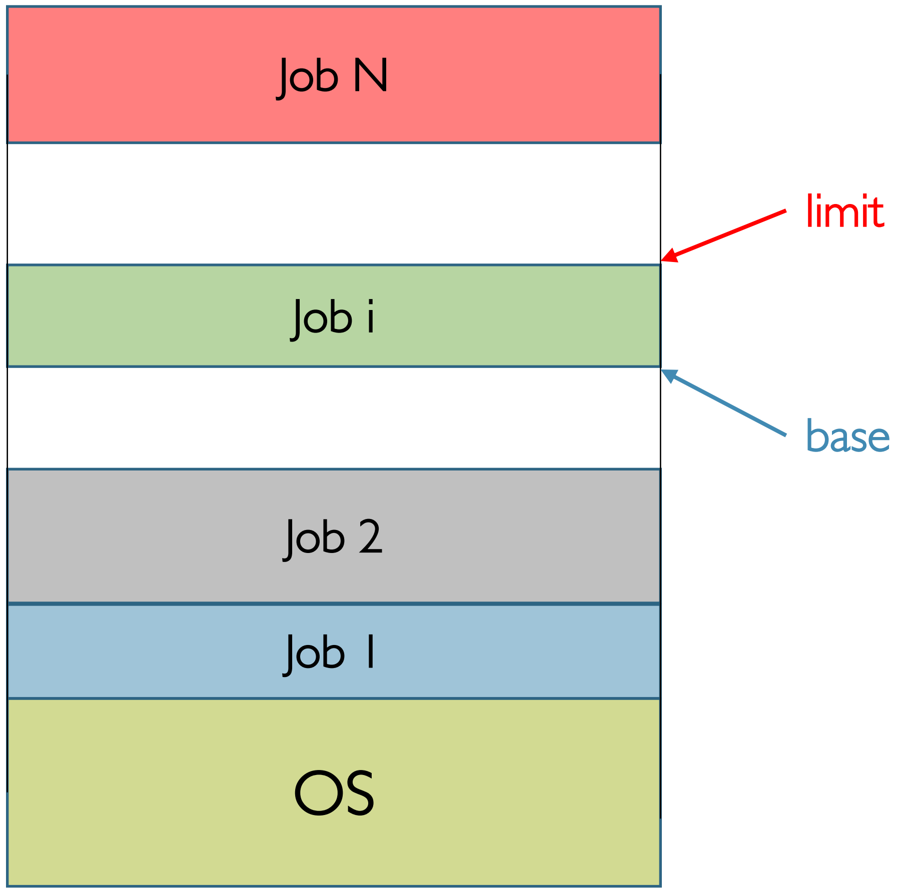

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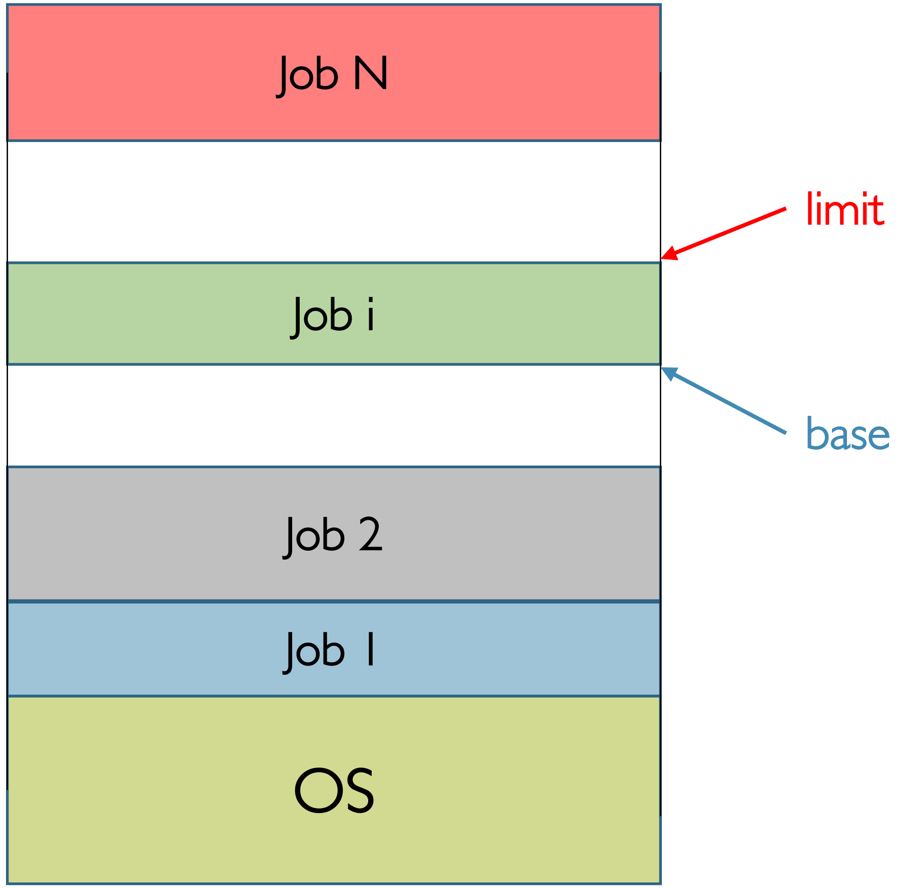

Memory Protection

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  - base → contains the starting valid memory address
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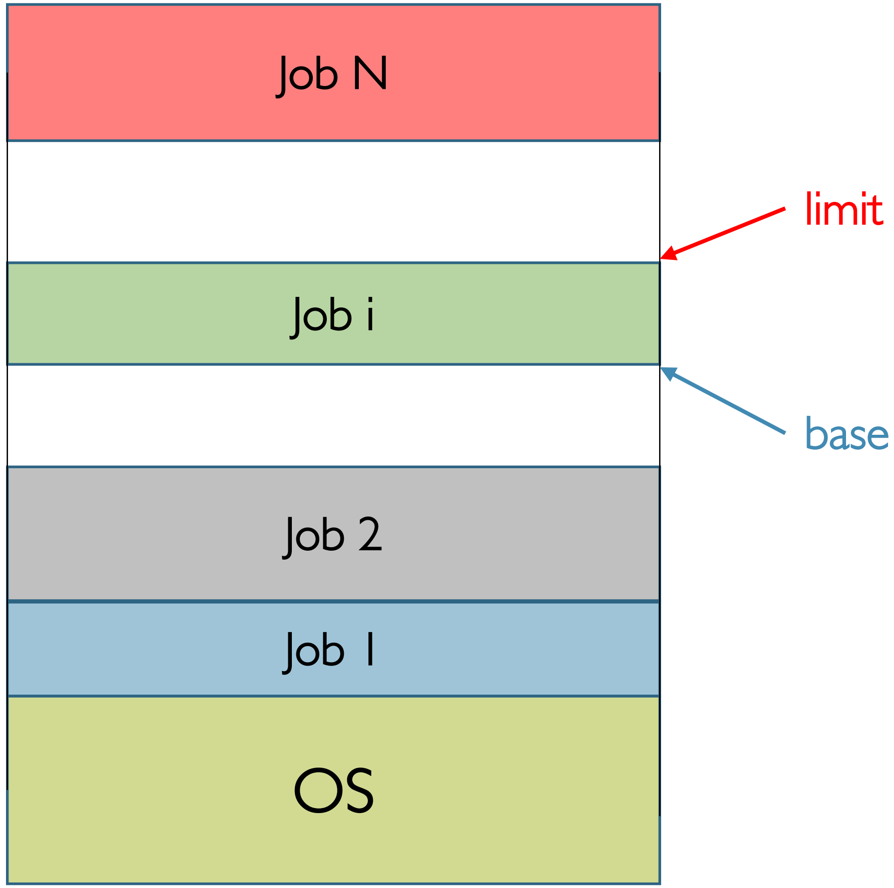
- The CPU checks each memory address referenced by user program falls between base and limit values



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Crossing protection boundaries using system calls

Exceptions and Interrupts

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  - software-generated
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- Interrupts
  - hardware-generated (by external devices)
  - e.g., I/O completion or timer interrupt on a multi-tasking system

A Quick Note on Terminology

TRAP

We will refer to trap as any event that causes switch to OS kernel mode

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SYSTEM CALL
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synchronous
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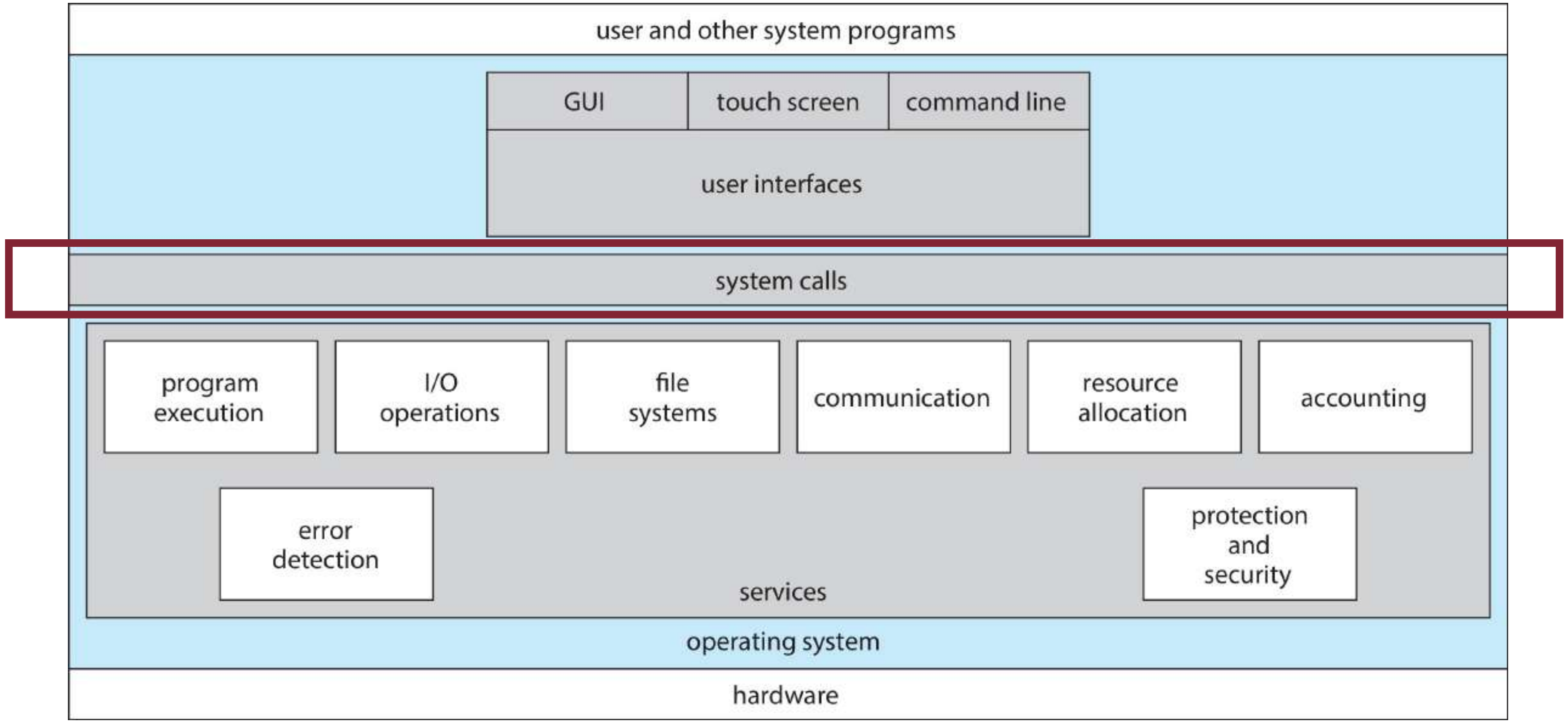
INTERRUPT

asynchronous
HW-initiated

e.g., network packet arrived, I/O completion, timer

User Programs-OS Interface



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- OS procedures that execute privileged instructions (e.g., I/O)
- Programming interface to the services provided by the OS
- Typically written in a high-level language (C or C++)
- Mostly accessed by programs via a high-level Application Programming Interface (API) rather than direct system call
  - GNU C Library (POSIX-based systems like UNIX, Linux, macOS)
  - Win32 API (Windows systems)
  - Java API (JVM)

System Calls: Categories

- 6 main categories of system calls:
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  - File management
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  - Information maintenance
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- When processes stop abnormally it may be necessary to provide core dumps and/or other diagnostic or recovery tools

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- The actual directory structure may be implemented using ordinary files on the file system, or through other means (more on this later)

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- Devices may be physical (e.g., disk drives), or virtual/abstract (e.g., files, partitions, and RAM disks)
- Some systems represent devices as special files in the file system, so that accessing the "file" calls upon the appropriate OS device driver
  - e.g., the `/dev` directory on any UNIX system

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- Systems may also provide the ability to dump memory at any time
- Single step programs pausing execution after each instruction, and tracing the operation of programs (debugging)

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- 2 models of communication:
  - message passing
  - shared memory

Communication: Message Passing

- The message passing model must support calls to:
  - Identify a remote process and/or host with which communicate to
  - Establish a connection between the two processes
  - Open and close the connection as needed
  - Transmit messages along the connection
  - Wait for incoming messages, in either a blocking or non-blocking state
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Simpler and easier (particularly for inter-computer communications) and generally appropriate for small amounts of data

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Faster and generally the better approach where large amounts of data are to be shared

Ideal when most processes need to read data rather than write

System Calls: Protection

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- System calls allow the access mechanisms to be adjusted as needed
- Non-priveleged users may temporarily be granted elevated access permissions under specific circumstances
- Crucial in the age of ubiquitous network connectivity

The Anatomy of a System Call

System Call: **`read`** (C Library)

EXAMPLE OF STANDARD API

As an example of a standard API, consider the `read()` function that is available in UNIX and Linux systems. The API for this function is obtained from the `man` page by invoking the command

```
man read
```

on the command line. A description of this API appears below:

```
#include <unistd.h>

ssize_t    read(int fd, void *buf, size_t count)
```

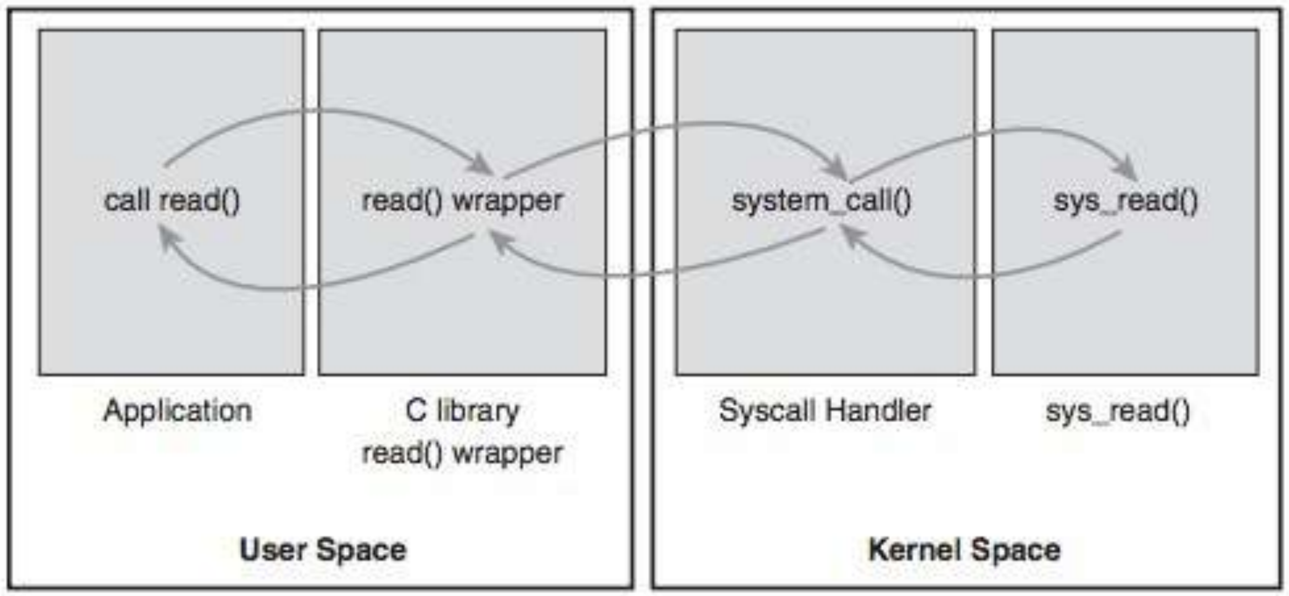
return value	function name	parameters
`ssize_t`	`read`	`(int fd, void *buf, size_t count)`

A program that uses the `read()` function must include the `unistd.h` header file, as this file defines the `ssize_t` and `size_t` data types (among other things). The parameters passed to `read()` are as follows:

- `int fd`—the file descriptor to be read
- `void *buf`—a buffer into which the data will be read
- `size_t count`—the maximum number of bytes to be read into the buffer

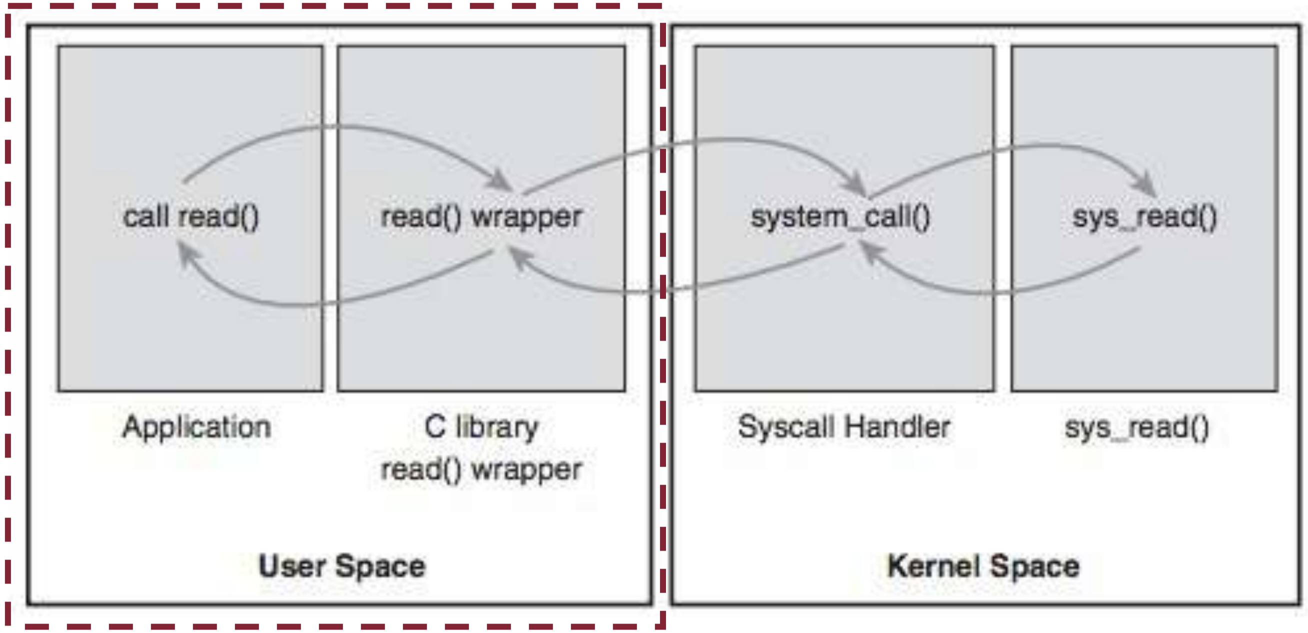
On a successful read, the number of bytes read is returned. A return value of 0 indicates end of file. If an error occurs, `read()` returns –1.

System Call: Flow



System Call: Flow

The caller (user program) doesn't have to know how the system call is implemented



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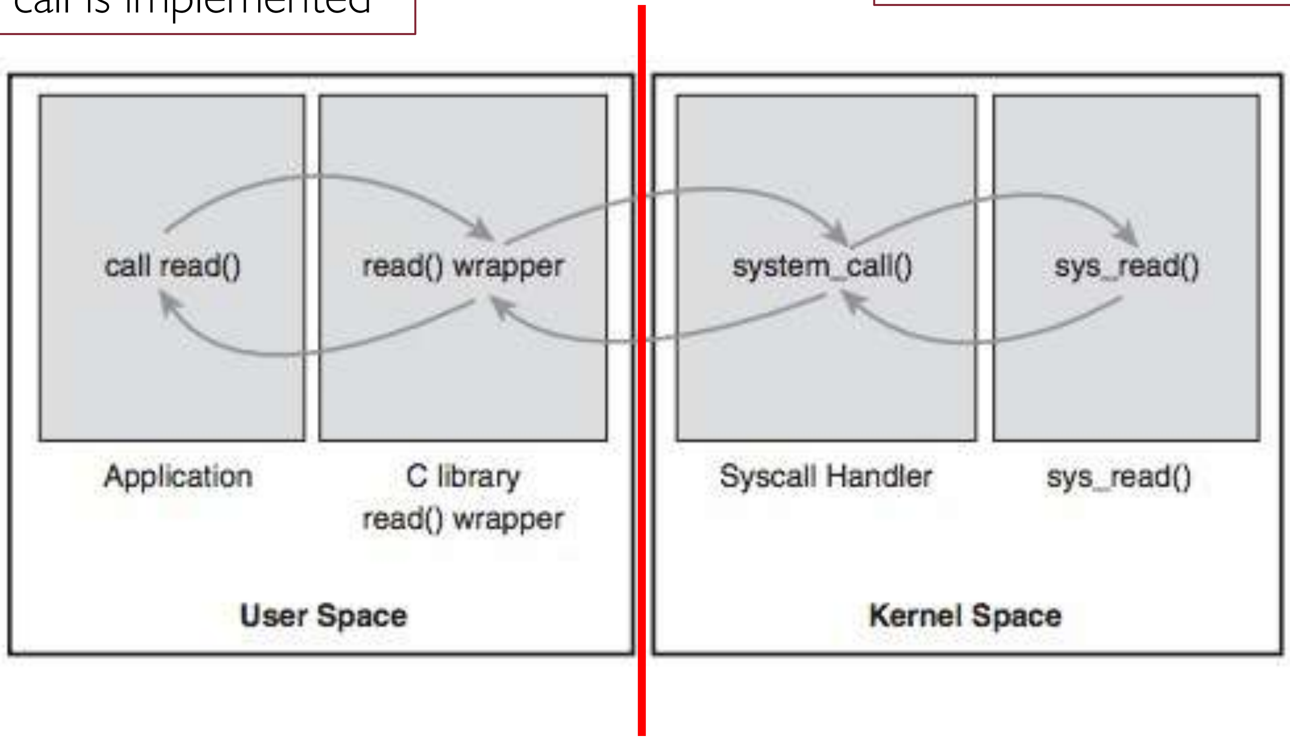

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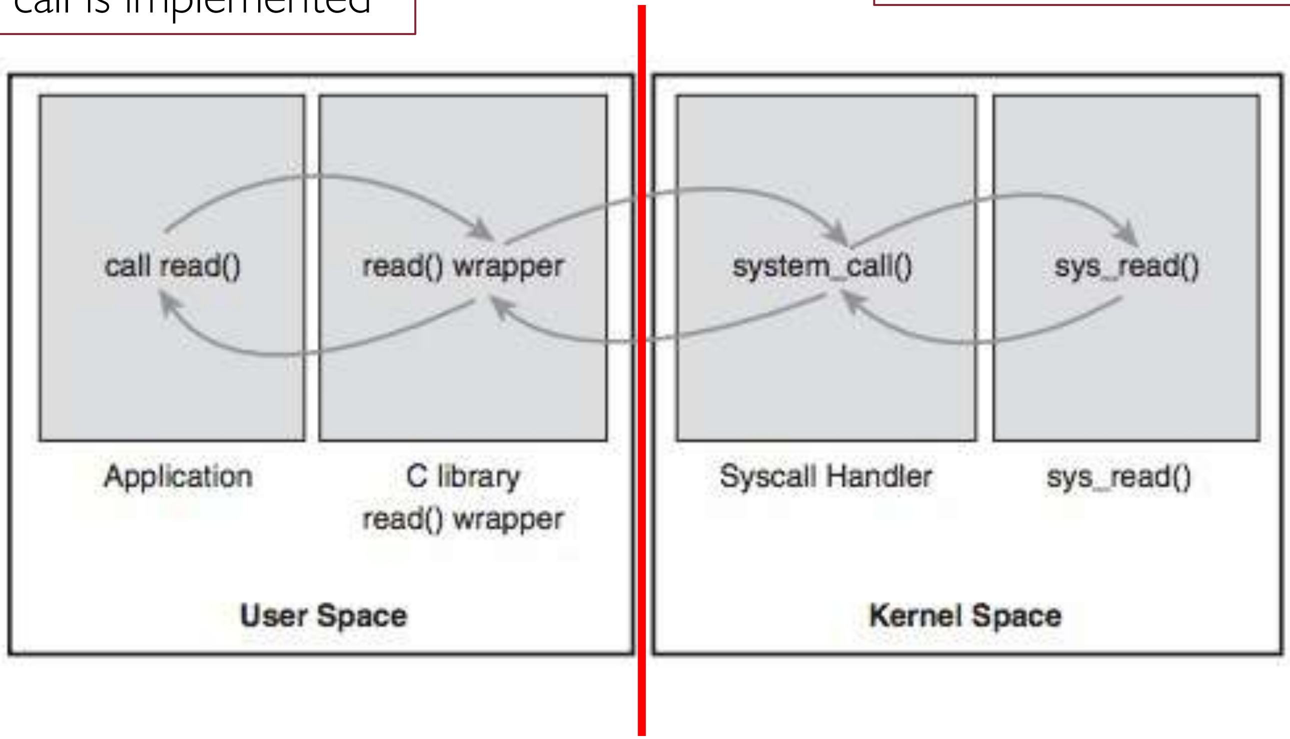

The caller must only obey to the API
(know the input arguments and the expected output from the OS)

System Call Example: Reading from File

```
int main() {
    …
    int nRead = read(fd, buf, count);
    …
}
```

C library's **read** function call

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…
MOV %eax, $sys_read
INT $0x80
…
```

store the number which uniquely identifies the system call requested

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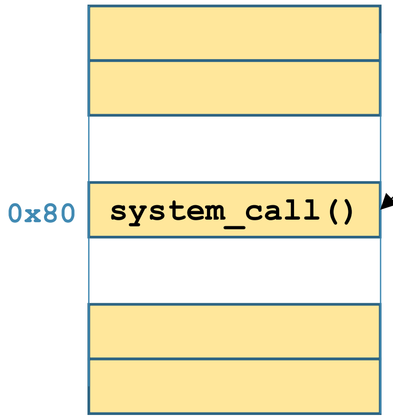
A trap jumps to the interrupt vector table (IVT) in the OS kernel



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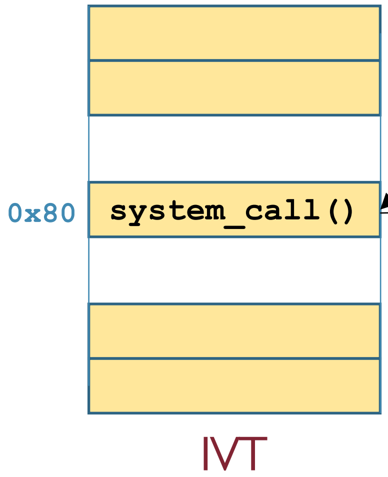

System Call Handler

```
system_call() {
    …
    sys_call_table[%eax]()
    …
}
```

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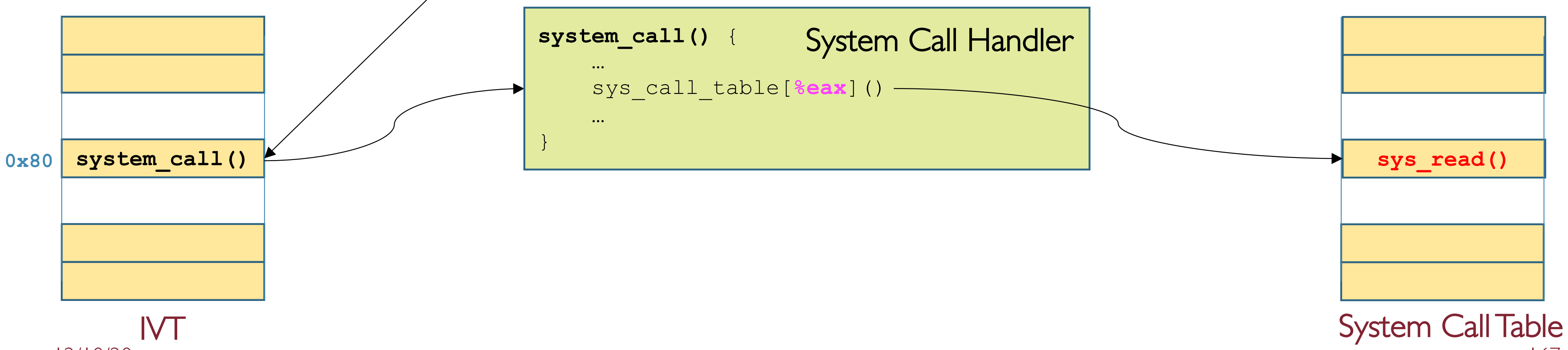

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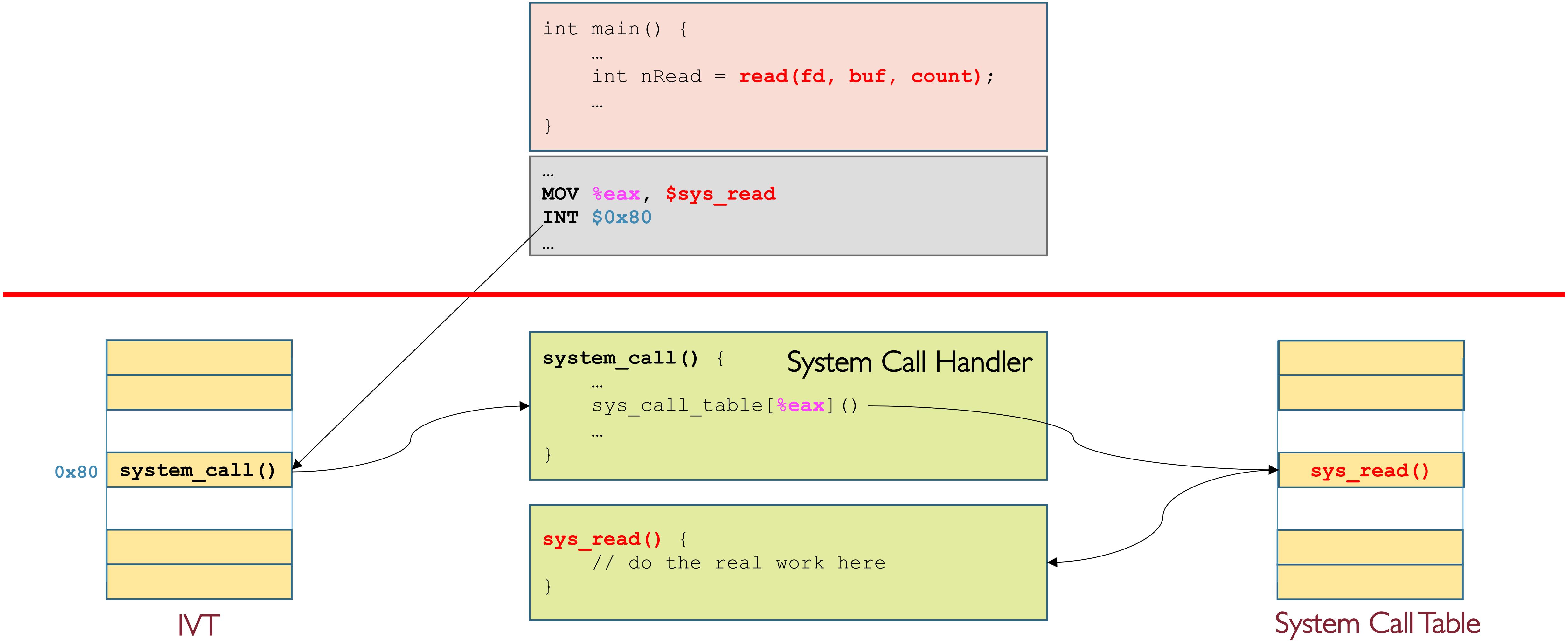

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- The **system call handler** is responsible for:
  - saving the status of user-mode computation on dedicated registers
  - finding and jumping to the correct routine for that trap (e.g., **`sys_read()`**)
  - restoring user-mode program's state upon the service routine is done (e.g., **`IRET`** privileged instruction)

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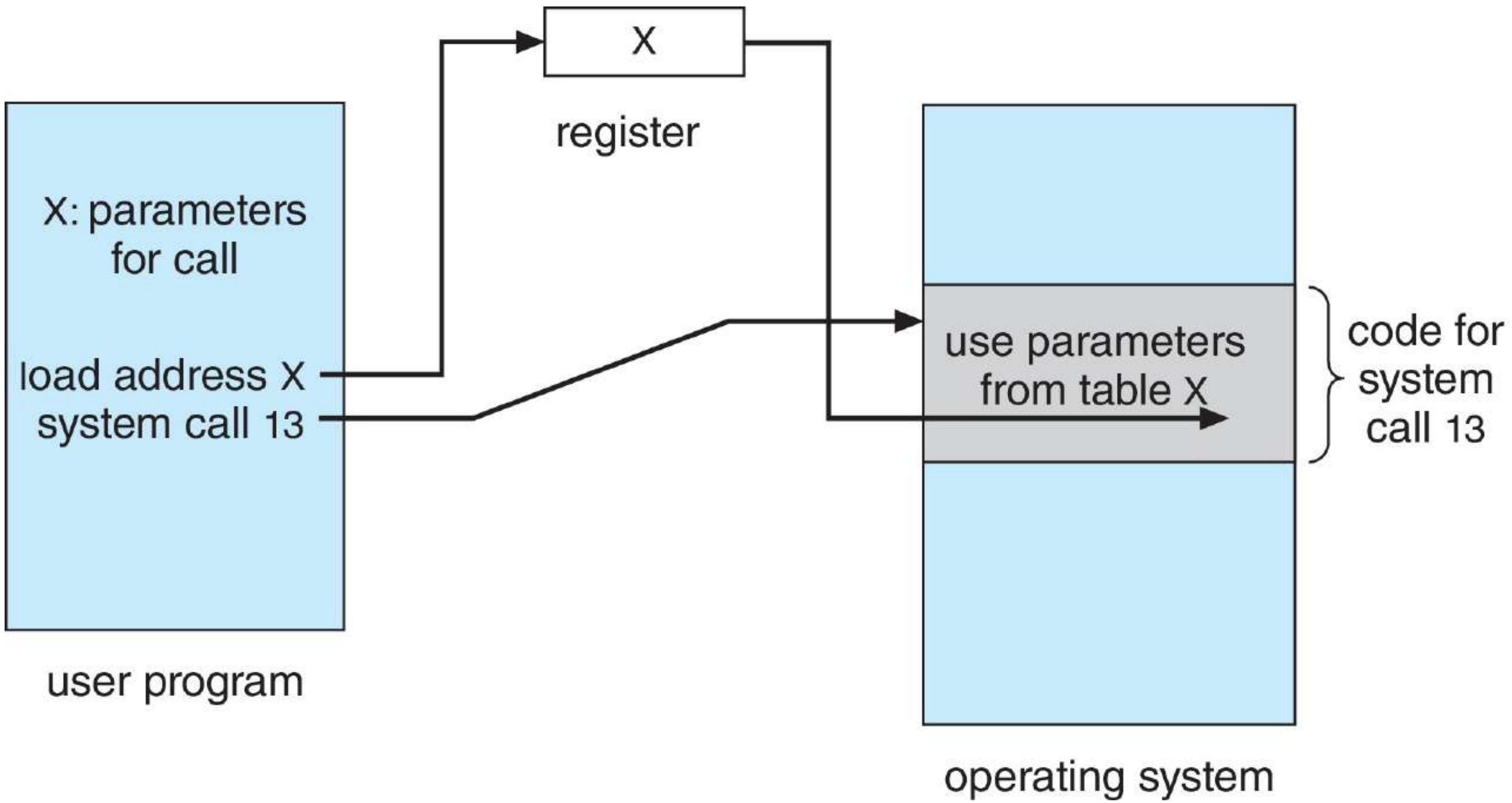
Block and stack methods do not limit the number or length of parameters being passed

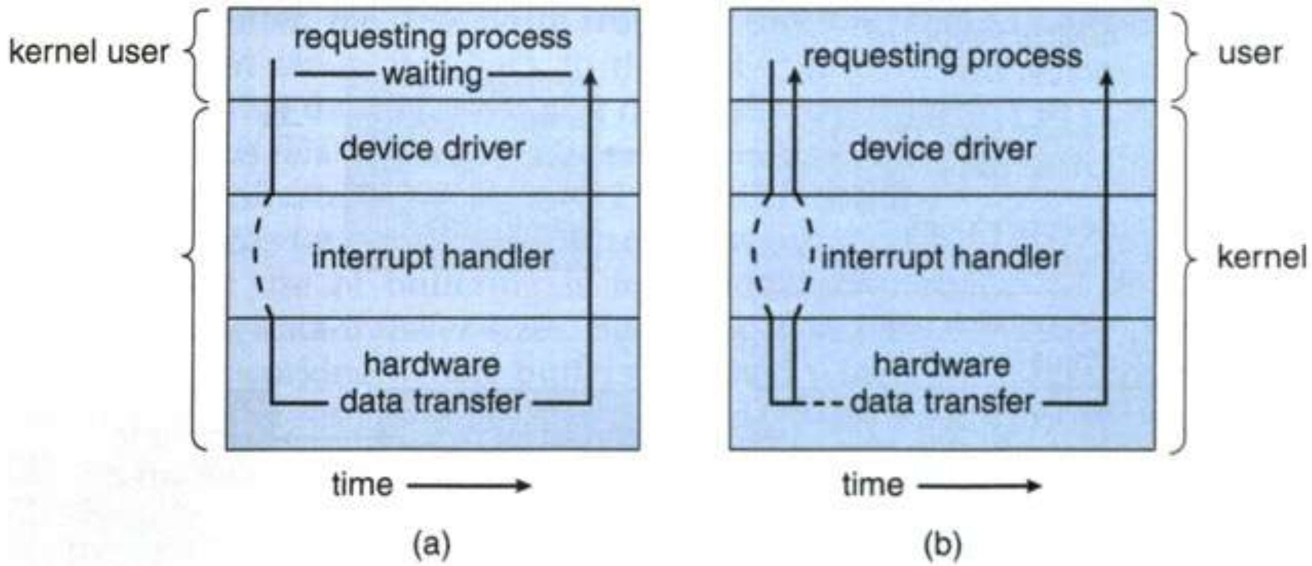
Parameter Passing via Table



Blocking vs. Non-Blocking I/O

synchronous

asynchronous



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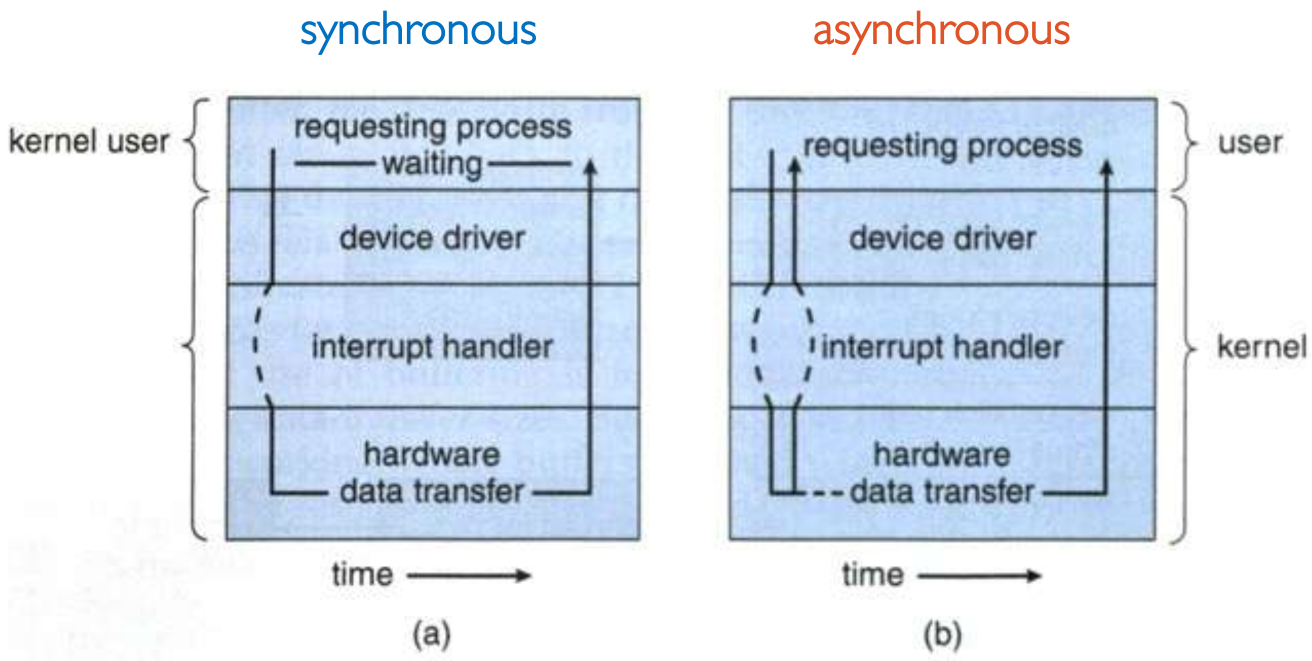

NOTE

In a multi-programming and multi-tasking system, blocking I/O will not leave the CPU idle until I/O task is completed! In fact, the CPU will schedule another (ready) process to take over

System Calls: Windows vs. UNIX APIs

EXAMPLES OF WINDOWS AND UNIX SYSTEM CALLS

The following illustrates various equivalent system calls for Windows and UNIX operating systems.

	Windows	Unix

Process control	`CreateProcess()`
	`ExitProcess()`
	`WaitForSingleObject()`
		`fork()`
		`exit()`
		`wait()`

File management	`CreateFile()`
	`ReadFile()`
	`WriteFile()`
	`CloseHandle()`
		`open()`
		`read()`
		`write()`
		`close()`

Device management	`SetConsoleMode()`
	`ReadConsole()`
	`WriteConsole()`
		`ioctl()`
		`read()`
		`write()`

Information maintenance	`GetCurrentProcessID()`
	`SetTimer()`
	`Sleep()`
		`getpid()`
		`alarm()`
		`sleep()`

Communications	`CreatePipe()`
	`CreateFileMapping()`
	`MapViewOfFile()`
		`pipe()`
		`shm_open()`
		`mmap()`

Protection	`SetFileSecurity()`
	`InitlializeSecurityDescriptor()`
	`SetSecurityDescriptorGroup()`
		`chmod()`
		`umask()`
		`chown()`

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- In multi-tasking systems, allows the CPU not to be monopolized by "selfish" processes
- The timer generates an interrupt every, say, 100 microseconds
- At each timer interrupt, the CPU scheduler takes over and decides which process to execute next

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- OS must be able to synchronize the activities of cooperating, concurrent processes
- Hardware must ensure that short sequences of instructions (e.g., read-modify-write) are executed atomically by either:
  - Disabling interrupts before the sequence and re-enable them afterwards

  or

  - Special instructions that are natively executed atomically

Architectural Features Enabling OS Services

OS Service	HW Support
Protection and Security	Kernel/user mode, protected instructions, base/limit registers
System calls	Trap instructions and interrupt vectors
Exception handling	Trap instructions and interrupt vectors
I/O operations	Trap instructions, interrupt vectors, and memory mapping
Scheduling	Timer
Synchronization	Atomic instructions
Virtual memory	Translation Look-aside Buffer (TLB)

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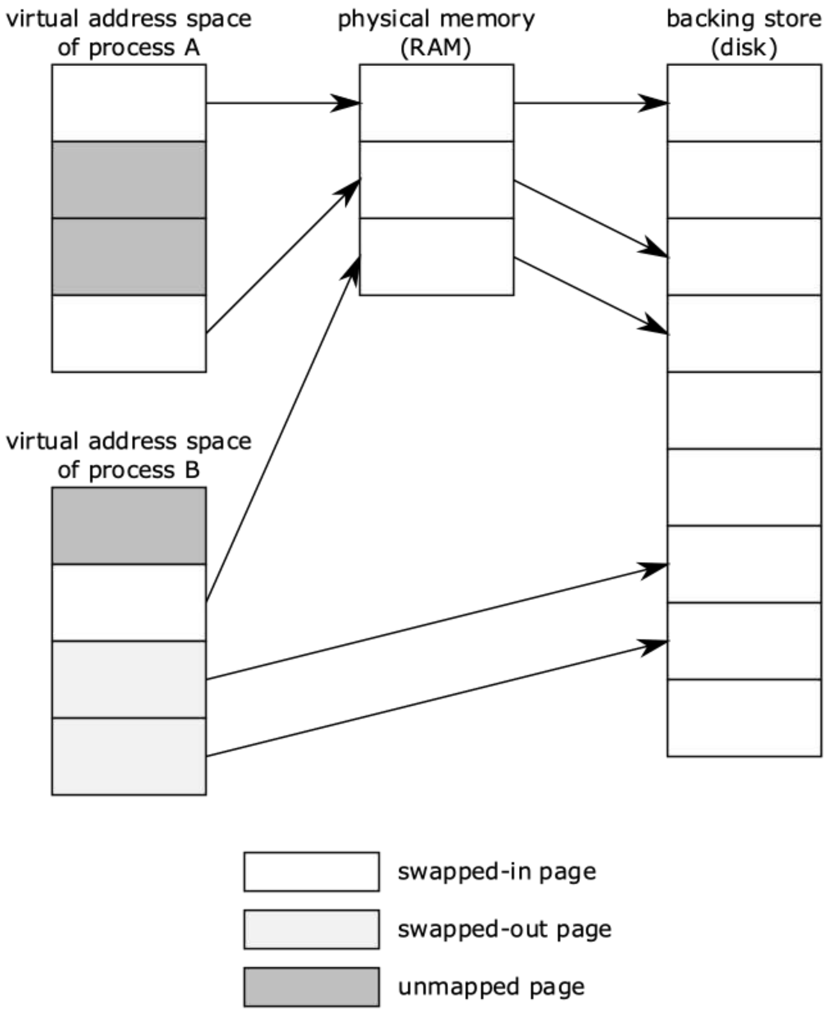
- It gives each process the illusion that physical memory is just a contiguous address space (virtual address space)
- It allows to run programs without them being entirely loaded in main memory
  - They are entirely loaded in virtual memory, though!
- Implemented both in HW (MMU) and SW (OS)
  - MMU is responsible for translating virtual addresses into physical ones
  - OS is responsible for managing virtual address spaces

Virtual vs. Physical Address Space

- On a 64 bit system the CPU is able to address 2^{64} bytes = 16 exbibytes (EiB)
- Virtual address space ranges from 0 to $2^{64} - 1$
- This is about a billion times more than main memory capacity currently available!
- Virtual address space is typically divided into contiguous blocks of the same size (e.g., 4 KiB), called pages
- Pages which are not loaded in main memory are stored on disk

Virtual vs. Physical Address Space



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- Uses a cache called Translation Look-aside Buffer (TLB) with "recent mappings" for quicker lookups
- The OS must be aware of which pages are loaded in main memory and which ones are on disk

Outline of this Lecture

1. Computer architecture review
2. HW support for OS functionalities and services
3. OS design and implementation

Design Goals

- The internal structure of different OSs can vary widely

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  - easy to use vs. easy to design/implement

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- User vs. System goals
  - easy to use vs. easy to design/implement
- It is crucial to separate policies from mechanisms
  - policy → *what* will be done
  - mechanism → *how* to do it

Policy vs. Mechanism

- Decoupling policy logic from the underlying mechanism is a general design principle in computer science, as it improves system's:
  - flexibility → addition and modification of policies can be easily supported
  - reusability → existing mechanisms can be reused for implementing new policies
  - stability → adding a new policy doesn't necessarily destabilize the system

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- Policy changes can be easily adjusted without re-writing the code

OS Implementation

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  - PRO → direct control over the HW (high efficiency)
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- Early OSs developed in assembly language,
  - PRO → direct control over the HW (high efficiency)
  - CON → bound to a specific HW (low portability)
- Today, a mixture of languages:
  - Lowest levels in assembly
  - Main body in C
  - Systems programs in C, C++, scripting languages like PERL, Python, etc.

OS Structure

- OS should be partitioned into separate subsystems, each with carefully defined tasks, inputs, outputs, and performance characteristics

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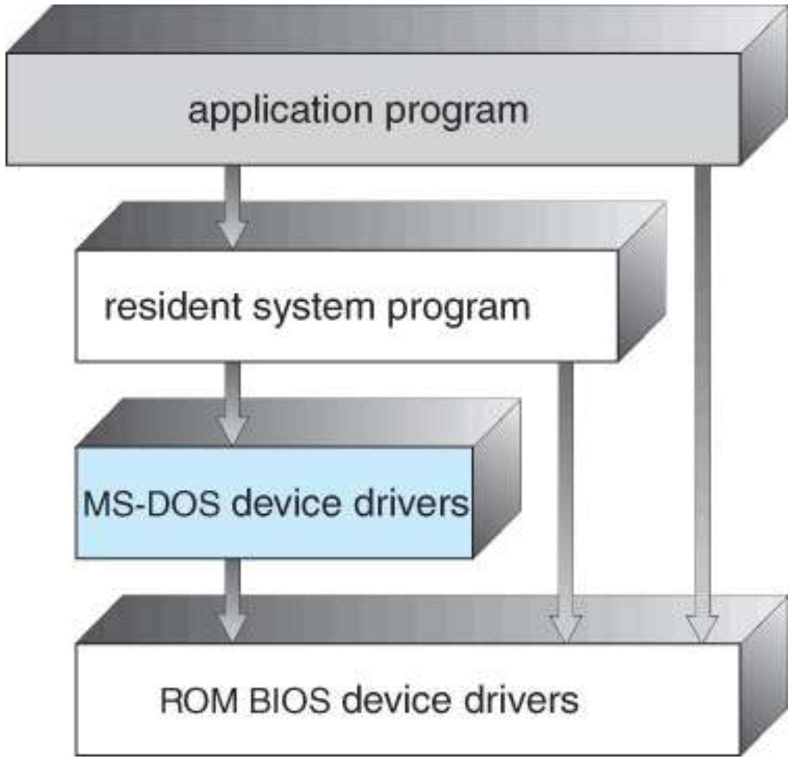
- OS should be partitioned into separate subsystems, each with carefully defined tasks, inputs, outputs, and performance characteristics
- Various ways to structure an operating system:
  - Simple → MS-DOS
  - Complex → UNIX
  - Layered → MULTICS
  - Microkernel → Mach

MS-DOS Structure: Simple Structure

No modular subsystems at all!

No separation between
user and kernel mode



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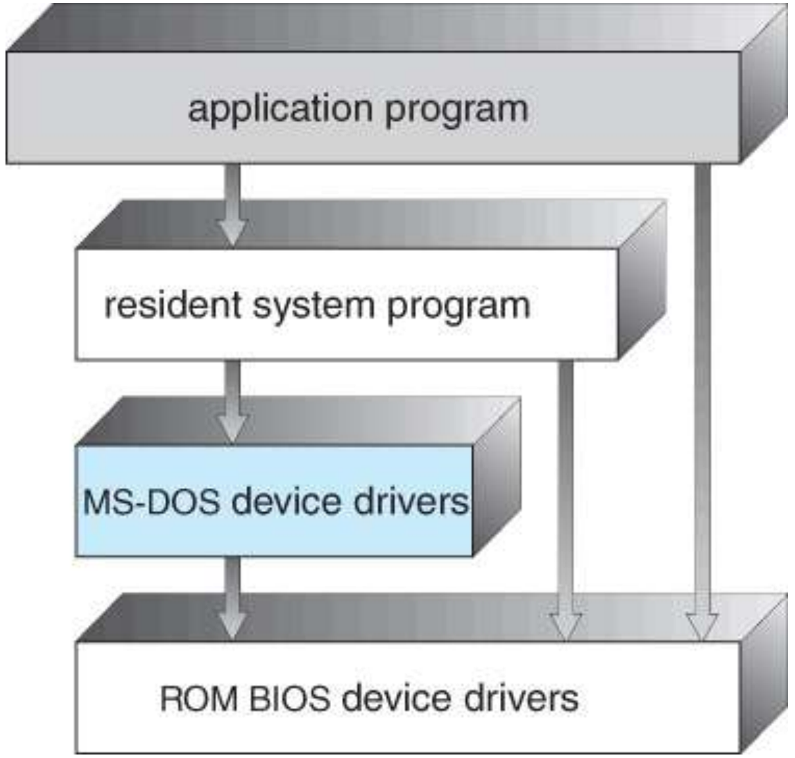
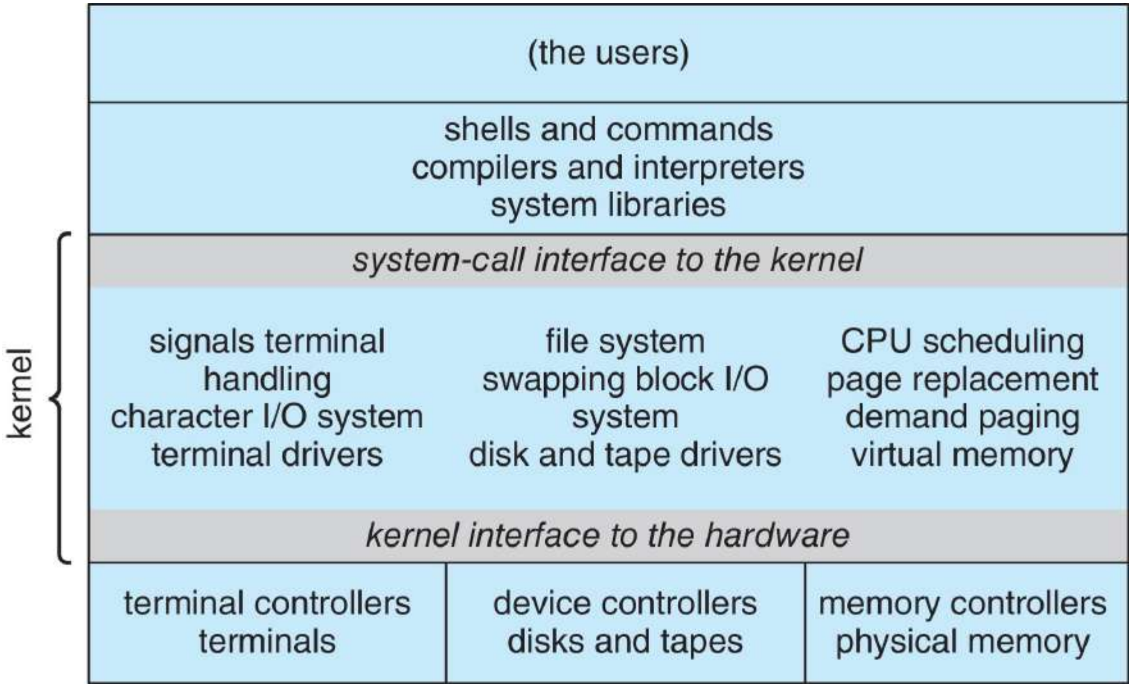


UNIX Structure: Traditional Monolithic Kernel

Essentially, one huge piece of software with all services living in the same address space as one big process

Most of modern OSs are variant of this traditional monolithic structure



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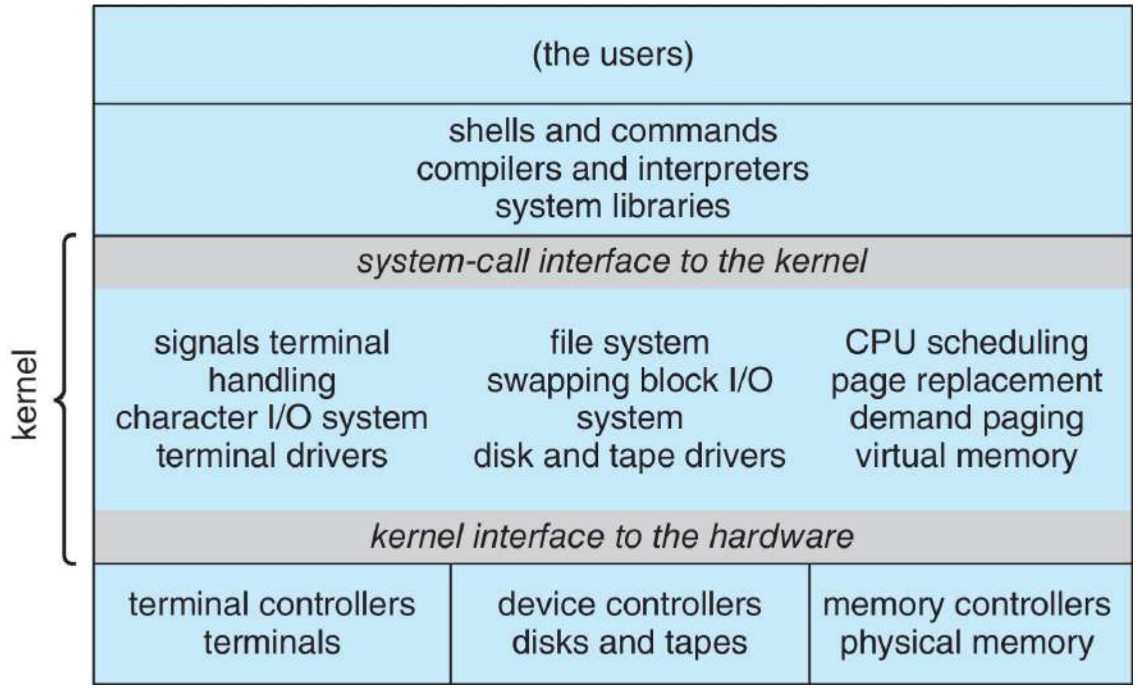
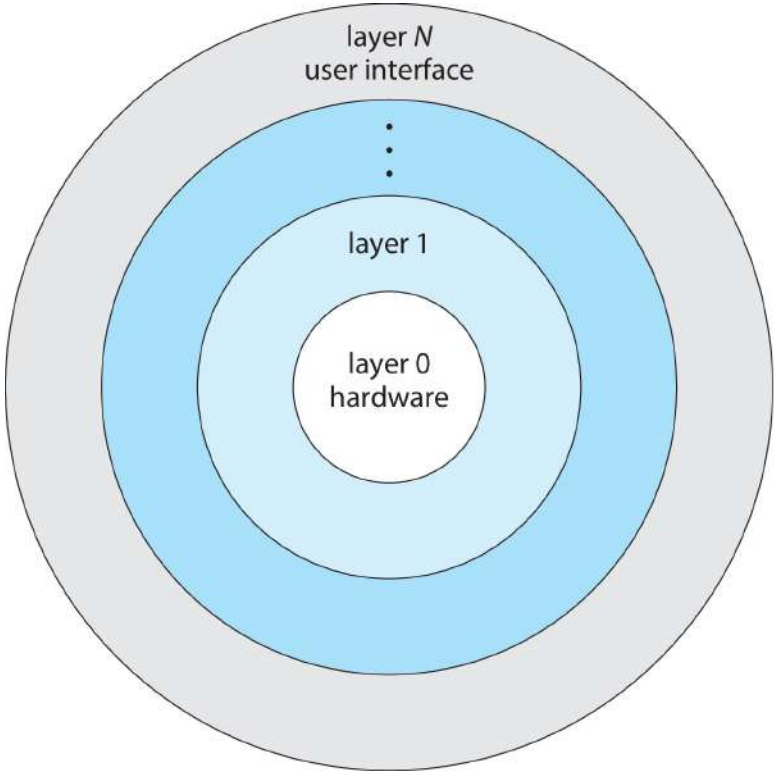


Layered Structure

The OS is divided into *N* layers
(HW = layer 0)

Each layer *L* uses the functionalities implemented by the layer *L-1* to expose new functionalities to layer *L+1*



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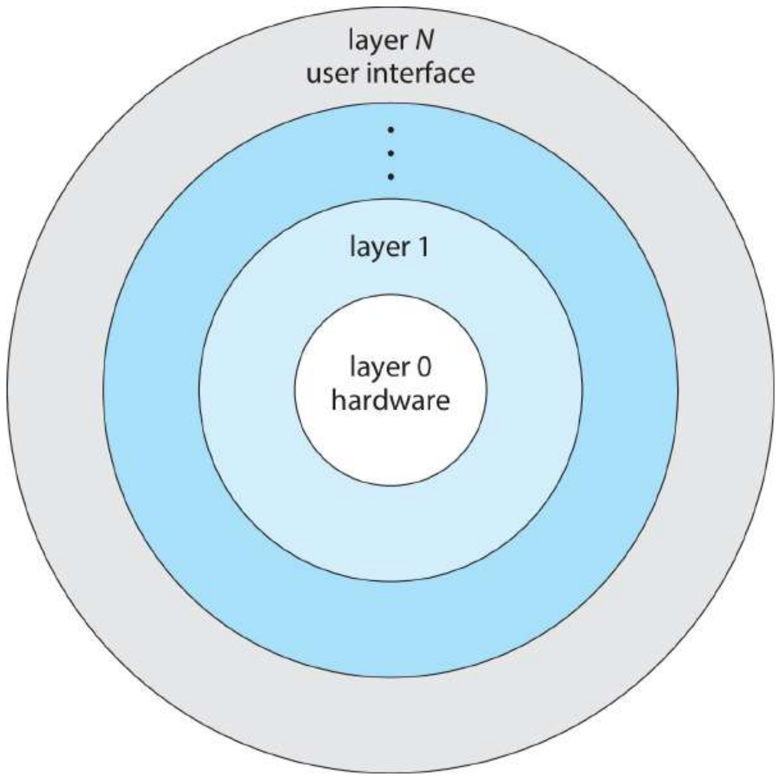
PROs: modularity, portability, easy to debug

CONs: communication overhead, extra copy

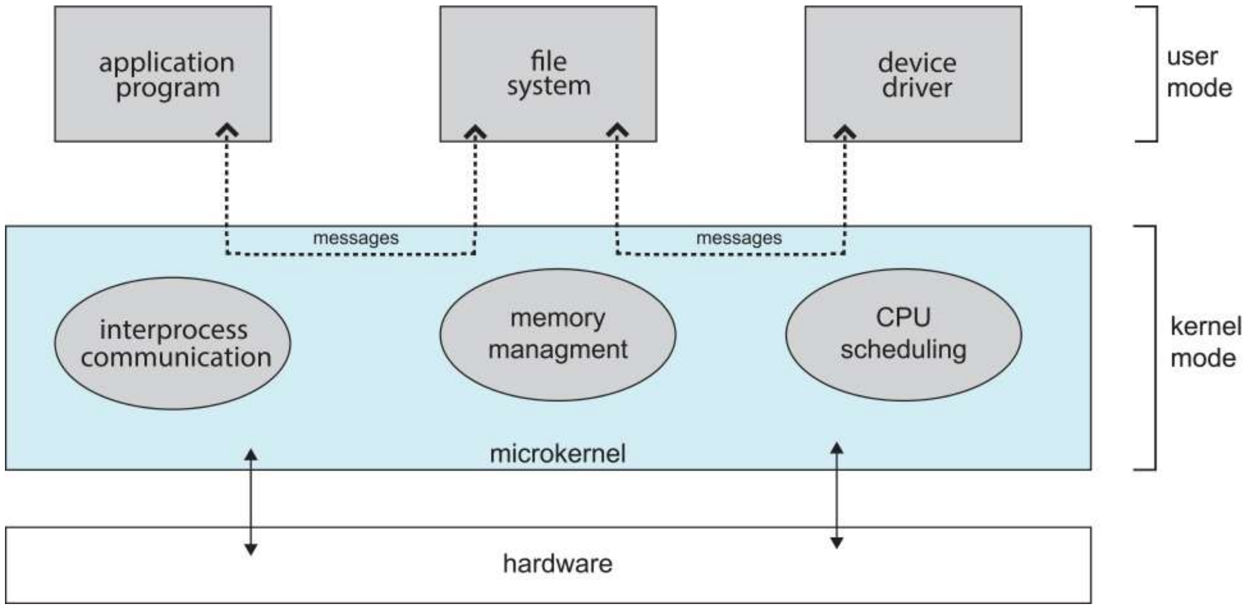


Microkernel Structure

The opposite approach of monolithic

The kernel just contains very basic functionalities, everything else which is still logically part of the OS runs in user mode

Policy (user mode) vs. mechanism (microkernel) separation



Microkernel Structure

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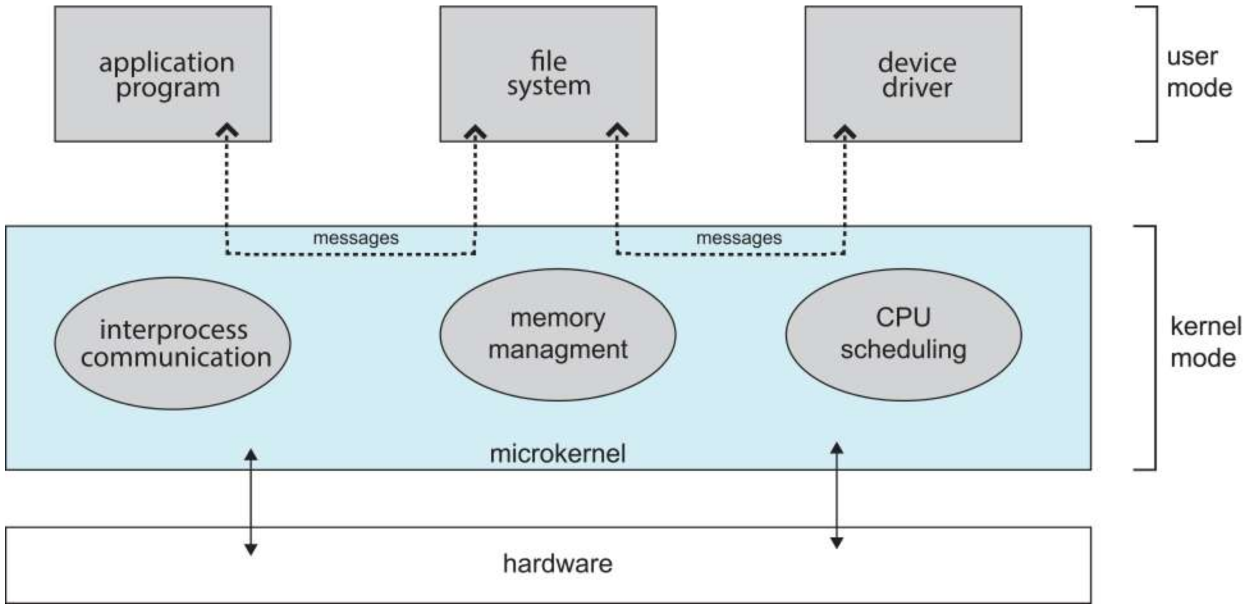
Policy (user mode) vs. mechanism (microkernel) separation

PROs: security, reliability, extendibility

CONs: efficiency (message passing)



Loadable Kernel Modules (LKMs)

- Many modern OSs use loadable kernel modules (LKMs)
  - Uses object-oriented approach
  - Each core component is separate
  - Each talks to the others over known interfaces
  - Each is loadable as needed within the kernel (i.e., in kernel space)
- Similar to layered structure but more flexible

Monolithic vs. Microkernel: Hybrid Trade-off

- Try to get the best out of both approaches
  - combining multiple approaches to address performance, security, usability needs
- Linux and Solaris: monolithic + LKMs (i.e., modular monolithic)
- Windows NT: mostly monolithic + microkernel for different subsystems
- Apple Mac OS X: monolithic (BSD UNIX) + microkernel (Mach) + LKMs

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- Architecture support is key to OS design
- Most of the services provided by the OS to the applications rely on specific HW features
- The OS is tightly coupled to the HW of the host machine
- Several approaches to OS design and implementation
- Advice: Keep your Computer Architecture book at hand!