Computer Systems

IN BA4

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Introduction

This document is designed to offer a LaTeX-styled overview of the Computer Systems course, emphasizing brevity and clarity. Should there be any inaccuracies or areas for improvement, please reach out at ali.elazdi@epfl.ch for corrections. For the latest version of the PDF, you can check the following link: `https://elazdi-al.github.io/comparch/index.html`. Feel free to send a pull request to propose any changes you think might be a useful addition to the course content or a modification.
`https://github.com/elazdi-al/comparch/blob/main/main.pdf`

Contents

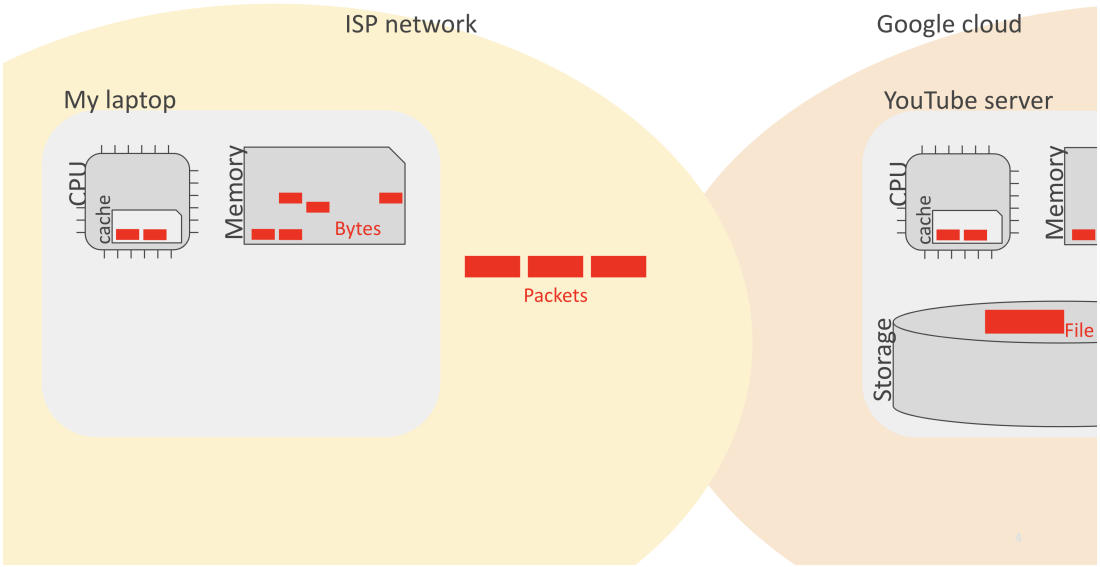
Chapter 1

Lecture 01: Introduction

In this lecture we explore the journey of a YouTube video—from its storage as a file to its transformation into bytes, its transmission over networks, and finally, its display on your device. We will introduce key concepts such as processes, threads, distributed applications, system calls, and the role of the operating system in managing hardware resources.

1.1 The Journey of a YouTube Video

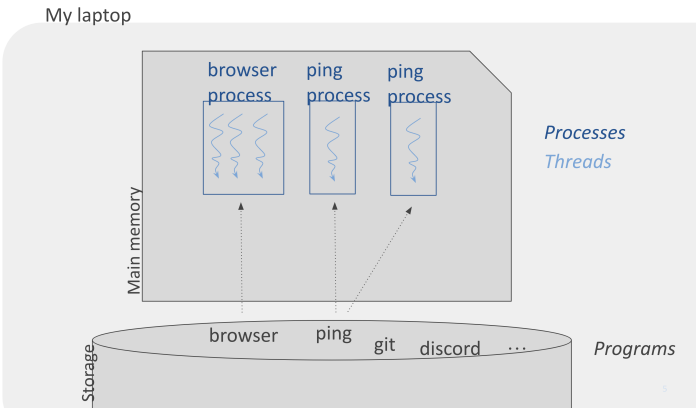
To illustrate these ideas, consider the journey of a YouTube video. The video begins its existence as a file stored on a storage device, is loaded into memory as bytes, transmitted as packets over the Internet, and finally rendered on your screen.



1.1.1 Start of the Journey: Inside the Laptop

The journey begins on your laptop.

A computer hosts many different programs (e.g., a web browser, a ping utility, a git client). These programs, stored as files on disk, are invoked by user actions such as clicking an icon or typing a command. When a program is invoked, the computer creates a new *process* in main memory. A process represents a running instance of a program and may consist of one or more *threads*—individual units of execution within the process.

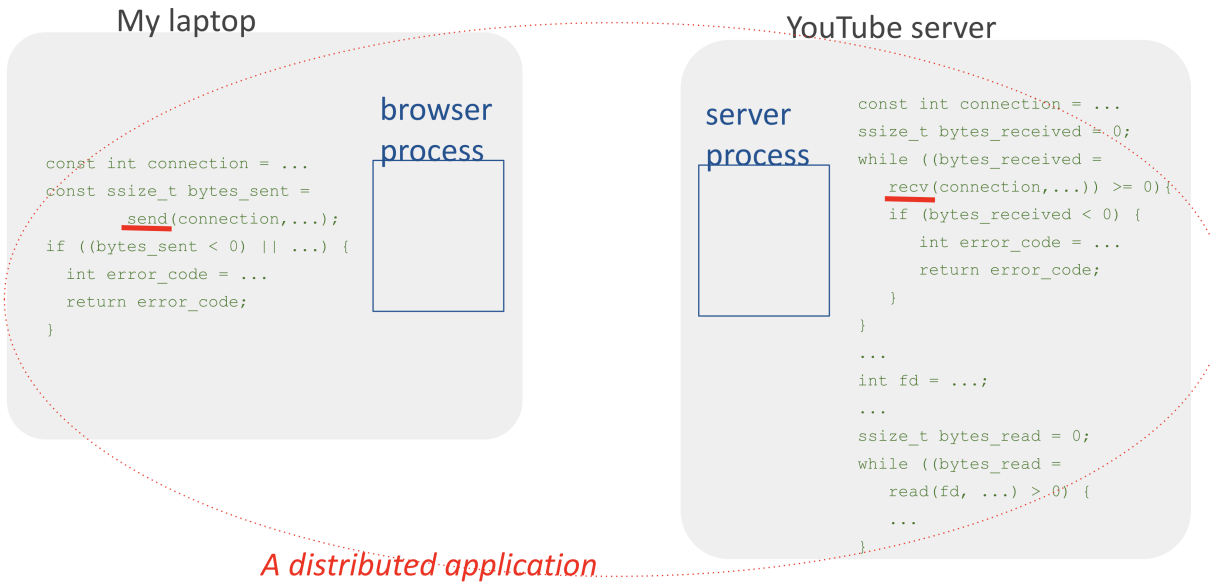


Definition: Programs, Processes, and Threads

Definition 1.1.1 (Program, Process, Thread)**.** A **program** is a set of instructions stored as a file on disk. When a program is invoked, the computer creates a **process**—a running instance of that program in main memory. A process may consist of one or more **threads**, which are the individual sequences of execution within the process.

1.1.2 Accessing a Video: A Distributed Application

When you use your web browser to access a video, the browser sends a message (or request) to a remote YouTube server. The browser process (running on your laptop) and the server process (running on a different computer) work together as parts of a *distributed application*.

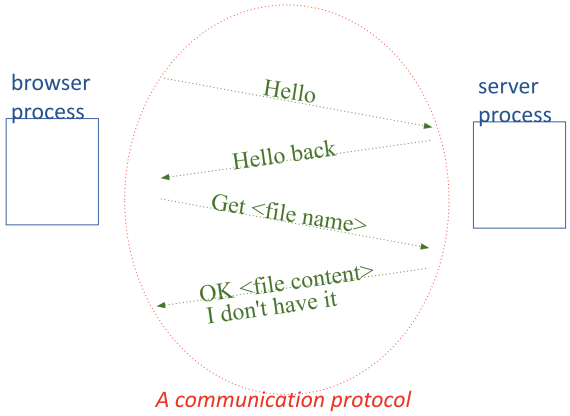


1.1.3 Communication Protocols

For two processes running on different devices to work together, they must follow a predetermined set of rules known as a **communication protocol**. For example, a simple protocol might involve:

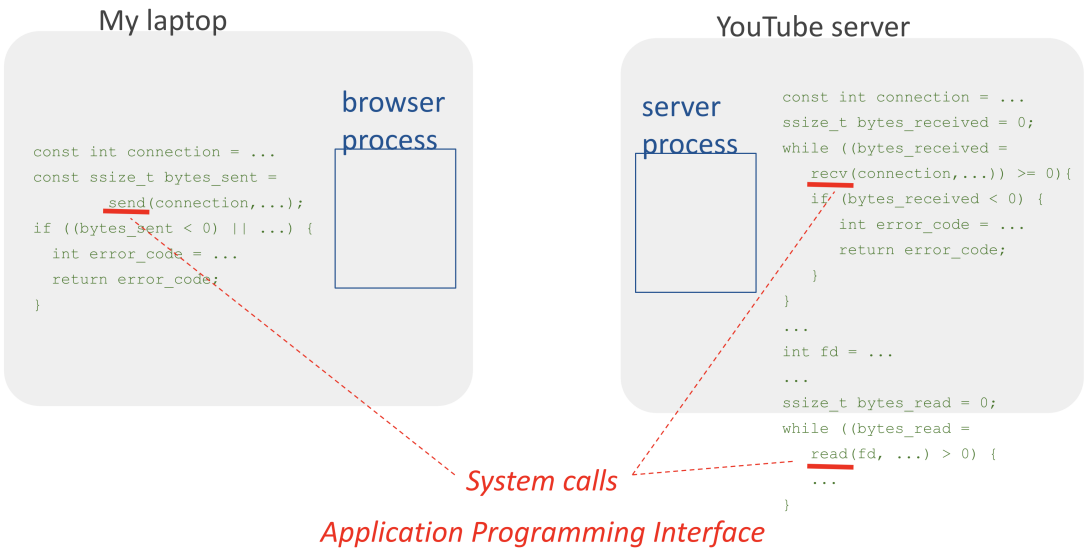
- One process sending "hello" and waiting for a "hello back."
- A subsequent request for a specific file (e.g., `xyz`) with the server responding with the file or an error message.

Much like human communication, these protocols ensure that both parties know what to expect, enabling effective interaction.



1.1.4 Distributed Applications and APIs

Distributed applications consist of separate pieces of code running as processes on different machines but working toward a common goal. These processes exchange messages over the Internet by following communication protocols. To simplify the development of these applications, developers use *system calls* (or **syscalls**). Syscalls are special functions provided by the operating system that allow processes to access resources (e.g., network and storage) without needing to know the low-level details.
The set of syscalls available to an application forms its **Application Programming Interface** (API), abstracting away the complexities of resource management.

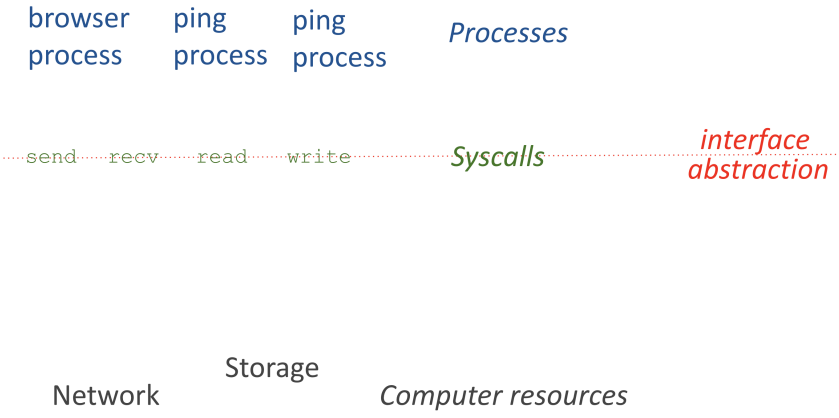


1.1.5 Definition: Interface (Abstraction)

Definition 1.1.2 (Interface)**.** An **interface** is a set of rules that defines how different components communicate. For instance, when sending a letter via the postal system, one must follow specific rules (e.g., write the address and affix a stamp). This interface abstracts the complexities of the postal system so that users do not need to understand its internal operations.

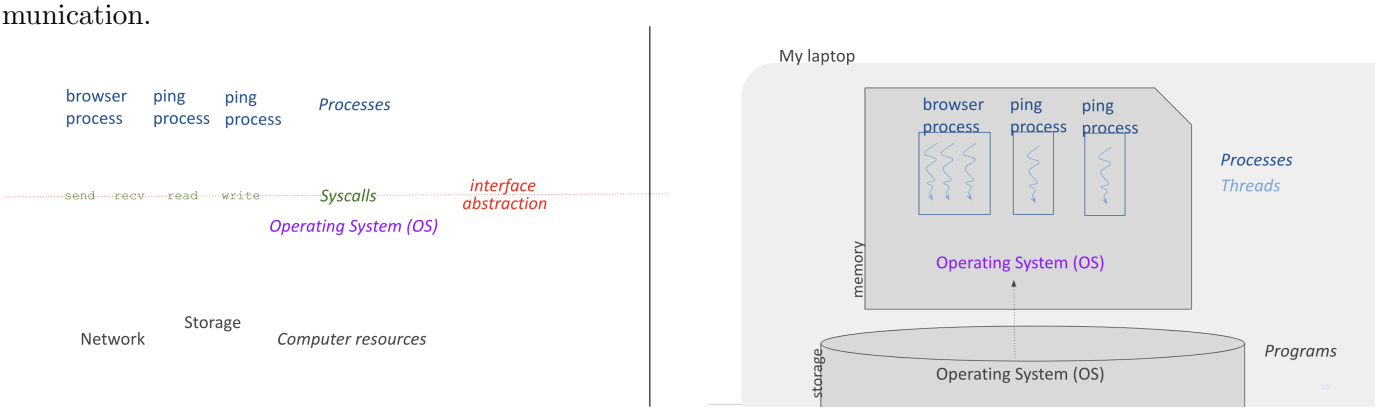
1.1.6 System Calls (Syscalls)

Syscalls form the interface between a process and external resources (like network and storage). They provide an abstraction of these resources, allowing a process to use them without knowing their intricate details. For example, when a process makes a syscall such as `send` or `recv`, the operating system's network stack handles the details of the communication.



1.2 The Operating System

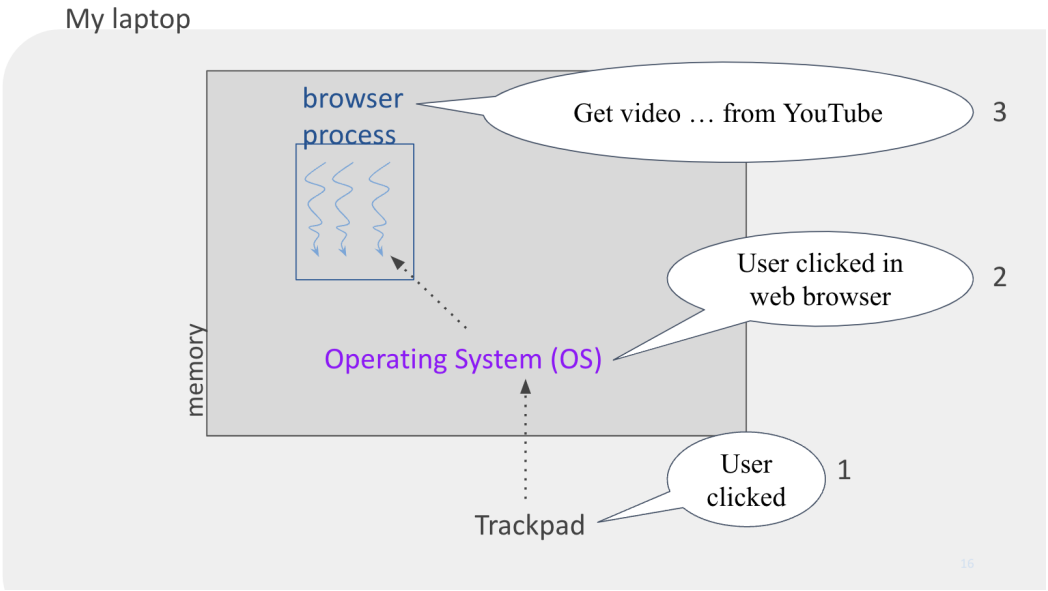
Conceptually, the OS sits between running processes and the underlying hardware resources. It provides the syscall interface and handles tasks such as file system management and network communication.



1.2.1 Example: Execution When Fetching a Video from YouTube

When you click a YouTube link, the following sequence of events occurs:

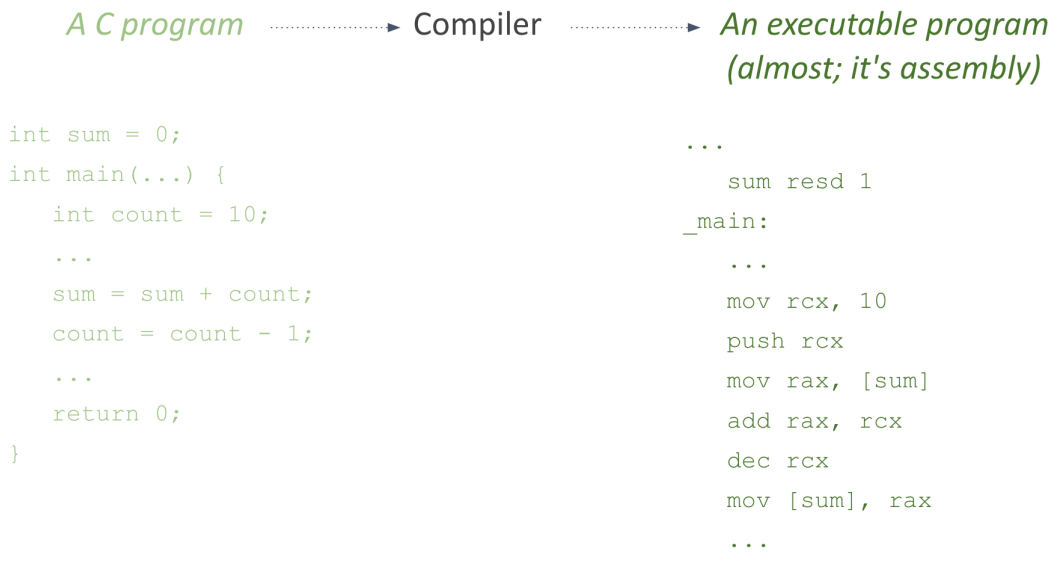
1. Your trackpad detects the click and notifies the OS.
2. The OS identifies that the click occurred within the web browser window and alerts the corresponding process.
3. The browser process initiates a chain of events that eventually fetches and displays the video.



1.3 Definition: Program and ISA

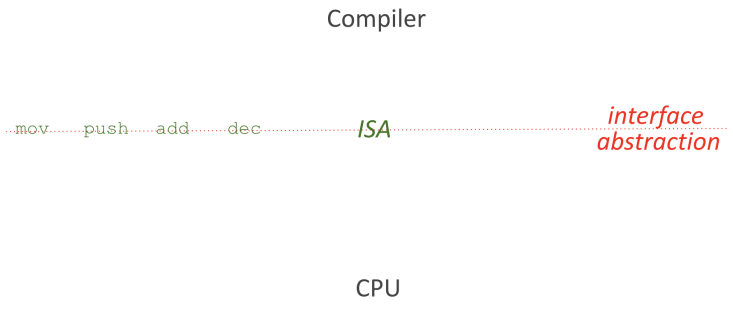
1.3.1 Program

A **program** is a set of instructions written by a human in a high-level programming language (such as C, Java, or Python) that implements an algorithm. When compiled, a program is translated into an *executable* (or binary) that the CPU can run. The executable is expressed in the language defined by the computer's **Instruction Set Architecture** (ISA).



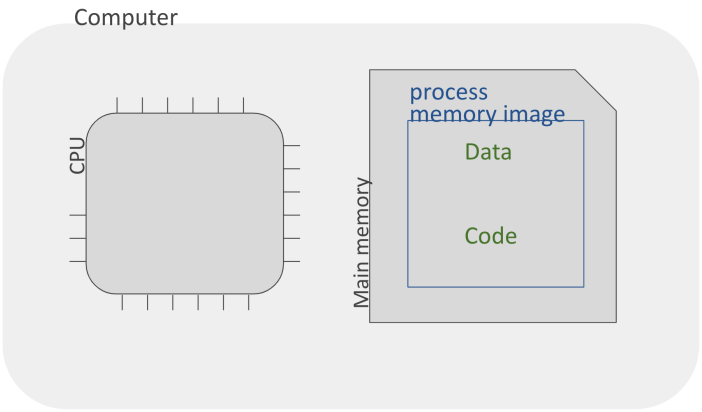
1.3.2 Definition: Instruction Set Architecture (ISA)

Definition 1.3.1 (ISA)**.** The **Instruction Set Architecture** (ISA) is the set of all instructions that a CPU can understand and execute. It forms an interface between the compiler (which translates high-level code into machine code) and the CPU.



1.3.3 Definition: The Von Neumann Architecture

The vast majority of computers today follow the **Von Neumann architecture**, which is characterized by a single main memory that holds both data and instructions.



The Von Neumann architecture

1.4 Definition: CPU Frequency

A CPU's frequency indicates how many cycles it can perform in one second. For example, a 4.05 GHz CPU performs 4.05 billion cycles per second. In this context, a **cycle** is the minimum time needed for the CPU to complete an operation or for a result to become ready.

Question: What is the meaning of the Hz metric?

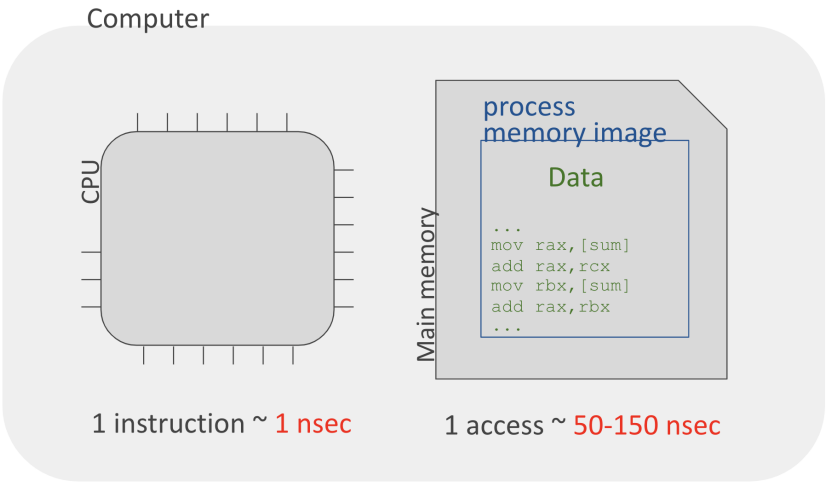
Answer: Hertz (Hz) measures the number of cycles per second.

Question: In the context of a CPU, what is a cycle?

Answer: A cycle is the minimum unit of time required for the CPU to produce a result from executing an instruction.

1.5 Frequency Imbalance and CPU Caching

Modern systems exhibit a *frequency imbalance* between the CPU and main memory. While the CPU might complete an instruction in approximately 1 nsec, accessing data from DRAM typically takes 50–150 nsec. As a result, the CPU can spend a significant amount of time idle, waiting for data.

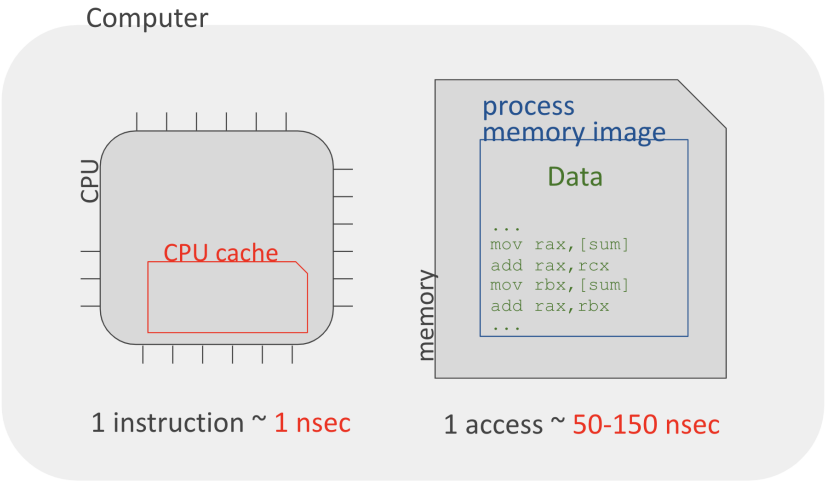


Question: How can we improve the efficiency of a system with such a frequency imbalance?

Answer: We can improve efficiency by using caching. A small, fast memory (the CPU cache) stores recently accessed data so that subsequent accesses are much faster.

1.5.1 CPU Caching

CPU caching adds a small amount of high-speed memory inside the CPU. When data is requested, the cache is checked first. If the data is already in the cache (a cache hit), the CPU retrieves it quickly. Otherwise (a cache miss), the data is fetched from the slower main memory and stored in the cache for future accesses.



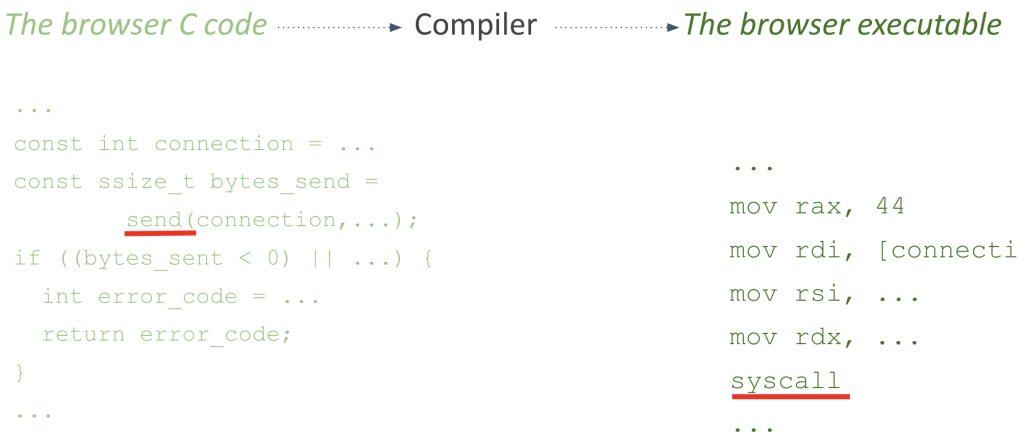
1.6 Memory Accesses vs. I/O

1.6.1 Memory Accesses

When a process reads or writes data in main memory, it uses fast CPU instructions (load/store). These operations are efficient and do not interrupt the normal flow of the process.

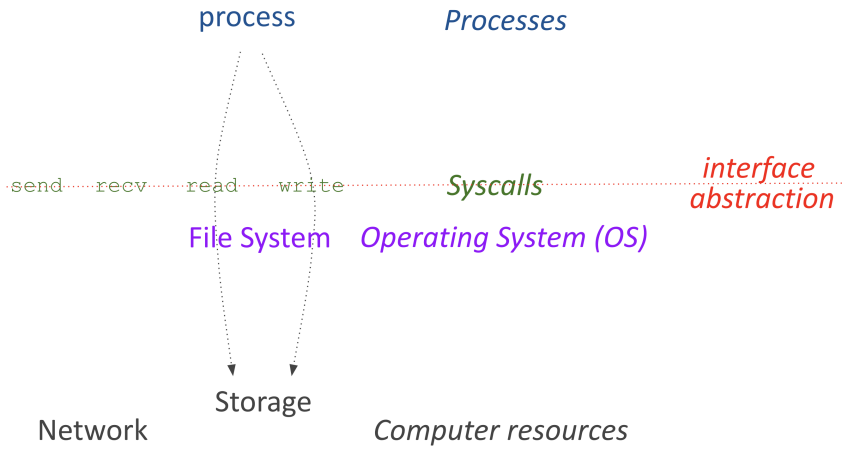
1.6.2 Back to YouTube Fetching: System Calls in Action

Returning to our YouTube example, when the browser process calls a `send` syscall to request a video, the CPU stops executing the browser's code and switches to executing the more privileged code in the OS. This is because accessing external resources (network or storage) requires a syscall.



1.6.3 Mixing Interfaces

When a process makes a syscall for network communication (such as `send` or `recv`), the CPU transitions from running the process's code to running the OS code associated with the network stack. This is an example of mixing different interfaces: the process interface (its own code) and the OS interface (syscalls).



1.6.4 Definition: Memory Access vs. I/O

Definition 1.6.1 (Memory Access and I/O)**. Memory Access** refers to the CPU's direct read/write operations using load/store instructions in main memory. In contrast, **I/O (Input/Output)** involves accessing external devices (such as storage or network) via system calls. I/O operations are generally more expensive because they require the CPU to switch context to execute privileged OS code.

Exam Question: How is reading from main memory different from reading from storage or the network?

Answer: Reading from main memory uses direct CPU instructions (load/store) and is very fast (tens to hundreds of nanoseconds), whereas reading from storage or the network requires a syscall, which interrupts the process and involves additional overhead (microseconds to milliseconds).

1.6.5 Definition: I/O

Definition 1.6.2 (I/O)**. I/O** (Input/Output) refers to operations that allow a process to access resources outside of its immediate control, such as storage devices or the network, via system calls. I/O operations are generally slower than direct memory accesses.

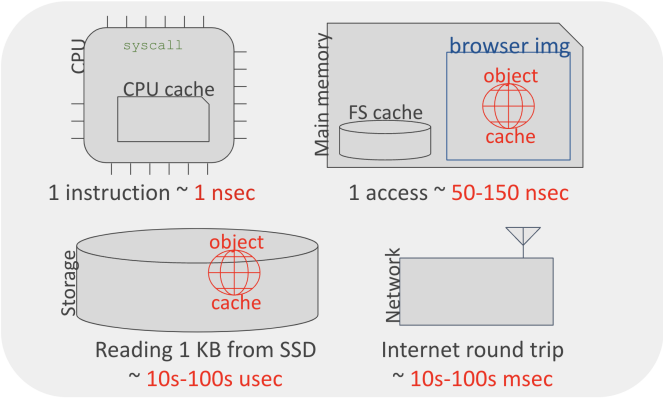
Exam Question: If a program does not create or manipulate any data, will executing this program require reading anything from memory?

Answer: Yes, executing the program will still require reading something from memory. Even if the program does not create or manipulate any data, the CPU must at least fetch the instructions of the program itself from memory

1.7 Communication Over the Internet

Internet communication involves transferring data over a network where different latencies are encountered:

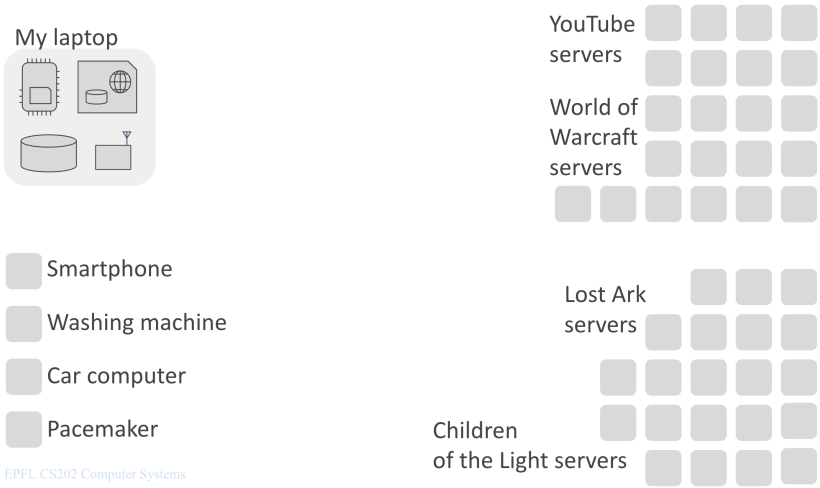
- Simple CPU instructions: ∼1 nsec.
- Main memory accesses: tens to hundreds of nanoseconds.
- Reading 1 KB from an SSD: tens to hundreds of microseconds.
- Requesting data over the Internet: several to hundreds of milliseconds.



These delays make network communication expensive in terms of time, which is why caching is critical.

1.7.1 End Systems

The Internet is composed of **end systems**—devices that use the network for communication. These include laptops, smartphones, household appliances, connected cars, and even medical devices, as well as large cloud servers.

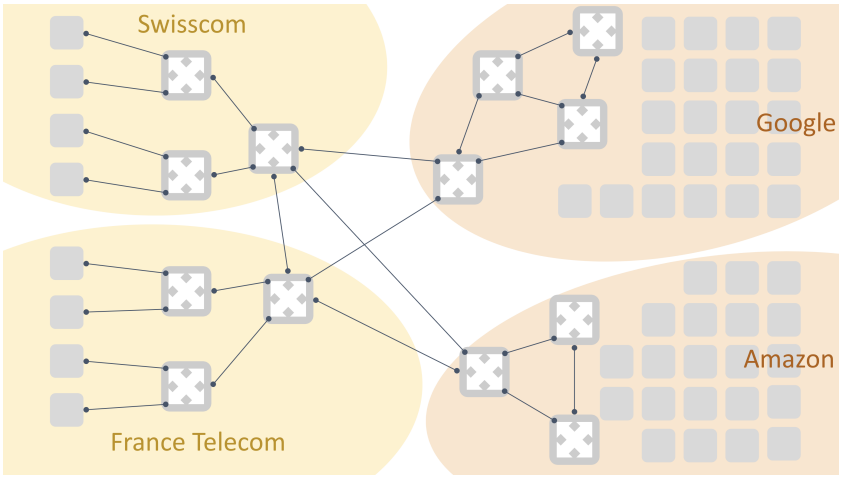


1.7.2 Packet Switches and Network Links

In addition to end systems, the Internet relies on:

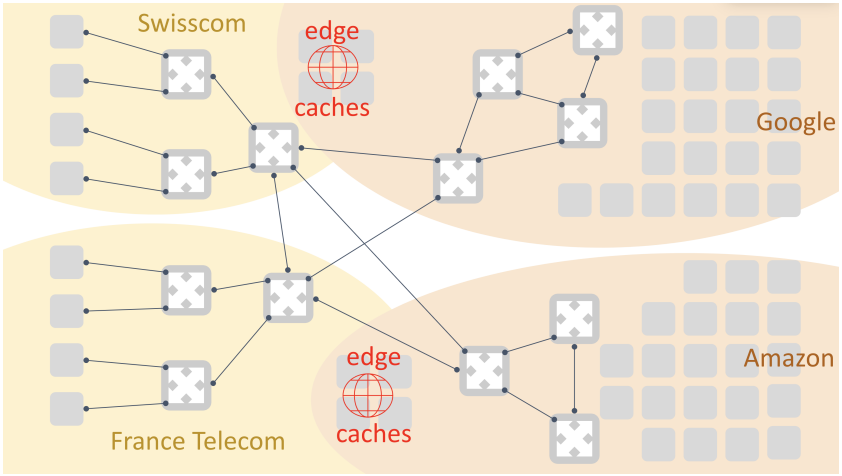
- **Packet Switches**: Devices that route data between end systems.
- **Network Links**: Physical connections that interconnect packet switches and end systems.

These components are managed by Internet Service Providers (ISPs) as well as major cloud providers.



1.7.3 Edge Caches

To reduce the load on cloud data centers and improve user performance, large cloud providers often deploy **edge caches** within ISP networks. These caches store frequently accessed content closer to the end-users, reducing latency and network traffic.

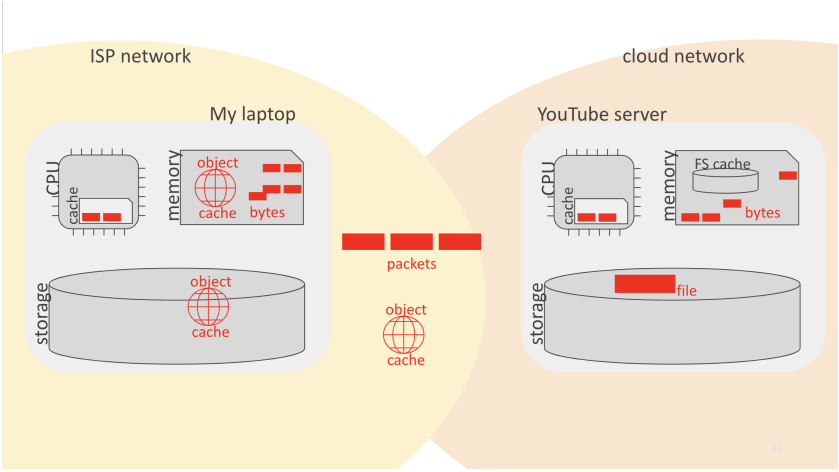


1.8 Summary

In this lecture, we traced the journey of a YouTube video and introduced several fundamental concepts:

- **Programs, Processes, and Threads:** Programs stored on disk become processes (and threads) when executed.
- **Distributed Applications:** Different processes communicate over networks using well-defined communication protocols.

- **Interfaces and Abstractions:** System calls, APIs, and caching abstract the complexity of hardware resources.
- **The Operating System:** Acts as an intermediary between processes and hardware resources.
- **Performance Considerations:** Frequency imbalances between the CPU and memory are mitigated by caching at various levels (CPU cache, file system cache, object caches).



This lecture lays the foundation for understanding how low-level system components interact to support both local and distributed applications. In subsequent lectures, we will delve deeper into topics such as process management, communication protocols, and more advanced aspects of operating systems.

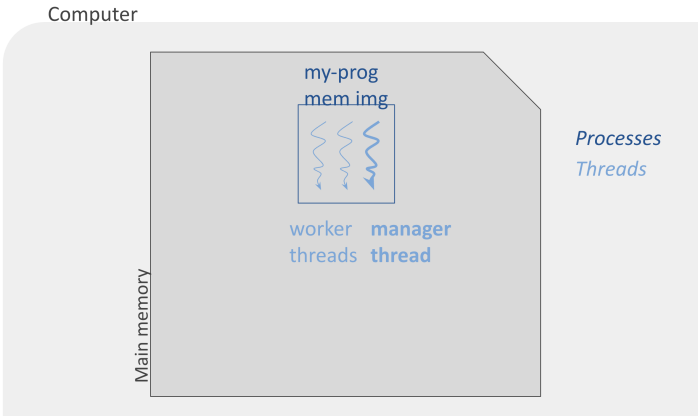
Chapter 2

L2 - All About Processes

This chapter provides an overview of the fundamental concepts underlying modern process management and memory organization in computer systems. We discuss multithreading, CPU registers, the role of compilers, and memory organization—including both stack and heap memory—as well as virtualization techniques that allow multiple processes to coexist seamlessly.

2.1 Multithreading

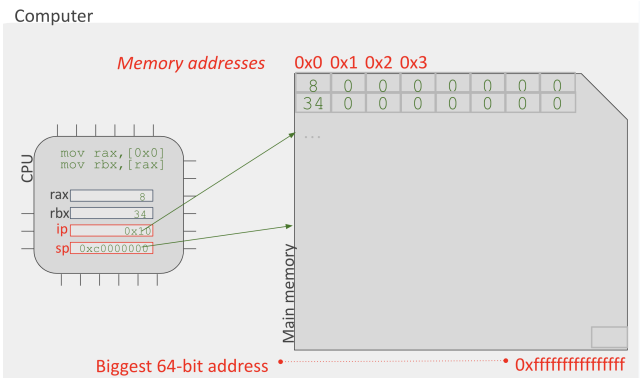
When a program runs, the processor loads it into main memory and creates a thread. In a multithreaded program, there is typically one *manager* thread that delegates work to several *worker* threads. For instance, when computing the sum of a large set of numbers, the workload can be divided into subsets, with each worker thread processing a portion of the data while the manager coordinates the overall computation.



2.2 Registers

CPU registers are small storage locations within the processor that hold data and instructions needed during execution. For example, the `mov` instruction might transfer data from one register (or memory location) to another. Key registers include:

- **Instruction Pointer (IP):** Keeps track of the next instruction to be executed.
- **Stack Pointer (SP):** Points to the current top of the stack in main memory.



Definition 2.2.1 (Compiler)**.** A compiler translates high-level source code (such as C) into low-level executable code (often Assembly language). This translation involves parsing, optimization, and the generation of machine-specific instructions.

2.3 Memory Organization

I'll go a little bit deeper for our fellow syscoms, I also recommend understanding how LIFO works before reading this, if you're too lazy for that, it's basically in the name Last In First Out, means that the last item pushed onto the stack is the first one to be removed, just like stacking plates— you take the top plate first before reaching the ones below.
In modern computer architectures, a process's memory is divided into several distinct segments, each serving a specific role during program execution. Understanding these segments is fundamental for effective programming and debugging. The primary segments include:

Definition 2.3.1 (Memory Segments)**.** A process's memory image is typically divided into the following segments:

- **Text Segment:** Contains the executable code and embedded constants. It is usually marked as read-only to prevent accidental modification.
- **Data Segment:** Stores global and static variables. This segment is often subdivided into:
  - **Initialized Data:** Variables explicitly initialized by the programmer.
  - **Uninitialized Data (BSS):** Variables that are declared but not explicitly initialized, and are set to zero by default.
- **Heap Segment:** Used for dynamic memory allocation. Memory here is allocated and deallocated during runtime by the programmer (or automatically via garbage collection in some languages). The heap typically grows upward (from lower to higher memory addresses).
- **Stack:** Manages function calls, local variables, and function parameters. The stack is automatically managed by the CPU, growing downward (from higher to lower memory addresses) as functions are called.

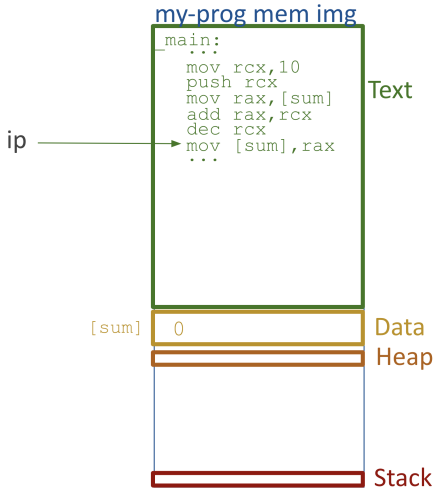
2.3.1 The Stack

The stack is a dedicated region of memory that the CPU uses to manage function calls and local variables. When a function is invoked:

1. The CPU executes a `call` instruction, which pushes the return address onto the stack.
2. A new *stack frame* is created to store local variables and function-specific data.
3. Upon function return, the stack frame is removed (or "unwound"), and control returns to the calling function.

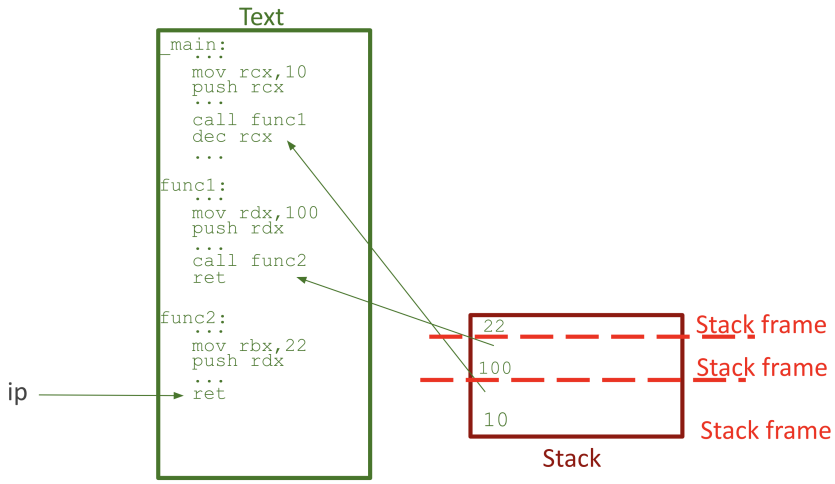
Key Characteristics of the Stack:

- **Automatic Management:** The CPU automatically handles pushing and popping of data.
- **Growth Direction:** Grows downward, from higher to lower memory addresses.
- **Contents:** Stores return addresses, local variables, and sometimes function arguments.



Stack Frames

Each function call creates its own *stack frame*, a self-contained section that isolates the function's local data. This segmentation helps maintain the correct scope and lifetime for local variables and ensures that return addresses are preserved. The following diagram illustrates the organization of stack frames during nested function calls:



2.3.2 Heap Memory

The heap is used for dynamic memory allocation, where memory is allocated and deallocated as needed during runtime. Unlike the stack:

- **Manual vs. Automatic Management:** In languages such as C or C++, the programmer is responsible for explicitly allocating (using `malloc` or `new`) and deallocating (using `free` or `delete`) heap memory. In contrast, some modern languages employ automatic garbage collection.
- **Growth Direction:** The heap typically grows upward, from lower to higher memory addresses.
- **Lifetime:** Data allocated on the heap persists beyond the scope of the function that created it, until it is explicitly freed or garbage collected.

2.3.3 Data and Text Segments

Text Segment: This segment contains the program's executable code and constant values. Its read-only nature helps prevent inadvertent modifications during execution. **Data Segment:** This segment holds global and static variables. It is divided into:

- **Initialized Data:** Variables that have been assigned an initial value at compile time.
- **Uninitialized Data (BSS):** Variables that are declared but not explicitly initialized; these are automatically set to zero at program startup.

2.3.4 Important Registers

Definition 2.3.2 (CPU Registers)**.** Two registers are critical for process execution:

- **Instruction Pointer (IP):** Points to the next instruction in the text segment.
- **Stack Pointer (SP):** Points to the top of the stack.

2.3.5 Process and Thread Identifiers

Definition 2.3.3 (Process and Thread Identifiers)**.**

- **Process ID (PID):** A unique identifier assigned to each process.
- **Thread ID (TID):** A unique identifier for each thread, which may be unique within a process or across the entire system, depending on the operating system.

Process/Thread Status

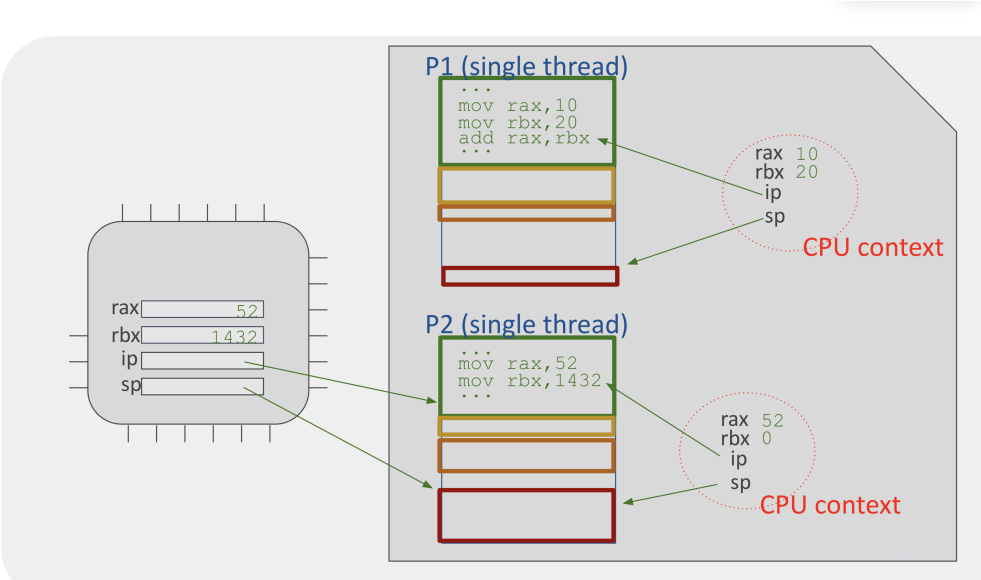
A process is considered to be *running* if at least one of its threads is executing; otherwise, it is not running.

Definition 2.3.4 (Resource Sharing)**.** Processes and threads share system resources such as CPU and memory. Each thread is given the illusion of having exclusive access to the CPU, and each process appears to have dedicated memory, even though these resources are actually shared.

Definition 2.3.5 (CPU Sharing)**.** The CPU is time-shared among multiple threads. This virtualization is achieved through context switching, where the CPU rapidly switches between threads, giving each one the impression of exclusive use of the processor.

Example: Two Programs Running on a Single Core

Example 2.3.1. Consider two programs running on a single-core processor. Each program is assigned a CPU context, which includes register values such as `rax`, `rbx`, the stack pointer (SP), and the instruction pointer (IP). When switching between programs, the CPU saves the current context to memory and loads the context of the next program, allowing the programs to resume correctly.



2.3.6 Thread's CPU Context

Definition 2.3.6 (Thread's CPU Context)**.** A thread's CPU context comprises the values of all CPU registers at the moment it was last executing. In a single-threaded process, this context represents the entire process state.

2.3.7 Context Switching

Definition 2.3.7 (Context Switching)**.** Context switching is the process by which the CPU switches from executing one thread to another. It involves:

1. Saving the current thread's CPU context to memory.
2. Restoring the CPU context of the thread to be executed next.

This mechanism enables CPU virtualization but introduces performance overhead due to additional memory accesses.

2.3.8 Definition of a Process

Definition 2.3.8 (Process)**.** A process is defined by:

- A unique Process ID (PID).
- A memory image that includes the text, data, heap, and stack segments.
- The CPU contexts of each thread within the process.
- Associated resources such as file descriptors.

2.3.9 Memory Sharing and Virtualization

Definition 2.3.9 (Memory Sharing)**.** Memory in a system is space-shared among processes; however, virtualization ensures that each process operates within its own isolated address space. This is achieved through virtual-to-physical address translation.

2.3.10 Virtual and Physical Addresses

Virtual addresses allow processes to operate as if they have exclusive access to memory. For example, two processes might both use the virtual address `0x400000`; however, these addresses map to different physical addresses:

- Process P_1: Virtual `0x400000` $\rightarrow$ Physical `0x1234AFF8`
- Process P_2: Virtual `0x400000` $\rightarrow$ Physical `0xABCD5678`

2.3.11 Process Virtual Address Space and Address Translation

Definition 2.3.10 (Virtual Address Space)**.** Each process is allocated its own virtual address space, which is shared among all its threads. This abstraction allows developers to ignore the complexities of physical memory allocation.

Address Translation

Definition 2.3.11 (Address Translation)**.** Address translation is the process by which a virtual memory address is converted into a physical memory address. While essential for memory virtualization, this translation incurs a performance cost.

2.3.12 Summary: CPU and Memory Virtualization

- **CPU Virtualization:** Threads time-share the CPU through context switching, which gives each thread the illusion of exclusive CPU access.
- **Memory Virtualization:** Processes space-share memory via virtual-to-physical address translation, ensuring that each process operates in its own isolated address space.

2.3.13 Conclusion

Modern operating systems are designed to enable multiple programs to share CPU and memory resources seamlessly. Through context switching and address translation, both the CPU and memory are effectively virtualized. This abstraction simplifies development, as compilers and developers can design programs without needing to manage these low-level resource-sharing details directly.